REVIEW OF PARTICLE PHYSICS*

Particle Data Group

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Abstract

This biennial review summarizes much of Particle Physics. Using data from previous editions, plus 1900 new measurements from 700 papers, we list, evaluate, and average measured properties of gauge bosons, leptons, quarks, mesons, and baryons. We also summarize searches for hypothetical particles such as Higgs bosons, heavy neutrinos, and supersymmetric particles. All the particle properties and search limits are listed in Summary Tables. We also give numerous tables, figures, formulae, and reviews of topics such as the Standard Model, particle detectors, probability, and statistics. A booklet is available containing the Summary Tables and abbreviated versions of some of the other sections of this full *Review*.

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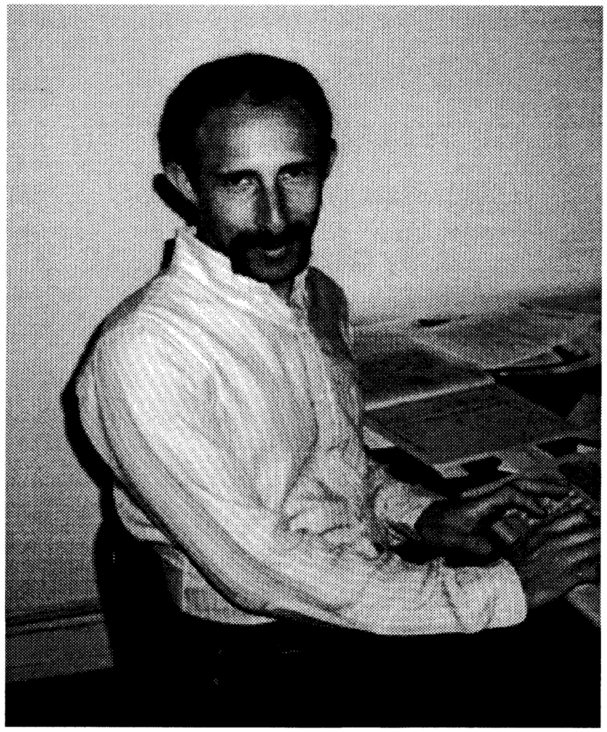
†In memoriam: Gary S. Wagman, 1954–1995



Gary Wagman, Programmer for the Particle Data Group from 1985 to 1995, died of AIDS on Friday, April 21, 1995. Gary, a respected member of the gay community, was a native of Houston, Texas, and graduated from the University of Houston in Computer Science.

Gary made many contributions to the Particle Data Group, and thus to the entire international high-energy physics community. He did much of the intricate design and all of the advanced programming that brought the *Review of Particle Physics* from its primitive state in 1984 to the beautiful and valuable document it is today, in both its printed and electronic forms. He was recognized a few months before his death with a Lawrence Berkeley Laboratory Outstanding Performance Award for these achievements. Gary's work was characterized by his constant striving for perfection, by his deep concern for accuracy, and by his understanding of our scientific mission.

In addition to his work as a programmer, Gary loved to travel. He was intrigued by exotic and magical places, visiting the pyramids in Egypt and the Taj Mahal in India. Europe was another favorite destination where he enjoyed speaking French. Gary traveled to Israel several times, once spending six months on a kibbutz picking grapefruit. An avid hiker and camper, he also explored many parts the United States.

Gary's meticulous nature led him to excel at woodworking, and he spent several years remodeling his house in San Francisco. A member of the Dahlia Society, he further enhanced his home and garden through his love of flowers. He was also a connoisseur of fine food, eating, and baking, delighting the PDG with many wonderful birthday cakes.

Always interested in spirituality and mysticism, Gary had recently begun studying Sufism. This spiritual practice was so meaningful to him that, in December 1995, he insisted on participating in a Sufi turning exhibition even though he was very ill.

In October 1995, a memorial service was held for Gary at the Pinnacles National Monument in California, one of his favorite spiritual places.

Gary was our friend and colleague for ten years, and all of us who had the privilege of knowing him miss him greatly.

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PARTICLE LISTINGS*

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*The colored divider sheets give more detailed indices for each main section of the Particle Listings.

INTRODUCTION

ONLINE PARTICLE PHYSICS INFORMATION

INTRODUCTION

1. Overview

The *Review of Particle Physics* and the abbreviated version, the *Particle Physics Booklet,* are reviews of the field of Particle Physics. This complete *Review* includes a compilation/evaluation of data on particle properties, called the "Particle Listings." These Listings include 1900 new measurements from 700 papers, in addition to the 14,000 measurements from 4000 papers that first appeared in previous editions.

Both books include Summary Tables with our best values and limits for particle properties such as masses, widths or lifetimes, and branching fractions, as well as an extensive summary of searches for hypothetical particles. In addition, we give a long section of "Reviews, Tables, and Plots" on a wide variety of theoretical and experimental topics, a quick reference for the practicing particle physicist.

The *Review* and the *Booklet* are published in even-numbered years. This edition is an updating through December 1995 (and, in some areas, well into 1996). As described in the section "Using Particle Physics Databases" following this introduction, the content of this *Review* is available on the World-Wide Web, and is updated between printed editions (`http://pdg.lbl.gov/`).

The Summary Tables give our best values of the properties of the particles we consider to be well established, a summary of search limits for hypothetical particles, and a summary of experimental tests of conservation laws.

The Particle Listings contain all the data used to get the values given in the Summary Tables. Other measurements considered recent enough or important enough to mention, but which for one reason or another are not used to get the best values, appear separately just beneath the data we do use for the Summary Tables. The Particle Listings also give information on unconfirmed particles and on particle searches, as well as short "reviews" on subjects of particular interest or controversy.

The Particle Listings were once an archive of all published data on particle properties. This is no longer possible because of the large quantity of data. We refer interested readers to earlier editions for data now considered to be obsolete.

We organize the particles into six categories:

- Gauge and Higgs bosons
- Leptons
- Quarks
- Mesons
- Baryons
- Searches for monopoles, supersymmetry, compositeness, *etc.*

The last category only includes searches for particles that do not belong to the previous groups; searches for heavy charged leptons and massive neutrinos, by contrast, are with the leptons.

In Sec. 2 of this Introduction, we list the main areas of responsibility of the authors, and also list our large number of consultants, without whom we would not have been able to produce this *Review.* In Sec. 3, we mention briefly the naming scheme for hadrons. In Sec. 4, we discuss our procedures for choosing among measurements of particle properties and for obtaining best values of the properties from the measurements.

The accuracy and usefulness of this *Review* depend in large part on interaction between its users and the authors. We appreciate comments, criticisms, and suggestions for improvements of any kind. Please send them to the appropriate author, according to the list of responsibilities in Sec. 2 below, or to the LBNL addresses below.

To order a copy of the *Review* or the *Particle Physics Booklet* from North and South America, Australia, and the Far East, write to

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3. Naming scheme for hadrons

We introduced in the 1986 edition [2] a new naming scheme for the hadrons. Changes from older terminology affected mainly the heavier mesons made of u, d, and s quarks. Otherwise, the only important change to known hadrons was that the $F^{\pm}$ became the $D_s^{\pm}$. None of the lightest pseudoscalar or vector mesons changed names, nor did the $c\bar{c}$ or $b\bar{b}$ mesons (we do, however, now use χ_c for the $c\bar{c}$ χ states), nor did any of the established baryons. The Summary Tables give both the new and old names whenever a change has occurred.

The scheme is described in "Naming Scheme for Hadrons" (p. 76) of this *Review*.

We give here our conventions on type-setting style. Particle symbols are italic (or slanted) characters: e^-, p, Λ, π^0, K_L, D_s^+, b. Charge is indicated by a superscript: B^-, Δ^{++}. Charge is not normally indicated for p, n, or the quarks, and is optional for neutral isosinglets: η or η^0. Antiparticles and particles are distinguished by charge for charged leptons and mesons: τ^+, K^-. Otherwise, distinct antiparticles are indicated by a bar (overline): $\overline{\nu}_\mu$, $\overline{t}$, $\overline{p}$, $\overline{K}^0$, and $\overline{\Sigma}^+$ (the antiparticle of the Σ^-).

4. Procedures

4.1. ***Selection and treatment of data:*** The Particle Listings contain all relevant data known to us that are published in journals. With very few exceptions, we do not include results from preprints or conference reports. Nor do we include data that are of historical importance only (the Listings are not an archival record). We search every volume of 20 journals through our cutoff date for relevant data. We also include later published papers that are sent to us by the authors (or others).

In the Particle Listings, we clearly separate measurements that are used to calculate or estimate values given in the Summary Tables from measurements that are not used. We give explanatory comments in many such cases. Among the reasons a measurement might be excluded are the following:

- It is superseded by or included in later results.
- No error is given.
- It involves assumptions we question.
- It has a poor signal-to-noise ratio, low statistical significance, or is otherwise of poorer quality than other data available.

- It is clearly inconsistent with other results that appear to be more reliable. Usually we then state the criterion, which sometimes is quite subjective, for selecting "more reliable" data for averaging. See Sec. 4.
- It is not independent of other results.
- It is not the best limit (see below).
- It is quoted from a preprint or a conference report.

In some cases, *none* of the measurements is entirely reliable and no average is calculated. For example, the masses of many of the baryon resonances, obtained from partial-wave analyses, are quoted as estimated ranges thought to probably include the true values, rather than as averages with errors. This is discussed in the Baryon Particle Listings.

For upper limits, we normally quote in the Summary Tables the strongest limit. We do not average or combine upper limits except in a very few cases where they may be re-expressed as measured numbers with Gaussian errors.

As is customary, we assume that particle and antiparticle share the same spin, mass, and mean life. The Tests of Conservation Laws table, following the Summary Tables, lists tests of CPT as well as other conservation laws.

We use the following indicators in the Particle Listings to tell how we get values from the tabulated measurements:

- OUR AVERAGE—From a weighted average of selected data.
- OUR FIT—From a constrained or overdetermined multi-parameter fit of selected data.
- OUR EVALUATION—Not from a direct measurement, but evaluated from measurements of related quantities.
- OUR ESTIMATE—Based on the observed range of the data. Not from a formal statistical procedure.
- OUR LIMIT—For special cases where the limit is evaluated by us from measured ratios or other data. Not from a direct measurement.

An experimentalist who sees indications of a particle will of course want to know what has been seen in that region in the past. Hence we include in the Particle Listings all reported states that, in our opinion, have sufficient statistical merit and that have not been disproved by more reliable data. However, we promote to the Summary Tables only those states that we feel are well established. This judgment is, of course, somewhat subjective and no precise criteria can be given. For more detailed discussions, see the minireviews in the Particle Listings.

4.2. *Averages and fits*: We divide this discussion on obtaining averages and errors into three sections: (1) treatment of errors; (2) unconstrained averaging; (3) constrained fits.

4.2.1. *Treatment of errors:* In what follows, the "error" δx means that the range $x \pm \delta x$ is intended to be a 68.3% confidence interval about the central value x. We treat this error as if it were Gaussian. Thus when the error *is* Gaussian, δx is the usual one standard deviation (1σ). Many experimenters now give statistical and systematic errors separately, in which case we usually quote both errors, with the statistical error first. For averages and fits, we then add the the two errors in quadrature and use this combined error for δx.

When experimenters quote asymmetric errors $(\delta x)^+$ and $(\delta x)^-$ for a measurement x, the error that we use for that measurement in making an average or a fit with other measurements is a continuous function of these three quantities. When the resultant average or fit $\overline{x}$ is less than $x-(\delta x)^-$, we use $(\delta x)^-$; when it is greater than $x+(\delta x)^+$, we use $(\delta x)^+$. In between, the error we use is a linear function of x. Since the errors we use are functions of the result, we iterate to get the final result. Asymmetric output errors are determined from the input errors assuming a linear relation between the input and output quantities.

In fitting or averaging, we usually do not include correlations between different measurements, but we try to select data in such a way as to reduce correlations. Correlated errors are, however, treated explicitly when there are a number of results of the form $A_i \pm \sigma_i \pm \Delta$ that have identical systematic errors Δ. In this case, one can first average the $A_i \pm \sigma_i$ and then combine the resulting statistical error with Δ. One obtains, however, the same result by averaging $A_i \pm (\sigma_i^2 + \Delta_i^2)^{1/2}$, where $\Delta_i = \sigma_i \Delta [\sum (1/\sigma_j^2)]^{1/2}$. This procedure has the advantage that, with the modified systematic errors Δ_i, each measurement may be treated as independent and averaged in the usual way with other data. Therefore, when appropriate, we adopt this procedure. We tabulate Δ and invoke an automated procedure that computes Δ_i before averaging and we include a note saying that there are common systematic errors.

Another common case of correlated errors occurs when experimenters measure two quantities and then quote the two and their difference, *e.g.*, m_1, m_2, and $\Delta = m_2 - m_1$. We cannot enter all of m_1, m_2 and Δ into a constrained fit because they are not independent. In some cases, it is a good approximation to ignore the quantity with the largest error and put the other two into the fit. However, in some cases correlations are such that the errors on m_1, m_2 and Δ are comparable and none of the three values can be ignored. In this case, we put all three values into the fit and invoke an automated procedure to increase the errors prior to fitting such that the three quantities can be treated as independent measurements in the constrained fit. We include a note saying that this has been done.

4.2.2. *Unconstrained averaging:* To average data, we use a standard weighted least-squares procedure and in some cases, discussed below, increase the errors with a "scale factor." We begin by assuming that measurements of a given quantity are uncorrelated, and calculate a weighted average and error as

$$\overline{x} \pm \delta\overline{x} = \frac{\sum_i w_i \, x_i}{\sum_i w_i} \pm \left(\textstyle\sum_i w_i\right)^{-1/2} , \tag{1}$$

where

$$w_i = 1/(\delta x_i)^2 \ .$$

Here x_i and δx_i are the value and error reported by the ith experiment, and the sums run over the N experiments. We then calculate $\chi^2 = \sum w_i(\overline{x} - x_i)^2$ and compare it with $N - 1$, which is the expectation value of χ^2 if the measurements are from a Gaussian distribution.

If $\chi^2/(N-1)$ is less than or equal to 1, and there are no known problems with the data, we accept the results.

If $\chi^2/(N-1)$ is very large, we may choose not to use the average at all. Alternatively, we may quote the calculated average, but then make an educated guess of the error, a conservative estimate designed to take into account known problems with the data.

Finally, if $\chi^2/(N-1)$ is greater than 1, but not greatly so, we still average the data, but then also do the following:

(a) We increase our quoted error, $\delta\overline{x}$ in Eq. (1), by a scale factor S defined as

$$S = \left[\chi^2/(N-1)\right]^{1/2} \ . \tag{2}$$

Our reasoning is as follows. The large value of the χ^2 is likely to be due to underestimation of errors in at least one of the experiments. Not knowing which of the errors are underestimated, we assume they are all underestimated by the same factor S. If we scale up all the input errors by this factor, the χ^2 becomes $N-1$, and of course the output error $\delta\overline{x}$ scales up by the same factor. See Ref. 3.

When combining data with widely varying errors, we modify this procedure slightly. We evaluate S using only the experiments with smaller errors. Our cutoff or ceiling on δx_i is arbitrarily chosen to be

$$\delta_0 = 3N^{1/2}\,\delta\overline{x} \ ,$$

where $\delta\overline{x}$ is the unscaled error of the mean of all the experiments. Our reasoning is that although the low-precision experiments have little influence on the values $\overline{x}$ and $\delta\overline{x}$, they can make significant contributions to the χ^2, and the contribution of the high-precision experiments thus tends to be obscured. Note that if each experiment has the same error δx_i, then $\delta\overline{x}$ is $\delta x_i/N^{1/2}$, so each δx_i is well below the cutoff. (More often, however, we simply exclude measurements with relatively large errors from averages and fits: new, precise data chase out old, imprecise data.)

Our scaling procedure has the property that if there are two values with comparable errors separated by much more than their stated errors (with or without a number of other values of lower accuracy), the scaled-up error $\delta\,\overline{x}$ is approximately half the interval between the two discrepant values.

We emphasize that our scaling procedure for *errors* in no way affects central values. And if you wish to recover the unscaled error $\delta\overline{x}$, simply divide the quoted error by S.

(b) If the number M of experiments with an error smaller than δ_0 is at least three, and if $\chi^2/(M-1)$ is greater than 1.25, we show in the Particle Listings an ideogram of the data. Fig. 1 is an example. Sometimes one or two data points lie apart from the main body; other times the data split into two or more groups. We extract no numbers from these ideograms; they are simply visual aids, which the reader may use as he or she sees fit.

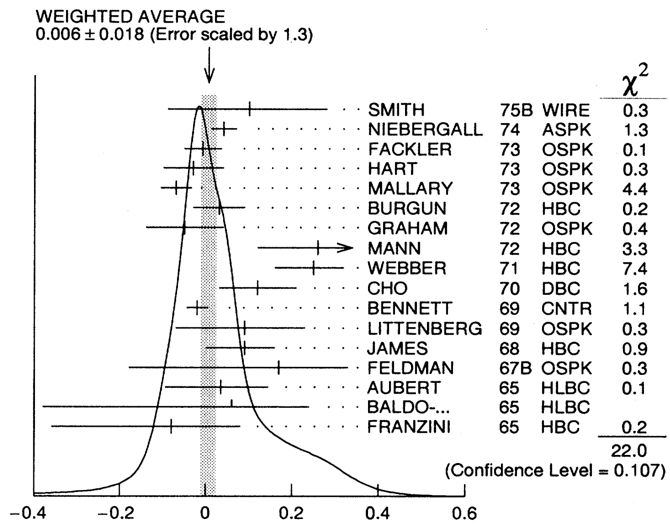

Figure 1: A typical ideogram. The arrow at the top shows the position of the weighted average, while the width of the shaded pattern shows the error in the average after scaling by the factor S. The column on the right gives the χ^2 contribution of each of the experiments. Note that the next-to-last experiment, denoted by the incomplete error flag ($\perp$), is not used in the calculation of S (see the text).

Each measurement in an ideogram is represented by a Gaussian with a central value x_i, error δx_i, and area proportional to $1/\delta x_i$. The choice of $1/\delta x_i$ for the area is somewhat arbitrary. With this choice, the center of gravity of the ideogram corresponds to an average that uses weights $1/\delta x_i$ rather than the $(1/\delta x_i)^2$ actually used in the averages. This may be appropriate when some of the experiments have seriously underestimated systematic errors. However, since for this choice of area the height of the Gaussian for each measurement is proportional to $(1/\delta\, x_i)^2$, the peak position of the ideogram will often favor the high-precision measurements at least as much as does the least-squares average. See our 1986 edition [2] for a detailed discussion of the use of ideograms.

4.2.3. *Constrained fits:* Except for trivial cases, all branching ratios and rate measurements are analyzed by making a simultaneous least-squares fit to all the data and extracting the partial decay fractions P_i, the partial widths Γ_i, the full width Γ (or mean life), and the associated error matrix.

Assume, for example, that a state has m partial decay fractions P_i, where $\sum P_i = 1$. These have been measured in N_r different ratios R_r, where, e.g., $R_1 = P_1/P_2$, $R_2 = P_1/P_3$, *etc.* [We can handle any ratio R of the form $\sum \alpha_i P_i / \sum \beta_i P_i$, where α_i and β_i are constants, usually 1 or 0. The forms $R = P_i P_j$ and $R = (P_i P_j)^{1/2}$ are also allowed.] Further assume that *each* ratio R has been measured by N_k experiments (we designate each experiment with a subscript k, e.g., R_{1k}). We then find the best values of the fractions P_i by minimizing the χ^2 as a function of the $m-1$ independent parameters:

$$\chi^2 = \sum_{r=1}^{N_r} \sum_{k=1}^{N_k} \left(\frac{R_{rk} - R_r}{\delta R_{rk}} \right)^2 , \tag{3}$$

where the R_{rk} are the measured values and R_r are the fitted values of the branching ratios.

In addition to the fitted values $\overline{P}_i$, we calculate an error matrix $\langle \delta\overline{P}_i \; \delta\overline{P}_j \rangle$. We tabulate the diagonal elements of $\delta\,\overline{P}_i = \langle \delta\,\overline{P}_i \; \delta\,\overline{P}_i \rangle^{1/2}$ (except that some errors are scaled as discussed below). In the Particle Listings, we give the complete correlation matrix; we also calculate the fitted value of each ratio, for comparison with the input data, and list it above the relevant input, along with a simple unconstrained average of the same input.

Three comments on the example above:

(1) There was no connection assumed between measurements of the full width and the branching ratios. But often we also have information on partial widths Γ_i as well as the total width Γ. In this case we must introduce Γ as a parameter in the fit, along with the P_i, and we give correlation matrices for the widths in the Particle Listings.

(2) We do *not* allow for correlations between input data. We *do* try to pick those ratios and widths that are as independent and as close to the original data as possible. When one experiment measures all the branching fractions and constrains their sum to be one, we leave one of them (usually the least well-determined one) out of the fit to make the set of input data more nearly independent.

(3) We calculate scale factors for both the R_r and P_i when the measurements for any R give a larger-than-expected contribution to the χ^2. According to Eq. (3), the double sum for χ^2 is first summed over experiments $k = 1$ to N_k, leaving a single sum over ratios $\chi^2 = \sum \chi_r^2$. One is tempted to define a scale factor for the ratio r as $S_r^2 = \chi_r^2 / \langle \chi_r^2 \rangle$. However, since $\langle \chi_r^2 \rangle$ is not a fixed quantity (it is somewhere between N_k and N_{k-1}), we do not know how to evaluate this expression. Instead we define

$$S_r^2 = \frac{1}{N_k} \sum_{k=1}^{N_k} \frac{\left(R_{rk} - \overline{R}_r\right)^2}{(\delta R_{rk})^2 - (\delta \overline{R}_r)^2} , \tag{4}$$

where $\delta\overline{R}_r$ is the fitted error for ratio r. With this definition the expected value of S_r^2 is one.

The fit is redone using errors for the branching ratios that are scaled by the larger of S_r and unity, from which new and often larger errors $\delta\overline{P}_i'$ are obtained. The scale factors we finally list in such cases are defined by $S_i = \delta\overline{P}_i' / \delta\overline{P}_i$. However, in line with our policy of not letting S affect the central values, we give the values of $\overline{P}_i$ obtained from the original (unscaled) fit.

There is one special case in which the errors that are obtained by the preceding procedure may be changed. When a fitted branching ratio (or rate) $\overline{P}_i$ turns out to be less than three standard deviations ($\delta\overline{P}_i'$) from zero, a new smaller error $(\delta\overline{P}_i'')^-$ is calculated on the low side by requiring the area under the Gaussian between $\overline{P}_i - (\delta\,\overline{P}_i'')^-$ and $\overline{P}_i$ to be 68.3% of the area between zero and $\overline{P}_i$. A similar correction is made for branching fractions that are within three standard deviations of one. This keeps the quoted errors from overlapping the boundary of the physical region.

4.3. ***Discussion***: The problem of averaging data containing discrepant values is nicely discussed by Taylor in Ref. 4. He considers a number of algorithms that attempt to incorporate inconsistent data into a meaningful average. However, it is difficult to develop a procedure that handles simultaneously in a reasonable way two basic types of situations: (a) data that lie apart from the main body of the data are incorrect (contain unreported errors); and (b) the opposite—it is the main body of data that is incorrect. Unfortunately, as Taylor shows, case (b) is not infrequent. He concludes that the choice of procedure is less significant than the initial choice of data to include or exclude.

We place much emphasis on this choice of data. Often we solicit the help of outside experts (consultants). Sometimes, however, it is simply impossible to determine which of a set of discrepant measurements are correct. Our scale-factor technique is an attempt to address this ignorance by increasing the error. In effect, we are saying that present experiments do not allow a precise determination of this quantity because of unresolvable discrepancies, and one must await further measurements. The reader is warned of this situation by the size of the scale factor, and if he or she desires can go back to the literature (via the Particle Listings) and redo the average with a different choice of data.

Our situation is less severe than most of the cases Taylor considers, such as estimates of the fundamental constants like $\hbar$, *etc.* Most of the errors in his case are dominated by systematic effects. For our data, statistical errors are often at least as large as systematic errors, and statistical errors are usually easier to estimate. A notable exception occurs in partial-wave analyses, where different techniques applied to the same data yield different results. In this case, as stated earlier, we often do not make an average but just quote a range of values.

A brief history of early Particle Data Group averages is given in Ref. 3. Figure 0.2 shows some histories of our values of a few particle properties. Sometimes large changes occur. These usually reflect the introduction of significant new data or the discarding of older data. Older data are discarded in favor of newer data when it is felt that the newer data have smaller systematic errors, or have more checks on systematic errors, or have made corrections unknown at the time of the older experiments, or simply have much smaller errors. Sometimes, the scale factor becomes large near the time at which a large jump takes place, reflecting the uncertainty introduced by the new and inconsistent data.

By and large, however, a full scan of our history plots shows a dull progression toward greater precision at central values quite consistent with the first data points shown.

We conclude that the reliability of the combination of experimental data and our averaging procedures is usually good, but it is important to be aware that fluctuations outside of the quoted errors can and do occur.

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We thank all those who have assisted in the many phases of preparing this *Review.* We particularly thank the many who have responded to our requests for verification of data entered in the Listings, and those who have made suggestions or pointed out errors. The CERN group wishes to thank Andrew Hicks for his technical help.

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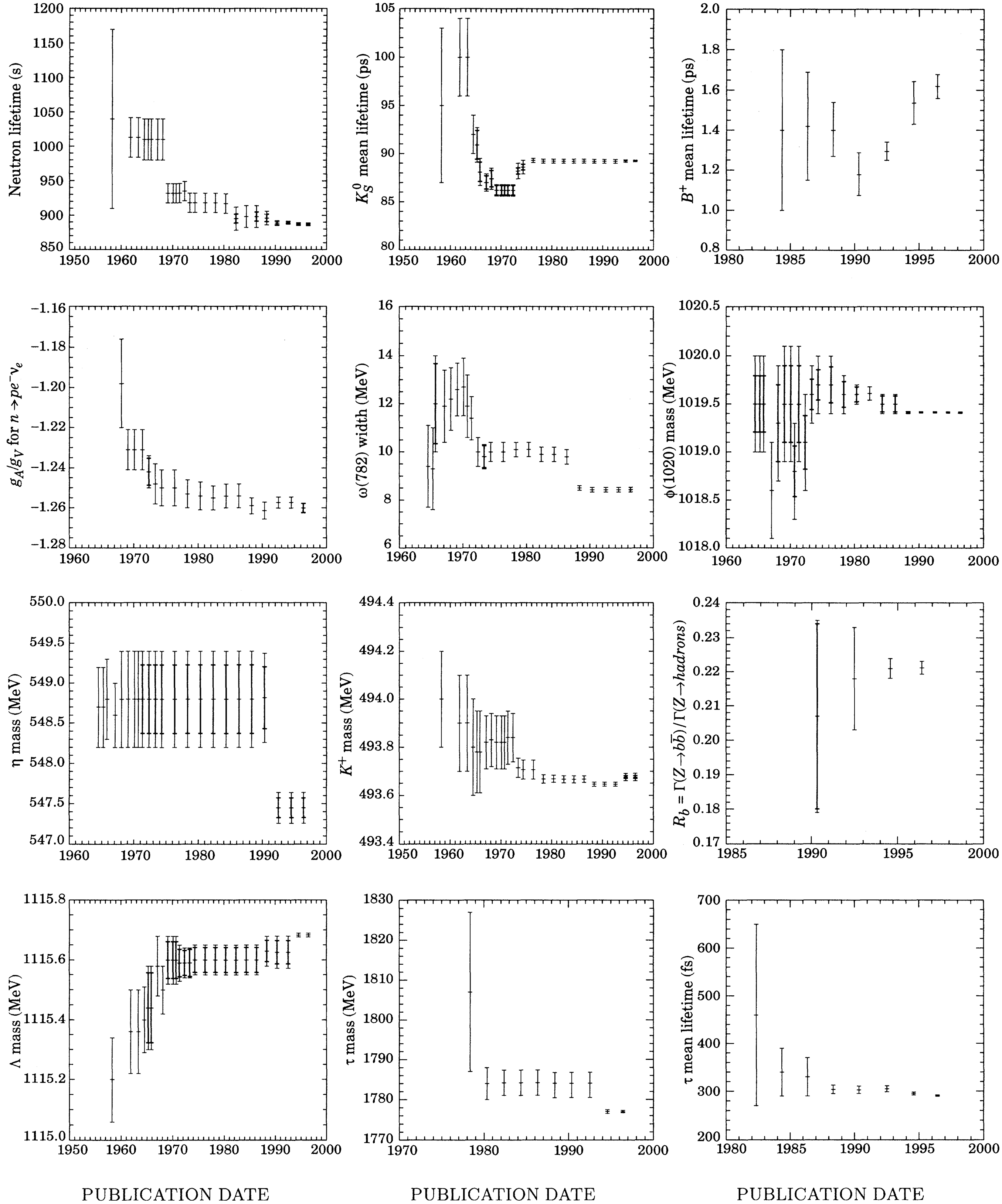

Figure 2: An historical perspective of values of a few particle properties tabulated in this *Review* as a function of date of publication of the *Review*. A full error bar indicates the quoted error; a thick-lined portion indicates the same but without the "scale factor."

Revised by P. Kreitz, May 1996

The purpose of this list is to organize a broad set of online catalogs, databases, directories, World-Wide Web (WWW) pages, *etc.*, that are of value to the particle physics physics community. While a substantial amount of particle physics physics information is computer accessible through the Internet's World-Wide Web, most listings do not provide descriptions of a resource's scope and content so that searchers know which source to use for a specific information need. This compilation lists the main information sources with brief annotations and basic Internet WWW addresses (URL's). Because this list must be fixed in print, it is important to consult the updated version of this compilation which includes newly added resources and hypertext links to more complete information at:

`http://www.slac.stanford.edu/library/pdg/hepinfo.html`

In this edition, a resource is excluded if it provides information primarily of interest to one institution. In some cases, multiple databases covering much the same material have been included with the assumption that users will make subsequent choices based on Internet speeds, search system interfaces, or differences in scope, presentation, and coverage. Databases and resources focusing primarily on accelerator physics have been excluded in deference to the excellent compilation at the World Wide Web Virtual Library of Accelerator Physics:

`http://beam.slac.stanford.edu/www/library/w3/alab.htmlx`

Please send suggestions, additions, changes, ideas for category groupings, exclusions, *etc.*, via the WWW form linked to the URL above, or by e-mail to `pkreitz@slac.stanford.edu`.

1. Particles & Properties Data:

- REVIEW OF PARTICLE PHYSICS (RPP): A comprehensive review of the field of Particle Physics produced by the Particle Data Group (PDG). Includes a compilation/evaluation of data on particle properties, summary tables with best values and limits for particle properties, extensive summaries of searches for hypothetical particles, and a long section of reviews, tables, and plots on a wide variety of theoretical and experimental topics of interest to particle and astrophysicists. The linked table of contents provides access to particle listings, reviews, summary tables, errata, indices, *etc.* The current printed version is Physical Review D54, xxx (1996). Maintained at:

  `http://pdg.lbl.gov/`

- PARTICLE PHYSICS BOOKLET: An extract from the most recent edition of the full Review of Particle Physics. Contains images in an easy-to-read print useful for classroom studies:

  `http://pdg.lbl.gov/rpp/booklet/contents.html`

- PARTICLE PROPERTIES Database: Durham/RAL provides a simple index to the PDG particle properties information contained in the Review of Particle Physics. Maintained at:

  `http://durpdg.dur.ac.uk/HEPDATA/PART`

- PARTICLE PHYSICS INTERACTIVE DATABASE: A searchable database containing information from the Review of Particle Physics. Updated around summer of every year. Available by telnet as follows:

  Telnet: `//pdg_public@muse.lbl.gov/`

  (User name `PDG_PUBLIC`, no password).

- COMPUTER-READABLE FILES: Currently available from the PDG: tables of masses, widths, and PDG Monte Carlo particle numbers and cross section data, including hadronic total and elastic cross sections vs laboratory momenta and total center-of-mass energy. Overview page at:

  `http://pdg.lbl.gov/computer_read.html`

- PARTICLE PHYSICS DATA SYSTEM: Maintained by the COMPAS group at IHEP, this system, currently under construction, provides an online version of the Guide to Experimental Elementary Particle Physics Literature (1895–1995). Permits searching by author, title, accelerator, detector, reaction, particle, *etc.* For research from 1950 to the present, it will provide online searching of compilations of integrated cross sections data and numerical data on observables in reactions. Also provides a chronology of key events in particle physics:

  `http://muse.lbl.gov:8001/ppds.html`

- REACTION DATA: A part of the HEPDATA databases at Durham/RAL, this database is a collaboration of Durham and the COMPAS Group for the PDG. Contains numerical values of cross sections, structure, functions, polarizations, *etc.*:

  `http://durpdg.dur.ac.uk/HEPDATA/REAC`

- PHYSICS AROUND THE WORLD: DATA AND TABLES: Includes links to periodic tables of elements, laws and constants, scales of measurement, particle and nuclear data, equations, and (peripheral) "more data and tables:"

  `http://www.physics.mcgill.ca:8081/`
  `physics-services/physics_tables.html`

2. Collaborations & Experiments:

- EXPERIMENTS Database: Contains more than 1,800 experiments in elementary particle physics. Search and browse by author; title; experiment number or prefix; institution; date approved, started or completed; accelerator or detector; polarization, reaction, final state or particle; or by papers produced. Maintained at SLAC for the LBNL Particle Data Group. Supplies the information for "Current Experiments in Particle Physics (LBL-91)." Updated every second year (next: Summer 1996):

  `http://www-spires.slac.stanford.edu/find/experiments`

- EXPERIMENTS ONLINE: Home Pages of HEP Experiments: A list from SLAC of accelerator and non-accelerator experiments with an active link to each home page. Accelerator experiments are organized by institution, machine, and experiment name:

  `http://www-spires.slac.stanford.edu/find/explist.html`

- HIGH ENERGY PHYSICS EXPERIMENTS: A HEPNET page providing links to HEP collaborations around the world. List arranged alphabetically by collaboration name:

  `http://www.hep.net/experiments/collabs.html`

3. Conferences:

- CONFERENCES: Contains conferences, schools, and meetings of interest to high-energy physicists. Searchable database produced jointly by the SLAC and DESY libraries of over 5,000 listings covering 1973 to 1999+. Search or browse by title, acronym, date, location. Includes links to the conference home page, information about published proceedings, links to submitted papers from the SPIRES-HEP database, and links to the electronic versions of the papers if available:

  `http://www-spires.slac.stanford.edu/`
  `spires/form/confspif.html`

- CONFERENCES, WORKSHOPS, AND SUMMER SCHOOLS: By The Internet Pilot to Physics. Several hundred listings, including those for regional meetings of national societies and meetings of ancillary groups such as physics teachers. Provides a WWW form for adding a conference, and automatically uploads new entries to the EPS EurophysNet meeting list.

  `http://www.tp.umu.se/TIPTOP/FORUM/CONF/`

- CONFNEWS: Provides listings of current and future conferences divided by subfield or by region. Also provides links to WWW conference pages and an e-mail interface (`robot@physics.umd.edu` with `CONFMENU` in the subject line):

  `http://www.physics.umd.edu/robot/confer/confmenu.html`

- EUROPHYSICS Meetings List: Meta-level list of other conference lists with active links to the URL of the organization's meeting calendar, the conference database, *etc.* Useful for searching by organization, providing access to meetings and conferences that are of interest, but not central to high-energy physics. Maintained by the European Physical Society but international in scope. Organized alphabetically by the name of the resource or organization:

  `http://epswww.epfl.ch/conf/urls.html`

- HEP EVENTS: A list maintained by CERN of upcoming conferences, schools, workshops, seminars, and symposia of interest to high-energy physics organized by type of meeting, *e.g.* school, workshop:

  `http://www.cern.ch/Physics/Conferences`

- PHYSICS CONFERENCE ANNOUNCEMENTS by Thread: Lists current year's conference announcements with links to WWW pages. Posting is voluntary, which is perhaps why this resource lacks the breadth of other databases covering conferences:

  `http://xxx.lanl.gov/Announce/Conference/`

4. Current Notices & Announcement Services:

- CONFERENCES, WORKSHOPS, AND SUMMER SCHOOLS: By The Internet Pilot to Physics. Provides a Web form for adding a conference and automatically uploads new entries to the EPS EurophysNet meeting list.

  `http://www.tp.umu.se/TIPTOP/FORUM/CONF/`

- CONFNEWS & WEBNEWS: Provides a system for broadcasting a conference or job opening to "a large number of physicists worldwide." For further information, e-mail: `kim@umdhep.umd.edu`

- E-PRINT ARCHIVES: The LANL-based E-Print Archives provides daily notices of what new high-energy physics preprints have been submitted to the archives as full text electronic documents. Use the WWW-accessible listings:

  `http://xxx.lanl.gov/`

  or subscribe:

  `http://xxx.lanl.gov/help/e-help`

  (under "Description of e-Mail Commands") to receive the automatic e-mail notices. Covers over two dozen subfields of high-energy physics, and provides active links to abstracts and full text versions of the preprints.

Note: Use the library pages below to find information on recently received books and proceedings. Use the online table of contents listings below to find journal table of contents. Conference announcements can also be sent via e-mail to most of the conference database providers listed above who often supply their e-mail address at the bottom of their Web page.

5. Directories:

5.1. *Directories – Organizations:*

- DIRECTORY OF RESEARCH INSTITUTES in High Energy Physics: Maintained by CERN and organized into three alphabetical lists by country, town, and institutional name. Provides addresses, and, where available, the following: phone and fax numbers; e-mail addresses; active URL links; and information about the institution's physics program:

  `http://preprints.cern.ch/institutes/welcome.html`

- HEP INSTITUTIONS ONLINE: Active links to the home pages of more than 200 HEP-related institutions with WWW servers. Maintained by SLAC and organized by country, and then alphabetically by institution:

  `http://www-spires.slac.stanford.edu/find/instlink.html`

- INSTITUTIONS: Database of over 5,000 high-energy physics Institutes, Laboratories, and University departments in which some research on elementary particle physics is performed. Covers six continents and almost one hundred countries, and is searchable by name, acronym, location, *etc.* Provides address, phone and fax numbers, and e-mail and URL addresses where available. Has pointers to the recent HEP papers from an institution. Maintained by SLAC:

  `http://www-spires.slac.stanford.edu/`
  `spires/form/instspif.html`

- PHYSICS: High-Energy Physics and Nuclear Physics Labs: This list of WWW home pages is usefully arranged into accelerator labs by country, research groups at universitites, and national and international institutes. The theoretical physics section is thin. Part of a larger effort maintained by Physics Around the World/TIPTOP to organize physics-related institutions by field of research:

  `http://www.physics.mcgill.ca:8081/`
  `physics-services/physics_hep_labs.html`

5.2. *Directories – People:*

- HEPNAMES: Searchable database of 25,500 e-mail addresses of people related to high-energy physics. Access by individual name, and, in the near future, by institution or place.

  `http://www-spires.slac.stanford.edu/find/hepnames`

  This site is mirrored at Durham under a different name (EMAIL-ID) and with a search interface written and maintained by Durham:

  `http://durpdg.dur.ac.uk/HEPDATA/ID`

- HEP VIRTUAL PHONEBOOK: A list of links to phonebooks and directories of high-energy physics sites around the world. Maintained by HEPNET:

  `http://www.hep.net/sites/directories.html`

5.3. *Directories – Publishers:*

- PHYSICS AROUND THE WORLD: A page of active links to institutions, societies, or companies involved in supplying physics-related information. Organized into sections, the most useful of which are: Preprint Archives, Journals, Magazines, Newsletters, Publishers, and Books:

  `http://www.physics.mcgill.ca:8081/`
  `physics-services/physics_publ2.html`

6. E-Prints/Pre-Prints, Papers & Reports:

- ALICE: The CERN Library's database which contains citations to more than 190,000 monographs, series, preprints and official committee documents held by the Library or the Archives:

  `http://wwwas.cern.ch/ASinfo/AS-SI/alice/ALICE.html`

Also provides links to CERN's full text preprint server:

  `http://preprints.cern.ch/` .

- HEP DATABASE (SLAC/SPIRES): Contains over 300,000 bibliographic summaries for particle physics papers (e-prints, journal articles, preprints, reports, theses, *etc.*). Covers 1974 to the present and is updated daily with links to electronic texts (*e.g.* from LANL, CERN, KEK, and other HEP servers). Searchable by all authors and authors' affiliations, title, topic, report number, citation, e-print archive number, date, *etc*: A joint project of the SLAC and DESY libraries with the collaboration of many other institutions including APS, Fermilab, and Kyoto.

  `http://www-spires.slac.stanford.edu/find/hep`

- KISS: KEK preprint database, contains bibliographic records of preprints and technical reports held in the KEK library with links to the full text images of over 90,000 items in their collection:

  `http://keklib.kek.jp/KISS.v2/kiss_prepri.html`

- LANL E-PRINT ARCHIVES: An automated electronic repository of physics preprints, primarily in the subfields of high-energy physics, but also in other physics fields such as chemical, nuclear, condensed matter, *etc.* Began with a core set of subfield archives in 1991. Provides access to the full text of the electronic versions of these preprints, and permits searching by author, title, key word in abstract, and by limiting by subfield archive or by date. Papers are sent electronically to the archives by the author:
  `http://xxx.lanl.gov`
- DOCUMENTS: (IHEP-COMPAS/PDG) A database providing the source information for the print publication "A Guide to Experimental Elementary Particle Physics Literature" (LBL-90). Provides bibliographic summaries of experimental papers which report new experimental data and theoretical papers which extract new information from experiments. Excludes instrumentation and papers mainly of interest only to nuclear physicists. Coverage is from 1895 to the present:
  `http://muse.lbl.gov:8001/ppds.html`

7. Particle Physics Libraries & Scholarly Societies:

- American Astronomical Society:
  `http://www.aas.org/AAS-homepage.html`
- American Institute of Physics:
  `http://aip.org/`
- American Physical Society:
  `http://aps.org/`
- Argonne National Lab Library:
  `http://www.ipd.anl.gov/aim/alec/`
- Brookhaven National Lab Library:
  `http://www.bnl.gov/RESLIB/reslib.html`
- European Laboratory for Particle Physics (CERN) Library:
  `http://wwwas.cern.ch/ASinfo/AS-SI/library_home.html`
- Institute of Physics:
  `http://www.iop.org/`
- Deutsches Elektronen-Synchrotron (DESY) Library:
  `http://www.desy.de/library/homepage.html`
- European Physical Society: EurophysNet
  `http://www.nikhef.nl/www/pub/eps/eps.html`
- Fermilab Library:
  `http://fnalpubs.fnal.gov/library/welcome.html`
- Institute of Physics:
  `http://www.iop.org/`
- National Laboratory for High Energy Physics (KEK) Library:
  `http://garnet.kek.jp/libhome.html`
- Los Alamos National Laboratory Library:
  `http://lib-www.lanl.gov/`
- Stanford Linear Accelerator Center Library:
  `http://www.slac.stanford.edu/FIND/spires.html`

8. Particle Physics Journals & Reviews:

8.1. *ONLINE JOURNALS*: (Note: some of these may limit access to subscribers; check with your institution's library.)

- American Journal of Physics
  `http://www.amherst.edu/~ajp/`
- Applied Physics Letters Online
  `http://www.aip.org/epub/aplointro.html`
- Astrophysical Journal and Letters
  `http://www.aas.org/ApJ/`
- Classical and Quantum Gravity
  `http://www.ioppublishing.com/EJ/Unreg/bin/main`
- Computers in Physics
  `http://www.aip.org/cip/ciphome.html`
- European Journal of Physics
  `http://www.ioppublishing.com/EJ/Unreg/bin/main`
- Journal of Physics A
  `http://www.ioppublishing.com/EJ/Unreg/bin/main`
- Journal of Physics G
  `http://www.ioppublishing.com/EJ/Unreg/bin/main`
- Nuclear Physics A
  `http://www.nucphys.nl/www/pub/nucphys/npe.html`
- Nuclear Physics B
  `http://www.nucphys.nl/www/pub/nucphys/npe.html`
- Nuclear Physics B (Proceedings Supplements)
  `http://www.nucphys.nl/www/pub/nucphys/npe.html`
- Physical Review D (Advanced papers accepted by PRD)
  `http://publish.aps.org/PRDO/prdhm.html`
- Physical Review Letters
  `http://publish.aps.org/PRL/prlinfo.html`
- Physics Express Letters (PEL)
  `http://www.iop.org/EJ/Unreg/bin/pelmain`
- Physics Today
  `http://www.aip.org/pt/phystoday.html`
- Physics - Uspekhi
  `http://ufn.ioc.ac.ru/ufn.html`
- Reviews of Modern Physics
  `http://www.phys.washington.edu/~rmp/`
- Science
  `http://science-mag.aaas.org/science/`

8.2. *ONLINE REVIEW PUBLICATIONS*:

- Net Advance of Physics: A free electronic journal/encyclopaedia of review articles and lecture notes in physics and allied sciences from around the Internet. Presently consists mainly of links to other sites, but welcomes contributions of original review articles:
  `http://web.mit.edu/afs/athena.mit.edu/user/r/e/redingtn/www/netadv/welcome.html`
- Physics Reports:
  `http://www.elsevier.nl/cas/estoc/contents/SAK/03701573.html`
- Reviews of Modern Physics

http://www.phys.washington.edu/~rmp/

- The Virtual Review (Brown U.): An informal journal which collects active hotlists of preprints which the editors find interesting, arranged by topic. Some editors' contributions include review and comment, some provide only listings with connections to the full text versions:
  http://www.het.brown.edu/physics/review/index.html

8.3. *ONLINE TABLES OF CONTENTS*:

- American Journal of Physics
  http://www.amherst.edu/~ajp/toc/toc.html
- Astroparticle Physics
  http://www.elsevier.nl/cas/estoc/contents/SAK/09276505.html
- Classical and Quantum Gravity
  http://www.ioppublishing.com/EJ/Unreg/bin/main
- European Journal of Physics
  http://www.ioppublishing.com/EJ/Unreg/bin/main
- Journal of Physics A
  http://www.ioppublishing.com/EJ/Unreg/bin/main
- Journal of Physics G
  http://www.ioppublishing.com/EJ/Unreg/bin/main
- Nuclear Instruments and Methods in Physics Research, Section B
  http://www.elsevier.nl/cas/estoc/contents/SAK/0168583X.html
- Nuclear Physics A
  http://www.elsevier.nl:80/cas/estoc/contents/SAK/03759474.html
- Nuclear Physics B
  http://www.elsevier.nl:80/cas/estoc/contents/SAK/05503213.html
- Nuclear Physics B (Proceedings Supplements)
  http://www.elsevier.nl:80/cas/estoc/contents/SAK/09205632.html
- Physica A
  http://www.elsevier.nl/cas/estoc/contents/SAK/03784371.html
- Physica B
  http://www.elsevier.nl/cas/estoc/contents/SAK/09214526.html
- Physica C
  http://www.elsevier.nl/cas/estoc/contents/SAK/09214534.html
- Physica D
  http://www.elsevier.nl/cas/estoc/contents/SAK/01672789.html
- Physical Review D
  http://publish.aps.org/PRTOC/hometoc.html#prd
- Physical Review Letters
  http://publish.aps.org/PRTOC/hometoc.html#prl
- Physics Letters B
  http://www.elsevier.nl/cas/estoc/contents/SAK/03702693.html
- Physics Reports
  http://www.elsevier.nl/cas/estoc/contents/SAK/03701573.html
- Physics Today
  http://www.aip.org/pt/contmenu.html
- Progress in Particle and Nuclear Physics
  http://www.elsevier.nl/cas/estoc/contents/SAK/01466410.html
- Reviews of Modern Physics
  http://www.phys.washington.edu/~rmp/contents.html
- Science
  http://science-mag.aaas.org/science/home/browse.shtml

9. Particle Physics Education Sites:

- Brookhaven National Laboratory:
  http://sun20.ccd.bnl.gov/~scied/
- CEBAF:
  http://www.cebaf.gov/services/pced/pcedhome.html
- Contemporary Physics Education Project (CPEP):
  http://pdg.lbl.gov/cpep.html
- Center for Particle Astrophysics in Berkeley:
  http://physics7.berkeley.edu/home.html
- Fermilab:
  http://www-ed.fnal.gov/
- Stanford Linear Accelerator Center:
  http://www.slac.stanford.edu/winters/pub/www/education/education.html

10. Software Directories:

- CERNLIB: CERN program library:
  http://wwwcn.cern.ch/pl/index.html
- FREEHEP: A collection of software and information about software useful in high-energy physics. Searching either by title, subject, date acquired, or date updated, or by browsing alphabetical list of all packages:
  http://www-spires.slac.stanford.edu/find/fhmain.html
- FERMITOOLS: Software repository of Fermilab-developed software packages of value to the HEP community. Permits searching for packages by title or subject, by browsing FTP site, and by recent acquisitions:
  http://www.fnal.gov/fermitools/
  http://www.hep.net/software.html
- HEPIC: Software used in HEP research:
- MATHEMATICAL & OTHER SOFTWARE: A comprehensive list maintained by Physics Around the World/TIPTOP of software packages, libraries, companies, archives, languages and computing-related journals. Organized by scope: e.g. "Software, Free & Commercial;" "Field-Specific Programs/Programming" (see Astronomy & Astrophysics, HEPNP, Graphics & Visualization); "Program Archives by Platform and Language." Also provides links to other Web compendia of software repositories and directories:
  http://www.physics.mcgill.ca:8081/physics-services/physics_software.html

SUMMARY TABLES OF PARTICLE PHYSICS

* There are also search limits in the Summary Tables for the Gauge and Higgs Bosons, the Leptons, the Quarks, and the Mesons.

SUMMARY TABLES OF PARTICLE PROPERTIES

July 1996

Particle Data Group

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(Approximate closing date for data: January 1, 1996)

GAUGE AND HIGGS BOSONS

γ

$I(J^{PC}) = 0,1(1^{--})$

Mass $m < 6 \times 10^{-16}$ eV, CL = 99.7%
Charge $q < 5 \times 10^{-30}$ e
Mean life τ = Stable

g or gluon

$I(J^P) = 0(1^-)$

Mass $m = 0$ [a]
SU(3) color octet

W

$J = 1$

Charge = ± 1 e
Mass $m = 80.33 \pm 0.15$ GeV
$m_Z - m_W = 10.85 \pm 0.15$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.07 \pm 0.06$ GeV

W^- modes are charge conjugates of the modes below.

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.8±0.4) %		40110
$e^+\nu$		(10.8±0.4) %		40110
$\mu^+\nu$		(10.4±0.6) %		40110
$\tau^+\nu$		(10.9±1.0) %		40110
hadrons		(67.9±1.5) %		–
$\pi^+\gamma$		< 5 × 10^{-4}	95%	40110

Z

$J = 1$

Charge = 0
Mass $m = 91.187 \pm 0.007$ GeV [c]
Full width $\Gamma = 2.490 \pm 0.007$ GeV
$\Gamma(\ell^+\ell^-) = 83.83 \pm 0.27$ MeV [b]
Γ(invisible) = 498.3 ± 4.2 MeV [d]
Γ(hadrons) = 1740.7 ± 5.9 MeV
$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.000 \pm 0.005$
$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) = 0.998 \pm 0.005$ [e]

Average charged multiplicity

$\langle N_{charged} \rangle = 20.99 \pm 0.14$

Couplings to leptons

$g_V^\ell = -0.0376 \pm 0.0012$
$g_A^\ell = -0.5008 \pm 0.0008$
$g^{\nu_e} = 0.53 \pm 0.09$
$g^{\nu_\mu} = 0.502 \pm 0.017$

Asymmetry parameters [f]

$A_e = 0.156 \pm 0.008$ (S = 1.2)
$A_\tau = 0.145 \pm 0.009$
$A_c = 0.59 \pm 0.19$
$A_b = 0.89 \pm 0.11$

Charge asymmetry (%) at Z pole

$A_{FB}^{(0\ell)} = 1.59 \pm 0.18$
$A_{FB}^{(0s)} = 13 \pm 4$
$A_{FB}^{(0c)} = 7.22 \pm 0.67$
$A_{FB}^{(0b)} = 9.92 \pm 0.35$

Z DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
e^+e^-			(3.366±0.008) %		45600
$\mu^+\mu^-$			(3.367±0.013) %		45600
$\tau^+\tau^-$			(3.360±0.015) %		45600
$\ell^+\ell^-$		[b]	(3.366±0.006) %		45600
invisible			(20.01 ±0.16) %		–
hadrons			(69.90 ±0.15) %		–
$(u\overline{u}+c\overline{c})/2$			(9.6 ±1.3) %		–
$(d\overline{d}+s\overline{s}+b\overline{b})/3$			(16.9 ±0.9) %		–
$c\overline{c}$			(11.0 ±0.7) %		–
$b\overline{b}$			(15.46 ±0.14) %		–
$\pi^0\gamma$			< 5.2 × 10^{-5}	95%	45600
$\eta\gamma$			< 5.1 × 10^{-5}	95%	45600
$\omega\gamma$			< 6.5 × 10^{-4}	95%	45600
$\eta'(958)\gamma$			< 4.2 × 10^{-5}	95%	45600
$\gamma\gamma$			< 5.2 × 10^{-5}	95%	45600
$\gamma\gamma\gamma$			< 1.0 × 10^{-5}	95%	45600
$\pi^\pm W^\mp$		[g]	< 7 × 10^{-5}	95%	10300
$\rho^\pm W^\mp$		[g]	< 8.3 × 10^{-5}	95%	10300
$J/\psi(1S)X$			(3.80 ±0.27) × 10^{-3}		–
$\psi(2S)X$			(1.60 ±0.33) × 10^{-3}		–
$\chi_{c1}(1P)X$			(6.0 ±1.9) × 10^{-3}		–
ΥX			(1.0 ±0.5) × 10^{-4}		–
$(D^0/\overline{D}^0)$ X			(20.7 ±2.0) %		–
$D^\pm$X			(12.2 ±1.7) %		–
$D^*(2010)^\pm$X		[g]	(11.4 ±1.3) %		–
B_s^0X			seen		–
anomalous γ+ hadrons		[h]	< 3.2 × 10^{-3}	95%	–
$e^+e^-\gamma$		[h]	< 5.2 × 10^{-4}	95%	45600
$\mu^+\mu^-\gamma$		[h]	< 5.6 × 10^{-4}	95%	45600
$\tau^+\tau^-\gamma$		[h]	< 7.3 × 10^{-4}	95%	45600
$\ell^+\ell^-\gamma\gamma$		[i]	< 6.8 × 10^{-6}	95%	45600
$q\overline{q}\gamma\gamma$		[i]	< 5.5 × 10^{-6}	95%	–
$\nu\overline{\nu}\gamma\gamma$		[i]	< 3.1 × 10^{-6}	95%	45600
$e^\pm\mu^\mp$	LF	[g]	< 1.7 × 10^{-6}	95%	45600
$e^\pm\tau^\mp$	LF	[g]	< 9.8 × 10^{-6}	95%	45600
$\mu^\pm\tau^\mp$	LF	[g]	< 1.7 × 10^{-5}	95%	45600

Gauge & Higgs Boson Summary Table

Higgs Bosons — H^0 and $H^{\pm}$, Searches for

H^0 Mass $m >$ 58.4 GeV, CL = 95%

H_1^0 in Supersymmetric Models ($m_{H_1^0} < m_{H_2^0}$) [j]

Mass $m >$ 44 GeV, CL = 95%

A^0 Pseudoscalar Higgs Boson in Supersymmetric Models [j]

Mass $m >$ 24.3 GeV, CL = 95% $\tan\beta > 1$, $m_t < 200$ GeV

$H^{\pm}$ Mass $m >$ 43.5 GeV, CL = 95%

See the Particle Listings for a Note giving details of Higgs Bosons.

Heavy Bosons Other Than Higgs Bosons, Searches for

Additional *W* Bosons

W_R — right-handed W
Mass $m >$ 406 GeV, CL = 90%
(assuming light right-handed neutrino)

W' with standard couplings decaying to $e\nu$, $\mu\nu$
Mass $m >$ 652 GeV, CL = 95%

Additional *Z* Bosons

Z'_{SM} with standard couplings
Mass $m >$ 505 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 779 GeV, CL = 95% (electroweak fit)

Z_{LR} of $SU(2)_L \times SU(2)_R \times U(1)$
(with $g_L = g_R$)
Mass $m >$ 445 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 389 GeV, CL = 95% (electroweak fit)

Z_χ of $SO(10) \to SU(5) \times U(1)_\chi$
(coupling constant derived from G.U.T.)
Mass $m >$ 425 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 321 GeV, CL = 95% (electroweak fit)

Z_ψ of $E_6 \to SO(10) \times U(1)_\psi$
(coupling constant derived from G.U.T.)
Mass $m >$ 415 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 160 GeV, CL = 95% (electroweak fit)

Z_η of $E_6 \to SU(3) \times SU(2) \times U(1) \times U(1)_\eta$
(coupling constant derived from G.U.T.);
charges are $Q_\eta = \sqrt{3/8}Q_\chi - \sqrt{5/8}Q_\psi$)
Mass $m >$ 440 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 182 GeV, CL = 95% (electroweak fit)

Scalar Leptoquarks

Mass $m >$ 116 GeV, CL = 95% (1st generation, pair prod.)
Mass $m >$ 230 GeV, CL = 95% (1st gener., single prod.)
Mass $m >$ 97 GeV, CL = 95% (2nd gener., pair prod.)
Mass $m >$ 73 GeV, CL = 95% (2nd gener., single prod.)
Mass $m >$ 45 GeV, CL = 95% (3rd gener., pair prod.)
(The second, fourth, and fifth limits above are for charge $-1/3$, weak isoscalar.)

Axions (A^0) and Other Very Light Bosons, Searches for

The standard Peccei-Quinn axion is ruled out. Variants with reduced couplings or much smaller masses are constrained by various data. The Particle Listings in the full *Review* contain a Note discussing axion searches.

The best limit for the half-life of neutrinoless double beta decay with Majoron emission is $> 7.2 \times 10^{24}$ years (CL = 90%).

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when S > 1, which often indicates that the measurements are inconsistent. When S > 1.25, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame.

[a] Theoretical value. A mass as large as a few MeV may not be precluded.

[b] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[c] The Z-boson mass listed here corresponds to a Breit-Wigner resonance parameter. It lies approximately 34 MeV above the real part of the position of the pole (in the energy-squared plane) in the Z-boson propagator.

[d] This partial width takes into account Z decays into $\nu\overline{\nu}$ and any other possible undetected modes.

[e] This ratio has not been corrected for the τ mass.

[f] Here $A \equiv 2g_V g_A/(g_V^2 + g_A^2)$.

[g] The value is for the sum of the charge states of particle/antiparticle states indicated.

[h] See the Z Particle Listings for the γ energy range used in this measurement.

[i] For $m_{\gamma\gamma} = (60 \pm 5)$ GeV.

[j] The limits assume no invisible decays.

LEPTONS

e

$J = \frac{1}{2}$

Mass $m = 0.51099907 \pm 0.00000015$ MeV [a]
$= (5.48579903 \pm 0.00000013) \times 10^{-4}$ u
$(m_{e^+} - m_{e^-})/m < 4 \times 10^{-8}$, CL = 90%
$|q_{e^+} + q_{e^-}|/e < 4 \times 10^{-8}$
Magnetic moment $\mu = 1.001159652193 \pm 0.000000000010\ \mu_B$
$(g_{e^+} - g_{e^-}) / g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$
Electric dipole moment $d = (-0.3 \pm 0.8) \times 10^{-26}$ $e$cm
Mean life $\tau > 4.3 \times 10^{23}$ yr, CL = 68% [b]

μ

$J = \frac{1}{2}$

Mass $m = 105.658389 \pm 0.000034$ MeV [c]
$= 0.113428913 \pm 0.000000017$ u
Mean life $\tau = (2.19703 \pm 0.00004) \times 10^{-6}$ s
$\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$
$c\tau = 658.654$ m
Magnetic moment $\mu = 1.001165923 \pm 0.000000008\ e\hbar/2m_\mu$
$(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}} = (-2.6 \pm 1.6) \times 10^{-8}$
Electric dipole moment $d = (3.7 \pm 3.4) \times 10^{-19}$ $e$cm

Decay parameters [d]

$\rho = 0.7518 \pm 0.0026$
$\eta = -0.007 \pm 0.013$
$\delta = 0.749 \pm 0.004$
$\xi P_\mu = 1.003 \pm 0.008$ [e]
$\xi P_\mu \delta/\rho > 0.99682$, CL = 90% [e]
$\xi' = 1.00 \pm 0.04$
$\xi'' = 0.7 \pm 0.4$
$\alpha/A = (0 \pm 4) \times 10^{-3}$
$\alpha'/A = (0 \pm 4) \times 10^{-3}$
$\beta/A = (4 \pm 6) \times 10^{-3}$
$\beta'/A = (2 \pm 6) \times 10^{-3}$
$\overline{\eta} = 0.02 \pm 0.08$

μ^+ modes are charge conjugates of the modes below.

μ^- DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^- \overline{\nu}_e \nu_\mu$			$\approx 100\%$		53
$e^- \overline{\nu}_e \nu_\mu \gamma$		[f]	(1.4 ± 0.4) %		53
$e^- \overline{\nu}_e \nu_\mu e^+ e^-$		[g]	$(3.4 \pm 0.4) \times 10^{-5}$		53
Lepton Family number (*LF*) violating modes					
$e^- \nu_e \overline{\nu}_\mu$	LF	[h]	< 1.2 %	90%	53
$e^- \gamma$	LF		$< 4.9 \times 10^{-11}$	90%	53
$e^- e^+ e^-$	LF		$< 1.0 \times 10^{-12}$	90%	53
$e^- 2\gamma$	LF		$< 7.2 \times 10^{-11}$	90%	53

τ

$J = \frac{1}{2}$

Mass $m = 1777.00^{+0.30}_{-0.27}$ MeV
Mean life $\tau = (291.0 \pm 1.5) \times 10^{-15}$ s
$c\tau = 87.2\ \mu$m
Electric dipole moment $d < 5 \times 10^{-17}$ $e$cm, CL = 95%

Weak dipole moment

$\text{Re}(d_\tau^w) < 7.8 \times 10^{-18}$ $e$cm, CL = 95%
$\text{Im}(d_\tau^w) < 4.5 \times 10^{-17}$ $e$cm, CL = 95%

Decay parameters

See the τ Particle Listings for a note concerning τ-decay parameters.

$\rho^\tau(e \text{ or } \mu) = 0.742 \pm 0.027$
$\rho^\tau(e) = 0.736 \pm 0.028$
$\rho^\tau(\mu) = 0.74 \pm 0.04$
$\xi^\tau(e \text{ or } \mu) = 1.03 \pm 0.12$
$\xi^\tau(e)$ PARAMETER $= 1.03 \pm 0.25$
$\xi^\tau(\mu)$ PARAMETER $= 1.23 \pm 0.24$
$\eta^\tau(e \text{ or } \mu)$ PARAMETER $= -0.01 \pm 0.14$
$\eta^\tau(\mu)$ PARAMETER $= -0.24 \pm 0.29$
$(\delta\xi)^\tau(e \text{ or } \mu)$ PARAMETER $= 0.76 \pm 0.11$ (S = 1.3)
$(\delta\xi)^\tau(e)$ PARAMETER $= 1.11 \pm 0.18$
$(\delta\xi)^\tau(\mu)$ PARAMETER $= 0.71 \pm 0.15$
$\xi^\tau(\pi) = 0.99 \pm 0.06$
$\xi^\tau(\rho) = 1.04 \pm 0.07$
$\xi^\tau(a_1) = 1.01 \pm 0.04$
$\xi^\tau(\text{all hadronic modes}) = 1.011 \pm 0.027$

τ^+ modes are charge conjugates of the modes below. "$h^\pm$" stands for $\pi^\pm$ or $K^\pm$. "ℓ" stands for e or μ. "Neutral" means neutral hadron whose decay products include γ's and/or π^0's.

τ^- DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Modes with one charged particle				
particle$^- \geq 0$ neutrals $\geq 0K_L^0 \nu_\tau$ ("1-prong")		(84.96 ± 0.14) %	S=1.3	–
particle$^- \geq 0$ neutrals $\geq 0K^0 \nu_\tau$		(85.53 ± 0.14) %	S=1.3	–
$\mu^- \overline{\nu}_\mu \nu_\tau$	[i]	(17.35 ± 0.10) %		885
$\mu^- \overline{\nu}_\mu \nu_\tau \gamma$ ($E_\gamma > 37$ MeV)		$(2.3 \pm 1.0) \times 10^{-3}$		–
$e^- \overline{\nu}_e \nu_\tau$	[i]	(17.83 ± 0.08) %		888
$h^- \geq 0$ neutrals $\geq 0K_L^0\ \nu_\tau$		(49.78 ± 0.17) %	S=1.2	–
$h^- \geq 0K_L^0\ \nu_\tau$		(12.51 ± 0.13) %	S=1.1	–
$h^- \nu_\tau$		(12.03 ± 0.14) %	S=1.1	–
$\pi^- \nu_\tau$	[i]	(11.31 ± 0.15) %	S=1.1	883
$K^- \nu_\tau$	[i]	$(7.1 \pm 0.5) \times 10^{-3}$		820
$h^- \geq 1\pi^0 \nu_\tau$		(36.97 ± 0.18) %	S=1.1	–
$h^- \pi^0 \nu_\tau$		(25.76 ± 0.15) %	S=1.1	–
$\pi^- \pi^0 \nu_\tau$	[i]	(25.24 ± 0.16) %	S=1.1	878
$\pi^- \pi^0$ non-$\rho(770) \nu_\tau$		$(3.0 \pm 3.2) \times 10^{-3}$		878
$K^- \pi^0 \nu_\tau$	[i]	$(5.2 \pm 0.5) \times 10^{-3}$		814
$h^- \geq 2\pi^0 \nu_\tau$		(10.95 ± 0.16) %	S=1.1	–
$h^- 2\pi^0 \nu_\tau$		(9.50 ± 0.14) %	S=1.1	–
$h^- 2\pi^0 \nu_\tau (\text{ex.}K^0)$		(9.35 ± 0.14) %	S=1.1	–
$\pi^- 2\pi^0 \nu_\tau (\text{ex.}K^0)$	[i]	(9.27 ± 0.14) %	S=1.1	862
$K^- 2\pi^0 \nu_\tau (\text{ex.}K^0)$	[i]	$(8.1 \pm 2.7) \times 10^{-4}$		796
$h^- \geq 3\pi^0 \nu_\tau$		(1.46 ± 0.11) %	S=1.1	–
$h^- 3\pi^0 \nu_\tau$		(1.28 ± 0.10) %		–
$\pi^- 3\pi^0 \nu_\tau (\text{ex.}K^0)$	[i]	(1.14 ± 0.14) %		836
$K^- 3\pi^0 \nu_\tau (\text{ex.}K^0)$	[i]	$(5.0\ ^{+10.0}_{-3.3}) \times 10^{-4}$		766
$h^- 4\pi^0 \nu_\tau (\text{ex.}K^0)$		$(1.8 \pm 0.6) \times 10^{-3}$		–
$h^- 4\pi^0 \nu_\tau (\text{ex.}K^0,\eta)$	[i]	$(1.2 \pm 0.6) \times 10^{-3}$		–
$K^- \geq 1\ (\pi^0 \text{ or } K^0)\ \nu_\tau$		$(9.4 \pm 1.0) \times 10^{-3}$		–
Modes with K^0's				
$h^- \overline{K}^0 \geq 0$ neutrals $\geq 0K_L^0 \nu_\tau$		(1.54 ± 0.10) %	S=1.3	–
$h^- \overline{K}^0 \nu_\tau$		$(9.2 \pm 0.8) \times 10^{-3}$	S=1.3	–
$\pi^- \overline{K}^0 \nu_\tau$	[i]	$(7.7 \pm 0.8) \times 10^{-3}$	S=1.3	812
$\pi^- \overline{K}^0$ (non-$K^*(892)^-$)ν_τ		$< 1.7 \times 10^{-3}$	CL=95%	812
$K^- K^0 \nu_\tau$	[i]	$(1.55 \pm 0.28) \times 10^{-3}$		737
$h^- \overline{K}^0 \pi^0 \nu_\tau$		$(5.5 \pm 0.5) \times 10^{-3}$		–
$\pi^- \overline{K}^0 \pi^0 \nu_\tau$	[i]	$(4.1 \pm 0.6) \times 10^{-3}$		794
$K^- K^0 \pi^0 \nu_\tau$	[i]	$(1.38 \pm 0.32) \times 10^{-3}$		685
$h^- K_S^0 K_S^0 \nu_\tau$		$(2.5 \pm 0.6) \times 10^{-4}$		–
$\pi^- K^0 \overline{K}^0 \nu_\tau$	[i]	$(1.01 \pm 0.23) \times 10^{-3}$		682
$K^- K^0 \geq 0$ neutrals ν_τ		$(2.9 \pm 0.4) \times 10^{-3}$		–
$K^- \geq 0\pi^0 \geq 0K^0\ \nu_\tau$		(1.65 ± 0.10) %		–
K^0(particles)$^- \nu_\tau$		(1.58 ± 0.10) %	S=1.2	–
$K^0 h^+ h^- h^- \geq 0$ neut. ν_τ		$< 1.7 \times 10^{-3}$	CL=95%	–

Modes with three charged particles

Mode		Fraction	Scale factor/ Confidence level	p
$h^- h^- h^+ \geq$ 0neut. ν_τ ("3-prong")		(14.91± 0.14) %	S=1.3	–
$h^- h^- h^+ \geq$ 0 neutrals ν_τ (ex. $K^0_S \to \pi^+\pi^-$)		(14.36± 0.14) %	S=1.3	–
$\pi^-\pi^+\pi^- \geq$ 0 neutrals ν_τ		(14.09± 0.31) %		–
$h^- h^- h^+ \nu_\tau$		(9.80± 0.10) %	S=1.1	–
$h^- h^- h^+ \nu_\tau$ (ex.K^0)		(9.48± 0.10) %	S=1.1	–
$h^- h^- h^+ \nu_\tau$ (ex.K^0,ω)	[l]	(9.44± 0.10) %	S=1.1	–
$h^- h^- h^+ \geq$ 1 neutrals ν_τ		(5.08± 0.11) %	S=1.2	–
$h^- h^- h^+ \geq$ 1 neutrals ν_τ (ex. $K^0_S \to \pi^+\pi^-$)		(4.88± 0.11) %	S=1.2	–
$h^- h^- h^+ \pi^0 \nu_\tau$		(4.44± 0.09) %	S=1.1	–
$h^- h^- h^+ \pi^0 \nu_\tau$ (ex.K^0)		(4.25± 0.09) %	S=1.1	–
$h^- h^- h^+ \pi^0 \nu_\tau$ (ex. K^0, ω)	[l]	(2.55± 0.09) %		–
$h^- (\rho\pi)^0 \nu_\tau$		(2.84± 0.34) %		–
$(a_1(1260)h)^- \nu_\tau$		< 2.0 %	CL=95%	–
$h^- \rho\pi^0 \nu_\tau$		(1.33± 0.20) %		–
$h^- \rho^+ h^- \nu_\tau$		(4.4 ± 2.2) × 10^{-3}		–
$h^- \rho^- h^+ \nu_\tau$		(1.15± 0.23) %		–
$h^- h^- h^+ 2\pi^0 \nu_\tau$		(5.2 ± 0.5) × 10^{-3}		–
$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0)		(5.1 ± 0.5) × 10^{-3}		–
$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0,ω,η)	[l]	(1.0 ± 0.4) × 10^{-3}		–
$h^- h^- h^+ \geq 3\pi^0 \nu_\tau$	[l]	(1.1 ± 0.6) × 10^{-3}		–
$K^- h^+ h^- \geq$ 0 neutrals ν_τ		< 6 × 10^{-3}	CL=90%	–
$K^- \pi^+ \pi^- \geq$ 0 neut. ν_τ		(3.9 $^{+1.9}_{-1.6}$) × 10^{-3}	S=1.5	–
$K^- \pi^+ K^- \geq$ 0 neut. ν_τ		< 9 × 10^{-4}	CL=95%	
$K^- K^+ \pi^- \geq$ 0 neut. ν_τ		(1.5 $^{+0.9}_{-0.8}$) × 10^{-3}		–
$K^- K^+ \pi^- \nu_\tau$		(2.2 $^{+1.8}_{-1.2}$) × 10^{-3}		685
$\phi\pi^- \nu_\tau$		< 3.5 × 10^{-4}	CL=90%	585
$K^- K^+ K^- \geq$ 0 neut. ν_τ		< 2.1 × 10^{-3}	CL=95%	–
$\pi^- K^+ \pi^- \geq$ 0 neut. ν_τ		< 2.5 × 10^{-3}	CL=95%	–
$e^- e^- e^+ \overline{\nu}_e \nu_\tau$		(2.8 ± 1.5) × 10^{-5}		888
$\mu^- e^- e^+ \overline{\nu}_\mu \nu_\tau$		< 3.6 × 10^{-5}	CL=90%	885

Modes with five charged particles

Mode		Fraction	Scale factor/ Confidence level	p
$3h^- 2h^+ \geq$ 0 neutrals ν_τ (ex. $K^0_S \to \pi^-\pi^+$) ("5-prong")		(9.7 ± 0.7) × 10^{-4}		–
$3h^- 2h^+ \nu_\tau$ (ex.K^0)	[l]	(7.5 ± 0.7) × 10^{-4}		–
$3h^- 2h^+ \pi^0 \nu_\tau$ (ex.K^0)	[l]	(2.2 ± 0.5) × 10^{-4}		–
$3h^- 2h^+ 2\pi^0 \nu_\tau$		< 1.1 × 10^{-4}	CL=90%	–

Miscellaneous other allowed modes

Mode		Fraction	Scale factor/ Confidence level	p
$(5\pi)^- \nu_\tau$		(3.3 ± 0.7) × 10^{-3}		–
$4h^- 3h^+ \geq$ 0 neutrals ν_τ ("7-prong")		< 1.9 × 10^{-4}	CL=90%	–
$K^*(892)^- \geq 0(h^0 \neq K^0_S)\nu_\tau$		(1.94± 0.31) %		–
$K^*(892)^- \geq$ 0 neutrals ν_τ		(1.33± 0.13) %		–
$K^*(892)^- \nu_\tau$		(1.28± 0.08) %		665
$K^*(892)^0 K^- \geq$ 0 neutrals ν_τ		(3.2 ± 1.4) × 10^{-3}		–
$K^*(892)^0 K^- \nu_\tau$		(2.0 ± 0.6) × 10^{-3}		539
$\overline{K}^*(892)^0 \pi^- \geq$ 0 neutrals ν_τ		(3.8 ± 1.7) × 10^{-3}		–
$\overline{K}^*(892)^0 \pi^- \nu_\tau$		(2.5 ± 1.1) × 10^{-3}		653
$K_1(1270)^- \nu_\tau$		(4 ± 4) × 10^{-3}		433
$K_1(1400)^- \nu_\tau$		(8 ± 4) × 10^{-3}		335
$K^*_2(1430)^- \nu_\tau$		< 3 × 10^{-3}	CL=95%	317
$\eta\pi^- \nu_\tau$		< 1.4 × 10^{-4}	CL=95%	798
$\eta\pi^-\pi^0 \nu_\tau$	[l]	(1.71± 0.28) × 10^{-3}		778
$\eta\pi^-\pi^0\pi^0 \nu_\tau$		< 4.3 × 10^{-4}	CL=95%	746
$\eta K^- \nu_\tau$		(2.6 ± 0.7) × 10^{-4}		720
$\eta\pi^+\pi^-\pi^- \geq$ 0 neutrals ν_τ		< 3 × 10^{-3}	CL=90%	–
$\eta\eta\pi^- \nu_\tau$		< 1.1 × 10^{-4}	CL=95%	637
$\eta\eta\pi^-\pi^0 \nu_\tau$		< 2.0 × 10^{-4}	CL=95%	559
$h^- \omega \geq$ 0 neutrals ν_τ		(2.32± 0.11) %		–
$h^- \omega \nu_\tau$	[l]	(1.91± 0.09) %		–
$h^- \omega \pi^0 \nu_\tau$	[l]	(4.1 ± 0.6) × 10^{-3}		–

Lepton Family number (*LF*), Lepton number (*L*), or Baryon number (*B*) violating modes
(In the modes below, ℓ means a sum over *e* and μ modes)

L means lepton number violation (*e.g.* $\tau^- \to e^+\pi^-\pi^-$). Following common usage, *LF* means lepton family violation *and not* lepton number violation (*e.g.* $\tau^- \to e^-\pi^+\pi^-$).

Mode		Fraction	Confidence level	p
$e^-\gamma$	*LF*	< 1.1 × 10^{-4}	CL=90%	888
$\mu^-\gamma$	*LF*	< 4.2 × 10^{-6}	CL=90%	885
$e^-\pi^0$	*LF*	< 1.4 × 10^{-4}	CL=90%	883
$\mu^-\pi^0$	*LF*	< 4.4 × 10^{-5}	CL=90%	880
$e^- K^0$	*LF*	< 1.3 × 10^{-3}	CL=90%	819
$\mu^- K^0$	*LF*	< 1.0 × 10^{-3}	CL=90%	815
$e^-\eta$	*LF*	< 6.3 × 10^{-5}	CL=90%	804
$\mu^-\eta$	*LF*	< 7.3 × 10^{-5}	CL=90%	800
$e^-\rho^0$	*LF*	< 4.2 × 10^{-6}	CL=90%	722
$\mu^-\rho^0$	*LF*	< 5.7 × 10^{-6}	CL=90%	718
$e^- K^*(892)^0$	*LF*	< 6.3 × 10^{-6}	CL=90%	663
$\mu^- K^*(892)^0$	*LF*	< 9.4 × 10^{-6}	CL=90%	657
$\pi^-\gamma$	*L*	< 2.8 × 10^{-4}	CL=90%	883
$\pi^-\pi^0$	*L*	< 3.7 × 10^{-4}	CL=90%	878
$e^- e^+ e^-$	*LF*	< 3.3 × 10^{-6}	CL=90%	888
$e^-\mu^+\mu^-$	*LF*	< 3.6 × 10^{-6}	CL=90%	882
$e^+\mu^-\mu^-$	*LF*	< 3.5 × 10^{-6}	CL=90%	882
$\mu^- e^+ e^-$	*LF*	< 3.4 × 10^{-6}	CL=90%	885
$\mu^+ e^- e^-$	*L*	< 3.4 × 10^{-6}	CL=90%	885
$\mu^-\mu^+\mu^-$	*LF*	< 1.9 × 10^{-6}	CL=90%	873
$e^-\pi^+\pi^-$	*LF*	< 4.4 × 10^{-6}	CL=90%	877
$e^+\pi^-\pi^-$	*L*	< 4.4 × 10^{-6}	CL=90%	877
$\mu^-\pi^+\pi^-$	*LF*	< 7.4 × 10^{-6}	CL=90%	866
$\mu^+\pi^-\pi^-$	*L*	< 6.9 × 10^{-6}	CL=90%	866
$e^-\pi^+ K^-$	*LF*	< 7.7 × 10^{-6}	CL=90%	813
$e^-\pi^- K^+$	*LF*	< 4.6 × 10^{-6}	CL=90%	813
$e^+\pi^- K^-$	*L*	< 4.5 × 10^{-6}	CL=90%	813
$\mu^-\pi^+ K^-$	*LF*	< 8.7 × 10^{-6}	CL=90%	800
$\mu^-\pi^- K^+$	*LF*	< 1.5 × 10^{-5}	CL=90%	800
$\mu^+\pi^- K^-$	*L*	< 2.0 × 10^{-5}	CL=90%	800
$\overline{p}\gamma$	*L,B*	< 2.9 × 10^{-4}	CL=90%	641
$\overline{p}\pi^0$	*L,B*	< 6.6 × 10^{-4}	CL=90%	632
$\overline{p}\eta$	*L,B*	< 1.30 × 10^{-3}	CL=90%	475
$e^-\overline{K}^*(892)^0$	*LF*	< 1.1 × 10^{-5}	CL=90%	663
$\mu^-\overline{K}^*(892)^0$	*LF*	< 8.7 × 10^{-6}	CL=90%	657
e^- light boson	*LF*	< 2.7 × 10^{-3}	CL=95%	–
μ^- light boson	*LF*	< 5 × 10^{-3}	CL=95%	–

Heavy Charged Lepton Searches

$L^\pm$ – charged lepton

Mass $m >$ 42.7 GeV, CL = 95% $m_\nu \approx 0$

$L^\pm$ – stable charged heavy lepton

Mass $m >$ 42.8 GeV, CL = 95%

Neutrinos

See the Particle Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

ν_e

$J = \frac{1}{2}$

Mass m: Unexplained effects have resulted in significantly negative m^2 in the new, precise tritium beta decay experiments. It is felt that a real neutrino mass as large as 10–15 eV would cause observable spectral distortions even in the presence of the end-point count excesses.

Mean life/mass, $\tau/m_{\nu_e} >$ 300 s/eV, CL = 90%

Magnetic moment $\mu < 1.8 \times 10^{-10}\ \mu_B$, CL = 90%

ν_μ

$J = \frac{1}{2}$

Mass $m <$ 0.17 MeV, CL = 90%

Mean life/mass, $\tau/m_{\nu_\mu} >$ 15.4 s/eV, CL = 90%

Magnetic moment $\mu < 7.4 \times 10^{-10}\ \mu_B$, CL = 90%

ν_τ

$J = \frac{1}{2}$

Mass $m <$ 24 MeV, CL = 95%
Magnetic moment $\mu < 5.4 \times 10^{-7}$ μ_B, CL = 90%

Number of Light Neutrino Types

(including ν_e, ν_μ, and ν_τ)
Number $N = 2.991 \pm 0.016$ (Standard Model fits to LEP data)
Number $N = 3.09 \pm 0.13$ (Direct measurement of invisible Z width)

Massive Neutrinos and Lepton Mixing, Searches for

For excited leptons, see Compositeness Limits below.

See the Particle Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

No direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained. Sample limits are:
Mass $m >$ 45.0, CL = 95% (Dirac)
Mass $m >$ 39.5, CL = 95% (Majorana)

ν oscillation: $\nu_\mu \to \nu_e$ (θ = mixing angle)
Mass $m >$ 19.6 GeV, CL = 95% (all $|U_{\ell j}|^2$) (Dirac)
Mass $m >$ 45.7 GeV or $m < 25$, CL = 95% ($|U_{\ell j}|^2 > 10^{-13}$ (Dirac)

ν oscillation: $\overline{\nu}_e \not\to \overline{\nu}_e$
$\Delta(m^2) < 0.0075$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 0.02$, CL = 90% (if $\Delta(m^2)$ is large)

ν oscillation: $\nu_\mu \to \nu_e$ (θ = mixing angle)
$\Delta(m^2) < 0.09$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 2.5 \times 10^{-3}$, CL = 90% (if $\Delta(m^2)$ is large)

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when S > 1, which often indicates that the measurements are inconsistent. When S > 1.25, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame.

[a] The ucertainty in the electron mass in unified atomic mass units (u) is ten times smaller than that given by the 1986 CODATA adjustment, quoted in the Table of Physical Contants (Section 1). The conversion to MeV via the factor 931.49432(28) MeV/u is more uncertain because of the electron charge uncertainty. Our value in MeV differs slightly from the 1986 CODATA result.

[b] This is the best "electron disappearance" limit. The best limit for the mode $e^- \to \nu\gamma$ is $> 2.35 \times 10^{25}$ yr (CL=68%).

[c] The muon mass is most precisely known in u (unified atomic mass units). The conversion factor to MeV via the factor 931.49432(28) MeV/u is more uncertain because of the electron charge uncertainty.

[d] See the "Note on Muon Decay Parameters" in the μ Particle Listings for definitions and details.

[e] P_μ is the longitudinal polarization of the muon from pion decay. In standard $V-A$ theory, $P_\mu = 1$ and $\rho = \delta = 3/4$.

[f] This only includes events with the γ energy > 10 MeV. Since the $e^-\overline{\nu}_e\nu_\mu$ and $e^-\overline{\nu}_e\nu_\mu\gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

[g] See the μ Particle Listings for the energy limits used in this measurement.

[h] A test of additive vs. multiplicative lepton family number conservation.

[i] Basis mode for the τ.

QUARKS

The *u*-, *d*-, and *s*-quark masses are estimates of so-called "current-quark masses," in a mass-independent subtraction scheme such as $\overline{\text{MS}}$ at a scale $\mu \approx 1$ GeV. The *c*- and *b*-quark masses are estimated from charmonium, bottomonium, *D*, and *B* masses. They are the "running" masses in the $\overline{\text{MS}}$ scheme. These can be different from the heavy quark masses obtained in potential models.

u

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 2 to 8 MeV [a] Charge = $\frac{2}{3}\,e$ $I_z = +\frac{1}{2}$

m_u/m_d = 0.25 to 0.70

d

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 5 to 15 MeV [a] Charge = $-\frac{1}{3}\,e$ $I_z = -\frac{1}{2}$

m_s/m_d = 17 to 25

s

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 100 to 300 MeV [a] Charge = $-\frac{1}{3}\,e$ Strangeness = −1

$(m_s - (m_u + m_d)/2)/(m_d - m_u)$ = 34 to 51

c

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 1.0 to 1.6 GeV Charge = $\frac{2}{3}\,e$ Charm = +1

b

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 4.1 to 4.5 GeV Charge = $-\frac{1}{3}\,e$ Bottom = −1

t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge = $\frac{2}{3}\,e$ Top = +1

Mass m = 180 ± 12 GeV (direct observation of top events)
Mass $m = 179 \pm 8^{+17}_{-20}$ GeV (Standard Model electroweak fit)

b′ (4th Generation) Quark, Searches for

Mass $m >$ 85 GeV, CL = 95% ($p\overline{p}$, charged current decays)
Mass $m >$ 46.0 GeV, CL = 95% (e^+e^-, all decays)

Free Quark Searches

All searches since 1977 have had negative results.

NOTES

[*a*] The ratios m_u/m_d and m_s/m_d are extracted from pion and kaon masses using chiral symmetry. The estimates of *u* and *d* masses are not without controversy and remain under active investigation. Within the literature there are even suggestions that the *u* quark could be essentially massless. The *s*-quark mass is estimated from SU(3) splittings in hadron masses.

LIGHT UNFLAVORED MESONS $(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ $(\eta, \eta', h, h', \omega, \phi, f, f')$: $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.56995 \pm 0.00035$ MeV
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.017 \pm 0.008$
$F_A = 0.0116 \pm 0.0016$ (S = 1.3)
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(1.24 \pm0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(1.61 \pm0.23) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.025 \pm0.034) \times 10^{-8}$		4
$e^+\nu_e e^+e^-$		$(3.2 \pm0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes				
$\mu^+\overline{\nu}_e$	*L* [d]	$< 1.5 \times 10^{-3}$	90%	30
$\mu^+\nu_e$	*LF* [d]	$< 8.0 \times 10^{-3}$	90%	30
$\mu^-e^+e^+\nu$	*LF*	$< 1.6 \times 10^{-6}$	90%	30

π^0

$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 134.9764 \pm 0.0006$ MeV
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.4 \pm 0.6) \times 10^{-17}$ s (S = 3.0)
$c\tau = 25.1$ nm

π^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ		(98.798 ± 0.032) %	S=1.1	67
$e^+e^-\gamma$		(1.198 ± 0.032) %	S=1.1	67
γ positronium		$(1.82 \pm0.29) \times 10^{-9}$		67
$e^+e^+e^-e^-$		$(3.14 \pm0.30) \times 10^{-5}$		67
e^+e^-		$(7.5 \pm2.0) \times 10^{-8}$		67
4γ		$< 2 \times 10^{-8}$	CL=90%	67
$\nu\overline{\nu}$	[e]	$< 8.3 \times 10^{-7}$	CL=90%	67
$\nu_e\overline{\nu}_e$		$< 1.7 \times 10^{-6}$	CL=90%	67
$\nu_\mu\overline{\nu}_\mu$		$< 3.1 \times 10^{-6}$	CL=90%	67
$\nu_\tau\overline{\nu}_\tau$		$< 2.1 \times 10^{-6}$	CL=90%	67
Charge conjugation (*C*) or Lepton Family number (*LF*) violating modes				
3γ	*C*	$< 3.1 \times 10^{-8}$	CL=90%	67
$\mu^+e^- + e^-\mu^+$	*LF*	$< 1.72 \times 10^{-8}$	CL=90%	26

η

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 547.45 \pm 0.19$ MeV (S = 1.6)
Full width $\Gamma = 1.18 \pm 0.11$ keV [f] (S = 1.8)

***C*-nonconserving decay parameters** [g]

$\pi^+\pi^-\pi^0$ Left-right asymmetry $= (0.09 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ Sextant asymmetry $= (0.18 \pm 0.16) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ Quadrant asymmetry $= (-0.17 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\gamma$ Left-right asymmetry $= (0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ β (*D*-wave) $= 0.05 \pm 0.06$ (S = 1.5)

η DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
neutral modes		(71.4 ± 0.6) %	S=1.3	–
2γ	[f]	(39.25 ± 0.31) %	S=1.3	274
$3\pi^0$		(32.1 ± 0.4) %	S=1.2	180
$\pi^0 2\gamma$		$(7.1 \pm1.4) \times 10^{-4}$		258
other neutral modes		< 2.8 %	CL=90%	–
charged modes		(28.6 ± 0.6) %	S=1.3	–
$\pi^+\pi^-\pi^0$		(23.2 ± 0.5) %	S=1.3	175
$\pi^+\pi^-\gamma$		(4.78 ± 0.12) %	S=1.2	236
$e^+e^-\gamma$		$(4.9 \pm1.1) \times 10^{-3}$		274
$\mu^+\mu^-\gamma$		$(3.1 \pm0.4) \times 10^{-4}$		253
e^+e^-		$< 3 \times 10^{-4}$	CL=90%	274
$\mu^+\mu^-$		$(5.8 \pm0.8) \times 10^{-6}$		253
$\pi^+\pi^-e^+e^-$		$(1.3 {}^{+1.2}_{-0.8}) \times 10^{-3}$		236
$\pi^+\pi^-2\gamma$		$< 2.1 \times 10^{-3}$		236
$\pi^+\pi^-\pi^0\gamma$		$< 6 \times 10^{-4}$	CL=90%	175
$\pi^0\mu^+\mu^-\gamma$		$< 3 \times 10^{-6}$	CL=90%	211
Charge conjugation (*C*), Parity (*P*), or Charge conjugation × Parity (*CP*) violating modes				
$\pi^+\pi^-$	*P,CP*	$< 1.5 \times 10^{-3}$		236
3γ	*C*	$< 5 \times 10^{-4}$	CL=95%	274
$\pi^0e^+e^-$	*C* [h]	$< 4 \times 10^{-5}$	CL=90%	258
$\pi^0\mu^+\mu^-$	*C* [h]	$< 5 \times 10^{-6}$	CL=90%	211

$f_0(400\text{–}1200)$ [i] or σ

$I^G(J^{PC}) = 0^+(0^{++})$

The interpretation of this entry as a particle is controversial. See the "Note on scalar mesons" in the Particle Listings under the $f_0(1370)$.

Mass $m = (400\text{–}1200)$ MeV
Full width $\Gamma = (600\text{–}1000)$ MeV

$f_0(400\text{–}1200)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	dominant	–
$\gamma\gamma$	seen	–

$\rho(770)$ [j]

$I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 768.5 \pm 0.6$ MeV (S = 1.2)
Full width $\Gamma = 150.7 \pm 1.2$ MeV
$\Gamma_{ee} = 6.77 \pm 0.32$ keV

$\rho(770)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$		~ 100 %		358
$\rho(770)^{\pm}$ decays				
$\pi^{\pm}\gamma$		$(4.5 \pm0.5) \times 10^{-4}$	S=2.2	372
$\pi^{\pm}\eta$		$< 6 \times 10^{-3}$	CL=84%	146
$\pi^{\pm}\pi^+\pi^-\pi^0$		$< 2.0 \times 10^{-3}$	CL=84%	249
$\rho(770)^0$ decays				
$\pi^+\pi^-\gamma$		$(9.9 \pm1.6) \times 10^{-3}$		358
$\pi^0\gamma$		$(7.9 \pm2.0) \times 10^{-4}$		372
$\eta\gamma$		$(3.8 \pm0.7) \times 10^{-4}$		189
$\mu^+\mu^-$	[k]	$(4.60\pm0.28) \times 10^{-5}$		369
e^+e^-	[k]	$(4.48\pm0.22) \times 10^{-5}$		384
$\pi^+\pi^-\pi^0$		$< 1.2 \times 10^{-4}$	CL=90%	319
$\pi^+\pi^-\pi^+\pi^-$		$< 2 \times 10^{-4}$	CL=90%	246
$\pi^+\pi^-\pi^0\pi^0$		$< 4 \times 10^{-5}$	CL=90%	252

$\omega(782)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 781.94 \pm 0.12$ MeV (S = 1.5)
Full width $\Gamma = 8.43 \pm 0.10$ MeV
$\Gamma_{ee} = 0.60 \pm 0.02$ keV

$\omega(782)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi^+\pi^-\pi^0$	(88.8 ± 0.7) %		327
$\pi^0\gamma$	(8.5 ± 0.5) %		379
$\pi^+\pi^-$	(2.21 ± 0.30) %		365
neutrals (excluding $\pi^0\gamma$)	$(5.3 {}^{+8.7}_{-3.5}) \times 10^{-3}$		–
$\eta\gamma$	$(8.3 \pm2.1) \times 10^{-4}$		199
$\pi^0e^+e^-$	$(5.9 \pm1.9) \times 10^{-4}$		379
$\pi^0\mu^+\mu^-$	$(9.6 \pm2.3) \times 10^{-5}$		349

e^+e^-	$(7.15\pm0.19)\times10^{-5}$		391
$\pi^+\pi^-\pi^0\pi^0$	<2 %	90%	261
$\pi^+\pi^-\gamma$	$<3.6\times10^{-3}$	95%	365
$\pi^+\pi^-\pi^+\pi^-$	$<1\times10^{-3}$	90%	256
$\pi^0\pi^0\gamma$	$(7.2\pm2.5)\times10^{-5}$		367
$\mu^+\mu^-$	$<1.8\times10^{-4}$	90%	376
3γ	$<2\times10^{-4}$	90%	391
Charge conjugation (C)			
$\eta\pi^0$	C $<1\times10^{-3}$	90%	162
$3\pi^0$	C $<3\times10^{-4}$	90%	329

$\eta'(958)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 957.77 \pm 0.14$ MeV
Full width $\Gamma = 0.201 \pm 0.016$ MeV (S = 1.3)

$\eta'(958)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\pi^-\eta$	(43.7 ± 1.5) %	S=1.1	232
$\rho^0\gamma$	(30.2 ± 1.3) %	S=1.1	169
$\pi^0\pi^0\eta$	(20.8 ± 1.3) %	S=1.2	239
$\omega\gamma$	(3.02 ± 0.30) %		160
$\gamma\gamma$	(2.12 ± 0.13) %	S=1.2	479
$3\pi^0$	$(1.55\pm0.26)\times10^{-3}$		430
$\mu^+\mu^-\gamma$	$(1.04\pm0.26)\times10^{-4}$		467
$\pi^+\pi^-\pi^0$	<5 %	CL=90%	427
$\pi^0\rho^0$	<4 %	CL=90%	118
$\pi^+\pi^-$	<2 %	CL=90%	458
$\pi^0e^+e^-$	<1.3 %	CL=90%	469
ηe^+e^-	<1.1 %	CL=90%	322
$\pi^+\pi^+\pi^-\pi^-$	<1 %	CL=90%	372
$\pi^+\pi^+\pi^-\pi^-$ neutrals	<1 %	CL=95%	–
$\pi^+\pi^+\pi^-\pi^-\pi^0$	<1 %	CL=90%	298
6π	<1 %	CL=90%	189
$\pi^+\pi^-e^+e^-$	$<6\times10^{-3}$	CL=90%	458
$\pi^0\pi^0$	$<9\times10^{-4}$	CL=90%	459
$\pi^0\gamma\gamma$	$<8\times10^{-4}$	CL=90%	469
$4\pi^0$	$<5\times10^{-4}$	CL=90%	379
3γ	$<1.0\times10^{-4}$	CL=90%	479
$\mu^+\mu^-\pi^0$	$<6.0\times10^{-5}$	CL=90%	445
$\mu^+\mu^-\eta$	$<1.5\times10^{-5}$	CL=90%	274
e^+e^-	$<2.1\times10^{-7}$	CL=90%	479

$f_0(980)$ [l]

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 980 \pm 10$ MeV
Full width $\Gamma = 40$ to 100 MeV

$f_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi\pi$	(78.1 ± 2.4) %		470
$K\overline{K}$	(21.9 ± 2.4) %		–
$\gamma\gamma$	$(1.19\pm0.33)\times10^{-5}$		490
e^+e^-	$<3\times10^{-7}$	90%	490

$a_0(980)$ [l]

$I^G(J^{PC}) = 1^-(0^{++})$

Mass $m = 983.5 \pm 0.9$ MeV
Full width $\Gamma = 50$ to 100 MeV

$a_0(980)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi$	dominant	321
$K\overline{K}$	seen	–
$\gamma\gamma$	seen	492

$\phi(1020)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1019.413 \pm 0.008$ MeV
Full width $\Gamma = 4.43 \pm 0.05$ MeV
$\Gamma_{ee} = 1.37 \pm 0.05$ keV

$\phi(1020)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
K^+K^-	(49.1 ± 0.6) %	S=1.2	127
$K_L^0K_S^0$	(34.1 ± 0.5) %	S=1.1	110
$\rho\pi$	(12.9 ± 0.7) %		181
$\pi^+\pi^-\pi^0$	(2.7 ± 0.9) %	S=1.1	462
$\eta\gamma$	(1.26 ± 0.06) %	S=1.1	363
$\pi^0\gamma$	$(1.31\pm0.13)\times10^{-3}$		501
e^+e^-	$(3.00\pm0.06)\times10^{-4}$	S=1.1	510
$\mu^+\mu^-$	$(2.48\pm0.34)\times10^{-4}$		499
ηe^+e^-	$(1.3\ ^{+0.8}_{-0.6})\times10^{-4}$		363
$\pi^+\pi^-$	$(8\ ^{+5}_{-4})\times10^{-5}$	S=1.5	490
$\omega\gamma$	<5 %	CL=84%	210
$\rho\gamma$	<2 %	CL=84%	219
$\pi^+\pi^-\gamma$	$<7\times10^{-3}$	CL=90%	490
$\pi^0\pi^0\gamma$	$<1\times10^{-3}$	CL=90%	492
$\pi^+\pi^-\pi^+\pi^-$	$<8.7\times10^{-4}$	CL=90%	410
$\eta'(958)\gamma$	$<4.1\times10^{-4}$	CL=90%	60
$\pi^+\pi^+\pi^-\pi^-\pi^0$	$<1.5\times10^{-4}$	CL=95%	341
$\pi^0e^+e^-$	$<1.2\times10^{-4}$	CL=90%	501
$a_0(980)\gamma$	$<5\times10^{-3}$	CL=90%	36

$h_1(1170)$

$I^G(J^{PC}) = 0^-(1^{+-})$

Mass $m = 1170 \pm 20$ MeV
Full width $\Gamma = 360 \pm 40$ MeV

$h_1(1170)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	310

$b_1(1235)$

$I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 1231 \pm 10$ MeV [l]
Full width $\Gamma = 142 \pm 8$ MeV (S = 1.1)

$b_1(1235)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\omega\pi$	dominant		348
[D/S amplitude ratio $= 0.26 \pm 0.04$]			
$\pi^\pm\gamma$	$(1.6\pm0.4)\times10^{-3}$		608
$\eta\rho$	seen		–
$\pi^+\pi^+\pi^-\pi^0$	<50 %	84%	536
$(K\overline{K})^\pm\pi^0$	<8 %	90%	248
$K_S^0K_L^0\pi^\pm$	<6 %	90%	238
$K_S^0K_S^0\pi^\pm$	<2 %	90%	238
$\pi\phi$	<1.5 %	84%	146

$a_1(1260)$ [m]

$I^G(J^{PC}) = 1^-(1^{++})$

Mass $m = 1230 \pm 40$ MeV [l]
Full width $\Gamma \sim 400$ MeV

$a_1(1260)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	dominant	356
$\pi\gamma$	seen	607
$K\overline{K}^*(892)$	possibly seen	–

$f_2(1270)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 1275 \pm 5$ MeV [l]
Full width $\Gamma = 185 \pm 20$ MeV [l]

$f_2(1270)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$	$(84.7\ ^{+2.6}_{-1.2})$ %	S=1.3	622
$\pi^+\pi^-2\pi^0$	$(7.2\ ^{+1.4}_{-2.9})$ %	S=1.3	562
$K\overline{K}$	(4.6 ± 0.5) %	S=2.8	403
$2\pi^+2\pi^-$	(2.8 ± 0.4) %	S=1.2	559
$\eta\eta$	$(4.5\pm1.0)\times10^{-3}$	S=2.4	327
$4\pi^0$	$(3.0\pm1.0)\times10^{-3}$		564
$\gamma\gamma$	$(1.32\ ^{+0.18}_{-0.16})\times10^{-5}$		637
$\eta\pi\pi$	$<8\times10^{-3}$	CL=95%	475
$K^0K^-\pi^+$ + c.c.	$<3.4\times10^{-3}$	CL=95%	293
e^+e^-	$<9\times10^{-9}$	CL=90%	637

$f_1(1285)$ $\quad I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1282.2 \pm 0.7$ MeV [l] (S = 1.7)
Full width $\Gamma = 24.8 \pm 1.3$ MeV [l] (S = 1.3)

$f_1(1285)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
4π	(29 ± 6) %		563
$\pi^0\pi^0\pi^+\pi^-$	$(15 {}^{+9}_{-8})$ %	S=1.1	–
$2\pi^+2\pi^-$	(15 ± 6) %		563
$\rho^0\pi^+\pi^-$	dominates $2\pi^+ 2\pi^-$		340
$4\pi^0$	$< 7 \times 10^{-4}$	CL=90%	568
$\eta\pi\pi$	(54 ± 15) %		479
$a_0(980)\pi$ [ignoring $a_0(980) \to K\overline{K}$]	(44 ± 7) %	S=1.1	234
$\eta\pi\pi$ [excluding $a_0(980)\pi$]	$(10 {}^{+7}_{-6})$ %	S=1.1	–
$K\overline{K}\pi$	(9.7 ± 1.6) %	S=1.2	308
$K\overline{K}^*(892)$	not seen		–
$\gamma\rho^0$	(6.6 ± 1.3) %	S=1.5	410
$\phi\gamma$	$(8.0 \pm 3.1) \times 10^{-4}$		236

$\eta(1295)$ $\quad I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 1295 \pm 4$ MeV
Full width $\Gamma = 53 \pm 6$ MeV

$\eta(1295)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi^+\pi^-$	seen	488
$a_0(980)\pi$	seen	245

$\pi(1300)$ $\quad I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 1300 \pm 100$ MeV [l]
Full width $\Gamma = 200$ to 600 MeV

$\pi(1300)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	406
$\pi(\pi\pi)_{S\text{-wave}}$	seen	612

$a_2(1320)$ $\quad I^G(J^{PC}) = 1^-(2^{++})$

Mass $m = 1318.1 \pm 0.7$ MeV (S = 1.2)
Full width $\Gamma = 107 \pm 5$ MeV [l] ($K^\pm K^0_S$ and $\eta\pi$ modes)

$a_2(1320)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\rho\pi$	(70.1 ± 2.7) %	S=1.2	419
$\eta\pi$	(14.5 ± 1.2) %		535
$\omega\pi\pi$	(10.6 ± 3.2) %	S=1.3	362
$K\overline{K}$	(4.9 ± 0.8) %		437
$\eta'(958)\pi$	$(5.7 \pm 1.1) \times 10^{-3}$		287
$\pi^\pm\gamma$	$(2.8 \pm 0.6) \times 10^{-3}$		652
$\gamma\gamma$	$(9.7 \pm 1.0) \times 10^{-6}$		659
$\pi^+\pi^-\pi^-$	< 8 %	CL=90%	621
e^+e^-	$< 2.3 \times 10^{-7}$	CL=90%	659

$f_0(1370)$ [i]
was $f_0(1300)$ $\quad I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 1200$ to 1500 MeV
Full width $\Gamma = 300$ to 500 MeV

In two-particle decay modes the $\pi\pi$ decay is dominant. We include here the resonance observed in 4π under the same entry as the one decaying to 2 pseudoscalars. See also the minireview under non-$q\overline{q}$ candidates.

$f_0(1370)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	seen	–
4π	seen	–
$2\pi^+2\pi^-$	seen	–
$\pi^+\pi^-2\pi^0$	seen	–
$\eta\eta$	seen	–
$K\overline{K}$	seen	–
$\gamma\gamma$	seen	–
e^+e^-	not seen	–

$f_1(1420)$ [n] $\quad I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1426.8 \pm 2.3$ MeV (S = 1.3)
Full width $\Gamma = 53 \pm 5$ MeV

$f_1(1420)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}\pi$	dominant	439
$\eta\pi\pi$	possibly seen	571

$\omega(1420)$ [o] $\quad I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1419 \pm 31$ MeV
Full width $\Gamma = 174 \pm 60$ MeV

$\omega(1420)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	dominant	488

$\eta(1440)$ [p] $\quad I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 1415 \pm 10$ MeV [l]
Full width $\Gamma = 60 \pm 20$ MeV [l]

$\eta(1440)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}\pi$	seen	429
$\eta\pi\pi$	seen	564
$a_0(980)\pi$	seen	347
4π	seen	637

$\rho(1450)$ [q] $\quad I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 1465 \pm 25$ MeV [l]
Full width $\Gamma = 310 \pm 60$ MeV [l]

$\rho(1450)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi\pi$	seen		719
4π	seen		665
e^+e^-	seen		732
$\eta\rho$	<4 %		317
$\omega\pi$	<2.0 %	95%	512
$\phi\pi$	<1 %		358
$K\overline{K}$	$<1.6 \times 10^{-3}$	95%	541

$f_0(1500)$ [r]
was $f_0(1525)$ and $f_0(1590)$ $\quad I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 1503 \pm 11$ MeV
Full width $\Gamma = 120 \pm 19$ MeV

$f_0(1500)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\eta'(958)$	seen	–
$\eta\eta$	seen	515
$4\pi^0$	seen	690
$\pi^0\pi^0$	seen	739
$2\pi^+2\pi^-$	seen	686

$f_1(1510)$ $\quad I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 1512 \pm 4$ MeV
Full width $\Gamma = 35 \pm 15$ MeV

$f_1(1510)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}^*(892)$+ c.c.	seen	292

$f_2'(1525)$ $I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 1525 \pm 5$ MeV [l]
Full width $\Gamma = 76 \pm 10$ MeV [l]

$f_2'(1525)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	(88.8 ±3.1) %	581
$\eta\eta$	(10.3 ±3.1) %	531
$\pi\pi$	(8.2 ±1.5) $\times 10^{-3}$	750
$\gamma\gamma$	(1.32±0.21) $\times 10^{-6}$	763

$\omega(1600)$ [s] $I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1649 \pm 24$ MeV (S = 2.3)
Full width $\Gamma = 220 \pm 35$ MeV (S = 1.6)

$\omega(1600)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	637
$\omega\pi\pi$	seen	601
e^+e^-	seen	824

$\omega_3(1670)$ $I^G(J^{PC}) = 0^-(3^{--})$

Mass $m = 1667 \pm 4$ MeV
Full width $\Gamma = 168 \pm 10$ MeV [l]

$\omega_3(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi$	seen	647
$\omega\pi\pi$	seen	614
$b_1(1235)\pi$	possibly seen	359

$\pi_2(1670)$ $I^G(J^{PC}) = 1^-(2^{-+})$

Mass $m = 1670 \pm 20$ MeV [l]
Full width $\Gamma = 258 \pm 18$ MeV [l] (S = 1.7)
$\Gamma_{ee} = 1.35 \pm 0.26$ keV

$\pi_2(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
3π	(95.8±1.4) %	–
$f_2(1270)\pi$	(56.2±3.2) %	325
$\rho\pi$	(31 ±4) %	649
$f_0(1370)\pi$	(8.7±3.4) %	–
$K\overline{K}^*(892)$+ c.c.	(4.2±1.4) %	453
$\gamma\gamma$	(5.2±1.1) $\times 10^{-6}$	835

$\phi(1680)$ $I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 1680 \pm 20$ MeV [l]
Full width $\Gamma = 150 \pm 50$ MeV [l]

$\phi(1680)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}^*(892)$+ c.c.	dominant	463
$K_S^0 K\pi$	seen	620
$K\overline{K}$	seen	681
e^+e^-	seen	840
$\omega\pi\pi$	not seen	622

$\rho_3(1690)$ $I^G(J^{PC}) = 1^+(3^{--})$

J^P from the 2π and $K\overline{K}$ modes.
Mass $m = 1691 \pm 5$ MeV [l]
Full width $\Gamma = 160 \pm 10$ MeV [l] (S = 1.5)

$\rho_3(1690)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
4π	(71.1 ± 1.9) %		788
$\pi^\pm\pi^+\pi^-\pi^0$	(67 ±22) %		788
$\pi\pi$	(23.6 ± 1.3) %		834
$\omega\pi$	(16 ± 6) %		656
$K\overline{K}\pi$	(3.8 ± 1.2) %		628
$K\overline{K}$	(1.58± 0.26) %	1.2	686
$\eta\pi^+\pi^-$	seen		728

$\rho(1700)$ [q] $I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 1700 \pm 20$ MeV [l] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)
Full width $\Gamma = 235 \pm 50$ MeV [l] ($\eta\rho^0$ and $\pi^+\pi^-$ modes)

$\rho(1700)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\rho\pi\pi$	dominant	640
$\rho^0\pi^+\pi^-$	large	640
$\rho^\pm\pi^\mp\pi^0$	large	642
$2(\pi^+\pi^-)$	large	792
$\pi^+\pi^-$	seen	838
$K\overline{K}^*(892)$+ c.c.	seen	479
$\eta\rho$	seen	533
$K\overline{K}$	seen	692
e^+e^-	seen	850

$f_J(1710)$ [t] $I^G(J^{PC}) = 0^+(\text{even}^{++})$

Mass $m = 1697 \pm 4$ MeV (S = 1.4)
Full width $\Gamma = 175 \pm 9$ MeV (S = 1.7)

$f_J(1710)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	seen	690
$\eta\eta$	seen	648
$\pi\pi$	seen	837

$\phi_3(1850)$ $I^G(J^{PC}) = 0^-(3^{--})$

Mass $m = 1854 \pm 7$ MeV
Full width $\Gamma = 87^{+28}_{-23}$ MeV (S = 1.2)

$\phi_3(1850)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\overline{K}$	seen	785
$K\overline{K}^*(892)$+ c.c.	seen	602

$f_2(2010)$ $I^G(J^{PC}) = 0^+(2^{++})$

Seen by one group only.
Mass $m = 2011^{+60}_{-80}$ MeV
Full width $\Gamma = 202 \pm 60$ MeV

$f_2(2010)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	–

$f_4(2050)$ $I^G(J^{PC}) = 0^+(4^{++})$

Mass $m = 2044 \pm 11$ MeV (S = 1.4)
Full width $\Gamma = 208 \pm 13$ MeV (S = 1.2)

$f_4(2050)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\omega\omega$	(26 ±6) %	658
$\pi\pi$	(17.0±1.5) %	1012
$K\overline{K}$	($6.8^{+3.4}_{-1.8}$) $\times 10^{-3}$	895
$\eta\eta$	(2.1±0.8) $\times 10^{-3}$	863
$4\pi^0$	< 1.2 %	977

$f_2(2300)$ $I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 2297 \pm 28$ MeV
Full width $\Gamma = 149 \pm 40$ MeV

$f_2(2300)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	529

$f_2(2340)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 2339 \pm 60$ MeV
Full width $\Gamma = 319^{+80}_{-70}$ MeV

$f_2(2340)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\phi\phi$	seen	573

STRANGE MESONS
($S = \pm 1$, $C = B = 0$)

$K^+ = u\overline{s}$, $K^0 = d\overline{s}$, $\overline{K}^0 = \overline{d}s$, $K^- = \overline{u}s$, similarly for K^*'s

$K^\pm$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [u] (S = 2.8)
Mean life $\tau = (1.2386 \pm 0.0024) \times 10^{-8}$ s (S = 2.0)
$c\tau = 3.713$ m

Slope parameter g [v]

(See Particle Listings for quadratic coefficients)
$K^+ \to \pi^+\pi^+\pi^- = -0.2154 \pm 0.0035$ (S = 1.4)
$K^- \to \pi^-\pi^-\pi^+ = -0.217 \pm 0.007$ (S = 2.5)
$K^\pm \to \pi^\pm\pi^0\pi^0 = 0.594 \pm 0.019$ (S = 1.3)

$K^\pm$ decay form factors [a,w]

K^+_{e3} $\lambda_+ = 0.0286 \pm 0.0022$
$K^+_{\mu 3}$ $\lambda_+ = 0.033 \pm 0.008$ (S = 1.6)
$K^+_{\mu 3}$ $\lambda_0 = 0.004 \pm 0.007$ (S = 1.6)
K^+_{e3} $|f_S/f_+| = 0.084 \pm 0.023$ (S = 1.2)
K^+_{e3} $|f_T/f_+| = 0.38 \pm 0.11$ (S = 1.1)
$K^+_{\mu 3}$ $|f_T/f_+| = 0.02 \pm 0.12$
$K^+ \to e^+\nu_e\gamma$ $|F_A + F_V| = 0.148 \pm 0.010$
$K^+ \to \mu^+\nu_\mu\gamma$ $|F_A + F_V| < 0.23$, CL = 90%
$K^+ \to e^+\nu_e\gamma$ $|F_A - F_V| < 0.49$
$K^+ \to \mu^+\nu_\mu\gamma$ $|F_A - F_V| = -2.2$ to 0.3

K^- modes are charge conjugates of the modes below.

K^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\mu^+\nu_\mu$		(63.51±0.18) %	S=1.3	236
$e^+\nu_e$		(1.55±0.07) × 10^{-5}		247
$\pi^+\pi^0$		(21.16±0.14) %	S=1.1	205
$\pi^+\pi^+\pi^-$		(5.59±0.05) %	S=1.8	125
$\pi^+\pi^0\pi^0$		(1.73±0.04) %	S=1.2	133
$\pi^0\mu^+\nu_\mu$ Called $K^+_{\mu 3}$.		(3.18±0.08) %	S=1.5	215
$\pi^0 e^+\nu_e$ Called K^+_{e3}.		(4.82±0.06) %	S=1.3	228
$\pi^0\pi^0 e^+\nu_e$		(2.1 ±0.4) × 10^{-5}		206
$\pi^+\pi^- e^+\nu_e$		(3.91±0.17) × 10^{-5}		203
$\pi^+\pi^-\mu^+\nu_\mu$		(1.4 ±0.9) × 10^{-5}		151
$\pi^0\pi^0\pi^0 e^+\nu_e$		< 3.5 × 10^{-6}	CL=90%	135
$\pi^+\gamma\gamma$	[x]	< 1 × 10^{-6}	CL=90%	227
$\pi^+ 3\gamma$	[x]	< 1.0 × 10^{-4}	CL=90%	227
$\mu^+\nu_\mu\nu\overline{\nu}$		< 6.0 × 10^{-6}	CL=90%	236
$e^+\nu_e\nu\overline{\nu}$		< 6 × 10^{-5}	CL=90%	247
$\mu^+\nu_\mu e^+e^-$		(1.06±0.32) × 10^{-6}		236
$e^+\nu_e e^+e^-$		(2.1 $^{+2.1}_{-1.1}$) × 10^{-7}		247
$\mu^+\nu_\mu\mu^+\mu^-$		< 4.1 × 10^{-7}	CL=90%	185
$\mu^+\nu_\mu\gamma$	[x,y]	(5.50±0.28) × 10^{-3}		236
$\pi^+\pi^0\gamma$	[x,y]	(2.75±0.15) × 10^{-4}		205
$\pi^+\pi^0\gamma$(DE)	[x,z]	(1.8 ±0.4) × 10^{-5}		205
$\pi^+\pi^+\pi^-\gamma$	[x,y]	(1.04±0.31) × 10^{-4}		125
$\pi^+\pi^0\pi^0\gamma$	[x,y]	(7.5 $^{+5.5}_{-3.0}$) × 10^{-6}		133
$\pi^0\mu^+\nu_\mu\gamma$	[x,y]	< 6.1 × 10^{-5}	CL=90%	215
$\pi^0 e^+\nu_e\gamma$	[x,y]	(2.62±0.20) × 10^{-4}		228
$\pi^0 e^+\nu_e\gamma$(SD)	[aa]	< 5.3 × 10^{-5}	CL=90%	228
$\pi^0\pi^0 e^+\nu_e\gamma$		< 5 × 10^{-6}	CL=90%	206

Lepton Family number (LF), Lepton number (L), $\Delta S = \Delta Q$ (SQ) violating modes, or $\Delta S = 1$ weak neutral current ($S1$) modes

			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi^+\pi^+ e^-\overline{\nu}_e$	SQ		< 1.2 × 10^{-8}	CL=90%	203
$\pi^+\pi^+\mu^-\overline{\nu}_\mu$	SQ		< 3.0 × 10^{-6}	CL=95%	151
$\pi^+ e^+e^-$	$S1$		(2.74±0.23) × 10^{-7}		227
$\pi^+\mu^+\mu^-$	$S1$		< 2.3 × 10^{-7}	CL=90%	172
$\pi^+\nu\overline{\nu}$	$S1$		< 2.4 × 10^{-9}	CL=90%	227
$\mu^-\nu e^+e^+$	LF		< 2.0 × 10^{-8}	CL=90%	236
$\mu^+\nu_e$	LF	[d]	< 4 × 10^{-3}	CL=90%	236
$\pi^+\mu^+e^-$	LF		< 2.1 × 10^{-10}	CL=90%	214
$\pi^+\mu^-e^+$	LF		< 7 × 10^{-9}	CL=90%	214
$\pi^-\mu^+e^+$	L		< 7 × 10^{-9}	CL=90%	214
$\pi^- e^+e^+$	L		< 1.0 × 10^{-8}	CL=90%	227
$\pi^-\mu^+\mu^+$	L		< 1.5 × 10^{-4}	CL=90%	172
$\mu^+\overline{\nu}_e$	L	[d]	< 3.3 × 10^{-3}	CL=90%	236
$\pi^0 e^+\overline{\nu}_e$	L	[d]	< 3 × 10^{-3}	CL=90%	228

K^0

$I(J^P) = \frac{1}{2}(0^-)$

50% K_S, 50% K_L
Mass $m = 497.672 \pm 0.031$ MeV
$m_{K^0} - m_{K^\pm} = 3.995 \pm 0.034$ MeV (S = 1.1)
$|m_{K^0} - m_{\overline{K}^0}| / m_{\text{average}} < 9 \times 10^{-19}$ [bb]

K^0_S

$I(J^P) = \frac{1}{2}(0^-)$

Mean life $\tau = (0.8927 \pm 0.0009) \times 10^{-10}$ s
$c\tau = 2.6762$ cm

CP-violation parameters [cc]

$\text{Im}(\eta_{+-0}) = -0.015 \pm 0.030$
$\text{Im}(\eta_{000})^2 < 0.1$, CL = 90%

K^0_S DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\pi^-$		(68.61±0.28) %	S=1.2	206
$\pi^0\pi^0$		(31.39±0.28) %	S=1.2	209
$\pi^+\pi^-\gamma$	[y,dd]	(1.78±0.05) × 10^{-3}		206
$\gamma\gamma$		(2.4 ±0.9) × 10^{-6}		249
$\pi^+\pi^-\pi^0$		(3.9 $^{+5.5}_{-1.9}$) × 10^{-7}		133
$3\pi^0$		< 3.7 × 10^{-5}	CL=90%	139
$\pi^\pm e^\mp\nu$	[ee]	(6.70±0.07) × 10^{-4}	S=1.3	229
$\pi^\pm\mu^\mp\nu$	[ee]	(4.69±0.06) × 10^{-4}	S=1.2	216
$\Delta S = 1$ weak neutral current ($S1$) modes				
$\mu^+\mu^-$	$S1$	< 3.2 × 10^{-7}	CL=90%	225
e^+e^-	$S1$	< 2.8 × 10^{-6}	CL=90%	249
$\pi^0 e^+e^-$	$S1$	< 1.1 × 10^{-6}	CL=90%	231

K^0_L

$I(J^P) = \frac{1}{2}(0^-)$

$m_{K_L} - m_{K_S} = (0.5304 \pm 0.0014) \times 10^{10}\ \hbar\ s^{-1}$
$= (3.491 \pm 0.009) \times 10^{-12}$ MeV
Mean life $\tau = (5.17 \pm 0.04) \times 10^{-8}$ s (S = 1.1)
$c\tau = 15.51$ m

Slope parameter g [v]

(See Particle Listings for quadratic coefficients)
$K^0_L \to \pi^+\pi^-\pi^0 = 0.670 \pm 0.014$ (S = 1.6)

K_L decay form factors [w]

K^0_{e3} $\lambda_+ = 0.0300 \pm 0.0016$ (S = 1.2)
$K^0_{\mu 3}$ $\lambda_+ = 0.034 \pm 0.005$ (S = 2.3)
$K^0_{\mu 3}$ $\lambda_0 = 0.025 \pm 0.006$ (S = 2.3)
K^0_{e3} $|f_S/f_+| < 0.04$, CL = 68%
K^0_{e3} $|f_T/f_+| < 0.23$, CL = 68%
$K^0_{\mu 3}$ $|f_T/f_+| = 0.12 \pm 0.12$
$K_L \to e^+e^-\gamma$: $\alpha_{K^*} = -0.28 \pm 0.08$

CP-violation parameters [cc]

$\delta = (0.327 \pm 0.012)\%$

$|\eta_{00}| = (2.275 \pm 0.019) \times 10^{-3}$ (S = 1.1)

$|\eta_{+-}| = (2.285 \pm 0.019) \times 10^{-3}$

$|\eta_{00}/\eta_{+-}| = 0.9956 \pm 0.0023$ [ff] (S = 1.8)

$\epsilon'/\epsilon = (1.5 \pm 0.8) \times 10^{-3}$ [ff] (S = 1.8)

$\phi_{+-} = (43.7 \pm 0.6)°$

$\phi_{00} = (43.5 \pm 1.0)°$

$\phi_{00} - \phi_{+-} = (-0.2 \pm 0.8)°$

j for $K^0_L \to \pi^+\pi^-\pi^0 = 0.0011 \pm 0.0008$

$|\eta_{+-\gamma}| = (2.35 \pm 0.07) \times 10^{-3}$

$\phi_{+-\gamma} = (44 \pm 4)°$

$|\epsilon'_{+-\gamma}|/\epsilon < 0.3$, CL = 90%

$\Delta S = -\Delta Q$ in $K^0_{\ell 3}$ decay

Re $x = 0.006 \pm 0.018$ (S = 1.3)

Im $x = -0.003 \pm 0.026$ (S = 1.2)

CPT-violation parameters

Re $\Delta = 0.018 \pm 0.020$

Im $\Delta = 0.02 \pm 0.04$

K^0_L DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$3\pi^0$		(21.12 ± 0.27) %	S=1.1	139
$\pi^+\pi^-\pi^0$		(12.56 ± 0.20) %	S=1.7	133
$\pi^\pm\mu^\mp\nu$ Called $K^0_{\mu 3}$.	[gg]	(27.17 ± 0.25) %	S=1.1	216
$\pi^\pm e^\mp\nu_e$ Called K^0_{e3}.	[gg]	(38.78 ± 0.27) %	S=1.1	229
2γ		$(5.92 \pm 0.15) \times 10^{-4}$		249
3γ		$< 2.4 \times 10^{-7}$	CL=90%	249
$\pi^0 2\gamma$	[hh]	$(1.70 \pm 0.28) \times 10^{-6}$		231
$\pi^0\pi^\pm e^\mp\nu$	[gg]	$(5.18 \pm 0.29) \times 10^{-5}$		207
$(\pi\mu\text{atom})\nu$		$(1.06 \pm 0.11) \times 10^{-7}$		–
$\pi^\pm e^\mp\nu_e\gamma$	[y,gg,hh]	(1.3 ± 0.8) %		229
$\pi^+\pi^-\gamma$	[y,hh]	$(4.61 \pm 0.14) \times 10^{-5}$		206
$\pi^0\pi^0\gamma$		$< 5.6 \times 10^{-6}$		209
Charge conjugation × Parity (CP, CPV) or Lepton Family number (LF) violating modes, or $\Delta S = 1$ weak neutral current (S1) modes				
$\pi^+\pi^-$	CPV	$(2.067 \pm 0.035) \times 10^{-3}$	S=1.1	206
$\pi^0\pi^0$	CPV	$(9.36 \pm 0.20) \times 10^{-4}$		209
$\mu^+\mu^-$	S1	$(7.2 \pm 0.5) \times 10^{-9}$	S=1.4	225
$\mu^+\mu^-\gamma$	S1	$(3.23 \pm 0.30) \times 10^{-7}$		225
e^+e^-	S1	$< 4.1 \times 10^{-11}$	CL=90%	249
$e^+e^-\gamma$	S1	$(9.1 \pm 0.5) \times 10^{-6}$		249
$e^+e^-\gamma\gamma$	S1 [hh]	$(6.5 \pm 1.2) \times 10^{-7}$		249
$\pi^+\pi^-e^+e^-$	S1	$< 2.5 \times 10^{-6}$	CL=90%	206
$\mu^+\mu^-e^+e^-$	S1	$< 4.9 \times 10^{-6}$	CL=90%	225
$e^+e^-e^+e^-$	S1 [ii]	$(4.1 \pm 0.8) \times 10^{-8}$	S=1.2	249
$\pi^0\mu^+\mu^-$	CP,S1 [jj]	$< 5.1 \times 10^{-9}$	CL=90%	177
$\pi^0 e^+e^-$	CP,S1 [jj]	$< 4.3 \times 10^{-9}$	CL=90%	231
$\pi^0\nu\overline{\nu}$	CP,S1 [kk]	$< 5.8 \times 10^{-5}$	CL=90%	231
$e^\pm\mu^\mp$	LF [gg]	$< 3.3 \times 10^{-11}$	CL=90%	238

$K^*(892)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(892)^\pm$ mass $m = 891.59 \pm 0.24$ MeV (S = 1.1)

$K^*(892)^0$ mass $m = 896.10 \pm 0.28$ MeV (S = 1.4)

$K^*(892)^\pm$ full width $\Gamma = 49.8 \pm 0.8$ MeV

$K^*(892)^0$ full width $\Gamma = 50.5 \pm 0.6$ MeV (S = 1.1)

$K^*(892)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K\pi$	~ 100 %		291
$K^0\gamma$	$(2.30 \pm 0.20) \times 10^{-3}$		310
$K^\pm\gamma$	$(1.01 \pm 0.09) \times 10^{-3}$		309
$K\pi\pi$	$< 7 \times 10^{-4}$	95%	224

$K_1(1270)$

$I(J^P) = \frac{1}{2}(1^+)$

Mass $m = 1273 \pm 7$ MeV [l]

Full width $\Gamma = 90 \pm 20$ MeV [l]

$K_1(1270)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\rho$	(42 ± 6) %	76
$K^*_0(1430)\pi$	(28 ± 4) %	–
$K^*(892)\pi$	(16 ± 5) %	301
$K\omega$	(11.0 ± 2.0) %	–
$K f_0(1370)$	(3.0 ± 2.0) %	–

$K_1(1400)$

$I(J^P) = \frac{1}{2}(1^+)$

Mass $m = 1402 \pm 7$ MeV

Full width $\Gamma = 174 \pm 13$ MeV (S = 1.6)

$K_1(1400)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K^*(892)\pi$	(94 ± 6) %	401
$K\rho$	(3.0 ± 3.0) %	298
$K f_0(1370)$	(2.0 ± 2.0) %	–
$K\omega$	(1.0 ± 1.0) %	285

$K^*(1410)$

$I(J^P) = \frac{1}{2}(1^-)$

Mass $m = 1412 \pm 12$ MeV (S = 1.1)

Full width $\Gamma = 227 \pm 22$ MeV (S = 1.1)

$K^*(1410)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K^*(892)\pi$	> 40 %	95%	408
$K\pi$	(6.6 ± 1.3) %		611
$K\rho$	< 7 %	95%	309

$K^*_0(1430)$ [ll]

$I(J^P) = \frac{1}{2}(0^+)$

Mass $m = 1429 \pm 6$ MeV

Full width $\Gamma = 287 \pm 23$ MeV

$K^*_0(1430)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	(93 ± 10) %	621

$K^*_2(1430)$

$I(J^P) = \frac{1}{2}(2^+)$

$K^*_2(1430)^\pm$ mass $m = 1425.4 \pm 1.3$ MeV (S = 1.1)

$K^*_2(1430)^0$ mass $m = 1432.4 \pm 1.3$ MeV

$K^*_2(1430)^\pm$ full width $\Gamma = 98.4 \pm 2.3$ MeV

$K^*_2(1430)^0$ full width $\Gamma = 109 \pm 5$ MeV (S = 1.9)

$K^*_2(1430)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$K\pi$	(49.7 ± 1.2) %		622
$K^*(892)\pi$	(25.2 ± 1.7) %		423
$K^*(892)\pi\pi$	(13.0 ± 2.3) %		375
$K\rho$	(8.8 ± 0.8) %	S=1.2	331
$K\omega$	(2.9 ± 0.8) %		319
$K^+\gamma$	$(2.4 \pm 0.5) \times 10^{-3}$		627
$K\eta$	$(1.4^{+2.8}_{-0.9}) \times 10^{-3}$	S=1.1	492
$K\omega\pi$	$< 7.2 \times 10^{-4}$	CL=95%	110
$K^0\gamma$	$< 9 \times 10^{-4}$	CL=90%	631

$K^*(1680)$

$I(J^P) = \frac{1}{2}(1^-)$

Mass $m = 1714 \pm 20$ MeV (S = 1.1)
Full width $\Gamma = 323 \pm 110$ MeV (S = 4.2)

$K^*(1680)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	(38.7 ± 2.5) %	779
$K\rho$	$(31.4^{+4.7}_{-2.1})$ %	571
$K^*(892)\pi$	$(29.9^{+2.2}_{-4.7})$ %	615

$K_2(1770)$ [mm]

$I(J^P) = \frac{1}{2}(2^-)$

Mass $m = 1773 \pm 8$ MeV
Full width $\Gamma = 186 \pm 14$ MeV

$K_2(1770)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi\pi$		–
$K_2^*(1430)\pi$	dominant	287
$K^*(892)\pi$	seen	653
$K f_2(1270)$	seen	–
$K\phi$	seen	441
$K\omega$	seen	608

$K_3^*(1780)$

$I(J^P) = \frac{1}{2}(3^-)$

Mass $m = 1770 \pm 10$ MeV (S = 1.7)
Full width $\Gamma = 164 \pm 17$ MeV (S = 1.1)

$K_3^*(1780)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$K\rho$	(45 ± 4) %	S=1.4	612
$K^*(892)\pi$	(27.3 ± 3.2) %	S=1.5	651
$K\pi$	(19.3 ± 1.0) %		810
$K\eta$	(8.0 ± 1.5) %	S=1.4	715
$K_2^*(1430)\pi$	< 21 %	CL=95%	284

$K_2(1820)$ [nn]

$I(J^P) = \frac{1}{2}(2^-)$

Mass $m = 1816 \pm 13$ MeV
Full width $\Gamma = 276 \pm 35$ MeV

$K_2(1820)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\phi$	possibly seen	481
$K_2^*(1430)\pi$	seen	325
$K^*(892)\pi$	seen	680
$K f_2(1270)$	seen	186
$K\omega$	seen	638

$K_4^*(2045)$

$I(J^P) = \frac{1}{2}(4^+)$

Mass $m = 2045 \pm 9$ MeV (S = 1.1)
Full width $\Gamma = 198 \pm 30$ MeV

$K_4^*(2045)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$K\pi$	(9.9 ± 1.2) %	958
$K^*(892)\pi\pi$	(9 ± 5) %	800
$K^*(892)\pi\pi\pi$	(7 ± 5) %	764
$\rho K\pi$	(5.7 ± 3.2) %	742
$\omega K\pi$	(5.0 ± 3.0) %	736
$\phi K\pi$	(2.8 ± 1.4) %	591
$\phi K^*(892)$	(1.4 ± 0.7) %	363

CHARMED MESONS
($C = \pm 1$)

$D^+ = c\overline{d}$, $D^0 = c\overline{u}$, $\overline{D}^0 = \overline{c}u$, $D^- = \overline{c}d$, similarly for D^*'s

$D^\pm$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.3 \pm 0.5$ MeV (S = 1.1)
Mean life $\tau = (1.057 \pm 0.015) \times 10^{-12}$ s
$c\tau = 317$ μm

CP-violation decay-rate asymmetries

$A_{CP}(K^+K^-\pi^\pm) = -0.03 \pm 0.07$
$A_{CP}(K^\pm K^{*0}) = -0.12 \pm 0.13$
$A_{CP}(\phi\pi^\pm) = 0.07 \pm 0.09$

$D^+ \to \overline{K}^*(892)^0 \ell^+ \nu_\ell$ form factors

$r_2 = 0.73 \pm 0.15$
$r_v = 1.90 \pm 0.25$
$\Gamma_L/\Gamma_T = 1.23 \pm 0.13$
$\Gamma_+/\Gamma_- = 0.16 \pm 0.04$

D^- modes are charge conjugates of the modes below.

D^+ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Inclusive modes			
e^+ anything	(17.2 ± 1.9) %		–
K^- anything	(24.2 ± 2.8) %	S=1.4	–
$\overline{K}^0$ anything + K^0 anything	(59 ± 7) %		–
K^+ anything	(5.8 ± 1.4) %		–
η anything	[oo] < 13 %	CL=90%	–
Leptonic and semileptonic modes			
$\mu^+\nu_\mu$	$< 7.2 \times 10^{-4}$	CL=90%	932
$\overline{K}^0 \ell^+ \nu_\ell$	[pp] (6.7 ± 0.8) %		868
$\overline{K}^0 e^+ \nu_e$	(6.6 ± 0.9) %		868
$\overline{K}^0 \mu^+ \nu_\mu$	$(7.0 ^{+3.0}_{-2.0})$ %		865
$K^-\pi^+ e^+ \nu_e$	$(4.2 ^{+0.9}_{-0.7})$ %		863
$\overline{K}^*(892)^0 e^+ \nu_e$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(3.2 ± 0.33) %		720
$K^-\pi^+ e^+ \nu_e$ nonresonant	$< 7 \times 10^{-3}$	CL=90%	863
$K^-\pi^+\mu^+\nu_\mu$	(3.2 ± 0.4) %	S=1.1	851
$\overline{K}^*(892)^0 \mu^+ \nu_\mu$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(3.0 ± 0.4) %		715
$K^-\pi^+\mu^+\nu_\mu$ nonresonant	$(2.7 \pm 1.1) \times 10^{-3}$		851
$(\overline{K}^*(892)\pi)^0 e^+ \nu_e$	< 1.2 %	CL=90%	714
$(\overline{K}\pi\pi)^0 e^+ \nu_e$ non-$\overline{K}^*(892)$	$< 9 \times 10^{-3}$	CL=90%	846
$K^-\pi^+\pi^0\mu^+\nu_\mu$	$< 1.4 \times 10^{-3}$	CL=90%	825
$\pi^0 \ell^+ \nu_\ell$	[qq] $(5.7 \pm 2.2) \times 10^{-3}$		930
Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.			
$\overline{K}^*(892)^0 \ell^+ \nu_\ell$	[pp] (4.8 ± 0.4) %		720
$\overline{K}^*(892)^0 e^+ \nu_e$	(4.8 ± 0.5) %		720
$\overline{K}^*(892)^0 \mu^+ \nu_\mu$	(4.5 ± 0.6) %	S=1.1	715
$\rho^0 e^+ \nu_e$	$< 3.7 \times 10^{-3}$	CL=90%	776
$\rho^0 \mu^+ \nu_\mu$	$(2.0 ^{+1.5}_{-1.3}) \times 10^{-3}$		772
$\phi e^+ \nu_e$	< 2.09 %	CL=90%	657
$\phi \mu^+ \nu_\mu$	< 3.72 %	CL=90%	651
$\eta'(958)\mu^+\nu_\mu$	$< 9 \times 10^{-3}$	CL=90%	684
Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$			
$\overline{K}^0\pi^+$	(2.74 ± 0.29) %		862
$K^-\pi^+\pi^+$	[rr] (9.1 ± 0.6) %		845
$\overline{K}^*(892)^0\pi^+$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(1.28 ± 0.13) %		712
$\overline{K}_0^*(1430)^0\pi^+$ $\times$ B($\overline{K}_0^*(1430)^0 \to K^-\pi^+$)	(2.3 ± 0.3) %		368
$\overline{K}^*(1680)^0\pi^+$ $\times$ B($\overline{K}^*(1680)^0 \to K^-\pi^+$)	$(3.7 \pm 0.8) \times 10^{-3}$		65
$K^-\pi^+\pi^+$ nonresonant	(8.6 ± 0.9) %		845

$\overline{K}^0\pi^+\pi^0$	[rr]	(9.7 ±3.0) %	S=1.1	845
$\overline{K}^0\rho^+$		(6.6 ±2.5) %		680
$\overline{K}^*(892)^0\pi^+ \times B(\overline{K}^{*0} \to \overline{K}^0\pi^0)$		(6.4 ±0.6) × 10^{-3}		712
$\overline{K}^0\pi^+\pi^0$ nonresonant		(1.3 ±1.1) %		845
$K^-\pi^+\pi^+\pi^0$	[rr]	(6.4 ±1.1) %		816
$\overline{K}^*(892)^0\rho^+$ total $\times B(\overline{K}^{*0} \to K^-\pi^+)$		(1.4 ±0.9) %		423
$\overline{K}_1(1400)^0\pi^+ \times B(\overline{K}_1(1400)^0 \to K^-\pi^+\pi^0)$		(2.2 ±0.6) %		390
$K^-\rho^+\pi^+$ total		(3.1 ±1.1) %		616
$K^-\rho^+\pi^+$ 3-body		(1.1 ±0.4) %		616
$\overline{K}^*(892)^0\pi^+\pi^0$ total $\times B(\overline{K}^{*0} \to K^-\pi^+)$		(4.5 ±0.9) %		687
$\overline{K}^*(892)^0\pi^+\pi^0$ 3-body $\times B(\overline{K}^{*0} \to K^-\pi^+)$		(2.8 ±0.9) %		687
$K^*(892)^-\pi^+\pi^+$ 3-body $\times B(K^{*-} \to K^-\pi^0)$		(7 ±3) × 10^{-3}		688
$K^-\pi^+\pi^+\pi^0$ nonresonant	[ss]	(1.2 ±0.6) %		816
$\overline{K}^0\pi^+\pi^+\pi^-$	[rr]	(7.0 ±1.0) %		814
$\overline{K}^0 a_1(1260)^+ \times B(a_1(1260)^+ \to \pi^+\pi^+\pi^-)$		(4.0 ±0.9) %		328
$\overline{K}_1(1400)^0\pi^+ \times B(\overline{K}_1(1400)^0 \to \overline{K}^0\pi^+\pi^-)$		(2.2 ±0.6) %		390
$K^*(892)^-\pi^+\pi^+$ 3-body $\times B(K^{*-} \to \overline{K}^0\pi^-)$		(1.4 ±0.6) %		688
$\overline{K}^0\rho^0\pi^+$ total		(4.2 ±0.9) %		614
$\overline{K}^0\rho^0\pi^+$ 3-body		(5 ±5) × 10^{-3}		614
$\overline{K}^0\pi^+\pi^+\pi^-$ nonresonant		(8 ±4) × 10^{-3}		814
$K^-\pi^+\pi^+\pi^+\pi^-$		(8.2 ±1.4) × 10^{-3}		772
$\overline{K}^*(892)^0\pi^+\pi^+\pi^- \times B(\overline{K}^{*0} \to K^-\pi^+)$		(6.8 ±1.8) × 10^{-3}		642
$\overline{K}^*(892)^0\rho^0\pi^+ \times B(\overline{K}^{*0} \to K^-\pi^+)$		(5.1 ±2.2) × 10^{-3}		242
$K^-\pi^+\pi^+\pi^0\pi^0$		(2.2 $^{+5.0}_{-0.9}$) %		775
$\overline{K}^0\pi^+\pi^+\pi^-\pi^0$		(5.4 $^{+3.0}_{-1.4}$) %		773
$\overline{K}^0\pi^+\pi^+\pi^+\pi^-\pi^-$		(8 ±7) × 10^{-4}		714
$K^-\pi^+\pi^+\pi^+\pi^-\pi^0$		(2.0 ±1.8) × 10^{-3}		718
$\overline{K}^0\overline{K}^0K^+$		(1.8 ±0.8) %		545

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

$\overline{K}^0\rho^+$		(6.6 ±2.5) %		680
$\overline{K}^0 a_1(1260)^+$		(8.1 ±1.7) %		328
$\overline{K}^0 a_2(1320)^+$		< 3 × 10^{-3}	CL=90%	199
$\overline{K}^*(892)^0\pi^+$		(1.92±0.19) %		712
$\overline{K}^*(892)^0\rho^+$ total		(2.1 ±1.4) %		423
$\overline{K}^*(892)^0\rho^+$ S-wave	[ss]	(1.7 ±1.6) %		423
$\overline{K}^*(892)^0\rho^+$ P-wave		< 1 × 10^{-3}	CL=90%	423
$\overline{K}^*(892)^0\rho^+$ D-wave		(10 ±7) × 10^{-3}		423
$\overline{K}^*(892)^0\rho^+$ D-wave longitudinal		< 7 × 10^{-3}	CL=90%	423
$\overline{K}_1(1270)^0\pi^+$		< 7 × 10^{-3}	CL=90%	487
$\overline{K}_1(1400)^0\pi^+$		(5.0 ±1.3) %		390
$\overline{K}^*(1410)^0\pi^+$		< 7 × 10^{-3}	CL=90%	382
$\overline{K}_0^*(1430)^0\pi^+$		(3.7 ±0.4) %		368
$\overline{K}^*(1680)^0\pi^+$		(1.45±0.31) %		65
$\overline{K}^*(892)^0\pi^+\pi^0$ total		(6.7 ±1.4) %		687
$\overline{K}^*(892)^0\pi^+\pi^0$ 3-body		(4.2 ±1.4) %		687
$K^*(892)^-\pi^+\pi^+$ 3-body		(2.1 ±0.9) %		688
$K^-\rho^+\pi^+$ total		(3.1 ±1.1) %		616
$K^-\rho^+\pi^+$ 3-body		(1.1 ±0.4) %		616
$\overline{K}^0\rho^0\pi^+$ total		(4.2 ±0.9) %	CL=90%	614
$\overline{K}^0\rho^0\pi^+$ 3-body		(5 ±5) × 10^{-3}		614
$\overline{K}^0 f_0(980)\pi^+$		< 5 × 10^{-3}	CL=90%	461
$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$		(1.02±0.27) %		642
$\overline{K}^*(892)^0\rho^0\pi^+$		(7.7 ±3.3) × 10^{-3}		242

Pionic modes

$\pi^+\pi^0$		(2.5 ±0.7) × 10^{-3}		925
$\pi^+\pi^+\pi^-$		(3.2 ±0.6) × 10^{-3}		908
$\rho^0\pi^+$		< 1.4 × 10^{-3}	CL=90%	769
$\pi^+\pi^+\pi^-$ nonresonant		(2.5 ±0.7) × 10^{-3}		908
$\pi^+\pi^+\pi^-\pi^0$		(1.9 $^{+1.5}_{-1.2}$) %		882
$\eta\pi^+ \times B(\eta \to \pi^+\pi^-\pi^0)$		(1.8 ±0.6) × 10^{-3}		848
$\omega\pi^+ \times B(\omega \to \pi^+\pi^-\pi^0)$		< 6 × 10^{-3}	CL=90%	764
$\pi^+\pi^+\pi^+\pi^-\pi^-$		(1.0 $^{+0.8}_{-0.7}$) × 10^{-3}		845
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$		(2.9 $^{+2.9}_{-2.0}$) × 10^{-3}		799

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

$\eta\pi^+$		(7.5 ±2.5) × 10^{-3}		848
$\rho^0\pi^+$		< 1.4 × 10^{-3}	CL=90%	769
$\omega\pi^+$		< 7 × 10^{-3}	CL=90%	764
$\eta\rho^+$		< 1.2 %	CL=90%	658
$\eta'(958)\pi^+$		< 9 × 10^{-3}	CL=90%	680
$\eta'(958)\rho^+$		< 1.5 %	CL=90%	355

Hadronic modes with a $K\overline{K}$ pair

$K^+\overline{K}^0$		(7.2 ±1.2) × 10^{-3}		792
$K^+K^-\pi^+$	[rr]	(8.9 ±0.8) × 10^{-3}		744
$\phi\pi^+ \times B(\phi \to K^+K^-)$		(3.0 ±0.3) × 10^{-3}		647
$K^+\overline{K}^*(892)^0 \times B(\overline{K}^{*0} \to K^-\pi^+)$		(2.8 ±0.4) × 10^{-3}		610
$K^+K^-\pi^+$ nonresonant		(4.6 ±0.9) × 10^{-3}		744
$K^0\overline{K}^0\pi^+$				741
$K^*(892)^+\overline{K}^0 \times B(K^{*+} \to K^0\pi^+)$		(2.0 ±0.9) %		611
$K^+K^-\pi^+\pi^0$				682
$\phi\pi^+\pi^0 \times B(\phi \to K^+K^-)$		(1.1 ±0.5) %		619
$\phi\rho^+ \times B(\phi \to K^+K^-)$		< 7 × 10^{-3}	CL=90%	268
$K^+K^-\pi^+\pi^0$ non-ϕ		(1.5 $^{+0.7}_{-0.6}$) %		682
$K^+\overline{K}^0\pi^+\pi^-$		< 2 %	CL=90%	678
$K^0K^-\pi^+\pi^+$		(1.0 ±0.6) %		678
$K^*(892)^+\overline{K}^*(892)^0 \times B^2(K^* \to K\pi^+)$		(1.2 ±0.5) %		273
$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$		< 7.9 × 10^{-3}	CL=90%	678
$K^+K^-\pi^+\pi^+\pi^-$				600
$\phi\pi^+\pi^+\pi^- \times B(\phi \to K^+K^-)$		< 1 × 10^{-3}	CL=90%	565
$K^+K^-\pi^+\pi^+\pi^-$ nonresonant		< 3 %	CL=90%	600

Fractions of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

$\phi\pi^+$		(6.1 ±0.6) × 10^{-3}		647
$\phi\pi^+\pi^0$		(2.3 ±1.0) %		619
$\phi\rho^+$		< 1.5 %	CL=90%	268
$\phi\pi^+\pi^+\pi^-$		< 2 × 10^{-3}	CL=90%	565
$K^+\overline{K}^*(892)^0$		(4.2 ±0.5) × 10^{-3}		610
$K^*(892)^+\overline{K}^0$		(3.0 ±1.4) %		611
$K^*(892)^+\overline{K}^*(892)^0$		(2.6 ±1.1) %		273

Doubly Cabibbo suppressed (*DC*) modes, $\Delta C = 1$ weak neutral current (*C1*) modes, or Lepton Family number (*LF*) or Lepton number (*L*) violating modes

$K^+\pi^+\pi^-$	DC		(6.5 ±2.6) × 10^{-4}		845
$K^+\rho^0$	DC		< 6 × 10^{-4}	CL=90%	681
$K^*(892)^0\pi^+$	DC		< 1.9 × 10^{-4}	CL=90%	712
$K^+K^+K^-$	DC		< 1.5 × 10^{-4}	CL=90%	550
ϕK^+	DC		< 1.3 × 10^{-4}	CL=90%	527
$\pi^+e^+e^-$	C1		< 6.6 × 10^{-5}	CL=90%	929
$\pi^+\mu^+\mu^-$	C1		< 1.8 × 10^{-5}	CL=90%	917
$\rho^+\mu^+\mu^-$	C1		< 5.6 × 10^{-4}	CL=90%	759
$K^+e^+e^-$		[tt]	< 4.8 × 10^{-3}	CL=90%	869
$K^+\mu^+\mu^-$		[tt]	< 3.2 × 10^{-4}	CL=90%	856
$\pi^+e^\pm\mu^\mp$	LF	[gg]	< 3.8 × 10^{-3}	CL=90%	926
$\pi^+e^+\mu^-$	LF		< 3.3 × 10^{-3}	CL=90%	926
$\pi^+e^-\mu^+$	LF		< 3.3 × 10^{-3}	CL=90%	926
$K^+e^+\mu^-$	LF		< 3.4 × 10^{-3}	CL=90%	866
$K^+e^-\mu^+$	LF		< 3.4 × 10^{-3}	CL=90%	866
$\pi^-e^+e^+$	L		< 4.8 × 10^{-3}	CL=90%	929
$\pi^-\mu^+\mu^+$	L		< 2.2 × 10^{-4}	CL=90%	917
$\pi^-e^+\mu^+$	L		< 3.7 × 10^{-3}	CL=90%	926
$\rho^-\mu^+\mu^+$	L		< 5.6 × 10^{-4}	CL=90%	759
$K^-e^+e^+$	L		< 9.1 × 10^{-3}	CL=90%	869
$K^-\mu^+\mu^+$	L		< 3.2 × 10^{-4}	CL=90%	856
$K^-e^+\mu^+$	L		< 4.0 × 10^{-3}	CL=90%	866
$K^*(892)^-\mu^+\mu^+$	L		< 8.5 × 10^{-4}	CL=90%	703

D^0

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1864.5 \pm 0.5$ MeV (S = 1.1)
$|m_{D_1^0} - m_{D_2^0}| < 21 \times 10^{10}\ \hbar\ s^{-1}$, CL = 90% [uu]
$m_{D^\pm} - m_{D^0} = 4.78 \pm 0.10$ MeV
Mean life $\tau = (0.415 \pm 0.004) \times 10^{-12}$ s
$c\tau = 124.4\ \mu$m
$|\Gamma_{D_1^0} - \Gamma_{D_2^0}|/\Gamma_{D^0} < 0.17$, CL = 90% [uu]
$\frac{\Gamma(K^+\pi^- \text{ or } K^+\pi^-\pi^+\pi^- (\text{via } \overline{D}^0))}{\Gamma(K^-\pi^+ \text{ or } K^-\pi^+\pi^+\pi^-)} < 0.0037$, CL = 90%
$\Gamma(\mu^- X \text{ (via } \overline{D}^0))/\Gamma(\mu^+ X) < 0.0056$, CL = 90%

CP-violation decay-rate asymmetries

$A_{CP}(K^+K^-) = 0.06 \pm 0.05$
$A_{CP}(K_S^0\phi) = -0.03 \pm 0.09$
$A_{CP}(K_S^0\pi^0) = -0.018 \pm 0.030$

$\overline{D}^0$ modes are charge conjugates of the modes below.

D^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Inclusive modes				
e^+ anything		(7.7 ±1.2) %	S=1.1	–
μ^+ anything	[vv]	(6.8 ±1.0) %		–
K^- anything		(53 ±4) %	S=1.3	–
$\overline{K}^0$ anything + K^0 anything		(42 ±5) %		–
K^+ anything		(3.4 $^{+0.6}_{-0.4}$) %		–
η anything	[oo]	< 13 %	CL=90%	–
Semileptonic modes				
$K^-\ell^+\nu_\ell$	[pp]	(3.48±0.16) %	S=1.1	867
$K^-e^+\nu_e$		(3.64±0.20) %	S=1.1	867
$K^-\mu^+\nu_\mu$		(3.23±0.19) %		863
$K^-\pi^0e^+\nu_e$		(1.6 $^{+1.3}_{-0.5}$) %		861
$\overline{K}^0\pi^-e^+\nu_e$		(2.8 $^{+1.7}_{-0.9}$) %		860
$\overline{K}^*(892)^-e^+\nu_e$ × B($K^{*-} \to \overline{K}^0\pi^-$)		(1.34±0.22) %		719
$K^-\pi^+\pi^-\mu^+\nu_\mu$		< 1.2 × 10^{-3}	CL=90%	821
$(\overline{K}^*(892)\pi)^-\mu^+\nu_\mu$		< 1.4 × 10^{-3}	CL=90%	693
$\pi^-e^+\nu_e$		(3.8 $^{+1.2}_{-1.0}$) × 10^{-3}		927

A fraction of the following resonance mode has already appeared above as a submode of a charged-particle mode.

$K^*(892)^-e^+\nu_e$		(2.01±0.33) %		719
Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$				
$K^-\pi^+$		(3.83±0.12) %		861
$\overline{K}^0\pi^0$		(2.11±0.21) %	S=1.1	860
$\overline{K}^0\pi^+\pi^-$	[rr]	(5.4 ±0.4) %	S=1.2	842
$\overline{K}^0\rho^0$		(1.20±0.17) %		676
$\overline{K}^0f_0(980)$ × B($f_0 \to \pi^+\pi^-$)		(3.0 ±0.8) × 10^{-3}		549
$\overline{K}^0f_2(1270)$ × B($f_2 \to \pi^+\pi^-$)		(2.3 ±0.9) × 10^{-3}		263
$\overline{K}^0f_0(1370)$ × B($f_0 \to \pi^+\pi^-$)		(4.3 ±1.3) × 10^{-3}		–
$K^*(892)^-\pi^+$ × B($K^{*-} \to \overline{K}^0\pi^-$)		(3.3 ±0.3) %		711
$K_0^*(1430)^-\pi^+$ × B($K_0^*(1430)^- \to \overline{K}^0\pi^-$)		(6.4 ±1.6) × 10^{-3}		364
$\overline{K}^0\pi^+\pi^-$ nonresonant		(1.46±0.24) %		842
$K^-\pi^+\pi^0$	[rr]	(13.9 ±0.9) %	S=1.3	844
$K^-\rho^+$		(10.8 ±1.0) %		678
$K^*(892)^-\pi^+$ × B($K^{*-} \to K^-\pi^0$)		(1.7 ±0.2) %		711
$\overline{K}^*(892)^0\pi^0$ × B($\overline{K}^{*0} \to K^-\pi^+$)		(2.1 ±0.3) %		709
$K^-\pi^+\pi^0$ nonresonant		(6.9 ±2.5) × 10^{-3}		844
$\overline{K}^0\pi^0\pi^0$				843
$\overline{K}^*(892)^0\pi^0$ × B($\overline{K}^{*0} \to \overline{K}^0\pi^0$)		(1.0 ±0.2) %		709
$\overline{K}^0\pi^0\pi^0$ nonresonant		(7.8 ±2.0) × 10^{-3}		843
$K^-\pi^+\pi^+\pi^-$	[rr]	(7.5 ±0.4) %	S=1.1	812
$K^-\pi^+\rho^0$ total		(6.3 ±0.4) %		612
$K^-\pi^+\rho^0$ 3-body		(4.7 ±2.1) × 10^{-3}		612
$\overline{K}^*(892)^0\rho^0$ × B($\overline{K}^{*0} \to K^-\pi^+$)		(9.8 ±2.2) × 10^{-3}		418
$K^-a_1(1260)^+$ × B($a_1(1260)^+ \to \pi^+\pi^+\pi^-$)		(3.6 ±0.6) %		327
$\overline{K}^*(892)^0\pi^+\pi^-$ total × B($\overline{K}^{*0} \to K^-\pi^+$)		(1.5 ±0.4) %		683
$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body × B($\overline{K}^{*0} \to K^-\pi^+$)		(9.5 ±2.1) × 10^{-3}		683
$K_1(1270)^-\pi^+$ × B($K_1(1270)^- \to K^-\pi^+\pi^-$)	[ss]	(3.6 ±1.0) × 10^{-3}		483
$K^-\pi^+\pi^+\pi^-$ nonresonant		(1.75±0.25) %		812
$\overline{K}^0\pi^+\pi^-\pi^0$	[rr]	(10.0 ±1.2) %		812
$\overline{K}^0\eta$ × B($\eta \to \pi^+\pi^-\pi^0$)		(1.6 ±0.3) × 10^{-3}		772
$\overline{K}^0\omega$ × B($\omega \to \pi^+\pi^-\pi^0$)		(1.9 ±0.4) %		670
$K^*(892)^-\rho^+$ × B($K^{*-} \to \overline{K}^0\pi^-$)		(4.0 ±1.6) %		422
$\overline{K}^*(892)^0\rho^0$ × B($\overline{K}^{*0} \to \overline{K}^0\pi^0$)		(4.9 ±1.1) × 10^{-3}		418
$K_1(1270)^-\pi^+$ × B($K_1(1270)^- \to \overline{K}^0\pi^-\pi^0$)	[ss]	(5.1 ±1.4) × 10^{-3}		483
$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body × B($\overline{K}^{*0} \to \overline{K}^0\pi^0$)		(4.7 ±1.1) × 10^{-3}		683
$\overline{K}^0\pi^+\pi^-\pi^0$ nonresonant		(2.1 ±2.1) %		812
$K^-\pi^+\pi^0\pi^0$		(15 ±5) %		815
$K^-\pi^+\pi^+\pi^-\pi^0$		(4.0 ±0.4) %		771
$\overline{K}^*(892)^0\pi^+\pi^-\pi^0$ × B($\overline{K}^{*0} \to K^-\pi^+$)		(1.2 ±0.6) %		641
$\overline{K}^*(892)^0\eta$ × B($\overline{K}^{*0} \to K^-\pi^+$) × B($\eta \to \pi^+\pi^-\pi^0$)		(3.0 ±0.8) × 10^{-3}		580
$K^-\pi^+\omega$ × B($\omega \to \pi^+\pi^-\pi^0$)		(2.7 ±0.5) %		605
$\overline{K}^*(892)^0\omega$ × B($\overline{K}^{*0} \to K^-\pi^+$) × B($\omega \to \pi^+\pi^-\pi^0$)		(7 ±3) × 10^{-3}		406
$\overline{K}^0\pi^+\pi^+\pi^-\pi^-$		(5.8 ±1.6) × 10^{-3}		768
$\overline{K}^0\pi^+\pi^-\pi^0\pi^0(\pi^0)$		(10.6 $^{+7.3}_{-3.0}$) %		771
$\overline{K}^0K^+K^-$		(9.3 ±1.0) × 10^{-3}		544
$\overline{K}^0\phi$ × B($\phi \to K^+K^-$)		(4.2 ±0.5) × 10^{-3}		520
$\overline{K}^0K^+K^-$ non-ϕ		(5.0 ±0.8) × 10^{-3}		544
$K_S^0K_S^0K_S^0$		(9.7 ±2.3) × 10^{-4}		538
$K^+K^-K^-\pi^+$		(2.1 ±0.5) × 10^{-4}		434
$K^+K^-\overline{K}^0\pi^0$		(7.2 $^{+4.8}_{-3.5}$) × 10^{-3}		435

Fractions of many of the following modes with resonances have already appeared above as submodes of particular charged-particle modes. (Modes for which there are only upper limits and $\overline{K}^*(892)\rho$ submodes only appear below.)

$\overline{K}^0\eta$		(7.0 ±1.0) × 10^{-3}		772
$\overline{K}^0\rho^0$		(1.20±0.17) %		676
$K^-\rho^+$		(10.8 ±1.0) %	S=1.2	678
$\overline{K}^0\omega$		(2.1 ±0.4) %		670
$\overline{K}^0\eta'(958)$		(1.70±0.26) %		565
$\overline{K}^0f_0(980)$		(5.7 ±1.6) × 10^{-3}		549
$\overline{K}^0\phi$		(8.5 ±1.0) × 10^{-3}		520
$K^-a_1(1260)^+$		(7.3 ±1.1) %		327
$\overline{K}^0a_1(1260)^0$		< 1.9 %	CL=90%	322
$\overline{K}^0f_2(1270)$		(4.1 ±1.5) × 10^{-3}		263
$\overline{K}^0f_0(1370)$		(6.9 ±2.1) × 10^{-3}		–
$K^-a_2(1320)^+$		< 2 × 10^{-3}	CL=90%	197
$K^*(892)^-\pi^+$		(5.0 ±0.4) %	S=1.2	711
$\overline{K}^*(892)^0\pi^0$		(3.1 ±0.4) %		709
$\overline{K}^*(892)^0\pi^+\pi^-$ total		(2.3 ±0.5) %		683
$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body		(1.42±0.32) %		683
$K^-\pi^+\rho^0$ total		(6.3 ±0.4) %		612
$K^-\pi^+\rho^0$ 3-body		(4.7 ±2.1) × 10^{-3}		612
$\overline{K}^*(892)^0\rho^0$		(1.47±0.33) %		418
$\overline{K}^*(892)^0\rho^0$ transverse		(1.5 ±0.5) %		418
$\overline{K}^*(892)^0\rho^0$ *S*-wave		(2.8 ±0.6) %		418
$\overline{K}^*(892)^0\rho^0$ *S*-wave long.		< 3 × 10^{-3}	CL=90%	418
$\overline{K}^*(892)^0\rho^0$ *P*-wave		< 3 × 10^{-3}	CL=90%	418
$\overline{K}^*(892)^0\rho^0$ *D*-wave		(1.9 ±0.6) %		418

Mode	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K^*(892)^- \rho^+$	(6.0 ±2.4) %		422
$K^*(892)^- \rho^+$ longitudinal	(2.9 ±1.2) %		422
$K^*(892)^- \rho^+$ transverse	(3.2 ±1.8) %		422
$K^*(892)^- \rho^+$ P-wave	< 1.5 %	CL=90%	422
$K^- \pi^+ f_0(980)$	< 1.1 %	CL=90%	459
$\overline{K}^*(892)^0 f_0(980)$	< 7 $\times 10^{-3}$	CL=90%	–
$K_1(1270)^- \pi^+$	[ss] (1.06±0.29) %		483
$K_1(1400)^- \pi^+$	< 1.2 %	CL=90%	386
$\overline{K}_1(1400)^0 \pi^0$	< 3.7 %	CL=90%	387
$K^*(1410)^- \pi^+$	< 1.2 %	CL=90%	378
$K_0^*(1430)^- \pi^+$	(1.04±0.26) %		364
$K_2^*(1430)^- \pi^+$	< 8 $\times 10^{-3}$	CL=90%	367
$\overline{K}_2^*(1430)^0 \pi^0$	< 4 $\times 10^{-3}$	CL=90%	363
$\overline{K}^*(892)^0 \pi^+ \pi^- \pi^0$	(1.8 ±0.9) %		641
$\overline{K}^*(892)^0 \eta$	(1.9 ±0.5) %		580
$K^- \pi^+ \omega$	(3.0 ±0.6) %		605
$\overline{K}^*(892)^0 \omega$	(1.1 ±0.4) %		406
$K^- \pi^+ \eta'(958)$	(7.0 ±1.8) $\times 10^{-3}$		479
$\overline{K}^*(892)^0 \eta'(958)$	< 1.1 $\times 10^{-3}$	CL=90%	99
Pionic modes			
$\pi^+ \pi^-$	(1.52±0.11) $\times 10^{-3}$		922
$\pi^0 \pi^0$	(8.4 ±2.2) $\times 10^{-4}$		922
$\pi^+ \pi^- \pi^0$	(1.6 ±1.1) %	S=2.7	907
$\pi^+ \pi^+ \pi^- \pi^-$	(7.4 ±0.6) $\times 10^{-3}$		879
$\pi^+ \pi^+ \pi^- \pi^- \pi^0$	(1.9 ±0.4) %		844
$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^-$	(4.0 ±3.0) $\times 10^{-4}$		795
Hadronic modes with a $K\overline{K}$ pair			
$K^+ K^-$	(4.33±0.27) $\times 10^{-3}$		791
$K^0 \overline{K}^0$	(1.3 ±0.4) $\times 10^{-3}$		788
$K^0 K^- \pi^+$	(6.4 ±1.0) $\times 10^{-3}$	S=1.1	739
$\overline{K}^*(892)^0 K^0$ $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)	< 1.1 $\times 10^{-3}$	CL=90%	605
$K^*(892)^+ K^-$ $\times$ B($K^{*+} \to K^0 \pi^+$)	(2.3 ±0.5) $\times 10^{-3}$		610
$K^0 K^- \pi^+$ nonresonant	(2.3 ±2.3) $\times 10^{-3}$		739
$\overline{K}^0 K^+ \pi^-$	(4.9 ±1.0) $\times 10^{-3}$		739
$K^*(892)^0 \overline{K}^0$ $\times$ B($K^{*0} \to K^+ \pi^-$)	< 5 $\times 10^{-4}$	CL=90%	605
$K^*(892)^- K^+$ $\times$ B($K^{*-} \to \overline{K}^0 \pi^-$)	(1.2 ±0.7) $\times 10^{-3}$		610
$\overline{K}^0 K^+ \pi^-$ nonresonant	(3.8 $^{+2.3}_{-1.9}$) $\times 10^{-3}$		739
$K^+ K^- \pi^+ \pi^-$	[ww] (2.58±0.28) $\times 10^{-3}$		676
$\phi \pi^+ \pi^-$ $\times$ B($\phi \to K^+ K^-$)	(5.3 ±1.4) $\times 10^{-4}$		614
$\phi \rho^0$ $\times$ B($\phi \to K^+ K^-$)	(5.3 ±1.4) $\times 10^{-4}$		260
$K^+ K^- \rho^0$ 3-body	(9.0 ±2.3) $\times 10^{-4}$		309
$K^*(892)^0 K^- \pi^+$ $\times$ B($K^{*0} \to K^+ \pi^-$)	(2.1 ±0.9) $\times 10^{-3}$		528
$\overline{K}^*(892)^0 K^+ \pi^-$ $\times$ B($\overline{K}^{*0} \to K^- \pi^+$)	(1.1 ±0.8) $\times 10^{-3}$		528
$K^*(892)^0 \overline{K}^*(892)^0$ $\times$ B^2($K^{*0} \to K^+ \pi^-$)	(6 ±2) $\times 10^{-4}$		257
$K^+ K^- \pi^+ \pi^-$ non-ϕ	(1.7 ±0.5) $\times 10^{-3}$		676
$K^+ K^- \pi^+ \pi^-$ nonresonant	< 8 $\times 10^{-4}$	CL=90%	676
$K^0 \overline{K}^0 \pi^+ \pi^-$	(6.8 ±2.7) $\times 10^{-3}$		673
$K^+ K^- \pi^+ \pi^- \pi^0$	(3.1 ±2.0) $\times 10^{-3}$		600

Fractions of most of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

Mode	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\overline{K}^*(892)^0 K^0$	< 1.6 $\times 10^{-3}$	CL=90%	605
$K^*(892)^+ K^-$	(3.5 ±0.8) $\times 10^{-3}$		610
$K^*(892)^0 \overline{K}^0$	< 8 $\times 10^{-4}$	CL=90%	605
$K^*(892)^- K^+$	(1.8 ±1.0) $\times 10^{-3}$		610
$\phi \pi^0$	< 1.4 $\times 10^{-3}$	CL=90%	644
$\phi \eta$	< 2.8 $\times 10^{-3}$	CL=90%	489
$\phi \omega$	< 2.1 $\times 10^{-3}$	CL=90%	239
$\phi \pi^+ \pi^-$	(1.07±0.29) $\times 10^{-3}$		614
$\phi \rho^0$	(1.07±0.29) $\times 10^{-3}$		260
$\phi \pi^+ \pi^-$ 3-body	< 5 $\times 10^{-4}$	CL=90%	614
$K^*(892)^0 K^- \pi^+$	(3.2 ±1.3) $\times 10^{-3}$		528
$\overline{K}^*(892)^0 K^+ \pi^-$	(1.7 ±1.2) $\times 10^{-3}$		528
$K^*(892)^0 \overline{K}^*(892)^0$	(1.4 ±0.5) $\times 10^{-3}$		257

Doubly Cabibbo suppressed (DC) modes, $\Delta C = 2$ forbidden via mixing ($C2M$) modes, $\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton Family number (LF) violating modes

Mode	Type	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$K^+ \pi^-$	DC	(2.9 ±1.4) $\times 10^{-4}$		861
$K^+ \pi^-$ (via $\overline{D}^0$)	C2M	< 1.9 $\times 10^{-4}$	CL=90%	861
$K^+ \pi^- \pi^+ \pi^-$	DC	< 1.4 $\times 10^{-3}$	CL=90%	812
$K^+ \pi^- \pi^+ \pi^-$ (via $\overline{D}^0$)	C2M	< 4 $\times 10^{-4}$	CL=90%	812
μ^- anything (via $\overline{D}^0$)	C2M	< 4 $\times 10^{-4}$	CL=90%	–
$e^+ e^-$	C1	< 1.3 $\times 10^{-5}$	CL=90%	932
$\mu^+ \mu^-$	C1	< 7.6 $\times 10^{-6}$	CL=90%	926
$\pi^0 e^+ e^-$	C1	< 4.5 $\times 10^{-5}$	CL=90%	927
$\pi^0 \mu^+ \mu^-$	C1	< 1.8 $\times 10^{-4}$	CL=90%	915
$\eta e^+ e^-$	C1	< 1.1 $\times 10^{-4}$	CL=90%	852
$\eta \mu^+ \mu^-$	C1	< 5.3 $\times 10^{-4}$	CL=90%	838
$\rho^0 e^+ e^-$	C1	< 1.0 $\times 10^{-4}$	CL=90%	773
$\rho^0 \mu^+ \mu^-$	C1	< 2.3 $\times 10^{-4}$	CL=90%	756
$\omega e^+ e^-$	C1	< 1.8 $\times 10^{-4}$	CL=90%	768
$\omega \mu^+ \mu^-$	C1	< 8.3 $\times 10^{-4}$	CL=90%	751
$\phi e^+ e^-$	C1	< 5.2 $\times 10^{-5}$	CL=90%	654
$\phi \mu^+ \mu^-$	C1	< 4.1 $\times 10^{-4}$	CL=90%	631
$\overline{K}^0 e^+ e^-$		[tt] < 1.1 $\times 10^{-4}$	CL=90%	866
$\overline{K}^0 \mu^+ \mu^-$		[tt] < 2.6 $\times 10^{-4}$	CL=90%	852
$\overline{K}^*(892)^0 e^+ e^-$		[tt] < 1.4 $\times 10^{-4}$	CL=90%	717
$\overline{K}^*(892)^0 \mu^+ \mu^-$		[tt] < 1.18 $\times 10^{-3}$	CL=90%	698
$\pi^+ \pi^- \pi^0 \mu^+ \mu^-$	C1	< 8.1 $\times 10^{-4}$	CL=90%	863
$\mu^\pm e^\mp$	LF	[gg] < 1.9 $\times 10^{-5}$	CL=90%	929
$\pi^0 e^\pm \mu^\mp$	LF	[gg] < 8.6 $\times 10^{-5}$	CL=90%	924
$\eta e^\pm \mu^\mp$	LF	[gg] < 1.0 $\times 10^{-4}$	CL=90%	848
$\rho^0 e^\pm \mu^\mp$	LF	[gg] < 4.9 $\times 10^{-5}$	CL=90%	769
$\omega e^\pm \mu^\mp$	LF	[gg] < 1.2 $\times 10^{-4}$	CL=90%	764
$\phi e^\pm \mu^\mp$	LF	[gg] < 3.4 $\times 10^{-5}$	CL=90%	648
$\overline{K}^0 e^\pm \mu^\mp$	LF	[gg] < 1.0 $\times 10^{-4}$	CL=90%	862
$\overline{K}^*(892)^0 e^\pm \mu^\mp$	LF	[gg] < 1.0 $\times 10^{-4}$	CL=90%	712

$D^*(2007)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2006.7 \pm 0.5$ MeV (S = 1.1)
$m_{D^{*0}} - m_{D^0} = 142.12 \pm 0.07$ MeV
Full width $\Gamma < 2.1$ MeV, CL = 90%

$\overline{D}^*(2007)^0$ modes are charge conjugates of modes below.

$D^*(2007)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0 \pi^0$	(61.9±2.9) %	43
$D^0 \gamma$	(38.1±2.9) %	137

$D^*(2010)^\pm$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

Mass $m = 2010.0 \pm 0.5$ MeV (S = 1.1)
$m_{D^*(2010)^+} - m_{D^+} = 140.64 \pm 0.09$ MeV
$m_{D^*(2010)^+} - m_{D^0} = 145.42 \pm 0.05$ MeV
Full width $\Gamma < 0.131$ MeV, CL = 90%

$D^*(2010)^-$ modes are charge conjugates of the modes below.

$D^*(2010)^\pm$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0 \pi^+$	(68.3±1.4) %	39
$D^+ \pi^0$	(30.6±2.5) %	38
$D^+ \gamma$	(1.1 $^{+2.1}_{-0.7}$) %	136

$D_1(2420)^0$

$I(J^P) = \frac{1}{2}(1^+)$
I, J, P need confirmation.

Mass $m = 2422.2 \pm 1.8$ MeV (S = 1.2)
Full width $\Gamma = 18.9^{+4.6}_{-3.5}$ MeV

$\overline{D}_1(2420)^0$ modes are charge conjugates of modes below.

$D_1(2420)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^*(2010)^+ \pi^-$	seen	355
$D^+ \pi^-$	not seen	474

$D_2^*(2460)^0$

$I(J^P) = \frac{1}{2}(2^+)$

$J^P = 2^+$ assignment strongly favored (ALBRECHT 89B).

Mass $m = 2458.9 \pm 2.0$ MeV (S = 1.2)
Full width $\Gamma = 23 \pm 5$ MeV

$\overline{D}_2^*(2460)^0$ modes are charge conjugates of modes below.

$D_2^*(2460)^0$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^+\pi^-$	seen	503
$D^*(2010)^+\pi^-$	seen	387

$D_2^*(2460)^\pm$

$I(J^P) = \frac{1}{2}(2^+)$

$J^P = 2^+$ assignment strongly favored (ALBRECHT 89B).

Mass $m = 2459 \pm 4$ MeV (S = 1.7)
$m_{D_2^*(2460)^\pm} - m_{D_2^*(2460)^0} = 0.9 \pm 3.3$ MeV (S = 1.1)
Full width $\Gamma = 25^{+8}_{-7}$ MeV

$D_2^*(2460)^-$ modes are charge conjugates of modes below.

$D_2^*(2460)^\pm$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0\pi^+$	seen	508
$D^{*0}\pi^+$	seen	390

CHARMED, STRANGE MESONS ($C = S = \pm1$)

$D_s^+ = c\overline{s}$, $D_s^- = \overline{c}s$, similarly for D_s^*'s

$D_s^\pm$ was $F^\pm$

$I(J^P) = 0(0^-)$

Mass $m = 1968.5 \pm 0.6$ MeV (S = 1.1)
$m_{D_s^\pm} - m_{D^\pm} = 99.2 \pm 0.5$ MeV (S = 1.1)
Mean life $\tau = (0.467 \pm 0.017) \times 10^{-12}$ s
$c\tau = 140$ μm

D_s^+ form factors

$r_2 = 1.6 \pm 0.4$
$r_v = 1.5 \pm 0.5$
$\Gamma_L/\Gamma_T = 0.72 \pm 0.18$

Branching fractions for modes with a resonance in the final state include all the decay modes of the resonance. D_s^- modes are charge conjugates of the modes below.

D_s^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Inclusive modes				
K^- anything		$(13\ ^{+14}_{-12})$ %		–
$\overline{K}^0$ anything + K^0 anything		(39 ± 28) %		–
K^+ anything		$(20\ ^{+18}_{-14})$ %		–
non-$K\overline{K}$ anything		(64 ± 17) %		–
e^+ anything		< 20 %	90%	–
Leptonic and semileptonic modes				
$\mu^+\nu_\mu$		$(9 \pm 4) \times 10^{-3}$		981
$\phi\ell^+\nu_\ell$	[xx]	(1.9 ± 0.5) %		–
$\eta\ell^+\nu_\ell$ + $\eta'(958)\ell^+\nu_\ell$		(3.3 ± 1.0) %		–
$\eta\ell^+\nu_\ell$		(2.5 ± 0.7) %		–
$\eta'(958)\ell^+\nu_\ell$		$(8.7 \pm 3.4) \times 10^{-3}$		–
Hadronic modes with a $K\overline{K}$ pair (including from a ϕ)				
$K^+\overline{K}^0$		(3.6 ± 1.1) %		850
$K^+K^-\pi^+$	[rr,yy]	(4.6 ± 1.2) %		805
$\phi\pi^+$		(3.6 ± 0.9) %		712
$K^+\overline{K}^*(892)^0$		(3.4 ± 0.9) %		682
$f_0(980)\pi^+$		(1.1 ± 0.4) %		732
$K^+\overline{K}_0^*(1430)^0$		$(7 \pm 4) \times 10^{-3}$		186
$f_J(1710)\pi^+ \to K^+K^-\pi^+$	[zz]	$(1.5 \pm 2.0) \times 10^{-3}$		204
$K^+K^-\pi^+$ nonresonant		$(9 \pm 4) \times 10^{-3}$		805
$K^0\overline{K}^0\pi^+$				802
$K^*(892)^+\overline{K}^0$		(4.3 ± 1.4) %		683
$K^+K^-\pi^+\pi^0$				748
$\phi\pi^+\pi^0$		(9 ± 5) %		687
$\phi\rho^+$		(6.7 ± 2.3) %		407
$\phi\pi^+\pi^0$ 3-body		< 2.6 %	90%	687
$K^+K^-\pi^+\pi^0$ non-ϕ		< 9 %	90%	748
$K^+\overline{K}^0\pi^+\pi^-$		< 2.8 %	90%	744
$K^0K^-\pi^+\pi^+$		(4.3 ± 1.5) %		744
$K^*(892)^+\overline{K}^*(892)^0$		(5.8 ± 2.5) %		412
$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$		< 2.9 %	90%	744
$K^+K^-\pi^+\pi^+\pi^-$				673
$\phi\pi^+\pi^+\pi^-$		(1.8 ± 0.6) %		640
$K^+K^-\pi^+\pi^+\pi^-$ non-ϕ		$(3.0^{+3.0}_{-2.0}) \times 10^{-3}$		673
Other hadronic modes (0, 1, or 3 K's)				
$\pi^+\pi^+\pi^-$		(1.4 ± 0.4) %		959
$\rho^0\pi^+$		< 2.9 $\times 10^{-3}$	90%	827
$f_0(980)\pi^+$		(1.2 ± 0.5) %		732
$\pi^+\pi^+\pi^-$ nonresonant		(1.0 ± 0.4) %		959
$\pi^+\pi^+\pi^-\pi^0$		< 12 %	90%	935
$\eta\pi^+$		(2.0 ± 0.6) %		902
$\omega\pi^+$		< 1.8 %	90%	822
$\pi^+\pi^+\pi^+\pi^-\pi^-$		$(3.0^{+4.0}_{-3.0}) \times 10^{-3}$		899
$\pi^+\pi^+\pi^-\pi^0\pi^0$				902
$\eta\rho^+$		(10.3 ± 3.2) %		727
$\eta\pi^+\pi^0$ 3-body		< 3.0 %	90%	886
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$		(4.9 ± 3.2) %		856
$\eta'(958)\pi^+$		(4.9 ± 1.8) %		743
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$				803
$\eta'(958)\rho^+$		(12 ± 4) %		470
$\eta'(958)\pi^+\pi^0$ 3-body		< 3.1 %	90%	720
$K^0\pi^+$		< 8 $\times 10^{-3}$	90%	916
$K^+\pi^+\pi^-$		(1.0 ± 0.4) %		900
$K^+\rho^0$		< 2.9 $\times 10^{-3}$	90%	747
$K^*(892)^0\pi^+$		$(6.5 \pm 2.8) \times 10^{-3}$		773
$K^+K^+K^-$		< 6 $\times 10^{-4}$	90%	628
ϕK^+		< 5 $\times 10^{-4}$	90%	607
$\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton number (L) violating modes				
$\pi^+\mu^+\mu^-$	[aaa]	< 4.3 $\times 10^{-4}$	90%	968
$K^+\mu^+\mu^-$	$C1$	< 5.9 $\times 10^{-4}$	90%	909
$K^*(892)^+\mu^+\mu^-$	$C1$	< 1.4 $\times 10^{-3}$	90%	765
$\pi^-\mu^+\mu^+$	L	< 4.3 $\times 10^{-4}$	90%	968
$K^-\mu^+\mu^+$	L	< 5.9 $\times 10^{-4}$	90%	909
$K^*(892)^-\mu^+\mu^+$	L	< 1.4 $\times 10^{-3}$	90%	765

$D_s^{*\pm}$

$I(J^P) = ?(?^?)$

Mass $m = 2112.4 \pm 0.7$ MeV (S = 1.1)
$m_{D_s^{*\pm}} - m_{D_s^\pm} = 143.8 \pm 0.4$ MeV
Full width $\Gamma < 1.9$ MeV, CL = 90%

D_s^{*-} modes are charge conjugates of the modes below.

D_s^{*+} DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D_s^+ \gamma$	seen	139
$D_s^+ \pi^0$	seen	48

$D_{s1}(2536)^\pm$

$I(J^P) = 0(1^+)$
I, J, P need confirmation.

Mass $m = 2535.35 \pm 0.34$ MeV
Full width $\Gamma < 2.3$ MeV, CL = 90%

$D_{s1}(2536)^-$ modes are charge conjugates of the modes below.

$D_{s1}(2536)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^*(2010)^+ K^0$	seen	150
$D^*(2007)^0 K^+$	seen	169
$D^+ K^0$	not seen	382
$D^0 K^+$	not seen	392
$D_s^{*+} \gamma$	possibly seen	389

$D_{sJ}(2573)^\pm$

$I(J^P) = ?(?^?)$

J^P is natural, width and decay modes consistent with 2^+[2].

Mass $m = 2573.5 \pm 1.7$ MeV
Full width $\Gamma = 15^{+5}_{-4}$ MeV

$D_{sJ}(2573)^-$ modes are charge conjugates of the modes below.

$D_{sJ}(2573)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$D^0 K^+$	seen	436
$D^*(2007)^0 K^+$	seen	245

BOTTOM MESONS
($B = \pm1$)

$B^+ = u\overline{b}$, $B^0 = d\overline{b}$, $\overline{B}^0 = \overline{d}b$, $B^- = \overline{u}b$, similarly for B^*'s

B-particle organization

Many measurements of B decays involve admixtures of B hadrons. Previously we arbitrarily included such admixtures in the $B^\pm$ section, but because of their importance we have created two new sections: "$B^\pm/B^0$ Admixture" for $\Upsilon(4S)$ results and "$B^\pm/B^0/B_s^0/b$-baryon Admixture" for results at higher energies. Most inclusive decay branching fractions are found in the Admixture sections. B^0-$\overline{B}^0$ mixing data are found in the B^0 section, while B_s^0-$\overline{B}_s^0$ mixing data and B-$\overline{B}$ mixing data for a B^0/B_s^0 admixture are found in the B_s^0 section. CP-violation data are found in the B^0 section. b-baryons are found near the end of the Baryon section.

The organization of the B sections is now as follows, where bullets indicate particle sections and brackets indicate reviews.

[Production and Decay of b-flavored Hadrons]
[Semileptonic Decays of B Mesons]
- $B^\pm$
  - mass
  - mean life
  - branching fractions
- B^0
  - mass
  - mean life
  - branching fractions
  - polarization in B^0 decay
  - B^0-$\overline{B}^0$ mixing
  - [B^0-$\overline{B}^0$ Mixing and CP Violation in B Decay]
  - CP violation
- $B^\pm$ B^0 Admixtures
  - branching fractions
- $B^\pm/B^0/B_s^0/b$-baryon Admixtures
  - mean life
  - production fractions
  - branching fractions
- B^*
  - mass
- B_s^0
  - mass
  - mean life
  - branching fractions
  - polarization in B_s^0 decay
  - B_s^0-$\overline{B}_s^0$ mixing
  - B-$\overline{B}$ mixing (admixture of B^0, B_s^0)

At end of Baryon Listings:
- Λ_b
  - mass
  - mean life
  - branching fractions

$B^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^{\pm}} = 5278.9 \pm 1.8$ MeV

Mean life $\tau_{B^{\pm}} = (1.62 \pm 0.06) \times 10^{-12}$ s

$c\tau = 462$ μm

B^- modes are charge conjugates of the modes below. Modes which do not identify the charge state of the B are listed in the $B^{\pm}/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed D, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

B^+ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic and leptonic modes			
$\ell^+\nu_\ell$ anything	[qq] (10.1 ±2.3) %		–
$\overline{D}^0\ell^+\nu_\ell$	[qq] (1.6 ±0.7) %		–
$\overline{D}^*(2007)^0\ell^+\nu_\ell$	[qq] (5.3 ±0.8) %		–
$\pi^0 e^+\nu_e$	< 2.2 × 10^{-3}	CL=90%	2638
$\omega\ell^+\nu_\ell$	[qq] < 2.1 × 10^{-4}	CL=90%	–
$\rho^0\ell^+\nu_\ell$	[qq] < 2.1 × 10^{-4}	CL=90%	–
$e^+\nu_e$	< 1.5 × 10^{-5}	CL=90%	2639
$\mu^+\nu_\mu$	< 2.1 × 10^{-5}	CL=90%	2638
$\tau^+\nu_\tau$	< 1.8 × 10^{-3}	CL=90%	2340
D, D^*, or D_s modes			
$\overline{D}^0\pi^+$	(5.3 ±0.5) × 10^{-3}		2308
$\overline{D}^0\rho^+$	(1.34±0.18) %		2238
$\overline{D}^0\pi^+\pi^+\pi^-$	(1.1 ±0.4) %		2289
$\overline{D}^0\pi^+\pi^+\pi^-$ nonresonant	(5 ±4) × 10^{-3}		2289
$\overline{D}^0\pi^+\rho^0$	(4.2 ±3.0) × 10^{-3}		2209
$\overline{D}^0 a_1(1260)^+$	(5 ±4) × 10^{-3}		2123
$D^*(2010)^-\pi^+\pi^+$	(2.1 ±0.6) × 10^{-3}		2247
$D^-\pi^+\pi^+$	< 1.4 × 10^{-3}	CL=90%	2299
$\overline{D}^*(2007)^0\pi^+$	(5.2 ±0.8) × 10^{-3}		2256
$\overline{D}^*(2007)^0\rho^+$	(1.55±0.31) %		2183
$\overline{D}^*(2007)^0\pi^+\pi^+\pi^-$	(9.4 ±2.6) × 10^{-3}		2236
$\overline{D}^*(2007)^0 a_1(1260)^+$	(1.9 ±0.5) %		2062
$D^*(2010)^-\pi^+\pi^+\pi^0$	(1.5 ±0.7) %		2235
$D^*(2010)^-\pi^+\pi^+\pi^+\pi^-$	< 1 %	CL=90%	2217
$\overline{D}_1^*(2420)^0\pi^+$	(1.5 ±0.6) × 10^{-3}	S=1.3	2081
$\overline{D}_1^*(2420)^0\rho^+$	< 1.4 × 10^{-3}	CL=90%	1997
$\overline{D}_2^*(2460)^0\pi^+$	< 1.3 × 10^{-3}	CL=90%	2064
$\overline{D}_2^*(2460)^0\rho^+$	< 4.7 × 10^{-3}	CL=90%	1979
$\overline{D}^0 D_s^+$	(1.7 ±0.6) %		1815
$\overline{D}^0 D_s^{*+}$	(1.2 ±1.0) %		1734
$\overline{D}^*(2007)^0 D_s^+$	(10 ±7) × 10^{-3}		1737
$\overline{D}^*(2007)^0 D_s^{*+}$	(2.3 ±1.4) %		1650
$D_s^+\pi^0$	< 2.0 × 10^{-4}	CL=90%	2270
$D_s^{*+}\pi^0$	< 3.3 × 10^{-4}	CL=90%	2214
$D_s^+\eta$	< 5 × 10^{-4}	CL=90%	2235
$D_s^{*+}\eta$	< 8 × 10^{-4}	CL=90%	2177
$D_s^+\rho^0$	< 4 × 10^{-4}	CL=90%	2198
$D_s^{*+}\rho^0$	< 5 × 10^{-4}	CL=90%	2139
$D_s^+\omega$	< 5 × 10^{-4}	CL=90%	2195
$D_s^{*+}\omega$	< 7 × 10^{-4}	CL=90%	2136
$D_s^+ a_1(1260)^0$	< 2.2 × 10^{-3}	CL=90%	2079
$D_s^{*+} a_1(1260)^0$	< 1.6 × 10^{-3}	CL=90%	2014
$D_s^+\phi$	< 3.2 × 10^{-4}	CL=90%	2141
$D_s^{*+}\phi$	< 4 × 10^{-4}	CL=90%	2079
$D_s^+\overline{K}^0$	< 1.1 × 10^{-3}	CL=90%	2241
$D_s^{*+}\overline{K}^0$	< 1.1 × 10^{-3}	CL=90%	2184
$D_s^+\overline{K}^*(892)^0$	< 5 × 10^{-4}	CL=90%	2171
$D_s^{*+}\overline{K}^*(892)^0$	< 4 × 10^{-4}	CL=90%	2110
$D_s^-\pi^+K^+$	< 8 × 10^{-4}	CL=90%	2222
$D_s^{*-}\pi^+K^+$	< 1.2 × 10^{-3}	CL=90%	2164
$D_s^-\pi^+K^*(892)^+$	< 6 × 10^{-3}	CL=90%	2137
$D_s^{*-}\pi^+K^*(892)^+$	< 8 × 10^{-3}	CL=90%	2075
Charmonium modes			
$J/\psi(1S)K^+$	(1.01±0.14) × 10^{-3}		1683
$J/\psi(1S)K^+\pi^+\pi^-$	(1.4 ±0.6) × 10^{-3}		1612
$J/\psi(1S)K^*(892)^+$	(1.7 ±0.5) × 10^{-3}		1571
$J/\psi(1S)\pi^-$	(4.4 ±2.4) × 10^{-5}		1727
$\psi(2S)K^+$	(6.9 ±3.1) × 10^{-4}	S=1.3	1284
$\psi(2S)K^*(892)^+$	< 3.0 × 10^{-3}	CL=90%	1115
$\psi(2S)K^*(892)^+\pi^+\pi^-$	(1.9 ±1.2) × 10^{-3}		909
$\chi_{c1}(1P)K^+$	(1.0 ±0.4) × 10^{-3}		1411
$\chi_{c1}(1P)K^*(892)^+$	< 2.1 × 10^{-3}	CL=90%	1265
K or K^* modes			
$K^0\pi^+$	< 4.8 × 10^{-5}	CL=90%	2614
$K^+\pi^0$	< 1.4 × 10^{-5}	CL=90%	2615
$K^*(892)^0\pi^+$	< 4.1 × 10^{-5}	CL=90%	2561
$K^*(892)^+\pi^0$	< 9.9 × 10^{-5}	CL=90%	2562
$K^+\pi^-\pi^+$(no charm)	< 1.9 × 10^{-4}	CL=90%	2609
$K_1(1400)^0\pi^+$	< 2.6 × 10^{-3}	CL=90%	2451
$K_2^*(1430)^0\pi^+$	< 6.8 × 10^{-4}	CL=90%	2443
$K^+\rho^0$	< 1.9 × 10^{-5}	CL=90%	2559
$K^0\rho^+$	< 4.8 × 10^{-5}	CL=90%	2559
$K^*(892)^+\pi^+\pi^-$	< 1.1 × 10^{-3}	CL=90%	2556
$K^*(892)^+\rho^0$	< 9.0 × 10^{-4}	CL=90%	2505
$K_1(1400)^+\rho^0$	< 7.8 × 10^{-4}	CL=90%	2389
$K_2^*(1430)^+\rho^0$	< 1.5 × 10^{-3}	CL=90%	2382
$K^+K^-K^+$	< 3.1 × 10^{-4}	CL=90%	2522
$K^+\phi$	< 1.2 × 10^{-5}	CL=90%	2516
$K^*(892)^+K^+K^-$	< 1.6 × 10^{-3}	CL=90%	2466
$K^*(892)^+\phi$	< 7.0 × 10^{-5}	CL=90%	2460
$K_1(1400)^+\phi$	< 1.1 × 10^{-3}	CL=90%	2339
$K_2^*(1430)^+\phi$	< 3.4 × 10^{-3}	CL=90%	2332
$K^+f_0(980)$	< 8 × 10^{-5}	CL=90%	2524
$K^*(892)^+\gamma$	(5.7 ±3.3) × 10^{-5}		2564
$K_1(1270)^+\gamma$	< 7.3 × 10^{-3}	CL=90%	2486
$K_1(1400)^+\gamma$	< 2.2 × 10^{-3}	CL=90%	2453
$K_2^*(1430)^+\gamma$	< 1.4 × 10^{-3}	CL=90%	2447
$K^*(1680)^+\gamma$	< 1.9 × 10^{-3}	CL=90%	2361
$K_3^*(1780)^+\gamma$	< 5.5 × 10^{-3}	CL=90%	2343
$K_4^*(2045)^+\gamma$	< 9.9 × 10^{-3}	CL=90%	2243
Light unflavored meson modes			
$\pi^+\pi^0$	< 1.7 × 10^{-5}	CL=90%	2636
$\pi^+\pi^+\pi^-$	< 1.9 × 10^{-4}	CL=90%	2630
$\rho^0\pi^+$	< 4.3 × 10^{-5}	CL=90%	2582
$\pi^+f_0(980)$	< 1.4 × 10^{-4}	CL=90%	2547
$\pi^+f_2(1270)$	< 2.4 × 10^{-4}	CL=90%	2483
$\pi^+\pi^0\pi^0$	< 8.9 × 10^{-4}	CL=90%	2631
$\rho^+\pi^0$	< 7.7 × 10^{-5}	CL=90%	2582
$\pi^+\pi^-\pi^+\pi^0$	< 4.0 × 10^{-3}	CL=90%	2621
$\rho^+\rho^0$	< 1.0 × 10^{-3}	CL=90%	2525
$a_1(1260)^+\pi^0$	< 1.7 × 10^{-3}	CL=90%	2494
$a_1(1260)^0\pi^+$	< 9.0 × 10^{-4}	CL=90%	2494
$\omega\pi^+$	< 4.0 × 10^{-4}	CL=90%	2580
$\eta\pi^+$	< 7.0 × 10^{-4}	CL=90%	2609
$\pi^+\pi^+\pi^+\pi^-\pi^-$	< 8.6 × 10^{-4}	CL=90%	2608
$\rho^0 a_1(1260)^+$	< 6.2 × 10^{-4}	CL=90%	2434
$\rho^0 a_2(1320)^+$	< 7.2 × 10^{-4}	CL=90%	2411
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$	< 6.3 × 10^{-3}	CL=90%	2592
$a_1(1260)^+a_1(1260)^0$	< 1.3 %	CL=90%	2335
Baryon modes			
$p\overline{p}\pi^+$	< 1.6 × 10^{-4}	CL=90%	2439
$p\overline{p}\pi^+\pi^+\pi^-$	< 5.2 × 10^{-4}	CL=90%	2369
$p\overline{\Lambda}$	< 6 × 10^{-5}	CL=90%	2430
$p\overline{\Lambda}\pi^+\pi^-$	< 2.0 × 10^{-4}	CL=90%	2367
$\overline{\Delta}^0 p$	< 3.8 × 10^{-4}	CL=90%	2402
$\Delta^{++}\overline{p}$	< 1.5 × 10^{-4}	CL=90%	2402

Lepton Family number (*LF*) or Lepton number (*L*) violating modes, or $\Delta B = 1$ weak neutral current (*B1*) modes

$\pi^+ e^+ e^-$	*B1*	< 3.9	$\times 10^{-3}$	CL=90%	2638
$\pi^+ \mu^+ \mu^-$	*B1*	< 9.1	$\times 10^{-3}$	CL=90%	2633
$K^+ \mu^+ \mu^-$	*B1*	< 1.7	$\times 10^{-4}$	CL=90%	2612
$K^*(892)^+ e^+ e^-$	*B1*	< 6.9	$\times 10^{-4}$	CL=90%	2564
$K^*(892)^+ \mu^+ \mu^-$	*B1*	< 1.2	$\times 10^{-3}$	CL=90%	2560
$\pi^+ e^+ \mu^-$	*LF*	< 6.4	$\times 10^{-3}$	CL=90%	2637
$\pi^+ e^- \mu^+$	*LF*	< 6.4	$\times 10^{-3}$	CL=90%	2637
$K^+ e^+ \mu^-$	*LF*	< 6.4	$\times 10^{-3}$	CL=90%	2615
$K^+ e^- \mu^+$	*LF*	< 6.4	$\times 10^{-3}$	CL=90%	2615
$\pi^- e^+ e^+$	*L*	< 3.9	$\times 10^{-3}$	CL=90%	2638
$\pi^- \mu^+ \mu^+$	*L*	< 9.1	$\times 10^{-3}$	CL=90%	2633
$\pi^- e^+ \mu^+$	*L*	< 6.4	$\times 10^{-3}$	CL=90%	2637
$K^- e^+ e^+$	*L*	< 3.9	$\times 10^{-3}$	CL=90%	2616
$K^- \mu^+ \mu^+$	*L*	< 9.1	$\times 10^{-3}$	CL=90%	2612
$K^- e^+ \mu^+$	*L*	< 6.4	$\times 10^{-3}$	CL=90%	2615

B^0

$I(J^P) = \frac{1}{2}(0^-)$

I, *J*, *P* need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^0} = 5279.2 \pm 1.8$ MeV
$m_{B^0} - m_{B^\pm} = 0.35 \pm 0.29$ MeV (S = 1.1)
Mean life $\tau_{B^0} = (1.56 \pm 0.06) \times 10^{-12}$ s
$c\tau = 468\ \mu$m
$\tau_{B^+}/\tau_{B^0} = 1.02 \pm 0.05$ (average of direct and inferred)
$\tau_{B^+}/\tau_{B^0} = 1.03 \pm 0.06$ (direct measurements)
$\tau_{B^+}/\tau_{B^0} = 0.93 \pm 0.22$ (inferred from branching fractions)

B^0-$\overline{B}^0$ mixing parameters

$\chi_d = 0.175 \pm 0.016$
$\Delta m_{B^0} = m_{B^0_H} - m_{B^0_L} = (0.474 \pm 0.031) \times 10^{12}\ \hbar\ s^{-1}$
$x_d = \Delta m_{B^0}/\Gamma_{B^0} = 0.73 \pm 0.05$

CP violation parameters

$|\text{Re}(\epsilon_{B^0})| < 0.045$

$\overline{B}^0$ modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing. Modes which do not identify the charge state of the *B* are listed in the $B^\pm/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed *D*, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

B^0 DECAY MODES		Fraction (Γ_i/Γ)		Scale factor/ Confidence level	*p* (MeV/c)
Semileptonic and leptonic modes					
$\ell^+ \nu_\ell$ anything	[*qq*]	(10.3 ±1.0) %			–
$D^- \ell^+ \nu_\ell$	[*qq*]	(1.9 ±0.5) %			–
$D^*(2010)^- \ell^+ \nu_\ell$	[*qq*]	(4.56±0.27) %			–
$\rho^- \ell^+ \nu_\ell$	[*qq*]	< 4.1	$\times 10^{-4}$	CL=90%	–
D, D^*, or D_s modes					
$D^- \pi^+$		(3.0 ±0.4) $\times 10^{-3}$			2306
$D^- \rho^+$		(7.8 ±1.4) $\times 10^{-3}$			2236
$\overline{D}^0 \pi^+ \pi^-$		< 1.6	$\times 10^{-3}$	CL=90%	2301
$D^*(2010)^- \pi^+$		(2.6 ±0.4) $\times 10^{-3}$			2254
$D^- \pi^+ \pi^+ \pi^-$		(8.0 ±2.5) $\times 10^{-3}$			2287
($D^- \pi^+ \pi^+ \pi^-$) nonresonant		(3.9 ±1.9) $\times 10^{-3}$			2287
$D^- \pi^+ \rho^0$		(1.1 ±1.0) $\times 10^{-3}$			2207
$D^- a_1(1260)^+$		(6.0 ±3.3) $\times 10^{-3}$			2121
$D^*(2010)^- \pi^+ \pi^0$		(1.5 ±0.5) %			2247
$D^*(2010)^- \rho^+$		(7.3 ±1.5) $\times 10^{-3}$			2181
$D^*(2010)^- \pi^+ \pi^+ \pi^-$		(7.6 ±1.7) $\times 10^{-3}$		S=1.3	2235
($D^*(2010)^- \pi^+ \pi^+ \pi^-$) non-resonant		(0.0 ±2.5) $\times 10^{-3}$			2235
$D^*(2010)^- \pi^+ \rho^0$		(5.7 ±3.1) $\times 10^{-3}$			2151
$D^*(2010)^- a_1(1260)^+$		(1.30±0.27) %			2061
$D^*(2010)^- \pi^+ \pi^+ \pi^- \pi^0$		(3.4 ±1.8) %			2218
$\overline{D}{}_2^*(2460)^- \pi^+$		< 2.2	$\times 10^{-3}$	CL=90%	2064
$\overline{D}{}_2^*(2460)^- \rho^+$		< 4.9	$\times 10^{-3}$	CL=90%	1979
$D^- D_s^+$		(7 ±4) $\times 10^{-3}$			1812
$D^*(2010)^- D_s^+$		(1.2 ±0.6) %			1735
$D^- D_s^{*+}$		(2.0 ±1.5) %			1731
$D^*(2010)^- D_s^{*+}$		(1.9 ±1.2) %			1649
$D_s^+ \pi^-$		< 2.8	$\times 10^{-4}$	CL=90%	2270
$D_s^{*+} \pi^-$		< 5	$\times 10^{-4}$	CL=90%	2214
$D_s^+ \rho^-$		< 7	$\times 10^{-4}$	CL=90%	2198
$D_s^{*+} \rho^-$		< 8	$\times 10^{-4}$	CL=90%	2139
$D_s^+ a_1(1260)^-$		< 2.6	$\times 10^{-3}$	CL=90%	2079
$D_s^{*+} a_1(1260)^-$		< 2.2	$\times 10^{-3}$	CL=90%	2014
$D_s^- K^+$		< 2.4	$\times 10^{-4}$	CL=90%	2242
$D_s^{*-} K^+$		< 1.7	$\times 10^{-4}$	CL=90%	2185
$D_s^- K^*(892)^+$		< 9.9	$\times 10^{-4}$	CL=90%	2172
$D_s^{*-} K^*(892)^+$		< 1.1	$\times 10^{-3}$	CL=90%	2112
$D_s^- \pi^+ K^0$		< 5	$\times 10^{-3}$	CL=90%	2221
$D_s^{*-} \pi^+ K^0$		< 3.1	$\times 10^{-3}$	CL=90%	2164
$D_s^- \pi^+ K^*(892)^0$		< 4	$\times 10^{-3}$	CL=90%	2136
$D_s^{*-} \pi^+ K^*(892)^0$		< 2.0	$\times 10^{-3}$	CL=90%	2074
$\overline{D}^0 \pi^0$		< 4.8	$\times 10^{-4}$	CL=90%	2308
$\overline{D}^0 \rho^0$		< 5.5	$\times 10^{-4}$	CL=90%	2238
$\overline{D}^0 \eta$		< 6.8	$\times 10^{-4}$	CL=90%	2274
$\overline{D}^0 \eta'$		< 8.6	$\times 10^{-4}$	CL=90%	2198
$\overline{D}^0 \omega$		< 6.3	$\times 10^{-4}$	CL=90%	2235
$\overline{D}^*(2007)^0 \pi^0$		< 9.7	$\times 10^{-4}$	CL=90%	2256
$\overline{D}^*(2007)^0 \rho^0$		< 1.17	$\times 10^{-3}$	CL=90%	2183
$\overline{D}^*(2007)^0 \eta$		< 6.9	$\times 10^{-4}$	CL=90%	2220
$\overline{D}^*(2007)^0 \eta'$		< 2.7	$\times 10^{-3}$	CL=90%	2141
$\overline{D}^*(2007)^0 \omega$		< 2.1	$\times 10^{-3}$	CL=90%	2180
Charmonium modes					
$J/\psi(1S) K^0$		(7.5 ±2.1) $\times 10^{-4}$			1683
$J/\psi(1S) K^+ \pi^-$		(1.1 ±0.6) $\times 10^{-3}$			1652
$J/\psi(1S) K^*(892)^0$		(1.58±0.27) $\times 10^{-3}$			1570
$J/\psi(1S) \pi^0$		< 6.9	$\times 10^{-5}$	CL=90%	1728
$\psi(2S) K^0$		< 8	$\times 10^{-4}$	CL=90%	1283
$\psi(2S) K^+ \pi^-$		< 1	$\times 10^{-3}$	CL=90%	1238
$\psi(2S) K^*(892)^0$		(1.4 ±0.9) $\times 10^{-3}$			1113
$\chi_{c1}(1P) K^0$		< 2.7	$\times 10^{-3}$	CL=90%	1411
$\chi_{c1}(1P) K^*(892)^0$		< 2.1	$\times 10^{-3}$	CL=90%	1263
K or K^* modes					
$K^+ \pi^-$		< 1.7	$\times 10^{-5}$	CL=90%	2615
$K^0 \pi^0$		< 4.0	$\times 10^{-5}$	CL=90%	2614
$K^+ K^-$		< 4	$\times 10^{-6}$	CL=90%	2593
$K^+ \rho^-$		< 3.5	$\times 10^{-5}$	CL=90%	2559
$K^0 \rho^0$		< 3.9	$\times 10^{-5}$	CL=90%	2559
$K^0 f_0(980)$		< 3.6	$\times 10^{-4}$	CL=90%	2523
$K^*(892)^+ \pi^-$		< 7.2	$\times 10^{-5}$	CL=90%	2562
$K^*(892)^0 \pi^0$		< 2.8	$\times 10^{-5}$	CL=90%	2562
$K_2^*(1430)^+ \pi^-$		< 2.6	$\times 10^{-3}$	CL=90%	2445
$K^0 K^+ K^-$		< 1.3	$\times 10^{-3}$	CL=90%	2522
$K^0 \phi$		< 8.8	$\times 10^{-5}$	CL=90%	2516
$K^- \pi^+ \pi^+ \pi^-$	[*bbb*]	< 2.1	$\times 10^{-4}$	CL=90%	2600
$K^*(892)^0 \pi^+ \pi^-$		< 1.4	$\times 10^{-3}$	CL=90%	2556
$K^*(892)^0 \rho^0$		< 4.6	$\times 10^{-4}$	CL=90%	2504
$K^*(892)^0 f_0(980)$		< 1.7	$\times 10^{-4}$	CL=90%	2467
$K_1(1400)^+ \pi^-$		< 1.1	$\times 10^{-3}$	CL=90%	2451
$K^- a_1(1260)^+$	[*bbb*]	< 3.9	$\times 10^{-4}$	CL=90%	2471
$K^*(892)^0 K^+ K^-$		< 6.1	$\times 10^{-4}$	CL=90%	2466
$K^*(892)^0 \phi$		< 4.3	$\times 10^{-5}$	CL=90%	2459
$K_1(1400)^0 \rho^0$		< 3.0	$\times 10^{-3}$	CL=90%	2389
$K_1(1400)^0 \phi$		< 5.0	$\times 10^{-3}$	CL=90%	2339
$K_2^*(1430)^0 \rho^0$		< 1.1	$\times 10^{-3}$	CL=90%	2380
$K_2^*(1430)^0 \phi$		< 1.4	$\times 10^{-3}$	CL=90%	2330
$K^*(892)^0 \gamma$		(4.0 ±1.9) $\times 10^{-5}$			2564
$K_1(1270)^0 \gamma$		< 7.0	$\times 10^{-3}$	CL=90%	2486
$K_1(1400)^0 \gamma$		< 4.3	$\times 10^{-3}$	CL=90%	2453
$K_2^*(1430)^0 \gamma$		< 4.0	$\times 10^{-4}$	CL=90%	2445
$K^*(1680)^0 \gamma$		< 2.0	$\times 10^{-3}$	CL=90%	2361
$K_3^*(1780)^0 \gamma$		< 1.0	%	CL=90%	2343
$K_4^*(2045)^0 \gamma$		< 4.3	$\times 10^{-3}$	CL=90%	2244
$\phi \phi$		< 3.9	$\times 10^{-5}$	CL=90%	2435

Light unflavored meson modes

Mode		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi^+\pi^-$		$< 2.0 \times 10^{-5}$	CL=90%	2636
$\pi^0\pi^0$		$< 9.1 \times 10^{-6}$	CL=90%	2636
$\eta\pi^0$		$< 2.5 \times 10^{-4}$	CL=90%	2609
$\eta\eta$		$< 4.1 \times 10^{-4}$	CL=90%	2582
$\pi^+\pi^-\pi^0$		$< 7.2 \times 10^{-4}$	CL=90%	2631
$\rho^0\pi^0$		$< 2.4 \times 10^{-5}$	CL=90%	2582
$\rho^\mp\pi^\pm$	[gg]	$< 8.8 \times 10^{-5}$	CL=90%	2582
$\pi^+\pi^-\pi^+\pi^-$		$< 2.8 \times 10^{-4}$	CL=90%	2621
$\rho^0\rho^0$		$< 2.8 \times 10^{-4}$	CL=90%	2525
$a_1(1260)^\mp\pi^\pm$	[gg]	$< 4.9 \times 10^{-4}$	CL=90%	2494
$a_2(1320)^\mp\pi^\pm$	[gg]	$< 3.0 \times 10^{-4}$	CL=90%	2473
$\pi^+\pi^-\pi^0\pi^0$		$< 3.1 \times 10^{-3}$	CL=90%	2622
$\rho^+\rho^-$		$< 2.2 \times 10^{-3}$	CL=90%	2525
$a_1(1260)^0\pi^0$		$< 1.1 \times 10^{-3}$	CL=90%	2494
$\omega\pi^0$		$< 4.6 \times 10^{-4}$	CL=90%	2580
$\pi^+\pi^+\pi^-\pi^-\pi^0$		$< 9.0 \times 10^{-3}$	CL=90%	2609
$a_1(1260)^+\rho^-$		$< 3.4 \times 10^{-3}$	CL=90%	2434
$a_1(1260)^0\rho^0$		$< 2.4 \times 10^{-3}$	CL=90%	2434
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$		$< 3.0 \times 10^{-3}$	CL=90%	2592
$a_1(1260)^+a_1(1260)^-$		$< 2.8 \times 10^{-3}$	CL=90%	2336
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$		< 1.1 %	CL=90%	2572

Baryon modes

Mode		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$p\overline{p}$		$< 3.4 \times 10^{-5}$	CL=90%	2467
$p\overline{p}\pi^+\pi^-$		$< 2.5 \times 10^{-4}$	CL=90%	2406
$p\overline{\Lambda}\pi^-$		$< 1.8 \times 10^{-4}$	CL=90%	2401
$\Delta^0\overline{\Delta}^0$		$< 1.5 \times 10^{-3}$	CL=90%	2334
$\Delta^{++}\Delta^{--}$		$< 1.1 \times 10^{-4}$	CL=90%	2334
$\overline{\Sigma}_c^{--}\Delta^{++}$		$< 1.2 \times 10^{-3}$	CL=90%	1839

Lepton Family number (*LF*) violating modes, or $\Delta B = 1$ weak neutral current (*B1*) modes

Mode			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\gamma\gamma$	*B1*		$< 3.9 \times 10^{-5}$	CL=90%	2640
e^+e^-	*B1*		$< 5.9 \times 10^{-6}$	CL=90%	2640
$\mu^+\mu^-$	*B1*		$< 5.9 \times 10^{-6}$	CL=90%	2637
$K^0e^+e^-$	*B1*		$< 3.0 \times 10^{-4}$	CL=90%	2616
$K^0\mu^+\mu^-$	*B1*		$< 3.6 \times 10^{-4}$	CL=90%	2612
$K^*(892)^0e^+e^-$	*B1*		$< 2.9 \times 10^{-4}$	CL=90%	2564
$K^*(892)^0\mu^+\mu^-$	*B1*		$< 2.3 \times 10^{-5}$	CL=90%	2559
$e^\pm\mu^\mp$	*LF*	[gg]	$< 5.9 \times 10^{-6}$	CL=90%	2639
$e^\pm\tau^\mp$	*LF*	[gg]	$< 5.3 \times 10^{-4}$	CL=90%	2341
$\mu^\pm\tau^\mp$	*LF*	[gg]	$< 8.3 \times 10^{-4}$	CL=90%	2339

$B^\pm/B^0$ ADMIXTURE

The branching fraction measurements are for an admixture of B mesons at the $\Upsilon(4S)$. The values quoted assume that $B(\Upsilon(4S) \to B\overline{B}) = 100\%$.

For inclusive branching fractions, *e.g.*, $B \to D^\pm$ anything, the treatment of multiple D's in the final state must be defined. One possiblity would be to count the number of events with one-or-more D's and divide by the total number of B's. Another possibility would be to count the total number of D's and divide by the total number of B's, which is the definition of average multiplicity. The two definitions are identical when only one of the specified particles is allowed in the final state. Even though the "one-or-more" definition seems sensible, for practical reasons inclusive branching fractions are almost always measured using the multiplicity definition. For heavy final state particles, authors call their results inclusive branching fractions while for light particles some authors call their results multiplicities. In the B sections, we list all results as inclusive branching fractions, adopting a multiplicity definition. This means that inclusive branching fractions can exceed 100% and that inclusive partial widths can exceed total widths, just as inclusive cross sections can exceed total cross sections.

$\overline{B}$ modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing.

B DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic and leptonic modes				
$e^+\nu_e$ anything	[ccc]	(10.4 ± 0.4) %	S=1.3	–
$\overline{p}e^+\nu_e$ anything		$< 1.6 \times 10^{-3}$	CL=90%	–
$\mu^+\nu_\mu$ anything	[ccc]	(10.3 ± 0.5) %		–
$\ell^+\nu_\ell$ anything	[qq,ccc]	(10.43 ± 0.24) %		–
$D^-\ell^+\nu_\ell$ anything	[qq]	(2.7 ± 0.8) %		–
$\overline{D}^0\ell^+\nu_\ell$ anything	[qq]	(7.0 ± 1.4) %		–
$\overline{D}^{**}\ell^+\nu_\ell$	[qq,ddd]	(2.7 ± 0.7) %		–
$\overline{D}_1(2420)^0\ell^+\nu_\ell$ anything		seen		–
$\overline{D}_2^*(2460)^0\ell^+\nu_\ell$ anything		not seen		–
$D^{*-}\pi^+\ell^+\nu_\ell$ anything		(1.00 ± 0.34) %		–
$D_s^-\ell^+\nu_\ell$ anything	[qq]	$< 9 \times 10^{-3}$	CL=90%	–
$D_s^-\ell^+\nu_\ell K^+$ anything	[qq]	$< 6 \times 10^{-3}$	CL=90%	–
$D_s^-\ell^+\nu_\ell K^0$ anything	[qq]	$< 9 \times 10^{-3}$	CL=90%	–
$K^+\ell^+\nu_\ell$ anything	[qq]	(6.0 ± 0.5) %		–
$K^-\ell^+\nu_\ell$ anything	[qq]	$(10 \pm 4) \times 10^{-3}$		–
$K^0/\overline{K}^0\ell^+\nu_\ell$ anything	[qq]	(4.4 ± 0.5) %		–
D*, *D*, or *D_s* modes**				
$D^\pm$ anything		(24.2 ± 3.3) %		–
$D^0/\overline{D}^0$ anything		(58 ± 5) %	S=1.1	–
$D^*(2010)^\pm$ anything		(23.1 ± 3.3) %	S=1.1	–
$D_s^\pm$ anything	[gg]	(8.6 ± 1.6) %		–
D_sD, D_s^*D, D_sD^*, or $D_s^*D^*$	[gg]	(4.9 ± 1.1) %		–
$D^*(2010)\gamma$		$< 1.1 \times 10^{-3}$	CL=90%	–
$D_s^+\pi^-$, $D_s^{*+}\pi^-$, $D_s^+\rho^-$, $D_s^{*+}\rho^-$, $D_s^+\pi^0$, $D_s^{*+}\pi^0$, $D_s^+\eta$, $D_s^{*+}\eta$, $D_s^+\rho^0$, $D_s^{*+}\rho^0$, $D_s^+\omega$, $D_s^{*+}\omega$	[gg]	$< 5 \times 10^{-4}$	CL=90%	–
Charmonium modes				
$J/\psi(1S)$ anything		(1.14 ± 0.06) %		–
$J/\psi(1S)$(direct) anything		$(8.0 \pm 0.8) \times 10^{-3}$		–
$\psi(2S)$ anything		$(3.5 \pm 0.5) \times 10^{-3}$		–
$\chi_{c1}(1P)$ anything		$(4.2 \pm 0.7) \times 10^{-3}$		–
$\chi_{c1}(1P)$(direct) anything		$(3.7 \pm 0.7) \times 10^{-3}$		–
$\chi_{c2}(1P)$ anything		$< 3.8 \times 10^{-3}$	CL=90%	–
$\eta_c(1S)$ anything		$< 9 \times 10^{-3}$	CL=90%	–
K* or *K* modes**				
$K^\pm$ anything	[gg]	(78.9 ± 2.5) %		–
K^+ anything		(66 ± 5) %		–
K^- anything		(13 ± 4) %		–
$K^0/\overline{K}^0$ anything	[gg]	(64 ± 4) %		–
$K^*(892)^\pm$ anything		(18 ± 6) %		–
$K^*(892)^0/\overline{K}^*(892)^0$ anything	[gg]	(14.6 ± 2.6) %		–
$K_1(1400)\gamma$		$< 4.1 \times 10^{-4}$	CL=90%	–
$K_2^*(1430)\gamma$		$< 8.3 \times 10^{-4}$	CL=90%	–
$K_2(1770)\gamma$		$< 1.2 \times 10^{-3}$	CL=90%	–
$K_3^*(1780)\gamma$		$< 3.0 \times 10^{-3}$	CL=90%	–
$K_4^*(2045)\gamma$		$< 1.0 \times 10^{-3}$	CL=90%	–
$b \to s\gamma$		$(2.3 \pm 0.7) \times 10^{-4}$		–
Light unflavored meson modes				
$\pi^\pm$ anything	[gg,eee]	(359 ± 7) %		–
ρ^0 anything		(21 ± 5) %		–
ω anything		< 81 %	CL=90%	–
ϕ anything		(3.5 ± 0.7) %	S=1.8	–
Baryon modes				
charmed-baryon anything		(6.4 ± 1.1) %		–
$\overline{\Sigma}_c^{--}$ anything		$(4.8 \pm 2.5) \times 10^{-3}$		–
$\overline{\Sigma}_c^-$ anything		< 1.1 %	CL=90%	–
$\overline{\Sigma}_c^0$ anything		$(5.2 \pm 2.5) \times 10^{-3}$		–
$\overline{\Sigma}_c^0 N (N = p$ or $n)$		$< 1.7 \times 10^{-3}$	CL=90%	–
$p/\overline{p}$ anything	[gg]	(8.0 ± 0.4) %		–
$p/\overline{p}$(direct) anything	[gg]	(5.5 ± 0.5) %		–
$\Lambda/\overline{\Lambda}$ anything	[gg]	(4.0 ± 0.5) %		–
$\Xi^-/\overline{\Xi}^+$ anything	[gg]	$(2.7 \pm 0.6) \times 10^{-3}$		–
baryons anything		(6.8 ± 0.6) %		–
$p\overline{p}$ anything		(2.47 ± 0.23) %		–
$\Lambda\overline{p}/\overline{\Lambda}p$ anything	[gg]	(2.5 ± 0.4) %		–
$\Lambda\overline{\Lambda}$ anything		$< 5 \times 10^{-3}$	CL=90%	–

$\Delta B = 1$ weak neutral current ($B1$) modes

$e^+ e^-$ anything	$B1$	$<$ 2.4	$\times 10^{-3}$	CL=90%	–
$\mu^+ \mu^-$ anything	$B1$	$<$ 2.4	$\times 10^{-3}$	CL=90%	–

$B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE

These measurements are for an admixture of bottom particles at high energy (LEP, Tevatron, $Sp\overline{p}S$).

Mean life $\tau = (1.549 \pm 0.020) \times 10^{-12}$ s

Mean life $\tau = (1.72 \pm 0.10) \times 10^{-12}$ s Charged b-hadron admixture

Mean life $\tau = (1.58 \pm 0.14) \times 10^{-12}$ s Neutral b-hadron admixture

$\tau_{\text{charged } b-\text{hadron}}/\tau_{\text{neutral } b-\text{hadron}} = 1.09 \pm 0.13$

The branching fraction measurements are for an admixture of B mesons and baryons at energies above the $\Upsilon(4S)$. Only the highest energy results (LEP, Tevatron, $Sp\overline{p}S$) are used in the branching fraction averages. The production fractions give our best current estimate of the admixture at LEP.

For inclusive branching fractions, *e.g.*, $B \to D^{\pm}$anything, the treatment of multiple D's in the final state must be defined. One possiblity would be to count the number of events with one-or-more D's and divide by the total number of B's. Another possibility would be to count the total number of D's and divide by the total number of B's, which is the definition of average multiplicity. The two definitions are identical when only one of the specified particles is allowed in the final state. Even though the "one-or-more" definition seems sensible, for practical reasons inclusive branching fractions are almost always measured using the multiplicity definition. For heavy final state particles, authors call their results inclusive branching fractions while for light particles some authors call their results multiplicities. In the B sections, we list all results as inclusive branching fractions, adopting a multiplicity definition. This means that inclusive branching fractions can exceed 100% and that inclusive partial widths can exceed total widths, just as inclusive cross sections can exceed total cross sections.

The modes below are listed for a $\overline{b}$ initial state. b modes are their charge conjugates. Reactions indicate the weak decay vertex and do not include mixing.

$\overline{b}$ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)

PRODUCTION FRACTIONS

The production fractions for weakly decaying b-hadrons at the Z have been calculated from the best values of mean lives, mixing parameters, and branching fractions in this edition by O. Hayes (CERN) and M. Jimack (U. Birmingham) as described in the note "Production and Decay of b-Flavored Hadrons" in the $B^{\pm}$ Particle Listings. Values assume

$$B(\overline{b} \to B^+) = B(\overline{b} \to B^0)$$
$$B(\overline{b} \to B^+) + B(\overline{b} \to B^0) + B(\overline{b} \to B^0_s) + B(b \to \Lambda_b) = 100\ \%.$$

The notation for production fractions varies in the literature (f_{B^0}, $f(b \to \overline{B}^0)$, $Br(b \to \overline{B}^0)$). We use our own branching fraction notation here, $B(\overline{b} \to B^0)$.

$\overline{b} \to B^+$		(37.8 ± 2.2) %		–
$\overline{b} \to B^0$		(37.8 ± 2.2) %		–
$\overline{b} \to B^0_s$		($11.2 ^{+1.8}_{-1.9}$) %		–
$b \to \Lambda_b$		(13.2 ± 4.1) %		–

DECAY MODES

Semileptonic and leptonic modes

$\overline{b} \to e^+ \nu_e$ anything	[ccc]	(11.1 ± 1.0) %		–
$\overline{b} \to \mu^+ \nu_\mu$ anything	[ccc]	(10.7 ± 0.7) %		–
$\overline{b} \to \ell^+ \nu_\ell$ anything	[qq,ccc]	(11.13± 0.29) %		–
$\overline{b} \to D^- \ell^+ \nu_\ell$ anything	[qq]	(2.01± 0.29) %		–
$\overline{b} \to \overline{D}^0 \ell^+ \nu_\ell$ anything	[qq]	(6.6 ± 0.6) %		–
$\overline{b} \to D^{*-} \ell^+ \nu_\ell$ anything	[qq]	(2.76± 0.29) %		–
$\overline{b} \to \overline{D}^0_j \ell^+ \nu_\ell$ anything	[qq,fff]	seen		–
$\overline{b} \to D^-_j \ell^+ \nu_\ell$ anything	[qq,fff]	seen		–
$\overline{b} \to \overline{D}^*_2(2460)^0 \ell^+ \nu_\ell$ anything		seen		–
$\overline{b} \to D^*_2(2460)^- \ell^+ \nu_\ell$ anything		seen		–
$\overline{b} \to \tau^+ \nu_\tau$ anything		(2.7 ± 0.4) %		–
$\overline{b} \to \overline{b} \to \overline{c} \to \ell^- \overline{\nu}_\ell$ anything	[qq]	(7.9 ± 0.8) %		–

Charmonium modes

$\overline{b} \to J/\psi(1S)$anything		(1.16± 0.10) %		–
$\overline{b} \to \psi(2S)$anything		(4.8 ± 2.4) $\times 10^{-3}$		–
$\overline{b} \to \chi_{c1}(1P)$anything		(1.8 ± 0.5) %		–

K or K^* modes

$\overline{b} \to \overline{s}\gamma$		$<$ 1.2 $\times 10^{-3}$	90%	–
$\overline{b} \to K^{\pm}$anything		(88 ±19) %		–
$\overline{b} \to K^0_S$anything		(29.0 ± 2.9) %		–

Baryon modes

$\overline{b} \to p/\overline{p}$anything		(14 ± 6) %		–
$\overline{b} \to \Lambda/\overline{\Lambda}$anything		(5.9 ± 1.1) %		–

Other modes

$\overline{b} \to$ charged anything	[eee]	(584 ±40) %		–

$\Delta B = 1$ weak neutral current ($B1$) modes

$\overline{b} \to \mu^+ \mu^-$ anything	$B1$	$<$ 5.0 $\times 10^{-5}$	90%	–
$\overline{b} \to \nu\overline{\nu}$anything	$B1$	$<$ 3.9 $\times 10^{-4}$		–

B^*

$I(J^P) = \frac{1}{2}(1^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^*} = 5324.8 \pm 1.8$ MeV

$m_{B^*} - m_B = 45.7 \pm 0.4$ MeV

B^* DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$B\gamma$	dominant	46

BOTTOM, STRANGE MESONS ($B = \pm 1$, $S = \mp 1$)

$B^0_s = s\overline{b}$, $\overline{B}^0_s = \overline{s}b$, similarly for B^*_s's

B^0_s

$I(J^P) = 0(0^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^0_s} = 5369.3 \pm 2.0$ MeV

Mean life $\tau = (1.61 ^{+0.10}_{-0.09}) \times 10^{-12}$ s

$c\tau = 483$ μm

B^0_s-$\overline{B}^0_s$ mixing parameters

$\chi_s > 0.49$, CL = 95%

χ_B at high energy $= f_d \chi_d + f_s \chi_s = 0.126 \pm 0.008$

$\Delta m_{B^0_s} = m_{B^0_{sH}} - m_{B^0_{sL}} > 5.9 \times 10^{12}$ $\hbar$ s^{-1}, CL = 95%

$x_s = \Delta m_{B^0_s}/\Gamma_{B^0_s} > 9.5$, CL = 95%

These branching fractions all scale with $B(\overline{b} \to B^0_s)$, the LEP B^0_s production fraction. The first four were evaluated using $B(\overline{b} \to B^0_s) = (11.2^{+1.8}_{-1.9})$% and the rest assume $B(\overline{b} \to B^0_s) = 12\%$.

The branching fraction $B(B^0_s \to D^-_s \ell^+ \nu_\ell$anything) is not a pure measurement since the measured product branching fraction $B(\overline{b} \to B^0_s) \times B(B^0_s \to D^-_s \ell^+ \nu_\ell$anything) was used to determine $B(\overline{b} \to B^0_s)$, as described in the note on "Production and Decay of b-Flavored Hadrons."

B^0_s DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
D^-_s anything		(87 ±31) %		–
$D^-_s \ell^+ \nu_\ell$anything	[ggg]	(7.6 ± 2.4) %		–
$D^-_s \pi^+$		$<$ 12 %		2321
$J/\psi(1S)\phi$		$<$ 6 $\times 10^{-3}$		1590
$\psi(2S)\phi$		seen		1122
$\pi^0\pi^0$		$<$ 2.1 $\times 10^{-4}$	90%	2861
$\eta\pi^0$		$<$ 1.0 $\times 10^{-3}$	90%	2655
$\eta\eta$		$<$ 1.5 $\times 10^{-3}$	90%	2628
$\pi^+ K^-$		$<$ 2.6 $\times 10^{-4}$	90%	2660
$K^+ K^-$		$<$ 1.4 $\times 10^{-4}$	90%	2639

$\Delta B = 1$ weak neutral current ($B1$) modes

$\gamma\gamma$	$B1$	$<$ 1.48 $\times 10^{-4}$	90%	2685

$c\overline{c}$ MESONS

$\eta_c(1S)$

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 2979.8 \pm 2.1$ MeV (S = 2.1)
Full width $\Gamma = 13.2^{+3.8}_{-3.2}$ MeV

$\eta_c(1S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Decays involving hadronic resonances			
$\eta'(958)\pi\pi$	(4.1 ±1.7) %		1319
$\rho\rho$	(2.6 ±0.9) %		1275
$K^*(892)^0 K^-\pi^+$ + c.c.	(2.0 ±0.7) %		1273
$K^*(892)\overline{K}^*(892)$	(8.5 ±3.1) × 10^{-3}		1193
$\phi\phi$	(7.1 ±2.8) × 10^{-3}		1086
$a_0(980)\pi$	< 2 %	90%	1323
$a_2(1320)\pi$	< 2 %	90%	1193
$K^*(892)\overline{K}$ + c.c.	< 1.28 %	90%	1307
$f_2(1270)\eta$	< 1.1 %	90%	1142
$\omega\omega$	< 3.1 × 10^{-3}	90%	1268
Decays into stable hadrons			
$K\overline{K}\pi$	(5.5 ±1.7) %		1378
$\eta\pi\pi$	(4.9 ±1.8) %		1425
$\pi^+\pi^- K^+ K^-$	(2.0 $^{+0.7}_{-0.6}$) %		1342
$2(K^+K^-)$	(2.1 ±1.2) %		1053
$2(\pi^+\pi^-)$	(1.2 ±0.4) %		1457
$p\overline{p}$	(1.2 ±0.4) × 10^{-3}		1157
$K\overline{K}\eta$	< 3.1 %	90%	1262
$\pi^+\pi^- p\overline{p}$	< 1.2 %	90%	1023
$\Lambda\overline{\Lambda}$	< 2 × 10^{-3}	90%	987
Radiative decays			
$\gamma\gamma$	(3.0 ±1.2) × 10^{-4}		1489

$J/\psi(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3096.88 \pm 0.04$ MeV
Full width $\Gamma = 87 \pm 5$ keV
$\Gamma_{ee} = 5.26 \pm 0.37$ keV (Assuming $\Gamma_{ee} = \Gamma_{\mu\mu}$)

$J/\psi(1S)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons		(87.7 ±0.5) %		–
virtual$\gamma \to$ hadrons		(17.0 ±2.0) %		–
e^+e^-		(6.02±0.19) %		1548
$\mu^+\mu^-$		(6.01±0.19) %		1545
Decays involving hadronic resonances				
$\rho\pi$		(1.28±0.10) %		1449
$\rho^0\pi^0$		(4.2 ±0.5) × 10^{-3}		1449
$a_2(1320)\rho$		(1.09±0.22) %		1125
$\omega\pi^+\pi^+\pi^-\pi^-$		(8.5 ±3.4) × 10^{-3}		1392
$\omega\pi^+\pi^-$		(7.2 ±1.0) × 10^{-3}		1435
$K^*(892)^0\overline{K}^*_2(1430)^0$ + c.c.		(6.7 ±2.6) × 10^{-3}		1005
$\omega K^*(892)\overline{K}$ + c.c.		(5.3 ±2.0) × 10^{-3}		1098
$\omega f_2(1270)$		(4.3 ±0.6) × 10^{-3}		1143
$K^+\overline{K}^*(892)^-$ + c.c.		(5.0 ±0.4) × 10^{-3}		1373
$K^0\overline{K}^*(892)^0$ + c.c.		(4.2 ±0.4) × 10^{-3}		1371
$\omega\pi^0\pi^0$		(3.4 ±0.8) × 10^{-3}		1436
$b_1(1235)^\pm\pi^\mp$	[gg]	(3.0 ±0.5) × 10^{-3}		1299
$\omega K^\pm K^0_S\pi^\mp$	[gg]	(3.0 ±0.7) × 10^{-3}		1210
$b_1(1235)^0\pi^0$		(2.3 ±0.6) × 10^{-3}		1299
$\phi K^*(892)\overline{K}$ + c.c.		(2.04±0.28) × 10^{-3}		969
$\omega K\overline{K}$		(1.9 ±0.4) × 10^{-3}		1268
$\omega f_J(1710) \to \omega K\overline{K}$		(4.8 ±1.1) × 10^{-4}		878
$\phi 2(\pi^+\pi^-)$		(1.60±0.32) × 10^{-3}		1318
$\Delta(1232)^{++}\overline{p}\pi^-$		(1.6 ±0.5) × 10^{-3}		1030
$\omega\eta$		(1.58±0.16) × 10^{-3}		1394
$\phi K\overline{K}$		(1.48±0.22) × 10^{-3}		1179
$\phi f_J(1710) \to \phi K\overline{K}$		(3.6 ±0.6) × 10^{-4}		875
$p\overline{p}\omega$		(1.30±0.25) × 10^{-3}	S=1.3	769
$\Delta(1232)^{++}\overline{\Delta}(1232)^{--}$		(1.10±0.29) × 10^{-3}		938
$\Sigma(1385)^-\overline{\Sigma}(1385)^+$ (or c.c.)	[gg]	(1.03±0.13) × 10^{-3}		692
$p\overline{p}\eta'(958)$		(9 ±4) × 10^{-4}	S=1.7	596
$\phi f'_2(1525)$		(8 ±4) × 10^{-4}	S=2.7	871
$\phi\pi^+\pi^-$		(8.0 ±1.2) × 10^{-4}		1365
$\phi K^\pm K^0_S\pi^\mp$	[gg]	(7.2 ±0.9) × 10^{-4}		1114
$\omega f_1(1420)$		(6.8 ±2.4) × 10^{-4}		1062
$\phi\eta$		(6.5 ±0.7) × 10^{-4}		1320
$\Xi(1530)^-\overline{\Xi}^+$		(5.9 ±1.5) × 10^{-4}		597
$pK^-\overline{\Sigma}(1385)^0$		(5.1 ±3.2) × 10^{-4}		645
$\omega\pi^0$		(4.2 ±0.6) × 10^{-4}	S=1.4	1447
$\phi\eta'(958)$		(3.3 ±0.4) × 10^{-4}		1192
$\phi f_0(980)$		(3.2 ±0.9) × 10^{-4}	S=1.9	1182
$\Xi(1530)^0\overline{\Xi}^0$		(3.2 ±1.4) × 10^{-4}		608
$\Sigma(1385)^-\overline{\Sigma}^+$ (or c.c.)	[gg]	(3.1 ±0.5) × 10^{-4}		857
$\phi f_1(1285)$		(2.6 ±0.5) × 10^{-4}	S=1.1	1032
$\rho\eta$		(1.93±0.23) × 10^{-4}		1398
$\omega\eta'(958)$		(1.67±0.25) × 10^{-4}		1279
$\omega f_0(980)$		(1.4 ±0.5) × 10^{-4}		1271
$\rho\eta'(958)$		(1.05±0.18) × 10^{-4}		1283
$p\overline{p}\phi$		(4.5 ±1.5) × 10^{-5}		527
$a_2(1320)^\pm\pi^\mp$	[gg]	< 4.3 × 10^{-3}	CL=90%	1263
$K\overline{K}^*_2(1430)$ + c.c.		< 4.0 × 10^{-3}	CL=90%	1159
$K^*_2(1430)^0\overline{K}^*_2(1430)^0$		< 2.9 × 10^{-3}	CL=90%	588
$K^*(892)^0\overline{K}^*(892)^0$		< 5 × 10^{-4}	CL=90%	1263
$\phi f_2(1270)$		< 3.7 × 10^{-4}	CL=90%	1036
$p\overline{p}\rho$		< 3.1 × 10^{-4}	CL=90%	779
$\phi\eta(1440) \to \phi\eta\pi\pi$		< 2.5 × 10^{-4}	CL=90%	946
$\omega f'_2(1525)$		< 2.2 × 10^{-4}	CL=90%	1003
$\Sigma(1385)^0\overline{\Lambda}$		< 2 × 10^{-4}	CL=90%	911
$\Delta(1232)^+\overline{p}$		< 1 × 10^{-4}	CL=90%	1100
$\Sigma^0\overline{\Lambda}$		< 9 × 10^{-5}	CL=90%	1032
$\phi\pi^0$		< 6.8 × 10^{-6}	CL=90%	1377
Decays into stable hadrons				
$2(\pi^+\pi^-)\pi^0$		(3.37±0.26) %		1496
$3(\pi^+\pi^-)\pi^0$		(2.9 ±0.6) %		1433
$\pi^+\pi^-\pi^0$		(1.50±0.20) %		1533
$\pi^+\pi^-\pi^0 K^+K^-$		(1.20±0.30) %		1368
$4(\pi^+\pi^-)\pi^0$		(9.0 ±3.0) × 10^{-3}		1345
$\pi^+\pi^- K^+K^-$		(7.2 ±2.3) × 10^{-3}		1407
$K\overline{K}\pi$		(6.1 ±1.0) × 10^{-3}		1440
$p\overline{p}\pi^+\pi^-$		(6.0 ±0.5) × 10^{-3}	S=1.3	1107
$2(\pi^+\pi^-)$		(4.0 ±1.0) × 10^{-3}		1517
$3(\pi^+\pi^-)$		(4.0 ±2.0) × 10^{-3}		1466
$n\overline{n}\pi^+\pi^-$		(4 ±4) × 10^{-3}		1106
$\Sigma\overline{\Sigma}$		(3.8 ±0.5) × 10^{-3}		992
$2(\pi^+\pi^-)K^+K^-$		(3.1 ±1.3) × 10^{-3}		1320
$p\overline{p}\pi^+\pi^-\pi^0$	[hhh]	(2.3 ±0.9) × 10^{-3}	S=1.9	1033
$p\overline{p}$		(2.14±0.10) × 10^{-3}		1232
$p\overline{p}\eta$		(2.09±0.18) × 10^{-3}		948
$p\overline{n}\pi^-$		(2.00±0.10) × 10^{-3}		1174
$n\overline{n}$		(1.9 ±0.5) × 10^{-3}		1231
$\Xi\overline{\Xi}$		(1.8 ±0.4) × 10^{-3}	S=1.8	818
$\Lambda\overline{\Lambda}$		(1.35±0.14) × 10^{-3}	S=1.2	1074
$p\overline{p}\pi^0$		(1.09±0.09) × 10^{-3}		1176
$\Lambda\overline{\Sigma}^-\pi^+$ (or c.c.)	[gg]	(1.06±0.12) × 10^{-3}		945
$pK^-\overline{\Lambda}$		(8.9 ±1.6) × 10^{-4}		876
$2(K^+K^-)$		(7.0 ±3.0) × 10^{-4}		1131
$pK^-\overline{\Sigma}^0$		(2.9 ±0.8) × 10^{-4}		820
K^+K^-		(2.37±0.31) × 10^{-4}		1468
$\Lambda\overline{\Lambda}\pi^0$		(2.2 ±0.7) × 10^{-4}		998
$\pi^+\pi^-$		(1.47±0.23) × 10^{-4}		1542
$K^0_S K^0_L$		(1.08±0.14) × 10^{-4}		1466
$\Lambda\overline{\Sigma}$ + c.c.		< 1.5 × 10^{-4}	CL=90%	1032
$K^0_S K^0_S$		< 5.2 × 10^{-6}	CL=90%	1466
Radiative decays				
$\gamma\eta_c(1S)$		(1.3 ±0.4) %		116
$\gamma\pi^+\pi^- 2\pi^0$		(8.3 ±3.1) × 10^{-3}		1518
$\gamma\eta\pi\pi$		(6.1 ±1.0) × 10^{-3}		1487
$\gamma\eta(1440) \to \gamma K\overline{K}\pi$	[p]	(9.1 ±1.8) × 10^{-4}		1223
$\gamma\eta(1440) \to \gamma\gamma\rho^0$		(6.4 ±1.4) × 10^{-5}		1223
$\gamma\rho\rho$		(4.5 ±0.8) × 10^{-3}		1343
$\gamma\eta'(958)$		(4.31±0.30) × 10^{-3}		1400
$\gamma 2\pi^+ 2\pi^-$		(2.8 ±0.5) × 10^{-3}	S=1.9	1517
$\gamma f_4(2050)$		(2.7 ±0.7) × 10^{-3}		874
$\gamma\omega\omega$		(1.59±0.33) × 10^{-3}		1337
$\gamma\eta(1440) \to \gamma\rho^0\rho^0$		(1.7 ±0.4) × 10^{-3}	S=1.3	1223
$\gamma f_2(1270)$		(1.38±0.14) × 10^{-3}		1286
$\gamma f_J(1710) \to \gamma K\overline{K}$		(9.7 ±1.2) × 10^{-4}		1075
$\gamma\eta$		(8.6 ±0.8) × 10^{-4}		1500

$\gamma f_1(1420) \to \gamma K \overline{K} \pi$	$(8.3 \pm 1.5) \times 10^{-4}$		1220
$\gamma f_1(1285)$	$(6.5 \pm 1.0) \times 10^{-4}$		1283
$\gamma f_2'(1525)$	$(6.3 \pm 1.0) \times 10^{-4}$		1173
$\gamma \phi \phi$	$(4.0 \pm 1.2) \times 10^{-4}$	S=2.1	1166
$\gamma p \overline{p}$	$(3.8 \pm 1.0) \times 10^{-4}$		1232
$\gamma \eta(2225)$	$(2.9 \pm 0.6) \times 10^{-4}$		834
$\gamma \eta(1760) \to \gamma \rho^0 \rho^0$	$(1.3 \pm 0.9) \times 10^{-4}$		1048
$\gamma \pi^0$	$(3.9 \pm 1.3) \times 10^{-5}$		1546
$\gamma p \overline{p} \pi^+ \pi^-$	$< 7.9 \times 10^{-4}$	CL=90%	1107
$\gamma \gamma$	$< 5 \times 10^{-4}$	CL=90%	1548
$\gamma \Lambda \overline{\Lambda}$	$< 1.3 \times 10^{-4}$	CL=90%	1074
3γ	$< 5.5 \times 10^{-5}$	CL=90%	1548
$\gamma f_0(1370)$	$(3.4 \pm 0.7) \times 10^{-4}$		–
$\gamma f_0(1500)$	$(8.2 \pm 1.5) \times 10^{-4}$		1184

$\chi_{c0}(1P)$

$I^G(J^{PC}) = 0^+(0^{++})$

Mass $m = 3415.1 \pm 1.0$ MeV
Full width $\Gamma = 14 \pm 5$ MeV

$\chi_{c0}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Hadronic decays			
$2(\pi^+\pi^-)$	(3.7 ± 0.7) %		1679
$\pi^+\pi^- K^+ K^-$	(3.0 ± 0.7) %		1580
$\rho^0 \pi^+ \pi^-$	(1.6 ± 0.5) %		1608
$3(\pi^+\pi^-)$	(1.5 ± 0.5) %		1633
$K^+ \overline{K}^*(892)^0 \pi^-$ + c.c.	(1.2 ± 0.4) %		1522
$\pi^+\pi^-$	$(7.5 \pm 2.1) \times 10^{-3}$		1702
$K^+ K^-$	$(7.1 \pm 2.4) \times 10^{-3}$		1635
$\pi^+\pi^- p \overline{p}$	$(5.0 \pm 2.0) \times 10^{-3}$		1320
$\pi^0 \pi^0$	$(3.1 \pm 0.6) \times 10^{-3}$		1702
$\eta \eta$	$(2.5 \pm 1.1) \times 10^{-3}$		1617
$p \overline{p}$	$< 9.0 \times 10^{-4}$	90%	1427
Radiative decays			
$\gamma J/\psi(1S)$	$(6.6 \pm 1.8) \times 10^{-3}$		303
$\gamma \gamma$	$(4.0 \pm 2.3) \times 10^{-4}$		1708

$\chi_{c1}(1P)$

$I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 3510.53 \pm 0.12$ MeV
Full width $\Gamma = 0.88 \pm 0.14$ MeV

$\chi_{c1}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
Hadronic decays		
$3(\pi^+\pi^-)$	(2.2 ± 0.8) %	1683
$2(\pi^+\pi^-)$	(1.6 ± 0.5) %	1727
$\pi^+\pi^- K^+ K^-$	$(9 \pm 4) \times 10^{-3}$	1632
$\rho^0 \pi^+ \pi^-$	$(3.9 \pm 3.5) \times 10^{-3}$	1659
$K^+ \overline{K}^*(892)^0 \pi^-$ + c.c.	$(3.2 \pm 2.1) \times 10^{-3}$	1576
$\pi^+\pi^- p \overline{p}$	$(1.4 \pm 0.9) \times 10^{-3}$	1381
$p \overline{p}$	$(8.6 \pm 1.2) \times 10^{-5}$	1483
$\pi^+\pi^- + K^+ K^-$	$< 2.1 \times 10^{-3}$	–
Radiative decays		
$\gamma J/\psi(1S)$	(27.3 ± 1.6) %	389

$\chi_{c2}(1P)$

$I^G(J^{PC}) = 0^+(2^{++})$

Mass $m = 3556.17 \pm 0.13$ MeV
Full width $\Gamma = 2.00 \pm 0.18$ MeV

$\chi_{c2}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
Hadronic decays			
$2(\pi^+\pi^-)$	(2.2 ± 0.5) %		1751
$\pi^+\pi^- K^+ K^-$	(1.9 ± 0.5) %		1656
$3(\pi^+\pi^-)$	(1.2 ± 0.8) %		1707
$\rho^0 \pi^+ \pi^-$	$(7 \pm 4) \times 10^{-3}$		1683
$K^+ \overline{K}^*(892)^0 \pi^-$ + c.c.	$(4.8 \pm 2.8) \times 10^{-3}$		1601
$\pi^+\pi^- p \overline{p}$	$(3.3 \pm 1.3) \times 10^{-3}$		1410
$\pi^+\pi^-$	$(1.9 \pm 1.0) \times 10^{-3}$		1773
$K^+ K^-$	$(1.5 \pm 1.1) \times 10^{-3}$		1708
$p \overline{p}$	$(10.0 \pm 1.0) \times 10^{-5}$		1510
$\pi^0 \pi^0$	$(1.10 \pm 0.28) \times 10^{-3}$		1773
$\eta \eta$	$(8 \pm 5) \times 10^{-4}$		1692
$J/\psi(1S) \pi^+ \pi^- \pi^0$	< 1.5 %	90%	185
Radiative decays			
$\gamma J/\psi(1S)$	(13.5 ± 1.1) %		430
$\gamma \gamma$	$(1.6 \pm 0.5) \times 10^{-4}$		1778

$\psi(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3686.00 \pm 0.09$ MeV
Full width $\Gamma = 277 \pm 31$ keV (S = 1.1)
$\Gamma_{ee} = 2.14 \pm 0.21$ keV (Assuming $\Gamma_{ee} = \Gamma_{\mu\mu}$)

$\psi(2S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons	(98.10 ± 0.30) %		–
virtual$\gamma \to$ hadrons	(2.9 ± 0.4) %		–
$e^+ e^-$	$(8.8 \pm 1.3) \times 10^{-3}$		1843
$\mu^+ \mu^-$	$(7.7 \pm 1.7) \times 10^{-3}$		1840
Decays into $J/\psi(1S)$ and anything			
$J/\psi(1S)$ anything	(57 ± 4) %		–
$J/\psi(1S)$ neutrals	(23.2 ± 2.6) %		–
$J/\psi(1S) \pi^+ \pi^-$	(32.4 ± 2.6) %		477
$J/\psi(1S) \pi^0 \pi^0$	(18.4 ± 2.7) %		481
$J/\psi(1S) \eta$	(2.7 ± 0.4) %	S=1.7	200
$J/\psi(1S) \pi^0$	$(9.7 \pm 2.1) \times 10^{-4}$		527
Hadronic decays			
$3(\pi^+\pi^-)\pi^0$	$(3.5 \pm 1.6) \times 10^{-3}$		1746
$2(\pi^+\pi^-)\pi^0$	$(3.1 \pm 0.7) \times 10^{-3}$		1799
$\pi^+\pi^- K^+ K^-$	$(1.6 \pm 0.4) \times 10^{-3}$		1726
$\pi^+\pi^- p \overline{p}$	$(8.0 \pm 2.0) \times 10^{-4}$		1491
$K^+ \overline{K}^*(892)^0 \pi^-$ + c.c.	$(6.7 \pm 2.5) \times 10^{-4}$		1673
$2(\pi^+\pi^-)$	$(4.5 \pm 1.0) \times 10^{-4}$		1817
$\rho^0 \pi^+ \pi^-$	$(4.2 \pm 1.5) \times 10^{-4}$		1751
$\overline{p} p$	$(1.9 \pm 0.5) \times 10^{-4}$		1586
$3(\pi^+\pi^-)$	$(1.5 \pm 1.0) \times 10^{-4}$		1774
$\overline{p} p \pi^0$	$(1.4 \pm 0.5) \times 10^{-4}$		1543
$K^+ K^-$	$(1.0 \pm 0.7) \times 10^{-4}$		1776
$\pi^+\pi^-\pi^0$	$(9 \pm 5) \times 10^{-5}$		1830
$\pi^+\pi^-$	$(8 \pm 5) \times 10^{-5}$		1838
$\Lambda \overline{\Lambda}$	$< 4 \times 10^{-4}$	CL=90%	1467
$\Xi^- \overline{\Xi}^+$	$< 2 \times 10^{-4}$	CL=90%	1285
$\rho \pi$	$< 8.3 \times 10^{-5}$	CL=90%	1760
$K^+ K^- \pi^0$	$< 2.96 \times 10^{-5}$	CL=90%	1754
$K^+ \overline{K}^*(892)^-$ + c.c.	$< 5.4 \times 10^{-5}$	CL=90%	1698
Radiative decays			
$\gamma \chi_{c0}(1P)$	(9.3 ± 0.8) %		261
$\gamma \chi_{c1}(1P)$	(8.7 ± 0.8) %		171
$\gamma \chi_{c2}(1P)$	(7.8 ± 0.8) %		127
$\gamma \eta_c(1S)$	$(2.8 \pm 0.6) \times 10^{-3}$		639
$\gamma \pi^0$	$< 5.4 \times 10^{-3}$	CL=95%	1841
$\gamma \eta'(958)$	$< 1.1 \times 10^{-3}$	CL=90%	1719
$\gamma \gamma$	$< 1.6 \times 10^{-4}$	CL=90%	1843
$\gamma \eta(1440) \to \gamma K \overline{K} \pi$	$< 1.2 \times 10^{-4}$	CL=90%	1569

$\psi(3770)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 3769.9 \pm 2.5$ MeV (S = 1.8)
Full width $\Gamma = 23.6 \pm 2.7$ MeV (S = 1.1)
$\Gamma_{ee} = 0.26 \pm 0.04$ keV (S = 1.2)

$\psi(3770)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$D \overline{D}$	dominant		242
$e^+ e^-$	$(1.12 \pm 0.17) \times 10^{-5}$	1.2	1885

$\psi(4040)$ [iii]

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4040 \pm 10$ MeV
Full width $\Gamma = 52 \pm 10$ MeV
$\Gamma_{ee} = 0.75 \pm 0.15$ keV

$\psi(4040)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$e^+ e^-$	$(1.4 \pm 0.4) \times 10^{-5}$	2020
$D^0 \overline{D}^0$	seen	777
$D^*(2007)^0 \overline{D}^0$ + c.c.	seen	578
$D^*(2007)^0 \overline{D}^*(2007)^0$	seen	232

$\psi(4160)$ [iii]

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4159 \pm 20$ MeV
Full width $\Gamma = 78 \pm 20$ MeV
$\Gamma_{ee} = 0.77 \pm 0.23$ keV

$\psi(4160)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	$(10\pm4)\times10^{-6}$	2079

$\psi(4415)$ [iii]

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4415 \pm 6$ MeV
Full width $\Gamma = 43 \pm 15$ MeV (S = 1.8)
$\Gamma_{ee} = 0.47 \pm 0.10$ keV

$\psi(4415)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
hadrons	dominant	–
e^+e^-	$(1.1\pm0.4)\times10^{-5}$	2207

$b\overline{b}$ MESONS

$\Upsilon(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 9460.37 \pm 0.21$ MeV (S = 2.7)
Full width $\Gamma = 52.5 \pm 1.8$ keV
$\Gamma_{ee} = 1.32 \pm 0.05$ keV

$\Upsilon(1S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\tau^+\tau^-$	$(2.67^{+0.14}_{-0.16})$ %		4384
e^+e^-	(2.52 ± 0.17) %		4730
$\mu^+\mu^-$	(2.48 ± 0.07) %	S=1.1	4729
Hadronic decays			
$J/\psi(1S)$anything	$(1.1\ \pm0.4\ )\times10^{-3}$		4223
$\rho\pi$	$<2\ \times10^{-4}$	CL=90%	4698
$\pi^+\pi^-$	$<5\ \times10^{-4}$	CL=90%	4728
K^+K^-	$<5\ \times10^{-4}$	CL=90%	4704
$p\overline{p}$	$<5\ \times10^{-4}$	CL=90%	4636
Radiative decays			
$\gamma 2h^+2h^-$	$(7.0\ \pm1.5\ )\times10^{-4}$		4720
$\gamma 3h^+3h^-$	$(5.4\ \pm2.0\ )\times10^{-4}$		4703
$\gamma 4h^+4h^-$	$(7.4\ \pm3.5\ )\times10^{-4}$		4679
$\gamma\pi^+\pi^-K^+K^-$	$(2.9\ \pm0.9\ )\times10^{-4}$		4686
$\gamma 2\pi^+2\pi^-$	$(2.5\ \pm0.9\ )\times10^{-4}$		4720
$\gamma 3\pi^+3\pi^-$	$(2.5\ \pm1.2\ )\times10^{-4}$		4703
$\gamma 2\pi^+2\pi^-K^+K^-$	$(2.4\ \pm1.2\ )\times10^{-4}$		4658
$\gamma\pi^+\pi^-p\overline{p}$	$(1.5\ \pm0.6\ )\times10^{-4}$		4604
$\gamma 2\pi^+2\pi^-p\overline{p}$	$(4\ \ \pm6\ \ )\times10^{-5}$		4563
$\gamma 2K^+2K^-$	$(2.0\ \pm2.0\ )\times10^{-5}$		4601
$\gamma\eta'(958)$	$<1.3\ \times10^{-3}$	CL=90%	4682
$\gamma\eta$	$<3.5\ \times10^{-4}$	CL=90%	4714
$\gamma f'_2(1525)$	$<1.4\ \times10^{-4}$	CL=90%	4607
$\gamma f_2(1270)$	$<1.3\ \times10^{-4}$	CL=90%	4644
$\gamma\eta(1440)$	$<8.2\ \times10^{-5}$	CL=90%	4624
$\gamma f_J(1710)\to\gamma K\overline{K}$	$<2.6\ \times10^{-4}$	CL=90%	4576
$\gamma f_0(2200)\to\gamma K^+K^-$	$<2\ \times10^{-4}$	CL=90%	4475
$\gamma f_J(2220)\to\gamma K^+K^-$	$<1.5\ \times10^{-5}$	CL=90%	4469
$\gamma\eta(2225)\to\gamma\phi\phi$	$<3\ \times10^{-3}$	CL=90%	4469
γX (X = pseudoscalar with $m<7.2$ GeV)	$<3\ \times10^{-5}$	CL=90%	–
$\gamma X\overline{X}$ ($X\overline{X}$ = vectors with $m<3.1$ GeV)	$<1\ \times10^{-3}$	CL=90%	–

$\chi_{b0}(1P)$ [jjj]

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

Mass $m = 9859.8 \pm 1.3$ MeV

$\chi_{b0}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\gamma\Upsilon(1S)$	<6 %	90%	391

$\chi_{b1}(1P)$ [jjj]

$I^G(J^{PC}) = 0^+(1^{++})$
J needs confirmation.

Mass $m = 9891.9 \pm 0.7$ MeV

$\chi_{b1}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\Upsilon(1S)$	(35 ± 8) %	422

$\chi_{b2}(1P)$ [jjj]

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

Mass $m = 9913.2 \pm 0.6$ MeV

$\chi_{b2}(1P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\Upsilon(1S)$	(22 ± 4) %	443

$\Upsilon(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 10.02330 \pm 0.00031$ GeV
Full width $\Gamma = 44 \pm 7$ keV
$\Gamma_{ee} = 0.52 \pm 0.03$ keV

$\Upsilon(2S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Upsilon(1S)\pi^+\pi^-$	$(18.5\ \pm0.8\ )$ %		475
$\Upsilon(1S)\pi^0\pi^0$	$(\ 8.8\ \pm1.1\ )$ %		480
$\tau^+\tau^-$	$(\ 1.7\ \pm1.6\ )$ %		4686
$\mu^+\mu^-$	$(\ 1.31\pm0.21)$ %		5011
e^+e^-	seen		5012
$\Upsilon(1S)\pi^0$	$<8\ \times10^{-3}$	90%	531
$\Upsilon(1S)\eta$	$<2\ \times10^{-3}$	90%	127
$J/\psi(1S)$anything	$<6\ \times10^{-3}$	90%	4533
Radiative decays			
$\gamma\chi_{b1}(1P)$	$(\ 6.7\ \pm0.9\ )$ %		131
$\gamma\chi_{b2}(1P)$	$(\ 6.6\ \pm0.9\ )$ %		110
$\gamma\chi_{b0}(1P)$	$(\ 4.3\ \pm1.0\ )$ %		162
$\gamma f_J(1710)$	$<5.9\ \times10^{-4}$	90%	4866
$\gamma f'_2(1525)$	$<5.3\ \times10^{-4}$	90%	4896
$\gamma f_2(1270)$	$<2.41\ \times10^{-4}$	90%	4931

$\chi_{b0}(2P)$ [jjj]

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

Mass $m = 10.2321 \pm 0.0006$ GeV

$\chi_{b0}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\Upsilon(2S)$	(4.6 ± 2.1) %	210
$\gamma\Upsilon(1S)$	$(9\ \pm6\ )\times10^{-3}$	746

$\chi_{b1}(2P)$ [jjj]

$I^G(J^{PC}) = 0^+(1^{++})$
J needs confirmation.

Mass $m = 10.2552 \pm 0.0005$ GeV
$m_{\chi_{b1}(2P)} - m_{\chi_{b0}(2P)} = 23.5 \pm 1.0$ MeV

$\chi_{b1}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\gamma\Upsilon(2S)$	$(21\ \pm4\ )$ %	1.5	229
$\gamma\Upsilon(1S)$	$(\ 8.5\pm1.3)$ %	1.3	764

$\chi_{b2}(2P)$ [jjj]

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

Mass $m = 10.2685 \pm 0.0004$ GeV
$m_{\chi_{b2}(2P)} - m_{\chi_{b1}(2P)} = 13.5 \pm 0.6$ MeV

$\chi_{b2}(2P)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\gamma\Upsilon(2S)$	(16.2 ± 2.4) %	242
$\gamma\Upsilon(1S)$	$(\ 7.1\pm1.0)$ %	776

Meson Summary Table

$\Upsilon(3S)$

$I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 10.3553 \pm 0.0005$ GeV
Full width $\Gamma = 26.3 \pm 3.5$ keV

$\Upsilon(3S)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\Upsilon(2S)$ anything	(10.6 ±0.8) %		296
$\Upsilon(2S)\pi^+\pi^-$	(2.8 ±0.6) %	2.2	177
$\Upsilon(2S)\pi^0\pi^0$	(2.00±0.32) %		190
$\Upsilon(2S)\gamma\gamma$	(5.0 ±0.7) %		327
$\Upsilon(1S)\pi^+\pi^-$	(4.48±0.21) %		814
$\Upsilon(1S)\pi^0\pi^0$	(2.06±0.28) %		816
$\mu^+\mu^-$	(1.81±0.17) %		5177
e^+e^-	seen		5177
Radiative decays			
$\gamma\chi_{b2}(2P)$	(11.4 ±0.8) %	1.3	87
$\gamma\chi_{b1}(2P)$	(11.3 ±0.6) %		100
$\gamma\chi_{b0}(2P)$	(5.4 ±0.6) %	1.1	123

$\Upsilon(4S)$ or $\Upsilon(10580)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 10.5800 \pm 0.0035$ GeV
Full width $\Gamma = 21 \pm 4$ MeV (S = 2.3)
$\Gamma_{ee} = 0.248 \pm 0.031$ keV (S = 1.3)

$\Upsilon(4S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$B\overline{B}$	dominant		–
e^+e^-	$(2.8\pm0.7)\times10^{-5}$		5290
$J/\psi(3097)$ anything	$(2.2\pm0.7)\times10^{-3}$		–
D^{*+} anything + c.c.	< 7.4 %	90%	5099
ϕanything	$< 2.3 \times 10^{-3}$	90%	5240
$\Upsilon(1S)$ anything	$< 4 \times 10^{-3}$	90%	1053
non-$B\overline{B}$	< 4 %	95%	–

$\Upsilon(10860)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 10.865 \pm 0.008$ GeV (S = 1.1)
Full width $\Gamma = 110 \pm 13$ MeV
$\Gamma_{ee} = 0.31 \pm 0.07$ keV (S = 1.3)

$\Upsilon(10860)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	$(2.8\pm0.7)\times10^{-6}$	5432

$\Upsilon(11020)$

$I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 11.019 \pm 0.008$ GeV
Full width $\Gamma = 79 \pm 16$ MeV
$\Gamma_{ee} = 0.130 \pm 0.030$ keV

$\Upsilon(11020)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
e^+e^-	$(1.6\pm0.5)\times10^{-6}$	5509

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when S > 1, which often indicates that the measurements are inconsistent. When S > 1.25, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame.

[a] See the "Note on $\pi^\pm \to \ell^\pm\nu\gamma$ and $K^\pm \to \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ Particle Listings for definitions and details.

[b] Measurements of $\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ always include decays with γ's, and measurements of $\Gamma(e^+\nu_e\gamma)$ and $\Gamma(\mu^+\nu_\mu\gamma)$ never include low-energy γ's. Therefore, since no clean separation is possible, we consider the modes with γ's to be subreactions of the modes without them, and let $[\Gamma(e^+\nu_e) + \Gamma(\mu^+\nu_\mu)]/\Gamma_{\text{total}} = 100\%$.

[c] See the $\pi^\pm$ Particle Listings for the energy limits used in this measurement; low-energy γ's are not included.

[d] Derived from an analysis of neutrino-oscillation experiments.

[e] Astrophysical and cosmological arguments give limits of order 10^{-13}; see the π^0 Particle Listings.

[f] See the "Note on the Decay Width $\Gamma(\eta \to \gamma\gamma)$" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1451.

[g] See the "Note on η Decay Parameters" in the η Particle Listings.

[h] C parity forbids this to occur as a single-photon process.

[i] See the "Note on scalar mesons" in the $f_0(1370)$ Particle Listings.

[j] See the "Note on $\rho(770)$" in the $\rho(770)$ Particle Listings.

[k] The e^+e^- branching fraction is from $e^+e^- \to \pi^+\pi^-$ experiments only. The $\omega\rho$ interference is then due to $\omega\rho$ mixing only, and is expected to be small. If $e\mu$ universality holds, $\Gamma(\rho^0 \to \mu^+\mu^-) = \Gamma(\rho^0 \to e^+e^-) \times 0.99785$.

[l] This is only an educated guess; the error given is larger than the error on the average of the published values. See the Particle Listings for details.

[m] See the "Note on $a_1(1260)$" in the $a_1(1260)$ Particle Listings.

[n] See the "Note on the $f_1(1420)$" in the $f_1(1420)$ Particle Listings.

[o] See also the $\omega(1600)$ Particle Listings.

[p] See the "Note on the $\eta(1440)$" in the $\eta(1440)$ Particle Listings.

[q] See the "Note on the $\rho(1450)$ and the $\rho(1700)$" in the $\rho(1700)$ Particle Listings.

[r] See the "Note on non-$q\overline{q}$ mesons" in the Particle Listings (see the index for the page number).

[s] See also the $\omega(1420)$ Particle Listings.

[t] See the "Note on $f_J(1710)$" in the $f_J(1710)$ Particle Listings.

[u] See the note in the $K^\pm$ Particle Listings.

[v] The definition of the slope parameter g of the $K \to 3\pi$ Dalitz plot is as follows (see also "Note on Dalitz Plot Parameters for $K \to 3\pi$ Decays" in the $K^\pm$ Particle Listings):

$$|M|^2 = 1 + g(s_3 - s_0)/m_{\pi^+}^2 + \cdots .$$

[w] For more details and definitions of parameters see the Particle Listings.

[x] See the $K^\pm$ Particle Listings for the energy limits used in this measurement.

[y] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[z] Direct-emission branching fraction.

[aa] Structure-dependent part.

[bb] Derived from measured values of ϕ_{+-}, ϕ_{00}, $|\eta|$, $\tau_{K_S^0}$, and $|m_{K_L^0} - m_{K_S^0}|$, as described in the introduction to "Tests of Conservation Laws."

[*cc*] The *CP*-violation parameters are defined as follows (see also "Note on *CP* Violation in $K_S \to 3\pi$" and "Note on *CP* Violation in K_L^0 Decay" in the Particle Listings):

$$\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = \epsilon + \epsilon'$$

$$\eta_{00} = |\eta_{00}|e^{i\phi_{00}} = \frac{A(K_L^0 \to \pi^0\pi^0)}{A(K_S^0 \to \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

$$\delta = \frac{\Gamma(K_L^0 \to \pi^-\ell^+\nu) - \Gamma(K_L^0 \to \pi^+\ell^-\nu)}{\Gamma(K_L^0 \to \pi^-\ell^+\nu) + \Gamma(K_L^0 \to \pi^+\ell^-\nu)},$$

$$\mathrm{Im}(\eta_{+-0})^2 = \frac{\Gamma(K_S^0 \to \pi^+\pi^-\pi^0)^{CP\ \mathrm{viol.}}}{\Gamma(K_L^0 \to \pi^+\pi^-\pi^0)},$$

$$\mathrm{Im}(\eta_{000})^2 = \frac{\Gamma(K_S^0 \to \pi^0\pi^0\pi^0)}{\Gamma(K_L^0 \to \pi^0\pi^0\pi^0)}.$$

where for the last two relations *CPT* is assumed valid, *i.e.*, $\mathrm{Re}(\eta_{+-0}) \simeq 0$ and $\mathrm{Re}(\eta_{000}) \simeq 0$.

[*dd*] See the K_S^0 Particle Listings for the energy limits used in this measurement.

[*ee*] Calculated from K_L^0 semileptonic rates and the K_S^0 lifetime assuming $\Delta S = \Delta Q$.

[*ff*] ϵ'/ϵ is derived from $|\eta_{00}/\eta_{+-}|$ measurements using theoretical input on phases.

[*gg*] The value is for the sum of the charge states of particle/antiparticle states indicated.

[*hh*] See the K_L^0 Particle Listings for the energy limits used in this measurement.

[*ii*] $m_{e^+e^-} > 470$ MeV.

[*jj*] Allowed by higher-order electroweak interactions.

[*kk*] Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed.

[*ll*] See the "Note on $f_0(1370)$" in the $f_0(1370)$ Particle Listings and in the 1994 edition.

[*mm*] See the note in the $L(1770)$ Particle Listings in Reviews of Modern Physics **56** No. 2 Pt. II (1984), p. S200. See also the "Note on $K_2(1770)$ and the $K_2(1820)$" in the $K_2(1770)$ Particle Listings.

[*nn*] See the "Note on $K_2(1770)$ and the $K_2(1820)$" in the $K_2(1770)$ Particle Listings.

[*oo*] This is a weighted average of $D^\pm$ (44%) and D^0 (56%) branching fractions. See "D^+ and $D^0 \to$ (η anything) / (total D^+ and D^0)" under "D^+ Branching Ratios" in the Particle Listings.

[*pp*] This value averages the e^+ and μ^+ branching fractions, after making a small phase-space adjustment to the μ^+ fraction to be able to use it as an e^+ fraction; hence our ℓ^+ is really an e^+.

[*qq*] ℓ indicates e or μ mode, not sum over modes.

[*rr*] The branching fractions for this mode may differ from the sum of the submodes that contribute to it, due to interference effects. See the relevant papers in the Particle Listings.

[*ss*] The two experiments determining this ratio are in serious disagreement. See the Particle Listings.

[*tt*] This mode is not a useful test for a $\Delta C=1$ weak neutral current because both quarks must change flavor in this decay.

[*uu*] The D_1^0-D_2^0 limits are inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ via $\overline{D}^0)$ / $\Gamma(K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-)$.

[*vv*] This value is calculated from the ratio $\Gamma(K^-\mu^+\nu_\mu)/\Gamma(\mu^+ \mathrm{anything})$ in the D^0 Particle Listings.

[*ww*] The experiments on the division of this charge mode amongst its submodes disagree, and the submode branching fractions here add up to considerably more than the charged-mode fraction.

[*xx*] For now, we average together measurements of the $\phi e^+\nu_e$ and $\phi\mu^+\nu_\mu$ branching fractions. This is the *average*, not the *sum*.

[*yy*] This branching fraction is calculated from appropriate fractions of the next three branching fractions.

[*zz*] This value includes only K^+K^- decays of the $f_J(1710)$, because branching fractions of this resonance are not known.

[*aaa*] This mode is not a useful test for a $\Delta C=1$ weak neutral current because both quarks must change flavor in this decay.

[*bbb*] B^0 and B_s^0 contributions not separated. Limit is on weighted average of the two decay rates.

[*ccc*] These values are model dependent. See 'Note on Semileptonic Decays' in the B^+ Particle Listings.

[*ddd*] D^{**} stands for the sum of the $D(1\,^1P_1)$, $D(1\,^3P_0)$, $D(1\,^3P_1)$, $D(1\,^3P_2)$, $D(2\,^1S_0)$, and $D(2\,^1S_1)$ resonances.

[*eee*] Inclusive branching fractions have a multiplicity definition and can be greater than 100%.

[*fff*] D_j represents an unresolved mixture of pseudoscalar and tensor D^{**} (*P*-wave) states.

[*ggg*] Not a pure measurement. See note at head of B_s^0 Decay Modes.

[*hhh*] Includes $p\overline{p}\pi^+\pi^-\gamma$ and excludes $p\overline{p}\eta$, $p\overline{p}\omega$, $p\overline{p}\eta'$.

[*iii*] J^{PC} known by production in e^+e^- via single photon annihilation. I^G is not known; interpretation of this state as a single resonance is unclear because of the expectation of substantial threshold effects in this energy region.

[*jjj*] Spectroscopic labeling for these states is theoretical, pending experimental information.

Meson Summary Table

See also the table of suggested $q\overline{q}$ quark-model assignments in the Quark Model section.

- • Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.
- † Indicates that the value of J given is preferred, but needs confirmation.

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$
• $\pi^{\pm}$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(400\text{–}1200)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+?})$
$\hat{\rho}(1405)$	$1^-(1^{-+})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $\eta(1440)$	$0^+(0^{-+})$
$a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $f_0(1500)$	$0^+(0^{++})$
• $f_1(1510)$	$0^+(1^{++})$
• $f'_2(1525)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$
• $\omega(1600)$	$0^-(1^{--})$
$X(1600)$	$2^+(2^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\omega_3(1670)$	$0^-(3^{--})$
• $\pi_2(1670)$	$1^-(2^{-+})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
• $f_J(1710)$	$0^+(\text{even}^{++})$
$X(1740)$	$0^+(\text{even}^{++})$
$\eta(1760)$	$0^+(0^{-+})$
$\pi(1800)$	$1^-(0^{-+})$
$X(1775)$	$1^-(?^{-+})$
$f_2(1810)$	$0^+(2^{++})$
• $\phi_3(1850)$	$0^-(3^{--})$
$\eta_2(1870)$	$0^+(2^{-+})$
$X(1910)$	$0^+(?^{?+})$
$f_2(1950)$	$0^+(2^{++})$
$X(2000)$	$1^-(?^{?+})$
• $f_2(2010)$	$0^+(2^{++})$
$a_4(2040)$	$1^-(4^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$a_6(2450)$	$1^-(6^{++})$
$f_6(2510)$	$0^+(6^{++})$
$X(3250)$	$?^?(?^{??})$

OTHER LIGHT UNFLAVORED ($S = C = B = 0$)

$e^+e^-(1100\text{–}2200)$	$?^?(1^{--})$
$\overline{N}N(1100\text{–}3600)$	
$X(1900\text{–}3600)$	

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^{\pm}$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^{\pm}$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^{\pm}$	$1/2(1^-)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^{\pm}$	$1/2(?^?)$
• $D^*_2(2460)^0$	$1/2(2^+)$
• $D^*_2(2460)^+$	$1/2(2^+)$

CHARMED, STRANGE ($C = S = \pm1$)

• $D^{\pm}_s$	$0(0^-)$
• $D^{*\pm}_s$	$?(?^?)$
• $D_{s1}(2536)^{\pm}$	$0(1^+)$
• $D_{sJ}(2573)^{\pm}$	$?(?^?)$

BOTTOM ($B = \pm1$)

• $B^{\pm}$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• B^*	$1/2(1^-)$
$B^*_J(5732)$	$?(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

	$I^G(J^{PC})$
• B^0_s	$0(0^-)$
B^*_s	$?(?^?)$
$B^*_{sJ}(5850)$	$?(?^?)$

$c\overline{c}$

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
$\eta_c(2S)$	$?^?(?^{?+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$?^?(1^{--})$
• $\psi(4040)$	$?^?(1^{--})$
• $\psi(4160)$	$?^?(1^{--})$
• $\psi(4415)$	$?^?(1^{--})$

$b\overline{b}$

• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$?^?(1^{--})$
• $\Upsilon(11020)$	$?^?(1^{--})$

NON-$q\overline{q}$ CANDIDATES

Non-$q\overline{q}$ Candidates

Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the main Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the short table are not established as baryons. The names with masses are of baryons that decay strongly. See our 1986 edition (Physics Letters **170B**) for listings of evidence for Z baryons (KN resonances).

p	P_{11}	****	$\Delta(1232)$	P_{33}	****	Λ	P_{01}	****	Σ^+	P_{11}	****	Ξ^0	P_{11}	****
n	P_{11}	****	$\Delta(1600)$	P_{33}	***	$\Lambda(1405)$	S_{01}	****	Σ^0	P_{11}	****	Ξ^-	P_{11}	****
$N(1440)$	P_{11}	****	$\Delta(1620)$	S_{31}	****	$\Lambda(1520)$	D_{03}	****	Σ^-	P_{11}	****	$\Xi(1530)$	P_{13}	****
$N(1520)$	D_{13}	****	$\Delta(1700)$	D_{33}	****	$\Lambda(1600)$	P_{01}	***	$\Sigma(1385)$	P_{13}	****	$\Xi(1620)$		*
$N(1535)$	S_{11}	****	$\Delta(1750)$	P_{31}	*	$\Lambda(1670)$	S_{01}	****	$\Sigma(1480)$		*	$\Xi(1690)$		***
$N(1650)$	S_{11}	****	$\Delta(1900)$	S_{31}	***	$\Lambda(1690)$	D_{03}	****	$\Sigma(1560)$		**	$\Xi(1820)$	D_{13}	***
$N(1675)$	D_{15}	****	$\Delta(1905)$	F_{35}	****	$\Lambda(1800)$	S_{01}	***	$\Sigma(1580)$	D_{13}	**	$\Xi(1950)$		***
$N(1680)$	F_{15}	****	$\Delta(1910)$	P_{31}	****	$\Lambda(1810)$	P_{01}	***	$\Sigma(1620)$	S_{11}	**	$\Xi(2030)$		***
$N(1700)$	D_{13}	***	$\Delta(1920)$	P_{33}	***	$\Lambda(1820)$	F_{05}	****	$\Sigma(1660)$	P_{11}	***	$\Xi(2120)$		*
$N(1710)$	P_{11}	***	$\Delta(1930)$	D_{35}	***	$\Lambda(1830)$	D_{05}	****	$\Sigma(1670)$	D_{13}	****	$\Xi(2250)$		**
$N(1720)$	P_{13}	****	$\Delta(1940)$	D_{33}	*	$\Lambda(1890)$	P_{03}	****	$\Sigma(1690)$		**	$\Xi(2370)$		**
$N(1900)$	P_{13}	**	$\Delta(1950)$	F_{37}	****	$\Lambda(2000)$		*	$\Sigma(1750)$	S_{11}	***	$\Xi(2500)$		*
$N(1990)$	F_{17}	**	$\Delta(2000)$	F_{35}	**	$\Lambda(2020)$	F_{07}	*	$\Sigma(1770)$	P_{11}	*			
$N(2000)$	F_{15}	**	$\Delta(2150)$	S_{31}	*	$\Lambda(2100)$	G_{07}	****	$\Sigma(1775)$	D_{15}	****	Ω^-		****
$N(2080)$	D_{13}	**	$\Delta(2200)$	G_{37}	*	$\Lambda(2110)$	F_{05}	***	$\Sigma(1840)$	P_{13}	*	$\Omega(2250)^-$		***
$N(2090)$	S_{11}	*	$\Delta(2300)$	H_{39}	**	$\Lambda(2325)$	D_{03}	*	$\Sigma(1880)$	P_{11}	**	$\Omega(2380)^-$		**
$N(2100)$	P_{11}	*	$\Delta(2350)$	D_{35}	*	$\Lambda(2350)$	H_{09}	***	$\Sigma(1915)$	F_{15}	****	$\Omega(2470)^-$		**
$N(2190)$	G_{17}	****	$\Delta(2390)$	F_{37}	*	$\Lambda(2585)$		**	$\Sigma(1940)$	D_{13}	***			
$N(2200)$	D_{15}	**	$\Delta(2400)$	G_{39}	**				$\Sigma(2000)$	S_{11}	*	Λ_c^+		****
$N(2220)$	H_{19}	****	$\Delta(2420)$	$H_{3,11}$	****				$\Sigma(2030)$	F_{17}	****	$\Lambda_c(2593)^+$		***
$N(2250)$	G_{19}	****	$\Delta(2750)$	$I_{3,13}$	**				$\Sigma(2070)$	F_{15}	*	$\Lambda_c(2625)^+$		***
$N(2600)$	$I_{1,11}$	***	$\Delta(2950)$	$K_{3,15}$	**				$\Sigma(2080)$	P_{13}	**	$\Sigma_c(2455)$		****
$N(2700)$	$K_{1,13}$	**							$\Sigma(2100)$	G_{17}	*	$\Sigma_c(2530)$		*
									$\Sigma(2250)$		***	Ξ_c^+		***
									$\Sigma(2455)$		**	Ξ_c^0		***
									$\Sigma(2620)$		**	$\Xi_c(2645)$		***
									$\Sigma(3000)$		*	Ω_c^0		***
									$\Sigma(3170)$		*			
												Λ_b^0		***
												Ξ_b^0, Ξ_b^-		*

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

* Evidence of existence is poor.

N BARYONS
$(S = 0,\ I = 1/2)$

$p,\ N^+ = uud;\quad n,\ N^0 = udd$

p

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 938.27231 \pm 0.00028$ MeV [a]
$= 1.007276470 \pm 0.000000012$ u
$\left|\frac{q_{\overline{p}}}{m_{\overline{p}}}\right| / (\frac{q_p}{m_p}) = 1.0000000015 \pm 0.0000000011$
$|q_p + q_{\overline{p}}|/e < 2 \times 10^{-5}$
$|q_p + q_e|/e < 1.0 \times 10^{-21}$ [b]
Magnetic moment $\mu = 2.79284739 \pm 0.00000006\ \mu_N$
Electric dipole moment $d = (-4 \pm 6) \times 10^{-23}$ $e$cm
Electric polarizability $\overline{\alpha} = (12.1 \pm 0.9) \times 10^{-4}$ fm^3
Magnetic polarizability $\overline{\beta} = (2.1 \pm 0.9) \times 10^{-4}$ fm^3
Mean life $\tau > 1.6 \times 10^{25}$ years (independent of mode)
$= > 10^{31} - 5 \times 10^{32}$ years [c] (mode dependent)

Below, for N decays, p and n distinguish proton and neutron partial lifetimes. See also the "Note on Nucleon Decay" in our 1994 edition (Phys. Rev. **D50**, 1673) for a short review.

The "partial mean life" limits tabulated here are the limits on τ/B_i, where τ is the total mean life and B_i is the branching fraction for the mode in question.

p DECAY MODES	Partial mean life (10^{30} years)	Confidence level	p (MeV/c)
Antilepton + meson			
$N \to e^+\pi$	> 130 (n), > 550 (p)	90%	459
$N \to \mu^+\pi$	> 100 (n), > 270 (p)	90%	453
$N \to \nu\pi$	> 100 (n), > 25 (p)	90%	459
$p \to e^+\eta$	> 140	90%	309
$p \to \mu^+\eta$	> 69	90%	296
$n \to \nu\eta$	> 54	90%	310
$N \to e^+\rho$	> 58 (n), > 75 (p)	90%	153
$N \to \mu^+\rho$	> 23 (n), > 110 (p)	90%	119
$N \to \nu\rho$	> 19 (n), > 27 (p)	90%	153
$p \to e^+\omega$	> 45	90%	142
$p \to \mu^+\omega$	> 57	90%	104
$n \to \nu\omega$	> 43	90%	144
$N \to e^+K$	> 1.3 (n), > 150 (p)	90%	337
$p \to e^+K^0_S$	> 76	90%	337
$p \to e^+K^0_L$	> 44	90%	337
$N \to \mu^+K$	> 1.1 (n), > 120 (p)	90%	326
$p \to \mu^+K^0_S$	> 64	90%	326
$p \to \mu^+K^0_L$	> 44	90%	326
$N \to \nu K$	> 86 (n), > 100 (p)	90%	339
$p \to e^+K^*(892)^0$	> 52	90%	45
$N \to \nu K^*(892)$	> 22 (n), > 20 (p)	90%	45
Antilepton + mesons			
$p \to e^+\pi^+\pi^-$	> 21	90%	448
$p \to e^+\pi^0\pi^0$	> 38	90%	449
$n \to e^+\pi^-\pi^0$	> 32	90%	449
$p \to \mu^+\pi^+\pi^-$	> 17	90%	425
$p \to \mu^+\pi^0\pi^0$	> 33	90%	427
$n \to \mu^+\pi^-\pi^0$	> 33	90%	427
$n \to e^+K^0\pi^-$	> 18	90%	319
Lepton + meson			
$n \to e^-\pi^+$	> 65	90%	459
$n \to \mu^-\pi^+$	> 49	90%	453
$n \to e^-\rho^+$	> 62	90%	154
$n \to \mu^-\rho^+$	> 7	90%	120
$n \to e^-K^+$	> 32	90%	340
$n \to \mu^-K^+$	> 57	90%	330
Lepton + mesons			
$p \to e^-\pi^+\pi^+$	> 30	90%	448
$n \to e^-\pi^+\pi^0$	> 29	90%	449
$p \to \mu^-\pi^+\pi^+$	> 17	90%	425
$n \to \mu^-\pi^+\pi^0$	> 34	90%	427
$p \to e^-\pi^+K^+$	> 20	90%	320
$p \to \mu^-\pi^+K^+$	> 5	90%	279
Antilepton + photon(s)			
$p \to e^+\gamma$	> 460	90%	469
$p \to \mu^+\gamma$	> 380	90%	463
$n \to \nu\gamma$	> 24	90%	470
$p \to e^+\gamma\gamma$	> 100	90%	469
Three leptons			
$p \to e^+e^+e^-$	> 510	90%	469
$p \to e^+\mu^+\mu^-$	> 81	90%	457
$p \to e^+\nu\nu$	> 11	90%	469
$n \to e^+e^-\nu$	> 74	90%	470
$n \to \mu^+e^-\nu$	> 47	90%	464
$n \to \mu^+\mu^-\nu$	> 42	90%	458
$p \to \mu^+e^+e^-$	> 91	90%	464
$p \to \mu^+\mu^+\mu^-$	> 190	90%	439
$p \to \mu^+\nu\nu$	> 21	90%	463
$p \to e^-\mu^+\mu^+$	> 6	90%	457
$n \to 3\nu$	> 0.0005	90%	470
Inclusive modes			
$N \to e^+$anything	> 0.6 (n, p)	90%	–
$N \to \mu^+$anything	> 12 (n, p)	90%	–
$N \to e^+\pi^0$anything	> 0.6 (n, p)	90%	–
$\Delta B = 2$ dinucleon modes			
The following are lifetime limits per iron nucleus.			
$pp \to \pi^+\pi^+$	> 0.7	90%	–
$pn \to \pi^+\pi^0$	> 2	90%	–
$nn \to \pi^+\pi^-$	> 0.7	90%	–
$nn \to \pi^0\pi^0$	> 3.4	90%	–
$pp \to e^+e^+$	> 5.8	90%	–
$pp \to e^+\mu^+$	> 3.6	90%	–
$pp \to \mu^+\mu^+$	> 1.7	90%	–
$pn \to e^+\overline{\nu}$	> 2.8	90%	–
$pn \to \mu^+\overline{\nu}$	> 1.6	90%	–
$nn \to \nu_e\overline{\nu}_e$	> 0.000012	90%	–
$nn \to \nu_\mu\overline{\nu}_\mu$	> 0.000006	90%	–

$\overline{p}$ DECAY MODES

$\overline{p}$ DECAY MODES	Partial mean life (years)	Confidence level	p (MeV/c)
$\overline{p} \to e^-\gamma$	> 1848	95%	469
$\overline{p} \to e^-\pi^0$	> 554	95%	459
$\overline{p} \to e^-\eta$	> 171	95%	309
$\overline{p} \to e^-K^0_S$	> 29	95%	337
$\overline{p} \to e^-K^0_L$	> 9	95%	337

n

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 939.56563 \pm 0.00028$ MeV [a]
$= 1.008664904 \pm 0.000000014$ u
$m_n - m_p = 1.293318 \pm 0.000009$ MeV
$= 0.001388434 \pm 0.000000009$ u
Mean life $\tau = 887.0 \pm 2.0$ s (S = 1.3)
$c\tau = 2.659 \times 10^8$ km
Magnetic moment $\mu = -1.9130428 \pm 0.0000005\ \mu_N$
Electric dipole moment $d < 1.1 \times 10^{-25}$ $e$cm, CL = 95%
Electric polarizability $\alpha = (0.98^{+0.19}_{-0.23}) \times 10^{-3}$ fm^3 (S = 1.1)
Charge $q = (-0.4 \pm 1.1) \times 10^{-21}$ e
Mean $n\overline{n}$-oscillation time $> 1.2 \times 10^8$ s, CL = 90% [d] (bound n)
$> 0.86 \times 10^8$ s, CL = 90% (free n)

Decay parameters [e]

$pe^-\overline{\nu}_e$	$g_A/g_V = -1.2601 \pm 0.0025$ (S = 1.1)
"	$A = -0.1139 \pm 0.0011$ (S = 1.3)
"	$B = 0.990 \pm 0.008$
"	$a = -0.102 \pm 0.005$
"	$\phi_{AV} = (180.07 \pm 0.18)^\circ$ [f]
"	$D = (-0.5 \pm 1.4) \times 10^{-3}$

n DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$pe^-\overline{\nu}_e$	100 %		1.19
Charge conservation (Q) violating mode			
$p\nu_e\overline{\nu}_e$	Q < 9×10^{-24}	90%	1.29

N(1440) P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 1430 to 1470 (≈ 1440) MeV
Full width Γ = 250 to 450 (≈ 350) MeV
p_{beam} = 0.61 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 31.0 mb

N(1440) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	60–70 %	397
$N\pi\pi$	30–40 %	342
$\Delta\pi$	20–30 %	143
$N\rho$	<8 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–10 %	–
$p\gamma$	0.035–0.048 %	414
$p\gamma$, helicity=1/2	0.035–0.048 %	414
$n\gamma$	0.009–0.032 %	413
$n\gamma$, helicity=1/2	0.009–0.032 %	413

N(1520) D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Mass m = 1515 to 1530 (≈ 1520) MeV
Full width Γ = 110 to 135 (≈ 120) MeV
p_{beam} = 0.74 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 23.5 mb

N(1520) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	50–60 %	456
$N\pi\pi$	40–50 %	410
$\Delta\pi$	15–25 %	228
$N\rho$	15–25 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<8 %	–
$p\gamma$	0.46–0.56 %	470
$p\gamma$, helicity=1/2	0.001–0.034 %	470
$p\gamma$, helicity=3/2	0.44–0.53 %	470
$n\gamma$	0.30–0.53 %	470
$n\gamma$, helicity=1/2	0.04–0.10 %	470
$n\gamma$, helicity=3/2	0.25–0.45 %	470

N(1535) S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$

Mass m = 1520 to 1555 (≈ 1535) MeV
Full width Γ = 100 to 250 (≈ 150) MeV
p_{beam} = 0.76 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 22.5 mb

N(1535) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	35–55 %	467
$N\eta$	30–55 %	182
$N\pi\pi$	1–10 %	422
$\Delta\pi$	<1 %	242
$N\rho$	<4 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<3 %	–
$N(1440)\pi$	<7 %	†
$p\gamma$	0.08–0.27 %	481
$p\gamma$, helicity=1/2	0.08–0.27 %	481
$n\gamma$	0.004–0.29 %	480
$n\gamma$, helicity=1/2	0.004–0.29 %	480

N(1650) S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$

Mass m = 1640 to 1680 (≈ 1650) MeV
Full width Γ = 145 to 190 (≈ 150) MeV
p_{beam} = 0.96 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 16.4 mb

N(1650) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	55–90 %	547
$N\eta$	3–10 %	346
ΛK	3–11 %	161
$N\pi\pi$	10–20 %	511
$\Delta\pi$	1–7 %	344
$N\rho$	4–12 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<4 %	–
$N(1440)\pi$	<5 %	147
$p\gamma$	0.04–0.18 %	558
$p\gamma$, helicity=1/2	0.04–0.18 %	558
$n\gamma$	0.003–0.17 %	557
$n\gamma$, helicity=1/2	0.003–0.17 %	557

N(1675) D_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$

Mass m = 1670 to 1685 (≈ 1675) MeV
Full width Γ = 140 to 180 (≈ 150) MeV
p_{beam} = 1.01 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 15.4 mb

N(1675) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	40–50 %	563
ΛK	<1 %	209
$N\pi\pi$	50–60 %	529
$\Delta\pi$	50–60 %	364
$N\rho$	< 1–3 %	†
$p\gamma$	0.004–0.023 %	575
$p\gamma$, helicity=1/2	0.0–0.015 %	575
$p\gamma$, helicity=3/2	0.0–0.011 %	575
$n\gamma$	0.02–0.12 %	574
$n\gamma$, helicity=1/2	0.006–0.046 %	574
$n\gamma$, helicity=3/2	0.01–0.08 %	574

N(1680) F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$

Mass m = 1675 to 1690 (≈ 1680) MeV
Full width Γ = 120 to 140 (≈ 130) MeV
p_{beam} = 1.01 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 15.2 mb

N(1680) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	60–70 %	567
$N\pi\pi$	30–40 %	532
$\Delta\pi$	5–15 %	369
$N\rho$	3–15 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–20 %	–
$p\gamma$	0.21–0.32 %	578
$p\gamma$, helicity=1/2	0.001–0.011 %	578
$p\gamma$, helicity=3/2	0.20–0.32 %	578
$n\gamma$	0.021–0.046 %	577
$n\gamma$, helicity=1/2	0.004–0.029 %	577
$n\gamma$, helicity=3/2	0.01–0.024 %	577

N(1700) D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Mass m = 1650 to 1750 (≈ 1700) MeV
Full width Γ = 50 to 150 (≈ 100) MeV
p_{beam} = 1.05 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 14.5 mb

N(1700) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	580
ΛK	<3 %	250
$N\pi\pi$	85–95 %	547
$N\rho$	<35 %	†
$p\gamma$	0.01–0.05 %	591
$p\gamma$, helicity=1/2	0.0–0.024 %	591
$p\gamma$, helicity=3/2	0.002–0.026 %	591
$n\gamma$	0.01–0.13 %	590
$n\gamma$, helicity=1/2	0.0–0.09 %	590
$n\gamma$, helicity=3/2	0.01–0.05 %	590

$N(1710)\ P_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 1680 to 1740 (≈ 1710) MeV
Full width Γ = 50 to 250 (≈ 100) MeV
p_{beam} = 1.07 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 14.2 mb

N(1710) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	587
ΛK	5–25 %	264
$N\pi\pi$	40–90 %	554
$\Delta\pi$	15–40 %	393
$N\rho$	5–25 %	48
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	10–40 %	–
$p\gamma$	0.002–0.05%	598
$p\gamma$, helicity=1/2	0.002–0.05%	598
$n\gamma$	0.0–0.02%	597
$n\gamma$, helicity=1/2	0.0–0.02%	597

$N(1720)\ P_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$

Mass m = 1650 to 1750 (≈ 1720) MeV
Full width Γ = 100 to 200 (≈ 150) MeV
p_{beam} = 1.09 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 13.9 mb

N(1720) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	594
ΛK	1–15 %	278
$N\pi\pi$	>70 %	561
$N\rho$	70–85 %	104
$p\gamma$	0.003–0.10 %	604
$p\gamma$, helicity=1/2	0.003–0.08 %	604
$p\gamma$, helicity=3/2	0.001–0.03 %	604
$n\gamma$	0.002–0.39 %	603
$n\gamma$, helicity=1/2	0.0–0.002 %	603
$n\gamma$, helicity=3/2	0.001–0.39 %	603

$N(2190)\ G_{17}$

$I(J^P) = \frac{1}{2}(\frac{7}{2}^-)$

Mass m = 2100 to 2200 (≈ 2190) MeV
Full width Γ = 350 to 550 (≈ 450) MeV
p_{beam} = 2.07 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 6.21 mb

N(2190) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	888

$N(2220)\ H_{19}$

$I(J^P) = \frac{1}{2}(\frac{9}{2}^+)$

Mass m = 2180 to 2310 (≈ 2220) MeV
Full width Γ = 320 to 550 (≈ 400) MeV
p_{beam} = 2.14 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 5.97 mb

N(2220) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	905

$N(2250)\ G_{19}$

$I(J^P) = \frac{1}{2}(\frac{9}{2}^-)$

Mass m = 2170 to 2310 (≈ 2250) MeV
Full width Γ = 290 to 470 (≈ 400) MeV
p_{beam} = 2.21 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 5.74 mb

N(2250) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	923

$N(2600)\ I_{1,11}$

$I(J^P) = \frac{1}{2}(\frac{11}{2}^-)$

Mass m = 2550 to 2750 (≈ 2600) MeV
Full width Γ = 500 to 800 (≈ 650) MeV
p_{beam} = 3.12 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 3.86 mb

N(2600) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–10 %	1126

Δ BARYONS
($S = 0,\ I = 3/2$)

$\Delta^{++} = uuu,\ \ \Delta^+ = uud,\ \ \Delta^0 = udd,\ \ \Delta^- = ddd$

$\Delta(1232)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Mass m = 1230 to 1234 (≈ 1232) MeV
Full width Γ = 115 to 125 (≈ 120) MeV
p_{beam} = 0.30 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 94.8 mb

Δ(1232) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	>99 %	227
$N\gamma$	0.54–0.61 %	259
$N\gamma$, helicity=1/2	0.12–0.14 %	259
$N\gamma$, helicity=3/2	0.41–0.47 %	259

$\Delta(1600)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Mass m = 1550 to 1700 (≈ 1600) MeV
Full width Γ = 250 to 450 (≈ 350) MeV
p_{beam} = 0.87 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 18.6 mb

Δ(1600) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–25 %	512
$N\pi\pi$	75–90 %	473
$\Delta\pi$	40–70 %	301
$N\rho$	<25 %	†
$N(1440)\pi$	10–35 %	74
$N\gamma$	0.001–0.02 %	525
$N\gamma$, helicity=1/2	0.0–0.02 %	525
$N\gamma$, helicity=3/2	0.001–0.005 %	525

$\Delta(1620)\ S_{31}$

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$

Mass m = 1615 to 1675 (≈ 1620) MeV
Full width Γ = 120 to 180 (≈ 150) MeV
p_{beam} = 0.91 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 17.7 mb

Δ(1620) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	20–30 %	526
$N\pi\pi$	70–80 %	488
$\Delta\pi$	30–60 %	318
$N\rho$	7–25 %	†
$N\gamma$	0.004–0.044 %	538
$N\gamma$, helicity=1/2	0.004–0.044 %	538

$\Delta(1700)\ D_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$

Mass m = 1670 to 1770 (≈ 1700) MeV
Full width Γ = 200 to 400 (≈ 300) MeV
p_{beam} = 1.05 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 14.5 mb

Δ(1700) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	580
$N\pi\pi$	80–90 %	547
$\Delta\pi$	30–60 %	385
$N\rho$	30–55 %	†
$N\gamma$	0.12–0.26 %	591
$N\gamma$, helicity=1/2	0.08–0.16 %	591
$N\gamma$, helicity=3/2	0.025–0.12 %	591

$\Delta(1900)\ S_{31}$

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$

Mass m = 1850 to 1950 (≈ 1900) MeV
Full width Γ = 140 to 240 (≈ 200) MeV
p_{beam} = 1.44 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 9.71 mb

Δ(1900) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–30 %	710

$\Delta(1905)\ F_{35}$

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$

Mass m = 1870 to 1920 ($\approx$ 1905) MeV
Full width Γ = 280 to 440 ($\approx$ 350) MeV
p_{beam} = 1.45 GeV/c $\quad 4\pi\lambda\!\!\!^{-2}$ = 9.62 mb

Δ(1905) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	713
$N\pi\pi$	85–95 %	687
$\Delta\pi$	<25 %	542
$N\rho$	>60 %	421
$N\gamma$	0.01–0.03 %	721
$N\gamma$, helicity=1/2	0.0–0.1 %	721
$N\gamma$, helicity=3/2	0.004–0.03 %	721

$\Delta(1910)\ P_{31}$

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$

Mass m = 1870 to 1920 ($\approx$ 1910) MeV
Full width Γ = 190 to 270 ($\approx$ 250) MeV
p_{beam} = 1.46 GeV/c $\quad 4\pi\lambda\!\!\!^{-2}$ = 9.54 mb

Δ(1910) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	15–30 %	716
$N\gamma$	0.0–0.2 %	725
$N\gamma$, helicity=1/2	0.0–0.2 %	725

$\Delta(1920)\ P_{33}$

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

Mass m = 1900 to 1970 ($\approx$ 1920) MeV
Full width Γ = 150 to 300 ($\approx$ 200) MeV
p_{beam} = 1.48 GeV/c $\quad 4\pi\lambda\!\!\!^{-2}$ = 9.37 mb

Δ(1920) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–20 %	722

$\Delta(1930)\ D_{35}$

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$

Mass m = 1920 to 1970 ($\approx$ 1930) MeV
Full width Γ = 250 to 450 ($\approx$ 350) MeV
p_{beam} = 1.50 GeV/c $\quad 4\pi\lambda\!\!\!^{-2}$ = 9.21 mb

Δ(1930) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	10–20 %	729
$N\gamma$	0.0–0.02 %	737
$N\gamma$, helicity=1/2	0.0–0.01 %	737
$N\gamma$, helicity=3/2	0.0–0.01 %	737

$\Delta(1950)\ F_{37}$

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$

Mass m = 1940 to 1960 ($\approx$ 1950) MeV
Full width Γ = 290 to 350 ($\approx$ 300) MeV
p_{beam} = 1.54 GeV/c $\quad 4\pi\lambda\!\!\!^{-2}$ = 8.91 mb

Δ(1950) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	35–40 %	741
$N\pi\pi$		716
$\Delta\pi$	20–30 %	574
$N\rho$	<10 %	469
$N\gamma$	0.08–0.13 %	749
$N\gamma$, helicity=1/2	0.03–0.055 %	749
$N\gamma$, helicity=3/2	0.05–0.075 %	749

$\Delta(2420)\ H_{3,11}$

$I(J^P) = \frac{3}{2}(\frac{11}{2}^+)$

Mass m = 2300 to 2500 ($\approx$ 2420) MeV
Full width Γ = 300 to 500 ($\approx$ 400) MeV
p_{beam} = 2.64 GeV/c $\quad 4\pi\lambda\!\!\!^{-2}$ = 4.68 mb

Δ(2420) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	5–15 %	1023

Λ BARYONS
($S = -1,\ I = 0$)

$\Lambda^0 = uds$

Λ

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 1115.684 $\pm$ 0.006 MeV
Mean life τ = (2.632 $\pm$ 0.020) $\times 10^{-10}$ s (S = 1.6)
$c\tau$ = 7.89 cm
Magnetic moment $\mu = -0.613 \pm 0.004\ \mu_N$
Electric dipole moment $d < 1.5 \times 10^{-16}$ $e$cm, CL = 95%

Decay parameters

$p\pi^-$	$\alpha_- = 0.642 \pm 0.013$
"	$\phi_- = (-6.5 \pm 3.5)^\circ$
"	$\gamma_- = 0.76$ [g]
"	$\Delta_- = (8 \pm 4)^\circ$ [g]
$n\pi^0$	$\alpha_0 = +0.65 \pm 0.05$
$pe^-\overline{\nu}_e$	$g_A/g_V = -0.718 \pm 0.015$ [e]

Λ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$p\pi^-$	(63.9 $\pm$0.5) %	101
$n\pi^0$	(35.8 $\pm$0.5) %	104
$n\gamma$	(1.75$\pm$0.15) $\times 10^{-3}$	162
$p\pi^-\gamma$	[h] (8.4 $\pm$1.4) $\times 10^{-4}$	101
$pe^-\overline{\nu}_e$	(8.32$\pm$0.14) $\times 10^{-4}$	163
$p\mu^-\overline{\nu}_\mu$	(1.57$\pm$0.35) $\times 10^{-4}$	131

$\Lambda(1405)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass m = 1407 $\pm$ 4 MeV
Full width Γ = 50.0 $\pm$ 2.0 MeV
Below $\overline{K}N$ threshold

Λ(1405) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma\pi$	100 %	152

$\Lambda(1520)\ D_{03}$

$I(J^P) = 0(\frac{3}{2}^-)$

Mass m = 1519.5 $\pm$ 1.0 MeV [i]
Full width Γ = 15.6 $\pm$ 1.0 MeV [i]
p_{beam} = 0.39 GeV/c $\quad 4\pi\lambda\!\!\!^{-2}$ = 82.8 mb

Λ(1520) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	45 $\pm$ 1%	244
$\Sigma\pi$	42 $\pm$ 1%	267
$\Lambda\pi\pi$	10 $\pm$ 1%	252
$\Sigma\pi\pi$	0.9 $\pm$ 0.1%	152
$\Lambda\gamma$	0.8 $\pm$ 0.2%	351

$\Lambda(1600)\ P_{01}$

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 1560 to 1700 ($\approx$ 1600) MeV
Full width Γ = 50 to 250 ($\approx$ 150) MeV
p_{beam} = 0.58 GeV/c $\quad 4\pi\lambda\!\!\!^{-2}$ = 41.6 mb

Λ(1600) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	15–30 %	343
$\Sigma\pi$	10–60 %	336

$\Lambda(1670)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass m = 1660 to 1680 ($\approx$ 1670) MeV
Full width Γ = 25 to 50 ($\approx$ 35) MeV
$p_{\mathrm{beam}} = 0.74$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 28.5$ mb

Λ(1670) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	15–25 %	414
$\Sigma\pi$	20–60 %	393
$\Lambda\eta$	15–35 %	64

$\Lambda(1690)\ D_{03}$

$I(J^P) = 0(\frac{3}{2}^-)$

Mass m = 1685 to 1695 ($\approx$ 1690) MeV
Full width Γ = 50 to 70 ($\approx$ 60) MeV
$p_{\mathrm{beam}} = 0.78$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 26.1$ mb

Λ(1690) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–30 %	433
$\Sigma\pi$	20–40 %	409
$\Lambda\pi\pi$	$\sim$ 25 %	415
$\Sigma\pi\pi$	$\sim$ 20 %	350

$\Lambda(1800)\ S_{01}$

$I(J^P) = 0(\frac{1}{2}^-)$

Mass m = 1720 to 1850 ($\approx$ 1800) MeV
Full width Γ = 200 to 400 ($\approx$ 300) MeV
$p_{\mathrm{beam}} = 1.01$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 17.5$ mb

Λ(1800) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	25–40 %	528
$\Sigma\pi$	seen	493
$\Sigma(1385)\pi$	seen	345
$N\overline{K}^*(892)$	seen	†

$\Lambda(1810)\ P_{01}$

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 1750 to 1850 ($\approx$ 1810) MeV
Full width Γ = 50 to 250 ($\approx$ 150) MeV
$p_{\mathrm{beam}} = 1.04$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 17.0$ mb

Λ(1810) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–50 %	537
$\Sigma\pi$	10–40 %	501
$\Sigma(1385)\pi$	seen	356
$N\overline{K}^*(892)$	30–60 %	†

$\Lambda(1820)\ F_{05}$

$I(J^P) = 0(\frac{5}{2}^+)$

Mass m = 1815 to 1825 ($\approx$ 1820) MeV
Full width Γ = 70 to 90 ($\approx$ 80) MeV
$p_{\mathrm{beam}} = 1.06$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 16.5$ mb

Λ(1820) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	55–65 %	545
$\Sigma\pi$	8–14 %	508
$\Sigma(1385)\pi$	5–10 %	362

$\Lambda(1830)\ D_{05}$

$I(J^P) = 0(\frac{5}{2}^-)$

Mass m = 1810 to 1830 ($\approx$ 1830) MeV
Full width Γ = 60 to 110 ($\approx$ 95) MeV
$p_{\mathrm{beam}} = 1.08$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 16.0$ mb

Λ(1830) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	3–10 %	553
$\Sigma\pi$	35–75 %	515
$\Sigma(1385)\pi$	>15 %	371

$\Lambda(1890)\ P_{03}$

$I(J^P) = 0(\frac{3}{2}^+)$

Mass m = 1850 to 1910 ($\approx$ 1890) MeV
Full width Γ = 60 to 200 ($\approx$ 100) MeV
$p_{\mathrm{beam}} = 1.21$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 13.6$ mb

Λ(1890) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–35 %	599
$\Sigma\pi$	3–10 %	559
$\Sigma(1385)\pi$	seen	420
$N\overline{K}^*(892)$	seen	233

$\Lambda(2100)\ G_{07}$

$I(J^P) = 0(\frac{7}{2}^-)$

Mass m = 2090 to 2110 ($\approx$ 2100) MeV
Full width Γ = 100 to 250 ($\approx$ 200) MeV
$p_{\mathrm{beam}} = 1.68$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 8.68$ mb

Λ(2100) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	25–35 %	751
$\Sigma\pi$	$\sim$ 5 %	704
$\Lambda\eta$	<3 %	617
ΞK	<3 %	483
$\Lambda\omega$	<8 %	443
$N\overline{K}^*(892)$	10–20 %	514

$\Lambda(2110)\ F_{05}$

$I(J^P) = 0(\frac{5}{2}^+)$

Mass m = 2090 to 2140 ($\approx$ 2110) MeV
Full width Γ = 150 to 250 ($\approx$ 200) MeV
$p_{\mathrm{beam}} = 1.70$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 8.53$ mb

Λ(2110) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	5–25 %	757
$\Sigma\pi$	10–40 %	711
$\Lambda\omega$	seen	455
$\Sigma(1385)\pi$	seen	589
$N\overline{K}^*(892)$	10–60 %	524

$\Lambda(2350)\ H_{09}$

$I(J^P) = 0(\frac{9}{2}^+)$

Mass m = 2340 to 2370 ($\approx$ 2350) MeV
Full width Γ = 100 to 250 ($\approx$ 150) MeV
$p_{\mathrm{beam}} = 2.29$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 5.85$ mb

Λ(2350) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	$\sim$ 12 %	915
$\Sigma\pi$	$\sim$ 10 %	867

Σ BARYONS
$(S = -1, I = 1)$

$\Sigma^+ = uus, \quad \Sigma^0 = uds, \quad \Sigma^- = dds$

Σ^+

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1189.37 \pm 0.07$ MeV (S = 2.2)
Mean life $\tau = (0.799 \pm 0.004) \times 10^{-10}$ s
$c\tau = 2.396$ cm
Magnetic moment $\mu = 2.458 \pm 0.010\ \mu_N$ (S = 2.1)
$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\overline{\nu}) < 0.043$

Decay parameters

$p\pi^0$	$\alpha_0 = -0.980^{+0.017}_{-0.015}$
"	$\phi_0 = (36 \pm 34)^\circ$
"	$\gamma_0 = 0.16$ [g]
"	$\Delta_0 = (187 \pm 6)^\circ$ [g]
$n\pi^+$	$\alpha_+ = 0.068 \pm 0.013$
"	$\phi_+ = (167 \pm 20)^\circ$ (S = 1.1)
"	$\gamma_+ = -0.97$ [g]
"	$\Delta_+ = (-73^{+133}_{-10})^\circ$ [g]
$p\gamma$	$\alpha_\gamma = -0.76 \pm 0.08$

Σ^+ DECAY MODES		Fraction (Γ_i/Γ)		Confidence level	p (MeV/c)
$p\pi^0$		(51.57 ± 0.30) %			189
$n\pi^+$		(48.31 ± 0.30) %			185
$p\gamma$		$(1.23 \pm 0.05) \times 10^{-3}$			225
$n\pi^+\gamma$	[h]	$(4.5 \pm 0.5) \times 10^{-4}$			185
$\Lambda e^+\nu_e$		$(2.0 \pm 0.5) \times 10^{-5}$			71
$\Delta S = \Delta Q$ (SQ) violating modes or $\Delta S = 1$ weak neutral current (S1) modes					
$ne^+\nu_e$	SQ	< 5	$\times 10^{-6}$	90%	224
$n\mu^+\nu_\mu$	SQ	< 3.0	$\times 10^{-5}$	90%	202
pe^+e^-	S1	< 7	$\times 10^{-6}$		225

Σ^0

$I(J^P) = 1(\frac{1}{2}^+)$

J^P not measured; assumed to be the same as for the Σ^+ and Σ^-.

Mass $m = 1192.55 \pm 0.08$ MeV (S = 1.2)
$m_{\Sigma^-} - m_{\Sigma^0} = 4.88 \pm 0.08$ MeV (S = 1.2)
$m_{\Sigma^0} - m_\Lambda = 76.87 \pm 0.08$ MeV (S = 1.2)
Mean life $\tau = (7.4 \pm 0.7) \times 10^{-20}$ s
$c\tau = 2.22 \times 10^{-11}$ m
Transition magnetic moment $|\mu_{\Sigma\Lambda}| = 1.61 \pm 0.08\ \mu_N$

Σ^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda\gamma$		100 %		74
$\Lambda\gamma\gamma$		< 3 %	90%	74
Λe^+e^-	[i]	5×10^{-3}		74

Σ^-

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1197.436 \pm 0.033$ MeV (S = 1.2)
$m_{\Sigma^-} - m_{\Sigma^+} = 8.07 \pm 0.08$ MeV (S = 1.9)
$m_{\Sigma^-} - m_\Lambda = 81.752 \pm 0.034$ MeV (S = 1.2)
Mean life $\tau = (1.479 \pm 0.011) \times 10^{-10}$ s (S = 1.3)
$c\tau = 4.434$ cm
Magnetic moment $\mu = -1.160 \pm 0.025\ \mu_N$ (S = 1.7)

Decay parameters

$n\pi^-$	$\alpha_- = -0.068 \pm 0.008$
"	$\phi_- = (10 \pm 15)^\circ$
"	$\gamma_- = 0.98$ [g]
"	$\Delta_- = (249^{+12}_{-120})^\circ$ [g]
$ne^-\overline{\nu}_e$	$g_A/g_V = 0.340 \pm 0.017$ [e]
"	$f_2(0)/f_1(0) = 0.97 \pm 0.14$
"	$D = 0.11 \pm 0.10$
$\Lambda e^-\overline{\nu}_e$	$g_V/g_A = 0.01 \pm 0.10$ [e] (S = 1.5)
"	$g_{WM}/g_A = 2.4 \pm 1.7$ [e]

Σ^- DECAY MODES		Fraction (Γ_i/Γ)	p (MeV/c)
$n\pi^-$		(99.848 ± 0.005) %	193
$n\pi^-\gamma$	[h]	$(4.6 \pm 0.6) \times 10^{-4}$	193
$ne^-\overline{\nu}_e$		$(1.017 \pm 0.034) \times 10^{-3}$	230
$n\mu^-\overline{\nu}_\mu$		$(4.5 \pm 0.4) \times 10^{-4}$	210
$\Lambda e^-\overline{\nu}_e$		$(5.73 \pm 0.27) \times 10^{-5}$	79

$\Sigma(1385)\ P_{13}$

$I(J^P) = 1(\frac{3}{2}^+)$

$\Sigma(1385)^+$ mass $m = 1382.8 \pm 0.4$ MeV (S = 2.0)
$\Sigma(1385)^0$ mass $m = 1383.7 \pm 1.0$ MeV (S = 1.4)
$\Sigma(1385)^-$ mass $m = 1387.2 \pm 0.5$ MeV (S = 2.2)
$\Sigma(1385)^+$ full width $\Gamma = 35.8 \pm 0.8$ MeV
$\Sigma(1385)^0$ full width $\Gamma = 36 \pm 5$ MeV
$\Sigma(1385)^-$ full width $\Gamma = 39.4 \pm 2.1$ MeV (S = 1.7)
Below $\overline{K}N$ threshold

$\Sigma(1385)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\pi$	88 ± 2 %	208
$\Sigma\pi$	12 ± 2 %	127

$\Sigma(1660)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$

Mass $m = 1630$ to 1690 (≈ 1660) MeV
Full width $\Gamma = 40$ to 200 (≈ 100) MeV
$p_{beam} = 0.72$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 29.9$ mb

$\Sigma(1660)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	10–30 %	405
$\Lambda\pi$	seen	439
$\Sigma\pi$	seen	385

$\Sigma(1670)\ D_{13}$

$I(J^P) = 1(\frac{3}{2}^-)$

Mass $m = 1665$ to 1685 (≈ 1670) MeV
Full width $\Gamma = 40$ to 80 (≈ 60) MeV
$p_{beam} = 0.74$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 28.5$ mb

$\Sigma(1670)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	7–13 %	414
$\Lambda\pi$	5–15 %	447
$\Sigma\pi$	30–60 %	393

$\Sigma(1750)\ S_{11}$

$I(J^P) = 1(\frac{1}{2}^-)$

Mass $m = 1730$ to 1800 (≈ 1750) MeV
Full width $\Gamma = 60$ to 160 (≈ 90) MeV
$p_{beam} = 0.91$ GeV/c $\quad 4\pi\lambda\!\!\!^-{}^2 = 20.7$ mb

$\Sigma(1750)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	10–40 %	486
$\Lambda\pi$	seen	507
$\Sigma\pi$	<8 %	455
$\Sigma\eta$	15–55 %	81

$\Sigma(1775)\ D_{15}$

$I(J^P) = 1(\frac{5}{2}^-)$

Mass m = 1770 to 1780 (≈ 1775) MeV
Full width Γ = 105 to 135 (≈ 120) MeV
p_{beam} = 0.96 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 19.0 mb

Σ(1775) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	37–43%	508
$\Lambda\pi$	14–20%	525
$\Sigma\pi$	2–5%	474
$\Sigma(1385)\pi$	8–12%	324
$\Lambda(1520)\pi$	17–23%	198

$\Sigma(1915)\ F_{15}$

$I(J^P) = 1(\frac{5}{2}^+)$

Mass m = 1900 to 1935 (≈ 1915) MeV
Full width Γ = 80 to 160 (≈ 120) MeV
p_{beam} = 1.26 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 12.8 mb

Σ(1915) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	5–15 %	618
$\Lambda\pi$	seen	622
$\Sigma\pi$	seen	577
$\Sigma(1385)\pi$	<5 %	440

$\Sigma(1940)\ D_{13}$

$I(J^P) = 1(\frac{3}{2}^-)$

Mass m = 1900 to 1950 (≈ 1940) MeV
Full width Γ = 150 to 300 (≈ 220) MeV
p_{beam} = 1.32 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 12.1 mb

Σ(1940) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	<20 %	637
$\Lambda\pi$	seen	639
$\Sigma\pi$	seen	594
$\Sigma(1385)\pi$	seen	460
$\Lambda(1520)\pi$	seen	354
$\Delta(1232)\overline{K}$	seen	410
$N\overline{K}^*(892)$	seen	320

$\Sigma(2030)\ F_{17}$

$I(J^P) = 1(\frac{7}{2}^+)$

Mass m = 2025 to 2040 (≈ 2030) MeV
Full width Γ = 150 to 200 (≈ 180) MeV
p_{beam} = 1.52 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 9.93 mb

Σ(2030) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	17–23 %	702
$\Lambda\pi$	17–23 %	700
$\Sigma\pi$	5–10 %	657
ΞK	<2 %	412
$\Sigma(1385)\pi$	5–15 %	529
$\Lambda(1520)\pi$	10–20 %	430
$\Delta(1232)\overline{K}$	10–20 %	498
$N\overline{K}^*(892)$	<5 %	438

$\Sigma(2250)$

$I(J^P) = 1(?^?)$

Mass m = 2210 to 2280 (≈ 2250) MeV
Full width Γ = 60 to 150 (≈ 100) MeV
p_{beam} = 2.04 GeV/c $4\pi\lambda\!\!\!^{-2}$ = 6.76 mb

Σ(2250) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	<10 %	851
$\Lambda\pi$	seen	842
$\Sigma\pi$	seen	803

Ξ BARYONS
($S = -2, I = 1/2$)

$\Xi^0 = uss$, $\Xi^- = dss$

Ξ^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

P is not yet measured; + is the quark model prediction.

Mass m = 1314.9 ± 0.6 MeV
$m_{\Xi^-} - m_{\Xi^0}$ = 6.4 ± 0.6 MeV
Mean life τ = (2.90 ± 0.09) × 10^{-10} s
$c\tau$ = 8.71 cm
Magnetic moment μ = −1.250 ± 0.014 μ_N

Decay parameters

$\Lambda\pi^0$	$\alpha = -0.411 \pm 0.022$ (S = 2.1)
"	$\phi = (21 \pm 12)^\circ$
"	$\gamma = 0.85$ [g]
"	$\Delta = (218^{+12}_{-19})^\circ$ [g]
$\Lambda\gamma$	$\alpha = 0.4 \pm 0.4$
$\Sigma^0\gamma$	$\alpha = 0.20 \pm 0.32$

Ξ^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda\pi^0$		(99.54±0.05) %		135
$\Lambda\gamma$		(1.06±0.16) × 10^{-3}		184
$\Sigma^0\gamma$		(3.5 ±0.4) × 10^{-3}		117
$\Sigma^+ e^- \overline{\nu}_e$		< 1.1 × 10^{-3}	90%	120
$\Sigma^+ \mu^- \overline{\nu}_\mu$		< 1.1 × 10^{-3}	90%	64
ΔS = ΔQ (SQ) violating modes or ΔS = 2 forbidden (S2) modes				
$\Sigma^- e^+ \nu_e$	SQ	< 9 × 10^{-4}	90%	112
$\Sigma^- \mu^+ \nu_\mu$	SQ	< 9 × 10^{-4}	90%	49
$p\pi^-$	S2	< 4 × 10^{-5}	90%	299
$p e^- \overline{\nu}_e$	S2	< 1.3 × 10^{-3}		323
$p \mu^- \overline{\nu}_\mu$	S2	< 1.3 × 10^{-3}		309

Ξ^-

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

P is not yet measured; + is the quark model prediction.

Mass m = 1321.32 ± 0.13 MeV
Mean life τ = (1.639 ± 0.015) × 10^{-10} s
$c\tau$ = 4.91 cm
Magnetic moment μ = −0.6507 ± 0.0025 μ_N

Decay parameters

$\Lambda\pi^-$	$\alpha = -0.456 \pm 0.014$ (S = 1.8)
"	$\phi = (4 \pm 4)^\circ$
"	$\gamma = 0.89$ [g]
"	$\Delta = (188 \pm 8)^\circ$ [g]
$\Lambda e^- \overline{\nu}_e$	$g_A/g_V = -0.25 \pm 0.05$ [e]

Ξ^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Lambda\pi^-$		(99.887±0.035) %		139
$\Sigma^-\gamma$		(1.27 ±0.23) × 10^{-4}		118
$\Lambda e^- \overline{\nu}_e$		(5.63 ±0.31) × 10^{-4}		190
$\Lambda \mu^- \overline{\nu}_\mu$		(3.5 $^{+3.5}_{-2.2}$) × 10^{-4}		163
$\Sigma^0 e^- \overline{\nu}_e$		(8.7 ±1.7) × 10^{-5}		122
$\Sigma^0 \mu^- \overline{\nu}_\mu$		< 8 × 10^{-4}	90%	70
$\Xi^0 e^- \overline{\nu}_e$		< 2.3 × 10^{-3}	90%	6
ΔS = 2 forbidden (S2) modes				
$n\pi^-$	S2	< 1.9 × 10^{-5}	90%	303
$n e^- \overline{\nu}_e$	S2	< 3.2 × 10^{-3}	90%	327
$n \mu^- \overline{\nu}_\mu$	S2	< 1.5 %	90%	314
$p\pi^-\pi^-$	S2	< 4 × 10^{-4}	90%	223
$p\pi^- e^- \overline{\nu}_e$	S2	< 4 × 10^{-4}	90%	304
$p\pi^- \mu^- \overline{\nu}_\mu$	S2	< 4 × 10^{-4}	90%	250
$p\mu^-\mu^-$	L	< 4 × 10^{-4}	90%	272

$\Xi(1530)\ P_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$

$\Xi(1530)^0$ mass $m = 1531.80 \pm 0.32$ MeV (S = 1.3)
$\Xi(1530)^-$ mass $m = 1535.0 \pm 0.6$ MeV
$\Xi(1530)^0$ full width $\Gamma = 9.1 \pm 0.5$ MeV
$\Xi(1530)^-$ full width $\Gamma = 9.9^{+1.7}_{-1.9}$ MeV

Ξ(1530) DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\Xi\pi$	100 %		152
$\Xi\gamma$	<4 %	90%	200

$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$

Mass $m = 1690 \pm 10$ MeV [i]
Full width $\Gamma < 50$ MeV

Ξ(1690) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	seen	240
$\Sigma\overline{K}$	seen	51
$\Xi^-\pi^+\pi^-$	possibly seen	214

$\Xi(1820)\ D_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$

Mass $m = 1823 \pm 5$ MeV [i]
Full width $\Gamma = 24^{+15}_{-10}$ MeV [i]

Ξ(1820) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	large	400
$\Sigma\overline{K}$	small	320
$\Xi\pi$	small	413
$\Xi(1530)\pi$	small	234

$\Xi(1950)$

$I(J^P) = \frac{1}{2}(?^?)$

Mass $m = 1950 \pm 15$ MeV [i]
Full width $\Gamma = 60 \pm 20$ MeV [i]

Ξ(1950) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	seen	522
$\Sigma\overline{K}$	possibly seen	460
$\Xi\pi$	seen	518

$\Xi(2030)$

$I(J^P) = \frac{1}{2}(\geq \frac{5}{2}^?)$

Mass $m = 2025 \pm 5$ MeV [i]
Full width $\Gamma = 20^{+15}_{-5}$ MeV [i]

Ξ(2030) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda\overline{K}$	~ 20 %	589
$\Sigma\overline{K}$	~ 80 %	533
$\Xi\pi$	small	573
$\Xi(1530)\pi$	small	421
$\Lambda\overline{K}\pi$	small	501
$\Sigma\overline{K}\pi$	small	430

Ω BARYONS
($S=-3, I=0$)

$\Omega^- = sss$

Ω^-

$I(J^P) = 0(\frac{3}{2}^+)$

J^P is not yet measured; $\frac{3}{2}^+$ is the quark model prediction.

Mass $m = 1672.45 \pm 0.29$ MeV
Mean life $\tau = (0.822 \pm 0.012) \times 10^{-10}$ s
$c\tau = 2.46$ cm
Magnetic moment $\mu = -2.02 \pm 0.05\ \mu_N$

Decay parameters

ΛK^- $\alpha = -0.026 \pm 0.026$
$\Xi^0\pi^-$ $\alpha = 0.09 \pm 0.14$
$\Xi^-\pi^0$ $\alpha = 0.05 \pm 0.21$

Ω^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
ΛK^-		(67.8±0.7) %		211
$\Xi^0\pi^-$		(23.6±0.7) %		294
$\Xi^-\pi^0$		(8.6±0.4) %		290
$\Xi^-\pi^+\pi^-$		$(4.3^{+3.4}_{-1.3}) \times 10^{-4}$		190
$\Xi(1530)^0\pi^-$		$(6.4^{+5.1}_{-2.0}) \times 10^{-4}$		17
$\Xi^0 e^-\overline{\nu}_e$		$(5.6\pm2.8) \times 10^{-3}$		319
$\Xi^-\gamma$		$< 4.6 \times 10^{-4}$	90%	314
$\Delta S = 2$ forbidden ($S2$) modes				
$\Lambda\pi^-$	$S2$	$< 1.9 \times 10^{-4}$	90%	449

$\Omega(2250)^-$

$I(J^P) = 0(?^?)$

Mass $m = 2252 \pm 9$ MeV
Full width $\Gamma = 55 \pm 18$ MeV

$\Omega(2250)^-$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Xi^-\pi^+K^-$	seen	531
$\Xi(1530)^0 K^-$	seen	437

CHARMED BARYONS
($C=+1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

Λ_c^+

$I(J^P) = 0(\frac{1}{2}^+)$

J not confirmed; $\frac{1}{2}$ is the quark model prediction.

Mass $m = 2284.9 \pm 0.6$ MeV
Mean life $\tau = (0.206 \pm 0.012) \times 10^{-12}$ s
$c\tau = 61.8\ \mu$m

Decay asymmetry parameters

$\Lambda\pi^+$ $\alpha = -0.98 \pm 0.19$
$\Sigma^+\pi^0$ $\alpha = -0.45 \pm 0.32$
$\Lambda\ell^+\nu_\ell$ $\alpha = -0.82^{+0.11}_{-0.07}$

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Hadronic modes with a p and one $\overline{K}$				
$p\overline{K}^0$		(2.2 ± 0.4) %		872
$pK^-\pi^+$		(4.4 ± 0.6) %		822
$p\overline{K}^*(892)^0$	[k]	(1.6 ± 0.4) %		681
$\Delta(1232)^{++}K^-$		$(7 \pm 4) \times 10^{-3}$		709
$\Lambda(1520)\pi^+$	[k]	$(4.0^{+2.0}_{-1.7}) \times 10^{-3}$		626
$pK^-\pi^+$ nonresonant		$(2.5^{+0.5}_{-0.6})$ %		822
$p\overline{K}^0\eta$		(1.10± 0.29) %		567

$pK^0\pi^+\pi^-$		(2.1 ± 0.8) %		753
$pK^-\pi^+\pi^0$		seen		758
$pK^*(892)^-\pi^+$	[k]	(9 ± 5) × 10^{-3}		579
$p(K^-\pi^+)_{nonresonant}\pi^0$		(3.2 ± 0.7) %		758
$\Delta(1232)\overline{K}^*(892)$		seen		416
$pK^-\pi^+\pi^+\pi^-$		(10 ± 7) × 10^{-4}		670
$pK^-\pi^+\pi^0\pi^0$		(7.0 ± 3.5) × 10^{-3}		676
$pK^-\pi^+\pi^0\pi^0\pi^0$		(4.4 ± 2.8) × 10^{-3}		573
Hadronic modes with a p and zero or two K's				
$p\pi^+\pi^-$		(3.0 ± 1.6) × 10^{-3}		926
$pf_0(980)$	[k]	(2.4 ± 1.6) × 10^{-3}		621
$p\pi^+\pi^+\pi^-\pi^-$		(1.6 ± 1.0) × 10^{-3}		851
pK^+K^-		(2.0 ± 0.6) × 10^{-3}		615
$p\phi$	[k]	(1.06± 0.33) × 10^{-3}		589
Hadronic modes with a hyperon				
$\Lambda\pi^+$		(7.9 ± 1.8) × 10^{-3}		863
$\Lambda\pi^+\pi^0$		(3.2 ± 0.9) %		843
$\Lambda\rho^0$		< 4 %	CL=95%	638
$\Lambda\pi^+\pi^+\pi^-$		(2.9 ± 0.6) %		806
$\Lambda\pi^+\eta$		(1.5 ± 0.4) %		690
$\Sigma(1385)^+\eta$	[k]	(7.5 ± 2.4) × 10^{-3}		569
$\Lambda K^+\overline{K}^0$		(5.3 ± 1.4) × 10^{-3}		441
$\Sigma^0\pi^+$		(8.8 ± 2.0) × 10^{-3}		824
$\Sigma^+\pi^0$		(8.8 ± 2.2) × 10^{-3}		826
$\Sigma^+\eta$		(4.8 ± 1.7) × 10^{-3}		712
$\Sigma^+\pi^+\pi^-$		(3.0 ± 0.6) %		803
$\Sigma^+\rho^0$		< 1.2 %	CL=95%	578
$\Sigma^-\pi^+\pi^+$		(1.6 ± 0.6) %		798
$\Sigma^0\pi^+\pi^0$		(1.6 ± 0.6) %		802
$\Sigma^0\pi^+\pi^+\pi^-$		(9.2 ± 3.4) × 10^{-3}		762
$\Sigma^+\pi^+\pi^-\pi^0$				766
$\Sigma^+\omega$	[k]	(2.4 ± 0.7) %		568
$\Sigma^+\pi^+\pi^+\pi^-\pi^-$		($2.6^{+3.5}_{-1.8}$) × 10^{-3}		707
$\Sigma^+K^+K^-$		(3.1 ± 0.8) × 10^{-3}		346
$\Sigma^+\phi$	[k]	(3.0 ± 1.3) × 10^{-3}		292
$\Sigma^+K^+\pi^-$		($5.7^{+5.3}_{-3.2}$) × 10^{-3}		668
Ξ^0K^+		(3.4 ± 0.9) × 10^{-3}		652
$\Xi^-K^+\pi^+$		(4.3 ± 1.1) × 10^{-3}		564
$\Xi(1530)^0K^+$	[k]	(2.3 ± 0.7) × 10^{-3}		471
Semileptonic modes				
$\Lambda\ell^+\nu_\ell$	[l]	(2.3 ± 0.5) %		–
e^+ anything		(4.5 ± 1.7) %		–
pe^+ anything		(1.8 ± 0.9) %		–
Λe^+ anything		(1.6 ± 0.6) %		–
$\Lambda\mu^+$ anything		(1.5 ± 0.9) %		–
Inclusive modes				
p anything		(50 ±16) %		–
p anything (no Λ)		(12 ±19) %		–
n anything		(50 ±16) %		–
n anything (no Λ)		(29 ±17) %		–
Λ anything		(35 ±11) %	S=1.4	–
$\Sigma^\pm$ anything	[m]	(10 ± 5) %		–
$\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton number (L) violating modes				
$p\mu^+\mu^-$	$C1$	< 3.4 × 10^{-4}	CL=90%	936
$\Sigma^-\mu^+\mu^+$	L	< 7.0 × 10^{-4}	CL=90%	811

$\Lambda_c(2593)^+$

$I(J^P) = 0(\frac{1}{2}^-)$

The spin-parity follows from the fact that $\Sigma_c(2455)\pi$ decays, with little available phase space, dominate.

Mass $m = 2593.6 \pm 1.0$ MeV (S = 1.2)
$m - m_{\Lambda_c^+} = 308.6 \pm 0.8$ MeV (S = 1.3)
Full width $\Gamma = 3.9^{+2.4}_{-1.6}$ MeV

$\Lambda_c^+\pi\pi$ and $\Sigma_c(2455)\pi$ — the latter just barely — are the only strong decays allowed to an excited Λ_c^+ having this mass; and the $\Lambda_c^+\pi^+\pi^-$ mode seems to be largely via $\Sigma_c^{++}\pi^-$ or $\Sigma_c^0\pi^+$.

$\Lambda_c(2593)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_c^+\pi^+\pi^-$	seen	124
$\Sigma_c(2455)^{++}\pi^-$	large	17
$\Sigma_c(2455)^0\pi^+$	large	23
$\Lambda_c^+\pi^+\pi^-$ 3-body	small	124
$\Lambda_c^+\pi^0$	not seen	261
$\Lambda_c^+\gamma$	not seen	290

$\Lambda_c(2625)^+$

$I(J^P) = 0(?^?)$

J^P is expected to be $3/2^-$.

Mass $m = 2626.4 \pm 0.9$ MeV (S = 1.3)
$m - m_{\Lambda_c^+} = 341.5 \pm 0.8$ MeV (S = 1.9)
Full width Γ < 1.9 MeV, CL = 90%

$\Lambda_c^+\pi\pi$ and $\Sigma(2455)\pi$ are the only strong decays allowed to an excited Λ_c^+ having this mass.

$\Lambda_c(2625)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_c^+\pi^+\pi^-$	seen	184
$\Sigma_c(2455)^{++}\pi^-$	small	100
$\Sigma_c(2455)^0\pi^+$	small	101
$\Lambda_c^+\pi^+\pi^-$ 3-body	large	184
$\Lambda_c^+\pi^0$	not seen	293
$\Lambda_c^+\gamma$	not seen	319

$\Sigma_c(2455)$

$I(J^P) = 1(\frac{1}{2}^+)$

J^P not confirmed; $\frac{1}{2}^+$ is the quark model prediction.

$\Sigma_c(2455)^{++}$ mass $m = 2452.9 \pm 0.6$ MeV
$\Sigma_c(2455)^+$ mass $m = 2453.5 \pm 0.9$ MeV
$\Sigma_c(2455)^0$ mass $m = 2452.1 \pm 0.7$ MeV
$m_{\Sigma_c^{++}} - m_{\Lambda_c^+} = 167.95 \pm 0.25$ MeV
$m_{\Sigma_c^+} - m_{\Lambda_c^+} = 168.5 \pm 0.7$ MeV (S = 1.1)
$m_{\Sigma_c^0} - m_{\Lambda_c^+} = 167.2 \pm 0.4$ MeV (S = 1.1)
$m_{\Sigma_c^{++}} - m_{\Sigma_c^0} = 0.79 \pm 0.33$ MeV (S = 1.2)
$m_{\Sigma_c^+} - m_{\Sigma_c^0} = 1.4 \pm 0.6$ MeV

$\Lambda_c^+\pi$ is the only strong decay allowed to a Σ_c having this mass.

$\Sigma_c(2455)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_c^+\pi$	≈ 100 %	90

Ξ_c^+

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$I(J^P)$ not confirmed; $\frac{1}{2}(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 2465.6 \pm 1.4$ MeV
Mean life $\tau = (0.35^{+0.07}_{-0.04}) \times 10^{-12}$ s
$c\tau = 106$ μm

Ξ_c^+ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda K^-\pi^+\pi^+$	seen	784
$\Lambda\overline{K}^*(892)^0\pi^+$	not seen	601
$\Sigma(1385)^+K^-\pi^+$	not seen	676
$\Sigma^+K^-\pi^+$	seen	808
$\Sigma^+\overline{K}^*(892)^0$	seen	653
$\Sigma^0K^-\pi^+\pi^+$	seen	733
$\Xi^0\pi^+$	seen	875
$\Xi^-\pi^+\pi^+$	seen	850
$\Xi(1530)^0\pi^+$	not seen	748
$\Xi^0\pi^+\pi^0$	seen	854
$\Xi^0\pi^+\pi^+\pi^-$	seen	817
$\Xi^0e^+\nu_e$	seen	882

Ξ_c^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$I(J^P)$ not confirmed; $\frac{1}{2}(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 2470.3 \pm 1.8$ MeV (S = 1.3)
$m_{\Xi_c^0} - m_{\Xi_c^+} = 4.7 \pm 2.1$ MeV (S = 1.2)
Mean life $\tau = (0.098^{+0.023}_{-0.015}) \times 10^{-12}$ s
$c\tau = 29\ \mu$m

Ξ_c^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda \overline{K}^0$	seen	864
$\Xi^- \pi^+$	seen	875
$\Xi^- \pi^+ \pi^+ \pi^-$	seen	816
$p K^- \overline{K}^*(892)^0$	seen	406
$\Omega^- K^+$	seen	522
$\Xi^- e^+ \nu_e$	seen	882
$\Xi^- \ell^+$ anything	seen	–

$\Xi_c(2645)$

$I(J^P) = ?(?^?)$

Mass $m = 2643.8 \pm 1.8$ MeV
$m_{\Xi_c(2645)^0} - m_{\Xi_c^+} = 178.2 \pm 1.1$ MeV
Full width $\Gamma < 5.5$ MeV, CL = 90%

$\Xi_c \pi$ is the only strong decay allowed to a Ξ_c resonance having this mass.

$\Xi_c(2645)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Xi_c^+ \pi^-$	seen	107

Ω_c^0

$I(J^P) = 0(\frac{1}{2}^+)$

$I(J^P)$ not confirmed; $0(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 2704 \pm 4$ MeV (S = 1.8)
Mean life $\tau = (0.064 \pm 0.020) \times 10^{-12}$ s
$c\tau = 19\ \mu$m

Ω_c^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma^+ K^- K^- \pi^+$	seen	697
$\Xi^- K^- \pi^+ \pi^+$	seen	838
$\Omega^- \pi^+$	seen	827
$\Omega^- \pi^- \pi^+ \pi^+$	seen	759

BOTTOM (BEAUTY) BARYONS ($B = -1$)

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$

Λ_b^0

$I(J^P) = 0(\frac{1}{2}^+)$

$I(J^P)$ not yet measured; $0(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 5641 \pm 50$ MeV
Mean life $\tau = (1.14 \pm 0.08) \times 10^{-12}$ s
$c\tau = 342\ \mu$m

These branching fractions are actually an average over weakly decaying b-baryons weighted by their production rates in Z decay (or high-energy $p\overline{p}$), branching ratios, and detection efficiencies. They scale with the LEP Λ_b production fraction $B(b \to \Lambda_b)$ and are evaluated for our value $B(b \to \Lambda_b) = (13.2 \pm 4.1)\%$.

The branching fractions $B(\Lambda_b^0 \to \Lambda \ell^- \overline{\nu}_\ell$ anything) and $B(\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell$ anything) are not pure measurements because the underlying measured products of these with $B(b \to \Lambda_b)$ were used to determine $B(b \to \Lambda_b)$, as described in the note "Production and Decay of b-Flavored Hadrons."

Λ_b^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$J/\psi(1S)\Lambda$	(1.4± 0.9) %	1756
$p D^0 \pi^-$	seen	2383
$\Lambda_c^+ \pi^+ \pi^- \pi^-$	seen	2336
$p \mu^- \overline{\nu}$ anything	(3.7± 1.7) %	–
$\Lambda \ell^- \overline{\nu}_\ell$ anything	[n] (2.5± 0.5) %	–
$\Lambda_c^+ \ell^- \overline{\nu}_\ell$ anything	[n] (10.0± 3.0) %	–
$\Lambda / \overline{\Lambda}$ anything	($17\ ^{+11}_{-8}$) %	–

NOTES

This Summary Table only includes established baryons. The Particle Listings include evidence for other baryons. The masses, widths, and branching fractions for the resonances in this Table are Breit-Wigner parameters. The Particle Listings also give, where available, pole parameters. See, in particular, the *Note on N and Δ Resonances.*

For most of the resonances, the parameters come from various partial-wave analyses of more or less the same sets of data, and it is not appropriate to treat the results of the analyses as independent or to average them together. Furthermore, the systematic errors on the results are not well understood. Thus, we usually only give ranges for the parameters. We then also give a best guess for the mass (as part of the name of the resonance) and for the width. The *Note on N and Δ Resonances* and the *Note on Λ and Σ Resonances* in the Particle Listings review the partial-wave analyses.

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when $S > 1$, which often indicates that the measurements are inconsistent. When $S > 1.25$, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

A decay momentum p is given for each decay mode. For a 2-body decay, p is the momentum of each decay product in the rest frame of the decaying particle. For a 3-or-more-body decay, p is the largest momentum any of the products can have in this frame. For any resonance, the *nominal* mass is used in calculating p. A dagger ("†") in this column indicates that the mode is forbidden when the nominal masses of resonances are used, but is in fact allowed due to the nonzero widths of the resonances.

[*a*] The masses of the p and n are most precisely known in u (unified atomic mass units). The conversion factor to MeV, 1 u = 931.49432 ± 0.00028 MeV, is less well known than are the masses in u.

[*b*] The limit is from neutrality-of-matter experiments; it assumes $q_n = q_p + q_e$. See also the charge of the neutron.

[*c*] The first limit is geochemical and independent of decay mode. The second entry, a range of limits, assumes the dominant decay modes are among those investigated. For antiprotons the best limit, inferred from the observation of cosmic ray $\overline{p}$'s is $\tau_{\overline{p}} > 10^7$ yr, the cosmic-ray storage time, but this limit depends on a number of assumptions. The best direct observation of stored antiprotons gives $\tau_{\overline{p}}/B(\overline{p} \to e^- \gamma) > 1848$ yr.

[*d*] There is some controversy about whether nuclear physics and model dependence complicate the analysis for bound neutrons (from which the best limit comes). The second limit here is from reactor experiments with free neutrons.

[*e*] The parameters g_A, g_V, and g_{WM} for semileptonic modes are defined by $\overline{B}_f[\gamma_\lambda(g_V + g_A\gamma_5) + i(g_{WM}/m_{B_i})\ \sigma_{\lambda\nu}\ q^\nu]B_i$, and ϕ_{AV} is defined by $g_A/g_V = |g_A/g_V|e^{i\phi_{AV}}$. See the "Note on Baryon Decay Parameters" in the neutron Particle Listings.

[*f*] Time-reversal invariance requires this to be 0° or 180°.

[*g*] The decay parameters γ and Δ are calculated from α and ϕ using

$$\gamma = \sqrt{1-\alpha^2}\ \cos\phi\ , \qquad \tan\Delta = -\frac{1}{\alpha}\ \sqrt{1-\alpha^2}\ \sin\phi\ .$$

See the "Note on Baryon Decay Parameters" in the neutron Particle Listings.

[*h*] See the Particle Listings for the pion momentum range used in this measurement.

[*i*] The error given here is only an educated guess. It is larger than the error on the weighted average of the published values.

[*j*] A theoretical value using QED.

[*k*] This branching fraction includes all the decay modes of the final-state resonance.

[*l*] ℓ indicates e or μ mode, not sum over modes.

[*m*] The value is for the sum of the charge states of particle/antiparticle states indicated.

[*n*] Not a pure measurement. See note at head of Λ_b^0 Decay Modes.

MONOPOLES, SUPERSYMMETRY, COMPOSITENESS, etc., SEARCHES FOR

Magnetic Monopole Searches

Isolated candidate events have not been confirmed. Most experiments obtain negative results.

Supersymmetric Particle Searches

Limits are based on the Minimal Supersymmetric Standard Model.
Assumptions include: 1) $\widetilde{\chi}_1^0$ (or $\widetilde{\gamma}$) is lightest supersymmetric particle; 2) R-parity is conserved; 3) $m_{\widetilde{f}_L} = m_{\widetilde{f}_R}$, and all scalar quarks (except $\widetilde{t}_L$ and $\widetilde{t}_R$) are degenerate in mass.
See the Particle Listings for a Note giving details of supersymmetry.

$\widetilde{\chi}_i^0$ — neutralinos (mixtures of $\widetilde{\gamma}$, $\widetilde{Z}^0$, and $\widetilde{H}_i^0$)
Mass $m_{\widetilde{\gamma}}$ > 15 GeV, CL = 90% [if $m_{\widetilde{f}}$ = 100 GeV (from cosmology)]
Mass $m_{\widetilde{\chi}_1^0}$ > 23 GeV, CL = 95% [tanβ >3]
Mass $m_{\widetilde{\chi}_2^0}$ > 52 GeV, CL = 95% [tanβ >3]
Mass $m_{\widetilde{\chi}_3^0}$ > 84 GeV, CL = 95% [tanβ >3]
Mass $m_{\widetilde{\chi}_4^0}$ > 127 GeV, CL = 95% [tanβ >3]

$\widetilde{\chi}_i^\pm$ — charginos (mixtures of $\widetilde{W}^\pm$ and $\widetilde{H}_i^\pm$)
Mass $m_{\widetilde{\chi}_1^\pm}$ > 45 GeV, CL = 95% [all $m_{\widetilde{\chi}_1^0}$]
Mass $m_{\widetilde{\chi}_2^\pm}$ > 99 GeV, CL = 95% [GUT relations assumed]

$\widetilde{\nu}$ — scalar neutrino (sneutrino)
Mass m > 37.1 GeV, CL = 95% [one flavor]
Mass m > 41.8 GeV, CL = 95% [three degenerate flavors]

$\widetilde{e}$ — scalar electron (selectron)
Mass m > 65 GeV, CL = 95% [if $m_{\widetilde{\gamma}} = 0$]
Mass m > 50 GeV, CL = 95% [if $m_{\widetilde{\gamma}}$ < 5 GeV]
Mass m > 45 GeV, CL = 95% [if $m_{\widetilde{\chi}_1^0}$ < 41 GeV]

$\widetilde{\mu}$ — scalar muon (smuon)
Mass m > 45 GeV, CL = 95% [if $m_{\widetilde{\chi}_1^0}$ < 41 GeV]

$\widetilde{\tau}$ — scalar tau (stau)
Mass m > 45 GeV, CL = 95% [if $m_{\widetilde{\chi}_1^0}$ < 38 GeV]

$\widetilde{q}$ — scalar quark (squark)

These limits include the effects of cascade decays, evaluated assuming a fixed value of the parameters μ and tanβ. The limits are weakly sensitive to these parameters over much of parameter space. Limits assume GUT relations between gaugino masses and the gauge coupling; in particular that for $|\mu|$ not small, $m_{\widetilde{\chi}_1^0} \approx m_{\widetilde{g}}/6$.

Mass m > 176 GeV, CL = 95% [any $m_{\widetilde{g}}$ <300 GeV, $\mu = -250$ GeV, tanβ = 2]
Mass m > 224 GeV, CL = 95% [$m_{\widetilde{g}} \leq m_{\widetilde{q}}$, $\mu = -400$ GeV, tanβ = 4]

$\widetilde{g}$ — gluino

There is some controversy about a low-mass window ($1 \lesssim m_{\widetilde{g}} \lesssim 4$ GeV). Several experiments cast doubt on the existence of this window.

These limits include the effects of cascade decays, evaluated assuming a fixed value of the parameters μ and tanβ. The limits are weakly sensitive to these parameters over much of parameter space. Limits assume GUT relations between gaugino masses and the gauge coupling; in particular that for $|\mu|$ not small, $m_{\widetilde{\chi}_1^0} \approx m_{\widetilde{g}}/6$.

Mass m > 154 GeV, CL = 95% [$m_{\widetilde{g}} \leq m_{\widetilde{q}}$, $\mu = -400$ GeV, tanβ = 4]
Mass m > 212 GeV, CL = 95% [$m_{\widetilde{g}} \geq m_{\widetilde{q}}$, $\mu = -250$ GeV, tanβ = 2]

Quark and Lepton Compositeness, Searches for

Scale Limits Λ for Contact Interactions (the lowest dimensional interactions with four fermions)

If the Lagrangian has the form

$$\pm \frac{g^2}{2\Lambda^2} \overline{\psi}_L \gamma_\mu \psi_L \overline{\psi}_L \gamma^\mu \psi_L$$

(with $g^2/4\pi$ set equal to 1), then we define $\Lambda \equiv \Lambda_{LL}^\pm$. For the full definitions and for other forms, see the Note in the Listings on Searches for Quark and Lepton Compositeness in the full *Review* and the original literature.

$\Lambda_{LL}^+(eeee)$ > 1.6 TeV, CL = 95%
$\Lambda_{LL}^-(eeee)$ > 3.6 TeV, CL = 95%
$\Lambda_{LL}^+(ee\mu\mu)$ > 2.6 TeV, CL = 95%
$\Lambda_{LL}^-(ee\mu\mu)$ > 1.9 TeV, CL = 95%
$\Lambda_{LL}^+(ee\tau\tau)$ > 1.9 TeV, CL = 95%
$\Lambda_{LL}^-(ee\tau\tau)$ > 2.9 TeV, CL = 95%
$\Lambda_{LL}^+(\ell\ell\ell\ell)$ > 3.5 TeV, CL = 95%
$\Lambda_{LL}^-(\ell\ell\ell\ell)$ > 2.8 TeV, CL = 95%
$\Lambda_{LL}^+(eeqq)$ > 2.3 TeV, CL = 95%
$\Lambda_{LL}^-(eeqq)$ > 2.2 TeV, CL = 95%
$\Lambda_{LL}^+(\mu\mu qq)$ > 1.4 TeV, CL = 95%
$\Lambda_{LL}^-(\mu\mu qq)$ > 1.6 TeV, CL = 95%
$\Lambda_{LR}^\pm(\nu_\mu \nu_e \mu e)$ > 3.1 TeV, CL = 90%
$\Lambda_{LL}^\pm(qqqq)$ > 1.4 TeV, CL = 95%

Recent CDF measurements of the inclusive jet cross section in $p\overline{p}$ collisions could be interpreted as tentative evidence for a four-quark contact interaction with $\Lambda_{LL}^\pm(qqqq) \sim 1.6$ TeV. However, CDF notes that uncertainty in the parton distribution functions, higher-order QCD corrections, and detector calibration may possibly account for the effect.

Excited Leptons

The limits from $\ell^{*+}\ell^{*-}$ do not depend on λ (where λ is the $\ell\ell^*$ transition coupling). The λ-dependent limits assume chiral coupling, except for the third limit for e^* which is for nonchiral coupling. For chiral coupling, this limit corresponds to $\lambda_\gamma = \sqrt{2}$.

$e^{*\pm}$ — excited electron
Mass m > 46.1 GeV, CL = 95% (from $e^{*+}e^{*-}$)
Mass m > 91 GeV, CL = 95% (if λ_Z > 1)
Mass m > 146 GeV, CL = 95% (if λ_γ = 1)

$\mu^{*\pm}$ — excited muon
Mass m > 46.1 GeV, CL = 95% (from $\mu^{*+}\mu^{*-}$)
Mass m > 91 GeV, CL = 95% (if λ_Z > 1)

$\tau^{*\pm}$ — excited tau
Mass m > 46.0 GeV, CL = 95% (from $\tau^{*+}\tau^{*-}$)
Mass m > 90 GeV, CL = 95% (if λ_Z > 0.18)

ν^* — excited neutrino
Mass m > 47 GeV, CL = 95% (from $\nu^*\overline{\nu}^*$)
Mass m > 91 GeV, CL = 95% (if λ_Z > 1)

q^* — excited quark
Mass m > 45.6 GeV, CL = 95% (from $q^*\overline{q}^*$)
Mass m > 88 GeV, CL = 95% (if λ_Z > 1)
Mass m > 570 GeV, CL = 95% ($p\overline{p} \to q^*X$)

Color Sextet and Octet Particles

Color Sextet Quarks (q_6)
Mass m > 84 GeV, CL = 95% (Stable q_6)

Color Octet Charged Leptons (ℓ_8)
Mass m > 86 GeV, CL = 95% (Stable ℓ_8)

Color Octet Neutrinos (ν_8)
Mass m > 110 GeV, CL = 90% ($\nu_8 \to \nu g$)

TESTS OF CONSERVATION LAWS

Revised by L. Wolfenstein and T.G. Trippe, June 1996.

In keeping with the current interest in tests of conservation laws, we collect together a Table of experimental limits on all weak and electromagnetic decays, mass differences, and moments, and on a few reactions, whose observation would violate conservation laws. The Table is given only in the full *Review of Particle Physics*, not in the Particle Physics Booklet. For the benefit of Booklet readers, we include the best limits from the Table in the following text. The Table is in two parts: "Discrete Space-Time Symmetries," *i.e.*, C, P, T, CP, and CPT; and "Number Conservation Laws," *i.e.*, lepton, baryon, hadronic flavor, and charge conservation. The references for these data can be found in the the Particle Listings in the *Review*. A discussion of these tests follows.

CPT INVARIANCE

General principles of relativistic field theory require invariance under the combined transformation CPT. The simplest tests of CPT invariance are the equality of the masses and lifetimes of a particle and its antiparticle. The best test comes from the limit on the mass difference between K^0 and $\overline{K}^0$. Any such difference contributes to the CP-violating parameter ϵ. Assuming CPT invariance, ϕ_ϵ, the phase of ϵ should be very close to 44°. (See the "Note on CP Violation in K_L^0 Decay" in the Particle Listings.) In contrast, if the entire source of CP violation in K^0 decays were a $K^0 - \overline{K}^0$ mass difference, ϕ_ϵ would be $44° + 90°$. It is possible to deduce that [1]

$$m_{\overline{K}^0} - m_{K^0} \approx \frac{2(m_{K_L^0} - m_{K_S^0})\,|\eta|\,(\frac{2}{3}\phi_{+-} + \frac{1}{3}\phi_{00} - \phi_\epsilon)}{\sin\phi_\epsilon}\,.$$

Using our best values of the CP-violation parameters, we get $|(m_{\overline{K}^0} - m_{K^0})/m_{K^0}| \leq 9 \times 10^{-19}$ (CL = 90%). Limits can also be placed on specific CPT-violating decay amplitudes. Given the small value of $(1-|\eta_{00}/\eta_{+-}|)$, the value of $\phi_{00}-\phi_{+-}$ provides a measure of CPT violation in $K_L^0 \to 2\pi$ decay. Results from CERN [1] and Fermilab [2] indicate no CPT-violating effect.

CP AND T INVARIANCE

Given CPT invariance, CP violation and T violation are equivalent. So far the only evidence for CP or T violation comes from the measurements of η_{+-}, η_{00}, and the semileptonic decay charge asymmetry for K_L, *e.g.*, $|\eta_{+-}| = |A(K_L^0 \to \pi^+\pi^-)/A(K_S^0 \to \pi^+\pi^-)| = (2.285 \pm 0.019) \times 10^{-3}$ and $[\Gamma(K_L^0 \to \pi^- e^+ \nu) - \Gamma(K_L^0 \to \pi^+ e^- \overline{\nu})]/[\text{sum}] = (0.333 \pm 0.014)\%$. Other searches for CP or T violation divide into (a) those that involve weak interactions or parity violation, and (b) those that involve processes otherwise allowed by the strong or electromagnetic interactions. In class (a) the most sensitive are probably the searches for an electric dipole moment of the neutron, measured to be $< 1.1 \times 10^{-25}$ e cm (95% CL), and the electron $(-0.3 \pm 0.8) \times 10^{-26}$ e cm. A nonzero value requires both P and T violation. Class (b) includes the search for C violation in η decay, believed to be an electromagnetic process, *e.g.*, as measured by $\Gamma(\eta \to \mu^+\mu^-\pi^0)/\Gamma(\eta \to \text{all}) < 5 \times 10^{-6}$, and searches for T violation in a number of nuclear and electromagnetic reactions.

CONSERVATION OF LEPTON NUMBERS

Present experimental evidence and the standard electroweak theory are consistent with the absolute conservation of three separate lepton numbers: electron number L_e, muon number L_μ, and tau number L_τ. Searches for violations are of the following types:

a) $\Delta L = 2$ for one type of lepton. The best limit comes from the search for neutrinoless double beta decay $(Z, A) \to (Z+2, A) + e^- + e^-$. The best laboratory limit is $t_{1/2} > 5.6 \times 10^{24}$ yr (CL=90%) for ^{76}Ge.

b) Conversion of one lepton type to another. For purely leptonic processes, the best limits are on $\mu \to e\gamma$ and $\mu \to 3e$, measured as $\Gamma(\mu \to e\gamma)/\Gamma(\mu \to \text{all}) < 5 \times 10^{-11}$ and $\Gamma(\mu \to 3e)/\Gamma(\mu \to \text{all}) < 1.0 \times 10^{-12}$. For semileptonic processes, the best limit comes from the coherent conversion process in a muonic atom, $\mu^- + (Z, A) \to e^- + (Z, A)$, measured as $\Gamma(\mu^-\text{Ti} \to e^-\text{Ti})/\Gamma(\mu^-\text{Ti} \to \text{all}) < 4 \times 10^{-12}$. Of special interest is the case in which the hadronic flavor also changes, as in $K_L \to e\mu$ and $K^+ \to \pi^+ e^- \mu^+$, measured as $\Gamma(K_L \to e\mu)/\Gamma(K_L \to \text{all}) < 3.3 \times 10^{-11}$ and $\Gamma(K^+ \to \pi^+ e^- \mu^+)/\Gamma(K^+ \to \text{all}) < 2.1 \times 10^{-10}$. Limits on the conversion of τ into e or μ are found in τ decay and are much less stringent than those for $\mu \to e$ conversion, *e.g.*, $\Gamma(\tau \to \mu\gamma)/\Gamma(\tau \to \text{all}) < 4.2 \times 10^{-6}$ and $\Gamma(\tau \to e\gamma)/\Gamma(\tau \to \text{all}) < 1.1 \times 10^{-4}$.

c) Conversion of one type of lepton into another type of antilepton. The case most studied is $\mu^- + (Z, A) \to e^+ + (Z-2, A)$, the strongest limit being $\Gamma(\mu^-\text{Ti} \to e^+\text{Ca})/\Gamma(\mu^-\text{Ti} \to \text{all}) < 9 \times 10^{-11}$.

d) Relation to neutrino mass. If neutrinos have mass, then it is expected even in the standard electroweak theory that the lepton numbers are not separately conserved, as a consequence of lepton mixing analogous to Cabibbo quark mixing. However, in this case lepton-number-violating processes such as $\mu \to e\gamma$ are expected to have extremely small probability. For small neutrino masses, the lepton-number violation would be observed first in neutrino oscillations, which have been the subject of extensive experimental searches. For example, searches for $\overline{\nu}_e$ disappearance, which we label as $\overline{\nu}_e \not\to \overline{\nu}_e$, give measured limits $\Delta(m^2) < 0.0075$ eV^2 for $\sin^2(2\theta) = 1$, and $\sin^2(2\theta) < 0.02$ for large $\Delta(m^2)$, where θ is the neutrino mixing angle. Searches for $\nu_\mu \to \nu_e$ limit $\sin^2(2\theta) < 0.0025$ for large $\Delta(m^2)$. For larger neutrino masses ($\gg 1$ keV), lepton-number violation is searched for by looking for anomalous decays such as $\pi \to e\nu_x$, where ν_x is a massive neutrino. If the $\Delta L = 2$ type of violation occurs, it is expected that neutrinos will have a nonzero mass of the Majorana type.

CONSERVATION OF HADRONIC FLAVORS

In strong and electromagnetic interactions, hadronic flavor is conserved, *i.e.* the conversion of a quark of one flavor (d, u, s, c, b, t) into a quark of another flavor is forbidden. In the Standard Model, the weak interactions violate these conservation laws in a manner described by the Cabibbo-Kobayashi-Maskawa mixing (see the section "Cabibbo-Kobayashi-Maskawa Mixing Matrix"). The way in which these conservation laws are violated is tested as follows:

a) $\Delta S = \Delta Q$ rule. In the semileptonic decay of strange particles, the strangeness change equals the change in charge of the hadrons. Tests come from limits on decay rates such as $\Gamma(\Sigma^+ \to n e^+ \nu)/\Gamma(\Sigma^+ \to \text{all}) < 5 \times 10^{-6}$, and from a detailed analysis of $K_L \to \pi e \nu$, which yields the parameter x, measured to be $(\text{Re}\,x, \text{Im}\,x) = (0.006 \pm 0.018, -0.003 \pm 0.026)$. Corresponding rules are $\Delta C = \Delta Q$ and $\Delta B = \Delta Q$.

b) Change of flavor by two units. In the Standard Model this occurs only in second-order weak interactions. The classic example is $\Delta S = 2$ via $K^0 - \overline{K}^0$ mixing, which is directly measured by $m(K_S) - m(K_L) = (3.491 \pm 0.009) \times 10^{-12}$ MeV. There

Tests of Conservation Laws

is now evidence for $B^0-\overline{B}^0$ mixing ($\Delta B=2$), with the corresponding mass difference between the eigenstates $(m_{B^0_H}-m_{B^0_L})$ $=(0.73\pm0.05)\Gamma_{B^0}=(3.12\pm0.21)\times10^{-10}$ MeV, and for B^0_s–$\overline{B}^0_s$ mixing, with $(m_{B^0_{sH}}-m_{B^0_{sL}})>9.5\Gamma_{B^0_s}$ or $>4\times10^{-9}$ MeV. No evidence exists for $D^0-\overline{D}^0$ mixing, which is expected to be much smaller in the Standard Model.

c) Flavor-changing neutral currents. In the Standard Model the neutral-current interactions do not change flavor. The low rate $\Gamma(K_L\to\mu^+\mu^-)/\Gamma(K_L\to\text{all})=(7.2\pm0.5)\times10^{-9}$ puts limits on such interactions; the nonzero value for this rate is attributed to a combination of the weak and electromagnetic interactions. The best test should come from a limit on $K^+\to\pi^+\nu\overline{\nu}$, which occurs in the Standard Model only as a second-order weak process with a branching fraction of $(1\text{ to }8)\times10^{-10}$. The current limit is $\Gamma(K^+\to\pi^+\nu\overline{\nu})/\Gamma(K^+\to\text{all})<2.4\times10^{-9}$. Limits for charm-changing or bottom-changing neutral currents are much less stringent: $\Gamma(D^0\to\mu^+\mu^-)/\Gamma(D^0\to\text{all})<8\times10^{-6}$ and $\Gamma(B^0\to\mu^+\mu^-)/\Gamma(B^0\to\text{all})<5.9\times10^{-6}$. One cannot isolate flavor-changing neutral current (FCNC) effects in non leptonic decays. For example, the FCNC transition $s\to d+(\overline{u}+u)$ is equivalent to the charged-current transition $s\to u+(\overline{u}+d)$. Tests for FCNC are therefore limited to hadron decays into lepton pairs. Such decays are expected only in second-order in the electroweak coupling in the Standard Model.

References

1. R. Carosi *et al.*, Phys. Lett. **B237**, 303 (1990).
2. M. Karlsson *et al.*, Phys. Rev. Lett. **64**, 2976 (1990); L.K. Gibbons *et al.*, Phys. Rev. Lett. **70**, 1199 (1993).
3. B. Schwingenheuer *et al.*, Phys. Rev. Lett. **74**, 4376 (1995).

TESTS OF DISCRETE SPACE-TIME SYMMETRIES

CHARGE CONJUGATION (*C*) INVARIANCE

$\Gamma(\pi^0\to3\gamma)/\Gamma_{total}$		$<3.1\times10^{-8}$, CL = 90%
η *C*-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry parameter		$(0.09\pm0.17)\times10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry parameter		$(0.18\pm0.16)\times10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry parameter		$(-0.17\pm0.17)\times10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry parameter		$(0.9\pm0.4)\times10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (*D*-wave)		0.05 ± 0.06 (S = 1.5)
$\Gamma(\eta\to3\gamma)/\Gamma_{total}$		$<5\times10^{-4}$, CL = 95%
$\Gamma(\eta\to\pi^0e^+e^-)/\Gamma_{total}$	[a]	$<4\times10^{-5}$, CL = 90%
$\Gamma(\eta\to\pi^0\mu^+\mu^-)/\Gamma_{total}$	[a]	$<5\times10^{-6}$, CL = 90%
$\Gamma(\omega(782)\to\eta\pi^0)/\Gamma_{total}$		$<1\times10^{-3}$, CL = 90%
$\Gamma(\omega(782)\to3\pi^0)/\Gamma_{total}$		$<3\times10^{-4}$, CL = 90%

PARITY (*P*) INVARIANCE

e electric dipole moment	$(-0.3\pm0.8)\times10^{-26}$ *e*cm
μ electric dipole moment	$(3.7\pm3.4)\times10^{-19}$ *e*cm
τ electric dipole moment	$<5\times10^{-17}$ *e*cm, CL = 95%
$\Gamma(\eta\to\pi^+\pi^-)/\Gamma_{total}$	$<1.5\times10^{-3}$
p electric dipole moment	$(-4\pm6)\times10^{-23}$ *e*cm
n electric dipole moment	$<1.1\times10^{-25}$ *e*cm, CL = 95%
Λ electric dipole moment	$<1.5\times10^{-16}$ *e*cm, CL = 95%

TIME REVERSAL (*T*) INVARIANCE

Limits on *e*, μ, τ, *p*, *n*, and Λ electric dipole moments under Parity above are also tests of Time Reversal Invariance.

μ decay parameters		
transverse e^+ polarization normal to plane of μ spin, e^+ momentum		0.007 ± 0.023
α'/A		$(0\pm4)\times10^{-3}$
β'/A		$(2\pm6)\times10^{-3}$
τ electric dipole moment		$<5\times10^{-17}$ *e*cm, CL = 95%
Im(ξ) in $K^\pm_{\mu3}$ decay (from transverse μ pol.)		-0.017 ± 0.025
Im(ξ) in $K^0_{\mu3}$ decay (from transverse μ pol.)		-0.007 ± 0.026
$n\to pe^-\nu$ decay parameters		
ϕ_{AV}, phase of g_A relative to g_V	[b]	$(180.07\pm0.18)^\circ$
triple correlation coefficient *D*		$(-0.5\pm1.4)\times10^{-3}$
triple correlation coefficient *D* for $\Sigma^-\to ne^-\overline{\nu}_e$		0.11 ± 0.10

CP INVARIANCE

Re(d^W_τ)		$<7.8\times10^{-18}$ *e*cm, CL = 95%
$\Gamma(\eta\to\pi^+\pi^-)/\Gamma_{total}$		$<1.5\times10^{-3}$
$K^\pm\to\pi^\pm\pi^+\pi^-$ rate difference/average		(0.07 ± 0.12)%
$K^\pm\to\pi^\pm\pi^0\pi^0$ rate difference/average		(0.0 ± 0.6)%
$K^\pm\to\pi^\pm\pi^0\gamma$ rate difference/average		(0.9 ± 3.3)%
$(g_{\tau^+}-g_{\tau^-})\,/\,(g_{\tau^+}+g_{\tau^-})$ for $K^\pm\to\pi^\pm\pi^+\pi^-$		(-0.7 ± 0.5)%
CP-violation parameters in K^0_S decay		
$\text{Im}(\eta_{+-0})=\text{Im}(A(K^0_S\to\pi^+\pi^-\pi^0,$ *CP*-violating) / $A(K^0_L\to\pi^+\pi^-\pi^0))$		-0.015 ± 0.030
$\text{Im}(\eta_{000})^2=\Gamma(K^0_S\to3\pi^0)\,/\,\Gamma(K^0_L\to3\pi^0)$		<0.1, CL = 90%
charge asymmetry *j* for $K^0_L\to\pi^+\pi^-\pi^0$		0.0011 ± 0.0008
$\lvert\epsilon'_{+-\gamma}\rvert/\epsilon$		<0.3, CL = 90%
$\Gamma(K^0_L\to\pi^0\mu^+\mu^-)/\Gamma_{total}$	[c]	$<5.1\times10^{-9}$, CL = 90%
$\Gamma(K^0_L\to\pi^0e^+e^-)/\Gamma_{total}$	[c]	$<4.3\times10^{-9}$, CL = 90%
$\Gamma(K^0_L\to\pi^0\nu\overline{\nu})/\Gamma_{total}$	[d]	$<5.8\times10^{-5}$, CL = 90%
$A_{CP}(K^+K^-\pi^\pm)$ in $D^\pm\to K^+K^-\pi^\pm$		-0.03 ± 0.07
$A_{CP}(K^\pm K^{*0})$ in $D^+\to K^+\overline{K}^{*0}$ and $D^-\to K^-K^{*0}$		-0.12 ± 0.13
$A_{CP}(\phi\pi^\pm)$ in $D^\pm\to\phi\pi^\pm$		0.07 ± 0.09
$A_{CP}(K^+K^-)$ in D^0, $\overline{D}^0\to K^+K^-$		0.06 ± 0.05
$A_{CP}(K^0_S\phi)$ in D^0, $\overline{D}^0\to K^0_S\phi$		-0.03 ± 0.09
$A_{CP}(K^0_S\pi^0)$ in D^0, $\overline{D}^0\to K^0_S\pi^0$		-0.018 ± 0.030
$\lvert\text{Re}(\epsilon_{B^0})\rvert$		<0.045
$[\alpha_-(\Lambda)+\alpha_+(\overline{\Lambda})]\,/\,[\alpha_-(\Lambda)-\alpha_+(\overline{\Lambda})]$		-0.03 ± 0.06

CP VIOLATION OBSERVED

K^0_L branching ratios		
charge asymmetry in $K^0_{\ell3}$ decays		
$\delta(\mu)=[\Gamma(\pi^-\mu^+\nu_\mu)-\Gamma(\pi^+\mu^-\overline{\nu}_\mu)]$/sum		(0.304 ± 0.025)%
$\delta(e)=[\Gamma(\pi^-e^+\nu_e)-\Gamma(\pi^+e^-\overline{\nu}_e)]$/sum		(0.333 ± 0.014)%
parameters for $K^0_L\to2\pi$ decay		
$\lvert\eta_{00}\rvert=\lvert A(K^0_L\to2\pi^0)\,/\,A(K^0_S\to2\pi^0)\rvert$		$(2.275\pm0.019)\times10^{-3}$ (S = 1.1)
$\lvert\eta_{+-}\rvert=\lvert A(K^0_L\to\pi^+\pi^-)\,/\,A(K^0_S\to\pi^+\pi^-)\rvert$		$(2.285\pm0.019)\times10^{-3}$
$\epsilon'/\epsilon\approx\text{Re}(\epsilon'/\epsilon)=(1-\lvert\eta_{00}/\eta_{+-}\rvert)/3$	[e]	$(1.5\pm0.8)\times10^{-3}$ (S = 1.8)
ϕ_{+-}, phase of η_{+-}		$(43.7\pm0.6)^\circ$
ϕ_{00}, phase of η_{00}		$(43.5\pm1.0)^\circ$
parameters for $K^0_L\to\pi^+\pi^-\gamma$ decay		
$\lvert\eta_{+-\gamma}\rvert=\lvert A(K^0_L\to\pi^+\pi^-\gamma$, *CP* violating)$/A(K^0_S\to\pi^+\pi^-\gamma)\rvert$		$(2.35\pm0.07)\times10^{-3}$
$\phi_{+-\gamma}$ = phase of $\eta_{+-\gamma}$		$(44\pm4)^\circ$
$\Gamma(K^0_L\to\pi^+\pi^-)/\Gamma_{total}$		$(2.067\pm0.035)\times10^{-3}$ (S = 1.1)
$\Gamma(K^0_L\to\pi^0\pi^0)/\Gamma_{total}$		$(9.36\pm0.20)\times10^{-4}$

CPT INVARIANCE

$(m_{W^+} - m_{W^-}) / m_{\rm average}$		-0.002 ± 0.007
$(m_{e^+} - m_{e^-}) / m_{\rm average}$		$<4 \times 10^{-8}$, CL = 90%
$\lvert q_{e^+} + q_{e^-} \rvert / e$		$<4 \times 10^{-8}$
$(g_{e^+} - g_{e^-}) / g_{\rm average}$		$(-0.5 \pm 2.1) \times 10^{-12}$
$(\tau_{\mu^+} - \tau_{\mu^-}) / \tau_{\rm average}$		$(2 \pm 8) \times 10^{-5}$
$(g_{\mu^+} - g_{\mu^-}) / g_{\rm average}$		$(-2.6 \pm 1.6) \times 10^{-8}$
$(m_{\pi^+} - m_{\pi^-}) / m_{\rm average}$		$(2 \pm 5) \times 10^{-4}$
$(\tau_{\pi^+} - \tau_{\pi^-}) / \tau_{\rm average}$		$(6 \pm 7) \times 10^{-4}$
$(m_{K^+} - m_{K^-}) / m_{\rm average}$		$(-0.6 \pm 1.8) \times 10^{-4}$
$(\tau_{K^+} - \tau_{K^-}) / \tau_{\rm average}$		$(0.11 \pm 0.09)\%$ (S = 1.2)
$K^\pm \to \mu^\pm \nu_\mu$ rate difference/average		$(-0.5 \pm 0.4)\%$
$K^\pm \to \pi^\pm \pi^0$ rate difference/average	[f]	$(0.8 \pm 1.2)\%$
$\lvert m_{K^0} - m_{\overline{K}^0} \rvert / m_{\rm average}$	[g]	$<9 \times 10^{-19}$
phase difference $\phi_{00} - \phi_{+-}$		$(-0.2 \pm 0.8)^\circ$
CPT-violation parameters in K^0 decay		
real part of Δ		0.018 ± 0.020
imaginary part of Δ		0.02 ± 0.04
$(\lvert \frac{q_{\overline{p}}}{m_{\overline{p}}} \rvert - \frac{q_p}{m_p}) / \lvert \frac{q}{m} \rvert_{\rm average}$		$(1.5 \pm 1.1) \times 10^{-9}$
$\lvert q_p + q_{\overline{p}} \rvert / e$		$<2 \times 10^{-5}$
$(\mu_p - \lvert \mu_{\overline{p}} \rvert) / \lvert \mu_{\rm average} \rvert$		$(-2.6 \pm 2.9) \times 10^{-3}$
$(m_n - m_{\overline{n}}) / m_{\rm average}$		$(9 \pm 5) \times 10^{-5}$
$(m_\Lambda - m_{\overline{\Lambda}}) / m_\Lambda$		$(-1.0 \pm 0.9) \times 10^{-5}$
$(\tau_\Lambda - \tau_{\overline{\Lambda}}) / \tau_{\rm average}$		0.04 ± 0.09
$(\mu_{\Sigma^+} - \lvert \mu_{\overline{\Sigma}^-} \rvert) / \lvert \mu \rvert_{\rm average}$		0.014 ± 0.015
$(m_{\Xi^-} - m_{\overline{\Xi}^+}) / m_{\rm average}$		$(1.1 \pm 2.7) \times 10^{-4}$
$(\tau_{\Xi^-} - \tau_{\overline{\Xi}^+}) / \tau_{\rm average}$		0.02 ± 0.18
$(m_{\Omega^-} - m_{\overline{\Omega}^+}) / m_{\rm average}$		$(0 \pm 5) \times 10^{-4}$

TESTS OF NUMBER CONSERVATION LAWS

LEPTON FAMILY NUMBER

Lepton family number conservation means separate conservation of each of L_e, L_μ, L_τ.

$\Gamma(Z \to e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<1.7 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to e^\pm \tau^\mp)/\Gamma_{\rm total}$	[h]	$<9.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to \mu^\pm \tau^\mp)/\Gamma_{\rm total}$	[h]	$<1.7 \times 10^{-5}$, CL = 95%
limit on $\mu^- \to e^-$ conversion		
$\sigma(\mu^- \, {}^{32}{\rm S} \to e^- \, {}^{32}{\rm S})$ / $\sigma(\mu^- \, {}^{32}{\rm S} \to \nu_\mu \, {}^{32}{\rm P}^*)$		$<7 \times 10^{-11}$, CL = 90%
$\sigma(\mu^- \, {\rm Ti} \to e^- \, {\rm Ti})$ / $\sigma(\mu^- \, {\rm Ti} \to$ capture)		$<4.3 \times 10^{-12}$, CL = 90%
$\sigma(\mu^- \, {\rm Pb} \to e^- \, {\rm Pb})$ / $\sigma(\mu^- \, {\rm Pb} \to$ capture)		$<4.6 \times 10^{-11}$, CL = 90%
limit on muonium $\to$ antimuonium conversion $R_g = G_C / G_F$		<0.13, CL = 90%
$\Gamma(\mu^- \to e^- \nu_e \overline{\nu}_\mu)/\Gamma_{\rm total}$	[i]	$<1.2 \times 10^{-2}$, CL = 90%
$\Gamma(\mu^- \to e^- \gamma)/\Gamma_{\rm total}$		$<4.9 \times 10^{-11}$, CL = 90%
$\Gamma(\mu^- \to e^- e^+ e^-)/\Gamma_{\rm total}$		$<1.0 \times 10^{-12}$, CL = 90%
$\Gamma(\mu^- \to e^- 2\gamma)/\Gamma_{\rm total}$		$<7.2 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^- \gamma)/\Gamma_{\rm total}$		$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \gamma)/\Gamma_{\rm total}$		$<4.2 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^0)/\Gamma_{\rm total}$		$<1.4 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^0)/\Gamma_{\rm total}$		$<4.4 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- K^0)/\Gamma_{\rm total}$		$<1.3 \times 10^{-3}$, CL = 90%
$\Gamma(\tau^- \to \mu^- K^0)/\Gamma_{\rm total}$		$<1.0 \times 10^{-3}$, CL = 90%
$\Gamma(\tau^- \to e^- \eta)/\Gamma_{\rm total}$		$<6.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \eta)/\Gamma_{\rm total}$		$<7.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- \rho^0)/\Gamma_{\rm total}$		$<4.2 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \rho^0)/\Gamma_{\rm total}$		$<5.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- K^*(892)^0)/\Gamma_{\rm total}$		$<6.3 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- K^*(892)^0)/\Gamma_{\rm total}$		$<9.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- e^+ e^-)/\Gamma_{\rm total}$		$<3.3 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \mu^+ \mu^-)/\Gamma_{\rm total}$		$<3.6 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+ \mu^- \mu^-)/\Gamma_{\rm total}$		$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- e^+ e^-)/\Gamma_{\rm total}$		$<3.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \mu^+ \mu^-)/\Gamma_{\rm total}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^+ \pi^-)/\Gamma_{\rm total}$		$<4.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^+ \pi^-)/\Gamma_{\rm total}$		$<7.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^+ K^-)/\Gamma_{\rm total}$		$<7.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^- K^+)/\Gamma_{\rm total}$		$<4.6 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^+ K^-)/\Gamma_{\rm total}$		$<8.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^- K^+)/\Gamma_{\rm total}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- \overline{K}^*(892)^0)/\Gamma_{\rm total}$		$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \overline{K}^*(892)^0)/\Gamma_{\rm total}$		$<8.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-$ light boson$)/\Gamma_{\rm total}$		$<2.7 \times 10^{-3}$, CL = 95%
$\Gamma(\tau^- \to \mu^-$ light boson$)/\Gamma_{\rm total}$		$<5 \times 10^{-3}$, CL = 95%

ν oscillations. (For other lepton mixing effects in particle decays, see the Particle Listings.)

$\overline{\nu}_e \not\to \overline{\nu}_e$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.0075 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.02, CL = 90%
$\nu_e \to \nu_\tau$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<9 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.25, CL = 90%
$\overline{\nu}_e \to \overline{\nu}_\tau$		
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.7, CL = 90%
$\nu_\mu \to \nu_e$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.09 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<2.5 \times 10^{-3}$, CL = 90%
$\overline{\nu}_\mu \to \overline{\nu}_e$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.14 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.004, CL = 95%
$\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.075 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<3 \times 10^{-3}$, CL = 90%
$\nu_\mu \to \nu_\tau$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.9 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.004, CL = 90%
$\overline{\nu}_\mu \to \overline{\nu}_\tau$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<2.2 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<4.4 \times 10^{-2}$, CL = 90%
$\nu_\mu(\overline{\nu}_\mu) \to \nu_\tau(\overline{\nu}_\tau)$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<1.5 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<8 \times 10^{-3}$, CL = 90%
$\nu_e \not\to \nu_e$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.17 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<7 \times 10^{-2}$, CL = 90%
$\nu_\mu \not\to \nu_\mu$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.23 or >1500 eV^2
$\sin^2(2\theta)$ for $\Delta(m^2) = 100$eV^2	[j]	<0.02, CL = 90%
$\overline{\nu}_\mu \not\to \overline{\nu}_\mu$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<7 or >1200 eV^2
$\sin^2(2\theta)$ for 190 eV^2 $< \Delta(m^2) <$ 320 eV^2	[k]	<0.02, CL = 90%

$\Gamma(\pi^+ \to \mu^+ \nu_e)/\Gamma_{\rm total}$	[l]	$<8.0 \times 10^{-3}$, CL = 90%
$\Gamma(\pi^+ \to \mu^- e^+ e^+ \nu)/\Gamma_{\rm total}$		$<1.6 \times 10^{-6}$, CL = 90%
$\Gamma(\pi^0 \to \mu^+ e^- + e^- \mu^+)/\Gamma_{\rm total}$		$<1.72 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \to \mu^- \nu e^+ e^+)/\Gamma_{\rm total}$		$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \to \mu^+ \nu_e)/\Gamma_{\rm total}$	[l]	$<4 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^+ \mu^+ e^-)/\Gamma_{\rm total}$		$<2.1 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^+ \mu^- e^+)/\Gamma_{\rm total}$		$<7 \times 10^{-9}$, CL = 90%
$\Gamma(K^0_L \to e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<3.3 \times 10^{-11}$, CL = 90%
$\Gamma(D^+ \to \pi^+ e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<3.8 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^+ e^+ \mu^-)/\Gamma_{\rm total}$		$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^+ e^- \mu^+)/\Gamma_{\rm total}$		$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to K^+ e^+ \mu^-)/\Gamma_{\rm total}$		$<3.4 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to K^+ e^- \mu^+)/\Gamma_{\rm total}$		$<3.4 \times 10^{-3}$, CL = 90%
$\Gamma(D^0 \to \mu^\pm e^\mp)/\Gamma_{\rm total}$	[h]	$<1.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^0 e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<8.6 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \eta e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \rho^0 e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<4.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \omega e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \phi e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<3.4 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{K}^0 e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \overline{K}^*(892)^0 e^\pm \mu^\mp)/\Gamma_{\rm total}$	[h]	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(B^+ \to \pi^+ e^+ \mu^-)/\Gamma_{\rm total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^+ e^- \mu^+)/\Gamma_{\rm total}$		$<6.4 \times 10^{-3}$, CL = 90%

Limits are given at the 90% confidence level, while errors are given as ±1 standard deviation.

Tests of Conservation Laws

$\Gamma(B^+ \to K^+ e^+ \mu^-)/\Gamma_{total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^+ e^- \mu^+)/\Gamma_{total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^0 \to e^\pm \mu^\mp)/\Gamma_{total}$	[h]	$<5.9 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to e^\pm \tau^\mp)/\Gamma_{total}$	[h]	$<5.3 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \to \mu^\pm \tau^\mp)/\Gamma_{total}$	[h]	$<8.3 \times 10^{-4}$, CL = 90%

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- {}^{32}S \to e^+ {}^{32}Si^*)$ / $\sigma(\mu^- {}^{32}S \to \nu_\mu {}^{32}P^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- {}^{127}I \to e^+ {}^{127}Sb^*)$ / $\sigma(\mu^- {}^{127}I \to$ anything)		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- Ti \to e^+ Ca)$ / $\sigma(\mu^- Ti \to$ capture)		$<8.9 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to \pi^- \gamma)/\Gamma_{total}$		$<2.8 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \pi^- \pi^0)/\Gamma_{total}$		$<3.7 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ e^- e^-)/\Gamma_{total}$		$<3.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+ \pi^- \pi^-)/\Gamma_{total}$		$<4.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ \pi^- \pi^-)/\Gamma_{total}$		$<6.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^+ \pi^- K^-)/\Gamma_{total}$		$<4.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ \pi^- K^-)/\Gamma_{total}$		$<2.0 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \gamma)/\Gamma_{total}$		$<2.9 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \pi^0)/\Gamma_{total}$		$<6.6 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \eta)/\Gamma_{total}$		$<1.30 \times 10^{-3}$, CL = 90%
$\nu_e \to (\overline{\nu}_e)_L$		
$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.14 eV^2, CL = 90%
$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.032, CL = 90%
$\nu_\mu \to (\overline{\nu}_e)_L$		
$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.16 eV^2, CL = 90%
$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.001, CL = 90%
$\Gamma(\pi^+ \to \mu^+ \overline{\nu}_e)/\Gamma_{total}$	[l]	$<1.5 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^- \mu^+ e^+)/\Gamma_{total}$		$<7 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \pi^- e^+ e^+)/\Gamma_{total}$		$<1.0 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{total}$		$<1.5 \times 10^{-4}$, CL = 90%
$\Gamma(K^+ \to \mu^+ \overline{\nu}_e)/\Gamma_{total}$	[l]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0 e^+ \overline{\nu}_e)/\Gamma_{total}$	[l]	$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^- e^+ e^+)/\Gamma_{total}$		$<4.8 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{total}$		$<2.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to \pi^- e^+ \mu^+)/\Gamma_{total}$		$<3.7 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \rho^- \mu^+ \mu^+)/\Gamma_{total}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- e^+ e^+)/\Gamma_{total}$		$<9.1 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to K^- \mu^+ \mu^+)/\Gamma_{total}$		$<3.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- e^+ \mu^+)/\Gamma_{total}$		$<4.0 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to K^*(892)^- \mu^+ \mu^+)/\Gamma_{total}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{total}$		$<4.3 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \to K^- \mu^+ \mu^+)/\Gamma_{total}$		$<5.9 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \to K^*(892)^- \mu^+ \mu^+)/\Gamma_{total}$		$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- e^+ e^+)/\Gamma_{total}$		$<3.9 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{total}$		$<9.1 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- e^+ \mu^+)/\Gamma_{total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^- e^+ e^+)/\Gamma_{total}$		$<3.9 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^- \mu^+ \mu^+)/\Gamma_{total}$		$<9.1 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^- e^+ \mu^+)/\Gamma_{total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(\Xi^- \to p \mu^- \mu^-)/\Gamma_{total}$		$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \Sigma^- \mu^+ \mu^+)/\Gamma_{total}$		$<7.0 \times 10^{-4}$, CL = 90%

BARYON NUMBER

$\Gamma(\tau^- \to \overline{p} \gamma)/\Gamma_{total}$		$<2.9 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \pi^0)/\Gamma_{total}$		$<6.6 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \eta)/\Gamma_{total}$		$<1.30 \times 10^{-3}$, CL = 90%
p mean life		$>1.6 \times 10^{25}$ years

A few examples of proton or bound neutron decay follow. For limits on many other nucleon decay channels, see the Baryon Summary Table.

$\tau(N \to e^+ \pi)$		> 130 (n), > 550 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+ \pi)$		> 100 (n), > 270 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to e^+ K)$		> 1.3 (n), > 150 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+ K)$		> 1.1 (n), > 120 (p) $\times 10^{30}$ years, CL = 90%
(bound n		
mean time for $n\overline{n}$ transition in vacuum	[m]	$>1.2 \times 10^8$ s, CL = 90%
(free n		
limit on $n\overline{n}$ oscillations		$>0.86 \times 10^8$ s, CL = 90%

ELECTRIC CHARGE (Q)

e mean life / branching fraction	[n]	$>4.3 \times 10^{23}$ yr, CL = 68%
$\Gamma(n \to p \nu_e \overline{\nu}_e)/\Gamma_{total}$		$<9 \times 10^{-24}$, CL = 90%

$\Delta S = \Delta Q$ RULE

Allowed in second-order weak interactions.

$\Gamma(K^+ \to \pi^+ \pi^+ e^- \overline{\nu}_e)/\Gamma_{total}$	$<1.2 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \to \pi^+ \pi^+ \mu^- \overline{\nu}_\mu)/\Gamma_{total}$	$<3.0 \times 10^{-6}$, CL = 95%
$x = A(\overline{K}^0 \to \pi^- \ell^+ \nu)/A(K^0 \to \pi^- \ell^+ \nu) = A(\Delta S{=}-\Delta Q)/A(\Delta S{=}\Delta Q)$	
real part of x	0.006 ± 0.018 (S = 1.3)
imaginary part of x	-0.003 ± 0.026 (S = 1.2)
$\Gamma(\Sigma^+ \to n \ell^+ \nu)/\Gamma(\Sigma^- \to n \ell^- \overline{\nu})$	<0.043
$\Gamma(\Sigma^+ \to n e^+ \nu_e)/\Gamma_{total}$	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\Sigma^+ \to n \mu^+ \nu_\mu)/\Gamma_{total}$	$<3.0 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^0 \to \Sigma^- e^+ \nu_e)/\Gamma_{total}$	$<9 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^0 \to \Sigma^- \mu^+ \nu_\mu)/\Gamma_{total}$	$<9 \times 10^{-4}$, CL = 90%

$\Delta S = 2$ FORBIDDEN

Allowed in second-order weak interactions.

$\Gamma(\Xi^0 \to p \pi^-)/\Gamma_{total}$	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^0 \to p e^- \overline{\nu}_e)/\Gamma_{total}$	$<1.3 \times 10^{-3}$
$\Gamma(\Xi^0 \to p \mu^- \overline{\nu}_\mu)/\Gamma_{total}$	$<1.3 \times 10^{-3}$
$\Gamma(\Xi^- \to n \pi^-)/\Gamma_{total}$	$<1.9 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^- \to n e^- \overline{\nu}_e)/\Gamma_{total}$	$<3.2 \times 10^{-3}$, CL = 90%
$\Gamma(\Xi^- \to n \mu^- \overline{\nu}_\mu)/\Gamma_{total}$	$<1.5 \times 10^{-2}$, CL = 90%
$\Gamma(\Xi^- \to p \pi^- \pi^-)/\Gamma_{total}$	$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^- \to p \pi^- e^- \overline{\nu}_e)/\Gamma_{total}$	$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^- \to p \pi^- \mu^- \overline{\nu}_\mu)/\Gamma_{total}$	$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Omega^- \to \Lambda \pi^-)/\Gamma_{total}$	$<1.9 \times 10^{-4}$, CL = 90%

$\Delta S = 2$ VIA MIXING

Allowed in second-order weak interactions, e.g. mixing.

$m_{K_L^0} - m_{K_S^0}$	$(0.5304 \pm 0.0014) \times 10^{10}\ \hbar\ s^{-1}$
$m_{K_L^0} - m_{K_S^0}$	$(3.491 \pm 0.009) \times 10^{-12}$ MeV

Limits are given at the 90% confidence level, while errors are given as ±1 standard deviation.

$\Delta C = 2$ VIA MIXING

Allowed in second-order weak interactions, e.g. mixing.

$\lvert m_{D_1^0} - m_{D_2^0} \rvert$	[o]	$<21 \times 10^{10}\ \hbar\ s^{-1}$, CL = 90%
$\Gamma(K^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+)$		<0.005, CL = 90%
$\Gamma(K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+\pi^+\pi^-)$		<0.005, CL = 90%
$\Gamma(\mu^-$ anything (via $\overline{D}^0))/\Gamma(\mu^+$ anything)		<0.0056, CL = 90%
$\Gamma(D^0 \to K^+\pi^-$ (via $\overline{D}^0))/\Gamma_{total}$		$<1.9 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0))/\Gamma_{total}$		$<4 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \mu^-$ anything (via $\overline{D}^0))/\Gamma_{total}$		$<4 \times 10^{-4}$, CL = 90%

$\Delta B = 2$ VIA MIXING

Allowed in second-order weak interactions, e.g. mixing.

x_d	0.175 ± 0.016
$\Delta m_{B^0} = m_{B_H^0} - m_{B_L^0}$	$(0.474 \pm 0.031) \times 10^{12}\ \hbar\ s^{-1}$
$x_d = \Delta m_{B^0}/\Gamma_{B^0}$	0.73 ± 0.05
x_s	>0.49, CL = 95%
$\Delta m_{B_s^0} = m_{B_{sH}^0} - m_{B_{sL}^0}$	$>5.9 \times 10^{12}\ \hbar\ s^{-1}$, CL = 95%
$x_s = \Delta m_{B_s^0}/\Gamma_{B_s^0}$	>9.5, CL = 95%

$\Delta S = 1$ WEAK NEUTRAL CURRENT FORBIDDEN

Allowed by higher-order electroweak interactions.

$\Gamma(K^+ \to \pi^+ e^+ e^-)/\Gamma_{total}$		$(2.74 \pm 0.23) \times 10^{-7}$
$\Gamma(K^+ \to \pi^+ \mu^+ \mu^-)/\Gamma_{total}$		$<2.3 \times 10^{-7}$, CL = 90%
$\Gamma(K^+ \to \pi^+ \nu\overline{\nu})/\Gamma_{total}$		$<2.4 \times 10^{-9}$, CL = 90%
$\Gamma(K_S^0 \to \mu^+ \mu^-)/\Gamma_{total}$		$<3.2 \times 10^{-7}$, CL = 90%
$\Gamma(K_S^0 \to e^+ e^-)/\Gamma_{total}$		$<2.8 \times 10^{-6}$, CL = 90%
$\Gamma(K_S^0 \to \pi^0 e^+ e^-)/\Gamma_{total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(K_L^0 \to \mu^+ \mu^-)/\Gamma_{total}$		$(7.2 \pm 0.5) \times 10^{-9}$ (S = 1.4)
$\Gamma(K_L^0 \to \mu^+ \mu^- \gamma)/\Gamma_{total}$		$(3.23 \pm 0.30) \times 10^{-7}$
$\Gamma(K_L^0 \to e^+ e^-)/\Gamma_{total}$		$<4.1 \times 10^{-11}$, CL = 90%
$\Gamma(K_L^0 \to e^+ e^- \gamma)/\Gamma_{total}$		$(9.1 \pm 0.5) \times 10^{-6}$
$\Gamma(K_L^0 \to e^+ e^- \gamma\gamma)/\Gamma_{total}$	[p]	$(6.5 \pm 1.2) \times 10^{-7}$
$\Gamma(K_L^0 \to \pi^+ \pi^- e^+ e^-)/\Gamma_{total}$		$<2.5 \times 10^{-6}$, CL = 90%
$\Gamma(K_L^0 \to \mu^+ \mu^- e^+ e^-)/\Gamma_{total}$		$<4.9 \times 10^{-6}$, CL = 90%
$\Gamma(K_L^0 \to e^+ e^- e^+ e^-)/\Gamma_{total}$	[q]	$(4.1 \pm 0.8) \times 10^{-8}$ (S = 1.2)
$\Gamma(K_L^0 \to \pi^0 \mu^+ \mu^-)/\Gamma_{total}$		$<5.1 \times 10^{-9}$, CL = 90%
$\Gamma(K_L^0 \to \pi^0 e^+ e^-)/\Gamma_{total}$		$<4.3 \times 10^{-9}$, CL = 90%
$\Gamma(K_L^0 \to \pi^0 \nu\overline{\nu})/\Gamma_{total}$		$<5.8 \times 10^{-5}$, CL = 90%
$\Gamma(\Sigma^+ \to p e^+ e^-)/\Gamma_{total}$		$<7 \times 10^{-6}$

$\Delta C = 1$ WEAK NEUTRAL CURRENT FORBIDDEN

Allowed by higher-order electroweak interactions.

$\Gamma(D^+ \to \pi^+ e^+ e^-)/\Gamma_{total}$	$<6.6 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \pi^+ \mu^+ \mu^-)/\Gamma_{total}$	$<1.8 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \rho^+ \mu^+ \mu^-)/\Gamma_{total}$	$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to e^+ e^-)/\Gamma_{total}$	$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \mu^+ \mu^-)/\Gamma_{total}$	$<7.6 \times 10^{-6}$, CL = 90%
$\Gamma(D^0 \to \pi^0 e^+ e^-)/\Gamma_{total}$	$<4.5 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^0 \mu^+ \mu^-)/\Gamma_{total}$	$<1.8 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \eta e^+ e^-)/\Gamma_{total}$	$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \eta \mu^+ \mu^-)/\Gamma_{total}$	$<5.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \rho^0 e^+ e^-)/\Gamma_{total}$	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \rho^0 \mu^+ \mu^-)/\Gamma_{total}$	$<2.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \omega e^+ e^-)/\Gamma_{total}$	$<1.8 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \omega \mu^+ \mu^-)/\Gamma_{total}$	$<8.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \phi e^+ e^-)/\Gamma_{total}$	$<5.2 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \phi \mu^+ \mu^-)/\Gamma_{total}$	$<4.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \pi^+ \pi^- \pi^0 \mu^+ \mu^-)/\Gamma_{total}$	$<8.1 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \to K^+ \mu^+ \mu^-)/\Gamma_{total}$	$<5.9 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \to K^*(892)^+ \mu^+ \mu^-)/\Gamma_{total}$	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\Lambda_c^+ \to p \mu^+ \mu^-)/\Gamma_{total}$	$<3.4 \times 10^{-4}$, CL = 90%

Limits are given at the 90% confidence level, while errors are given as ±1 standard deviation.

$\Delta B = 1$ WEAK NEUTRAL CURRENT FORBIDDEN

Allowed by higher-order electroweak interactions.

$\Gamma(B^+ \to \pi^+ e^+ e^-)/\Gamma_{total}$	$<3.9 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^+ \mu^+ \mu^-)/\Gamma_{total}$	$<9.1 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^+ e^+ e^-)/\Gamma_{total}$	$<6 \times 10^{-5}$, CL = 90%
$\Gamma(B^+ \to K^+ \mu^+ \mu^-)/\Gamma_{total}$	$<1.7 \times 10^{-4}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^+ e^+ e^-)/\Gamma_{total}$	$<6.9 \times 10^{-4}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^+ \mu^+ \mu^-)/\Gamma_{total}$	$<1.2 \times 10^{-3}$, CL = 90%
$\Gamma(B^0 \to \gamma\gamma)/\Gamma_{total}$	$<3.9 \times 10^{-5}$, CL = 90%
$\Gamma(B^0 \to e^+ e^-)/\Gamma_{total}$	$<5.9 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to \mu^+ \mu^-)/\Gamma_{total}$	$<5.9 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to K^0 e^+ e^-)/\Gamma_{total}$	$<3.0 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \to K^0 \mu^+ \mu^-)/\Gamma_{total}$	$<3.6 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \to K^*(892)^0 e^+ e^-)/\Gamma_{total}$	$<2.9 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \to K^*(892)^0 \mu^+ \mu^-)/\Gamma_{total}$	$<2.3 \times 10^{-5}$, CL = 90%
$\Gamma(B \to e^+ e^-$ anything$)/\Gamma_{total}$	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(B \to \mu^+ \mu^-$ anything$)/\Gamma_{total}$	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(\overline{b} \to \mu^+ \mu^-$ anything$)/\Gamma_{total}$	$<5.0 \times 10^{-5}$, CL = 90%
$\Gamma(\overline{b} \to \nu\overline{\nu}$anything$)/\Gamma_{total}$	$<3.9 \times 10^{-4}$
$\Gamma(B_s^0 \to \gamma\gamma)/\Gamma_{total}$	$<1.48 \times 10^{-4}$, CL = 90%

NOTES

In this Summary Table:

When a quantity has "(S = ...)" to its right, the error on the quantity has been enlarged by the "scale factor" S, defined as $S = \sqrt{\chi^2/(N-1)}$, where N is the number of measurements used in calculating the quantity. We do this when $S > 1$, which often indicates that the measurements are inconsistent. When $S > 1.25$, we also show in the Particle Listings an ideogram of the measurements. For more about S, see the Introduction.

[a] C parity forbids this to occur as a single-photon process.

[b] Time-reversal invariance requires this to be 0° or 180°.

[c] Allowed by higher-order electroweak interactions.

[d] Violates CP in leading order. Test of direct CP violation since the indirect CP-violating and CP-conserving contributions are expected to be suppressed.

[e] ϵ'/ϵ is derived from $\lvert \eta_{00}/\eta_{+-} \rvert$ measurements using theoretical input on phases.

[f] Neglecting photon channels. See, *e.g.*, A. Pais and S.B. Treiman, Phys. Rev. **D12**, 2744 (1975).

[g] Derived from measured values of ϕ_{+-}, ϕ_{00}, $\lvert\eta\rvert$, $\tau_{K_S^0}$, and $\lvert m_{K_L^0} - m_{K_S^0} \rvert$, as described in the introduction to "Tests of Conservation Laws."

[h] The value is for the sum of the charge states of particle/antiparticle states indicated.

[i] A test of additive vs. multiplicative lepton family number conservation.

[j] $\Delta(m^2) = 100$ eV^2.

[k] 190 eV^2 $< \Delta(m^2) <$ 320 eV^2.

[l] Derived from an analysis of neutrino-oscillation experiments.

[m] There is some controversy about whether nuclear physics and model dependence complicate the analysis for bound neutrons (from which the best limit comes). The second limit here is from reactor experiments with free neutrons.

[n] This is the best "electron disappearance" limit. The best limit for the mode $e^- \to \nu\gamma$ is $> 2.35 \times 10^{25}$ yr (CL=68%).

[o] The D_1^0-D_2^0 limits are inferred from the D^0-$\overline{D}^0$ mixing ratio $[\Gamma(K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ via $\overline{D}^0)] / \Gamma(K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-)$.

[p] See the K_L^0 Particle Listings for the energy limits used in this measurement.

[q] $m_{e^+e^-} > 470$ MeV.

REVIEWS, TABLES, AND PLOTS

MAJOR REVIEWS IN THE PARTICLE LISTINGS

Additional Reviews and Notes related to specific particles are located in the Particle Listings.

1. PHYSICAL CONSTANTS

Table 1.1. Reviewed 1995 by B.N. Taylor, NIST. Based mainly on the "1986 Adjustment of the Fundamental Physical Constants" by E.R. Cohen and B.N. Taylor, Rev. Mod. Phys. **59**, 1121 (1987). The last group of constants (beginning with the Fermi coupling constant) comes from the Particle Data Group. The figures in parentheses after the values give the 1-standard-deviation uncertainties in the last digits; the corresponding uncertainties in parts per million (ppm) are given in the last column. This set of constants (aside from the last group) is recommended for international use by CODATA (the Committee on Data for Science and Technology).

Since the 1986 adjustment, new experiments have yielded improved values for a number of constants, including the Rydberg constant R_∞, the Planck constant h, the fine-structure constant α, and the molar gas constant R, and hence also for constants directly derived from these, such as the Boltzmann constant k and Stefan-Boltzmann constant σ. The new results and their impact on the 1986 recommended values are discussed extensively in "Recommended Values of the Fundamental Physical Constants: A Status Report," B.N. Taylor and E.R. Cohen, J. Res. Natl. Inst. Stand. Technol. **95**, 497 (1990); see also E.R. Cohen and B.N. Taylor, "The Fundamental Physical Constants," Phys. Today, August 1995 Part 2, BG9. In general, the new results give uncertainties for the affected constants that are 5 to 7 times smaller than the 1986 uncertainties, but the changes in the values themselves are smaller than twice the 1986 uncertainties. Because the output values of a least-squares adjustment are correlated, the new results cannot readily be incorporated with the 1986 values. Until the next complete adjustment of the constants, the 1986 CODATA set, given (in part) below, remains the set of choice.

Quantity	Symbol, equation	Value	Uncert. (ppm)
speed of light in vacuum	c	299 792 458 m s^{-1}	exact*
Planck constant	h	6.626 075 5(40)$\times 10^{-34}$ J s	0.60
Planck constant, reduced	$\hbar \equiv h/2\pi$	1.054 572 66(63)$\times 10^{-34}$ J s	0.60
		= 6.582 122 0(20)$\times 10^{-22}$ MeV s	0.30
electron charge magnitude	e	1.602 177 33(49)$\times 10^{-19}$ C = 4.803 206 8(15)$\times 10^{-10}$ esu	0.30, 0.30
conversion constant	$\hbar c$	197.327 053(59) MeV fm	0.30
conversion constant	$(\hbar c)^2$	0.389 379 66(23) GeV^2 mbarn	0.59
electron mass	m_e	0.510 999 06(15) MeV/c^2 = 9.109 389 7(54)$\times 10^{-31}$ kg	0.30, 0.59
proton mass	m_p	938.272 31(28) MeV/c^2 = 1.672 623 1(10)$\times 10^{-27}$ kg	0.30, 0.59
		= 1.007 276 470(12) u = 1836.152 701(37) m_e	0.012, 0.020
deuteron mass	m_d	1875.613 39(57) MeV/c^2	0.30
unified atomic mass unit (u)	(mass ^{12}C atom)/12 = (1 g)/(N_A mol)	931.494 32(28) MeV/c^2 = 1.660 540 2(10)$\times 10^{-27}$ kg	0.30, 0.59
permittivity of free space	ϵ_0 } $\epsilon_0\mu_0 = 1/c^2$	8.854 187 817 ... $\times 10^{-12}$ F m^{-1}	exact
permeability of free space	μ_0 }	$4\pi \times 10^{-7}$ N A^{-2} = 12.566 370 614 ... $\times 10^{-7}$ N A^{-2}	exact
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	1/137.035 989 5(61)†	0.045
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 92(38)$\times 10^{-15}$ m	0.13
electron Compton wavelength	$\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e\alpha^{-1}$	3.861 593 23(35)$\times 10^{-13}$ m	0.089
Bohr radius ($m_{\text{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	0.529 177 249(24)$\times 10^{-10}$ m	0.045
wavelength of 1 eV/c particle	hc/e	1.239 842 44(37)$\times 10^{-6}$ m	0.30
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	13.605 698 1(40) eV	0.30
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	0.665 246 16(18) barn	0.27
Bohr magneton	$\mu_B = e\hbar/2m_e$	5.788 382 63(52)$\times 10^{-11}$ MeV T^{-1}	0.089
nuclear magneton	$\mu_N = e\hbar/2m_p$	3.152 451 66(28)$\times 10^{-14}$ MeV T^{-1}	0.089
electron cyclotron freq./field	$\omega^e_{\text{cycl}}/B = e/m_e$	1.758 819 62(53)$\times 10^{11}$ rad s^{-1} T^{-1}	0.30
proton cyclotron freq./field	$\omega^p_{\text{cycl}}/B = e/m_p$	9.578 830 9(29)$\times 10^{7}$ rad s^{-1} T^{-1}	0.30
gravitational constant	G_N	6.672 59(85)$\times 10^{-11}$ m^3 kg^{-1} s^{-2}	128
		= 6.707 11(86)$\times 10^{-39}$ $\hbar c$ (GeV/c^2)$^{-2}$	128
standard grav. accel., sea level	g	9.806 65 m s^{-2}	exact
Avogadro constant	N_A	6.022 136 7(36)$\times 10^{23}$ mol^{-1}	0.59
Boltzmann constant	k	1.380 658(12)$\times 10^{-23}$ J K^{-1}	8.5
		= 8.617 385(73)$\times 10^{-5}$ eV K^{-1}	8.4
molar volume, ideal gas at STP	$N_A k$(273.15 K)/(101 325 Pa)	22.414 10(19)$\times 10^{-3}$ m^3 mol^{-1}	8.4
Wien displacement law constant	$b = \lambda_{\max}T$	2.897 756(24)$\times 10^{-3}$ m K	8.4
Stefan-Boltzmann constant	$\sigma = \pi^2k^4/60\hbar^3c^2$	5.670 51(19)$\times 10^{-8}$ W m^{-2} K^{-4}	34
Fermi coupling constant‡	$G_F/(\hbar c)^3$	1.166 39(2)$\times 10^{-5}$ GeV^{-2}	20
weak mixing angle	$\sin^2\widehat{\theta}(M_Z)$ ($\overline{\text{MS}}$)	0.2315(4)	2200
$W^\pm$ boson mass	m_W	80.33(15) GeV/c^2	1900
Z^0 boson mass	m_Z	91.187(7) GeV/c^2	77
strong coupling constant	$\alpha_s(m_Z)$	0.118(3)	25000

π = 3.141 592 653 589 793 238	e = 2.718 281 828 459 045 235	γ = 0.577 215 664 901 532 861

1 in ≡ 0.0254 m	1 G ≡ 10^{-4} T	1 eV = 1.602 177 33(49) × 10^{-19} J	kT at 300 K = [38.681 49(33)]$^{-1}$ eV
1 Å ≡ 0.1nm	1 dyne ≡ 10^{-5} N	1 eV/c^2 = 1.782 662 70(54) × 10^{-36} kg	0 °C ≡ 273.15 K
1 barn ≡ 10^{-28} m^2	1 erg ≡ 10^{-7} J	2.997 924 58 × 10^9 esu = 1 C	1 atmosphere ≡ 760 torr ≡ 101 325 Pa

* The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.
† At $Q^2 = 0$. At $Q^2 \approx m_W^2$ the value is approximately 1/128.
‡ See discussion in Sec. 10 "Standard Model of electroweak interactions."

2. ASTROPHYSICAL CONSTANTS

Table 2.1. Written and revised with the help of K.R. Lang, K.A. Olive, J. Primack, S. Rudaz, E.M. Standish, Jr., and M.S. Turner. The figures in parentheses after some values give the 1-standard deviation uncertainties in the last digit(s). While every effort has been made to obtain the most accurate current values of the listed quantities, the table does not represent a critical review or adjustment of the constants, and is not intended as a primary reference.

Quantity	Symbol, equation	Value	Reference
speed of light	c	$299\,792\,458$ m s^{-1}	defined [1]
Newtonian gravitational constant	G_N	$6.672\,59(85) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	[2]
astronomical unit	AU	$1.495\,978\,706\,6(2) \times 10^{11}$ m	[3,4]
tropical year (equinox to equinox) (1994)	yr	$31\,556\,925.2$ s	[3]
sidereal year (fixed star to fixed star) (1994)		$31\,558\,149.8$ s	[3]
mean sidereal day		$23^{\rm h}\,56^{\rm m}\,04^{\rm s}\!.090\,53$	[3]
Jansky	Jy	10^{-26} W m^{-2} Hz^{-1}	
Planck mass	$\sqrt{\hbar c/G_N}$	$1.221\,047(79) \times 10^{19}$ GeV/c^2	uses [2]
		$= 2.176\,71(14) \times 10^{-8}$ kg	
parsec (1 AU/1 arc sec)	pc	$3.085\,677\,580\,7(4) \times 10^{16}$ m $= 3.262\ldots$ ly	[5]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,1\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,08$ km	[6]
solar mass	$M_\odot$	$1.988\,92(25) \times 10^{30}$ kg	[7]
solar luminosity	$L_\odot$	3.846×10^{26} W	[8]
solar equatorial radius	$R_\odot$	6.96×10^{8} m	[3]
Earth equatorial radius	$R_\oplus$	$6.378\,140 \times 10^{6}$ m	[3]
Earth mass	$M_\oplus$	$5.973\,70(76) \times 10^{24}$ kg	[9]
luminosity conversion	L	$3.02 \times 10^{28} \times 10^{-0.4\,M_b}$ W	[10]
		(M_b = absolute bolometric magnitude	
		= bolometric magnitude at 10 pc)	
flux conversion	$\mathcal{F}$	$2.52 \times 10^{-8} \times 10^{-0.4\,m_b}$ W m^{-2}	from above
		(m_b = apparent bolometric magnitude)	
$v_\odot$ around center of Galaxy	$\Theta_\circ$	$220(20)$ km s^{-1}	[11]
solar distance from galactic center	$R_\circ$	$8.0(5)$ kpc	[12]
Hubble constant†	H_0	$100\,h_0$ km s^{-1} Mpc^{-1}	
		$= h_0 \times (9.778\,13$ Gyr$)^{-1}$	[13]
normalized Hubble constant†	h_0	$0.5 < h_0 < 0.85$	[14,15,16]
critical density of the universe†	$\rho_c = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\,h_0^2\,M_\odot$Mpc^{-3}	
		$= 1.878\,82(24) \times 10^{-29}\,h_0^2$ g cm^{-3}	
		$= 1.053\,94(13) \times 10^{-5}\,h_0^2$ GeV cm^{-3}	
local disk density	$\rho_{\rm disk}$	3–12 $\times 10^{-24}$ g cm^{-3} $\approx$ 2–7 GeV/c^2 cm^{-3}	[17]
local halo density	$\rho_{\rm halo}$	2–13 $\times 10^{-25}$ g cm^{-3} $\approx$ 0.1–0.7 GeV/c^2 cm^{-3}	[18]
density parameter of the universe†	$\Omega_0 \equiv \rho_0/\rho_c$	$0.1 < \Omega_0 < 2$	[19]
scaled cosmological constant†	$\lambda_0 = \Lambda c^2/3H_0^2$	$-1 < \lambda_0 < 2$	[20,21]
scale factor for cosmological constant†	$c^2/3H_0^2$	$2.853 \times 10^{51}\,h_0^{-2}$ m^2	
age of the universe†	t_0	$15(5)$ Gyr	[10]
	$\Omega_0 h_0^2$	≤ 2.4 for $t_0 \ge 10$ Gyr	[10]
		≤ 1 for $t_0 \ge 10$ Gyr, $h_0 > 0.4$	[10]
cosmic background radiation (CBR) temperature†	T_0	2.726 ± 0.005 K	[22,23]
solar velocity with respect to CBR		369.5 ± 3.0 km s^{-1}	[23,24]
energy density of CBR	ρ_γ	$4.647\,7 \times 10^{-34}\,(T/2.726)^4$ g cm^{-3}	[10,23]
		$= 0.260\,71\,(T/2.726)^4$ eV cm^{-3}	
number density of CBR photons	n_γ	$410.89\,(T/2.726)^3$ cm^{-3}	[10,23]
entropy density/Boltzmann constant	s/k	$2\,892.4\,(T/2.726)^3$ cm^{-3}	[10]

† Subscript 0 indicates present-day values.

References:

1. B.W. Petley, Nature **303**, 373 (1983).
2. E.R. Cohen and B.N. Taylor, Rev. Mod. Phys. **59**, 1121 (1987). The set of constants resulting from this adjustment has been recommended for international use by CODATA (Committee on Data for Science and Technology).
3. *The Astronomical Almanac for the year 1994*, U.S. Government Printing Office, Washington, and Her Majesty's Stationary Office, London (1993). Where possible, the values as adjusted for the fitting of the ephemerides to all the observational data are used.
4. JPL Planetary Ephemerides, E. Myles Standish, Jr., private communication (1989).
5. 1 AU divided by $\pi/648\,000$; quoted error is from the JPL Planetary Ephemerides value of the AU [4].
6. Heliocentric gravitational constant from Ref. 3 times $2/c^2$. The given 9-place accuracy appears to be consistent with uncertainties in actually defining the earth's orbital parameters.
7. Obtained from the heliocentric gravitational constant [3] and G_N [2]. The error is the 128 ppm standard deviation quoted for G_N.
8. It is surprisingly difficult to find a definitive value for this important constant. In all cases, the solar luminosity is calculated as $4\pi \times (1\ \mathrm{AU})^2$ times the solar constant (or total solar irradiance, TSI). The luminosity given is reduced from TSI $= 1367.51 \pm 0.01$ W m^{-2}, obtained from SMM/ACRIMI spacecraft measurements during the interval 2/80–6/89 [25]. While the time constant for energy production by the sun is very long, radiation from the surface might be modulated or otherwise modified by sunspots; this has apparently not been taken into account. Accordingly, we quote 4-place accuracy. We do not know the actual error, but suppose it might be 5 or 10 in the last place. Sackmann *et al.* [26] use TSI $= 1370 \pm 2$ W m^{-2}, but conclude that the solar luminosity ($L_\odot = 3.853 \times 10^{26}$ J s^{-1}) has an uncertainty of 1.5%. Their value is based on three 1977–83 papers, and they comment that the error is based on scatter among the reported values, which is substantially in excess of that expected from the individual quoted errors. The conclusion of the 1971 review by Thekaekara and Drummond [27] ($1353 \pm 1\%$ W m^{-2}) is often quoted [28], and a luminosity based on this value was tabulated in the last two editions of this Review. The conversion to luminosity is not given in the Thekaekara and Drummond paper, and we cannot exactly reproduce the solar luminosity given in Ref. 28. Finally, a value based on the 1954 spectral curve due to Johnson [29] ($1395 \pm 1\%$ W m^{-2}, or $L_\odot = 3.92 \times 10^{26}$ J s^{-1}) has been used widely, and may be the basis for higher value of the solar luminosity and corresponding lower value of the solar absolute bolometric magnitude (4.72) still common in the literature [10].
9. Obtained from the geocentric gravitational constant [3] and G_N [2]. The error is the 128 ppm standard deviation quoted for G_N.
10. E.W. Kolb and M.S. Turner, *The Early Universe*, Addison-Wesley (1990).
11. F.J. Kerr and D. Lynden-Bell, Mon. Not. R. Astr. Soc. **221**, 1023–1038 (1985). "On the basis of this review these [$R_\circ = 8.5 \pm 1.1$ kpc and $\Theta_\circ = 220 \pm 20$ km s^{-1}] were adopted by resolution of IAU Commission 33 on 1985 November 21 at Delhi".
12. M.J. Reid, Annu. Rev. Astron. Astrophys. **31**, 345–372 (1993). Note that $\Theta_\circ$ from the 1985 IAU Commission 33 recommendations is adopted in this review, although the new value for $R_\circ$ is smaller.
13. Conversion using length of tropical year.
14. P.J.E. Peebles, *Principles of Physical Cosmology,* Princeton University Press (1993.).
15. Kolb and Turner [10] give the more conservative limits $0.4 < h_0 < 1$. For other conclusions, see the recent reviews by Jacoby *et al.* [30], who say "Using the weighted or unweighted Virgo distances to bootstrap to the Coma cluster, we find the Hubble constant to be either 80 ± 11 or 73 ± 11 km s^{-1} Mpc^{-1}, respectively," and Huchra [31], who concludes that "Values are still clustered about two numbers, but these numbers are now 50 and 85. A preponderance of the newest local estimates favors the higher value of 85 km s^{-1} Mpc^{-1}...".
16. See the section on the Hubble Constant (Sec. 17 of this *Review*).
17. G. Gilmore, R.F.G. Wyse, and K. Kuijken, Annu. Rev. Astron. Astrophys. **27**, 555 (1989).
18. E.I. Gates, G. Gyuk, and M.S. Turner (Astrophys. J. **449**, L133 (1995)) find the local halo density to be $9.2^{+3.8}_{-3.1} \times 10^{-25}$ g cm^{-3}, but also comment that previously published estimates are in the range 1–10 $\times 10^{-25}$ g cm^{-3}. The value 0.3 GeV/c^2 has been taken as "standard" in several papers setting limits on WIMP mass limits, *e.g.* in M. Mori *et al.*, Phys. Lett. **B289**, 463 (1992).
19. Tonry gives $0.2 < \Omega_0 < 2$ [20]. We extend the lower limit so as not to exclude the absence of nonbaryonic dark matter.
20. J. L. Tonry, in *Proc. Texas/PASCOS 92: Relativistic Astrophysics and Particle Cosmology*, ed. C.W. Akerlof and M. Srednicki (Ann. NY Acad. Sci. **688**, 113 (1993).
21. S.M. Carroll and W. H. Press, Annu. Rev. Astron. Astrophys. **30**, 499 (1992).
22. J. C. Mather *et al.*, Astrophy. J. **420**, 439 (1994). Error quoted here is $1\,\sigma$.
23. See the section on Cosmic Background Radiation (Sec. 19 of this *Review*).
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3. INTERNATIONAL SYSTEM OF UNITS (SI)

See "The International System of Units (SI)," NIST Special Publication **330**, B.N. Taylor, ed. (USGPO, Washington, DC, 1991); and "Guide for the Use of the International System of Units (SI)," NIST Special Publication **811**, 1995 edition, B.N. Taylor (USGPO, Washington, DC, 1995).

Physical quantity	Name of unit	Symbol
Base units		
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd
Derived units with special names		
plane angle	radian	rad
solid angle	steradian	sr
frequency	hertz	Hz
energy	joule	J
force	newton	N
pressure	pascal	Pa
power	watt	W
electric charge	coulomb	C
electric potential	volt	V
electric resistance	ohm	Ω
electric conductance	siemens	S
electric capacitance	farad	F
magnetic flux	weber	Wb
inductance	henry	H
magnetic flux density	tesla	T
luminous flux	lumen	lm
illuminance	lux	lx
celsius temperature	degree celsius	°C
activity (of a radioactive source)*	becquerel	Bq
absorbed dose (of ionizing radiation)*	gray	Gy
dose equivalent*	sievert	Sv

*See our section 25, on "Radioactivity and radiation protection," p. 150.

SI prefixes

10^{24}	yotta	(Y)
10^{21}	zetta	(Z)
10^{18}	exa	(E)
10^{15}	peta	(P)
10^{12}	tera	(T)
10^{9}	giga	(G)
10^{6}	mega	(M)
10^{3}	kilo	(k)
10^{2}	hecto	(h)
10	deca	(da)
10^{-1}	deci	(d)
10^{-2}	centi	(c)
10^{-3}	milli	(m)
10^{-6}	micro	(μ)
10^{-9}	nano	(n)
10^{-12}	pico	(p)
10^{-15}	femto	(f)
10^{-18}	atto	(a)
10^{-21}	zepto	(z)
10^{-24}	yocto	(y)

4. PERIODIC TABLE OF THE ELEMENTS

Table 4.1. Revised 1995. The atomic number (top left) is the number of protons in the nucleus. The atomic mass (bottom) is weighted by isotopic abundances in the Earth's surface. Atomic masses are relative to the mass of the carbon-12 isotope, defined to be exactly 12 unified atomic mass units (u). Errors range from 1 to 9 in the last digit quoted. Relative isotopic abundances often vary considerably, both in natural and commercial samples. A number in parentheses is the mass of the longest-lived isotope of that element—no stable isotope exists. For elements 110–112, the atomic numbers of known isotopes are given. However, although Th, Pa, and U have no stable isotopes, they do have characteristic terrestrial compositions, and meaningful weighted masses can be given. Adapted from "Atomic Weights of the Elements 1993," Pure and Applied Chemistry **66**, 2423 (1994), and G. Audi and A.H. Wapstra, "The 1993 Mass Evaluation," Nucl. Phys. **A565**, 1 (1993). The names given below for elements 104 to 109 have been adopted by the American Chemical Society. The nomenclature committee of the International Union of Pure and Applied Chemistry in 1994 recommended different names for elements 104 to 108, but in the subsequent uproar has postponed a final decision until 1997.

PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989768	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosph. 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.93805	26 Fe Iron 55.845	27 Co Cobalt 58.93320	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907215)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57–71 Lantha- nides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.08	79 Au Gold 196.96654	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium (208.982415)	85 At Astatine (209.987131)	86 Rn Radon (222.017570)
87 Fr Francium (223.019731)	88 Ra Radium (226.025402)	89–103 Actinides	104 Rf Rutherford. (261.1089)	105 Ha Hahnium (262.1144)	106 Sg Seaborg. (263.1186)	107 Ns Nielsbohr. (262.1231)	108 Hs Hassium (265.1306)	109 Mt Meitner. (266.1378)	110 (269, 273)	111 (272)	112 (277)						

57 La Lanthan. 138.9055	58 Ce Cerium 140.115	59 Pr Praseodym. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.912745)	62 Sm Samarium 150.36	63 Eu Europium 151.965	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967	Lanthanide series
89 Ac Actinium (227.027747)	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237.048166)	94 Pu Plutonium (244.064197)	95 Am Americ. (243.061372)	96 Cm Curium (247.070346)	97 Bk Berkelium (247.070298)	98 Cf Californ. (251.079579)	99 Es Einstein. (252.08297)	100 Fm Fermium (257.095096)	101 Md Mendelev. (258.098427)	102 No Nobelium (259.1011)	103 Lr Lawrenc. (262.1098)	Actinide series

5. ELECTRONIC STRUCTURE OF THE ELEMENTS

Table 5.1. Reviewed 1995 by W.C. Martin, NIST. The electronic configurations and ionization energies here are taken from "Atomic Spectroscopy," W.C. Martin and W.L. Wiese, in *Atomic, Molecular, and Optical Physics Reference Book*, G.W.F. Drake, ed., Amer. Inst. Phys., 1995. The electron configuration for, say, iron indicates an argon electronic core (see argon) plus six $3d$ electrons and two $4s$ electrons. The ionization energy is the least energy necessary to remove to infinity one electron from an *atom* of the element.

Element			Electron configuration ($3d^5$ = five $3d$ electrons, *etc.*)		Ground state $^{2S+1}L_J$	Ionization energy (eV)
1	H	Hydrogen	$1s$		$^2S_{1/2}$	13.5984
2	He	Helium	$1s^2$		$^1S_0$	24.5874
3	Li	Lithium	(He) $2s$		$^2S_{1/2}$	5.3917
4	Be	Beryllium	(He) $2s^2$		$^1S_0$	9.3227
5	B	Boron	(He) $2s^2$ $2p$		$^2P_{1/2}$	8.2980
6	C	Carbon	(He) $2s^2$ $2p^2$		$^3P_0$	11.2603
7	N	Nitrogen	(He) $2s^2$ $2p^3$		$^4S_{3/2}$	14.5341
8	O	Oxygen	(He) $2s^2$ $2p^4$		$^3P_2$	13.6181
9	F	Fluorine	(He) $2s^2$ $2p^5$		$^2P_{3/2}$	17.4228
10	Ne	Neon	(He) $2s^2$ $2p^6$		$^1S_0$	21.5646
11	Na	Sodium	(Ne) $3s$		$^2S_{1/2}$	5.1391
12	Mg	Magnesium	(Ne) $3s^2$		$^1S_0$	7.6462
13	Al	Aluminum	(Ne) $3s^2$ $3p$		$^2P_{1/2}$	5.9858
14	Si	Silicon	(Ne) $3s^2$ $3p^2$		$^3P_0$	8.1517
15	P	Phosphorus	(Ne) $3s^2$ $3p^3$		$^4S_{3/2}$	10.4867
16	S	Sulfur	(Ne) $3s^2$ $3p^4$		$^3P_2$	10.3600
17	Cl	Chlorine	(Ne) $3s^2$ $3p^5$		$^2P_{3/2}$	12.9676
18	Ar	Argon	(Ne) $3s^2$ $3p^6$		$^1S_0$	15.7596
19	K	Potassium	(Ar) $4s$		$^2S_{1/2}$	4.3407
20	Ca	Calcium	(Ar) $4s^2$		$^1S_0$	6.1132
21	Sc	Scandium	(Ar) $3d$ $4s^2$	Transition elements	$^2D_{3/2}$	6.5615
22	Ti	Titanium	(Ar) $3d^2$ $4s^2$		$^3F_2$	6.8281
23	V	Vanadium	(Ar) $3d^3$ $4s^2$		$^4F_{3/2}$	6.7463
24	Cr	Chromium	(Ar) $3d^5$ $4s$		$^7S_3$	6.7665
25	Mn	Manganese	(Ar) $3d^5$ $4s^2$		$^6S_{5/2}$	7.4340
26	Fe	Iron	(Ar) $3d^6$ $4s^2$		$^5D_4$	7.9024
27	Co	Cobalt	(Ar) $3d^7$ $4s^2$		$^4F_{9/2}$	7.8810
28	Ni	Nickel	(Ar) $3d^8$ $4s^2$		$^3F_4$	7.6398
29	Cu	Copper	(Ar) $3d^{10}4s$		$^2S_{1/2}$	7.7264
30	Zn	Zinc	(Ar) $3d^{10}4s^2$		$^1S_0$	9.3942
31	Ga	Gallium	(Ar) $3d^{10}4s^2$ $4p$		$^2P_{1/2}$	5.9993
32	Ge	Germanium	(Ar) $3d^{10}4s^2$ $4p^2$		$^3P_0$	7.8994
33	As	Arsenic	(Ar) $3d^{10}4s^2$ $4p^3$		$^4S_{3/2}$	9.7886
34	Se	Selenium	(Ar) $3d^{10}4s^2$ $4p^4$		$^3P_2$	9.7524
35	Br	Bromine	(Ar) $3d^{10}4s^2$ $4p^5$		$^2P_{3/2}$	11.8138
36	Kr	Krypton	(Ar) $3d^{10}4s^2$ $4p^6$		$^1S_0$	13.9996
37	Rb	Rubidium	(Kr) $5s$		$^2S_{1/2}$	4.1771
38	Sr	Strontium	(Kr) $5s^2$		$^1S_0$	5.6949
39	Y	Yttrium	(Kr) $4d$ $5s^2$	Transition elements	$^2D_{3/2}$	6.2171
40	Zr	Zirconium	(Kr) $4d^2$ $5s^2$		$^3F_2$	6.6339
41	Nb	Niobium	(Kr) $4d^4$ $5s$		$^6D_{1/2}$	6.7589
42	Mo	Molybdenum	(Kr) $4d^5$ $5s$		$^7S_3$	7.0924
43	Tc	Technetium	(Kr) $4d^5$ $5s^2$		$^6S_{5/2}$	7.28
44	Ru	Ruthenium	(Kr) $4d^7$ $5s$		$^5F_5$	7.3605
45	Rh	Rhodium	(Kr) $4d^8$ $5s$		$^4F_{9/2}$	7.4589
46	Pd	Palladium	(Kr) $4d^{10}$		$^1S_0$	8.3369
47	Ag	Silver	(Kr) $4d^{10}5s$		$^2S_{1/2}$	7.5763
48	Cd	Cadmium	(Kr) $4d^{10}5s^2$		$^1S_0$	8.9938

49	In	Indium	(Kr) $4d^{10}5s^2$ $5p$		$^2P_{1/2}$	5.7864
50	Sn	Tin	(Kr) $4d^{10}5s^2$ $5p^2$		$^3P_0$	7.3439
51	Sb	Antimony	(Kr) $4d^{10}5s^2$ $5p^3$		$^4S_{3/2}$	8.6084
52	Te	Tellurium	(Kr) $4d^{10}5s^2$ $5p^4$		$^3P_2$	9.0096
53	I	Iodine	(Kr) $4d^{10}5s^2$ $5p^5$		$^2P_{3/2}$	10.4513
54	Xe	Xenon	(Kr) $4d^{10}5s^2$ $5p^6$		$^1S_0$	12.1298
55	Cs	Cesium	(Xe) $6s$		$^2S_{1/2}$	3.8939
56	Ba	Barium	(Xe) $6s^2$		$^1S_0$	5.2117
57	La	Lanthanum	(Xe) $5d$ $6s^2$		$^2D_{3/2}$	5.5770
58	Ce	Cerium	(Xe) $4f$ $5d$ $6s^2$		$^1G_4$	5.5387
59	Pr	Praseodymium	(Xe) $4f^3$ $6s^2$	Lanthanides	$^4I_{9/2}$	5.464
60	Nd	Neodymium	(Xe) $4f^4$ $6s^2$		$^5I_4$	5.5250
61	Pm	Promethium	(Xe) $4f^5$ $6s^2$		$^6H_{5/2}$	5.58
62	Sm	Samarium	(Xe) $4f^6$ $6s^2$		$^7F_0$	5.6436
63	Eu	Europium	(Xe) $4f^7$ $6s^2$		$^8S_{7/2}$	5.6704
64	Gd	Gadolinium	(Xe) $4f^7$ $5d$ $6s^2$		$^9D_2$	6.1501
65	Tb	Terbium	(Xe) $4f^9$ $6s^2$		$^6H_{15/2}$	5.8638
66	Dy	Dysprosium	(Xe) $4f^{10}$ $6s^2$		$^5I_8$	5.9389
67	Ho	Holmium	(Xe) $4f^{11}$ $6s^2$		$^4I_{15/2}$	6.0215
68	Er	Erbium	(Xe) $4f^{12}$ $6s^2$		$^3H_6$	6.1077
69	Tm	Thulium	(Xe) $4f^{13}$ $6s^2$		$^2F_{7/2}$	6.1843
70	Yb	Ytterbium	(Xe) $4f^{14}$ $6s^2$		$^1S_0$	6.2542
71	Lu	Lutetium	(Xe) $4f^{14}5d$ $6s^2$		$^2D_{3/2}$	5.4259
72	Hf	Hafnium	(Xe) $4f^{14}5d^2$ $6s^2$	Transition elements	$^3F_2$	6.8251
73	Ta	Tantalum	(Xe) $4f^{14}5d^3$ $6s^2$		$^4F_{3/2}$	7.5496
74	W	Tungsten	(Xe) $4f^{14}5d^4$ $6s^2$		$^5D_0$	7.8640
75	Re	Rhenium	(Xe) $4f^{14}5d^5$ $6s^2$		$^6S_{5/2}$	7.8335
76	Os	Osmium	(Xe) $4f^{14}5d^6$ $6s^2$		$^5D_4$	8.28
77	Ir	Iridium	(Xe) $4f^{14}5d^7$ $6s^2$		$^4F_{9/2}$	9.02
78	Pt	Platinum	(Xe) $4f^{14}5d^9$ $6s$		$^3D_3$	8.9587
79	Au	Gold	(Xe) $4f^{14}5d^{10}6s$		$2S_{1/2}$	9.2255
80	Hg	Mercury	(Xe) $4f^{14}5d^{10}6s^2$		$^1S_0$	10.4375
81	Tl	Thallium	(Xe) $4f^{14}5d^{10}6s^2$ $6p$		$^2P_{1/2}$	6.1082
82	Pb	Lead	(Xe) $4f^{14}5d^{10}6s^2$ $6p^2$		$^3P_0$	7.4167
83	Bi	Bismuth	(Xe) $4f^{14}5d^{10}6s^2$ $6p^3$		$^4S_{3/2}$	7.2856
84	Po	Polonium	(Xe) $4f^{14}5d^{10}6s^2$ $6p^4$		$^3P_2$	8.4167
85	At	Astatine	(Xe) $4f^{14}5d^{10}6s^2$ $6p^5$		$^2P_{3/2}$	
86	Rn	Radon	(Xe) $4f^{14}5d^{10}6s^2$ $6p^6$		$^1S_0$	10.7485
87	Fr	Francium	(Rn) $7s$		$^2S_{1/2}$	4.0727
88	Ra	Radium	(Rn) $7s^2$		$^1S_0$	5.2784
89	Ac	Actinium	(Rn) $6d$ $7s^2$		$^2D_{3/2}$	5.17
90	Th	Thorium	(Rn) $6d^2$ $7s^2$		$^3F_2$	6.3067
91	Pa	Protactinium	(Rn) $5f^2$ $6d$ $7s^2$	Actinides	$^4K_{11/2}$	5.89
92	U	Uranium	(Rn) $5f^3$ $6d$ $7s^2$		$^5L_6$	6.1941
93	Np	Neptunium	(Rn) $5f^4$ $6d$ $7s^2$		$^6L_{11/2}$	6.2657
94	Pu	Plutonium	(Rn) $5f^6$ $7s^2$		$^7F_0$	6.0262
95	Am	Americium	(Rn) $5f^7$ $7s^2$		$^8S_{7/2}$	5.9738
96	Cm	Curium	(Rn) $5f^7$ $6d$ $7s^2$		$^9D_2$	6.02
97	Bk	Berkelium	(Rn) $5f^9$ $7s^2$		$^6H_{15/2}$	6.23
98	Cf	Californium	(Rn) $5f^{10}$ $7s^2$		$^5I_8$	6.30
99	Es	Einsteinium	(Rn) $5f^{11}$ $7s^2$		$^4I_{15/2}$	6.42
100	Fm	Fermium	(Rn) $5f^{12}$ $7s^2$		$^3H_6$	6.50
101	Md	Mendelevium	(Rn) $5f^{13}$ $7s^2$		$^2F_{7/2}$	6.58
102	No	Nobelium	(Rn) $5f^{14}$ $7s^2$		$^1S_0$	6.65
103	Lr	Lawrencium	(Rn) $5f^{14}$ $7s^2$ $7p$?		$^2P_{1/2}$?	
104	Rf	Rutherfordium	(Rn) $5f^{14}6d^2$ $7s^2$?		$^3F_2$?	6.0?

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Table revised May 1996. Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line.

Material	Z	A	Nuclear[a] total cross section σ_T {barn}	Nuclear[b] inelastic cross section σ_I {barn}	Nuclear[c] collision length λ_T {g/cm^2}	Nuclear[c] interaction length λ_I {g/cm^2}	$dE/dx\vert_{\rm min}$[d] $\left\{\frac{\rm MeV}{\rm g/cm^2}\right\}$	Radiation length[e] X_0 {g/cm^2}	X_0 {cm}	Density {g/cm^2} ({g/ℓ} for gas)	Refractive index n ($(n-1)\times10^6$ for gas)
H_2 gas	1	1.01	0.0387	0.033	43.3	50.8	(4.103)	63.05	(752300)	(0.0838)[0.0899]	[139.2]
H_2 (BP 20.39 K)	1	1.01	0.0387	0.033	43.3	50.8	4.045[f]	63.05	890	0.0708	1.112
D_2 (BP 23.65 K)	1	2.01	0.073	0.061	45.7	54.7	(2.052)	125.98	754	0.169[0.179]	1.128 [138]
He (BP 4.224 K)	2	4.00	0.133	0.102	49.9	65.1	(1.937)	94.32	756	0.1248[0.1786]	1.024 [34.9]
Li	3	6.94	0.211	0.157	54.6	73.4	1.639	82.76	155	0.534	—
Be	4	9.01	0.268	0.199	55.8	75.2	1.594	65.19	35.3	1.848	—
C	6	12.01	0.331	0.231	60.2	86.3	1.745	42.70	18.8	2.265[g]	—
N_2 (BP 77.36 K)	7	14.01	0.379	0.265	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	1.205 [298]
O_2 (BP 90.18 K)	8	16.00	0.420	0.292	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	1.22 [296]
Ne (BP 27.09 K)	10	20.18	0.507	0.347	66.1	96.6	(1.724)	28.94	24.0	1.206[0.9003]	1.092 [67.1]
Al	13	26.98	0.634	0.421	70.6	106.4	1.615	24.01	8.9	2.70	—
Si	14	28.09	0.660	0.440	70.6	106.0	1.664	21.82	9.36	2.33	—
Ar (BP 87.28 K)	18	39.95	0.868	0.566	76.4	117.2	(1.519)	19.55	14.0	1.393[1.782]	1.233 [283]
Ti	22	47.88	0.995	0.637	79.9	124.9	1.476	16.17	3.56	4.54	—
Fe	26	55.85	1.120	0.703	82.8	131.9	1.451	13.84	1.76	7.87	—
Cu	29	63.55	1.232	0.782	85.6	134.9	1.403	12.86	1.43	8.96	—
Ge	32	72.59	1.365	0.858	88.3	140.5	1.371	12.25	2.30	5.323	—
Sn	50	118.69	1.967	1.21	100.2	163	1.264	8.82	1.21	7.31	—
Xe (BP 165.0 K)	54	131.29	2.120	1.29	102.8	169	(1.255)	8.48	2.40	3.52[5.858]	[701]
W	74	183.85	2.767	1.65	110.3	185	1.145	6.76	0.35	19.3	—
Pt	78	195.08	2.861	1.708	113.3	189.7	1.129	6.54	0.305	21.45	—
Pb	82	207.19	2.960	1.77	116.2	194	1.123	6.37	0.56	11.35	—
U	92	238.03	3.378	1.98	117.0	199	1.082	6.00	≈0.32	≈18.95	—
Air, (20°C, 1 atm.), [STP]					62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	(273) [293]
H_2O					60.1	84.9	1.991	36.08	36.1	1.00	1.33
CO_2					62.4	90.5	(1.819)	36.2	[18310]	[1.977]	[410]
Shielding concrete[h]					67.4	99.9	1.711	26.7	10.7	2.5	—
Borosilicate glass (Pyrex)[i]					66.2	97.6	1.695	28.3	12.7	2.23	1.474
SiO_2 (fused quartz)					67.0	99.2	1.70[j]	27.05	12.3	2.20[k]	1.458
Methane (CH_4) (BP 111.7 K)					54.7	74.0	(2.417)	46.5	[64850]	0.4241[0.717]	[444]
Ethane (C_2H_6) (BP 184.5 K)					55.73	75.71	(2.304)	45.66	[34035]	0.509(1.356)[ℓ]	(1.038)[ℓ]
Propane (C_3H_8) (BP 231.1 K)					—	—	(2.262)	—	—	(1.879)	
Isobutane ($(CH_3)_2CHCH_3$) (BP 261.42 K)					56.3	77.4	(2.239)	45.2	[16930]	[2.67]	[1900]
Octane, liquid ($CH_3(CH_2)_6CH_3$)					—	—	2.123	—	—	0.703	
Paraffin wax ($CH_3(CH_2)_nCH_3$, $\langle n\rangle \approx 25$)					—	—	2.087	—	—	0.93	
Nylon, type 6					—	—	1.974	—	—	1.14	
Polycarbonate (Lexan)					—	—	1.886	—	—	1.200	
Polyethylene terephthlate (Mylar) ($C_5H_4O_2$)					60.2	85.7	1.848	39.95	28.7	1.39	—
Polyethylene (monomer $CH_2=CH_2$)					56.9	78.8	2.076	44.8	≈47.9	0.92–0.95	—
Polyimide film (Kapton)					—	—	1.820	—	—	1.420	
Polymethylmethacralate (Lucite, Plexiglas) (monomer $CH_2=C(CH_3)CO_2CH_3$)					59.2	83.6	1.929	40.55	≈34.4	1.16–1.20	≈1.49
Polystyrene, scintillator (monomer $C_6H_5CH=CH_2$)					58.4	82.0	1.936	43.8	42.4	1.032	1.581
Polytetrafluoroethylene (Teflon) (monomer $CF_2=CF_2$)					—	—	1.671	—	—	2.20	
Polyvinyltolulene, scintillator (monomer 2-$CH_3C_6H_4CH=CH_2$)					—	—	1.956	—	—	1.032	
Barium fluoride (BaF_2)					92.1	146	1.303	9.91	2.05	4.89	1.56
Bismuth germanate (BGO) ($Bi_4Ge_3O_{12}$)					97.4	156	1.251	7.98	1.12	7.1	2.15
Cesium iodide (CsI)					—	167	1.243	8.38	1.85	4.53	1.80
Lithium fluoride (LiF)					62.00	88.24	1.614	39.25	14.91	2.632	1.392
Sodium fluoride (NaF)					66.78	97.57	1.69	29.87	11.68	2.558	1.336
Sodium iodide (NaI)					94.8	152	1.305	9.49	2.59	3.67	1.775
Silica Aerogel[m]					65.5	95.7	1.83	29.85	≈150	0.1–0.3	1.0+0.25ρ
NEMA G10 plate[n]					62.6	90.2	1.87	33.0	19.4	1.7	—

Material	Dielectric constant ($\kappa = \epsilon/\epsilon_0$) () is $(\kappa-1)\times 10^6$ for gas	Young's modulus [10^6 psi]	Coeff. of thermal expansion [10^{-6}cm/cm-°C]	Specific heat [cal/g-°C]	Electrical resistivity [$\mu\Omega$cm(@°C)]	Thermal conductivity [cal/cm-°C-sec]
H_2	(253.9)	—	—	—	—	—
He	(64)	—	—	—	—	—
Li	—	—	56	0.86	8.55(0°)	0.17
Be	—	37	12.4	0.436	5.885(0°)	0.38
C	—	0.7	0.6–4.3	0.165	1375(0°)	0.057
N_2	(548.5)	—	—	—	—	—
O_2	(495)	—	—	—	—	—
Ne	(127)	—	—	—	—	—
Al	—	10	23.9	0.215	2.65(20°)	0.53
Si	11.9	16	2.8–7.3	0.162	—	0.20
Ar	(517)	—	—	—	—	—
Ti	—	16.8	8.5	0.126	50(0°)	—
Fe	—	28.5	11.7	0.11	9.71(20°)	0.18
Cu	—	16	16.5	0.092	1.67(20°)	0.94
Ge	16.0	—	5.75	0.073	—	0.14
Sn	—	6	20	0.052	11.5(20°)	0.16
Xe	—	—	—	—	—	—
W	—	50	4.4	0.032	5.5(20°)	0.48
Pt	—	21	8.9	0.032	9.83(0°)	0.17
Pb	—	2.6	29.3	0.038	20.65(20°)	0.083
U	—	—	36.1	0.028	29(20°)	0.064

σ_T, σ_I, λ_T, and λ_I are energy dependent. Values quoted apply to high energy range given in footnote *a* or *b*, where energy dependence is weak.

a. $\sigma_{\rm total}$ at 80–240 GeV for neutrons ($\approx \sigma$ for protons) from Murthy *et al.*, Nucl. Phys. **B92**, 269 (1975). This scales approximately as $A^{0.77}$.

b. $\sigma_{\rm inelastic} = \sigma_{\rm total} - \sigma_{\rm elastic} - \sigma_{\rm quasielastic}$; for neutrons at 60–375 GeV from Roberts *et al.*, Nucl. Phys. **B159**, 56 (1979). For protons and other particles, see Carroll *et al.*, Phys. Lett. **80B**, 319 (1979); note that $\sigma_I(p) \approx \sigma_I(n)$. σ_I scales approximately as $A^{0.71}$.

c. Mean free path between collisions (λ_T) or inelastic interactions (λ_I), calculated from $\lambda = A/(N \times \sigma)$, where N is Avogadro's number.

d. For minimum-ionizing heavy particles (calculated for pions; results are very slightly different for other particles). Minimum dE/dx calculated in 1994, using density effect correction coefficients from R. M. Sternheimer, M. J. Berger, and S. M. Seltzer, Atomic Data and Nuclear Data Tables **30**, 261–271 (1984). For electrons and positrons see S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **35**, 665–676 (1984). Ionization energy loss is discussed in Sec. 22.

e. From Y.S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); X_0 data for all elements up to uranium are given. Corrections for molecular binding applied for H_2 and D_2.

f. Density effect constants evaluated for $\rho = 0.0600$ g/cm^3 (H_2 bubble chamber?).

g. For pure graphite; industrial graphite density may vary 2.1–2.3 g/cm^3.

h. Standard shielding blocks, typical composition O_2 52%, Si 32.5%, Ca 6%, Na 1.5%, Fe 2%, Al 4%, plus reinforcing iron bars. The attenuation length, $\ell = 115 \pm 5$ g/cm^2, is also valid for earth (typical $\rho = 2.15$), from CERN-LRL-RHEL Shielding exp., UCRL-17841 (1968).

i. Main components: 80% SiO_2 + 12% B_2O_3 + 5% Na_2O.

j. Calculated using Sternheimer's density effect parameterization for $\rho = 2.32$ g cm^{-3}. Actual value may be slightly lower.

k. For typical fused quartz. The specific gravity of crystalline quartz is 2.64.

ℓ. Solid ethane density at −60°C; gaseous refractive index at 0°C, 546 mm pressure.

m. $n(SiO_2) + 2n(H_2O)$ used in Čerenkov counters, ρ = density in g/cm^3. From M. Cantin *et al.*, Nucl. Instr. and Meth. **118**, 177 (1974).

n. G10-plate, typical 60% SiO_2 and 40% epoxy.

7. ELECTROMAGNETIC RELATIONS

Quantity	Gaussian CGS	SI
Conversion factors:		
Charge:	$2.997\,924\,58 \times 10^9$ esu	$= 1$ C $= 1$ A s
Potential:	(1/299.792 458) statvolt (ergs/esu)	$= 1$ V $= 1$ J C^{-1}
Magnetic field:	10^4 gauss $= 10^4$ dyne/esu	$= 1$ T $= 1$ N $A^{-1}m^{-1}$
Lorentz force:	$\mathbf{F} = q\,(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B})$	$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$
Maxwell equations:	$\nabla \cdot \mathbf{D} = 4\pi\rho$ $\nabla \times \mathbf{H} - \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} = \frac{4\pi}{c}\mathbf{J}$ $\nabla \cdot \mathbf{B} = 0$ $\nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = 0$	$\nabla \cdot \mathbf{D} = \rho$ $\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}$ $\nabla \cdot \mathbf{B} = 0$ $\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$
Constitutive relations:	$\mathbf{D} = \mathbf{E} + 4\pi\mathbf{P}, \quad \mathbf{H} = \mathbf{B} - 4\pi\mathbf{M}$	$\mathbf{D} = \epsilon_0\mathbf{E} + \mathbf{P}, \quad \mathbf{H} = \mathbf{B}/\mu_0 - \mathbf{M}$
Linear media:	$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{H} = \mathbf{B}/\mu$	$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{H} = \mathbf{B}/\mu$
Permitivity of free space:	1	$\epsilon_0 = 8.854\,187\ldots \times 10^{-12}$ F m^{-1}
Permeability of free space:	1	$\mu_0 = 4\pi \times 10^{-7}$ N A^{-2}
Fields from potentials:	$\mathbf{E} = -\nabla V - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \nabla \times \mathbf{A}$	$\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \nabla \times \mathbf{A}$
Static potentials: (coulomb gauge)	$V = \sum_{\text{charges}} \frac{q_i}{r_i} = \int \frac{\rho(\mathbf{r}')}{\lvert\mathbf{r}-\mathbf{r}'\rvert}\, d^3x'$ $\mathbf{A} = \frac{1}{c}\sum_{\text{currents}} \frac{\mathbf{I}_i}{r_i} = \frac{1}{c}\int \frac{\mathbf{J}(\mathbf{r}')}{\lvert\mathbf{r}-\mathbf{r}'\rvert}\, d^3x'$	$V = \frac{1}{4\pi\epsilon_0}\sum_{\text{charges}} \frac{q_i}{r_i} = \frac{1}{4\pi\epsilon_0}\int \frac{\rho(\mathbf{r}')}{\lvert\mathbf{r}-\mathbf{r}'\rvert}\, d^3x'$ $\mathbf{A} = \frac{\mu_0}{4\pi}\sum_{\text{currents}} \frac{\mathbf{I}_i}{r_i} = \frac{\mu_0}{4\pi}\int \frac{\mathbf{J}(\mathbf{r}')}{\lvert\mathbf{r}-\mathbf{r}'\rvert}\, d^3x'$
Relativistic transformations: (**v** is the velocity of the primed frame as seen in the unprimed frame)	$\mathbf{E}'_\parallel = \mathbf{E}_\parallel$ $\mathbf{E}'_\perp = \gamma(\mathbf{E}_\perp + \frac{1}{c}\mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_\parallel = \mathbf{B}_\parallel$ $\mathbf{B}'_\perp = \gamma(\mathbf{B}_\perp - \frac{1}{c}\mathbf{v} \times \mathbf{E})$	$\mathbf{E}'_\parallel = \mathbf{E}_\parallel$ $\mathbf{E}'_\perp = \gamma(\mathbf{E}_\perp + \mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_\parallel = \mathbf{B}_\parallel$ $\mathbf{B}'_\perp = \gamma(\mathbf{B}_\perp - \frac{1}{c^2}\mathbf{v} \times \mathbf{E})$

$\frac{1}{4\pi\epsilon_0} = c^2 \times 10^{-7}$ N $A^{-2} = 8.987\,55\ldots \times 10^9$ m F^{-1} ; $\frac{\mu_0}{4\pi} = 10^{-7}$ N A^{-2} ; $c = \frac{1}{\sqrt{\mu_0\epsilon_0}} = 2.997\,924\,58 \times 10^8$ m s^{-1}

7.1. Impedances (SI units)

ρ = resistivity at room temperature in $10^{-8}\ \Omega$ m:

$\sim$ 1.7 for Cu $\quad\sim$ 5.5 for W
$\sim$ 2.4 for Au $\quad\sim$ 73 for SS 304
$\sim$ 2.8 for Al $\quad\sim$ 100 for Nichrome
(Al alloys may have double the Al value.)

For alternating currents, instantaneous current I, voltage V, angular frequency ω:

$$V = V_0\, e^{j\omega t} = ZI \ . \tag{7.1}$$

Impedance of self-inductance L: $Z = j\omega L$.

Impedance of capacitance C: $Z = 1/j\omega C$.

Impedance of free space: $Z = \sqrt{\mu_0/\epsilon_0} = 376.7\ \Omega$.

High-frequency surface impedance of a good conductor:

$$Z = \frac{(1+j)\,\rho}{\delta} \ , \quad \text{where } \delta = \text{skin depth} \ ; \tag{7.2}$$

$$\delta = \sqrt{\frac{\rho}{\pi\nu\mu}} \approx \frac{6.6\text{ cm}}{\sqrt{\nu\,(\text{Hz})}} \quad \text{for Cu} \ . \tag{7.3}$$

7.2. Capacitance $\widehat{C}$ and inductance $\widehat{L}$ per unit length (SI units) [negligible skin depth]

Flat rectangular plates of width w, separated by $d \ll w$ with linear medium (ϵ,μ) between:

$$\widehat{C} = \epsilon\,\frac{w}{d} \ ; \qquad \widehat{L} = \mu\,\frac{d}{w} \ ; \tag{7.4}$$

$$\epsilon/\epsilon_0 = 2 \text{ to } 6 \text{ for plastics; } 4 \text{ to } 8 \text{ for porcelain, glasses;} \tag{7.5}$$

$$\mu/\mu_0 \simeq 1 \ . \tag{7.6}$$

Coaxial cable of inner radius r_1, outer radius r_2:

$$\widehat{C} = \frac{2\pi\,\epsilon}{\ln\,(r_2/r_1)} \ ; \qquad \widehat{L} = \frac{\mu}{2\pi}\,\ln\,(r_2/r_1) \ . \tag{7.7}$$

Transmission lines (no loss):

$$\text{Impedance: } Z = \sqrt{\widehat{L}/\widehat{C}} \ . \tag{7.8}$$

$$\text{Velocity: } v = 1/\sqrt{\widehat{L}\,\widehat{C}} = 1/\sqrt{\mu\epsilon} \ . \tag{7.9}$$

7.3. Synchrotron radiation (CGS units)

For a particle of charge e, velocity $v = \beta c$, and energy $E = \gamma mc^2$, traveling in a circular orbit of radius R, the classical energy loss per revolution δE is

$$\delta E = \frac{4\pi}{3}\,\frac{e^2}{R}\,\beta^3\,\gamma^4 \ . \tag{7.10}$$

For high-energy electrons or positrons ($\beta \approx 1$), this becomes

$$\delta E\ (\text{in MeV}) \approx 0.0885\ [E(\text{in GeV})]^4/R(\text{in m}) \ . \tag{7.11}$$

For $\gamma \gg 1$, the energy radiated per revolution into the photon energy interval $d(\hbar\omega)$ is

$$dI = \frac{8\pi}{9}\alpha\,\gamma\,F(\omega/\omega_c)\,d(\hbar\omega) \ , \tag{7.12}$$

where $\alpha = e^2/\hbar c$ is the fine-structure constant and

$$\omega_c = \frac{3\gamma^3 c}{2R} \tag{7.13}$$

is the critical frequency. The normalized function $F(y)$ is

$$F(y) = \frac{9}{8\pi}\sqrt{3}\,y \int_y^\infty K_{5/3}\,(x)\ dx \ , \tag{7.14}$$

where $K_{5/3}\,(x)$ is a modified Bessel function of the third kind. For electrons or positrons,

$$\hbar\omega_c\,(\text{in keV}) \approx 2.22\ [E(\text{in GeV})]^3/R(\text{in m}) \ . \tag{7.15}$$

Fig. 7.1 shows $F(y)$ over the important range of y.

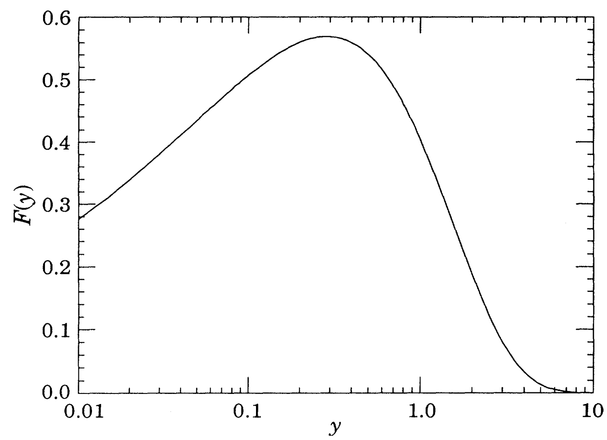

Figure 7.1: The normalized synchrotron radiation spectrum $F(y)$.

For $\gamma \gg 1$ and $\omega \ll \omega_c$,

$$\frac{dI}{d(\hbar\omega)} \approx 3.3\alpha\,(\omega R/c)^{1/3} \ , \tag{7.16}$$

whereas for

$\gamma \gg 1$ and $\omega \gtrsim 3\omega_c$,

$$\frac{dI}{d(\hbar\omega)} \approx \sqrt{\frac{3\pi}{2}}\,\alpha\,\gamma\left(\frac{\omega}{\omega_c}\right)^{1/2} e^{-\omega/\omega_c}\left[1 + \frac{55}{72}\frac{\omega_c}{\omega} + \ldots\right] \ . \tag{7.17}$$

The radiation is confined to angles $\lesssim 1/\gamma$ relative to the instantaneous direction of motion. The mean number of photons emitted per revolution is

$$N_\gamma = \frac{5\pi}{\sqrt{3}}\alpha\gamma \ , \tag{7.18}$$

and the mean energy per photon is

$$\langle\hbar\omega\rangle = \frac{8}{15\sqrt{3}}\hbar\omega_c \ . \tag{7.19}$$

When $\langle\hbar\omega\rangle \gtrsim \mathrm{O}(E)$, quantum corrections are important.

See J.D. Jackson, *Classical Electrodynamics*, 2nd edition (John Wiley & Sons, New York, 1975) for more formulae and details. In his book, Jackson uses a definition of ω_c that is twice as large as the customary one given above.

8. NAMING SCHEME FOR HADRONS

8.1. Introduction

We introduced in the 1986 edition [1] a new naming scheme for the hadrons. Changes from older terminology affected mainly the heavier mesons made of the light (u, d, and s) quarks. Old and new names were listed alongside until 1994. Names also change from edition to edition because some characteristic like mass or spin changes. The Summary Tables give both the new and old names whenever a change occurred.

8.2. "Neutral-flavor" mesons ($S=C=B=T=0$)

Table 8.1 shows the names for mesons having the strangeness and all heavy-flavor quantum numbers equal to zero. The scheme is designed for all ordinary non-exotic mesons, but it will work for many exotic types too, if needed.

Table 8.1: Symbols for mesons with the strangeness and all heavy-flavor quantum numbers equal to zero.

	$J^{PC} =$	0^{-+}, 2^{-+}, $\vdots$	1^{+-}, 3^{+-}, $\vdots$	1^{--}, 2^{--}, $\vdots$	0^{++}, 1^{++}, $\vdots$
$q\overline{q}$ content	$^{2S+1}L_J =$	$^1(L\,\text{even})_J$	$^1(L\,\text{odd})_J$	$^3(L\,\text{even})_J$	$^3(L\,\text{odd})_J$
$u\overline{d}, u\overline{u}-d\overline{d}, d\overline{u}$	$(I=1)$	π	b	ρ	a
$d\overline{d}+u\overline{u}$ and/or $s\overline{s}$	$(I=0)$	η, η'	h, h'	ω, ϕ	f, f'
$c\overline{c}$		η_c	h_c	$\psi^\dagger$	χ_c
$b\overline{b}$		η_b	h_b	Υ	χ_b
$t\overline{t}$		η_t	h_t	θ	χ_t

†The J/ψ remains the J/ψ.

First, we assign names to those states with quantum numbers compatible with being $q\overline{q}$ states. The rows of the Table give the possible $q\overline{q}$ content. The columns give the possible parity/charge-conjugation states,

$$PC = -+,\ +-,\ --,\ \text{and}\ ++\ ;$$

these combinations correspond one-to-one with the angular-momentum state $^{2S+1}L_J$ of the $q\overline{q}$ system being

$$^1(L\ \text{even})_J,\ ^1(L\ \text{odd})_J,\ ^3(L\ \text{even})_J,\ \text{or}\ ^3(L\ \text{odd})_J\ .$$

Here S, L, and J are the spin, orbital, and total angular momenta of the $q\overline{q}$ system. The quantum numbers are related by

$$P = (-1)^{L+1},\ C = (-1)^{L+S},\ \text{and}\ G\ \text{parity}\ = (-1)^{L+S+I},$$

where of course the C quantum number is only relevant to neutral mesons.

The entries in the Table give the meson names. The spin J is added as a subscript except for pseudoscalar and vector mesons, and the mass is added in parentheses for mesons that decay strongly. However, for the lightest meson resonances, we omit the mass.

Measurements of the mass, quark content (where relevant), and quantum numbers I, J, P, and C (or G) of a meson thus fix its symbol. Conversely, these properties may be inferred unambiguously from the symbol.

If the main symbol cannot be assigned because the quantum numbers are unknown, X is used. Sometimes it is not known whether a meson is mainly the isospin-0 mix of $u\overline{u}$ and $d\overline{d}$ or is mainly $s\overline{s}$. A prime (or pair ω, ϕ) may be used to distinguish two such mixing states.

We follow custom and use spectroscopic names such as $\Upsilon(1S)$ as the primary name for most of those ψ, Υ, and χ states whose spectroscopic identity is known. We use the form $\Upsilon(9460)$ as an alternative, and as the primary name when the spectroscopic identity is not known.

Names are assigned for $t\overline{t}$ mesons, although the top quark is evidently so heavy that it is expected to decay too rapidly for bound states to form.

Gluonium states or other mesons that are not $q\overline{q}$ states are, if the quantum numbers are *not* exotic, to be named just as are the $q\overline{q}$ mesons. Such states will probably be difficult to distinguish from $q\overline{q}$ states and will likely mix with them, and we make no attempt to distinguish those "mostly gluonium" from those "mostly $q\overline{q}$."

An "exotic" meson with J^{PC} quantum numbers that a $q\overline{q}$ system cannot have, namely $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \cdots$, would use the same symbol as does an ordinary meson with all the same quantum numbers as the exotic meson except for the C parity. But then the J subscript may still distinguish it; for example, an isospin-0 1^{-+} meson could be denoted ω_1.

8.3. Mesons with nonzero S, C, B, and/or T

Since the strangeness or a heavy flavor of these mesons is nonzero, none of them are eigenstates of charge conjugation, and in each of them one of the quarks is heavier than the other. The rules are:

1. The main symbol is an upper-case italic letter indicating the heavier quark as follows:
$$s \to \overline{K} \qquad c \to D \qquad b \to \overline{B} \qquad t \to T\ .$$
We use the convention that *the flavor and the charge of a quark have the same sign.* Thus the strangeness of the s quark is negative, the charm of the c quark is positive, and the bottom of the b quark is negative. In addition, I_3 of the u and d quarks are positive and negative, respectively. The effect of this convention is as follows: *Any flavor carried by a charged meson has the same sign as its charge.* Thus the K^+, D^+, and B^+ have positive strangeness, charm, and bottom, respectively, and all have positive I_3. The D_s^+ has positive charm *and* strangeness. Furthermore, the $\Delta(\text{flavor}) = \Delta Q$ rule, best known for the kaons, applies to every flavor.
2. If the lighter quark is not a u or a d quark, its identity is given by a subscript. The D_s^+ is an example.
3. If the spin-parity is in the "normal" series, $J^P = 0^+, 1^-, 2^+, \cdots$, a superscript "*" is added.
4. The spin is added as a subscript except for pseudoscalar or vector mesons.

8.4. Baryons

The symbols N, Δ, Λ, Σ, Ξ, and Ω used for more than 30 years for the baryons made of light quarks (u, d, and s quarks) tell the isospin and quark content, and the same information is conveyed by the symbols used for the baryons containing one or more heavy quarks (c, b, and t quarks). The rules are:

1. Baryons with *three* u and/or d quarks are N's (isospin 1/2) or Δ's (isospin 3/2).
2. Baryons with *two* u and/or d quarks are Λ's (isospin 0) or Σ's (isospin 1). If the third quark is a c, b, or t quark, its identity is given by a subscript.
3. Baryons with *one* u or d quark are Ξ's (isospin 1/2). One or two subscripts are used if one or both of the remaining quarks are heavy: thus Ξ_c, Ξ_{cc}, Ξ_b, *etc.*
4. Baryons with *no* u or d quarks are Ω's (isospin 0), and subscripts indicate any heavy-quark content.

In short, the number of u plus d quarks together with the isospin determine the main symbol, and subscripts indicate any content of heavy quarks. A Σ always has isospin 1, an Ω always has isospin 0, *etc.*

Reference:

1. Particle Data Group: M. Aguilar-Benitez *et al.*, Phys. Lett. **170B** (1986).

9. QUANTUM CHROMODYNAMICS

9.1. The QCD Lagrangian

Prepared August 1995 by I. Hinchliffe.

Quantum Chromodynamics (QCD), the gauge field theory which describes the strong interactions of colored quarks and gluons, is one of the components of the SU(3)×SU(2)×U(1) Standard Model. A quark of specific flavor (such as a charm quark) comes in 3 colors; gluons come in eight colors; hadrons are color-singlet combinations of quarks, anti-quarks, and gluons. The Lagrangian describing the interactions of quarks and gluons is (up to gauge-fixing terms)

$$L_{\rm QCD} = -\frac{1}{4}F^{(a)}_{\mu\nu}\,F^{(a)\mu\nu} + i\sum_q \overline{\psi}^i_q\,\gamma^\mu\,(D_\mu)_{ij}\,\psi^j_q - \sum_q m_q\,\overline{\psi}^i_q\,\psi_{qi}\ , \tag{9.1}$$

$$F^{(a)}_{\mu\nu} = \partial_\mu\,A^a_\nu - \partial_\nu\,A^a_\mu + g_s\,f_{abc}\,A^b_\mu\,A^c_\nu\ , \tag{9.2}$$

$$(D_\mu)_{ij} = \delta_{ij}\,\partial_\mu - ig_s\,\sum_a \frac{\lambda^a_{i,j}}{2}A^a_\mu\ , \tag{9.3}$$

where g_s is the QCD coupling constant, and the f_{abc} are the structure constants of the SU(3) algebra (the λ matrices and values for f_{abc} can be found in "SU(3) Isoscalar Factors and Representation Matrices," Sec. 32 of this *Review*). The $\psi^i_q(x)$ are the 4-component Dirac spinors associated with each quark field of (3) color i and flavor q, and the $A^a_\mu(x)$ are the (8) Yang-Mills (gluon) fields. A complete list of the Feynman rules which derive from this Lagrangian, together with some useful color-algebra identities, can be found in Ref. 1.

The principle of "asymptotic freedom" (see below) determines that the renormalized QCD coupling is small only at high energies, and it is only in this domain that high-precision tests—similar to those in QED—can be performed using perturbation theory. Nonetheless, there has been in recent years much progress in understanding and quantifying the predictions of QCD in the nonperturbative domain, for example, in soft hadronic processes and on the lattice [2]. This short review will concentrate on QCD at short distances (large momentum transfers), where perturbation theory is the standard tool. It will discuss the processes that are used to determine the coupling constant of QCD. Other recent reviews of the coupling constant measurements may be consulted for a different perspective [3].

9.2. The QCD coupling and renormalization scheme

The renormalization scale dependence of the effective QCD coupling $\alpha_s = g_s^2/4\pi$ is controlled by the β-function:

$$\mu\frac{\partial\alpha_s}{\partial\mu} = -\frac{\beta_0}{2\pi}\,\alpha_s^2 - \frac{\beta_1}{4\pi^2}\,\alpha_s^3 - \frac{\beta_2}{64\pi^3}\,\alpha_s^4 - \cdots\ , \tag{9.4a}$$

$$\beta_0 = 11 - \frac{2}{3}n_f\ , \tag{9.4b}$$

$$\beta_1 = 51 - \frac{19}{3}n_f\ , \tag{9.4c}$$

$$\beta_2 = 2857 - \frac{5033}{9}n_f + \frac{325}{27}n_f^2\ ; \tag{9.4d}$$

where n_f is the number of quarks with mass less than the energy scale μ. In solving this differential equation for α_s, a constant of integration is introduced. This constant is the one fundamental constant of QCD that must be determined from experiment. The most sensible choice for this constant is the value of α_s at a fixed-reference scale μ_0, but it is more conventional to introduce the dimensional parameter Λ, since this provides a parametrization of the μ dependence of α_s. The definition of Λ is arbitrary. One way to define it (adopted here) is to write a solution of Eq. (9.4) as an expansion in inverse powers of $\ln(\mu^2)$:

$$\alpha_s(\mu) = \frac{4\pi}{\beta_0\,\ln(\mu^2/\Lambda^2)}\left[1 - \frac{2\beta_1}{\beta_0^2}\,\frac{\ln\left[\ln(\mu^2/\Lambda^2)\right]}{\ln(\mu^2/\Lambda^2)} + \frac{4\beta_1^2}{\beta_0^4\ln^2(\mu^2/\Lambda^2)} \times\left(\left(\ln\left[\ln(\mu^2/\Lambda^2)\right] - \frac{1}{2}\right)^2 + \frac{\beta_2\beta_0}{8\beta_1^2} - \frac{5}{4}\right)\right]\ . \tag{9.5a}$$

The last term in this expansion is

$$\mathcal{O}\left(\frac{\ln^2\left[\ln(\mu^2/\Lambda^2)\right]}{\ln^3(\mu^2/\Lambda^2)}\right)\ , \tag{9.5b}$$

and is usually neglected in the definition of Λ. We choose to include it even though its effect on $\alpha_s(\mu)$ is smaller than the experimental errors. For a fixed value of $\alpha_s(M_Z)$, the inclusion of this term shifts the value of Λ by ~ 15 MeV. This solution illustrates the *asymptotic freedom* property: $\alpha_s \to 0$ as $\mu \to \infty$. Alternative definitions of Λ are possible. We adopt this as the standard. Values given by experiments using other definitions are adjusted as needed to meet our definition.

Consider a "typical" QCD cross section which, when calculated perturbatively, starts at $\mathcal{O}(\alpha_s)$:

$$\sigma = A_1\,\alpha_s + A_2\,\alpha_s^2 + \cdots\ . \tag{9.6}$$

The coefficients A_1, A_2 come from calculating the appropriate Feynman diagrams. In performing such calculations, various divergences arise, and these must be regulated in a consistent way. This requires a particular renormalization scheme (RS). The most commonly used one is the modified minimal subtraction ($\overline{\rm MS}$) scheme [4]. This involves continuing momentum integrals from 4 to 4–2ϵ dimensions, and then subtracting off the resulting $1/\epsilon$ poles and also $(\ln 4\pi - \gamma_E)$, which is another artifact of continuing the dimension. (Here γ_E is the Euler-Mascheroni constant.) To preserve the dimensionless nature of the coupling, a mass scale μ must also be introduced: $g \to \mu^\epsilon g$. The finite coefficients A_i thus obtained depend implicitly on the renormalization convention used and explicitly on the scale μ.

The first two coefficients (β_0, β_1) in Eq. (9.4) are independent of the choice of RS's. In contrast, the coefficients of terms proportional to α_s^n for $n > 3$ *are* RS-dependent. The form given above for β_2 is in the $\overline{\rm MS}$ scheme. It has become conventional to use the $\overline{\rm MS}$ scheme for calculating QCD cross sections beyond leading order.

The fundamental theorem of RS dependence is straightforward. Physical quantities, in particular the cross section, calculated to all orders in perturbation theory, do not depend on the RS. It follows that a truncated series *does* exhibit RS dependence. In practice, QCD cross sections are known to leading order (LO), or to next-to-leading order (NLO), or in a few cases, to next-to-next-to-leading order (NNLO); and it is only the latter two cases, which have reduced RS dependence, that are useful for precision tests. At NLO the RS dependence is completely given by one condition which can be taken to be the value of the renormalization scale μ. At NNLO this is not sufficient, and μ is no longer equivalent to a choice of scheme; both must now be specified. One, therefore, has to address the question of what is the "best" choice for μ. There is no definite answer to this question—higher-order corrections do not "fix" the scale, rather they render the theoretical predictions less sensitive to its variation.

One could imagine that choosing a scale μ characteristic of the typical energy scale (E) in the process would be most appropriate. In general, a poor choice of scale generates terms of order $\ln(E/\mu)$ in the A_i's. Various methods have been proposed including choosing: the scale for which the next-to-leading-order correction vanishes ("Fastest Apparent Convergence [5]"); the scale for which the next-to-leading-order prediction is stationary [6], (*i.e.*, the value of μ where $d\sigma/d\mu = 0$); or the scale dictated by the effective charge scheme [7] or by the BLM scheme [8]. By comparing the values of α_s that different reasonable schemes give, an estimate of theoretical errors can be obtained.

An important corollary is that if the higher-order corrections are naturally small, then the additional uncertainties introduced by the μ dependence are likely to be less than the experimental measurement errors. There are some processes, however, for which the choice of scheme *can* influence the extracted value of $\Lambda_{\overline{\rm MS}}$. There is no resolution to this problem other than to try to calculate even more terms in the perturbation series. It is important to note that, since the perturbation series is an asymptotic expansion, there is a limit to the precision with which any theoretical quantity can be calculated. In some processes, the highest-order perturbative terms may be comparable in size to nonperturbative corrections (sometimes called higher-twist or renormalon effects, for a discussion see [9]); an estimate of these terms and their uncertainties is required if a value of α_s is to be extracted.

In the cases where the higher-order corrections to a process are known and are large, some caution should be exercised when quoting the value of α_s. In what follows, we will attempt to indicate the size of the theoretical uncertainties on the extracted value of α_s. There are two simple ways to determine this error. First, we can estimate it by comparing the value of $\alpha_s(\mu)$ obtained by fitting data using the QCD formula to highest known order in α_s, and then comparing it with the value obtained using the next-to-highest-order formula (μ is chosen as the typical energy scale in the process). The corresponding Λ's are then obtained by evolving $\alpha_s(\mu)$ to $\mu = m_Z$ using Eq. (9.4) to the same order in α_s as the fit, and then converting to $\Lambda^{(4)}$ using Eq. (9.7). Alternatively, we can vary the value of μ over a reasonable range, extracting a value of Λ for each choice of μ. This method is of its nature imprecise, since "reasonable" involves a subjective judgment. In either case, if the perturbation series is well behaved, the resulting error on Λ will be small.

In the above discussion we have ignored quark-mass effects, *i.e.*, we have assumed an idealized situation where quarks of mass greater than μ are neglected completely. In this picture, the β-function coefficients change by discrete amounts as flavor thresholds are crossed when integrating the differential equation for α_s. It follows that, for a relationship such as Eq. (9.5) to remain valid for all values of μ, Λ must also change as flavor thresholds are crossed. This leads to the concept of a different Λ for each range of μ corresponding to an effective number of massless quarks: $\Lambda \to \Lambda^{(n_f)}$. There is some arbitrariness in how this relationship is set up. As an idealized case, consider QCD with $n_f - 1$ massless quarks and one quark of mass M. Now imagine an experiment at energy scale μ; for example, this could be $e^+e^- \to$ *hadrons* at center-of-mass energy μ. If $\mu \gg M$, the mass M is negligible and the process is well described by QCD with n_f massless flavors and its parameter $\Lambda^{(n_f)}$ up to terms of order M^2/μ^2. Conversely if $\mu \ll M$, the heavy quark plays no role and the process is well described by QCD with $n_f - 1$ massless flavors and its parameter $\Lambda^{(n_f-1)}$ up to terms of order μ^2/M^2. If $\mu \sim M$, the effects of the quark mass are process-dependent and cannot be absorbed into the running coupling.

A mass scale μ' is chosen where the relationship between $\Lambda^{(n_f-1)}$ and $\Lambda^{(n_f)}$ will be fixed. μ' should be of order M and the relationship should not depend on it. A prescription has been given [10] which has this property. We use this procedure choosing $\mu' = M_Q$, where M_Q is the mass of the value of the running quark mass defined in the $\overline{\rm MS}$ scheme (see the note on "Quark Masses" in the Particle Listings for more details), *i.e.*, where $M_{\overline{\rm MS}}(M_Q) = M_Q$. Then [10]

$$\begin{aligned}
\beta_0^{n_f-1} \ln\left(\frac{\Lambda^{(n_f)}}{\Lambda^{(n_f-1)}}\right)^2 &= (\beta_0^{n_f} - \beta_0^{n_f-1}) \ln\left(\frac{M_Q}{\Lambda^{(n_f)}}^2\right) \\
&+ 2\left(\frac{\beta_1^{n_f}}{\beta_0^{n_f}} - \frac{\beta_1^{n_f-1}}{\beta_0^{n_f-1}}\right) \ln\left[\ln\left(\frac{M_Q}{\Lambda^{(n_f)}}\right)^2\right] \\
&- \frac{2\beta_1^{n_f-1}}{\beta_0^{n_f-1}} \ln\left(\frac{\beta_0^{n_f}}{\beta_0^{n_f-1}}\right) \\
&+ \frac{4\frac{\beta_1^{n_f}}{(\beta_0^{n_f})^2}\left(\frac{\beta_1^{n_f}}{\beta_0^{n_f}} - \frac{\beta_1^{n_f-1}}{\beta_0^{n_f-1}}\right) \ln\left[\ln\left(\frac{M_Q}{\Lambda^{n_f}}\right)^2\right]}{\ln\left(\frac{M_Q}{\Lambda^{(n_f)}}\right)^2} \\
&+ \frac{\frac{1}{\beta_0^{n_f}}\left[\left(\frac{2\beta_1^{n_f}}{\beta_0^{n_f}}\right)^2 - \left(\frac{2\beta_1^{n_f-1}}{\beta_0^{n_f-1}}\right)^2 - \frac{2\beta_2^{n_f}}{\beta_0^{n_f}} + \frac{2\beta_2^{n_f-1}}{\beta_0^{n_f-1}} - \frac{14}{9}\right]}{\ln\left(\frac{M_Q}{\Lambda^{(n_f)}}\right)^2} .
\end{aligned} \tag{9.7}$$

This result is valid to order α_s^3 (or alternatively to terms of order $1/\ln^2[(M_Q/\Lambda^{(n_f)})^2]$).

An alternative matching procedure can be used [11]. This procedure requires the equality $\alpha_s(\mu)^{(n_f)} = \alpha_s(\mu)^{(n_f-1)}$ for $\mu = M_Q$. This matching is somewhat arbitrary; a different relation between $\Lambda^{(n_f)}$ and $\Lambda^{(n_f-1)}$ would result if $\mu = M_Q/2$ were used. In practice, the differences between these procedures are very small. $\Lambda^{(5)} = 200$ MeV corresponds to $\Lambda^{(4)} = 289$ MeV in the scheme of Ref. 11 and $\Lambda^{(4)} = 280$ MeV in the scheme adopted above. Note that the differences between $\Lambda^{(5)}$ and $\Lambda^{(4)}$ are numerically very significant.

Data from deep-inelastic scattering are in a range of energy where the bottom quark is not readily excited, and hence, these experiments quote $\Lambda^{(4)}_{\overline{\rm MS}}$. Most data from PEP, PETRA, TRISTAN, LEP, and SLC quote a value of $\Lambda^{(5)}_{\overline{\rm MS}}$ since these data are in an energy range where the bottom quark is light compared to the available energy. We have converted it to $\Lambda^{(4)}_{\overline{\rm MS}}$ as required. A few measurements, including the lattice gauge theory values from the ψ system and from τ decay are at sufficiently low energy that $\Lambda^{(3)}_{\overline{\rm MS}}$ is appropriate.

We turn now to a discussion of renormalization-scheme dependence in QCD. Although necessarily rather technical, this discussion is vital to understanding how α_s (or Λ) values can be measured and compared. See the review by Duke and Roberts [12] for further details.

In order to compare the values of α_s from various experiments, they must be evolved using the renormalization group to a common scale. For convenience, this is taken to be the mass of the Z boson. This evolution uses third-order perturbation theory and can introduce additional errors particularly if extrapolation from very small scales is used. The variation in the charm and bottom quark masses ($m_b = 4.3 \pm 0.2$ and $m_c = 1.3 \pm 0.3$ are used) can also introduce errors. These result in a fixed value of $\alpha_s(2$ GeV$)$, giving an uncertainty in $\alpha_s(M_Z) = \pm 0.001$ if only perturbative evolution is used. There could be additional errors from nonperturbative effects that enter at low energy. All values are in the $\overline{\rm MS}$ scheme unless otherwise noted.

9.3. QCD in deep-inelastic scattering

The original and still one of the most powerful quantitative tests of perturbative QCD is the breaking of Bjorken scaling in deep-inelastic lepton-hadron scattering. In the leading-logarithm approximation, the measured structure functions $F_i(x, Q^2)$ are related to the quark distribution functions $q_i(x, Q^2)$ according to the naive parton model, by the formulae in "Cross-section Formulae for Specific Processes," Sec. 35 of this *Review*. (In that section, q_i is denoted by the notation f_q). In describing the way in which scaling is broken in QCD, it is convenient to define nonsinglet and singlet quark distributions:

$$F^{NS} = q_i - q_j \qquad F^S = \sum_i (q_i + \overline{q}_i) \ . \tag{9.8}$$

The nonsinglet structure functions have nonzero values of flavor quantum numbers such as isospin or baryon number. The variation with Q^2 of these is described by the so-called DGLAP equations [13,14]:

$$Q^2 \frac{\partial F^{NS}}{\partial Q^2} = \frac{\alpha_s(|Q|)}{2\pi} P^{qq} * F^{NS} \tag{9.9a}$$

$$Q^2 \frac{\partial}{\partial Q^2} \begin{pmatrix} F^S \\ G \end{pmatrix} = \frac{\alpha_s(|Q|)}{2\pi} \begin{pmatrix} P^{qq} & 2n_f P^{qg} \\ P^{gq} & P^{gg} \end{pmatrix} * \begin{pmatrix} F^S \\ G \end{pmatrix} \tag{9.9b}$$

where $*$ denotes a convolution integral:

$$f * g = \int_x^1 \frac{dy}{y} f(y)\, g\left(\frac{x}{y}\right) \ . \tag{9.10}$$

The leading-order Altarelli-Parisi [14] splitting functions are

$$P^{qq} = \frac{4}{3}\left[\frac{1 + x^2}{(1-x)_+}\right] + 2\delta(1-x) \ , \tag{9.11a}$$

$$P^{qg} = \frac{1}{2}\left[x^2 + (1-x)^2\right] , \tag{9.11b}$$

$$P^{gq} = \frac{4}{3}\left[\frac{1+(1-x)^2}{x}\right] , \tag{9.11c}$$

$$P^{gg} = 6\left[\frac{1-x}{x} + x(1-x) + \frac{x}{(1-x)_+} + \frac{11}{12}\delta(1-x)\right] - \frac{n_f}{3}\delta(1-x) . \tag{9.11d}$$

Here the gluon distribution $G(x,Q^2)$ has been introduced and $1/(1-x)_+$ means

$$\int_0^1 dx \frac{f(x)}{(1-x)_+} = \int_0^1 dx \, \frac{f(x)-f(1)}{(1-x)} . \tag{9.12}$$

The precision of contemporary experimental data demands that higher-order corrections also be included [15]. The above results are for massless quarks. Algorithms exist for the inclusion of nonzero quark masses [16]. At low Q^2 values, there are also important "higher-twist" (HT) contributions of the form:

$$F_i(x,Q^2) = F_i^{(LT)}\,(x,Q^2) + \frac{F_i^{(HT)}(x,Q^2)}{Q^2} + \cdots . \tag{9.13}$$

Leading twist (LT) indicates a term whose behavior is predicted by perturbative QCD. These corrections are numerically important only for $Q^2 < \mathcal{O}(10\,\text{GeV}^2)$ except for x very close to 1.

A detailed review of the current status of the experimental data can be found, for example, in Refs. [17–20], and only a brief summary will be presented here. We shall only include determinations of Λ from the recently published results; the earlier editions of this *Review* should be consulted for the earlier data. In any event, the recent results will dominate the average since their errors are smaller. Data have now appeared from HERA at much smaller values of x than the previous data. They provide valuable information about the shape of the antiquark and gluon distribution functions at $x \sim 10^{-3}$ [21].

From Eq. (9.9), it is clear that a nonsinglet structure function offers in principle the most precise test of the theory, since the Q^2 evolution is independent of the unmeasured gluon distribution. The CCFR collaboration fit to the Gross-Llewellyn Smith sum rule [22] is known to order α_s^3 [23]

$$\int_0^1 dx(F_3^{\overline{\nu}p}(x,Q^2) + F_3^{\nu p}(x,Q^2)) = 3\left[(1 - \frac{\alpha_s}{\pi}(1 + 3.58\frac{\alpha_s}{\pi} + 19.0(\frac{\alpha_s}{\pi})^2) - \Delta HT\right] , \tag{9.14}$$

where the higher-twist contribution $\Delta HT = (0.09 \pm 0.045)/Q^2$ [23,24]. Using the CCFR data [25], this gives α_s (1.76 GeV) $= 0.26 \pm 0.035$ (expt.) ± 0.03 (theory). The error from higher-twist terms dominates the theoretical error, the higher-twist term being approximately 50% larger than the α_s^3 term.

A measurement of Λ has been made using F_3 in neutrino scattering [27]. The result is $\Lambda^{(4)}_{\overline{\rm MS}} = 179 \pm 36 \pm 41$ MeV. The errors are statistical and systematic but do not include (theoretical) errors arising from the choice of μ^2. Measurements involving singlet-dominated structure functions, such as F_2, result in correlated measurements of $\Lambda^{(4)}_{\overline{\rm MS}}$ and the gluon distribution. By utilizing high-statistics data at large x (> 0.25) and large Q^2, where F_2 behaves like an nonsinglet and F_3 at smaller x, a nonsinglet fit can be performed with better statistical precision, and hence, the error on the measured value of $\Lambda^{(4)}_{\overline{\rm MS}}$ is much reduced. CCFR gives $\Lambda^{(4)}_{\overline{\rm MS}} = 210 \pm 28 \pm 41$ MeV [27] from $F_2(\nu N)$ and $F_3(\nu N)$. There is an additional uncertainty of ± 59 MeV from the choice of scale. The NMC collaboration [28] gives $\alpha_s(7\ \text{GeV}^2) = 0.264 \pm 0.018(\text{stat.}) \pm 0.070(\text{syst.}) \pm 0.013(\text{ higher-twist})$. The systematic error is larger than the CCFR result, partially because the data are at smaller values of x and the gluon distribution is more important. A reanalysis [29] of EMC data [30] gives $\Lambda^{(4)}_{\overline{\rm MS}} = 211 \pm 80 \pm 80$ MeV from $F_2(\nu N)$. Finally a combined analysis [31] of SLAC [32] and BCDMS [33] data gives $\Lambda^{(4)}_{\overline{\rm MS}} = 263 \pm 42 \pm 55$ MeV. Here the systematic error is an estimate of the uncertainty due to the choice of Q^2 used in the argument of α_s, and in the scale at which the structure functions (factorization scale) used in the QCD calculation are evaluated.

The results from Refs. [27–29] and [31] can be combined to give $\alpha_s(M_Z) = 0.112 \pm 0.002 \pm 0.004$, or equivalently $\Lambda^{(4)}_{\overline{\rm MS}} = 234 \pm 26 \pm 50$ MeV. Here the first error is a combination of statistical and systematic errors, and the second error is due to the scale uncertainty. This result is an average of the results weighted by their statistical and systematic errors. The scale error which is common to all is then reapplied to the average.

The spin-dependent structure functions can also be used to determine α_s. Here the values of $Q^2 \sim 2.5\ \text{GeV}^2$ are small and higher-twist corrections are again important. The values extracted are consistent with the average quote below [26].

At very small values of x and large Q^2, the x-dependence of the structure functions is predicted by perturbative QCD [34]. Here terms to all orders in $\alpha_s \ln(1/x)$ are summed. The data from HERA [21] on $F_2^{ep}(x,Q^2)$ have been fitted to the this form [35], including the NLO terms which are required to fix the Q^2 scale. The data are dominated by $4\ \text{GeV}^2 < Q^2 < 100\ \text{GeV}^2$. The fit gives $\alpha_s(M_Z) = 0.120 \pm 0.005$ (expt.) ± 0.009 (theory). The dominant part of the theoretical error is from the scale dependence. The fit neglects terms which are suppressed by $1/\ln(1/x)$. Hence, the uncertainties from this source cannot be estimated and are not included in the quoted error. This result is not averaged with the other ones from scaling violations, since the values there are derived from the Q^2 dependence alone, and this possible source of error is not present.

Typically, Λ is extracted from the data by parametrizing the parton densities in a simple analytic way at some Q_0^2, evolving to higher Q^2 using the next-to-leading-order evolution equations, and fitting globally to the measured structure functions to obtain $\Lambda^{(4)}_{\overline{\rm MS}}$. Thus, an important by-product of such studies is the extraction of parton densities at a fixed-reference value of Q_0^2. These can then be evolved in Q^2 and used as input for phenomenological studies in hadron-hadron collisions (see below). To avoid having to evolve from the starting Q_0^2 value each time, a parton density is required; it is useful to have available a simple analytic approximation to the densities valid over a range of x and Q^2 values. A package is available from the CERN computer library that includes an exhaustive set of fits [36]. Some of these fits are obsolete. In using a parameterization to predict event rates, a next-to-leading order fit must be used if the process being calculated is known to next-to-leading order in QCD perturbation theory. In such a case, there is an additional scheme dependence; this scheme dependence is reflected in the $\mathcal{O}(\alpha_s)$ corrections that appear in the relations between the structure functions and the quark distribution functions. There are two common schemes: a deep-inelastic scheme where there are no order α_s corrections in the formula for $F_2(x,Q^2)$ and the minimal subtraction scheme. It is important when these next-to-leading order fits are used in other processes (see below), that the same scheme is used in the calculation of the partonic rates.

9.4. QCD in decays of the τ lepton

The semi-leptonic branching ratio of the tau ($\tau \to \nu_\tau + hadrons$, R_τ) is an inclusive quantity. It is related to the contribution of hadrons to the imaginary part of the W self energy $(\Pi(s))$. However, it is more inclusive than R since it involves an integral

$$R_\tau \sim \int_0^{m_\tau^2} \frac{ds}{m_\tau^2}(1 - \frac{s}{m_\tau^2})^2\ \text{Im}\,(\Pi(s)) .$$

Since the scale involved is low, one must take into account nonperturbative (higher-twist) contributions which are suppressed by powers of the τ mass.

$$R_\tau = 3.058\left[1 + \frac{\alpha_s(m_\tau)}{\pi} + 5.2\left(\frac{\alpha_s(m_\tau)}{\pi}\right)^2 + 26.4\left(\frac{\alpha_s(m_\tau)}{\pi}\right)^3 + \right.$$

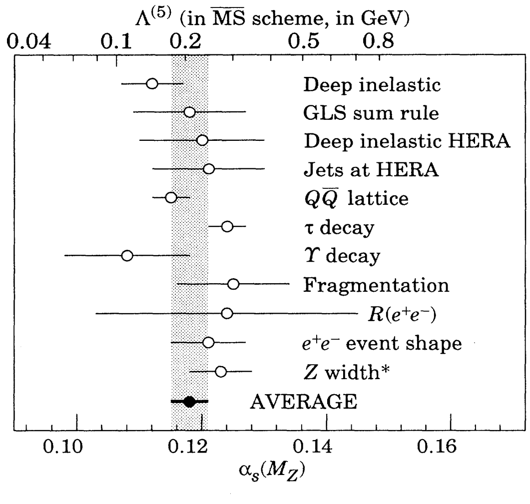

Figure 9.1: Summary of the values of $\alpha_s(M_Z)$ and $\Lambda^{(5)}$ from various processes ordered from top to bottom by increasing energy scale of the measurements. The values shown indicate the process and the measured value of α_s extrapolated up to $\mu = M_Z$. The error shown is the *total* error including theoretical uncertainties. The value denoted by '*' is not used in the average (see text).

$$a\frac{m^2}{m_\tau^2} + b\frac{m\psi\overline{\psi}}{m_\tau^4} + c\frac{\psi\overline{\psi}\psi\overline{\psi}}{m_\tau^6} + \cdots \Bigg] . \qquad (9.15)$$

Here a, b, and c are dimensionless constants and m is a light quark mass. The term of order $1/m_\tau^2$ is a kinematical effect due to the light quark masses and is consequently very small. The nonperturbative terms are estimated using sum rules [37]. In total, they are estimated to be -0.007 ± 0.004 [38]. This estimate relies on there being no term of order Λ^2/m_τ^2 $\left(\text{note that } \frac{\alpha_s(m_\tau)}{\pi} \sim (\frac{0.5 \text{ GeV}}{m_\tau})^2\right)$. The a, b, and c can be determined from the data [39] by fitting to moments of the $\Pi(s)$. The values so extracted [40,41] are consistent with the theoretical estimates. If the nonperturbative terms are omitted from the fit, the extracted value of $\alpha_s(m_\tau)$ decreases by ~ 0.02.

For $\alpha_s(m_\tau) = 0.37$ the perturbative series for R_τ is $R_\tau \sim 3.058(1 + 0.118 + 0.072 + 0.043)$. The size (estimated error) of the nonperturbative term is 20% (7%) of the size of the order α_s^3 term. The perturbation series in not very well convergent; if the order α_s^3 term is omitted, the extracted value of $\alpha_s(m_\tau)$ increases by 0.05. R_τ, can be extracted from the semi-leptonic branching ratio from the relation $R_\tau = 1/(\text{B}(\tau \to e\nu\overline{\nu}) - 1.97256$; where $\text{B}(\tau \to e\nu\overline{\nu})$ is measured directly or extracted from the lifetime, the muon mass and the muon lifetime assuming universality of lepton couplings. Using the average lifetime of 291.3 ± 1.6 fs [42] and a τ mass of $1.776.96 \pm 0.30$ [43] gives $R_\tau = 3.633 \pm 0.031$. Assuming e/μ universality, the data give $\text{B}(\tau \to e\nu\overline{\nu}) = 0.1780 \pm 0.0006$ [44]. Averaging these yields $\alpha_s(m_\tau) = 0.370 \pm 0.008$ using the experimental error alone. This result is consistent with measurements reported recently by other collaborations [45,46]. The value of $\alpha_s(m_\tau) = 0.306 \pm 0.017$ quoted by CLEO [41] uses the measured moments and the average value $\text{B}(\tau \to e\nu\overline{\nu}) = 0.1810 \pm 0.0012$ from the 1992 edition of this review. We assign a theoretical error equal to 1/2 of the contribution from the order α^3 term and all of the nonperturbative contributions. This then gives $\alpha_s(m_\tau) = 0.370 \pm 0.033$ for the final result. Note that the theoretical errors are dominant. The small theoretical errors have been criticized [47].

9.5. QCD in high-energy hadron collisions

There are many ways in which perturbative QCD can be tested in high-energy hadron colliders. The quantitative tests are only useful if the process in question has been calculated beyond leading order in QCD perturbation theory. The production of hadrons with large transverse momentum in hadron-hadron collisions provides a direct probe of the scattering of quarks and gluons: $qq \to qq$, $qg \to qg$, $gg \to gg$, *etc.* The present generation of $p\overline{p}$ colliders provide center-of-mass energies which are sufficiently high that these processes can be unambiguously identified in two-jet production at large transverse momentum. Recent higher-order QCD calculations of the jet rates [48] and shapes are in impressive agreement with data [49]. As an example, Fig. 36.7 in this *Review* shows the inclusive jet cross section at zero pseudorapidity as a function of the jet transverse momentum for $p\overline{p}$ collisions. The QCD prediction combines the parton distributions with the leading-order $2 \to 2$ parton scattering amplitudes. Data are also available on the angular distribution of jets; these are also in agreement with QCD expectations [50,51].

QCD corrections to Drell-Yan type cross sections (*i.e.*, the production in hadron collisions by quark-antiquark annihilation of lepton pairs of invariant mass Q from virtual photons, or of real W or Z bosons), are known [52]. These $\mathcal{O}(\alpha_s)$ QCD corrections are sizable at small values of Q.

It is interesting to note that the corresponding correction to W and Z production, as measured in $p\overline{p}$ collisions at $\sqrt{s} = 0.63$ TeV and $\sqrt{s} = 1.8$ TeV, has essentially the same theoretical form and is of order 30%.

The production of W and Z bosons and photons at large transverse momentum can also be used to determine α_s. The leading-order QCD subprocesses are $q\overline{q} \to \gamma g$ and $qg \to \gamma q$. If the parton distributions are taken from other processes and a value of $\Lambda^{(4)}_{\overline{\rm MS}}$ assumed, then an absolute prediction is obtained. Conversely, the data can be used to extract information on quark and gluon distributions and on the value of $\Lambda^{(4)}_{\overline{\rm MS}}$. The next-to-leading-order QCD corrections are known [53,54] (for photons), and for W/Z production [55], and so a precision test is possible in principle. Data exist from the CDF and DØ collaborations [56,57]. The UA2 collaboration [58] has extracted a value of $\alpha_s(M_W) = 0.123 \pm 0.018(\text{stat.}) \pm 0.017(\text{syst.})$ from the measured ratio $R_W = \frac{\sigma(W + 1jet)}{\sigma(W + 0jet)}$. The result depends on the algorithm used to define a jet, and the dominant systematic errors due to fragmentation and corrections for underlying events (the former causes jet energy to be lost, the latter causes it to be increased) are connected to the algorithm. The scale at which $\alpha_s(M)$ is to be evaluated is not clear. A change from $\mu = M_W$ to $\mu = M_W/2$ causes a shift of 0.01 in the extracted α_s. The quoted error should be increased to take this into account. There is dependence on the parton distribution functions, and hence, α_s appears explicitly in the formula for R_W, and implicitly in the distribution functions. The DØ collaboration has performed an analysis similar to UA2. They are unable to obtain a fit where the two values of α_s are consistent with one another, and do not quote a value of α_s [59]. The values from this process are no longer used in determining the overall average value of α_s.

9.6. QCD in heavy-quarkonium decay

Under the assumption that the hadronic and leptonic decay widths of heavy $Q\overline{Q}$ resonances can be factorized into a nonperturbative part—dependent on the confining potential—and a calculable perturbative part, the ratios of partial decay widths allow measurements of α_s at the heavy-quark mass scale. The most precise data come from the decay widths of the 1^{--} $J/\psi(1S)$ and Υ resonances. The total decay width of the Υ is predicted by perturbative QCD [60]

$$R_\Upsilon = \frac{\Gamma(\Upsilon \to \text{hadrons})}{\Gamma(\Upsilon \to \mu^+\mu^-)}$$

$$= \frac{10(\pi^2-9)\alpha_s^3(M)}{9\pi\alpha_{\rm em}^2} \times \left[1+\frac{\alpha_s}{\pi}\left(-19.4+\frac{3\beta_0}{2}\left(1.162+\ln\left(\frac{2M}{M_\Upsilon}\right)\right)\right)\right] . \quad (9.16)$$

Data are available for the Υ, Υ', Υ'' and ψ. The result is very sensitive to α_s and the data are sufficiently precise ($R_\mu(\Upsilon) = 32.5 \pm 0.9$) [61] that the theoretical errors will dominate. There are theoretical corrections to this simple formula due to the relativistic nature of the $Q\overline{Q}$ system; $v^2/c^2 \sim 0.1$ for the Υ. They are more severe for the ψ. There are also nonperturbative corrections of the form Λ^2/m_Υ^2; again these are more severe for the ψ. A fit to Υ, Υ', and Υ'' [62] gives $\alpha_s(M_Z) = 0.108 \pm 0.001$ (expt.). The results from each state separately and also from the ψ are consistent with each other. There is an uncertainty of order ± 0.005 from the choice of scale; the error from v^2/c^2 corrections is a little larger. $\alpha_s(M_Z) = 0.108 \pm 0.010$ is a fair representation of the total error including the possibility of nonperturbative corrections.

9.7. Perturbative QCD in e^+e^- collisions

The total cross section for $e^+e^- \to$ hadrons is obtained (at low values of $\sqrt{s}$) by multiplying the muon-pair cross section by the factor $R = 3\Sigma_q e_q^2$. The higher-order QCD corrections to this quantity have been calculated, and the results can be expressed in terms of the factor:

$$R = R^{(0)}\left[1+\frac{\alpha_s}{\pi}+C_2\left(\frac{\alpha_s}{\pi}\right)^2+C_3\left(\frac{\alpha_s}{\pi}\right)^3+\cdots\right] , \quad (9.17)$$

where $C_2 = 1.411$ and $C_3 = -12.8$ [63].

$R^{(0)}$ can be obtained from the formula for $d\sigma/d\Omega$ for $e^+e^- \to f\overline{f}$ by integrating over Ω. The formula is given in Sec. 35.2 of this *Review*. This result is only correct in the zero-quark-mass limit. The $\mathcal{O}(\alpha_s)$ corrections are also known for massive quarks [64]. The principal advantage of determining α_s from R in e^+e^- annihilation is that there is no dependence on fragmentation models, jet algorithms, *etc.*

A comparison of the theoretical prediction of Eq. (9.17) (corrected for the b-quark mass), with all the available data at values of $\sqrt{s}$ between 20 and 65 GeV, gives [65] $\alpha_s(35 \text{ GeV}) = 0.146 \pm 0.030$. The size of the order α_s^3 term is of order 40% of that of the order α_s^2 and 3% of the order α_s. If the order α_s^3 term is not included, a fit to the data yields α_s (34 GeV) $= 0.142 \pm 0.03$, indicating that the theoretical uncertainty is smaller than the experimental error.

Measurements of the ratio of hadronic to leptonic width of the Z at LEP and SLC, Γ_h/Γ_μ probe the same quantity as R. Using the average of $\Gamma_h/\Gamma_\mu = 20.788 \pm 0.032$ gives $\alpha_s(M_Z) = 0.123 \pm 0.004 \pm 0.002$ [66]. There are theoretical errors arising from the values of the top-quark and Higgs masses which enter due to electroweak corrections to the Z width and from the choice of scale.

While this method has small theoretical uncertainties from QCD itself, it relies sensitively on the electroweak couplings of the Z to quarks [67]. The experimental results on $\Gamma(Z \to b\overline{b})$ and $\Gamma(Z \to c\overline{c})$ are not in agreement with the Standard Model [68]. If these widths are taken from experiment (rather than from the Standard Model), the extracted vale of $\alpha_s(M_Z)$ is 0.183. If the Standard Model is used for $\Gamma(Z \to c\overline{c})$, $\alpha_s(M_Z) = 0.104$ results. In view of these problems, the value from Γ_h/Γ_μ is not included in the final average.

An alternative method of determining α_s in e^+e^- annihilation is from measuring quantities that are sensitive to the relative rates of two-, three-, and four-jet events. A recent review should be consulted for more details [69] of the issues mentioned briefly here. In addition to simply counting jets, there are many possible choices of such "shape variables": thrust [70], energy-energy correlations [71], planar triple-energy correlations [72], average jet mass, *etc.* All of these are infrared safe, which means they can be reliably calculated in perturbation theory. The starting point for all these quantities is the multijet cross section. For example, at order α_s, for the process $e^+e^- \to qqg$:

$$\frac{1}{\sigma}\frac{d^2\sigma}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi}\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)} , \quad (9.18)$$

where

$$x_i = \frac{2E_i}{\sqrt{s}} \quad (9.19)$$

are the center-of-mass energy fractions of the final-state (massless) quarks. A distribution in a "three-jet" variable, such as those listed above, is obtained by integrating this differential cross section over an appropriate phase space region for a fixed value of the variable. The order α_s^2 corrections to this process have been computed, as well as the 4-jet final states such as $e^+e^- \to qqgg$ [73].

There are many methods used by the e^+e^- experimental groups to determine α_s from the event topology. The jet-counting algorithm, originally introduced by the JADE collaboration [74], has been used by the LEP groups. Here, particles of momenta p_i and p_j are combined into a pseudo-particle of momentum $p_i + p_j$ if the invariant mass of the pair is less than $y_0\sqrt{s}$. The process is then iterated until no more pairs of particles or pseudo-particles remain. The remaining number is then defined to be the number of jets in the event, and can be compared to the QCD prediction. The Durham algorithm is slightly different: in computing the mass of a pair of partons, it uses $M^2 = 2\min(E_1^2, E_2^2)(1 - \cos\theta_{ij})$ for partons of energies E_i and E_j separated by angle θ_{ij} [75].

There are theoretical ambiguities in the way this process is carried out. Quarks and gluons are massless, whereas the observed hadrons are not, so that the massive jets that result from this scheme (the so-called E-0 scheme) cannot be compared directly to the massless jets of perturbative QCD. Different recombination schemes have been tried, for example combining 3-momenta and then rescaling the energy of the cluster so that it remains massless (p scheme). These schemes result in the same data giving a slightly different values [76,77] of α_s. These differences can be used to determine a systematic error. In addition, since what is observed are hadrons rather than quarks and gluons, a model is needed to describe the evolution of a partonic final state into one involving hadrons, so that detector corrections can be applied. The QCDmatrix elements are combined with a parton-fragmentation model. This model can then be used to correct the data for a direct comparison with the parton calculation. The different hadronization models that are used [78–81] model the dynamics that are controlled by nonperturbative QCD effects which we cannot yet calculate. The fragmentation parameters of these Monte Carlos are tuned to get agreement with the observed data. The differences between these models contribute to the systematic errors. The systematic errors from recombination schemes and fragmentation effects dominate over the statistical and other errors of the LEP/SLD experiments.

The scale M at which $\alpha_s(M)$ is to be evaluated is not clear. The invariant mass of a typical jet (or $\sqrt{sy_0}$) is probably a more appropriate choice than the e^+e^- center-of-mass energy. If the value is allowed to float in the fit to the data, the data tend to prefer values of order $\sqrt{s}/10$ [82]; the exact value depends on the variable that is fitted. The dominant uncertainties arise from the choice of M and from the freedom in the fragmentation Monte Carlos.

The perturbative QCD formulae can break down in special kinematical configurations. For example, the thrust distribution contains terms of the type $\alpha_s \ln^2(1-T)$. The higher orders in the perturbation expansion contain terms of order $\alpha_s^n \ln^m(1-T)$. For $T \sim 1$ (the region populated by 2-jet events), the perturbation expansion is unreliable. The terms with $n \le m$ can be summed to all orders in α_s [83]. If the jet recombination methods are used higher-order terms involve $\alpha_s^n \ln^m y_0$), these too can be resummed [84]. The resummed results give better agreement with the data at large values of T. Some caution should be exercised in using these resummed results because of the possibility of overcounting; the showering Monte Carlos that are used for the fragmentation corrections also generate some of these leading-log corrections. Different schemes for combining the order α_s^2 and the resummations are available [85]. These different schemes result in shifts in α_s of order ± 0.002 [86].

An average of the recent results from SLD [86], OPAL [87], L3 [88], ALEPH [89], and DELPHI [90], using the combined α_s^2 and resummation fitting to a large set of shape variables, gives $\alpha_s(M_Z) = 0.122 \pm 0.007$. The errors in the values of $\alpha_s(M_Z)$ from these shape variables are totally dominated by the theoretical uncertainties associated with the choice of scale, and the effects of hadronization Monte Carlos on the different quantities fitted.

Similar studies on event shapes have been undertaken at TRISTAN, at PEP/PETRA, and at CLEO. A combined result from various shape parameters by the TOPAZ collaboration gives α_s (58 GeV) = 0.125 ± 0.009, using the fixed order QCD result, and α_s (58 GeV) = 0.132 ± 0.008 (corresponding to $\alpha_s(M_Z) = 0.123 \pm 0.007$), using the same method as in the SLD and LEP average [91].

The measurements of event shapes at PEP/PETRA are summarized in earlier editions of this note. The results are consistent with those from Z decay, but have larger errors. We use α_s (34 GeV) = 0.14 ± 0.02 [92]. A recent analysis by the TPC group [93] gives α_s (29 GeV) = 0.160 ± 0.012, using the same method as TOPAZ. This value corresponds to $\alpha_s(M_Z) = 0.131 \pm 0.010$

The CLEO collaboration fits to the order α_s^2 results for the two jet fraction at $\sqrt{s} = 10.53$ GeV, and obtains $\alpha_s(10.93)$ = 0.164 ± 0.004 (expt.) ± 0.014 (theory) [94]. The dominant systematic error arises from the choice of scale (μ), and is determined from the range of α_s that results from fit with $\mu = 10.53$ GeV, and a fit where μ is allowed to vary to get the lowest χ^2. The latter results in $\mu = 1.2$ GeV. Since the quoted result corresponds to $\alpha_s(1.2) = 0.35$, it is by no means clear that the perturbative QCD expression is reliable and the resulting error should, therefore, be treated with caution. A fit to many different variables as is done in the LEP/SLC analyses would give added confidence to the quoted error.

Since the errors in the event shape measurements are dominantly systematic, and are common to the experiments, the results from PEP/PETRA, TRISTAN, LEP, SLC, and CLEO are combined to give $\alpha_s(M_Z) = 0.122 \pm 0.007$. This result is used in forming the final average value of α_s.

The total cross section $e^+e^- \to b\bar{b} + X$ near threshold can be used to determine α_s [95]. The result quoted is $\alpha_s(M_Z) = 0.109 \pm 0.001$. The relevant process is only calculated to leading order and the BLM scheme [8] is used. This results in $\alpha_s(0.632\ m_b)$. If $\alpha_s(m_b)$ is used, the resulting $\alpha_s(M_Z)$ shifts to ~ 0.117. This result is not used in the average.

9.8. Scaling violations in fragmentation functions

Measurements of the fragmentation function $d_i(z, E)$, being the probability that a hadron of type i be produced with energy zE in e^+e^- collisions at $\sqrt{s} = 2E$, can be used to determine α_s. As in the case of scaling violations in structure functions, QCD predicts only the E dependence. Hence, measurements at different energies are needed to extract a value of α_s. Because the QCD evolution mixes the fragmentation functions for each quark flavor with the gluon fragmentation function, it is necessary to determine each of these before α_s can be extracted. The ALEPH collaboration has used data from energies ranging from $\sqrt{s} = 22$ GeV to $\sqrt{s} = 91$ GeV. A flavor tag is used to discriminate between different quark species, and the longitudinal and transverse cross sections are used to extract the gluon fragmentation function [96]. The result obtained is $\alpha_s(M_Z) = 0.126 \pm 0.007$ (expt.) ± 0.006 (theory) [97]. The theory error is due mainly to the choice of scale. The OPAL collaboration [98] has also extracted the separate fragmentation functions. DELPHI [99] has also performed a similar analysis using data from other experiments at lower energy with the result $\alpha_s(M_Z) = 0.122 \pm 0.012 \pm 0.006$ (theory). An earlier analysis by this collaboration [100], is consistent with this result, but used fixed order QCD. The older result is not used in the average, which is determined to be $\alpha_s(M_Z) = 0.125 \pm 0.006 \pm 0.006$ (theory)

9.9. Jet rates in *ep* collisions

At lowest order in α_s, the *ep* scattering process produces a final state of (1+1) jets, one from the proton fragment and the other from the quark knocked out by the process $e + quark \to e + quark$. At next order in α_s, a gluon can be radiated, and hence a (2+1) jet final state produced. By comparing the rates for these (1+1) and (1+2) jet processes, a value of α_s can be obtained. A NLO QCD calculation is available [101]. The basic methodology is similar to that used in the jet counting experiments in e^+e^- annihilation discussed above. Unlike those measurements, the ones in *ep* scattering are not at a fixed value of Q^2. In addition to the systematic errors associated with the jet definitions, there are additional ones since the structure functions enter into the rate calculations. Results from H1 [102] and ZEUS [103] can be combined to give $\alpha_s(M_Z) = 0.121 \pm 0.004$ (stat.) ± 0.008 (syst.). The contributions to the systematic errors from experimental effects (mainly the hadronic energy scale) are comparable to the theoretical ones arising from scale choice, structure functions, and jet definitions. These errors are common to the two measurements; therefore, we have not reduced the systematic error after forming the average.

9.10. Lattice QCD

Lattice gauge theory calculations can be used to calculate the energy levels of a $Q\overline{Q}$ system and then extract α_s. The masses of the $Q\overline{Q}$ states depend only on the quark mass and on α_s. A limitation is that calculations cannot be performed for three light quark flavors. Results are available for zero (quenched approximation) and two light flavors, which allow extrapolation to three. The coupling constant so extracted is in a lattice renormalization scheme, and must be converted to the $\overline{\text{MS}}$ scheme for comparison with other results. Using the mass differences of Υ and Υ' and Υ and χ_b, Davies *et al.* [104] extract a value of $\alpha_s(M_Z) = 0.115 \pm 0.002$. The result is consistent with an earlier result by the same group based on quenched approximation ($\alpha_s(M_Z) = 0.112 \pm 0.004$) [105]. The error is dominated by the conversion between the coupling constants, which is performed at next-to-leading order in perturbation theory. It is estimated by making an assumption about the size of the NNLO term in this conversion. If it is estimated as one-half of the NLO term, then the resulting value is $\alpha_s(M_Z) = 0.115 \pm 0.003$.

A similar result with larger errors is reported by [106], where results are consistent with $\alpha_s(M_Z) = 0.111 \pm 0.006$. This result confirms that obtained in quenched approximation by [107]. A calculation [108] using the strength of the force between two heavy quarks computed in the quenched approximation obtains a value of $\alpha_s(5$ GeV$)$ that is consistent with these results.

The result with a more conservative error $\alpha_s(M_Z) = 0.115 \pm 0.003$ will be used in the average, although a recent reviewer quotes an error of ± 0.007 [109].

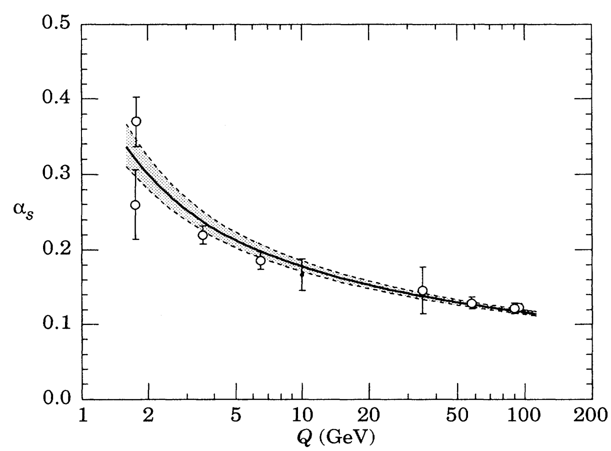

Figure 9.2: Summary of the values of $\alpha_s(Q)$ at the values of Q where they are measured. The lines show the central values and the $\pm 1\sigma$ limits of our average. The figure clearly shows the decrease in $\alpha_s(Q)$ with increasing Q.

9.11. Conclusions

The need for brevity has meant that many other important topics in QCD phenomenology have had to be omitted from this review. One should mention in particular the study of exclusive processes (form factors, elastic scattering, ...), the behavior of quarks and gluons in nuclei, the spin properties of the theory, the interface of soft and hard QCD as manifest, for example, by minijet production and hard diffractive processes, and QCD effects in hadron spectroscopy.

In this short review, we have focused on those high-energy processes which currently offer the most quantitative tests of perturbative QCD. Figure 9.1 shows the values of $\alpha_s(M_Z)$ deduced from the various experiments. Figure 9.2 shows the values and the values of Q where they are measured. This figure clearly shows the experimental evidence for the variation of $\alpha_s(Q)$ with Q.

An average of the values in Fig. 9.1 (except the one from the width of the Z) gives $\alpha_s(M_z) = 0.118$, with a total χ^2 of 9.1 for ten fitted points, showing good consistency among the data. The error on the average, assuming that all of the errors in the contributing results are uncorrelated, is ± 0.0017, and is surely an underestimate. All the values are dominated by systematic, usually theoretical, errors. The two results with the smallest errors (± 0.003) are the ones from τ decay and lattice gauge theory. If these errors are increased to ± 0.006, the average is unchanged. There has been discussion of systematic differences in the data. The measurements which are dominated by low-energy (deep-inelastic scattering (not including HERA), τ decay, Υ width, lattice) average to $\alpha_s(M_z) = 0.118$ ($\chi^2 = 8.3$ for 5 points). Results from space-like momentum transfers (all ep results) average to $\alpha_s(M_z) = 0.114 \pm 0.004$, which might indicate some lack of theoretical understanding in comparing the data. Since, in most cases, the dominant error is systematic (mainly theoretical), a more conservative estimate of the final error is obtained by using the smallest of the individual errors on the experimental results, *i.e.*, ± 0.003. Our average value is then $\alpha_s(M_z) = 0.118 \pm 0.003$, which corresponds to $\Lambda^{(5)} = 209^{+39}_{-33}$ MeV.

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10. STANDARD MODEL OF ELECTROWEAK INTERACTIONS

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The standard electroweak model is based on the gauge group [1] SU(2) × U(1), with gauge bosons W_μ^i, $i = 1, 2, 3$, and B_μ for the SU(2) and U(1) factors, respectively, and the corresponding gauge coupling constants g and g'. The left-handed fermion fields $\psi_i = \begin{pmatrix} \nu_i \\ \ell_i^- \end{pmatrix}$ and $\begin{pmatrix} u_i \\ d_i' \end{pmatrix}$ of the i^{th} fermion family transform as doublets under SU(2), where $d_i' \equiv \sum_j V_{ij}\, d_j$, and V is the Cabibbo-Kobayashi-Maskawa mixing matrix. (Constraints on V are discussed in the section on the Cabibbo-Kobayashi-Maskawa mixing matrix.) The right-handed fields are SU(2) singlets. In the minimal model there are three fermion families and a single complex Higgs doublet $\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$.

After spontaneous symmetry breaking the Lagrangian is

$$\begin{aligned}\mathscr{L}_F = &\sum_i \overline{\psi}_i \left(i \not\partial - m_i - \frac{g m_i H}{2M_W} \right) \psi_i \\ &- \frac{g}{2\sqrt{2}} \sum_i \overline{\psi}_i\, \gamma^\mu\, (1-\gamma^5)(T^+\, W_\mu^+ + T^-\, W_\mu^-)\, \psi_i \\ &- e \sum_i q_i\, \overline{\psi}_i\, \gamma^\mu\, \psi_i\, A_\mu \\ &- \frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i\, \gamma^\mu (g_V^i - g_A^i \gamma^5)\, \psi_i\, Z_\mu\ . \end{aligned} \tag{10.1}$$

$\theta_W \equiv \tan^{-1}(g'/g)$ is the weak angle; $e = g\sin\theta_W$ is the positron electric charge; and $A \equiv B\cos\theta_W + W^3 \sin\theta_W$ is the (massless) photon field. $W^\pm \equiv (W^1 \mp iW^2)/\sqrt{2}$ and $Z \equiv -B\sin\theta_W + W^3\cos\theta_W$ are the massive charged and neutral weak boson fields, respectively. T^+ and T^- are the weak isospin raising and lowering operators. The vector and axial couplings are

$$g_V^i \equiv t_{3L}(i) - 2q_i \sin^2\theta_W \tag{10.2}$$

$$g_A^i \equiv t_{3L}(i)\ , \tag{10.3}$$

where $t_{3L}(i)$ is the weak isospin of fermion i ($+1/2$ for u_i and ν_i; $-1/2$ for d_i and e_i) and q_i is the charge of ψ_i in units of e.

The second term in $\mathscr{L}_F$ represents the charged-current weak interaction [2]. For example, the coupling of a W to an electron and a neutrino is

$$-\frac{e}{2\sqrt{2}\sin\theta_W}\left[W_\mu^-\, \overline{e}\, \gamma^\mu(1-\gamma^5)\nu + W_\mu^+\, \overline{\nu}\, \gamma^\mu\, (1-\gamma^5)e\right]\ . \tag{10.4}$$

For momenta small compared to M_W, this term gives rise to the effective four-fermion interaction with the Fermi constant given (at tree level, *i.e.*, lowest order in perturbation theory) by $G_F/\sqrt{2} = g^2/8M_W^2$. *CP* violation is incorporated in the Standard Model by a single observable phase in V_{ij}. The third term in $\mathscr{L}_F$ describes electromagnetic interactions (QED), and the last is the weak neutral-current interaction.

In Eq. (10.1), m_i is the mass of the i^{th} fermion ψ_i. For the quarks these are the current masses. For the light quarks, as described in the Particle Listings, $m_u \approx 2$–8 MeV, $m_d \approx 5$–15 MeV, and $m_s \approx 100$–300 MeV (these are running masses evaluated at 1 GeV). For the heavier quarks, the "pole" masses are $m_c \approx 1.2$–1.9 GeV and $m_b \approx 4.5$–4.9 GeV. The average of the recent CDF [4] and DØ [5] values for m_t is 180 ± 12 GeV. See "The Note on Quark Masses" in the Particle Listings for more information.

H is the physical neutral Higgs scalar which is the only remaining part of ϕ after spontaneous symmetry breaking. The Yukawa coupling of H to ψ_i, which is flavor diagonal in the minimal model, is $gm_i/2M_W$. The H mass is not predicted by the model. Experimental limits are given in the Higgs section. In nonminimal models there are additional charged and neutral scalar Higgs particles [6].

10.1. Renormalization and radiative corrections

The Standard Model has three parameters (not counting M_H and the fermion masses and mixings). A particularly useful set is:

(*a*) The fine structure constant $\alpha = 1/137.036$, determined from the quantum Hall effect. In most electroweak-renormalization schemes, it is convenient to define a running α dependent on the energy scale of the process, with $\alpha^{-1} \sim 137$ appropriate at low energy. At energies of order M_Z, $\alpha^{-1} \sim 128$. For example, in the modified minimal subtraction ($\overline{\text{MS}}$) scheme, one has $\widehat{\alpha}(M_Z)^{-1} = 127.90 \pm 0.09$ [7], while the conventional (on-shell) QED renormalization yields [8] $\alpha(M_Z)^{-1} = 128.90 \pm 0.09$, which differs by finite constants from $\widehat{\alpha}(M_Z)^{-1}$. The uncertainty, due to the low-energy hadronic contribution to vacuum polarization, is the dominant theoretical uncertainty in the interpretation of precision data. The values include recent reevaluations [8–12] of this effect, which, following a correction to [11], are now in reasonable agreement. Further improvement will require improved measurements of the cross section for $e^+e^- \to$ hadrons at low energy.

(*b*) The Fermi constant, $G_F = 1.16639(2) \times 10^{-5}$ GeV^{-2}, determined from the muon lifetime formula [13]:

$$\begin{aligned}\tau_\mu^{-1} = &\frac{G_F^2 m_\mu^5}{192\pi^3}\, F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right) \\ &\times \left[1 + \frac{\alpha(m_\mu)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right]\ ,\end{aligned} \tag{10.5a}$$

where

$$F(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \tag{10.5b}$$

and

$$\alpha(m_\mu)^{-1} = \alpha^{-1} - \frac{2}{3\pi}\ln\left(\frac{m_\mu}{m_e}\right) + \frac{1}{6\pi} \approx 136\ . \tag{10.5c}$$

The uncertainty in G_F from the input quantities is 1.1×10^{-10} GeV^{-2}. The quoted uncertainty of 2×10^{-10} is dominated by second order radiative corrections, estimated from the magnitude of the known $\alpha^2 \ln(m_\mu/m_e)$ term to be $\sim 1.8 \times 10^{-10}$ (alternately, one can view Eq. (10.5) as the exact definition of G_F; then the theoretical uncertainty appears instead in the formulae for quantities derived from G_F).

(*c*) $\sin^2\theta_W$, determined from the Z mass and other Z-pole observables, the W mass, and neutral-current processes [14]. The value of $\sin^2\theta_W$ depends on the renormalization prescription. There are a number of popular schemes [16–21] leading to $\sin^2\theta_W$ values which differ by small factors which depend on m_t and M_H. The notation for these schemes is shown in Table 10.1. Discussion of the schemes follows the table.

Table 10.1: Notations used to indicate the various schemes discussed in the text. Each definition of $\sin\theta_W$ leads to values that differ by small factors depending on m_t and M_H.

Scheme	Notation
On-shell	$s_W = \sin\theta_W$
NOV	$s_{M_Z} = \sin\theta_W$
$\overline{\text{MS}}$	$\widehat{s}_Z = \sin\theta_W$
$\overline{\text{MS}}$ *ND*	$\widehat{s}_{ND} = \sin\theta_W$
Effective angle	$\overline{s}_f = \sin\theta_W$

(*i*) The on-shell scheme promotes the tree-level formula $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ to a definition of the renormalized $\sin^2\theta_W$ to all orders in perturbation theory, *i.e.*, $\sin^2\theta_W \to s_W^2 \equiv 1 - M_W^2/M_Z^2$. This scheme is simple conceptually. However, M_W is known much less precisely than M_Z and in practice one extracts s_W^2 from M_Z alone using

$$M_W = \frac{A_0}{s_W(1-\Delta r)^{1/2}} \tag{10.6a}$$

$$M_Z = \frac{M_W}{c_W}\ , \tag{10.6b}$$

where $s_W \equiv \sin\theta_W$, $c_W \equiv \cos\theta_W$, $A_0 = (\pi\alpha/\sqrt{2}G_F)^{1/2} = 37.2802$ GeV, and Δr includes the radiative corrections relating α, $\alpha(M_Z)$, G_F, M_W, and M_Z. One finds $\Delta r \sim \Delta r_0 - \rho_t/\tan^2\theta_W$, where $\Delta r_0 \approx 1 - \alpha/\alpha(M_Z) \approx 0.06$ is due to the running of α and $\rho_t = 3G_F\, m_t^2/8\sqrt{2}\pi^2 \approx 0.0100\ (m_t/180\ \text{GeV})^2$ represents the dominant (quadratic) m_t dependence. There are additional contributions to Δr from bosonic loops, including those which depend logarithmically on the Higgs mass M_H. One has $\Delta r = 0.0376 \pm 0.0025 \pm 0.0007$ for $(m_t, M_H) = (180 \pm 7, 300)$, where the second uncertainty is from $\alpha(M_Z)$. Thus the value of s_W^2 extracted from M_Z includes a large uncertainty (~ 0.0008) from the currently allowed range of m_t.

(*ii*) A more precisely determined quantity $s_{M_Z}^2$ can be obtained from M_Z by removing the (m_t, M_H) dependent term from Δr [17], *i.e.*,

$$s_{M_Z}^2 c_{M_Z}^2 \equiv \frac{\pi\alpha(M_Z)}{\sqrt{2}\,G_F\,M_Z^2}\ . \tag{10.7}$$

This yields $s_{M_Z}^2 = 0.2311 \pm 0.0002$, with most of the uncertainty from α rather than M_Z. Scheme (*ii*) is equivalent to using M_Z rather than $\sin^2\theta_W$ as the third fundamental parameter. However, it recognizes that $s_{M_Z}^2$ is still a useful derived quantity. The small uncertainty in $s_{M_Z}^2$ compared to other schemes is because the m_t dependence has been removed by definition. However, the m_t uncertainty reemerges when other quantities (*e.g.*, M_W or other Z-pole observables) are predicted in terms of M_Z.

Both s_W^2 and $s_{M_Z}^2$ depend not only on the gauge couplings but also on the spontaneous-symmetry breaking, and both definitions are awkward in the presence of any extension of the Standard Model which perturbs the value of M_Z (or M_W). Other definitions are motivated by the tree-level coupling constant definition $\theta_W = \tan^{-1}(g'/g)$.

(*iii*) In particular, the modified minimal subtraction ($\overline{\text{MS}}$) scheme introduces the quantity $\sin^2\widehat{\theta}_W(\mu) \equiv \widehat{g}'^2(\mu)/[\widehat{g}^2(\mu) + \widehat{g}'^2(\mu)]$, where the couplings $\widehat{g}$ and $\widehat{g}'$ are defined by modified minimal subtraction and the scale μ is conveniently chosen to be M_Z for electroweak processes. The value of $\widehat{s}_Z^2 = \sin^2\widehat{\theta}_W(M_Z)$ extracted from M_Z is less sensitive than s_W^2 to m_t (by a factor of $\tan^2\theta_W$), and is less sensitive to most types of new physics than s_W^2 or $s_{M_Z}^2$. It is also very useful for comparing with the predictions of grand unification. There are actually several variant definitions of $\sin^2\widehat{\theta}_W(M_Z)$, differing according to whether or how finite $\alpha\ln(m_t/M_Z)$ terms are decoupled (subtracted from the couplings). One cannot entirely decouple the $\alpha\ln(m_t/M_Z)$ terms from all electroweak quantities because $m_t \gg m_b$ breaks SU(2) symmetry. The scheme that will be adopted here decouples the $\alpha\ln(m_t/M_Z)$ terms from the $\gamma - Z$ mixing [7,18], essentially eliminating any $\ln(m_t/M_Z)$ dependence in the formulae for asymmetries at the Z pole when written in terms of $\widehat{s}_Z^2$. The various definitions are related by

$$\widehat{s}_Z^2 = c\,(m_t, M_H) s_W^2 = \overline{c}\,(m_t, M_H)\, s_{M_Z}^2\ , \tag{10.8}$$

where $c = 1.035 \pm 0.003$ for $m_t = 180 \pm 7$ GeV and $M_H = 300$ GeV. Similarly $\overline{c} = 1.002 \pm 0.001$. The quadratic m_t dependence is given by $c \sim 1 + \rho_t/\tan^2\theta_W$. The expressions for M_W and M_Z in the $\overline{\text{MS}}$ scheme are

$$M_W = \frac{A_0}{\widehat{s}_Z(1-\Delta\widehat{r}_W)^{1/2}} \tag{10.9a}$$

$$M_Z = \frac{M_W}{\widehat{\rho}^{1/2}\widehat{c}_Z}\ . \tag{10.9b}$$

One predicts $\Delta\widehat{r}_W = 0.0705 \pm 0.0001 \pm 0.0007$ for $m_t = 180 \pm 7$ GeV and $M_H = 300$ GeV. $\Delta\widehat{r}_W$ has no quadratic m_t dependence, because shifts in M_W are absorbed into the observed G_F, so that $\Delta\widehat{r}_W$ is dominated by $\Delta r_0 = 1 - \alpha/\alpha(M_Z)$. Similarly, $\widehat{\rho} \sim 1 + \rho_t$. Including bosonic loops, $\widehat{\rho} = 0.0103 \pm 0.0008$ for $m_t = 180 \pm 7$ GeV.

(*iv*) A variant $\overline{\text{MS}}$ quantity $\widehat{s}_{\text{ND}}^2$ (used in the 1992 edition of this *Review*) does not decouple the $\alpha\ln(m_t/M_Z)$ terms [19]. It is related to $\widehat{s}_Z^2$ by

$$\widehat{s}_Z^2 = \widehat{s}_{\text{ND}}^2 \Big/ \left(1 + \frac{\widehat{\alpha}}{\pi} d\right) \tag{10.10a}$$

$$d = \frac{1}{3}\left(\frac{1}{\widehat{s}^2} - \frac{8}{3}\right)\left[(1 + \frac{\widehat{\alpha}_s}{\pi})\ln\frac{m_t}{M_Z} - \frac{15\widehat{\alpha}_s}{\pi}\right]\ , \tag{10.10b}$$

where $\widehat{\alpha}_s$ is the QCD coupling at M_Z. Thus, $\widehat{s}_Z^2 - \widehat{s}_{\text{ND}}^2 \sim -0.0002$ for $(m_t, M_H) = (180, 300)$ GeV.

(*v*) Yet another definition, the effective angle [20,21] $\overline{s}_f^2$ for Z coupling to fermion f, is described below.

Experiments are now at such a level of precision that complete $\mathcal{O}(\alpha)$ radiative corrections must be applied. For neutral-current and Z-pole processes, these corrections are conveniently divided into two classes:

1. QED diagrams involving the emission of real photons or the exchange of virtual photons in loops, but not including vacuum polarization diagrams. These graphs yield finite and gauge-invariant contributions to observable processes. However, they are dependent on energies, experimental cuts, *etc.*, and must be calculated individually for each experiment.
2. Electroweak corrections, including $\gamma\gamma$, γZ, ZZ, and WW vacuum polarization diagrams, as well as vertex corrections, box graphs, *etc.*, involving virtual W's and Z's. Many of these corrections are absorbed into the renormalized Fermi constant defined in Eq. (10.5). Others modify the tree-level expressions for Z-pole observables and neutral-current amplitudes in several ways [14]. One-loop corrections are included for all processes. In addition, certain two-loop corrections are also important. In particular, two-loop corrections involving the top-quark [22] modify ρ_t in $\widehat{\rho}$, Δr, and elsewhere by

$$\rho_t \to \rho_t[1 + R(M_H/m_t)\rho_t/3]\ , \tag{10.11}$$

where $-3.8 > R > -11.8$ is strongly dependent on M_H/m_t: $R = -3.8$ for M_H at its lower direct limit and $R = -7.8$ for $M_H = 1.7m_t \approx 300$ GeV. -11.8 is in absolute lower bound for R which is assumed for large M_H. Mixed QCD-electroweak loops of order $\alpha\alpha_s m_t^2$ [23] and $\alpha\alpha_s^2 m_t^2$ [24] multiply ρ_t by $1 - 2\alpha_s(0.3m_t)(\pi^2+3)/9\pi \sim 0.88$, where the three-loop result is included through the use of a lower scale for α_s. These mixed corrections increase the predicted value of m_t by 6%. Analogous electroweak and mixed two-loop terms are also known for the $Z \to b\overline{b}$ vertex [22,25].

10.2. Cross section and asymmetry formulas

It is convenient to write the four-fermion interactions relevant to ν-hadron, νe, and parity-violating e-hadron neutral-current processes in a form that is valid in an arbitrary gauge theory (assuming massless left-handed neutrinos). One has

$$-\mathscr{L}^{\nu\text{Hadron}} = \frac{G_F}{\sqrt{2}}\,\overline{\nu}\,\gamma^\mu\,(1-\gamma^5)\nu \times \sum_i \left[\epsilon_L(i)\,\overline{q}_i\,\gamma_\mu(1-\gamma^5)q_i + \epsilon_R(i)\,\overline{q}_i\,\gamma_\mu(1+\gamma^5)q_i\right] , \quad (10.12)$$

$$-\mathscr{L}^{\nu e} = \frac{G_F}{\sqrt{2}}\,\overline{\nu}_\mu\,\gamma^\mu(1-\gamma^5)\nu_\mu\,\overline{e}\,\gamma_\mu(g_V^{\nu e} - g_A^{\nu e}\gamma^5)e \quad (10.13)$$

(for $\nu_e e$ or $\overline{\nu}_e e$, the charged-current contribution must be included), and

$$-\mathscr{L}^{e\text{Hadron}} = -\frac{G_F}{\sqrt{2}} \times \sum_i \left[C_{1i}\,\overline{e}\,\gamma_\mu\,\gamma^5\,e\,\overline{q}_i\,\gamma^\mu\,q_i + C_{2i}\,\overline{e}\,\gamma_\mu\,e\,\overline{q}_i\,\gamma^\mu\,\gamma^5\,q_i\right] \quad (10.14)$$

(One must add the parity-conserving QED contribution.)

The Standard Model expressions for $\epsilon_{L,R}(i)$, $g_{V,A}^{\nu e}$, and C_{ij} are given in Table 10.2. Note that $g_{V,A}^{\nu e}$ and the other quantities are coefficients of effective four-fermi operators, which differ from the quantities defined in Eq. (10.2) and Eq. (10.3) in the radiative corrections and in the presence of possible physics beyond the Standard Model.

A precise determination of the on-shell s_W^2, which depends only very weakly on m_t and M_H, is obtained from deep inelastic neutrino scattering from (approximately) isoscalar targets [26]. The ratio $R_\nu \equiv \sigma_{\nu N}^{NC}/\sigma_{\nu N}^{CC}$ of neutral- to charged-current cross sections has been measured to 1% accuracy by the CDHS [27] and CHARM [28] collaborations [29,30] at CERN, and the CCFR collaboration at Fermilab [31] has obtained an even more precise result, so it is important to obtain theoretical expressions for R_ν and $R_{\overline{\nu}} \equiv \sigma_{\overline{\nu}N}^{NC}/\sigma_{\overline{\nu}N}^{CC}$ (as functions of $\sin^2\theta_W$) to comparable accuracy. Fortunately, most of the uncertainties from the strong interactions and neutrino spectra cancel in the ratio.

A simple zeroth-order approximation is

$$R_\nu = g_L^2 + g_R^2 r \quad (10.15a)$$

$$R_{\overline{\nu}} = g_L^2 + \frac{g_R^2}{r} , \quad (10.15b)$$

where

$$g_L^2 \equiv \epsilon_L\,(u)^2 + \epsilon_L\,(d)^2 \approx \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \quad (10.16a)$$

$$g_R^2 \equiv \epsilon_R\,(u)^2 + \epsilon_R\,(d)^2 \approx \frac{5}{9}\sin^4\theta_W , \quad (10.16b)$$

and $r \equiv \sigma_{\overline{\nu}N}^{CC}/\sigma_{\nu N}^{CC}$ is the ratio of $\overline{\nu}$ and ν charged-current cross sections, which can be measured directly. [In the simple parton model, ignoring hadron energy cuts, $r \approx (\frac{1}{3}+\epsilon)/(1+\frac{1}{3}\epsilon)$, where $\epsilon \sim 0.125$ is the ratio of the fraction of the nucleon's momentum carried by antiquarks to that carried by quarks.] In practice, Eq. (10.15) must be corrected for quark mixing, the s and c seas, c-quark threshold effects, nonisoscalar target effects, W-Z propagator differences, and radiative corrections (which lower the extracted value of $\sin^2\theta_W$ by ~ 0.009). Details of the neutrino spectra, experimental cuts, x and Q^2 dependence of structure functions, and longitudinal structure functions enter only at the level of these corrections and therefore lead to very small uncertainties. The largest theoretical uncertainty is associated with the c threshold, which mainly affects σ^{CC}. Using the slow rescaling prescription [14] the central value of $\sin^2\theta_W$ varies as 0.013 $[m_c(\text{GeV})-1.3]$, where m_c is the effective mass. For $m_c = 1.31 \pm 0.24$ GeV (determined from ν-induced dimuon production [31]) this contributes ± 0.003 to the total theoretical uncertainty $\Delta\sin^2\theta_W \sim \pm 0.004$. This would require a high-energy neutrino beam for improvement. (The experimental uncertainty is ± 0.003). The CCFR group quotes $s_W^2 = 0.2218 \pm 0.0059$ for $(m_t, M_H) = (150, 100)$, but this result is insensitive to (m_t, M_H). Combining all of the precise deep-inelastic measurements, one obtains $s_W^2 = 0.2259 \pm 0.0043$ for (m_t, M_H) in the allowed range.

Table 10.2: Standard Model expressions for the neutral-current parameters for ν-hadron, νe, and e-hadron processes. If radiative corrections are ignored, $\rho = \kappa = 1$, $\lambda = 0$. At $\mathscr{O}(\alpha)$ in the on-shell scheme, $\rho_{\nu N}^{NC} = 1.0095$, $\kappa_{\nu N} = 1.0382$, $\lambda_{u_L} = -0.0032$, $\lambda_{d_L} = -0.0026$, and $\lambda_{u_R} = 1/2\,\lambda_{d_R} = 3.6\times 10^{-5}$ for $m_t = 180$ GeV, $M_H = 300$ GeV, $M_Z = 91.1884$ GeV, and $\langle Q^2\rangle = 20$ GeV^2. For νe scattering, $\kappa_{\nu e} = 1.0385$ and $\rho_{\nu e} = 1.0143$ (at $\langle Q^2\rangle = 0.$). For atomic parity violation, $\rho'_{eq} = 0.9884$ and $\kappa'_{eq} = 1.036$. For the SLAC polarized electron experiment, $\rho'_{eq} = 0.979$, $\kappa'_{eq} = 1.034$, $\rho_{eq} = 1.002$, and $\kappa_{eq} = 1.06$ after incorporating additional QED corrections, while $\lambda_{2u} = -0.013$, $\lambda_{2d} = 0.003$. The dominant m_t dependence is given by $\rho \sim 1 + \rho_t$, while $\kappa \sim 1 + \rho_t/\tan^2\theta_W$ (on-shell) or $\kappa \sim 1(\overline{\text{MS}})$.

Quantity	Standard Model Expression
$\epsilon_L(u)$	$\rho_{\nu N}^{NC}\left(\frac{1}{2} - \frac{2}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{uL}\right)$
$\epsilon_L(d)$	$\rho_{\nu N}^{NC}\left(-\frac{1}{2} + \frac{1}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{dL}\right)$
$\epsilon_R(u)$	$\rho_{\nu N}^{NC}\left(-\frac{2}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{uR}\right)$
$\epsilon_R(d)$	$\rho_{\nu N}^{NC}\left(\frac{1}{3}\kappa_{\nu N}\sin^2\theta_W + \lambda_{dR}\right)$
$g_V^{\nu e}$	$\rho_{\nu e}\left(-\frac{1}{2} + 2\kappa_{\nu e}\sin^2\theta_W\right)$
$g_A^{\nu e}$	$\rho_{\nu e}\left(-\frac{1}{2}\right)$
C_{1u}	$\rho'_{eq}\left(-\frac{1}{2} + \frac{4}{3}\kappa'_{eq}\sin^2\theta_W\right)$
C_{1d}	$\rho'_{eq}\left(\frac{1}{2} - \frac{2}{3}\kappa'_{eq}\sin^2\theta_W\right)$
C_{2u}	$\rho_{eq}\left(-\frac{1}{2} + 2\kappa_{eq}\sin^2\theta_W\right) + \lambda_{2u}$
C_{2d}	$\rho_{eq}\left(\frac{1}{2} - 2\kappa_{eq}\sin^2\theta_W\right) + \lambda_{2d}$

The laboratory cross section for $\nu_\mu e \to \nu_\mu e$ or $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ elastic scattering is

$$\frac{d\sigma_{\nu_\mu,\overline{\nu}_\mu}}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi} \times \left[(g_V^{\nu e} \pm g_A^{\nu e})^2 + (g_V^{\nu e} \mp g_A^{\nu e})^2(1-y)^2 - (g_V^{\nu e 2} - g_A^{\nu e 2})\frac{y\,m_e}{E_\nu}\right] , \quad (10.17)$$

where the upper (lower) sign refers to $\nu_\mu(\overline{\nu}_\mu)$, and $y \equiv E_e/E_\nu$ [which runs from 0 to $(1 + m_e/2E_\nu)^{-1}$] is the ratio of the kinetic energy of the recoil electron to the incident ν or $\overline{\nu}$ energy. For $E_\nu \gg m_e$ this yields a total cross section

$$\sigma = \frac{G_F^2\,m_e\,E_\nu}{2\pi}\left[(g_V^{\nu e} \pm g_A^{\nu e})^2 + \frac{1}{3}(g_V^{\nu e} \mp g_A^{\nu e})^2\right] . \quad (10.18)$$

The most accurate leptonic measurements [32–34] of $\sin^2\theta_W$ are from the ratio $R \equiv \sigma_{\nu_\mu e}/\sigma_{\overline{\nu}_\mu e}$ in which many of the systematic uncertainties cancel. Radiative corrections (other than m_t effects) are small compared to the precision of present experiments and have negligible effect on the extracted $\sin^2\theta_W$. The most precise (CHARM II) experiment [34] determined not only $\sin^2\theta_W$ but $g_{V,A}^{\nu e}$ as well. The cross sections for $\nu_e e$ and $\overline{\nu}_e e$ may be obtained from

Eq. (10.17) by replacing $g_{V,A}^{\nu e}$ by $g_{V,A}^{\nu e}+1$, where the 1 is due to the charged-current contribution.

The SLAC polarized-electron experiment [35] measured the parity-violating asymmetry

$$A=\frac{\sigma_R-\sigma_L}{\sigma_R+\sigma_L}\ , \tag{10.19}$$

where $\sigma_{R,L}$ is the cross section for the deep-inelastic scattering of a right- or left-handed electron: $e_{R,L}N\rightarrow e$X. In the quark parton model

$$\frac{A}{Q^2}=a_1+a_2\,\frac{1-(1-y)^2}{1+(1-y)^2}\ , \tag{10.20}$$

where $Q^2>0$ is the momentum transfer and y is the fractional energy transfer from the electron to the hadrons. For the deuteron or other isoscalar target, one has, neglecting the s quark and antiquarks,

$$a_1=\frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{1u}-\frac{1}{2}C_{1d}\right)\approx\frac{3G_F}{5\sqrt{2}\pi\alpha}\left(-\frac{3}{4}+\frac{5}{3}\sin^2\theta_W\right) \tag{10.21a}$$

$$a_2=\frac{3G_F}{5\sqrt{2}\pi\alpha}\left(C_{2u}-\frac{1}{2}C_{2d}\right)\approx\frac{9G_F}{5\sqrt{2}\pi\alpha}\left(\sin^2\theta_W-\frac{1}{4}\right)\ . \tag{10.21b}$$

Radiative corrections (other than m_t effects) lower the extracted value of $\sin^2\theta_W$ by $\sim$ 0.005.

There are now precise experiments measuring atomic parity violation [36] in cesium [37], bismuth [38], lead [39], and thallium [40]. The uncertainties associated with atomic wave functions are quite small for cesium, for which the theoretical uncertainty is $\sim 1\%$ [41] but somewhat larger for the other atoms. For heavy atoms one determines the "weak charge"

$$\begin{aligned}Q_W&=-2\left[C_{1u}\,(2Z+N)+C_{1d}(Z+2N)\right]\\&\approx Z(1-4\sin^2\theta_W)-N\ .\end{aligned} \tag{10.22}$$

Radiative corrections increase the extracted $\sin^2\theta_W$ by ~ 0.008.

In the future it should be possible to reduce the theoretical wave function uncertainties by taking the ratios of parity violation in different isotopes [36,42]. There would still be some residual uncertainties from differences in the neutron charge radii, however [43].

The forward-backward asymmetry for $e^+e^-\rightarrow\ell\overline{\ell}$, $\ell=\mu$ or τ, is defined as

$$A_{FB}\equiv\frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B}\ , \tag{10.23}$$

where $\sigma_F(\sigma_B)$ is the cross section for ℓ^- to travel forward (backward) with respect to the e^- direction. A_{FB} and R, the total cross section relative to pure QED, are given by

$$R=F_1 \tag{10.24}$$

$$A_{FB}=3F_2/4F_1\ , \tag{10.25}$$

where

$$F_1=1-2\chi_0\,g_V^e\,g_V^\ell\,\cos\delta_R+\chi_0^2\left(g_V^{e2}+g_A^{e2}\right)\left(g_V^{\ell2}+g_A^{\ell2}\right) \tag{10.26a}$$

$$F_2=-2\chi_0\,g_A^e\,g_A^\ell\,\cos\delta_R+4\chi_0^2\,g_A^e\,g_A^\ell\,g_V^e\,g_V^\ell\ , \tag{10.26b}$$

where

$$\tan\delta_R=\frac{M_Z\Gamma_Z}{M_Z^2-s} \tag{10.27}$$

$$\chi_0=\frac{G_F}{2\sqrt{2}\pi\alpha}\,\frac{sM_Z^2}{\left[(M_Z^2-s)^2+M_Z^2\Gamma_Z^2\right]^{1/2}} \tag{10.28}$$

and $\sqrt{s}$ is the CM energy. Eq. (10.26) is valid at tree level. If the data are radiatively corrected for QED effects (as described above), then the remaining electroweak corrections can be incorporated [44] (in an approximation adequate for existing PEP, PETRA, and TRISTAN data, which are well below the Z pole) by replacing χ_0 by $\chi(s)\equiv(1+\rho_t)\chi_0(s)\alpha/\alpha(s)$, where $\alpha(s)$ is the running QED coupling, and evaluating g_V in the $\overline{\rm MS}$ scheme. Formulas for $e^+e^-\rightarrow$ *hadrons* may be found in Ref. 45.

At LEP and SLC, there are high-precision measurements of various Z-pole observables [46–49]. These include the Z mass and total width Γ_Z, and partial widths $\Gamma(f\overline{f})$ for $Z\rightarrow f\overline{f}$ for fermion f ($f=e$, μ, τ, hadrons, b, c, and ν). The data is consistent with lepton-family universality $\Gamma(e^+e^-)=\Gamma(\mu^+\mu^-)=\Gamma(\tau^+\tau^-)$, so one may work with an average width $\Gamma(\ell\overline{\ell})$. It is convenient to use the variables M_Z, Γ_Z, $R\equiv\Gamma(\text{had})/\Gamma(\ell\overline{\ell})$, $\sigma_{\text{had}}\equiv12\pi\Gamma(e^+e^-)\Gamma(\text{had})/M_Z^2\Gamma_Z^2$, $R_b\equiv\Gamma(b\overline{b})/\Gamma(\text{had})$, and $R_c\equiv\Gamma(c\overline{c})/\Gamma(\text{had})$, most of which are weakly correlated experimentally. (Γ(had) is the partial width into hadrons.) The largest correlation coefficient of -0.35 occurs between R_b and R_c. R is insensitive to m_t except for $Z\rightarrow b\overline{b}$ vertex and final state corrections and the implicit dependence through $\sin^2\theta_W$. Thus it is especially useful for constraining α_s. The width for invisible decays, $\Gamma(\text{inv})=\Gamma_Z-3\Gamma(\ell\overline{\ell})-\Gamma(\text{had})=499.9\pm2.5$ MeV, can be used to determine the number of neutrino flavors lighter than $M_Z/2$, $N_\nu=\Gamma_{\text{inv}}/\Gamma(\nu\overline{\nu})=2.991\pm0.016$.

There are also measurements of various asymmetries. These include the polarization or left-right asymmetry

$$A_{LR}\equiv\frac{\sigma_L-\sigma_R}{\sigma_L+\sigma_R}\ , \tag{10.29}$$

where $\sigma_L(\sigma_R)$ is the cross section for a left- (right)-handed incident electron. A_{LR} has been measured precisely by the SLD collaboration at SLC [48] and has the advantages of being extremely sensitive to $\sin^2\theta_W$ and insensitive to QED radiative corrections. Other asymmetries are the forward-backward asymmetries $A_{FB}^{(0,f)}$ for $f=e$, μ, τ, b, c ($A_{FB}^{(0,e)}$, $A_{FB}^{(0,\mu)}$, $A_{FB}^{(0,\tau)}$ are consistent with lepton-family universality, allowing an average value $A_{FB}^{(0,\ell)}$), the hadronic-charge asymmetry, the τ polarization P_τ, and its angular distribution. Further details, including references to the data from the LEP experiments (ALEPH, DELPHI, L3, OPAL) may be found in the Particle Listings in the 'Note on the Z Boson' and in [46–49]. At tree level and neglecting QED effects and terms of order $(\Gamma_Z/M_Z)^2$, one has

$$A_{FB}^{(0,f)}\approx\frac{3}{4}A_f\,\frac{A_e+P_e}{1+P_eA_e} \tag{10.30}$$

$$A_{LR}\approx A_eP_e\ , \tag{10.31}$$

where P_e is the initial e^- polarization and

$$A_f\equiv\frac{2g_V^f\,g_A^f}{g_V^{f2}+g_A^{f2}}\ . \tag{10.32}$$

Similarly, A_τ is given by the negative total τ polarization, and A_e can be extracted from the angular distribution of the polarization. In addition, the SLD collaboration [49] has extracted the final-state couplings A_b and A_c from the left-right forward-backward asymmetry, using

$$\frac{\sigma_{LF}-\sigma_{LB}-\sigma_{RF}+\sigma_{RB}}{\sigma_{LF}+\sigma_{LB}+\sigma_{RF}+\sigma_{RB}}=A_f\ , \tag{10.33}$$

where, for example, σ_{LF} is the cross section for a left-handed incident electron to produce a fermion f traveling in the forward hemisphere.

It has become customary for the experimental groups to present corrected asymmetries A^0, in which photon exchange and γ-Z interference, QED corrections, and corrections for $\sqrt{s}\neq M_Z$ are removed from the data, leaving the pure electroweak asymmetries. Ignoring negligible electroweak boxes, these corrected asymmetries are expressed using effective tree-level expression *e.g.*, $A_{FB}^{(0,f)}=\frac{3}{4}\overline{A}_f\overline{A}_e$ (for $P_e=0$) and $A_{LR}^0=\overline{A}_e$, where

$$\overline{A}_f=\frac{2\overline{g}_V^f\,\overline{g}_A^f}{\overline{g}_V^{f2}+\overline{g}_A^{f2}}\ , \tag{10.34a}$$

and

$$\bar{g}_V^f = \sqrt{\rho_f}\,(t_{3L}^{(f)} - 2q_f\kappa_f \sin^2\theta_W) \tag{10.34b}$$

$$\bar{g}_A^f = \sqrt{\rho_f}\, t_{3L}^{(f)} \ . \tag{10.34c}$$

The electroweak-radiative corrections have been absorbed into corrections $\rho_f - 1$ and $\kappa_f - 1$, which depend on the fermion f and on the renormalization scheme. In the on-shell scheme, the quadratic m_t dependence is given by $\rho_f \sim 1 + \rho_t$, $\kappa_f \sim \kappa_f^{os} \sim 1 + \rho_t/\tan^2\theta_W$, while in $\overline{\rm MS}$, $\rho_f \sim \widehat{\rho}$, $\kappa_f \equiv \widehat{\kappa}_f \sim 1$. In practice, additional bosonic loops, vertex corrections, *etc.*, must be included. For example, in the $\overline{\rm MS}$ scheme one has, for $(m_t, M_H) = (180, 300)$, $\rho_\ell = 1.0053$ and $\widehat{\kappa}_\ell = 1.0012$. It is convenient to define an effective angle $\bar{s}_f^2 \equiv \sin^2\bar{\theta}_{Wf} \equiv \widehat{\kappa}_f \widehat{s}_Z^{\,2} = \kappa_f^{os} s_W^2$, in terms of which $\bar{g}_V^f$ and $\bar{g}_A^f$ are given by $\sqrt{\rho_f}$ times their tree-level formulae. Because $\bar{g}_V^\ell$ is very small, not only A_{LR}^0 $A_{FB}^{(0,\ell)}$, and P_τ^0, but also $A_{FB}^{(0,b)}$, $A_{FB}^{(0,c)}$, and the hadronic-charge asymmetry are mainly sensitive to $\bar{s}_\ell^2$. One finds that $\widehat{\kappa}_f$ is almost independent of (m_t, M_H), so that

$$\bar{s}_\ell^2 \sim \widehat{s}_Z^{\,2} + 0.00028 \tag{10.35}$$

using Ref. 20, or $\bar{s}_\ell^2 \sim \widehat{s}_Z^{\,2} + 0.0002$ from Ref. 21 (the small difference is an indication of theoretical uncertainties from higher-order terms, *etc.*). In any case, the asymmetries determine values of $\bar{s}_\ell^2$ and $\widehat{s}_Z^{\,2}$ almost independent of m_t, while the κ's for the other schemes are m_t dependent.

10.3. *W* and *Z* decays

The partial decay width for gauge bosons to decay into massless fermions $f_1\bar{f}_2$ is

$$\Gamma(W^+ \to e^+\nu_e) = \frac{G_F M_W^3}{6\sqrt{2}\pi} \approx 226 \pm 1 \text{ MeV} \tag{10.36a}$$

$$\Gamma(W^+ \to u_i\bar{d}_j) = \frac{C G_F M_W^3}{6\sqrt{2}\pi}\, |V_{ij}|^2 \approx (705 \pm 4)\, |V_{ij}|^2 \text{ MeV} \tag{10.36b}$$

$$\Gamma(Z \to \psi_i\bar{\psi}_i) = \frac{C G_F M_Z^3}{6\sqrt{2}\pi}\left[g_V^{i2} + g_A^{i2}\right] \tag{10.36c}$$

$$\approx \begin{cases} 167.2 \pm 0.1 \text{ MeV } (\nu\bar{\nu}), & 84.0 \pm 0.1 \text{ MeV } (e^+e^-), \\ 300.6 \pm 0.3 \text{ MeV } (u\bar{u}), & 383.3 \pm 0.3 \text{ MeV } (d\bar{d}), \\ 375.9 \mp 0.2 \text{ MeV } (b\bar{b}). & \end{cases}$$

For leptons $C = 1$, while for quarks $C = 3\Big(1 + \alpha_s(M_V)/\pi + 1.409\alpha_s^2/\pi^2 - 12.77\alpha_s^3/\pi^3\Big)$, where the 3 is due to color and the factor in parentheses represents the universal QCD corrections for massless quarks [50]. The $Z \to f\bar{f}$ widths contain a number of additional corrections [51]: universal (non-singlet) top-mass contributions [52]; fermion mass effects and further QCD corrections proportional to m_q^2 [53] (m_q is the running quark mass evaluated at the Z scale) which are different for vector and axial-vector partial widths; and singlet contributions starting from two loop order which are large, strongly top-mass dependent, family universal and flavor non-universal [54]. All QCD effects are known and included up to three loop order with the exception of order $\alpha_s^3 m_b^2$ corrections which are very small. The QED factor $1 + 3\alpha q_f^2/4\pi$ and order $\alpha\alpha_s$ corrections [55] have to be included, as well. Expressing the widths in terms of $G_F M_{W,Z}^3$ incorporates the bulk of the low-energy radiative corrections [16,56]. The electroweak corrections are incorporated by replacing $g_{V,A}^{i2}$ by $\bar{g}_{V,A}^{i2}$. Hence, the widths are proportional to $\rho_i \sim 1 + \rho_t$. There is additional (negative) quadratic m_t dependence in the $Z \to b\bar{b}$ vertex corrections [57] which causes $\Gamma(b\bar{b})$ to decrease with m_t. The dominant effect is to multiply $\Gamma(b\bar{b})$ by the vertex correction $1 + \delta\rho_{b\bar{b}}$, where $\delta\rho_{b\bar{b}} \sim 10^{-2}(-\frac{1}{2}\frac{m_t^2}{M_Z^2} + \frac{1}{5})$. In practice, the corrections are included in ρ_b and κ_b.

For 3 fermion families the total widths are predicted to be

$$\Gamma_Z \approx 2.497 \pm 0.002 \text{ GeV} \tag{10.37}$$

$$\Gamma_W \approx 2.09 \pm 0.01 \text{ GeV} \ . \tag{10.38}$$

The numerical values for the widths assume $M_Z = 91.1884 \pm 0.0022$ GeV, $M_W = 80.26 \pm 0.16$ GeV, $\alpha_s = 0.123$, and $m_t = 180 \pm 7$ GeV, where the α_s and m_t values are predicted by the global fits for $M_H = 300$ GeV. The uncertainties for Γ_W and Γ_Z are dominated by ΔM_W and Δm_t, respectively. The uncertainty in α_s, ± 0.004, introduces an additional uncertainty of 0.13% in the hadronic widths, corresponding to ± 2 MeV in Γ_Z.

These predictions are to be compared with the experimental results $\Gamma_Z = 2.4963 \pm 0.0032$ GeV and $\Gamma_W = 2.08 \pm 0.07$ GeV.

10.4. Experimental results

The values of the principal Z-pole observables are listed in Table 10.3, along with the Standard Model predictions for $M_Z = 91.1884 \pm 0.0022$, $m_t = 180 \pm 7$ GeV (for $M_H = 300$ GeV), 60 GeV $< M_H < 1$ TeV, and $\alpha_s = 0.123 \pm 0.004$. Note that, the values of the Z-pole observables (as well as M_W) differ from those in the Particle Listings because they include recent preliminary results [47,49,59]. The values and predictions of M_W [59], the Q_W for cesium [36,41], and recent results from deep inelastic and $\nu_\mu e$ scattering are also listed. The agreement is generally excellent. Major exceptions are $R_b = \Gamma(b\bar{b})/\Gamma(\text{had})$ which is 3.7σ above the Standard Model prediction, and $R_c = \Gamma(c\bar{c})/\Gamma(\text{had})$ which is 2.4σ below. These are strongly correlated: if R_c is fixed at the Standard Model value of 0.172, then one obtains [47] $R_b = 0.2205 \pm 0.0016$, which is still 3.0σ too high. Within the Standard Model framework, these values must be considered large statistical fluctuations or systematic errors. However, R_b tends to favor small values of m_t, and when combined with other observables, small values for M_H. Many types of new physics could contribute to R_b (see also Sec. 14 on "Constraints on New Physics from Electroweak Analyses" in this *Review*). The implications of this possiblity for the value of $\alpha_s(M_Z)$ extracted from the fits are discussed below. The left-right asymmetry $A_{LR}^0 = 0.1551 \pm 0.0040$ [49] based on all data from 1992–1995 has moved closer to the Standard Model expectation of 0.144 ± 0.003 than the previous value 0.1637 ± 0.0075, from 1992–1993. However, because of the smaller error A_{LR}^0 is still 2.3σ above the Standard Model prediction. There is also an experimental difference of $\sim 1.5\sigma$ between the SLD value of $A_e^0 = A_{LR}^0$ and the LEP value $A_{\ell\text{LEP}}^0 \sim 0.147 \pm 0.004$ obtained from $A_{FB}^{(0,\ell)}$, $A_e^0(P_\tau)$, $A_\tau^0(P_\tau)$ assuming lepton family universality. Finally, the forward-backward asymmetry into τ's, $A_{FB}^{0\tau} = 0.0206 \pm 0.0023$ [47], is 2.2σ above the Standard Model prediction and 1.6σ above the average 0.0162 ± 0.0014 of A_{FB}^{0e} and $A_{FB}^{0\mu}$. This is small enough to be a fluctuation, so lepton-family universality will be assumed. The observables in Table 10.3 (including correlations on the LEP observables), as well as all low-energy neutral-current data [14,15], are used in the global fits described below. The parameter $\sin^2\theta_W$ can be determined from the Z-pole observables and M_W, and from a variety of neutral-current processes spanning a very wide Q^2 range. The results [14], shown in Table 10.4, are in impressive agreement with each other, indicating the quantitative success of the Standard Model. The one discrepancy is the value $\widehat{s}_Z^{\,2} = 0.2302 \pm 0.0005$ from A_{LR}^0 which is 2.1σ below the value (0.2315 ± 0.0004) from the global fit to all data and 2.6σ below the value 0.2318 ± 0.0004 obtained from all data other than A_{LR}^0.

The data allow a simultaneous determination of $\sin^2\theta_W$, m_t, and the strong coupling $\alpha_s(M_Z)$. The latter is determined mainly from Γ_Z and R, and is only weaky correlated with the other variables. The global fit to all data, including the CDF/DØ value $m_t = 180 \pm 12$ GeV, yields

$$\begin{aligned} \widehat{s}_Z^{\,2} &= 0.2315 \pm 0.0002 \pm 0.0003 \\ m_t &= 180 \pm 7^{+12}_{-13} \text{ GeV} \\ \alpha_s(M_Z) &= 0.123 \pm 0.004 \pm 0.002 \ , \end{aligned} \tag{10.39}$$

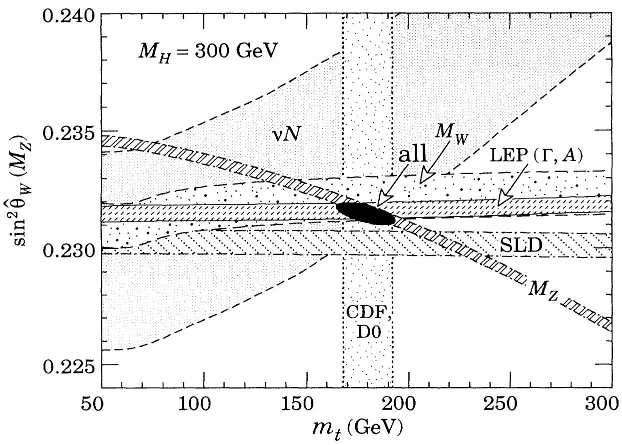

Figure 10.1: One-standard-deviation uncertainties in $\sin^2\hat\theta_W$ as a function of m_t, the direct CDF and DØ range 180 ± 12 GeV, and the 90% CL region in $\sin^2\hat\theta_W - m_t$ allowed by all data, assuming $M_H = 300$ GeV.

where the central values are for a Higgs mass of 300 GeV, and the second error bars are for $M_H \to 1000(+)$ or $60(-)$ GeV. In all fits, the errors include full statistical, systematic, and theoretical uncertainties. The $\hat{s}^2_Z$ error is dominated by m_t, and $\hat{s}^2_Z$ and m_t have a strong negative correlation of ~ -0.62. In the on-shell scheme one has $s^2_W = 0.2236 \pm 0.0008$, the larger error due to the stronger sensitivity to m_t. The extracted value of α_s is based on a formula which has almost no theoretical uncertainty (if one assumes the exact validity of the Standard Model), and is in excellent agreement with the values 0.122 ± 0.007 from jet-event shapes in e^+e^- annihilation, and the average 0.118 ± 0.003 from all data (including the Z-lineshape data), as described in our Section 9 on "Quantum Chromodynamics" in this *Review*. However, it is higher than some of the individual values extracted from low-energy data, such as deep-inelastic scattering (0.112 ± 0.002 (exp) ± 0.004 (scale)) or lattice calculations of the $b\bar{b}$ and $c\bar{c}$ spectra (0.115 ± 0.003). It has been suggested [60] that there is a real discrepancy. However, caution is requred since most of the determinations are dominated by theory errors.

The value of R_b is more than 3σ above the Standard Model expectation. If this is not just a fluctuation but is due to a new physics contribution to the $Z \to b\bar{b}$ vertex (many types would couple preferentially to the third family), the value of $\alpha_s(M_Z)$ extracted from the hadronic Z width would be reduced [15]. Allowing for this possibility one obtains $\alpha_s(M_Z) = 0.101 \pm 0.008$. (See also Sec. 14 on "Constraints on New Physics from Electroweak Analyses." in this *Review*)

In principle the low value of R_c could also be due to new physics. However, allowing for new physics contributions to R_c alone, one obtains $\alpha_s(M_Z) = 0.19 \pm 0.03$, which is clearly inconsistent with low-energy determinations. Allowing new contributions to both R_b and R_c yields the slightly lower but still high value of $\alpha_s(M_Z) = 0.16 \pm 0.04$. We will, therefore, take the view that the R_c value is a fluctuation. We keep the experimental values $R_b = 0.2219(17)$ and $R_c = 0.1540(74)$ and their correlation (-0.35) in all fits, but do not allow any special vertex corrections for $Z \to c\bar{c}$. This is effectively equivalent to using the lower value 0.2205(16) that the LEP experimenters obtain for R_b when they constrain R_c to the Standard Model value of 0.172.

One can also carry out a fit to the indirect data alone, *i.e.*, without including the value $m_t = 180 \pm 12$ GeV observed directly by CDF and DØ. (The indirect prediction is for the pole mass, which should correspond approximately to the kinematic mass extracted from the collider events.) One obtains $m_t = 179 \pm 8^{+17}_{-20}$ GeV, with little change in the $\sin^2\theta_W$ and α_s values, in remarkable agreement with the direct CDF/DØ value. The results of fits to various combinations of the data are shown in Table 10.5 and the relation between $\hat{s}^2_Z$ and m_t for various observables in Fig. 10.1.

The data indicate a preference for a small Higgs mass. This is because there is a strong correlation between the quadratic ρ_t terms and logarithmic M_H effects in all of the indirect data except the $Z \to b\bar{b}$ vertex. The latter favor a smaller m_t and therefore a smaller M_H. The difference in χ^2 for the global fit is $\Delta\chi^2 = \chi^2(M_H = 1000 \text{ GeV}) - \chi^2(M_H = 60 \text{ GeV}) = 7.9$. Hence, the data favor a small value of M_H, as in supersymmetric extensions of the Standard Model, and m_t on the lower side of the allowed range; including the direct constraint $M_H \geq 60$ GeV, the best fit is for $M_H = 60$ GeV, with the limit $M_H < 320(430)$ GeV at 90(95)% CL. However, one should be cautious because the M_H constraint is driven almost entirely by R_b and A_{LR}, both of which deviate from the Standard Model prediction. Using $\alpha(M_Z)$ and $\hat{s}^2_Z$ as inputs, one can predict $\alpha_s(M_Z)$ assuming grand unification. One predicts [61] $\alpha_s(M_Z) = 0.130 \pm 0.001 \pm 0.01$ for the simplest theories based on the minimal supersymmetric extension of the Standard Model, where the first (second) uncertainty is from the inputs (thresholds). This is consistent with the experimental $\alpha_s(M_Z) = 0.121(4)(1)$ from the Z-lineshape (using the lower M_H range appropriate for supersymmetry) and with the average 0.118 ± 0.003 (see our Section 9 on "Quantum Chromodynamics" in this *Review*), but is high compared to some low-energy determinations of α_s [60]. Nonsupersymmetric unified theories predict the low value $\alpha_s(M_Z) = 0.073 \pm 0.001 \pm 0.001$.

One can also determine the radiative correction parameters Δr: including the CDF and DØ data, one obtains $\Delta r = 0.039 \pm 0.003$ and $\Delta\hat{r}_W = 0.068 \pm 0.0013$, where the error includes m_t and M_H, in excellent agreement with the predictions 0.038 ± 0.005 and 0.0705 ± 0.0007.

Table 10.4: Values obtained for s^2_W (on-shell) and $\hat{s}^2_Z(\overline{\text{MS}})$ from various reactions assuming the global best fit value $m_t = 180 \pm 07$ GeV (for $M_H = 300$ GeV), and $\alpha_s = 0.123 \pm 0.004$. The uncertainties include the effect of 60 GeV $< M_H <$ 1 TeV. The determination from $\Gamma_Z, R,$ and σ_{had} uses the experimental value of M_Z, so that the values obtained are from the vertices and not the overall scale.

Reaction	s^2_W	$\hat{s}^2_Z$
M_Z	0.2237 ± 0.0010	0.2316 ± 0.0005
M_W	0.2242 ± 0.0011	0.2321 ± 0.0009
$\Gamma_Z,\ R, \sigma_{\text{had}}$	0.2239 ± 0.0013	0.2317 ± 0.0013
$A^{(0,\ell)}_{FB}$	0.2228 ± 0.0009	0.2307 ± 0.0007
LEP asymmetries	0.2237 ± 0.0007	0.2316 ± 0.0003
A^0_{LR}	0.2223 ± 0.0008	0.2302 ± 0.0005
$\overline{A}_b, \overline{A}_c$	0.250 ± 0.021	0.259 ± 0.022
Deep inelastic (isocalar)	0.226 ± 0.004	0.234 ± 0.005
$\nu_\mu(\overline{\nu}_\mu)p \to \nu_\mu(\overline{\nu}_\mu)p$	0.205 ± 0.030	0.212 ± 0.031
$\nu_\mu(\overline{\nu}_\mu)e \to \nu_\mu(\overline{\nu}_\mu)e$	0.221 ± 0.007	0.228 ± 0.008
atomic parity violation	0.216 ± 0.008	0.223 ± 0.008
SLAC eD	0.216 ± 0.017	0.223 ± 0.018
All data	0.2236 ± 0.0008	0.2315 ± 0.0004

10.5. Deviations from the Standard Model

The Z pole, W mass, and neutral-current data can be used to search for and set limits on deviations from the Standard Model.

For example, the relation between M_W and M_Z is modified if there are Higgs multiplets with weak isospin $> 1/2$ with significant vacuum expectation values. In order to calculate to higher orders in such theories one must define a set of four fundamental renormalized parameters. It is convenient to take these as α, G_F, M_Z, and M_W,

Table 10.3: Principal LEP and other recent observables, compared with the Standard Model predictions for $M_Z = 91.1884 \pm 0.0022$ GeV, 60 GeV $< M_H <$ 1 TeV, the global best fit value $m_t = 180 \pm 7$ GeV (for $M_H = 300$ GeV), $\alpha_s = 0.123 \pm 0.004$, and $\alpha_s(M_Z)^{-1} = 128.90 \pm 0.09$. The LEP averages [58] of the ALEPH, DELPHI, L3, and OPAL results include common systematic errors and correlations [58]. $\bar{s}^2_\ell(A^{(0,q)}_{FB})$ is the effective angle extracted from the hadronic-charge asymmetry. A^0_{LR} includes all data from 1992–1995 [48,49]. The values of $\Gamma(\ell\bar{\ell})$, $\Gamma(\text{had})$, and $\Gamma(\text{inv})$ are not independent of Γ_Z, R, and σ_{had}. The M_W value is from CDF, UA2, and DØ [59]. M_W and M_Z are correlated, but the effect is negligible due to the tiny M_Z error. The two values of s^2_W from deep-inelastic scattering are from CCFR [31] and the global average, respectively. The $g^{\nu e}_{V,A}$ are from CHARM II [34]. The second error in Q_W (for cesium) is theoretical [41]. Older low-energy results are not listed but are included in the fits. In the Standard Model predictions, the first uncertainty is from M_Z and Δr, while the second is from m_t and M_H. The $\Delta\alpha_s = 0.004$ uncertainty leads to additional errors of 0.002 (Γ_Z), 0.02 (R), 0.02 (σ), 2.0 ($\Gamma(\text{had})$).

Quantity	Value	Standard Model
M_Z (GeV)	91.1884 ± 0.0022	input
Γ_Z (GeV)	2.4963 ± 0.0032	$2.497 \pm 0.001 \pm 0.002$
R	20.788 ± 0.032	$20.77 \pm 0.004 \pm 0.002$
$\sigma_{\text{had}}(nb)$	41.488 ± 0.078	$41.45 \pm 0.002 \pm 0.004$
R_b	0.2219 ± 0.0017	$0.2156 \pm 0 \pm 0.0003$
R_c	0.1540 ± 0.0074	$0.172 \pm 0 \pm 0$
$A^{(0,\ell)}_{FB}$	0.0172 ± 0.0012	$0.0155 \pm 0.0004 \pm 0.0004$
$A^0_\tau(P_\tau)$	0.1418 ± 0.0075	$0.144 \pm 0.002 \pm 0.002$
$A^0_e(P_\tau)$	0.1390 ± 0.0089	$0.144 \pm 0.002 \pm 0.002$
$A^{(0,b)}_{FB}$	0.0997 ± 0.0031	$0.101 \pm 0.001 \pm 0.001$
$A^{(0,c)}_{FB}$	0.0729 ± 0.0058	$0.072 \pm 0.001 \pm 0.001$
A^0_{LR}	0.1551 ± 0.0040	$0.144 \pm 0.002 \pm 0.002$
$\overline{A}_b$	0.841 ± 0.053	$0.934 \pm 0 \pm 0$
$\overline{A}_c$	0.606 ± 0.090	$0.667 \pm 0.001 \pm 0.001$
$\bar{s}^2_\ell(A^{(0,q)}_{FB})$	0.2325 ± 0.0013	$0.2319 \pm 0.0002 \pm 0.0002$
$\Gamma(\ell\bar{\ell})$ (MeV)	83.93 ± 0.14	$83.97 \pm 0.01 \pm 0.06$
$\Gamma(\text{had})$ (MeV)	1744.8 ± 3.0	$1743.8 \pm 0.2 \pm 1.2$
$\Gamma(\text{inv})$ (MeV)	499.9 ± 2.5	$501.6 \pm 0 \pm 0.3$
M_W (GeV)	80.26 ± 0.16	$80.34 \pm 0.01 \pm 0.04$
Q_W	$-71.04 \pm 1.58 \pm 0.88$	$-72.88 \pm 0.05 \pm 0.03$
$s^2_W = 1 - \frac{M^2_W}{M^2_Z}$	0.2218 ± 0.0059 0.2260 ± 0.0048	$0.2237 \pm 0.0002 \pm 0.0008$
$g^{\nu e}_A$	-0.503 ± 0.017	$-0.507 \pm 0 \pm 0.0004$
$g^{\nu e}_V$	-0.035 ± 0.017	$-0.037 \pm 0.0005 \pm 0.0003$

since M_W and M_Z are directly measurable. Then $\widehat{s}^2_Z$ and ρ_0 can be considered dependent parameters defined by

$$\widehat{s}^2_Z \equiv A^2_0/M^2_W(1 - \Delta\widehat{r}_W) \tag{10.40}$$

and

$$\rho_0 \equiv M^2_W/(M^2_Z\,\widehat{c}^2_Z\,\widehat{\rho}) \ . \tag{10.41}$$

Provided that the new physics which yields $\rho_0 \neq 1$ is a small perturbation which does not significantly affect the radiative corrections, ρ_0 can be regarded as a phenomenological parameter which multiplies G_F in Eqs. (10.12)–(10.14), (10.28), and Γ_Z in Eq. (10.36). (Also, the expression for M_Z is divided by $\sqrt{\rho_0}$; the M_W formula is unchanged.) There is now enough data to determine ρ_0, $\sin^2\theta_W$, m_t, and α_s simultaneously. In particular, R_b and the direct CDF and DØ events yield m_t independent of ρ_0, the asymmetries yield $\widehat{s}^2_Z$, R gives α_s, and M_Z and the widths constrain ρ_0. From the global fit (including CDF and DØ),

Table 10.5: Values of $\widehat{s}^2_Z$ and s^2_W (in parentheses), α_s, and m_t for various combinations of observables. The central values are for $M_H = 300$ GeV, and the second set of errors is for $M_H \to 1000(+), 60(-)$.

Data	$\widehat{s}^2_Z$ (s^2_W)	α_s (M_Z)	m_t (GeV)
Indirect + CDF + DØ	0.2315(2)(3) (0.2236 ± 0.0008)	0.123(4)(2)	$180 \pm 7^{+12}_{-13}$
All indirect	0.2315(2)(2) (0.2236 ± 0.0009)	0.123(4)(2)	$179 \pm 8^{+17}_{-20}$
All LEP	0.2318(3)(2) (0.2246 ± 0.0011)	0.124(4)(2)	$171 \pm 10^{+18}_{-20}$
SLD + M_Z	0.2302(5)(0) (0.2184 ± 0.0020)	—	220^{+14+19}_{-15-24}
Z pole (LEP + SLD)	0.2314(3)(1) (0.2234 ± 0.0010)	0.123(4)(2)	181^{+8+18}_{-9-20}

$$\rho_0 = 1.0012 \pm 0.0013 \pm 0.0018 \tag{10.42}$$

$$\widehat{s}^2_Z = 0.2314 \pm 0.0002 \pm 0.0002 \tag{10.43}$$

$$\alpha_s = 0.121 \pm 0.004 \pm 0.001 \tag{10.44}$$

$$m_t = 171 \pm 12 \ , \tag{10.45}$$

where the second error is from M_H. This is in remarkable agreement with the Standard Model expectation $\rho_0 = 1$, and constrains any higher-dimensional Higgs representation to have vacuum expectation values of less than a few percent of those of the doublets. The allowed regions in the $\rho_0 - \widehat{s}^2_Z$ plane are shown in Fig. 10.2. Allowing for new physics in R_b, one obtains $\rho_0 = 1.0002(14)(18)$ and $\alpha_s = 0.101(8)(1)$. The effects of other types of new physics are described in Sec. 14 on "Constraints on New Physics from Electroweak Analyses" in this *Review*.

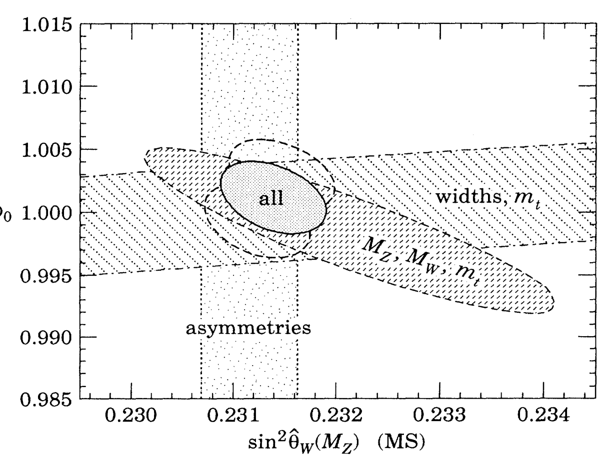

Figure 10.2: The allowed regions in $\sin^2\widehat{\theta}_W - \rho_0$ at 90% CL. m_t is a free parameter and $M_H = 300$ GeV is assumed. (The upper (lower) dashed contours are for $M_H = 1000$ (60) GeV.) The horizontal (width) band uses the experimental value of M_Z in Eq. (10.36).

Most of the parameters relevant to ν-hadron, νe, e-hadron, and e^+e^- processes are determined uniquely and precisely from the data in "model independent" fits (*i.e.*, fits which allow for an arbitrary electroweak gauge theory). The values for the parameters defined in Eqs. (10.12)–(10.14) are given in Table 10.6 along with the predictions of the Standard Model. The agreement is excellent. The low-energy e^+e^- results are difficult to present in a model-independent way because Z-propagator effects are non-negligible at TRISTAN, PETRA, and PEP energies. However, assuming e-μ-τ universality, the lepton asymmetries imply [45] $4(g_A^e)^2 = 0.99 \pm 0.05$, in good agreement with the Standard Model prediction $\simeq 1$. The much more precisely measured Z-pole parameters in Table 10.3 are in excellent agreement with the Standard Model.

Table 10.6: Values of the model-independent neutral-current parameters, compared with the Standard Model prediction using $M_Z = 91.1884$ GeV for $m_t = 180 \pm 7$ GeV and $M_H = 300$ GeV. There is a second $g_{V,A}^{\nu e}$ solution, given approximately by $g_V^{\nu e} \leftrightarrow g_A^{\nu e}$, which is eliminated by e^+e^- data under the assumption that the neutral current is dominated by the exchange of a single Z. θ_i, $i = L$ or R, is defined as $\tan^{-1}[\epsilon_i(u)/\epsilon_i(d)]$.

Quantity	Experimental Value	Standard Model Prediction	Correlation	
$\epsilon_L(u)$	0.332 $\pm$0.016	0.345$\pm$0.0003		
$\epsilon_L(d)$	−0.438 $\pm$0.012	−0.429$\pm$0.0004		non-
$\epsilon_R(u)$	−0.178 $\pm$0.013	−0.156		Gaussian
$\epsilon_R(d)$	−0.026 $^{+0.075}_{-0.048}$	0.078		
g_L^2	0.3017$\pm$0.0033	0.303$\pm$0.0005		
g_R^2	0.0326$\pm$0.0033	0.030		small
θ_L	2.50 $\pm$0.035	2.46		
θ_R	4.58 $^{+0.46}_{-0.28}$	5.18		
$g_A^{\nu e}$	−0.507 $\pm$0.014	−0.507$\pm$0.0004		−0.04
$g_V^{\nu e}$	−0.041 $\pm$0.015	−0.037$\pm$0.0003		
C_{1u}	−0.214 $\pm$0.046	−0.190$\pm$0.0005	−0.995	−0.79
C_{1d}	0.359 $\pm$0.041	0.342$\pm$0.0004		0.79
$C_{2u} - \frac{1}{2}C_{2d}$	−0.04 $\pm$0.13	−0.052$\pm$0.0009		

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11. THE CABIBBO-KOBAYASHI-MASKAWA MIXING MATRIX

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In the Standard Model with SU(2) × U(1) as the gauge group of electroweak interactions, both the quarks and leptons are assigned to be left-handed doublets and right-handed singlets. The quark mass eigenstates are not the same as the weak eigenstates, and the matrix relating these bases was defined for six quarks and given an explicit parametrization by Kobayashi and Maskawa [1] in 1973. It generalizes the four-quark case, where the matrix is parametrized by a single angle, the Cabibbo angle [2].

By convention, the three charge $2e/3$ quarks (u, c, and t) are unmixed, and all the mixing is expressed in terms of a 3×3 unitary matrix V operating on the charge $-e/3$ quarks (d, s, and b):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} . \qquad (11.1)$$

The values of individual matrix elements can in principle all be determined from weak decays of the relevant quarks, or, in some cases, from deep inelastic neutrino scattering. Using the constraints discussed below together with unitarity, and assuming only three generations, the 90% confidence limits on the magnitude of the elements of the complete matrix are:

$$\begin{pmatrix} 0.9745 \text{ to } 0.9757 & 0.219 \text{ to } 0.224 & 0.002 \text{ to } 0.005 \\ 0.218 \text{ to } 0.224 & 0.9736 \text{ to } 0.9750 & 0.036 \text{ to } 0.046 \\ 0.004 \text{ to } 0.014 & 0.034 \text{ to } 0.046 & 0.9989 \text{ to } 0.9993 \end{pmatrix} . \qquad (11.2)$$

The ranges shown are for the individual matrix elements. The constraints of unitarity connect different elements, so choosing a specific value for one element restricts the range of others.

There are several parametrizations of the Cabibbo-Kobayashi-Maskawa matrix. In view of the need for a "standard" parametrization in the literature, we advocate:

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \qquad (11.3)$$

proposed by Chau and Keung [3]. The choice of rotation angles follows earlier work of Maiani [4], and the placement of the phase follows that of Wolfenstein [5]. The notation used is that of Harari and Leurer [6] who, along with Fritzsch and Plankl [7], proposed this parametrization as a particular case of a form generalizable to an arbitrary number of "generations." The general form was also put forward by Botella and Chau [8]. Here $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$, with i and j being "generation" labels, $\{i, j = 1, 2, 3\}$. In the limit $\theta_{23} = \theta_{13} = 0$ the third generation decouples, and the situation reduces to the usual Cabibbo mixing of the first two generations with θ_{12} identified with the Cabibbo angle [2].

The real angles θ_{12}, θ_{23}, θ_{13} can all be made to lie in the first quadrant by an appropriate redefinition of quark field phases. Then all s_{ij} and c_{ij} are positive, $|V_{us}| = s_{12}c_{13}$, $|V_{ub}| = s_{13}$, and $|V_{cb}| = s_{23}c_{13}$. As c_{13} is known to deviate from unity only in the fifth decimal place, $|V_{us}| = s_{12}$, $|V_{ub}| = s_{13}$, and $|V_{cb}| = s_{23}$ to an excellent approximation. The phase δ_{13} lies in the range $0 \le \delta_{13} < 2\pi$, with non-zero values generally breaking CP invariance for the weak interactions. The generalization to the n generation case contains $n(n-1)/2$ angles and $(n-1)(n-2)/2$ phases [6,7,8]. The range of matrix elements in Eq. (11.2) corresponds to 90% CL limits on the angles of $s_{12} = 0.219$ to $0.223, s_{23} = 0.036$ to 0.046, and $s_{13} = 0.002$ to 0.005.

Kobayashi and Maskawa [1] originally chose a parametrization involving the four angles, θ_1, θ_2, θ_3, δ:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3-s_2s_3e^{i\delta} & c_1c_2s_3+s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3+c_2s_3e^{i\delta} & c_1s_2s_3-c_2c_3e^{i\delta} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} , \qquad (11.4)$$

where $c_i = \cos\theta_i$ and $s_i = \sin\theta_i$ for $i = 1, 2, 3$. In the limit $\theta_2 = \theta_3 = 0$, this reduces to the usual Cabibbo mixing with θ_1 identified (up to a sign) with the Cabibbo angle [2]. Slightly different forms of the Kobayashi-Maskawa parametrization are found in the literature. The CKM matrix used in the 1982 *Review of Particle Properties* is obtained by letting $s_1 \to -s_1$ and $\delta \to \delta + \pi$ in the matrix given above. An alternative is to change Eq. (11.4) by $s_1 \to -s_1$ but leave δ unchanged. With this change in s_1, the angle θ_1 becomes the usual Cabibbo angle, with the "correct" sign (*i.e.* $d' = d\cos\theta_1 + s\sin\theta_1$) in the limit $\theta_2 = \theta_3 = 0$. The angles θ_1, θ_2, θ_3 can, as before, all be taken to lie in the first quadrant by adjusting quark field phases. Since all these parametrizations are referred to as "the" Kobayashi-Maskawa form, some care about which one is being used is needed when the quadrant in which δ lies is under discussion.

Other parametrizations, mentioned above, are due to Maiani [4] and to Wolfenstein [5]. Still other parametrizations [9] have come into the literature in connection with attempts to define "maximal CP violation". No physics can depend on which of the above parametrizations (or any other) is used as long as a single one is used consistently and care is taken to be sure that no other choice of phases is in conflict.

Our present knowledge of the matrix elements comes from the following sources:

(1) New analyses have been performed comparing nuclear beta decay to muon decay. The previous radiative corrections [10] already included order $Z\alpha^2$ effects and more recent results [11–15] concentrate on nuclear mismatch and structure-dependent radiative corrections. The results in Ref. 15 violate CVC, and the updated [13] average ft values for superallowed 0^+ to 0^+ transitions of Refs. 11 and 12 do not agree with each other within the estimated uncertainties:

$$ft = 3150.8 \pm 1.7 \text{ sec} \quad \text{(Refs. 11 and 13)} ,$$

$$ft = 3145.7 \pm 1.5 \text{ sec} \quad \text{(Refs. 12 and 13)} , \qquad (11.5)$$

The common experimental error is ± 0.82. We have taken an average of the above values and scaled up the error to take account of the uncertainty in the nuclear structure dependent radiative corrections and corresponding inconsistency of the theoretical results. This transforms to

$$|V_{ud}| = 0.9736 \pm 0.0010 , \qquad (11.6)$$

which is almost one standard deviation smaller than the result in the previous *Review of Particle Physics*. It is consistent with the result $|V_{ud}| = 0.9734 \pm 0.0007$ from the update in Ref. 14.

(2) Analysis of K_{e3} decays yields [16]

$$|V_{us}| = 0.2196 \pm 0.0023 . \qquad (11.7)$$

With isospin violation taken into account in K^+ and K^0 decays, the extracted values of $|V_{us}|$ are in agreement at the 1% level. A reanalysis [13] obtains essentially the same value, but quotes a somewhat smaller error which is only statistical. The analysis of hyperon decay data has larger theoretical uncertainties because of first order SU(3) symmetry breaking effects in the axial-vector couplings, but due account of symmetry breaking [17] applied to the WA2 data [18] gives a corrected value [19] of 0.222 ± 0.003. We average these two results to obtain:

$$|V_{us}| = 0.2205 \pm 0.0018 . \qquad (11.8)$$

(3) The magnitude of $|V_{cd}|$ may be deduced from neutrino and antineutrino production of charm off valence d quarks. The dimuon production cross sections of the CDHS group [20] yield $\overline{B}_c\,|V_{cd}|^2 = 0.41 \pm 0.07 \times 10^{-2}$, where $\overline{B}_c$ is the semileptonic branching fraction of the charmed hadrons produced. The corresponding value from a more recent Tevatron experiment [21], where a next-to-leading-order

QCD analysis has been carried out, is $0.534 \pm 0.021^{+0.025}_{-0.051} \times 10^{-2}$, where the last error is from the scale uncertainty. Assuming a similar scale error for the CDHS result and averaging these two results gives $0.49 \pm 0.05 \times 10^{-2}$. Supplementing this with data [22] on the mix of charmed particle species produced by neutrinos and PDG values for their semileptonic branching fractions to give [21] $\overline{B}_c = 0.099 \pm 0.012$, yields

$$|V_{cd}| = 0.224 \pm 0.016 \tag{11.9}$$

(4) Values of $|V_{cs}|$ from neutrino production of charm are dependent on assumptions about the strange quark density in the parton-sea. The most conservative assumption, that the strange-quark sea does not exceed the value corresponding to an SU(3) symmetric sea, leads to a lower bound [20], $|V_{cs}| > 0.59$. It is more advantageous to proceed analogously to the method used for extracting $|V_{us}|$ from K_{e3} decay; namely, we compare the experimental value for the width of D_{e3} decay with the expression [23] that follows from the standard weak interaction amplitude:

$$\Gamma(D \to \overline{K}e^+\nu_e) = |f_+^D(0)|^2\,|V_{cs}|^2\,(1.54 \times 10^{11}\ \mathrm{s}^{-1}) \ . \tag{11.10}$$

Here $f_+^D(q^2)$, with $q = p_D - p_K$, is the form factor relevant to D_{e3} decay; its variation has been taken into account with the parametrization $f_+^D(t)/f_+^D(0) = M^2/(M^2 - t)$ and $M = 2.1\ \mathrm{GeV}/c^2$, a form and mass consistent with Mark III and E691 measurements [24,25]. Combining data on branching ratios for D_{e3} decays from Mark III, E691, and CLEO experiments [24–26] with accurate values [27] for τ_{D^+} and τ_{D^0}, yields $(0.762 \pm 0.055) \times 10^{11}\ \mathrm{s}^{-1}$ for $\Gamma(D \to \overline{K}e^+\nu_e)$. Therefore

$$|f_+^D(0)|^2\,|V_{cs}|^2 = 0.495 \pm 0.036 \ . \tag{11.11}$$

A very conservative assumption is that $|f_+^D(0)| < 1$, from which it follows that $|V_{cs}| > 0.62$. Calculations of the form factor either performed [28,29] directly at $q^2 = 0$, or done [30] at the maximum value of $q^2 = (m_D - m_K)^2$ and interpreted at $q^2 = 0$ using the measured q^2 dependence, gives the value $f_+^D(0) = 0.7 \pm 0.1$. It follows that

$$|V_{cs}| = 1.01 \pm 0.18 \ . \tag{11.12}$$

The constraint of unitarity when there are only three generations gives a much tighter bound (see below).

(5) The ratio $|V_{ub}/V_{cb}|$ can be obtained from the semileptonic decay of B mesons produced on the $\Upsilon(4S)$ $b\bar{b}$ resonance by measuring the lepton energy spectrum above the endpoint of the $b \to c\ell\nu$ spectrum. There the $b \to u\ell\nu$ decay rate can be obtained by subtracting the background from nonresonant e^+e^- reactions. This continuum background is determined from auxiliary measurements off the $\Upsilon(4S)$. Both the CLEO [31] and ARGUS [32] collaborations have reported evidence for $b \to u$ transitions in semileptonic B decays. The interpretation of the result in terms of $|V_{ub}/V_{cb}|$ depends fairly strongly on the theoretical model used to generate the lepton energy spectrum, especially for $b \to u$ transitions [29,30,33]. Combining the experimental and theoretical uncertainties, we quote

$$|V_{ub}/V_{cb}| = 0.08 \pm 0.02 \ . \tag{11.13}$$

(6) The heavy quark effective theory [34](HQET) provides a nearly model-independent treatment of B semileptonic decays to charmed mesons. From measurements [35–37] of the exclusive decay $B \to \overline{D}^*\bar{\ell}\nu_\ell$, the value $|V_{cb}| = 0.041 \pm 0.003 \pm 0.002$ has been extracted [38] using corrections based on the HQET. A new analysis of inclusive decays [39], where the measured semileptonic bottom hadron partial width is assumed to be that of a b quark decaying through the usual $V - A$ interaction, gives $|V_{cb}| \cdot (\tau_b/1.5\ \mathrm{ps})^{1/2} = 0.041 \pm 0.002$. Using a value [40] for the b lifetime $\tau_b = 1.55 \pm 0.06$ ps and combining with the exclusive result, we obtain

$$|V_{cb}| = 0.041 \pm 0.003 \ . \tag{11.14}$$

The results for three generations of quarks, from Eqs. 11.6, 11.8, 11.9, 11.12, 11.13, and 11.14 plus unitarity, are summarized in the matrix in Eq. (11.2). The ranges given there are different from those given in Eqs. (11.6)–(11.14) because of the inclusion of unitarity, but are consistent with the one-standard-deviation errors on the input matrix elements. Note in particular that the unitarity constraint has pushed $|V_{ud}|$ about one standard deviation higher than given in Eq. (11.6).

The data do not preclude there being more than three generations. Moreover, the entries deduced from unitarity might be altered when the CKM matrix is expanded to accommodate more generations. Conversely, the known entries restrict the possible values of additional elements if the matrix is expanded to account for additional generations. For example, unitarity and the known elements of the first row require that any additional element in the first row have a magnitude $|V_{ub'}| < 0.08$. When there are more than three generations the allowed ranges (at 90% CL) of the matrix elements connecting the first three generations are

$$\begin{pmatrix} 0.9720 \text{ to } 0.9752 & 0.217 \text{ to } 0.223 & 0.002 \text{ to } 0.005 & \ldots \\ 0.199 \text{ to } 0.234 & 0.818 \text{ to } 0.975 & 0.036 \text{ to } 0.046 & \ldots \\ 0 \text{ to } 0.11 & 0 \text{ to } 0.52 & 0 \text{ to } 0.9993 & \ldots \\ \vdots & \vdots & \vdots & \end{pmatrix} , \tag{11.15}$$

where we have used unitarity (for the expanded matrix) and Eqs. 11.6, 11.8, 11.9, 11.12, 11.13, and 11.14.

Further information, particularly on CKM matrix elements involving the top quark, can be obtained from flavor-changing processes that occur at the one-loop level. We have not used this information in the discussion above since the derivation of values for V_{td} and V_{ts} in this manner from, for example, B mixing, $b \to s\gamma$, or $K \to \pi\nu\bar{\nu}$, requires an additional assumption that the top-quark loop, rather than new physics, gives the dominant contribution to the process in question.

The measured value [41] of $\Delta M_d = 0.496 \pm 0.032\ \mathrm{ps}^{-1}$ from $B_d^0 - \overline{B}_d^0$ mixing can be turned in this way into information on $|V_{tb}^* V_{td}|$. Using $\widehat{B}_{B_d} f_{B_d}^2 = (1.2 \pm 0.2)(173 \pm 40\ \mathrm{MeV})^2$ from lattice QCD calculations [42], next-to-leading-order QCD corrections [43], and $m_t = 174 \pm 16$ GeV as input,

$$|V_{tb}^*\, V_{td}| = 0.009 \pm 0.003 \ , \tag{11.16}$$

where the error bar comes primarily from the theoretical uncertainty in the hadronic matrix elements.

In the ratio of B_s to B_d mass differences, many of the factors (such as the QCD correction and dependence on the t-quark mass) cancel, and we have

$$\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \frac{\widehat{B}_{B_s} f_{B_s}^2}{\widehat{B}_{B_d} f_{B_d}^2} \frac{|V_{tb}^* \cdot V_{ts}|^2}{|V_{tb}^* \cdot V_{td}|^2} \ . \tag{11.17}$$

With $\widehat{B}_{B_s} \approx \widehat{B}_{B_d}$ and $f_{B_s}/f_{B_d} = 1.16 \pm 0.10$ from lattice QCD [42] and the experimental limit [41] $\Delta M_{B_s}/\Delta M_{B_d} > 11.6$,

$$|V_{td}|/|V_{ts}| < 0.37 \ . \tag{11.18}$$

The CLEO observation [44] of $b \to s\gamma$ can be translated [45] similarly into $|V_{ts}|/|V_{cb}| = 1.1 \pm 0.43$, where the large uncertainty is again dominantly theoretical. Ultimately $K \to \pi\nu\bar{\nu}$ decays offer high precision because the matrix elements can be directly measured, but experiment is presently several orders of magnitude away from the requisite sensitivity. All these additional indirect constraints are consistent with the matrix elements obtained from the direct measurements plus unitarity, assuming three generations; adding the indirect constraints to the fit leaves the ranges of CKM matrix elements in Eq. (11.2) essentially unchanged.

Direct and indirect information on the CKM matrix is neatly summarized in terms of the "unitarity triangle." The name arises since unitarity of the 3×3 CKM matrix applied to the first and third columns yields

$$V_{ud}\, V_{ub}^* + V_{cd}\, V_{cb}^* + V_{td} V_{tb}^* = 0 \ . \tag{11.19}$$

The unitarity triangle is just a geometrical presentation of this equation in the complex plane [46]. We can always choose to orient the triangle so that $V_{cd} V_{cb}^*$ lies along the horizontal; in the parametrization we have chosen, V_{cb} is real, and V_{cd} is real to a very good approximation in any case. Setting cosines of small angles to unity, Eq. (11.19) becomes

$$V_{ub}^* + V_{td} = s_{12} V_{cb}^* \,, \tag{11.20}$$

which is shown as the unitarity triangle in Fig. 11.1(a). Rescaling the triangle by a factor $[1/|s_{12} V_{cb}|]$, the coordinates of the vertices become

$$A\big(\mathrm{Re}(V_{ub})/|s_{12} V_{cb}|, -\mathrm{Im}(V_{ub})/|s_{12} V_{cb}|\big) \ , \ B(1,0) \ , \ C(0,0) \ . \tag{11.21}$$

In the approximation of the Wolfenstein parametrization [5], with matrix elements expressed in powers of the Cabibbo angle, $\lambda \sim s_{12}$:

$$\begin{aligned} V_{us} &\sim \lambda \\ V_{ub} &\sim \lambda^3 A(\rho - i\eta) \\ V_{cb} &\sim \lambda^2 A \\ V_{td} &\sim \lambda^3 A(1 - \rho - i\eta) \ , \end{aligned} \tag{11.22}$$

the coordinates of the vertex A of the unitarity triangle are simply (ρ, η), as shown in Fig. 11.1(b).

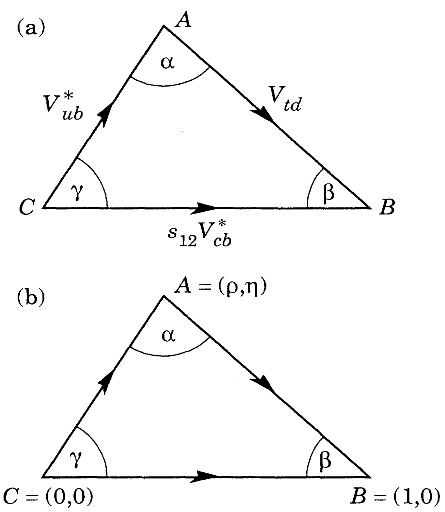

Figure 11.1: (a) Representation in the complex plane of the triangle formed by the CKM matrix elements V_{ub}^*, V_{td}, and $s_{12} V_{cb}^*$. (b) Rescaled triangle with vertices $A(\rho,\eta)$, $B(1,0)$, and $C(0,0)$.

CP-violating processes will involve the phase in the CKM matrix, assuming that the observed CP violation is solely related to a nonzero value of this phase. This allows additional constraints to be brought to bear. More specifically, a necessary and sufficient condition for CP violation with three generations can be formulated in a parametrization-independent manner in terms of the non-vanishing of the determinant of the commutator of the mass matrices for the charge $2e/3$ and charge $-e/3$ quarks [47]. CP violating amplitudes or differences of rates all are proportional to the CKM factor in this quantity. This is the product of factors $s_{12}s_{13}s_{23}c_{12}c_{13}^2c_{23}s_{\delta_{13}}$ in the parametrization adopted above, and is $s_1^2 s_2 s_3 c_1 c_2 c_3 s_\delta$ in that of Ref. 1. With the approximation of setting cosines to unity, this is just twice the area of the unitarity triangle. While hadronic matrix elements whose values are imprecisely known generally now enter, the constraints from CP violation in the neutral kaon system are tight enough to very much restrict the range of angles and the phase of the CKM matrix. For example, the constraint obtained from the CP-violating parameter ϵ in the neutral K system corresponds to the vertex A of the unitarity triangle lying on a hyperbola for fixed values of the hadronic matrix elements. [48] For CP-violating asymmetries of neutral B mesons decaying to CP eigenstates, there is a direct relationship between the magnitude of the asymmetry in a given decay and $\sin 2\phi$, where $\phi = \alpha$, β, γ is an appropriate angle of the unitarity triangle [46].

The combination of all the direct and indirect information can be used to find the overall constraints on the CKM matrix and thence the implications for future measurements of CP violation in the B system [48].

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12. QUARK MODEL

12.1. Quantum numbers of the quarks

Each quark has spin 1/2 and baryon number 1/3. Table 12.1 gives the additive quantum numbers (other than baryon number) of the three generations of quarks. Our convention is that the *flavor* of a quark (I$_z$, S, C, B, or T) has the same sign as its *charge*. With this convention, any flavor carried by a *charged* meson has the same sign as its charge; *e.g.*, the strangeness of the K^+ is +1, the bottomness of the B^+ is +1, and the charm *and* strangeness of the D_s^- are each −1.

By convention, each quark is assigned positive parity. Then each antiquark has negative parity.

Table 12.1: Additive quantum numbers of the quarks.

Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I$_z$ – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	−1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	−1	0
T – topness	0	0	0	0	0	+1

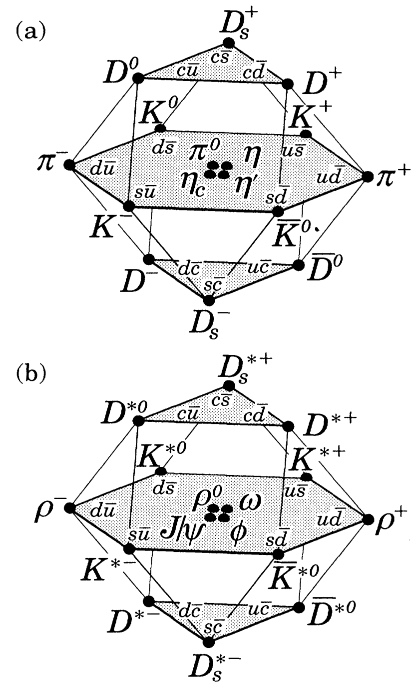

Figure 12.1: SU(4) 16-plets for the (a) pseudoscalar and (b) vector mesons made of u, d, s, and c quarks. The nonets of light mesons occupy the central planes, to which the $c\bar{c}$ states have been added. The neutral mesons at the centers of these planes are mixtures of $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$ states.

12.2. Mesons: $q\bar{q}$ states

Nearly all known mesons are bound states of a quark q and an antiquark $\bar{q}'$ (the flavors of q and q' may be different). If the orbital angular momentum of the $q\bar{q}'$ state is L, then the parity P is $(-1)^{L+1}$. A state $q\bar{q}$ of a quark and its own antiquark is also an eigenstate of charge conjugation, with $C = (-1)^{L+S}$, where the spin S is 0 or 1. The $L = 0$ states are the pseudoscalars, $J^P = 0^-$, and the vectors, $J^P = 1^-$. Assignments for many of the known mesons are given in Table 12.2. States in the "normal" spin-parity series, $P = (-1)^J$, must, according to the above, have $S = 1$ and hence $CP = +1$. Thus mesons with normal spin-parity and $CP = -1$ are forbidden in the $q\bar{q}'$ model. The $J^{PC} = 0^{--}$ state is forbidden as well. Mesons with such J^{PC} may exist, but would lie outside the $q\bar{q}'$ model.

The nine possible $q\bar{q}'$ combinations containing u, d, and s quarks group themselves into an octet and a singlet:

$$\mathbf{3} \otimes \overline{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1} \tag{12.1}$$

States with the same IJ^P and additive quantum numbers can mix. (If they are eigenstates of charge conjugation, they must also have the same value of C.) Thus the $I = 0$ member of the ground-state pseudoscalar octet mixes with the corresponding pseudoscalar singlet to produce the η and η'. These appear as members of a nonet, which is shown as the middle plane in Fig. 12.1(a). Similarly, the ground-state vector nonet appears as the middle plane in Fig. 12.1(b).

A fourth quark such as charm can be included in this scheme by extending the symmetry to SU(4), as shown in Fig. 12.1. Bottom extends the symmetry to SU(5); to draw the multiplets would require four dimensions.

For the pseudoscalar mesons, the Gell-Mann-Okubo formula is

$$m_\eta^2 = \frac{1}{3}(4m_K^2 - m_\pi^2) , \tag{12.2}$$

assuming no octet-singlet mixing. However, the octet η_8 and singlet η_1 mix because of SU(3) breaking. In general, the mixing angle is mass dependent and becomes complex for resonances of finite width. Neglecting this, the physical states η and η' are given in terms of a mixing angle θ_P by

$$\eta = \eta_8 \cos\theta_P - \eta_1 \sin\theta_P \tag{12.3a}$$

$$\eta' = \eta_8 \sin\theta_P + \eta_1 \cos\theta_P . \tag{12.3b}$$

These combinations diagonalize the mass-squared matrix

$$M^2 = \begin{pmatrix} M_{11}^2 & M_{18}^2 \\ M_{18}^2 & M_{88}^2 \end{pmatrix} , \tag{12.4}$$

where $M_{88}^2 = \frac{1}{3}(4m_K^2 - m_\pi^2)$. It follows that

$$\tan^2\theta_P = \frac{M_{88}^2 - m_\eta^2}{m_{\eta'}^2 - M_{88}^2} . \tag{12.5}$$

The sign of θ_P is meaningful in the quark model. If

$$\eta_1 = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3} \tag{12.6a}$$

$$\eta_8 = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6} , \tag{12.6b}$$

then the matrix element M_{18}^2, which is due mostly to the strange quark mass, is negative. From the relation

$$\tan\theta_P = \frac{M_{88}^2 - m_\eta^2}{M_{18}^2} , \tag{12.7}$$

we find that $\theta_P < 0$. However, caution is suggested in the use of the η-η' mixing-angle formulas, as they are extremely sensitive to SU(3)

Table 12.2: Suggested $q\overline{q}$ quark-model assignments for most of the known mesons. Some assignments, especially for the 0^{++} multiplet and for some of the higher multiplets, are controversial. Mesons in bold face are included in the Meson Summary Table. Of the light mesons in the Summary Table, the $f_1(1420)$, $f_0(1500)$, $f_J(1710)$, $f_2(2300)$, $f_2(2340)$, and the two peaks in the $\eta(1440)$ entry are not in this table. Within the $q\overline{q}$ model, it is especially hard to find a place for the first three of these f mesons and for one of the $\eta(1440)$ peaks. See the "Note on Non-$q\overline{q}$ Mesons" at the end of the Meson Listings.

$N\ ^{2S+1}L_J$	J^{PC}	$u\overline{d}$, $u\overline{u}$, $d\overline{d}$ $I=1$	$u\overline{u}$, $d\overline{d}$, $s\overline{s}$ $I=0$	$c\overline{c}$ $I=0$	$b\overline{b}$ $I=0$	$\overline{s}u$, $\overline{s}d$ $I=1/2$	$c\overline{u}$, $c\overline{d}$ $I=1/2$	$c\overline{s}$ $I=0$	$\overline{b}u$, $\overline{b}d$ $I=1/2$	$\overline{b}s$ $I=0$
$1\ ^1S_0$	0^{-+}	**π**	**η, η'**	**η_c**		**K**	**D**	**D_s**	**B**	**B_s**
$1\ ^3S_1$	1^{--}	**ρ**	**ω, ϕ**	**$J/\psi(1S)$**	**$\Upsilon(1S)$**	**$K^*(892)$**	**$D^*(2010)$**	**$D_s^*(2110)$**	**$B^*(5330)$**	
$1\ ^1P_1$	1^{+-}	**$b_1(1235)$**	**$h_1(1170)$**, $h_1(1380)$	$h_c(1P)$		**K_{1B}**†	**$D_1(2420)$**	**$D_{s1}(2536)$**		
$1\ ^3P_0$	0^{++}	*	*	**$\chi_{c0}(1P)$**	**$\chi_{b0}(1P)$**	**$K_0^*(1430)$**				
$1\ ^3P_1$	1^{++}	**$a_1(1260)$**	**$f_1(1285)$, $f_1(1510)$**	**$\chi_{c1}(1P)$**	**$\chi_{b1}(1P)$**	**K_{1A}**†				
$1\ ^3P_2$	2^{++}	**$a_2(1320)$**	**$f_2(1270)$, $f_2'(1525)$**	**$\chi_{c2}(1P)$**	**$\chi_{b2}(1P)$**	**$K_2^*(1430)$**	**$D_2^*(2460)$**			
$1\ ^1D_2$	2^{-+}	**$\pi_2(1670)$**				**$K_2(1770)$**				
$1\ ^3D_1$	1^{--}	**$\rho(1700)$**	**$\omega(1600)$**	**$\psi(3770)$**		**$K^*(1680)$**‡				
$1\ ^3D_2$	2^{--}					**$K_2(1820)$**				
$1\ ^3D_3$	3^{--}	**$\rho_3(1690)$**	**$\omega_3(1670)$, $\phi_3(1850)$**			**$K_3^*(1780)$**				
$1\ ^3F_4$	4^{++}	$a_4(2040)$	**$f_4(2050)$**, $f_4(2220)$			**$K_4^*(2045)$**				
$2\ ^1S_0$	0^{-+}	**$\pi(1300)$**	**$\eta(1295)$**	**$\eta_c(2S)$**		$K(1460)$				
$2\ ^3S_1$	1^{--}	**$\rho(1450)$**	**$\omega(1420)$, $\phi(1680)$**	**$\psi(2S)$**	**$\Upsilon(2S)$**	**$K^*(1410)$**‡				
$2\ ^3P_2$	2^{++}		$f_2(1810)$, **$f_2(2010)$**		**$\chi_{b2}(2P)$**	$K_2^*(1980)$				
$3\ ^1S_0$	0^{-+}	$\pi(1770)$	$\eta(1760)$			$K(1830)$				

* See our scalar minireview in the Particle Listings. The candidates for the $I=1$ states are $a_0(980)$ and $a_0(1450)$, while for $I=0$ they are: $f_0(400\text{–}1200)$, $f_0(980)$, and $f_0(1370)$. The light scalars are problematic, since there may be two poles for one $q\overline{q}$ state and $a_0(980)$, $f_0(980)$ may be $K\overline{K}$ bound states.

† The K_{1A} and K_{1B} are nearly equal (45°) mixes of the $K_1(1270)$ and $K_1(1400)$.

‡The $K^*(1410)$ could be replaced by the $K^*(1680)$ as the $2\ ^3S_1$ state.

If we allow $M_{88}^2 = \frac{1}{3}(4m_K^2 - m_\pi^2)\ (1+\Delta)$, the mixing angle is determined by

$$\tan^2\theta_P = 0.0319(1+17\Delta) \tag{12.8}$$

$$\theta_P = -10.1^\circ(1+8.5\Delta) \tag{12.9}$$

to first order in Δ. A small breaking of the Gell-Mann-Okubo relation can produce a major modification of θ_P.

For the vector mesons, $\pi\to\rho$, $K\to K^*$, $\eta\to\phi$, and $\eta'\to\omega$, so that

$$\phi = \omega_8\cos\theta_V - \omega_1\sin\theta_V \tag{12.10}$$

$$\omega = \omega_8\sin\theta_V + \omega_1\cos\theta_V\ . \tag{12.11}$$

For "ideal" mixing, $\phi = s\overline{s}$, so $\tan\theta_V = 1/\sqrt{2}$ and $\theta_V = 35.3^\circ$. Experimentally, θ_V is near 35°, the sign being determined by a formula like that for $\tan\theta_P$. Following this procedure we find the mixing angles given in Table 12.3.

Table 12.3: Singlet-octet mixing angles for several nonets, neglecting possible mass dependence and imaginary parts. The sign conventions are given in the text. The values of $\theta_{\rm quad}$ are obtained from the equations in the text, while those for $\theta_{\rm lin}$ are obtained by replacing m^2 by m throughout. Of the two isosinglets in a nonet, the mostly octet one is listed first.

J^{PC}	Nonet members	$\theta_{\rm quad}$	$\theta_{\rm lin}$
0^{-+}	π, K, η, η'	-10°	-23°
1^{--}	ρ, $K^*(892)$, ϕ, ω	39°	36°
2^{++}	$a_2(1320)$, $K_2^*(1430)$, $f_2'(1525)$, $f_2(1270)$	28°	26°
3^{--}	$\rho_3(1690)$, $K_3^*(1780)$, $\phi_3(1850)$, $\omega_3(1670)$	29°	28°

In the quark model, the coupling of neutral mesons to two photons is proportional to $\sum_i Q_i^2$, where Q_i is the charge of the i-th quark. This provides an alternative characterization of mixing. For example, defining

$$\mathrm{Amp}\,[P \to \gamma(k_1)\,\gamma(k_2)] = M\epsilon^{\mu\nu\alpha\beta}\,\epsilon^*_{1\mu}\,k_{1\nu}\,\epsilon^*_{2\alpha}\,k_{2\beta}\ , \qquad (12.12)$$

where $\epsilon_{i\lambda}$ is the λ component of the polarization vector of the i^{th} photon, one finds

$$\frac{M(\eta \to \gamma\gamma)}{M(\pi^0 \to \gamma\gamma)} = \frac{1}{\sqrt{3}}(\cos\theta_P - 2\sqrt{2}\sin\theta_P) = \frac{1.73 \pm 0.18}{\sqrt{3}} \qquad (12.13a)$$

$$\frac{M(\eta' \to \gamma\gamma)}{M(\pi^0 \to \gamma\gamma)} = 2\sqrt{2/3}\left(\cos\theta_P + \frac{\sin\theta_P}{2\sqrt{2}}\right) = 2\sqrt{2/3}\,(0.78 \pm 0.04)\ , \qquad (12.13b)$$

where the numbers with errors are experimental. These data favor $\theta_P \approx -20^\circ$, which is compatible with the quadratic mass mixing formula with about 12% SU(3) breaking in M^2_{88}.

12.3. Baryons: qqq states

All the established baryons are apparently 3-quark (qqq) states, and each such state is an SU(3) color singlet, a completely antisymmetric state of the three possible colors. Since the quarks are fermions, the state function for any baryon must be antisymmetric under interchange of any two equal-mass quarks (up and down quarks in the limit of isospin symmetry). Thus the state function may be written as

$$|\,qqq\,\rangle_A = |\,\mathrm{color}\,\rangle_A \times |\,\mathrm{space,\ spin,\ flavor}\,\rangle_S\ , \qquad (12.14)$$

where the subscripts S and A indicate symmetry or antisymmetry under interchange of any two of the equal-mass quarks. Note the contrast with the state function for the three nucleons in ^{3}H or ^{3}He:

$$|\,NNN\,\rangle_A = |\,\mathrm{space,\ spin,\ isospin}\,\rangle_A\ . \qquad (12.15)$$

This difference has major implications for internal structure, magnetic moments, *etc.* (For a nice discussion, see Ref. 1.)

The "ordinary" baryons are made up of u, d, and s quarks. The three flavors imply an approximate flavor SU(3), which requires that baryons made of these quarks belong to the multiplets on the right side of

$$\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3} = \mathbf{10}_S \oplus \mathbf{8}_M \oplus \mathbf{8}_M \oplus \mathbf{1}_A \qquad (12.16)$$

(see Sec. 33, on "SU(n) Multiplets and Young Diagrams"). Here the subscripts indicate symmetric, mixed-symmetry, or antisymmetric states under interchange of any two quarks. The $\mathbf{1}$ is a uds state (Λ_1) and the octet contains a similar state (Λ_8). If these have the same spin and parity they can mix. An example is the mainly octet D_{03} $\Lambda(1690)$ and mainly singlet D_{03} $\Lambda(1520)$. In the ground state multiplet, the SU(3) flavor singlet Λ is forbidden by Fermi statistics. The mixing formalism is the same as for η-η' or ϕ-ω (see above), except that for baryons the mass M instead of M^2 is used. Section 32, on "SU(3) Isoscalar Factors and Representation Matrices", shows how relative decay rates in, say, $\mathbf{10} \to \mathbf{8}\otimes\mathbf{8}$ decays may be calculated. A summary of results of fits to the observed baryon masses and decay rates for the best-known SU(3) multiplets is given in Appendix II of our 1982 edition [2].

The addition of the c quark to the light quarks extends the flavor symmetry to SU(4). Figures 12.2(a) and 12.2(b) show the (badly broken) SU(4) baryon multiplets that have as their "ground floors" the SU(3) octet that contains the nucleons and the SU(3) decuplet that contains the $\Delta(1232)$. All the particles in a given SU(4) multiplet have the same spin and parity. The only charmed baryons that have been discovered each contain one charmed quark. These belong to the first floor of the multiplet shown in Fig. 12.2(a); for details, see the "Note on Charmed Baryons" in the Baryon Particle Listings. The addition of a b quark extends the flavor symmetry to SU(5); it would require four dimensions to draw the multiplets.

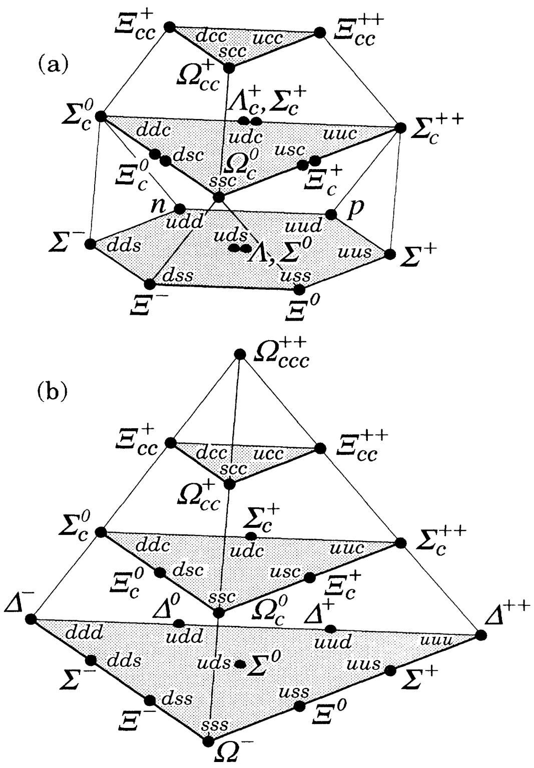

Figure 12.2: SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet. (b) The 20-plet with an SU(3) decuplet.

For the "ordinary" baryons, flavor and spin may be combined in an approximate flavor-spin SU(6) in which the six basic states are $d\uparrow$, $d\downarrow$, $\cdots$, $s\downarrow$ ($\uparrow$, $\downarrow$ = spin up, down). Then the baryons belong to the multiplets on the right side of

$$\mathbf{6}\otimes\mathbf{6}\otimes\mathbf{6} = \mathbf{56}_S \oplus \mathbf{70}_M \oplus \mathbf{70}_M \oplus \mathbf{20}_A\ . \qquad (12.17)$$

These SU(6) multiplets decompose into flavor SU(3) multiplets as follows:

$$\mathbf{56} = {}^4\mathbf{10} \oplus {}^2\mathbf{8} \qquad (12.18a)$$

$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1} \qquad (12.18b)$$

$$\mathbf{20} = {}^2\mathbf{8} \oplus {}^4\mathbf{1}\ , \qquad (12.18c)$$

where the superscript $(2S+1)$ gives the net spin S of the quarks for each particle in the SU(3) multiplet. The $J^P = 1/2^+$ octet containing the nucleon and the $J^P = 3/2^+$ decuplet containing the $\Delta(1232)$ together make up the "ground-state" 56-plet in which the orbital angular momenta between the quark pairs are zero (so that the spatial part of the state function is trivially symmetric). The $\mathbf{70}$ and $\mathbf{20}$ require some excitation of the spatial part of the state function in order to make the overall state function symmetric. States with nonzero orbital angular momenta are classified in SU(6)$\otimes$O(3) supermultiplets. Physical baryons with the same quantum numbers do not belong to a single supermultiplet, since SU(6) is broken by spin-dependent interactions, differences in quark masses, *etc.* Nevertheless, the SU(6)$\otimes$O(3) basis provides a suitable framework for describing baryon state functions.

It is useful to classify the baryons into bands that have the same number N of quanta of excitation. Each band consists of a number of supermultiplets, specified by (D, L_N^P), where D is the dimensionality of the SU(6) representation, L is the total quark orbital angular momentum, and P is the total parity. Supermultiplets contained in bands up to $N = 12$ are given in Ref. 3. The $N = 0$ band, which contains the nucleon and $\Delta(1232)$, consists only of the $(56,0_0^+)$ supermultiplet. The $N = 1$ band consists only of the $(70,1_1^-)$ multiplet and contains the negative-parity baryons with masses below about 1.9 GeV. The $N = 2$ band contains five supermultiplets: $(56,0_2^+)$, $(70,0_2^+)$, $(56,2_2^+)$, $(70,2_2^+)$, and $(20,1_2^+)$. Baryons belonging to the $(20,1_2^+)$ supermultiplet are not ever likely to be observed, since a coupling from the ground-state baryons requires a two-quark excitation. Selection rules are similarly responsible for the fact that many other baryon resonances have not been observed [4].

In Table 12.4, quark-model assignments are given for many of the established baryons whose SU(6)⊗O(3) compositions are relatively unmixed. We note that the unestablished resonances $\Sigma(1480)$, $\Sigma(1560)$, $\Sigma(1580)$, $\Sigma(1770)$, and $\Xi(1620)$ in our Baryon Particle Listings are too low in mass to be accommodated in most quark models [4,5].

Table 12.4: Quark-model assignments for many of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for some states, especially for the $\Lambda(1810)$, $\Lambda(2350)$, $\Xi(1820)$, and $\Xi(2030)$, are merely educated guesses.

J^P	(D, L_N^P)	S	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$3/2^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
			Decuplet members				
$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
$1/2^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$3/2^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$	
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

The quark model for baryons is extensively reviewed in Ref. 6 and 7.

12.4. Dynamics

Many specific quark models exist, but most contain the same basic set of dynamical ingredients. These include:

i) A confining interaction, which is generally spin-independent.

ii) A spin-dependent interaction, modeled after the effects of gluon exchange in QCD. For example, in the S-wave states, there is a spin-spin hyperfine interaction of the form

$$H_{HF} = -\alpha_S M \sum_{i>j} (\vec{\sigma}\lambda_a)_i (\vec{\sigma}\lambda_a)_j \ , \tag{12.19}$$

where M is a constant with units of energy, λ_a ($a = 1, \cdots, 8,$) is the set of SU(3) unitary spin matrices, defined in Sec. 32, on "SU(3) Isoscalar Factors and Representation Matrices," and the sum runs over constituent quarks or antiquarks. Spin-orbit interactions, although allowed, seem to be small.

iii) A strange quark mass somewhat larger than the up and down quark masses, in order to split the SU(3) multiplets.

iv) In the case of isoscalar mesons, an interaction for mixing $q\overline{q}$ configurations of different flavors (*e.g.*, $u\overline{u} \leftrightarrow d\overline{d} \leftrightarrow s\overline{s}$), in a manner which is generally chosen to be flavor independent.

These four ingredients provide the basic mechanisms that determine the hadron spectrum.

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13. *CP* VIOLATION

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The symmetries C (particle-antiparticle interchange) and P (space inversion) hold for strong and electromagnetic interactions. After the discovery of large C and P violation in the weak interactions, it appeared that the product CP was a good symmetry. Then CP violation was observed in K^0 decays at a level given by the parameter $\epsilon = 2.3 \times 10^{-3}$. Larger CP-violation effects are anticipated in B^0 decays.

The eigenstates of the K^0–$\overline{K}^0$ system can be written

$$|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle \ , \qquad |K_L\rangle = p|K^0\rangle - q|\overline{K}^0\rangle \ . \tag{13.1}$$

If CP invariance held, we would have $q = p$ so that K_S would be CP even and K_L CP odd. (We define $|\overline{K}^0\rangle$ as $CP\ |K^0\rangle$). CP violation in K^0–$\overline{K}^0$ mixing gives

$$\frac{p}{q} = \frac{(1+\widetilde{\epsilon})}{(1-\widetilde{\epsilon})} \ . \tag{13.2}$$

CP violation can also occur in the decay amplitudes

$$A\big(K^0 \to \pi\pi(I)\big) = A_I e^{i\delta_I} \ , \qquad A\big(\overline{K}^0 \to \pi\pi(I)\big) = A_I^* e^{i\delta_I} \ , \tag{13.3}$$

where I is the isospin of $\pi\pi$, δ_I is the final-state phase shift, and A_I would be real if CP invariance held. The ratios of CP-violating to CP-conserving amplitudes $\eta_{+-} = A(K_L^0 \to \pi^+\pi^-)/A(K_S^0 \to \pi^+\pi^-)$ and $\eta_{00} = A(K_L^0 \to \pi^0\pi^0)/A(K_S^0 \to \pi^0\pi^0)$ can be written as

$$\eta_{+-} = \epsilon + \epsilon' \ , \qquad \eta_{00} = \epsilon - 2\epsilon' \ , \tag{13.4a}$$

$$\epsilon = \widetilde{\epsilon} + i\ \left(\text{Im}\, A_0/\text{Re}\, A_0\right) \ , \tag{13.4b}$$

$$|\sqrt{2}\epsilon'| = (\text{Re}\, A_2/\text{Re}\, A_0)\ \left(\text{Im}\, A_2/\text{Re}\, A_2 - \text{Im}\, A_0/\text{Re}\, A_0\right) \ . \tag{13.4c}$$

If CP violation is confined to the mass matrix, as in a superweak theory, ϵ' is zero and $\eta_{+-} = \eta_{00} = \epsilon = \widetilde{\epsilon}$. The measurement of ϵ'/ϵ has as its goal finding an effect that requires CP violation in the decay amplitude; this corresponds to a relative phase between A_2 and A_0 as seen in Eq. (13.4*c*).

In the Standard Model, CP violation arises as a result of a single phase entering the CKM matrix (q.v.). As a result in what is now the standard phase convention, two elements have large phases, $V_{ub} \sim e^{-i\gamma}$, $V_{td} \sim e^{-i\beta}$. Because these elements have small magnitudes and involve the third generation, CP violation in the K^0 system is small. A definite nonzero value for ϵ'/ϵ is expected but hadronic uncertainties allow theoretical values between 10^{-4} and 3×10^{-3}. On the other hand, large effects are expected in the B^0 system, which is a major motivation for B factories.

The most clearcut experiments would be those that measure asymmetries between B^0 and $\overline{B}^0$ decays. The time-dependent rate to a CP eigenstate a is given by

$$\Gamma_a \sim e^{-\Gamma t}\Big(\big[1+|r_a|^2\big] \pm \big[1-|r_a|^2\big]\ \cos(\Delta M t) \mp 2\eta_a \text{Im}\, r_a\ \sin(\Delta M t)\Big) \ , \tag{13.5}$$

where the top sign is for B^0 and the bottom for $\overline{B}^0$, η_a is the CP eigenvalue and

$$r_a = (q_B/p_B)\ \overline{A}_a/A_a \ . \tag{13.6}$$

The quantity (q_B/p_B) comes from the analogue for B^0 of Eq. (13.1); however, for B^0 the eigenstates have a negligible lifetime difference and are distinguished only by the mass difference ΔM; also as a result $|q_B/p_B| \approx 1$ so that $\widetilde{\epsilon}_B$ is purely imaginary. A_a ($\overline{A}_a$) are the decay amplitudes to a for B^0 ($\overline{B}^0$). If only one quark weak transition contributes to the decay $|\overline{A}_a/A_a| = 1$ so that $|r_a| = 1$ and the $\cos(\Delta M t)$ term vanishes. The basic goal of the B factories is to observe the asymmetric $\sin(\Delta M t)$ term. For B^0 ($\overline{B}^0$) $\to \psi K_s$ from the transition $b \to c\overline{c}s$, one finds in the Standard Model the asymmetry parameter

$$-2\text{Im}\, r_a = \sin 2\beta \ . \tag{13.7}$$

The asymmetry is given directly in terms of a CKM phase with no hadronic uncertainty and is expected to be between 0.2 and 0.8. For B^0 ($\overline{B}^0$) $\to \pi^+\pi^-$ from the transition $b \to u\overline{u}d$

$$-2\text{Im}\, r_a = \sin 2(\beta+\gamma) \ . \tag{13.8}$$

(This result has some hadronic uncertainty due to penguin contributions, but these should be able to be estimated from other observations.) While either of these asymmetries could be ascribed to $B^0 - \overline{B}^0$ mixing (q_B/p_B or $\widetilde{\epsilon}_B$), the difference between the two asymmetries is evidence for direct CP violation. From Eq. (13.6) (with $\overline{A}_a/A_a = 1$) it is seen this corresponds to a phase difference between $A_{\psi K_S}$ and $A_{\pi^+\pi^-}$. Thus this is analogous to ϵ'. In the standard phase convention 2β in Eq. (13.7) and (13.8) arises from $B^0 - \overline{B}^0$ mixing whereas the 2γ comes from V_{bu} in the transition $b \to u\overline{u}d$.

CP violation in the decay amplitude is also revealed by the $\cos(\Delta M t)$ in Eq. (13.5) or by a difference in rates of B^+ and B^- to charge-conjugate states. These effects, however, require two contributing amplitudes to the decay (such as a tree amplitude plus a penguin) and also require final-state interaction phases. Predicted effects are very uncertain and are generally small.

For further details, see the notes on CP violation in the K_L^0, K_S^0, and B^0 Particle Listings of this *Review*.

14. CONSTRAINTS ON NEW PHYSICS FROM ELECTROWEAK ANALYSES

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Precision electroweak experiments are sensitive to loop effects, allowing a prediction of the top quark mass m_t, constraints on the Higgs mass M_H, and a search for certain types of new physics that have not been directly detected. This article will mainly discuss m_t, M_H, and the effects of exotic particles with masses large compared to M_Z on the gauge boson self-energies. Brief remarks are made on new physics which is not of this type. The effects of m_t and M_H on the radiative corrections are treated exactly to one-loop order. This can in principle be done for other types of new physics, but this necessitates a case-by-case discussion. Instead, the article will discuss in detail only the constraints on particles with heavy masses $M_{\rm new} \gg M_Z$ in an expansion in $M_Z/M_{\rm new}$. In this case, most of the effects on precision measurements can be described by three gauge self-energy parameters S, T, and U, and a $Zb\bar{b}$ vertex correction parameter γ_b.

A large value of $|m_t - m_b|$ breaks vector SU(2) symmetry and significantly affects many precision electroweak observables. The major sensitivity for processes involving light external fermions is through t- and b-quark loop contributions to the W and Z self-energies [1]. Most of the shift in M_W is absorbed into the measured value of the Fermi constant G_F, while the prediction for M_Z,

$$M_Z = \frac{M_W}{\hat{\rho}^{1/2}\hat{c}_Z} , \tag{14.1}$$

decreases rapidly for large m_t. In Eq. (14.1) $\hat{\rho} \simeq 1 + \rho_t$, where

$$\rho_t = \frac{3G_F m_t^2}{8\sqrt{2}\pi^2} \sim 0.0100 \left(\frac{m_t}{180 \text{ GeV}}\right)^2 , \tag{14.2}$$

and $\hat{c}_Z = \cos\hat{\theta}_W(M_Z)$, the cosine of the weak angle in the $\overline{\rm MS}$ scheme evaluated at M_Z [2]. In addition to M_Z itself, neutral current amplitudes and the coefficient of $G_F M_Z^3$ in the expression for Γ_Z are multiplied by $\hat{\rho}$. There is additional logarithmic m_t dependence in these quantities and in M_W. Vertex and box diagrams also introduce large (quadratic) m_t dependence, which is especially important in quantities involving external b quarks (in order to avoid mixing angle suppressions), such as in the $Z \to b\bar{b}$ partial width or in $B - \overline{B}$ mixing. Finally, in the on-shell renormalization scheme, significant but somewhat artificial m_t dependence is introduced into Z vertices through the definition [2] $s_W^2 \equiv 1 - M_W^2/M_Z^2$.

As discussed in the section on the Standard Model of Electroweak Interactions (Sec. 10) (see especially Fig. 10.1), the consistency of the various observables allows a prediction for m_t. A global fit to all indirect data (see Table 10.5 of the Standard Model Section) yields

$$m_t = 179 \pm 8^{+17}_{-20} \text{ GeV} , \tag{14.3}$$

where the central value is for a Higgs mass $M_H = 300$ GeV and the second uncertainty is from varying M_H in the range 60 GeV ($-$) to 1000 GeV ($+$). This is in remarkable agreement with the direct determination $m_t = 180 \pm 12$ GeV by the CDF [3] and DØ [4] collaborations. (The indirect prediction is for the pole mass, which corresponds approximately to the kinematic mass determined by CDF and DØ.) A combined fit to both the indirect and direct data yields [2]

$$m_t = 180 \pm 7^{+12}_{-13} \text{ GeV} . \tag{14.4}$$

As discussed in Ref. 2, the combination of indirect data with the direct CDF and DØ value for m_t allows stringent limits on new physics. In particular, many extensions of the Standard Model are described by the ρ_0 parameter:

$$\rho_0 \equiv M_W^2/(M_Z^2\,\hat{c}_Z^2\,\hat{\rho}) , \tag{14.5}$$

which describes new sources of SU(2) breaking that cannot be accounted for by Higgs doublets or m_t effects. It has previously been difficult to distinguish ρ_0 from $\hat{\rho} \simeq 1 + \rho_t$ experimentally, though some separation could be done utilizing R_b [5]. Using the direct m_t value as an independent constraint, however, one can calculate $\hat{\rho}$ and thus obtain the precise value [2] $\rho_0 = 1.0002 \pm 0.0013 \pm 0.0018$, where the second error is from M_H. In Ref. 2, this result was used to constrain the vacuum expectation values of higher-dimensional Higgs representations. It can also be used to constrain other types of new physics. For example, nondegenerate multiplets of heavy fermions or scalars break the vector part of weak SU(2) and lead to a decrease in the value of M_Z/M_W. A nondegenerate SU(2) doublet $\binom{f_1}{f_2}$ yields a positive contribution to ρ_t of [1]

$$\frac{CG_F}{8\sqrt{2}\pi^2}\Delta m^2 , \tag{14.6}$$

where

$$\Delta m^2 \equiv m_1^2 + m_2^2 - \frac{4m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\frac{m_1}{m_2} \geq (m_1 - m_2)^2 , \tag{14.7}$$

and $C = 1$ (3) for color singlets (triplets). Thus, in the presence of such multiplets, one has

$$\frac{3G_F}{8\sqrt{2}\pi^2}\sum_i \frac{C_i}{3}\Delta m_i^2 = \rho_0 - 1 , \tag{14.8}$$

where the sum includes fourth-family quark or lepton doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, and scalar doublets such as $\binom{\tilde{t}}{\tilde{b}}$ in supersymmetry (in the absence of $L - R$ mixing). This implies

$$\sum_i \frac{C_i}{3}\Delta m_i^2 < (76 \text{ GeV})^2 ,\ (98 \text{ GeV})^2 ,\ (122 \text{ GeV})^2 \tag{14.9}$$

for $M_H = 60$, 300, or 1000 GeV at 90% CL.

Nondegenerate multiplets usually imply $\rho_0 > 1$. Similarly, heavy Z' bosons decrease the prediction for M_Z due to mixing and generally lead to $\rho_0 > 1$ [6]. On the other hand, additional Higgs doublets which participate in spontaneous symmetry breaking [7], heavy lepton doublets involving Majorana neutrinos [8], and the vacuum expectation values of Higgs triplets or higher-dimensional representations can contribute to ρ_0 with either sign. Allowing for the presence of heavy degenerate chiral multiplets (the S parameter, to be discussed below) affects the determination of ρ_0 from the data, at present leading to a smaller value.

As discussed in the Standard Model of Electroweak Interactions section (Sec. 10), the indirect data exhibit a moderate preference for a smaller Higgs mass. The best fit to m_t as a function of M_H is roughly

$$m_t \sim 180 \pm 7 + 13 \ln\left(\frac{M_H}{300 \text{ GeV}}\right) \tag{14.10}$$

including the direct CDF/DØ constraint. The χ^2 for $M_H = 60$ GeV is lower by 7.9 than that for $M_H = 1000$ GeV, implying $M_H \lesssim 320(430)$ GeV at 90(95)% CL. This result is consistent with the minimal supersymmetric extension of the Standard Model, which acts much like the Standard Model with a light Higgs as far as precision experiments are concerned. However, the M_H constraint is largely driven by R_b and A_{LR}^0, which differ significantly from the Standard Model predictions. In particular, the conclusions for M_H could be invalidated if other new physics modifies the precision observables significantly [9–15].

A number of authors have considered the general effects on neutral current and Z and W-pole observables of various types of heavy (*i.e.*, $M \gg M_Z$) physics which contribute to the W and Z self-energies but which do not have any direct coupling to the ordinary fermions. In addition to nondegenerate multiplets, which break the vector part of weak SU(2), these include heavy degenerate multiplets of chiral fermions which break the axial generators. The effects of one degenerate chiral doublet are small, but in technicolor theories there may be many chiral doublets and therefore significant effects [9].

Such effects can be described by just three parameters, S, T, and U at the one (electroweak) loop level. (Three additional parameters are needed if the new physics scale is comparable to M_Z [16].) T is proportional to the difference between the W and Z self-energies at $Q^2=0$ (*i.e.*, vector SU(2)-breaking), while S ($S+U$) is associated with the difference between the Z (W) self-energy at $Q^2=M^2_{Z,W}$ and $Q^2=0$ (axial SU(2)-breaking). In the $\overline{\rm MS}$ scheme [10]

$$\alpha(M_Z)T \equiv \frac{\Pi^{\rm new}_{WW}(0)}{M_W^2} - \frac{\Pi^{\rm new}_{ZZ}(0)}{M_Z^2}$$

$$\frac{\alpha(M_Z)}{4\widehat{s}^2_Z\widehat{c}^2_Z} S \equiv \frac{\Pi^{\rm new}_{ZZ}(M_Z^2)-\Pi^{\rm new}_{ZZ}(0)}{M_Z^2}$$

$$\frac{\alpha(M_Z)}{4\widehat{s}^2_Z}(S+U) \equiv \frac{\Pi^{\rm new}_{WW}(M_W^2)-\Pi^{\rm new}_{WW}(0)}{M_W^2}\ , \qquad (14.11)$$

where $\Pi^{\rm new}_{WW}$ and $\Pi^{\rm new}_{ZZ}$ are respectively the contributions of the new physics to the W and Z self-energies, $\widehat{s}^2_Z=\sin^2\widehat{\theta}_W(M_Z)$, $\widehat{c}^2_Z=1-\widehat{s}^2_Z$, and $\alpha(M_Z)\sim 1/129$ [2] is the running coupling evaluated at M_Z. S, T, and U are defined with a factor of α removed, so that they are expected to be of order unity in the presence of new physics. S, T, and U are related to other parameters ($\widehat{\epsilon}_i$, h_i, S_i) defined in [10–12] by

$$T = h_V = \widehat{\epsilon}_1/\alpha$$

$$S = h_{AZ} = S_Z = 4\widehat{s}^2_Z\widehat{\epsilon}_3/\alpha$$

$$U = h_{AW}-h_{AZ} = S_W - S_Z = -4\widehat{s}^2_Z\widehat{\epsilon}_2/\alpha\ . \qquad (14.12)$$

A heavy nondegenerate multiplet of fermions or scalars contributes positively to T as

$$\rho_0 = \frac{1}{1-\alpha T} \simeq 1+\alpha T\ , \qquad (14.13)$$

where ρ_0 is given in Eq. (14.8). If there are non-doublet Higgs representations, their vacuum expectation values also contribute to ρ_0. The effects of such nonstandard Higgs representations cannot be separated from heavy nondegenerate multiplets unless the new physics has other consequences, such as vertex corrections. Most of the original papers defined T to include the effects of loops only. However, we will redefine T to include all new sources of SU(2) breaking, including nonstandard Higgs, so that T and ρ_0 are equivalent by Eq. (14.13).

A multiplet of heavy degenerate chiral fermions yields

$$S = C\sum_i \Big(t_{3L}(i)-t_{3R}(i)\Big)^2/3\pi\ , \qquad (14.14)$$

where $t_{3L,R}(i)$ is the third component of weak isospin of the left- (right-) handed component of fermion i and C is the number of colors. For example, a heavy degenerate ordinary or mirror family would contribute $2/3\pi$ to S. In technicolor models with QCD-like dynamics, one expects [9] $S\sim 0.45$ for an isodoublet of technifermions, assuming $N_{TC}=4$ technicolors, while $S\sim 1.62$ for a full technigeneration with $N_{TC}=4$; T is harder to estimate because it is model dependent. In these examples one has $S\geq 0$. However, the QCD-like models are excluded on other grounds (flavor-changing neutral currents, and too-light quarks and pseudo-Goldstone bosons [17]). In particular, these estimates do not apply to models of walking technicolor [17], for which S can be smaller or even negative [18]. Other situations in which $S<0$, such as loops involving scalars or Majorana particles, are also possible [19]. Supersymmetric extensions of the Standard Model generally give very small effects [20]. Most simple types of new physics yield $U=0$, although there are counter-examples, such as the effects of anomalous triple-gauge vertices [12].

It is also possible to parametrize the effects of large $m_t \gg M_Z$ (except for the $b\bar{b}$ vertex) or $M_H \gg M_Z$ in terms of S, T, and U. If one takes $m_t=m_t^{\rm ref}, M_H=M_H^{\rm ref}$ as a reference point, then other values of m_t and M_H can be expressed for large m_t, M_H as [11]

$$\Delta T = \frac{\rho_t(m_t)-\rho_t(m_t^{\rm ref})}{\alpha} - \frac{3G_F}{4\sqrt{2}\alpha\pi^2}(M_Z^2-M_W^2)\ln(M_H/M_H^{\rm ref})$$

$$\Delta S = c_S\ln(m_t/m_t^{\rm ref}) + \frac{1}{6\pi}\ln(M_H/M_H^{\rm ref})$$

$$\Delta U = c_U\ln(m_t/m_t^{\rm ref})\ , \qquad (14.15)$$

where the coefficients c_S and c_U depend on the renormalization scheme. Prior to the direct obsevation of the t quark it was difficult to separate the effects of m_t and M_H from the new physics contributions to S, T, and U. Most authors therefore picked fixed arbitrary reference values for m_t and M_H, so that the values of S,T,U extracted from the data included both new physics and $\Delta S,\Delta T,\Delta U$. Now that m_t is known independently this is no longer necessary [21]. In the following, S, T, and U will represent the contributions of new physics only. The full m_t and M_H dependence of all observables will be included in the fits separately, with the uncertainties in m_t and M_H appearing as uncertainties in the extracted S,T,U.

The Standard Model expressions for observables are replaced by

$$M_Z^2 = M_{Z0}^2\frac{1-\alpha T}{\rho_0}\frac{1}{1-G_F M_{Z0}^2 S/2\sqrt{2}\pi}$$

$$M_W^2 = M_{W0}^2\frac{1}{1-G_F M_{W0}^2(S+U)/2\sqrt{2}\pi}\ , \qquad (14.16)$$

where M_{Z0} and M_{W0} are the Standard Model expressions (as functions of m_t and M_H) in the $\overline{\rm MS}$ scheme. Furthermore,

$$\Gamma_Z = \frac{\rho_0}{1-\alpha T}M_Z^3\beta_Z$$

$$\Gamma_W = M_W^3\beta_W$$

$$A_i = \frac{\rho_0}{1-\alpha T}A_{i0}\ , \qquad (14.17)$$

where β_Z and β_W are the Standard Model expressions for the reduced widths Γ_{Z0}/M_{Z0}^3 and Γ_{W0}/M_{W0}^3, M_Z and M_W are the physical masses, and A_i (A_{i0}) is a neutral current amplitude (in the Standard Model).

The $Z\to b\bar{b}$ vertex is sensitive to certain types of new physics which primarily couple to heavy families. It is useful to introduce an additional parameter γ_b by [22]

$$\Gamma(Z\to b\bar{b}) = \Gamma^0(Z\to b\bar{b})(1+\gamma_b)\ , \qquad (14.18)$$

where Γ^0 is the Standard Model expression (or the expression modified by S, T, and U). Experimentally, $R_b\equiv\Gamma(Z\to b\bar{b})/\Gamma(\text{had})$ is more than 3σ above the Standard Model expectations, favoring a positive γ_b. (See the discussion in Ref. 2.) Extended technicolor interactions generally yield negative values of γ_b of a few percent [23], although it is possible to obtain a positive γ_b in models for which the extended technicolor group does not commute with the electroweak gauge group [24] or for which diagonal interactions related to the extended technicolor dominate [25]. Topcolor and topcolor-assisted technicolor models do not generally give a significant contribution to γ_b because the extended technicolor contribution to m_t is small [26]. Supersymmetry can yield (typically small) contributions of either sign [27,28].

The data allow a simultaneous determination of $\widehat{s}^2_Z$ (*e.g.*, from the Z-pole asymmetries), S (from M_Z), U (from M_W), T (*e.g.*, from the Z-decay widths), α_s (from $\Gamma(Z\to\text{had})/\Gamma(\ell\ell)$), m_t (from CDF and DØ), and γ_b (from R_b) with little correlation except between α_s and γ_b.

$$S = -0.28\pm 0.19^{-0.08}_{+0.17}$$

$$T = -0.20\pm 0.26^{+0.17}_{-0.12}$$

$$U = -0.31\pm 0.54$$

$$\gamma_b = 0.032\pm 0.010\ , \qquad (14.19)$$

and $\hat{s}^2_Z = 0.2311 \pm 0.0003$, $\alpha_s = 0.103 \pm 0.008$, $m_t = 181 \pm 12$ GeV, where the first uncertainties are from the inputs. The central values assume $M_H = 300$ GeV, and the second uncertainty, when given, is the change for $M_H = 1000$ GeV (upper) and 60 GeV (lower). S, T, and U, which are due to new physics only, are all consistent with the Standard Model value of zero at or near the 1σ level, although there is a slight tendency for negative S and T. Using Eq. (14.13) the value of ρ_0 corresponding to T is $0.9985 \pm 0.0019^{+0.0012}_{-0.0009}$. The values of the $\hat{\epsilon}$ parameters defined in Eq. (14.12) are

$$\begin{aligned} \hat{\epsilon}_3 &= -0.0022 \pm 0.0015^{-0.0007}_{+0.0013} \,, \\ \hat{\epsilon}_1 &= -0.0015 \pm 0.0019^{+0.0013}_{-0.0008} \,, \\ \hat{\epsilon}_2 &= +0.0024 \pm 0.0033 \,. \end{aligned} \qquad (14.20)$$

There is a strong correlation between γ_b and the predicted α_s, just as in the model with $S = T = U = 0$ [2,21]. For $\gamma_b = 0$ one obtains $\alpha_s = 0.122 \pm 0.005$ and $T = -0.04 \pm 0.25^{+0.17}_{-0.11}$, with little change in the other parameters. The allowed region in S–T is shown in Fig. 14.1. From Eq. (14.19) one obtains $S < 0.12\,(0.21)$ and $T < 0.29\,(0.38)$ at 90 (95)% CL. If one requires the constraint $S \geq 0$ (as in QCD-like technicolor models) then $S < 0.25\,(0.30)$. Allowing arbitrary S, only one heavy generation of ordinary fermions is allowed at 95% CL. The favored value of S is problematic for simple technicolor models with many techni-doublets and QCD-like dynamics, as is the value of γ_b. Although S is consistent with zero, the electroweak asymmetries, especially the SLD left-right asymmetry, favor $S < 0$. The simplest origin of $S < 0$ would probably be an additional heavy Z' boson [6], which could mimic $S < 0$. Similarly, there is a slight indication of negative T, while, as discussed above, nondegenerate scalar or fermion multiplets generally predict $T > 0$.

There is no simple parametrization that is powerful enough to describe the effects of every type of new physics on every possible observable. The S, T, and U formalism describes many types of heavy physics which affect only the gauge self-energies, and it can be applied to all precision observables. However, new physics which couples directly to ordinary fermions, such as heavy Z' bosons or mixing with exotic fermions cannot be fully parametrized in the S, T, and U framework. It is convenient to treat these types of new physics by parametrizations that are specialized to that particular class of theories (*e.g.*, extra Z' bosons), or to consider specific models (which might contain, *e.g.*, Z' bosons and exotic fermions with correlated parameters). Constraints on various types of new physics are reviewed in [29,30,31]. Fits to models with technicolor, extended technicolor, and supersymmetry are described respectively in [32], [24], and [33]. Versions of these which allow $\gamma_b > 0$ can, for that reason, give better fits than the Standard Model. An alternate formalism [34] defines parameters, ϵ_1, ϵ_2, ϵ_3, ϵ_b in terms of the specific observables M_W/M_Z, the leptonic Z width $\Gamma_{\ell\ell}$, the forward-backward asymmetry [2] at the Z pole $A^{(0,\ell)}_{FB}$, and R_b. The definitions coincide with those for $\hat{\epsilon}_i$ in Eqs. (14.11) and (14.12) for physics which affects gauge self-energies only, but the ϵ's now parametrize arbitrary types of new physics and can also incorporate all of the effects of m_t and M_H on the four basic observables. However, the ϵ's are not related to other observables unless additional model-dependent assumptions are made. Another approach [35,36] parametrizes new physics in terms of gauge-invariant sets of operators. It is especially powerful in studying the effects of new physics on nonabelian gauge vertices. The most general approach introduces deviation vectors [29]. Each type of new physics defines a deviation vector, the components of which are the deviations of each observable from its Standard Model prediction, normalized to the experimental uncertainty. The length (direction) of the vector represents the strength (type) of new physics.

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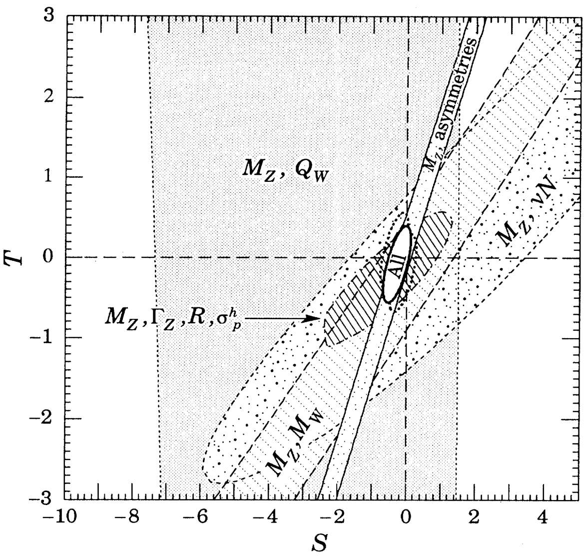

Figure 14.1: 90% CL limits on S and T from various inputs. S and T represent the contributions of new physics only: uncertainties from m_t are included in the errors. The contours assume $M_H = 300$ GeV, with the exception of the two contours for all data which are displaced slightly upward (downward), corresponding to $M_H = 1000$ (60) GeV. The fit to M_W and M_Z assumes $U = 0$, while U is arbitrary in the other fits.

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15. BIG-BANG COSMOLOGY

Revised November 1993 by K.A. Olive.

At early times, and today on a sufficently large scale, our Universe is very nearly homogeneous and isotropic. The most general space-time metric for a homogeneous, isotropic space is the Friedmann-Robertson-Walker metric (with $c = 1$) [1,2,3]:

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right] . \tag{15.1}$$

$R(t)$ is a scale factor for distances in comoving coordinates. With appropriate rescaling of the corrdinates, κ can be chosen to be $+1$, -1, or 0, corresponding to closed, open, or spatially flat geometries. Einstein's equations lead to the Friedmann equation

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi\, G_N\, \rho}{3} - \frac{\kappa}{R^2} + \frac{\Lambda}{3} , \tag{15.2}$$

as well as to

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}\ (\rho + 3p) , \tag{15.3}$$

where $H(t)$ is the Hubble parameter, ρ is the total mass-energy density, p is the isotropic pressure, and Λ is the cosmological constant. (For limits on Λ, see the Table of Astrophysical Constants; we will assume here $\Lambda = 0$.) The Friedmann equation serves to define the density parameter Ω_0 (subscript 0 indicates present-day values):

$$\kappa/R_0^2 = H_0^2(\Omega_0 - 1) , \qquad \Omega_0 = \rho_0/\rho_c ; \tag{15.4}$$

and the critical density is defined as

$$\rho_c \equiv \frac{3H^2}{8\pi\, G_N} = 1.88 \times 10^{-29}\, h^2 \text{ g cm}^{-3} , \tag{15.5}$$

with

$$H_0 = 100\, h_0 \text{ km s}^{-1}\text{ Mpc}^{-1} = h_0/(9.78 \text{ Gyr}) . \tag{15.6}$$

Observational bounds give $0.4 < h_0 < 1$. The three curvature signatures $\kappa = +1, -1$, and 0 correspond to $\Omega_0 > 1$, < 1, and $= 1$. Knowledge of Ω_0 is even poorer than that of h_0. Luminous matter (stars and associated material) contribute $\Omega_{\rm lum} \leq 0.01$. There is no lack of evidence for copious amounts of dark matter: rotation curves of spiral galaxies, virial estimates of cluster masses, gravitational lensing by clusters and individual galaxies, and so on. The minimum amount of dark matter required to explain the flat rotation curves of spiral galaxies only amounts to $\Omega_0 \sim 0.1$, while estimates for Ω_0 based upon cluster virial masses suggests $\Omega_0 \sim 0.2 - 0.4$. The highest estimates for the mass density come from studies of the peculiar motions of galaxies (including our own); estimates for Ω_0 obtained by relating peculiar velocity measurements to the distribution galaxies within a few hundred Mpc approach unity. A conservative range for the mass density is: $0.1 \leq \Omega_0 \leq 2$. The excess of Ω_0 over $\Omega_{\rm lum}$ leads to the inference that most of the matter in the Universe is nonluminous dark matter.

In an expanding universe, the wavelength of light emitted from a distant source is shifted towards the red. The redshift z is defined such that $1 + z$ is the ratio of the detected wavelength (λ) to emitted (laboratory) wavelength (λ_e) of some electromagnetic spectral feature. It follows from the metric given in Eq. (15.1) that

$$1 + z = \lambda/\lambda_e = R_0/R_e \tag{15.7}$$

where R_e is the value of the scale factor at the time the light was emitted. For light emitted in the not too distant past, one can expand R_e and write $R_e \simeq R_0 + (t_e - t_0)\dot{R}_0$. For small (compared to H_0^{-1}) $\Delta t = (t_e - t_0)$, Eq. (15.7) takes the form of Hubble's law

$$z \approx \Delta t \frac{\dot{R}_0}{R_0} \approx \ell H_0 , \tag{15.8}$$

where ℓ is the distance to the source.

Energy conservation implies that

$$\dot{\rho} = -3(\dot{R}/R)(\rho + p) , \tag{15.9}$$

so that for a matter-dominated ($p = 0$) universe $\rho \propto R^{-3}$, while for a radiation-dominated ($p = \rho/3$) universe $\rho \propto R^{-4}$. Thus the less singular curvature term κ/R^2 in the Friedmann equation can be neglected at early times when R is small. If the Universe expands adiabatically, the entropy per comoving volume ($\equiv R^3 s$) is constant, where the entropy density is $s = (\rho + p)/T$ and T is temperature. The energy density of radiation can be expressed (with $\hbar = c = 1$) as

$$\rho_r = \frac{\pi^2}{30}\, N(T)(kT)^4 , \tag{15.10}$$

where $N(T)$ counts the effectively massless degrees of freedom of bosons and fermions:

$$N(T) = \sum_B g_B + \frac{7}{8}\sum_F g_F . \tag{15.11}$$

For example, for $m_\mu > kT > m_e$, $N(T) = g_\gamma + 7/8\,(g_e + 3g_\nu) = 2 + 7/8\,[4 + 3(2)] = 43/4$. For $m_\pi > kT > m_\mu$, $N(T) = 57/4$. At temperatures less than about 1 MeV, neutrinos have decoupled from the thermal background, *i.e.*, the weak interaction rates are no longer fast enough compared with the expansion rate to keep neutrinos in equilibrium with the remaining thermal bath consisting of $\gamma, e^\pm$. Furthermore, at temperatures $kT < m_e$, by entropy conservation, the ratio of the neutrino temperature to the photon temperature is given by $(T_\nu/T_\gamma)^3 = g_\gamma/(g_\gamma + \frac{7}{8}g_e) = 4/11$.

In the early Universe when $\rho \approx \rho_r$, then $\dot{R} \propto 1/R$, so that $R \propto t^{1/2}$ and $Ht \to 1/2$ as $t \to 0$. The time-temperature relationship at very early times can then be found from the above equations:

$$t = \frac{2.42}{\sqrt{N(T)}}\left(\frac{1 \text{ MeV}}{kT}\right)^2 \text{ sec} . \tag{15.12}$$

At later times, since the energy density in radiation falls off as R^{-4} and the energy density in non-relativistic matter falls off as R^{-3}, the Universe eventually became matter dominated. The epoch of matter-radiation density equality is determined by equating the matter density at $t_{\rm eq}$, $\rho_m = \Omega_0\rho_c(R_0/R_{\rm eq})^3$ to the radiation density, $\rho_r = (\pi^2/30)[2 + (21/4)(4/11)^{4/3}](kT_0)^4(R_0/R_{\rm eq})^4$ where T_0 is the present temperature of the microwave background (see below). Solving for $(R_0/R_{\rm eq}) = 1 + z_{\rm eq}$ gives

$$\begin{aligned} z_{\rm eq} + 1 &= \Omega_0 h_0^2/4.2 \times 10^{-5} = 2.4 \times 10^4\, \Omega_0 h_0^2 ; \\ kT_{\rm eq} &= 5.6\, \Omega_0 h_0^2 \,\text{eV} ; \\ t_{\rm eq} &\approx 0.39(\Omega_0 H_0^2)^{-1/2}(1 + z_{\rm eq})^{-3/2} \\ &= 3.2 \times 10^{10}(\Omega_0 h_0^2)^{-2} \text{ sec} . \end{aligned} \tag{15.13}$$

Prior to this epoch the density was dominated by radiation (relativistic particles; see Eq. (15.10)), and at later epochs matter density dominated. Atoms formed at $z \approx 1300$, and by $z_{\rm dec} \approx 1100$ the free electron density was low enough that space became essentially transparent to photons and matter and radiation were decoupled. These are the photons observed in the microwave background today.

The age of the Universe today, t_0, is related to both the Hubble parameter and the value of Ω_0 (still assuming that $\Lambda = 0$). In the Standard Model, $t_0 \gg t_{\rm eq}$ and we can write

$$t_0 = H_0^{-1}\int_0^1 \left(1 - \Omega_0 + \Omega_0 x^{-1}\right)^{-1/2} dx . \tag{15.14}$$

Constraints on t_0 yield constraints on the combination $\Omega_0 h_0^2$. For example, $t_0 \geq 13 \times 10^9$ yr implies that $\Omega_0 h_0^2 \leq 0.25$ for $h_0 \geq 0.5$, or $\Omega_0 h_0^2 \leq 0.45$ for $h_0 \geq 0.4$, while $t_0 \geq 10 \times 10^9$ yr implies that $\Omega_0 h_0^2 \leq 0.8$ for $h_0 \geq 0.5$, or $\Omega_0 h_0^2 \leq 1.1$ for $h_0 \geq 0.4$.

The present temperature of the microwave background is $T_0 = 2.726 \pm 0.005$ K as measured by COBE [4], and the number density of photons $n_\gamma = (2\zeta(3)/\pi^2)(kT_0)^3 \approx 411\ \mathrm{cm}^{-3}$. The energy density in photons (for which $g_\gamma = 2$) is $\rho_\gamma = (\pi^2/15)(kT_0)^4$. At the present epoch, $\rho_\gamma = 4.65 \times 10^{-34}\,\mathrm{g\ cm}^{-3} = 0.26\ \mathrm{eV\ cm}^{-3}$. For nonrelativistic matter (such as baryons) today, the energy density is $\rho_B = m_B n_B$ with $n_B \propto R^{-3}$, so that for most of the history of the Universe n_B/s is constant. Today, the entropy density is related to the photon density by $s = (4/3)(\pi^2/30)[2 + (21/4)(4/11)](kT_0)^3 = 7.0\,n_\gamma$. Big Bang nucleosynthesis calculations limit $\eta = n_B/n_\gamma$ to $2.8 \times 10^{-10} \leq \eta \leq 4.0 \times 10^{-10}$. The parameter η is also related to the portion of Ω in baryons

$$\Omega_B = 3.66 \times 10^7 \eta\, h_0^{-2}\, (T_0/2.726\ \mathrm{K})^3\ , \tag{15.15}$$

so that $0.010 < \Omega_B\, h_0^2 < 0.015$, and hence the Universe cannot be closed by baryons.

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16. BIG-BANG NUCLEOSYNTHESIS

Written July 1995 by K.A. Olive and D.N. Schramm.

Among the successes of the standard big-bang model is the agreement between the predictions of big-bang nucleosynthesis (BBN) for the abundances of the light elements, D, ^{3}He, ^{4}He, and ^{7}Li, and the primordial abundances inferred from observational data (see [1–3] for a more complete discussion). These abundances span some nine orders of magnitude: ^{4}He has an abundance by number relative to hydrogen of about 0.08 (accounting for about 25% of the baryonic mass), while ^{7}Li, the least abundant of the elements with a big-bang origin, has a abundance by number relative to hydrogen of about $\sim 10^{-10}$.

16.1. Big-bang nucleosynthesis theory

The BBN theory matches the observationally determined abundances with a single well-defined parameter, the baryon-to-photon ratio, η. All the light-element abundances can be explained with η in the relatively narrow range (2.8–4.5) $\times 10^{-10}$, or $\eta_{10} \equiv \eta \times 10^{10} = 2.8$–$4.5$. (When possible systematic errors are allowed to take extreme values, the range becomes $\eta_{10} = 1.5$–6.3 [4]. We shall always quote this extreme range parenthetically following the best range.) Equivalently, this range can be expressed as the allowed range for the baryon mass density, $\rho_B = 1.9$–3.1 $(1.0$–$4.3) \times 10^{-31}$ g cm^{-3}, and can be converted to the fraction of the critical density, Ω.

The synthesis of the light elements was affected by conditions in the early Universe at temperatures $T \lesssim 1$ MeV, corresponding to an age as early as 1 s. At somewhat higher temperatures, weak-interaction rates were in equilibrium, thus fixing the ratio of the neutron and proton number densities. At $T \gg 1$ MeV, $n/p \approx 1$, since the ratio was given approximately by the Boltzmann factor, $n/p \approx e^{-Q/T}$, where Q is the neutron-proton mass difference. As the temperature fell, the Universe approached the point ("freeze-out") where the weak-interaction rates were no longer fast enough to maintain equilibrium. The final abundance of ^{4}He is very sensitive to the n/p ratio at freeze-out.

The nucleosynthesis chain begins with the formation of deuterium in the process $pn \to \mathrm{D}\gamma$. However, photo-dissociation by the high number density of photons $(n_\gamma/n_B = \eta^{-1} \sim 10^{10})$ delays production of deuterium (and other complex nuclei) well past the point where T reaches the binding energy of deuterium, $E_B = 2.2$ MeV. (The average photon energy in a blackbody is $\overline{E}_\gamma \approx 2.7\ T$.) When the quantity $\eta^{-1}\exp(-E_B/T)$ reaches about 1 (at $T \approx 0.1$ MeV), the photo-dissociation rate finally falls below the nuclear production rate.

The 25% fraction of mass in ^{4}He due to BBN is easily estimated by counting the number of neutrons present when nucleosynthesis begins. When the weak-interaction rates freeze-out at about $T \approx 0.8$ MeV, the n-to-p ratio is about 1/6. When free-neutron decays prior to deuterium formation are taken into account, the ratio drops to $n/p \lesssim 1/7$. Then simple counting yields a primordial ^{4}He mass fraction

$$Y_p = \frac{2(n/p)}{1+n/p} \lesssim 0.25\ . \qquad (16.1)$$

In the Standard Model, the ^{4}He mass fraction depends primarily on the baryon-to-photon ratio η, as it is this quantity that determines when nucleosynthesis via deuterium production may begin. But because the n/p ratio depends only weakly on η, the ^{4}He mass fraction is relatively flat as a function of η. The effect of the uncertainty in the neutron half-life, $\tau_n = 887 \pm 2$ s, is small. Lesser amounts of the other light elements are produced: D and ^{3}He at the level of a few times 10^{-5} by number relative to H, and ^{7}Li/H at the level of about 10^{-10}, when η is in the range $1 - 10 \times 10^{-10}$.

When we go beyond the Standard Model, the ^{4}He abundance is very sensitive to changes in the expansion rate, which can be related to the effective number of neutrino flavors. This will be discussed below.

The calculated abundances of the light elements are shown in Fig. 16.1 as a function of η_{10}. The curves for the ^{4}He mass fraction, Y_p, bracket the range based on the uncertainty of the neutron mean-life, $\tau_n = 887 \pm 2$ s. The spread in the ^{7}Li curves is due to the 1σ uncertainties in nuclear cross sections leading to ^{7}Li and ^{7}Be which subsequently decays to ^{7}Li [4,5,6]. The uncertainties in the D and ^{3}He predictions are small and have been neglected here. The boxes show to the observed abundances, discussed below. Since the observational boxes line up on top of each other, there is an overall agreement between theory and observations for η_{10} in the range 2.8–4.5 (1.5–6.3).

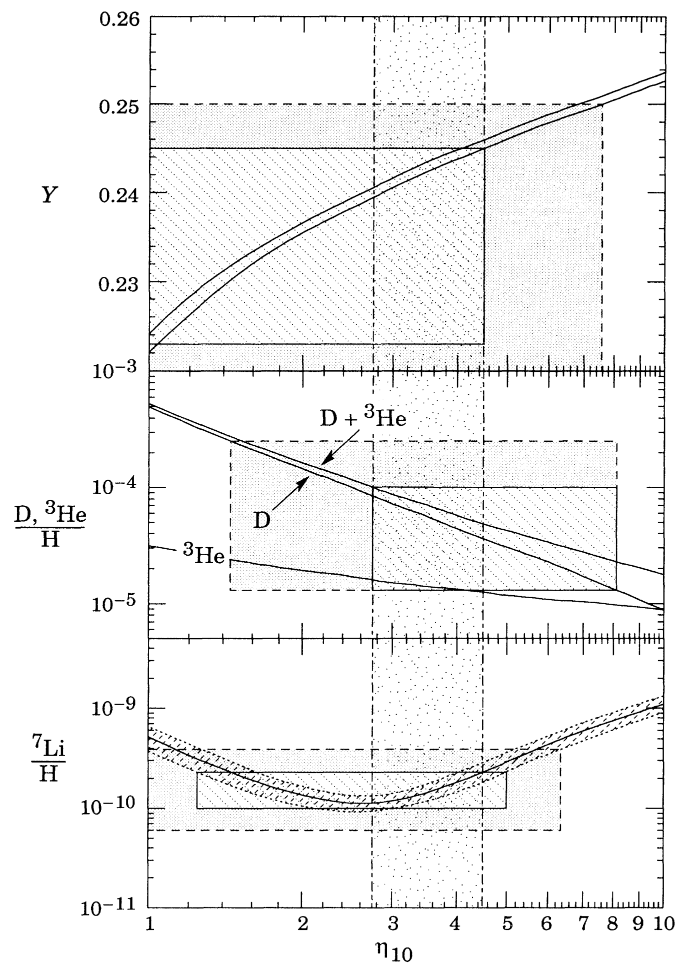

Figure 16.1: The abundances of D, ^{3}He, ^{4}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis. Also shown by a series of boxes is the comparison between these predictions and the observational determination of the light element abundances. See text for details.

16.2. Observations

Because stars produce helium as well as heavier elements, one must search for primordial helium in regions where stellar processing has been minimal, *i.e.*, in regions where abundances of elements such as carbon, nitrogen, and oxygen are very low. There are extensive compilations of observed abundances of ^{4}He, N, and O in many different extra-galactic regions of ionized H [7,8,9]. Extrapolating the ^{4}He abundances from the data leads to a observational estimate for Y_p of [10,11]

$$Y_p = 0.234 \pm 0.003 \pm 0.005\ . \qquad (16.2)$$

(Here and elsewhere, the first error is the statistical standard deviation, and the second systematic.) The large box in Fig. 16.1 bracketing the

^{4}He curves covers the range 0.223 to 0.245, where the half height is conservatively given as twice the statistical error plus the systematic error. There has been some debate on the size of systematic errors [4] and the dashed box is obtained using a larger systematic error of 0.01.

Observations for deuterium and ^{3}He abundances present larger problems. All deuterium is primordial [12], but some of the primordial deuterium has been destroyed. Thus, as can be seen in the figure, the present deuterium abundance gives an upper limit to η. However, to get more information requires either an understanding of galactic chemical evolution of deuterium or a direct measurement of primordial deuterium. Even more problematical is ^{3}He: Not only is primordial ^{3}He destroyed in stars but it is very likely that low-mass stars are net producers of ^{3}He. Neither the galactic chemical evolution of ^{3}He nor the production of ^{3}He in stars is well understood.

It appears that D/H has decreased over the age of the galaxy. Samples obtained deep inside meteorites provide measurements of the true (pre)-solar system abundance of ^{3}He, while measurements on meteoritic near-surface samples, the solar wind, and lunar soil samples also contain ^{3}He converted from deuterium in the early pre-main-sequence stage of the sun. The best current values are [13]

$$\left(\frac{\mathrm{D}+{}^3\mathrm{He}}{\mathrm{H}}\right)_{\odot} = (4.1 \pm 1.0) \times 10^{-5} \; ,$$

$$\left(\frac{{}^3\mathrm{He}}{\mathrm{H}}\right)_{\odot} = (1.5 \pm 0.3) \times 10^{-5} \; . \tag{16.3}$$

The difference between these, D/H $\approx (2.6 \pm 1.0) \times 10^{-5}$, is the pre-solar D abundance.

On the other hand, the present interstellar-medium abundance of D/H is [14]

$$\mathrm{D/H} = 1.60 \pm 0.09^{+0.05}_{-0.10} \times 10^{-5} \; . \tag{16.4}$$

It is this lowest value of D/H that provides the most robust upper bound on η, since D is only destroyed. It is shown (decreased by $2\sigma_{\rm stat} + \sigma_{\rm syst}$) as the lower side of the D and ^{3}He box in Fig. 16.1. If η_{10} is in the range 2.8–4.5 (1.5–6.3) then the primordial abundance of D/H is between 3.6–8 (2–25) $\times 10^{-5}$, and it would appear that significant destruction of deuterium has occurred. The upper side of the box in Fig. 16.1 comes from the upper limit on $(\mathrm{D} + {}^3\mathrm{He})_{\odot}$ under the assumption that at least 25% of a star's initial D + ^{3}He is returned to the interstellar medium [15].

Deuterium may have been detected in high-redshift, low-metallicity quasar absorption systems [16,17,18]. These measured abundances should represent the primordial value, but, they are not entirely consistent: One [16] gives D/H ≈ 1.9–2.5×10^{-4} while the other [17] gives D/H ≈ 1–2×10^{-5}. Most recently, measurements in three absorption systems show consistent values of D/H around $10^{-4.0\pm0.25}$ [18] and corresponds to a value of η in good agreement with that discussed in the previous section. The upper limit on D/H from the first observation is shown by the dashed box in Fig. 16.1. As one can see, the corresponding value of Y_p (at the same value of η as inferred by the observation of a high D/H) is in excellent agreement with the data. ^{7}Li is also acceptable at this value as well. However, due to the still somewhat preliminary status of this observation, it is premature to use it to fix the primordial abundance. A high value for the D abundance would require an even greater degree of D destruction over the age of the galaxy. The lower measurement for D/H is problematic for both ^{4}He and ^{7}Li and requires that systematics all work in the same direction to give a marginal overlap with this data.

Finally, we turn to ^{7}Li. In old, hot, population-II stars, ^{7}Li is found to have a very nearly uniform abundance. For stars with a surface temperature $T > 5500$ K and a metallicity less than about 1/20th solar (so that effects such as stellar convection may not be important), the abundances show little or no dispersion beyond that consistent with the errors of individual measurements. Much data has been obtained recently from a variety of sources, and the best estimate for the mean ^{7}Li abundance and its statistical uncertainty in halo stars is [19](the estimate of the systematic uncertainty discussed below is our own)

$$\mathrm{Li/H} = (1.6 \pm 0.1^{+0.4+1.6}_{-0.3-0.5}) \times 10^{-10} \; . \tag{16.5}$$

The first error is statistical, and the second is a systematic uncertainty that covers the range of abundances derived by various methods. The box in Fig. 16.1 corresponds to these errors (as before, with a half height of $2\sigma_{\rm stat} + \sigma_{\rm syst}$). The third set of errors in Eq. (16.5) accounts for the possibility that as much as half of the primordial ^{7}Li has been destroyed in stars, and that as much as 30% of the observed ^{7}Li was produced in cosmic ray collisions rather than in the Big Bang. These uncertainties are shown by the dashed box in Fig. 16.1. Observations of ^{6}Li, Be, and B help constrain the degree to which these effects play a role [20,21,22].

16.3. A consistent value for η

For the standard model of BBN to be deemed successful, theory and observation of the light element abundances must agree using a single value of η. We summarize the constraints on η from each of the light elements. From the ^{4}He mass fraction, $Y_p < 0.240$ (0.245–0.250), we have $\eta_{10} < 2.9$ (4.5–7.6) as a 2σ upper limit (the highest values use possible systematic errors up to their extreme range). Because of the sensitivity to the assumed upper limit on Y_p, the upper limit on η from D/H, is still of value. From D/H $> 1.3 \times 10^{-5}$, we have $\eta_{10} < 8.1$.

The lower limit on η_{10} comes from the upper limit on D + ^{3}He and is $\eta_{10} \gtrsim 2.8$ if one ignores ^{3}He production. We stress, however, that the upper limit on D + ^{3}He depends critically on models of galactic chemical evolution, which are far from being understood, and that one of the two measurements of D/H in quasar absorption systems indicates that $\eta_{10} \sim 1.5$.

Finally, ^{7}Li allows a broad range for η_{10} consistent with the other elements. When uncertainties in the reaction rates and systematic uncertainties in the observed abundances are both taken into account, ^{7}Li allows values of η_{10} between 1.3–5.0 (1–6.3). The resulting overall consistent range for η_{10} becomes 2.8–4.5 (1.5–6.3). These bounds on η_{10} constrain the fraction of critical density in baryons, Ω_B, to be

$$0.010 < \Omega_B h_0^2 < 0.016 \;\; (0.005 < \Omega_B h_0^2 < 0.023) \tag{16.6}$$

for a Hubble parameter, h_0, between 0.4 and 1.0. The corresponding range for Ω_B is 0.01–0.10 (0.005–0.14).

16.4. Beyond the Standard Model

Limits on particle physics beyond the Standard Model come mainly from the observational bounds on the ^{4}He abundance. As discussed earlier, the neutron-to-proton ratio is fixed by its equilibrium value at the freeze-out of the weak-interaction rates at a temperature $T_f \sim 1$ MeV, with corrections for free neutron decay. Furthermore, freeze-out is determined by the competition between the weak-interaction rates and the expansion rate of the Universe,

$$G_F{}^2 T_f{}^5 \sim \Gamma_{\rm wk}(T_f) = H(T_f) \sim \sqrt{G_N N(T_f)}\, T_f{}^2 \; , \tag{16.7}$$

where $N(T_f)$ counts the total (equivalent) number of relativistic particle species. The presence of additional neutrino flavors (or of any other relativistic species) at the time of nucleosynthesis increases the energy density of the Universe and hence the expansion rate, leading to a larger value of T_f, n/p, and ultimately Y_p. It is clear that just as one can place limits [23] on N, any changes in the weak or gravitational coupling constants can be similarly constrained.

In the Standard Model, the number of particle species can be written as $N = 5.5 + \frac{7}{4} N_\nu$ at $T_f = 1$ MeV; 5.5 accounts for photons and $e^\pm$; and N_ν is the number of light neutrino flavors. The helium curves in Fig. 16.1 were computed assuming $N_\nu = 3$, and the computed ^{4}He abundance scales roughly as $\Delta Y_{\rm BBN} \approx 0.012$–$0.014\ \Delta N_\nu$. Clearly the central value for N_ν from BBN will depend on η. If the best value for the observed primordial ^{4}He abundance is 0.234, then, for $\eta_{10} \sim 1.7$, the central value for N_ν is very close to 3. For $\eta_{10} > 2.8$ the central value for N_ν is less than 2.5. However, because of the uncertainties in the abundances, and thus in η, the upper limit on N_ν is more important here than the central value of N_ν. A straightforward propagation of errors leads to a 2σ upper limit of about 3.1 (3.5) on N_ν when systematic errors are included [10,24]. Other prescriptions, which involve renormalization of the probability distributions when the central value of N_ν falls below 3, give even higher upper limits to N_ν [25].

The limits on N_ν can be translated into limits on other types of particles or particle masses that would affect the expansion rate of the Universe just prior to nucleosynthesis. In some cases, it is the interaction strengths of new particles which are constrained. Particles with less than full weak strength interactions contribute less to the energy density than particles that remain in equilibrium up to the time of nucleosynthesis [26].

We close with a simple example. Suppose there exist three right-handed neutrinos with only right-handed interactions of strength $G_R < G_F$. The standard left-handed neutrinos are no longer in equilibrium at temperatures below $\sim$ 1 MeV. Particles with weaker interactions decouple at higher temperatures, and their number density ($\propto T^3$) relative to neutrinos is reduced by the annihilations of particles more massive than 1 MeV. If we use the upper bound $N_\nu < 3.1$, then the three right-handed neutrinos must have a temperature $3(T_{\nu_R}/T_{\nu_L})^4 < 0.1$. Since the temperature of the decoupled ν_R's is determined by entropy conservation, $T_{\nu_R}/T_{\nu_L} = [(43/4)/N(T_f)]^{1/3} < 0.4$, where T_f is the freeze-out temperature of the ν_R's. Thus $N(T_f) > 100$ and decoupling must have occurred at $T_f > M_W$ (since in the Standard Model, $N(T > M_W) = 106.75$). Finally, the decoupling temperature is related to G_R by $(G_R/G_F)^2 \sim (T_f/3\ \mathrm{MeV})^{-3}$, where 3 MeV corresponds to the decoupling temperature for ν_L. This yields a limit $G_R \lesssim 10^{-7}\ G_F$. Clearly these limits are strongly dependent on the assumed upper limit to N_ν; for $N_\nu < 3.5$, the limit on G_R is relaxed to $G_R < 0.002\ G_F$, since T_f is constrained only to be larger than the temperature corresponding to the QCD transition in the early Universe.

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17. THE HUBBLE CONSTANT

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In a uniform expanding universe, the position $\boldsymbol{r}$ and velocity $\boldsymbol{v}$ of any particle relative to another obey Hubble's relation $\boldsymbol{v} = H_0\boldsymbol{r}$, where H_0 is Hubble's constant.* As cosmological distances are measured in Mpc, the natural unit for H_0 is km s^{-1} Mpc^{-1}, which has the dimensions of inverse time: [100 km s^{-1} Mpc^{-1}]$^{-1}$ = 9.78×10^9 yr.

The real universe is nonuniform on small scales, and its motion obeys the Hubble relation only as a large scale average. But as typical non-Hubble motions ("peculiar velocities") are less than about 500 km s^{-1}, on scales more than about 5,000 km s^{-1} the deviations from Hubble flow are less than about 10%, so the notion of a global Hubble constant is well defined. The value of H_0 averaged over the local 15,000 km s^{-1} volume is known to lie within 10% of its global value even if H_0 itself is not known this precisely [1–3].

The Hubble constant is only meaningful on very large scales, but very large distances can only be measured indirectly. Distance ratios are measured with selected uniform types of astronomical systems ("Standard Candles") some examples of which are given below. These are used to tie distances to an absolute scale, either the nearby one based on trigonometric parallax or to some system where a physical model is precise enough to yield a distance directly from observed properties. There are many different ways to combine these tools to calibrate large distance, some of which are reviewed here. More complete reviews can be found in Refs. [4–7].

Using stars as standard candles and the Earth's orbit as a baseline, it is possible to tie distances throughout the Galaxy directly to trigonometric parallax measurements. A good landmark point for extragalactic studies is the Large Magellanic Cloud (LMC), a satellite galaxy of our Galaxy whose distance (50 kpc) is known to about 7% and provides confirmation and calibration of other measures. Beyond that, other galaxies in the Local Group (within about 1 Mpc) and other nearby groups provide stepping stones to the Virgo cluster (about 17 Mpc distant), and finally to the Coma cluster (about 100 Mpc distant) and others where the peculiar velocities introduce only small ambiguities. Most of the effort thus lies in obtaining an accurate ratio of distances in the range between Coma (or other similarly distant clusters) and the LMC.

Table 17.1 lists several candles and calibrators with a typical range of distance accessible to each. Usually the ends of the range are not precisely defined; the near end is plagued by small numbers of accessible objects and the far end by signal to noise. The precision quoted is a typical guideline which also varies depending on the sample used; it indicates the error in a distance ratio between an object and some standard reference, not including uncertainties in the absolute calibration of the reference distance (except for the first entry, which lists the typical absolute distance uncertainty in the Cepheid distance to a galaxy.) (The units are astronomical "distance modulus," given by $\mu = 5\log_{10}(\textit{distance in parsecs}) - 5.0$; a ± 0.1 magnitude error in magnitude or distance modulus corresponds to a 5% error in distance.) The verification of this precision is made by cross-checking against some other indicator on a galaxy-by-galaxy basis. This provides a control of systematic errors, since we do not expect detailed correlations between (for example) supernova brightness and host-galaxy rotation. Some examples are given in the next column, along with options often used for absolute calibration. The Hubble relation itself is included here, as it is the most precise indication of relative distance for large distances, and is used to verify the standardization of the other candles. As velocities are easy to measure at the relevant precision, a measurement of the Hubble constant is obtained from a calibrated distance measurement at a sufficiently large distance that the Hubble relation itself is precisely defined.

Table 17.1: Selected extragalactic distance indicators.†

Technique	Range of distance	Precision	Verification/ calibration
Cepheids	<LMC to 17 Mpc	0.15 mag	LMC/MWG
SNIa	4 Mpc to 2 Gpc	0.1-0.2 mag	Hubble/Model, Cepheid
EPM/SNII	LMC to 200 Mpc	0.4 mag	Hubble/Model, Cepheid
PNLF	1 Mpc to 20 Mpc	0.1 mag	SBF/Cepheid
SBF	1 Mpc to 60 Mpc	0.1 mag	PNLF/Cepheid
TF	1 Mpc to 100 Mpc	0.3 mag	Hubble/Cepheid
D_n-σ	10 Mpc to 60 Mpc	0.4 mag	Hubble/SBF
BCG	50 Mpc to 1 Gpc	0.2-0.3 mag	Hubble
GCLF	<LMC to 100 Mpc	0.4 mag	SBF/MWG
SZ	100 Mpc to > 1 Gpc	—	Hubble/Model
GL	~5 Gpc	—	Model
Hubble	20 Mpc to $\gtrsim$1Gpc	500 km s^{-1} $\div H_0D$	BCG, SNeIa/H_0

MWG = Milky Way Galaxy
†Extracted from [4-7].

17.1. Cepheid variables

The best studied and most trusted of the standard candles, Cepheids are bright stars undergoing overstable oscillations driven by the variation of helium opacity with temperature. The period of oscillation is tightly correlated with the absolute brightness of the star. The calibration of this "period-luminosity relation" ties galaxies to geometrical parallax measurements with about 0.15 mag or 7% precision [8]. There may be some indications of nonuniformity in different populations, but no evidence yet that they are significant. Cepheids have been identified in the Galaxy, the LMC, and in galaxies as distant as M100 in the Virgo cluster, at 17.1 ± 1.8 Mpc [9]. More measurements at large distances are expected from Hubble Space Telescope data. This is an important development because it allows direct absolute calibration of the best distant indicator, SNIa, as well as other methods, to better than 10% accuracy.

17.2. Type Ia supernovae (SNIa)

A SNIa occurs when a degenerate dwarf, of the order of a solar mass and of CNO composition, undergoes explosive detonation or deflagration by nuclear burning to iron-group elements (Ni, Co, Fe). Their uniformity arises because the degenerate material only becomes unstable when it is gravitationally compressed to where the electrons become close to relativistic, which requires nearly a Chandrasekhar mass (1.4 solar masses). Theoretical models of the explosion predict approximately the right peak brightness, but cannot be relied upon for a precise calibration. SNIa are very bright, so their brightness distribution can be studied using the distant Hubble flow as a reference. Indeed, the Hubble diagram of distant SNIa (as well as cases of two SNIa in a single galaxy) shows that they can serve as remarkably precise standard candles; even though they display large variations in brightness, with detailed knowledge of the shape of the light curve, the relative intrinsic brightness of a single SNIa can be predicted to $\Delta m = 0.15$ mag or better and its distance estimated to better than 7% accuracy [10–12]. (Note that distant SNIa can even measure deviation from a linear Hubble law with precision $\Delta q_0 \simeq \Delta m/z$.) Supernovae of all types are fairly rare events, occurring in a typical galaxy every hundred years, so it is only recently that a direct absolute calibration to SNIa host galaxies with Cepheids has been possible.

17.3. Type II supernovae (SNII)

A SNII occurs when a massive star has accumulated 1.4 solar masses of iron group elements in its core; there is then no source of nuclear energy and the core collapses by the Chandrasekhar instability. The collapse to a neutron star releases a large gravitational binding energy, some of which powers an explosion. The large variety of envelopes around collapsing cores means that SNII are not at all uniform in their properties. However, their distances can be calibrated absolutely by the fairly reliable "expanding photosphere method" (EPM). The principle is most easily understood for an expanding spherical blackbody. Even if the disk is unresolved, the continuum spectrum yields the angular size from spectral temperature and absolute flux. Spectral lines yield the expansion velocity, which from knowledge of the elapsed time gives a physical size and hence a distance. Models of real photospheres are not so simple but yield individual distances accurate to about 20% [13]. This is in principle an independent absolute distance, but is precisely verified by comparison with Cepheids in several cases, the distant Hubble diagram and Tully Fisher distance ratios (described below) in several others, and by multiple-epoch fits of the same object.

17.4. Planetary nebula luminosity function (PNLF)

A planetary nebula (PN) forms when the gaseous envelope is ejected from a low-mass star as its core collapses to a white dwarf. We see bright fluorescent radiation from the ejected gas shell, excited by UV light from the hot new white dwarf. The line radiation makes PN's easy to find and measure even in far-away galaxies; a bright galaxy can have tens of thousands, of which hundreds are bright enough to use to construct a PNLF. It is found empirically that the range of PN brightnesses has a sharp upper cutoff that appears to provide a good empirical standard candle, verified by comparison with SBF distance ratios.

17.5. Surface brightness fluctuations (SBF)

When galaxies are farther away than the Local Group, atmospheric blurring causes stellar images to blend together. However, with modern linear detectors, it is still possible to measure the moments of the distribution of stellar brightness in a population (in particular, the brightness-weighted average stellar brightness) through spatial fluctuations in the light. Stellar populations in elliptical galaxies appear to be universal enough for this to be a remarkably good standard candle, as verified by comparison with PNLF distance ratios. Note the problem of absolute calibration: as there are no elliptical galaxies with Cepheids, instead one uses the bulge components of nearby spirals, which have similar populations.

17.6. Tully-Fisher (TF)

The TF relation refers to a correlation of the properties of whole spiral galaxies, between rotational velocity and total luminosity. In rough terms, the relation can be understood as a relation between mass and luminosity, but given the variation in structural properties and stellar populations the narrow relation is a surprisingly good standard candle. Looking at a whole galaxy gives a long range and wide applicability. The TF distance ratios and precision have been verified by cross-checking against all of the above candles, and against the Hubble flow, particularly galaxy cluster averages, which permit greater precision. The absolute calibration of TF is traditionally made by a handful of local galaxies, with Cepheid calibration, and a major thrust now is to extend Cepheid measurements to a larger, more representative, and more distant sample, especially to galaxies in the Virgo cluster.

17.7. D_n–σ

A rough equivalent to TF for elliptical galaxies, D_n–σ is a correlation between galaxy size and velocity dispersion. It has a larger dispersion than TF and less opportunity for local calibration, but it is particularly useful for verifying distance ratios of galaxy clusters, whose cores contain almost no spirals.

17.8. Brightest cluster galaxies (BCG)

As a result of agglomeration, rich clusters of galaxies have accumulated the largest and brightest galaxies in the universe in their centers. They are very nearly all the same brightness; when account is taken of their light profiles, they are even more uniform. These provide the best check on the approach to uniform Hubble flow on large scales. (Quasars, which are even brighter, are far too variable to be good standard candles).

17.9. Globular cluster luminosity function (GCLF)

Many galaxies have systems of globular clusters orbiting them, each of which contain hundreds of thousands of stars and hence is visible at large distances. It is assumed that similar galaxies ought to have similar distributions of globular cluster luminosity, and current work is centered on verifying the precision of this assumption.

17.10. Sunyaev-Zeldovich effect (SZ)

The electron density and temperature of the hot plasma in a cluster of galaxies can be measured in two ways which depend differently on distance: the thermal x-ray emission, which is mostly bremsstrahlung by hot electrons, and the Sunyaev-Zeldovich effect on the microwave background, caused by Compton scattering off the electrons. This provides in principle an absolute calibration. Although the model has other unconstrained parameters, such as the gas geometry, which limit the precision and reliability of distances, in the handful of cases which have been studied most recently the distances are broadly in accord with those obtained by the other techniques.

17.11. Gravitational lenses (GL)

The time delay δt between different images of a high redshift gravitationally lensed quasar is $\delta t = C(z_Q, z_l)\delta\theta^2/H_0 \approx 1$ yr for image separations $\delta\theta$ of the order of arcseconds, with a numerical factor C of order unity determined by the specific lens geometry (the angular distribution of the lensing matter) and background cosmology. Variability of the double quasar 0957+561 has permitted measurements of δt from time series correlation, but these remain controversial and ambiguous, yielding correlation peaks at both 415 and 540 days. Although lensing does not yet provide a precise measurement, it is an amazing sanity check that this system, which relies on no other intermediate steps for its calibration, gives estimates on the scale of the Hubble length which are broadly consistent with local measures of H_0.

17.12. Estimates of H_0

The central idea is to find "landmark" systems whose distance is given by more than one technique. Systems are not always well defined, however. For example, the LMC size is a few percent of its distance, introducing errors of this order for any calibration based on an individual object within it. Nor are galaxy clusters as compact and well defined as individual galaxies; using galaxy clusters as calibrating systems often requires some assumptions and models about cluster membership (the most important example being the Virgo cluster, whose structure is somewhat amorphous, creating a ±20% or more distance ambiguity in some arguments). The best way to avoid this is to cross-correlate calibrators on a galaxy-by-galaxy basis, but this introduces problems of bias associated with sample selection that must be modeled. The basic difficulty remains that the nearby calibrators of any sort remain few and possibly anomalous.

The reason for the variable estimates of the Hubble constant lies in the many different ways to combine these techniques to obtain an absolute distance calibration in the Hubble flow, each involving several, usually individually reasonable, assumptions. Nevertheless there is broad agreement within the errors among a wide variety of independent ladders with different systematics. As examples, we cite a variety of (somewhat arbitrarily chosen) independent methods, which illustrate some of the choices and tradeoffs, summarized in Table 17.2.

1. Expanding photosphere method (EPM) distances give an absolute calibration to objects in the distant Hubble flow. A small sample of these direct distances with small flow corrections gives $H_0 = 73 \pm 6$ (statistical) ± 7 (systematic).The distance estimates and limits on the systematic error component are verified by Cepheid distances in three cases, where the Cepheid/EPM distances come out to 1.02 ± 0.08 (LMC), $1.01^{+0.23}_{-0.17}$ (M101) and 1.13 ± 0.28 (M100).
2. With HST, it is now possible to calibrate SNIa directly with Cepheid distances to host galaxies. The light from brighter SNIa decays more slowly than from faint ones, so the best fits to the distant Hubble diagram include information about the light curve shape ("LCS") rather than simply assuming uniformity; low values of H_0 arise in the latter case. There are several options for empirical calibration, among them: (a) Three individual SNIa host galaxy distances have been calibrated directly with Cepheids. There is evidence from their light curves that two of these calibrators may indeed be unusually bright, which explains why the value of H_0 depends on whether or not the LCS correction is applied (a fourth, SN 1990N in N4639 is appearing as this goes to press, with more on the way). (b) Alternatively, assuming that the mean of six well-studied SNIa in the Virgo cluster lies at the Cepheid Virgo distance of 17 Mpc yields $H_0 = 71 \pm 7$ km s^{-1} Mpc^{-1}.
3. The distance to Virgo or any other local cluster is tied to H_0 via the distant Hubble diagram for TF or D_n-σ distances for galaxies in distant clusters. This can be done with a large scale flow model fit to many clusters. Using a Virgo distance of 17 Mpc yields $H_0 = 82 \pm 11$ km s^{-1} Mpc^{-1}. Alternatively, we can use the distance ratio to a fiducial reference such as the Coma cluster, for which such models predict almost vanishing peculiar velocity, and which is in any case distant enough for flow to be unimportant. (The flow models give its Hubble velocity as 7170 ± 125 km s^{-1}; relative to the CMBR its velocity is 7197 ± 73 km s^{-1}.) If (as estimated from TF, D_n-σ, SNeI) the Coma to Virgo ratio lies in the range 5.5 to 5.75, 17 Mpc for Virgo leads to $H_0 = 77$ to 73 km s^{-1} Mpc^{-1}, subject to uncertainty over the Virgo depth. Nearly the same TF calibration is given by six local Cepheid calibrators, and by several more in the M101 group. This avoids the Virgo depth uncertainty, but replaces it with doubts about whether all of the local calibrators might be anomalous (although the apparent uniformity of galaxies elsewhere argues against this being a large effect.)
4. TF comparison with distant field galaxies in the Hubble flow (after corrections for Malmquist bias in the samples, which is worse than in cluster samples) yield $H_0 = 80 \pm 10$ km s^{-1} Mpc^{-1}.
5. For completeness, some recent SZ and GL estimates are shown. The GL estimate in the best model [25] depends on the convergence κ added to the main galaxy lens by the cluster potential; κ probably lies between 0.1 and 0.2, and must be greater than zero, providing a firm upper limit on H_0 and an estimate squarely in the range of the other techniques.

The central values by most reliably calibrated methods lie in the range $H_0 = 65$ to 85 km s^{-1} Mpc^{-1}, and indeed this corresponds roughly with the range of estimates expected from the internally estimated errors. Thus systematic errors are at least not dominant, although they could well be comparable to internal errors. The simplicity and apparent precision of the new Cepheid + SNIa ladder lead one to suspect a true value in the lower end of this range.

Footnote and References:

* To first order in v. For discussion of the second-order term, including the "deceleration parameter" q_0, see the Big-Bang Cosmology section (Sec. 15).

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Table 17.2: Some recent estimates of Hubble's constant

Technique	Calibration*	Ties to Hubble flow	Result* (km s^{-1} Mpc^{-1})	Ref.
EPM	Expanding photosphere model	Direct EPM Hubble Diagram + Flow model or TF	$73 \pm 6 \pm 7$	[13]
	Cepheids in 3 SNII hosts		same × [0.88, 1.26]	[14]
SNeIa		Direct SNIa Hubble Diagram		
	Cepheids (N5253 + SN1972E)	Direct + LCS correction	$62 - 67$	[11]
	Cepheids (N5253 + SN1972E)	Direct + LCS correction	67 ± 7	[12]
	Cepheids (N5253 + SN1972E)	Direct	54 ± 8	[15]
	Cepheids (IC4182 + SN1937C)	Direct + LCS correction	68–74 ± 6	[16]
	Cepheids (IC4182 + SN1937C)	Direct	52 ± 9	[17]
	Cepheids (N4536 + SN1981B)	Direct + LCS correction	67 ± 6	[18,19]
	Virgo mean (M100) + six Virgo SN hosts	Direct	$71 \pm 7^{\dagger}$	[14]
Clusters	Virgo mean (M100 Cepheids) + local + M101 Cepheids	Virgo infall model	$81 \pm 11^{\dagger}$	[14]
		Virgo/Coma ratio	73–77 $\pm 10^{\dagger}$	[14]
		Cluster TF + LS flow model fit	$82 \pm 11^{\dagger}$	[14]
	M96 Cepheids	LeoI to Virgo and Coma	$69 \pm 8^{\dagger}$	[20]
Field TF	Local Cepheids‡	Field TF Hubble Diagram + Malmquist bias correction	$\approx 80 \pm 10$	[21]
SZ	SZ model + X-ray maps + SZ maps	Direct single cluster velocities:		
		A2218	65 ± 25	[22]
		A2218,A665	55 ± 17	[22]
		Coma	74 ± 29	[23]
Gravitational lensing	Lens model, time delay	Direct, Q0957+561	<70	[24]
			$82.5^{+5.9}_{-3.0}(1-\kappa)\,(\delta t/1.1\text{yr})^{-1}$	[25]

* For all methods based on Cepheids, add a common multiplicative error of ± 0.15 mag or 7% in H_0.

† plus Virgo depth uncertainty (scales with M100/Virgo ratio)

‡ TF calibration from 6 local Cepheid calibration is verified by M101 group galaxies and (less directly) by M100 and NGC 4571 distance to Virgo TF galaxies [9,14,26].

18. DARK MATTER

Written September 1995 by M. Srednicki, University of California, Santa Barbara

There is strong evidence from a variety of different observations for a large amount of dark matter in the universe [1]. The phrase "dark matter" means matter whose existence has been inferred only through its gravitational effects. There is also extensive circumstantial evidence that at least some of this dark matter is nonbaryonic: that is, composed of elementary particles other than protons, neutrons, and electrons. These particles must have survived from the Big Bang, and therefore must either be stable or have lifetimes in excess of the current age of the universe.

The abundance of dark matter is usually quoted in terms of its mass density $\rho_{\rm dm}$ in units of the critical density, $\Omega_{\rm dm} = \rho_{\rm dm}/\rho_{\rm c}$; the critical density $\rho_{\rm c}$ is defined in Eq. (15.5) (in Section 15 on "Big-Bang Cosmology" in this *Review*). The total amount of visible matter (that is, matter whose existence is inferred from its emission or absorption of photons) is roughly $\Omega_{\rm vis} \simeq 0.005$, with an uncertainty of at least a factor of two.

The strongest evidence for dark matter is from the rotation curves of spiral galaxies [1,2]. In these observations, the circular velocity $v_{\rm c}$ of hydrogen clouds surrounding the galaxy is measured (via Doppler shift) as a function of radius r. If there were no dark matter, at large r we would find $v_{\rm c}^2 \simeq G_N M_{\rm vis}/r$, since the visible mass $M_{\rm vis}$ of a spiral galaxy is concentrated at its center. However, observations of many spiral galaxies instead indicate a velocity $v_{\rm c}$ which is independent of r at large r, with a typical value $v_{\rm c} \sim 200\,{\rm km\ s}^{-1}$. Such a "flat rotation curve" implies that the total mass within radius r grows linearly with r, $M_{\rm tot}(r) \simeq G_N^{-1} v_{\rm c}^2 r$. A self-gravitating ball of ideal gas at a uniform temperature of $kT = \frac{1}{2} m_{\rm dm} v_{\rm c}^2$ would have this mass profile; here $m_{\rm dm}$ is the mass of one dark matter particle. The rotation curves are measured out to some tens of kiloparsecs, implying a total mass within this radius which is typically about ten times the visible mass. This would imply $\Omega_{\rm dm} \gtrsim 10\,\Omega_{\rm vis} \simeq 0.05$. In our own galaxy, estimates of the local density of dark matter typically give $\rho_{\rm dm} \simeq 0.3\,{\rm GeV\ cm}^{-3}$, but this result depends sensitively on how the halo of dark matter is modeled.

Other indications of the presence of dark matter come from observations of the motion of galaxies and hot gas in clusters of galaxies [3]. The overall result is that $\Omega_{\rm dm} \sim 0.2$. Studies of large-scale velocity fields result in $\Omega_{\rm dm} \gtrsim 0.3$ [4]. However, these methods of determining $\Omega_{\rm dm}$ require some astrophysical assumptions about how galaxies form.

None of these observations give us any direct indication of the nature of the dark matter. If it is baryonic, the forms it can take are severely restricted, since most forms of ordinary matter readily emit and absorb photons in at least one observable frequency band [5]. Possible exceptions include remnants (white dwarfs, neutron stars, black holes) of an early generation of massive stars, or smaller objects which never initiated nuclear burning (and would therefore have masses less than about $0.1\,M_\odot$). These massive compact halo objects are collectively called machos. Preliminary results [6] of a search for machos via gravitational lensing effects indicate that a standard halo has a mass fraction of no more than 0.66 of machos with mass less than $0.1\,M_\odot$ at the 95% confidence level, but it is possible to construct models of an all-macho halo which are consistent with all observations.

There are, however, several indirect arguments which argue for a substantial amount of nonbaryonic dark matter. First, nucleosynthesis gives the limits $0.010 \le \Omega_{\rm b} h_0^2 \le 0.016$ for the total mass of baryons; h_0 is defined in Eq. (15.6) (in Section 15 on "Big-Bang Cosmology" in this *Review*). The upper limit on $\Omega_{\rm b}$ is substantially below the value $\Omega_{\rm dm} \gtrsim 0.3$ given by large scale measurements, even if h_0 is near the lower end of its optimistically allowed range, $0.4 \le h_0 \le 1.0$. A second, purely theoretical argument is that inflationary models (widely regarded as providing explanations of a number of otherwise puzzling paradoxes) generically predict $\Omega_{\rm total} = 1$. Finally, without nonbaryonic dark matter it is difficult to construct a model of galaxy formation that predicts sufficiently small fluctuations in the cosmic microwave background radiation [7].

For purposes of galaxy formation models, nonbaryonic dark matter is classified as "hot" or "cold," depending on whether the dark matter particles were relativistic or nonrelativistic at the time when the horizon of the universe enclosed enough matter to form a galaxy. If the dark matter particles are in thermal equilibrium with the baryons and radiation, then only the mass of a dark matter particle is relevant to knowing whether the dark matter is hot or cold, with the dividing line being $m_{\rm dm} \sim 1\,{\rm keV}$. In addition, specifying a model requires giving the power spectrum of initial density fluctuations. Inflationary models generically predict a power spectrum which is nearly scale invariant. Given this, models with only cold dark matter are much more successful than models with only hot dark matter at reproducing the observed structure of our universe. Some lingering discrepancies in the cold dark matter model are removed in models with both kinds of dark matter [8]. Another class of models uses mass fluctuations due to topological defects, but these are much harder to analyze with comparable quantitative detail [9].

The best candidate for hot dark matter is one of the three neutrinos, endowed with a Majorana mass m_ν. Such a neutrino would contribute $\Omega_\nu = 0.56\, G_N T_0^3 H_0^{-2} m_\nu = m_\nu/(92\, h_0^2\,{\rm eV})$, where T_0 is the present temperature of the cosmic microwave background radiation. There is another constraint on neutrinos (or any light fermions) if they are to comprise the halos of dwarf galaxies: the Pauli exclusion principle restricts the number that can fit into the phase space of a halo [10], which puts a lower limit on the neutrino mass of $m_\nu \gtrsim 80\,{\rm eV}$.

There are no presently known particles which could be cold dark matter. However, many proposed extensions of the Standard Model predict a stable (or sufficiently long lived) particle. The key question then becomes the predicted value of $\Omega_{\rm dm}$.

If the particle is its own antiparticle (or there are particles and antiparticles present in equal numbers), and these particles were in thermal equilibrium with radiation at least until they became nonrelativistic, then their relic abundance is determined by their annihilation cross section $\sigma_{\rm ann}$: $\Omega_{\rm dm} \sim G_N^{3/2} T_0^3 H_0^{-2} \langle \sigma_{\rm ann} v_{\rm rel} \rangle^{-1}$. Here $v_{\rm rel}$ is the relative velocity of the two incoming dark matter particles, and the angle brackets denote an averaging over a thermal distribution of velocities for each at the freezeout temperature $T_{\rm fr}$ when the dark matter particles go out of thermal equilibrium with radiation; typically $T_{\rm fr} \simeq \frac{1}{20} m_{\rm dm}$. One then finds (putting in appropriate numerical factors) that $\Omega_{\rm dm} h_0^2 \simeq 3 \times 10^{-27}\,{\rm cm}^3\,{\rm s}^{-1}/\langle \sigma_{\rm ann} v_{\rm rel} \rangle$. The value of $\langle \sigma_{\rm ann} v_{\rm rel} \rangle$ needed for $\Omega_{\rm dm} \simeq 1$ is remarkably close to what one would expect for a weakly interacting massive particle (wimp) with a mass of $m_{\rm dm} = 100\,{\rm GeV}$: $\langle \sigma_{\rm ann} v_{\rm rel} \rangle \sim \alpha^2/8\pi m_{\rm dm}^2 \sim 3 \times 10^{-27}\,{\rm cm}^3\,{\rm s}^{-1}$.

If the dark matter particle is not its own antiparticle, and the number of particles minus antiparticles is conserved, then an initial asymmetry in the abundances of particles and antiparticles will be preserved, and can give relic abundances much larger than those predicted above.

If the dark matter particles were never in thermal equilibrium with radiation, then their abundance today must be calculated in some other way, and will in general depend on the precise initial conditions which are assumed.

The two best known and most studied cold dark matter candidates are the neutralino and the axion. The neutralino is predicted by supersymmetric extensions of the Standard Model [11,12]. It qualifies as a wimp, with a theoretically expected mass in the range of tens to hundreds of GeV. The axion is predicted by extensions of the Standard Model which resolve the strong CP problem [13]. Its mass must be approximately $10^{-5}\,{\rm eV}$ if it is to be a significant component of the dark matter. Axions can occur in the early universe in the form of a Bose condensate which never comes into thermal equilibrium; these axions are always nonrelativistic, despite their small mass.

There are prospects for direct experimental detection of both these candidates (and other wimp candidates as well). Wimps will scatter off nuclei at a calculable rate, and produce observable nuclear recoils [12,14]. This technique has been used to show that all the dark matter cannot consist of massive Dirac neutrinos or scalar neutrinos (predicted by supersymmetric models) with masses in the range of $10\,\mathrm{GeV} \lesssim m_{\mathrm{dm}} \lesssim 4\,\mathrm{TeV}$ [15]. The neutralino is harder to detect because its scattering cross section with nuclei is considerably smaller. The axion can be detected by axion to photon conversion in an inhomogeneous magnetic field, and limits on the allowed axion-photon coupling have been set (which, however, do not exclude the theoretically favored value) [13]. Both types of detection experiments are in progress.

Wimp candidates can have indirect signatures as well, via present-day annihilations into particles which can be detected as cosmic rays [12]. The most promising possibility arises from the fact that wimps collect at the centers of the sun and the earth, thus greatly increasing their annihilation rate, and producing high energy neutrinos which can escape and arrive at the earth's surface in potentially observable numbers.

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19. COSMIC BACKGROUND RADIATION

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19.1. Introduction

The observed cosmic microwave background (CMB) radiation provides strong evidence for the hot big bang. The success of primordial nucleosynthesis calculations (see Sec. 16, "Big-bang nucleosynthesis") requires a cosmic background radiation (CBR) characterized by a temperature $kT \sim 1\,\mathrm{MeV}$ at a redshift of $z \simeq 10^9$. In their pioneering work, Gamow, Alpher, and Herman [1] realized this and predicted the existence of a faint residual relic, primordial radiation, with a present temperature of a few degrees. The observed CMB is interpreted as the current manifestation of the hypothesized CBR.

The CMB was serendipitously discovered by Penzias and Wilson [2] in 1965. Its spectrum is well characterized by a $2.73 \pm 0.01\,\mathrm{K}$ black-body (Planckian) spectrum over more than three decades in frequency (see Fig. 19.1). A non-interacting Planckian distribution of temperature T_i at redshift z_i transforms with the universal expansion to another Planckian distribution at redshift z_r with temperature $T_r/(1+z_r) = T_i/(1+z_i)$. Hence thermal equilibrium, once established (e.g. at the nucleosynthesis epoch), is preserved by the expansion, in spite of the fact that photons decoupled from matter at early times. Because there are about 10^9 photons per nucleon, the transition from the ionized primordial plasma to neutral atoms at $z \sim 1000$ does not significantly alter the CBR spectrum [3].

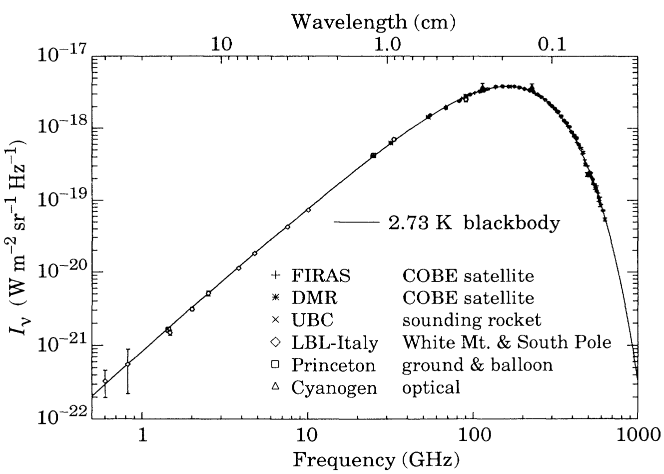

Figure 19.1: Precise measurements of the CMB spectrum. The line represents a 2.73 K blackbody, which describes the spectrum very well, especially around the peak of intensity. The spectrum is less well constrained at 10 cm and longer wavelengths. (References for this figure are at the end of this section under "CMB Spectrum References.")

19.2. Theoretical spectral distortions

The remarkable precision with which the CMB spectrum is fitted by a Planckian distribution provides limits on possible energy releases in the early Universe, at roughly the fractional level of 10^{-4} of the CBR energy, for redshifts $\lesssim 10^7$ (corresponding to epochs $\gtrsim 1$ year). The following three important classes of spectral distortions (see Fig. 19.2) generally correspond to energy releases at different epochs. The distortion results from the CBR photon interactions with a hot electron gas at temperature T_e.

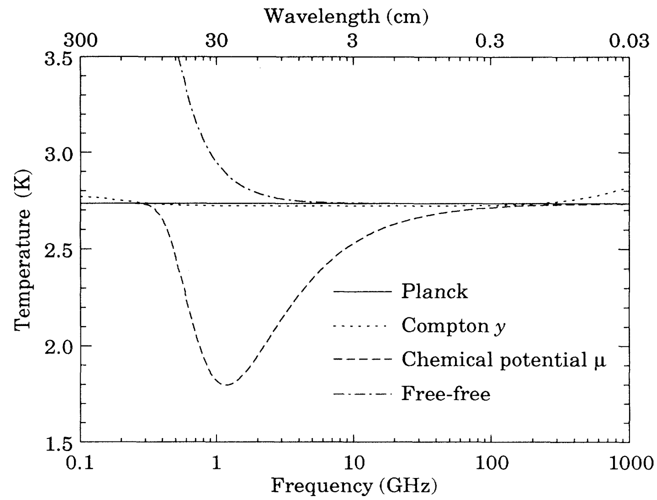

Figure 19.2: The shapes of expected, but so far unobserved, CMB distortions, resulting from energy-releasing processes at different epochs.

19.2.1. ***Compton distortion***: Late energy release ($z \lesssim 10^5$). Compton scattering ($\gamma e \to \gamma' e'$) of the CBR photons by a hot electron gas creates spectral distortions by transfering energy from the electrons to the photons. Compton scattering cannot achieve thermal equilibrium for $y < 1$, where

$$y = \int_0^z \frac{kT_e(z') - kT_\gamma(z')}{m_e c^2}\, \sigma_T\, n_e(z')\, c\, \frac{dt}{dz'}\, dz' \;, \tag{19.1}$$

is the integral of the number of interactions, $\sigma_T\, n_e(z)\, c\, dt$, times the mean-fractional photon-energy change per collision [4]. For $T_e \gg T_\gamma$ y is also proportional to the integral of the electron pressure $n_e k T_e$ along the line of sight. For standard thermal histories $y < 1$ for epochs later than $z \simeq 10^5$.

The resulting CMB distortion is a temperature decrement

$$\Delta T_{\rm RJ} = -2y\, T_\gamma \tag{19.2}$$

in the Rayleigh-Jeans ($h\nu/kT \ll 1$) portion of the spectrum, and a rapid rise in temperature in the Wien ($h\nu/kT \gg 1$) region, *i.e.* photons are shifted from low to high frequencies. The magnitude of the distortion is related to the total energy transfer [4] ΔE by

$$\Delta E/E_{\rm CBR} = e^{4y} - 1 \simeq 4y \;. \tag{19.3}$$

A prime candidate for producing a Comptonized spectrum is a hot intergalactic medium. A hot ($T_e > 10^5\,\mathrm{K}$) medium in clusters of galaxies can and does produce a partially Comptonized spectrum as seen through the cluster, known as the Sunyaev-Zel'dovich effect. Based upon X-ray data, the predicted large angular scale total combined effect of the hot intracluster medium should produce $y \lesssim 10^{-6}$ [5].

19.2.2. ***Bose-Einstein or chemical potential distortion***: Early energy release ($z \sim 10^5$–10^7). After many Compton scatterings ($y > 1$), the photons and electrons will reach statistical (not thermodynamic) equilibrium, because Compton scattering conserves photon number. This equilibrium is described by the Bose-Einstein distribution with non-zero chemical potential:

$$n = \frac{1}{e^{x+\mu_0} - 1} \;, \tag{19.4}$$

where $x \equiv h\nu/kT$ and $\mu_0 \simeq 1.4\; \Delta E/E_{\rm CBR}$, with μ_0 being the dimensionless chemical potential that is required.

The collisions of electrons with nuclei in the plasma produce free-free (thermal bremsstrahlung) radiation: $eZ \to eZ\gamma$. Free-free emission thermalizes the spectrum to the plasma temperature at long wavelengths. Including this effect, the chemical potential becomes frequency-dependent,

$$\mu(x) = \mu_0 e^{-2x_b/x} \ , \tag{19.5}$$

where x_b is the transition frequency at which Compton scattering of photons to higher frequencies is balanced by free-free creation of new photons. The resulting spectrum has a sharp drop in brightness temperature at centimeter wavelengths [6]. The minimum wavelength is determined by Ω_B.

The equilibrium Bose-Einstein distribution results from the oldest non-equilibrium processes ($10^5 < z < 10^7$), such as the decay of relic particles or primordial inhomogeneities. Note that free-free emission (thermal bremsstrahlung) and radiative-Compton scattering effectively erase any distortions [7] to a Planckian spectrum for epochs earlier than $z \sim 10^7$.

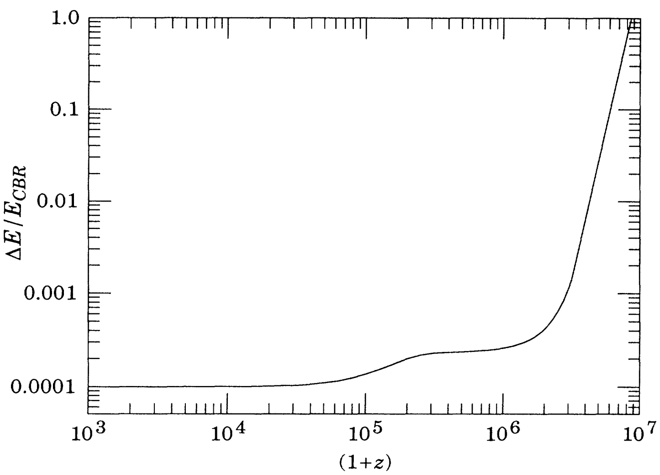

Figure 19.3: Upper Limits (95% CL) on fractional energy ($\Delta E/E_{\rm CBR}$) releases as set by lack of CMB spectral distortions resulting from processes at different epochs. These can be translated into constraints on the mass, lifetime and photon branching ratio of unstable relic particles, with some additional dependence on cosmological parameters such as Ω_B [9,10].

19.2.3. ***Free-free distortion***: Very late energy release ($z \ll 10^3$). Free-free emission can create rather than erase spectral distortion in the late universe, for recent reionization ($z < 10^3$) and from a warm intergalactic medium. The distortion arises because of the lack of Comptonization at recent epochs. The effect on the present-day CMB spectrum is described by

$$\Delta T_{ff} = T_\gamma \ Y_{ff}/x^2 , \tag{19.6}$$

where T_γ is the undistorted photon temperature, x is the dimensionless frequency, and Y_{ff}/x^2 is the optical depth to free-free emission:

$$Y_{ff} = \int_0^z \frac{T_e(z') - T_\gamma(z')}{T_e(z')} \frac{8\pi e^6 h^2 n_e^2 \, g}{3m_e(kT_\gamma)^3 \, \sqrt{6\pi \, m_e \, kT_e}} \frac{dt}{dz'} dz' \ . \tag{19.7}$$

Here h is Planck's constant, n_e is the electron density and g is the Gaunt factor [8].

19.2.4. ***Spectrum summary***: The CMB spectrum is consistent with a blackbody spectrum over more than three decades of frequency around the peak. A least-squares fit to all CMB measurements yields:

$$T_\gamma = 2.73 \pm 0.01 \ \mathrm{K}$$
$$n_\gamma = (2\zeta(3)/\pi^2) T_\gamma^3 \simeq 413 \, \mathrm{cm}^{-3}$$
$$\rho_\gamma = (\pi^2/15) T_\gamma^4 \simeq 4.68 \times 10^{-34} \, \mathrm{g\,cm}^{-3} \simeq 0.262 \, \mathrm{eV\,cm}^{-3}$$
$$|y| < 1.5 \times 10^{-5} \qquad (95\% \ \mathrm{CL})$$
$$|\mu_0| < 9 \times 10^{-5} \qquad (95\% \ \mathrm{CL})$$
$$|Y_{ff}| < 1.9 \times 10^{-5} \quad (95\% \ \mathrm{CL})$$

The limits here [11] correspond to limits [11–13] on energetic processes $\Delta E/E_{\rm CBR} < \ 2 \times 10^{-4}$ occurring between redshifts 10^3 and 5×10^6 (see Fig. 19.3). The best-fit temperature from the COBE FIRAS experiment is $T_\gamma = 2.728 \pm 0.002$ K [11].

19.3. Deviations from isotropy

Penzias and Wilson reported that the CMB was isotropic and unpolarized to the 10% level. Current observations show that the CMB is unpolarized at the 10^{-5} level but has a dipole anisotropy at the 10^{-3} level, with smaller-scale anisotropies at the 10^{-5} level. Standard theories predict anisotropies in linear polarization well below currently achievable levels, but temperature anisotropies of roughly the amplitude now being detected.

It is customary to express the CMB temperature on the sky in a spherical harmonic expansion,

$$T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi) \ , \tag{19.8}$$

and to discuss the various multipole amplitudes. The power at a given angular scale is roughly $\ell \sum_m |a_{\ell m}|^2 / 4\pi$, with $\ell \sim 1/\theta$.

19.3.1. ***The dipole***: The largest anisotropy is in the $\ell = 1$ (dipole) first spherical harmonic, with amplitude at the level of $\Delta T/T = 1.23 \times 10^{-3}$. The dipole is interpreted as the result of the Doppler shift caused by the solar system motion relative to the nearly isotropic blackbody field. The motion of the observer (receiver) with velocity $\beta = v/c$ relative to an isotropic Planckian radiation field of temperature T_0 produces a Doppler-shifted temperature

$$\begin{aligned} T(\theta) &= T_0 (1 - \beta^2)^{1/2} / (1 - \beta \cos\theta) \\ &= T_0 \left(1 + \beta\cos\theta + (\beta^2/2)\cos 2\theta + O(\beta^3)\right) \ . \end{aligned} \tag{19.9}$$

The implied velocity [11,14] for the solar-system barycenter is $\beta = 0.001236 \pm 0.000002$ (68% CL) or $v = 371 \pm 0.5 \, \mathrm{km\,s}^{-1}$, assuming a value $T_0 = 2.728 \pm 0.002$ K, towards $(\alpha, \delta) = (11.20^{\rm h} \pm 0.01^{\rm h}, -7.0^\circ \pm 0.2^\circ)$, or $(\ell, b) = (264.14^\circ \pm 0.15^\circ, 48.26^\circ \pm 0.15^\circ)$. Such a solar-system velocity implies a velocity for the Galaxy and the Local Group of galaxies relative to the CMB. The derived velocity is $v_{\rm LG} = 627 \pm 22 \, \mathrm{km\,s}^{-1}$ toward $(\ell, b) = (276^\circ \pm 3^\circ, 30^\circ \pm 3^\circ)$, where most of the error comes from uncertainty in the velocity of the solar system relative to the Local Group.

The Doppler effect of this velocity and of the velocity of the Earth around the Sun, as well as any velocity of the receiver relative to the Earth, is normally removed for the purposes of CMB anisotropy study. The resulting high degree of CMB isotropy is the strongest evidence for the validity of the Robertson-Walker metric.

19.3.2. ***The quadrupole***: The rms quadrupole anisotropy amplitude is defined through $Q_{\rm rms}^2/T_\gamma^2 = \sum_m |a_{2m}|^2 / 4\pi$. The current estimate of its value is $4\,\mu\mathrm{K} \le Q_{\rm rms} \le 28\,\mu\mathrm{K}$ for a 95% confidence interval [15]. The uncertainty here includes both statistical errors and systematic errors, which are dominated by the effects of galactic emission modelling. This level of quadrupole anisotropy allows one to set precise limits on anisotropic expansion, shear, and vorticity; all such dimensionless quantities are constrained to be less than about 10^{-5}.

19.3.3. ***Smaller angular scales***: The COBE-discovered [16] higher-order ($\ell > 2$) anisotropy is interpreted as being the result of perturbations in the energy density of the early Universe, manifesting themselves at the epoch of the CMB's last scattering. Hence the detection of these anisotropies has provided evidence for the existence of the density perturbations that seeded all the structure we observe today.

In the standard scenario the last scattering takes place at a redshift of approximately 1100, at which epoch the large number of photons was no longer able to keep the hydrogen sufficiently ionized. The optical thickness of the cosmic photosphere is roughly $\Delta z \sim 100$ or about 5 arcminutes, so that features smaller than this size are damped.

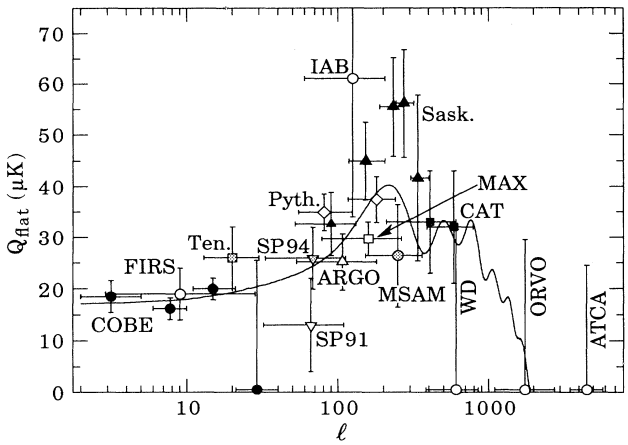

Figure 19.4: Current status of CMB anisotropy observations, adapted from Scott, Silk, & White (1995) [17]. This is a representation of the results from COBE, together with a wide range of ground- and balloon-based experiments which have operated in the last few years. Plotted are the quadrupole amplitudes for a flat (unprocessed scale-invariant spectrum of primordial perturbations, *i.e.*, a horizontal line) anisotropy spectrum that would give the observed results for each experiment. In other words each point is the normalization of a flat spectrum derived from the individual experiments. The vertical error bars represent estimates of 68% CL, while the upper limits are at 95% CL. Horizontal bars indicate the range of ℓ values sampled. The curve indicates the expected spectrum for a standard CDM model ($\Omega_0 = 1, \Omega_B = 0.05, h = 0.5$), although true comparison with models should involve convolution of this curve with each experimental filter function. (References for this figure are at the end of this section under "CMB Anisotropy References.")

Anisotropies are observed on angular scales larger than this damping scale (see Fig. 19.4), and are consistent with those expected from an initially scale-invariant power spectrum (flat = independent of scale) of potential and thus metric fluctuations. It is believed that the large scale structure in the Universe developed through the process of gravitational instability, where small primordial perturbations in energy density were amplified by gravity over the course of time. The initial spectrum of density perturbations can evolve significantly in the epoch $z > 1100$ for causally connected regions (angles $\lesssim 1° \ \Omega_{\rm tot}^{1/2}$). The primary mode of evolution is through adiabatic (acoustic) oscillations, leading to a series of peaks that encode information about the perturbations and geometry of the universe, as well as information on Ω_0, Ω_B, Ω_Λ (cosmological constant), and H_0 [17]. The location of the first acoustic peak is predicted to be at $\ell \sim 220 \ \Omega_{\rm tot}^{-1/2}$ or $\theta \sim 0.3° \ \Omega_{\rm tot}^{1/2}$ and its amplitude increases with increasing Ω_B.

Theoretical models often predict a power spectrum in spherical harmonic amplitudes, since the models lead to primordial fluctuations and thus $a_{\ell m}$ that are Gaussian random fields, and hence the power spectrum in ℓ is sufficient to characterize the results. The power at each ℓ is $(2\ell + 1)C_\ell/(4\pi)$, where $C_\ell \equiv \langle |a_{\ell m}|^2 \rangle$. For an idealized full-sky observation, the variance of each measured C_ℓ is $[2/(2\ell + 1)]C_\ell^2$. This sampling variance (known as cosmic variance) comes about because each C_ℓ is chi-squared distributed with $(2\ell + 1)$ degrees of freedom for our observable volume of the Universe [18].

Figure 19.5 shows the theoretically predicted anisotropy power spectrum for a sample of models, plotted as $\ell(\ell + 1)C_\ell$ versus ℓ which is the power per logarithmic interval in ℓ or, equivalently, the two-dimensional power spectrum. If the initial power spectrum of perturbations is the result of quantum mechanical fluctuations produced and amplified during inflation, then the shape of the anisotropy spectrum is coupled to the ratio of contributions from density (scalar) and gravity wave (tensor) perturbations. If the energy scale of inflation at the appropriate epoch is at the level of $\simeq 10^{16}$GeV, then detection of the effect of gravitons is possible, as well as partial reconstruction of the inflaton potential. If the energy scale is $\lesssim 10^{14}$GeV, then density fluctuations dominate and less constraint is possible.

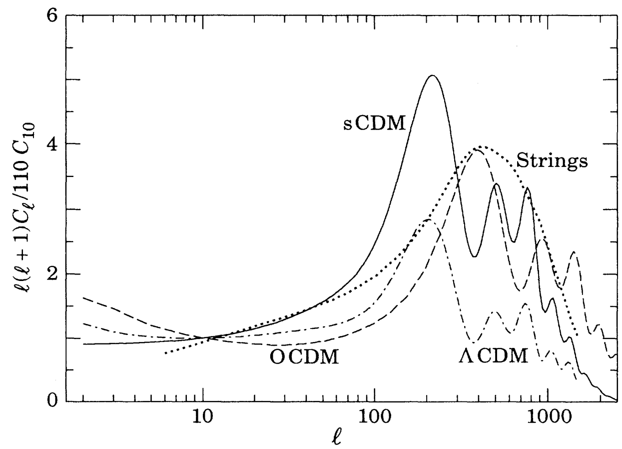

Figure 19.5: Examples of theoretically predicted $\ell(\ell + 1)C_\ell$ or CMB anisotropy power spectra. **sCDM** is the standard cold dark matter model with $h = 0.5$ and $\Omega_B = 0.05$. **ΛCDM** is a model with $\Omega_{\rm tot} = \Omega_\Lambda + \Omega_0 = 1$, with $\Omega_\Lambda = 0.3$ and $h = 0.8$. **OCDM** is an open model with $\Omega_0 = 0.3$ and $h = 0.75$ (see [19] for models). **Strings** is a model where cosmic strings are the primary source of large scale structure [20]. The plot indicates that precise measurements of the CMB anisotropy power spectrum could distinguish between current models.

Fits to data over smaller angular scales are often quoted as the expected value of the quadrupole $\langle Q \rangle$ for some specific theory, *e.g.* a model with power-law initial conditions (primordial density perturbation power spectrum $P(k) \propto k^n$). The full 4-year COBE DMR data give $\langle Q \rangle = 15.3^{+3.7}_{-2.8}\ \mu$K, after projecting out the slope dependence, while the best-fit slope is $n = 1.2 \pm 0.3$, and for a pure $n = 1$ (scale-invariant potential perturbation) spectrum $\langle Q \rangle (n = 1) = 18 \pm 1.6\,\mu$K [15,21]. The conventional notation is such that $\langle Q \rangle^2 / T_\gamma^2 = 5C_2/4\pi$. The fluctuations measured by other experiments can also be quoted in terms of $Q_{\rm flat}$, the equivalent value of the quadrupole for a flat ($n = 1$) spectrum, as presented in Fig. 19.4.

It now seems clear that there is more power at sub-degree scales than at COBE scales, which provides some model-dependent information on cosmological parameters [17,22], for example Ω_B. In terms of such parameters, fits to the COBE data alone yield $\Omega_0 > 0.34$ at 95% CL [23] and $\Omega_{\rm tot} < 1.5$ also at 95% CL [24], for inflationary models. Only somewhat weak conclusions can be drawn based on the current smaller angular scale data (see Fig. 19.4). A sample preliminary fit [25] finds $\Omega_{\rm tot} = 0.7^{+1.0}_{-0.4}$ and $30 < H_0 < 70$ km s^{-1}Mpc^{-1} for a limited range of cosmological models.

However, new data are being acquired at an increasing rate, with a large number of improved ground- and balloon-based experiments being developed. It appears that we are not far from being able to distinguish crudely between currently favored models, and to begin a more precise determination of cosmological parameters. A vigorous suborbital and interferometric program could map out the CMB anisotropy power spectrum to about 10% accuracy and determine several parameters at the 10 to 20% level in the next few years. Ultimately, on the scale of a perhaps 5–10 years, there is the prospect of another satellite mission which could provide a precise measurement of the power spectrum down to scales of 10 arcminutes, allowing us to decode essentially all of the information that it contains [26].

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20. COSMIC RAYS

Written 1995 by T.K. Gaisser and T. Stanev

20.1. Primary spectra

The cosmic radiation incident at the top of the terrestrial atmosphere includes all stable charged particles and nuclei with lifetimes of order 10^6 years or longer. Technically, "primary" cosmic rays are those particles accelerated at astrophysical sources and "secondaries" are those particles produced in interaction of the primaries with interstellar gas. Thus electrons, protons and helium, as well as carbon, oxygen, iron, and other nuclei synthesized in stars, are primaries. Nuclei such as lithium, beryllium, and boron (which are not abundant end-products of stellar nucleosynthesis) are secondaries. Antiprotons and positrons are partly, if not entirely, secondaries, but the fraction of these particles that may be primary is a question of current interest.

Apart from particles associated with solar flares, the cosmic radiation comes from outside the solar system. The incoming charged particles are "modulated" by the solar wind, the expanding magnetized plasma generated by the Sun, which decelerates and partially excludes the lower energy galactic cosmic rays from the inner solar system. There is a significant anticorrelation between solar activity (which has an eleven-year cycle) and the intensity of the cosmic rays with energies below about 10 GeV. In addition, the lower-energy cosmic rays are affected by the geomagnetic field, which they must penetrate to reach the top of the atmosphere. Thus the intensity of any component of the cosmic radiation in the GeV range depends both on the location and time.

There are four different ways to describe the spectra of the components of the cosmic radiation: (1) By particles per unit rigidity. Propagation (and probably also acceleration) through cosmic magnetic fields depends on gyroradius or *magnetic rigidity, R*, which is gyroradius multiplied by the magnetic field strength:

$$R = \frac{pc}{Ze} = r_L B \; . \tag{20.1}$$

(2) By particles per energy-per-nucleon. Fragmentation of nuclei propagating through the interstellar gas depends on energy per nucleon, since that quantity is approximately conserved when a nucleus breaks up on interaction with the gas. (3) By nucleons per energy-per-nucleon. Production of secondary cosmic rays in the atmosphere depends on the intensity of nucleons per energy-per-nucleon, approximately independently of whether the incident nucleons are free protons or bound in nuclei. (4) By particles per energy-per-nucleus. Air shower experiments that use the atmosphere as a calorimeter generally measure a quantity that is related to total energy per particle.

The units of differential intensity I are $[\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathcal{E}^{-1}]$, where $\mathcal{E}$ represents the units of one of the four variables listed above.

The intensity of primary nucleons in the energy range from several GeV to somewhat beyond 100 TeV is given approximately by

$$I_N(E) \approx 1.8\, E^{-\alpha}\, \frac{\text{nucleons}}{\text{cm}^2 \text{ s sr GeV}} \; , \tag{20.2}$$

where E is the energy-per-nucleon (including rest mass energy) and α ($\equiv \gamma + 1$) $= 2.7$ is the differential spectral index of the cosmic ray flux and γ is the integral spectral index. About 79% of the primary nucleons are free protons and about 70% of the rest are nucleons bound in helium nuclei. The fractions of the primary nuclei are nearly constant over this energy range (possibly with small but interesting variations). Fractions of both primary and secondary incident nuclei are listed in Table 20.1. Figure 20.1 [1] shows the major components as a function of energy at a particular epoch of the solar cycle.

The spectrum of electrons and positrons incident at the top of the atmosphere is steeper than the spectra of protons and nuclei, as shown in Fig. 20.2 [2]. The positron fraction is about 10% in the region in which it is measured (< 20 GeV), but it is not yet fully understood [5].

Above 10 GeV the fraction of antiprotons to protons is about 10^{-4}, and there is evidence for the kinematic suppression at lower energy expected for secondary antiprotons [5]. There is at this time no evidence for a significant primary component of antiprotons.

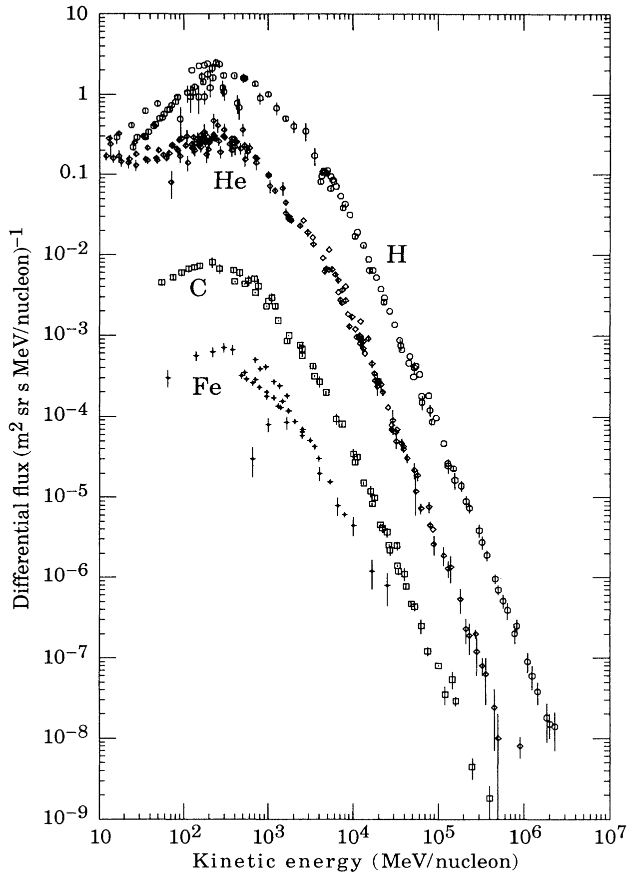

Figure 20.1: Major components of the primary cosmic radiation (from Ref. 1).

Table 20.1: Relative abundances F of cosmic-ray nuclei at 10.6 GeV/nucleon normalized to oxygen ($\equiv 1$) [3]. The oxygen flux at kinetic energy of 10.6 GeV/nucleon is 3.26×10^{-6} cm^{-2} s^{-1} sr^{-1} (GeV/nucleon)$^{-1}$. Abundances of hydrogen and helium are from Ref. 4.

Z	Element	F	Z	Element	F
1	H	730	13–14	Al-Si	0.19
2	He	34	15–16	P-S	0.03
3–5	Li-B	0.40	17–18	Cl-Ar	0.01
6–8	C-O	2.20	19–20	K-Ca	0.02
9–10	F-Ne	0.30	21–25	Sc-Mn	0.05
11–12	Na-Mg	0.22	26–28	Fe-Ni	0.12

20.2. Cosmic rays in the atmosphere

Figure 20.3 shows the vertical fluxes of the major cosmic ray components in the atmosphere in the energy region where the particles are most numerous (except for electrons, which are most numerous near their critical energy, which is about 81 MeV in air). Except for protons and electrons near the top of the atmosphere, all particles are produced in interactions of the primary cosmic rays in the air. Muons and neutrinos are products of the decay of charged mesons, while electrons and photons originate in decays of neutral mesons.

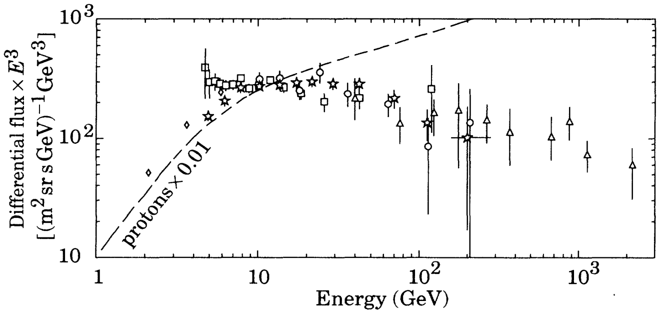

Figure 20.2: Differential spectrum of electrons plus positrons multiplied by E^3 (from Ref. 2).

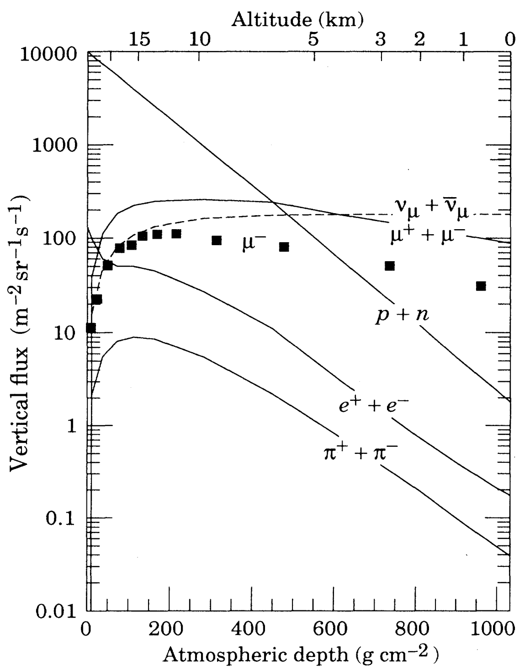

Figure 20.3: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (20.2). The points show measurements of negative muons with $E_\mu > 1$ GeV [7].

Most measurements are made at ground level or near the top of the atmosphere, but there are also measurements of muons and electrons from airplanes and balloons. Fig. 20.3 includes a recent measurement of negative muons [7]. Since $\mu^+(\mu^-)$ are produced in association with $\nu_\mu(\overline{\nu}_\mu)$, the measurement of muons near the maximum of the intensity curve for the parent pions serves to calibrate the atmospheric ν_μ beam [6]. Because muons typically lose almost two GeV in passing through the atmosphere, the comparison near the production altitude is important for the sub-GeV range of $\nu_\mu(\overline{\nu}_\mu)$ energies.

The flux of cosmic rays through the atmosphere is described by a set of coupled cascade equations with boundary conditions at the top of the atmosphere to match the primary spectrum. Numerical or Monte Carlo calculations are needed to account accurately for decay and energy-loss processes, and for the energy-dependences of the cross sections and of the primary spectral index γ. Approximate analytic solutions are, however, useful in limited regions of energy [8]. For example, the vertical intensity of nucleons at depth X (g cm^{-2}) in the atmosphere is given by

$$I_N(E, X) \approx I_N(E, 0)\, e^{-X/\Lambda} , \tag{20.3}$$

where Λ is the attenuation length of nucleons in air.

The corresponding expression for the vertical intensity of charged pions with energy $E_\pi \ll \epsilon_\pi = 115$ GeV is

$$I_\pi(E_\pi, X) \approx \frac{Z_{N\pi}}{\lambda_N} I_N(E_\pi, 0)\, e^{-X/\Lambda} \frac{X\, E_\pi}{\epsilon_\pi} . \tag{20.4}$$

This expression has a maximum at $t = \Lambda \approx 120$ g cm^{-2}, which corresponds to an altitude of 15 kilometers. The quantity $Z_{N\pi}$ is the spectrum-weighted moment of the inclusive distribution of charged pions in interactions of nucleons with nuclei of the atmosphere. The intensity of low-energy pions is much less than that of nucleons because $Z_{N\pi} \approx 0.079$ is small and because most pions with energy much less than the critical energy ϵ_π decay rather than interact.

20.3. Cosmic rays at the surface

20.3.1. ***Muons***: Muons are the most numerous charged particles at sea level (see Fig. 20.3). Most muons are produced high in the atmosphere (typically 15 km) and lose about 2 GeV to ionization before reaching the ground. Their energy and angular distribution reflect a convolution of production spectrum, energy loss in the atmosphere, and decay. For example, $E_\mu = 2.4$ GeV muons have a decay length of 15 km, which is reduced to 8.7 km by energy loss. The mean energy of muons at the ground is ≈ 4 GeV. The energy spectrum is almost flat below 1 GeV, steepens gradually to reflect the primary spectrum in the 10–100 GeV range, and steepens further at higher energies because pions with $E_\pi > \epsilon_\pi \approx 115$ GeV tend to interact in the atmosphere before they decay. Asymptotically ($E_\mu \gg 1$ TeV), the energy spectrum of atmospheric muons is one power steeper than the primary spectrum. The integral intensity of vertical muons above 1 GeV/c at sea level is ≈ 70 m^{-2}s^{-1}sr^{-1} [9,10]. Experimentalists are familiar with this number in the form $I \approx 1$ cm^{-2} min^{-1} for horizontal detectors.

The overall angular distribution of muons at the ground is $\propto \cos^2\theta$, which is characteristic of muons with $E_\mu \sim 3$ GeV. At lower energy the angular distribution becomes increasingly steeper, while at higher energy it flattens and approaches a $\sec\theta$ distribution for $E_\mu \gg \epsilon_\pi$ and $\theta < 70°$.

Figure 20.4 shows the muon energy spectrum at sea level for two angles. At large angles low energy muons decay before reaching the surface and high energy pions decay before they interact, thus the average muon energy increases. An approximate extrapolation formula valid when muon decay is negligible ($E_\mu > 100/\cos\theta$ GeV) and the curvature of the Earth can be neglected ($\theta < 70°$) is

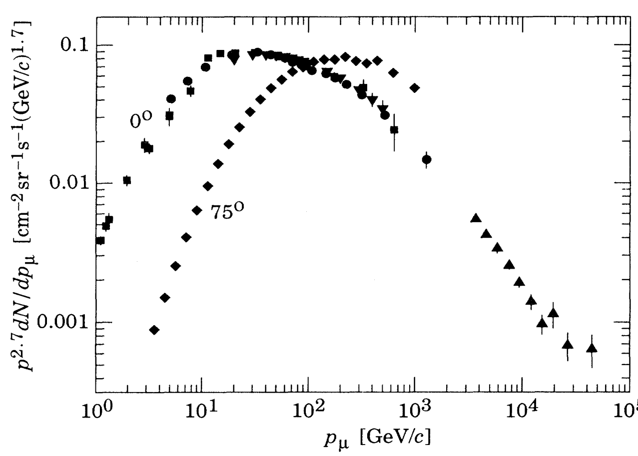

Figure 20.4: Spectrum of muons at $\theta = 0°$ (■ [12], ● [13], ▼ [14], ▲ [15]), and $\theta = 75°$ ◆ [16]).

$$\frac{dN_\mu}{dE_\mu} \approx \frac{0.14\,E^{-2.7}}{\text{cm}^2\ \text{s sr GeV}}$$
$$\times \left\{ \frac{1}{1+\frac{1.1E_\mu\cos\theta}{115\,\text{GeV}}} + \frac{0.054}{1+\frac{1.1E_\mu\cos\theta}{850\,\text{GeV}}} \right\}, \qquad (20.5)$$

where the two terms give the contribution of pions and charged kaons. Eq. (20.5) neglects a small contribution from charm and heavier flavors which is negligible except at very high energy [17].

The muon charge ratio reflects the excess of π^+ over π^- in the forward fragmentation region of proton initiated interactions together with the fact that there are more protons than neutrons in the primary spectrum. The charge ratio is between 1.2 and 1.3 from 250 MeV up to 100 GeV [9].

20.3.2. ***Electromagnetic component***: At the ground, this component consists of electrons, positrons, and photons primarily from electromagnetic cascades initiated by decay of neutral and charged mesons. Muon decay is the dominant source of low-energy electrons at sea level. Decay of neutral pions is more important at high altitude or when the energy threshold is high. Knock-on electrons also make a small contribution at low energy [11]. The integral vertical intensity of electrons plus positrons is very approximately 30, 6, and 0.2 $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$ above 10, 100, and 1000 MeV respectively [10,18], but the exact numbers depend sensitively on altitude, and the angular dependence is complex because of the different altitude dependence of the different sources of electrons [11,18,19]. The ratio of photons to electrons plus positrons is approximately 1.3 above a GeV and 1.7 below the critical energy [19].

20.3.3. ***Protons***: Nucleons above 1 GeV/c at ground level are degraded remnants of the primary cosmic radiation. The intensity is approximately represented by Eq. (20.3) with the replacement $t \to t/\cos\theta$ for $\theta < 70°$ and an attenuation length $\Lambda = 123$ g cm^{-2}. At sea level, about 1/3 of the nucleons in the vertical direction are neutrons (up from $\approx 10\%$ at the top of the atmosphere as the n/p ratio approaches equilibrium). The integral intensity of vertical protons above 1 GeV/c at sea level is $\approx 0.9\ \text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$ [10,20].

20.4. Cosmic rays underground

Only muons and neutrinos penetrate to significant depths underground. The muons produce tertiary fluxes of photons, electrons, and hadrons.

20.4.1. ***Muons***: As discussed in Section 22.9 of this *Review*, muons lose energy by ionization and by radiative processes: bremsstrahlung, direct production of e^+e^- pairs, and photonuclear interactions. The total muon energy loss may be expressed as a function of the amount of matter traversed as

$$-\frac{dE_\mu}{dX} = a + b\,E_\mu\,, \qquad (20.6)$$

where a is the ionization loss and b is the fractional energy loss by the three radiation processes. Both are slowly varying functions of energy. The quantity $\epsilon \equiv a/b$ (≈ 500 GeV in standard rock) defines a critical energy below which continuous ionization loss is more important the radiative losses. Table 20.2 shows a and b values for standard rock as a function of muon energy. The second column of Table 20.2 shows the muon range in standard rock ($A = 22$, $Z = 11$, $\rho = 2.65$ g cm^{-3}). These parameters are quite sensitive to the chemical composition of the rock, which must be evaluated for each experimental location.

The intensity of muons underground can be estimated from the muon intensity in the atmosphere and their rate of energy loss. To the extent that the mild energy dependence of a and b can be neglected, Eq. (20.6) can be integrated to provide the following relation between the energy $E_{\mu,0}$ of a muon at production in the atmosphere and its average energy E_μ after traversing a thickness X of rock (or ice or water):

$$E_\mu = (E_{\mu,0} + \epsilon)\,e^{-bX} - \epsilon\,. \qquad (20.7)$$

Table 20.2: Average muon range R and energy loss parameters calculated for standard rock. Range is given in km-water-equivalent, or 10^5 g cm^{-2}.

E_μ GeV	R km.w.e.	a MeV g^{-1} cm^2	b_{pair}	b_{brems} 10^{-6} g^{-1} cm^2	b_{nucl}	$\sum b_i$
10	0.05	2.15	0.73	0.74	0.45	1.91
100	0.41	2.40	1.15	1.56	0.41	3.12
1000	2.42	2.58	1.47	2.10	0.44	4.01
10000	6.30	2.76	1.64	2.27	0.50	4.40

Especially at high energy, however, fluctuations are important and an accurate calculation requires a simulation that accounts for stochastic energy-loss processes [21].

Fig. 20.5 shows the vertical muon intensity versus depth. In constructing this "depth-intensity curve," each group has taken account of the angular distribution of the muons in the atmosphere, the map of the overburden at each detector, and the properties of the local medium in connecting measurements at various slant depths and zenith angles to the vertical intensity. Use of data from a range of angles allows a fixed detector to cover a wide range of depths. The flat portion of the curve is due to muons produced locally by charged-current interactions of ν_μ.

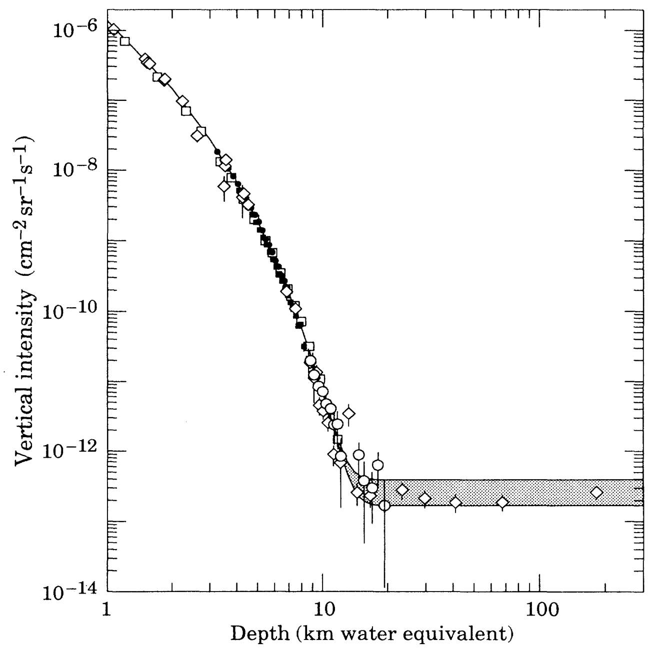

Figure 20.5: Vertical muon intensity *vs.* depth (1 km.w.e. = 10^5 g cm^{-2} of standard rock). The experimental data are from: ◊: the compilations of Crouch [29], □: Baksan [30], ○ : LVD [31], ● : MACRO [32], ■: Frejus [33]. The shaded area at large depths represents neutrino induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons.

The energy spectrum of atmospheric muons underground can be estimated from Eq. (20.7). The muon energy spectrum at slant depth X is

$$\frac{dN_\mu(X)}{dE_\mu} = \frac{dN_\mu}{dE_{\mu,0}}\,e^{bX}\,, \qquad (20.8)$$

where $E_{\mu,0}$ is the solution of Eq. (20.7). For $X \ll b^{-1} \approx 2.5$ km water equivalent, $E_{\mu,0} \approx E_\mu(X) + aX$. Thus at shallow depths the differential muon energy spectrum is approximately constant for

$E_\mu < aX$ and steepens to reflect the surface muon spectrum for $E_\mu > aX$. For $X \gg b^{-1}$ the differential spectrum underground is again constant for small muon energies but steepens to reflect the surface muon spectrum for $E_\mu > \epsilon \approx 0.5$ TeV. In this regime the shape is independent of depth although the intensity decreases exponentially with depth.

20.4.2. ***Neutrinos***: Because neutrinos have small interaction cross sections, measurements of atmospheric neutrinos require a deep detector to avoid backgrounds. There are two types of measurements: contained (or semi-contained) events, in which the vertex is determined to originate inside the detector, and neutrino-induced muons. The latter are muons that enter the detector from zenith angles so large (*e.g.*, nearly horizontal or upward) that they cannot be muons produced in the atmosphere. In neither case is the neutrino flux measured directly. What is measured is a convolution of the neutrino flux and cross section with the properties of the detector (which includes the surrounding medium in the case of entering muons).

Contained events reflect the neutrinos in the GeV region where the product of increasing cross section and decreasing flux is maximum. In this energy region the neutrino flux and its angular distribution depend on the geomagnetic location of the detector and to a lesser extent on the phase of the solar cycle. Naively, we expect $\nu_\mu/\nu_e = 2$ from counting the neutrinos of the two flavors coming from the chain of pion and muon decay. This ratio is only slightly modified by the details of the decay kinematics. Experimental measurements have also to account for the ratio of $\overline{\nu}/\nu$, which have cross sections different by a factor of 3 in this energy range. In addition, detectors will generally have different efficiencies for detecting muon neutrinos and electron neutrinos. Even after correcting for these and other effects, some detectors [22,23] infer a ν_μ/ν_e ratio lower by $\approx 4\sigma$ from the expected value. (See Tables in the Particle Listings of this *Review.*) This effect is sometimes cited as possible evidence of neutrino oscillations and is a subject of current investigation. Figure 20.6 shows the data of Refs. 22,23 for the distributions of visible energy in electron-like and muon-like charged-current events, which appear to be nearly equal in number. Corrections for detection efficiencies and backgrounds are insufficient to account for the difference from the expected value of two.

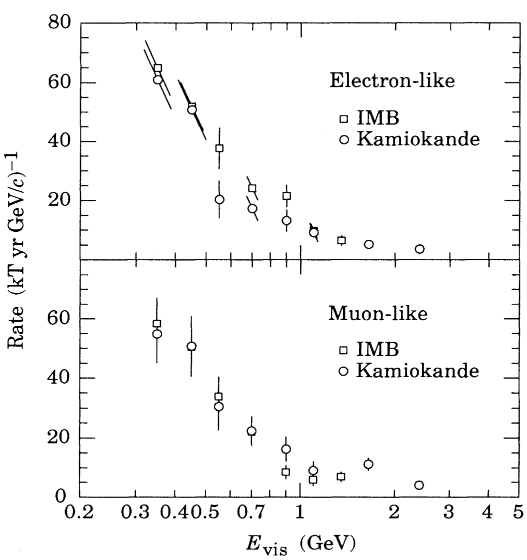

Figure 20.6: Contained neutrino interactions from IMB [23](□) and Kamiokande [22].

Muons that enter the detector from outside after production in charged-current interactions of neutrinos naturally reflect a higher energy portion of the neutrino spectrum than contained events because the muon range increases with energy as well as the cross section. The relevant energy range is $\sim 10 < E_\nu < 1000$ GeV, depending somewhat on angle. Like muons (see Eq. (20.5)), high energy neutrinos show a "secant theta" effect which causes the flux of horizontal neutrino induced muons to be approximately a factor two higher than the vertically upward flux. The upper and lower edges of the horizontal shaded region in Fig. 20.5 correspond to horizontal and vertical intensities of neutrino-induced muons. Table 20.3 gives the measured fluxes of neutrino induced muons.

Table 20.3: Measured fluxes (10^{-13} cm^{-2} s^{-1} sr^{-1}) of neutrino-induced muons as a function of the minimum muon energy E_μ.

$E_\mu >$	1 GeV	1 GeV	1 GeV	2 GeV	3 GeV
Ref.	CWI [24]	Baksan [25]	MACRO [26]	IMB [27]	Kam [28]
F_μ	2.17±0.21	2.77±0.17	2.48 ± 0.27	2.26±0.11	2.04±0.13

20.5. Air showers

So far we have discussed inclusive or uncorrelated fluxes of various components of the cosmic radiation. An air shower is caused by a single cosmic ray with energy high enough for its cascade to be detectable at the ground. The shower has a hadronic core, which acts as a collimated source of electromagnetic subshowers, generated mostly from $\pi^0 \to \gamma\gamma$. The resulting electrons and positrons are the most numerous particles in the shower. The number of muons, produced by decays of charged mesons, is an order of magnitude lower.

Air showers spread over a large area on the ground, and arrays of detectors operated for long times are useful for studying cosmic rays with primary energy $E_0 > 100$ TeV, where the low flux makes measurements with small detectors in balloons and satellites difficult.

Greisen [46] gives the following approximate expressions for the numbers and lateral distributions of particles in showers at ground level. The total number of muons N_μ with energies above 1 GeV is

$$N_\mu(> 1\ \text{GeV}) \approx 0.95 \times 10^5 \left(\frac{N_e}{10^6}\right)^{3/4} , \tag{20.9}$$

where N_e is the total number of charged particles in the shower (not just $e^\pm$). The number of muons per square meter, ρ_μ, as a function of the lateral distance r (in meters) from the center of the shower is

$$\rho_\mu = \frac{1.25\, N_\mu}{2\pi\, \Gamma(1.25)} \left(\frac{1}{320}\right)^{1.25} r^{-0.75} \left(1 + \frac{r}{320}\right)^{-2.5} , \tag{20.10}$$

where Γ is the gamma function. The number density of charged particles is

$$\rho_e = C_1(s, d, C_2)\, x^{(s-2)}(1+x)^{(s-4.5)}(1 + C_2 x^d) . \tag{20.11}$$

Here s, d, and C_2 are parameters in terms of which the overall normalization constant $C_1(s, d, C_2)$ is given by

$$C_1(s, d, C_2) = \frac{N_e}{2\pi r_1^2} [B(s, 4.5-2s) + C_2\, B(s+d,\, 4.5-d-2s)]^{-1} , \tag{20.12}$$

where $B(m, n)$ is the beta function. The values of the parameters depend on shower size (N_e), depth in the atmosphere, identity of the primary nucleus, etc. For showers with $N_e \approx 10^6$ at sea level, Greisen uses $s = 1.25$, $d = 1$, and $C_2 = 0.088$. Finally, x is r/r_1, where r_1 is the Molière radius, which depends on the density of the atmosphere and hence on the altitude at which showers are detected. At sea level $r_1 \approx 78$ m. It increases with altitude.

The lateral spread of a shower is determined largely by Coulomb scattering of the many low-energy electrons and is characterized by the Molière radius. The lateral spread of the muons (ρ_μ) is larger and depends on the transverse momenta of the muons at production as well as multiple scattering.

There are large fluctuations in development from shower to shower, even for showers of the same energy and primary mass—especially for small showers, which are usually well past maximum development when observed at the ground. Thus the shower size N_e and primary energy E_0 are only related in an average sense, and even this relation depends on depth in the atmosphere. One estimate of the relation is [35]

$$E_0 \sim 3.9 \times 10^6 \text{ GeV } (N_e/10^6)^{0.9} \qquad (20.13)$$

for vertical showers with $10^{14} < E < 10^{17}$ eV at 920 g cm^{-2} (965 m above sea level). Because of fluctuations, N_e as a function of E_0 is not the inverse of Eq. (20.13). As E_0 increases the shower maximum (on average) moves down into the atmosphere and the relation between N_e and E_0 changes. At the maximum of shower development, there are approximately 2/3 particles per GeV of primary energy.

Detailed simulations and cross-calibrations between different types of detectors are necessary to establish the primary energy spectrum from air-shower experiments [35,36]. Figure 20.7 shows the "all-particle" spectrum. In establishing this spectrum, efforts have been made to minimize the dependence of the analysis on the primary composition. In the energy range above 10^{17} eV, the Fly's Eye technique [48] is particularly useful because it can establish the primary energy in a model-independent way by observing most of the longitudinal development of each shower, from which E_0 is obtained by integrating the energy deposition in the atmosphere.

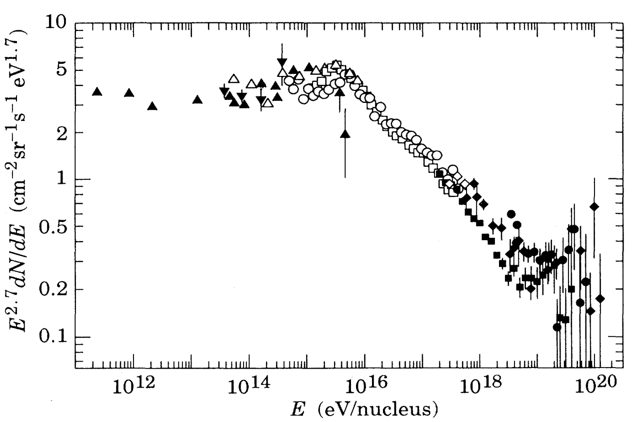

Figure 20.7: The all-particle spectrum: ▲ [37], ▼ [38], △ [39], □ [40], ○ [35], ■ [48], ● [42], ♦ [43].

In Fig. 20.7 the differential energy spectrum has been multiplied by $E^{2.7}$ in order to display the features of the steep spectrum that are otherwise difficult to discern. The steepening that occurs between 10^{15} and 10^{16} eV is known as the *knee* of the spectrum. The feature between 10^{18} and 10^{19} eV is called the *ankle* of the spectrum. Both these features are the subject of intense interest at present [44].

The *ankle* has the classical characteristic shape [45] of a higher energy population of particles overtaking a lower energy population. A possible interpretation is that the higher energy population represents cosmic rays of extragalactic origin. If this is the case and if the cosmic rays are cosmological in origin, then there should be a cutoff around 5×10^{19} eV, resulting from interactions with the microwave background [46,47]. It is therefore of special interest that several events have been assigned energies above 10^{20} eV [48,49,50].

If the cosmic ray spectrum below 10^{18} eV is of galactic origin, the *knee* could reflect the fact that some (but not all) cosmic accelerators have reached their maximum energy. Some types of expanding supernova remnants, for example, are estimated not to be able to accelerate particles above energies in the range of 10^{15} eV total energy per particle. Effects of propagation and confinement in the galaxy [51] also need to be considered.

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21. HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (I)

None of the colliders on this page are any longer working in elementary-particle physics. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions. Many of the numbers of course changed over the lifetimes of the colliders; only the end-of-service values are given here.

	SPEAR (SLAC)	DORIS (DESY)	PETRA (DESY)	PEP (SLAC)	TRISTAN (KEK)
Physics start date	1972	1973	1978	1980	1987
Physics end date	1990	1993	1986	1990	1995
Maximum beam energy (GeV)	4	5.6	23.4	15	32
Luminosity (10^{30} cm^{-2}s^{-1})	10 at 3 GeV	33 at 5.3 GeV	24 at 17.5 GeV	60	40
Time between collisions (μs)	0.75	0.965	3.8	2.44	5
Crossing half angle (μ rad)	0	0	0	0	0
Energy spread (units 10^{-3})	1	1.2 at 5 GeV	1.1 at 17.5 GeV	1	2.3
Bunch length (cm)	$\sigma_z \approx 4$	$\sigma \sim 2$ at 5 GeV	$\sigma \sim 1.3$ at 17.5 GeV	$\sigma_z = 2$	1.5
Beam radius (10^{-6} m)	H: 700 V: 50	H: 740 V: ~ 30 } at 5 GeV	H: 430 V: 13 } at 17.5 GeV	H: 340 V: 14	H: 280 V: 8
Free space at interaction point (m)	± 2.5	± 1.2	± 4.5	± 3.7	± 2.51
Luminosity lifetime (hr)	≈ 3	1.0–1.5	4 at 17.5 GeV	4	2
Filling time (min)	15	≈ 15	20	15	40
Acceleration period (s)	≤ 100	—	—	≤ 100	300
Injection energy (GeV)	2.5	up to 5.6	7	15	8
Transverse emittance ($10^{-9}\pi$ rad-m)	$H \approx 430$	H: 500 V: 5–50 } at 5 GeV	H: 140 V: 2	$H \approx 120$	H: 80 at 29 GeV
β^*, amplitude function at interaction point (m)	H: 1.2 V: 0.08	H: 0.59/12.3 V: 0.04/0.79	H: 1.3 V: 0.08	H: 1.0 V: 0.05	H: 1.0 V: 0.04
Beam-beam tune shift per crossing (units 10^{-4})	300	≤ 280 (space charge limit at 5.3 GeV)	H: 160 V: 400 } at 17.5 GeV	550	340
RF frequency (MHz)	358	500	500	352	508.5808
Particles per bunch (units 10^{10})	15	27	26	35	22
Bunches per ring per species	1	1	2	3	2
Average beam current per species (mA)	30	45 at 5.3 GeV	11 at 17.5 GeV	21	7
Circumference (km)	0.234	0.2892	2.304	2.2	3.02
Interaction regions	2	2	4	1	4
Utility insertions	18	10	4	5	8
Magnetic length of dipole (m)	2.35	3.2/1.1	5.38	5.4	5.86
Length of standard cell (m)	11.4	13.2	14.4	14.35	16.1
Phase advance per cell (deg)	H: 79 V: 90	H: 140 V: 50	H: 47 V: 40	H: 56 V: 33	60
Dipoles in ring	36	H: 28 V: 6	224	192	264 +8 weak
Quadrupoles in ring	46	68	360	248	392
Peak magnetic field (T)	1.1	1.5	0.4 at 23 GeV	0.36	0.41 at 30 GeV

HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (II)

The numbers here were received from representatives of the colliders in 1996. Many of the numbers of course change with time, and only the latest values (or estimates) are given here; those in brackets are for coming upgrades. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions.

	VEPP-2M [round beams] (Novosibirsk)	DAΦNE (Frascati)	ϕ FACTORY (Novosibirsk)	BEPC (China)	VEPP-4M (Novosibirsk)
Physics start date	1974 [1997]	1997	?	1989	1994
Maximum beam energy (GeV)	0.7 [0.55]	0.510 (0.75 max.)	0.55	2.2	6
Luminosity (10^{30} cm^{-2}s^{-1})	5 [100]	135(→540)	2500	10	50
Time between collisions (μs)	0.03	0.0108(→0.0027)	0.007	0.8	0.6
Crossing angle (μ rad)	0	$\pm(1.0$ to $1.5)\times10^4$	0	0	0
Energy spread (units 10^{-3})	0.6 [0.35]	0.40	0.5	0.58	1
Bunch length (cm)	3	3.0	1	≈ 5	5
Beam radius (10^{-6} m)	H/V: 400/10 [35 (round)]	H: 2100 V: 21	35 (beams are round)	H: 926 V: 61	H: 1000 V: 30
Free space at interaction point (m)	±1	±0.46 (±157 mrad cone)	±2	±2.5	±2
Luminosity lifetime (hr)	continuous	2	continuous	7–12	2
Filling time (min)	continuous	3 (topping up)	continuous	30	15
Acceleration period (s)	—	—	—	120	150
Injection energy (GeV)	0.2–0.7 [0.2–0.55]	0.510	—	1.3	1.8
Transverse emittance ($10^{-9}\pi$ rad-m)	H/V: 400/4 [150]	H: 1000 V: 10	125	H: 660 V: 43	H: 400 V: 20
β^*, amplitude function at interaction point (m)	H/V: 0.48/0.04 [0.05]	H: 4.5 V: 0.045	0.01	H: 1.3 V: 0.085	H: 0.75 V: 0.05
Beam-beam tune shift per crossing (units 10^{-4})	H/V: 200/500 [1000]	400	1000	420	500
RF frequency (MHz)	200	368.25	700	199.53	180
Particles per bunch (units 10^{10})	4 [6.7]	8.9	5	20 at 2 GeV	15
Bunches per ring per species	1	30(→120)	11	1	2
Average beam current per species (mA)	100 [160]	1313(→5250)	550	40 at 2 GeV	80
Circumference or length (km)	0.018	0.0977	0.047	0.2404	0.366
Interaction regions	2	2	1	2	1
Utility insertions	1	2 × 2	1	4	1
Magnetic length of dipole (m)	1	e^+: 1.21/0.99 e^-: 1.21/0.99	0.8	1.6	2
Length of standard cell (m)	4.5 [9.0]	—	—	6.6	7.2
Phase advance per cell (deg)	280 [560]	—	—	≈ 60	65
Dipoles in ring	8	e^+: 8(+4 wigglers) e^-: 8(+4 wigglers)	22	40 + 4 weak	78
Quadrupoles in ring	20 [12]	e^+/e^-: 53/53	22	68	150
Peak magnetic field (T)	1.8 [1.5]	1.2(→1.76) dipoles 1.8 wigglers	1.8	0.9028	0.6

HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (III)

The numbers here were received from representatives of the colliders in 1996. Many of the numbers of course change with time, and only the latest values (or estimates) are given here. Quantities are, where appropriate, r.m.s. H and V indicate horizontal and vertical directions; s.c. indicates superconducting.

	CESR (Cornell)	KEKB (KEK)	PEP-II (SLAC)	SLC (SLAC)	LEP (CERN)
Physics start date	1979	1999	1999	1989	1989
Maximum beam energy (GeV)	6	$e^- \times e^+$: 8×3.5	$e^- \times e^+$: 9×3.1 (6.5 GeV c.m. max)	50	87 in 1996 (97=max. foreseen)
Luminosity (10^{30} cm^{-2}s^{-1})	330 at 5.3 GeV (600 in mid-1996)	10000	3000	0.8	24 at Z^0 34 at 68 GeV
Time between collisions (μs)	0.028 to 0.22	0.002	0.0042	8300	22
Crossing angle (μ rad)	±2000	±11,000	0	0	0
Energy spread (units 10^{-3})	0.6 at 5.3 GeV	0.7	e^-/e^+: 0.61/0.77	1.2	1.0
Bunch length (cm)	1.8	0.4	e^-/e^+: 1.1/1.0	0.08	1.8
Beam radius (10^{-6} m)	H: 500 V: 11	H: 77 V: 1.9	H: 155 V: 6.2	H: 2.1 V: 0.6	H: 200 V: 8
Free space at interaction point (m)	±2.2 (±0.6 to REC quads)	±0.4, (+300/−500) mrad cone	±0.2, ±300 mrad cone	±2.8	±3.5
Luminosity lifetime (hr)	3–4	2	2.5	—	20
Filling time (min)	10 (topping up)	8 (topping up)	3 (topping up)	—	90
Acceleration period (s)	—	—	—	—	420
Injection energy (GeV)	6	e^-/e^+: 8/3.5	2.5–12	45.64	22
Transverse emittance ($10^{-9}\pi$ rad-m)	H: 240 V: 8	H: 18 V: 0.36	e^-: 48 (H), 1.9 (V) e^+: 64 (H), 2.6 (V)	H: 0.6 V: 0.1	H: $12 \to 4$ V: $0.5 \to 2$
β^*, amplitude function at interaction point (m)	H: 1.0 V: 0.018	H: 0.33 V: 0.01	e^-: 0.50 (H), 0.02 (V) e^+: 0.375 (H), 0.015 (V)	H: 0.01 V: 0.002	H: 2.5 V: 0.05
Beam-beam tune shift per crossing (units 10^{-4})	420	H: 390 V: 520	300	—	490
RF frequency (MHz)	500	508.887	476	—	352.2
Particles per bunch (units 10^{10})	11	1.3/3.2	e^-/e^+: 2.7/5.9	3.5	20 in collision 60 in single beam
Bunches per ring per species	9 trains of 2 bunches (of 3 bunches in mid-1996)	5120	1658	1	1995: 4 trains of 3 1996+: 4 trains of 2
Average beam current per species (mA)	120 (300 in mid-1996)	e^-/e^+: 1100/2600	e^-/e^+: 990/2140	0.0007	4
Beam polarization (%)	—	—	—	e^-: 80	55
Circumference or length (km)	0.768	3.016	2.2	1.45 +1.47	26.66
Interaction regions	1	1	1 (2 possible)	1	4
Utility insertions	3	3	5	—	4
Magnetic length of dipole (m)	1.6–6.6	e^-/e^+: 5.86/0.915	e^-/e^+: 5.4/0.45	2.5	11.66/pair
Length of standard cell (m)	16	e^-/e^+: 75.7/76.1	15.2	5.2	79
Phase advance per cell (deg)	45–90 (no standard cell)	450	e^-/e^+: 60/90	108	108/60
Dipoles in ring	86	e^-/e^+: 116/112	e^-/e^+: 192/192	460+440	3280+24 inj. + 64 weak
Quadrupoles in ring	104	e^-/e^+: 452/452	e^-/e^+: 290/326	—	520+288 + 8 s.c.
Peak magnetic field (T)	0.3 normal, 0.8 high field } at 8 GeV	e^-/e^+: 0.25/0.72	e^-/e^+: 0.18/0.75	0.597	0.135

HIGH-ENERGY COLLIDER PARAMETERS: *ep*, $\overline{p}p$, and *pp* Colliders

The numbers here were received from representatives of the colliders in 1996. Many of the numbers of course change with time, and only the latest values (or estimates) are given here. Quantities are, where appropriate, r.m.s. *H*, *V*, and, s.c. indicate horizontal and vertical directions, and superconducting. The SSC is kept for purposes of comparison.

	HERA (DESY)	$Sp\overline{p}S$ (CERN)	TEVATRON (Fermilab)	LHC (CERN)		SSC (USA)
Physics start date	1992	1981	1987	2004		Terminated
Physics end date	—	1990	—	—		—
Particles collided	*ep*	$p\overline{p}$	$p\overline{p}$	*pp*	Pb Pb	*pp*
Maximum beam energy (TeV)	*e*: 0.030 *p*: 0.82	0.315 (0.45 in pulsed mode)	0.9–1.0	7.0	2.76 TeV/u	20
Luminosity (10^{30} cm^{-2}s^{-1})	16	6	25 (1995) 200 (2000)	1.0×10^4	0.002	1000
Time between collisions (μs)	0.096	3.8	3.5	0.025	0.125	0.016678
Crossing angle (μ rad)	0	0	0	200	≤ 100	100 to 200 (135 nominal)
Energy spread (units 10^{-3})	*e*: 0.91 *p*: 0.2	0.35	0.15	0.1	0.1	0.055
Bunch length (cm)	*e*: 0.83 *p*: 8.5	20	50	7.5	7.5	6.0
Beam radius (10^{-6} m)	*e*: $280(H), 50(V)$ *p*: $265(H), 50(V)$	*p*: $73(H), 36(V)$ $\overline{p}$: $55(H), 27(V)$	36	16	15	4.8
Free space at interaction point (m)	±5.5	16	±6.5	38	38	±20
Luminosity lifetime (hr)	10	15	7–30	10	6.7	~24
Filling time (min)	*e*: 30 *p*: 120	0.5	120	6	20	72
Acceleration period (s)	600	10	86	1200		1500
Injection energy (TeV)	*e*: 0.012 *p*: 0.040	0.026	0.15	0.450	177.4 GeV/u	2
Transverse emittance ($10^{-9}\pi$ rad-m)	*e*: $39(H), 2(V)$ *p*: $7(H), 7(V)$	*p*: 9 $\overline{p}$: 5	*p*: 4 $\overline{p}$: 2.2	0.5	0.5	0.047
β^*, amplitude function at interaction point (m)	*e*: $2(H), 0.9(V)$ *p*: $7(H), 0.7(V)$	0.6 (H) 0.15 (V)	0.35	0.5	0.5	0.5
Beam-beam tune shift per crossing (units 10^{-4})	*e*: $190(H), 210(V)$ *p*: $12(H), 9(V)$	50	*p*: 40 $\overline{p}$: 75	34	—	8 head on 13 long range
RF frequency (MHz)	*e*: 499.7 *p*: 208.2/52.05	100+200	53	400.8	400.8	359.75
Particles per bunch (units 10^{10})	*e*: 3.65 *p*: 10	*p*: 15 $\overline{p}$: 8	*p*: 25 $\overline{p}$: 7.5	10.5	0.0094	0.8
Bunches per ring per species	180	6	6	2835	608	17,424
Average beam current per species (mA)	*e*: 58 *p*: 158	*p*: 6 $\overline{p}$: 3	*p*: 12.5 $\overline{p}$: 3.7	536	7.8	71
Circumference (km)	6.336	6.911	6.28	26.659		87.12
Interaction regions	*ep*: 2 *e*, *p*: 1 each, internal fixed target	2	2 high $\mathscr{L}$	2 high $\mathscr{L}$ +1	1	4
Utility insertions	4	—	4	4		2
Magnetic length of dipole (m)	*e*: 9.185 *p*: 8.82	6.26	6.12	14.2		Mostly 14.928
Length of standard cell (m)	*e*: 23.5 *p*: 47	64	59.5	106.92		180
Phase advance per cell (deg)	*e*: 60 *p*: 90	90	67.8	90		90
Dipoles in ring	*e*: 396 *p*: 416	744	774	1232 main dipoles		*H*: 8336 *V*: 88 } in 2 rings
Quadrupoles in ring	*e*: 580 *p*: 280	232	216	692 focussing +96 skew		2084 } 2 rings
Magnet type	*e*: C-shaped *p*: s.c., collared, cold iron	*H* type with bent-up coil ends	s.c. $\cos\theta$ warm iron	s.c. 2 in 1 cold iron		s.c. $\cos\theta$ cold iron
Peak magnetic field (T)	*e*: 0.274 *p*: 4.65	1.4 (2 in pulsed mode)	4.4	8.4		6.790
$\overline{p}$ source accum. rate (hr^{-1})	—	6×10^{10}	7×10^{10}	—		—
Max. no. $\overline{p}$ in accum. ring	—	1.2×10^{12}	2×10^{12}	—		—

22. PASSAGE OF PARTICLES THROUGH MATTER

Revised May 1996.

22.1. Notation

Table 22.1: Summary of variables used in this section. The kinematic variables β and γ have their usual meanings.

Symbol	Definition	Units or Value
α	Fine structure constant	1/137.035 989 5(61)
M	Incident particle mass	MeV/c^2
E	Incident particle energy γMc^2	MeV
T	Kinetic energy	MeV
m_ec^2	Electron mass $\times\, c^2$	0.510 999 06(15) MeV
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_ec^2$	2.817 940 92(38) fm
N_A	Avogadro's number	$6.022\,136\,7(36) \times 10^{23}$ mol^{-1}
ze	Charge of incident particle	
Z	Atomic number of medium	
A	Atomic mass of medium	g mol^{-1}
K/A	$4\pi N_A r_e^2 m_ec^2/A$	0.307 075 MeV g^{-1} cm^2 for $A = 1$ g mol^{-1}
I	Mean excitation energy	eV
δ	Density effect correction to ionization energy loss	
$\hbar\omega_p$	Plasma energy $\sqrt{4\pi N_e r_e^3}\; m_ec^2/\alpha$	$28.816\sqrt{\rho\langle Z/A\rangle}$ eV$^{(a)}$
w_j	Weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
X_0	Radiation length	g^{-1} cm^2
—	$4\alpha r e^2 N_A/A$	$(716.408 \text{ g cm}^{-2})^{-1}$ for $A = 1$ g mol^{-1}
E_c	Critical energy	MeV
E_s	Scale energy $\sqrt{4\pi/\alpha}\; m_ec^2$	21.2052 MeV
R_M	Molière radius	MeV g^{-1} cm^2

$^{(a)}$ For ρ in g cm^{-3}.

22.2. Ionization energy loss by heavy particles [1–5]

Moderately relativistic charged particles other than electrons lose energy in matter primarily by ionization. If the incident particle velocity βc is larger than that of orbital electrons ($\sim Z\alpha c$) and small enough that radiative effects do not dominate (for example, pion energy smaller than 100–200 GeV in iron), then the mean rate of energy loss (or stopping power) is given by the Bethe-Bloch equation,

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\rm max}}{I^2} - \beta^2 - \frac{\delta}{2}\right] . \qquad (22.1)$$

Here $T_{\rm max}$ is the maximum kinetic energy which can be imparted to a free electron in a single collision, and the other variables are defined in Table 22.1. The units are chosen so that dx is measured in mass per unit area, *e.g.*, in g cm^{-2}. The function as computed for pions on copper is shown by the solid curve in Fig. 22.1, and for pions on other materials in Fig. 22.2. A minor dependence on M at the highest energies is introduced through $T_{\rm max}$, but for all practical purposes in high-energy physics dE/dx in a given material is a function only of β. Except in hydrogen, particles of the same velocity have very similar rates of energy loss in different materials; there is a slow decrease in the rate of energy loss with increasing Z. The qualitative difference in stopping power behavior at high energies between a gas (He) and the other materials shown in Fig. 22.2 is due to the density effect correction, δ, discussed below. The stopping power functions are characterized by broad minima whose position drops from $\beta\gamma = 3.5$ to 3.0 as Z goes from 7 to 100.

In practical cases, most relativistic particles (*e.g.*, cosmic-ray muons) have energy loss rates close to the minimum, and are said to be minimum ionizing particles, or mip's.

Eq. (22.1) may be integrated to find the total range R for a particle which loses energy only through ionization. Since dE/dx depends only on β, R/M is a function of E/M or pc/M. In practice, range is a useful concept only for low-energy hadrons ($R \lesssim \lambda_I$, where λ_I is the nuclear interaction length), and for muons below a few hundred GeV (above which radiative effects dominate). R/M as a function of $\beta\gamma = pc/M$ is shown for a variety of materials in Fig. 22.3.

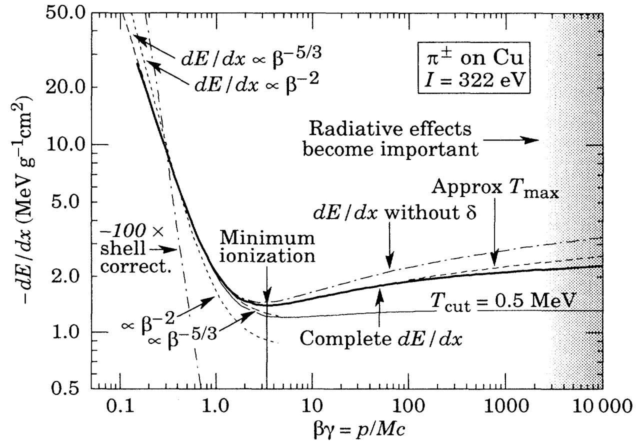

Figure 22.1: Energy loss rate in copper. The function without the density effect correction is also shown, as is the shell correction and two low-energy approximations.

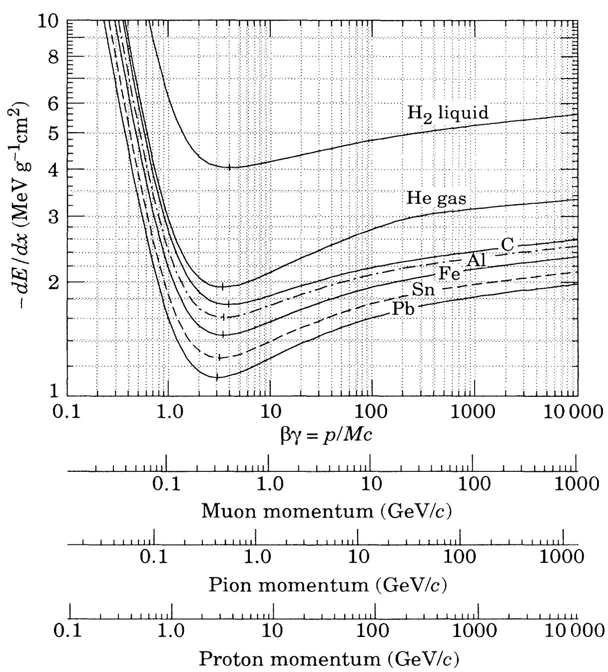

Figure 22.2: Energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, tin, and lead.

For a particle with mass M and momentum $M\beta\gamma c$, $T_{\rm max}$ is given by

$$T_{\rm max} = \frac{2m_ec^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2} . \qquad (22.2)$$

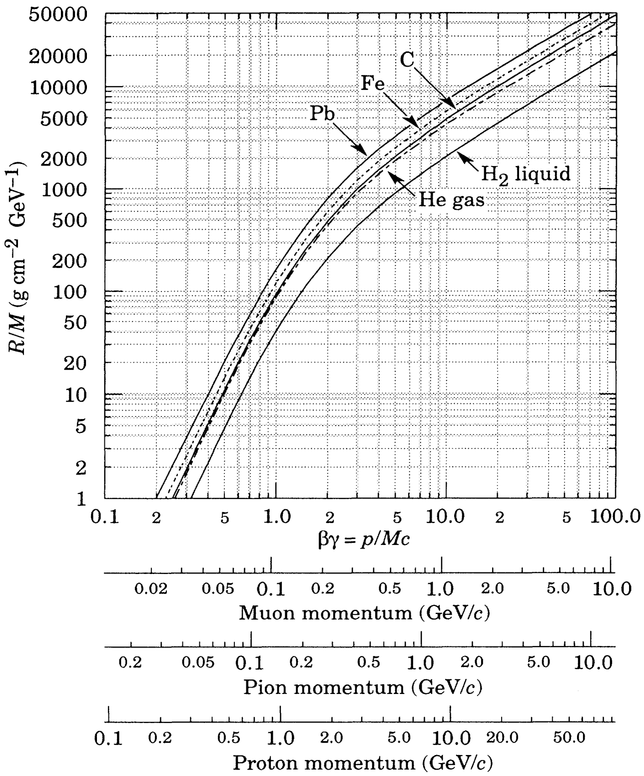

Figure 22.3: Range of heavy charged particles in liquid (bubble chamber) hydrogen, helium gas, carbon, iron, and lead. For example: For a K^+ whose momentum is 700 MeV/c, $\beta\gamma = 1.42$. For lead we read $R/M \approx 396$, and so the range is 195 g cm^{-2}.

It is usual [1,2] to make the "low-energy" approximation $T_{\max} = 2m_ec^2\beta^2\gamma^2$, valid for $2\gamma m_e/M \ll 1$; this, in fact, is done implicitly in many standard references. For pion in copper, the error thus introduced into dE/dx is greater than 6% at 100 GeV. The correct expression should be used.

At energies of order 100 GeV, the maximum 4-momentum transfer to the electron can exceed 1 GeV/c, where structure effects significantly modify the cross sections. This problem has been investigated by J.D. Jackson [6], who concluded that for hadrons (but not for large nuclei) corrections to dE/dx are negligible below energies where radiative effects dominate. While the cross section for rare hard collisions is modified, the average stopping power, dominated by many softer collisions, is almost unchanged.

The mean excitation energy I is $(10 \pm 1$ eV$) \times Z$ for elements heavier than oxygen. The values adopted by the ICRU for the chemical elements [7] are now in wide use; these are shown in Fig. 22.4. Machine-readable versions can also be found [8]. Given the availability of these constants and their variation with atomic structure, there seems little point to depending upon approximate formulae, as was done in the past.

A shell correction is often included in the square brackets of Eq. (22.1) [3,5,7], to correct for atomic binding having been neglected in calculating some of the contributions to Eq. (22.1). We show the Barkas form [3] in Fig. 22.1. For copper it contributes about 1% at $\beta\gamma = 0.3$ (kinetic energy 6 MeV for a pion), and the correction decreases very rapidly with energy. While it is negligible for high-energy physics applications, this and other low-energy corrections must be taken into account at lower energies, such as those encountered in medical physics.

As the particle energy increases, its electric field flattens and extends, so that the distant-collision contribution to Eq. (22.1) increases as $\ln\beta\gamma$. However, real media become polarized, limiting the field extension and effectively truncating this part of the logarithmic

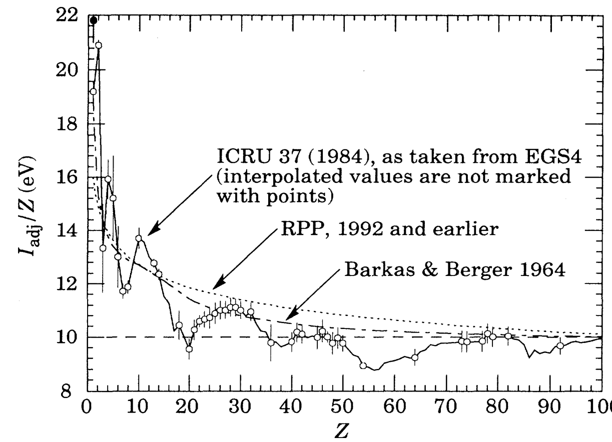

Figure 22.4: Excitation energies (divided by Z) as adopted by the ICRU [7]. Those based on measurement are shown by points with error flags; the interpolated values are simply joined. The solid point is for liquid H_2; the open point at 19.2 is for H_2 gas. Also shown are curves based on two approximate formulae.

rise [4,9–13]. At very high energies,

$$\delta/2 \to \ln(\hbar\omega_p/I) + \ln\beta\gamma - 1/2 \ , \qquad (22.3)$$

where $\delta/2$ is the density effect correction introduced in Eq. (22.1) and $\hbar\omega_p$ is the plasma energy defined in Table 22.1. A comparison with Eq. (22.1) shows that $|dE/dx|$ then grows as $\ln\beta\gamma$ rather than $\ln\beta^2\gamma^2$, and that the mean excitation energy I is replaced by the plasma energy $\hbar\omega_p$. The stopping power as calculated with and without the density effect correction is shown in Fig. 22.1. Since the plasma frequency scales as the square root of the electron density, the correction is much larger for a liquid or solid than for a gas, as is illustrated by the examples in Fig. 22.2.

The remaining relativistic rise can be attributed to large energy transfers to a few electrons. If these escape or are otherwise accounted for separately, the energy deposited in an absorbing layer (in contrast to the energy lost by the particle) approaches a constant value, the Fermi plateau (see Sec. 22.3 below). The curve in Fig. 22.1 labeled "$T_{\rm cut} = 0.5$ MeV" illustrates this behavior. At extreme energies (*e.g.*, 400 GeV for muons or pions in iron), radiative effects become important. These are especially relevant for high-energy muons, as discussed in Sec. 22.9.

For particles moving more slowly than atomic electrons, the above discussion is inapplicable. At velocities $\alpha z \gtrsim \beta \gtrsim 10^{-3}$ or slightly lower, the total energy-loss rate is proportional to β, and non-ionizing nuclear recoil energy loss contributes substantially to the total [14]. For protons in silicon, $|dE/dx| = 61.2\,\beta$ GeV cm^2 g^{-1} for $\beta < 0.005$; the peak occurs at $\beta = 0.0126$, where $|dE/dx| = 522$ MeV cm^2 g^{-1}. In neutron-scattering experiments, light output in scintillator has been observed for recoil protons with energies as low as 30 eV [15].

It is often stated that for $\beta \gtrsim z/137$, $|dE/dx|$ falls as β^{-2} before reaching the broad minimum at $\beta\gamma \approx 3.0$–3.5. In fact, the slope is nowhere this great, and $|dE/dx| \propto \beta^{-5/3}$ provides a very good approximation to the actual function out to $\beta\gamma > 1$. This behavior is shown in Fig. 22.1, along with the traditional β^{-2} proportionality.

The quantity $(dE/dx)\delta x$ is the mean energy loss via interaction with electrons in a layer of the medium with thickness δx. For finite δx, there are fluctuations in the actual energy loss. The distribution is skewed toward high values (the Landau tail) [1,16]. Only for a thick layer $[(dE/dx)\delta x \gg T_{\max}]$ is the distribution nearly Gaussian. The large fluctuations in the energy loss are due to the small number of collisions involving large energy transfers. The fluctuations are smaller for the so-called restricted energy loss rate, as discussed in Sec. 22.3 below.

A mixture or compound can be thought of as made up of thin layers of pure elements in the right proportion (Bragg additivity). In this case,

$$\frac{dE}{dx} = \sum w_j \left.\frac{dE}{dx}\right|_j , \tag{22.4}$$

where $dE/dx|_j$ is the mean rate of energy loss (in MeV g cm^{-2}) in the jth element. Eq. (22.1) can be inserted into Eq. (22.4) to find expressions for $\langle Z/A\rangle$, $\langle I\rangle$, and $\langle\delta\rangle$; for example, $\langle Z/A\rangle = \sum w_j Z_j/A_j = \sum n_j Z_j / \sum n_j A_j$. However, $\langle I\rangle$ as defined this way is an underestimate, because in a compound electrons are more tightly bound than in the free elements, and $\langle\delta\rangle$ as calculated this way has little relevance, because it is the electron density which matters. If possible, one uses the tables given in Refs. 13 and 12, which include effective excitation energies and interpolation coefficients for calculating the density effect correction for the chemical elements and nearly 200 mixtures and compounds. If a compound or mixture is not found, then one uses the recipe for δ given in Ref. 10 (or Ref. 8), and calculates $\langle I\rangle$ according to the discussion in Ref. 11. (Note the "13%" rule!)

Ionization losses by electrons and positrons [12] are not discussed here. Above the critical energy, which is a few tens of MeV in most materials, bremsstrahlung is the dominant source of energy loss. This important case is discussed below. The contributions of various electron energy-loss processes in lead are shown in Fig. 23.4.

22.3. Restricted energy loss rates for relativistic ionizing particles

Fluctuations in energy loss are due mainly to the production of a few high-energy knock-on electrons. Practical detectors often measure the energy *deposited*, not the energy *lost*. When energy is carried off by energetic knock-on electrons, it is more appropriate to consider the mean energy loss excluding energy transfers greater than some cutoff $T_{\rm cut}$. The restricted energy loss rate is

$$-\left.\frac{dE}{dx}\right|_{T<T_{\rm cut}} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\rm upper}}{I^2} -\frac{\beta^2}{2}\left(1+\frac{T_{\rm upper}}{T_{\rm max}}\right)-\frac{\delta}{2}\right] \tag{22.5}$$

where $T_{\rm upper} = {\rm MIN}(T_{\rm cut}, T_{\rm max})$. This form agrees with the equation given in previous editions of this *Review* [17] for $T_{\rm cut} \ll T_{\rm max}$ but smoothly joins the normal Bethe-Bloch function (Eq. (22.1)) for $T_{\rm cut} > T_{\rm max}$.

22.4. Energetic knock-on electrons (δ rays)

The distribution of secondary electrons with kinetic energies $T \gg I$ is given by [1]

$$\frac{d^2N}{dTdx} = \frac{1}{2}Kz^2\frac{Z}{A}\frac{1}{\beta^2}\frac{F(T)}{T^2} \tag{22.6}$$

for $I \ll T \le T_{\rm max}$, where $T_{\rm max}$ is given by Eq. (22.2). The factor F is spin-dependent, but is about unity for $T \ll T_{\rm max}$. For spin-0 particles $F(T) = (1-\beta^2T/T_{\rm max})$; forms for spins 1/2 and 1 are also given by Rossi [1]. When Eq. (22.6) is integrated from $T_{\rm cut}$ to $T_{\rm max}$, one obtains the difference between Eq. (22.1) and Eq. (22.5). For incident electrons, the indistinguishability of projectile and target means that the range of T extends only to half the kinetic energy of the incident particle. Additional formulae are given in Ref. 18. Equation (22.6) is inaccurate for T close to I: for $2I \lesssim T \lesssim 10I$, the $1/T^2$ dependence above becomes approximately $T^{-\eta}$, with $3 \lesssim \eta \lesssim 5$ [19].

22.5. Ionization yields

Physicists frequently relate total energy loss to the number of ion pairs produced near the particle's track. This relation becomes complicated for relativistic particles due to the wandering of energetic knock-on electrons whose ranges exceed the dimensions of the fiducial volume. For a qualitative appraisal of the nonlocality of energy deposition in various media by such modestly energetic knock-on electrons, see Ref. 20. The mean local energy dissipation per local ion pair produced, W, while essentially constant for relativistic particles, increases at slow particle speeds [21]. For gases, W can be surprisingly sensitive to trace amounts of various contaminants [21]. Furthermore, ionization yields in practical cases may be greatly influenced by such factors as subsequent recombination [22].

22.6. Multiple scattering through small angles

A charged particle traversing a medium is deflected by many small-angle scatters. Most of this deflection is due to Coulomb scattering from nuclei, and hence the effect is called multiple Coulomb scattering. (However, for hadronic projectiles, the strong interactions also contribute to multiple scattering.) The Coulomb scattering distribution is well represented by the theory of Molière [23]. It is roughly Gaussian for small deflection angles, but at larger angles (greater than a few θ_0, defined below) it behaves like Rutherford scattering, having larger tails than does a Gaussian distribution.

If we define

$$\theta_0 = \theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{2}}\theta^{\rm rms}_{\rm space} . \tag{22.7}$$

then it is sufficient for many applications to use a Gaussian approximation for the central 98% of the projected angular distribution, with a width given by [24,25]

$$\theta_0 = \frac{13.6\ {\rm MeV}}{\beta cp}\, z\,\sqrt{x/X_0}\Big[1+0.038\ln(x/X_0)\Big] . \tag{22.8}$$

Here p, βc, and z are the momentum, velocity, and charge number of the incident particle, and x/X_0 is the thickness of the scattering medium in radiation lengths (defined below). This value of θ_0 is from a fit to Molière distribution [23] for singly charged particles with $\beta = 1$ for all Z, and is accurate to 11% or better for $10^{-3} < x/X_0 < 100$.

Eq. (22.8) describes scattering from a single material, while the usual problem involves the multiple scattering of a particle traversing many different layers and mixtures. Since it is from a fit to a Molière distribution, it is incorrect to add the individual θ_0 contributions in quadrature; the result is systematically too small. It is much more accurate to apply Eq. (22.8) once, after finding x and X_0 for the combined scatterer.

Lynch and Dahl have extended this phenomenological approach, fitting Gaussian distributions to a variable fraction of the Molière distribution for arbitrary scatterers [25], and achieve accuracies of 2% or better.

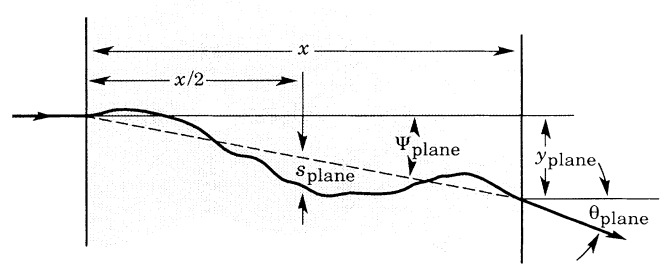

Figure 22.5: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

The nonprojected (space) and projected (plane) angular distributions are given approximately by [23]

$$\frac{1}{2\pi\,\theta_0^2}\,\exp\left\{-\frac{\theta_{\rm space}^2}{2\theta_0^2}\right\}\,d\Omega\ , \qquad (22.9)$$

$$\frac{1}{\sqrt{2\pi}\,\theta_0}\,\exp\left\{-\frac{\theta_{\rm plane}^2}{2\theta_0^2}\right\}\,d\theta_{\rm plane}\ , \qquad (22.10)$$

where θ is the deflection angle. In this approximation, $\theta_{\rm space}^2 \approx (\theta_{{\rm plane},x}^2 + \theta_{{\rm plane},y}^2)$, where the x and y axes are orthogonal to the direction of motion, and $d\Omega \approx d\theta_{{\rm plane},x}\,d\theta_{{\rm plane},y}$. Deflections into $\theta_{{\rm plane},x}$ and $\theta_{{\rm plane},y}$ are independent and identically distributed.

Figure 22.5 shows these and other quantities sometimes used to describe multiple Coulomb scattering. They are

$$\psi^{\rm\ rms}_{\rm\ plane} = \frac{1}{\sqrt{3}}\,\theta^{\rm\ rms}_{\rm\ plane} \quad = \frac{1}{\sqrt{3}}\,\theta_0\ , \qquad (22.11)$$

$$y^{\rm\ rms}_{\rm\ plane} = \frac{1}{\sqrt{3}}\,x\,\theta^{\rm\ rms}_{\rm\ plane} \quad = \frac{1}{\sqrt{3}}\,x\,\theta_0\ , \qquad (22.12)$$

$$s^{\rm\ rms}_{\rm\ plane} = \frac{1}{4\sqrt{3}}\,x\,\theta^{\rm\ rms}_{\rm\ plane} = \frac{1}{4\sqrt{3}}\,x\,\theta_0\ . \qquad (22.13)$$

All the quantitative estimates in this section apply only in the limit of small $\theta^{\rm\ rms}_{\rm\ plane}$ and in the absence of large-angle scatters. The random variables s, ψ, y, and θ in a given plane are distributed in a correlated fashion (see Sec. 27.1 of this *Review* for the definition of the correlation coefficient). Obviously, $y \approx x\psi$. In addition, y and θ have the correlation coefficient $\rho_{y\theta} = \sqrt{3}/2 \approx 0.87$. For Monte Carlo generation of a joint $(y_{\rm\ plane}, \theta_{\rm plane})$ distribution, or for other calculations, it may be most convenient to work with independent Gaussian random variables (z_1, z_2) with mean zero and variance one, and then set

$$\begin{aligned} y_{\rm plane} &= z_1\,x\,\theta_0(1-\rho_{y\theta}^2)^{1/2}/\sqrt{3} + z_2\,\rho_{y\theta}x\,\theta_0/\sqrt{3} \\ &= z_1\,x\,\theta_0/\sqrt{12} + z_2\,x\,\theta_0/2\ ; \qquad (22.14) \\ \theta_{\rm plane} &= z_2\,\theta_0\ . \qquad (22.15) \end{aligned}$$

Note that the second term for $y_{\rm\ plane}$ equals $x\,\theta_{\rm plane}/2$ and represents the displacement that would have occurred had the deflection $\theta_{\rm plane}$ all occurred at the single point $x/2$.

For heavy ions the multiple Coulomb scattering has been measured and compared with various theoretical distributions [26].

22.7. Radiation length and associated quantities

In dealing with electrons and photons at high energies, it is convenient to measure the thickness of the material in units of the radiation length X_0. This is the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung, and is the appropriate scale length for describing high-energy electromagnetic cascades. X_0 has been calculated and tabulated by Y.S. Tsai [27]:

$$\frac{1}{X_0} = 4\alpha r_e^2\frac{N_A}{A}\left\{Z^2\left[L_{\rm rad} - f(Z)\right] + Z\,L'_{\rm rad}\right\}\ . \qquad (22.16)$$

For $A = 1$ g mol^{-1}, $4\alpha r_e^2 N_A/A = (716.408\ {\rm g\ cm^{-2}})^{-1}$. $L_{\rm rad}$ and $L'_{\rm rad}$ are given in Table 22.2. The function $f(Z)$ is an infinite sum, but for elements up to uranium can be represented to 4-place accuracy by

$$\begin{aligned} f(Z) = a^2\big[&(1+a^2)^{-1} + 0.20206 \\ &-0.0369\,a^2 + 0.0083\,a^4 - 0.002\,a^6\big]\ , \qquad (22.17) \end{aligned}$$

where $a = \alpha Z$ [28].

Table 22.2: Tsai's $L_{\rm rad}$ and $L'_{\rm rad}$, for use in calculating the radiation length in an element using Eq. (22.16).

Element	Z	$L_{\rm rad}$	$L'_{\rm rad}$
H	1	5.31	6.144
He	2	4.79	5.621
Li	3	4.74	5.805
Be	4	4.71	5.924
Others	>4	$\ln(184.15\,Z^{-1/3})$	$\ln(1194\,Z^{-2/3})$

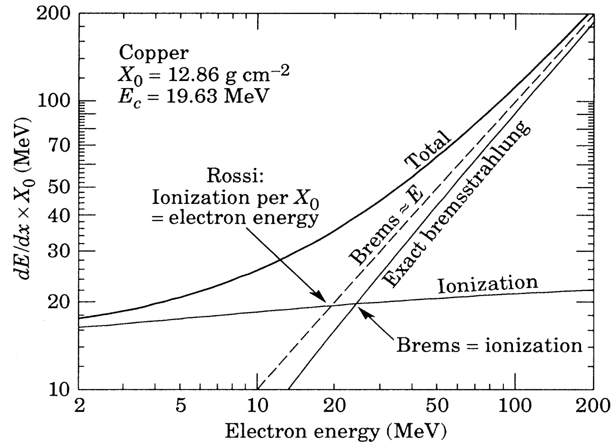

Figure 22.6: Two definitions of the critical energy E_c.

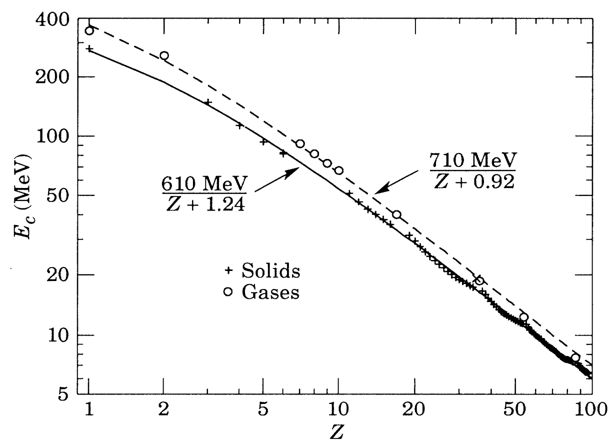

Figure 22.7: Electron critical energy for the chemical elements, using Rossi's definition [1]. The fits shown are for solids and liquids (solid line) and gases (dashed line). The rms deviation is 2.2% for the solids and 4.0% for the gases. (Computed with code supplied by A. Fassó.)

Although it is easy to use Eq. (22.16) to calculate X_0, the functional dependence on Z is somewhat hidden. Dahl provides a compact fit to the data [29]:

$$X_0 = \frac{716.4\ {\rm g\ cm^{-2}}\,A}{Z(Z+1)\ln(287/\sqrt{Z})} \qquad (22.18)$$

Results obtained with this formula agree with Tsai's values to better than 2.5% for all elements except helium, where the result is about 5% low.

The radiation length in a mixture or compound may be approximated by

$$1/X_0 = \sum w_j/X_j\ , \qquad (22.19)$$

where w_j and X_j are the fraction by weight and the radiation length for the jth element.

An electron loses energy by bremsstrahlung at a rate nearly proportional to its energy, while the ionization loss rate varies only logarithmically with the electron energy. The *critical energy* E_c is sometimes defined as the energy at which the two loss rates are equal [30]. Berger and Seltzer [30] also give the approximation $E_c = (800\ \text{MeV})/(Z + 1.2)$. This formula has been widely quoted, and has been given in previous editions of this *Review* [17]. Among alternate definitions is that of Rossi [1], who defines the critical energy as the energy at which the ionization loss per radiation length is equal to the electron energy. Equivalently, it is the same as the first definition with the approximation $|dE/dx|_{\text{brems}} \approx E/X_0$. These definitions are illustrated in the case of copper in Fig. 22.6 [31].

The accuracy of approximate forms for E_c has been limited by the failure to distinguish between gases and solid or liquids, where there is a substantial difference in ionization at the relevant energy because of the density effect. We distinguish these two cases in Fig. 22.7. Fits were also made with functions of the form $a/(Z + b)^\alpha$, but α was essentially unity.

The transverse development of electromagnetic showers in different materials scales fairly accurately with the *Molière radius* R_M, given by [32,33]

$$R_M = X_0\, E_s/E_c \ , \tag{22.20}$$

where $E_s \approx 21$ MeV (see Table 22.1), and the Rossi definition of E_c is used.

In a material containing a weight fraction w_j of the element with critical energy E_{cj} and radiation length X_j, the Molière radius is given by

$$\frac{1}{R_M} = \frac{1}{E_s}\sum \frac{w_j\, E_{cj}}{X_j} \ . \tag{22.21}$$

For very high-energy photons, the total e^+e^- pair-production cross section is approximately

$$\sigma = \tfrac{7}{9}(A/X_0 N_A) \ , \tag{22.22}$$

where A is the atomic weight of the material and N_A is Avogadro's number. Equation Eq. (22.22) is accurate to within a few percent down to energies as low as 1 GeV. The cross section decreases at lower energies, as shown in Fig. 23.4 of this *Review*. As the energy decreases, a number of other processes become important, as is shown in Fig. 23.3 of this *Review*.

22.8. Electromagnetic cascades

When a high-energy electron or photon is incident on a thick absorber, it initiates an electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energy. The longitudinal development is governed by the high-energy part of the cascade, and therefore scales as the radiation length in the material. Electron energies eventually fall below the critical energy, and then dissipate their energy by ionization and excitation rather than by the generation of more shower particles. In describing shower behavior, it is therefore convenient to introduce the scale variables

$$t = x/X_0$$
$$y = E/E_c \ , \tag{22.23}$$

so that distance is measured in units of radiation length and energy in units of critical energy.

Longitudinal profiles for an EGS4 [8] simulation of a 30 GeV electron-induced cascade in iron are shown in Fig. 22.8. The number of particles crossing a plane (very close to Rossi's Π function [1]) is sensitive to the cutoff energy, here chosen as a total energy of 1.5 MeV for both electrons and photons. The electron number falls off more quickly than energy deposition. This is because, with increasing depth, a larger fraction of the cascade energy is carried by photons.

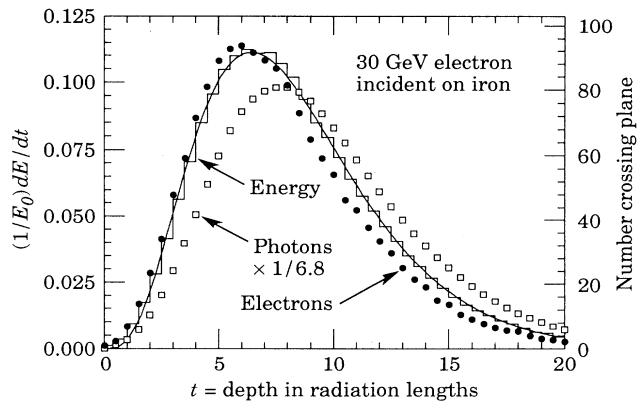

Figure 22.8: An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at $X_0/2$ intervals (scale on right) and the squares the number of photons with $E \geq 1.5$ MeV crossing the planes (scaled down to have same area as the electron distribution).

Exactly what a calorimeter measures depends on the device, but it is not likely to be exactly any of the profiles shown. In gas counters it may be very close to the electron number, but in glass Čerenkov detectors and other devices with "thick" sensitive regions it is closer to the energy deposition (total track length). In such detectors the signal is proportional to the "detectable" track length T_d, which is in general less than the total track length T. Practical devices are sensitive to electrons with energy above some detection threshold E_d, and $T_d = T\,F(E_d/E_c)$. An analytic form for $F(E_d/E_c)$ obtained by Rossi [1] is given by Fabjan [34]; see also Amaldi [35].

The mean longitudinal profile of the energy deposition in an electromagnetic cascade is reasonably well described by a gamma distribution [36]:

$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1}e^{-bt}}{\Gamma(a)} \tag{22.24}$$

The maximum t_{max} occurs at $(a - 1)/b$. We have made fits to shower profiles in elements ranging from carbon to uranium, at energies from 1 GeV to 100 GeV. The energy deposition profiles are well described by Eq. (22.24) with

$$t_{\text{max}} = (a-1)/b = 1.0 \times (\ln y + C_j) \ , \qquad j = e, \gamma \ , \tag{22.25}$$

where $C_e = -0.5$ for electron-induced cascades and $C_\gamma = +0.5$ for photon-induced cascades. To use Eq. (22.24), one finds $(a - 1)/b$ from Eq. (22.25) and Eq. (22.23), then finds a either by assuming $b \approx 0.5$ or by finding a more accurate value from Fig. 22.9. The results are very similar for the electron number profiles, but there is some dependence on the atomic number of the medium. A similar form for the electron number maximum was obtained by Rossi in the context of his "Approximation B," [1] (see Fabjan's review in Ref. 34), but with $C_e = -1.0$ and $C_\gamma = -0.5$; we regard this as superseded by the EGS4 result.

The "shower length" $X_s = X_0/b$ is less conveniently parametrized, since b depends upon both Z and incident energy, as shown in Fig. 22.9. As a corollary of this Z dependence, the number of electrons crossing a plane near shower maximum is underestimated using Rossi's approximation for carbon and seriously overestimated for uranium. Essentially the same b values are obtained for incident electrons and photons. For many purposes it is sufficient to take $b \approx 0.5$.

The gamma distribution is very flat near the origin, while the EGS4 cascade (or a real cascade) increases more rapidly. As a result Eq. (22.24) fails badly for about the first two radiation lengths; it was necessary to exclude this region in making fits.

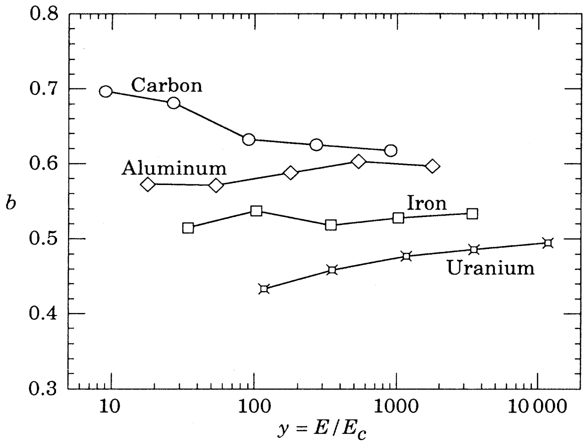

Figure 22.9: Fitted values of the scale factor b for energy deposition profiles obtained with EGS4 for a variety of elements for incident electrons with $1 \leq E_0 \leq 100$ GeV. Values obtained for incident photons are essentially the same.

Because fluctuations are important, Eq. (22.24) should be used only in applications where average behavior is adequate. Grindhammer *et al.* have developed fast simulation algorithms in which the variance and correlation of a and b are obtained by fitting Eq. (22.24) to individually simulated cascades, then generating profiles for cascades using a and b chosen from the correlated distributions [37].

Measurements of the lateral distribution in electromagnetic cascades are shown in Refs. 32 and 33. On the average, only 10% of the energy lies outside the cylinder with radius R_M. About 99% is contained inside of $3.5R_M$, but at this radius and beyond composition effects become important and the scaling with R_M fails. The distributions are characterized by a narrow core, and broaden as the shower develops. They are often represented as the sum of two Gaussians, and Grindhammer [37] describes them with the function

$$f(r) = \frac{2r\,R^2}{(r^2+R^2)^2} \ , \tag{22.26}$$

where R is a phenomenological function of x/X_0 and $\ln E$.

22.9. Muon energy loss at high energy

At sufficiently high energies, radiative processes become more important than ionization for all charged particles. For muons and pions in materials such as iron, this "critical energy" occurs at several hundred GeV. Radiative effects dominate the energy loss of energetic muons found in cosmic rays or produced at the newest accelerators. These processes are characterized by small cross sections, hard spectra, large energy fluctuations, and the associated generation of electromagnetic and (in the case of photonuclear interactions) hadronic showers [40–47]. As a consequence, at these energies the treatment of energy loss as a uniform and continuous process is for many purposes inadequate.

It is convenient to write the average rate of muon energy loss as [38]

$$-dE/dx = a(E) + b(E)\,E \ . \tag{22.27}$$

Here $a(E)$ is the ionization energy loss given by Eq. (22.1), and $b(E)$ is the sum of e^+e^- pair production, bremsstrahlung, and photonuclear contributions. To the approximation that these slowly-varying functions are constant, the mean range x_0 of a muon with initial energy E_0 is given by

$$x_0 \approx (1/b)\ln(1 + E_0/E_{\mu c}) \ , \tag{22.28}$$

where $E_{\mu c} = a/b$. Figure 22.10 shows contributions to $b(E)$ for iron. Since $a(E) \approx 0.002$ GeV g^{-1} cm^2, $b(E)E$ dominates the energy loss

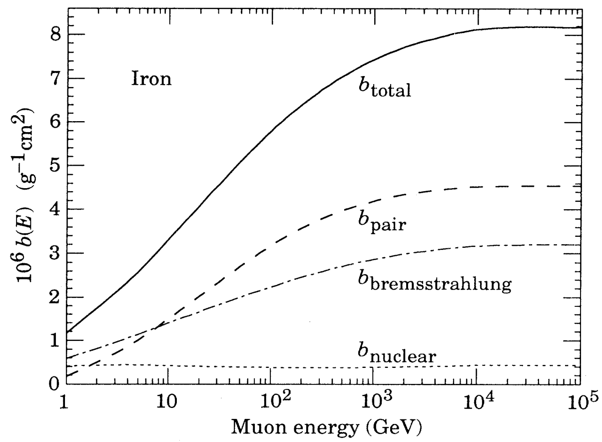

Figure 22.10: Contributions to the fractional energy loss by muons in iron due to e^+e^- pair production, bremsstrahlung, and photonuclear interactions, as obtained from Lohmann *et al.* [39].

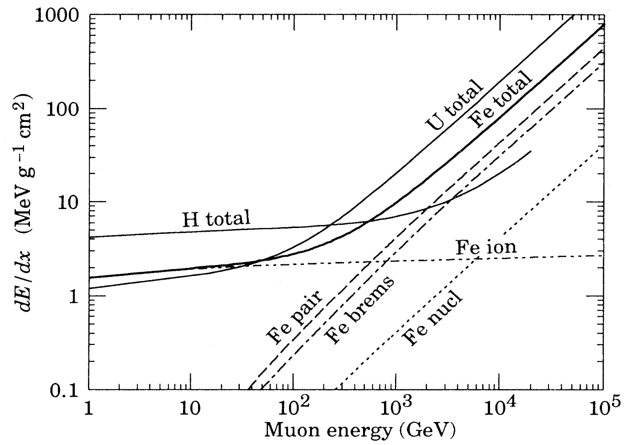

Figure 22.11: The average energy loss of a muon in hydrogen, iron, and uranium as a function of muon energy. Contributions to dE/dx in iron from ionization and the processes shown in Fig. 22.10 are also shown.

above several hundred GeV, where $b(E)$ is nearly constant. The rate of energy loss for muons in hydrogen, uranium, and iron is shown in Fig. 22.11 [39].

The "muon critical energy" $E_{\mu c}$ can be defined more exactly as the energy at which radiative and ionization losses are equal, and can be found by solving $E_{\mu c} = a(E_{\mu c})/b(E_{\mu c})$. This definition corresponds to the solid-line intersection in Fig. 22.6, and is different from the Rossi definition we used for electrons. It serves the same function: below $E_{\mu c}$ ionization losses dominate, and above $E_{\mu c}$ dominate. The dependence of $E_{\mu c}$ on atomic number Z is shown in Fig. 22.12.

The radiative cross sections are expressed as functions of the fractional energy loss ν. The bremsstrahlung cross section goes roughly as $1/\nu$ over most of the range, while for the pair production case the distribution goes as ν^{-3} to ν^{-2} (see Ref. 50). "Hard" losses are therefore more probable in bremsstrahlung, and in fact energy losses due to pair production may very nearly be treated as continuous. The calculated momentum distribution of an incident 1 TeV/c muon beam after it crosses 3 m of iron is shown in Fig. 22.13. The most probable loss is 9 GeV, or 3.8 MeV g^{-1}cm^2. The full width at half maximum is 7 GeV/c, or 0.7%. The radiative tail is almost entirely due to bremsstrahlung; this includes most of the 10% that lost more than 2.8% of their energy. Most of the 3.3% that lost more than 10% of their incident energy experienced photonuclear interactions, which are concentrated in rare, relatively hard collisions. The latter can exceed nominal detector resolution [51], necessitating the reconstruction

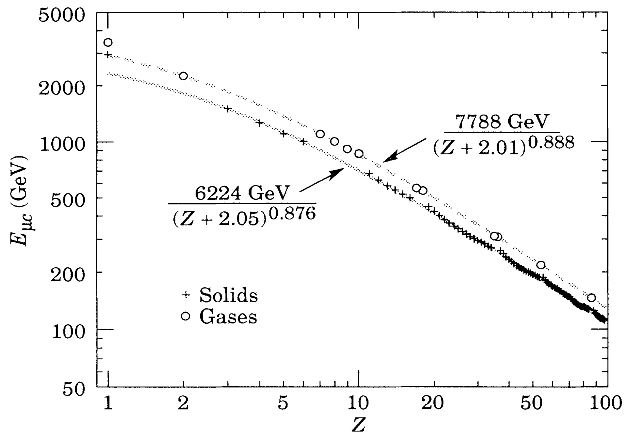

Figure 22.12: Muon critical energy for the chemical elements, defined as the energy at which radiative and ionization energy loss rates are equal. The equality comes at a higher energy for gases than for solids or liquids with the same atomic number because of a smaller density effect reduction of the ionization losses. The fits shown in the figure exclude hydrogen. Alkali metals fall 3–4% above the fitted function for alkali metals, while most other solids are within 2% of the function. Among the gases the worst fit is for neon (1.4% high). (Courtesy of N.V. Mokhov, using the MARS code system [48].)

of lost energy. Electromagnetic and hadronic cascades in detector materials can obscure muon tracks in detector planes and reduce tracking efficiency [52].

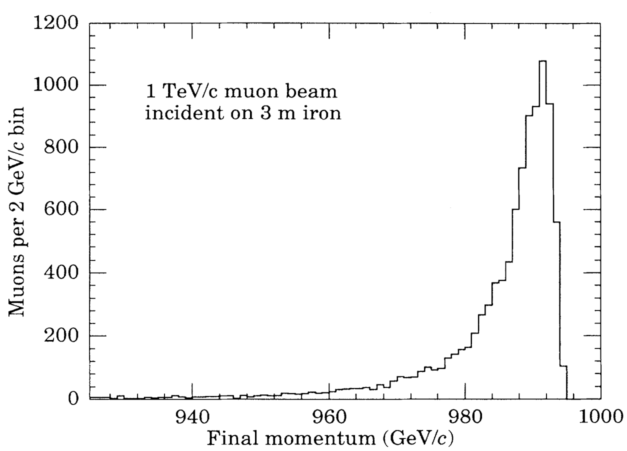

Figure 22.13: The momentum distribution of 1 TeV/c muons after traversing 3 m of iron, as obtained with Van Ginniken's TRAMU muon transport code [50].

22.10. Čerenkov and transition radiation [4,53,54]

A charged particle radiates if its velocity is greater than the local phase velocity of light (Čerenkov radiation) or if it crosses suddenly from one medium to another with different optical properties (transition radiation). Neither process is important for energy loss, but both are used in high-energy physics detectors.

Čerenkov Radiation. The half-angle θ_c of the Čerenkov cone for a particle with velocity βc in a medium with index of refraction n is

$$\begin{aligned}\theta_c &= \arccos(1/n\beta) \\ &\approx \sqrt{2(1-1/n\beta)} \quad \text{for small } \theta_c, \text{ e.g. in gases.}\end{aligned} \tag{22.29}$$

The threshold velocity β_t is $1/n$, and $\gamma_t = 1/(1-\beta_t^2)^{1/2}$. Therefore, $\beta_t\gamma_t = 1/(2\delta+\delta^2)^{1/2}$, where $\delta = n-1$. Values of δ for various commonly used gases are given as a function of pressure and wavelength in Ref. 55. For values at atmospheric pressure, see Table 6.1. Data for other commonly used materials are given in Ref. 56.

The number of photons produced per unit path length of a particle with charge ze and per unit energy interval of the photons is

$$\begin{aligned}\frac{d^2N}{dEdx} &= \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2}\left(1-\frac{1}{\beta^2 n^2(E)}\right) \\ &\approx 370\sin^2\theta_c(E)\ \text{eV}^{-1}\text{cm}^{-1} \qquad (z=1)\ ,\end{aligned} \tag{22.30}$$

or, equivalently,

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2(\lambda)}\right)\ . \tag{22.31}$$

The index of refraction is a function of photon energy E, as is the sensitivity of the transducer used to detect the light. For practical use, Eq. (22.30) must be multiplied by the the transducer response function and integrated over the region for which $\beta\, n(E) > 1$. Further details are given in the discussion of Čerenkov detectors in the Detectors section (Sec. 24 of this *Review*).

Transition Radiation. The energy radiated when a particle with charge ze crosses the boundary between vacuum and a medium with plasma frequency ω_p is

$$I = \alpha z^2\gamma\hbar\omega_p/3\ , \tag{22.32}$$

where

$$\begin{aligned}\hbar\omega_p &= \sqrt{4\pi N_e r_e^3}\ m_e c^2/\alpha \\ &= \sqrt{4\pi N_e a_\infty^3}\ 2\times 13.6\ \text{eV}\ .\end{aligned} \tag{22.33}$$

Here N_e is the electron density in the medium, r_e is the classical electron radius, and a_∞ is the Bohr radius. For styrene and similar materials, $\sqrt{4\pi N_e a_\infty^3} \approx 0.8$, so that $\hbar\omega_p \approx 20$ eV. The typical emission angle is $1/\gamma$.

The radiation spectrum is logarithmically divergent at low energies and decreases rapidly for $\hbar\omega/\gamma\hbar\omega_p > 1$. About half the energy is emitted in the range $0.1 \le \hbar\omega/\gamma\hbar\omega_p \le 1$. For a particle with $\gamma = 10^3$, the radiated photons are in the soft x-ray range 2 to 20 eV. The γ dependence of the emitted energy thus comes from the hardening of the spectrum rather than from an increased quantum yield. For a typical radiated photon energy of $\gamma\hbar\omega_p/4$, the quantum yield is

$$\begin{aligned}N_\gamma &\approx \frac{1}{2}\,\frac{\alpha z^2\gamma\hbar\omega_p}{3}\Big/\frac{\gamma\hbar\omega_p}{4} \\ &\approx \tfrac{2}{3}\alpha z^2 \approx 0.5\% \times z^2\ .\end{aligned} \tag{22.34}$$

More precisely, the number of photons with energy $\hbar\omega > \hbar\omega_0$ is given by [57]

$$N_\gamma(\hbar\omega > \hbar\omega_0) = \frac{\alpha z^2}{\pi}\left[\left(\ln\frac{\gamma\hbar\omega_p}{\hbar\omega_0} - 1\right)^2 + \frac{\pi^2}{12}\right]\ , \tag{22.35}$$

within corrections of order $(\hbar\omega_0/\gamma\hbar\omega_p)^2$. The number of photons above a fixed energy $\hbar\omega_0 \ll \gamma\hbar\omega_p$ thus grows as $(\ln\gamma)^2$, but the number above a fixed fraction of $\gamma\hbar\omega_p$ (as in the example above) is constant. For example, for $\hbar\omega > \gamma\hbar\omega_p/10$, $N_\gamma = 2.519\,\alpha z^2/\pi = 0.59\% \times z^2$.

The yield can be increased by using a stack of plastic foils with gaps between. However, interference can be important, and the soft x rays are readily absorbed in the foils. The first problem can be overcome by choosing thicknesses and spacings large compared to the "formation length" $D = \gamma c/\omega_p$, which in practical situations is tens of μm. Other practical problems are discussed in Sec. 24.

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23. PHOTON AND ELECTRON ATTENUATION

Photon Attenuation Length

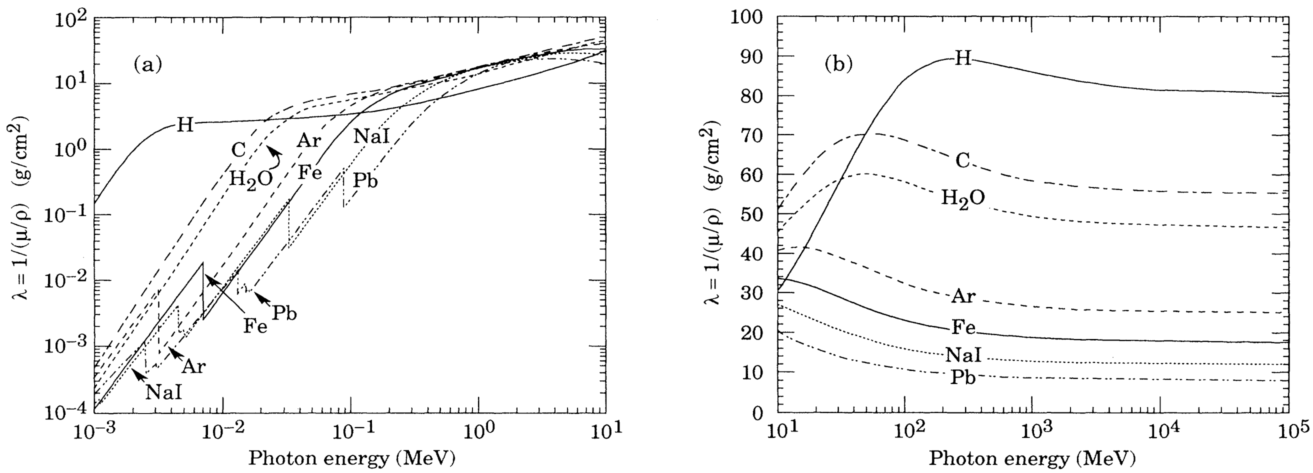

Figure 23.1: The photon mass attenuation length $\lambda = 1/(\mu/\rho)$ (also known as mfp, mean free path) for various absorbers as a function of photon energy, where μ is the mass attenuation coefficient. For a homogeneous medium of density ρ, the intensity I remaining after traversal of thickness t is given by the expression $I = I_0 \exp(-t\rho/\lambda)$. The accuracy is a few percent. Interpolation to other Z should be done in the cross section $\sigma = A/\lambda N_A$ cm^2/atom, where A is the atomic weight of the absorber material in grams and N_A is the Avogadro number. For a chemical compound or mixture, use $(1/\lambda)_{\rm eff} \approx \sum w_i(1/\lambda)_i$, accurate to a few percent, where w_i is the proportion by weight of the i^{th} constituent. The processes responsible for attenuation are given in Fig. 23.4. Not all of these processes necessarily result in detectable attenuation. For example, coherent Rayleigh scattering off an atom may occur at such low momentum transfer that the change in energy and momentum of the photon may not be significant.

(a) Low-energy region.

(b) The photon mass attenuation length, high-energy range (note that ordinate is linear scale). The attenuation length is constant beyond the range shown for at least two decades in energy.

From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (80). See also J.H. Hubbell, Int. J. of Applied Rad. and Isotopes **33**, 1269 (82). Data courtesy J.H. Hubbell.

Photon Pair Conversion Probability

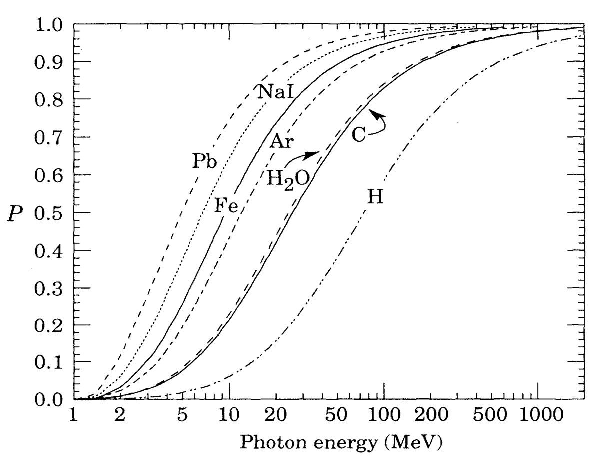

Figure 23.2: Probability P that a photon interaction will result in conversion to an e^+e^- pair. Except for a few-percent contribution from photonuclear absorption around 10 or 20 MeV, essentially all other interactions result in Compton scattering off an atomic electron. For a photon attenuation length λ (g/cm^2) (Fig. 23.1), the probability that a given photon will produce an electron pair (without first Compton scattering) in thickness t (cm) of absorber of density ρ (g/cm^3) is $P[1 - \exp(-t\rho/\lambda)]$.

Contributions to Photon Cross Section in Carbon and Lead

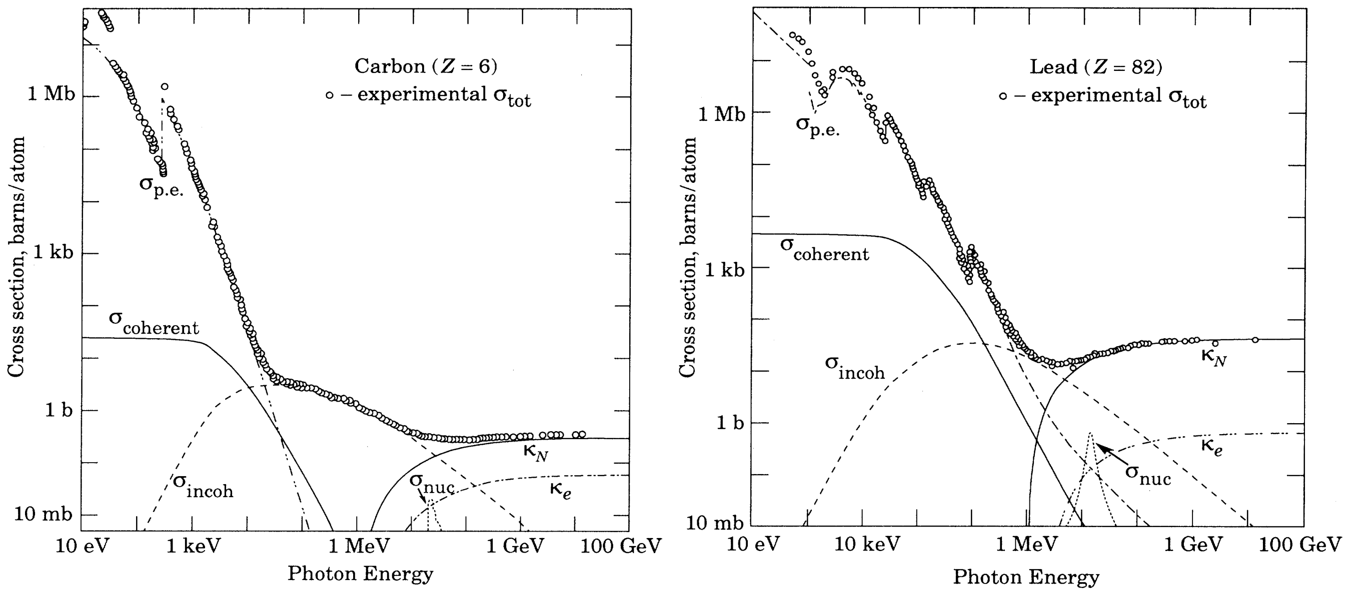

Figure 23.3: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes.

$\sigma_{\text{p.e.}}$ = Atomic photo-effect (electron ejection, photon absorption)

σ_{coherent} = Coherent scattering (Rayleigh scattering—atom neither ionized nor excited)

$\sigma_{\text{incoherent}}$ = Incoherent scattering (Compton scattering off an electron)

κ_n = Pair production, nuclear field

κ_e = Pair production, electron field

σ_{nuc} = Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)

From Hubbell, Gimm, and Øverbø, J. Phys. Chem. Ref. Data **9**, 1023 (80). The photon total cross section is assumed approximately flat for at least two decades beyond the energy range shown. Figures courtesy J.H. Hubbell.

Fractional Energy Loss for Electrons and Positrons in Lead

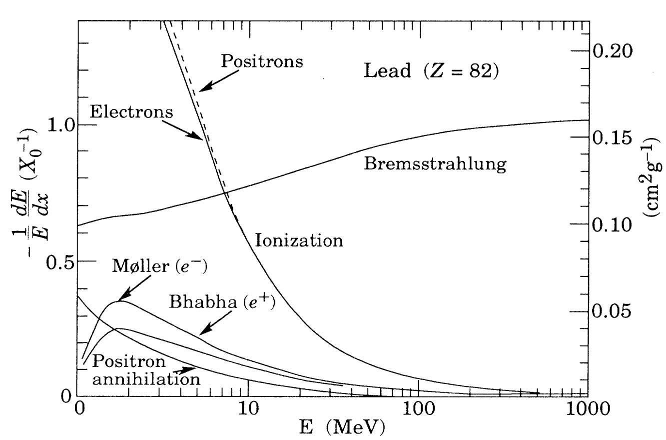

Figure 23.4: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Moller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use X_0(Pb) = 5.82 g/cm^2, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials, namely X_0(Pb) = 6.4 g/cm^2. The development of electron-photon cascades is approximately independent of absorber when the results are expressed in terms of inverse radiation lengths (*i.e.*, scale on left of plot).

24. PARTICLE DETECTORS

Contributed by D.G. Coyne, R.W. Fast, K. Johnson, R.D. Kephart, B. Mansoulie, H.F.W. Sadrozinski, H.G. Spieler, and C.L. Woody; revised 1995

In this section we give various parameters for common detector components. The quoted numbers are usually based on typical devices, and should be regarded only as rough approximations for new designs. A more detailed discussion of detectors can be found in Ref. 1. In Table 24.1 are given typical spatial and temporal resolutions of common detectors.

Table 24.1: Typical detector characteristics.

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10 to 150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	$\geq$ 300 μm[b,c]	50 ns	200 ns
Drift chamber	50 to 300 μm	2 ns[d]	100 ns
Scintillator	—	150 ps	10 ns
Emulsion	1 μm	—	—
Silicon strip	$\frac{\text{pitch}^e}{3 \text{ to } 7}$	*f*	*f*
Silicon pixel	2 μm[g]	*f*	*f*

[a] Multiple pulsing time.

[b] 300 μm is for 1 mm pitch.

[c] Delay line cathode readout can give $\pm$150 μm parallel to anode wire.

[d] For two chambers.

[e] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$25 μm) with pulse-height-weighted center finding.

[f] Limited at present by properties of the readout electronics. (Time resolution of $\leq$ 15 ns is planned for the SDC silicon tracker.)

[g] Analog readout of 34 μm pitch, monolithic pixel detectors.

24.1. Organic scintillators

Organic scintillators are broadly classed into three types, crystalline, liquid, and plastic, all of which utilize the ionization produced by charged particles (see the section on "Passage of particles through matter" (Sec. 22.2) of this *Review*) to generate optical photons, usually in the blue to green wavelength regions [2]. Plastic scintillators are by far the most widely used and we address them primarily; however, most of the discussion will also have validity for liquid scintillators with obvious caveats. Crystal organic scintillators are practically unused in high-energy physics.

Densities range from 1.03 to 1.20 g cm^{-3}. Typical photon yields are about 1 photon per 100 eV of energy deposit [3]. A one-cm-thick scintillator traversed by a minimum-ionizing particle will therefore yield $\approx 2 \times 10^4$ photons. The resulting photoelectron signal will depend on the collection and transport efficiency of the optical package and the quantum efficiency of the photodetector.

Plastic scintillators do not respond linearly to the ionization density. Very dense ionization columns emit less light than expected on the basis of dE/dx for minimum-ionizing particles. A widely used semi-empirical model by Birks posits that recombination and quenching effects between the excited molecules reduce the light yield [9]. These effects are more pronounced the greater the density of the excited molecules. Birks' formula is

$$\frac{d\mathscr{L}}{dx} = \mathscr{L}_0 \frac{dE/dx}{1 + k_B\, dE/dx} , \tag{24.1}$$

where $\mathscr{L}$ is the luminescence, $\mathscr{L}_0$ is the luminescence at low specific ionization density, and k_B is Birks' constant, which must be determined for each scintillator by measurement.

Decay times are in the ns range; risetimes are much faster. The combination of high light yield and fast response time allows the possibility of sub-ns timing resolution [4]. The fraction of light emitted during the decay "tail" can depend on the exciting particle. This allows pulse shape discrimination as a technique to carry out particle identification. Because of the hydrogen content (carbon to hydrogen ratio $\approx$ 1) plastic scintillator is sensitive to proton recoils from neutrons. Ease of fabrication into desired shapes and low cost has made plastic scintillators a common detector component. Recently, plastic scintillators in the form of scintillating fibers have found widespread use in tracking and calorimetry [5].

24.1.1. *Scintillation mechanism* :

Scintillation: A charged particle traversing matter leaves behind it a wake of excited molecules. Certain types of molecules, however, will release a small fraction ($\approx$ 3%) of this energy as optical photons. This process, scintillation, is especially marked in those organic substances which contain aromatic rings, such as polystyrene, polyvinyltoluene, and napthalene. Liquids which scintillate include toluene and xylene.

Fluorescence: In fluorescence, the initial excitation takes place via the absorption of a photon, and de-excitation by emission of a longer wavelength photon. Fluors are used as "waveshifters" to shift scintillation light to a more convenient wavelength. Occurring in complex molecules, the absorption and emission are spread out over a wide band of photon energies, and have some overlap, that is, there is some fraction of the emitted light which can be re-absorbed [6]. This "self-absorption" is undesirable for detector applications because it causes a shortened attenuation length. The wavelength difference between the major absorption and emission peaks is called the Stokes' shift. It is usually the case that the greater the Stokes' shift, the smaller the self absorption—thus, a large Stokes' shift is a desirable property for a fluor.

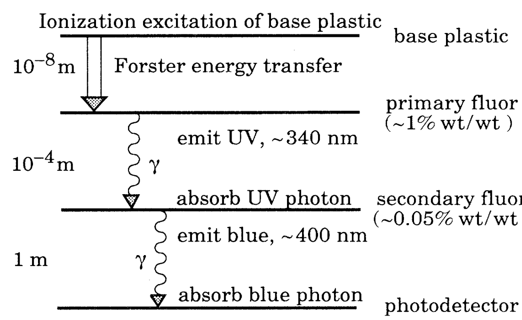

Figure 24.1: Cartoon of scintillation "ladder" depicting the operating mechanism of plastic scintillator. Approximate fluor concentrations and energy transfer distances for the separate sub-processes are shown.

Scintillators: The plastic scintillators used in high-energy physics are binary or ternary solutions of selected fluors in a plastic base containing aromatic rings. (See the appendix in Ref. 7 for a comprehensive list of plastic scintillator components.) Virtually all plastic scintillators contain as a base either polyvinyltoluene, polystyrene, or acrylic, whereby polyvinyltoluene-based scintillator can be up to 50% brighter than the others. Acrylic is non-aromatic and has therefore a very low scintillation efficiency. It becomes an acceptable scintillator when napthalene, a highly aromatic compound, is dissolved into the acrylic at 5% to 20% weight fraction. Thus, in "acrylic" scintillator the active component is napthalene. The fluors must satisfy additional conditions besides being fluorescent. They must be sufficiently stable, soluble, chemically inert, fast, radiation tolerant, and efficient.

The plastic base is the ionization-sensitive (*i.e.*, the scintillator) portion of the plastic scintillator (see Fig. 24.1). In the absence of fluors the base would emit UV photons with short attenuation length (several mm). Longer attenuation lengths are obtained by dissolving a "primary" fluor in high concentration (1% by weight) into the base, which is selected to efficiently reradiate absorbed energy at wavelengths where the base is more transparent.

The primary fluor has a second important function. The decay time of the scintillator base material can be quite long—in pure polystyrene it is 16 ns, for example. The addition of the primary fluor in high concentration can shorten the decay time by an order of magnitude and increase the total light yield. At the concentrations used (1% and greater), the average distance between a fluor molecule and an excited base unit is around 100 Å, much less than a wavelength of light. At these distances the predominant mode of energy transfer from base to fluor is not the radiation of a photon, but a resonant dipole-dipole interaction, first described by Foerster, which strongly couples the base and fluor [8]. The strong coupling sharply increases the speed and the light yield of the plastic scintillators.

Unfortunately, a fluor which fulfills other requirements is usually not completely adequate with respect to emission wavelength or attenuation length, so it is necessary to add yet another waveshifter (the "secondary" fluor), at fractional percent levels, and ocassionally a third (not shown in Fig. 24.1).

External wavelength shifters: Light emitted from a plastic scintillator may be absorbed in a (nonscintillating) base doped with a waveshifting fluor. Such wavelength shifters are widely used to aid light collection in complex geometries. The wavelength shifter must be insensitive to ionizing radiation and Čerenkov light. A typical wavelength shifter uses an acrylic base (without napthalene!) because of its good optical qualities, a single fluor to shift the light emerging from the plastic scintillator to the blue-green, and contains ultra-violet absorbing additives to deaden response to Čerenkov light.

24.1.2. ***Caveats and cautions***: Plastic scintillators are reliable, robust, and convenient. However, they possess quirks to which the experimenter must be alert.

Aging and Handling: Plastic scintillators are subject to aging which diminishes the light yield. Exposure to solvent vapors, high temperatures, mechanical flexing, irradiation, or rough handling will aggravate the process. A particularly fragile region is the surface which can "craze"—develop microcracks—which rapidly destroy the capability of plastic scintillators to transmit light by total internal reflection. Crazing is particularly likely where oils, solvents, or *fingerprints* have contacted the surface.

Attenuation length: The Stokes' shift is not the only factor determining attenuation length. Others are the concentration of fluors (the higher the concentration of a fluor, the greater will be its self-absorption); the optical clarity and uniformity of the bulk material; the quality of the surface; and absorption by additives, such as stabilizers, which may be present.

Afterglow: Plastic scintillators have a long-lived luminescence which does not follow a simple exponential decay. Intensities at the 10^{-4} level of the initial fluorescence can persist for hundreds of ns [10].

Atmospheric quenching: Plastic scintillators will decrease their light yield with increasing partial pressure of oxygen. This can be a 10% effect in an artificial atmosphere [11]. It is not excluded that other gasses may have similar quenching effects.

Magnetic field: The light yield of plastic scintillators may be changed by a magnetic field. The effect is very nonlinear and apparently not all types of plastic scintillators are so affected. Increases of $\approx 3\%$ at 0.45 T have been reported [12]. Data are sketchy and mechanisms are not understood.

Radiation damage: Irradiation of plastic scintillators creates color centers which absorb light more strongly in the UV and blue than at longer wavelengths. This poorly understood effect appears as a reduction both of light yield and attenuation length. Radiation damage depends not only on the integrated dose, but on the dose rate, atmosphere, and temperature, before, during and after irradiation, as well as the materials properties of the base such as glass transition temperature, polymer chain length, *etc.* Annealing also occurs, accelerated by the diffusion of atmospheric oxygen and elevated temperatures. The phenomena are complex, unpredictable, and not well understood [13]. Since color centers are less intrusive at longer wavelengths, the most reliable method of mitigating radiation damage is to shift emissions at every step to the longest practical wavelengths, *e.g.*, utilize fluors with large Stokes' shifts.

Table 24.2: Properties of several inorganic crystal scintillators.

NaI(Tl)	BGO	BaF_2	CsI(Tl)	CsI(pure)	$PbWO_4$	CeF_3
Density (g cm^{-3}):						
3.67	7.13	4.89	4.53	4.53	8.28	6.16
Radiation length (cm):						
2.59	1.12	2.05	1.85	1.85	0.89	1.68
Molière radius (cm):						
4.5	2.4	3.4	3.8	3.8	2.2	2.6
dE/dx (MeV/cm) (per mip):						
4.8	9.2	6.6	5.6	5.6	13.0	7.9
Nucl. int. length (cm):						
41.4	22.0	29.9	36.5	36.5	22.4	25.9
Decay time (ns):						
250	300	0.7^f 620^s	1000	$10, 36^f$ $\sim 1000^s$	5–15	10–30
Peak emission λ (nm):						
410	480	220^f 310^s	565	305^f $\sim 480^s$	440–500	310–340
Refractive index:						
1.85	2.20	1.56	1.80	1.80	2.16	1.68
Relative light output:						
1.00	0.15	0.05^f 0.20^s	0.40	0.10^f 0.02^s	0.01	0.10
Hygroscopic:						
very	no	slightly	somewhat	somewhat	no	no

f = fast component, s = slow component

24.2. Inorganic scintillators

Table 24.2 gives a partial list of commonly-used inorganic scintillators in high-energy and nuclear physics [14–21]. These scintillating crystals are generally used where high density and good energy resolution are required. In a crystal which contains nearly all of the energy deposited by an incident particle, the energy resolution is determined largely, but not totally, by the light output. The table gives the light output of the various materials relative to NaI, which has an intrinsic light output of about 40000 photons per MeV of energy deposit. The detected signal is usually quoted in terms of photoelectrons per MeV produced by a given photodetector. The relationship between photons/MeV produced and p.e.'s/MeV detected involves factors for light collection efficiency (typically 10–50%, depending on geometry) and the quantum efficiency of the detector ($\sim$ 15–20% for photomultiplier tubes and $\sim$ 70% for silicon photodiodes for visible wavelengths). The quantum efficiency of the detector is usually highly wavelength dependent and should be matched to the particular crystal of interest to give the highest quantum yield at the wavelength corresponding to the peak of the scintillation emission. The comparison of the light output given in Table 24.2 is for a standard photomultiplier tube with a bialkali photocathode. For scintillators which emit in the UV, a detector with a quartz window should be used.

24.3. Čerenkov detectors

Čerenkov detectors utilize one or more of the properties of Čerenkov radiation discussed in the Passages of Particles through Matter section (Sec. 22 of this *Review*): the existence of a *threshold* for radiation; the dependence of the Čerenkov cone half-angle θ_c on the *velocity* of the particle; the dependence of the *number of emitted photons* on the particle's velocity. The presence of the refractive index n in the relations allows tuning these quantities for a particular experimental application (*e.g.*, using pressurized gas and/or various liquids as radiators).

The number of photoelectrons (p.e.'s) detected in a given device or channel is

$$N_{\rm p.e.} = L\frac{\alpha^2 z^2}{r_e\, m_e c^2}\int \epsilon_{\rm coll}(E)\,\epsilon_{\rm det}(E)\sin^2\theta_c(E)dE\ , \tag{24.2}$$

where L is the path length in the radiator, $\epsilon_{\rm coll}$ is the efficiency for collecting the Čerenkov light, $\epsilon_{\rm det}$ is the quantum efficiency of the transducer (photomultiplier or equivalent), and $\alpha^2/(r_e\, m_e c^2) = 370\ {\rm cm}^{-1}{\rm eV}^{-1}$. The quantities $\epsilon_{\rm coll}$, $\epsilon_{\rm det}$, and θ_c are all functions of the photon energy E, although in typical detectors θ_c (or, equivalently, the index of refraction) is nearly constant over the useful range of photocathode sensitivity. In this case,

$$N_{\rm p.e.} \approx LN_0\left\langle\sin^2\theta_c\right\rangle \tag{24.3}$$

with

$$N_0 = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\int \epsilon_{\rm coll}\,\epsilon_{\rm det} dE\ . \tag{24.4}$$

We take $z = 1$, the usual case in high-energy physics, in the following discussion.

Threshold Čerenkov detectors make a simple yes/no decision based on whether the particle is above/below the Čerenkov threshold velocity $\beta_t = 1/n$. Careful designs give $\langle\epsilon_{\rm coll}\rangle \gtrsim 90\%$. For a photomultiplier with a typical bialkali cathode, $\int \epsilon_{\rm det}dE \approx 0.27$, so that

$$N_{\rm p.e.}/L \approx 90\ {\rm cm}^{-1}\left\langle\sin^2\theta_c\right\rangle \qquad (i.e.,\ N_0 = 90\ {\rm cm}^{-1})\ . \tag{24.5}$$

Suppose, for example, that n is chosen so that the threshold for species a is p_t; that is, at this momentum species a has velocity $\beta_a = 1/n$. A second, lighter, species b with the same momentum has velocity β_b, so $\cos\theta_c = \beta_a/\beta_b$, and

$$\frac{N_{\rm p.e.}}{L} \approx 90\ {\rm cm}^{-1}\,\frac{m_a^2 - m_b^2}{p_t^2 + m_a^2}\ . \tag{24.6}$$

For K/π separation at $p = 1$ GeV/c, $N_{\rm p.e.}/L \approx 16\ {\rm cm}^{-1}$ for π's and (by design) 0 for K's.

For limited path lengths $N_{\rm p.e.}$ can be small, and some minimum number is required to trigger external electronics. The overall efficiency of the device is controlled by Poisson fluctuations, which can be especially critical for separation of species where one particle type is dominant [22].

A related class of detectors uses the number of observed photoelectrons (or the calibrated pulse height) to discriminate between species or to set probabilities for each particle species [23].

Differential Čerenkov detectors exploit the dependence of θ_c on β, using optical focusing and/or geometrical masking to select particles having velocities in a specified region. With careful design, a velocity resolution of $\sigma_\beta/\beta \approx 10^{-4}$–$10^{-5}$ can be obtained [22,24].

Ring-Imaging Čerenkov detectors use all three properties of Čerenkov radiation in both small-aperture and 4π geometries. They are principally used as hypothesis-testing rather than yes/no devices; that is, the probability of various identification possibilities is established from θ_c and $N_{\rm p.e.}$ for a particle of known momentum. In most cases the optics map the Čerenkov cone onto a circle at the photodetector, often with distortions which must be understood.

Table 24.3: Momentum range for 3σ separation in the SLD ring-imaging Čerenkov detector.

Particle pair	Mom. range for 3 σ separation
e/π	$p \lesssim 5$ GeV/c
π/K	$0.23 \lesssim p \lesssim 20$ GeV/c
K/p	$0.82 \lesssim p \lesssim 30$ GeV/c

The 4π devices [25,26] typically have both liquid (C_6F_{14}, $n = 1.276$) and gas (C_5F_{12}, $n = 1.0017$) radiators, the light from the latter being focused by mirrors. They achieve 3 σ separation of $e/\pi/K/p$ over wide ranges, as shown in Table 24.3. Great attention to detail, especially with the minimization of UV-absorbing impurities, is required to get $\langle\epsilon_{\rm coll}\rangle \gtrsim 50\%$.

The phototransducer is typically a TPC/wire-chamber combination sensitive to single photoelectrons and having charge division or pads. This construction permits three-dimensional reconstruction of photoelectron origins, which is important for transforming the Čerenkov cone into a ring. Single photoelectrons are generated by doping the TPC gas (for instance, ethane/methane in some proportion) with $\sim 0.05\%$ TMAE [tetrakis(dimethylamino)ethylene] [27], leading to photon absorption lengths along the Čerenkov cone of ~ 30 mm. The readout wires must be equipped with special structures (blinds or wire gates) to prevent photon feedback from avalanches generating cross-talk photoelectrons in the TPC. Drift-gas purity must be maintained to assure mean drift lengths of the order of meters without recombination (*i.e.*, lifetimes of $\gtrsim$ 100 μs at typical drift velocities of $\gtrsim$ 4 cm/μs). The net $\langle\epsilon_{\rm det}\rangle$'s reach 30%, with the limitation being the TMAE quantum efficiency.

Photon energy cutoffs are set by the TMAE ($E > 5.4$ eV), the UV transparency of fused silica glass ($E < 7.4$ eV), and the C_6F_{14} ($E < 7.1$ eV). With effort one gets $50 \leq N_0 \leq 100$ for complete rings using liquid or gas. This includes losses due to electrostatic shielding wires and window/mirror reflections, but not gross losses caused by total internal reflection or inadequate coverage by the TPC's.

Such numbers allow determination of ring radii to $\sim$0.5% (liquid) and $\sim$2% (gas), leading to the particle species separations quoted above. Since the separation efficiencies may have "holes" as a function of p, detailed calculations are necessary.

24.4. Transition radiation detectors (TRD's)

It is clear from the discussion in the Passages of Particles Through Matter section (Sec. 22 of this *Review*) that transition radiation (TR) only becomes useful for particle detectors when the Lorentz factor $\gamma \gtrsim 10^3$. In practice, TRD's are used to provide e/π separation when $p \gtrsim 1$ GeV/c. (The momentum is usually measured elsewhere in the detector.) Since a soft x ray is radiated with about 1% probability per boundary crossing, practical detectors use radiators with several hundred interfaces, *e.g.* foils of lithium or plastic in a gas. Absorption inside the radiator and interference effects between interfaces are important [28,29].

A practical detector is composed of several similar modules, each consisting of a radiator and an x-ray detector. The radiator is made of foils or fibers of a low-Z material (for low absorption) in a low-Z gas such as helium. The x-ray detector is usually a wire chamber operated with a xenon-rich mixture in order to obtain a high conversion efficiency. As transition radiation is emitted at small angles, the chamber usually detects the sum of the ionization of the particle and of converted TR photons. The discrimination between electrons and pions can be based on the charges measured in each set, or on more sophisticated methods using pulse-shape analysis.

The major factor in the performance of a TRD is its overall length. Very roughly, the pion rejection factor for a detector with 90% electron efficiency is $10^{(L/20\ {\rm cm})}$, where L is the overall length of the detector.

Recent development work has aimed at adapting the technique to the very high particle rate at LHC, by distributing straw-tube detectors uniformly in the radiator foam, and using very fast electronics. The resulting detector is used as a tracking device as well as a TRD [30].

24.5. Silicon photodiodes and particle detectors

Silicon detectors are p-n junction diodes operated at reverse bias. This forms a sensitive region depleted of mobile charge and sets up an electric field that sweeps charge liberated by radiation to the electrodes. The thickness of the depleted region is

$$W = \sqrt{\frac{2\epsilon\,(V + V_{bi})}{ne}} = \sqrt{2\rho\mu\epsilon(V + V_{bi})} \;, \tag{24.7}$$

where V = external bias voltage

V_{bi} = "built-in" voltage (≈ 0.8 V for resistivities typically used in detectors

n = doping concentration

e = electron charge

ϵ = dielectric constant = $11.9\ \epsilon_0 \approx 1$ pF/cm

ρ = resistivity (typically 1–10 kΩ cm)

μ = charge carrier mobility

= 1350 cm^2 V^{-1} s^{-1} for electrons (n-type material)

= 450 cm^2 V^{-1} s^{-1} for holes (p-type material)

or

$$W = 0.5\ \mu\text{m} \times \sqrt{\rho(V + V_{bi})} \quad \text{for } n\text{-type material}, \tag{24.8}$$

and

$$W = 0.3\ \mu\text{m} \times \sqrt{\rho(V + V_{bi})} \quad \text{for } p\text{-type material}, \tag{24.9}$$

where V is in volts and ρ is in Ω cm.

The corresponding capacitance per unit area is

$$C = \frac{\epsilon}{W} \approx 1\,[\text{pF/cm}]\,\frac{1}{W} \;. \tag{24.10}$$

In strip detectors the capacitance is dominated by the strip-to-strip fringing capacitance of $\sim$ 1–1.5 pF cm^{-1} of strip length at a strip pitch of 25–50 μm.

About 3.6 eV is required to create an electron-hole pair. For minimum-ionizing particles, the most probable charge deposition in a 300 μm thick silicon detector is about 4 fC (25000 electrons). Readily available photodiodes have quantum efficiences > 70% for wavelengths between 600 nm and 1 μm. UV extended photodiodes have useful efficiency down to 200 nm. In applications in which photodiodes detect light from scintillators, care must be taken so that signal from the scintillator is larger than that produced by particles going through the photodiode.

Collection time decreases with increased depletion voltage, and can be reduced further by operating the detector with "overbias," *i.e.*, a bias voltage exceeding the value required to fully deplete the device. The collection time is limited by velocity saturation at high fields; at an average field of 10^4 V/cm, the collection times is about 15 ps/μm for electrons and 30 ps/μm for holes. In typical strip detectors of 300 μm thickness, electrons are collected within about 8 ns, and holes within about 25 ns.

Position resolution is limited by transverse diffusion during charge collection (typically 5 μm for 300 μm thickness) and by knock-on electrons. Resolutions of 3–4 μm (rms) have been obtained in beam tests. In magnetic fields, the Lorentz drift can increase the spatial spread appreciably (see "Hall effect" in semiconductor textbooks).

Radiation damage occurs through two basic mechanisms:

1. Bulk damage due to displacement of atoms from their lattice sites. This leads to increased leakage current, carrier trapping, and changes in doping concentration. Displacement damage depends on the nonionizing energy loss, *i.e.*, particle type and energy. The dose should be specified as a fluence of particles of a specific type and energy.
2. Surface damage due to charge build-up in surface layers, which leads to increased surface leakage currents. In strip detectors the inter-strip isolation is affected. The effects of charge build-up are strongly dependent on the device structure and on fabrication details. Since the damage is determined directly by the absorbed energy, the dose should be specified in these units (rad or Gray).

The increase in leakage current due to bulk damage is $\Delta i = \alpha\phi$ per unit volume, where ϕ is the particle fluence and α the damage coefficient ($\alpha \approx 2 \times 10^{-17}$ A/cm for minimum ionizing protons and pions after long-term annealing; roughly the same value applies for 1 MeV neutrons). The doping concentration in n-type silicon changes as $n = n_0 \exp(-\delta\phi) - \beta\phi$, where n_0 is the initial donor concentration, $\delta \approx 6 \times 10^{14}$ cm^2 determines donor removal, and $\beta \approx 0.03$ cm^{-1} describes acceptor creation. This leads to an initial increase in resisitivity until type-inversion changes the net doping from n to p. At this point the resistivity decreases, with a corresponding increase in depletion voltage. The safe operating limit of depletion voltage ultimately limits the detector lifetime. Strip detectors have remained functional at fluences beyond 10^{14} cm^{-2} for minimum ionizing protons. At this damage level, charge loss due to recombination and trapping also seems to become significant.

24.6. Proportional and drift chambers

Proportional chamber wire instability: The limit on the voltage V for a wire tension T, due to mechanical effects when the electrostatic repulsion of adjacent wires exceeds the restoring force of wire tension, is given by (SI units) [31]

$$V \le \frac{s}{\ell C}\sqrt{4\pi\epsilon_0 T} \;, \tag{24.11}$$

where s, ℓ, and C are the wire spacing, length, and capacitance per unit length. An approximation to C for chamber half-gap t and wire diameter d (good for $s \lesssim t$) gives [32]

$$V \lesssim 59 T^{1/2} \left[\frac{t}{\ell} + \frac{s}{\pi\ell}\ln\left(\frac{s}{\pi d}\right)\right] \;, \tag{24.12}$$

where V is in kV, and T is in grams-weight equivalent.

Proportional and drift chamber potentials: The potential distributions and fields in a proportional or drift chamber can usually be calculated with good accuracy from the exact formula for the potential around an array of parallel line charges q (coul/m) along z and located at $y = 0$, $x = 0$, $\pm s$, $\pm 2s$, ...,

$$V(x,y) = -\frac{q}{4\pi\,\epsilon_0}\ln\left\{4\left[\sin^2\left(\frac{\pi x}{s}\right) + \sinh^2\left(\frac{\pi y}{s}\right)\right]\right\} \;. \tag{24.13}$$

Errors from the presence of cathodes, mechanical defects, TPC-type edge effects, *etc.*, are usually small and are beyond the scope of this review.

24.7. Calorimeters

Electromagnetic calorimeters: The development of electromagnetic showers is discussed in the "Passage of Particles Through Matter" section (Sec. 22 of this *Review*). Formulae are given for the approximate description of average showers, but since the physics of electromagnetic showers is well understood, detailed and reliable Monte Carlo simulation is possible. EGS4 has emerged as the standard [33].

The resolution of sampling calorimeters (hadronic and electromagnetic) is usually dominated by sampling fluctuations, leading to fractional resolution σ/E scaling inversely as the square root of the incident energy. Homogenous calorimeters, such as solid NaI(Tl), will in general not have resolution varying as $1/\sqrt{E}$. At high energies deviations from $1/\sqrt{E}$ occur because of noise, pedestal fluctuations, nonuniformities, calibration errors, and incomplete shower containment. Such effects are usually included by adding a constant term to σ/E, either in quadrature or (incorrectly) directly. In the case of the hadronic cascades discussed below, noncompensation also contributes to the constant term.

In Table 24.4 we give resolution as measured in detectors using typical EM calorimeter technologies. In almost all cases the installed calorimeters yield worse resolution than test beam prototypes for a variety of practical reasons. Where possible actual detector performance is given. For a fixed number of radiation lengths, the FWHM in sandwich detectors would be expected to be proportional to $\sqrt{t}$ for t (= plate thickness) ≥ 0.2 radiation lengths [34].

Given sufficient transverse granularity early in the calorimeter, position resolution of the order of a millimeter can be obtained.

Table 24.4: Resolution of typical electromagnetic calorimeters. E is in GeV.

Detector	Resolution
NaI(Tl) (Crystal Ball [35]; 20 X_0)	$2.7\%/E^{1/4}$
Lead glass (OPAL [36])	$5\%/\sqrt{E}$
Lead-liquid argon (NA31 [37]; 80 cells: 27 X_0, 1.5 mm Pb + 0.6 mm Al + 0.8 mm G10 + 4 mm LA)	$7.5\%/\sqrt{E}$
Lead-scintillator sandwich (ARGUS [38], LAPP-LAL [39])	$9\%/\sqrt{E}$
Lead-scintillator spaghetti (CERN test module) [40]	$13\%/\sqrt{E}$
Proportional wire chamber (MAC; 32 cells: 13 X_0, 2.5 mm typemetal + 1.6 mm Al) [41]	$23\%/\sqrt{E}$

Hadronic calorimeters [42,43]: The length scale appropriate for hadronic cascades is the nuclear interaction length, given very roughly by

$$\lambda_I \approx 35 \text{ g cm}^{-2} A^{1/3} . \tag{24.14}$$

Longitudinal energy deposition profiles are characterized by a sharp peak near the first interaction point (from the fairly local deposition of EM energy resulting from π^0's produced in the first interaction), followed by a more gradual development with a maximum at

$$x/\lambda_I \equiv t_{\max} \approx 0.2 \ln(E/1 \text{ GeV}) + 0.7 \tag{24.15}$$

as measured from the front of the detector.

The depth required for containment of a fixed fraction of the energy also increases logarithmically with incident particle energy. The thickness of iron required for 95% (99%) containment of cascades induced by single hadrons is shown in Fig. 24.2 [44]. Two of the sets of data are from large neutrino experiments, while the third is from a commonly used parametrization. Depths as measured in nuclear interaction lengths presumably scale to other materials. From the same data it can be concluded that the requirement that 95% of the energy in 95% of the showers be contained requires 40 to 50 cm (2.4 to 3.0 λ_I) more material material than for an average 95% containment.

The transverse dimensions of hadronic showers also scale as λ_I, although most of the energy is contained in a narrow core.

The energy deposit in a hadronic cascade consists of a prompt EM component due to π^0 production and a slower component mainly due to low-energy hadronic activity. In general, these energy depositions are converted to electrical signals with different efficiencies [45]. The ratio of the conversion efficiencies is usually called the intrinsic e/h ratio. If $e/h = 1.0$ the calorimeter is said to be *compensating*. If it differs from unity by more than 5% or 10%, detector performance is compromised because of fluctuations in the π^0 content of the cascades. Problems include:

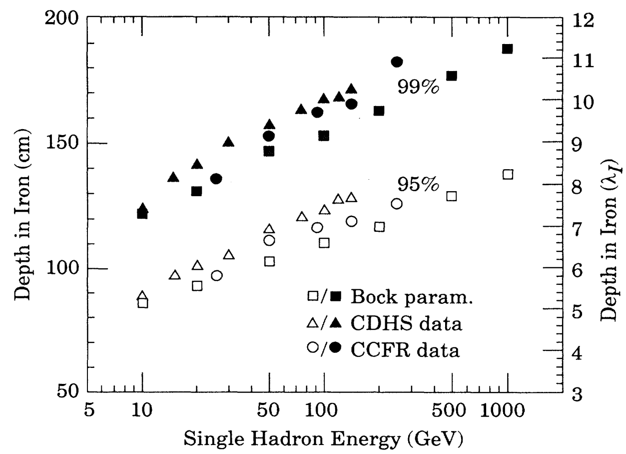

Figure 24.2: Required calorimeter thickness for 95% and 99% hadronic cascade containment in iron, on the basis of data from two large neutrino detectors and the parametrization of Bock *et al.* [44].

a) A skewed signal distribution;
b) A response ratio for electrons and hadrons (the "e/π ratio") which is different from unity and depends upon energy;
c) A nonlinear response to hadrons (the response per GeV is proportional to the reciprocal of e/π);
d) A constant contribution to detector resolution, almost proportional to the degree of noncompensation. The coefficient relating the constant term to $|1 - e/h|$ is 14% according to FLUKA simulations, and 21% according to Wigman's calculations [42].

In most cases e/h is greater than unity, particularly if little hydrogen is present or if the gate time is short. This is because much of the low-energy hadronic energy is "hidden" in nuclear binding energy release, low-energy spallation products, *etc.* Partial correction for these losses occurs in a sampling calorimeter with thick plates, because a disproportionate fraction of electromagnetic energy is deposited in the inactive region. For this reason, a fully sensitive detector such as BGO or glass cannot be made compensating.

Compensation has been demonstrated in calorimeters with 2.5 mm scintillator sheets sandwiched between 3 mm depleted uranium plates [47] or 10 mm lead plates [48]; resolutions σ/E of $0.34/\sqrt{E}$ and $0.44/\sqrt{E}$ were obtained for these cases (E in GeV). The former was shown to be linear to within 2% over three orders of magnitude in energy, with approximately Gaussian signal distributions.

24.8. Measurement of particle momenta in a uniform magnetic field [54]

The trajectory of a particle with momentum p (in GeV/c) and charge ze in a constant magnetic field $\vec{B}$ is a helix, with radius of curvature R and pitch angle λ. The radius of curvature and momentum component perpendicular to $\vec{B}$ are related by

$$p \cos\lambda = 0.3\, z\, B\, R , \tag{24.16}$$

where B is in tesla and R is in meters.

The distribution of measurements of the curvature $k \equiv 1/R$ is approximately Gaussian. The curvature error for a large number of uniformly spaced measurements on the trajectory of a charged particle in a uniform magnetic field can be approximated by

$$(\delta k)^2 = (\delta k_{\text{res}})^2 + (\delta k_{\text{ms}})^2 , \tag{24.17}$$

where δk = curvature error
δk_{res} = curvature error due to finite measurement resolution
δk_{ms} = curvature error due to multiple scattering.

If many (≥ 10) uniformly spaced position measurements are made along a trajectory in a uniform medium,

$$\delta k_{\rm res} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+4}} \ , \tag{24.18}$$

where N = number of points measured along track
L' = the projected length of the track onto the bending plane
ϵ = measurement error for each point, perpendicular to the trajectory.

If a vertex constraint is applied at the origin of the track, the coefficient under the radical becomes 320.

The contribution due to multiple Coulomb scattering is approximately

$$\delta k_{\rm ms} \approx \frac{(0.016)({\rm GeV}/c)z}{Lp\beta\cos^2\lambda}\sqrt{\frac{L}{X_0}} \ , \tag{24.19}$$

where p = momentum (GeV/c)
z = charge of incident particle in units of e
L = the total track length
X_0 = radiation length of the scattering medium (in units of length; the X_0 defined elsewhere must be multiplied by density)
β = the kinematic variable v/c.

More accurate approximations for multiple scattering may be found in the section on Passage of Particles Through Matter (Sec. 22 of this *Review*). The contribution to the curvature error is given approximately by $\delta k_{\rm ms} \approx 8 s^{\rm rms}_{\rm plane}/L^2$, where $s^{\rm rms}_{\rm plane}$ is defined there.

24.9. Superconducting solenoids for collider detectors

24.9.1. ***Basic (approximate) equations***: In all cases SI units are assumed, so that B is in tesla, E is in joules, dimensions are in meters, and $\mu_0 = 4\pi \times 10^{-7}$.

Magnetic field: The magnetic field at the center of a solenoid of length L and radius R, having N total turns and a current I is

$$B(0,0) = \frac{\mu_0 NI}{\sqrt{L^2+4R^2}} \ . \tag{24.20}$$

Stored energy: The energy stored in the magnetic field of any magnet is calculated by integrating B^2 over all space:

$$E = \frac{1}{2\mu_0}\int B^2 dV \ . \tag{24.21}$$

For a solenoid with an iron flux return in which the magnetic field is $< 2T$, the field in the aperture is approximately uniform and equal to $\mu_0 NI/L$. If the thickness of the coil is small, (which is the case if it is superconducting), then

$$E \approx (\pi/2\mu_0)B^2R^2L \ . \tag{24.22}$$

Cost of a superconducting solenoid [55]:

$$\text{Cost (in M\$)} = 0.523\,[(E/(1\ \text{MJ})]^{0.662} \tag{24.23}$$

Magnetostatic computer programs: It is too difficult to solve the Biot-Savart equation for a magnetic circuit which includes iron components and so iterative computer programs are used. These include POISSON, TOSCA [56], and ANSYS [57].

24.9.2. ***Scaling laws for thin solenoids***: For a detector in which the calorimetry is outside the aperture of the solenoid, the coil must be thin in terms of radiation and absorption lengths. This usually means that the coil is superconducting and that the vacuum vessel encasing it is of minimum real thickness and fabricated of a material with long radiation length. There are two major contributers to the thickness of a thin solenoid:

1. The conductor, consisting of the current-carrying superconducting material (usually Cu/Nb-Ti) and the quench protecting stabilizer (usually aluminum), is wound on the inside of a structural support cylinder (usually aluminum also). This package typically represents about 60% of the total thickness in radiation lengths. The thickness scales approximately as B^2R.
2. Approximately another 25% of the thickness of the magnet comes from the outer cylindrical shell of the vacuum vessel. Since this shell is susceptible to buckling collapse, its thickness is determined by the diameter, length, and the modulus of the material of which it is fabricated. When designing this shell to a typical standard, the real thickness is

$$t = P_c D^{2.5}[(L/D) - 0.45(t/D)^{0.5}]/2.6Y^{0.4} \ , \tag{24.24}$$

where t = shell thickness (in), D = shell diameter (in), L = shell length (in), Y = modulus of elasticity (psi), and P_c = design collapse pressure (= 30 psi). For most large-diameter detector solenoids, the thickness to within a few percent is given by [58]

$$t = P_c D^{2.5}(L/D)/2.6Y^{0.4} \ . \tag{24.25}$$

24.9.3. ***Properties of collider detector solenoids***: The physical dimensions, central field, stored energy and thickness in radiation lengths normal to the beam line of the superconducting solenoids associated with the major colliders are given in Table 24.5.

Table 24.5: Properties of superconducting collider detector solenoids.

Experiment–Lab	Field (T)	Bore Dia (m)	Length (m)	Energy (MJ)	Thickness (X_0)
CDF–Fermilab	1.5	2.86	5.07	30	0.86
Topaz–KEK	1.2	2.72	5.4	19.5	0.70
Venus–KEK	0.75	3.4	5.64	12	0.52
Cleo II–Cornell	1.5	2.9	3.8	25	2.5
Aleph–CERN	1.5	5.0	7.0	130	1.7
Delphi–CERN	1.2	5.2	7.4	109	4.0
H1–DESY	1.2	5.2	5.75	120	1.2
Zeus–DESY	1.8	1.72	2.85	10.5	0.9

The ratio of stored energy to cold mass (E/M) is a useful performance measure. One would like the cold mass to be as small as possible to minimize the thickness, but temperature rise during a quench must also be minimized. Ratios as large as 8 kJ/kg may be possible (final temperature of 80 K after a fast quench with homogenous energy dump), but some contingency is desirable. This quantity is shown as a function of total stored energy for some major collider detectors in Fig. 24.3.

24.10. Other observations

dE/dx resolution in argon: Particle identification by dE/dx is dependent on the width of the distribution. For relativistic incident particles with charge e in a multiple-sample Ar gas counter with no lead [49],

$$\left.\frac{dE}{dx}\right|_{\rm FWHM} \Big/ \left.\frac{dE}{dx}\right|_{\rm most\ probable} = 0.96\,N^{-0.46}\,(xp)^{-0.32} \ , \tag{24.26}$$

where N = number of samples, x = thickness per sample (cm), p = pressure (atm.). Most commonly used chamber gases (except Xe) give approximately the same resolution.

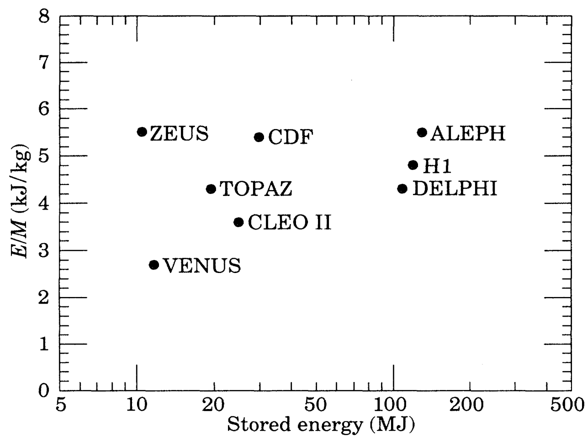

Figure 24.3: Ratio of stored energy to cold mass for existing thin detector solenoids.

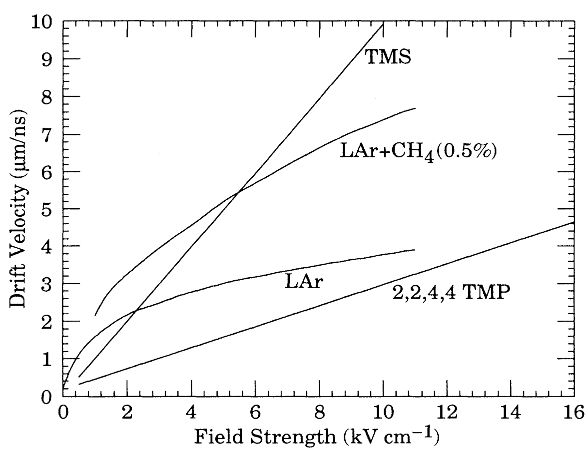

Figure 24.4: Electron drift velocity as a function of field strength for commonly used liquids.

Free electron drift velocities in liquid ionization chambers [50–53]: Velocity as a function of electric field strength is given in Fig. 24.4.

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25. RADIOACTIVITY & RADIATION PROTECTION

Revised Sept. 1995 by R.J. Donahue (LBNL) and A. Fasso (CERN).

25.1. Definitions

The International Commission on Radiation Units and Measurements (ICRU) recommends the use of SI units. Therefore we list SI units first, followed by cgs (or other common) units in parentheses, where they differ.

• **Unit of activity** = becquerel (curie):

$1\ \text{Bq} = 1$ disintegration s^{-1} $[= 1/(3.7 \times 10^{10})\ \text{Ci}]$

• **Unit of absorbed dose** = gray (rad):

$1\ \text{Gy} = 1$ joule kg^{-1} $(= 10^4\ \text{erg g}^{-1} = 100\ \text{rad})$

$= 6.24 \times 10^{12}$ MeV kg^{-1} deposited energy

• **Unit of exposure**, the quantity of x- or γ- radiation at a point in space integrated over time, in terms of charge of either sign produced by showering electrons in a small volume of air about the point:

$= 1$ coul kg^{-1} of air (roentgen; $1\ R = 2.58\times10^{-4}$ coul kg^{-1})

$= 1$ esu cm^{-3}($= 87.8$ erg released energy per g of air)

Implicit in the definition is the assumption that the small test volume is embedded in a sufficiently large uniformly irradiated volume that the number of secondary electrons entering the volume equals the number leaving. This unit is somewhat historical, but appears on many measuring instruments.

• **Unit of equivalent dose** (for biological damage) = sievert [= 100 rem (**r**oentgen **e**quivalent for **m**an)]: Equivalent dose in Sv = absorbed dose in grays $\times\ w_R$, where w_R (radiation weighting factor, formerly the quality factor Q) expresses long-term risk (primarily cancer and leukemia) from low-level chronic exposure. It depends upon the type of radiation and other factors, as follows [2]:

Table 25.1: Radiation weighting factors.

Radiation	w_R
X- and γ-rays, all energies	1
Electrons and muons, all energies	1
Neutrons < 10 keV	5
10–100 keV	10
> 100 keV to 2 MeV	20
2–20 MeV	10
> 20 MeV	5
Protons (other than recoils) > 2 MeV	5
Alphas, fission fragments, & heavy nuclei	20

25.2. Radiation levels [3]

• **Natural annual background**, all sources: Most world areas, whole-body equivalent dose rate $\approx$ (0.4–4) mSv (40–400 millirems). Can range up to 50 mSv (5 rems) in certain areas. U.S. average $\approx$ 3.6 mSv, including $\approx$ 2 mSv ($\approx$ 200 mrem) from inhaled natural radioactivity, mostly radon and radon daughters (0.1–0.2 mSv in open areas. Average is for a typical house and varies by more than an order of magnitude. It can be more than two orders of magnitude higher in poorly ventilated mines).

• **Cosmic ray background** in counters (Earth's surface): $\sim 1\ \text{min}^{-1}\ \text{cm}^{-2}$ sr. For more accurate estimates and details, see the Cosmic Rays section (Sec. 20 of this *Review*).

• **Fluxes** (per cm^2) to deposit one Gy, assuming uniform irradiation:

$\approx$ (**charged particles**) $6.24\times10^9/(dE/dx)$, where dE/dx (MeV $\text{g}^{-1}\ \text{cm}^2$), the energy loss per unit length, may be obtained from the Mean Range and Energy Loss figures.

$\approx 3.5 \times 10^9\ \text{cm}^{-2}$ minimum-ionizing singly-charged particles in carbon.

$\approx$ (**photons**) $6.24\times10^9/[Ef/\lambda]$, for photons of energy E (MeV), attenuation length λ (g cm^{-2}) (see Photon Attenuation Length figure), and fraction $f \lesssim 1$ expressing the fraction of the photon's energy deposited in a small volume of thickness $\ll \lambda$ but large enough to contain the secondary electrons.

$\approx 2 \times 10^{11}$ photons cm^{-2} for 1 MeV photons on carbon ($f \approx 1/2$).

(Quoted fluxes are good to about a factor of 2 for all materials.)

• **Recommended limits to exposure of radiation workers (whole-body dose):***

CERN: 15 mSv yr^{-1}

U.K.: 15 mSv yr^{-1}

U.S.: 50 mSv yr^{-1} (5 rem yr^{-1})†

• **Lethal dose:** Whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days (assuming no medical treatment) 2.5–3.0 Gy (250–300 rads), as measured internally on body longitudinal center line. Surface dose varies due to variable body attenuation and may be a strong function of energy.

25.3. Prompt neutrons at accelerators

25.3.1. ***Electron beams***: At electron accelerators neutrons are generated via photonuclear reactions from bremsstrahlung photons. Neutron yields from semi-infinite targets per unit electron beam power are plotted in Fig. 25.1 as a function of electron beam energy [4]. In the photon energy range 10–30 MeV neutron production results from the giant photonuclear resonance mechanism. Neutrons are produced roughly isotropically (within a factor of 2) and with a Maxwellian energy distribution described as:

$$\frac{dN}{dE_n} = \frac{E_n}{T^2} e^{-E_n/T} , \tag{25.1}$$

where T is the nuclear temperature characteristic of the target nucleus, generally in the range of $T = 0.5$–1.0 MeV. For higher energy photons the quasi-deuteron and photopion production mechanisms become important.

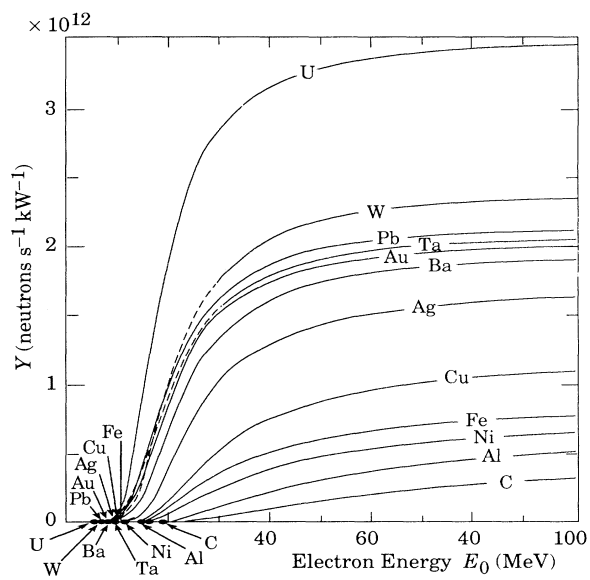

Figure 25.1: Neutron yields from semi-infinite targets, per kW of electron beam power, as a function of electron beam energy, disregarding target self-shielding.

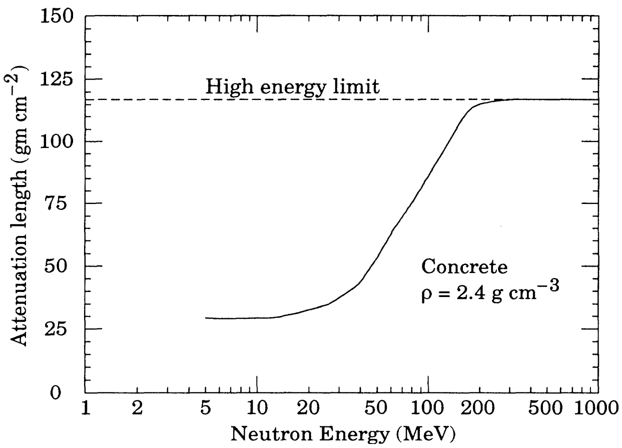

Figure 25.3: The variation of the attenuation length for monoenergetic neutrons in concrete as a function of neutron energy [5].

25.3.2. ***Proton beams***: At proton accelerators neutron yields emitted per incident proton by different target materials are roughly independent [5] of proton energy between 20 MeV and 1 GeV and are given by the ratio C:Al:Cu-Fe:Sn:Ta-Pb = 0.3 : 0.6 : 1.0 : 1.5 : 1.7. Above 1 GeV neutron yield [6] is proportional to E^m, where $0.80 \leq m \leq 0.85$.

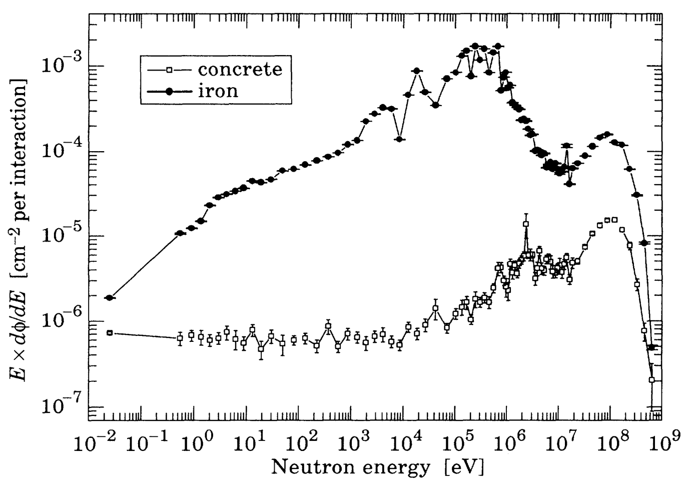

Figure 25.2: Calculated neutron spectrum from 205 GeV/c hadrons (2/3 protons and 1/3 π^+) on a thick copper target. Spectra are evaluated at 90° to beam and through 80 cm of normal density concrete or 40 cm of iron.

A typical neutron spectrum [7] outside a proton accelerator concrete shield is shown in Fig. 25.2. The shape of these spectra are generally characterized as having a thermal-energy peak which is very dependent on geometry and the presence of hydrogenic material, a low-energy evaporation peak around 2 MeV, and a high-energy spallation shoulder.

Letaw's [8] formula for the energy dependence of the inelastic proton cross-section (asymptotic values given in Table 6.1) for $E < 2$ GeV is:

$$\sigma(E) = \sigma_{\text{asympt}} \left[1 - 0.62 e^{-E/200} \sin(10.9 E^{-0.28})\right] , \tag{25.2}$$

and for $E > 2$ GeV:

$$\sigma_{\text{asympt}} = 45 A^{0.7} \left[1 + 0.016 \sin(5.3 - 2.63 \ln A)\right] , \tag{25.3}$$

where σ is in mb, E is the proton energy in MeV and A is the mass number.

The neutron-attenuation length, λ, is shown in Fig. 25.3 for monoenergetic broad-beam conditions. These values give a satisfactory representation at depths greater than 1 m in concrete.

25.4. Dose conversion factors

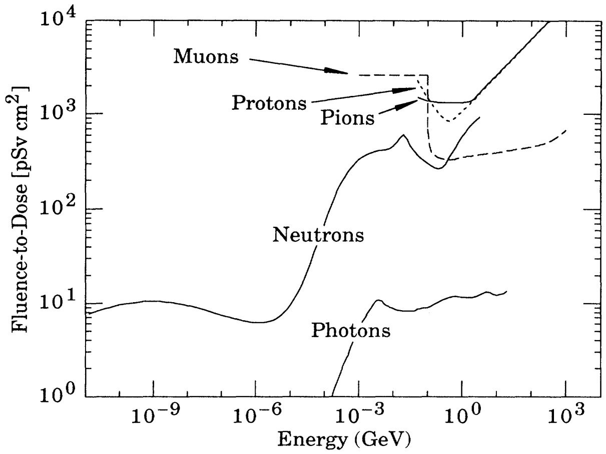

Figure 25.4: Fluence to dose equivalent conversion factors for various particles.

Fluence to dose equivalent factors are given in Fig. 25.4 for photons [9], neutrons [10], muons [11], protons and pions [12]. These factors can be used for converting particle fluence to dose for personnel protection purposes.

25.5. Accelerator-induced activity

The dose rate at 1 m due to spallation-induced activity by high energy hadrons in a 1 g medium atomic weight target can be estimated [13] from the following expression:

$$D = D_0 \; \Phi \; \ln[(T + t)/t] , \tag{25.4}$$

where T is the irradiation time, t is the decay time since irradiation, Φ is the flux of irradiating hadrons (hadrons cm^{-2} s^{-1}) and D_0 has a value of 5.2×10^{-17} [(Sv hr^{-1})/(hadron cm^{-2} s^{-1})]. This relation is essentially independent of hadron energy above 200 MeV.

Dose due to accelerator-produced induced activity can also be estimated with the use of "ω factors" [5]. These factors give the dose rate per unit star density (inelastic reaction for E > 50 MeV) after a 30 day irradiation and 1 day decay. The ω factors for concrete and steel are 1.2×10^{-8} (Sv cm^3/star) and 4.5×10^{-8} (Sv cm^3/star), respectively. These do not include contributions from thermal-neutron activation. This can vary widely depending on concrete composition, particularly with the concentration of trace quantities such as sodium. Additional information can be found in Barbier [14].

25.6. Photon sources

The dose rate from a gamma point source of C Curies emitting one photon of energy $0.07 < E < 4$ MeV per disintegration at a distance of 30 cm is 6CE (rem/hr), or 60CE (mSv/hr), ±20%.

The dose rate from a semi-infinite uniform photon source of specific activity C (μCi/g) and gamma energy E (MeV) is $1.07CE$ (rem/hr), or $10.7CE$ (mSv/hr).

25.7. Radiation levels in detectors at hadron colliders

An SSC Central Design Group task force studied the radiation levels to be expected in SSC detectors [15]. The study focused on scaling with energy, distance, and angle. As such, it is applicable to future detectors such as those at the LHC. Although superior detector-specific calculations have since been made, the scaling is in most cases not evident, and so the SSC results have some relevance. The SSC/CDG model assumed

- The machine luminosity at $\sqrt{s} = 40$ TeV is $\mathscr{L} = 10^{33}$ cm^{-2}s^{-1}, and the pp inelastic cross section is $\sigma_{\rm incl} = 100$ mb. This luminosity is effectively achieved for 10^7 s yr^{-1}. The interaction rate is thus 10^8 s^{-1}, or 10^{15} yr^{-1};
- All radiation comes from pp collisions at the interaction point;
- The charged particle distribution is (a) flat in pseudorapidity for $|\eta| < 6$ and (b) has a momentum distribution whose perpendicular component is independent of rapidity, which is taken as independent of pseudorapidity:

$$\frac{d^2N_{\rm ch}}{d\eta dp_\perp} = H\, f(p_\perp) \tag{25.5}$$

(where $p_\perp = p\sin\theta$). Integrals involving $f(p_\perp)$ are simplified by replacing $f(p_\perp)$ by $\delta(p_\perp - \langle p_\perp\rangle)$; in the worst case this approximation introduces an error of less than 10%;

- Gamma rays from π^0 decay are as abundant as charged particles. They have approximately the same η distribution, but half the mean momentum;
- At the SSC ($\sqrt{s} = 40$ TeV), $H \approx 7.5$ and $\langle p_\perp\rangle \approx 0.6$ GeV/c; assumed values at other energies are given in Table 25.3. Together with the model discussed above, these values are thought to describe particle production to within a factor of two or better.

It then follows that the flux of charged particles from the interaction point passing through a normal area da located a distance $r_\perp$ from the beam line is given by

$$\frac{dN_{\rm ch}}{da} = \frac{1.2\times 10^8\,{\rm s}^{-1}}{r_\perp^2}\ . \tag{25.6}$$

In a typical organic material, a relativistic charged particle flux of 3×10^9 cm^{-2} produces an ionizing radiation dose of 1 Gy, where 1 Gy $\equiv$ 1 joule kg^{-1} (= 100 rads). The above result may thus be rewritten as dose rate,

$$\dot{D} = \frac{0.4\ {\rm MGy\ yr}^{-1}}{(r_\perp/1\ {\rm cm})^2}\ . \tag{25.7}$$

If a magnetic field is present, "loopers" may increase this dose rate by a factor of two ore more.

In a medium in which cascades can develop, the ionizing dose or neutron fluence is proportional to $dN_{\rm ch}/da$ multiplied by $\langle E\rangle^\alpha$, where $\langle E\rangle$ is the mean energy of the particles going through da and the power α is slightly less than unity. Since $E \approx p = p_\perp/\sin\theta$ and $r_\perp = r\sin\theta$, the above expression for $dN_{\rm ch}/da$ becomes

$$\text{Dose or fluence}^\ddagger = \frac{A}{r^2}\cosh^{2+\alpha}\eta = \frac{A}{r^2\sin^{2+\alpha}\theta}\ . \tag{25.8}$$

The constant A contains the total number of interactions $\sigma_{\rm incl}\int\mathscr{L}dt$, so the ionizing dose or neutron fluence at another accelerator scales as $\sigma_{\rm incl}\int\mathscr{L}dt\ H\,\langle p_\perp\rangle^\alpha$.

The dose or fluence in a calorimeter scales as $1/r^2$, as does the neutron fluence inside a central cavity with characteristic dimension r.

Under all conditions so far studied, the neutron spectrum shows a broad log-normal distribution peaking at just under 1 MeV. In a 2 m radius central cavity of a detector with coverage down to $|\eta| = 3$, the average neutron flux is 2×10^{12} cm^{-2}yr^{-1}, including secondary scattering contributions.

Values of A and α are given in Table 25.2 for several relevant situations. Examples of scaling to other accelerators are given in Table 25.3. It should be noted that the assumption that all radiation comes from the interaction point does not apply to the present generation of accelerators.

The constant A includes factors evaluated with cascade simulation programs as well as constants describing particle production at the interaction point. It is felt that each could introduce an error as large as a factor of two in the results.

Table 25.2: Coefficients $A/(100\ {\rm cm})^2$ and α for the evaluation of calorimeter radiation levels at cascade maxima under SSC nominal operating conditions. At a distance r and angle θ from the interaction point the annual fluence or dose is $A/(r^2\sin^{2+\alpha}\theta)$.

Quantity	$A/(100\ {\rm cm})^2$	Units	$\langle p_\perp\rangle$	α
Neutron flux	1.5×10^{12}	cm^{-2}yr^{-1}	0.6 GeV/c	0.67
Dose rate from photons	124	Gy yr^{-1}	0.3 GeV/c	0.93
Dose rate from hadrons	29	Gy yr^{-1}	0.6 GeV/c	0.89

Table 25.3: A rough comparison of beam-collision induced radiation levels at the Tevatron, high-luminosity LHC, SSC, and a possible 100 TeV machine [16].

	Tevatron	LHC	SSC	100 TeV
$\sqrt{s}$ (TeV)	1.8	15.4	40	100
$\mathscr{L}_{\rm nom}$ (cm^{-2}s^{-1})	2×10^{30}	1.7×10^{34} [a]	1×10^{33}	1×10^{34}
$\sigma_{\rm incl}$	56 mb	84 mb	100 mb	134 mb
H	3.9	6.2	7.5	10.6
$\langle p_\perp\rangle$ (GeV/c)	0.46	0.55	0.60	0.70
Relative dose rate [b]	5×10^{-4}	11	1	20

[a] High-luminosity option.
[b] Proportional to $\mathscr{L}_{\rm nom}\,\sigma_{\rm incl}\,H\,\langle p_\perp\rangle^{0.7}$

Footnotes:

* The ICRP recomendation [2] is 20 mSv yr^{-1} averaged over 5 years, with the dose in any one year $\leq$ 50 mSv.

† Many laboratories in the U.S. and elsewhere set lower limits.

‡ *Dose* is the time integral of *dose rate*, and *fluence* is the time integral of *flux*.

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26. COMMONLY USED RADIOACTIVE SOURCES

Table 26.1. Updated November 1993 by E. Browne.

Nuclide	Half-life	Type of decay	Particle Energy (MeV)	Particle Emission prob.	Photon Energy (MeV)	Photon Emission prob.
$^{22}_{11}$Na	2.603 y	β^+, EC	0.545	90%	0.511	Annih.
					1.275	100%
$^{54}_{25}$Mn	0.855 y	EC			0.835	100%
					Cr K x rays	26%
$^{55}_{26}$Fe	2.73 y	EC			Mn K x rays:	
					0.00589	25%
					0.00649	3.4%
$^{57}_{27}$Co	0.744 y	EC			0.014	9%
					0.122	86%
					0.136	11%
					Fe K x rays	58%
$^{60}_{27}$Co	5.271 y	β^-	0.316	100%	1.173	100%
					1.333	100%
$^{68}_{32}$Ge	0.742 y	EC			Ga K x rays	44%
$\rightarrow$ $^{68}_{31}$Ga		β^+, EC	1.899	90%	0.511	Annih.
					1.077	3%
$^{90}_{38}$Sr	28.5 y	β^-	0.546	100%		
$\rightarrow$ $^{90}_{39}$Y		β^-	2.283	100%		
$^{106}_{44}$Ru	1.020 y	β^-	0.039	100%		
$\rightarrow$ $^{106}_{45}$Rh		β^-	3.541	79%	0.512	21%
					0.622	10%
$^{109}_{48}$Cd	1.267 y	EC	0.063 e^-	41%	0.088	3.6%
			0.084 e^-	45%	Ag K x rays	100%
			0.087 e^-	9%		
$^{113}_{50}$Sn	0.315 y	EC	0.364 e^-	29%	0.392	65%
			0.388 e^-	6%	In K x rays	97%
$^{137}_{55}$Cs	30.2 y	β^-	0.514 e^-	94%	0.662	85%
			1.176 e^-	6%		
$^{133}_{56}$Ba	10.54 y	EC	0.045 e^-	50%	0.081	34%
			0.075 e^-	6%	0.356	62%
					Cs K x rays	121%
$^{207}_{83}$Bi	31.8 y	EC	0.481 e^-	2%	0.569	98%
			0.975 e^-	7%	1.063	75%
			1.047 e^-	2%	1.770	7%
					Pb K x rays	78%
$^{228}_{90}$Th	1.912 y	6α:	5.341 to 8.785		0.239	44%
		3β^-:	0.334 to 2.246		0.583	31%
					2.614	36%
($\rightarrow$ $^{224}_{88}$Ra $\rightarrow$ $^{220}_{86}$Rn $\rightarrow$ $^{216}_{84}$Po $\rightarrow$ $^{212}_{82}$Pb $\rightarrow$ $^{212}_{83}$Bi $\rightarrow$ $^{212}_{84}$Po)						
$^{241}_{95}$Am	432.7 y	α	5.443	13%	0.060	36%
			5.486	85%	Np L x rays	38%
$^{241}_{95}$Am/Be	432.2 y	6×10^{-5} neutrons (4–8 MeV) and 4×10^{-5} γ's (4.43 MeV) per Am decay				
$^{244}_{96}$Cm	18.11 y	α	5.763	24%	Pu L x rays	$\sim$ 9%
			5.805	76%		
$^{252}_{98}$Cf	2.645 y	α (97%)	6.076	15%		
			6.118	82%		
		Fission (3.1%)				
		$\approx$ 20 γ's/fission; 80% < 1 MeV				
		$\approx$ 4 neutrons/fission; $\langle E_n \rangle = 2.14$ MeV				

"Emission probability" is the probability per decay of a given emission; because of cascades these may total more than 100%. Only principal emissions are listed. EC means electron capture, and e^- means monoenergetic internal conversion (Auger) electron. The intensity of 0.511 MeV e^+e^- annihilation photons depends upon the number of stopped positrons. Endpoint $\beta^\pm$ energies are listed. In some cases when energies are closely spaced, the γ-ray values are approximate weighted averages. Radiation from short-lived daughter isotopes is included where relevant.

Half-lives, energies, and intensities are from E. Browne and R.B. Firestone, *Table of Radioactive Isotopes* (John Wiley & Sons, New York, 1986), recent *Nuclear Data Sheets*, and *X-ray and Gamma-ray Standards for Detector Calibration*, IAEA-TECDOC-619 (1991).

Neutron data are from *Neutron Sources for Basic Physics and Applications* (Pergamon Press, 1983).

27. PROBABILITY

Revised May 1996.

27.1. General [1–5]

Let x be a possible outcome of an observation. The probability of x is the relative frequency with which that outcome occurs out of a (possibly hypothetical) large set of similar observations. If x can take any value from a *continuous* range, we write $f(x;\theta)\,dx$ as the probability of observing x between x and $x+dx$. The function $f(x;\theta)$ is the *probability density function* (p.d.f.) for the *random variable* x, which may depend upon one or more parameters θ. If x can take on only *discrete* values (*e.g.*, the non-negative integers), then $f(x;\theta)$ is itself a probability, but we shall still call it a p.d.f. The p.d.f. is always normalized to unit area (unit sum, if discrete). Both x and θ may have multiple components and are then often written as column vectors. If θ is unknown and we wish to estimate its value from a given set of data measuring x, we may use statistics (see Sec. 28).

The *cumulative distribution function* $F(a)$ is the probability that $x \le a$:

$$F(a) = \int_{-\infty}^{a} f(x)\,dx \; . \tag{27.1}$$

Here and below, if x is discrete-valued, the integral is replaced by a sum. The endpoint a is expressly included in the integral or sum. Then $0 \le F(x) \le 1$, $F(x)$ is nondecreasing, and $\text{Prob}(a < x \le b) = F(b) - F(a)$. If x is discrete, $F(x)$ is flat except at allowed values of x, where it has discontinuous jumps equal to $f(x)$.

Any function of random variables is itself a random variable, with (in general) a different p.d.f. The *expectation value* of any function $u(x)$ is

$$E\left[u(x)\right] = \int_{-\infty}^{\infty} u(x)\,f(x)\,dx \; , \tag{27.2}$$

assuming the integral is finite. For $u(x)$ and $v(x)$ any two functions of x, $E(u+v) = E(u) + E(v)$. For c and k constants, $E(cu+k) = cE(u) + k$.

The nth moment of a distribution is

$$\alpha_n \equiv E(x^n) = \int_{-\infty}^{\infty} x^n f(x) dx \; , \tag{27.3a}$$

and the nth moment about the mean of x, α_1, is

$$m_n \equiv E[(x-\alpha_1)^n] = \int_{-\infty}^{\infty} (x-\alpha_1)^n f(x) dx \; . \tag{27.3b}$$

The most commonly used moments are the mean μ and variance σ^2:

$$\mu \equiv \alpha_1 \tag{27.4a}$$

$$\sigma^2 \equiv \text{Var}(x) \equiv m_2 = \alpha_2 - \mu^2 \; . \tag{27.4b}$$

The mean is the location of the "center of mass" of the probability density function, and the variance is a measure of the square of its width. Note that $\text{Var}(cx+k) = c^2\text{Var}(x)$.

Any odd moment about the mean is a measure of the skewness of the p.d.f. The simplest of these is the dimensionless coefficient of skewness $\gamma_1 \equiv m_3/\sigma^3$.

Besides the mean, another useful indicator of the "middle" of the probability distribution is the *median* x_{med}, defined by $F(x_{\text{med}}) = 1/2$; *i.e.*, half the probability lies above and half lies below x_{med}. For a given *sample* of events, x_{med} is the value such that half the events have larger x and half have smaller x (not counting any that have the same x as the median). If the sample median lies between two observed x values, it is set by convention halfway between them. If the p.d.f. for x has the form $f(x-\mu)$ and μ is both mean and median, then for a large number of events N, the variance of the median approaches $1/[4Nf^2(0)]$, provided $f(0) > 0$.

Let x and y be two random variables with a joint p.d.f. $f(x,y)$. The *marginal* p.d.f. of x (the distribution of x with y unobserved) is

$$f_1(x) = \int_{-\infty}^{\infty} f(x,y)\,dy \; , \tag{27.5}$$

and similarly for the marginal p.d.f. $f_2(y)$. We define the *conditional* p.d.f. of x, given fixed y, by

$$f_3(y|x)\,f_1(x) = f(x,y) \; . \tag{27.6a}$$

Similarly, the conditional p.d.f. of y, given fixed x, is

$$f_4(x|y)\,f_2(y) = f(x,y) \; . \tag{27.6b}$$

From these definitions we immediately obtain Bayes' theorem [2]:

$$f_4(x|y) = \frac{f_3(y|x)\,f_1(x)}{f_2(y)} = \frac{f_3(y|x)\,f_1(x)}{\int f_3(y|x)\,f_1(x)\,dx} \; . \tag{27.7}$$

The mean of x is

$$\mu_x = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x\,f(x,y)\,dx\,dy = \int_{-\infty}^{\infty} x\,f_1(x)\,dx \; , \tag{27.8}$$

and similarly for y. The *correlation* between x and y is a measure of the dependence of one on the other:

$$\rho_{xy} = E\left[(x-\mu_x)(y-\mu_y)\right]/\sigma_x\,\sigma_y = \text{Cov}(x,y)/\sigma_x\,\sigma_y \; , \tag{27.9}$$

where σ_x and σ_y are defined in analogy with Eq. (27.4*b*). It can be shown that $-1 \le \rho_{xy} \le 1$. Here "Cov" is the covariance of x and y, a 2-dimensional analogue of the variance.

Two random variables are *independent* if and only if

$$f(x,y) = f_1(x)\,f_2(y) \; . \tag{27.10}$$

If x and y are independent then $\rho_{xy} = 0$; the converse is not necessarily true except for Gaussian-distributed x and y. If x and y are independent, $E[u(x)\,v(y)] = E[u(x)]\,E[v(y)]$, and $\text{Var}(x+y) = \text{Var}(x)+\text{Var}(y)$; otherwise, $\text{Var}(x+y) = \text{Var}(x)+\text{Var}(y)+2\text{Cov}(x,y)$, and $E(u\,v)$ does not factor.

In a *change of continuous random variables* from $\boldsymbol{x} \equiv (x_1,\ldots,x_n)$, with p.d.f. $f(\boldsymbol{x}) = f(x_1,\ldots,x_n)$, to $\boldsymbol{y} \equiv (y_1,\ldots,y_n)$, a one-to-one function of the x_i's, the p.d.f. $g(\boldsymbol{y}) = g(y_1,\ldots,y_n)$ is found by substitution for $(x_1,\ldots,x_n)$ in f followed by multiplication by the absolute value of the Jacobian of the transformation; that is,

$$g(\boldsymbol{y}) = f\left[w_1(\boldsymbol{y}),\ldots,w_n(\boldsymbol{y})\right]|J| \; . \tag{27.11}$$

The functions w_i express the *inverse* transformation, $x_i = w_i(\boldsymbol{y})$ for $i = 1,\ldots,n$, and $|J|$ is the absolute value of the determinant of the square matrix $J_{ij} = \partial x_i/\partial y_j$. If the transformation from $\boldsymbol{x}$ to $\boldsymbol{y}$ is not one-to-one, the situation is more complex and a unique solution may not exist. For example, if the change is to $m < n$ variables, then a given y may correspond to more than one x, leading to multiple integrals over the contributions [1].

To change variables for discrete random variables simply substitute; no Jacobian is necessary because now f is a probability rather than a probability density.

If f depends upon a parameter set $\boldsymbol{\alpha}$, a change to a different parameter set $\phi_i = \phi_i(\boldsymbol{\alpha})$ is made by simple substitution; no Jacobian is used.

27.2. Characteristic functions

The characteristic function $\phi(u)$ associated with the p.d.f. $f(x)$ is essentially its (inverse) Fourier transform, or the expectation value of $\exp(iux)$:

$$\phi(u) = E(e^{iux}) = \int_{-\infty}^{\infty} e^{iux} f(x) dx \ . \tag{27.12}$$

It is often useful, and several of its properties follow [1].

It follows from Eqs. (27.3a) and (27.12) that the nth moment of the distribution $f(x)$ is given by

$$i^{-n} \frac{d^n \phi}{du^n}\bigg|_{u=0} = \int_{-\infty}^{\infty} x^n f(x) dx = \alpha_n \ . \tag{27.13}$$

Thus it is often easy to calculate all the moments of a distribution defined by $\phi(u)$, even when $f(x)$ is difficult to obtain.

If $f_1(x)$ and $f_2(y)$ have characteristic functions $\phi_1(u)$ and $\phi_2(u)$, then the characteristic function of the weighted sum $ax + by$ is $\phi_1(au)\phi_2(bu)$. The addition rules for common distributions (*e.g.*, that the sum of two numbers from Gaussian distributions also has a Gaussian distribution) easily follow from this observation.

Let the (partial) characteristic function corresponding to the conditional p.d.f. $f_2(x|z)$ be $\phi_2(u|z)$, and the p.d.f. of z be $f_1(z)$. The characteristic function after integration over the conditional value is

$$\phi(u) = \int \phi_2(u|z) \, f_1(z) dz \ . \tag{27.14}$$

Suppose we can write ϕ_2 in the form

$$\phi_2(u|z) = A(u) e^{ig(u)z} \ . \tag{27.15}$$

Then

$$\phi(u) = A(u) \phi_1(g(u)) \ . \tag{27.16}$$

The semi-invariants κ_n are defined by

$$\phi(u) = \exp\left(\sum_1^{\infty} \frac{\kappa_n}{n!} (iu)^n \right) = \exp\left(i\kappa_1 u - \tfrac{1}{2}\kappa_2 u^2 + \ldots \right) \ . \tag{27.17}$$

The κ_n's are related to the moments α_n and m_n. The first few relations are

$$\begin{aligned} \kappa_1 &= \alpha_1 \ (= \mu, \text{ the mean}) \\ \kappa_2 &= m_2 \ = \alpha_2 - \alpha_1^2 \ (= \sigma^2, \ \text{ the variance}) \\ \kappa_3 &= m_3 = \alpha_3 - 3\alpha_1\alpha_2 + 2\alpha_1^2 \ . \end{aligned} \tag{27.18}$$

27.3. Some probability distributions

Table 27.1 gives a number of common probability density functions and corresponding characteristic functions, means, and variances. Further information may be found in Refs. 1–6; Ref. 6 has particularly detailed tables. Monte Carlo techniques for generating each of them may be found in our Sec. 29.4. We comment below on all except the trivial uniform distribution.

27.3.1. ***Binomial distribution***: A random process with exactly two possible outcomes is called a *Bernoulli* process. If the probability of obtaining a certain outcome (a "success") in each trial is p, then the probability of obtaining exactly r successes ($r = 0, 1, 2, \ldots, n$) in n trials, without regard to the order of the successes and failures, is given by the binomial distribution $f(r; n, p)$ in Table 27.1. If r successes are observed in n_r trials with probability p of a success, and if s successes are observed in n_s similar trials, then $t = r + s$ is also binomial with $n_t = n_r + n_s$.

27.3.2. ***Poisson distribution***: The Poisson distribution $f(r; \mu)$ gives the probability of finding exactly r events in a given interval of x (*e.g.*, space and time) when the events occur independently of one another and of x at an average rate of μ per the given interval. The variance σ^2 equals μ. It is the limiting case $p \to 0$, $n \to \infty$, $np = \mu$ of the binomial distribution. The Poisson distribution approaches the Gaussian distribution for large μ.

Two or more Poisson processes (*e.g.*, *signal* + *background*, with parameters μ_s and μ_b) that independently contribute amounts n_s and n_b to a given measurement will produce an observed number $n = n_s + n_b$, which is distributed according to a new Poisson distribution with parameter $\mu = \mu_s + \mu_b$.

27.3.3. ***Normal or Gaussian distribution***: The normal (or Gaussian) probability density function $f(x; \mu, \sigma^2)$ given in Table 27.1 has mean $\overline{x} = \mu$ and variance σ^2. Comparison of the characteristic function $\phi(u)$ given in Table 27.1 with Eq. (27.17) shows that all semi-invariants κ_n beyond κ_2 vanish; this is a unique property of the Gaussian distribution. Some properties of the distribution are:

- rms deviation $= \sigma$
- probability x in the range $\mu \pm \sigma = 0.6827$
- probability x in the range $\mu \pm 0.6745\sigma = 0.5$
- expection value of $|x - \mu|$, $E(|x - \mu|) = (2/\pi)^{1/2}\sigma = 0.7979\sigma$
- half-width at half maximum $= (2 \ln 2)^{1/2}\sigma = 1.177\sigma$

The cumulative distribution, Eq. (27.1), for a Gaussian with $\mu = 0$ and $\sigma^2 = 1$ is related to the error function $\text{erf}(y)$ by

$$F(x; 0, 1) = \tfrac{1}{2}\left[1 + \text{erf}(x/\sqrt{2})\right] \ . \tag{27.19}$$

The error function is tabulated in Ref. 6 and is available in computer math libraries and personel computer spreadsheets. For a mean μ and variance σ^2, replace x by $(x - \mu)/\sigma$. The probability of x in a given range can be calculated with Eq. (28.34).

For x and y independent and normally distributed, $z = ax + by$ obeys $f(z; a\mu_x + b\mu_y, a^2\sigma_x^2 + b^2\sigma_y^2)$; that is, the weighted means and variances add.

The Gaussian gets its importance in large part from the *central limit theorem*: If a continuous random variable x is distributed according to *any* p.d.f. with finite mean and variance, then the sample mean, $\overline{x}_n$, of n observations of x will have a p.d.f. that approaches a Gaussian as n increases. Therefore the end result $\sum^n x_i \equiv n\overline{x}_n$ of a large number of small fluctuations x_i will be distributed as a Gaussian, even if the x_i themselves are not.

For a set of n Gaussian random variables $\boldsymbol{x}$ with means $\boldsymbol{\mu}$ and corresponding Fourier variables $\boldsymbol{u}$, the characteristic function for a one-dimensional Gaussian is generalized to

$$\phi(\boldsymbol{x}; \boldsymbol{\mu}, S) = \exp\left[i\boldsymbol{\mu} \cdot \boldsymbol{u} - \tfrac{1}{2}\boldsymbol{u}^T S \boldsymbol{u}\right] \ . \tag{27.20}$$

From Eq. (27.13), the covariance about the mean is

$$E\left[(x_j - \mu_j)(x_k - \mu_k)\right] = S_{jk} \ . \tag{27.21}$$

If the $\boldsymbol{x}$ are independent, then $S_{jk} = \delta_{jk}\sigma_j^2$, and Eq. (27.20) is the product of the c.f.'s of n Gaussians.

The covariance matrix S can be related to the correlation matrix defined by Eq. (27.9) (a sort of normalized covariance matrix). With the definition $\sigma_k^2 \equiv S_{kk}$, we have $\rho_{jk} = S_{jk}/\sigma_j\sigma_k$.

The characteristic function may be inverted to find the corresponding p.d.f.

$$f(\boldsymbol{x}; \boldsymbol{\mu}, S) = \frac{1}{(2\pi)^{n/2}\sqrt{|S|}} \ \exp\left[-\tfrac{1}{2}(\boldsymbol{x} - \boldsymbol{\mu})^T S^{-1} (\boldsymbol{x} - \boldsymbol{\mu})\right] \ , \tag{27.22}$$

where the determinant $|S|$ must be greater than 0. For diagonal S (independent variables), $f(\boldsymbol{x}; \boldsymbol{\mu}, S)$ is the product of the p.d.f.'s of n Gaussian distributions.

Table 27.1: Some common probability density functions, with corresponding characteristic functions and means and variances. In the Table, $\Gamma(k)$ is the gamma function, equal to $(k-1)!$ when k is an integer.

Distribution	Probability density function f (variable; parameters)	Characteristic function $\phi(u)$	Mean	Variance σ^2
Uniform	$f(x;a,b) = \begin{cases} 1/(b-a) & a \le x \le b \\ 0 & \text{otherwise} \end{cases}$	$\dfrac{e^{ibu}-e^{iau}}{(b-a)iu}$	$\overline{x} = \dfrac{a+b}{2}$	$\dfrac{(b-a)^2}{12}$
Binomial	$f(r;n,p) = \dfrac{n!}{r!(n-r)!}\, p^r q^{n-r}$ $r = 0,1,2,\ldots,n\ ;\quad 0 \le p \le 1\ ;\quad q = 1-p$	$(q+pe^{iu})^n$	$\overline{r} = np$	npq
Poisson	$f(r;\mu) = \dfrac{\mu^r e^{-\mu}}{r!}\ ;\quad r = 0,1,2,\ldots\ ;\quad \mu > 0$	$\exp[\mu(e^{iu}-1)]$	$\overline{r} = \mu$	μ
Normal (Gaussian)	$f(x;\mu,\sigma^2) = \dfrac{1}{\sigma\sqrt{2\pi}}\exp(-(x-\mu)^2/2\sigma^2)$ $-\infty < x < \infty\ ;\quad -\infty < \mu < \infty\ ;\quad \sigma > 0$	$\exp(i\mu u - \frac{1}{2}\sigma^2 u^2)$	$\overline{x} = \mu$	σ^2
Multivariate Gaussian	$f(\boldsymbol{x};\boldsymbol{\mu},S) = \dfrac{1}{(2\pi)^{n/2}\sqrt{\lvert S \rvert}}$ $\times \exp\left[-\frac{1}{2}(\boldsymbol{x}-\boldsymbol{\mu})^T S^{-1}(\boldsymbol{x}-\boldsymbol{\mu})\right]$ $-\infty < x_j < \infty;\quad -\infty < x_j < \infty;\quad \det S > 0$	$\exp\left[i\boldsymbol{\mu}\cdot\boldsymbol{u} - \frac{1}{2}\boldsymbol{u}^T S \boldsymbol{u}\right]$	$\boldsymbol{\mu}$	S_{jk}
χ^2	$f(z;n) = \dfrac{z^{n/2-1}e^{-z/2}}{2^{n/2}\Gamma(n/2)}\ ;\quad z \ge 0$	$(1-2iu)^{-n/2}$	$\overline{z} = n$	$2n$
Student's t	$f(t;n) = \dfrac{1}{\sqrt{n\pi}}\dfrac{\Gamma[(n+1)/2]}{\Gamma(n/2)}\left(1+\dfrac{t^2}{n}\right)^{-(n+1)/2}$ $-\infty < t < \infty\ ;\quad n$ not required to be integer	—	$\overline{t} = 0$ for $n \ge 2$	$n/(n-2)$ for $n \ge 3$
Gamma	$f(x;\lambda,k) = \dfrac{x^{k-1}\lambda^k e^{-\lambda x}}{\Gamma(k)}\ ;\quad 0 < x < \infty\ ;$ k not required to be integer	$(1-iu/\lambda)^{-k}$	$\overline{x} = k/\lambda$	k/λ^2

For $n = 2$, $f(\boldsymbol{x};\boldsymbol{\mu},S)$ is

$$f(x_1,x_2;\ \mu_1,\mu_2,\sigma_1,\sigma_2,\rho) = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}}$$
$$\times\ \exp\left\{\frac{-1}{2(1-\rho^2)}\left[\frac{(x_1-\mu_1)^2}{\sigma_1^2} - \frac{2\rho(x_1-\mu_1)(x_2-\mu_2)}{\sigma_1\sigma_2} + \frac{(x_2-\mu_2)^2}{\sigma_2^2}\right]\right\}\ . \tag{27.23}$$

The marginal distribution of any x_i is a Gaussian with mean μ_i and variance S_{ii}. S is $n \times n$, symmetric, and positive definite. Therefore for any vector $\boldsymbol{X}$, the quadratic form $\boldsymbol{X}^T S^{-1} \boldsymbol{X} = C$, where C is any positive number, traces an n-dimensional ellipsoid as $\boldsymbol{X}$ varies. If $X_i = (x_i - \mu_i)/\sigma_i$, then C is a random variable obeying the $\chi^2(n)$ distribution, discussed in the following section. The probability that $\boldsymbol{X}$ corresponding to a set of Gaussian random variables $\boldsymbol{x}_i$ lies *outside* the ellipsoid characterized by a given value of C ($= \chi^2$) is given by Eq. (27.24) and may be read from Fig. 27.1. For example, the "s-standard-deviation ellipsoid" occurs at $C = s^2$. For the two-variable case ($n = 2$), the point $\boldsymbol{X}$ lies outside the one-standard-deviation ellipsoid with 61% probability. (This assumes that μ_i and σ_i are correct.) For $X_i = x_i/\sigma_i$, the ellipsoids of constant χ^2 have the same size and orientation but are centered at $\boldsymbol{\mu}$. The use of these ellipsoids as indicators of probable error is described in Sec. 28.6.1.

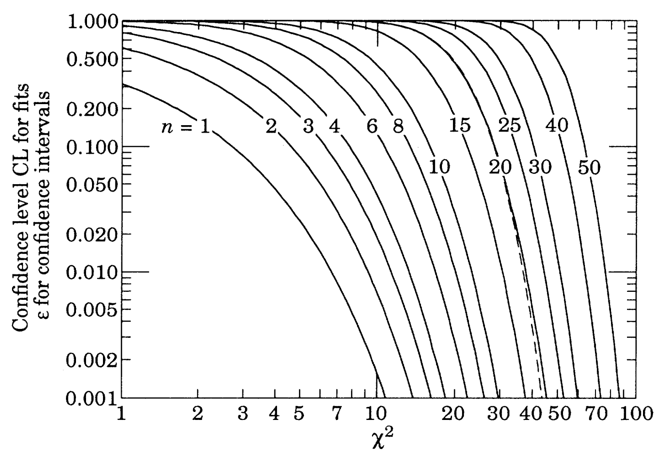

Figure 27.1: The confidence level versus χ^2 for n degrees of freedom, as defined in Eq. (27.24). The curve for a given n gives the probability that a value at least as large as χ^2 will be obtained in an experiment; *e.g.*, for $n = 10$, a value $\chi^2 \gtrsim 18$ will occur in 5% of a large number of experiments. For a fit, the CL is a measure of goodness-of-fit, in that a good fit to a correct model is expected to yield a low χ^2 (see Sec. 28.5.0). For a confidence interval, α measures the probability that the interval *does not* cover the true value of the quantity being estimated (see Sec. 28.6). The dashed curve for $n = 20$ is calculated using the approximation of Eq. (27.25).

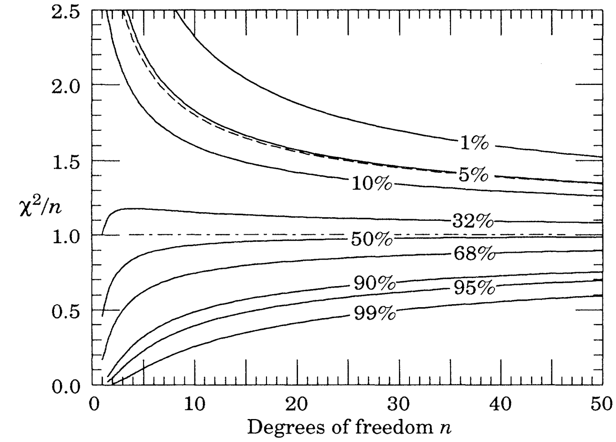

Figure 27.3: Confidence levels as a function of the "reduced χ^2" $\equiv \chi^2/n$ and the number of degrees of freedom n. Curves are labeled by the probability that a measurement will give a value of χ^2/n greater than that given on the y axis; *e.g.*, for $n = 10$, a value $\chi^2/n \gtrsim 1.8$ can be expected 5% of the time.

27.3.4. χ^2 *distribution*: If $x_1, \ldots, x_n$ are independent Gaussian distributed random variables, the sum $z = \sum^n (x_i - \mu_i)^2/\sigma_i^2$ is distributed as a χ^2 with n *degrees of freedom*, $\chi^2(n)$. Under a linear transformation to n dependent Gaussian variables x'_i, the χ^2 at each transformed point retains its value; then $z = \boldsymbol{X}'^T\, V^{-1} \boldsymbol{X}'$ as in the previous section. For a set of z_i, each of which is $\chi^2(n_i)$, $\sum z_i$ is a new random variable which is $\chi^2\,(\sum n_i)$.

Fig. 27.1 shows the confidence level (CL) obtained by integrating the tail of $f(z; n)$:

$$\mathrm{CL}(\chi^2) = \int_{\chi^2}^{\infty} f(z;\, n)\, dz\ . \tag{27.24}$$

This is shown for a special case in Fig. 27.2, and is equal to 1.0 minus the cumulative distribution function $F(z = \chi^2;\, n)$. It is useful in evaluating the consistency of data with a model (see Sec. 28): The CL is the probability that a random repeat of the given experiment would observe a greater χ^2, assuming the model is correct. It is also useful for confidence intervals for statistical estimators (see Sec. 28.6), in which case one is interested in the unshaded area of Fig. 27.2.

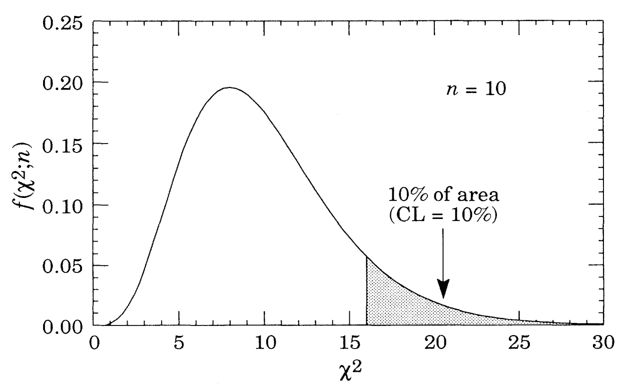

Figure 27.2: Illustration of the confidence level integral given in Eq. (27.24). This particular example is for $n = 10$, where the area above 15.99 is 0.1.

Since the mean of the χ^2 distribution is equal to n, one expects in a "reasonable" experiment to obtain $\chi^2 \approx n$. While caution is necessary because of the width and skewness of the distribution, the "reduced χ^2" $\equiv \chi^2/n$ is a sometimes useful quantity. Figure 27.3 shows χ^2/n for useful CL's as a function of n.

For large n, the CL is approximately given by [1,7]

$$\mathrm{CL}(\chi^2) \approx \frac{1}{\sqrt{2\pi}} \int_y^{\infty} e^{-x^2/2}\, dx\ , \tag{27.25}$$

where $y = \sqrt{2\chi^2} - \sqrt{2n-1}$. This approximation was used to draw the dashed curves in Fig. 27.1 (for $n = 20$) and Fig. 27.3 (for CL = 5%). Since all the functions and their inverses are now readily available in standard mathematical libraries (such as IMSL, used to generate these figures, and personal computer spreadsheets, such as Microsoft® Excel [8]), the approximation (and even figures and tables) are seldom needed.

27.3.5. *Student's t distribution*: Suppose that x and $x_1, \ldots, x_n$ are independent and Gaussian distributed with mean 0 and variance 1. We then define

$$z = \sum_1^n x_i^2\ , \quad \text{and} \quad t = \frac{x}{\sqrt{z/n}}\ . \tag{27.26}$$

The variable z thus belongs to a $\chi^2(n)$ distribution. Then t is distributed according to a Student's t distribution with n degrees of freedom, $f(t; n)$, given in Table 27.1.

The Student's t distribution resembles a Gaussian distribution with wide tails. As $n \to \infty$, the distribution approaches a Gaussian. If $n = 1$, the distribution is a *Cauchy* or *Breit-Wigner* distribution. The mean is finite only for $n > 1$ and the variance is finite only for $n > 2$, so for $n = 1$ or $n = 2$, t does not obey the central limit theorem.

As an example, consider the *sample mean* $\overline{x} = \sum x_i/n$ and the *sample variance* $s^2 = \sum (x_i - \overline{x})^2/(n-1)$ for normally distributed random variables x_i with unknown mean μ and variance σ^2. The sample mean has a Gaussian distribution with a variance σ^2/n, so the variable $(\overline{x} - \mu)/\sqrt{\sigma^2/n}$ is normal with mean 0 and variance 1. Similarly, $(n-1)\, s^2/\sigma^2$ is independent of this and is χ^2 distributed with $n - 1$ degrees of freedom. The ratio

$$t = \frac{(\overline{x} - \mu)/\sqrt{\sigma^2/n}}{\sqrt{(n-1)\, s^2/\sigma^2\,(n-1)}} = \frac{\overline{x} - \mu}{\sqrt{s^2/n}} \tag{27.27}$$

is distributed as $f(t;\, n-1)$. The unknown true variance σ^2 cancels, and t can be used to test the probability that the true mean is some particular value μ.

In Table 27.1, n in $f(t; n)$ is not required to be an integer. A Student's t distribution with nonintegral $n > 0$ is useful in certain applications.

27.3.6. *Gamma distribution*: For a process that generates events as a function of x (*e.g.*, space or time) according to a Poisson distribution, the distance in x from an arbitrary starting point (which may be some particular event) to the k^{th} event belongs to a *gamma* distribution, $f(x;\, \lambda,\, k)$. The Poisson parameter μ is λ per unit x. The special case $k = 1$ (*i.e.*, $f(x; \lambda, 1) = \lambda e^{-\lambda x}$) is called the *exponential* distribution. A sum of k' exponential random variables x_i is distributed as $f(\sum x_i;\, \lambda, k')$.

The parameter k is not required to be an integer. For $\lambda = 1/2$ and $k = n/2$, the gamma distribution reduces to the $\chi^2(n)$ distribution.

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8. Microsoft® is a registered trademark of Microsoft corporation.

28. STATISTICS

Revised May 1996.

28.1. General [1–6]

A probability density function with known parameters enables us to predict the frequency with which a random variable will take on a particular value (if discrete) or lie in a given range (if continuous). In *parametric* statistics we have the opposite problem of estimating the parameters of the p.d.f. from a set of actual observations.

We refer to the true p.d.f. as the *population*; the data form a *sample* from this population. A *statistic* is any function of the data, plus known constants, which does not depend upon any of the unknown parameters. A statistic is a random variable if the data have random errors. An *estimator* is any statistic whose value is intended as a meaningful guess for the value of an unknown parameter; we denote estimators with hats, *e.g.*, $\widehat{\alpha}$.

Often it is possible to construct more than one reasonable estimator. Let α represent the true value of a parameter to be estimated; α is a vector $\boldsymbol{\alpha}$ if there is more than one parameter. Then if $\widehat{\alpha}$ is an estimator for α, desirable properties for $\widehat{\alpha}$ are: (a) *Unbiased*; bias $b = E(\widehat{\alpha}) - \alpha$, where the expectation value is taken over a hypothetical set of similar experiments in which $\widehat{\alpha}$ is constructed the same way. The bias may be due to statistical properties of the estimator or to *systematic* errors in the experiment. If we can estimate the average bias b we usually subtract it from $\widehat{\alpha}$ to obtain a new $\widehat{\alpha}' \equiv \widehat{\alpha} - b$. However, b may depend upon α or other unknowns, in which case we usually try to choose an estimator which minimizes its average size. (b) *Minimum variance*; the minimum possible value of $\mathrm{Var}(\widehat{\alpha})$ is given by the Rao-Cramér-Frechet bound:

$$\mathrm{Var}_{\min} = \left[1 + \partial b/\partial\alpha\right]^2 / I(\alpha) \; ; \tag{28.1}$$

$$I(\alpha) = E\left\{\left[\frac{\partial}{\partial\alpha}\sum_{i=1}^{n} \ln f(x_i;\, \alpha)\right]^2\right\} .$$

(Compare with Eq. (28.6) below.) The sum is over all data and b is the bias, if any; the x_i are assumed independent and distributed as $f(x_i;\alpha)$, and the allowed range of x must not depend upon α. The ratio $\epsilon = \mathrm{Var}_{\min}/\mathrm{Var}(\widehat{\alpha})$ is the *efficiency*. An *efficient* estimator (with $\epsilon = 1$) exists only for certain cases. The square root of the variance expresses the expected spread of $\widehat{\alpha}$ about its average value, as would be observed in a large number of repeats of the same measurement. (c) *Minimum mean-squared error* (mse); $\mathrm{mse} = E[(\widehat{\alpha} - \alpha)^2] = V(\widehat{\alpha}) + b^2$. The mse combines the error due to any bias quadratically with the variance, which expresses only the spread about $E(\widehat{\alpha})$, as distinct from α, the true value. (d) *Robust*; a robust estimator is not sensitive to errors in our assumptions, *e.g.*, to departures from the assumed p.d.f. due to such factors as noise.

These criteria (and others) allow us to evaluate any procedure for obtaining $\widehat{\alpha}$. In many cases these criteria conflict. The bias, variance, and mse may depend on the unknown α. In this case the optimum prescription for $\widehat{\alpha}$ may depend on the range in which we assume α to lie.

Following are techniques in common use for obtaining estimators and their standard errors $\sigma(\widehat{\alpha}) = \sqrt{\mathrm{Var}(\widehat{\alpha})}$. When the conditions of the central limit theorem are satisfied, the interval $\widehat{\alpha} \pm \sigma(\widehat{\alpha})$ forms a 68.3% *confidence interval.* This is a random interval in that its endpoints depend upon the randomly sampled data; its meaning here will be taken to be that in 68.3% of all similar experiments the interval will include the true value α. One should be aware that in most practical cases the central limit theorem is only approximately satisfied and accordingly confidence intervals which depend on that are only approximate. Confidence intervals are discussed in Section 28.6 below.

28.2. Data with a common mean

Suppose we have a set of N independent measurements y_i assumed to be unbiased measurements of the same unknown quantity μ with a common, but unknown, variance σ^2 resulting from measurement error. Then

$$\widehat{\mu} = \frac{1}{N}\sum_{i=1}^{N} y_i = E(y) \tag{28.2}$$

$$\widehat{\sigma}^2 = \frac{1}{N-1}\sum_{i=1}^{N}(y_i - \widehat{\mu})^2 = \frac{N}{N-1}\left(E(y^2) - \widehat{\mu}^2\right) \tag{28.3}$$

are unbiased estimators of μ and σ^2. The variance of $\widehat{\mu}$ is σ^2/N. If the common p.d.f. of the y_i is Gaussian, these statistics are independent. Then, for large N, the standard deviation of $\widehat{\sigma}$ (the "error of the error") is $\sigma/\sqrt{2N}$. If the y_i are Gaussian or N is large enough that the central limit theorem applies, then $\widehat{\mu}$ is an efficient estimator for μ. Otherwise $\widehat{\mu}$ is sometimes subject to large fluctuations, *e.g.*, if the p.d.f. for y_i has long tails. In this case the median of the y_i may be a more robust estimator for μ, provided the median and mean are expected to lie at the same point in the p.d.f. for y. For Gaussian y, the median has asymptotic (large-N) efficiency $2/\pi \approx 0.64$. Student's t-distribution provides an example in which there are large tails. In this case, for large N the efficiency of the sample median relative to the sample mean is (∞, ∞, 1.62, 1.12, 0.96, 0.80, 0.64) for (1, 2, 3, 4, 5, 8, ∞) degrees of freedom.

If σ^2 is known, $\widehat{\mu}$ as given in Eq. (28.2) is still the best estimator for μ; if μ is known, substitute it for $\widehat{\mu}$ in Eq. (28.3) and replace $N-1$ by N, to obtain a somewhat better estimator $\widehat{\sigma}^2$.

If the y_i have different, known, variances σ_i^2, then

$$\widehat{\mu} = \frac{1}{w}\sum w_i\, y_i \; , \tag{28.4}$$

is an unbiased estimator for μ with smaller variance than Eq. (28.2), where $w_i = 1/\sigma_i^2$ and $w = \sum w_i$. The standard deviation of $\widehat{\mu}$ is $1/\sqrt{w}$.

28.3. The method of maximum likelihood

28.3.1. *General*:

"From a theoretical point of view, the most important general method of estimation so far known is the *method of maximum likelihood*" [1]. We suppose that a set of independently measured quantities x_i came from a p.d.f. $f(x;\boldsymbol{\alpha})$, where $\boldsymbol{\alpha}$ is an unknown set of parameters. The method of maximum likelihood consist of finding the set of values, $\widehat{\boldsymbol{\alpha}}$, which maximizes the joint probability density for all the data, given by

$$\mathscr{L}(\boldsymbol{\alpha}) = \prod_i f(x_i;\boldsymbol{\alpha}) \; , \tag{28.5}$$

where $\mathscr{L}$ is called the likelihood. It is usually easier to work with $\ln\mathscr{L}$, and since both are maximized for the same set of $\boldsymbol{\alpha}$, it is sufficient to solve the *likelihood equation*

$$\frac{\partial \ln\mathscr{L}}{\partial\alpha_n} = 0 \; . \tag{28.6}$$

The solution is called the *maximum likelihood estimate* of $\boldsymbol{\alpha}$. The importance of the approach is shown by the following proposition, proved in Ref. 1:

If an efficient estimate $\widehat{\boldsymbol{\alpha}}$ of $\boldsymbol{\alpha}$ exists, the likelihood equation will have a unique solution equal to $\widehat{\boldsymbol{\alpha}}$.

In evaluating $\mathscr{L}$, it is important that any normalization factors in the f's which involve $\boldsymbol{\alpha}$ be included. However, we will only be interested in the maximum of $\mathscr{L}$ and in ratios of $\mathscr{L}$ at different $\boldsymbol{\alpha}$'s;

hence any multiplicative factors which do not involve the parameters we want to estimate may be dropped; this includes factors which depend on the data but not on $\boldsymbol{\alpha}$.

If the solution to Eq. (28.6) is at a maximum, $\partial \ln \mathscr{L}/\partial\alpha_n$ will have negative slope in its vicinity. In many practical problems, one often uses nonlinear algorithms for finding the maximum, and must be alert to various possibilities for error: (a) Eq. (28.6) may yield a minimum, therefore one must check the second derivative; (b) there may be more than one maximum—one must try to find the global maximum; (c) the global maximum may lie at a boundary of the physical region, in which case Eq. (28.6) will not find it.

If an unbiased, efficient estimator exists, this method will find it. If $\partial \ln \mathscr{L}/\partial\alpha_n$ is linear in the vicinity of the root, an efficient estimator is guaranteed; other efficient cases are discussed in the literature. For large data samples, the central limit theorem will usually assure this condition in some significant neighborhood of zero; hence the estimator is usually efficient in that case, provided certain conditions are met (*e.g.*, that the solution does not lie on a boundary). In this case, in the neighborhood of the maximum $\ln\mathscr{L}$ is a downward-curving paraboloid and $\mathscr{L}$ is proportional to a multivariate Gaussian.

The results of two or more experiments may be combined by forming the product of the $\mathscr{L}$'s, or the sum of the $\ln\mathscr{L}$'s.

Under a one-to-one change of parameters from $\boldsymbol{\alpha}$ to $\boldsymbol{\beta} = \boldsymbol{\beta}(\boldsymbol{\alpha})$, the maximum likelihood estimate is simply $\boldsymbol{\beta}(\widehat{\boldsymbol{\alpha}})$, given the solution $\widehat{\boldsymbol{\alpha}}$ for $\boldsymbol{\alpha}$. That is, the maximum likelihood solution for $\boldsymbol{\beta}$ is found by simple substitution of $\widehat{\boldsymbol{\alpha}}$ into the transformation equation. It is possible that the new solution $\widehat{\boldsymbol{\beta}}$ will be a biased solution for the true value of $\boldsymbol{\beta}$ even if $\widehat{\boldsymbol{\alpha}}$ is not biased, and vice-versa. In the asymptotic limit (of large amounts of data) both $\widehat{\boldsymbol{\alpha}}$ and $\widehat{\boldsymbol{\beta}}$ will (usually) converge to unbiased solutions, but at different rates.

Except in special cases like the least-squares method, the value of the likelihood function at the solution does not necessarily tell us whether the final fit was a sensible description of the data or not. In special cases such as the one discussed in Sec. 28.3.3, one can define a quantity which approaches the χ^2-distribution in the limit of a large number of counts in the experiment, but in general some other strategy must be used. For example, data generated by Monte Carlo simulations of the experiment can be analyzed by the same method. If the experimental likelihood is lower than that of some agreed-upon fraction of these results, one should question the appropriateness of the p.d.f. At the same time one can check for bias in the solution.

28.3.2. *Error estimates*:

The covariance matrix V may be estimated from

$$V_{nm} = \left(E\left[-\frac{\partial^2 \ln\mathscr{L}}{\partial\alpha_n\,\partial\alpha_m}\bigg|_{\widehat{\alpha}} \right] \right)^{-1} . \tag{28.7}$$

If $\partial \ln\mathscr{L}/\partial\alpha_n$ is linear, the "expectation" operation in Eq. (28.7) has no effect because the second derivative of $\ln\mathscr{L}$ is constant. Otherwise, it may be approximated by taking the average of the quantity in square brackets over a range of α_n and α_m near the solution. For complex cases it may be more practical to evaluate s-standard-deviation errors from the contour

$$\ln\mathscr{L}(\boldsymbol{\alpha}) = \ln\mathscr{L}_{\rm max} - s^2/2 \ , \tag{28.8}$$

where $\ln\mathscr{L}_{\rm max}$ is the value of $\ln\mathscr{L}$ at the solution point (compare with Eq. (28.32), below). The extreme limits of this contour parallel to the α_n axis give an approximate s-standard-deviation confidence interval in α_n. These intervals may not be symmetric and they may even consist of two or more disjoint intervals. This procedure gives one-standard-deviation errors in α_n equal to $\sqrt{V_{nn}}$ (not summed) of Eq. (28.7) if the estimator is efficient. If it is not efficient, the level of confidence implied by the value of s is only approximate.

28.3.3. *Application to Poisson-distributed data*:

In the case of Poisson-distributed data in a counting experiment, the unbinned maximum likelihood method (where the index i in Eq. (28.5) labels events) is preferred if the total number of events is very small. If there are enough events to justify binning them in a histogram, then one may alternatively maximize the likelihood function for the contents of the bins (so i labels bins). This is equivalent to minimizing [7]

$$\chi^2 = \sum_i \left[2(N_i^{\rm th} - N_i^{\rm obs}) + 2N_i^{\rm obs}\ln(N_i^{\rm obs}/N_i^{\rm th}) \right] . \tag{28.9}$$

where $N_i^{\rm obs}$ and $N_i^{\rm th}$ are the observed and theoretical (from f) contents of the ith bin. In bins where $N_i^{\rm obs} = 0$, the second term is zero. This function asymptotically behaves like a classical χ^2 for purposes of point estimation, interval estimation, *and goodness-of-fit*. It also guarantees that the area under the fitted function f is equal to the sum of the histogram contents (as long as the overall normalization of f is effectively left unconstrained during the fit), which is not the case for χ^2 statistics based on a least-squares procedure with traditional weights.

28.4. Propagation of errors

Suppose that $F(x;\boldsymbol{\alpha})$ is some function of variable(s) x and the fitted parameters $\boldsymbol{\alpha}$, with a value $\widehat{F}$ at $\widehat{\boldsymbol{\alpha}}$. The variance matrix of the parameters is V_{mn}. To first order in $\alpha_m - \widehat{\alpha}_m$, F is given by

$$F = \widehat{F} + \sum_m \frac{\partial F}{\partial\alpha_m}(\alpha_m - \widehat{\alpha}_m) \ , \tag{28.10}$$

and the variance of F about its estimator is given by

$$(\Delta F)^2 = E[(F-\widehat{F})^2] = \sum_{mn} \frac{\partial F}{\partial\alpha_m}\frac{\partial F}{\partial\alpha_n} V_{mn} \ , \tag{28.11}$$

evaluated at the x of interest. For different functions F_j and F_k, the covariance is

$$E[(F_j - \widehat{F}_j)(F_k - \widehat{F}_k)] = \sum_{mn} \frac{\partial F_j}{\partial\alpha_m}\frac{\partial F_k}{\partial\alpha_n} V_{mn} \ . \tag{28.12}$$

If the first-order approximation is in serious error, the above results may be very approximate. $\widehat{F}$ may be a biased estimator of F even if the $\widehat{\boldsymbol{\alpha}}$ are unbiased estimators of $\boldsymbol{\alpha}$. Inclusion of higher-order terms or direct evaluation of F in the vicinity of $\widehat{\boldsymbol{\alpha}}$ will help to reduce the bias.

28.5. Method of least squares

The *method of least squares* can be derived from the maximum likelihood theorem. We suppose a set of N measurements at points x_i. The ith measurement y_i is assumed to be chosen from a Gaussian distribution with mean $F(x_i;\boldsymbol{\alpha})$ and variance σ_i^2. Then

$$\chi^2 = -2\ln\mathscr{L} + \text{constant} = \sum_1^N \frac{[y_i - F(x_i;\boldsymbol{\alpha})]^2}{\sigma_i^2} \ . \tag{28.13}$$

Finding the set of parameters $\boldsymbol{\alpha}$ which maximizes $\mathscr{L}$ is the same as finding the set which minimizes χ^2.

In many practical cases one further restricts the problem to the situation in which $F(x_i;\boldsymbol{\alpha})$ is a linear function of the α_m's,

$$F(x_i;\boldsymbol{\alpha}) = \sum_n \alpha_n f_n(x) \ , \tag{28.14}$$

where the f_n are k linearly independent functions (*e.g.*, 1, x, x^2, ..., or Legendre polynomials) which are single-valued over the allowed range of x. We require $k \le N$, and at least k of the x_i must be distinct. We wish to estimate the linear coefficients α_n. Later we will discuss the nonlinear case.

If the point errors $\epsilon_i = y_i - F(x_i;\boldsymbol{\alpha})$ are Gaussian, then the minimum χ^2 will be distributed as a χ^2 random variable with

$n = N - k$ degrees of freedom. We can then evaluate the goodness-of-fit (confidence level) from Figs. 27.1 or 27.3, as per the earlier discussion. The confidence level expresses the probability that a *worse* fit would be obtained in a large number of similar experiments under the assumptions that: (a) the model $y = \sum \alpha_n f_n$ is correct and (b) the errors ϵ_i are Gaussian and unbiased with variance σ_i^2. If this probability is larger than an agreed-upon value (0.001, 0.01, or 0.05 are common choices), the data are *consistent* with the assumptions; otherwise we may want to find improved assumptions. As for the converse, most people do not regard a model as being truly *inconsistent* unless the probability is as low as that corresponding to four or five standard deviations for a Gaussian (6×10^{-3} or 6×10^{-5}; see Sec. 28.6.1). If the ϵ_i are not Gaussian, the method of least squares still gives an answer, but the goodness-of-fit test would have to be done using the correct distribution of the random variable which is still called "χ^2."

Finding the minimum of χ^2 in the linear case is straightforward:

$$-\frac{1}{2}\frac{\partial\chi^2}{\partial\alpha_m} = \sum_i f_m(x_i)\left(\frac{y_i - \sum_n \alpha_n f_n(x_i)}{\sigma_i^2}\right)$$

$$= \sum_i \frac{y_i\, f_m(x_i)}{\sigma_i^2} - \sum_n \alpha_n \sum_i \frac{f_n(x_i)\, f_m(x_i)}{\sigma_i^2} . \qquad (28.15)$$

With the definitions

$$g_m = \sum_i y_i\, f_m(x_i)/\sigma_i^2 \qquad (28.16)$$

and

$$V_{mn}^{-1} = \sum_i f_n(x_i)\, f_m(x_i)/\sigma_i^2 , \qquad (28.17)$$

the k-element column vector of solutions $\widehat{\boldsymbol{\alpha}}$, for which $\partial\chi^2/\partial\alpha_m = 0$ for all m, is given by

$$\widehat{\boldsymbol{\alpha}} = V\,\boldsymbol{g} . \qquad (28.18)$$

With this notation, χ^2 for the special case of a linear fitting function (Eq. (28.14)) can be rewritten in the compact form

$$\chi^2 = \chi^2_{\rm min} + (\boldsymbol{\alpha} - \widehat{\boldsymbol{\alpha}})^T V^{-1} (\boldsymbol{\alpha} - \widehat{\boldsymbol{\alpha}}) . \qquad (28.19)$$

Nonindependent y_i's

Eq. (28.13) is based on the assumption that the likelihood function is the product of independent Gaussian distributions. More generally, the measured y_i's are not independent, and we must consider them as coming from a multivariate distribution with nondiagonal covariance matrix S, as described in Sec. 27.3.3. The generalization of Eq. (28.13) is

$$\chi^2 = \sum_{jk} [y_j - F(x_j;\boldsymbol{\alpha})] S_{jk}^{-1} [y_k - F(x_k;\boldsymbol{\alpha})] . \qquad (28.20)$$

In the case of a fitting function that is linear in the parameters, one may differentiate χ^2 to find the generalization of Eq. (28.15), and with the extended definitions

$$g_m = \sum_{jk} y_j\, f_m(x_k) S_{jk}^{-1}$$

$$V_{mn}^{-1} = \sum_{jk} f_n(x_j)\, f_m(x_k) S_{jk}^{-1} \qquad (28.21)$$

solve Eq. (28.18) for the estimators $\widehat{\boldsymbol{\alpha}}$.

The problem of constructing the covariance matrix S is simplified by the fact that contributions to S (not to its inverse) are additive. For example, suppose that we have three variables, all of which have independent statistical errors. The first two also have a common error resulting in a positive correlation, perhaps because a common baseline with its own statistical error (variance s^2) was subtracted from each. In addition, the second two have a common error (variance a^2), but this time the values are anticorrelated. This might happen, for example, if the sum of the two variables is a constant. Then

$$S = \begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{pmatrix} + \begin{pmatrix} s^2 & s^2 & 0 \\ s^2 & s^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & a^2 & -a^2 \\ 0 & -a^2 & a^2 \end{pmatrix} . \qquad (28.22)$$

If unequal amounts of the common baseline were subtracted from variables 1, 2, and 3—*e.g.*, fractions f_1, f_2, and f_3, then we would have

$$S = \begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{pmatrix} + \begin{pmatrix} f_1^2 s^2 & f_1 f_2 s^2 & f_1 f_3 s^2 \\ f_1 f_2 s^2 & f_2^2 s^2 & f_2 f_3 s^2 \\ f_1 f_3 s^2 & f_2 f_3 s^2 & f_3^2 s^2 \end{pmatrix} . \qquad (28.23)$$

While in general this "two-vector" representation is not possible, it underscores the procedure: Add zero-determinant correlation matrices to the matrix expressing the independent variation.

Care must be taken when fitting to correlated data, since off-diagonal contributions to χ^2 are not necessarily positive. It is even possible for all of the residuals to have the same sign.

Example: straight-line fit

For the case of a straight-line fit, $y(x) = \alpha_1 + \alpha_2\, x$, one obtains, for independent measurements y_i, the following estimates of α_1 and α_2,

$$\widehat{\alpha}_1 = (g_1\, V_{22}^{-1} - g_2\, V_{12}^{-1})/D , \qquad (28.24)$$

$$\widehat{\alpha}_2 = (g_2\, V_{11}^{-1} - g_1\, V_{12}^{-1})/D , \qquad (28.25)$$

where

$$(V_{11}^{-1}, V_{12}^{-1}, V_{22}^{-1}) = \sum (1, x_i, x_i^2)/\sigma_i^2 , \qquad (28.26a)$$

$$(g_1, g_2) = \sum (1, x_i) y_i/\sigma_i^2 . \qquad (28.26b)$$

respectively, and

$$D = V_{11}^{-1}\, V_{22}^{-1} - (V_{12}^{-1})^{\,2} . \qquad (28.27)$$

The covariance matrix of the fitted parameters is:

$$\begin{pmatrix} V_{11} & V_{12} \\ V_{12} & V_{22} \end{pmatrix} = \frac{1}{D} \begin{pmatrix} V_{22}^{-1} & -V_{12}^{-1} \\ -V_{12}^{-1} & V_{11}^{-1} \end{pmatrix} . \qquad (28.28)$$

The estimated variance of an interpolated or extrapolated value of y at point x is:

$$(\widehat{y} - y_{\rm true})^2\Big|_{\rm est} = \frac{1}{V_{11}^{-1}} + \frac{V_{11}^{-1}}{D}\left(x - \frac{V_{12}^{-1}}{V_{11}^{-1}}\right)^2 . \qquad (28.29)$$

28.5.1. *General comments*:

If y is not linear in the fitting parameters $\boldsymbol{\alpha}$, the solution vector may have to be found by iteration. If we have a first guess $\boldsymbol{\alpha}_0$, then we may expand to obtain

$$\left.\frac{\partial\chi^2}{\partial\alpha}\right|_{\alpha} = \left.\frac{\partial\chi^2}{\partial\alpha}\right|_{\alpha_0} + V_{\alpha_0}^{-1}\cdot(\boldsymbol{\alpha} - \boldsymbol{\alpha}_0) + \ldots , \qquad (28.30)$$

where $\partial\chi^2/\partial\alpha$ is a vector whose mth component is $\partial\chi^2/\partial\alpha_m$, and $(V_{mn}^{-1}) = \frac{1}{2}\partial^2\chi^2/\partial\alpha_m\partial\alpha_n$. (See Eqns. 28.7 and 28.17. When evaluated at $\hat{\boldsymbol{\alpha}}$, V^{-1} is the inverse of the covariance matrix.) The next iteration toward $\hat{\boldsymbol{\alpha}}$ can be obtained by setting $\partial\chi^2/\partial\alpha_m|_{\boldsymbol{\alpha}} = 0$ and neglecting higher-order terms:

$$\boldsymbol{\alpha} = \boldsymbol{\alpha}_0 - V_{\boldsymbol{\alpha}_0} \cdot \partial\chi^2/\partial\boldsymbol{\alpha}|_{\boldsymbol{\alpha}_0} \tag{28.31}$$

If V is constant in the vicinity of the minimum, as it is when the model function is linear in the parameters, then χ^2 is parabolic as a function of $\boldsymbol{\alpha}$ and Eq. (28.31) gives the solution immediately. Otherwise, further iteration is necessary. If the problem is highly nonlinear, considerable difficulty may be encountered. There may be secondary minima, and χ^2 may be decreasing at physical boundaries. Numerical methods have been devised to find such solutions without divergence [8,11]. In particular, the CERN program MINUIT [11] offers several iteration schemes for solving such problems.

Note that minimizing any function proportional to χ^2 (or maximizing any function proportional $\ln\mathscr{L}$) will result in the same parameter set $\hat{\boldsymbol{\alpha}}$. Hence, for example, if the variances σ_j^2 are unknown but assumed equal and independent, one can still solve for $\hat{\boldsymbol{\alpha}}$. One cannot, however, evaluate goodness-of-fit, and the covariance matrix is known only to within a constant multiplier. The scale can be estimated at least roughly from the size of χ^2 compared to its expected size.

Additional information can be extracted from the behavior of the (normalized) residuals, $r_j = (y_j - F(x_j;\boldsymbol{\alpha})/\sigma_j$, which should themselves distribute normally with a mean of 0.

If the data covariance matrix S has been correctly evaluated (or, equivalently, the σ_j's, if the data are independent), then the s-standard deviation limits on the parameters are given by a set $\boldsymbol{\alpha}'$ such that

$$\chi^2(\boldsymbol{\alpha}) = \chi^2_{\rm min} + s^2 \ . \tag{28.32}$$

This equation, a special case of 28.8, defines a contour in $\boldsymbol{\alpha}$-space; compare with the linear case in Eq. (28.19). It is often convenient for estimating errors in applications to nonlinear cases, where the matrix $V^{-1}|_{\boldsymbol{\alpha}}$ may be a rapidly varying function of $\boldsymbol{\alpha}$. If the problem is highly nonlinear, such contours only approximately define the desired confidence regions which would have some given probability of covering the true value of $\boldsymbol{\alpha}$.

The method of least squares is sometimes used in cases where the distribution is not Gaussian or not known to be Gaussian. In such cases it can still be used, but it is then not a special case of the maximum-likelihood method, and the theorems having to do with that approach no longer apply. However, if (a) the distribution of $y_i - \sum \alpha_k f_k(x_i)$ has an expectation value of zero (unbiased) and (b) has a finite, known, fixed variance σ_i^2 (does not depend on $\boldsymbol{\alpha}$), then estimates of $\boldsymbol{\alpha}$ obtained by minimizing χ^2 will be unbiased and have the smallest possible variance of all linear unbiased estimates (Gauss-Markov theorem). This statement is more general than the least-squares method as a special case of the maximum likelihood method in that the distributions do not have to be Gaussian, but more restrictive in that it applies only when the fitting function is linear in the α_k's.

28.6. Errors and confidence intervals

We measure a mass, lifetime, or other physical quantity under the assumption that a "true answer" α exists. The conditions of the measurement introduce a random element, and our measurement (or combination of measurements) $\widehat{\alpha}_{\rm exp}$ samples a distribution with p.d.f. $f(\widehat{\alpha};\alpha)$. The unknown constant α appears as a parameter. We suppose that for every value of α we can find two values $\gamma_1(\alpha,\varepsilon)$ and $\gamma_2(\alpha,\varepsilon)$ such that repeated experiments would produce results in the interval $\gamma_1 < \widehat{\alpha} < \gamma_2$ a fraction $1-\varepsilon$ of the time, where

$$1 - \varepsilon = \int_{\gamma_1}^{\gamma_2} f(\widehat{\alpha};\alpha)\, d\widehat{\alpha} \ . \tag{28.33}$$

This situation is shown in Fig. 28.1 (ignore the "unphysical region" part of the graph for now), where the region between the curves $\gamma_1(\alpha,\varepsilon)$ and $\gamma_2(\alpha,\varepsilon)$ is indicated by the domain $D(\varepsilon)$. It can be argued that since the point $(\alpha_{\rm actual},\widehat{\alpha}_{\rm exp})$ belongs to D, then our statement that repeated experiments would produce values of $\widehat{\alpha}$ in the interval $\gamma_1 < \widehat{\alpha} < \gamma_2$ is equivalent to the statement that the *confidence interval* $c_1 < \alpha < c_2$ includes $\alpha_{\rm actual}$ with probability $1-\varepsilon$ [1,6]. (We will call ε the *confidence coefficient.*) In this "confidence interval" or frequentist approach, α is a parameter, not a statistical variable. Instead, c_1 and c_2 vary from experiment to experiment and *are* statistical variables. It is very different to say that a lifetime τ is to be found in the interval $\tau_0 \pm \sigma_\tau$ with 68% probability than to say that the interval $\tau_0 \pm \sigma_\tau$ (which can vary from experiment to experiment) includes the actual, fixed, value of the lifetime with 68% probability.

The actual choice of γ_1 and γ_2, such that $\int_{\gamma_1}^{\gamma_2} f(\widehat{\alpha};\alpha)\, d\widehat{\alpha} = 1-\varepsilon$, can be made in an infinite number of ways, but in practical situations there are usually additional criteria. For a Gaussian distribution, for example, choosing the limits symmetric about the mean minimizes the length of the interval. The area of the excluded tail on either side is then $\varepsilon/2$. For a Poisson distribution negative values cannot occur, so $\gamma(\widehat{\alpha},\alpha)$ (with $\widehat{\alpha}$ an integer and α the Poisson mean) might be taken as the curve below which ε of the area under the distribution lies. (In this case the curve really consists of discrete points, since $\widehat{\alpha}$ can have only discrete values.) For $\varepsilon = 0.05$ the curve starts at $(\alpha,\widehat{\alpha}) = (3.0, 0)$. If in a given experiment no decays to a certain final state are seen, we might then conclude that $\alpha < 3.0$ excludes the actual value of α with 95% probability. This statement can be converted to a similar statement about the branching fraction.

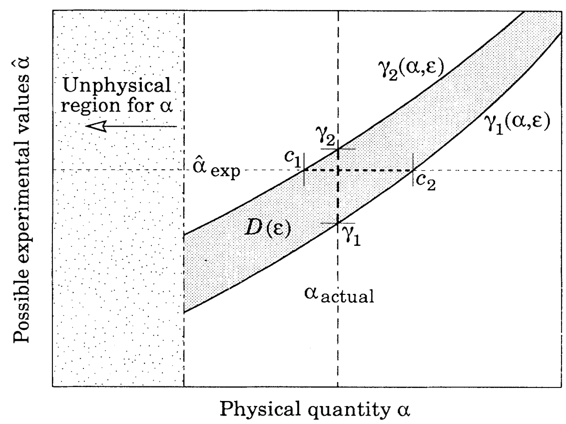

Figure 28.1: Confidence intervals for a single unknown parameter α. One might think of the p.d.f. $f(\widehat{\alpha};\alpha)$ as being plotted out of the paper as a function of $\widehat{\alpha}$ along each vertical line of constant α. The domain $D(\varepsilon)$ contains a fraction $1-\varepsilon$ of the area under each of these functions.

In Sec. 27 we discussed such confidence limits for a χ^2 distribution (where ε was called CL). Here we discuss confidence intervals for the Gaussian and Student's t-distribution, and confidence limits for the Poisson case. We then discuss the much more contentious situation in which the horizontal line at ordinate $\widehat{\alpha}$ in Fig. 28.1 enters $D(\varepsilon)$ at a boundary for unphysical values of α, so that at least c_1 is undefined—for example, if we find $\widehat{m}^2 = -30 \pm 50$ eV^2.

Extensive tables and graphs were once used to find confidence intervals and limits, but by now their main function is to confirm that software is working. FORTRAN mathematical libraries (IMSL, NAG, CERNLIB) are readily available, and a wide range of distributions are available in personal computer spreadsheet applications such as Microsoft® Excel [12]. Its built-in functions CHIDIST, NORMDIST, and TDIST (Student's t-distribution), along with "Solver," were used to produce or check the numbers given in this section.

Table 28.1: Area of the tails ε outside $\pm\delta$ from the mean of a Gaussian distribution.

ε (%)	δ	ε (%)	δ
31.73	1σ	20	1.28σ
4.55	2σ	10	1.64σ
0.27	3σ	5	1.96σ
6.3×10^{-3}	4σ	1	2.58σ
5.7×10^{-5}	5σ	0.1	3.29σ
2.0×10^{-7}	6σ	0.01	3.89σ

28.6.1. ***Gaussian errors***:

If the data are such that the distribution of the estimator(s) satisfies the central limit theorem discussed in Sec. 27.3.3, the Gaussian distribution is the basis of the error analysis. If there is more than one parameter being estimated, the multivariate Gaussian is used. For the univariate case with known σ,

$$1 - \varepsilon = \int_{\widehat{\mu}-\delta}^{\widehat{\mu}+\delta} f(x;\, \widehat{\mu},\, \sigma^2)\, dx = \mathrm{erf}\left(\frac{\delta}{\sqrt{2}\,\sigma}\right) \tag{28.34}$$

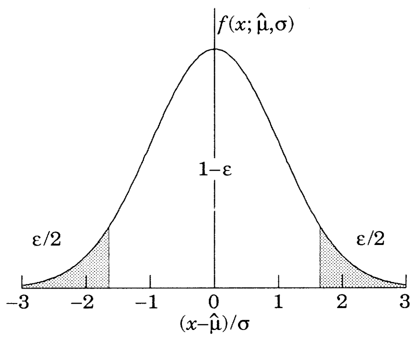

Figure 28.2: Illustration of a symetric 90% confidence interval (unshaded) for a measurement of a single quantity with Gaussian errors. Integrated probabilities, defined by ε, are as shown.

is the probability that the true value of μ will fall within $\pm\delta$ ($\delta > 0$) of the measured $\widehat{\mu}$. This interval will cover μ in a fraction $1-\varepsilon$ of all similar measurements. Fig. 28.2 shows a $\delta = 1.64\sigma$ confidence interval unshaded. The choice $\delta = \sqrt{\mathrm{Var}(\widehat{\mu})} \equiv \sigma$ gives an interval called the *standard error* which has $1 - \varepsilon = 68.27\%$ if σ is known. Confidence coefficients ε for other frequently used choices of δ are given in Table 28.1. For other δ, find ε as the ordinate of Fig. 27.1 on the $n = 1$ curve at $\chi^2 = (\delta/\sigma)^2$. We can set a one-sided (upper or lower) limit by excluding above $\widehat{\mu} + \delta$ (or below $\widehat{\mu} - \delta$); ε's for such limits are 1/2 the values in the table above.

We have increased confidence that the interval covers the true value as $1-\varepsilon$ increases, or χ^2 increases. We must be careful to distinguish this case from the other major use of Fig. 27.1, evaluation of goodness-of-fit (Sec. 28.5.0). In that case we have increased confidence in the fit as χ^2 decreases. In an attempt to reduce possible confusion in this discussion, we will use the ε notation (which corresponds to notation used in hypothesis testing [4]) when discussing confidence intervals and CL notation when discussing goodness-of-fit. Elsewhere in this *Review*, where the confusion between fit confidence level and interval (usually an upper or lower limit) confidence level does not arise, we follow the common practice of using "CL" to refer to the confidence level of the interval. This CL is understood to represent $1-\varepsilon$.

If the variance σ^2 of the estimator is not known, but must be estimated from the data, then we need to incorporate the error in $\widehat{\sigma}$ into our confidence interval using Student's t distribution. If we have N data points with which we estimate k parameters, the Gaussian approximation is adequate for $N - k \gg 1$. Otherwise replace δ by a factor $T\widehat{\sigma}$, T being defined by

$$1 - \varepsilon = \int_{-T}^{T} f(t; N-k)\, dt\ , \tag{28.35}$$

where f for the Student's t-distribution is defined in Table 27.1. T is tabulated in Ref. 13 and in Table 28.2.

Table 28.2: t limits containing $1-\varepsilon$ of the area of Student's t-distribution $f(t; N-k)$.

	ε (%)					
$N-k$	31.73	10.00	5.00	4.55	1.00	0.27
1	1.84	6.31	12.71	13.97	63.66	235.8
2	1.32	2.92	4.30	4.53	9.92	19.21
3	1.20	2.35	3.18	3.31	5.84	9.22
4	1.14	2.13	2.78	2.87	4.60	6.62
5	1.11	2.01	2.57	2.65	4.03	5.51
10	1.05	1.81	2.23	2.28	3.17	3.96
20	1.03	1.72	2.09	2.13	2.85	3.42
∞	1.00	1.64	1.96	2.00	2.58	3.00

For multivariate $\boldsymbol{\alpha}$ we must consider pairwise correlations. Assuming a multivariate Gaussian, Eq. (27.22), and subsequent discussion the standard error ellipse for the pair $(\widehat{\alpha}_m, \widehat{\alpha}_n)$ may be drawn as in Fig. 28.3.

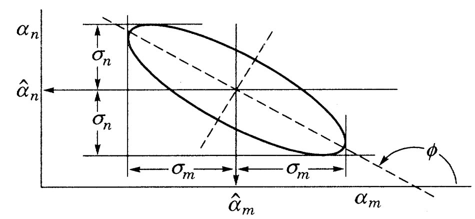

Figure 28.3: Standard error ellipse for the estimators $\widehat{\alpha}_m$ and $\widehat{\alpha}_n$. In this case the correlation is negative.

The minimum χ^2 or maximum likelihood solution is at $(\widehat{\alpha}_m, \widehat{\alpha}_n)$. The standard errors σ_m and σ_n are defined as shown, where the ellipse is at a constant value of $\chi^2 = \chi^2_{\rm min} + 1$ or $\ln\mathscr{L} = \ln\mathscr{L}_{\rm max} - 1/2$. The angle of the major axis of the ellipse is given by

$$\tan 2\phi = \frac{2\rho_{mn}\, \sigma_m\, \sigma_n}{\sigma_m^2 - \sigma_n^2}\ . \tag{28.36}$$

For non-Gaussian or nonlinear cases, one may construct an analogous contour from the same χ^2 or $\ln\mathscr{L}$ relations. Any other parameters $\widehat{\alpha}_\ell, \ell \neq m, n$ must be allowed freely to find their optimum values for every trial point.

For any unbiased procedure (*e.g.*, least squares or maximum likelihood) being used to estimate k parameters α_i, $i = 1, \ldots, k$, the probability $1-\varepsilon$ that the true values of all k lie within the s-standard deviation ellipsoid may be found from Fig. 27.1. Read the ordinate as ε; the correct value of ε occurs on the $n = k$ curve at $\chi^2 = s^2$. For example, for $k = 2$, the probability that the true values of α_1 and α_2 simultaneously lie within the one-standard-deviation error ellipse ($s = 1$), centered on $\widehat{\alpha}_1$ and $\widehat{\alpha}_2$, is 39%. This probability only assumes Gaussian errors, unbiased estimators, and that the model describing the data in terms of the α_i is correct.

28.6.2. ***Poisson processes—upper limits***:

Because the outcome of a Poisson process is an integral number of events, n_0, it is usually not possible to set confidence intervals for the true Poisson parameter μ at a certain exact ε. For large n_0 an approximate interval can be set using the Gaussian approximation, in our section on Probability, Sec. 27.3.2, and the techniques of Sec. 28.6.1.

For small n_0 we can define an upper limit N for μ as being that value of μ such that it would be at least $1-\varepsilon$ (*e.g.*, 90% or 95%) probable that a random observation of n would then lie above the observed n_0. Thus

$$1-\varepsilon = \sum_{n=n_0+1}^{\infty} f(n;N)\ ; \qquad \varepsilon = \sum_{n=0}^{n_0} f(n;N)\ . \qquad (28.37)$$

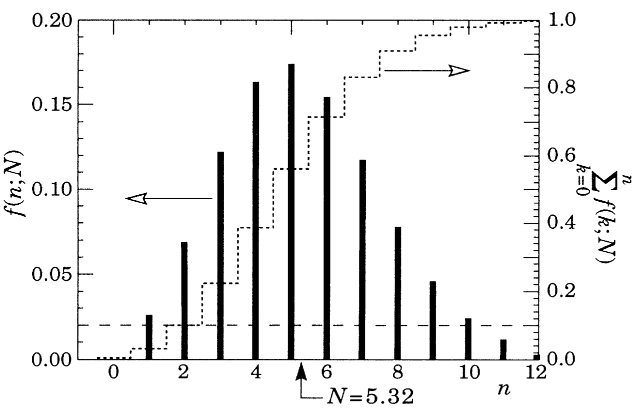

Figure 28.4: Illustration of Eq. (28.37) Poisson probabilities for an assumed mean of N. With an observed count $n_0 = 2$, $N = 5.32$ as shown gives summed probability $\varepsilon = 10\%$. The dotted summed probability curve (scale on right) has been displaced by -0.5 for clarity.

Fig. 28.4 illustrates the case with $n_0 = 2$ and $1-\varepsilon = 90\%$, for which it may be shown that $N = 5.32$. For any given n_0 and desired ε we can obtain N from the χ^2 Confidence Level figure because of a relation between the Poisson and the χ^2 distributions: read the ordinate as ε, find χ^2 on the curve for $n = 2(n_0+1)$; then $N = \chi^2/2$. Some useful values are given in Table 28.3.

The meaning of these upper limits is that, for a given true μ, the probability is *at least* $1-\varepsilon$ that one will observe n_0 which will result in N which is $\geq \mu$. The probability for that to occur may be higher than $1-\varepsilon$; for example, if $\mu \leq 2.30$ a "90%" upper limit will actually exceed μ 100% of the time. Note from Eq. (28.37) that for $n_0 = 0$, $N = -\ln\varepsilon$.

Table 28.3: Poisson upper limits N for n_0 observed events.

n_0	$\varepsilon =$ 10%	$\varepsilon =$ 5%	n_0	$\varepsilon =$ 10%	$\varepsilon =$ 5%
0	2.30	3.00	6	10.53	11.84
1	3.89	4.74	7	11.77	13.15
2	5.32	6.30	8	13.00	14.44
3	6.68	7.75	9	14.21	15.71
4	7.99	9.15	10	15.41	16.96
5	9.27	10.51	11	16.60	18.21

28.6.3. ***Bounded physical region****:

The measurement of a physical constant α results in an estimator $\widehat{\alpha}$, together with some knowledge of experimental error and therefore knowledge of $f(\widehat{\alpha};\alpha)$, the parameterized p.d.f. that allows us to state the probability with which repeated experiments would produce results in a given range. It does *not* permit us to comment about α itself, which in this language is a constant, not a statistical variable. At the beginning of this section we introduced the confidence interval, or frequentist, approach to the problem, and were able to say that with a given probability the unknown parameter could be found between (statistical) limits c_1 and c_2. But what if a physical boundary exists? Although polarization should be less than one and mass or its square should be greater than zero, experimental results do not always fall inside such a physical boundary because of statistical fluctuations.

However one might set a limit, there is little question about how to report and combine data [14]. A given experiment finds an unbiased estimator $\widehat{\alpha} = -5 \pm 10$ for a physical constant (*e.g.* the square of the mass of a neutrino, in eV^2). This value should be reported as the primary result. In case the true value is zero, for example, this "unphysical" result would not be unlikely. It can be combined with the results of other such experiments by forming the appropriately weighted average of unbiased results, including negative ones, to find an unbiased estimator which expresses our best knowledge of the parameter.

What if we wish to extend our concept of confidence limit to such a situation? The question of how to calculate an upper limit in the vicinity of a physical boundary is one of the most divisive in high-energy physics. We present two main approaches: The confidence interval, or frequentist, method, and the Bayesian method. "Classical method" is applied to one or the other by various writers, so we avoid the term.

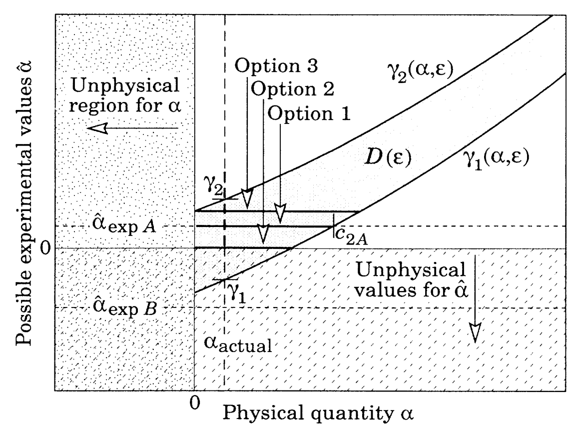

Figure 28.5: The situation near a physical boundary. In Fig. 28.1 the horizontal line for a given $\widehat{\alpha}_{\rm exp}$ crossed the domain $D(\varepsilon)$, bounded by $\gamma_1(\alpha,\epsilon)$ and $\gamma_2(\alpha,\epsilon)$ entirely in the physical region, entering at c_1 and leaving at c_2. The limits γ_1 and γ_2 cannot be defined in a region where α is not defined, so the functions cannot be continued into the unphysical region. As a result c_1 (for experiment A) or c_1 and c_2 (for experiment B) cannot be defined. Options 1, 2, and 3 label the ways one might define confidence intervals, as described in the text.

1. The method of confidence intervals [1,15]. This is the approach described in the introduction, and requires little further explanation. It is presently the method in favor [1,6,14]. For a Gaussian distribution it gives the same result as the Bayesian approach with a flat prior distribution (see below) if the region containing α with the stated probability is far from an unphysical region, as in Fig. 28.1. Two cases in which this is untrue are shown in Fig. 28.5, where as a matter of convenience we assume that α must be positive. As before, we can define limits γ_1 and γ_2 for each value of the unknown parameter α, such that we can expect that a fraction $1-\varepsilon$ of repeated experiments to produce results between these limits. Since this can be done for each value of α, the limits are described by the functions $\gamma_1(\alpha,\varepsilon)$ and $\gamma_2(\alpha,\varepsilon)$. However, these *cannot* be extended into a region in which α makes no sense. Experimental result $\widehat{\alpha}_{\exp A}$, indicated in Fig. 28.5, is positive, but if the true value is α_{actual} a significant fraction of repetitions of the experiment would produce negative $\widehat{\alpha}$. In these cases there is no horizontal intercept c_1, so without further assumptions we cannot make a statement about the region which would cover α_{actual} in a given fraction of experiments. Experimental result $\widehat{\alpha}_{\exp B}$ presents a more serious problem, since it is so negative that there is no physical α for which the point $(\widehat{\alpha},\alpha)$ lies in the domain $D(\varepsilon)$. The reason why the frequentist method gives no confidence interval is clear: This measured value of $\widehat{\alpha}$ would be unlikely *no matter what the true value of α was.*

There are several *ad hoc* ways to set confidence limits in such cases, although many frequentists would prefer to stop with the weighted average of unbiased results—if the outcome is exceedingly unlikely, one should look to the experiment, not to the statistics. The methods we list below all involve placing c_1 on the physical boundary, which in our example is at $\alpha = 0$.

1. If $\widehat{\alpha}_{\exp} > \gamma_1(0,\varepsilon)$, as in Experiment A, c_2 is defined. Use it for the upper limit, whether or not $\widehat{\alpha}_{\exp} > 0$.
2. If $\widehat{\alpha}_{\exp} < 0$, as in Experiment B, use the c_2 corresponding to $\widehat{\alpha}_{\exp} = 0$.
3. If c_1 is not defined, "lift up" $\widehat{\alpha}$ to $\gamma_2(0,\varepsilon)$, where $c_1 = 0$. Use the corresponding c_2 as the upper limit.

These three options are shown in in Fig. 28.5; note that there are regions where more than one of them can be used, with different results. The third option is certainly the most conservative. For Gaussian $f(\widehat{\alpha};\alpha)$ the upper limit c_2 is a one-sided Gaussian confidence limit; read the tables for a 90% two-sided limit to obtain 95% one-sided limit. Alternatively, read the intercepts of the dotted lines in Fig. 28.7. (The horizontal axis is incorrectly labeled for this application.)

2. The Bayesian approach [3]. This is the approach favored in the older literature, and has (unfortunately and incorrectly) been referred to as the "PDG method" in certain papers. To begin with, it is argued that while α is not a statistical variable, our *knowledge* of α is less than complete, and it is fair to describe our uncertainty by treating α as a statistical variable. The parameterized p.d.f. $f(\widehat{\alpha};\alpha)$ is replaced by the conditional p.d.f. $f(\widehat{\alpha}|\alpha)$. The confidence limit question can then be rephrased: Our measurements provide $f(\widehat{\alpha}|\alpha)$, that is, information about $\widehat{\alpha}$ for a fixed and unknown value of α, while we really want to know $g(\alpha|\widehat{\alpha})$, which tells us that, given our measurement $\widehat{\alpha}$, the "true answer" α lies between α and $\alpha + d\alpha$ with probability $g(\alpha|\widehat{\alpha})\,d\alpha$. The connection is provided by Bayes' theorem (Eq. (27.7):

$$g(\alpha|\widehat{\alpha}) = \frac{f(\widehat{\alpha}|\alpha)\,\pi(\alpha)}{\int f(\widehat{\alpha}|\alpha)\,\pi(\alpha)\,d\alpha}\ . \tag{28.38}$$

Here $\pi(\alpha)$ represents our "advance knowledge" of the value of α. In the usual case we claim no prior knowledge, so that before the experiment all physically reasonable values of α are equally probable: $\pi(\alpha)$ is a constant over the region of interest and zero in the unphysical region. This assumption leads to the conclusion that

$$g(\alpha|\widehat{\alpha}) = \begin{cases} f(\widehat{\alpha}|\alpha)/\int f(\widehat{\alpha}|\alpha)\,d\alpha & \text{if } \alpha \text{ is in the physical region;} \\ 0 & \text{otherwise;} \end{cases} \tag{28.39}$$

where this time the integral is over the physical region. In Fig. 28.6 we assume that an ensemble of experiments would produce values for $\widehat{\alpha}$ which distribute as shown, with a significant probability of obtaining results with unphysical values. With our assumed step function $\pi(\alpha)$, the effect of Eq. (28.38) or (28.39) is to replace this distribution with the function shown by the shaded region, except that it is renormalized to unit area. By stating our confidence at the 90% level that α lies below the beginning of the dark shaded region, we mean that 90% of the area in the physical region is in the light shaded region.

In most cases of interest in this Review, $\widehat{\alpha}$ is assumed to be a random value from a Gaussian distribution. Application of the procedure sketched in Fig. 28.6 then leads to the family of curves shown in Fig. 28.7. The confidence limit set by this method is always greater than the [one-sided] confidence interval set without the restriction of an unphysical region, and approaches it from above as the tail in the unphysical region becomes unimportant. It is also greater than any of the limits shown in Fig. 28.5. With a small modification (exclusion of that portion of the negative tail inside the physical region in the confidence interval definition), it smoothly approaches the usual two-sided confidence interval for Gaussian distributions.

Even so, it is not a valid confidence limit. If it were, the interval would include the true value of α with *exactly* $1-\varepsilon$ probability no matter what the true value was. If the true answer is zero, our procedure, by guaranteeing a limit greater than zero for any experiment, also guarantees that the confidence interval for any ε includes α_{actual} with 100% probability. Only as α increases does the probability decrease toward the α-independent Gaussian result.

The error function corresponding to the right axis of Fig. 28.7 shows the probability that $\widehat{\alpha}/\sigma$ at or below the given value should occur. If the experimental value is exceeding improbable, then the

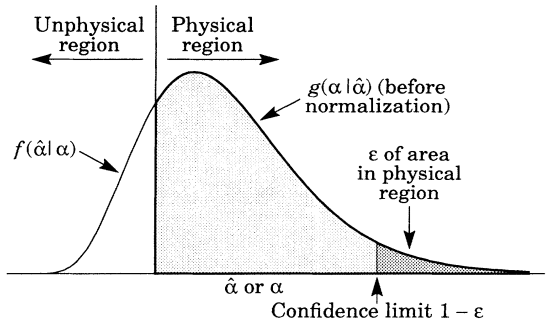

Figure 28.6: An example of a bounded physical region, in which a measurement $\widehat{\alpha}$ can fall in an unphysical region with significant probability. If we assume that α, the quantity we are trying to measure, cannot lie in the unphysical region (0 probability) but can lie anywhere in the physical region ("no prior knowledge"), then Bayes' theorem says that our new knowledge of the distribution of α, given our measurement $\widehat{\alpha}$, is given by the shaded function after appropriate renormalization.

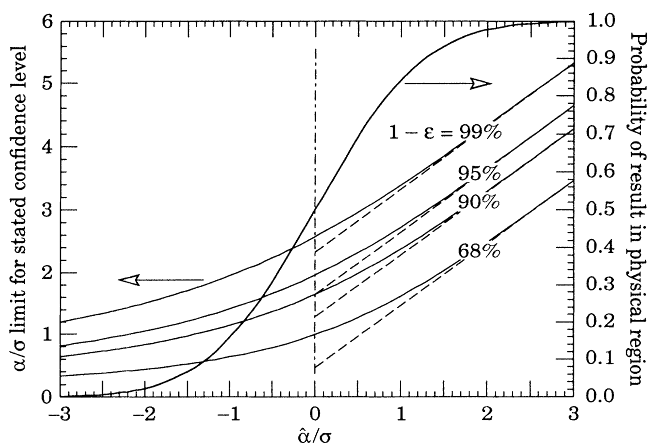

Figure 28.7: Application of the Bayesian scheme shown in Fig. 28.6 to the case of Gaussian $f(\widehat{\alpha}|\alpha)$. For example, if our measurement $\widehat{\alpha}$ is 1.0 standard deviations negative, then we conclude that $\alpha < 1.15\sigma$ with 90% probability—however, there is only a 31% probability that an experimental result as low as this would occur. Note that these are upper limits, so that the asymptote for large $\widehat{\alpha}/\sigma$ corresponds to a one-sided confidence interval, *e.g.*, the asymptote for a 95% confidence level is $\alpha < \widehat{\alpha} + 1.64\sigma$, corresponding to a 90% confidence interval for a two-sided distribution. The dashed lines show the frequentist limit; if Option 3 is used, these are extended horizontally to the right for negative $\widehat{\alpha}/\sigma$.

formal confidence limit obtained by this or any other method means very little.

What about the arbitrariness of $\pi(\alpha)$? If the square of the neutrino mass is measured ($\alpha = m_\nu^2$), then should we not take the prior knowledge distribution as proportional to $\sqrt{\alpha}$?† There are other attractive options. Jeffreys points out that if $\pi(\alpha)\,d\alpha = d\alpha/\alpha$, then the distributions for α and α^n are proportional [16], but there are practical difficulties with this approach. Lynch has investigated prior distributions that are constant in α, α^2, and $\sqrt{\alpha}$ in the context of Gaussian $f(\widehat{\alpha}|\alpha)$, and has observed that assuming a prior distribution that is flat in α gives results that are much more satisfactory than one gets from the others [17]: All three methods have the property that the probability that the calculated limit contains the correct answer is 100% when $\alpha = 0$ and approaches the proper value when $\alpha \gg \sigma$, but the approach to the proper value as α increases is much faster when the prior distribution is taken to be flat in α. In this case the approach is also monotonic, giving it the "conservative" property that for no value of α will the method produce a limit that has a probability of being correct that is less than the stated confidence limit. Although there is nothing unique about the limit calculated with a constant $\pi(\alpha)$, it has desirable features and no obvious replacement.

Summary: If there is a significant probability of obtaining an estimator corresponding to an unphysical value for a parameter, there is no universally accepted way way to make a statement of the sort "α is less that c_2 with probability $1 - \varepsilon$." A variety of upper limits can be defined, but no method is entirely satisfactory. The Bayesian method with a flat prior distribution gives a reasonable upper limit which combines everything we know about the unknown quantity α into a physically reasonable value, but it does not give a complete summary of the information contained in the experiment.

28.6.4. *Poisson processes with background* [18] :

If we observe n_0 events in a Poisson process which has two components, signal and background, estimating a limit on the signal is more complicated. Let μ_S be the unknown mean (the Poisson parameter) for the signal and μ_B be the mean for the sum of all backgrounds. Assume μ_B is known with negligible error; however we don't know n_B, the actual number of events resulting from the background. We do know that $n_B \le n_0$. If $\mu_B + \mu_S$ is large, the Gaussian approximation to the Poisson distribution (see Sec. 27.3.2) is usually adequate, and one can define confidence intervals or limits as above, assuming $\widehat{n}_B \approx \mu_B$ and therefore $\widehat{\mu}_S = n_0 - \mu_B$ with variance equal to n_0 (larger than $\widehat{\mu}_S$ to allow for the error in $\widehat{n}_B$).

Otherwise an upper limit can be defined by extension of the argument of the preceding section. Let N be the desired upper limit on μ_S with confidence coefficient ε. Set N to be that value of μ_S such that any random repeat of the current experiment with $\mu_S = N$ and the same μ_B would observe *more* than n_0 events in total *and* would have $n_B \le n_0$, all with probability $1 - \varepsilon$. For any assumed N and μ_B we can calculate this probability:

$$1 - \varepsilon = 1 - \frac{e^{-(\mu_B+N)} \displaystyle\sum_{n=0}^{n_0} \frac{(\mu_B + N)^n}{n!}}{e^{-\mu_B} \displaystyle\sum_{n=0}^{n_0} \frac{\mu_B^n}{n!}} \ . \tag{28.40}$$

We adjust N to obtain a desired ε. For $\mu_B = 0$ this converges to Eq. (28.37). As in that case (see the last paragraph of Section 28.6.2) this gives a *conservative* upper limit in that for any given true μ_S we get a true probability $\ge 1 - \varepsilon$ that $N \ge \mu_S$, averaged over a large set of identically performed experiments. For $\varepsilon = 0.10$, Fig. 28.8 shows N as a function of n_0 and μ_B.

Averaging of experiments and other comparisons require that n_0 and μ_B be quoted and the technique used for upper limit extraction be given.

If $\mu_B \gg n_0$ the experimenter should question the probability of observing n_B as that n_0. If this is very small the background, μ_B, may not have been calculated properly and the upper limit for μ_S obtained under those assumptions may be too low. For example, in

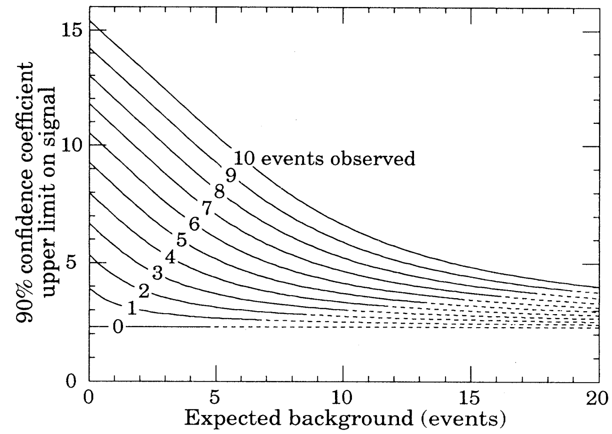

Figure 28.8: 90% confidence coefficient upper limit on the number of signal events as a function of the expected number of background events. For example, if the expected background is 8 events and 5 events are observed, then the signal is 4.0 (approximately) or less with 90% confidence. Dashed portions indicate regions where it is to be expected that the number observed would exceed the number actually observed $\ge$ 99% of the time, even in the complete absence of signal.

Fig. 28.8, the dashed portions of the curves lie in the region where n_0 is expected to exceed the observed value 99% of the time (or more), even in the complete absence of signal. In these regions one should be cautious about accepting the results of the measurement.

As in the Gaussian case (Sec. 28.6.3), whenever $n_0 < \mu_B$ some experimenters may prefer to use N calculated as if $n_0 \approx \mu_B$ rather than the smaller value obtained from the observed n_0.

28.7. Propagation of errors

Suppose we have a set of N random variables y_i which may be direct measurements or derived estimators $\widehat{\alpha}$, and we have a covariance matrix $V(y)$ for these. We can make a transformation to a different set of variables $f_n \equiv f_n(y)$, $j = 1, \ldots, M$ ($M \le N$) and obtain best estimates for the f_n from

$$\widehat{f}_n \approx f_n(\widehat{y}) + \frac{1}{2}\sum_{k,n}^{N} V_{kn}(\widehat{y}) \left[\frac{\partial^2 f_n}{\partial y_k\, \partial y_n}\right]_{\widehat{y}} \tag{28.41}$$

with covariance matrix

$$V_{ij}(\widehat{f}\,) \approx \sum_{n,m} \left.\frac{\partial f_i}{\partial y_n}\right|_{\widehat{y}} \left.\frac{\partial f_j}{\partial y_m}\right|_{\widehat{y}} V_{nm}(\widehat{y}) \ . \tag{28.42}$$

For a single-valued function f of a single measurement y with variance σ^2 (*i.e.*, $M = 1, N = 1$), this becomes

$$\begin{aligned} \widehat{f} &\approx f(\widehat{y}) + \frac{1}{2}\sigma^2 f''(\widehat{y}) \\ V(\widehat{f}\,) &\approx \sigma^2[f'(\widehat{y})]^2 \ , \end{aligned} \tag{28.43}$$

where the primes denote differentiation with respect to y, evaluated at $\widehat{y}$.

These approximations are based on a Taylor expansion of f about the true value of y. If f is approximately linear in y over a range of roughly $\widehat{y}_i \pm \sigma(y_i)$, the approximation is good and the second-order terms in (28.41) and (28.43) can be neglected. This is what is usually done. However, if linearity is badly violated (*e.g.*, $f \propto 1/y$ and $\widehat{y}$ is no more than a few σ from zero), it should be recognized that propagation of errors will give very approximate results. In such cases $\widehat{f} \approx f(\widehat{y})$ may be a biased estimator for f even if $\widehat{y}$ is unbiased for y, and the second-order terms in (28.41) and (28.43) will help to reduce that bias.

*In addition to the references cited, communications with R.D. Cousins, F. James, G. Lynch, and B. Roe have been invaluable in formulating this section.

†There is an additional problem: Even if we set a confidence limit on m_ν^2 by some particular recipe, it translates into a different confidence limit on $\sqrt{m_\nu^2}$ except when a Bayesian procedure with Jeffreys' $\pi(\alpha) \propto 1/\alpha$ prior distribution is used.

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29. MONTE CARLO TECHNIQUES

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Monte Carlo techniques are often the only practical way to evaluate difficult integrals or to sample random variables governed by complicated probability density functions. Here we describe an assortment of methods for sampling some commonly occurring probability density functions.

29.1. Sampling the uniform distribution

Most Monte Carlo sampling or integration techniques assume a "random number generator" which generates uniform statistically independent values on the half open interval $[0, 1)$. Although such a generator is, strictly speaking, impossible on a finite digital computer, generators are nevertheless available which pass extensive batteries of tests for statistical independence and which have periods which are so long that, for practical purposes, values from these generators can be considered to be uniform and statistically independent. In particular, the lagged-Fibonacci based generator introduced by Marsaglia, Zaman, and Tsang [1] is efficient, has a period of approximately 10^{43}, produces identical sequences on a wide variety of computers and, passes the extensive "DIEHARD" battery of tests [2]. Many commonly available congruential generators fail these tests and often have sequences (typically with periods less than 2^{32}) which can be easily exhausted on modern computers and should therefore be avoided [3].

29.2. Inverse transform method

If the desired probability density function is $f(x)$ on the range $-\infty < x < \infty$, its cumulative distribution function (expressing the probability that $x \le a$) is given by Eq. (27.1). If a is chosen with probability density $f(a)$, then the integrated probability up to point a, $F(a)$, is itself a random variable which will occur with uniform probability density on $[0, 1]$. If x can take on any value, and ignoring the endpoints, we can then find a unique x chosen from the p.d.f. $f(s)$ for a given u if we set

$$u = F(x) \; , \tag{29.1}$$

provided we can find an inverse of F, defined by

$$x = F^{-1}(u) \; . \tag{29.2}$$

This method is shown in Fig. 29.1a.

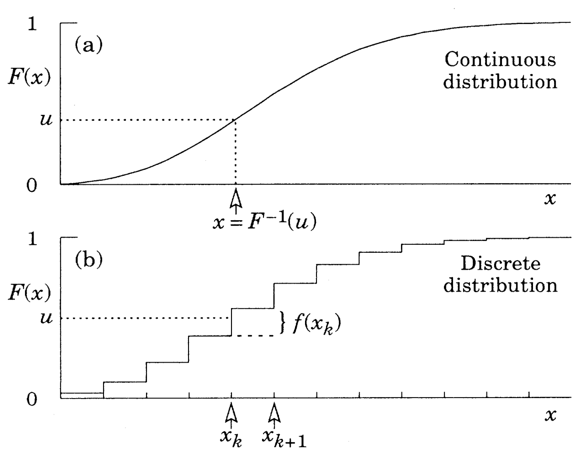

Figure 29.1: Use of a random number u chosen from a uniform distribution (0,1) to find a random number x from a distribution with cumulative distribution function $F(x)$.

For a discrete distribution, $F(x)$ will have a discontinuous jump of size $f(x_k)$ at each allowed $x_k, k = 1, 2, \cdots$. Choose u from a uniform distribution on (0,1) as before. Find x_k such that

$$F(x_{k-1}) < u \le F(x_k) \equiv \text{Prob}\,(x \le x_k) = \sum_{i=1}^{k} f(x_i) \; ; \tag{29.3}$$

then x_k is the value we seek (note: $F(x_0) \equiv 0$). This algorithm is illustrated in Fig. 29.1b.

29.3. Acceptance-rejection method (Von Neumann)

Very commonly an analytic form for $F(x)$ is unknown or too complex to work with, so that obtaining an inverse as in Eq. (29.2) is impractical. We suppose that for any given value of x the probability density function $f(x)$ can be computed and further that enough is known about $f(x)$ that we can enclose it entirely inside a shape which is C times an easily generated distribution $h(x)$ as illustrated in Fig. 29.2.

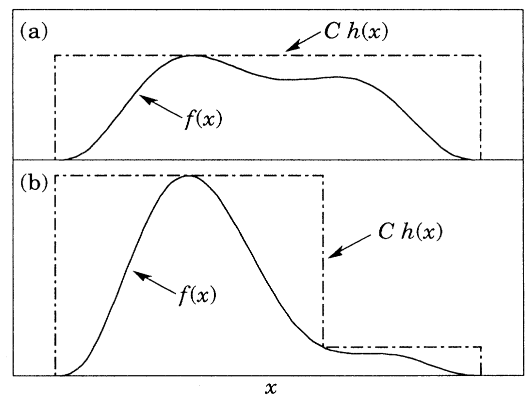

Figure 29.2: Illustration of the acceptance-rejection method. Random points are chosen inside the upper bounding figure, and rejected if the ordinate exceeds $f(x)$. Lower figure illustrates importance sampling.

Frequently $h(x)$ is uniform or is a normalized sum of uniform distributions. Note that both $f(x)$ and $h(x)$ must be normalized to unit area and therefore the proportionality constant $C > 1$. To generate $f(x)$, first generate a candidate x according to $h(x)$. Calculate $f(x)$ and the height of the envelope $C\,h(x)$; generate u and test if $uC\,h(x) \le f(x)$. If so, accept x; if not reject x and try again. If we regard x and $uC\,h(x)$ as the abscissa and ordinate of a point in a two-dimensional plot, these points will populate the entire area $C\,h(x)$ in a smooth manner; then we accept those which fall under $f(x)$. The efficiency is the ratio of areas, which must equal $1/C$; therefore we must keep C as close as possible to 1.0. Therefore we try to choose $C\,h(x)$ to be as close to $f(x)$ as convenience dictates, as in the lower part of Fig. 29.2. This practice is called importance sampling, because we generate more trial values of x in the region where $f(x)$ is most important.

29.4. Algorithms

Algorithms for generating random numbers belonging to many different distributions are given by Press [4], Ahrens and Dieter [5], Rubinstein [6], Everett and Cashwell [7], Devroye [8], and Walck [9]. For many distributions alternative algorithms exist, varying in complexity, speed, and accuracy. For time-critical applications, these algorithms may be coded in-line to remove the significant overhead often encountered in making function calls. Variables named "u" are assumed to be independent and uniform on (0,1).

In the examples given below, we use the notation for the variables and parameters given in Table 27.1.

29.4.1. *Sine and cosine of random angle*:

Generate u_1 and u_2. Then $v_1 = 2u_1 - 1$ is uniform on $(-1,1)$, and $v_2 = u_2$ is uniform on (0,1). Calculate $r^2 = v_1^2 + v_2^2$. If $r^2 > 1$, start over. Otherwise, the sine (S) and cosine (C) of a random angle are given by

$$S = 2v_1v_2/r^2 \quad \text{and} \quad C = (v_1^2 - v_2^2)/r^2 \; . \tag{29.4}$$

29.4.2. ***Gaussian distribution*:**

If u_1 and u_2 are uniform on (0,1), then

$$z_1 = \sin 2\pi u_1 \sqrt{-2\ln u_2} \quad \text{and} \quad z_2 = \cos 2\pi u_1 \sqrt{-2\ln u_2} \tag{29.5}$$

are independent and Gaussian distributed with mean 0 and $\sigma = 1$.

There are many faster variants of this basic algorithm. For example, construct $v_1 = 2u_1 - 1$ and $v_2 = 2u_2 - 1$, which are uniform on (−1,1). Calculate $r^2 = v_1^2 + v_2^2$, and if $r^2 > 1$ start over. If $r^2 < 1$, it is uniform on (0,1). Then

$$z_1 = v_1\sqrt{\frac{-2\ln r^2}{r^2}} \quad \text{and} \quad z_2 = v_2\sqrt{\frac{-2\ln r^2}{r^2}} \tag{29.6}$$

are independent numbers chosen from a normal distribution with mean 0 and variance 1. $z_i' = \mu + \sigma z_i$ distributes with mean μ and variance σ^2.

For a multivariate Gaussian, see the algorithm in Ref. 10.

29.4.3. $\chi^2(n)$ **distribution:**

For n even, generate $n/2$ uniform numbers u_i; then

$$y = -2\ln\left(\prod_{i=1}^{n/2} u_i\right) \quad \text{is} \quad \chi^2(n) \ . \tag{29.7}$$

For n odd, generate $(n-1)/2$ uniform numbers u_i and one Gaussian z as in Sec. 29.4.2; then

$$y = -2\ln\left(\prod_{i=1}^{(n-1)/2} u_i\right) + z^2 \quad \text{is} \quad \chi^2(n) \ . \tag{29.8}$$

For $n \gtrsim 30$ the much faster Gaussian approximation for the χ^2 may be preferable: generate z as in Sec. 29.4.2 and use $y = \left[z + \sqrt{2n-1}\right]^2/2$; if $z < -\sqrt{2n-1}$ reject and start over.

29.4.4. ***Gamma distribution*:**

All of the following algorithms are given for $\lambda = 1$. For $\lambda \neq 1$, divide the resulting random number x by λ.

- If $k = 1$ (the *exponential* distribution), accept $x = -(\ln u)$.
- If $0 < k < 1$, initialize with $v_1 = (e + k)/e$ (with $e = 2.71828...$ being the natural log base). Generate u_1, u_2. Define $v_2 = v_1 u_1$.

  Case 1: $v_2 \leq 1$. Define $x = v_2^{1/k}$. If $u_2 \leq e^{-x}$, accept x and stop, else restart by generating new u_1, u_2.
  Case 2: $v_2 > 1$. Define $x = -\ln([v_1 - v_2]/k)$. If $u_2 \leq x^{k-1}$, accept x and stop, else restart by generating new u_1, u_2. Note that, for $k < 1$, the probability density has a pole at $x = 0$, so that return values of zero due to underflow must be accepted or otherwise dealt with.

- Otherwise, if $k > 1$, initialize with $c = 3k - 0.75$. Generate u_1 and compute $v_1 = u_1(1 - u_1)$ and $v_2 = (u_1 - 0.5)\sqrt{c/v_1}$. If $x = k + v_2 - 1 \leq 0$, go back and generate new u_1; otherwise generate u_2 and compute $v_3 = 64v_1^3 u_2^2$. If $v_3 \leq 1 - 2v_2^2/x$ **or** if $\ln v_3 \leq 2\{[k-1]\ln[x/(k-1)] - v_2\}$, accept x and stop; otherwise go back and generate new u_1.

29.4.5. ***Binomial distribution*:**

If $p \leq 1/2$, iterate until a successful choice is made: begin with $k = 1$; compute $P_k = q^n$ [for $k \neq 1$ use $P_k \equiv f(r_k; n, p)$, and store P_k into B; generate u. If $u \leq B$ accept $r_k = k - 1$ and stop; otherwise increment k by 1 and compute next P_k and add to B; generate a new u and repeat. If we arrive at $k = n + 1$, stop and accept $r_{n+1} = n$. If $p > 1/2$ it will be more efficient to generate r from $f(r; n, q)$, *i.e.*, with p and q interchanged, and then set $r_k = n - r$.

29.4.6. ***Poisson distribution*:**

Iterate until a successful choice is made: Begin with $k = 1$ and set $A = 1$ to start. Generate u. Replace A with uA; if now $A < \exp(-\mu)$, where μ is the Poisson parameter, accept $n_k = k - 1$ and stop. Otherwise increment k by 1, generate a new u and repeat, always starting with the value of A left from the previous try. For large $\mu(\gtrsim 10)$ it may be satisfactory (and much faster) to approximate the Poisson distribution by a Gaussian distribution (see our Probability chapter, Sec. 27.3.3) and generate z from $f(z;0,1)$; then accept $x = \max(0, [\mu + z\sqrt{\mu} + 0.5])$ where [ ] signifies the greatest integer $\leq$ the expression.

29.4.7. ***Student's t* distribution:**

For $n > 0$ degrees of freedom (n not necessarily integer), generate x from a Gaussian with mean 0 and $\sigma^2 = 1$ according to the method of 29.4.2. Next generate y, an independent gamma random variate with $k = n/2$ degrees of freedom. Then $z = x\sqrt{2n}/\sqrt{y}$ is distributed as a t with n degrees of freedom.

For the special case $n = 1$, the Breit-Wigner distribution, generate u_1 and u_2; set $v_1 = 2u_1 - 1$ and $v_2 = 2u_2 - 1$. If $v_1^2 + v_2^2 \leq 1$ accept $z = v_1/v_2$ as a Breit-Wigner distribution with unit area, center at 0.0, and FWHM 2.0. Otherwise start over. For center M_0 and FWHM Γ, use $W = z\Gamma/2 + M_0$.

References:

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8. L. Devroye, *Non-Uniform Random Variate Generation* (Springer-Verlag, New York, 1986).
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10. F. James, Rept. on Prog. in Phys. **43**, 1145 (1980).

30. MONTE CARLO PARTICLE NUMBERING SCHEME

Updated May 1996 by G.R. Lynch and T.G. Trippe.

- NOTE: We have received a proposal for a significant revision to our numbering scheme. The revision would include numbering for particles expected in the quark model but not yet discovered and for hypothetical states such as supersymmetric particles. The proposal was developed by the QCD Monte Carlo Event Generators working group of a LEP2 Workshop in 1995 and conveyed to us by Ian Knowles and Torbjorn Sjöstrand [1]. Lynn Garren, who is responsible for the STDHEP standard [2] at Fermilab, is also involved. We will put this proposal on the Particle Data Group WWW page (`http://pdg.lbl.gov/`) in the near future to invite comment and to provide information on the status of its acceptance.

Most particle physics Monte Carlo and analysis systems use a numbering scheme to represent particles. The lack of standardization of such schemes inhibits interfacing different programs. The following table proposes a standard numbering scheme. Some of the properties of this scheme are:

1. Quarks and leptons are ordered by family, and within the family, by isospin. This puts the u and d in the opposite order than is often used in other numbering schemes. In our scheme we call the highest numbered quark the heaviest quark.
2. For multiple quark systems (mesons, baryons, and diquarks), the rightmost digit is generally $L = 2J + 1$. (The K_S^0 and K_L^0 are exceptions.) Particles with $J > 4$ have not been assigned numbers.
3. Mesons are represented by the form NML and baryons by $NMKL$, where N, M, and K are quark numbers.
4. For these systems the highest quark number (see quark list below) is usually on the left and the quarks are in decreasing order of quark number from left to right. One exception to this convention is the K_L^0-K_S^0 pair. A second exception is for the Λ's for which we invert the up and down quarks to distinguish the Λ from the Σ^0.
5. The other exception to this quark-number order rule is for some N's and Δ's. For N's, the u and d quark are reversed for spins 3/2 and 7/2. For Δ's, they are reversed for spins 1/2 and 5/2. The quarks are in the normal decreasing order when $I + J$ is odd.
6. Mesons, and only mesons, have the third digit nonzero and the fourth digit zero. (We designate the rightmost digit as the first digit.)
7. Only baryons and diquarks have the fourth digit nonzero.
8. Only quarks and diquarks have the second digit equal to zero.
9. Particles have positive numbers; each antiparticle has the negative of its counterpart.
10. The particle-antiparticle convention is the one used by the Particle Data Group, so that the K^+ and B^+ are particles.
11. The above rules imply that for mesons (as opposed to anti-mesons), when the number of the leftmost (heaviest) quark is even, it is a quark, and when the number of the leftmost quark is odd, it is an antiquark.
12. The gluon has two numbers. Its official number is 21 to place it with the other gauge bosons. Its number is also 9 so that a glueball is specified as 99.
13. The fifth digit is used to differentiate different particles with the same quark content and spin.
14. Although isospin is not manifest in this scheme, the isospin of any hadron can be determined from the number. Mesons with $11L$ are isospin 1 and those with $22L$ are isospin 0. For nonstrange baryons, if the quarks are in the normal decreasing order, then $I + J$ is odd, otherwise $I + J$ is even. If a strange baryon does not have the normal decreasing quark order, it has $I = 0$.

More details about the motivation behind, and properties of, this scheme can be found in Ref. 3. Although this scheme has the advantage that a particle's number has considerable physics content, it has the disadvantage that it is not compact. An algorithm that translates this scheme into a more compact scheme is needed for its implementation. Contact the Berkeley Particle Data Group for further information on such an algorithm.

A list of particle numbers follows.

References:

1. I. Knowles *et al.*, QCD Event Generators Report, LEP2 Workshop, 1995, CERN Yellow Report 96-01, vol. 2, p. 103.
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3. T.G. Trippe and G.R. Lynch, "Particle I.D. Numbers, Decay Tables, and Other Possible Contributions of the Particle Data Group to Monte Carlo Standards," LBL-24287, in *Proceedings of the Workshop on Detector Simulation for the SSC* (August 1987).

QUARKS

d	1
u	2
s	3
c	4
b	5
t	6

GAUGE AND HIGGS BOSONS

γ	22
W	24
Z	23
g	21 and 9
H_1^0	25
H_2^0	35
H_3^0	36
H^+	37

LEPTONS

ν_e	12
ν_μ	14
ν_τ	16
e	11
μ	13
τ	15

DIQUARKS

$(dd)_1$	1103
$(ud)_0$	2101
$(ud)_1$	2103
$(uu)_1$	2203
$(sd)_0$	3101
$(sd)_1$	3103
$(su)_0$	3201
$(su)_1$	3203

MESONS

π^+	211
π^0	111
η	221
$f_0(400\text{–}1200)$	60221
$\rho(770)$	113, 213
$\omega(782)$	223
$\eta'(958)$	331
$f_0(980)$	10221
$a_0(980)$	10111, 10211
$\phi(1020)$	333
$h_1(1170)$	10223
$b_1(1235)$	10113, 10213
$a_1(1260)$	20113, 20213
$f_2(1270)$	225
$f_1(1285)$	20223

MESONS (Cont'd)

$\eta(1295)$	20221
$\pi(1300)$	20111, 20211
$a_2(1320)$	115, 215
$f_0(1370)$	30221
$f_1(1420)$	30223
$\omega(1420)$	50223
$\eta(1440)$	40221
$\rho(1450)$	40113, 40213
$f_0(1500)$	50221
$f_1(1510)$	40223
$f'_2(1525)$	335
$\omega(1600)$	60223
$\omega_3(1670)$	227
$\pi_2(1670)$	10115, 10215
$\phi(1680)$	10333
$\rho_3(1690)$	117, 217
$\rho(1700)$	30113, 30213
$f_J(1710)$	30113, 30213
$\phi_3(1850)$	337
$f_2(2010)$	20225
$f_4(2050)$	229
$f_2(2300)$	30225
$f_2(2340)$	40225
K^+	321
K^0	311
K^0_S	310
K^0_L	130
$K^*(892)$	313, 323
$K_1(1270)$	10313, 10323
$K_1(1400)$	20313, 20323
$K^*(1410)$	30313, 30323
$K^*_0(1430)$	10311, 10321
$K^*_2(1430)$	315, 325
$K^*(1680)$	40313, 40323
$K_2(1770)$	10315, 10325
$K^*_3(1780)$	317, 327
$K_2(1820)$	20315, 20325
$K^*_4(2045)$	319, 329
D^+	411
D^0	421
$D^*(2007)^0$	423
$D^*(2010)^+$	413
$D_1(2420)^0$	10423
$D^*_2(2460)^0$	425
$D^*_2(2460)^+$	415
D^+_s	431
D^{*+}_s	433
$D_{s1}(2536)^+$	10433
B^+	521
B^0	511
B^*	513, 523
B^0_s	531

MESONS (Cont'd)

$\eta_c(1S)$	441
$J/\psi(1S)$	443
$\chi_{c0}(1P)$	10441
$\chi_{c1}(1P)$	10443
$\chi_{c2}(1P)$	445
$\psi(2S)$	20443
$\psi(3770)$	30443
$\psi(4040)$	40443
$\psi(4160)$	50443
$\psi(4415)$	60443
$\Upsilon(1S)$	553
$\chi_{b0}(1P)$	551
$\chi_{b1}(1P)$	10553
$\chi_{b2}(1P)$	555
$\Upsilon(2S)$	20553
$\chi_{b0}(2P)$	10551
$\chi_{b1}(2P)$	70553
$\chi_{b2}(2P)$	10555
$\Upsilon(3S)$	30553
$\Upsilon(4S)$	40553
$\Upsilon(10860)$	50553
$\Upsilon(11020)$	60553

BARYONS

p	P_{11}	2212
n	P_{11}	2112
$N(1440)$	P_{11}	12112, 12212
$N(1520)$	D_{13}	1214, 2124
$N(1535)$	S_{11}	22112, 22212
$N(1650)$	S_{11}	32112, 32212
$N(1675)$	D_{15}	2116, 2216
$N(1680)$	F_{15}	12116, 12216
$N(1700)$	D_{13}	21214, 22124
$N(1710)$	P_{11}	42112, 42212
$N(1720)$	P_{13}	31214, 32124
$N(2190)$	G_{17}	1218, 2128
$\Delta(1232)$	P_{33}	1114, 2114, 2214, 2224
$\Delta(1600)$	P_{33}	31114, 32114, 32214, 32224
$\Delta(1620)$	S_{31}	1112, 1212, 2122, 2222
$\Delta(1700)$	D_{33}	11114, 12114, 12214, 12224
$\Delta(1900)$	S_{31}	11112, 11212, 12122, 12222
$\Delta(1905)$	F_{35}	1116, 1216, 2126, 2226
$\Delta(1910)$	P_{31}	21112, 21212, 22122, 22222
$\Delta(1920)$	P_{33}	21114, 22114, 22214, 22224
$\Delta(1930)$	D_{35}	11116, 11216, 12126, 12226
$\Delta(1950)$	F_{37}	1118, 2118, 2218, 2228

BARYONS (Cont'd)

Λ	P_{01}	3122
$\Lambda(1405)$	S_{01}	13122
$\Lambda(1520)$	D_{03}	3124
$\Lambda(1600)$	P_{01}	23122
$\Lambda(1670)$	S_{01}	33122
$\Lambda(1690)$	D_{03}	13124
$\Lambda(1800)$	S_{01}	43122
$\Lambda(1810)$	P_{01}	53122
$\Lambda(1820)$	F_{05}	3126
$\Lambda(1830)$	D_{05}	13126
$\Lambda(1890)$	P_{03}	23124
$\Lambda(2100)$	G_{07}	3128
$\Lambda(2110)$	F_{05}	23126
Σ^+	P_{11}	3222
Σ^0	P_{11}	3212
Σ^-	P_{11}	3112
$\Sigma(1385)$	P_{13}	3114, 3214, 3224
$\Sigma(1660)$	P_{11}	13112, 13212, 13222
$\Sigma(1670)$	D_{13}	13114, 13214, 13224
$\Sigma(1750)$	S_{11}	23112, 23212, 23222
$\Sigma(1775)$	D_{15}	3116, 3216, 3226
$\Sigma(1915)$	F_{15}	13116, 13216, 13226
$\Sigma(1940)$	D_{13}	23114, 23214, 23224
$\Sigma(2030)$	F_{17}	3118, 3218, 3228
Ξ^0	P_{11}	3322
Ξ^-	P_{11}	3312
$\Xi(1530)$	P_{13}	3314, 3324
$\Xi(1820)$	D_{13}	13314, 13324
Ω^-		3334
Λ^+_c		4122
$\Lambda_c(2593)^+$		14122
$\Sigma_c(2455)$		4112, 4212, 4222
Ξ^+_c		4322
Ξ^0_c		4312
Ω^0_c		4332
Λ^0_b		5122

31. CLEBSCH-GORDAN COEFFICIENTS, SPHERICAL HARMONICS, AND d FUNCTIONS

Note: A square-root sign is to be understood over *every* coefficient, *e.g.*, for −8/15 read $-\sqrt{8/15}$.

Notation:

		J	J	...
		M	M	...
m_1	m_2			
m_1	m_2	Coefficients		
.	.			
.	.			

1/2×1/2

m_1	m_2	J=1, M=+1
+1/2	+1/2	1

m_1	m_2	J=1, M=0	J=0, M=0
+1/2	−1/2	1/2	1/2
−1/2	+1/2	1/2	−1/2

m_1	m_2	J=1, M=−1
−1/2	−1/2	1

1×1/2

m_1	m_2	J=3/2, M=+3/2
+1	+1/2	1

m_1	m_2	J=3/2, M=+1/2	J=1/2, M=+1/2
+1	−1/2	1/3	2/3
0	+1/2	2/3	−1/3

m_1	m_2	J=3/2, M=−1/2	J=1/2, M=−1/2
0	−1/2	2/3	1/3
−1	+1/2	1/3	−2/3

m_1	m_2	J=3/2, M=−3/2
−1	−1/2	1

2×1

m_1	m_2	J=3, M=+3
+2	+1	1

m_1	m_2	J=3, M=+2	J=2, M=+2
+2	0	1/3	2/3
+1	+1	2/3	−1/3

m_1	m_2	J=3, M=+1	J=2, M=+1	J=1, M=+1
+2	−1	1/15	1/3	3/5
+1	0	8/15	1/6	−3/10
0	+1	6/15	−1/2	1/10

m_1	m_2	J=3, M=0	J=2, M=0	J=1, M=0
+1	−1	1/5	1/2	3/10
0	0	3/5	0	−2/5
−1	+1	1/5	−1/2	3/10

m_1	m_2	J=3, M=−1	J=2, M=−1	J=1, M=−1
0	−1	6/15	1/2	1/10
−1	0	8/15	−1/6	−3/10
−2	+1	1/15	−1/3	3/5

m_1	m_2	J=3, M=−2	J=2, M=−2
−1	−1	2/3	1/3
−2	0	1/3	−2/3

m_1	m_2	J=3, M=−3
−2	−1	1

1×1

m_1	m_2	J=2, M=+2
+1	+1	1

m_1	m_2	J=2, M=+1	J=1, M=+1
+1	0	1/2	1/2
0	+1	1/2	−1/2

m_1	m_2	J=2, M=0	J=1, M=0	J=0, M=0
+1	−1	1/6	1/2	1/3
0	0	2/3	0	−1/3
−1	+1	1/6	−1/2	1/3

m_1	m_2	J=2, M=−1	J=1, M=−1
0	−1	1/2	1/2
−1	0	1/2	−1/2

m_1	m_2	J=2, M=−2
−1	−1	1

$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\sin\theta\, e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta\, e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\phi}$$

$$Y_\ell^{-m} = (-1)^m Y_\ell^{m*}$$

$$d^\ell_{m,0} = \sqrt{\frac{4\pi}{2\ell+1}}\, Y_\ell^m\, e^{-im\phi}$$

2×1/2

m_1	m_2	J=5/2, M=+5/2
+2	1/2	1

m_1	m_2	J=5/2, M=+3/2	J=3/2, M=+3/2
+2	−1/2	1/5	4/5
+1	+1/2	4/5	−1/5

m_1	m_2	J=5/2, M=+1/2	J=3/2, M=+1/2
+1	−1/2	2/5	3/5
0	+1/2	3/5	−2/5

m_1	m_2	J=5/2, M=−1/2	J=3/2, M=−1/2
0	−1/2	3/5	2/5
−1	+1/2	2/5	−3/5

m_1	m_2	J=5/2, M=−3/2	J=3/2, M=−3/2
−1	−1/2	4/5	1/5
−2	+1/2	1/5	−4/5

m_1	m_2	J=5/2, M=−5/2
−2	−1/2	1

3/2×1/2

m_1	m_2	J=2, M=+2
+3/2	+1/2	1

m_1	m_2	J=2, M=+1	J=1, M=+1
+3/2	−1/2	1/4	3/4
+1/2	+1/2	3/4	−1/4

m_1	m_2	J=2, M=0	J=1, M=0
+1/2	−1/2	1/2	1/2
−1/2	+1/2	1/2	−1/2

m_1	m_2	J=2, M=−1	J=1, M=−1
−1/2	−1/2	3/4	1/4
−3/2	+1/2	1/4	−3/4

m_1	m_2	J=2, M=−2
−3/2	−1/2	1

3/2×1

m_1	m_2	J=5/2, M=+5/2
+3/2	+1	1

m_1	m_2	J=5/2, M=+3/2	J=3/2, M=+3/2
+3/2	0	2/5	3/5
+1/2	+1	3/5	−2/5

m_1	m_2	J=5/2, M=+1/2	J=3/2, M=+1/2	J=1/2, M=+1/2
+3/2	−1	1/10	2/5	1/2
+1/2	0	3/5	1/15	−1/3
−1/2	+1	3/10	−8/15	1/6

m_1	m_2	J=5/2, M=−1/2	J=3/2, M=−1/2	J=1/2, M=−1/2
+1/2	−1	3/10	8/15	1/6
−1/2	0	3/5	−1/15	−1/3
−3/2	+1	1/10	−2/5	1/2

m_1	m_2	J=5/2, M=−3/2	J=3/2, M=−3/2
−1/2	−1	3/5	2/5
−3/2	0	2/5	−3/5

m_1	m_2	J=5/2, M=−5/2
−3/2	−1	1

$$\langle j_1 j_2 m_1 m_2 | j_1 j_2 J M\rangle = (-1)^{J-j_1-j_2}\langle j_2 j_1 m_2 m_1 | j_2 j_1 J M\rangle$$

$$d^j_{m',m} = (-1)^{m-m'} d^j_{m,m'} = d^j_{-m,-m'}$$

$$d^1_{0,0} = \cos\theta \qquad d^{1/2}_{1/2,1/2} = \cos\frac{\theta}{2} \qquad d^1_{1,1} = \frac{1+\cos\theta}{2}$$

$$d^{1/2}_{1/2,-1/2} = -\sin\frac{\theta}{2} \qquad d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}}$$

$$d^1_{1,-1} = \frac{1-\cos\theta}{2}$$

3/2×3/2

m_1	m_2	J=3, M=+3
+3/2	+3/2	1

m_1	m_2	J=3, M=+2	J=2, M=+2
+3/2	+1/2	1/2	1/2
+1/2	+3/2	1/2	−1/2

m_1	m_2	J=3, M=+1	J=2, M=+1	J=1, M=+1
+3/2	−1/2	1/5	1/2	3/10
+1/2	+1/2	3/5	0	−2/5
−1/2	+3/2	1/5	−1/2	3/10

m_1	m_2	J=3, M=0	J=2, M=0	J=1, M=0	J=0, M=0
+3/2	−3/2	1/20	1/4	9/20	1/4
+1/2	−1/2	9/20	1/4	−1/20	−1/4
−1/2	+1/2	9/20	−1/4	−1/20	1/4
−3/2	+3/2	1/20	−1/4	9/20	−1/4

m_1	m_2	J=3, M=−1	J=2, M=−1	J=1, M=−1
+1/2	−3/2	1/5	1/2	3/10
−1/2	−1/2	3/5	0	−2/5
−3/2	+1/2	1/5	−1/2	3/10

m_1	m_2	J=3, M=−2	J=2, M=−2
−1/2	−3/2	1/2	1/2
−3/2	−1/2	1/2	−1/2

m_1	m_2	J=3, M=−3
−3/2	−3/2	1

2×3/2

m_1	m_2	J=7/2, M=+7/2
+2	+3/2	1

m_1	m_2	J=7/2, M=+5/2	J=5/2, M=+5/2
+2	+1/2	3/7	4/7
+1	+3/2	4/7	−3/7

m_1	m_2	J=7/2, M=+3/2	J=5/2, M=+3/2	J=3/2, M=+3/2
+2	−1/2	1/7	16/35	2/5
+1	1/2	4/7	1/35	−2/5
0	3/2	2/7	−18/35	1/5

m_1	m_2	J=7/2, M=+1/2	J=5/2, M=+1/2	J=3/2, M=+1/2	J=1/2, M=+1/2
+2	−3/2	1/35	6/35	2/5	2/5
+1	−1/2	12/35	5/14	0	−3/10
0	1/2	18/35	−3/35	−1/5	1/5
−1	3/2	4/35	−27/70	2/5	−1/10

m_1	m_2	J=7/2, M=−1/2	J=5/2, M=−1/2	J=3/2, M=−1/2	J=1/2, M=−1/2
+1	−3/2	4/35	27/70	2/5	1/10
0	−1/2	18/35	3/35	−1/5	−1/5
−1	1/2	12/35	−5/14	0	3/10
−2	3/2	1/35	−6/35	2/5	−2/5

m_1	m_2	J=7/2, M=−3/2	J=5/2, M=−3/2	J=3/2, M=−3/2
0	−3/2	2/7	18/35	1/5
−1	−1/2	4/7	−1/35	−2/5
−2	1/2	1/7	−16/35	2/5

m_1	m_2	J=7/2, M=−5/2	J=5/2, M=−5/2
−1	−3/2	4/7	3/7
−2	−1/2	3/7	−4/7

m_1	m_2	J=7/2, M=−7/2
−2	−3/2	1

2×2

m_1	m_2	J=4, M=+4
+2	+2	1

m_1	m_2	J=4, M=+3	J=3, M=+3
+2	+1	1/2	1/2
+1	+2	1/2	−1/2

m_1	m_2	J=4, M=+2	J=3, M=+2	J=2, M=+2
+2	0	3/14	1/2	2/7
+1	1	4/7	0	−3/7
0	2	3/14	−1/2	2/7

m_1	m_2	J=4, M=+1	J=3, M=+1	J=2, M=+1	J=1, M=+1
+2	−1	1/14	3/10	3/7	1/5
+1	0	3/7	1/5	−1/14	−3/10
0	1	3/7	−1/5	−1/14	3/10
−1	2	1/14	−3/10	3/7	−1/5

m_1	m_2	J=4, M=0	J=3, M=0	J=2, M=0	J=1, M=0	J=0, M=0
+2	−2	1/70	1/10	2/7	2/5	1/5
+1	−1	8/35	2/5	1/14	−1/10	−1/5
0	0	18/35	0	−2/7	0	1/5
−1	1	8/35	−2/5	1/14	1/10	−1/5
−2	2	1/70	−1/10	2/7	−2/5	1/5

m_1	m_2	J=4, M=−1	J=3, M=−1	J=2, M=−1	J=1, M=−1
+1	−2	1/14	3/10	3/7	1/5
0	−1	3/7	1/5	−1/14	−3/10
−1	0	3/7	−1/5	−1/14	3/10
−2	1	1/14	−3/10	3/7	−1/5

m_1	m_2	J=4, M=−2	J=3, M=−2	J=2, M=−2
0	−2	3/14	1/2	2/7
−1	−1	4/7	0	−3/7
−2	0	3/14	−1/2	2/7

m_1	m_2	J=4, M=−3	J=3, M=−3
−1	−2	1/2	1/2
−2	−1	1/2	−1/2

m_1	m_2	J=4, M=−4
−2	−2	1

$$d^{3/2}_{3/2,3/2} = \frac{1+\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{3/2,1/2} = -\sqrt{3}\,\frac{1+\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3,2}_{3/2,-1/2} = \sqrt{3}\,\frac{1-\cos\theta}{2}\cos\frac{\theta}{2}$$

$$d^{3,2}_{3/2,-3/2} = -\frac{1-\cos\theta}{2}\sin\frac{\theta}{2}$$

$$d^{3/2}_{1/2,1/2} = \frac{3\cos\theta-1}{2}\cos\frac{\theta}{2}$$

$$d^{3/2}_{1/2,-1/2} = -\frac{3\cos\theta+1}{2}\sin\frac{\theta}{2}$$

$$d^2_{2,2} = \left(\frac{1+\cos\theta}{2}\right)^2$$

$$d^2_{2,1} = -\frac{1+\cos\theta}{2}\sin\theta$$

$$d^2_{2,0} = \frac{\sqrt{6}}{4}\sin^2\theta$$

$$d^2_{2,-1} = -\frac{1-\cos\theta}{2}\sin\theta$$

$$d^2_{2,-2} = \left(\frac{1-\cos\theta}{2}\right)^2$$

$$d^2_{1,1} = \frac{1+\cos\theta}{2}(2\cos\theta-1)$$

$$d^2_{1,0} = -\sqrt{\frac{3}{2}}\sin\theta\cos\theta$$

$$d^2_{1,-1} = \frac{1-\cos\theta}{2}(2\cos\theta+1)$$

$$d^2_{0,0} = \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

Figure 31.1: The sign convention is that of Wigner (*Group Theory*, Academic Press, New York, 1959), also used by Condon and Shortley (*The Theory of Atomic Spectra*, Cambridge Univ. Press, New York, 1953), Rose (*Elementary Theory of Angular Momentum*, Wiley, New York, 1957), and Cohen (*Tables of the Clebsch-Gordan Coefficients*, North American Rockwell Science Center, Thousand Oaks, Calif., 1974). The coefficients here have been calculated using computer programs written independently by Cohen and at LBNL.

32. SU(3) ISOSCALAR FACTORS AND REPRESENTATION MATRICES

The most commonly used SU(3) isoscalar factors, corresponding to the singlet, octet, and decuplet content of $8 \otimes 8$ and $10 \otimes 8$, are shown at the right. The notation uses particle names to identify the coefficients, so that the pattern of relative couplings may be seen at a glance. We illustrate the use of the coefficients below. See J.J de Swart, Rev. Mod. Phys. **35**, 916 (1963) for detailed explanations and phase conventions.

A $\sqrt{\ }$ *is to be understood over every integer in the matrices;* the exponent 1/2 on each matrix is a reminder of this. For example, the $\Xi \to \Omega K$ element of the $10 \to 10 \otimes 8$ matrix is $-\sqrt{6}/\sqrt{24} = -1/2$.

Intramultiplet relative decay strengths may be read directly from the matrices. For example, in decuplet → octet + octet decays, the ratio of $\Omega^* \to \Xi\overline{K}$ and $\Delta \to N\pi$ partial widths is, from the $10 \to 8 \times 8$ matrix,

$$\frac{\Gamma\left(\Omega^* \to \Xi\overline{K}\right)}{\Gamma\left(\Delta \to N\pi\right)} = \frac{12}{6} \times \text{(phase space factors)} \ . \qquad (32.1)$$

Including isospin Clebsch-Gordan coefficients, we obtain, *e.g.*,

$$\frac{\Gamma(\Omega^{*-} \to \Xi^0 K^-)}{\Gamma(\Delta^+ \to p\,\pi^0)} = \frac{1/2}{2/3} \times \frac{12}{6} \times p.s.f. = \frac{3}{2} \times p.s.f. \qquad (32.2)$$

Partial widths for $8 \to 8 \otimes 8$ involve a linear superposition of 8_1 (symmetric) and 8_2 (antisymmetric) couplings. For example,

$$\Gamma(\Xi^* \to \Xi\pi) \sim \left(-\sqrt{\frac{9}{20}}\, g_1 + \sqrt{\frac{3}{12}}\, g_2\right)^2 \ . \qquad (32.3)$$

The relations between g_1 and g_2 (with de Swart's normalization) and the standard D and F couplings that appear in the interaction Lagrangian,

$$\mathscr{L} = -\sqrt{2}\, D\, Tr\,(\{\overline{B}, B\}M) + \sqrt{2}\, F\, Tr\,([\overline{B}, B]\,M) \ , \qquad (32.4)$$

where $[\overline{B}, B] \equiv \overline{B}B - B\overline{B}$ and $\{\overline{B}, B\} \equiv \overline{B}B + B\overline{B}$, are

$$D = \frac{\sqrt{30}}{40}\, g_1 \ , \qquad F = \frac{\sqrt{6}}{24}\, g_2 \ . \qquad (32.5)$$

Thus, for example,

$$\Gamma(\Xi^* \to \Xi\pi) \sim (F - D)^2 \sim (1 - 2\alpha)^2 \ , \qquad (32.6)$$

where $\alpha \equiv D/(D + F)$.

The generators of SU(3) transformations, λ_a $(a = 1, 8)$, are 3×3 matrices that obey the following commutation and anticommutation relationships:

$$[\lambda_a,\ \lambda_b] \equiv \lambda_a\lambda_b - \lambda_b\lambda_a = 2i f_{abc}\lambda_c \qquad (32.7)$$

$$\{\lambda_a,\ \lambda_b\} \equiv \lambda_a\lambda_b + \lambda_b\lambda_a = \frac{4}{3}\delta_{ab} I + 2d_{abc}\lambda_c \ , \qquad (32.8)$$

where I is the 3×3 identity matrix, and δ_{ab} is the Kronecker delta symbol. The f_{abc} are odd under the permutation of any pair of indices, while the d_{abc} are even. The nonzero values are

1 → 8 ⊗ 8

$$(\Lambda) \to (N\overline{K}\ \ \Sigma\pi\ \ \Lambda\eta\ \ \Xi K) = \frac{1}{\sqrt{8}}\,(2\ \ 3\ \ -1\ \ -2)^{1/2}$$

8₁ → 8 ⊗ 8

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi\ \ N\eta\ \ \Sigma K\ \ \Lambda K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\pi\ \ \Sigma\eta\ \ \Xi K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\eta\ \ \Xi K \\ \Sigma\overline{K}\ \ \Lambda\overline{K}\ \ \Xi\pi\ \ \Xi\eta \end{pmatrix} = \frac{1}{\sqrt{20}} \begin{pmatrix} 9 & -1 & -9 & -1 & \\ -6 & 0 & 4 & 4 & -6 \\ 2 & -12 & -4 & -2 & \\ 9 & -1 & -9 & -1 & \end{pmatrix}^{1/2}$$

8₂ → 8 ⊗ 8

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi\ \ N\eta\ \ \Sigma K\ \ \Lambda K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\pi\ \ \Sigma\eta\ \ \Xi K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\eta\ \ \Xi K \\ \Sigma\overline{K}\ \ \Lambda\overline{K}\ \ \Xi\pi\ \ \Xi\eta \end{pmatrix} = \frac{1}{\sqrt{12}} \begin{pmatrix} 3 & 3 & 3 & -3 & \\ 2 & 8 & 0 & 0 & -2 \\ 6 & 0 & 0 & 6 & \\ 3 & 3 & 3 & -3 & \end{pmatrix}^{1/2}$$

10 → 8 ⊗ 8

$$\begin{pmatrix} \Delta \\ \Sigma \\ \Xi \\ \Omega \end{pmatrix} \to \begin{pmatrix} N\pi\ \ \Sigma K \\ N\overline{K}\ \ \Sigma\pi\ \ \Lambda\pi\ \ \Sigma\eta\ \ \Xi K \\ \Sigma\overline{K}\ \ \Lambda\overline{K}\ \ \Xi\pi\ \ \Xi\eta \\ \Xi\overline{K} \end{pmatrix} = \frac{1}{\sqrt{12}} \begin{pmatrix} -6\ \ 6 \\ -2\ \ 2\ \ -3\ \ 3\ \ 2 \\ 3\ \ -3\ \ 3\ \ 3 \\ 12 \end{pmatrix}^{1/2}$$

8 → 10 ⊗ 8

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} \Delta\pi\ \ \Sigma K \\ \Delta\overline{K}\ \ \Sigma\pi\ \ \Sigma\eta\ \ \Xi K \\ \Sigma\pi\ \ \Xi K \\ \Sigma\overline{K}\ \ \Xi\pi\ \ \Xi\eta\ \ \Omega K \end{pmatrix} = \frac{1}{\sqrt{15}} \begin{pmatrix} -12\ \ 3 \\ 8\ \ -2\ \ -3\ \ 2 \\ -9\ \ 6 \\ 3\ \ -3\ \ -3\ \ 6 \end{pmatrix}^{1/2}$$

10 → 10 ⊗ 8

$$\begin{pmatrix} \Delta \\ \Sigma \\ \Xi \\ \Omega \end{pmatrix} \to \begin{pmatrix} \Delta\pi\ \ \Delta\eta\ \ \Sigma K \\ \Delta\overline{K}\ \ \Sigma\pi\ \ \Sigma\eta\ \ \Xi K \\ \Sigma\overline{K}\ \ \Xi\pi\ \ \Xi\eta\ \ \Omega K \\ \Xi\overline{K}\ \ \Omega\eta \end{pmatrix} = \frac{1}{\sqrt{24}} \begin{pmatrix} 15\ \ 3\ \ -6 \\ 8\ \ 8\ \ 0\ \ -8 \\ 12\ \ 3\ \ -3\ \ -6 \\ 12\ \ -12 \end{pmatrix}^{1/2}$$

abc	f_{abc}	abc	d_{abc}	abc	d_{abc}
123	1	118	$1/\sqrt{3}$	355	$1/2$
147	$1/2$	146	$1/2$	366	$-1/2$
156	$-1/2$	157	$1/2$	377	$-1/2$
246	$1/2$	228	$1/\sqrt{3}$	448	$-1/(2\sqrt{3})$
257	$1/2$	247	$-1/2$	558	$-1/(2\sqrt{3})$
345	$1/2$	256	$1/2$	668	$-1/(2\sqrt{3})$
367	$-1/2$	338	$1/\sqrt{3}$	778	$-1/(2\sqrt{3})$
458	$\sqrt{3}/2$	344	$1/2$	888	$-1/\sqrt{3}$
678	$\sqrt{3}/2$				

The λ_a's are

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Equation (32.7) defines the Lie algebra of SU(3). A general d-dimensional representation is given by a set of $d \times d$ matrices satisfying Eq. (32.7) with the f_{abc} given above. Equation (32.8) is specific to the defining 3-dimensional representation.

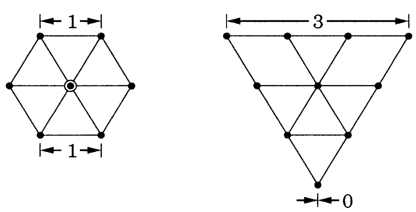
33. SU(n) MULTIPLETS AND YOUNG DIAGRAMS

This note tells (1) how SU(n) particle multiplets are identified or labeled, (2) how to find the number of particles in a multiplet from its label, (3) how to draw the Young diagram for a multiplet, and (4) how to use Young diagrams to determine the overall multiplet structure of a composite system, such as a 3-quark or a meson-baryon system.

In much of the literature, the word "representation" is used where we use "multiplet," and "tableau" is used where we use "diagram."

33.1. Multiplet labels

An SU(n) multiplet is uniquely identified by a string of $(n-1)$ nonnegative integers: $(\alpha, \beta, \gamma, \ldots)$. Any such set of integers specifies a multiplet. For an SU(2) multiplet such as an isospin multiplet, the single integer α is the number of *steps* from one end of the multiplet to the other (*i.e.*, it is one fewer than the number of particles in the multiplet). In SU(3), the two integers α and β are the numbers of steps across the top and bottom levels of the multiplet diagram. Thus the labels for the SU(3) octet and decuplet



are (1,1) and (3,0). For larger n, the interpretation of the integers in terms of the geometry of the multiplets, which exist in an $(n-1)$-dimensional space, is not so readily apparent.

The label for the SU(n) singlet is $(0, 0, \ldots, 0)$. In a flavor SU(n), the n quarks together form a $(1, 0, \ldots, 0)$ multiplet, and the n antiquarks belong to a $(0, \ldots, 0, 1)$ multiplet. These two multiplets are *conjugate* to one another, which means their labels are related by $(\alpha, \beta, \ldots) \leftrightarrow (\ldots, \beta, \alpha)$.

33.2. Number of particles

The number of particles in a multiplet, $N = N(\alpha, \beta, \ldots)$, is given as follows (note the pattern of the equations).

In SU(2), $N = N(\alpha)$ is

$$N = \frac{(\alpha + 1)}{1} \; . \tag{33.1}$$

In SU(3), $N = N(\alpha, \beta)$ is

$$N = \frac{(\alpha + 1)}{1} \cdot \frac{(\beta + 1)}{1} \cdot \frac{(\alpha + \beta + 2)}{2} \; . \tag{33.2}$$

In SU(4), $N = N(\alpha, \beta, \gamma)$ is

$$N = \frac{(\alpha{+}1)}{1} \cdot \frac{(\beta{+}1)}{1} \cdot \frac{(\gamma{+}1)}{1} \cdot \frac{(\alpha{+}\beta{+}2)}{2} \cdot \frac{(\beta{+}\gamma{+}2)}{2} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}3)}{3} \; . \tag{33.3}$$

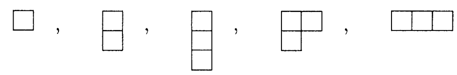
Note that in Eq. (33.3) there is no factor with $(\alpha + \gamma + 2)$: only a *consecutive* sequence of the label integers appears in any factor. One more example should make the pattern clear for any SU(n). In SU(5), $N = N(\alpha, \beta, \gamma, \delta)$ is

$$N = \frac{(\alpha{+}1)}{1} \cdot \frac{(\beta{+}1)}{1} \cdot \frac{(\gamma{+}1)}{1} \cdot \frac{(\delta{+}1)}{1} \cdot \frac{(\alpha{+}\beta{+}2)}{2} \cdot \frac{(\beta{+}\gamma{+}2)}{2}$$
$$\times \frac{(\gamma{+}\delta{+}2)}{2} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}3)}{3} \cdot \frac{(\beta{+}\gamma{+}\delta{+}3)}{3} \cdot \frac{(\alpha{+}\beta{+}\gamma{+}\delta{+}4)}{4} \; . \tag{33.4}$$

From the symmetry of these equations, it is clear that multiplets that are conjugate to one another have the same number of particles, but so can other multiplets. For example, the SU(4) multiplets (3,0,0) and (1,1,0) each have 20 particles. Try the equations and see.

33.3. Young diagrams

A Young diagram consists of an array of boxes (or some other symbol) arranged in one or more *left-justified* rows, with each row being *at least as long* as the row beneath. The correspondence between a diagram and a multiplet label is: The top row juts out α boxes to the right past the end of the second row, the second row juts out β boxes to the right past the end of the third row, *etc.* A diagram in SU(n) has at most n rows. There can be any number of "completed" columns of n boxes buttressing the left of a diagram; these don't affect the label. Thus in SU(3) the diagrams

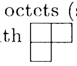


represent the multiplets (1,0), (0,1), (0,0), (1,1), and (3,0). In any SU(n), the quark multiplet is represented by a single box, the antiquark multiplet by a column of $(n-1)$ boxes, and a singlet by a completed column of n boxes.

33.4. Coupling multiplets together

The following recipe tells how to find the multiplets that occur in coupling two multiplets together. To couple together more than two multiplets, first couple two, then couple a third with each of the multiplets obtained from the first two, *etc.*

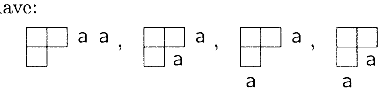
First a definition: A sequence of the letters $a, b, c, \ldots$ is *admissible* if at any point in the sequence at least as many a's have occurred as b's, at least as many b's have occurred as c's, *etc.* Thus *abcd* and *aabcb* are admissible sequences and *abb* and *acb* are not. Now the recipe:

(a) Draw the Young diagrams for the two multiplets, but in one of the diagrams replace the boxes in the first row with a's, the boxes in the second row with b's, *etc.* Thus, to couple two SU(3) octets (such as the π-meson octet and the baryon octet), we start with  and

a a
b

. The *unlettered* diagram forms the *upper left-hand corner* of all the enlarged diagrams constructed below.

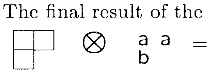
(b) Add the a's from the lettered diagram to the right-hand ends of the rows of the unlettered diagram to form all possible legitimate Young diagrams that have no more than one a per column. In general, there will be several distinct diagrams, and all the a's appear in each diagram. At this stage, for the coupling of the two SU(3) octets, we have:

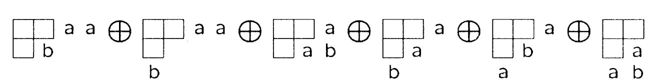


(c) Use the b's to further enlarge the diagrams already obtained, subject to the same rules. Then throw away any diagram in which the full sequence of letters formed by reading *right to left* in the first row, then the second row, *etc.*, is not admissible.

(d) Proceed as in (c) with the c's (if any), *etc.*

The final result of the coupling of the two SU(3) octets is:





Here only the diagrams with admissible sequences of a's and b's and with fewer than four rows (since $n = 3$) have been kept. In terms of multiplet labels, the above may be written

$$(1,1) \otimes (1,1) = (2,2) \oplus (3,0) \oplus (0,3) \oplus (1,1) \oplus (1,1) \oplus (0,0) \; .$$

In terms of numbers of particles, it may be written

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1} \; .$$

The product of the numbers on the left here is equal to the sum on the right, a useful check. (See also Sec. 12 on the Quark Model.)

34. KINEMATICS

Revised May 1996.

Throughout this section units are used in which $\hbar = c = 1$. The following conversions are useful: $\hbar c = 197.3$ MeV fm, $(\hbar c)^2 = 0.3894$ (GeV)^2 mb.

34.1. Lorentz transformations

The energy E and 3-momentum $\boldsymbol{p}$ of a particle of mass m form a 4-vector $p = (E, \boldsymbol{p})$ whose square $p^2 \equiv E^2 - |\boldsymbol{p}|^2 = m^2$. The velocity of the particle is $\boldsymbol{\beta} = \boldsymbol{p}/E$. The energy and momentum $(E^*, \boldsymbol{p}^*)$ viewed from a frame moving with velocity $\boldsymbol{\beta}_f$ are given by

$$\begin{pmatrix} E^* \\ p^*_{\|} \end{pmatrix} = \begin{pmatrix} \gamma_f & -\gamma_f\beta_f \\ -\gamma_f\beta_f & \gamma_f \end{pmatrix} \begin{pmatrix} E \\ p_{\|} \end{pmatrix}, \quad p^*_T = p_T , \tag{34.1}$$

where $\gamma_f = (1 - \beta_f^2)^{-1/2}$ and p_T $(p_{\|})$ are the components of $\boldsymbol{p}$ perpendicular (parallel) to $\boldsymbol{\beta}_f$. Other 4-vectors, such as the space-time coordinates of events, of course transform in the same way. The scalar product of two 4-momenta $p_1 \cdot p_2 = E_1 E_2 - \boldsymbol{p}_1 \cdot \boldsymbol{p}_2$ is invariant (frame independent).

34.2. Center-of-mass energy and momentum

In the collision of two particles of masses m_1 and m_2 the total center-of-mass energy can be expressed in the Lorentz-invariant form

$$\begin{aligned} E_{\rm cm} &= \left[(E_1 + E_2)^2 - (\boldsymbol{p}_1 + \boldsymbol{p}_2)^2\right]^{1/2} , \\ &= \left[m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta)\right]^{1/2} , \end{aligned} \tag{34.2}$$

where θ is the angle between the particles. In the frame where one particle (of mass m_2) is at rest (lab frame),

$$E_{\rm cm} = (m_1^2 + m_2^2 + 2E_{1\,\rm lab}\, m_2)^{1/2} . \tag{34.3}$$

The velocity of the center-of-mass in the lab frame is

$$\boldsymbol{\beta}_{\rm cm} = \boldsymbol{p}_{\rm lab}/(E_{1\,\rm lab} + m_2) , \tag{34.4}$$

where $\boldsymbol{p}_{\rm lab} \equiv \boldsymbol{p}_{1\,\rm lab}$ and

$$\gamma_{\rm cm} = (E_{1\,\rm lab} + m_2)/E_{\rm cm} . \tag{34.5}$$

The c.m. momenta of particles 1 and 2 are of magnitude

$$p_{\rm cm} = p_{\rm lab}\frac{m_2}{E_{\rm cm}} . \tag{34.6}$$

For example, if a 0.80 GeV/c kaon beam is incident on a proton target, the center of mass energy is 1.699 GeV and the center of mass momentum of either particle is 0.442 GeV/c. It is also useful to note that

$$E_{\rm cm}\, dE_{\rm cm} = m_2\, dE_{1\,\rm lab} = m_2\, \beta_{1\,\rm lab}\, dp_{\rm lab} . \tag{34.7}$$

34.3. Lorentz-invariant amplitudes

The matrix elements for a scattering or decay process are written in terms of an invariant amplitude $-i\mathscr{M}$. As an example, the S-matrix for $2 \to 2$ scattering is related to $\mathscr{M}$ by

$$\begin{aligned} \langle p_1' p_2' \, |S| \, p_1 p_2 \rangle &= I - i(2\pi)^4\, \delta^4(p_1 + p_2 - p_1' - p_2') \\ &\times \frac{\mathscr{M}(p_1, p_2; p_1', p_2')}{(2E_1)^{1/2}\,(2E_2)^{1/2}\,(2E_1')^{1/2}\,(2E_2')^{1/2}} . \end{aligned} \tag{34.8}$$

The state normalization is such that

$$\langle p' | p \rangle = (2\pi)^3 \delta^3(\boldsymbol{p} - \boldsymbol{p}') . \tag{34.9}$$

34.4. Particle decays

The partial decay rate of a particle of mass M into n bodies in its rest frame is given in terms of the Lorentz-invariant matrix element $\mathscr{M}$ by

$$d\Gamma = \frac{(2\pi)^4}{2M}\, |\mathscr{M}|^2\, d\Phi_n\,(P;\, p_1, \ldots, p_n), \tag{34.10}$$

where $d\Phi_n$ is an element of n-body phase space given by

$$d\Phi_n(P;\, p_1, \ldots, p_n) = \delta^4\,(P - \sum_{i=1}^n p_i) \prod_{i=1}^n \frac{d^3 p_i}{(2\pi)^3 2E_i} . \tag{34.11}$$

This phase space can be generated recursively, viz.

$$\begin{aligned} d\Phi_n(P;\, p_1, \ldots, p_n) &= d\Phi_j(q;\, p_1, \ldots, p_j) \\ &\times\, d\Phi_{n-j+1}\,(P;\, q, p_{i+1}, \ldots, p_n)(2\pi)^3 dq^2 , \end{aligned} \tag{34.12}$$

where $q^2 = (\sum_{i=1}^j E_i)^2 - \left|\sum_{i=1}^j \boldsymbol{p}_i\right|^2$. This form is particularly useful in the case where a particle decays into another particle that subsequently decays.

34.4.1. ***Survival probability***: If a particle of mass M has mean proper lifetime τ $(= 1/\Gamma)$ and has momentum $(E, \boldsymbol{p})$, then the probability that it lives for a time t_0 or greater before decaying is given by

$$P(t_0) = e^{-t_0\,\Gamma/\gamma} = e^{-Mt_0\,\Gamma/E} , \tag{34.13}$$

and the probability that it travels a distance x_0 or greater is

$$P(x_0) = e^{-Mx_0\,\Gamma/|\boldsymbol{p}|} . \tag{34.14}$$

34.4.2. ***Two-body decays***:

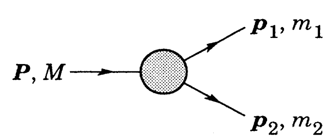


Figure 34.1: Definitions of variables for two-body decays.

In the rest frame of a particle of mass M, decaying into 2 particles labeled 1 and 2,

$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} , \tag{34.15}$$

$$\begin{aligned} |\boldsymbol{p}_1| &= |\boldsymbol{p}_2| \\ &= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M} , \end{aligned} \tag{34.16}$$

and

$$d\Gamma = \frac{1}{32\pi^2}\, |\mathscr{M}|^2\, \frac{|\boldsymbol{p}_1|}{M^2}\, d\Omega , \tag{34.17}$$

where $d\Omega = d\phi_1 d(\cos\theta_1)$ is the solid angle of particle 1.

34.4.3. *Three-body decays*:

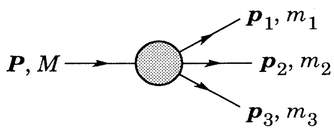


Figure 34.2: Definitions of variables for three-body decays.

Defining $p_{ij} = p_i + p_j$ and $m_{ij}^2 = p_{ij}^2$, then $m_{12}^2 + m_{23}^2 + m_{13}^2 = M^2 + m_1^2 + m_2^2 + m_3^2$ and $m_{12}^2 = (P - p_3)^2 = M^2 + m_3^2 - 2ME_3$, where E_3 is the energy of particle 3 in the rest frame of M. In that frame, the momenta of the three decay particles lie in a plane. The relative orientation of these three momenta is fixed if their energies are known. The momenta can therefore be specified in space by giving three Euler angles (α, β, γ) that specify the orientation of the final system relative to the initial particle. Then

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M} |\mathscr{M}|^2 \, dE_1 \, dE_2 \, d\alpha \, d(\cos\beta) \, d\gamma \, . \tag{34.18}$$

Alternatively

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M^2} |\mathscr{M}|^2 \, |\boldsymbol{p}_1^*| \, |\boldsymbol{p}_3| \, dm_{12} \, d\Omega_1^* \, d\Omega_3 \, , \tag{34.19}$$

where $(|\boldsymbol{p}_1^*|, \Omega_1^*)$ is the momentum of particle 1 in the rest frame of 1 and 2, and Ω_3 is the angle of particle 3 in the rest frame of the decaying particle. $|\boldsymbol{p}_1^*|$ and $|\boldsymbol{p}_3|$ are given by

$$|\boldsymbol{p}_1^*| = \frac{\left[\left(m_{12}^2 - (m_1 + m_2)^2\right)\left(m_{12}^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2m_{12}} \, , \tag{34.20a}$$

and

$$|\boldsymbol{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2\right)\left(M^2 - (m_{12} - m_3)^2\right)\right]^{1/2}}{2M} \, . \tag{34.20b}$$

[Compare with Eq. (34.16).]

If the decaying particle is a scalar or we average over its spin states, then integration over the angles in Eq. (34.18) gives

$$\begin{aligned} d\Gamma &= \frac{1}{(2\pi)^3} \frac{1}{8M} \overline{|\mathscr{M}|^2} \, dE_1 \, dE_2 \\ &= \frac{1}{(2\pi)^3} \frac{1}{32M^3} \overline{|\mathscr{M}|^2} \, dm_{12}^2 \, dm_{23}^2 \, . \end{aligned} \tag{34.21}$$

This is the standard form for the Dalitz plot.

34.4.3.1. *Dalitz plot:* For a given value of m_{12}^2, the range of m_{23}^2 is determined by its values when $\boldsymbol{p}_2$ is parallel or antiparallel to $\boldsymbol{p}_3$:

$$(m_{23}^2)_{\max} = (E_2^* + E_3^*)^2 - \left(\sqrt{E_2^{*2} - m_2^2} - \sqrt{E_3^{*2} - m_3^2}\right)^2 \, , \tag{34.22a}$$

$$(m_{23}^2)_{\min} = (E_2^* + E_3^*)^2 - \left(\sqrt{E_2^{*2} - m_2^2} + \sqrt{E_3^{*2} - m_3^2}\right)^2 \, . \tag{34.22b}$$

Here $E_2^* = (m_{12}^2 - m_1^2 + m_2^2)/2m_{12}$ and $E_3^* = (M^2 - m_{12}^2 - m_3^2)/2m_{12}$ are the energies of particles 2 and 3 in the m_{12} rest frame. The scatter plot in m_{12}^2 and m_{23}^2 is called a Dalitz plot. If $\overline{|\mathscr{M}|^2}$ is constant, the allowed region of the plot will be uniformly populated with events [see Eq. (34.21)]. A nonuniformity in the plot gives immediate information on $|\mathscr{M}|^2$. For example, in the case of $D \to K\pi\pi$, bands appear when $m_{(K\pi)} = m_{K^*(892)}$, reflecting the appearance of the decay chain $D \to K^*(892)\pi \to K\pi\pi$.

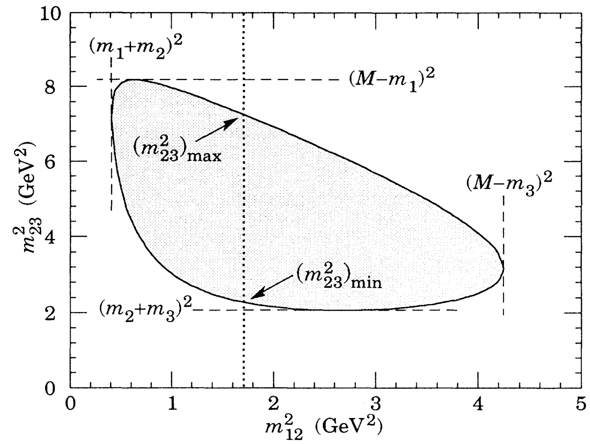


Figure 34.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+ \overline{K}^0 p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

34.4.4. *Kinematic limits*: In a three-body decay the maximum of $|\boldsymbol{p}_3|$, [given by Eq. (34.20)], is achieved when $m_{12} = m_1 + m_2$, *i.e.*, particles 1 and 2 have the same vector velocity in the rest frame of the decaying particle. If, in addition, $m_3 > m_1, m_2$, then $|\boldsymbol{p}_3|_{\max} > |\boldsymbol{p}_1|_{\max}, |\boldsymbol{p}_2|_{\max}$.

34.4.5. *Multibody decays*: The above results may be generalized to final states containing any number of particles by combining some of the particles into "effective particles" and treating the final states as 2 or 3 "effective particle" states. Thus, if $p_{ijk\ldots} = p_i + p_j + p_k + \ldots$, then

$$m_{ijk\ldots} = \sqrt{p^2{}_{ijk\ldots}} \, , \tag{34.23}$$

and $m_{ijk\ldots}$ may be used in place of *e.g.*, m_{12} in the relations in Sec. 34.4.3 or 34.4.3.1 above.

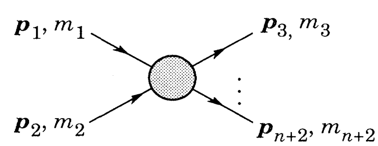


Figure 34.4: Definitions of variables for production of an n-body final state.

34.5. Cross sections

The differential cross section is given by

$$d\sigma = \frac{(2\pi)^4 |\mathscr{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi_n(p_1 + p_2; \, p_3, \ldots, p_{n+2}) \, . \tag{34.24}$$

[See Eq. (34.11).] In the rest frame of m_2(lab),

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = m_2 p_{1\,\text{lab}} \, ; \tag{34.25a}$$

while in the center-of-mass frame

$$\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2} = p_{1\text{cm}} \sqrt{s} \, . \tag{34.25b}$$

34.5.1. *Two-body reactions*:

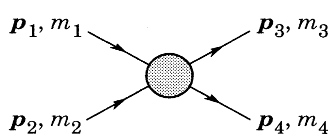


Figure 34.5: Definitions of variables for a two-body final state.

Two particles of momenta p_1 and p_2 and masses m_1 and m_2 scatter to particles of momenta p_3 and p_4 and masses m_3 and m_4; the Lorentz-invariant Mandelstam variables are defined by

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2 = m_1^2 + 2E_1E_2 - 2\boldsymbol{p}_1 \cdot \boldsymbol{p}_2 + m_2^2 \ , \tag{34.26}$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2 = m_1^2 - 2E_1E_3 + 2\boldsymbol{p}_1 \cdot \boldsymbol{p}_3 + m_3^2 \ , \tag{34.27}$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2 = m_1^2 - 2E_1E_4 + 2\boldsymbol{p}_1 \cdot \boldsymbol{p}_4 + m_4^2 \ , \tag{34.28}$$

and they satisfy

$$s + t + u = m_1^2 + m_2^2 + m_3^2 + m_4^2 \ . \tag{34.29}$$

The two-body cross section may be written as

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\boldsymbol{p}_{1\text{cm}}|^2} |\mathscr{M}|^2 \ . \tag{34.30}$$

In the center-of-mass frame

$$\begin{aligned} t &= (E_{1\text{cm}} - E_{3\text{cm}})^2 - (p_{1\text{cm}} - p_{3\text{cm}})^2 \\ &\quad -4p_{1\text{cm}}\, p_{3\text{cm}} \sin^2(\theta_{\text{cm}}/2) \\ &= t_0 - 4p_{1\text{cm}}\, p_{3\text{cm}} \sin^2(\theta_{\text{cm}}/2) \ , \end{aligned} \tag{34.31}$$

where θ_{cm} is the angle between particle 1 and 3. The limiting values t_0 ($\theta_{\text{cm}} = 0$) and t_1 ($\theta_{\text{cm}} = \pi$) for $2 \to 2$ scattering are

$$t_0(t_1) = \left[\frac{m_1^2 - m_3^2 - m_2^2 + m_4^2}{2\sqrt{s}}\right]^2 - (p_{1\,\text{cm}} \mp p_{3\,\text{cm}})^2 \ . \tag{34.32}$$

In the literature the notation t_{min} (t_{max}) for t_0 (t_1) is sometimes used, which should be discouraged since $t_0 > t_1$. The center-of-mass energies and momenta of the incoming particles are

$$E_{1\text{cm}} = \frac{s + m_1^2 - m_2^2}{2\sqrt{s}} \ , \qquad E_{2\text{cm}} = \frac{s + m_2^2 - m_1^2}{2\sqrt{s}} \ , \tag{34.33}$$

For $E_{3\text{cm}}$ and $E_{4\text{cm}}$, change m_1 to m_3 and m_2 to m_4. Then

$$p_{i\,\text{cm}} = \sqrt{E_{i\,\text{cm}}^2 - m_i^2} \text{ and } p_{1\text{cm}} = \frac{p_{1\,\text{lab}}\, m_2}{\sqrt{s}} \ . \tag{34.34}$$

Here the subscript lab refers to the frame where particle 2 is at rest. [For other relations see Eqs. (34.2)–(34.4).]

34.5.2. *Inclusive reactions*:

Choose some direction (usually the beam direction) for the z-axis; then the energy and momentum of a particle can be written as

$$E = m_T \cosh y \ , \ p_x \ , \ p_y \ , \ p_z = m_T \sinh y \ , \tag{34.35}$$

where m_T is the transverse mass

$$m_T^2 = m^2 + p_x^2 + p_y^2 \ , \tag{34.36}$$

and the rapidity y is defined by

$$\begin{aligned} y &= \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z}\right) \\ &= \ln \left(\frac{E + p_z}{m_T}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right) \ . \end{aligned} \tag{34.37}$$

Under a boost in the z-direction to a frame with velocity β, $y \to y - \tanh^{-1}\beta$. Hence the shape of the rapidity distribution dN/dy is invariant. The invariant cross section may also be rewritten

$$E\frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi\, dy\, p_T dp_T} \Longrightarrow \frac{d^2\sigma}{\pi\, dy\, d(p_T^2)} \ . \tag{34.38}$$

The second form is obtained using the identity $dy/dp_z = 1/E$, and the third form represents the average over ϕ.

Feynman's x variable is given by

$$x = \frac{p_z}{p_{z\,\text{max}}} \approx \frac{E + p_z}{(E + p_z)_{\text{max}}} \quad (p_T \ll |p_z|) \ . \tag{34.39}$$

In the c.m. frame,

$$x \approx \frac{2p_{z\,\text{cm}}}{\sqrt{s}} = \frac{2m_T \sinh y_{\text{cm}}}{\sqrt{s}} \tag{34.40}$$

and

$$= (y_{\text{cm}})_{\text{max}} = \ln(\sqrt{s}/m) \ . \tag{34.41}$$

For $p \gg m$, the rapidity [Eq. (34.37)] may be expanded to obtain

$$\begin{aligned} y &= \frac{1}{2} \ln \frac{\cos^2(\theta/2) + m^2/4p^2 + \ldots}{\sin^2(\theta/2) + m^2/4p^2 + \ldots} \\ &\approx -\ln \tan(\theta/2) \equiv \eta \end{aligned} \tag{34.42}$$

where $\cos\theta = p_z/p$. The pseudorapidity η defined by the second line is approximately equal to the rapidity y for $p \gg m$ and $\theta \gg 1/\gamma$, and in any case can be measured when the mass and momentum of the particle is unknown. From the definition one can obtain the identities

$$\sinh\eta = \cot\theta \ , \quad \cosh\eta = 1/\sin\theta \ , \quad \tanh\eta = \cos\theta \ . \tag{34.43}$$

34.5.3. *Partial waves*:

The amplitude in the center of mass for elastic scattering of spinless particles may be expanded in Legendre polynomials

$$f(k, \theta) = \frac{1}{k} \sum_\ell (2\ell + 1) a_\ell P_\ell(\cos\theta) \ , \tag{34.44}$$

where k is the c.m. momentum, θ is the c.m. scattering angle, $a_\ell = (\eta_\ell e^{2i\delta_\ell} - 1)/2i$, $0 \le \eta_\ell \le 1$, and δ_ℓ is the phase shift of the ℓ^{th} partial wave. For purely elastic scattering, $\eta_\ell = 1$. The differential cross section is

$$\frac{d\sigma}{d\Omega} = |f(k, \theta)|^2 \ . \tag{34.45}$$

The optical theorem states that

$$\sigma_{\text{tot}} = \frac{4\pi}{k} \text{Im} f(k, 0) \ , \tag{34.46}$$

and the cross section in the ℓ^{th} partial wave is therefore bounded:

$$\sigma_\ell = \frac{4\pi}{k^2}(2\ell + 1)|a_\ell|^2 \le \frac{4\pi(2\ell + 1)}{k^2} \ . \tag{34.47}$$

The evolution with energy of a partial-wave amplitude a_ℓ can be displayed as a trajectory in an Argand plot, as shown in Fig. 34.6.

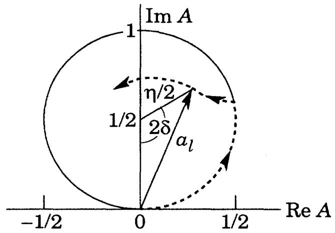


Figure 34.6: Argand plot showing a partial-wave amplitude a_ℓ as a function of energy. The amplitude leaves the unitary circle where inelasticity sets in ($\eta_\ell < 1$).

The usual Lorentz-invariant matrix element $\mathscr{M}$ (see Sec. 34.3 above) for the elastic process is related to $f(k,\theta)$ by

$$\mathscr{M} = -8\pi\sqrt{s}\, f(k,\theta) \ , \tag{34.48}$$

so

$$\sigma_{\rm tot} = -\frac{1}{2p_{\rm lab}\, m_2}\, {\rm Im}\, \mathscr{M}(t=0) \ , \tag{34.49}$$

where s and t are the center-of-mass energy squared and momentum transfer squared, respectively (see Sec. 34.4.1).

34.5.3.1. *Resonances:* The Breit-Wigner (nonrelativistic) form for an elastic amplitude a_ℓ with a resonance at c.m. energy E_R, elastic width $\Gamma_{\rm el}$, and total width $\Gamma_{\rm tot}$ is

$$a_\ell = \frac{\Gamma_{\rm el}/2}{E_R - E - i\Gamma_{\rm tot}/2} \ , \tag{34.50}$$

where E is the c.m. energy. As shown in Fig. 34.7, in the absence of background the elastic amplitude traces a counterclockwise circle with center $ix_{\rm el}/2$ and radius $x_{\rm el}/2$, where the elasticity $x_{\rm el} = \Gamma_{\rm el}/\Gamma_{\rm tot}$. The amplitude has a pole at $E = E_R - i\Gamma_{\rm tot}/2$.

The spin-averaged Breit-Wigner cross section for a spin-J resonance produced in the collision of particles of spin S_1 and S_2 is

$$\sigma_{BW}(E) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)}\frac{\pi}{k^2}\frac{B_{\rm in}B_{\rm out}\Gamma^2_{\rm tot}}{(E-E_R)^2+\Gamma^2_{\rm tot}/4} \ , \tag{34.51}$$

where k is the c.m. momentum, E is the c.m. energy, and $B_{\rm in}$ and $B_{\rm out}$ are the branching fractions of the resonance into the entrance and exit channels. The $2S+1$ factors are the multiplicities of the incident spin states, and are replaced by 2 for photons. This expression is valid only for an isolated state. If the width is not small, $\Gamma_{\rm tot}$ cannot be treated as a constant independent of E. There are many other forms for σ_{BW}, all of which are equivalent to the one given here in the narrow-width case. Some of these forms may be more appropriate if the resonance is broad.

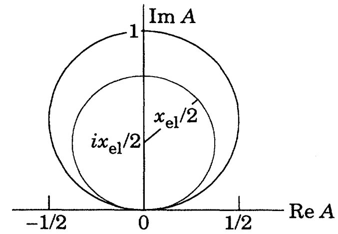


Figure 34.7: Argand plot for a resonance.

The relativistic Breit-Wigner form corresponding to Eq. (34.50) is:

$$a_\ell = \frac{-m\Gamma_{\rm el}}{s - m^2 + im\Gamma_{\rm tot}} \ . \tag{34.52}$$

A better form incorporates the known kinematic dependences, replacing $m\Gamma_{\rm tot}$ by $\sqrt{s}\,\Gamma_{\rm tot}(s)$, where $\Gamma_{\rm tot}(s)$ is the width the resonance particle would have if its mass were $\sqrt{s}$, and correspondingly $m\Gamma_{\rm el}$ by $\sqrt{s}\,\Gamma_{\rm el}(s)$ where $\Gamma_{\rm el}(s)$ is the partial width in the incident channel for a mass $\sqrt{s}$:

$$a_\ell = \frac{-\sqrt{s}\,\Gamma_{\rm el}(s)}{s - m^2 + i\sqrt{s}\,\Gamma_{\rm tot}(s)} \ . \tag{34.53}$$

For the Z boson, all the decays are to particles whose masses are small enough to be ignored, so on dimensional grounds $\Gamma_{\rm tot}(s) = \sqrt{s}\,\Gamma_0/m_Z$, where Γ_0 defines the width of the Z, and $\Gamma_{\rm el}(s)/\Gamma_{\rm tot}(s)$ is constant. A full treatment of the line shape requires consideration of dynamics, not just kinematics. For the Z this is done by calculating the radiative corrections in the Standard Model.

35. CROSS-SECTION FORMULAE FOR SPECIFIC PROCESSES

35.1. Leptoproduction

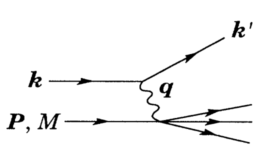


Figure 35.1: Kinematic quantities for description of lepton-nucleon scattering. k and k' are the four-momenta of incoming and outgoing leptons, P is the four-momentum of a nucleon with mass M. The exchanged particle is a γ, $W^{\pm}$, or Z^0; it transfers four-momentum $q = k - k'$ to the target.

Invariant quantities:

$\nu = \dfrac{q \cdot P}{M} = E - E'$ is the lepton's energy loss in the lab (in earlier literature sometimes $\nu = q \cdot P$). Here, E and E' are the initial and final lepton energies in the lab.

$Q^2 = -q^2 = 2(EE' - \overrightarrow{k} \cdot \overrightarrow{k}') - m_\ell^2 - m_{\ell'}^2$ where $m_\ell(m_{\ell'})$ is the initial (final) lepton mass. If $EE' \sin^2(\theta/2) \gg m_\ell^2,\, m_{\ell'}^2$, then

$\approx 4EE' \sin^2(\theta/2)$, where θ is the lepton's scattering angle in the lab.

$x = \dfrac{Q^2}{2M\nu}$ In the parton model, x is the fraction of the target nucleon's momentum carried by the struck quark. [See section on Quantum Chromodynamics (Sec. 9 of this *Review*.]

$y = \dfrac{q \cdot P}{k \cdot P} = \dfrac{\nu}{E}$ is the fraction of the lepton's energy lost in the lab.

$W^2 = (P+q)^2 = M^2 + 2M\nu - Q^2$ is the mass squared of the system recoiling against the lepton.

$s = (k+P)^2 = \dfrac{Q^2}{xy} + M^2$

35.1.1. *Leptoproduction cross sections*:

$$\frac{d^2\sigma}{dx\,dy} = \nu\,(s - M^2)\,\frac{d^2\sigma}{d\nu\,dQ^2} = \frac{2\pi\,M\nu}{E'}\,\frac{d^2\sigma}{d\Omega_{\rm lab}\,dE'}$$
$$= x(s - M^2)\,\frac{d^2\sigma}{dx\,dQ^2}\,. \tag{35.1}$$

35.1.2. *Electroproduction structure functions*:

The neutral-current process, $eN \to eX$, is parity conserving at low Q^2 and can be written in terms of two structure functions $F_1^{\rm NC}(x,Q^2)$ and $F_2^{\rm NC}(x,Q^2)$:

$$\frac{d^2\sigma}{dx\,dy} = \frac{4\pi\,\alpha^2(s - M^2)}{Q^4}$$
$$\times \left[(1-y)\,F_2^{\rm NC} + y^2\,xF_1^{\rm NC} - \frac{M^2}{(s-M^2)}\,xy\,F_2^{\rm NC}\right]\,. \tag{35.2}$$

The charged-current processes, $e^-N \to \nu X$, $\nu N \to e^-X$, and $\overline{\nu}N \to e^+X$, are parity violating and can be written in terms of three structure functions $F_1^{\rm CC}(x,Q^2)$, $F_2^{\rm CC}(x,Q^2)$, and $F_3^{\rm CC}(x,Q^2)$:

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2\,(s-M^2)}{2\pi}\,\frac{M_W^4}{(Q^2+M_W^2)^2} \tag{35.3}$$
$$\times\left\{\left[1 - y - \frac{M^2xy}{(s-M^2)}\right]F_2^{\rm CC} + \frac{y^2}{2}\,2x\,F_1^{\rm CC} \pm (y - \frac{y^2}{2})\,x\,F_3^{\rm CC}\right\}\,,$$

where the last term is positive for the e^- and ν reactions and negative for $\overline{\nu}N \to e^+X$.

35.1.3. *The QCD parton model*:

In the QCD parton model, the structure functions defined above can be expressed in terms of parton distribution functions. The quantity $f_i(x,Q^2)dx$ is the probability that a parton of type i (quark, antiquark, or gluon), carries a momentum fraction between x and $x+dx$ of the nucleon's momentum in a frame where the nucleon's momentum is large. For the cross section corresponding to the *neutral-current process* $ep \to eX$, we have for $s \gg M^2$ (in the case where the incoming electron is either left- (L) or right- (R) handed):

$$\frac{d^2\sigma}{dx\,dy} = \frac{\pi\alpha^2}{sx^2\,y^2}\left[\sum_q (x\,f_q\,(x,\,Q^2) + x\,f_{\overline{q}}\,(x,\,Q^2)\right]$$
$$\times\left[A_q + (1-y)^2\,B_q\right]\,. \tag{35.4}$$

Here the index q refers to a quark flavor (*i.e.*, u, d, s, c, b, or t), and

$$A_q = \left(-q_q + g_{Lq}\,g_{Le}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 + \left(-q_q + g_{Rq}\,g_{Re}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2, \tag{35.5}$$

$$B_q = \left(-q_q + g_{Rq}\,g_{Le}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2 + \left(-q_q + g_{Lq}\,g_{Re}\,\frac{Q^2}{Q^2+M_Z^2}\right)^2. \tag{35.6}$$

Here q_q is the charge of flavor q. For a left-handed electron, $g_{Re} = 0$ and $g_{Le} = (-1/2 + \sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$, while for a right-handed one, $g_{Le} = 0$ and $g_{Re} = (\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$. For the quarks, $g_{Lq} = (T_3 - q_q\sin^2\theta_W)/(\sin\theta_W\cos\theta_W)$, and $g_{Rq} = (-q_q\sin^2\theta_W)\,/\,(\sin\theta_W\cos\theta_W)$.

For neutral-current *neutrino* (*antineutrino*) *scattering*, the same formula applies with g_{Le} replaced by $g_{L\nu} = 1/(2\sin\theta_W\cos\theta_W)$ ($g_{L\overline{\nu}} = 0$) and g_{Re} replaced by $g_{R\nu} = 0$ [$g_{R\overline{\nu}} = -1/(2\sin\theta_W\cos\theta_W)$].

In the case of the *charged-current processes* $e_L^-p \to \nu X$ and $\overline{\nu}p \to e^+X$, Eq. (35.3) applies with

$$F_2 = 2xF_1 = 2x\Big[f_u(x,Q^2) + f_c(x,Q^2)$$
$$+\; f_t(x,Q^2) + f_{\overline{d}}\,(x,Q^2) + f_{\overline{s}}\,(x,Q^2) + f_{\overline{b}}\,(x,Q^2)\Big]\,, \tag{35.7}$$

$$F_3 = 2\Big[f_u(x,Q^2) + f_c(x,Q^2)$$
$$+\; f_t(x,Q^2) - f_{\overline{d}}\,(x,Q^2) - f_{\overline{s}}\,(x,Q^2) - f_{\overline{b}}\,(x,Q^2)\Big]\,. \tag{35.8}$$

For the process $\nu p \to e^-X$:

$$F_2 = 2xF_1 = 2x\Big[f_d(x,Q^2) + f_s(x,Q^2)$$
$$+\; f_b(x,Q^2) + f_{\overline{u}}\,(x,Q^2) + f_{\overline{c}}\,(x,Q^2) + f_{\overline{t}}\,(x,Q^2)\Big]\,, \tag{35.9}$$

$$F_3 = 2\Big[f_d(x,Q^2) + f_s(x,Q^2)$$
$$+\; f_b(x,Q^2) - f_{\overline{u}}\,(x,Q^2) - f_{\overline{c}}\,(x,Q^2) - f_{\overline{t}}\,(x,Q^2)\Big]\,. \tag{35.10}$$

35.2. e^+e^- annihilation

For pointlike spin-1/2 fermions in the c.m., the differential cross section for $e^+e^- \to f\bar{f}$ via single photon annihilation is

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\,\beta\,\left[1+\cos^2\theta + (1-\beta^2)\sin^2\theta\right] Q_f^2\ , \tag{35.11}$$

where β is the velocity of the final state fermion in the center of mass and Q_f is the charge of the fermion in units of the proton charge. For $\beta \to 1$,

$$\sigma = \frac{4\pi\alpha^2}{3s}\,Q_f^2 = \frac{86.8\,Q_f^2\ nb}{s(\mathrm{GeV}^2)}\ . \tag{35.12}$$

At higher energies the Z^0 (mass M_Z and width Γ_Z) must be included, and the differential cross section for $e^+e^- \to f\bar{f}$ becomes

$$\begin{aligned}\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\,\beta\,\Big[&Q_f^2[1+\cos^2\theta+(1-\beta^2)\sin^2\theta]\\ &-2Q_f\,\chi_1\Big\{VV_f\,[1+\cos^2\theta+(1-\beta^2)\sin^2\theta]-2a_f\,\beta\cos\theta\Big\}\\ &+\chi_2\Big\{V_f^2\,(1+V^2)\,[1+\cos^2\theta+(1-\beta^2)\sin^2\theta]\\ &+\beta^2\,a_f^2(1+V^2)\,[1+\cos^2\theta]-8\beta\,VV_f\,a_f\cos\theta\Big\}\Big]\ ,\end{aligned} \tag{35.13}$$

$$\chi_1 = \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\ \frac{s(s-M_Z^2)}{(s-M_Z^2)^2+\Gamma_Z^2M_Z^2}\ , \tag{35.14}$$

$$\chi_2 = \frac{1}{256\sin^4\theta_W\cos^4\theta_W}\ \frac{s^2}{(s-M_Z^2)^2+\Gamma_Z^2M_Z^2}\ , \tag{35.15}$$

$$V = -1+4\sin^2\theta_W\ , \tag{35.16}$$

$$a_f = 2T_{3f}\ , \tag{35.17}$$

$$V_f = 2T_{3f}-4Q_f\sin^2\theta_W\ , \tag{35.18}$$

where the subscript f refers to the particular fermion and

$$T_3 = +1/2 \quad \text{for } \nu_e,\ \nu_\mu,\ \nu_\tau,\ u,\ c,\ t, \tag{35.19a}$$

$$T_3 = -1/2 \quad \text{for } e^-,\ \mu^-,\ \tau^-,\ d,\ s,\ b. \tag{35.19b}$$

35.3. Two-photon process at e^+e^- colliders

When an e^+ and an e^- collide with energies E_1 and E_2, they emit dn_1 and dn_2 virtual photons with energies ω_1 and ω_2 and 4-momenta q_1 and q_2. In the equivalent photon approximation, the cross section for $e^+e^- \to e^+e^-X$ is related to the cross section for $\gamma\gamma \to X$ by (Ref. 1)

$$d\sigma_{e^+e^-\to e^+e^-X}\,(s) = dn_1\,dn_2\,d\sigma_{\gamma\gamma\to X}\,(W^2) \tag{35.20}$$

where $s = 4E_1E_2$, $W^2 = 4\omega_1\omega_2$ and

$$dn_i = \frac{\alpha}{\pi}\left[1-\frac{\omega_i}{E_i}+\frac{\omega_i^2}{2E_i^2}-\frac{m_e^2\omega_i^2}{(-q_i^2)E_i^2}\right]\frac{d\omega_i}{\omega_i}\,\frac{d(-q_i^2)}{(-q_i^2)}\ . \tag{35.21}$$

After integration (including that over q_i^2 in the region $m_e^2\omega_i^2/E_i(E_i-\omega_i) \le -q_i^2 \le (-q^2)_{\max}$), the cross section is

$$\begin{aligned}\sigma_{e^+e^-\to e^+e^-X}\,(s) = &\frac{\alpha^2}{\pi^2}\int_{z_{th}}^1\frac{dz}{z}\left[f(z)\left(\ln\frac{(-q^2)_{\max}}{m_e^2 z}-1\right)^2\right.\\ &\left.-\tfrac{1}{3}\left(\ln\frac{1}{z}\right)^3\right]\sigma_{\gamma\gamma\to X}\,(zs)\ ;\\ f(z) = &\left(1+\tfrac{1}{2}z\right)^2\ln\frac{1}{z}-\tfrac{1}{2}(1-z)(3+z)\ ;\\ z = &\frac{W^2}{s}\ .\end{aligned} \tag{35.22}$$

The quantity $(-q^2)_{\max}$ depends on properties of the produced system X, in particular, $(-q^2)_{\max} \sim m_\rho^2$ for hadron production ($X = h$) and $(-q^2)_{\max} \sim W^2$ for lepton pair production ($X = \ell^+\ell^-$, $\ell = e,\ \mu,\ \tau$).

For production of a resonance of mass m_R and spin $J \neq 1$

$$\begin{aligned}\sigma_{e^+e^-\to e^+e^-R}\,(s) = &(2J+1)\frac{8\alpha^2\Gamma_{R\to\gamma\gamma}}{m_R^3}\\ &\times\left[f(m_R^2/s)\left(\ln\frac{sm_V^2}{m_e^2m_R^2}-1\right)^2-\frac{1}{3}\left(\ln\frac{s}{m_R^2}\right)^3\right]\end{aligned} \tag{35.23}$$

where m_V is the mass that enters into the form factor of the $\gamma\gamma \to R$ transition: $m_V \sim m_\rho$ for $R = \pi^0,\ \rho^0,\ \omega,\ \phi,\ \ldots$, $m_V \sim m_R$ for $R = c\bar{c}$ or $b\bar{b}$ resonances.

35.4. Inclusive hadronic reactions

One-particle inclusive cross sections $Ed^3\sigma/d^3p$ for the production of a particle of momentum p are conveniently expressed in terms of rapidity (see above) and the momentum p_T transverse to the beam direction (defined in the center-of-mass frame)

$$E\frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi\,dy\,p_T dp_T}\ . \tag{35.24}$$

In the case of processes where p_T is large or the mass of the produced particle is large (here large means greater than 10 GeV), the parton model can be used to calculate the rate. Symbolically

$$\sigma_{\text{hadronic}} = \sum_{ij}\int f_i(x_1,\,Q^2)\,f_j(x_2,\,Q^2)\,dx_1\,dx_2\,\widehat{\sigma}_{\text{partonic}}\ , \tag{35.25}$$

where $f_i(x,\,Q^2)$ is the parton distribution introduced above and Q is a typical momentum transfer in the partonic process and $\widehat{\sigma}$ is the partonic cross section. Two examples will help to clarify. The production of a W^+ in pp reactions at rapidity y in the center-of-mass frame is given by

$$\begin{aligned}\frac{d\sigma}{dy} = &\frac{G_F\,\pi\sqrt{2}}{3}\\ &\times\tau\Big[\cos^2\theta_c\Big(u(x_1\,,\,M_W^2)\,\bar{d}\,(x_2,M_W^2)\\ &\qquad+u(x_2\,,\,M_W^2)\,\bar{d}\,(x_1,M_W^2)\Big)\\ &\quad+\sin^2\theta_c\Big(u(x_1\,,\,M_W^2)\,\bar{s}\,(x_2\,,\,M_W^2)\\ &\qquad+s(x_2,M_W^2)\,\bar{u}\,(x_1,M_W^2)\Big)\Big]\ ,\end{aligned} \tag{35.26}$$

where $x_1 = \sqrt{\tau}\,e^y$, $x_2 = \sqrt{\tau}\,e^{-y}$, and $\tau = M_W^2/s$. Similarly the production of a jet in pp (or $p\bar{p}$) collisions is given by

$$\begin{aligned}\frac{d^3\sigma}{d^2p_T\,dy} = &\sum_{ij}\int f_i(x_1\,,\,p_T^2)\,f_j(x_2,p_T^2)\\ &\times\left[\widehat{s}\,\frac{d\widehat{\sigma}}{d\widehat{t}}\right]_{ij}dx_1\,dx_2\,\delta(\widehat{s}+\widehat{t}+\widehat{u})\ ,\end{aligned} \tag{35.27}$$

where the summation is over quarks, gluons, and antiquarks. Here

$$s = (p_1 + p_2)^2 , \tag{35.28}$$

$$t = (p_1 - p_{\rm jet})^2 , \tag{35.29}$$

$$u = (p_2 - p_{\rm jet})^2 , \tag{35.30}$$

p_1 and p_2 are the momenta of the incoming p and p (or $\overline{p}$) and $\widehat{s}$, $\widehat{t}$, and $\widehat{u}$ are s, t, and u with $p_1 \to x_1 p_1$ and $p_2 \to x_2 p_2$. The partonic cross section $\widehat{s}\,[\,(d\widehat{\sigma})/(d\widehat{t}\,)\,]$ can be found in Ref. 2. Example: for the process $gg \to q\overline{q}$,

$$\widehat{s}\,\frac{d\sigma}{dt} = 3\alpha_s^2\,\frac{(\widehat{t}^{\,2} + \widehat{u}^2)}{8\widehat{s}}\left[\frac{4}{9\,\widehat{t}\,\widehat{u}} - \frac{1}{\widehat{s}^{\,2}}\right] . \tag{35.31}$$

The prediction of Eq. (35.27) is compared to data from the UA1 and UA2 collaborations in Fig. 36.7 in the Plots of Cross Sections and Related Quantities section of this *Review*.

35.5. One-particle inclusive distributions

In order to describe one-particle inclusive production in e^+e^- annihilation or deep inelastic scattering, it is convenient to introduce a fragmentation function $D_i^h\,(z,Q^2)$ where $D_i^h\,(z,Q^2)$ is the number of hadrons of type h and momentum between zp and $(z + dz)p$ produced in the fragmentation of a parton of type i. The Q^2 evolution is predicted by QCD and is similar to that of the parton distribution functions [see section on Quantum Chromodynamics (Sec. 9 of this *Review*)]. The $D_i^h(z,Q^2)$ are normalized so that

$$\sum_h \int z D_i^h\,(z,Q^2) dz = 1 . \tag{35.32}$$

If the contributions of the Z boson and three-jet events are neglected, the cross section for producing a hadron h in e^+e^- annihilation is given by

$$\frac{1}{\sigma_{\rm had}}\,\frac{d\sigma}{dz} = \frac{\sum_i e_i^2\,D_i^h\,(z,Q^2)}{\sum_i e_i^2} , \tag{35.33}$$

where e_i is the charge of quark-type i, $\sigma_{\rm had}$ is the total hadronic cross section, and the momentum of the hadron is $zE_{\rm cm}/2$.

In the case of deep inelastic muon scattering, the cross section for producing a hadron of energy E_h is given by

$$\frac{1}{\sigma_{\rm tot}}\,\frac{d\sigma}{dz} = \frac{\sum_i e_i^2\,q_i(x,Q^2)\,D_i^h(z,Q^2)}{\sum_i e_i^2\,q_i(x,Q^2)} , \tag{35.34}$$

where $E_h = \nu z$. (For the kinematics of deep inelastic scattering, see Sec. 34.4.2 of the Kinematics section of this *Review*.) The fragmentation functions for light and heavy quarks have a different z dependence; the former peak near $z = 0$. They are illustrated in Fig. 36.13 in the section on Plots of Cross Sections and Related Quantities (Sec. 36 of this *Review*).

References:

1. V.M. Budnev, I.F. Ginzburg, G.V. Meledin, and V.G. Serbo,Phys. Reports **15C**, 181 (1975);

   See also S. Brodsky, T. Kinoshita, and H. Terazawa, Phys. Rev. **D4**, 1532 (1971).

2. G.F. Owens, F. Reya, and M. Glück, Phys. Rev. **D18**, 1501 (1978).

36. PLOTS OF CROSS SECTIONS AND RELATED QUANTITIES

NOTE: THE FIGURES IN THIS SECTION ARE INTENDED TO SHOW THE REPRESENTATIVE DATA. THEY ARE NOT MEANT TO BE COMPLETE COMPILATIONS OF ALL THE WORLD'S RELIABLE DATA.

Structure Functions

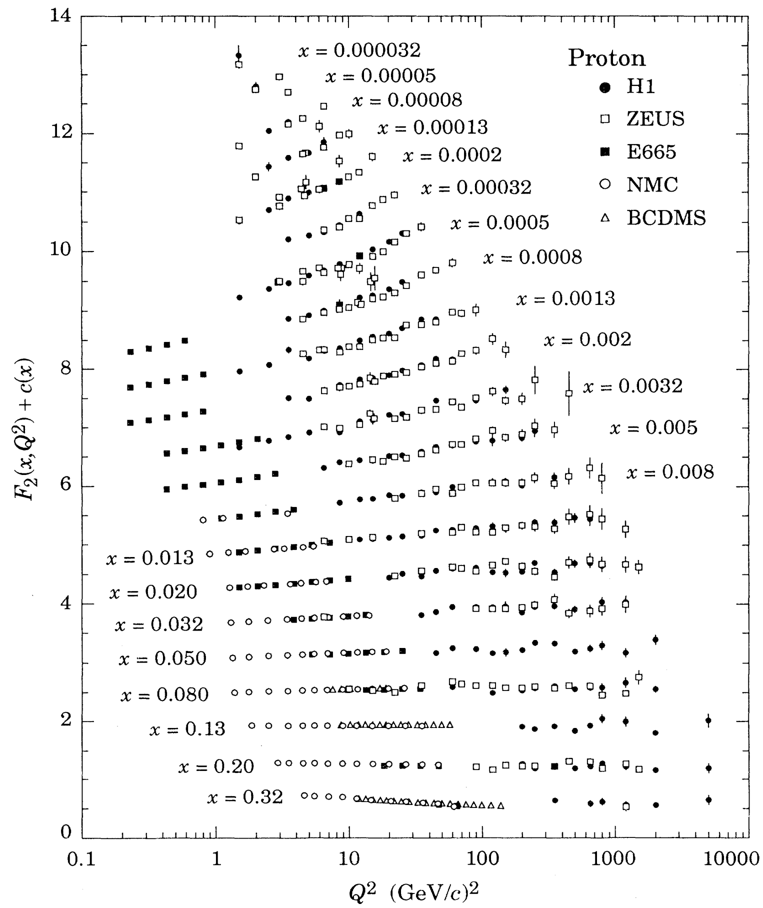


Figure 36.1: The proton structure function F_2^p measured in electromagnetic scattering of electrons (H1, ZEUS) and muons (BCDMS, E665, NMC), in the kinematic domain of the HERA data. Only statistical errors are shown. The data are plotted as a function of Q^2 in bins of fixed x. The H1 binning in x was chosen for this plot; the ZEUS, BCDMS, E665, and NMC data are rebinned to the x values of the H1 data using a phenomenological parametrization.. For the purpose of plotting, a constant $c(x) = 0.6(i_x - 0.4)$ is added to F_2^p, where i_x is the number of the x bin ranging from $i_x = 1$ ($x = 0.32$) to $i_x = 21$ ($x = 0.000032$). References: **H1**—S. Aid *et al.*, DESY 96-039 (1996), subm. to Nucl. Phys. **B**; **ZEUS**—M. Derrick *et al.*, Z. Phys. **C69**, 607 (1996) and DESY 96-076 (1996), subm. to Z. Phys. **C**; **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B223**, 485 (1989); **E665**—M.R. Adams *et al.*, FNAL-PUB-95/396-E, subm. to Phys. Rev. **D**; **NMC**—M. Arneodo *et al.*, Phys. Lett. **B364**, 107 (1995). (Courtesy of R. Voss, 1996.)

Structure Functions

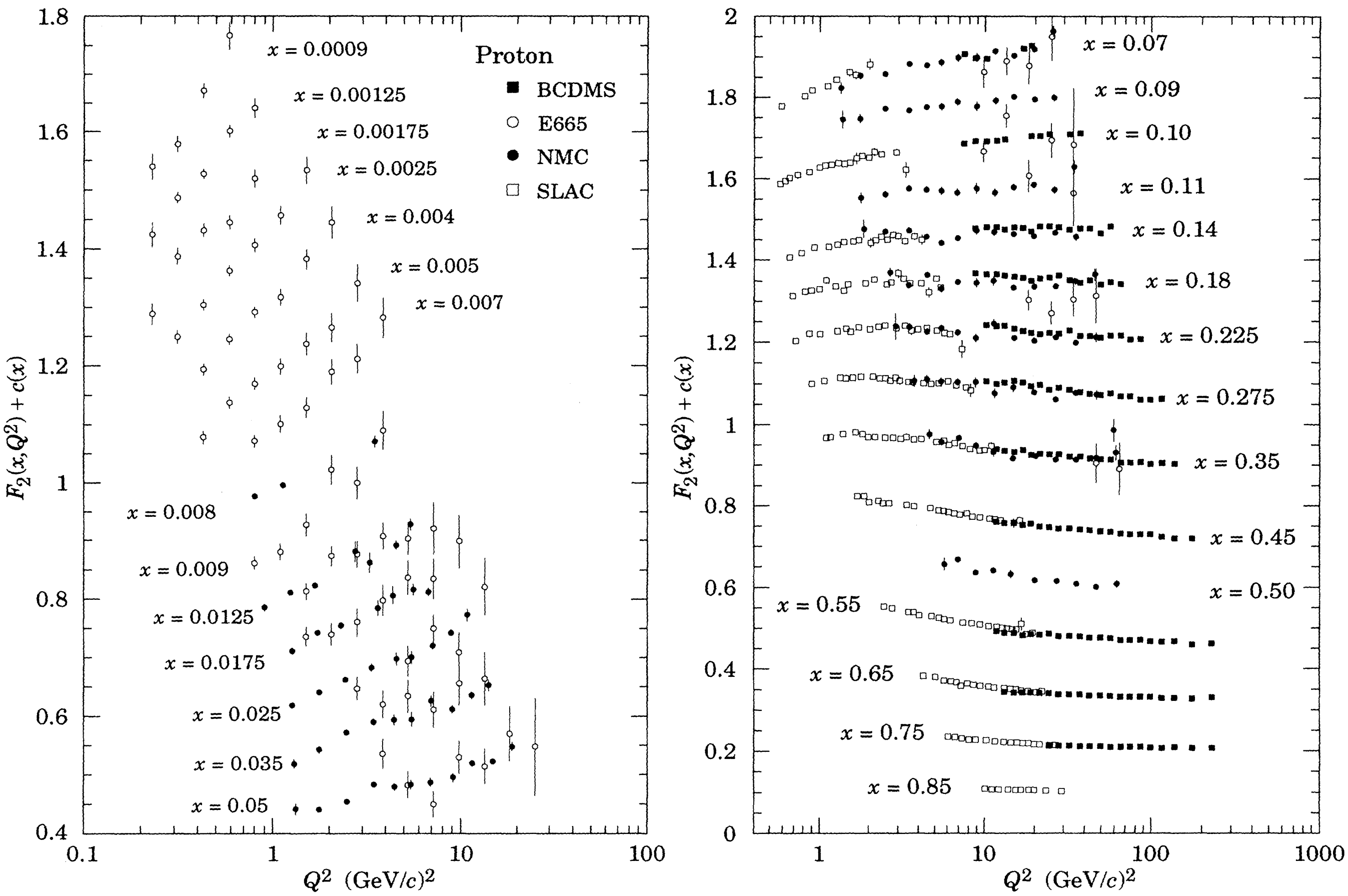


Figure 36.2: The proton structure function F_2^p measured in electromagnetic scattering of electrons (SLAC) and muons (BCDMS, E665, NMC), shown as a function of Q^2 for bins of fixed x. Only statistical errors are shown. For the purpose of plotting, a constant $c(x) = 0.1 i_x$ is added to F_2^p where i_x is the number of the x bin, ranging from 1 ($x = 0.05$) to 14 ($x = 0.0009$) on the left-hand figure, and from 1 ($x = 0.85$) to 15 ($x = 0.007$) on the right-hand figure. For HERA data in the kinematic range of this figure, see Fig. 36.1. References: **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B223**, 485 (1989); **E665**—M.R. Adams *et al.*, FNAL-PUB-95/396-E, subm. to Phys. Rev. D; **NMC**—M. Arneodo *et al.*Phys. Lett. **B364**, 107 (1995); **SLAC**—L.W. Whitlow *et al.*, Phys. Lett. **B282**, 475 (1992). (Courtesy of R. Voss, 1996.)

Structure Functions

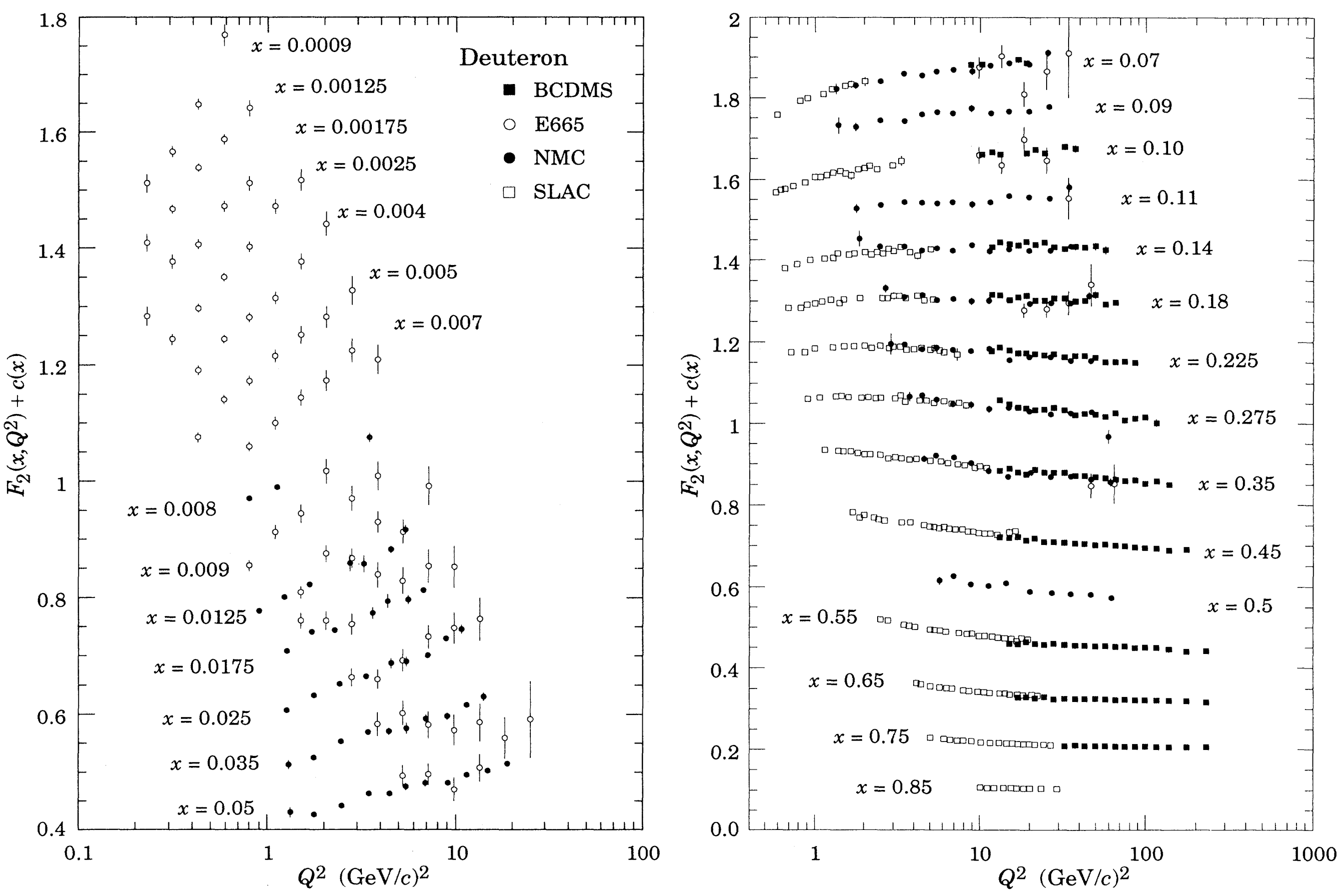


Figure 36.3: As Fig. 36.2, for the deuteron structure function F_2^d. References: **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B237**, 592 (1990); **E665, NMC, SLAC**—same references as Fig. 36.2. (Courtesy of R. Voss, 1996.)

Structure Functions

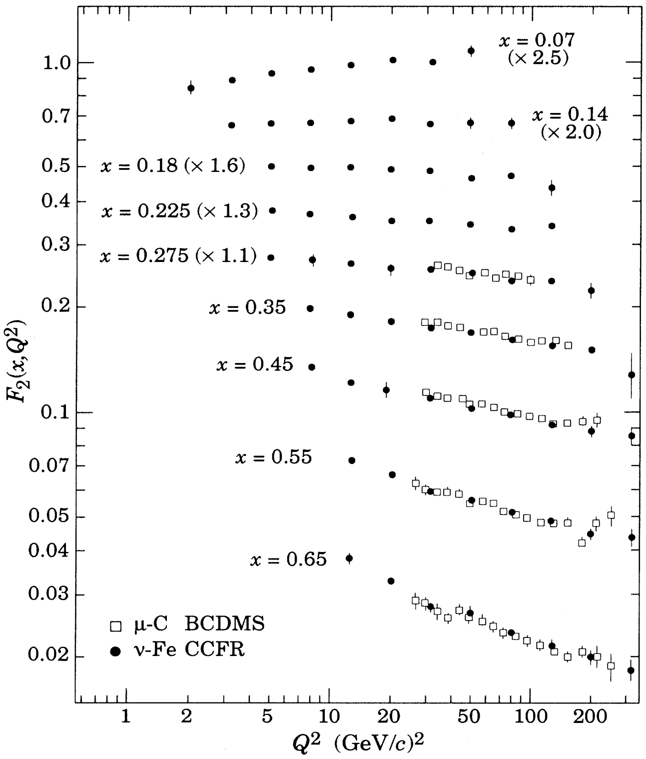


Figure 36.4: The nucleon structure function F_2 measured in deep inelastic scattering of muons on carbon (BCDMS) and neutrinos on iron (CCFR). The data are shown versus Q^2, for bins of fixed x, and have been scaled by the factors shown in parentheses. References: **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B195**, 91 (1987); **CCFR**—S.R. Mishra *et al.*, NEVIS-1465 (1992). (Courtesy of R. Voss, 1996.)

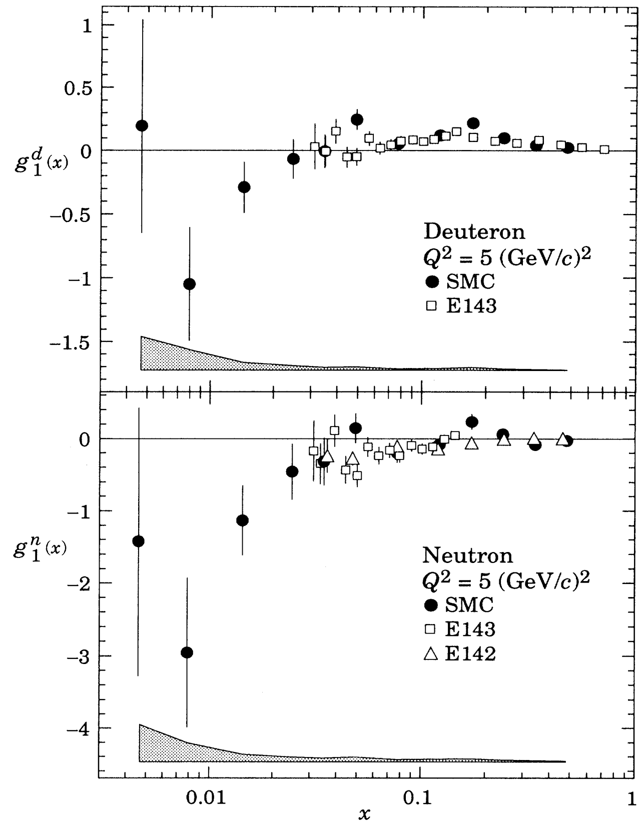


Figure 36.6: The spin-dependent structure function $g_1(x)$ of the deuteron and the neutron measured in deep inelastic scattering of polarised electrons (E142, E143) and muons (SMC), shown at $Q^2 = 5$ GeV^2. The SMC and E143 results for the neutron are evaluated from the difference of deuteron and proton data; the E142 results were obtained with a polarised ^{3}He target. Only statistical errors are shown with the data points. As an example, the SMC systematic error is indicated by the shaded area. References: **E142**—P.L. Anthony *et al.*, Phys. Rev. Lett. **71**, 959 (1993); **E143**—K. Abe *et al.*, Phys. Rev. Lett. **75**, 25 (1995); **SMC**—D. Adams *et al.*, Phys. Lett. **B357**, 248 (1995). (Courtesy of R. Voss, 1996.)

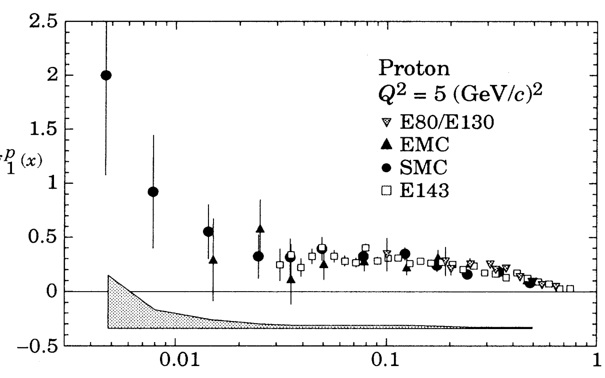


Figure 36.5: The spin-dependent structure function $g_1(x)$ of the proton measured in deep inelastic scattering of polarised electrons (E80, E130, E143) and muons (EMC, SMC), shown at $Q^2 = 5$ GeV^2. Only statistical errors are shown with the data points. As an example, the SMC systematic error is indicated by the shaded area. References: **E80**—M.J. Alguard *et al.*, Phys. Rev. Lett. **37**, 1261 (1976); ibid. **41**, 70 (1978); **E130**—G. Baum *et al.*, Phys. Rev. Lett. **51**, 1135 (1983); **E143**—K. Abe *et al.*, Phys. Rev. Lett. **74**, 346 (1995); **EMC**—J. Ashman *et al.*, Nucl. Phys. **B328**, 1 (1989); **SMC**—D. Adams *et al.*, Phys. Lett. **B329**, 399 (1994) **B339**, 332 (1994) (E). In this plot, the E80, E130, and EMC data have been reevaluated using up-to-date parametrizations of F_2^p and $R = \sigma_L/\sigma_T$. (Courtesy of R. Voss, 1996.)

Jet Production in pp and $\bar{p}p$ Interactions

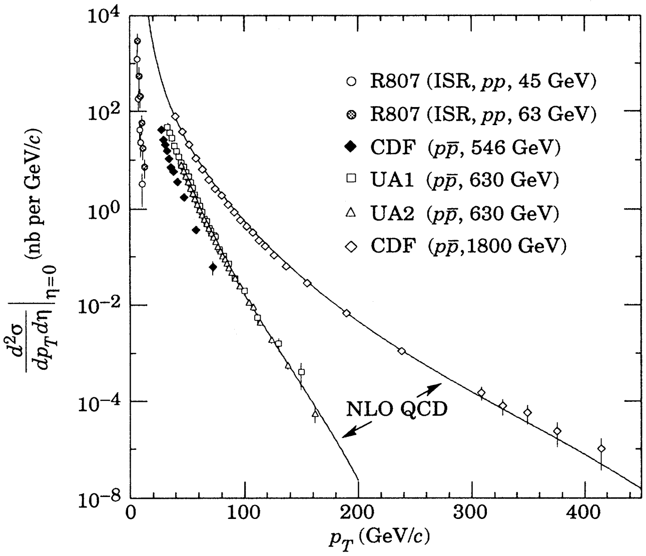


Figure 36.7: Differential cross sections for observation of a single jet of pseudorapidity $\eta = 0$ as a function of the jet transverse momentum. **CDF**—F. Abe *et al.*, Phys. Rev. Lett. **70**, 1376 (1993); **UA1**—G. Arnison *et al.*, Phys. Lett. **B172**, 461 (1986); **UA2**—J. Alitti *et al.*, Phys. Lett. **B257**, 232 (1991); **R807**—T. Akesson *et al.*, Phys. Lett. **B123**, 133 (1983). Next-to-leading order QCD curves are shown for 630 GeV and 1800 GeV. (Courtesy of S. Geer, FNAL, 1995.)

Direct γ Production in $\bar{p}p$ Interactions

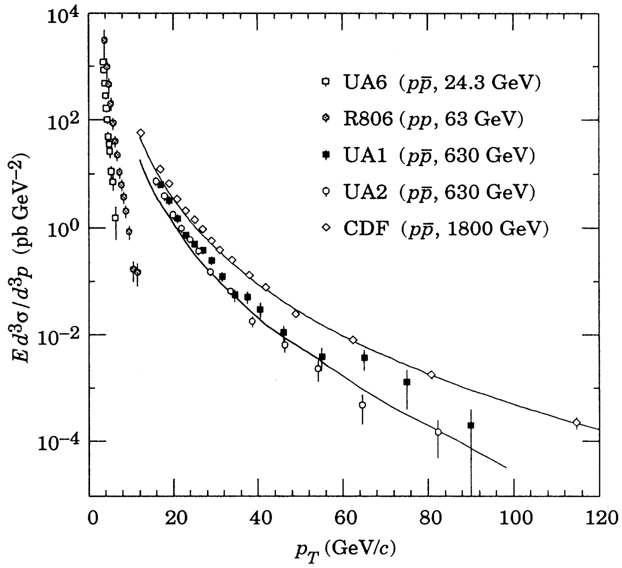


Figure 36.8: Differential cross sections for observation of a single photon of pseudorapidity $\eta = 0$ as a function of the photon transverse momentum **R806**—E. Anassontzis *et al.*, Z. Phys. **C13**, 277 (1982); **UA6**—A. Bernasconi *et al.*, Phys. Lett. **B206**, 163 (1988); **UA1**—C. Albajar *et al.*, Phys. Lett. **B209**, 385 (1988); **UA2**—J. Alitti *et al.*, Phys. Lett. **B288**, 386 (1992); **CDF**—F. Abe *et al.*, Phys. Rev. Lett. **73**, 2662 (1994). Next-to-leading order QCD curves are shown for 630 GeV and 1800 GeV. (Courtesy of S. Geer, FNAL, 1995.)

Pseudorapidity Distributions in $\bar{p}p$ Interactions

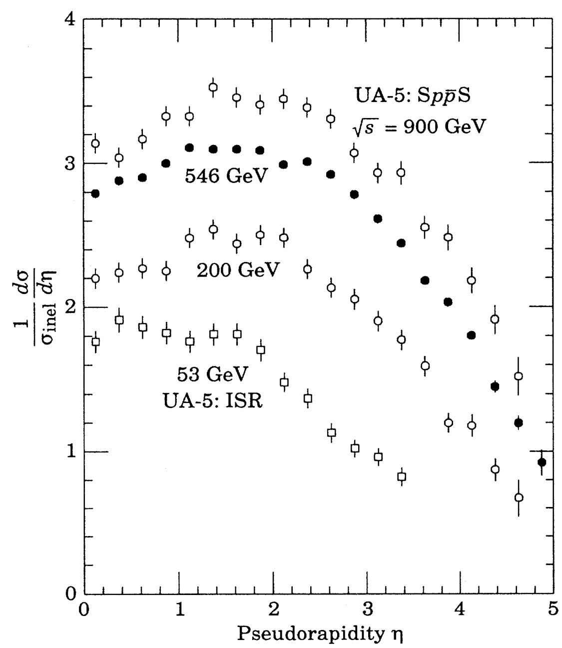


Figure 36.9: Charge particle pseudorapidity distributions in $\bar{p}p$ collisions for 53 GeV $\leq \sqrt{s} \leq$ 900 GeV. The number per pseudorapidity interval is about 10% higher if the rate is normalized excluding singly diffractive events rather than to the total inelastic rate. S$\bar{p}p$S data are from G.J. Alner *et al.*, Z. Phys. **C33**, 1 (1986), and ISR data are from K. Alpgård *et al.*, Phys. Lett. **112B**, 193 (1982). CDF nonsingle-diffractive results at $\sqrt{s}$ = 630 and 1800 GeV are given in F. Abe *et al.*, Phys. Rev. **D41**, 2330 (1990). (Courtesy of D.R. Ward, Cambridge Univ., 1991.)

Average Hadron Multiplicities in Hadronic e^+e^- Annihilation Events

Table 36.1: Average hadron multiplicity per e^+e^- annihilation event at $\sqrt{s} \approx 10$, 29–35, and 91 GeV. The rates given include decay products from resonances with $c\tau < 10$ cm, and include charge conjugated states. (Updated July 1995 by O. Biebel.)

Particle	$\sqrt{s} \approx 10$ GeV		$\sqrt{s} = 29$–35 GeV		$\sqrt{s} = 91$ GeV	
Pseudoscalar mesons:						
π^+	6.6	$\pm$ 0.2	10.3	$\pm$ 0.4	17.1	$\pm$ 0.4
π^0	3.2	$\pm$ 0.3	5.83	$\pm$ 0.28	9.18	$\pm$ 0.73
K^+	0.90	$\pm$ 0.04	1.48	$\pm$ 0.09	2.39	$\pm$ 0.12
K^0	0.91	$\pm$ 0.05	1.48	$\pm$ 0.07	2.01	$\pm$ 0.04
η	0.20	$\pm$ 0.04	0.61	$\pm$ 0.07	0.95	$\pm$ 0.11
$\eta'(958)$	0.03	$\pm$ 0.01	0.26	$\pm$ 0.10	0.17	$\pm$ 0.06
D^+	0.16	$\pm$ 0.03	0.17	$\pm$ 0.03	0.20	$\pm$ 0.03
D^0	0.37	$\pm$ 0.06	0.45	$\pm$ 0.07	0.40	$\pm$ 0.06
D_s^+	0.13	$\pm$ 0.02	0.45	$\pm$ 0.20$^{(a)}$	—	
B^+, B_d^0	—		—		0.165	$\pm$ 0.026$^{(b)}$
B_s^0	—		—		0.057	$\pm$ 0.013$^{(b)}$
Scalar mesons:						
$f_0(980)$	0.024	$\pm$ 0.006	0.05	$\pm$ 0.02$^{(c)}$	0.14	$\pm$ 0.06$^{(d)}$
Vector mesons:						
$\rho(770)^0$	0.35	$\pm$ 0.04	0.81	$\pm$ 0.08	1.21	$\pm$ 0.16
$\omega(782)$	0.30	$\pm$ 0.08	—		—	
$K^*(892)^+$	0.27	$\pm$ 0.03	0.64	$\pm$ 0.05	0.715	$\pm$ 0.059
$K^*(892)^0$	0.29	$\pm$ 0.03	0.56	$\pm$ 0.06	0.742	$\pm$ 0.042
$\phi(1020)$	0.044	$\pm$ 0.003	0.085	$\pm$ 0.011	0.100	$\pm$ 0.008
$D^*(2010)^+$	0.22	$\pm$ 0.04	0.43	$\pm$ 0.07	0.180	$\pm$ 0.013
$D^*(2007)^0$	0.23	$\pm$ 0.06	0.27	$\pm$ 0.11	—	
$B^{*\ (e)}$	—		—		0.288	$\pm$ 0.026
$J/\psi(1S)$	—		—		0.0054	$\pm$ 0.0005$^{(f)}$
$\psi(2S)$	—		—		0.0023	$\pm$ 0.0011$^{(f)}$
Pseudovector mesons:						
$\chi_{c1}(1P)$	—		—		0.0087	$\pm$ 0.0028$^{(f)}$
Tensor mesons:						
$f_2(1270)$	0.09	$\pm$ 0.02	0.14	$\pm$ 0.04	0.31	$\pm$ 0.12
$K_2^*(1430)^+$	—		0.09	$\pm$ 0.03	—	
$K_2^*(1430)^0$	—		0.12	$\pm$ 0.06	0.19	$\pm$ 0.07$^{(g)}$
$B^{**\ (h)}$	—		—		0.12	$\pm$ 0.24
Baryons:						
p	0.253	$\pm$ 0.016	0.640	$\pm$ 0.050	0.964	$\pm$ 0.102
Λ	0.080	$\pm$ 0.007	0.205	$\pm$ 0.010	0.368	$\pm$ 0.014
Σ^0	0.023	$\pm$ 0.008	—		—	
$\Sigma^\pm$	—		—		0.170	$\pm$ 0.063
Ξ^-	0.0059	$\pm$ 0.0007	0.0176	$\pm$ 0.0027	0.0227	$\pm$ 0.0018
$\Delta(1232)^{++}$	0.040	$\pm$ 0.010	—		0.022	$\pm$ 0.06
$\Sigma(1385)^-$	0.006	$\pm$ 0.002	0.017	$\pm$ 0.004	—	
$\Sigma(1385)^+$	0.005	$\pm$ 0.001	0.017	$\pm$ 0.004	—	
$\Sigma(1385)^\pm$	0.0106	$\pm$ 0.0020	0.033	$\pm$ 0.008	0.0380	$\pm$ 0.0062
$\Xi(1530)^0$	0.0015	$\pm$ 0.0006	—		0.0048	$\pm$ 0.0005
Ω^-	0.0007	$\pm$ 0.0004	0.014	$\pm$ 0.007	0.0050	$\pm$ 0.0015
Λ_c^+	0.100	$\pm$ 0.030$^{(i)}$	0.110	$\pm$ 0.050	—	
Λ_b^0	—		—		0.031	$\pm$ 0.016
$\Sigma_c^{++}, \Sigma_c^0$	0.014	$\pm$ 0.007	—		—	

All average multiplicites are per hadronic e^+e^- annihilation event.

(a) $B(D_s \to \eta\pi,\ \eta'\pi)$ has been used (RPP 1994).
(b) The Standard Model $B(Z \to b\bar{b}) = 0.217$ was used.
(c) $x_p = p/p_{\rm beam} > 0.1$ only.
(d) Extrapolation to the unobserved region using the shape predicted by JETSET.
(e) Any charge state (*i.e.*, B_d^*, B_u^*, or B_s^*).
(f) $B(Z \to \text{hadrons}) = 0.699$ has been used (RPP 1994).
(g) $x_E = E[K_2^*(1430)0]/E_{\rm beam} < 0.3$ only.
(h) Any charge state (*i.e.*, B_d^{**}, B_u^{**}, or B_s^{**}).
(i) The value was taken from the cross section of the $\Lambda_c^+ \to p\pi K$, assuming the branching fraction to be $(3.2\pm0.7)\%$ (RPP 1992).

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Fragmentation in e^+e^- Annihilation

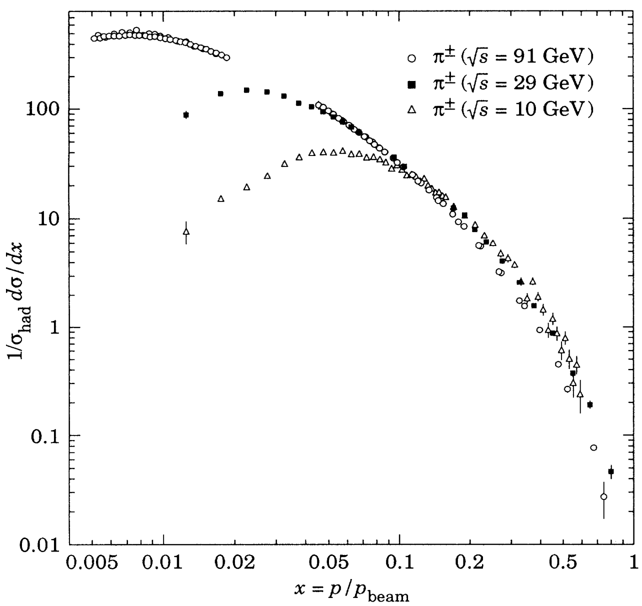

Figure 36.10: Fragmentation into $\pi^{\pm}$ in e^+e^- annihilations: Inclusive cross sections $(1/\sigma_{\rm had})(d\sigma/dx)$, with $x = p/p_{\rm beam}$. The indicated errors are statistical and systematic errors added in quadrature.

△: rate at $\sqrt{s}$ = 9.98 GeV; an overall uncertainty of 1.8%: **ARGUS**—H. Albrecht *et al.*, Z. Phys. **C44**, 547 (1989).

■: rate at $\sqrt{s}$ = 29 GeV **TPC**—H. Aihara *et al.*, Phys. Rev. Lett. **61**, 1263 (1988).

○: rate for hadronic decays of the Z at $\sqrt{s}$ = 91.2 GeV **ALEPH**—D. Buskulic *et al.*, Z. Phys. **C66**, 355 (1995); **OPAL**—R. Akers *et al.*, Z. Phys. **C63**, 181 (1994). (Courtesy of O. Biebel, S. Bethke, and D. Lanske, RWTH, Aachen, 1995.)

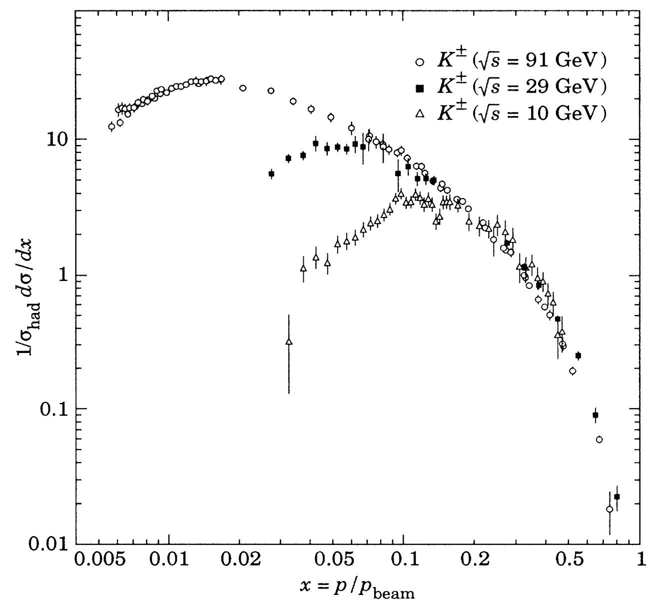

Figure 36.11: Fragmentation into $K^{\pm}$ in e^+e^- annihilations: Inclusive cross sections $(1/\sigma_{\rm had})(d\sigma/dx)$, with $x = p/p_{\rm beam}$. The indicated errors are statistical and systematic errors added in quadrature.

△: rate at $\sqrt{s}$ = 9.98 GeV; an overall uncertainty of 1.8%: **ARGUS**—H. Albrecht *et al.*, Z. Phys. **C44**, 547 (1989).

■: rate at $\sqrt{s}$ = 29 GeV **TPC**—H. Aihara *et al.*, Phys. Rev. Lett. **61**, 1263 (1988).

○: rate for hadronic decays of the Z at $\sqrt{s}$ = 91.2 GeV **ALEPH**—D. Buskulic *et al.*, Z. Phys. **C66**, 355 (1995); **DELPHI**—P. Abreu *et al.*, Nucl. Phys. **B444**, 3 (1995); **OPAL**—R. Akers *et al.*, Z. Phys. **C63**, 181 (1994). (Courtesy of O. Biebel, S. Bethke, and D. Lanske, RWTH, Aachen, 1995.)

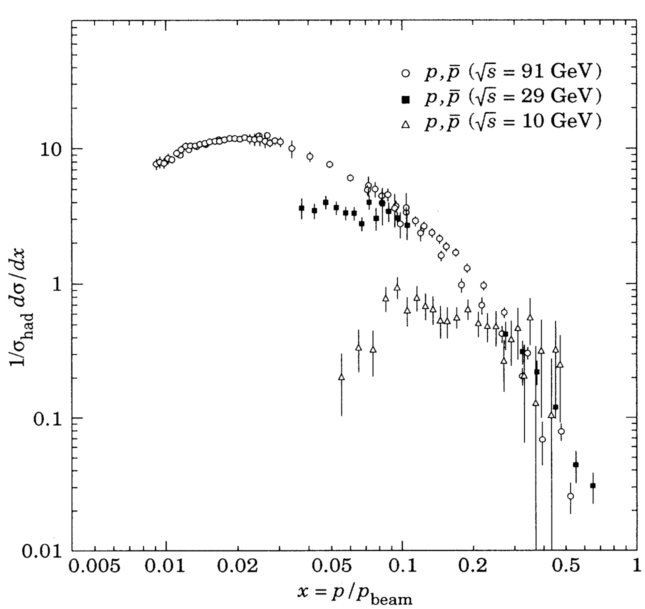

Figure 36.12: Fragmentation into $p\bar{p}$ in e^+e^- annihilations: Inclusive cross sections $(1/\sigma_{\rm had})(d\sigma/dx)$, with $x = p/p_{\rm beam}$. The indicated errors are statistical and systematic errors added in quadrature.

△: rate at $\sqrt{s}$ = 9.98 GeV; an overall uncertainty of 1.8%. This rate is obtained from the measured $\bar{p}$ rate by scaling with a factor of two: **ARGUS**—H. Albrecht *et al.*, Z. Phys. **C44**, 547 (1989).

■: rate at $\sqrt{s}$ = 29 GeV: **TPC**—H. Aihara *et al.*, Phys. Rev. Lett. **61**, 1263 (1988).

○: rate for hadronic decays of the Z at $\sqrt{s}$ = 91.2 GeV: **ALEPH**—D. Buskulic *et al.*, Z. Phys. **C66**, 355 (1995). **DELPHI**—P. Abreu *et al.*, Nucl. Phys. **B444**, 3 (1995). **OPAL**—R. Akers *et al.*, Z. Phys. **C63**, 181 (1994). (Courtesy of O. Biebel, S. Bethke, and D. Lanske, RWTH, Aachen, 1995.)

Heavy Quark Fragmentation in e^+e^- Annihilation

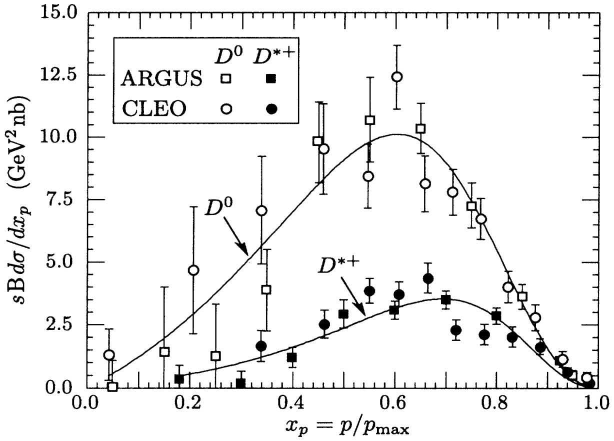

Figure 36.13: Heavy quark fragmentation: Shown are the **CLEO**—D. Bortoletto *et al.*, Phys. Rev. **D37**, 1719 (1988) and **ARGUS**—H. Albrecht *et al.*, Z. Phys. **C52**, 353 (1991) inclusive cross sections ($s\,\mathrm{B}\,d\sigma/dx_p$, with $x_p = p/p_{\max}$) for the production of pseudoscalar D^0 and vector D^{*+} in e^+e^- annihilations at $\sqrt{s}$ ~10 GeV. For the D^0, B is the branching ratio for $D^0 \to K^-\pi^+$, while in the D^{*+} case B is the product branching ratio for $D^{*+} \to D^0\pi^+$ followed by $D^0 \to K^-\pi^+$. These inclusive spectra have not been corrected for cascades from higher states, nor for radiative effects. Many functional forms have been suggested to describe these "hard" spectra, characteristic of charmed particles produced in e^+e^- annihilations. The parameterization given by Peterson *et al.*, (Phys. Rev. **D27**, 105, (1983)) in terms of just one variable ϵ_p has found the most use:

$$\frac{dN}{dx_p} = \frac{1}{x_p[1 - (1/x_p) - \epsilon_p/(1 - x_p)]^2} \;.$$

Fits to the combined CLEO and ARGUS D^0 and D^{*+} data give $\epsilon_p(D^0) = 0.135 \pm 0.010$ and $\epsilon_p(D^*) = 0.078 \pm 0.008$; these are indicated by the solid curves.

Spin-dependent effects have been observed in, *e.g.*, the polarization of D^{*+} mesons as a function of x_p. Recent measurements of ϵ_p for D^{**} and D_{sJ} mesons by **CLEO**—J. Alexander *et al.*, Phys. Lett. **B303**, 377 (1993) and **ARGUS**—H. Albrecht *et al.*, Phys. Lett. **B221**, 422 (1989) and Phys. Lett. **B232**, 398, (1989) also indicate that the fragmentation functions of such orbitally excited charmed mesons are distinctly harder than for D or D^* mesons. How much of this is a mass effect and how much is truly a spin effect has not yet been fully determined. (Courtesy of D. Besson, Univ. of Kansas, 1994.)

Average e^+e^-, pp, and $\overline{p}p$ Multiplicity

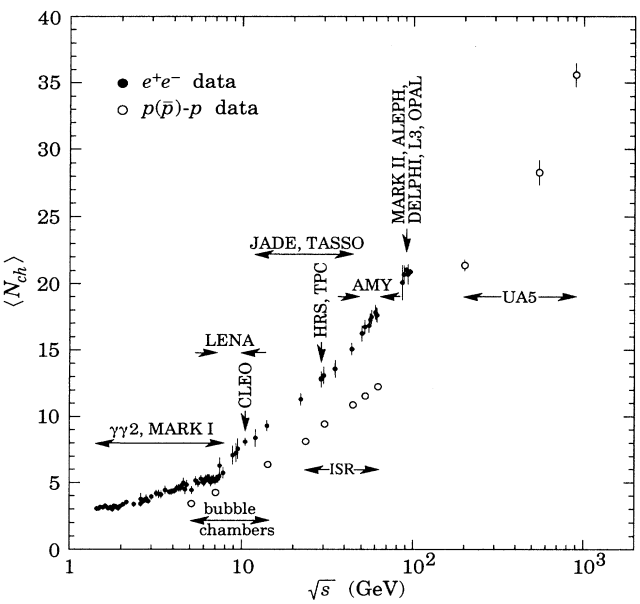

Figure 36.14: Average multiplicity as a a function of $\sqrt{s}$ for e^+e^- and $p\overline{p}$ annihilations and and pp collisions. The indicated errors are statistical and systematic errors added in quadrature, except when no systematic errors are given.
e^+e^-: All measurements include contributions from K^0_S and Λ decays. The $\gamma\gamma2$ and MARK I measurements contain a systematic 5% error. The five points at the Z resonance have been spread horizontally for clarity: **OPAL**—P.D. Acton *et al.*, Z. Phys. **C53**, 539 (1992) and references therein, R. Akers *et al.*, Z. Phys. **C68**, 203 (1995); **ALEPH**—D. Buskulic *et al.*, Z. Phys. **C**, CERN PPE/95-82.
$p^{(}\overline{p}^{)}$: The values measured by UA5 exclude single diffractive dissociation: J. Benecke *et al.* (bubble chamber), Nucl. Phys. **B76**, 29 (1976), W.M. Morse *et al.* (bubble chamber), Phys. Rev. **D15**, 66 (1977); **ISR**—A. Breakstone *et al.*, Phys. Rev. **D30**, 528 (1984); **UA5**—G.J. Alner *et al.*, Phys. Lett. **167B**, 476 (1986), Ansorge *et al.*, Z. Phys. **C43**, 357 (1989). (Courtesy of O. Biebel, S. Bethke, and D. Lanske, RWTH, Aachen, 1994.)

Annihilation Cross Section Near M_Z

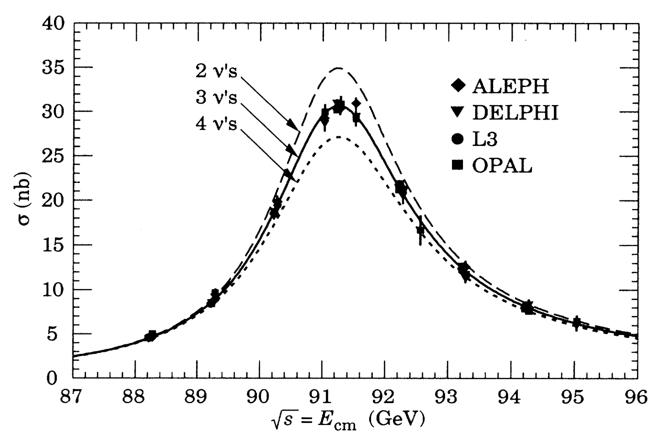

Figure 36.15: Data from the ALEPH, DELPHI, L3, and OPAL Collaborations for the cross section in e^+e^- annihilation into hadronic final states as a function of c.m. energy near the Z. LEP detectors obtained data at the same energies; some of the points are obscured by overlap. The curves show the predictions of the Standard Model with three species (solid curve) and four species (dashed curve) of light neutrinos. The asymmetry of the curves is produced by initial-state radiation. References:

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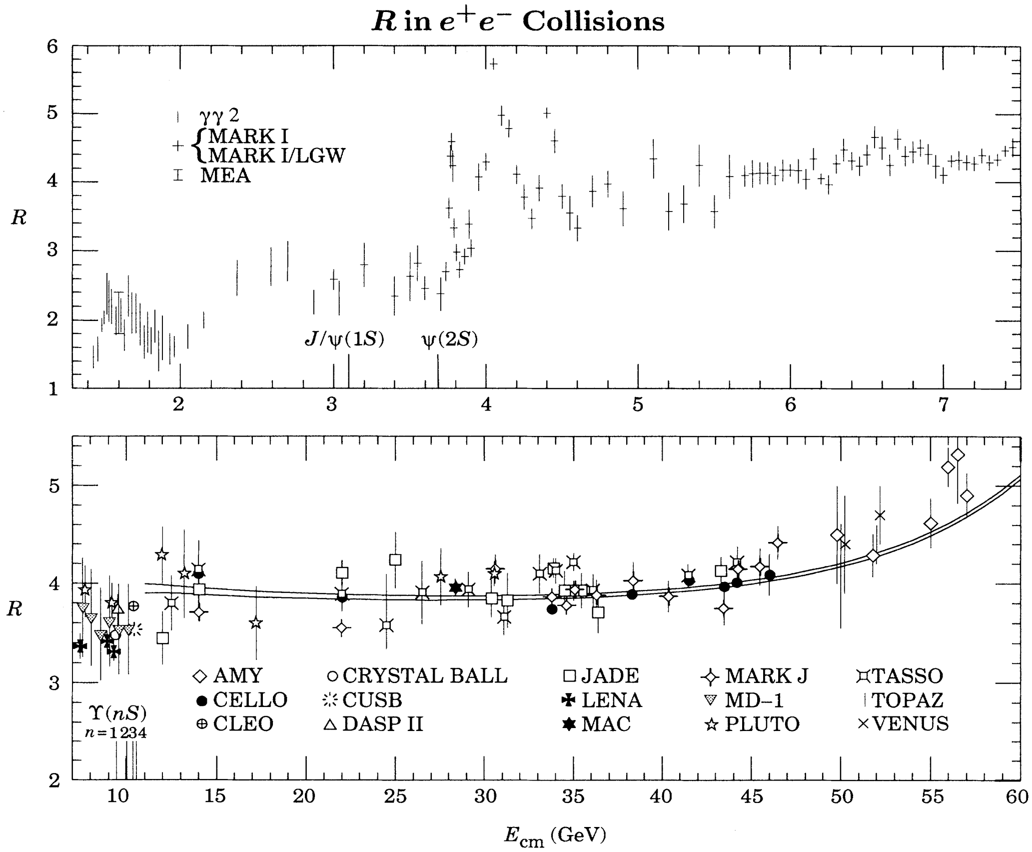

Figure 36.16: Selected measurements of $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$, where the annihilation in the numerator proceeds via one photon or via the Z. Measurements in the vicinity of the Z mass are shown in the following figure. The denominator is the calculated QED single-photon process; see the section on Cross-Section Formulae for Specific Processes. Radiative corrections and, where important, corrections for two-photon processes and τ production have been made. Note that the ADONE data ($\gamma\gamma2$ and MEA) is for ≥ 3 hadrons. The points in the $\psi(3770)$ region are from the MARK I—Lead Glass Wall experiment. To preserve clarity only a representative subset of the available measurements is shown—references to additional data are included below. Also for clarity, some points have been combined or shifted slightly ($< 4\%$) in $E_{\rm cm}$, and some points with low statistical significance have been omitted. Systematic normalization errors are not included; they range from ~5–20%, depending on experiment. We caution that especially the older experiments tend to have large normalization uncertainties. Note the suppressed zero. The horizontal extent of the plot symbols has no significance. The positions of the $J/\psi(1S)$, $\psi(2S)$, and the four lowest Υ vector-meson resonances are indicated. Two curves are overlaid for $E_{\rm cm} > 11$ GeV, showing the theoretical prediction for R, including higher order QCD [M. Dine and J. Sapirstein, Phys. Rev. Lett. **43**, 668 (1979)] and electroweak corrections. The Λ values are for 5 flavors in the $\overline{\rm MS}$ scheme and are $\Lambda^{(5)}_{\overline{\rm MS}} = 60$ MeV (lower curve) and $\Lambda^{(5)}_{\overline{\rm MS}} = 250$ MeV (upper curve). (Courtesy of F. Porter, 1992.) References (including several references to data not appearing in the figure and some references to preliminary data):

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Collisions: pp, $\overline{p}p$, pn, and $\overline{p}n$ $p_{\rm lab} > 50$ GeV/c, $\chi^2\,/\,dof = 2.82$

	Value	X_{pn}	Y_{pp}	$Y_{\overline{p}p}$	Y_{pn}	$Y_{\overline{p}n}$	η	ε
X_{pp}	22.0 ± 0.6	99.0	37.0	60.0	38.0	59.0	75.0	−98.0
X_{pn}	22.3 ± 0.6		40.0	63.0	37.0	60.0	76.0	−97.0
Y_{pp}	56.1 ± 4.4			96.0	93.0	93.0	88.0	−21.0
$Y_{\overline{p}p}$	98.2 ± 9.5				91.0	98.0	98.0	−45.0
Y_{pn}	55.0 ± 4.1					94.0	86.0	−22.0
$Y_{\overline{p}n}$	92.7 ± 8.6						96.0	−44.0
η	0.46 ± 0.3							−62.0
ε	0.079 ± 0.003				Correlations %			

Collisions: pd and $\overline{p}d$, $p_{\rm lab} > 50$ GeV/c, $\chi^2\,/\,dof = 1.77$

	Value	Y_{pd}	$Y_{\overline{p}d}$	η	ε
X_{pd}	35.7 ± 2.5	−27.0	9.0	56.0	−99.0
Y_{pd}	179.0 ± 18.8		93.0	64.0	36.0
$Y_{\overline{p}d}$	270.6 ± 29.3			87.0	1.0
η	0.45 ± 0.03				−47.0
ε	0.090 ± 0.008		Correlations %		

Collisions: π^+p and π^-p, $p_{\rm lab} > 10$ GeV/c, $\chi^2\,/\,dof = 1.66$

	Value	Y_{π^+}	Y_{π^-}	η	ε
X	13.7 ± 0.6	−44.0	11.0	86.0	−99.0
Y_{π^+}	27.8 ± 0.8		83.0	8.0	52.0
Y_{π^-}	35.9 ± 1.1			60.0	−1.3
η	0.45 ± 0.01				−80.0
ε	0.079 ± 0.004		Correlations %		

Collisions: π^+d and π^-d, $p_{\rm lab} > 10$ GeV/c, $\chi^2\,/\,dof = 1.44$

	Value	Y	η	ε
X	23.2 ± 2.1	73.0	95.0	−99.7
Y	85.5 ± 7.6		91.0	−68.0
η	0.43 ± 0.04			−92.0
ε	0.088 ± 0.010		Correlations %	

Collisions: K^+p, K^+n, K^-p, and K^-n, $p_{\rm lab} > 10$ GeV/c, $\chi^2\,/\,dof = 4.23$

	Value	Y_+	Y_-	η	ε
X	12.2 ± 0.6	−95.0	−59.0	13.0	−99.0
Y_+	8.3 ± 1.8		77.0	12.0	96.0
Y_-	26.4 ± 2.7			70.0	64.0
η	0.50 ± 0.03				−5.0
ε	0.079 ± 0.006		Correlations %		

Collisions: K^+d and K^-d, $p_{\rm lab} > 10$ GeV/c, $\chi^2\,/\,dof = 1.9$

	Value	Y_+	Y_-	η	ε
X	21.7 ± 0.7	−92.0	−27.0	60.0	−99.7
Y_+	26.2 ± 2.8		57.0	−30.0	94.0
Y_-	64.8 ± 3.4			60.0	33.0
η	0.47 ± 0.01				−54.0
ε	0.082 ± 0.004		Correlations %		

Collisions: γp, $p_{\rm lab} > 12$ GeV/c, $\chi^2\,/\,dof = 0.57$

	Value	Y	η	ε
X	0.071 ± 0.018	76.0	97.0	−99.5
Y	0.12 ± 0.04		90.0	−70.0
η	0.46 ± 0.25			−94.0
ε	0.075 ± 0.030		Correlations %	

Table 36.2: Regge theory provides a simple and compact description of total cross sections (A. Donnachie and P.V. Landshoff, Phys. Lett. **B296**, 227 (1992)): it is sufficient to write $\sigma_{\rm tot} = X\,s^{\varepsilon} + Y\,s^{-\eta}$, where the first term arises from pomeron exchange and the second from ρ, ω, f, and a exchange. Simultaneous fits are shown below for groups of reactions within which ε and η have the same values, and $X_{ab} = X_{\overline{a}b}$. As can be seen from Fig. 36.17, the fitted exponents are consistent with having the same values for all reactions. The fitted functions are shown in the figures, along with the correlated one-standard-deviation error bands which, when the reduced χ^2 is greater than one, include a scale factor that is defined as the square root of the reduced χ^2. Vertical arrows indicate lower limits on the momentum range used in the fits (these momenta are also given in the table). Curves and error bands are extrapolated to lower momenta; the user may decide on the range of applicability. Data used were extracted from the CS database of the Particle Physics Data System (PPDS), accessible throught the WWW at `http://pdg.lbl.gov/`. Computer-readable data files are also available through `http://pdg.lbl.gov/`. (Courtesy of V.V. Ezhela, S.B. Lugovsky, and N.P. Tkachenko, COMPAS Group, IHEP, Protvino.)

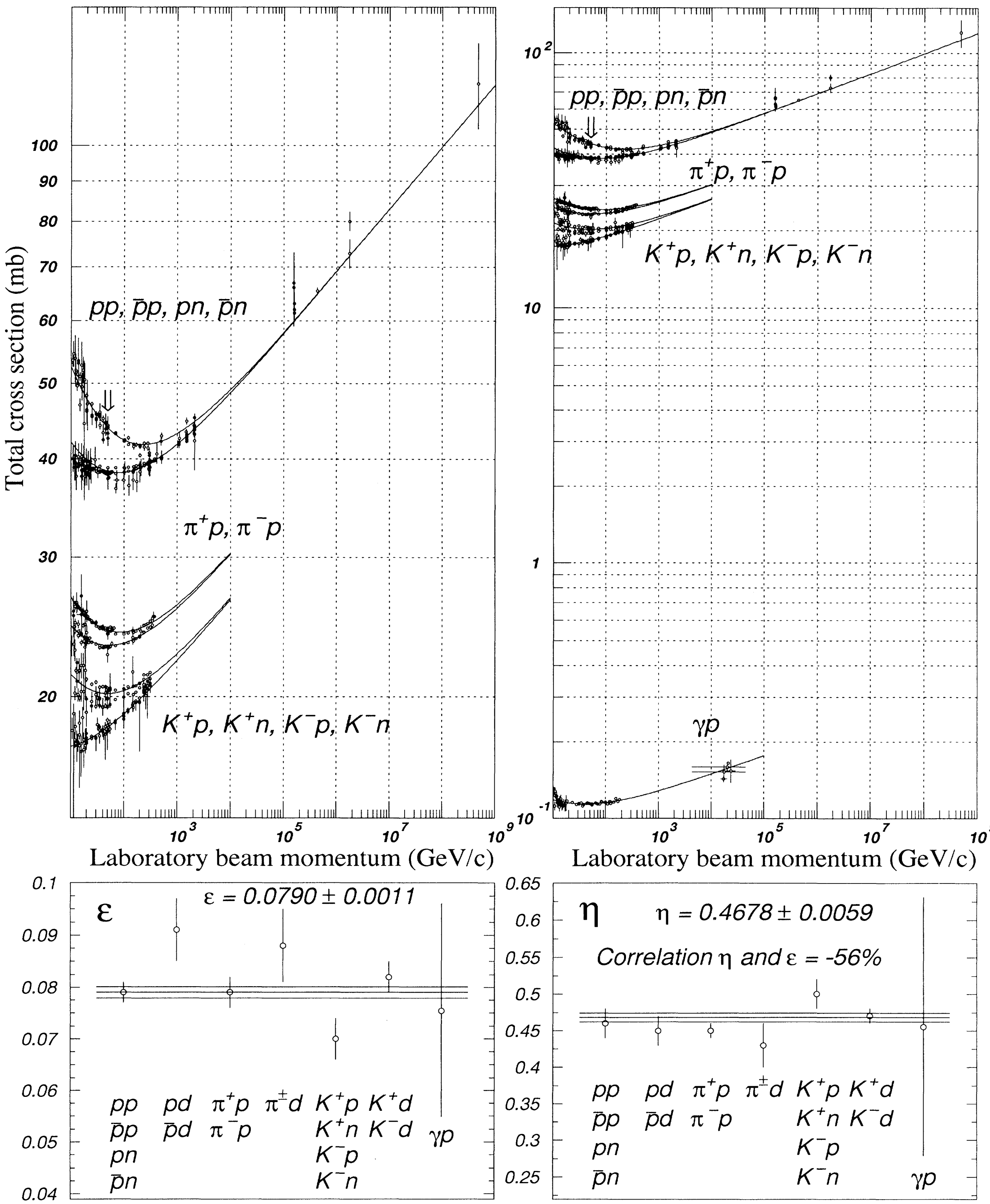


Figure 36.17: Summary of hadronic and γp total cross sections (top), and fit results to exponents for cross sections. (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, 1996.)

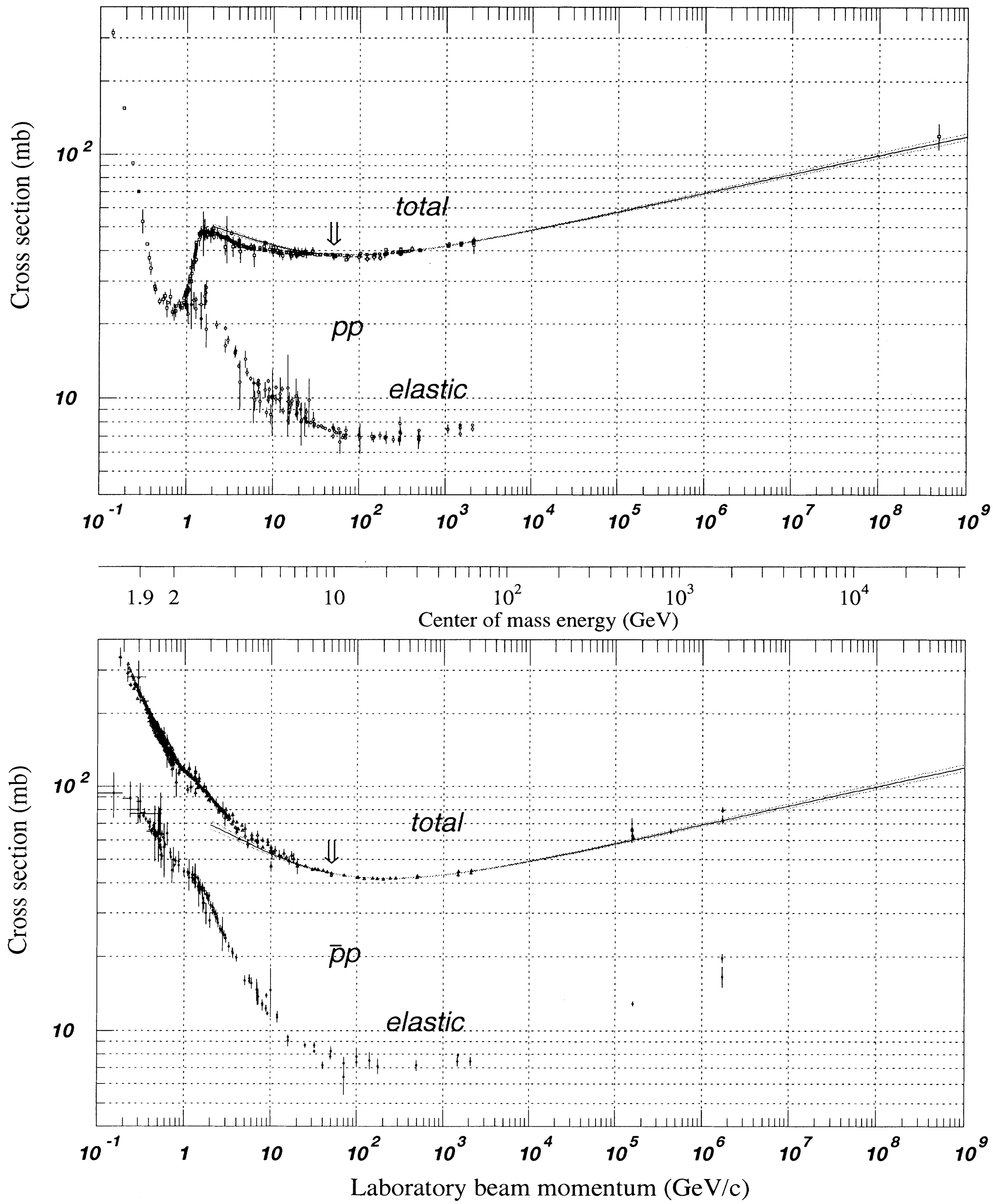


Figure 36.18: Total and elastic cross sections for pp and $\bar{p}p$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, 1996.)

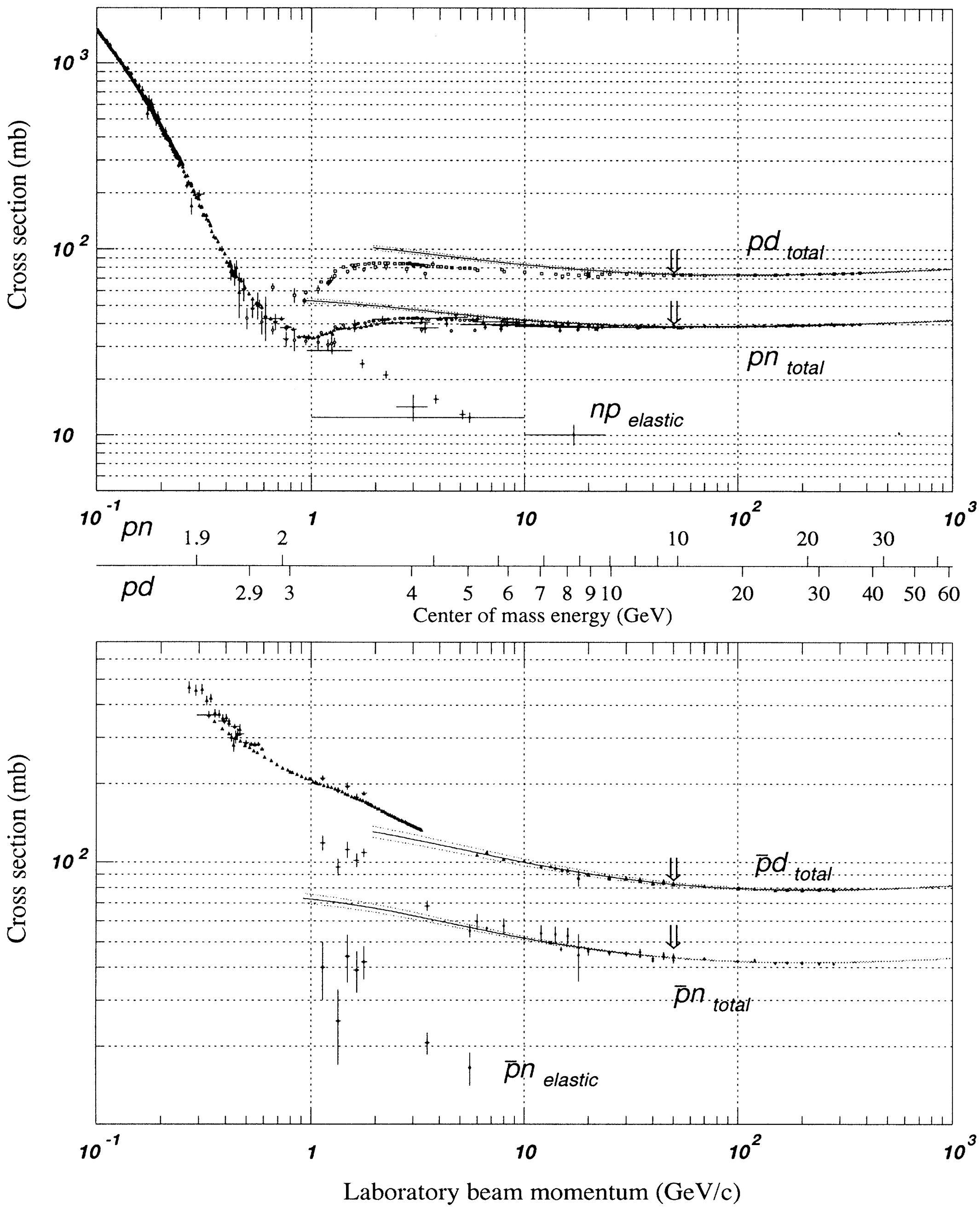


Figure 36.19: Total and elastic cross sections for pd (total only), np, $\overline{p}d$ (total only), and $\overline{p}n$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, 1996.)

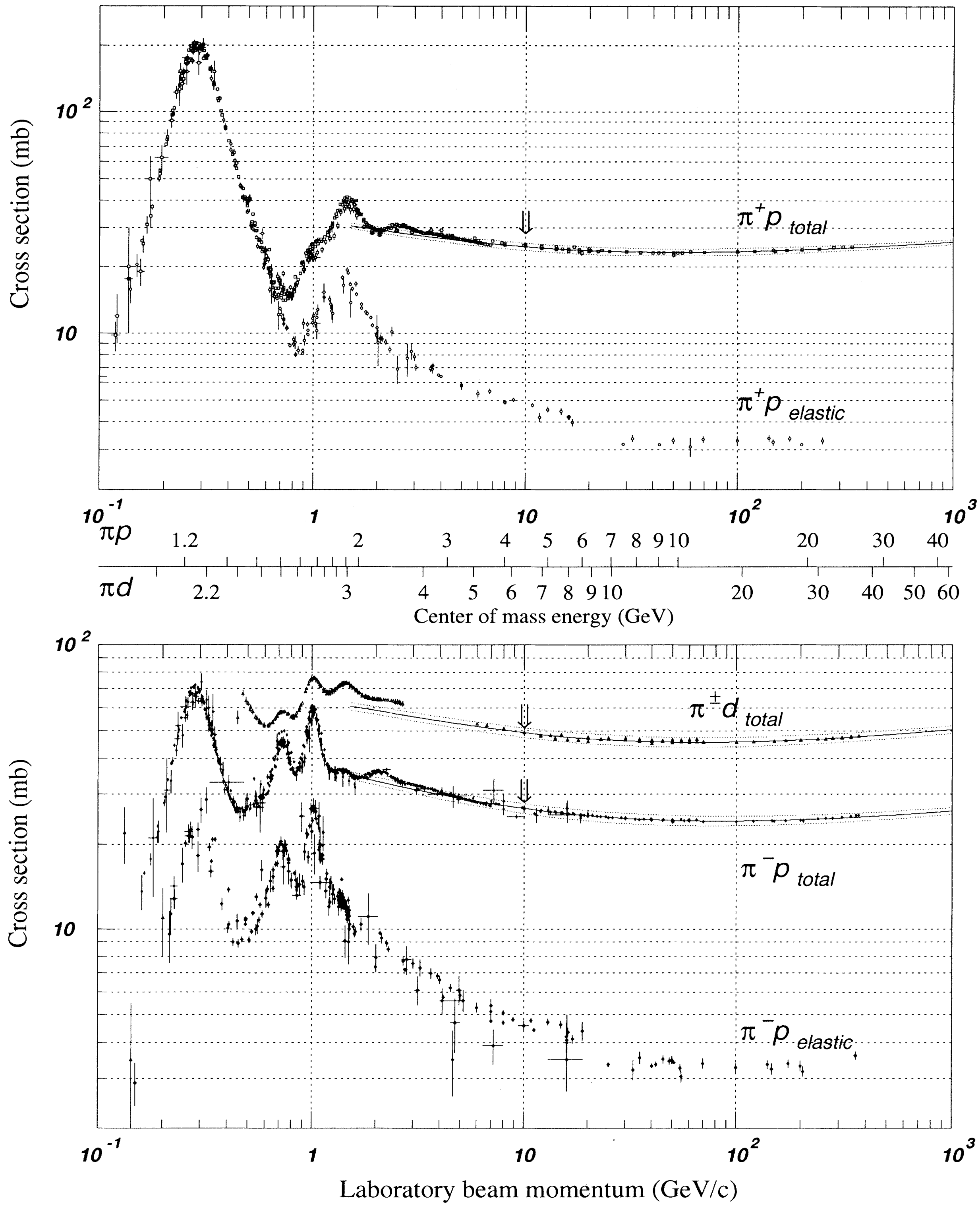


Figure 36.20: Total and elastic cross sections for $\pi^+ p$, $\pi^\pm d$ (total only), and $\pi^- p$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, 1996.)

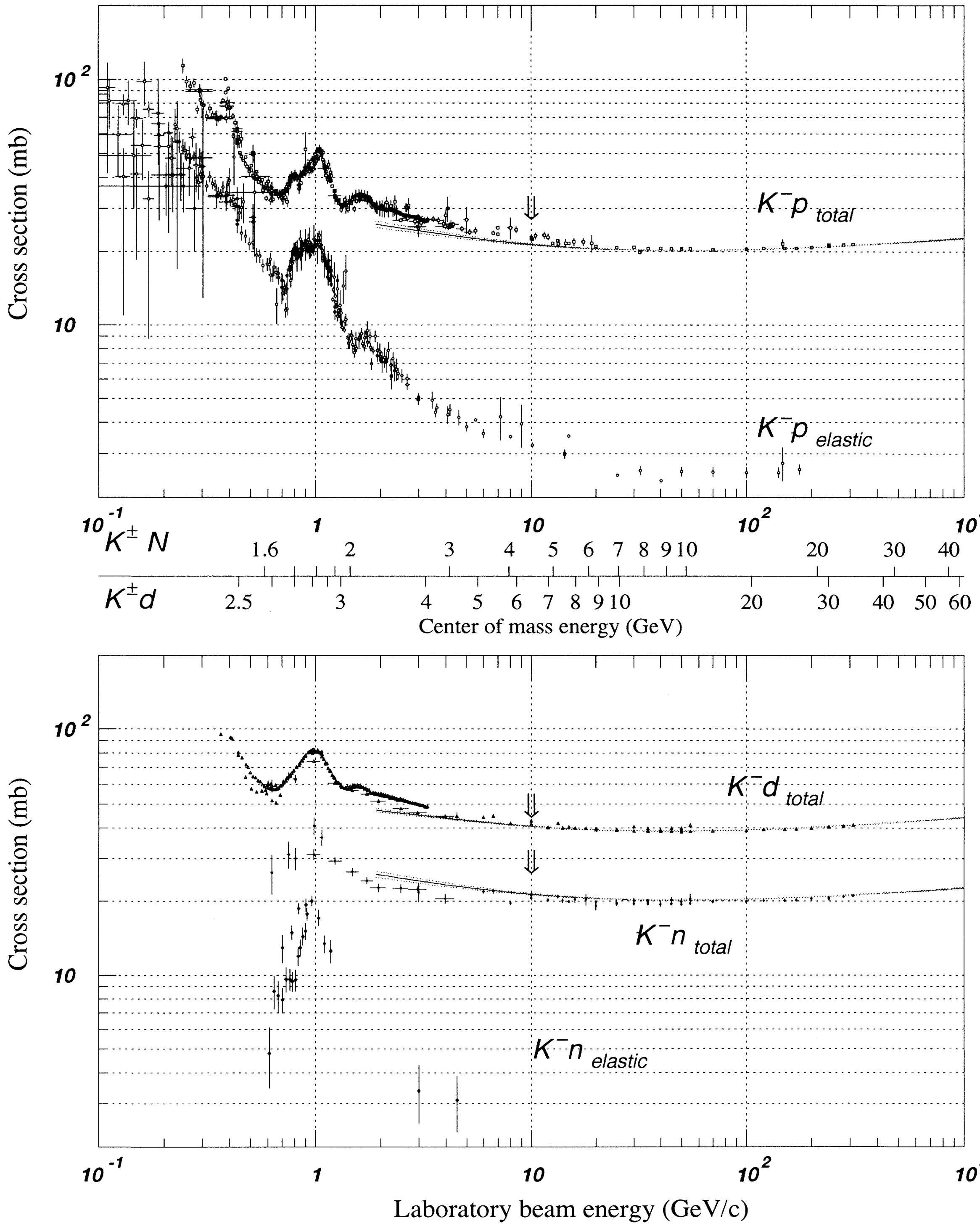


Figure 36.21: Total and elastic cross sections for K^-p, K^-d (total only), and K^-n collisions as a function of laboratory beam momentum and total center-of-mass energy. Computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, 1996.)

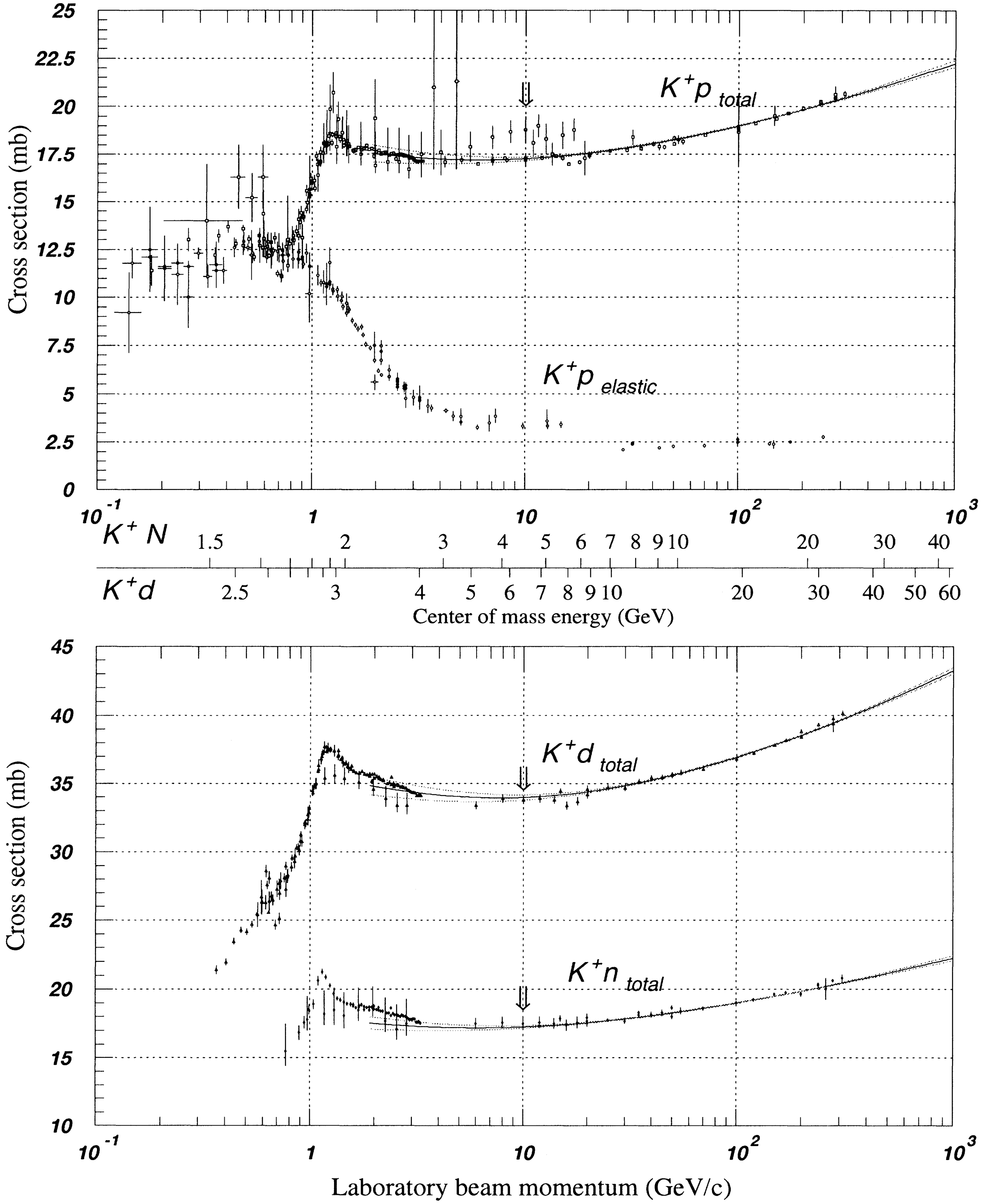


Figure 36.22: Total and elastic cross sections for K^+p and total cross sections for K^+d and K^+n collisions as a function of laboratory beam momentum and total center-of-mass energy. Computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, 1996.)

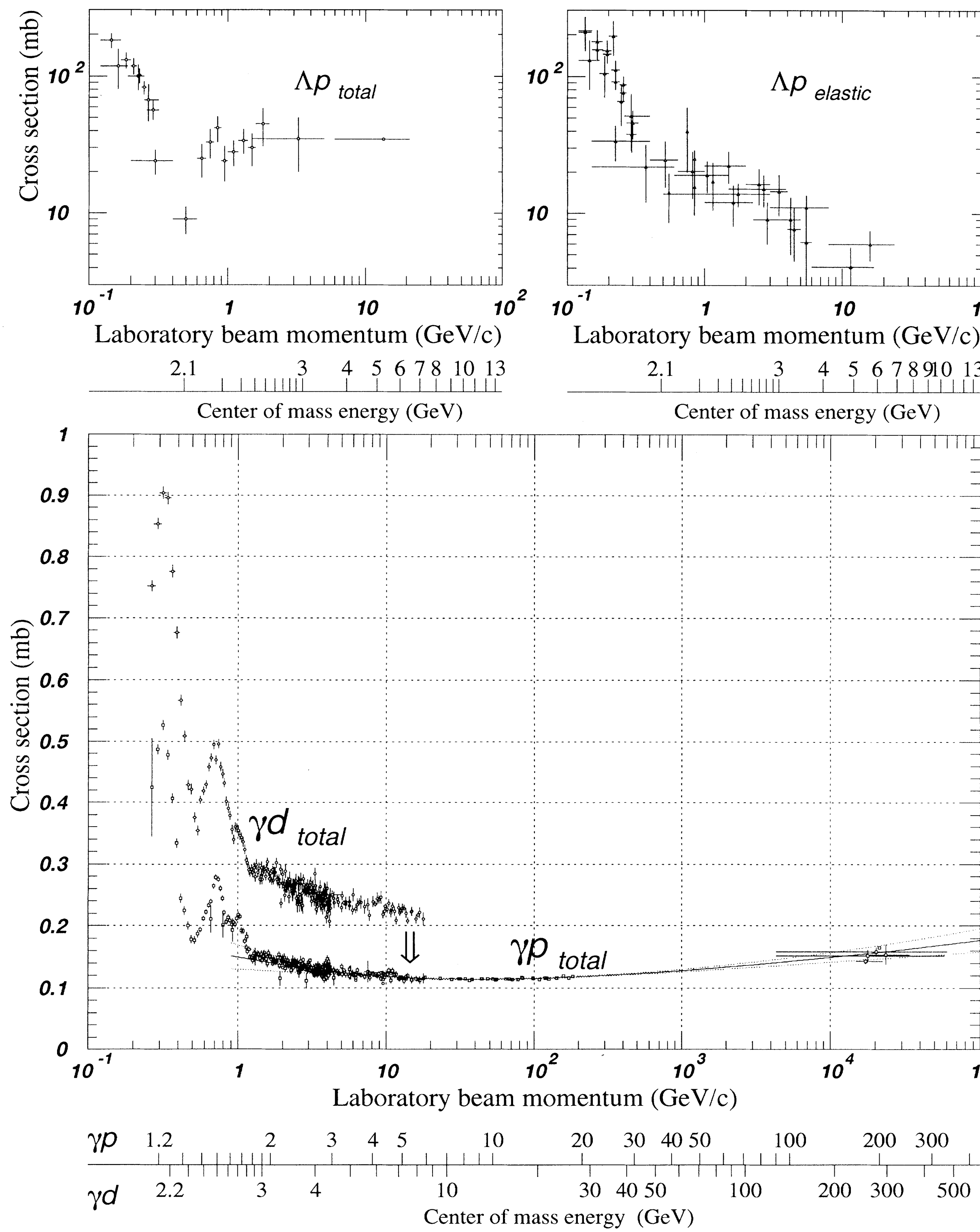


Figure 36.23: Total and elastic cross sections for Λp and total cross sections for γd and γp collisions as a function of laboratory beam momentum and total center-of-mass energy. Computer-readable data files may be found at `http://pdg.lbl.gov/xsect/contents.html` (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, 1996.)

INTRODUCTION TO THE PARTICLE LISTINGS

Illustrative Key to the Particle Listings

$a_0(1200)$

$I^G(J^{PC}) = 1^-(0^{++})$

OMITTED FROM SUMMARY TABLE

Evidence not compelling, may be a kinematic effect.

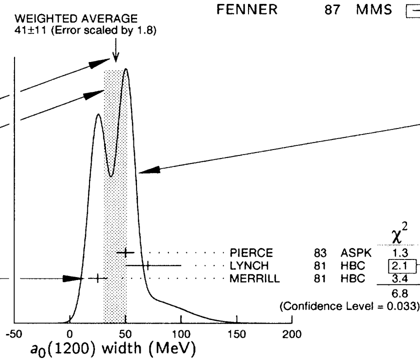
$a_0(1200)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1206 ± 7 OUR AVERAGE						
1210 ± 8 ± 9	3000	FENNER	87	MMS	−	3.5 $\pi^- p$
1198 ± 10		PIERCE	83	ASPK	+	2.1 $K^- p$
1216 ± 11 ± 9	1500	[1] MERRILL	81	HBC	0	3.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1192 ± 16	200	LYNCH	81	HBC	±	2.7 $\pi^- p$

[1] Systematic error was added quadratically by us in our 1986 edition.

$a_0(1200)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
41 ± 11 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.						
50 ± 8		PIERCE	83	ASPK	+	2.1 $K^- p$
70^{+30}_{-20}	200	LYNCH	81	HBC	±	2.7 $\pi^- p$
25 ± 5 ± 7		MERRILL	81	HBC	0	3.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<60		FENNER	87	MMS	−	3.5 $\pi^- p$



$a_0(1200)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	3π	(65.2 ± 1.3) %	S=1.7
Γ_2	$K\overline{K}$	(34.8 ± 1.3) %	S=1.7
Γ_3	$\eta\pi^\pm$	< 4.9 × 10^{-4}	CL=95%

$a_0(1200)$ BRANCHING RATIOS

$\Gamma(3\pi)/\Gamma_{total}$ **Γ_1/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.652 ± 0.013 OUR FIT Error includes scale factor of 1.7.					
0.643 ± 0.010 OUR AVERAGE					
0.64 ± 0.01	PIERCE	83	ASPK	+	2.1 $K^- p$
0.74 ± 0.06	MERRILL	81	HBC	0	3.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.48 ± 0.15	[2] LYNCH	81	HBC	±	2.7 $\pi^- p$

[2] Data has questionable background subtraction.

$\Gamma(K\overline{K})/\Gamma_{total}$ **Γ_2/Γ**

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.348 ± 0.013 OUR FIT Error includes scale factor of 1.7.					
0.35 ± 0.05	PIERCE	83	ASPK	+	2.1 $K^- p$

$\Gamma(K\overline{K})/\Gamma(3\pi)$ **Γ_2/Γ_1**

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.535 ± 0.030 OUR FIT Error includes scale factor of 1.7.					
0.50 ± 0.03	MERRILL	81	HBC	0	3.2 $K^- p$

$\Gamma(\eta(\text{neutral decay})\pi^\pm)/\Gamma_{total}$ **$0.71\Gamma_3/\Gamma$**

VALUE (units 10^{-4})	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
<3.5	95	PIERCE	83	ASPK	+	2.1 $K^- p$

$a_0(1200)$ REFERENCES

FENNER	87	PRL 55 14	+Watson, Willis, Zorn	(SLAC)
PIERCE	83	PL 123B 230		(FNAL) IJP
LYNCH	81	PR D24 610	+Jones+	(CLEO Collab.)
MERRILL	81	PRL 47 143	+Armstrong, Harper, Rittenberg, Wagman	(SACL, CERN)

Name of particle. "Old" name used before 1986 renaming scheme also given if different. See the section "Naming Scheme for Hadrons" for details.

Quantity tabulated below.

Top line gives our best value (and error) of quantity tabulated here, based on weighted average of measurements used. Could also be from fit, best limit, estimate, or other evaluation. See next page for details.

Footnote number linking measurement to text of footnote.

Number of events *above background*.

Measured value used in averages, fits, limits, etc.

Error in measured value (often statistical only; followed by systematic if separately known; the two are combined in quadrature for averaging and fitting.)

Measured value *not used* in averages, fits, limits, etc. See the Introductory Text for explanations.

Arrow points to weighted average.

Shaded pattern extends $\pm 1\sigma$ (scaled by "scale factor" S) from weighted average.

Value and error for each experiment.

Partial decay mode (labeled by Γ_i).

Branching ratio.

Our best value (and error) of quantity tabulated, as determined from constrained fit (using *all significant* measured branching ratios for this particle).

Weighted average of measurements of this ratio only.

Footnote (referring to LYNCH 81).

Confidence level for measured upper limit.

References, ordered inversely by year, then author.

"Document id" used on data entries above.

Journal, report, preprint, etc. (See abbreviations on next page.)

Particle quantum numbers (where known).

Indicates particle omitted from Particle Physics Summary Table, implying particle's existence is not confirmed.

General comments on particle.

"Document id" for this result; full reference given below.

Measurement technique. (See abbreviations on next page.)

Scale factor > 1 indicates possibly inconsistent data.

Reaction producing particle, or general comments.

"Change bar" indicates result added or changed since previous edition.

Charge(s) of particle(s) detected.

Ideogram to display possibly inconsistent data. Curve is sum of Gaussians, one for each experiment (area of Gaussian = 1/error; width of Gaussian = ±error). See Introductory Text for discussion.

Contribution of experiment to χ^2 (if no entry present, experiment not used in calculating χ^2 or scale factor because of very large error).

Our best value for branching fraction as determined from data averaging, fitting, evaluating, limit selection, etc. This list is basically a compact summary of results in the Branching Ratio section below.

Branching ratio in terms of partial decay mode(s) Γ_i above.

Partial list of author(s) in addition to first author.

Quantum number determinations in this reference.

Institution(s) of author(s). (See abbreviations on next page.)

Abbreviations Used in the Particle Listings

Indicator of Procedure Used to Obtain Our Result

OUR AVERAGE	From a weighted average of selected data.
OUR FIT	From a constrained or overdetermined multiparameter fit of selected data.
OUR EVALUATION	Not from a direct measurement, but evaluated from measurements of other quantities.
OUR ESTIMATE	Based on the observed range of the data. Not from a formal statistical procedure.
OUR LIMIT	For special cases where the limit is evaluated by us from measured ratios or other data. Not from a direct measurement.

Measurement Techniques
(*i.e., Detectors and Methods of Analysis*)

ACCM	ACCMOR Collaboration
AEMS	Argonne effective mass spectrometer
ALEP	ALEPH – CERN LEP detector
AMY	AMY detector at KEK-TRISTAN
ARG	ARGUS detector at DORIS
ARGD	Fit to semicircular amplitude path on Argand diagram
ASP	Anomalous single-photon detector
ASPK	Automatic spark chambers
ASTE	ASTERIX detector at LEAR
ASTR	Astronomy
B787	BNL experiment 787 detector
B791	BNL experiment 791 detector
B845	BNL experiment 845 detector
BAKS	Baksan underground scintillation telescope
BC	Bubble chamber
BDMP	Beam dump
BEAT	CERN BEATRICE Collab.
BEBC	Big European bubble chamber at CERN
BES	BES Beijing Spectrometer at Beijing Electron-Positron Collider
BIS2	BIS-2 spectrometer at Serpukhov
BKEI	BENKEI spectrometer system at KEK Proton Synchroton
BONA	Bonanza nonmagnetic detector at DORIS
BPWA	Barrelet-zero partial-wave analysis
CALO	Calorimeter
CBAL	Crystal Ball detector at SLAC-SPEAR or DORIS
CBAR	Crystal Barrel detector at CERN-LEAR
CBOX	Crystal Box at LAMPF
CC	Cloud chamber
CCFR	Columbia-Chicago-Fermilab-Rochester detector
CDF	Collider detector at Fermilab
CDHS	CDHS neutrino detector at CERN
CELL	CELLO detector at DESY
CHER	Cherenkov detector
CHM2	CHARM-II neutrino detector (glass) at CERN
CHRM	CHARM neutrino detector (marble) at CERN
CIBS	CERN-IHEP boson spectrometer
CLE2	CLEO II detector at CESR
CLEO	Cornell magnetic detector at CESR
CMD	Cryogenic magnetic detector at VEPP-2M, Novosibirsk
CMD2	Cryogenic magnetic detector 2 at VEPP-2M, Novosibirsk
CNTR	Counters
COSM	Cosmology and astrophysics
CPLR	CPLEAR Collaboration
CSB2	Columbia U. - Stony Brook BGO calorimeter inserted in NaI array
CUSB	Columbia U. - Stony Brook segmented NaI detector at CESR
D0	D0 detector at Fermilab Tevatron Collider
DASP	DESY double-arm spectrometer
DBC	Deuterium bubble chamber
DLCO	DELCO detector at SLAC-SPEAR or SLAC-PEP
DLPH	DELPHI detector at LEP
DM1	Magnetic detector no. 1 at Orsay DCI collider
DM2	Magnetic detector no. 2 at Orsay DCI collider
DPWA	Energy-dependent partial-wave analysis
E621	Fermilab E621 detector
E653	Fermilab E653 detector
E687	Fermilab E687 detector
E691	Fermilab E691 detector
E705	Fermilab E705 Spectrometer-Calorimeter
E731	Fermilab E731 Spectrometer-Calorimeter
E761	Fermilab E761 detector
E773	Fermilab E773 Spectrometer-Calorimeter
E789	Fermilab E789 detector
E791	Fermilab E791 detector
E799	Fermilab E799 Spectrometer-Calorimeter
EHS	Four-pi detector at CERN
ELEC	Electronic combination
EMC	European muon collaboration detector at CERN
EMUL	Emulsions
FBC	Freon bubble chamber
FIT	Fit to previously existing data
FMPS	Fermilab Multiparticle Spectrometer
FRAB	ADONE $B\overline{B}$ group detector
FRAG	ADONE $\gamma\gamma$ group detector
FRAM	ADONE MEA group detector
FREJ	FREJUS Collaboration – modular flash chamber detector (calorimeter)
GA24	Hodoscope Cherenkov γ calorimeter (IHEP GAMS-2000) (CERN GAMS-4000)
GALX	GALLEX solar neutrino detector in the Gran Sasso Underground Lab.
GAM2	IHEP hodoscope Cherenkov γ calorimeter GAMS-2000
GAM4	CERN hodoscope Cherenkov γ calorimeter GAMS-4000
GOLI	CERN Goliath spectrometer
H1	H1 detector at DESY/HERA
HBC	Hydrogen bubble chamber
HDBC	Hydrogen and deuterium bubble chambers
HEBC	Helium bubble chamber
HEPT	Helium proportional tubes
HLBC	Heavy-liquid bubble chamber
HOME	Homestake underground scintillation detector
HPW	Harvard-Pennsylvania-Wisconsin detector
HRS	SLAC high-resolution spectrometer
HYBR	Hybrid: bubble chamber + electronics
IMB	Irvine-Michigan-Brookhaven underground Cherenkov detector
IMB3	Irvine-Michigan-Brookhaven underground Cherenkov detector
INDU	Magnetic induction
IPWA	Energy-independent partial-wave analysis
JADE	JADE detector at DESY
KAM2	KAMIOKANDE-II underground Cherenkov detector
KAMI	KAMIOKANDE underground Cherenkov detector
KARM	KARMEN calorimeter at the ISIS neutron spallation source at Rutherford
KOLR	Kolar Gold Field underground detector
L3	L3 detector at LEP
LASS	Large-angle superconducting solenoid spectrometer at SLAC
LEBC	Little European bubble chamber at CERN
LENA	Nonmagnetic lead-glass NaI detector at DORIS
LEPS	Low-Energy Pion Spectrometer at the Paul Scherrer Institute
MAC	MAC detector at PEP/SLAC
MBR	Molecular beam resonance technique
MCRO	MACRO detector in Gran Sasso
MD1	Magnetic detector at VEEP-4, Novosibirsk
MDRP	Millikan drop measurement
MICA	Underground mica deposits
MLEV	Magnetic levitation
MMS	Missing mass spectrometer
MPS	Multiparticle spectrometer at BNL
MPS2	Multiparticle spectrometer upgrade at BNL
MPSF	Multiparticle spectrometer at Fermilab
MPWA	Model-dependent partial-wave analysis
MRK1	SLAC Mark-I detector
MRK2	SLAC Mark-II detector
MRK3	SLAC Mark-III detector
MRKJ	Mark-J detector at DESY
MRS	Magnetic resonance spectrometer
NA14	CERN
NA31	CERN NA31 Spectrometer-Calorimeter
NA32	CERN NA32 Spectrometer
ND	NaI detector at VEPP-2M, Novosibirsk
NICE	Serpukhov nonmagnetic precision spectrometer
NMR	Nuclear magnetic resonance
NUSX	Mont Blanc NUSEX underground detector
OBLX	OBELIX detector at LEAR
OLYA	Detector at VEPP-2M and VEPP-4, Novosibirsk
OMEG	CERN OMEGA spectrometer
OPAL	OPAL detector at LEP
OSPK	Optical spark chamber
PLAS	Plastic detector
PLUT	DESY PLUTO detector
PWA	Partial-wave analysis

Abbreviations Used in the Particle Listings *(Cont'd)*

REDE	Resonance depolarization
RVUE	Review of previous data
SAGE	US - Russian Gallium Experiment
SFM	CERN split-field magnet
SHF	SLAC Hybrid Facility Photon Collaboration
SIGM	Serpukhov CERN-IHEP magnetic spectrometer (SIGMA)
SILI	Silicon detector
SLD	SLC Large Detector for e^+e^- colliding beams at SLAC
SOUD	Soudan underground detector
SPEC	Spectrometer
SPED	From maximum of speed plot or resonant amplitude
SPRK	Spark chamber
SQID	SQUID device
STRC	Streamer chamber
TASS	DESY TASSO detector
THEO	Theoretical or heavily model-dependent result
THY	Theory
TOF	Time-of-flight
TOPZ	TOPAZ detector at KEK-TRISTAN
TPC	TPC detector at PEP/SLAC
TPS	Tagged photon spectrometer at Fermilab
TRAP	Penning trap
UA1	UA1 detector at CERN
UA2	UA2 detector at CERN
UA5	UA5 detector at CERN
VES	Vertex Spectrometer Facility at 70 GeV IHEP accelerator
VNS	VENUS detector at KEK-TRISTAN
WA75	CERN WA75 experiment
WA82	CERN WA82 experiment
WA89	CERN WA89 experiment
WIRE	Wire chamber
XEBC	Xenon bubble chamber
ZEUS	ZEUS detector at DESY/HERA

Conferences

Conferences are generally referred to by the location at which they were held (e.g., HAMBURG, TORONTO, CORNELL, BRIGHTON, etc.).

Journals

AA	Astronomy and Astrophysics
ADVP	Advances in Physics
AFIS	Anales de Fisica
AJP	American Journal of Physics
ANP	Annals of Physics
ANPL	Annals of Physics (Leipzig)
ANYAS	Annals of the New York Academy of Sciences
AP	Atomic Physics
APAH	Acta Physica Academiae Scientiarum Hungaricae
APJ	Astrophysical Journal
APJS	Astrophysical Journal Suppl.
APP	Acta Physica Polonica
ARNPS	Annual Review of Nuclear and Particle Science
ARNS	Annual Review of Nuclear Science
ASP	Astroparticle Physics
BAPS	Bulletin of the American Physical Society
BASUP	Bulletin of the Academy of Science, USSR (Physics)
CJNP	Chinese Journal of Nuclear Physics
CJP	Canadian Journal of Physics
CNPP	Comments on Nuclear and Particle Physics
CZJP	Czechoslovak Journal of Physics
DANS	Doklady Akademii nauk SSSR
EPL	Europhysics Letters
FECAY	Fizika Elementarnykh Chastits i Atomnogo Yadra
HADJ	Hadronic Journal
IJMP	International Journal of Modern Physics
JAP	Journal of Applied Physics
JETP	English Translation of Soviet Physics ZETF
JETPL	English Translation of Soviet Physics ZETF Letters
JINR	Joint Inst. for Nuclear Research
JPA	Journal of Physics, A
JPB	Journal of Physics, B
JPCRD	Journal of Physical and Chemical Reference Data
JPG	Journal of Physics, G
JPSJ	Journal of the Physical Society of Japan
LNC	Lettere Nuovo Cimento
MNRA	Monthly Notices of the Royal Astronomical Society
MPL	Modern Physics Letters
NAT	Nature
NC	Nuovo Cimento
NIM	Nuclear Instruments and Methods
NP	Nuclear Physics
NPBPS	Nuclear Physics B Proceedings Supplement
PAN	Physics of Atomic Nuclei (formerly SJNP)
PD	Physics Doklady (Magazine)
PDAT	Physik Daten
PL	Physics Letters
PN	Particles and Nuclei
PPN	Physics of Particles and Nuclei (formerly SJPN)
PPNP	Progress in Particles and Nuclear Physics
PPSL	Proc. of the Physical Society of London
PR	Physical Review
PRAM	Pramana
PRL	Physical Review Letters
PRPL	Physics Reports (Physics Letters C)
PRSE	Proc. of the Royal Society of Edinburgh
PRSL	Proc. of the Royal Society of London, Section A
PS	Physica Scripta
PTP	Progress of Theoretical Physics
PTRSL	Phil. Trans. Royal Society of London
RA	Radiochimica Acta
RMP	Reviews of Modern Physics
RNC	La Rivista del Nuovo Cimento
RPP	Reports on Progress in Physics
RRP	Revue Roumaine de Physique
SCI	Science
SJNP	Soviet Journal of Nuclear Physics
SJPN	Soviet Journal of Particles and Nuclei
SPD	Soviet Physics Doklady (Magazine)
SPU	Soviet Physics - Uspekhi
YAF	Yadernaya Fizika
ZETF	Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki
ZETFP	Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, Pis'ma v Redakts
ZNAT	Zeitschrift fur Naturforschung
ZPHY	Zeitschrift fur Physik

Institutions

AACH	Phys. Inst. der Techn. Hochschule **Aachen** (Historical, use for general Inst. der Techn. Hochschule)	Aachen, Germany
AACH1	I Phys. Inst. der Techn. Hochschule **Aachen**	Aachen, Germany
AACH3	III Phys. Inst. der Techn. Hochschule **Aachen**	Aachen, Germany
AACHT	Institut für Theoretische Physik	**Aachen**, Germany
AARH	Univ. of **Aarhus**	Aarhus C, Denmark
ABO	**Åbo** Akademi University	Åbo (Turku), Finland
ADEL	**Adelphi** Univ.	Garden City, NY, USA
ADLD	The Univ. of **Adelaide**	Adelaide, SA, Australia
AERE	Atomic Energy Research Estab.	Didcot, United Kingdom
AFRR	**Armed Forces** Radiobiology Res. Inst.	Bethesda, MD, USA
AHMED	Physical Research Lab.	**Ahmedabad**, Gujarat, India
AICH	**Aichi** Univ. of Education	Aichi, Japan
AKIT	**Akita** Univ.	Akita, Japan
ALAH	Univ. of **Alabama (Huntsville)**	Huntsville, AL, USA
ALAT	Univ. of **Alabama (Tuscaloosa)**	Tuscaloosa, AL, USA
ALBA	**SUNY at Albany**	Albany, NY, USA
ALBE	Univ. of **Alberta**	Edmonton, AB, Canada
AMES	**Ames Lab.**	Ames, IA, USA
AMHT	**Amherst** College	Amherst, MA, USA
AMST	Univ. van **Amsterdam**	Amsterdam, The Netherlands
ANIK	NIKHEF	**Amsterdam**, The Netherlands
ANKA	**Middle East** Technical Univ.	Ankara, Turkey
ANL	**Argonne** National Lab.	Argonne, IL, USA
ANSM	**St. Anselm** Coll.	Manchester, NH, USA
ARCBO	**Arecibo** Observatory	Arecibo, PR, USA
ARIZ	Univ. of **Arizona**	Tucson, AZ, USA

Abbreviations Used in the Particle Listings *(Cont'd)*

ARZS	**Arizona State** Univ.	Tempe, AZ, USA
ASCI	Russian Academy of Sciences	**Moscow**, Russian Federation
AST	**Inst. of Phys.**	Nankang, Taipei, The Republic of China (Taiwan)
ATEN	NCSR **"Demokritos"**	**Aghia** Paraskevi Attikis, Greece
ATHU	Univ. of **Athens**	Athens, Greece
AUCK	Univ. of **Auckland**	Auckland, New Zealand
BAKU	Inst. of Physics	**Baku**, Azerbaijan
BANGB	**Bangabasi** College	Calcutta, India
BARC	Univ. Autónoma de **Barcelona**	Bellaterra (Barcelona), Spain
BARI	Univ. di **Bari**	Bari, Italy
BART	Univ. of **Delaware**; **Bartol** Research Inst.	Newark, DE, USA
BASL	Inst. für Physik der Univ. **Basel**	Basel, Switzerland
BAYR	Univ. **Bayreuth**	Bayreuth, Germany
BCEN	Centre d'Etudes Nucleaires de **Bordeaux-Gradignan**	Gradignan, France
BEIJT	**Inst. of Theoretical Physics**	**Beijing**, The People's Republic of China
BELG	Inter-University Inst. for High Energies (ULB-VUB)	**Bruxelles**, Belgium
BELL	AT & T **Bell** Labs	Murray Hill, NJ, USA
BERG	Univ. of **Bergen**	Bergen, Norway
BERL	**DESY** - Inst. für Hochenergiephysik Zeuthen	**Zeuthen**, Germany
BERN	Univ. of **Berne**	Berne, Switzerland
BGNA	Univ. di **Bologna**	Bologna, Italy
BGUN	**Ben-Gurion** Univ.	Beer-Sheva, Israel
BHAB	**Bhabha Atomic** Research Center	Trombay, Bombay, India
BHEP	**Inst. of High Energy Physics**	**Beijing**, The People's Republic of China
BIEL	Univ. **Bielefeld**	Bielefeld, Germany
BING	**SUNY at Binghamton**	Binghamton, NY, USA
BIRK	**Birkbeck** College, Univ. of London	London, United Kingdom
BIRM	Univ. of **Birmingham**	Edgbaston, Birmingham, United Kingdom
BLSU	**Bloomsburg** Univ.	Bloomsburg, PA, USA
BNL	**Brookhaven National Lab.**	Upton, NY, USA
BOCH	**Ruhr** Univ. **Bochum**	Bochum, Germany
BOHR	**Niels Bohr Inst.**	Copenhagen Ø, Denmark
BOIS	**Boise** State Univ.	Boise, ID, USA
BOMB	Univ. of **Bombay**	Bombay, India
BONN	**Rheinische Friedr.-Wilhelms-Univ. Bonn**	Bonn, Germany
BORD	Univ. de **Bordeaux I**	Gradignan, France
BOSE	S.N. **Bose** National Centre for Basis Sciences	Calcutta, India
BOSK	**"Rudjer Bošković"** Inst.	Zagreb, Croatia
BOST	**Boston** Univ.	Boston, MA, USA
BRAN	**Brandeis** Univ.	Waltham, MA, USA
BRCO	Univ. of **British Columbia**	Vancouver, BC, Canada
BRIS	Univ. of **Bristol**	Bristol, United Kingdom
BROW	**Brown** Univ.	Providence, RI, USA
BRUX	Univ. Libre de **Bruxelles**; Service de Physique des Particules Elémentaires	Bruxelles, Belgium
BRUXT	Univ. Libre de **Bruxelles**; Physique Théorique	Bruxelles, Belgium
BUCH	Univ. of **Bucharest**	Bucharest-Magurele, Romania
BUDA	KFKI Research Inst. for Particle & Nuclear Physics	**Budapest**, Hungary
BUFF	**SUNY at Buffalo**	Buffalo, NY, USA
BURE	Inst. des Hautes Etudes Scientifiques	**Bures-sur-Yvette**, France
CAEN	Lab. de Physique Corpusculaire, **ISMRA**	**Caen**, France
CAGL	Univ. di **Cagliari**	Cagliari, Italy
CAIR	**Cairo** University	Orman, Giza, Cairo, Egypt
CAIW	**Carnegie Inst.** of Washington	Washington, DC, USA
CALC	Univ. of **Calcutta**	Calcutta, India
CAMB	Univ. of **Cambridge**	Cambridge, United Kingdom
CAMP	Univ. de **Campinas**	**Campinas**, SP, Brasil
CANB	**Australian National Univ.**	Canberra, ACT, Australia
CAPE	University of **Capetown**	Rondebosch, Cape, South Africa
CARA	Univ. Central de **Venezuela**	Caracas, Venezuela
CARL	**Carleton** Univ.	Ottawa, ON, Canada
CARLC	**Carleton** College	Northfield, MN, USA
CASE	**Case** Western Reserve Univ.	Cleveland, OH, USA
CAST	**China** Center of Advanced Science and Technology	Beijing, The People's Republic of China
CATA	Univ. di **Catania**	Catania, Italy
CATH	**Catholic** Univ. of America	Washington, DC, USA
CAVE	**Cavendish** Lab.	Cambridge, United Kingdom
CBNM	CBNM	**Geel**, Belgium
CCAC	**Allegheny** College	Meadville, PA, USA
CDEF	**Collège de France**	Paris, France
CEA	Cambridge Electron Accelerator (Historical)	**Cambridge, MA**, USA
CENG	Centre d'Etudes Nucleaires	**Grenoble**, France
CERN	**CERN**, European Laboratory for Particle Physics	Genève, Switzerland
CFPA	Univ. of **California, (Berkeley)**	Berkeley, CA, USA
CHIC	Univ. of **Chicago**	Chicago, IL, USA
CIAE	**China Institute of Atomic Energy**	Beijing, The People's Republic of China
CINC	Univ. of **Cincinnati**	Cincinnati, OH, USA
CINV	CINVESTAV-IPN, Centro de Investigacion y de Estudios Avanzados del IPN	**México**, DF, Mexico
CIT	**California Inst. of Tech.**	Pasadena, CA, USA
CLER	Univ. de **Clermont-Ferrand**	Aubière, France
CLEV	**Cleveland** State Univ.	Cleveland, OH, USA
CMNS	**Comenius** Univ.	**Bratislava**, Slovak Republic
CMU	**Carnegie Mellon** Univ.	Pittsburgh, PA, USA
CNEA	**Comisión Nacional de Energía Atómica**	Buenos Aires, Argentina
CNRC	Centre for Research in Particle Physics	Ottawa, ON, Canada
COLO	Univ. of **Colorado**	Boulder, CO, USA
COLU	**Columbia** Univ.	New York, NY, USA
CONC	**Concordia** University	Montreal, PQ, Canada
CORN	**Cornell** Univ.	Ithaca, NY, USA
COSU	**Colorado State** Univ.	Fort Collins, CO, USA
CPPM	Centre National de la Recherche Scientifique, Luminy	**Marseille**, France
CRAC	**Kraków** Inst. of Nuclear Physics	Kraków, Poland
CRNL	**Chalk River** Labs.	Chalk River, ON, Canada
CSOK	**Oklahoma** Central State Univ.	Edmond, OK, USA
CST	Univ. of **Science and Technology** of China	**Hefei**, Anhui 230027, The People's Republic of China
CSULB	**California** State Univ.	Long Beach, CA, USA
CUNY	**City College** of **New York**	New York, NY, USA
CURIN	**Univ. Pierre et Marie Curie** (Paris VI), LPNHE	Paris, France
CURIT	**Univ. Pierre et Marie Curie** (Paris VI), LPTHE	Paris, France
DALH	**Dalhousie** Univ.	Halifax, NS, Canada
DARE	**Daresbury** Lab	Cheshire, United Kingdom
DARM	Tech. Hochschule **Darmstadt**	Darmstadt, Germany
DELA	Univ. of **Delaware**	Newark, DE, USA
DELH	Univ. of **Delhi**	Delhi, India
DESY	**DESY**, Deutsches Elektronen-Synchrotron	Hamburg, Germany
DFAB	Escuela de Ingenieros	**Bilbao**, Spain
DOE	**Department of Energy**	Germantown, MD, USA
DORT	Univ. **Dortmund**	Dortmund, Germany
DUKE	**Duke** Univ.	Durham, NC, USA
DURH	Univ. of **Durham**	Durham City, United Kingdom
DUUC	**University** College	Dublin, Ireland
EDIN	Univ. of **Edinburgh**	Edinburgh, United Kingdom
EFI	**Enrico Fermi Inst.**	**Chicago**, IL, USA
ELMT	**Elmhurst** College	Elmhurst, IL, USA
ENSP	**l'Ecole Normale Supérieure**	**Paris**, France
EOTV	**Eötvös** University	Budapest, Hungary

Abbreviations Used in the Particle Listings *(Cont'd)*

EPOL	**École Polytechnique**	**Palaiseau**, France
ERLA	Univ. **Erlangen-Nürnberg**	Erlangen, Germany
ETH	**Univ. Zürich**	Zürich, Switzerland
FERR	Univ. di **Ferrara**	Ferrara, Italy
FIRZ	Univ. di **Firenze**	Firenze, Italy
FISK	**Fisk** Univ.	Nashville, TN, USA
FLOR	Univ. of **Florida**	Gainesville, FL, USA
FNAL	**Fermilab**	Batavia, IL, USA
FOM	**FOM**, Stichting voor Fundamenteel Onderzoek der Materie	JP **Utrecht**, The Netherlands
FRAN	Univ. **Frankfurt**	Frankfurt am Main, Germany
FRAS	Lab. Nazionali de **Frascati** dell'INFN	Frascati (Roma), Italy
FREIB	**Albert-Ludwigs** Univ.	**Freiburg**, Germany
FREIE	**Freie Univ. Berlin**	Berlin, Germany
FRIB	Univ. de **Fribourg**	Fribourg, Switzerland
FSU	**Florida State** University	Tallahassee, FL, USA
FSUSC	**Florida State** Univ.	Tallahassee, FL, USA
FUKI	**Fukui** Univ.	Fukui, Japan
FUKU	**Fukushima** Univ.	Fukushima, Japan
GENO	Univ. di **Genova**	Genova, Italy
GEOR	**Georgian Academy of Sciences**	Tbilisi, Republic of Georgia
GESC	**General Electric** Co.	Schenectady, NY, USA
GEVA	Univ. de **Genève**	Genève, Switzerland
GIES	Univ. **Giessen**	Giessen, Germany
GIFU	**Gifu** Univ.	Gifu, Japan
GLAS	Univ. of **Glasgow**	Glasgow, United Kingdom
GMAS	**George Mason** Univ.	Fairfax, VA, USA
GOET	Univ. **Göttingen**	Göttingen, Germany
GRAN	Univ. de **Granada**	Granada, Spain
GRAZ	Univ. **Graz**	Graz, Austria
GRON	Univ. of **Groningen**	Groningen, The Netherlands
GSCO	**Geological Survey of Canada**	Ottawa, ON, Canada
GSI	**Darmstadt Gesellschaft** fur Schwerionenforschung	Darmstadt, Germany
GUEL	Univ. of **Guelph**	Guelph, ON, Canada
GWU	**George Washington** Univ.	Washington, DC, USA
HAHN	**Hahn-Meitner** Inst. Berlin GmbH	Berlin, Germany
HAIF	**Technion** – Israel Inst. of Tech.	Technion, Haifa, Israel
HAMB	Univ. **Hamburg**; I Inst. für Experimentalphysik; II Inst. für Experimentalphysik	Hamburg, Germany
HANN	Univ. **Hannover**	Hannover, Germany
HARC	**Houston Advanced Research Ctr.**	The Woodlands, TX, USA
HARV	**Harvard** Univ.	Cambridge, MA, USA
HAWA	Univ. of **Hawai'i**	Honolulu, HI, USA
HEBR	**Hebrew** Univ.	Jerusalem, Israel
HEID	Univ. **Heidelberg** (Historical)	Heidelberg, Germany
HEIDH	Univ. **Heidelberg**; Inst. für Hochenergiephysik	Heidelberg, Germany
HEIDP	Univ. **Heidelberg**; Physik Inst.	Heidelberg, Germany
HEIDT	Univ. **Heidelberg**; Inst. für Theoretische Physik	Heidelberg, Germany
HELS	Univ. of **Helsinki**	University of Helsinki, Finland
HIRO	**Hiroshima** Univ.	Higashi-Hiroshima, Japan
HOUS	Univ. of **Houston**	Houston, TX, USA
HPC	**Hewlett-Packard** Corp.	Cupertino, CA, USA
HSCA	**Harvard-Smithsonian** Center for Astrophysics	Cambridge, MA, USA
IAS	**Inst. for Advanced Study**	Princeton, NJ, USA
IASD	**Dublin** Inst. for Advanced Studies	Dublin, Ireland
IBAR	**Ibaraki** Univ.	Ibaraki, Japan
IBM	**IBM** Corp.	Palo Alto, CA, USA
IBMY	**IBM**	Yorktown Heights, NY, USA
IBS	Inst. for **Boson Studies**	Pasadena, CA, USA
ICEPP	Univ. of **Tokyo**; Int. Center for Elementary Particle Physics (ICEPP)	Tokyo, Japan
ICRR	Univ. of **Tokyo**; **Inst. for Cosmic Ray Research**	Tokyo, Japan
ICTP	Int'l Centre for Theoretical Physics	**Trieste**, Italy
IFIC	Univ. de **Valencia** – CSIC	Burjassot, Valencia, Spain
IFRJ	Univ. Federal do **Rio de Janeiro**	Rio de Janeiro, RJ, Brasil
IIT	**Illinois Inst. of Tech. Center**	Chicago, IL, USA
ILL	Univ. of **Illinois at Urbana-Champaign**	Urbana, IL, USA
ILLC	Univ. of **Illinois at Chicago**	Chicago, IL, USA
ILLG	Inst. **Laue-Langevin**	Grenoble, France
IND	**Indiana** Univ.	Bloomington, IN, USA
INEL	E G and G **Idaho**, Inc.	Idaho Falls, ID, USA
INFN	Ist. Nazionale di Fisica Nuclear (Generic INFN, unknown location)	Various places, Italy
INNS	**Leopold-Franzens** Univ.	**Innsbruck**, Austria
INRM	**INR**, Inst. for Nucl. Research	**Moscow**, Russian Federation
INUS	Univ. of **Tokyo**; **Inst. for Nuclear Study**	Tokyo, Japan
IOAN	Univ. of **Ioannina**	Ioannina, Greece
IOFF	A.F. **Ioffe** Phys. Tech. Inst.	St. **Petersburg**, Russian Federation
IOWA	Univ. of **Iowa**	Iowa City, IA, USA
IPN	**IPN**, Inst. de Phys. Nucl.	**Orsay**, France
IPNP	Univ. Pierre et Marie Curie (**Paris** VI)	Paris, France
IRAD	Inst. du Radium (Historical)	**Paris**, France
ISNG	Inst. des Sciences Nucleaires (ISN)	**Grenoble**, France
ISU	**Iowa State** Univ.	Ames, IA, USA
ITEP	**ITEP**, Inst. of Theor. and Exp. Physics	**Moscow**, Russian Federation
ITHA	**Ithaca** College	Ithaca, NY, USA
IUPU	**Indiana** Univ., **Purdue** Univ. **Indianapolis**	Indianapolis, IN, USA
JADA	**Jadavpur** Univ.	Calcutta, India
JAGL	**Jagiellonian** Univ.	Kraków, Poland
JHU	**Johns Hopkins** Univ.	Baltimore, MD, USA
JINR	**JINR**, Joint Inst. for Nucl. Research	**Dubna**, Russian Federation
JULI	**Julich**, Forschungszentrum	Julich, Germany
JYV	Univ. of **Jyväskylä**	Jyväskylä, Finland
KAGO	Univ. of **Kagoshima**	Kagoshima-shi, Japan
KANS	Univ. of **Kansas**	Lawrence, KS, USA
KARL	Univ. **Karlsruhe** (Historical)	Karlsruhe, Germany
KARLE	Univ. **Karlsruhe**; Inst. für Experimentelle Kernphysik	Karlsruhe, Germany
KARLK	Forschungszentrum **Karlsruhe**	Karlsruhe, Germany
KARLT	Univ. **Karlsruhe**; Inst. für Theoretische Teilchenphysik	Karlsruhe, Germany
KAZA	**Kazakh** Inst. of High Energy Physics	Alma Ata, Kazakhstan
KEK	**KEK**, National Lab. for High Energy Phys.	Ibaraki-ken, Japan
KENT	Univ. of **Kent**	Canterbury, United Kingdom
KEYN	**Open** Univ.	Milton Keynes, United Kingdom
KFTI	**Kharkov** Inst. of Physics and Tech. (KFTI)	Kharkov, Ukraine
KIAE	**Kurchatov** Inst.	**Moscow**, Russian Federation
KIAM	**Keldysh** Inst. of Applied Math., Acad. Sci., Russia	Moscow, Russian Federation
KIDR	**Inst. of Nuclear Sciences**, Vinča (Formerly Boris Kidrič Inst.)	Beograd, Serbia, Yugoslavia
KIEV	**Institute for Nuclear Research**	**Kiev**, Ukraine
KINK	**Kinki** Univ.	Osaka, Japan
KNTY	Univ. of **Kentucky**	Lexington, KY, USA
KOBE	**Kobe** Univ.	Kobe, Japan
KOMAB	Univ. of **Tokyo, Komaba**	Tokyo, Japan
KONAN	**Konan** Univ.	Kobe, Japan
KOSI	Inst. of Experimental Physics	**Košice**, Slovak Republic
KYOT	**Kyoto** Univ.	Kyoto, Japan
KYOTY	**Kyoto** Univ.; **Yukawa** Inst. for Theor. Physics	Kyoto, Japan
KYUN	**Kyungpook** National Univ.	Taegu, Republic of Korea

Abbreviations Used in the Particle Listings *(Cont'd)*

LALO	**LAL**, Laboratoire de l'Accélérateur Linéaire	**Orsay**, France
LANC	Univ. of **Lancaster**	Lancaster, United Kingdom
LANL	**Los Alamos National Lab.** (LANL)	Los Alamos, NM, USA
LAPP	**LAPP**, Lab. d'Annecy-le-Vieux de Phys. des Particules	**Annecy-le-Vieux**, France
LASL	U.C. **Los Alamos Scientific** Lab. (Old name for LANL)	Los Alamos, NM, USA
LATV	**Latvian** State Univ.	Riga, Latvia
LAUS	Univ. de **Lausanne**	Lausanne, Switzerland
LAVL	Univ. **Laval**	Quebec, PQ, Canada
LBL	**Lawrence Berkeley National Lab.**	Berkeley, CA, USA
LCGT	Univ. di **Torino**	Turin, Italy
LEBD	**Lebedev** Physical Inst.	**Moscow**, Russian Federation
LECE	Univ. di **Lecce**	Lecce, Italy
LEED	Univ. of **Leeds**	Leeds, United Kingdom
LEHI	**Lehigh** Univ.	Bethlehem, PA, USA
LEHM	**Lehman** College of CUNY	Bronx, NY, USA
LEID	Univ. of **Leiden**	Leiden, The Netherlands
LEMO	**Le Moyne** Coll.	Syracuse, NY, USA
LEUV	Katholieke Univ. **Leuven**	Leuven, Belgium
LINZ	Univ. **Linz**	Linz, Austria
LISB	Inst. Nacional de Investigacion Cientifica	**Lisboa** CODEX, Portugal
LISBT	Univ. Técnica de Lisboa, Inst. Superior Técnico	**Lisboa**, Portugal
LIVP	Univ. of **Liverpool**	Liverpool, United Kingdom
LLL	**Lawrence Livermore Lab.** (Old name for LLNL)	Livermore, CA, USA
LLNL	**Lawrence Livermore National Lab.**	Livermore, CA, USA
LOCK	**Lockheed** Palo Alto Res. Lab	Palo Alto, CA, USA
LOIC	**Imperial** College of Science Tech. & Medicine	London, United Kingdom
LOQM	**Univ. of London**, Queen Mary & Westfield College	London, United Kingdom
LOUC	**University College** London	London, United Kingdom
LOUV	Univ. Catholique de **Louvain**	Louvain-la-Neuve, Belgium
LOWC	**Westfield** College (Historical, see LOQM (Queen Mary and Westfield joined))	London, United Kingdom
LRL	U.C. Lawrence Radiation Lab. (Old name for LBL)	**Berkeley**, CA, USA
LSU	**Louisiana** State Univ.	Baton Rouge, LA, USA
LUND	Univ. of **Lund**	Lund, Sweden
LYON	Institute de Physique Nucléaire de **Lyon** (IPN)	Villeurbanne, France
MADE	Inst. de Estructura de la Materia	**Madrid**, Spain
MADR	**C.I.E.M.A.T**	**Madrid**, Spain
MADU	Univ. Autónoma de **Madrid**	Madrid, Spain
MANI	Univ. of **Manitoba**	Winnipeg, MB, Canada
MANZ	**Johannes-Gutenberg-Univ.**	**Mainz**, Germany
MARB	Univ. **Marburg**	Marburg, Germany
MARS	Centre de Physique des Particules de **Marseille**	Marseille, France
MASA	Univ. of **Massachusetts**	**Amherst**, MA, USA
MASB	Univ. of **Massachusetts** at Boston	**Boston**, MA, USA
MASD	Univ. of **Massachusetts** Dartmouth	N. **Dartmouth**, MA, USA
MCGI	**McGill** Univ.	Montreal, QC, Canada
MCHS	Univ. of **Manchester**	Manchester, United Kingdom
MCMS	**McMaster** Univ.	Hamilton, ON, Canada
MEHTA	**Mehta** Research Inst.	Allahabad, India
MEIS	**Meisei** Univ.	Tokyo, Japan
MELB	Univ. of **Melbourne**	Parkville, Victoria, Australia
MEUD	Observatoire de **Meudon**	Meudon, France
MICH	Univ. of **Michigan**	Ann Arbor, MI, USA
MILA	Univ. di **Milano**	Milano, Italy
MINN	Univ. of **Minnesota**	Minneapolis, MN, USA
MISS	Univ. of **Mississippi**	University, MS, USA
MIT	**MIT Massachusetts Inst. of Technology**	Cambridge, MA, USA
MIU	**Maharishi** International Univ.	Fairfield, IA, USA
MIYA	**Miyazaki** Univ.	Miyazaki-shi, Japan
MONP	Univ. de **Montpellier** II	Montpellier, France
MONS	Univ. de **Mons-Hainaut**	**Mons**, Belgium
MONT	Univ. de **Montréal**; Laboratoire de physique nucléaire	Montréal, PQ, Canada
MONTC	Univ. de **Montréal**; Centre de recherches mathématiques	Montréal, PQ, Canada
MOSU	**Moscow** State Univ.	**Moscow**, Russian Federation
MPCM	Max Planck Inst. fur Chemie	**Mainz**, Germany
MPEI	**Moscow Physical Engineering** Inst.	Moscow, Russian Federation
MPIA	**Max-Planck**-Institute für Astrophysik	Garching, Germany
MPIH	**Max-Planck-Inst.** für Kernphysik	**Heidelberg**, Germany
MPIM	**Max-Planck-Inst.** für Physik	**München**, Germany
MSU	**Michigan State** Univ.	East Lansing, MI, USA
MTHO	**Mount Holyoke** College	South Hadley, MA, USA
MULH	Centre Univ. du **Haut-Rhin**	Mulhouse, France
MUNI	Univ. of **München**	Garching, Germany
MUNT	Tech. Univ. **München**	Garching, Germany
MURA	**Midwestern** Univ. Research Assoc. (Historical)	Stroughton, WI, USA
NAAS	North Americal Aviation Science Center (Historical)	Thousand Oaks, CA, USA
NAGO	**Nagoya** Univ.	Nagoya, Japan
NAPL	Univ. di **Napoli**	Napoli, Italy
NASA	**NASA**	Greenbelt, MD, USA
NBS	U.S **National Bureau of Standards** (Old name for NIST)	Gaithersburg, MD, USA
NBSB	**National Inst. Standards Tech.**	Boulder, CO, USA
NCAR	**National Center for Atmospheric Research**	Boulder, CO, USA
NDAM	Univ. of **Notre Dame**	Notre Dame, IN, USA
NEAS	**Northeastern** Univ.	Boston, MA, USA
NEUC	Univ. de **Neuchâtel**	Neuchâtel, Switzerland
NICEA	Univ. de **Nice**	Nice, France
NICEO	Observatoire de **Nice**	Nice, France
NIHO	**Nihon** Univ.	Tokyo, Japan
NIIG	**Niigata** Univ.	Niigata, Japan
NIJM	Univ. of **Nijmegen**	Nijmegen, The Netherlands
NIRS	Nat. Inst. Radiological Sciences	**Chiba**, Japan
NIST	**National Institute of Standards & Technology**	Gaithersburg, MD, USA
NIU	**Northern Illinois** Univ.	De Kalb, IL, USA
NMSU	**New Mexico** State Univ.	Las Cruces, NM, USA
NORD	**Nordita**	Copenhagen Ø, Denmark
NOTT	Univ. of **Nottingham**	Nottingham, United Kingdom
NOVM	Inst. of Mathematics	**Novosibirsk**, Russian Federation
NOVO	BINP, **Budker** Inst. of Nuclear Physics	**Novosibirsk**, Russian Federation
NPOL	Polytechnic of **North London**	London, United Kingdom
NRL	**Naval Research** Lab	Washington, DC, USA
NSF	**National Science Foundation**	Arlington, VA, USA
NTHU	**National Tsing Hua** Univ.	Hsinchu, The Republic of China (Taiwan)
NTUA	**National Tech. Univ. of Athens**	Athens, Greece
NWES	**Northwestern** Univ.	Evanston, IL, USA
NYU	**New York** Univ.	New York, NY, USA
OBER	**Oberlin** College	Oberlin, OH, USA
OHIO	**Ohio** Univ.	Athens, OH, USA
OKAY	**Okayama** Univ.	Okayama, Japan
OKLA	Univ. of **Oklahoma**	Norman, OK, USA
OKSU	**Oklahoma State** Univ.	Stillwater, OK, USA
OREG	Univ. of **Oregon**	Eugene, OR, USA
ORNL	**Oak Ridge** National Laboratory	Oak Ridge, TN, USA
ORSAY	Univ. de Paris Sud	**Orsay**, France
ORST	**Oregon State** Univ.	Corvallis, OR, USA
OSAK	**Osaka** Univ.	Osaka, Japan

Abbreviations Used in the Particle Listings *(Cont'd)*

OSKC	**Osaka City** Univ.	Osaka-shi, Japan
OSLO	Univ. of **Oslo**	Oslo, Norway
OSU	**Ohio State** Univ.	Columbus, OH, USA
OTTA	Univ. of **Ottawa**	Ottawa, ON, Canada
OXF	University of **Oxford**	Oxford, United Kingdom
OXFTP	Univ. of **Oxford**	Oxford, United Kingdom
PADO	Univ. di **Padova**, "G. Galilei"	Padova, Italy
PARIN	**Univ. Paris VI et Paris VII**, IN^2P^3/CNRS	Paris, France
PARIS	Univ. de Paris (Historical)	**Paris**, France
PARM	Univ. di **Parma**	Parma, Italy
PAST	Institut **Pasteur**	**Paris**, France
PATR	Univ. of **Patras**	Patras, Greece
PAVI	Univ. di **Pavia**	Pavia, Italy
PENN	Univ. of **Pennsylvania**	Philadelphia, PA, USA
PGIA	Univ. di **Perugia**	Perugia, Italy
PISA	Univ. di **Pisa**	Pisa, Italy
PISAI	**INFN, Sez. di Pisa**	Pisa, Italy
PITT	Univ. of **Pittsburgh**	Pittsburgh, PA, USA
PLAT	**SUNY at Plattsburgh**	Plattsburgh, NY, USA
PLRM	Univ. di **Palermo**	Palermo, Italy
PNL	**Battelle Memorial** Inst.	Richland, WA, USA
PNPI	**Petersburg** Nuclear Physics Inst.	Gatchina, Russian Federation
PPA	Princeton-Penn. Proton Accelerator (Historical)	Princeton, NJ, USA
PRAG	Inst. of Physics, **ASCR**	**Prague**, Czech Republic
PRIN	**Princeton** Univ.	Princeton, NJ, USA
PSI	Paul Scherrer Inst.	**Villigen** PSI, Switzerland
PSLL	**Physical Science Lab**	Las Cruces, NM, USA
PSU	**Penn State** Univ.	University Park, PA, USA
PUCB	**Pontifícia Univ. Católica do Rio de Janeiro**	Rio de Janeiro, RJ, Brasil
PUEB	High Energy Physics Group, **FCFM – BUAP**	**Puebla**, Pue, Mexico
PURD	**Purdue** Univ.	Lafayette, IN, USA
QUKI	**Queen's** Univ.	Kingston, ON, Canada
RAL	**Rutherford Appleton** Lab.	Chilton, Didcot, Oxon., United Kingdom
REGE	Univ. **Regensburg**	Regensburg, Germany
REHO	**Weizmann** Inst. of Science	Rehovot, Israel
RHBL	**Royal Holloway & Bedford** New College	Egham, Surrey, United Kingdom
RHEL	**Rutherford** High Energy Lab (Old name for RAL)	Chilton, Didcot, Oxon., United Kingdom
RICE	**Rice** Univ.	Houston, TX, USA
RIKEN	**Riken** Accelerator Research Facility (RARF)	Saitama, Japan
RIKK	**Rikkyo** Univ.	Tokyo, Japan
RIS	**Rowland** Inst. for Science	Cambridge, MA, USA
RISC	**Rockwell** International	Thousand Oaks, CA, USA
RISL	**Universities Research Reactor**	**Risley**, Warrington, United Kingdom
RISO	**Riso** National Laboratory	Roskilde, Denmark
RL	**Rutherford** High Energy Lab (Old name for RAL)	Chilton, Didcot, Oxon., United Kingdom
RMCS	**Royal Military** Coll. of Science	Swindon, Wilts., United Kingdom
ROCH	Univ. of **Rochester**	Rochester, NY, USA
ROCK	**Rockefeller** Univ.	New York, NY, USA
ROMA	Univ. di **Roma** (Historical)	**Roma**, Italy
ROMA2	Univ. di **Roma**, "Tor Vergata"	Roma, Italy
ROMAI	**INFN, Sez. di Roma**	Roma, Italy
ROSE	**Rose-Hulman** Inst. of Technology	Terre Haute IN, USA
RPI	**Rensselaer Polytechnic** Inst.	Troy, NY, USA
RUTG	**Rutgers** Univ.	Piscataway, NJ, USA
SACL	**CE Saclay**	Gif-sur-Yvette, France
SACLD	**CE Saclay**; DAPNIA	Gif-sur-Yvette, France
SAGA	**Saga** Univ.	Saga-shi, Japan
SANG	**Kyoto Sangyo** Univ.	Kyoto-shi, Japan
SANI	Physics Lab., Ist. Superiore di Sanità	**Roma**, Italy
SASK	Univ. of **Saskatchewan**	Saskatoon, SK, Canada
SASSO	Lab. Naz. del **Gran Sasso** dell'INFN	**Assergi** (L'Aquila), Italy
SAVO	Univ. de **Savoie**	Chambery, France
SBER	**California** State Univ.	**San Bernardino**, CA, USA
SCIT	**Science** Univ. of **Tokyo**	Tokyo, Japan
SCOT	**Scottish** Univ. Research and Reactor Ctr.	Glasgow, United Kingdom
SCUC	Univ. of **South Carolina**	Columbia, SC, USA
SEAT	**Seattle Pacific** Coll.	Seattle, WA, USA
SEIB	Austrian Research Center, **Seibersdorf** LTD.	Seibersdorf, Austria
SEOU	**Korea** Univ.	Seoul, Republic of Korea
SEOUL	**Seoul** National Univ.	Seoul, Republic of Korea
SERP	**IHEP**, Inst. for High Energy Physics (Also known as Serpukhov)	Protvino, Russian Federation
SETO	**Seton Hall** Univ.	South Orange, NJ, USA
SFLA	Univ. of **South Florida**	Tampa, FL, USA
SFRA	**Simon Fraser University**	Burnaby, BC, Canada
SFSU	**California** State Univ.	**San Francisco**, CA, USA
SHEF	Univ. of **Sheffield**	Sheffield, United Kingdom
SHMP	Univ. of **Southampton**	Southampton, United Kingdom
SIEG	Univ.-Gesamthochschule-**Siegen**	Siegen, Germany
SILES	Univ. of **Silesia**	Katowice, Poland
SIN	Swiss Inst. of Nuclear Research (Old name for VILL)	**Villigen**, Switzerland
SING	**National Univ.** of Singapore	Kent Ridge, Singapore
SISSA	Scuola Internazionale Superiore di Studi Avanzati	**Trieste**, Italy
SLAC	**Stanford Linear Accelerator Center**	Stanford, CA, USA
SLOV	Inst. of Physics, Slovak Acad. of Sciences	**Bratislava**, Slovak Republic
SMU	**Southern Methodist** Univ.	Dallas, TX, USA
SNSP	**Scuola Normale Superiore**	**Pisa**, Italy
SOFI	Inst. for Nuclear Research and Nuclear Energy	**Sofia**, Bulgaria
SOFU	Univ. of **Sofia**	Sofia, Bulgaria
SPAUL	Univ. de **São Paulo**	São Paulo, SP, Brasil
SPIFT	Inst. de Física Teórica (**IFT**)	**São Paulo**, SP, Brasil
SSL	Univ. of **California (Berkeley)**; Space Sciences Lab	Berkeley, CA, USA
STAN	**Stanford** Univ.	Stanford, CA, USA
STEV	**Stevens** Inst. of Tech.	Hoboken, NJ, USA
STLO	**St. Louis** Univ.	St. Louis, MO, USA
STOH	**Stockholm** Univ.	Stockholm, Sweden
STON	**SUNY at Stony Brook**	Stony Brook, NY, USA
STRB	**CRN**, Centre des Recherches Nucl.	**Strasbourg**, France
STUT	Univ. **Stuttgart**	Stuttgart, Germany
STUTM	Max-Planck-Inst.	**Stuttgart**, Germany
SUGI	**Sugiyama Jogakuen** Univ.	Aichi, Japan
SURR	Univ. of **Surrey**	Guildford, Surrey, United Kingdom
SUSS	Univ. of **Sussex**	Brighton, United Kingdom
SYDN	Univ. of **Sydney**	Sydney, NSW, Australia
SYRA	**Syracuse** Univ.	Syracuse, NY, USA
TAJK	Acad. Sci., Tadzhik SSR	**Dushanbe**, Tadzhikstan
TAMU	**Texas A&M** Univ.	College Station, TX, USA
TATA	**Tata** Inst. of Fundamental Research	Bombay, India
TBIL	**Tbilisi State University**	Tbilisi, Republic of Georgia
TELA	**Tel-Aviv** Univ.	Tel Aviv, Israel
TELE	**Teledyne Brown** Engineering	Huntsville, AL, USA
TEMP	**Temple** Univ.	Philadelphia, PA, USA
TENN	Univ. of **Tennessee**	Knoxville, TN, USA
TEXA	Univ. of **Texas at Austin**	Austin, TX, USA
TGAK	**Tokyo Gakugei** Univ.	Tokyo, Japan
TGU	**Tohoku Gakuin** Univ.	Miyagi, Japan
THES	Aristotle Univ. of **Thessaloniki**	Thessaloniki, Greece
TINT	**Tokyo Inst. of Technology**	Tokyo, Japan
TISA	**Sagamihara** Inst. of Space & Astronautical Sci.	Kanagawa, Japan
TMSK	Inst. Nuclear Physics	**Tomsk**, Russian Federation
TMTC	**Tokyo Metropolitan** Coll. Tech.	Tokyo, Japan
TMU	**Tokyo Metropolitan Univ.**	Tokyo, Japan

Abbreviations Used in the Particle Listings *(Cont'd)*

TNTO	Univ. of **Toronto**	Toronto, ON, Canada
TOHO	**Toho** Univ.	Chiba, Japan
TOHOK	**Tohoku** Univ.	Sendai, Japan
TOKA	**Tokai** Univ.	Shimizu, Japan
TOKMS	Univ. of **Tokyo**; Meson Science Laboratory	Tokyo, Japan
TOKU	Univ. of **Tokushima**	Tokushima-shi, Japan
TOKY	Univ. of **Tokyo**; Physics Dept.	Tokyo, Japan
TOKYC	Univ. of **Tokyo**; Dept. of Chemistry	Tokyo, Japan
TORI	Univ. degli Studi di **Torino**	Torino, Italy
TPTI	Lab. of High Energy Phys.	**Tashkent**, Republic of Uzbekistan
TRIN	**Trinity** College	**Dublin**, Ireland
TRIU	**TRIUMF**	Vancouver, BC, Canada
TRST	Univ. degli Studi di **Trieste**	Trieste, Italy
TRSTI	INFN, Sez. di **Trieste**	Trieste, Italy
TRSTT	Univ. di **Trieste**	**Trieste**, Italy
TSUK	Univ. of **Tsukuba**	Ibaraki-ken, Japan
TTAM	**Tamagawa** Univ.	Tokyo, Japan
TUAT	**Tokyo** Univ. of Agriculture Tech.	Tokyo, Japan
TUBIN	Univ. **Tübingen**	Tübingen, Germany
TUFTS	**Tufts** Univ.	Medford, MA, USA
TUW	**Technische** Univ. **Wien**	Vienna, Austria
UCB	Univ. of **California (Berkeley)**	Berkeley, CA, USA
UCD	Univ. of **California (Davis)**	Davis, CA, USA
UCI	Univ. of **California (Irvine)**	Irvine, CA, USA
UCLA	Univ. of **California (Los Angeles)**	Los Angeles, CA, USA
UCND	**Union Carbide** Corp.	Oak Ridge, TN, USA
UCR	Univ. of **California (Riverside)**	Riverside, CA, USA
UCSB	Univ. of **California (Santa Barbara)**	Santa Barbara, CA, USA
UCSBT	**Inst. for Theoretical Physics**	Santa Barbara, CA, USA
UCSC	Univ. of **California (Santa Cruz)**	Santa Cruz, CA, USA
UCSD	Univ. of **California (San Diego)**	La Jolla, CA, USA
UMD	Univ. of **Maryland**	College Park, MD, USA
UNC	Univ. of **North Carolina**	Greensboro, NC, USA
UNCCH	Univ. of **North Carolina** at **Chapel Hill**	Chapel Hill, NC, USA
UNCS	**Union** College	Schenectady, NY, USA
UNH	Univ. of **New Hampshire**	Durham, NH, USA
UNM	Univ. of **New Mexico**	Albuquerque, NM, USA
UOEH	Univ. of Occupational and Environmental Health	**Kitakyushu**, Japan
UPNJ	**Upsala** College	East Orange, NJ, USA
UPPS	**Uppsala** Univ.	**Uppsala**, Sweden
UPR	Univ. of **Puerto Rico**	Rio Piedras, PR, USA
URI	Univ. of **Rhode Island**	Kingston, RI, USA
USC	Univ. of **Southern California**	Los Angeles, CA, USA
USF	Univ. of **San Francisco**	San Francisco, CA, USA
UTAH	Univ. of **Utah**	Salt Lake City, UT, USA
UTRE	Univ. of **Utrecht**	Utrecht, The Netherlands
UTRO	Univ. of **Trondheim**	Dragvoll, Norway
UZINR	Acad. Sci., **Ukrainian** SSR	**Uzhgorod**, Ukraine
VALE	Univ. de **Valencia**	Burjassot, **Valencia**, Spain
VALP	**Valparaiso** Univ.	Valparaiso, IN, USA
VAND	**Vanderbilt** Univ.	Nashville, TN, USA
VASS	**Vassar** College	Poughkeepsie, NY, USA
VICT	Univ. of **Victoria**	Victoria, BC, Canada
VIEN	Inst. für Hochenergiephysik (HEPHY)	**Vienna**, Austria
VILL	Inst. for Particle Physics of ETH Zürich	**Villigen** PSI, Switzerland
VIRG	Univ. of **Virginia**	Charlottesville, VA, USA
VPI	**Virginia Tech.**	Blacksburg, VA, USA
VRIJ	**Vrije** Univ.	HV **Amsterdam**, The Netherlands
WABRN	Eidgenossisches Amt für Messwesen	**Waber**, Switzerland
WARS	**Warsaw** Univ.	Warsaw, Poland
WASCR	**Waseda** Univ.; Cosmic Ray Division	Tokyo, Japan
WASH	Univ. of **Washington**	Seattle, WA, USA
WASU	**Waseda** Univ.	Tokyo, Japan
WAYN	**Wayne** State Univ.	Detroit, MI, USA
WESL	**Wesleyan** Univ.	Middletown, CT, USA
WIEN	Univ. **Wien**	Vienna, Austria
WILL	Coll. of **William and Mary**	Williamsburg, VA, USA
WINR	Inst. for Nuclear Studies	**Warsaw**, Poland
WISC	Univ. of **Wisconsin**	Madison, WI, USA
WITW	Univ. of the **Witwatersrand**	Wits, South Africa
WMIU	**Western Michigan** Univ.	Kalamazoo, MI, USA
WONT	The Univ. of **Western Ontario**	London, ON, Canada
WOOD	**Woodstock** College (No longer in existence)	Woodstock, MD, USA
WUPP	Univ. of **Wuppertal**	Wuppertal, Germany
WURZ	Univ. **Würzburg**	Würzburg, Germany
WUSL	**Washington** Univ.	St. Louis, MO, USA
WYOM	Univ. of **Wyoming**	Laramie, WY, USA
YALE	**Yale** Univ.	New Haven, CT, USA
YARO	**Yaroslavl** State Univ.	Yaroslavl, Russian Federation
YCC	**Yokohama** Coll. of Commerce	Yokohama, Japan
YERE	**Yerevan** Physics Inst.	Yerevan, Armenia
YOKO	**Yokohama National** Univ.	Yokohama-shi, Japan
YORKC	**York** Univ.	North York, ON, Canada
ZAGR	**Zagreb** Univ.	Zagreb, Croatia
ZARA	Univ. de **Zaragoza**	Zaragoza, Spain
ZEEM	Univ. van **Amsterdam**	TV Amsterdam, The Netherlands
ZURI	Univ. **Zürich**	Zürich, Switzerland

GAUGE AND HIGGS BOSONS

Notes in the Gauge and Higgs Boson Listings

GAUGE AND HIGGS BOSONS

γ

$I(J^{PC}) = 0,1(1^{--})$

γ MASS

For a review of the photon mass, see BYRNE 77.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
< 6 × 10⁻¹⁶	99.7	DAVIS	75		Jupiter magnetic field
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 9 \times 10^{-16}$	90	[1] FISCHBACH	94		Earth magnetic field
$<(4.73\pm0.45) \times 10^{-12}$		[2] CHERNIKOV	92	SQID	Ampere-law null test
$<(9.0 \pm 8.1) \times 10^{-10}$		[3] RYAN	85		Coulomb-law null test
$< 3 \times 10^{-27}$		[4] CHIBISOV	76		Galactic magnetic field
$< 7.3 \times 10^{-16}$		HOLLWEG	74		Alfven waves
$< 6 \times 10^{-17}$		[5] FRANKEN	71		Low freq. res. cir.
$< 1 \times 10^{-14}$		WILLIAMS	71	CNTR	Tests Gauss law
$< 2.3 \times 10^{-15}$		GOLDHABER	68		Satellite data
$< 6 \times 10^{-15}$		[5] PATEL	65		Satellite data
$< 6 \times 10^{-15}$		GINTSBURG	64		Satellite data

[1] FISCHBACH 94 report $< 8 \times 10^{-16}$ with unknown CL. We report Baysian CL used elsewhere in these Listings and described in the Statistics section.
[2] CHERNIKOV 92 measures the photon mass at 1.24 K, following a theoretical suggestion that electromagnetic gauge invariance might break down at some low critical temperature. See the erratum for a correction, included here, to the published result.
[3] RYAN 85 measures the photon mass at 1.36 K (see the footnote to CHERNIKOV 92).
[4] CHIBISOV 76 depends in critical way on assumptions such as applicabilty of virial theorem. Some of the arguments given only in unpublished references.
[5] See criticism questioning the validity of these results in KROLL 71 and GOLDHABER 71.

γ CHARGE

VALUE (e)	DOCUMENT ID		TECN	COMMENT
<5 × 10⁻³⁰	[6] RAFFELT	94	TOF	Pulsar $f_1 - f_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-28}$	[7] COCCONI	92		VLBA radio telescope resolution
$<2 \times 10^{-32}$	COCCONI	88	TOF	Pulsar $f_1 - f_2$ TOF

[6] RAFFELT 94 notes that COCCONI 88 neglects the fact that the time delay due to dispersion by free electrons in the interstellar medium has the same photon energy dependence as that due to bending of a charged photon in the magnetic field. His limit is based on the assumption that the entire observed dispersion is due to photon charge. It is a factor of 200 less stringent than the COCCONI 88 limit.
[7] See COCCONI 92 for less stringent limits in other frequency ranges. Also see RAFFELT 94 note.

γ REFERENCES

FISCHBACH	94	PRL 73 514	+Kloor, Langel+	(PURD, JHU+)
RAFFELT	94	PR D50 7729		(MPIM)
CHERNIKOV	92	PRL 68 3383	+Gerber, Ott, Gerber	(ETH)
Also	92B	PRL 69 2999 (erratum)	Chernikov, Gerber, Ott, Gerber	(ETH)
COCCONI	92	AJP 60 750		(CERN)
COCCONI	88	PL B206 705		(CERN)
RYAN	85	PR D32 802	+Accetta, Austin	(PRIN)
BYRNE	77	Ast.Sp.Sci. 46 115		(LOIC)
CHIBISOV	76	SPU 19 624		(LEBD)
DAVIS	75	PRL 35 1402	+Goldhaber, Nieto	(CIT, STON, LASL)
HOLLWEG	74	PRL 32 961		(NCAR)
FRANKEN	71	PRL 26 115	+Ampulski	(MICH)
GOLDHABER	71	RMP 43 277	+Nieto	(STON, BOHR, UCSB)
KROLL	71	PRL 26 1395		(SLAC)
WILLIAMS	71	PRL 26 721	+Faller, Hill	(WESL)
GOLDHABER	68	PRL 21 567	+Nieto	(STON)
PATEL	65	PL 14 105		(DUKE)
GINTSBURG	64	Sov. Astr. AJ7 536		(ASCI)

g or gluon

$I(J^P) = 0(1^-)$

SU(3) color octet

Mass $m = 0$. Theoretical value. A mass as large as a few MeV may not be precluded, see YNDURAIN 95.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	ABREU	92E	DLPH	Spin 1, not 0
	ALEXANDER	91H	OPAL	Spin 1, not 0
	BEHREND	82D	CELL	Spin 1, not 0
	BERGER	80D	PLUT	Spin 1, not 0
	BRANDELIK	80C	TASS	Spin 1, not 0

gluon REFERENCES

YNDURAIN	95	PL B345 524		(MADU)
ABREU	92E	PL B274 498	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ALEXANDER	91H	ZPHY C52 543	+Allison, Allport, Anderson+	(OPAL Collab.)
BEHREND	82D	PL B110 329	+Chen, Field, Guempel, Schroeder+	(CELLO Collab.)
BERGER	80D	PL B97 459	+Genzel, Grigull, Lackas+	(PLUTO Collab.)
BRANDELIK	80C	PL B97 453	+Braunschweig, Gather, Kadansky+	(TASSO Collab.)

graviton

$J = 2$

OMITTED FROM SUMMARY TABLE

graviton MASS

All of the following limits are obtained assuming Yukawa potential in weak field limit. VANDAM 70 argue that a massive field cannot approach general relativity in the zero-mass limit; however, see GOLDHABER 74 and references therein. h_0 is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}.

VALUE (eV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[1] DAMOUR	91	Binary pulsar PSR 1913+16
$< 2 \times 10^{-29}\, h_0^{-1}$	GOLDHABER	74	Rich clusters
$<7 \times 10^{-28}$	HARE	73	Galaxy
$<8 \times 10^{4}$	HARE	73	2γ decay

[1] DAMOUR 91 is an analysis of the orbital period change in binary pulsar PSR 1913+16, and confirms the general relativity prediction to 0.8%. "The theoretical importance of the [rate of orbital period decay] measurement has long been recognized as a direct confirmation that the gravitational interaction propagates with velocity c (which is the immediate cause of the appearance of a damping force in the binary pulsar system) and thereby as a test of the existence of gravitational radiation and of its quadrupolar nature." TAYLOR 93 adds that orbital parameter studies now agree with general relativity to 0.5%, and set limits on the level of scalar contribution in the context of a family of tensor [spin 2]-biscalar theories.

graviton REFERENCES

TAYLOR	93	Nature 355 132	+Wolszczan, Damour+	(PRIN, ARCBO, BURE, CARLC) J
DAMOUR	91	APJ 366 501	+Taylor	(BURE, MEUD, PRIN)
GOLDHABER	74	PR D9 119	+Nieto	(LANL, STON)
HARE	73	CJP 51 431		(SASK)
VANDAM	70	NP B22 397	van Dam, Veltman	(UTRE)

W

$J = 1$

W MASS

OUR FIT uses the W and Z mass, mass difference, and mass ratio measurements.

Because of the high current interest, we mention the following preliminary results here, but do not average them or include them in the Listings or Tables. Performing an overall fit (assuming the Standard Model) of published and unpublished (CDF and DØ) collider results ($M_W = 80.33 \pm 0.15$ GeV), of the νN results ($1 - M_W^2/M_Z^2 = 0.2257 \pm 0.0047$) and of published and unpublished LEP and SLD preliminary electroweak results (as of end of March 1996), the W mass is fitted to be $M_W = (80.350 \pm 0.042^{+0.016}_{-0.025})$ GeV (the second errors correspond to varying the Higgs mass in the interval 60–1000 GeV).

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
80.33 ± 0.15 OUR FIT					
80.32 ± 0.19 OUR AVERAGE Error includes scale factor of 1.2.					
80.410 ± 0.180	8986	[1] ABE	95P	CDF	$E_{cm}^{p\bar{p}} = 1800$ GeV
79.91 ± 0.39	1722	[2] ABE	90G	CDF	$E_{cm}^{p\bar{p}} = 1800$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$80.84 \pm 0.22 \pm 0.83$	2065	[3] ALITTI	92B	UA2	See W/Z ratio below
$80.79 \pm 0.31 \pm 0.84$		[4] ALITTI	90B	UA2	$E_{cm}^{p\bar{p}} = 546,630$ GeV
$80.0 \pm 3.3 \pm 2.4$	22	[5] ABE	89I	CDF	$E_{cm}^{p\bar{p}} = 1800$ GeV
$82.7 \pm 1.0 \pm 2.7$	149	[6] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}} = 546,630$ GeV
$81.8 {}^{+6.0}_{-5.3} \pm 2.6$	46	[7] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}} = 546,630$ GeV
$89 \pm 3 \pm 6$	32	[8] ALBAJAR	89	UA1	$E_{cm}^{p\bar{p}} = 546,630$ GeV
$80.2 \pm 0.6 \pm 1.4$	251	[9] ANSARI	87	UA2	Repl. by ALITTI 90B
$81.2 \pm 1.0 \pm 1.4$	119	[9] APPEL	86	UA2	Repl. by ANSARI 87
$83.5 {}^{+1.1}_{-1.0} \pm 2.7$	86	[10] ARNISON	86	UA1	Repl. by ALBAJAR 89
$81. {}^{+6.}_{-7.}$	14	[11] ARNISON	84D	UA1	Repl. by ALBAJAR 89
$83.1 \pm 1.9 \pm 1.3$	37	BAGNAIA	84	UA2	Repl. by ALITTI 90B
$81. \pm 5.$	6	ARNISON	83	UA1	Repl. by ARNISON 83D
80.9 ± 2.9	27	ARNISON	83D	UA1	Repl. by ARNISON 86
81.0 ± 2.8		BAGNAIA	83	UA2	Repl. by BAGNAIA 84
$80. {}^{+10.}_{-6.}$	4	BANNER	83B	UA2	Repl. by ALITTI 90B

[1] ABE 95P use 3268 $W \rightarrow \mu\nu_\mu$ events to find $M = 80.310 \pm 0.205 \pm 0.130$ GeV and 5718 $W \rightarrow e\nu_e$ events to find $M = 80.490 \pm 0.145 \pm 0.175$ GeV. The result given here combines these while accounting for correlated uncertainties.
[2] ABE 90G result from $W \rightarrow e\nu$ is $79.91 \pm 0.35 \pm 0.24 \pm 0.19$(scale) GeV and from $W \rightarrow \mu\nu$ is $79.90 \pm 0.53 \pm 0.32 \pm 0.08$(scale) GeV.
[3] ALITTI 92B result has two contributions to the systematic error (± 0.83); one (± 0.81) cancels in m_W/m_Z and one (± 0.17) is noncancelling. These were added in quadrature. We choose the ALITTI 92B value without using the LEP m_Z value, because we perform our own combined fit.

[4] There are two contributions to the systematic error (± 0.84): one (± 0.81) which cancels in m_W/m_Z and one (± 0.21) which is non-cancelling. These were added in quadrature.
[5] ABE 89I systematic error dominated by the uncertainty in the absolute energy scale.
[6] ALBAJAR 89 result is from a total sample of 299 $W \to e\nu$ events.
[7] ALBAJAR 89 result is from a total sample of 67 $W \to \mu\nu$ events.
[8] ALBAJAR 89 result is from $W \to \tau\nu$ events.
[9] There are two contributions to the systematic error (± 1.4): one (± 1.3) which cancels in m_W/m_Z and one (± 0.5) which is non-cancelling. These were added in quadrature.
[10] This is enhanced subsample of 172 total events.
[11] Using $W^\pm \to \mu^\pm \nu$.

W/Z MASS RATIO

The fit uses the W and Z mass, mass difference, and mass ratio measurements.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.8810±0.0016 OUR FIT				
0.8813±0.0036±0.0019	156	[12] ALITTI 92B	UA2	$E_{cm}^{p\overline{p}} = 630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.8831±0.0048±0.0026		[12] ALITTI 90B	UA2	$E_{cm}^{p\overline{p}} = 546{,}630$ GeV

[12] Scale error cancels in this ratio.

$m_Z - m_W$

The fit uses the W and Z mass, mass difference, and mass ratio measurements.

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
10.85±0.15 OUR FIT			
10.4 ±1.4 ±0.8	ALBAJAR 89	UA1	$E_{cm}^{p\overline{p}} = 546{,}630$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
11.3 ±1.3 ±0.9	ANSARI 87	UA2	$E_{cm}^{p\overline{p}} = 546{,}630$ GeV

$m_{W^+} - m_{W^-}$

Test of CPT invariance.

VALUE (GeV)	EVTS	DOCUMENT ID	TECN	COMMENT
−0.19±0.58	1722	ABE 90G	CDF	$E_{cm}^{p\overline{p}} = 1800$ GeV

W WIDTH

The CDF and D∅ widths labelled "extracted value" are obtained by measuring $R = [\sigma(W)/\sigma(Z)]\,[\Gamma(W \to e\nu_e)]/(B(Z \to ee)\Gamma(W))$ where the bracketed quantities can be calculated with plausible reliability. $\Gamma(W)$ is then extracted by using a value of $B(Z \to ee)$ measured at LEP. The UA1 and UA2 widths used $R = [\sigma(W)/\sigma(Z)]\,[\Gamma(W \to e\nu_e)/\Gamma(Z \to ee)]\,\Gamma(Z)/\Gamma(W)$ and the measured value of $\Gamma(Z)$. The Standard Model prediction is 2.067 ± 0.021 (ROSNER 94).

VALUE (GeV)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
2.07 ±0.06 OUR AVERAGE					
2.044±0.093		13k	[13] ABACHI 95D	D0	Extracted value
2.11 ±0.28 ±0.16		58	[14] ABE 95C	CDF	Direct meas.
2.064±0.060±0.059			[15] ABE 95W	CDF	Extracted value
$2.10\ ^{+0.14}_{-0.13}$ ±0.09		3559	[16] ALITTI 92	UA2	Extracted value
$2.18\ ^{+0.26}_{-0.24}$ ±0.04			[17] ALBAJAR 91	UA1	Extracted value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.16 ±0.17			[18] ABE 92I	CDF	Repl. by ABE 95W
2.12 ±0.20			[19] ABE 90	CDF	Repl. by ABE 92I
2.30 ±0.19 ±0.06			[20] ALITTI 90C	UA2	Extracted value
<5.4	90	149	[21] ALBAJAR 89	UA1	$E_{cm}^{p\overline{p}} = 546{,}630$ GeV
$2.8\ ^{+1.4}_{-1.5}$ ±1.3		149	[21] ALBAJAR 89	UA1	$E_{cm}^{p\overline{p}} = 546{,}630$ GeV
<7	90	251	ANSARI 87	UA2	$E_{cm}^{p\overline{p}} = 546{,}630$ GeV
<7	90	119	APPEL 86	UA2	$E_{cm}^{p\overline{p}} = 546{,}630$ GeV
<6.5	90	86	[22] ARNISON 86	UA1	Repl. by ALBAJAR 89
<7	90	27	ARNISON 83D	UA1	Repl. by ARNISON 86

[13] ABACHI 95D measured $R = 10.90 \pm 0.49$ and used the measured value $B(Z \to \ell\ell) = (3.367 \pm 0.006)\%$ from LEP.
[14] ABE 95C use the tail of the transverse mass distribution of $W \to e\nu_e$ decays.
[15] ABE 95W measured $R = 10.90 \pm 0.32 \pm 0.29$. They use $m_W = 80.23 \pm 0.18$ GeV, $\sigma(W)/\sigma(Z) = 3.35 \pm 0.03$, $\Gamma(W \to e\nu) = 225.9 \pm 0.9$ MeV, $\Gamma(Z \to e^+e^-) = 83.98 \pm 0.18$ MeV, and $\Gamma(Z) = 2.4969 \pm 0.0038$ GeV.
[16] ALITTI 92 measured $R = 10.4^{+0.7}_{-0.6} \pm 0.3$. The values of $\sigma(Z)$ and $\sigma(W)$ come from $O(\alpha_s^2)$ calculations using $m_W = 80.14 \pm 0.27$ GeV, and $m_Z = 91.175 \pm 0.021$ GeV along with the corresponding value of $\sin^2\theta_W = 0.2274$. They use $\sigma(W)/\sigma(Z) = 3.26 \pm 0.07 \pm 0.05$ and $\Gamma(Z) = 2.487 \pm 0.010$ GeV.
[17] ALBAJAR 91 measured $R = 9.5^{+1.1}_{-1.0}$ (stat. + syst.). $\sigma(W)/\sigma(Z)$ is calculated in QCD at the parton level using $m_W = 80.18 \pm 0.28$ GeV and $m_Z = 91.172 \pm 0.031$ GeV along with $\sin^2\theta_W = 0.2322 \pm 0.0014$. They use $\sigma(W)/\sigma(Z) = 3.23 \pm 0.05$ and $\Gamma(Z) = 2.498 \pm 0.020$ GeV.
[18] ABE 92I report $1216 \pm 38^{+27}_{-31}$ $W \to \mu\nu$ and $106 \pm 10^{+0.2}_{-1}$ $Z \to \mu^+\mu^-$ events which are combined with 2426 $W \to e\nu$ events of ABE 91C to derive the ratio $\sigma_W\,B(W \to \ell\nu)/\sigma_Z\,B(Z \to \ell^+\ell^-) = 10.0 \pm 0.6 \pm 0.4$. Finally the value of $\Gamma(Z)$ measured by LEP 92 is used to extract $\Gamma(W)$.
[19] ABE 90 extract $\Gamma(W) = 2.19 \pm 0.20$ by using the value $\Gamma(Z) = 2.57 \pm 0.07$ GeV. However, in ABE 91C they update their analysis with a new LEP value $\Gamma(Z) = 2.496 \pm 0.016$; the value $\Gamma(W) = 2.12 \pm 0.20$ above reflects this update. They measured $R = 10.2 \pm 0.8 \pm 0.4$, assumed $\sin^2\theta_W = 0.229 \pm 0.007$, and took predicted values $\sigma(W)/\sigma(Z) = 3.23 \pm 0.03$ and $\Gamma(W \to e\nu)/\Gamma(Z \to ee) = 2.70 \pm 0.02$. This yields $\Gamma(W)/\Gamma(Z) = 0.85 \pm 0.08$. The quoted error for $\Gamma(W)$ includes systematic uncertainties. $E_{cm}^{p\overline{p}} = 1800$ GeV.
[20] ALITTI 90C used the same technique as described for ABE 90. They measured $R = 9.38^{+0.82}_{-0.72} \pm 0.25$, obtained $\Gamma(W)/\Gamma(Z) = 0.902 \pm 0.074 \pm 0.024$. Using $\Gamma(Z) = 2.546 \pm 0.032$ GeV, they obtained the $\Gamma(W)$ value quoted above and the limits $\Gamma(W) < 2.56$ (2.64) GeV at the 90% (95%) CL. $E_{cm}^{p\overline{p}} = 546{,}630$ GeV.
[21] ALBAJAR 89 result is from a total sample of 299 $W \to e\nu$ events.
[22] If systematic error is neglected, result is $2.7^{+1.4}_{-1.5}$ GeV. This is enhanced subsample of 172 total events.

W ANOMALOUS MAGNETIC MOMENT ($\Delta\kappa$)

The full magnetic moment is given by $\mu_W = e(1+\kappa+\lambda)/2m_W$. In the Standard Model, at tree level, $\kappa = 1$ and $\lambda = 0$. Some papers have defined $\Delta\kappa = 1-\kappa$ and assume that $\lambda = 0$. Note that the electric quadrupole moment is given by $-e(\kappa-\lambda)/m_W^2$. A description of the parameterization of these moments and additional references can be found in HAGIWARA 87 and BAUR 88. The parameter Λ appearing in the theoretical limits below is a regularization cutoff which roughly corresponds to the energy scale where the structure of the W boson becomes manifest.

VALUE ($e/2m_W$)	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
	[23] ABE 95G	
	[24] ALITTI 92C	UA2
	[25] SAMUEL 92	THEO
	[26] SAMUEL 91	THEO
	[27] GRIFOLS 88	THEO
	[28] GROTCH 87	THEO
	[29] VANDERBIJ 87	THEO
	[30] GRAU 85	THEO
	[31] SUZUKI 85	THEO
	[32] HERZOG 84	THEO

[23] ABE 95G report $-1.3 < \kappa < 3.2$ for λ=0 and $-0.7 < \lambda < 0.7$ for κ=1 in $p\overline{p} \to e\nu_e\gamma X$ and $\mu\nu_\mu\gamma X$ at $\sqrt{s} = 1800$ GeV.
[24] ALITTI 92C measure $\kappa = 1^{+2.6}_{-2.2}$ and $\lambda = 0^{+1.7}_{-1.8}$ in $p\overline{p} \to e\nu\gamma + X$ at $\sqrt{s} = 630$ GeV. At 95%CL they report $-3.5 < \kappa < 5.9$ and $-3.6 < \lambda < 3.5$.
[25] SAMUEL 92 use preliminary CDF and UA2 data and find $-2.4 < \kappa < 3.7$ at 96%CL and $-3.1 < \kappa < 4.2$ at 95%CL respectively. They use data for $W\gamma$ production and radiative W decay.
[26] SAMUEL 91 use preliminary CDF data for $p\overline{p} \to W\gamma X$ to obtain $-11.3 \le \Delta\kappa \le 10.9$. Note that their $\kappa = 1-\Delta\kappa$.
[27] GRIFOLS 88 uses deviation from ρ parameter to set limit $\Delta\kappa \lesssim 65\ (M_W^2/\Lambda^2)$.
[28] GROTCH 87 finds the limit $-37 < \Delta\kappa < 73.5$ (90% CL) from the experimental limits on $e^+e^- \to \nu\overline{\nu}\gamma$ assuming three neutrino generations and $-19.5 < \Delta\kappa < 56$ for four generations. Note their $\Delta\kappa$ has the opposite sign as our definition.
[29] VANDERBIJ 87 uses existing limits to the photon structure to obtain $|\Delta\kappa| < 33$ (m_W/Λ). In addition VANDERBIJ 87 discusses problems with using the ρ parameter of the Standard Model to determine $\Delta\kappa$.
[30] GRAU 85 uses the muon anomaly to derive a coupled limit on the anomalous magnetic dipole and electric quadrupole (λ) moments $1.05 > \Delta\kappa\ \ln(\Lambda/m_W) + \lambda/2 > -2.77$. In the Standard Model $\lambda = 0$.
[31] SUZUKI 85 uses partial-wave unitarity at high energies to obtain $|\Delta\kappa| \lesssim 190$ $(m_W/\Lambda)^2$. From the anomalous magnetic moment of the muon, SUZUKI 85 obtains $|\Delta\kappa| \lesssim 2.2/\ln(\Lambda/m_W)$. Finally SUZUKI 85 uses deviations from the ρ parameter and obtains a very qualitative, order-of-magnitude limit $|\Delta\kappa| \lesssim 150\ (m_W/\Lambda)^4$ if $|\Delta\kappa| \ll 1$.
[32] HERZOG 84 consider the contribution of W-boson to muon magnetic moment including anomalous coupling of $WW\gamma$. Obtain a limit $-1 < \Delta\kappa < 3$ for $\Lambda \gtrsim 1$ TeV.

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a] (10.8±0.4) %	
Γ_2	$e^+\nu$	(10.8±0.4) %	
Γ_3	$\mu^+\nu$	(10.4±0.6) %	
Γ_4	$\tau^+\nu$	(10.9±1.0) %	
Γ_5	hadrons	(67.9±1.5) %	
Γ_6	$\pi^+\gamma$	< 5 $\times 10^{-4}$	95%

[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 8 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 1.7 for 5 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i / \Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	44		
x_4	43	19	
x_5	−73	−65	−84
	x_2	x_3	x_4

W BRANCHING RATIOS

$\Gamma(\ell^+\nu)/\Gamma_{total}$ — Γ_1/Γ

ℓ indicates average over e, μ, and τ modes, not sum over modes.

Currently only e and μ data enter this average because there are no absolute τ data, only the τ/e ratio.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.108±0.004 OUR AVERAGE Includes data from the 2 datablocks that follow this one.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.104±0.008	3642	[33] ABE 92I	CDF	$E^{p\bar{p}}_{cm}$= 1.8 TeV

[33] $1216 \pm 38^{+27}_{-31}$ $W \rightarrow \mu\nu$ events from ABE 92I and 2426$W \rightarrow e\nu$ events of ABE 91C. ABE 92I give the inverse quantity as 9.6 ± 0.7 and we have inverted.

$\Gamma(e^+\nu)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
0.108 ±0.004 OUR FIT				
0.109 ±0.004 OUR AVERAGE				
0.1094±0.0033±0.0031		[34] ABE 95W	CDF	$E^{p\bar{p}}_{cm}$= 1800 GeV
0.10 ±0.014 $^{+0.02}_{-0.03}$	248	[35] ANSARI 87C	UA2	$E^{p\bar{p}}_{cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.106 ±0.0096	2426	[36] ABE 91C	CDF	Repl. by ABE 94B
seen	299	[37] ALBAJAR 89	UA1	$E^{p\bar{p}}_{cm}$= 546,630 GeV
seen	119	APPEL 86	UA2	$E^{p\bar{p}}_{cm}$= 546,630 GeV
seen	172	ARNISON 86	UA1	Repl. by ALBAJAR 89

[34] ABE 95W result is from a measurement of $\sigma B(W \rightarrow e\nu)/\sigma B(Z \rightarrow e^+e^-) = 10.90 \pm 0.32 \pm 0.29$, the theoretical prediction for the cross section ratio, the experimental knowledge of $\Gamma(Z \rightarrow e^+e^-) = 83.98 \pm 0.18$ MeV, and $\Gamma(Z) = 2.4969 \pm 0.0038$.

[35] The first error was obtained by adding the statistical and systematic experimental uncertainties in quadrature. The second error reflects the dependence on theoretical prediction of total W cross section: $\sigma(546 \text{ GeV}) = 4.7^{+1.4}_{-0.7}$ nb and $\sigma(630 \text{ GeV}) = 5.8^{+1.8}_{-1.0}$ nb. See ALTARELLI 85B.

[36] ABE 91C result is from a measurement of $\sigma B(W \rightarrow e\nu)/\sigma B(Z \rightarrow e^+e^-)$, the theoretical prediction for the cross section ratio, and the experimental knowledge of $\Gamma(Z \rightarrow e^+e^-)/\Gamma(Z \rightarrow \text{all})$.

[37] ALBAJAR 89 experiment determines values of branching ratio times production cross section.

$\Gamma(\mu^+\nu)/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
0.104±0.006 OUR FIT				
0.10 ±0.01	1216	[38] ABE 92I	CDF	$E^{p\bar{p}}_{cm}$= 1.8 TeV

[38] ABE 92I quote the inverse quantity as 9.9 ± 1.2 which we have inverted.

$\Gamma(\tau^+\nu)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID
0.109±0.010 OUR FIT	

$\Gamma(\text{hadrons})/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID
0.679±0.015 OUR FIT	

$\Gamma(\mu^+\nu)/\Gamma(e^+\nu)$ — Γ_3/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.95±0.05 OUR FIT				
0.97±0.06 OUR AVERAGE				
0.89±0.10	13k	[39] ABACHI 95D	D0	$E^{p\bar{p}}_{cm}$= 1.8 TeV
1.02±0.08	1216	[40] ABE 92I	CDF	$E^{p\bar{p}}_{cm}$= 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.00±0.14±0.08	67	ALBAJAR 89	UA1	$E^{p\bar{p}}_{cm}$= 546,630 GeV
$1.24^{+0.6}_{-0.4}$	14	ARNISON 84D	UA1	Repl. by ALBAJAR 89

[39] ABACHI 95D obtain this result from the measured $\sigma_W B(W \rightarrow \mu\nu) = 2.09 \pm 0.23 \pm 0.11$ nb and $\sigma_W B(W \rightarrow e\nu) = 2.36 \pm 0.07 \pm 0.13$ nb in which the first error is the combined statistical and systematic uncertainty, the second reflects the uncertainty in the luminosity.

[40] ABE 92I obtain $\sigma_W B(W \rightarrow \mu\nu) = 2.21 \pm 0.07 \pm 0.21$ and combine with ABE 91C $\sigma_W B((W \rightarrow e\nu))$ to give a ratio of the couplings from which we derive this measurement.

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ — Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.00 ±0.08 OUR FIT				
1.00 ±0.08 OUR AVERAGE				
0.94 ±0.14	179	[41] ABE 92E	CDF	$E^{p\bar{p}}_{cm}$= 1.8 TeV
1.04 ±0.08 ±0.08	754	[42] ALITTI 92F	UA2	$E^{p\bar{p}}_{cm}$= 630 GeV
1.02 ±0.20 ±0.12	32	ALBAJAR 89	UA1	$E^{p\bar{p}}_{cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.995±0.112±0.083	198	ALITTI 91C	UA2	Repl. by ALITTI 92F
1.02 ±0.20 ±0.10	32	ALBAJAR 87	UA1	Repl. by ALBAJAR 89

[41] ABE 92E use two procedures for selecting $W \rightarrow \tau\nu_\tau$ events. The missing E_T trigger leads to $132 \pm 14 \pm 8$ events and the τ trigger to $47 \pm 9 \pm 4$ events. Proper statistical and systematic correlations are taken into account to arrive at $\sigma B(W \rightarrow \tau\nu) = 2.05 \pm 0.27$ nb. Combined with ABE 91C result on $\sigma B(W \rightarrow e\nu)$, ABE 92E quote a ratio of the couplings from which we derive this measurement.

[42] This measurement is derived by us from the ratio of the couplings of ALITTI 92F.

$\Gamma(\pi^+\gamma)/\Gamma(e^+\nu)$ — Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$< 7.5 \times 10^{-3}$	95	ABE 92K	CDF	$E^{p\bar{p}}_{cm}$= 1.8 TeV
$\mathbf{< 4.9 \times 10^{-3}}$	95	[43] ALITTI 92D	UA2	$E^{p\bar{p}}_{cm}$= 630 GeV
$<58 \times 10^{-3}$	95	[44] ALBAJAR 90	UA1	$E^{p\bar{p}}_{cm}$= 546, 630 GeV

[43] ALITTI 92D limit is 3.8×10^{-3} at 90%CL.

[44] ALBAJAR 90 obtain < 0.048 at 90%CL.

W REFERENCES

ABACHI	95D	PRL 75 1456	+Abbott, Abolins, Acharya+	(D0 Collab.)
ABE	95C	PRL 74 341	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABE	95G	PRL 74 1936	+Albrow, Amidei, Antos+	(CDF Collab.)
ABE	95P	PRL 75 11	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
Also	95Q	PR D52 4784	Abe, Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABE	95W	PR D52 2624	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
Also	94B	PRL 73 220	Abe, Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ABE	94B	PRL 73 220	+Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ROSNER	94	PR D49 1363	+Worah, Takeuchi	(EFI, FNAL)
ABE	92E	PRL 68 3398	+Amidei, Apollinari, Atac+	(CDF Collab.)
ABE	92I	PRL 69 28	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	92K	PRL 69 2160	+Amidei, Anway-Weiss+	(CDF Collab.)
ALITTI	92	PL B276 365	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92B	PL B276 354	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92C	PL B277 194	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92D	PL B277 203	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92F	PL B280 137	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
LEP	92	PL B276 247	+ALEPH, DELPHI, L3, OPAL	(LEP Collabs.)
SAMUEL	92	PL B280 124	+Li, Sinha, Sinha, Sundaresan	(OKSU, CARL)
ABE	91C	PR D44 29	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALBAJAR	91	PL B253 503	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
ALITTI	91C	ZPHY C52 209	+Ambrosini, Ansari, Autiero+	(UA2 Collab.)
SAMUEL	91	PRL 67 9	+Li, Sinha, Sinha, Sundaresan	(OKSU, CARL)
Also	91C	PRL 67 2920 erratum		
ABE	90	PRL 64 152	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
Also	91C	PR D44 29	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90G	PRL 65 2243	+Amidei, Apollinari, Atac+	(CDF Collab.)
Also	91B	PR D43 2070	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALBAJAR	90	PL B241 283	+Albrow, Allkofer+	(UA1 Collab.)
ALITTI	90B	PL B241 150	+Ansari, Ansorge, Autiero+	(UA2 Collab.)
ALITTI	90C	ZPHY C47 11	+Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
ABE	89I	PRL 62 1005	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BAUR	88	NP B308 127	+Zeppenfeld	(FSU, WISC)
GRIFOLS	88	IJMP A3 225	+Peris, Sola	(BARC, DESY)
Also	87	PL B197 437	Grifols, Peris, Sola	(BARC, DESY)
ALBAJAR	87	PL B185 233	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
ANSARI	87	PL B186 440	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ANSARI	87C	PL B194 158	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
GROTCH	87	PR D36 2153	+Robinett	(PSU)
HAGIWARA	87	NP B282 253	+Peccei, Zeppenfeld, Hikasa	(KEK, UCLA, FSU)
VANDERBIJ	87	PR D35 1088	van der Bij	(FNAL)
APPEL	86	ZPHY C30 1	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ARNISON	86	PL 166B 484	+Albrow, Allkofer, Astbury+	(UA1 Collab.) J
ALTARELLI	85B	ZPHY C27 617	+Ellis, Martinelli	(CERN, FNAL, FRAS)
GRAU	85	PL 154B 283	+Grifols	(BARC)
SUZUKI	85	PL 153B 289		(LBL)
ARNISON	84D	PL 134B 469	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BAGNAIA	84	ZPHY C24 1	+Banner, Battiston, Blech+	(UA2 Collab.)
HERZOG	84	PL 148B 355		(WISC)
Also	84B	PL 155B 468 erratum	Herzog	(WISC)
ARNISON	83	PL 122B 103	+Astbury, Aubert, Bacci+	(UA1 Collab.)
ARNISON	83D	PL 129B 273	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BAGNAIA	83	PL 129B 130	+Banner, Battiston, Bloch+	(UA2 Collab.)
BANNER	83B	PL 122B 476	+Battiston, Bloch, Bonaudi+	(UA2 Collab.)

Z

$J = 1$

THE Z BOSON

(by C. Caso, Univ. di Genova and A. Gurtu, Tata Inst.)

Precision measurements at the Z-boson resonance using electron-positron colliding beams began in 1989 at the SLC and at LEP. During 1989–95, the four CERN experiments have made high-statistics studies of the Z. The availability of longitudinally polarized electron beams at the SLC since 1993 has enabled a precision determination of the effective electroweak mixing angle $\sin^2\overline{\theta}_W$ that is competitive with the CERN results on this parameter.

The Z-boson properties reported in this section may broadly be categorized as:

- The standard 'lineshape' parameters of the Z consisting of its mass, M_Z, its total width, Γ_Z, and its partial decay widths, Γ(hadrons) and $\Gamma(\ell\overline{\ell})$ where $\ell = e, \mu, \tau, \nu$;
- The b- and c-quark-related partial widths and charge asymmetries which require special techniques;
- Determination of rare Z decay modes and the search for modes that violate known conservation laws.

For the lineshape-related Z properties there are no new published LEP results after those included in the 1994 edition of this compilation. The reason for this is the identification in mid 1995 of a new systematic effect which shifts the LEP energy by a few MeV. This is due to a drift of the dipole field in the LEP magnets caused by parasitic currents generated by electrically powered trains in the Geneva area. The LEP Energy Working Group is studying the implications of this for the Z-lineshape properties which would be obtained after analysis of the high statistics 1993–95 data. The main consequence of this effect is expected to be in the determination of the Z mass.

Details on Z-parameter determination and the study of $Z \to b\overline{b}, c\overline{c}$ at LEP and SLC are given in this note.

The standard 'lineshape' parameters of the Z are determined with increasing precision from an analysis of the production cross sections of these final states in e^+e^- collisions. The $Z \to \nu\overline{\nu}(\gamma)$ state is identified directly by detecting single photon production and indirectly by subtracting the visible partial widths from the total width. Inclusion in this analysis of the forward-backward asymmetry of charged leptons, $A_{FB}^{(0,\ell)}$, of the τ polarization, $P(\tau)$, and its forward-backward asymmetry, $P(\tau)^{fb}$, enables the separate determination of the effective vector ($\overline{g}_V$) and axial vector ($\overline{g}_A$) couplings of the Z to these leptons and the ratio ($\overline{g}_V/\overline{g}_A$) which is related to the effective electroweak mixing angle $\sin^2\overline{\theta}_W$ (see the Standard Model review).

Determination of the b- and c-quark-related partial widths and charge asymmetries involves tagging the b and c quarks. Traditionally this was done by requiring the presence of a prompt lepton in the event with high momentum and high transverse momentum (with respect to the accompanying jet). Precision vertex measurement with silicon detectors has enabled one to do impact parameter and lifetime tagging. Neural-network techniques have also been used to classify events as b or non-b on a statistical basis using event-shape variables. Finally, the presence of a charmed meson (D/D^*) has been used to tag heavy quarks.

Z-parameter determination

LEP is run at a few energy points on and around the Z mass constituting an energy 'scan.' The shape of the cross-section variation around the Z peak can be described by a Breit-Wigner *ansatz* with an energy-dependent total width [1]. The **three** main properties of this distribution, viz., the **position** of the peak, the **width** of the distribution, and the **height** of the peak, determine respectively the values of M_Z, Γ_Z, and $\Gamma(e^+e^-) \times \Gamma(f\overline{f})$, where $\Gamma(e^+e^-)$ and $\Gamma(f\overline{f})$ are the electron and fermion partial widths of the Z. The quantitative determination of these parameters is done by writing analytic expressions for these cross sections in terms of the parameters and fitting the calculated cross sections to the measured ones by varying these parameters, taking properly into account all the errors. Single-photon exchange (σ^0_γ) and γ-Z interference ($\sigma^0_{\gamma Z}$) are included, and the large (~25 %) initial-state radiation (ISR) effects are taken into account by convoluting the analytic expressions over a 'Radiator Function [1,2]' $H(s, s')$. Thus for the process $e^+e^- \to f\overline{f}$:

$$\sigma_f(s) = \int H(s,s')\ \sigma^0_f(s')\ ds' \tag{1}$$

$$\sigma^0_f(s) = \sigma^0_Z + \sigma^0_\gamma + \sigma^0_{\gamma Z} \tag{2}$$

$$\sigma^0_Z = \frac{12\pi}{M_Z^2}\ \frac{\Gamma(e^+e^-)\Gamma(f\overline{f})}{\Gamma_Z^2}\ \frac{s\ \Gamma_Z^2}{(s-M_Z^2)^2\ +\ s^2\Gamma_Z^2/M_Z^2} \tag{3}$$

$$\sigma^0_\gamma = \frac{4\pi\alpha^2(s)}{3s}\ Q_f^2 N_c^f \tag{4}$$

$$\sigma^0_{\gamma Z} = -\frac{2\sqrt{2}\alpha(s)}{3}\ (Q_f G_F N_c^f g_{Ve} g_{Vf}) \times \frac{(s-M_Z^2)M_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} \tag{5}$$

where Q_f is the charge of the fermion, $N_c^f = 3(1)$ for quark (lepton) and g_{Vf} is the neutral vector coupling of the Z to the fermion-antifermion pair $f\overline{f}$.

Since $\sigma^0_{\gamma Z}$ is expected to be much less than σ^0_Z, the LEP collaborations have generally calculated the interference term in the framework of the Standard Model using the best known values of g_V. This fixing of $\sigma^0_{\gamma Z}$ leads to a tighter constraint on M_Z and consequently a smaller error on its fitted value.

Defining

$$A_f = 2\frac{g_{Vf}\cdot g_{Af}}{(g_{Vf}^2 + g_{Af}^2)} \tag{6}$$

where g_{Af} is the neutral axial-vector coupling of the Z to $f\overline{f}$, the lowest-order expressions for the various lepton-related asymmetries on the Z pole are [3] $A_{FB}^{(0,\ell)} = (3/4)A_e A_f$, $P(\tau) = -A_\tau$,

$P(\tau)^{fb} = -(3/4)A_e$, $A_{LR} = A_e$. The full analysis takes into account the energy dependence of the asymmetries. Experimentally A_{LR} is defined as $(\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$ where $\sigma_{L(R)}$ are the $e^+e^- \to Z$ production cross sections with left- (right)-handed electrons.

In terms of g_A and g_V, the partial decay width of the Z to $f\overline{f}$ can be written as

$$\Gamma(f\overline{f}) = \frac{G_F M_Z^3}{6\sqrt{2}\pi}\,(g_{Vf}^2 + g_{Af}^2)\; N_c^f(1+\delta_{\rm QED})(1+\delta_{\rm QCD}) \quad (7)$$

where $\delta_{\rm QED} = 3\alpha Q_f^2/4\pi$ accounts for final-state photonic corrections and $\delta_{\rm QCD} = 0$ for leptons and $\delta_{\rm QCD} = (\alpha_s/\pi) + 1.409(\alpha_s/\pi)^2 - 12.77(\alpha_s/\pi)^3$ for quarks, α_s being the strong coupling constant at $\mu = M_Z$.

In the above framework, the QED radiative corrections have been explicitly taken into account by convoluting over the ISR and allowing the electromagnetic coupling constant to run [4]: $\alpha(s) = \alpha/(1 - \Delta\alpha)$. On the other hand, weak radiative corrections that depend upon the assumptions of the electroweak theory and on the values of the unknown $M_{\rm top}$ and $M_{\rm Higgs}$ are accounted for by **absorbing them into the couplings**, which are then called the *effective* couplings $\overline{g}_V$ and $\overline{g}_A$ (or alternatively the effective parameters of the $\star$ scheme of Kennedy and Lynn [5]).

S-matrix approach to the Z

While practically all experimental analyses of LEP/SLC data have followed the 'Breit-Wigner' approach described above, an alternative S-matrix-based analysis is also possible. The Z, like all unstable particles, is associated with a complex pole in the S matrix. The pole position is process independent and gauge invariant. The mass, $\overline{M}_Z$, and width, $\overline{\Gamma}_Z$, can be defined in terms of the pole in the energy plane via [6]

$$\overline{s} = \overline{M}_Z^2 - i\overline{M}_Z\overline{\Gamma}_Z \quad (8)$$

leading to the relations

$$\overline{M}_Z = M_Z/\sqrt{1+\Gamma_Z^2/M_Z^2} \quad (9)$$

$$\approx M_Z \;\; - 34 \text{ MeV} \quad (10)$$

$$\overline{\Gamma}_Z = \Gamma_Z/\sqrt{1+\Gamma_Z^2/M_Z^2} \quad (11)$$

$$\approx \Gamma_Z \;\; - 0.9 \text{ MeV} \quad (12)$$

Some authors [7] choose to define the Z mass and width via

$$\overline{s} = (\overline{M}_Z - \frac{i}{2}\overline{\Gamma}_Z)^2 \quad (13)$$

which yields $\overline{M}_Z \approx M_Z - 26$ MeV, $\overline{\Gamma}_Z \approx \Gamma_Z - 1.2$ MeV.

The L3 collaboration at LEP (ACCIARRI 96B) have analyzed their data using the S-matrix approach as defined in Eq. (8), in addition to the conventional one. They observe a downward shift in the Z mass as expected.

Handling the large-angle e^+e^- final state

Unlike other $f\overline{f}$ decay final states of the Z, the e^+e^- final state has a contribution not only from the s-channel but also from the t-channel and s-t interference. The full amplitude is not amenable to fast calculation, which is essential if one has to carry out minimization fits within reasonable computer time. The usual procedure is to calculate the non-s channel part of the cross section separately using the Standard Model program ALIBABA [8] using the measured value of $M_{\rm top}$, and the 'central' value of $M_{\rm Higgs}$ (300 GeV) and add it to the s-channel cross section calculated as for other channels. This leads to two additional sources of error in the analysis: firstly, the theoretical calculation in ALIBABA itself is known to be accurate to $\sim 0.5\%$, and secondly, there is uncertainty due to the error on $M_{\rm top}$ and the unknown value of $M_{\rm Higgs}$ (60–1000 GeV). These additional errors are propagated into the analysis by including them in the systematic error on the e^+e^- final state.

Errors due to uncertainty in LEP energy determination [9]

The systematic errors related to the LEP energy measurement can be classified as:

- The absolute energy scale error;
- Energy-point-to-energy-point errors due to the non-linear response of the magnets to the exciting currents;
- Energy-point-to-energy-point errors due to possible higher-order effects in the relationship between the dipole field and beam energy;
- Energy reproducibility errors due to various unknown uncertainties in temperatures, tidal effects, corrector settings, RF status *etc.* Since one groups together data taken at 'nominally same' energies in different fills, it can be assumed that these errors are uncorrelated and are reduced by $\sqrt{\overline{N}_{\rm fill}}$ where $\overline{N}_{\rm fill}$ is the (luminosity weighted) effective number of fills at a particular energy point.

At each energy point the last two errors can be summed into one point-to-point error.

Choice of fit parameters

The LEP collaborations have chosen the following primary set of parameters for fitting: M_Z, Γ_Z, $\sigma^0_{\rm hadron}$, R(lepton), $A_{FB}^{(0,\ell)}$, where R(lepton) $= \Gamma$(hadrons)$/\Gamma$(lepton), $\sigma^0_{\rm hadron} = 12\pi\Gamma(e^+e^-)\Gamma(\text{hadrons})/M_Z^2\Gamma_Z^2$. With a knowledge of these fitted parameters and their covariance matrix, any other parameter can be derived. The main advantage of these parameters is that they form the **least correlated** set of parameters, so that it becomes easy to combine results from the different LEP experiments.

Thus, the most general fit carried out to cross section and asymmetry data determines the **nine parameters**: M_Z, Γ_Z, $\sigma^0_{\rm hadron}$, $R(e)$, $R(\mu)$, $R(\tau)$, $A_{FB}^{(0,e)}$, $A_{FB}^{(0,\mu)}$, $A_{FB}^{(0,\tau)}$. Assumption of lepton universality leads to a **five-parameter fit** determining M_Z, Γ_Z, $\sigma^0_{\rm hadron}$, R(lepton), $A_{FB}^{(0,\ell)}$. The use of **only** cross-section data leads to six- or four-parameter fits if lepton universality is or is not assumed, *i.e.*, $A_{FB}^{(0,\ell)}$ values are not determined.

In order to determine the best values of the effective vector and axial vector couplings of the charged leptons to the Z, the above mentioned nine- and five-parameter fits are carried out with added constraints from the measured values of A_τ and A_e obtained from τ polarization studies at LEP and the determination of A_{LR} at SLC.

Combining results from the LEP and SLC experiments [10]

Each LEP experiment provides the values of the parameters mentioned above together with the full covariance matrix. The statistical and experimental systematic errors are assumed to be uncorrelated among the four experiments. The sources of **common** systematic errors are i) the LEP energy uncertainties, and ii) the effect of theoretical uncertainty in calculating the small-angle Bhabha cross section for luminosity determination and in estimating the non-s channel contribution to the large-angle Bhabha cross section. Using this information, a full covariance matrix, V, of all the input parameters is constructed and a combined parameter set is obtained by minimizing $\chi^2 = \Delta^T V^{-1} \Delta$, where Δ is the vector of residuals of the combined parameter set to the results of individual experiments.

Non-LEP measurement of a Z parameter, (*e.g.*, $\Gamma(e^+e^-)$ from SLD) is included in the overall fit by calculating its value using the fit parameters and constraining it to the measurement.

Study of $Z \to b\bar{b}$ and $Z \to c\bar{c}$

In the sector of c- and b-physics the LEP experiments have measured the ratios of partial widths $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ and $R_c = \Gamma(Z \to c\bar{c})/\Gamma(Z \to \text{hadrons})$ and the forward-backward (charge) asymmetries $A_{FB}^{b\bar{b}}$ and $A_{FB}^{c\bar{c}}$. Several of the analyses have also determined other quantities, in particular the semileptonic branching ratios $B(b \to \ell)$ and $B(b \to c \to \ell^+)$ and the average $B^0\overline{B}^0$ mixing parameter $\overline{\chi}$. The latter measurements do not concern properties of the Z boson and hence they are not covered in this section. However, they are correlated with the electroweak parameters, and since the mixture of b-hadrons is different from the one at the $\Upsilon(4S)$, their values might differ from those measured at the $\Upsilon(4S)$.

All the above quantities are correlated to each other since:

- Several analyses (for example the lepton fits) determine more than one parameter simultaneously;
- Some of the electroweak parameters depend explicitly on the values of other parameters (for example R_b depends on R_c);
- Common tagging and analysis techniques produce common systematic uncertainties.

The LEP Electroweak Heavy Flavour Working Group has then developed [11] a procedure for combining the measurements taking into account known sources of correlation. The combining procedure determines seven parameters: the four parameters of interest in the electroweak sector, R_b, R_c, $A_{FB}^{b\bar{b}}$, and $A_{FB}^{c\bar{c}}$ and, in addition, $B(b \to \ell)$, $B(b \to c \to \ell^+)$ and $\overline{\chi}$, to take into account their correlations with the electroweak parameters. Before the fit both the peak and off-peak asymmetries are translated to $\sqrt{s} = 91.26$ GeV using the predicted dependence from ZFITTER [2].

Summary of the measurements and of the various kinds of analysis

The measurements of R_b and R_c fall into two classes. In the first, named single-tag measurement, a method for selecting b and c events is applied and the number of tagged events is counted. The second technique, named double-tag measurement, is based on the following principle: if the number of events with a single hemisphere tagged is N_t and with both hemispheres tagged is N_{tt}, then given a total number of N_{had} hadronic Z decays one has:

$$\frac{N_t}{2N_{\text{had}}} = \varepsilon_b R_b + \varepsilon_c R_c + \varepsilon_{uds}(1 - R_b - R_c) \tag{14}$$

$$\frac{N_{tt}}{N_{\text{had}}} = \mathcal{C}_b \varepsilon_b^2 R_b + \varepsilon_c^2 R_c + \varepsilon_{uds}^2(1 - R_b - R_c) \tag{15}$$

where ε_b, ε_c, and ε_{uds} are the tagging efficiencies per hemisphere for b, c, and light quark events, and $\mathcal{C}_b \approx 1$ accounts for the fact that the tagging efficiencies between the hemispheres are correlated. Neglecting the c and uds background and the hemisphere correlation, these equations give:

$$\varepsilon_b = 2N_{tt}/N_t \tag{16}$$

$$R_b = N_t^2/(4N_{tt}N_{\text{had}}) \tag{17}$$

The double-tagging method has thus the great advantage that the tagging efficiency is directly derived from the data, reducing the systematic error of the measurement. The backgrounds, dominated by $c\bar{c}$ events, obviously complicate this simple picture, and their level must still be inferred by other means. The rate of charm background in these analyses depends explicitly on the value of R_c. The correlations in the tagging efficiencies between the hemispheres (due for instance to correlations in momentum between the b-hadrons in the two hemispheres) are small but nevertheless lead to further systematic uncertainties.

The measurements in the b- and c-sector can be grouped in the following categories:

- Lepton fits which use hadronic events with one or more leptons in the final state. Each analysis usually gives several electroweak parameters chosen among: R_b, R_c, $A_{FB}^{b\bar{b}}$, $A_{FB}^{c\bar{c}}$, $B(b \rightarrow \ell)$, $B(b \rightarrow c \rightarrow \ell^+)$ and $\overline{\chi}$. The output parameters are then correlated. The dominant sources of systematics are due to lepton identification, to other semileptonic branching ratios and to the modelling of the semileptonic decay;
- Event shape tag for R_b (both single and double-tagging have been used);
- Lifetime (and lepton) double-tagging measurements of R_b. These are the most precise measurements of R_b and obviously dominate the combined result. The main sources of systematics come from the assumed properties of the $c\bar{c}$ events and from estimating the hemisphere b-tagging efficiency correlation;
- Measurements of $A_{FB}^{b\bar{b}}$ using lifetime tagged events with a measurement of the jet charge. Their contribution to the combined result has roughly the same weight as the lepton fits;
- Analyses with $D/D^{*\pm}$ to measure R_c. These measurements separate charmed hadrons coming from $b\bar{b}$ and $c\bar{c}$ decays on a statistical basis; thus R_c depends on properties of $b\bar{b}$ events but not on the value of R_b;
- Analyses with $D^{*\pm}$ to measure simultaneously $A_{FB}^{b\bar{b}}$ and $A_{FB}^{c\bar{c}}$.

Averaging procedure

All the measurements are provided by the LEP Collaborations in the form of tables with a detailed breakdown of the systematic errors of each measurement and its dependence on other electroweak parameters.

The average proceeds via the following steps:

- Define and propagate a consistent set of external inputs such as branching ratios, hadron lifetimes, fragmentation models *etc.* All the measurements are also consistently checked to ensure that all use a common set of assumptions (for instance for the lifetime/jet-charge measurements of asymmetries, where the QCD effects are already included as an inherent part of the analysis, a QCD correction is subtracted before combining);
- Form the full (statistical and systematic) covariance matrix of the measurements. The systematic correlations between different analyses are calculated from the detailed error breakdown in the measurement tables. The correlations relating several measurements made by the same analysis are also considered;
- Take into account any explicit dependence of a measurement on the other electroweak parameters. As an example of this dependence we illustrate the case of the double-tag measurement of R_b, where c-quarks constitute the main background. The normalization of the charm contribution is not fixed by the data and the measurement of R_b depends on the assumed value of R_c, which can be written as:

$$R_b = R_b^{\rm meas} + a(R_c)\frac{(R_c - R_c^{\rm used})}{R_c} \;, \qquad (18)$$

  where $R_b^{\rm meas}$ is the result of the analysis which assumed a value of $R_c = R_c^{\rm used}$ and $a(R_c)$ is the constant which gives the dependence on R_c. It is worth noting that the combining procedure shows that the only significant correlation between any of the resulting electroweak parameters turns out to be just between R_b and R_c. With the data contained in the present Listing the correlation coefficient between these two variables amounts to -0.39;
- Perform a χ^2 minimization with respect to the combined electroweak parameters.

After the fit the average peak asymmetries $A_{FB}^{c\bar{c}}$ and $A_{FB}^{b\bar{b}}$ are corrected for the energy shift and for QED, QCD, γ exchange, and γZ interference effects to obtain the corresponding pole asymmetries $A_{FB}^{0,c}$ and $A_{FB}^{0,b}$. A small correction is also applied to both R_b and R_c to account for the contribution of γ exchange.

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Z MASS

The fit is performed using the Z mass and width, the Z hadronic pole cross section, the ratios of hadronic to leptonic partial widths, and the Z pole forward-backward lepton asymmetries. We believe that this set is the most free of correlations. Common systematic errors are taken into account. For more details, see the 'Note on the Z Boson.'

The Z-boson mass listed here corresponds to a Breit-Wigner resonance parameter. The value is 34 MeV greater than the real part of the position of the pole (in the energy-squared plane) in the Z-boson propagator. Also the LEP experiments have generally assumed a fixed value of the $\gamma - Z$ interferences term based on the standard model. Keeping this term as free parameter leads to a somewhat larger error on the fitted Z mass. See ACCIARRI 96B and ADRIANI 93H for a detailed investigation of both these issues.

A new source of LEP energy variation was discovered in mid 1995: an energy change of a few MeV is correlated with the passage of a train on nearby railway tracks. The LEP energy working group is studying the implications of this effect for the high statistics data recorded since 1993. The main consequence of this is expected to be a shift in the overall LEP energy values leading to a corresponding shift in the value of m_Z. The LEP collaborations have consequently deferred publication of their results on Z lineshape and lepton forward-backward asymmetries based on 1993 and later data.

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
91.187±0.007 OUR FIT					
91.188±0.007 OUR AVERAGE					
91.187±0.007±0.006	1.16M	[1] ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
91.195±0.006±0.007	1.19M	[1] ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
91.182±0.007±0.006	1.33M	[1] AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
91.187±0.007±0.006	1.27M	[1] BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
91.162±0.011	1.2M	[2] ACCIARRI	96B	L3	E^{ee}_{cm}= 88–94, 130–140 GeV
91.151±0.008		[3] MIYABAYASHI	95	TOPZ	E^{ee}_{cm}= 57.8 GeV
91.181±0.007±0.006	512k	[4] ACTON	93D	OPAL	Repl. by AKERS 94
91.195±0.009	460k	[5] ADRIANI	93F	L3	Repl. by ACCIARRI 94
91.160±0.010	463k	[6] ADRIANI	93H	L3	Repl. by ACCIARRI 96B
91.187±0.009	520k	[7] BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
91.187±0.007	2.2M	[8] LEP	93	RVUE	E^{ee}_{cm}= 88–94 GeV
91.187±0.007	1.9M	[9] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV
91.74 ±0.28 ±0.93	156	[10] ALITTI	92B	UA2	$E^{p\bar{p}}_{cm}$= 630 GeV
$89.2\ ^{+2.1}_{-1.8}$		[11] ADACHI	90F	RVUE	
90.9 ±0.3 ±0.2	188	[12] ABE	89C	CDF	$E^{p\bar{p}}_{cm}$= 1800 GeV
91.14 ±0.12	480	[13] ABRAMS	89B	MRK2	E^{ee}_{cm}= 89–93 GeV
93.1 ±1.0 ±3.0	24	[14,15] ALBAJAR	89	UA1	$E^{p\bar{p}}_{cm}$= 546,630 GeV
$88.6\ ^{+2.0}_{-1.8}$		[11] MORI	89	RVUE	

[1] The second error of 6.3 MeV is due to a common LEP energy uncertainty.
[2] ACCIARRI 96B interpret the s-dependence of the cross sections and lepton forward-backward asymmetries in the framework of the S-matrix ansatz. The high-energy data constrains the γZ interference terms. As expected, this result is below the mass values obtained with a standard Breit-Wigner parametrization.
[3] MIYABAYASHI 95 combine their low energy total hadronic cross-section measurement with the ACTON 93D data and perform a fit using an S-matrix formalism. As expected, this result is below the mass values obtained with the standard Breit-Wigner parametrization.
[4] The systematic error in ACTON 93D is from the uncertainty in the LEP energy calibration.
[5] The error in ADRIANI 93F includes 6 MeV due to the uncertainty in LEP energy calibration.
[6] ADRIANI 93H use the S-matrix approach to determine the pole position for the Z boson. Note the shift of this result with respect to the standard Breit-Wigner parametrization.
[7] BUSKULIC 93J supersedes DECAMP 92B. The error includes 6 MeV due to the uncertainty in LEP energy calibration.
[8] The LEP 93 error due to the experiments is 4 MeV and the uncertainty due to the absolute LEP energy scale is 6 MeV.
[9] QUAST 93 is a combined analysis of LEP results as of Feb. 1993. A common systematic error of 6 MeV is taken into account.
[10] Enters fit through W/Z mass ratio given in the W Particle Listings. The ALITTI 92B systematic error (±0.93) has two contributions: one (±0.92) cancels in m_W/m_Z and one (±0.12) is noncancelling. These were added in quadrature.
[11] MORI 89, ADACHI 90F use a Breit-Wigner resonance shape fit and combine their results with published data of PEP and PETRA.
[12] First error of ABE 89 is combination of statistical and systematic contributions; second is mass scale uncertainty.
[13] ABRAMS 89B uncertainty includes 35 MeV due to the absolute energy measurement.
[14] Enters fit through Z-W mass difference given in the W Particle Listings.
[15] ALBAJAR 89 result is from a total sample of 33 $Z \rightarrow e^+e^-$ events.

Z WIDTH

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2.490±0.007 OUR FIT					
2.491±0.007 OUR AVERAGE					
2.483±0.011±0.0045	1.16M	[16] ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
2.494±0.009±0.0045	1.19M	[16] ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
2.483±0.011±0.0045	1.33M	[16] AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
2.501±0.011±0.0045	1.27M	[16] BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.492±0.010	1.2M	[17] ACCIARRI	96B	L3	E^{ee}_{cm}= 88–94, 130–140 GeV
2.483±0.011±0.004	512k	[18] ACTON	93D	OPAL	Repl. by AKERS 94
2.490±0.011	460k	[19] ADRIANI	93F	L3	Repl. by ACCIARRI 94
2.492±0.012	463k	[20] ADRIANI	93H	L3	Repl. by ACCIARRI 96B
2.501±0.012	520k	[21] BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
2.490±0.007	1.9M	[22] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV
3.8 ±0.8 ±1.0	188	ABE	89C	CDF	$E^{p\bar{p}}_{cm}$= 1800 GeV
$2.42\ ^{+0.45}_{-0.35}$	480	[23] ABRAMS	89B	MRK2	E^{ee}_{cm}= 89–93 GeV
$2.7\ ^{+1.2}_{-1.0}$ ±1.3	24	[24] ALBAJAR	89	UA1	$E^{p\bar{p}}_{cm}$= 546,630 GeV
2.7 ±2.0 ±1.0	25	[25] ANSARI	87	UA2	$E^{p\bar{p}}_{cm}$= 546,630 GeV

[16] The second error of 4.5 MeV is due to a common LEP energy uncertainty.
[17] ACCIARRI 96B interpret the s-dependence of the cross sections and lepton forward-backward asymmetries in the framework of the S-matrix ansatz. The high-energy data constrains the γZ interference terms. The fitted width is expected to be 0.9 MeV less than that obtained using the standard Breit-Wigner parametrization (see 'Note on the Z Boson').
[18] The systematic error is from the uncertainty in the LEP energy calibration.
[19] The error in ADRIANI 93F includes 4 MeV due to the uncertainty in LEP energy calibration.
[20] ADRIANI 93H use the S-matrix approach to determine the pole position for the Z boson. The fitted width is expected to be 0.9 MeV less than that obtained using the standard Breit-Wigner parametrization (see 'Note on the Z Boson').
[21] The error in BUSKULIC 93J includes 4 MeV due to the uncertainty in LEP energy calibration.
[22] QUAST 93 is a combined analysis of LEP results as of Feb. 1993. A common systematic error of 4 MeV is taken into account.
[23] ABRAMS 89B uncertainty includes 50 MeV due to the miniSAM background subtraction error.
[24] ALBAJAR 89 result is from a total sample of 33 $Z \rightarrow e^+e^-$ events.
[25] Quoted values of ANSARI 87 are from direct fit. Ratio of Z and W production gives either $\Gamma(Z) < (1.09 \pm 0.07) \times \Gamma(W)$, CL = 90% or $\Gamma(Z) = (0.82^{+0.19}_{-0.14} \pm 0.06) \times \Gamma(W)$. Assuming Standard-Model value $\Gamma(W) = 2.65$ GeV then gives $\Gamma(Z) < 2.89 \pm 0.19$ or $= 2.17^{+0.50}_{-0.37} \pm 0.16$.

Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	e^+e^-		(3.366±0.008) %	
Γ_2	$\mu^+\mu^-$		(3.367±0.013) %	
Γ_3	$\tau^+\tau^-$		(3.360±0.015) %	
Γ_4	$\ell^+\ell^-$	[a]	(3.366±0.006) %	
Γ_5	invisible		(20.01 ±0.16) %	
Γ_6	hadrons		(69.90 ±0.15) %	
Γ_7	$(u\bar{u}+c\bar{c})/2$		(9.6 ±1.3) %	
Γ_8	$(d\bar{d}+s\bar{s}+b\bar{b})/3$		(16.9 ±0.9) %	
Γ_9	$c\bar{c}$		(11.0 ±0.7) %	
Γ_{10}	$b\bar{b}$		(15.46 ±0.14) %	
Γ_{11}	$\pi^0\gamma$		$< 5.2 \times 10^{-5}$	95%
Γ_{12}	$\eta\gamma$		$< 5.1 \times 10^{-5}$	95%
Γ_{13}	$\omega\gamma$		$< 6.5 \times 10^{-4}$	95%
Γ_{14}	$\eta'(958)\gamma$		$< 4.2 \times 10^{-5}$	95%
Γ_{15}	$\gamma\gamma$		$< 5.2 \times 10^{-5}$	95%
Γ_{16}	$\gamma\gamma\gamma$		$< 1.0 \times 10^{-5}$	95%
Γ_{17}	$\pi^\pm W^\mp$	[b]	$< 7 \times 10^{-5}$	95%
Γ_{18}	$\rho^\pm W^\mp$	[b]	$< 8.3 \times 10^{-5}$	95%
Γ_{19}	$J/\psi(1S)X$		$(3.80 \pm 0.27) \times 10^{-3}$	

Γ_{20}	$\psi(2S)X$			$(1.60 \pm 0.33) \times 10^{-3}$		
Γ_{21}	$\chi_{c1}(1P)X$			$(6.0 \pm 1.9) \times 10^{-3}$		
Γ_{22}	ΥX			$(1.0 \pm 0.5) \times 10^{-4}$		
Γ_{23}	$(D^0/\overline{D}^0)$ X			(20.7 ± 2.0) %		
Γ_{24}	$D^{\pm}$X			(12.2 ± 1.7) %		
Γ_{25}	$D^*(2010)^{\pm}$X		[b]	(11.4 ± 1.3) %		
Γ_{26}	BX					
Γ_{27}	B^*X					
Γ_{28}	B^0_sX			seen		
Γ_{29}	anomalous $\gamma+$ hadrons		[c]	< 3.2	$\times 10^{-3}$	95%
Γ_{30}	$e^+e^-\gamma$		[c]	< 5.2	$\times 10^{-4}$	95%
Γ_{31}	$\mu^+\mu^-\gamma$		[c]	< 5.6	$\times 10^{-4}$	95%
Γ_{32}	$\tau^+\tau^-\gamma$		[c]	< 7.3	$\times 10^{-4}$	95%
Γ_{33}	$\ell^+\ell^-\gamma\gamma$		[d]	< 6.8	$\times 10^{-6}$	95%
Γ_{34}	$q\overline{q}\gamma\gamma$		[d]	< 5.5	$\times 10^{-6}$	95%
Γ_{35}	$\nu\overline{\nu}\gamma\gamma$		[d]	< 3.1	$\times 10^{-6}$	95%
Γ_{36}	$e^{\pm}\mu^{\mp}$	LF	[b]	< 1.7	$\times 10^{-6}$	95%
Γ_{37}	$e^{\pm}\tau^{\mp}$	LF	[b]	< 9.8	$\times 10^{-6}$	95%
Γ_{38}	$\mu^{\pm}\tau^{\mp}$	LF	[b]	< 1.7	$\times 10^{-5}$	95%

[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[b] The value is for the sum of the charge states of particle/antiparticle states indicated.

[c] See the Particle Listings below for the γ energy range used in this measurement.

[d] For $m_{\gamma\gamma} = (60 \pm 5)$ GeV.

Z PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_1

For the LEP experiments, this parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
83.82±0.30 OUR FIT					
82.89±1.20±0.89		[26] ABE	95J	SLD	E^{ee}_{cm}= 91.31 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
83.31±0.54	31.4k	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
83.43±0.52	38k	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
83.63±0.53	42k	AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
84.61±0.49	45.8k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
83.03±0.66	17k	ACTON	93D	OPAL	Repl. by AKERS 94
83.0 ±0.6	16k	ADRIANI	93M	L3	Repl. by ACCIARRI 94
84.43±0.60		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
83.30±0.35	70k	[27] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV

[26] ABE 95J obtain this measurement from Bhabha events in a restricted fiducial region to improve systematics. They use the values 91.187 and 2.489 GeV for the Z mass and total decay width to extract this partial width.

[27] QUAST 93 is a combined analysis of LEP results as of Feb. 1993.

$\Gamma(\mu^+\mu^-)$ — Γ_2

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
83.83±0.39 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
84.15±0.77	45.6k	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
83.20±0.79	34k	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
83.83±0.65	57k	AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
83.62±0.75	46.4k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
84.43±0.92	23k	ACTON	93D	OPAL	Repl. by AKERS 94
82.8 ±1.0	14k	ADRIANI	93M	L3	Repl. by ACCIARRI 94
83.66±0.95		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
83.82±0.52	70k	[28] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV

[28] QUAST 93 is a combined analysis of LEP results as of Feb. 1993.

$\Gamma(\tau^+\tau^-)$ — Γ_3

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
83.67±0.44 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
83.55±0.91	25k	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
84.04±0.94	25k	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
82.90±0.77	47k	AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
84.18±0.79	45.1k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
82.2 ±1.1	18k	ACTON	93D	OPAL	Repl. by AKERS 94
84.6 ±1.2	10k	ADRIANI	93M	L3	Repl. by ACCIARRI 94
84.09±1.10		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
83.54±0.62	50k	[29] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV

[29] QUAST 93 is a combined analysis of LEP results as of Feb. 1993.

$\Gamma(\ell^+\ell^-)$ — Γ_4

In our fit $\Gamma(\ell^+\ell^-)$ is defined as the partial Z width for the decay into a pair of massless charged leptons. This parameter is not directly used in the 5-parameter fit assuming lepton universality but is derived using the fit results. See the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
83.83±0.27 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
83.56±0.45	102k	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
83.49±0.46	97k	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
83.55±0.44	146k	AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
84.40±0.43	137.3k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
83.27±0.50	58k	ACTON	93D	OPAL	Repl. by AKERS 94
83.1 ±0.5	40k	ADRIANI	93F	L3	Repl. by ACCIARRI 94
84.22±0.48		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
83.40±0.29	190k	[30] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV

[30] QUAST 93 is a combined analysis of LEP results as of Feb. 1993.

Γ(invisible) — Γ_5

We use only direct measurements of the invisible partial width to obtain the average value quoted below. The fit value is obtained as a difference between the total and the observed partial widths assuming lepton universality.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
498.3± 4.2 OUR FIT					
517 ±22 OUR AVERAGE					
539 ±26 ±17	410	AKERS	95C	OPAL	E^{ee}_{cm}= 88–94 GeV
450 ±34 ±34	258	BUSKULIC	93L	ALEP	E^{ee}_{cm}= 88–94 GeV
540 ±80 ±40	52	ADEVA	92	L3	E^{ee}_{cm}= 88–94 GeV
524 ±40 ±20	172	[31] ADRIANI	92E	L3	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
509.4± 7.0		ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
496.5± 7.9		ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
490.3± 7.3		AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
501 ± 6		BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
495 ±10		ACTON	93D	OPAL	Repl. by AKERS 94
494 ±10		ADRIANI	93M	L3	Repl. by ACCIARRI 94
498 ± 9		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
499 ± 6		[32] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV

[31] ADRIANI 92E improves but does not supersede ADEVA 92, obtained with 1990 data only.

[32] QUAST 93 is a combined analysis of LEP results as of Feb. 1993. Assumes lepton universality.

Γ(hadrons) — Γ_6

This parameter is not directly used in the 5-parameter fit assuming lepton universality, but is derived using the fit results. See the 'Note on the Z Boson.'

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1740.7± 5.9 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1723 ±10	1.05M	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
1748 ±10	1.09M	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
1741 ±10	1.19M	[33] AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
1746 ±10	1.27M	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
1738 ±12	454k	[34] ACTON	93D	OPAL	Repl. by AKERS 94
1747 ±11	420k	ADRIANI	93F	L3	Repl. by ACCIARRI 94
1751 ±11		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
1741 ± 7	1.7M	[35] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV

[33] AKERS 94 assumes lepton universality. Without this assumption, it becomes 1742 ± 11 MeV.

[34] ACTON 93D assumes lepton universality. Without this assumption it becomes 1743 ± 15 MeV.

[35] QUAST 93 is a combined analysis of LEP results as of Feb. 1993. Assumes lepton universality.

Z BRANCHING RATIOS

Γ(hadrons)/$\Gamma(e^+e^-)$ — Γ_6/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
20.77± 0.08 OUR FIT					
20.74± 0.18	31.4k	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
20.96± 0.15	38k	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
20.83± 0.16	42k	AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
20.59± 0.15	45.8k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
20.99± 0.25	17k	ACTON	93D	OPAL	Repl. by AKERS 94
20.69± 0.21		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
20.92± 0.12	70k	[36] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV
$27.0\ ^{+11.7}_{-\ 8.8}$	12	[37] ABRAMS	89D	MRK2	E^{ee}_{cm}= 89–93 GeV

[36] QUAST 93 is a combined analysis of LEP results as of Feb. 1993.

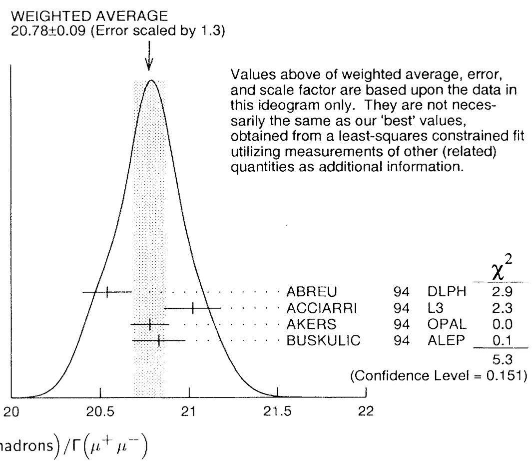
[37] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.

$\Gamma(\text{hadrons})/\Gamma(\mu^+\mu^-)$ — Γ_6/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
20.76±0.07 OUR FIT					
20.78±0.09 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
20.54±0.14	45.6k	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
21.02±0.16	34k	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
20.78±0.11	57k	AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
20.83±0.15	46.4k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
20.65±0.17	23k	ACTON	93D	OPAL	Repl. by AKERS 94
20.88±0.20		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
20.79±0.10	70k	[38] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV
$18.9\ ^{+7.1}_{-5.3}$	13	[39] ABRAMS	89D	MRK2	E^{ee}_{cm}= 89–93 GeV

[38] QUAST 93 is a combined analysis of LEP results as of Feb. 1993.

[39] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.



$\Gamma(\text{hadrons})/\Gamma(\tau^+\tau^-)$ — Γ_6/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
20.80±0.08 OUR FIT					
20.81±0.08 OUR AVERAGE					
20.68±0.18	25k	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
20.80±0.20	25k	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
21.01±0.15	47k	AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
20.70±0.16	45.1k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
21.22±0.25	18k	ACTON	93D	OPAL	Repl. by AKERS 94
20.77±0.23		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
20.86±0.13	50k	[40] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV
$15.2\ ^{+4.8}_{-3.9}$	21	[41] ABRAMS	89D	MRK2	E^{ee}_{cm}= 89–93 GeV

[40] QUAST 93 is a combined analysis of LEP results as of Feb. 1993.

[41] ABRAMS 89D have included both statistical and systematic uncertainties in their quoted errors.

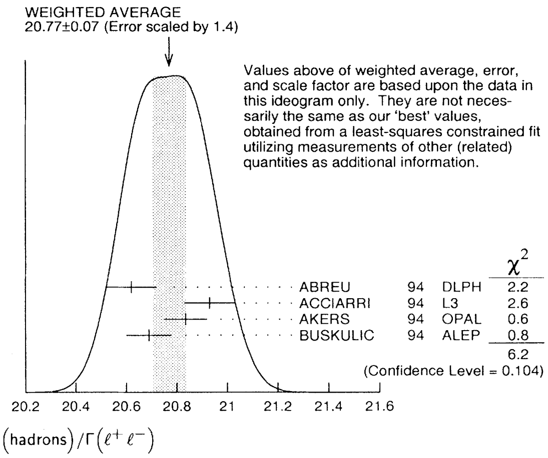
$\Gamma(\text{hadrons})/\Gamma(\ell^+\ell^-)$ — Γ_6/Γ_4

ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

Our fit result is obtained requiring lepton universality.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
20.76 ±0.05 OUR FIT					
20.77 ±0.07 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.			
20.62 ±0.10	102k	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
20.93 ±0.10	97k	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
20.835±0.086	146k	AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
20.69 ±0.09	137.3k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
20.88 ±0.13	58k	ACTON	93D	OPAL	Repl. by AKERS 94
21.00 ±0.15	40k	ADRIANI	93M	L3	Repl. by ACCIARRI 94
20.78 ±0.13		BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
20.87 ±0.07	190k	[42] QUAST	93	RVUE	E^{ee}_{cm}= 88–94 GeV
$18.9\ ^{+3.6}_{-3.2}$	46	ABRAMS	89B	MRK2	E^{ee}_{cm}= 89–93 GeV

[42] QUAST 93 is a combined analysis of LEP results as of Feb. 1993. Assumes lepton universality.



$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ — Γ_6/Γ

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.6990±0.0015 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.6983±0.0023	1.14M	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
0.6993±0.0031	570k	[43] LEP	92	RVUE	E^{ee}_{cm}= 88–94 GeV

[43] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included. Assumes lepton universality.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ — Γ_1/Γ

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.03366±0.00008 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.03383±0.00013	45.8k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
0.03345±0.00020	19k	[44] LEP	92	RVUE	E^{ee}_{cm}= 88–94 GeV

[44] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_2/Γ

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.03367±0.00013 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.03344±0.00026	46.4k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
0.03351±0.00034	21k	[45] LEP	92	RVUE	E^{ee}_{cm}= 88–94 GeV

[45] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

$\Gamma(\tau^+\tau^-)/\Gamma_{\text{total}}$ — Γ_3/Γ

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.03360±0.00015 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.03366±0.00028	45.1k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
0.03328±0.00040	17k	[46] LEP	92	RVUE	E^{ee}_{cm}= 88–94 GeV

[46] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

$\Gamma(\ell^+\ell^-)/\Gamma_{\text{total}}$ — Γ_4/Γ

ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

Our fit result assumes lepton universality.

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.03366±0.00006 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.03375±0.00009	137.3k	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
0.03347±0.00013	57k	[47] LEP	92	RVUE	E^{ee}_{cm}= 88–94 GeV

[47] LEP 92 is combined analysis by the four LEP experiments as of December 1991. Systematic errors are included.

$\Gamma(\text{invisible})/\Gamma_{\text{total}}$ — Γ_5/Γ

See the data, the note, and the fit result for the partial width, Γ_5, above.

VALUE	DOCUMENT ID
0.2001±0.0016 OUR FIT	

$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ — Γ_2/Γ_1

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	DOCUMENT ID
1.000±0.005 OUR FIT	

$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-)$ — Γ_3/Γ_1

This parameter is not directly used in the overall fit but is derived using the fit results; see the 'Note on the Z Boson.'

VALUE	DOCUMENT ID
0.998±0.005 OUR FIT	

$\Gamma((u\overline{u}+c\overline{c})/2)/\Gamma(\text{hadrons})$ — Γ_7/Γ_6

This quantity is the branching ratio of $Z \to$ "up-type" quarks to $Z \to$ hadrons. The values of $Z \to$ "up-type" and $Z \to$ "down-type" branchings are extracted from measurements of Γ(hadrons), and $\Gamma(Z \to \gamma + \text{jets})$ where γ is a high-energy (>5 GeV) isolated photon. As the experiments use slightly different values of M_Z, Γ(hadrons) and α_s in their extraction procedures, our average has to be taken with caution.

VALUE	DOCUMENT ID		TECN	COMMENT
0.138±0.019 OUR AVERAGE				
$0.137^{+0.038}_{-0.054}$	[48] ABREU	95X	DLPH	E^{ee}_{cm}= 88–94 GeV
0.139±0.026	[49] ACTON	93F	OPAL	E^{ee}_{cm}= 88–94 GeV
0.137±0.033	[50] ADRIANI	93	L3	E^{ee}_{cm}= 91.2 GeV

[48] ABREU 95X use M_Z = 91.187 ± 0.009 GeV, Γ(hadrons) = 1725 ± 12 MeV and α_s = 0.123 ± 0.005. To obtain this branching ratio we divide their value of $C_{2/3} = 0.91^{+0.25}_{-0.36}$ by their value of $(3C_{1/3} + 2C_{2/3})$ = 6.66 ± 0.05.

[49] ACTON 93F use the LEP 92 value of Γ(hadrons) = 1740 ± 12 MeV and α_s = $0.122^{+0.006}_{-0.005}$.

[50] ADRIANI 93 use M_Z = 91.181 ± 0.022 GeV, Γ(hadrons) = 1742 ± 19 MeV and α_s = 0.125 ± 0.009. To obtain this branching ratio we divide their value of $C_{2/3}$ = 0.92 ± 0.22 by their value of $(3C_{1/3} + 2C_{2/3})$ = 6.720 ± 0.076.

$\Gamma((d\overline{d}+s\overline{s}+b\overline{b})/3)/\Gamma(\text{hadrons})$ — Γ_8/Γ_6

This quantity is the branching ratio of $Z \to$ "down-type" quarks to $Z \to$ hadrons. The values of $Z \to$ "up-type" and $Z \to$ "down-type" branchings are extracted from measurements of Γ(hadrons), and $\Gamma(Z \to \gamma + \text{jets})$ where γ is a high-energy (>5 GeV) isolated photon. As the experiments use slightly different values of M_Z, Γ(hadrons) and α_s in their extraction procedures, our average has to be taken with caution.

VALUE	DOCUMENT ID		TECN	COMMENT
0.242±0.012 OUR AVERAGE				
$0.243^{+0.036}_{-0.026}$	[51] ABREU	95X	DLPH	E^{ee}_{cm}= 88–94 GeV
0.241±0.017	[52] ACTON	93F	OPAL	E^{ee}_{cm}= 88–94 GeV
0.243±0.022	[53] ADRIANI	93	L3	E^{ee}_{cm}= 91.2 GeV

[51] ABREU 95X use M_Z = 91.187 ± 0.009 GeV, Γ(hadrons) = 1725 ± 12 MeV and α_s = 0.123 ± 0.005. To obtain this branching ratio we divide their value of $C_{1/3} = 1.62^{+0.24}_{-0.17}$ by their value of $(3C_{1/3} + 2C_{2/3})$ = 6.66 ± 0.05.

[52] ACTON 93F use the LEP 92 value of Γ(hadrons) = 1740 ± 12 MeV and α_s = $0.122^{+0.006}_{-0.005}$.

[53] ADRIANI 93 use M_Z = 91.181 ± 0.022 GeV, Γ(hadrons) = 1742 ± 19 MeV and α_s = 0.125 ± 0.009. To obtain this branching ratio we divide their value of $C_{1/3}$ = 1.63 ± 0.15 by their value of $(3C_{1/3} + 2C_{2/3})$ = 6.720 ± 0.076.

$R_c = \Gamma(c\overline{c})/\Gamma(\text{hadrons})$ — Γ_9/Γ_6

OUR FIT is obtained by a simultaneous fit to several c- and b-quark measurements as explained in the "Note on the Z boson." As a cross check we have also performed a weighted average of the R_c measurements taking into account the various common systematic errors. Assuming that the smallest common systematic error is fully correlated, we obtain R_c = 0.157 ± 0.010.

Because of the high current interest, we mention the following preliminary results here, but do not average them or include them in the Listings or Tables. Combining published and unpublished preliminary LEP and SLD electroweak results (as of end of March 1996) yields R_c = 0.1598 ± 0.0069. This value appears to be 1.8 s.d. below its Standard Model prediction of 0.1725 for m_t = 175 GeV and M_H = 300 GeV.

VALUE	DOCUMENT ID		TECN	COMMENT
0.158 ±0.010 OUR FIT				
0.1623±0.0085±0.0209	[54] ABREU	95D	DLPH	E^{ee}_{cm}= 88–94 GeV
0.142 ±0.008 ±0.014	[55] AKERS	95O	OPAL	E^{ee}_{cm}= 88–94 GeV
0.165 ±0.005 ±0.020	[56] BUSKULIC	94G	ALEP	E^{ee}_{cm}= 88–94 GeV
0.187 ±0.031 ±0.023	[57] ABREU	93I	DLPH	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.151 ±0.008 ±0.041	[58] ABREU	92O	DLPH	E^{ee}_{cm}= 88–94 GeV

[54] ABREU 95D perform a maximum likelihood fit to the combined p and p_T distributions of single and dilepton samples. The second error includes an uncertainty of ±0.0124 due to models and branching ratios.

[55] AKERS 95O use the presence of a $D^{*\pm}$ to tag $Z \to c\overline{c}$ with $D^* \to D^0\pi$ and $D^0 \to K\pi$. They measure $P_c * \Gamma(c\overline{c})/\Gamma(\text{hadrons})$ to be $(1.006 \pm 0.055 \pm 0.061) \times 10^{-3}$, where P_c is the product branching ratio $B(c \to D^*)B(D^* \to D^0\pi)B(D^0 \to K\pi)$. Assuming that P_c remains unchanged with energy, they use its value $(7.1 \pm 0.5) \times 10^{-3}$ determined at CESR/PETRA to obtain $\Gamma(c\overline{c})/\Gamma(\text{hadrons})$. The second error of AKERS 95O includes an uncertainty of ±0.011 from the uncertainty on P_c.

[56] BUSKULIC 94G perform a simultaneous fit to the p and p_T spectra of both single and dilepton events.

[57] ABREU 93I assume that the D_s and charmed baryons are equally produced at LEP and CLEO (10 GeV) energies.

[58] ABREU 92O use the neural network techinque to tag heavy flavour events among a sample of 123k selected hadronic events. The systematic error consists of three parts: due to Monte Carlo (MC) parametrization (0.023), choice of MC model (0.033) and detector effects (0.009) added in quadrature.

$R_b = \Gamma(b\overline{b})/\Gamma(\text{hadrons})$ — Γ_{10}/Γ_6

OUR FIT is obtained by a simultaneous fit to several c- and b-quark measurements as explained in the "Note on the Z boson." As a cross check we have also performed a weighted average of the R_b measurements taking into account the various common systematic errors. We have assumed that the smallest common systematic error is fully correlated. For R_c = 0.158 (as given by OUR FIT above), we obtain R_b = 0.2213 ± 0.0019. For an expected Standard Model value of R_c = 0.172, our weighted average gives R_b = 0.2200 ± 0.0019 while OUR FIT value becomes R_b = 0.2202 ± 0.0018.

Because of the high current interest, we mention the following preliminary results here, but do not average them or include them in the Listings or Tables. Combining published and unpublished preliminary LEP and SLD electroweak results (as of end of March 1996) yields R_b = 0.2211 ± 0.0016. This value appears to be 3.5 s.d. above its Standard Model prediction of 0.2155 for m_t = 175 GeV and M_H = 300 GeV (this apparent discrepancy has led to some speculation concerning new physics beyond the Standard Model).

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.2212±0.0019 OUR FIT					
0.2216±0.0016±0.0021		[59] ABREU	96	DLPH	E^{ee}_{cm}= 88–94 GeV
0.2145±0.0089±0.0067		[60] ABREU	95D	DLPH	E^{ee}_{cm}= 88–94 GeV
0.2171±0.0021±0.0021		[61] AKERS	95B	OPAL	E^{ee}_{cm}= 88–94 GeV
0.219 ±0.006 ±0.005		[62] BUSKULIC	94G	ALEP	E^{ee}_{cm}= 88–94 GeV
0.222 ±0.003 ±0.007		[63] ADRIANI	93E	L3	E^{ee}_{cm}= 88–94 GeV
0.222 ±0.011 ±0.007		[64] AKERS	93B	OPAL	E^{ee}_{cm}= 88–94 GeV
0.2192±0.0022±0.0031		[65] BUSKULIC	93M	ALEP	E^{ee}_{cm}= 91.3 GeV
0.228 ±0.005 ±0.005		[66] BUSKULIC	93N	ALEP	E^{ee}_{cm}= 88–94 GeV
0.251 ±0.049 ±0.030	32	[67] JACOBSEN	91	MRK2	E^{ee}_{cm}= 91 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.2217±0.0020±0.0033		[68] ABREU	95D	DLPH	Repl. by ABREU 96
0.2241±0.0063±0.0046		[69] ABREU	95J	DLPH	Repl. by ABREU 96
0.218 ±0.006 ±0.010		[70] AKERS	94D	OPAL	Repl. by AKERS 95B
0.220 ±0.002 ±0.013	11893	[71] ACTON	93I	OPAL	Repl. by AKERS 95B
0.222 ±0.007 ±0.008		[72] ACTON	93M	OPAL	Repl. by AKERS 95B
$0.222\ ^{+0.033}_{-0.031}$ ±0.017		[73] ABREU	92	DLPH	E^{ee}_{cm}= 88–94 GeV
0.219 ±0.014 ±0.019		[74] ABREU	92K	DLPH	E^{ee}_{cm}= 88–94 GeV
0.232 ±0.005 ±0.017		[75] ABREU	92O	DLPH	E^{ee}_{cm}= 88–94 GeV
$0.23\ ^{+0.10}_{-0.08}\ ^{+0.05}_{-0.04}$	15	[76] KRAL	90	MRK2	E^{ee}_{cm}= 89–93 GeV

[59] ABREU 96 obtain this result combining several analyses (double lifetime tag, mixed tag and multivariate analysis). This value is obtained assuming $R_c = \Gamma(c\overline{c})/\Gamma(\text{hadrons})$ = 0.172. For a value of R_c different from this by an amount ΔR_c the change in the value is given by $-0.087 \cdot \Delta R_c$.

[60] ABREU 95D perform a maximum likelihood fit to the combined p and p_T distributions of single and dilepton samples. The second error includes an uncertainty of ±0.0023 due to models and branching ratios.

[61] AKERS 95B select events based on the lepton and/or vertex tag independently in each hemisphere. Comparing the numbers of single- and double-tagged events, they determine the b-tagging efficiency directly from data.

[62] BUSKULIC 94G perform a simultaneous fit to the p and p_T spectra of both single and dilepton events.

[63] ADRIANI 93E use a multidimensional analysis based on a neural network approach.

[64] AKERS 93B use a simultaneous fit to single and dilepton events (electrons and muons) to tag $Z \to b\overline{b}$.

[65] BUSKULIC 93M use a method which tags the $Z \to b\overline{b}$ decays through the lifetime of the produced heavy hadrons. The systematic error includes a contribution of ±0.0016 due to the uncertainty of the charm partial width.

[66] BUSKULIC 93N use event shape and high p_T lepton discriminators applied to both hemispheres.

[67] JACOBSEN 91 tagged $b\overline{b}$ events by requiring coincidence of $\geq$ 3 tracks with significant impact parameters using vertex detector. Systematic error includes lifetime and decay uncertainties (±0.014).

[68] ABREU 95D obtain this result combining several analyses (double-lifetime tag and mixed tags). The second error contains an uncertainty of ±0.0029 due to the total systematics and an uncertainty of ±0.0016 due to an 8% variation of $\Gamma(c\overline{c})/\Gamma(\text{hadrons})$ around its Standard Model value (0.171 ± 0.014). Combining with their own lepton analysis, ABREU 95D obtain 0.2210 ± 0.0033 ± 0.0003 (models) ±0.0014 [$\Gamma(c\overline{c})/\Gamma(\text{hadrons})$].

[69] ABREU 95J obtain this value with a multivariate analysis based on event shape and particle trajectories near the interaction point. The second error contains an uncertainty of ±0.0012 due to an 8% variation of $\Gamma(c\overline{c})/\Gamma(\text{hadrons})$ around its Standard Model value (0.171 ± 0.014).

[70] AKERS 94D perform an analysis based on a "mixed tag" method (impact parameter and lepton tagging). The systematic error includes a contribution (±0.007) due to the $\Gamma(c\overline{c})/\Gamma(\text{hadrons})$ uncertainty.

[71] ACTON 93I use both electrons and muons to tag B semileptonic decays. The systematic error includes components due to b and c quark fragmentation uncertainties, decay branching ratios, and $\Gamma(c\overline{c})/\Gamma(\text{hadrons})$.

[72] ACTON 93M tagged $Z \to b\overline{b}$ events using the impact parameter technique.

[73] ABREU 92 result is from an indirect technique. They measure the lifetime τ_B, but use a world average of τ_B independent of $\Gamma(b\overline{b})$ and compare to their $\Gamma(b\overline{b})$ dependent lifetime from a hadron sample.

[74] ABREU 92K use boosted–sphericity technique to tag and enrich the b-$\overline{b}$ content with a sample of 50k hadronic events. Most of the systematic error is from hadronization uncertainty.

[75] ABREU 92O use the neural network technique to tag heavy flavour events among a sample of 123k selected hadronic events. The systematic error consists of three parts: due to Monte Carlo (MC) parametrization (0.010), choice of MC model (0.008), and detector effects (0.011) added in quadrature.
[76] KRAL 90 used isolated leptons and found $\Gamma(b\bar{b})/\Gamma(\text{total}) = 0.17^{+0.07}_{-0.06}{}^{+0.04}_{-0.03}$.

$\Gamma(\pi^0\gamma)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.2 × 10⁻⁵	95	[77] ACCIARRI	95G	L3	E^{ee}_{cm}= 88–94 GeV
<5.5 × 10⁻⁵	95	ABREU	94B	DLPH	E^{ee}_{cm}= 88–94 GeV
<2.1 × 10⁻⁴	95	DECAMP	92	ALEP	E^{ee}_{cm}= 88–94 GeV
<1.4 × 10⁻⁴	95	AKRAWY	91F	OPAL	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.2 × 10⁻⁴	95	[78] ADRIANI	92B	L3	Repl. by ACCIARRI 95G

[77] This limit is for both decay modes $Z \to \pi^0\gamma/\gamma\gamma$ which are indistinguishable in ACCIARRI 95G.
[78] This limit is for both decay modes $Z \to \pi^0\gamma/\gamma\gamma$ which are indistinguishable in ADRIANI 92B.

$\Gamma(\eta\gamma)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7.6 × 10⁻⁵	95	ACCIARRI	95G	L3	E^{ee}_{cm}= 88–94 GeV
<8.0 × 10⁻⁵	95	ABREU	94B	DLPH	E^{ee}_{cm}= 88–94 GeV
<5.1 × 10⁻⁵	95	DECAMP	92	ALEP	E^{ee}_{cm}= 88–94 GeV
<2.0 × 10⁻⁴	95	AKRAWY	91F	OPAL	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.8 × 10⁻⁴	95	ADRIANI	92B	L3	Repl. by ACCIARRI 95G

$\Gamma(\omega\gamma)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<6.5 × 10⁻⁴	95	ABREU	94B	DLPH	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\eta'(958)\gamma)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.2 × 10⁻⁵	95	DECAMP	92	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{15}/Γ

This decay would violate the Landau-Yang theorem.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.2 × 10⁻⁵	95	[79] ACCIARRI	95G	L3	E^{ee}_{cm}= 88–94 GeV
<5.5 × 10⁻⁵	95	ABREU	94B	DLPH	E^{ee}_{cm}= 88–94 GeV
<1.4 × 10⁻⁴	95	AKRAWY	91F	OPAL	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.2 × 10⁻⁴	95	[80] ADRIANI	92B	L3	Repl. by ACCIARRI 95G

[79] This limit is for both decay modes $Z \to \pi^0\gamma/\gamma\gamma$ which are indistinguishable in ACCIARRI 95G.
[80] This limit is for both decay modes $Z \to \pi^0\gamma/\gamma\gamma$ which are indistinguishable in ADRIANI 92B.

$\Gamma(\gamma\gamma\gamma)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.0 × 10⁻⁵	95	[81] ACCIARRI	95C	L3	E^{ee}_{cm}= 88–94 GeV
<1.7 × 10⁻⁵	95	[81] ABREU	94B	DLPH	E^{ee}_{cm}= 88–94 GeV
<6.6 × 10⁻⁵	95	AKRAWY	91F	OPAL	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.3 × 10⁻⁵	95	ADRIANI	92B	L3	Repl. by ACCIARRI 95C

[81] Limit derived in the context of composite Z model.

$\Gamma(\pi^\pm W^\mp)/\Gamma_{total}$ — Γ_{17}/Γ

The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7 × 10⁻⁵	95	DECAMP	92	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\rho^\pm W^\mp)/\Gamma_{total}$ — Γ_{18}/Γ

The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8.3 × 10⁻⁵	95	DECAMP	92	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(J/\psi(1S)X)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (units 10⁻³)	EVTS	DOCUMENT ID		TECN	COMMENT
3.80±0.27 OUR AVERAGE					
3.9 ±0.2 ±0.3	511	[82] ALEXANDER	96B	OPAL	E^{ee}_{cm}= 88–94 GeV
3.73±0.39±0.36	153	[83] ABREU	94P	DLPH	E^{ee}_{cm}= 88–94 GeV
3.6 ±0.5 ±0.4	121	[83] ADRIANI	93J	L3	E^{ee}_{cm}= 88–94 GeV

[82] ALEXANDER 96B identify $J/\psi(1S)$ from the decays into lepton pairs.
[83] Combining $\mu^+\mu^-$ and e^+e^- channels and taking into account the common systematic errors.

$\Gamma(\psi(2S)X)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10⁻³)	EVTS	DOCUMENT ID		TECN	COMMENT
1.60±0.33 OUR AVERAGE					
1.6 ±0.3 ±0.2	46.9	[84] ALEXANDER	96B	OPAL	E^{ee}_{cm}= 88–94 GeV
1.60±0.73±0.33	5.4	[85] ABREU	94P	DLPH	E^{ee}_{cm}= 88–94 GeV

[84] ALEXANDER 96B measure this branching ratio via the decay channel $\psi(2S) \to J/\psi\pi^+\pi^-$, with $J/\psi \to \ell^+\ell^-$.
[85] ABREU 94P measure this branching ratio via decay channel $\psi(2S) \to J/\psi\pi^+\pi^-$, with $J/\psi \to \mu^+\mu^-$.

$\Gamma(\chi_{c1}(1P)X)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10⁻³)	EVTS	DOCUMENT ID		TECN	COMMENT
6.0±1.9 OUR AVERAGE					
$5.0\pm2.1^{+1.5}_{-0.9}$	6.4	[86] ABREU	94P	DLPH	E^{ee}_{cm}= 88–94 GeV
7.5±2.9±0.6	19	[86] ADRIANI	93J	L3	E^{ee}_{cm}= 88–94 GeV

[86] This branching ratio is measured via the decay channel $\chi_{c1} \to J/\psi + \gamma$, with $J/\psi \to \mu^+\mu^-$.

$\Gamma(\Upsilon X)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10⁻⁴)	EVTS	DOCUMENT ID		TECN	COMMENT
1.0±0.4±0.22	6.4	[87] ALEXANDER	96F	OPAL	E^{ee}_{cm}= 88–94 GeV

[87] ALEXANDER 96F identify the Υ (which refers to any of the three lowest bound states) through its decay into e^+e^- and $\mu^+\mu^-$. The systematic error includes an uncertainty of ±0.2 due to the production mechanism.

$\Gamma((D^0/\overline{D}^0)X)/\Gamma(\text{hadrons})$ — Γ_{23}/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.296±0.019±0.021	369	[88] ABREU	93I	DLPH	E^{ee}_{cm}= 88–94 GeV

[88] The $(D^0/\overline{D}^0)$ states in ABREU 93I are detected by the $K\pi$ decay mode. This is a corrected result (see the erratum of ABREU 93I).

$\Gamma(D^\pm X)/\Gamma(\text{hadrons})$ — Γ_{24}/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.174±0.016±0.018	539	[89] ABREU	93I	DLPH	E^{ee}_{cm}= 88–94 GeV

[89] The $D^\pm$ states in ABREU 93I are detected by the $K\pi\pi$ decay mode. This is a corrected result (see the erratum of ABREU 93I).

$\Gamma(D^*(2010)^\pm X)/\Gamma(\text{hadrons})$ — Γ_{25}/Γ_6

The value is for the sum of the charge states indicated.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.163±0.019 OUR AVERAGE	Error includes scale factor of 1.3.				
0.155±0.010±0.013	358	[90] ABREU	93I	DLPH	E^{ee}_{cm}= 88–94 GeV
0.21 ±0.04	362	[91] DECAMP	91J	ALEP	E^{ee}_{cm}= 88–94 GeV

[90] $D^*(2010)^\pm$ in ABREU 93I are reconstructed from $D^0\pi^\pm$, with $D^0 \to K^-\pi^+$. The new CLEO II measurement of $B(D^{*\pm} \to D^0\pi^\pm) = (68.1 \pm 1.6)$ % is used. This is a corrected result (see the erratum of ABREU 93I).
[91] DECAMP 91J report $B(D^*(2010)^+ \to D^0\pi^+)\, B(D^0 \to K^-\pi^+)\, \Gamma(D^*(2010)^\pm X)$ / $\Gamma(\text{hadrons}) = (5.11 \pm 0.34) \times 10^{-3}$. They obtained the above number assuming $B(D^0 \to K^-\pi^+) = (3.62\pm0.34\pm0.44)\%$ and $B(D^*(2010)^+ \to D^0\pi^+) = (55\pm4)\%$. We have rescaled their original result of 0.26 ± 0.05 taking into account the new CLEO II branching ratio $B(D^*(2010)^+ \to D^0\pi^+) = (68.1 \pm 1.6)\%$.

$\Gamma(B^0_s X)/\Gamma(\text{hadrons})$ — Γ_{28}/Γ_6

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[92] ABREU	92M	DLPH	E^{ee}_{cm}= 88–94 GeV

[92] ABREU 92M reported value is $\Gamma(B^0_s X) * B(B^0_s \to D_s \mu\nu_\mu X) * B(D_s \to \phi\pi)/\Gamma(\text{hadrons}) = (18 \pm 8) \times 10^{-5}$.

$\Gamma(B^*X)/[\Gamma(BX) + \Gamma(B^*X)]$ — $\Gamma_{27}/(\Gamma_{26}+\Gamma_{27})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.75 ±0.04 OUR AVERAGE					
0.771±0.026±0.070		[93] BUSKULIC	96D	ALEP	E^{ee}_{cm}= 88–94 GeV
0.72 ±0.03 ±0.06		[94] ABREU	95R	DLPH	E^{ee}_{cm}= 88–94 GeV
0.76 ±0.08 ±0.06	1378	[95] ACCIARRI	95B	L3	E^{ee}_{cm}= 88–94 GeV

[93] BUSKULIC 96D use an inclusive reconstruction of B hadrons and assume a (12.2 ± 4.3)% b-baryon contribution. The value refers to a b-flavored mixture of B_u, B_d, and B_s.
[94] ABREU 95R use an inclusive B-reconstruction method and assume a (10 ± 4)% b-baryon contribution. The value refers to a b-flavored meson mixture of B_u, B_d, and B_s.
[95] ACCIARRI 95B assume a 9.4% b-baryon contribution. The value refers to a b-flavored mixture of B_u, B_d, and B_s.

$\Gamma(\text{anomalous } \gamma + \text{hadrons})/\Gamma_{total}$ — Γ_{29}/Γ

Limits on additional sources of prompt photons beyond expectations for final-state bremsstrahlung.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.2 × 10⁻³	95	[96] AKRAWY	90J	OPAL	E^{ee}_{cm}= 88–94 GeV

[96] AKRAWY 90J report $\Gamma(\gamma X) <$ 8.2 MeV at 95%CL. They assume a three-body $\gamma q\bar{q}$ distribution and use $E(\gamma) >$ 10 GeV.

$\Gamma(e^+e^-\gamma)/\Gamma_{total}$ — Γ_{30}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.2 x 10^{-4}	95	[97] ACTON	91B	OPAL	E^{ee}_{cm}= 91.2 GeV

[97] ACTON 91B looked for isolated photons with $E>2\%$ of beam energy ($>$ 0.9 GeV).

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{total}$ — Γ_{31}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.6 x 10^{-4}	95	[98] ACTON	91B	OPAL	E^{ee}_{cm}= 91.2 GeV

[98] ACTON 91B looked for isolated photons with $E>2\%$ of beam energy ($>$ 0.9 GeV).

$\Gamma(\tau^+\tau^-\gamma)/\Gamma_{total}$ — Γ_{32}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7.3 x 10^{-4}	95	[99] ACTON	91B	OPAL	E^{ee}_{cm}= 91.2 GeV

[99] ACTON 91B looked for isolated photons with $E>2\%$ of beam energy ($>$ 0.9 GeV).

$\Gamma(\ell^+\ell^-\gamma\gamma)/\Gamma_{total}$ — Γ_{33}/Γ

The value is the sum over $\ell = e, \mu, \tau$.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<6.8 x 10^{-6}	95	[100] ACTON	93E	OPAL	E^{ee}_{cm}= 88–94 GeV

[100] For $m_{\gamma\gamma} = 60 \pm 5$ GeV.

$\Gamma(q\overline{q}\gamma\gamma)/\Gamma_{total}$ — Γ_{34}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.5 x 10^{-6}	95	[101] ACTON	93E	OPAL	E^{ee}_{cm}= 88–94 GeV

[101] For $m_{\gamma\gamma} = 60 \pm 5$ GeV.

$\Gamma(\nu\overline{\nu}\gamma\gamma)/\Gamma_{total}$ — Γ_{35}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.1 x 10^{-6}	95	[102] ACTON	93E	OPAL	E^{ee}_{cm}= 88–94 GeV

[102] For $m_{\gamma\gamma} = 60 \pm 5$ GeV.

$\Gamma(e^\pm\mu^\mp)/\Gamma(e^+e^-)$ — Γ_{36}/Γ_1

Test of lepton family number conservation. The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.07	90	ALBAJAR	89	UA1	$E^{p\overline{p}}_{cm}$= 546,630 GeV

$\Gamma(e^\pm\mu^\mp)/\Gamma_{total}$ — Γ_{36}/Γ

Test of lepton family number conservation. The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.7 x 10^{-6}	95	AKERS	95W	OPAL	E^{ee}_{cm}= 88–94 GeV
<3.2 × 10^{-5}	95	ABREU	93B	DLPH	E^{ee}_{cm}= 88–94 GeV
<0.6 × 10^{-5}	95	ADRIANI	93I	L3	E^{ee}_{cm}= 88–94 GeV
<2.6 × 10^{-5}	95	DECAMP	92	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(e^\pm\tau^\mp)/\Gamma_{total}$ — Γ_{37}/Γ

Test of lepton family number conservation. The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9.8 x 10^{-6}	95	AKERS	95W	OPAL	E^{ee}_{cm}= 88–94 GeV
<1.1 × 10^{-4}	95	ABREU	93B	DLPH	E^{ee}_{cm}= 88–94 GeV
<1.3 × 10^{-5}	95	ADRIANI	93I	L3	E^{ee}_{cm}= 88–94 GeV
<1.2 × 10^{-4}	95	DECAMP	92	ALEP	E^{ee}_{cm}= 88–94 GeV

$\Gamma(\mu^\pm\tau^\mp)/\Gamma_{total}$ — Γ_{38}/Γ

Test of lepton family number conservation. The value is for the sum of the charge states indicated.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.7 x 10^{-5}	95	AKERS	95W	OPAL	E^{ee}_{cm}= 88–94 GeV
<1.4 × 10^{-4}	95	ABREU	93B	DLPH	E^{ee}_{cm}= 88–94 GeV
<1.9 × 10^{-5}	95	ADRIANI	93I	L3	E^{ee}_{cm}= 88–94 GeV
<1.0 × 10^{-4}	95	DECAMP	92	ALEP	E^{ee}_{cm}= 88–94 GeV

AVERAGE PARTICLE MULTIPLICITIES IN HADRONIC Z DECAY

Summed over particle and antiparticle, when appropriate.

$\langle N_{\pi^\pm}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
17.05±0.43	AKERS	94P	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\pi^0}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
9.83±0.31 OUR AVERAGE				
9.90±0.02±0.33	ACCIARRI	96	L3	E^{ee}_{cm}= 91.2 GeV
9.2 ±0.2 ±1.0	ADAM	96	DLPH	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
9.18±0.03±0.73	ACCIARRI	94B	L3	Repl. by ACCIARRI 96

$\langle N_{\eta}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.93 ±0.01 ±0.09	ACCIARRI	96	L3	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.91 ±0.02 ±0.11	ACCIARRI	94B	L3	Repl. by ACCIARRI 96
0.298±0.023±0.021	[103] BUSKULIC	92D	ALEP	E^{ee}_{cm}= 91.2 GeV

[103] BUSKULIC 92D obtain this value for $x>$ 0.1.

$\langle N_{\rho^0}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
1.30±0.12 OUR AVERAGE				
1.45±0.06±0.20	BUSKULIC	96H	ALEP	E^{ee}_{cm}= 91.2 GeV
1.21±0.04±0.15	ABREU	95L	DLPH	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.43±0.12±0.22	ABREU	93	DLPH	Repl. by ABREU 95L

$\langle N_{\omega}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
1.07±0.06±0.13	BUSKULIC	96H	ALEP	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\eta'}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.068±0.018±0.016	[104] BUSKULIC	92D	ALEP	E^{ee}_{cm}= 91.2 GeV

[104] BUSKULIC 92D obtain this value for $x>$ 0.1.

$\langle N_{f_0(980)}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.098±0.016	[105] ABREU	95L	DLPH	E^{ee}_{cm}= 91.2 GeV
0.10 ±0.03 ±0.019	[106] ABREU	93	DLPH	Repl. by ABREU 95L

[105] ABREU 95L obtain this value for $0.05 < x < 0.6$.
[106] ABREU 93 obtain this value for $x>$ 0.05.

$\langle N_{\phi}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.110±0.011 OUR AVERAGE Error includes scale factor of 1.8.				
0.122±0.004±0.008	BUSKULIC	96H	ALEP	E^{ee}_{cm}= 91.2 GeV
0.100±0.004±0.007	AKERS	95X	OPAL	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.086±0.015±0.010	ACTON	92O	OPAL	Repl. by AKERS 95X

$\langle N_{f_2(1270)}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.170±0.043	[107] ABREU	95L	DLPH	E^{ee}_{cm}= 91.2 GeV
0.11 ±0.04 ±0.03	[108] ABREU	93	DLPH	Repl. by ABREU 95L

[107] ABREU 95L obtain this value for $x>$ 0.05.
[108] ABREU 93 obtain this value for $x>$ 0.1.

$\langle N_{f'_2(1525)}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.020±0.005±0.006	ABREU	96C	DLPH	E^{ee}_{cm}= 91.2 GeV

$\langle N_{K^\pm}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
2.37±0.11 OUR AVERAGE				
2.26±0.01±0.18	ABREU	95F	DLPH	E^{ee}_{cm}= 91.2 GeV
2.42±0.13	AKERS	94P	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{K^0}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
2.010±0.027 OUR AVERAGE				
1.962±0.022±0.056	ABREU	95L	DLPH	E^{ee}_{cm}= 91.2 GeV
1.99 ±0.01 ±0.04	AKERS	95U	OPAL	E^{ee}_{cm}= 91.2 GeV
2.04 ±0.02 ±0.14	ACCIARRI	94B	L3	E^{ee}_{cm}= 91.2 GeV
2.061±0.047	BUSKULIC	94K	ALEP	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.12 ±0.05 ±0.04	ABREU	92G	DLPH	Repl. by ABREU 95L

$\langle N_{K^*(892)^\pm}\rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.72 ±0.05 OUR AVERAGE				
0.712±0.031±0.059	ABREU	95L	DLPH	E^{ee}_{cm}= 91.2 GeV
0.72 ±0.02 ±0.08	ACTON	93	OPAL	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.33 ±0.11 ±0.24	ABREU	92G	DLPH	Repl. by ABREU 95L

$\langle N_{K^*(892)^0} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.76±0.04 OUR AVERAGE				
0.83±0.01±0.09	BUSKULIC	96H	ALEP	E^{ee}_{cm}= 91.2 GeV
0.74±0.03±0.03	AKERS	95X	OPAL	E^{ee}_{cm}= 91.2 GeV
0.97±0.18±0.31	ABREU	93	DLPH	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.76±0.07±0.06	ACTON	92O	OPAL	Repl. by AKERS 95X

$\langle N_{K^*_2(1430)} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.19±0.04±0.06	[109] AKERS	95X	OPAL	E^{ee}_{cm}= 91.2 GeV

[109] AKERS 95X obtain this value for $x<$ 0.3.

$\langle N_{D^\pm} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.221±0.026 OUR AVERAGE	Error includes scale factor of 1.1.			
0.251±0.026±0.025	BUSKULIC	94J	ALEP	E^{ee}_{cm}= 91.2 GeV
0.199±0.019±0.024	[110] ABREU	93I	DLPH	E^{ee}_{cm}= 91.2 GeV

[110] See ABREU 95 (erratum).

$\langle N_{D^0} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.46 ±0.06 OUR AVERAGE	Error includes scale factor of 1.3.			
0.518±0.052±0.035	BUSKULIC	94J	ALEP	E^{ee}_{cm}= 91.2 GeV
0.403±0.038±0.044	[111] ABREU	93I	DLPH	E^{ee}_{cm}= 91.2 GeV

[111] See ABREU 95 (erratum).

$\langle N_{D^*(2010)^\pm} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.181±0.010 OUR AVERAGE				
0.183±0.009±0.011	[112] AKERS	95O	OPAL	E^{ee}_{cm}= 91.2 GeV
0.187±0.015±0.013	BUSKULIC	94J	ALEP	E^{ee}_{cm}= 91.2 GeV
0.171±0.012±0.016	[113] ABREU	93I	DLPH	E^{ee}_{cm}= 91.2 GeV

[112] AKERS 95O systematic error includes an uncertainty of ±0.008 due to the $D^{*\pm}$ and D^0 branching ratios [they use B($D^* \rightarrow D^0\pi$) = 0.681 ± 0.016 and B($D^0 \rightarrow K\pi$) = 0.0401 ± 0.0014 to obtain this measurement].

[113] See ABREU 95 (erratum).

$\langle N_{B^*} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.28 ±0.01 ±0.03	[114] ABREU	95R	DLPH	E^{ee}_{cm}= 91.2 GeV

[114] ABREU 95R quote this value for a flavor-averaged excited state.

$\langle N_{J/\psi(1S)} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0056±0.0003±0.0004	[115] ALEXANDER	96B	OPAL	E^{ee}_{cm}= 91.2 GeV

[115] ALEXANDER 96B identify $J/\psi(1S)$ from the decays into lepton pairs.

$\langle N_{\psi(2S)} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0023±0.0004±0.0003	ALEXANDER	96B	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_p \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.98±0.09 OUR AVERAGE				
1.07±0.01±0.14	ABREU	95F	DLPH	E^{ee}_{cm}= 91.2 GeV
0.92±0.11	AKERS	94P	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Delta(1232)^{++}} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.087±0.033 OUR AVERAGE	Error includes scale factor of 2.4.			
0.079±0.009±0.011	ABREU	95W	DLPH	E^{ee}_{cm}= 91.2 GeV
0.22 ±0.04 ±0.04	ALEXANDER	95D	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_\Lambda \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.367±0.010 OUR AVERAGE				
0.37 ±0.01 ±0.04	ACCIARRI	94B	L3	E^{ee}_{cm}= 91.2 GeV
0.386±0.016	BUSKULIC	94K	ALEP	E^{ee}_{cm}= 91.2 GeV
0.357±0.003±0.017	ABREU	93L	DLPH	E^{ee}_{cm}= 91.2 GeV
0.351±0.019	ACTON	92J	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Sigma^\pm} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.170±0.014±0.061	ABREU	95O	DLPH	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Sigma^0} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.070±0.010±0.010	ADAM	96B	DLPH	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Sigma(1385)^\pm} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.038 ±0.004 OUR AVERAGE				
0.0382±0.0028±0.0045	ABREU	95O	DLPH	E^{ee}_{cm}= 91.2 GeV
0.0380±0.0062	ACTON	92J	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Xi^-} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0226±0.0022 OUR AVERAGE	Error includes scale factor of 1.4.			
0.0250±0.0009±0.0021	ABREU	95O	DLPH	E^{ee}_{cm}= 91.2 GeV
0.0206±0.0021	ACTON	92J	OPAL	E^{ee}_{cm}= 91.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.020 ±0.004 ±0.003	ABREU	92G	DLPH	Repl. by ABREU 95O

$\langle N_{\Xi(1530)^0} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0044±0.0008 OUR AVERAGE	Error includes scale factor of 1.5.			
0.0041±0.0004±0.0004	ABREU	95O	DLPH	E^{ee}_{cm}= 91.2 GeV
0.0063±0.0014	ACTON	92J	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{\Omega^-} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0017±0.0010 OUR AVERAGE	Error includes scale factor of 2.3.			
0.0014±0.0002±0.0004	ADAM	96B	DLPH	E^{ee}_{cm}= 91.2 GeV
0.0050±0.0015	ACTON	92J	OPAL	E^{ee}_{cm}= 91.2 GeV

$\langle N_{charged} \rangle$

VALUE	DOCUMENT ID		TECN	COMMENT
20.99±0.14 OUR AVERAGE				
21.05±0.20	AKERS	95Z	OPAL	E^{ee}_{cm}= 91.2 GeV
21.40±0.43	ACTON	92B	OPAL	E^{ee}_{cm}= 91.2 GeV
20.71±0.04±0.77	ABREU	91H	DLPH	E^{ee}_{cm}= 91.2 GeV
20.7 ±0.7	ADEVA	91I	L3	E^{ee}_{cm}= 91.2 GeV
20.85±0.02±0.24	DECAMP	91K	ALEP	E^{ee}_{cm}= 91.2 GeV
20.1 ±1.0 ±0.9	ABRAMS	90	MRK2	E^{ee}_{cm}= 91.1 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
21.3 ±0.1 ±0.6	DECAMP	90Q	ALEP	Repl. by DECAMP 91K

Z HADRONIC POLE CROSS SECTION

This quantity is defined as

$$\sigma_h^0 = \frac{12\pi}{M_Z^2} \frac{\Gamma(e^+e^-)\,\Gamma(\text{hadrons})}{\Gamma_Z^2}$$

It is one of the parameters used in the *Z* lineshape fit. (See the 'Note on the *Z* Boson.')

VALUE (nb)	EVTS	DOCUMENT ID		TECN	COMMENT
41.54±0.14 OUR FIT					
41.49±0.10 OUR AVERAGE					
41.23±0.20	1.05M	ABREU	94	DLPH	E^{ee}_{cm}= 88–94 GeV
41.39±0.26	1.09M	ACCIARRI	94	L3	E^{ee}_{cm}= 88–94 GeV
41.70±0.23	1.19M	AKERS	94	OPAL	E^{ee}_{cm}= 88–94 GeV
41.60±0.16	1.27M	BUSKULIC	94	ALEP	E^{ee}_{cm}= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
41.45±0.31	512k	ACTON	93D	OPAL	Repl. by AKERS 94
41.34±0.28	460k	ADRIANI	93M	L3	Repl. by ACCIARRI 94
41.60±0.27	520k	BUSKULIC	93J	ALEP	Repl. by BUSKULIC 94
42 ±4	450	ABRAMS	89B	MRK2	E^{ee}_{cm}= 89.2–93.0 GeV

Z VECTOR COUPLINGS TO CHARGED LEPTONS

These quantities are the effective vector couplings of the *Z* to charged leptons. Their magnitude is derived from a measurement of the *Z* lineshape and the forward-backward lepton asymmetries as a function of energy around the *Z* mass. The relative sign among the vector to axial-vector couplings is obtained from a measurement of the *Z* asymmetry parameters, A_e and A_τ, or ν_e scattering. The fit values quoted below correspond to global nine- or five-parameter fits to lineshape, lepton forward-backward asymmetry, and A_e and A_τ measurements. See "Note on the *Z* boson" for details.

Within the current data set, the reason for the smallness of g_V^μ compared to g_V^e and g_V^τ is due to the large value of A_e which is heavily weighted by the SLD result. This large value of A_e leads to a large value of g_V^e. Since g_V^μ is obtained using the relation $A_{FB}^\mu = 0.75 \times A_e \times A_\mu$, a large value of g_V^e leads to a SMALL value of g_V^μ. Concerning the τ, its g_V gets mainly determined directly from A_τ which is obtained from a measurement of the τ polarization (see "Note on the *Z* boson").

g_V^e

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.0393±0.0018 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.0414 ± 0.0020		[116] ABE	95J SLD	E_{cm}^{ee} = 91.31 GeV
$-0.0364^{+0.0096}_{-0.0082}$	38k	[117] ACCIARRI	94 L3	E_{cm}^{ee} = 88–94 GeV
$-0.036\ \pm0.005$	45.8k	[118] BUSKULIC	94 ALEP	E_{cm}^{ee} = 88–94 GeV
$-0.040\ ^{+0.013}_{-0.011}$		[119] ADRIANI	93M L3	Repl. by ACCIARRI 94
$-0.034\ ^{+0.006}_{-0.005}$		[117] BUSKULIC	93J ALEP	Repl. by BUSKULIC 94
$-0.035\ \pm0.005$	70k	[120] QUAST	93 RVUE	E_{cm}^{ee} = 88–94 GeV

[116] ABE 95J obtain this result combining polarized Bhabha results with the A_{LR} measurement of ABE 94C. The Bhabha results alone give $-0.0507 \pm 0.0096 \pm 0.0020$.
[117] The τ polarization result has been included.
[118] BUSKULIC 94 use the added constraint of τ polarization.
[119] ADRIANI 93M use their measurement of the τ polarization in addition to forward-backward lepton asymmetries.
[120] QUAST 93 is a combined analysis of LEP results as of Feb. 1993. QUAST 93 use also the average LEP values for τ polarization and the forward–backward τ polarisation asymmetry.

g_V^μ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$-0.0276^{+0.0056}_{-0.0057}$ OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$-0.0402^{+0.0153}_{-0.0211}$	34k	[121] ACCIARRI	94 L3	E_{cm}^{ee} = 88–94 GeV
$-0.034\ \pm0.013$	46.4k	[122] BUSKULIC	94 ALEP	E_{cm}^{ee} = 88–94 GeV
$-0.048\ ^{+0.021}_{-0.033}$		[123] ADRIANI	93M L3	Repl. by ACCIARRI 94
$-0.019\ ^{+0.018}_{-0.019}$		[121] BUSKULIC	93J ALEP	Repl. by BUSKULIC 94
$-0.029\ \pm0.010$	70k	[124] QUAST	93 RVUE	E_{cm}^{ee} = 88–94 GeV

[121] The τ polarization result has been included.
[122] BUSKULIC 94 use the added constraint of τ polarization.
[123] ADRIANI 93M use their measurement of the τ polarization in addition to forward-backward lepton asymmetries.
[124] QUAST 93 is a combined analysis of LEP results as of Feb. 1993. QUAST 93 use also the average LEP values for τ polarization and the forward–backward τ polarisation asymmetry.

g_V^τ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.0374±0.0022 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.0384 ± 0.0078	25k	[125] ACCIARRI	94 L3	E_{cm}^{ee} = 88–94 GeV
$-0.038\ \pm0.005$	45.1k	[126] BUSKULIC	94 ALEP	E_{cm}^{ee} = 88–94 GeV
$-0.037\ \pm0.008$	7441	[127] ADRIANI	93M L3	Repl. by ACCIARRI 94
$-0.039\ \pm0.006$		[125] BUSKULIC	93J ALEP	Repl. by BUSKULIC 94
$-0.039\ \pm0.004$	50k	[128] QUAST	93 RVUE	E_{cm}^{ee} = 88–94 GeV

[125] The τ polarization result has been included.
[126] BUSKULIC 94 use the added constraint of τ polarization.
[127] ADRIANI 93M use their measurement of the τ polarization in addition to forward-backward lepton asymmetries.
[128] QUAST 93 is a combined analysis of LEP results as of Feb. 1993. QUAST 93 use also the average LEP values for τ polarization and the forward–backward τ polarisation asymmetry.

g_V^ℓ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.0376±0.0012 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$-0.039\ \pm0.004$	50.3k	[129] ABREU	94 DLPH	E_{cm}^{ee} = 88–94 GeV
$-0.0378^{+0.0045}_{-0.0042}$	97k	[130] ACCIARRI	94 L3	E_{cm}^{ee} = 88–94 GeV
$-0.034\ \pm0.004$	146k	[129] AKERS	94 OPAL	E_{cm}^{ee} = 88–94 GeV
$-0.038\ \pm0.004$	137.3k	[129] BUSKULIC	94 ALEP	E_{cm}^{ee} = 88–94 GeV
$-0.027\ \pm0.008$	58k	[129] ACTON	93D OPAL	Repl. by AKERS 94
$-0.040\ ^{+0.006}_{-0.005}$		[130] ADRIANI	93M L3	Repl. by ACCIARRI 94
$-0.034\ ^{+0.004}_{-0.003}$		[130] BUSKULIC	93J ALEP	Repl. by BUSKULIC 94
-0.0355 ± 0.0025	190k	[131] QUAST	93 RVUE	E_{cm}^{ee} = 88–94 GeV

[129] Using forward-backward lepton asymmetries.
[130] The τ polarization result has been included.
[131] QUAST 93 is a combined analysis of LEP results as of Feb. 1993. QUAST 93 use also the average LEP values for τ polarization and the forward–backward τ polarisation asymmetry. Assumes lepton universality.

Z AXIAL-VECTOR COUPLINGS TO CHARGED LEPTONS

These quantities are the effective axial-vector couplings of the Z to charged leptons. Their magnitude is derived from a measurement of the Z lineshape and the forward-backward lepton asymmetries as a function of energy around the Z mass. The relative sign among the vector to axial-vector couplings is obtained from a measurement of the Z asymmetry parameters, A_e and A_τ, or ν_e scattering. The fit values quoted below correspond to global nine- or five-parameter fits to lineshape, lepton forward-backward asymmetry, and A_e and A_τ measurements. See "Note on the Z boson" for details.

g_A^e

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.5007±0.0009 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.4977 ± 0.0045		[132] ABE	95J SLD	E_{cm}^{ee} = 91.31 GeV
-0.4998 ± 0.0016	38k	[133] ACCIARRI	94 L3	E_{cm}^{ee} = 88–94 GeV
$-0.503\ \pm0.002$	45.8k	BUSKULIC	94 ALEP	E_{cm}^{ee} = 88–94 GeV
-0.4980 ± 0.0021		[133] ADRIANI	93M L3	Repl. by ACCIARRI 94
-0.5029 ± 0.0018		[133] BUSKULIC	93J ALEP	Repl. by BUSKULIC 94

[132] ABE 95J obtain this result combining polarized Bhabha results with the A_{LR} measurement of ABE 94C. The Bhabha results alone give $-0.4968 \pm 0.0039 \pm 0.0027$.
[133] The τ-polarization constraint has been included.

g_A^μ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.5015±0.0012 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$-0.4987^{+0.0030}_{-0.0026}$	34k	[134] ACCIARRI	94 L3	E_{cm}^{ee} = 88–94 GeV
$-0.501\ \pm0.002$	46.4k	BUSKULIC	94 ALEP	E_{cm}^{ee} = 88–94 GeV
$-0.4968^{+0.0050}_{-0.0037}$		[134] ADRIANI	93M L3	Repl. by ACCIARRI 94
-0.5014 ± 0.0029		[134] BUSKULIC	93J ALEP	Repl. by BUSKULIC 94

[134] The τ-polarization constraint has been included.

g_A^τ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.5009±0.0013 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.5014 ± 0.0029	25k	[135] ACCIARRI	94 L3	E_{cm}^{ee} = 88–94 GeV
$-0.502\ \pm0.003$	45.1k	BUSKULIC	94 ALEP	E_{cm}^{ee} = 88–94 GeV
-0.5032 ± 0.0038	7441	[135] ADRIANI	93M L3	Repl. by ACCIARRI 94
-0.5016 ± 0.0033		[135] BUSKULIC	93J ALEP	Repl. by BUSKULIC 94

[135] The τ-polarization constraint has been included.

g_A^ℓ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.5008±0.0008 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.4999 ± 0.0014	71k	ABREU	94 DLPH	E_{cm}^{ee} = 88–94 GeV
-0.4998 ± 0.0014	97k	[136] ACCIARRI	94 L3	E_{cm}^{ee} = 88–94 GeV
$-0.500\ \pm0.001$	146k	AKERS	94 OPAL	E_{cm}^{ee} = 88–94 GeV
$-0.502\ \pm0.001$	137k	BUSKULIC	94 ALEP	E_{cm}^{ee} = 88–94 GeV
-0.4998 ± 0.0016	58k	ACTON	93D OPAL	Repl. by AKERS 94
-0.4986 ± 0.0015		[136] ADRIANI	93M L3	Repl. by ACCIARRI 94
-0.5022 ± 0.0015		[136] BUSKULIC	93J ALEP	Repl. by BUSKULIC 94

[136] The τ-polarization constraint has been included.

Z COUPLINGS TO NEUTRAL LEPTONS

These quantities are the effective couplings of the Z to neutral leptons. $\nu_e e$ and $\nu_\mu e$ scattering results are combined with g_A^e and g_V^e measurements at the Z mass to obtain g^{ν_e} and g^{ν_μ} following NOVIKOV 93C.

g^{ν_e}

VALUE	DOCUMENT ID	TECN	COMMENT
0.528±0.085	[137] VILAIN 94	CHM2	From $\nu_\mu e$ and $\nu_e e$ scattering

[137] VILAIN 94 derive this value from their value of g^{ν_μ} and their ratio $g^{\nu_e}/g^{\nu_\mu} = 1.05^{+0.15}_{-0.18}$.

g^{ν_μ}

VALUE	DOCUMENT ID	TECN	COMMENT
0.502±0.017	[138] VILAIN 94	CHM2	From $\nu_\mu e$ scattering

[138] VILAIN 94 derive this value from their measurement of the couplings $g_A^{e\nu_\mu} = -0.503 \pm 0.017$ and $g_V^{e\nu_\mu} = -0.035 \pm 0.017$ obtained from $\nu_\mu e$ scattering. We have re-evaluated this value using the current PDG values for g_A^e and g_V^e.

Z ASYMMETRY PARAMETERS

For each fermion-antifermion pair coupling to the Z these quantities are defined as

$$A_f = \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}$$

where g_V^f and g_A^f are the effective vector and axial-vector couplings. For their relation to the various lepton asymmetries see the 'Note on the Z Boson.'

A_e

Using polarized beams, this quantity can also be measured as $(\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$, where σ_L and σ_R are the e^+e^- production cross sections for Z bosons produced with left-handed and right-handed electrons respectively.

Because of the high current interest, we mention the following preliminary results here, but do not average them or include them in the Listings or Tables. An unpublished preliminary value of A_{LR} ($= A_e$) from SLD which includes all previous SLD data is 0.1551 ± 0.0040 (combining statistical and systematic errors). If the ABE 94C value is replaced by this value, the average is 0.153 ± 0.004 with no scale factor.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.156 ±0.008 OUR AVERAGE		Error includes scale factor of 1.2.			
0.202 ±0.038 ±0.008		[139] ABE	95J	SLD	$E_{\rm cm}^{ee}$= 91.31 GeV
0.136 ±0.027 ±0.003		[140] ABREU	95I	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
0.122 ±0.030 ±0.012	30663	[140] AKERS	95	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV
0.129 ±0.016 ±0.005	33000	[141] BUSKULIC	95Q	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV
0.1656±0.0071±0.0028	49392	[142] ABE	94C	SLD	$E_{\rm cm}^{ee}$= 91.26 GeV
0.157 ±0.020 ±0.005	86000	[140] ACCIARRI	94E	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
0.097 ±0.044 ±0.004	10224	[143] ABE	93	SLD	$E_{\rm cm}^{ee}$= 91.26 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.120 ±0.026		[140] BUSKULIC	93P	ALEP	Repl. by BUSKULIC 95Q

[139] ABE 95J obtain this result from polarized Bhabha scattering.
[140] Derived from the measurement of forward-backward τ polarization asymmetry.
[141] BUSKULIC 95Q obtain this result fitting the τ polarization as a function of the polar τ production angle.
[142] ABE 94C measured the left-right asymmetry in Z production. This value leads to $\sin^2\theta_W$ = 0.2292 ± 0.0009 ± 0.0004.
[143] ABE 93 measured the left-right asymmetry in Z production.

A_τ

This quantity is derived from the measurement of the average τ polarization.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.145±0.009 OUR AVERAGE					
0.148±0.017±0.014		ABREU	95I	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
0.153±0.019±0.013	30663	AKERS	95	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV
0.136±0.012±0.009	33000	[144] BUSKULIC	95Q	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV
0.150±0.013±0.009	86000	ACCIARRI	94E	L3	$E_{\rm cm}^{ee}$= 88–94 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.132±0.033	10732	ADRIANI	93M	L3	Repl. by ACCIARRI 94E
0.143±0.023		BUSKULIC	93P	ALEP	Repl. by BUSKULIC 95Q
0.24 ±0.07	2021	ABREU	92N	DLPH	Repl. by ABREU 95I

[144] BUSKULIC 95Q obtain this result fitting the τ polarization as a function of the polar τ production angle.

A_c

This quantity is directly extracted from a measurement of the left-right forward-backward asymmetry in $c\overline{c}$ production at SLC using polarized electron beam. This double asymmetry eliminates the dependence on the Z-e-e coupling parameter A_e.

VALUE	DOCUMENT ID		TECN	COMMENT
0.59±0.19 OUR AVERAGE				
0.37±0.23±0.21	[145] ABE	95L	SLD	$E_{\rm cm}^{ee}$= 91.26 GeV
0.73±0.22±0.10	[146] ABE,K	95	SLD	$E_{\rm cm}^{ee}$= 91.26 GeV

[145] ABE 95L tag b and c quarks through their semileptonic decays into electrons and muons. A maximum likelihood fit is performed to extract A_b and A_c.
[146] ABE,K 95 tag $Z \to c\overline{c}$ events using D^{*+} and D^+ meson production. To take care of the $b\overline{b}$ contamination in their analysis they use A_b^D= 0.64 ± 0.11 (which is A_b from D^*/D tagging). This is obtained by starting with a Standard Model value of 0.935, assigning it an estimated error of ±0.105 to cover LEP and SLD measurements, and finally taking into account B-$\overline{B}$ mixing ($1-2\chi_{\rm mix}$ = 0.72 ± 0.09). Combining with ABE 95L they quote 0.59 ± 0.19.

A_b

This quantity is directly extracted from a measurement of the left-right forward-backward asymmetry in $b\overline{b}$ production at SLC using polarized electron beam. This double asymmetry eliminates the dependence on the Z-e-e coupling parameter A_e.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.89±0.11 OUR AVERAGE					
0.87±0.11±0.09	4032	[147] ABE	95K	SLD	$E_{\rm cm}^{ee}$= 91.26 GeV
0.91±0.14±0.07		[148] ABE	95L	SLD	$E_{\rm cm}^{ee}$= 91.26 GeV

[147] ABE 95K obtain an enriched sample of $b\overline{b}$ events tagging with the impact parameter. A momentum-weighted charge sum is used to identify the charge of the underlying b quark.
[148] ABE 95L tag b and c quarks through their semileptonic decays into electrons and muons. A maximum likelihood fit is performed to extract A_b and A_c. Combining with ABE 95K, they quote 0.89 ± 0.09 ± 0.06.

$A_{FB}^{(0,e)}$ CHARGE ASYMMETRY IN $e^+e^- \to e^+e^-$ (including radiative corrections)

For the Z peak, we report the pole asymmetry defined by $(3/4)A_e^2$ as determined by the nine-parameter fit to cross-section and lepton forward-backward asymmetry data. For details see the "Note on the Z boson."

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
1.51±0.40 OUR FIT					
1.5 ±0.4 OUR AVERAGE					
2.5 ±0.9		91.2	ABREU	94	DLPH
1.04±0.92		91.2	ACCIARRI	94	L3
0.62±0.80		91.2	AKERS	94	OPAL
1.85±0.66		91.2	BUSKULIC	94	ALEP

$A_{FB}^{(0,\mu)}$ CHARGE ASYMMETRY IN $e^+e^- \to \mu^+\mu^-$ (including radiative corrections)

For the Z peak, we report the pole asymmetry defined by $(3/4)A_eA_\mu$ as determined by the nine-parameter fit to cross-section and lepton forward-backward asymmetry data. For details see the "Note on the Z boson."

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
1.33± 0.26 OUR FIT					
1.34± 0.24 OUR AVERAGE					
1.4 ± 0.5		91.2	ABREU	94	DLPH
1.79± 0.61		91.2	ACCIARRI	94	L3
0.99± 0.42		91.2	AKERS	94	OPAL
1.46± 0.48		91.2	BUSKULIC	94	ALEP
• • • We do not use the following data for averages, fits, limits, etc. • • •					
9 ±30	−2	20	[149] ABREU	95M	DLPH
7 ±26	−10	40	[149] ABREU	95M	DLPH
−11 ±33	−25	57	[149] ABREU	95M	DLPH
−62 ±17	−45	69	[149] ABREU	95M	DLPH
−56 ±10	−58	79	[149] ABREU	95M	DLPH
−13 ± 5	−23	87.5	[149] ABREU	95M	DLPH
$-29.0\ ^{+\ 5.0}_{-\ 4.8}$ ±0.5	−32.1	56.9	[150] ABE	90I	VNS
− 9.9 ± 1.5 ±0.5	−9.2	35	HEGNER	90	JADE
0.05± 0.22	0.026	91.14	[151] ABRAMS	89D	MRK2
−43.4 ±17.0	−24.9	52.0	[152] BACALA	89	AMY
−11.0 ±16.5	−29.4	55.0	[152] BACALA	89	AMY
−30.0 ±12.4	−31.2	56.0	[152] BACALA	89	AMY
−46.2 ±14.9	−33.0	57.0	[152] BACALA	89	AMY
−29 ±13	−25.9	53.3	ADACHI	88C	TOPZ
+ 5.3 ± 5.0 ±0.5	−1.2	14.0	ADEVA	88	MRKJ
−10.4 ± 1.3 ±0.5	−8.6	34.8	ADEVA	88	MRKJ
−12.3 ± 5.3 ±0.5	−10.7	38.3	ADEVA	88	MRKJ
−15.6 ± 3.0 ±0.5	−14.9	43.8	ADEVA	88	MRKJ
− 1.0 ± 6.0	−1.2	13.9	BRAUNSCH...	88D	TASS
− 9.1 ± 2.3 ±0.5	−8.6	34.5	BRAUNSCH...	88D	TASS
$-10.6\ ^{+\ 2.2}_{-\ 2.3}$ ±0.5	−8.9	35.0	BRAUNSCH...	88D	TASS
$-17.6\ ^{+\ 4.4}_{-\ 4.3}$ ±0.5	−15.2	43.6	BRAUNSCH...	88D	TASS
− 4.8 ± 6.5 ±1.0	−11.5	39	BEHREND	87C	CELL
−18.8 ± 4.5 ±1.0	−15.5	44	BEHREND	87C	CELL
+ 2.7 ± 4.9	−1.2	13.9	BARTEL	86C	JADE
−11.1 ± 1.8 ±1.0	−8.6	34.4	BARTEL	86C	JADE
−17.3 ± 4.8 ±1.0	−13.7	41.5	BARTEL	86C	JADE
−22.8 ± 5.1 ±1.0	−16.6	44.8	BARTEL	86C	JADE
− 6.3 ± 0.8 ±0.2	−6.3	29	ASH	85	MAC
− 4.9 ± 1.5 ±0.5	−5.9	29	DERRICK	85	HRS
− 7.1 ± 1.7	−5.7	29	LEVI	83	MRK2
−16.1 ± 3.2	−9.2	34.2	BRANDELIK	82C	TASS

[149] ABREU 95M perform this measurement using radiative muon-pair events associated with high-energy isolated photons.
[150] ABE 90I measurements in the range 50 ≤ $\sqrt{s}$ ≤ 60.8 GeV.
[151] ABRAMS 89D asymmetry includes both 9 $\mu^+\mu^-$ and 15 $\tau^+\tau^-$ events.
[152] BACALA 89 systematic error is about 5%.

$A_{FB}^{(0,\tau)}$ CHARGE ASYMMETRY IN $e^+e^- \to \tau^+\tau^-$ (including radiative corrections)

For the Z peak, we report the pole asymmetry defined by $(3/4)A_eA_\tau$ as determined by the nine-parameter fit to cross-section and lepton forward-backward asymmetry data. For details see the "Note on the Z boson."

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
2.12± 0.32 OUR FIT					
2.13± 0.31 OUR AVERAGE					
2.2 ± 0.7		91.2	ABREU	94	DLPH
2.65± 0.88		91.2	ACCIARRI	94	L3
2.05± 0.52		91.2	AKERS	94	OPAL
1.97± 0.56		91.2	BUSKULIC	94	ALEP

• • • We do not use the following data for averages, fits, limits, etc. • • •

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
$-32.8\ ^{+6.4}_{-6.2}\ \pm1.5$	-32.1	56.9	[153] ABE	90I	VNS
$-\ 8.1 \pm 2.0 \pm0.6$	-9.2	35	HEGNER	90	JADE
-18.4 ± 19.2	-24.9	52.0	[154] BACALA	89	AMY
-17.7 ± 26.1	-29.4	55.0	[154] BACALA	89	AMY
-45.9 ± 16.6	-31.2	56.0	[154] BACALA	89	AMY
-49.5 ± 18.0	-33.0	57.0	[154] BACALA	89	AMY
-20 ± 14	-25.9	53.3	ADACHI	88C	TOPZ
$-10.6 \pm 3.1 \pm1.5$	-8.5	34.7	ADEVA	88	MRKJ
$-\ 8.5 \pm 6.6 \pm1.5$	-15.4	43.8	ADEVA	88	MRKJ
$-\ 6.0 \pm 2.5 \pm1.0$	8.8	34.6	BARTEL	85F	JADE
$-11.8 \pm 4.6 \pm1.0$	14.8	43.0	BARTEL	85F	JADE
$-\ 5.5 \pm 1.2 \pm0.5$	-0.063	29.0	FERNANDEZ	85	MAC
$-\ 4.2 \pm 2.0$	0.057	29	LEVI	83	MRK2
-10.3 ± 5.2	-9.2	34.2	BEHREND	82	CELL
$-\ 0.4 \pm 6.6$	-9.1	34.2	BRANDELIK	82C	TASS

[153] ABE 90I measurements in the range $50 \leq \sqrt{s} \leq 60.8$ GeV.
[154] BACALA 89 systematic error is about 5%.

$A_{FB}^{(0,\ell)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow \ell^+\ell^-$ (including radiative corrections)

For the Z peak, we report the pole asymmetry defined by $(3/4)A_\ell^2$ as determined by the five-parameter fit to cross-section and lepton forward-backward asymmetry data assuming lepton universality. For details see the "Note on the Z boson."

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
1.59±0.18 OUR FIT					
1.60±0.18 OUR AVERAGE					
1.77±0.37		91.2	ABREU	94	DLPH
1.84±0.45		91.2	ACCIARRI	94	L3
1.28±0.30		91.2	AKERS	94	OPAL
1.71±0.33		91.2	BUSKULIC	94	ALEP

$A_{FB}^{(0,s)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow s\bar{s}$

The s-quark asymmetry is derived from measurements of the forward-backward asymmetry of fast hadrons containing an s quark.

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
13.1±3.5±1.3		91.2	[155] ABREU	95G	DLPH

[155] ABREU 95G require the presence of a high-momentum charged kaon or Λ^0 to tag the s quark. An unresolved s- and d-quark asymmetry of $(11.2 \pm 3.1 \pm 5.4)$% is obtained by tagging the presence of a high-energy neutron or neutral kaon in the hadron calorimeter.

$A_{FB}^{(0,c)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow c\bar{c}$

OUR FIT, which is obtained by a simultaneous fit to several c- and b-quark measurements as explained in the "Note on the Z boson," refers to the Z pole asymmetry. As a cross check we have also performed a weighted average of the "near peak" measurements taking into account the various common systematic errors. We have assumed that the smallest common systematic error is fully correlated. Applying to this combined "peak" measurement QCD, QED, and energy-dependence corrections, our weighted average gives a pole asymmetry of (7.35 ± 0.74)%.

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
7.22± 0.67 OUR FIT					
$6.00\pm 0.67\pm0.52$		91.24	[156] ALEXANDER	96	OPAL
$7.7 \pm 2.9 \pm1.2$		91.27	[157] ABREU	95E	DLPH
$8.3 \pm 2.2 \pm1.6$		91.27	[158] ABREU	95K	DLPH
$6.99\pm 2.05\pm1.02$		91.24	[159] BUSKULIC	95I	ALEP
$9.9 \pm 2.0 \pm1.7$		91.24	[160] BUSKULIC	94G	ALEP
$3.8 \pm 4.4 \pm1.0$	5.4	91.28	[161] AKERS	93D	OPAL
$8.3 \pm 3.8 \pm2.7$	5.6	91.24	[162] ADRIANI	92D	L3
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$-\ 7.5 \pm 3.4 \pm0.6$	-3.5	89.52	[156] ALEXANDER	96	OPAL
$14.1 \pm 2.8 \pm0.9$	12.0	92.94	[156] ALEXANDER	96	OPAL
$6.8 \pm 4.2 \pm0.9$		91.25	[163] BUSKULIC	94J	ALEP
$1.4 \pm 3.0 \pm2.0$	5.6	91.24	[164] ACTON	93K	OPAL
$-14 \pm14 \pm3$	-2	89.75	[161] AKERS	93D	OPAL
$18 \pm12 \pm3$	12	92.64	[161] AKERS	93D	OPAL
$-12.9 \pm 7.8 \pm5.5$	-13.6	35	BEHREND	90D	CELL
$7.7 \pm13.4 \pm5.0$	-22.1	43	BEHREND	90D	CELL
$-12.8 \pm 4.4 \pm4.1$	-13.6	35	ELSEN	90	JADE
$-10.9 \pm12.9 \pm4.6$	-23.2	44	ELSEN	90	JADE
-14.9 ± 6.7	-13.3	35	OULD-SAADA	89	JADE

[156] ALEXANDER 96 tag heavy flavors using one or two identified leptons. This allows the simultaneous fitting of the b and c quark forward-backward asymmetries as well as the average B^0-$\overline{B}^0$ mixing.
[157] ABREU 95E require the presence of a $D^{*\pm}$ to identify c and b quarks.
[158] ABREU 95K identify c and b quarks using both electron and muon semileptonic decays.
[159] BUSKULIC 95I require the presence of a high momentum $D^{*\pm}$ to have an enriched sample of $Z \rightarrow c\bar{c}$ events.
[160] BUSKULIC 94G perform a simultaneous fit to the p and p_T spectra of both single and dilepton events.
[161] AKERS 93D identify the b and c decays using D^*.
[162] ADRIANI 92D use both electron and muon semileptonic decays.
[163] BUSKULIC 94J Identify the b and c decays using D^*. Repl. by BUSKULIC 95I.
[164] ACTON 93K use the lepton tagging technique. Repl. by ALEXANDER 96.

$A_{FB}^{(0,b)}$ CHARGE ASYMMETRY IN $e^+e^- \rightarrow b\bar{b}$

OUR FIT, which is obtained by a simultaneous fit to several c- and b-quark measurements as explained in the "Note on the Z boson," refers to the Z pole asymmetry. As a cross check we have also performed a weighted average of the "near peak" measurements taking into account the various common systematic errors. We have assumed that the smallest common systematic error is fully correlated. Applying to this combined "peak" measurement QCD, QED, and energy-dependence corrections, our weighted average gives a pole asymmetry of (9.96 ± 0.39)%. For the jet-charge measurements (where the QCD corrections are already included since they represent an inherent part of the analysis), we subtract the QCD correction before combining.

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
9.92± 0.35 OUR FIT					
$9.06\pm 0.51\pm 0.23$		91.24	[165] ALEXANDER	96	OPAL
$5.9 \pm 6.2 \pm 2.4$		91.27	[166] ABREU	95E	DLPH
$10.4 \pm 1.3 \pm 0.5$		91.27	[167] ABREU	95K	DLPH
$11.5 \pm 1.7 \pm 1.0$		91.27	[168] ABREU	95K	DLPH
$9.63\pm 0.67\pm 0.38$		91.25	[169] AKERS	95S	OPAL
$8.7 \pm 1.1 \pm 0.4$		91.3	[170] ACCIARRI	94D	L3
$8.7 \pm 1.4 \pm 0.2$		91.24	[171] BUSKULIC	94G	ALEP
$9.92\pm 0.84\pm 0.46$		91.19	[172] BUSKULIC	94I	ALEP
$13.9 \pm 9.7 \pm 4.9$	9.4	91.28	[173] AKERS	93D	OPAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$5.5 \pm 2.4 \pm 0.3$	5.5	89.52	[165] ALEXANDER	96	OPAL
$11.7 \pm 2.0 \pm 0.3$	11.4	92.94	[165] ALEXANDER	96	OPAL
$6.2 \pm 3.4 \pm 0.2$		89.52	[169] AKERS	95S	OPAL
$17.2 \pm 2.8 \pm 0.7$		92.94	[169] AKERS	95S	OPAL
$3.8 \pm 6.7 \pm 0.5$		88.24	[174] BUSKULIC	94G	ALEP
$-\ 1.7 \pm 7.6 \pm 0.3$		89.24	[174] BUSKULIC	94G	ALEP
$4.5 \pm 6.0 \pm 0.5$		90.24	[174] BUSKULIC	94G	ALEP
$7.0 \pm 5.5 \pm 0.7$		92.24	[174] BUSKULIC	94G	ALEP
$12.1 \pm 6.9 \pm 1.1$		93.24	[174] BUSKULIC	94G	ALEP
$14.5 \pm 8.1 \pm 1.3$		94.24	[174] BUSKULIC	94G	ALEP
$7.1 \pm 5.4 \pm 0.7$	5.2	89.66	[175] ACTON	93K	OPAL
$9.2 \pm 1.8 \pm 0.8$	8.5	91.24	[175] ACTON	93K	OPAL
$13.1 \pm 4.7 \pm 1.3$	10.8	92.75	[175] ACTON	93K	OPAL
9.3 ± 1.1		91.2	[176] QUAST	93	RVUE
$16.1 \pm 6.0 \pm 2.1$		91.2	[177] ABREU	92H	DLPH
$8.6 \pm 1.5 \pm 0.7$	8.2	91.24	[178] ADRIANI	92D	L3
$2.5 \pm 5.1 \pm 0.7$	5.3	89.67	[179] ADRIANI	92D	L3
$9.7 \pm 1.7 \pm 0.7$	8.2	91.24	[179] ADRIANI	92D	L3
$6.2 \pm 4.2 \pm 0.7$	10.8	92.81	[179] ADRIANI	92D	L3
$-71 \pm34\ ^{+7}_{-8}$	-58	58.3	SHIMONAKA	91	TOPZ
$-22.2 \pm 7.7 \pm 3.5$	-26.0	35	BEHREND	90D	CELL
$-49.1 \pm16.0 \pm 5.0$	-39.7	43	BEHREND	90D	CELL
-28 ± 11	-23	35	BRAUNSCH...	90	TASS
$-16.6 \pm 7.7 \pm 4.8$	-24.3	35	ELSEN	90	JADE
$-33.6 \pm22.2 \pm 5.2$	-39.9	44	ELSEN	90	JADE
$3.4 \pm 7.0 \pm 3.5$	-16.0	29.0	BAND	89	MAC
$-72 \pm28 \pm13$	-56	55.2	SAGAWA	89	AMY

[165] ALEXANDER 96 tag heavy flavors using one or two identified leptons. This allows the simultaneous fitting of the b and c quark forward-backward asymmetries as well as the average B^0-$\overline{B}^0$ mixing.
[166] ABREU 95E require the presence of a $D^{*\pm}$ to identify c and b quarks.
[167] ABREU 95K identify c and b quarks using both electron and muon semileptonic decays. The systematic error includes an uncertainty of ±0.3 due to the mixing correction ($\chi = 0.115 \pm 0.011$).
[168] ABREU 95K tag b quarks using lifetime; the quark charge is identified using jet charge. The systematic error includes an uncertainty of ±0.3 due to the mixing correction ($\chi = 0.115 \pm 0.011$).
[169] AKERS 95S tag b quarks using lifetime; the quark charge is measured using jet charge. These asymmetry values are obtained using $R_b = \Gamma(b\bar{b})/\Gamma(\text{hadrons}) = 0.216$. For a value of R_b different from this by an amount ΔR_b, the change in the asymmetry values is given by $-K\Delta R_b$, where $K = 0.082$, 0.471, and 0.855 for $\sqrt{s}$ values of 89.52, 91.25, and 92.94 GeV respectively.
[170] ACCIARRI 94D use both electron and muon semileptonic decays.
[171] BUSKULIC 94G perform a simultaneous fit to the p and p_T spectra of both single and dilepton events.
[172] BUSKULIC 94I use the lifetime tag method to obtain a high purity sample of $Z \rightarrow b\bar{b}$ events and the hemisphere charge technique to obtain the jet charge.
[173] AKERS 93D identify the b and c decays using D^*.
[174] BUSKULIC 94G perform a high p_T lepton analysis using single- and double-tagged events.
[175] ACTON 93K use the lepton tagging technique. The systematic error includes the uncertainty on the mixing parameter. Replaced by ALEXANDER 96.
[176] QUAST 93 is a combined analysis of LEP results as of Feb. 1993.

[177] B tagging via its semimuonic decay. Experimental value corrected using average LEP B^0-$\overline{B}^0$ mixing parameter $\chi = 0.143 \pm 0.023$.

[178] ADRIANI 92D use both electron and muon semileptonic decays. For this measurement ADRIANI 92D average over all $\sqrt{s}$ values to obtain a single result.

[179] ADRIANI 92D use both electron and muon semileptonic decays. The quoted systematic error is common to all measurements. The peak value is superseded by ACCIARRI 94D.

CHARGE ASYMMETRY IN $e^+e^- \rightarrow q\overline{q}$

Summed over five lighter flavors.

Experimental and Standard Model values are somewhat event-selection dependent. Standard Model expectations contain some assumptions on B^0-$\overline{B}^0$ mixing and on other electroweak parameters.

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.93 ± 0.65		91.2	[180] QUAST	93	RVUE
$-0.76 \pm 0.12 \pm 0.15$		91.2	[181] ABREU	92I	DLPH
$4.0 \pm 0.4 \pm 0.63$	4.0	91.3	[182] ACTON	92L	OPAL
$9.1 \pm 1.4 \pm 1.6$	9.0	57.9	ADACHI	91	TOPZ
$-0.84 \pm 0.15 \pm 0.04$		91	DECAMP	91B	ALEP
$8.3 \pm 2.9 \pm 1.9$	8.7	56.6	STUART	90	AMY
$11.4 \pm 2.2 \pm 2.1$	8.7	57.6	ABE	89L	VNS
6.0 ± 1.3	5.0	34.8	GREENSHAW	89	JADE
8.2 ± 2.9	8.5	43.6	GREENSHAW	89	JADE

[180] QUAST 93 is a combined analysis of LEP results as of Feb. 1993.

[181] ABREU 92I has 0.14 systematic error due to uncertainty of quark fragmentation.

[182] ACTON 92L use the weight function method on 259k selected $Z \rightarrow$ hadrons events. The systematic error includes a contribution of 0.2 due to B^0-$\overline{B}^0$ mixing effect, 0.4 due to Monte Carlo (MC) fragmentation uncertainties and 0.3 due to MC statistics. ACTON 92L derive a value of $\sin^2\theta_W^{\rm eff}$ to be $0.2321 \pm 0.0017 \pm 0.0028$.

CHARGE ASYMMETRY IN $p\overline{p} \rightarrow Z \rightarrow e^+e^-$

ASYMMETRY (%)	STD. MODEL	$\sqrt{s}$ (GeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$5.2 \pm 5.9 \pm 0.4$		91	ABE	91E	CDF

Z REFERENCES

ABREU	96	ZPHY C70 531	+Adam, Adye+	(DELPHI Collab.)
ABREU	96C	PL B379 309	+Adam, Adye+	(DELPHI Collab.)
ACCIARRI	96	PL B371 126	+Adam, Adriani+	(L3 Collab.)
ACCIARRI	96B	PL B370 195	+Adam, Adriani+	(L3 Collab.)
ADAM	96	ZPHY C69 561	+Adye, Agasi+	(DELPHI Collab.)
ADAM	96B	ZPHY C70 371	+Adye, Agasi+	(DELPHI Collab.)
ALEXANDER	96	ZPHY C (submitted) CERN-PPE/95-179	+Allison, Altekamp+	(OPAL Collab.)
ALEXANDER	96B	ZPHY C70 197	+Allison, Altekamp+	(OPAL Collab.)
ALEXANDER	96F	PL B370 185	+Allison, Altekamp+	(OPAL Collab.)
BUSKULIC	96D	ZPHY C69 393	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	96H	ZPHY C69 379	+Casper, De Bonis+	(ALEPH Collab.)
ABE	95J	PRL 74 2880	+Abt, Ahn, Akagi+	(SLD Collab.)
ABE	95K	PRL 74 2890	+Abt, Ahn, Akagi+	(SLD Collab.)
ABE	95L	PRL 74 2895	+Abt, Ahn, Akagi+	(SLD Collab.)
ABE,K	95	PRL 75 3609	+Abt, Ahn, Akagi+	(SLD Collab.)
ABREU	95	ZPHY C65 709 erratum	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95D	ZPHY C66 323	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95E	ZPHY C66 341	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95F	NP B444 3	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95G	ZPHY C67 1	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95I	ZPHY C67 183	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95J	ZPHY C65 555	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95K	ZPHY C65 569	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95L	ZPHY C65 587	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95M	ZPHY C65 603	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ABREU	95O	ZPHY C67 543	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95R	ZPHY C68 353	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95W	PL B361 207	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95X	ZPHY C69 1	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	95B	PL B345 589	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	95C	PL B345 609	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	95G	PL B353 136	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
AKERS	95	ZPHY C65 1	+Alexander, Allison+	(OPAL Collab.)
AKERS	95B	ZPHY C65 17	+Alexander, Allison+	(OPAL Collab.)
AKERS	95C	ZPHY C65 47	+Alexander, Allison+	(OPAL Collab.)
AKERS	95O	ZPHY C67 27	+Alexander, Allison+	(OPAL Collab.)
AKERS	95S	ZPHY C67 365	+Alexander, Allison+	(OPAL Collab.)
AKERS	95U	ZPHY C67 389	+Alexander, Allison+	(OPAL Collab.)
AKERS	95W	ZPHY C67 555	+Alexander, Allison+	(OPAL Collab.)
AKERS	95X	ZPHY C68 1	+Alexander, Allison+	(OPAL Collab.)
AKERS	95Z	ZPHY C68 203	+Alexander, Allison+	(OPAL Collab.)
ALEXANDER	95D	PL B358 162	+Allison, Altekamp+	(OPAL Collab.)
BUSKULIC	95I	PL B352 479	+Casper, De Bonis+	(ALEPH Collab.)
BUSKULIC	95Q	ZPHY C69 183	+Casper, De Bonis+	(ALEPH Collab.)
MIYABAYASHI	95	PL B347 171	+Adachi, Fujii+	(TOPAZ Collab.)
ABE	94C	PRL 73 25	+Abt, Ash, Aston, Bacchetta, Baird+	(SLD Collab.)
ABREU	94	NP B418 403	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	94B	PL B327 386	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	94P	PL B341 109	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACCIARRI	94	ZPHY C62 551	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	94B	PL B328 223	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	94D	PL B335 542	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ACCIARRI	94E	PL B341 245	+Adam, Adriani+	(L3 Collab.)
AKERS	94	ZPHY C61 19	+Alexander, Allison+	(OPAL Collab.)
AKERS	94D	ZPHY C61 357	+Alexander, Allison+	(OPAL Collab.)
AKERS	94P	ZPHY C63 181	+Alexander, Allison+	(OPAL Collab.)
BUSKULIC	94	ZPHY C62 539	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
BUSKULIC	94G	ZPHY C62 179	+Casper, De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	94I	PL B335 99	+Casper, De Bonis+	(ALEPH Collab.)
BUSKULIC	94J	ZPHY C62 1	+De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	94K	ZPHY C64 361	+De Bonis, Decamp+	(ALEPH Collab.)
VILAIN	94	PL B320 203	+Wilquet, Beyer+	(CHARM II Collab.)
ABE	93	PRL 70 2515	+Abt, Acton+	(SLD Collab.)
ABREU	93	PL B298 236	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	93B	PL B298 247	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	93I	ZPHY C59 533	+Adam, Adye, Agasi+	(DELPHI Collab.)
Also	95	ZPHY C65 709 erratum	Abreu, Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	93L	PL B318 249	+Adam, Adami, Adye+	(DELPHI Collab.)
ACTON	93	PL B305 407	+Alexander, Allison+	(OPAL Collab.)
ACTON	93D	ZPHY C58 219	+Alexander, Allison+	(OPAL Collab.)
ACTON	93E	PL B311 391	+Akers, Alexander+	(OPAL Collab.)
ACTON	93F	ZPHY C58 405	+Alexander, Allison+	(OPAL Collab.)
ACTON	93I	ZPHY C58 523	+Alexander, Allison+	(OPAL Collab.)
ACTON	93K	ZPHY C60 19	+Akers, Alexander+	(OPAL Collab.)
ACTON	93M	ZPHY C60 579	+Akers, Alexander+	(OPAL Collab.)
ADRIANI	93	PL B301 136	+Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADRIANI	93E	PL B307 237	+Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADRIANI	93F	PL B309 451	+Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADRIANI	93H	PL B315 494	+Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADRIANI	93I	PL B316 427	+Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADRIANI	93J	PL B317 467	+Aguilar-Benitez, Ahlen, Alcaraz+	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
AKERS	93B	ZPHY C60 199	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
AKERS	93D	ZPHY C60 601	+Alexander, Allison+	(OPAL Collab.)
BUSKULIC	93J	ZPHY C60 71	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
BUSKULIC	93L	PL B313 520	+De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	93M	PL B313 535	+De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	93N	PL B313 549	+De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	93P	ZPHY C59 369	+Decamp, Goy+	(ALEPH Collab.)
LEP	93	PL B307 187	+LEP Energy Group, LEP Collabs	(LEP Collabs.)
NOVIKOV	93C	PL B298 453	+Okun, Vysotsky	(ITEP)
QUAST	93	MPL A8 675		(DESY)
ABREU	92	ZPHY C53 567	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92G	PL B275 231	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92H	PL B276 536	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92I	PL B277 371	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92K	PL B281 383	+Adam, Adami, Adye+	(DELPHI Collab.)
ABREU	92M	PL B289 199	+Adam, Adye, Agasi, Alekseev+	(DELPHI Collab.)
ABREU	92N	ZPHY C55 555	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	92O	PL B295 383	+Adam, Adami, Adye+	(DELPHI Collab.)
ACTON	92B	ZPHY C53 539	+Alexander, Allisson, Allport+	(OPAL Collab.)
ACTON	92J	PL B291 503	+Alexander, Allison, Allport+	(OPAL Collab.)
ACTON	92L	PL B294 436	+Alexander, Allison, Allport+	(OPAL Collab.)
ACTON	92O	ZPHY C56 521	+Alexander, Allison+	(OPAL Collab.)
ADEVA	92	PL B275 209	+Adriani, Aguilar-Benitez+	(L3 Collab.)
ADRIANI	92B	PL B288 404	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
ADRIANI	92D	PL B292 454	+Aguilar-Benitez, Ahlen, Akbari+	(L3 Collab.)
ADRIANI	92E	PL B292 463	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
ALITTI	92B	PL B276 354	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
BUSKULIC	92D	PL B292 210	+Decamp, Goy, Lees+	(ALEPH Collab.)
DECAMP	92	PRPL 216 253	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	92B	ZPHY C53 1	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
LEP	92	PL B276 247	+ALEPH, DELPHI, L3, OPAL	(LEP Collabs.)
ABE	91E	PRL 67 1502	+Amidei, Apollinari+	(CDF Collab.)
ABREU	91H	ZPHY C50 185	+Adam, Adami, Adye+	(DELPHI Collab.)
ACTON	91B	PL B273 338	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ADACHI	91	PL B255 613	+Anazawa, Doser, Enomoto+	(TOPAZ Collab.)
ADEVA	91I	PL B259 199	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
AKRAWY	91F	PL B257 531	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
DECAMP	91B	PL B259 377	+Deschizeaux, Goy+	(ALEPH Collab.)
DECAMP	91J	PL B266 218	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
DECAMP	91K	PL B273 181	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
JACOBSEN	91	PRL 67 3347	+Koetke, Adolphsen, Fujino+	(Mark II Collab.)
SHIMONAKA	91	PL B268 457	+Fujii, Miyamoto+	(TOPAZ Collab.)
ABE	90I	ZPHY C48 13	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ABRAMS	90	PRL 64 1334	+Adolphsen, Averill, Ballam+	(Mark II Collab.)
ADACHI	90F	PL B234 525	+Doser, Enomoto, Fujii+	(TOPAZ Collab.)
AKRAWY	90J	PL B246 285	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
BEHREND	90D	ZPHY C47 333	+Criegee, Field, Franke, Jung+	(CELLO Collab.)
BRAUNSCH...	90	ZPHY C48 433	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
DECAMP	90Q	PL B234 209	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
ELSEN	90	ZPHY C46 349	+Allison, Ambrus, Barlow, Bartel+	(JADE Collab.)
HEGNER	90	ZPHY C46 547	+Naroska, Schroth, Allison+	(JADE Collab.)
KRAL	90	PRL 64 1211	+Abrams, Adolphsen, Averill, Ballam+	(Mark II Collab.)
STUART	90	PRL 64 983	+Breedon, Kim, Ko, Lander, Maeshima+	(AMY Collab.)
ABE	89	PRL 62 613	+Amidei, Apollinari, Ascori, Atac+	(CDF Collab.)
ABE	89C	PRL 63 720	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	89L	PL B232 425	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ABRAMS	89B	PRL 63 2173	+Adolphsen, Averill, Ballam, Barish+	(Mark II Collab.)
ABRAMS	89D	PRL 63 2780	+Adolphsen, Averill, Ballam, Barish+	(Mark II Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BACALA	89	PL B218 112	+Malchow, Sparks, Imlay, Kirk+	(AMY Collab.)
BAND	89	PL B218 369	+Camporesi, Chadwick, Delfino, Desangro+	(MAC Collab.)
GREENSHAW	89	ZPHY C42 1	+Warming, Allison, Ambrus, Barlow+	(JADE Collab.)
MORI	89	PL B218 499	+Nozaki, Blanis, Bodek, Budd+	(AMY Collab.)
OULD-SAADA	89	ZPHY C44 567	+Allison, Ambrus, Barlow, Bartel+	(JADE Collab.)
SAGAWA	89	PRL 63 2341	+Lim, Abe, Fujii, Higashi+	(AMY Collab.)
ADACHI	88C	PL B208 319	+Aihara, Dijkstra, Enomoto, Fujii+	(TOPAZ Collab.)
ADEVA	88	PR D38 2665	+Anderhub, Ansari, Becker+	(Mark-J Collab.)
BRAUNSCH...	88D	ZPHY C40 163	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
ANSARI	87	PL B186 440	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
BEHREND	87C	PL B191 209	+Buerger, Criegee, Dainton+	(CELLO Collab.)
BARTEL	86C	ZPHY C30 371	+Becker, Cords, Felst, Haidt+	(JADE Collab.)
Also	85B	ZPHY C26 507	Bartel, Becker, Bowdery, Cords+	(JADE Collab.)
Also	82	PL 108B 140	Bartel, Cords, Dittmann, Eichler+	(JADE Collab.)
ASH	85	PRL 55 1831	+Band, Blume, Camporesi+	(MAC Collab.)
BARTEL	85F	PL 161B 188	+Becker, Cords, Felst+	(JADE Collab.)
DERRICK	85	PR D31 2352	+Fernandez, Fries, Hyman+	(HRS Collab.)
FERNANDEZ	85	PRL 54 1624	+Ford, Qi, Read+	(MAC Collab.)
LEVI	83	PRL 51 1941	+Blocker, Strait+	(Mark II Collab.)
BEHREND	82	PL 114B 282	+Chen, Fenner, Field+	(CELLO Collab.)
BRANDELIK	82C	PL 110B 173	+Braunschweig, Gather	(TASSO Collab.)

Higgs Bosons — H^0 and $H^\pm$, Searches for

THE HIGGS BOSON

(by I. Hinchliffe, LBNL)

The Standard Model [1] contains one neutral scalar Higgs boson, which is a remnant of the mechanism that breaks the SU(2) × U(1) symmetry and generates the W and Z boson masses. The Higgs couples to quarks and leptons of mass m_f with a strength $gm_f/2M_W$. Its coupling to W and Z bosons is of strength g, where g is the coupling constant of the SU(2) gauge theory. Consequently its coupling to stable matter is very small, and its production and detection in experiments is difficult. An exception is its production in the decay of the Z boson. Since large numbers of Z's can be produced and the coupling of the Z to the Higgs is unsuppressed, experiments at LEP are now able to rule out a significant range of Higgs masses. The branching ratio of the Higgs boson into various final states is shown in Fig. 1.

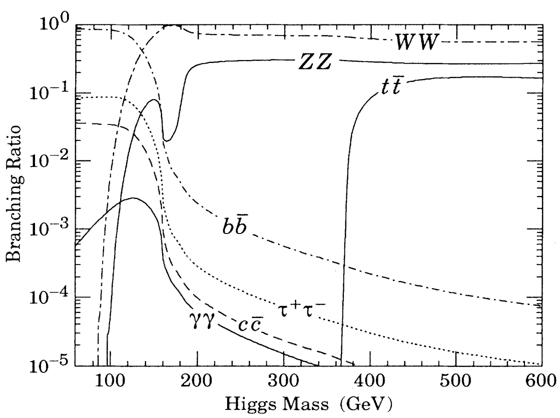


Figure 1: The branching ratio of the Higgs boson into $\gamma\gamma$, $\tau\overline{\tau}$, $b\overline{b}$, $t\overline{t}$, $c\overline{c}$, ZZ, and WW as a function of the Higgs mass. In the latter cases, if $M_H < 2M_Z$ (or $M_H < 2M_W$), the value indicated is the rate to ZZ^* (or WW^*) where Z^* (W^*) denotes a virtual Z (W). The $c\overline{c}$ rate depends sensitively on the poorly-determined charmed quark mass.

If the Higgs mass is very large, the couplings of the Higgs to itself and to longitudinally polarized gauge bosons become large. Requiring that these couplings remain weak enough so that perturbation theory is applicable implies that $M_H \lesssim 1$ TeV [2]. While this is not an absolute bound, it is an indication of the mass scale at which one can no longer speak of an elementary Higgs boson. This fact is made more clear if one notes that the width of the Higgs boson is proportional to the cube of its mass (for $M_H > 2M_Z$) and that a boson of mass 1 TeV has a width of 500 GeV.

It is believed that scalar field theories of the type used to describe Higgs self-interactions can only be effective theories valid over a limited range of energies if the Higgs self-coupling and hence Higgs mass is nonzero. A theory of this type that is valid at all energy scales must have zero coupling. The range of energies over which the interacting theory is valid is a function of the Higgs self-coupling and hence its mass. An upper bound on the Higgs mass can then be determined by requiring that the theory be valid (*i.e.*, have a nonzero value of the renormalized Higgs self-coupling) at all scales up to the Higgs mass [3]. Nonperturbative calculations using lattice [4] gauge theory that can be used to compute at arbitrary values of the Higgs mass indicate that $M_H \lesssim 770$ GeV.

If the Higgs mass were small, then the vacuum (ground) state with the correct value of M_W would cease to be the true ground state of the theory [5]. A theoretical constraint can then be obtained from the requirement that this is not the case, *i.e.*, that our universe is in the true minimum of the Higgs potential. The constraint depends upon the top quark mass and upon the scale (Λ) up to which the Standard Model remains valid. This scale must be at least 1 TeV, resulting in the constraint [7] $M_H > 72$ GeV $+ 0.9$ ($m_{\rm top}$–174 GeV). The bound increases monotonically with the scale, for $\Lambda = 10^{19}$ GeV, $M_H > 135$ GeV $+ 2.1$ ($m_{\rm top}$–174 GeV). This constraint may be too restrictive. Strictly speaking we can only require that the predicted lifetime of our universe, if it is not at the true minimum of the Higgs potential, be longer than its observed age [8,9]. For $\Lambda = 1$ TeV there is no constraint; and for $\Lambda = 10^{19}$ GeV $M_H > 120$ GeV $+ 2.3$ ($m_{\rm top} - 174$ GeV) [10].

Experiments at LEP are able to exclude a large range of Higgs masses. They search for the decay $Z \to HZ^*$. Here Z^* refers to a virtual Z boson that can appear in the detector as e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\overline{\nu}$ (*i.e.*, missing energy) or hadrons. The experimental searches have considered both $H \to$ hadrons and $H \to \tau^+\tau^-$. The best limits are shown in the Particle Listings below.

Precision measurement of electroweak parameters such as M_W and the various asymmetries at LEP and SLC are becoming sensitive enough that they can in principle constrain the Higgs mass through its effect in radiative corrections. Currently, the precision tests allow the entire range from the direct LEP limit ($M_H \gtrsim 60$ GeV) to 1 TeV [11] at 95% confidence level although fits prefer the lower end of this range. The recent determination of the top mass has improved the constraint on M_H. See the article in this volume on the "Standard Model of Electroweak Interactions."

The search range for Higgs bosons will expand shortly when LEP begins operation at higher energy. The process $e^+e^- \to ZH$ [12] should enable neutral Higgs bosons of masses up to ~ 0.97 $(\sqrt{s} - M_Z)$ to be discovered [13]. If the Higgs is heavier than this, its discovery will probably have to wait until experiments at the LHC have data. If the neutral Higgs boson has mass greater than $2M_Z$, it will likely be discovered via its decay to ZZ and the subsequent decay of the Z's to charged leptons (electrons or muons) or of one Z to charged leptons and the other to neutrinos. A challenging region is that between the ultimate limit of LEP and $2M_Z$. At the upper end of this range the decay to a real and a virtual Z, followed by the decay to charged leptons is available. The decay rate of the Higgs boson into this channel falls rapidly as M_H is reduced and becomes too small for $M_H \lesssim 140$ GeV. For masses below this, the decays $H \to \gamma\gamma$ and possibly $H \to b\bar{b}$ [14] are expected to be used. The former has a small branching ratio and large background, the latter has a large branching ratio, larger background and a final state that is difficult to fully reconstruct [15].

Extensions of the Standard Model, such as those based on supersymmetry [16], can have more complicated spectra of Higgs bosons. The simplest extension has two Higgs doublets whose neutral components have vacuum expectation values v_1 and v_2, both of which contribute to the W and Z masses. The physical particle spectrum contains one charged Higgs boson ($H^{\pm}$), two neutral scalars (H_1, H_2),* and one pseudoscalar (A). In the simplest version of the supersymmetric model, the mass the lightest of these scalars depends upon the top quark mass, the ratio v_2/v_1, and the masses of the other supersymmetric particles. For m_t = 174 GeV, there is a bound $M_{H_1} \lesssim 125$ GeV [18,19]. In models where all fermions of the same electric charge receive their masses from only one of the two doublets (v_2 gives mass to the charge 2/3 quarks, while v_1 gives mass to the charged leptons and the charge 1/3 quarks), there are, as in the Standard Model, no flavor-changing neutral currents at lowest order in perturbation theory. The H_1, H_2^0, and A couplings to fermions depend on v_2/v_1 and are either enhanced or suppressed relative to the couplings in the Standard Model. Experiments at LEP are able to exclude ranges of masses for neutral Higgs particles in these models. These ranges depend on the values of v_2/v_1. See the Particle Listings below on H_1^0, Mass Limits in Supersymmetric Models.

Charged Higgs bosons can be pair produced in e^+e^- annihilation. Searches for charged Higgs bosons depend on the assumed branching fractions to $\nu\tau$, $c\bar{s}$, and $c\bar{b}$. Data from LEP now exclude charged Higgs bosons of mass less than 43.5 GeV [20]. See the Particle Listings for details of the $H^{\pm}$ Mass Limit.

A charged Higgs boson could be produced in the decay of a top quark, $t \to H^+ b$. Searches for this decay at hadron colliders should be possible [21].

Notes and References

*H_1 and H_2 are usually called h and H in the literature.

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H^0 (Higgs Boson) MASS LIMITS

These limits apply to the Higgs boson of the three-generation Standard Model with the minimal Higgs sector. Limits that depend on the $Ht\bar{t}$ coupling may also apply to a Higgs boson of an extended Higgs sector whose couplings to up-type quarks are comparable to or larger than those of the standard one-doublet model H^0 couplings.

For comprehensive reviews, see Gunion, Haber, Kane, and Dawson, "The Higgs Hunter's Guide," (Addison-Wesley, Menlo Park, CA, 1990) and R.N. Cahn, Reports on Progress in Physics **52** 389 (1989). For a review of theoretical bounds on the Higgs mass, see M. Sher, Physics Reports (Physics Letters C) **179** 273 (1989).

Limits from Coupling to $Z/W^{\pm}$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>55.7	95	[1] ABREU	94G	DLPH	$Z \to H^0 Z^*$
>56.9	95	[2] AKERS	94B	OPAL	$Z \to H^0 Z^*$
>57.7	95	[3] ADRIANI	93C	L3	$Z \to H^0 Z^*$
>58.4	95	[4] BUSKULIC	93H	ALEP	$Z \to H^0 Z^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>60	95	[5] GROSS	93	RVUE	$Z \to H^0 Z^*$
		[6] ABREU	92D	DLPH	$Z \to H^0 \gamma$
>38	95	[7] ABREU	92J	DLPH	$Z \to H^0 Z^*$
>52	95	[8] ADEVA	92B	L3	$Z \to H^0 Z^*$
		[9] ADRIANI	92F	L3	$Z \to H^0 \gamma$
>48	95	[10] DECAMP	92	ALEP	$Z \to H^0 Z^*$
> 0.21	99	[11] ABREU	91B	DLPH	$Z \to H^0 Z^*$
>11.3	95	[12] ACTON	91	OPAL	$H^0 \to$ anything
>41.8	95	[13] ADEVA	91	L3	$Z \to H^0 Z^*$
		[14] ADEVA	91D	L3	$Z \to H^0 \gamma$
none 3–44	95	[15] AKRAWY	91	OPAL	$Z \to H^0 Z^*$
none 3–25.3	95	[16] AKRAWY	91C	OPAL	$Z \to H^0 Z^*$
none 0.21–0.818	90	[17] ABE	90E	CDF	$p\bar{p} \to (W^{\pm}, Z) + H^0 + X$
none 0.846–0.987	90	[17] ABE	90E	CDF	$p\bar{p} \to (W^{\pm}, Z) + H^0 + X$
none 0.21–14	95	[18] ABREU	90C	DLPH	$Z \to H^0 Z^*$
none 2–32	95	[19] ADEVA	90H	L3	$Z \to H^0 Z^*$
> 2	99	[20] ADEVA	90N	L3	$Z \to H^0 Z^*$
none 3.0–19.3	95	[21] AKRAWY	90C	OPAL	$Z \to H^0 Z^*$
> 0.21	95	[22] AKRAWY	90P	OPAL	$Z \to H^0 Z^*$
none 0.032–15	95	[23] DECAMP	90	ALEP	$Z \to H^0 Z^*$
none 11–24	95	[24] DECAMP	90H	ALEP	$Z \to H^0 Z^*$
> 0.057	95	[25] DECAMP	90M	ALEP	$Z \to H^0 ee, H^0 \mu\mu$
none 11–41.6	95	[26] DECAMP	90N	ALEP	$Z \to H^0 Z^*$

[1] ABREU 94G searched for $Z \to H^0 + (e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \nu\bar{\nu})$ with $H^0 \to q\bar{q}$. Four $\ell^+\ell^-$ candidates were found (all yielding low mass) consistent with expected backgrounds.

[2] AKERS 94B searched for $Z \to H^0 + (e^+e^-, \mu^+\mu^-, \nu\bar{\nu})$ with $H^0 \to q\bar{q}$. One $\nu\bar{\nu}$ and one $\mu^+\mu^-$ candidate were found consistent with expected backgrounds.

[3] ADRIANI 93C searched for $Z \to H^0 + (\nu\bar{\nu}, e^+e^-, \mu^+\mu^-)$ with H^0 decaying hadronically or to $\tau\bar{\tau}$. Two e^+e^- and one $\mu^+\mu^-$ candidates are found consistent with expected background.

[4] BUSKULIC 93H searched for $Z \to H^0\nu\bar{\nu}$ (acoplanar jets) and $Z \to H^0 + (e^+e^-, \mu^+\mu^-)$ (lepton pairs in hadronic events).

[5] GROSS 93 combine data taken by four LEP experiments through 1991.

[6] ABREU 92D give $\sigma(e^+e^- \to Z \to H^0\gamma)\cdot B(H^0 \to \text{hadrons}) < 8$ pb (95% CL) for $m_{H^0} < 75$ GeV and $E_\gamma > 8$ GeV.

[7] ABREU 92J searched for $Z \to H^0 + (ee, \mu\mu, \tau\tau, \nu\bar{\nu})$ with $H^0 \to q\bar{q}$. Only one candidate was found, in the channel ee + 2jets, with a dijet mass 35.4 ± 5 GeV/c^2, consistent with the expected background of 1.0 ± 0.2 events in the 3 channels e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, and of 2.8 ± 1.3 events in all 4 channels. This paper excludes 12–38 GeV. The range 0–12 GeV is eliminated by combining with the analyses of ABREU 90C and ABREU 91B.

[8] ADEVA 92B searched for $Z \to H^0 + (\nu\bar{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \to$ anything, $Z \to H^0 + \tau\tau$ with $H^0 \to q\bar{q}$, and $Z \to H^0 + q\bar{q}$ with $H^0 \to \tau\tau$. The analysis excludes the range $30 < m_{H^0} < 52$ GeV.

[9] ADRIANI 92F give $\sigma(e^+e^- \to Z \to H^0\gamma)\cdot B(H^0 \to \text{hadrons}) < (2\text{–}10)$ pb (95% CL) for $m_{\chi^0} = 25\text{–}85$ GeV. Using $\sigma(e^+e^- \to Z) = 30$ nb, we obtain $B(Z \to H^0\gamma)B(H^0 \to \text{hadrons}) < (0.7\text{–}3) \times 10^{-4}$ (95% CL).

[10] DECAMP 92 searched for most possible final states for $Z \to H^0 Z^*$.

[11] ABREU 91B searched for $Z \to H^0 + \ell\bar{\ell}$ with missing H^0 and $Z \to H^0 + (\nu\bar{\nu}, \ell\bar{\ell}, q\bar{q})$ with $H^0 \to ee$.

[12] ACTON 91 searched for $e^+e^- \to Z^* H^0$ where $Z^* \to e^+e^-, \mu^+\mu^-$, or $\nu\bar{\nu}$ and $H^0 \to$ anything. Without assuming the minimal Standard Model mass-lifetime relationship, the limit is $m_{H^0} > 9.5$ GeV.

[13] ADEVA 91 searched for $Z \to H^0 + (\mu\mu, ee, \nu\bar{\nu})$. This paper only excludes $15 < m_{H^0} < 41.8$ GeV. The 0–15 GeV range is excluded by combining with the analyses of previous L3 papers.

[14] ADEVA 91D obtain a limit $B(Z \to H^0\gamma)\cdot B(H^0 \to \text{hadrons}) < 4.7 \times 10^{-4}$ (95%CL) for $m_{H^0} = 30\text{–}86$ GeV. The limit is not sensitive enough to exclude a standard H^0.

[15] AKRAWY 91 searched for the channels $Z \to H^0 + (\nu\bar{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \to q\bar{q}, \tau\tau$, and $Z \to H^0 q\bar{q}$ with $H^0 \to \tau\tau$.

[16] AKRAWY 91C searched the decay channels $Z \to H^0 + (\nu\bar{\nu}, ee, \mu\mu)$ with $H^0 \to q\bar{q}$.

[17] ABE 90E looked for associated production of H^0 with $W^{\pm}$ or Z in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. Searched for H^0 decays into $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^-. Most of the excluded region is also excluded at 95% CL.

[18] ABREU 90C searched for the channels $Z \to H^0 + (\nu\bar{\nu}, ee, \mu\mu)$ and $H^0 + q\bar{q}$ for $m_H < 1$ GeV.

[19] ADEVA 90H searched for $Z \to H^0 + (\mu\mu, ee, \nu\bar{\nu})$.

[20] ADEVA 90N looked for $Z \to H^0 + (ee, \mu\mu)$ with missing H^0 and with $H^0 \to ee, \mu\mu, \pi^+\pi^-, K^+K^-$.

[21] AKRAWY 90C based on 825 nb^{-1}. The decay $Z \to H^0\nu\bar{\nu}$ with $H^0 \to \tau\bar{\tau}$ or $q\bar{q}$ provides the most powerful search means, but the quoted results sum all channels.

[22] AKRAWY 90P looked for $Z \to H^0 + (ee, \mu\mu)$ (H^0 missing) and $Z \to H^0\nu\bar{\nu}$, $H^0 \to e^+e^-, \gamma\gamma$.

[23] DECAMP 90 limits based on 11,550 Z events. They searched for $Z \to H^0 + (\nu\bar{\nu}, ee, \mu\mu, \tau\tau, q\bar{q})$. The decay $Z \to H^0\nu\bar{\nu}$ provides the most powerful search means, but the quoted results sum all channels. Different analysis methods are used for $m_{H^0} < 2m_\mu$ where Higgs would be long-lived. The 99% confidence limits exclude $m_{H^0} = 0.040\text{–}12$ GeV.

[24] DECAMP 90H limits based on 25,000 $Z \to$ hadron events.

[25] DECAMP 90M looked for $Z \to H^0\ell\ell$, where H^0 decays outside the detector.

[26] DECAMP 90N searched for the channels $Z \to H^0 + (\nu\bar{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \to$ (hadrons,$\tau\tau$).

Limits from Other Techniques

H^0 Indirect Mass Limits from Electroweak Analysis

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
63^{+97}_{-0}		[27] CHANKOWSKI	95	RVUE	
<730	95	[28] ERLER	95	RVUE	
<740	95	[29] MATSUMOTO	95	RVUE	
35^{+205}_{-26}		[30] ELLIS	94	RVUE	
45^{+95}_{-28}		[31] ELLIS	94B	RVUE	
69^{+188}_{-9}		[32] GURTU	94	RVUE	
		[33] MONTAGNA	94	RVUE	
73^{+178}_{-13}		[34] BLONDEL	93	RVUE	
10^{+25}_{-8}		[35] ELLIS	93B	RVUE	
10^{+60}_{-8}		[36] NOVIKOV	93B	RVUE	
		[37] DELAGUILA	92B	RVUE	
> 1.4	68	[38] ELLIS	92	RVUE	Electroweak
25^{+275}_{-19}		[39] ELLIS	92E	RVUE	
50^{+353}_{-0}		[40] RENTON	92	RVUE	
		[41] SCHAILE	92	RVUE	

[27] CHANKOWSKI 95 fit to LEP, SLD, and W mass data available in the spring of 1995 plus $m_t = 176 \pm 13$ GeV. Exclusion of the SLD data increases the mass to $m_H = 121^{+207}_{-58}$ GeV ($m_H < 800$ GeV at 95% CL).

[28] ERLER 95 fit to LEP, SLC, W mass, and various low-energy data available in the summer of 1994 plus $m_t = 174 \pm 16$ GeV from CDF. The limit without m_t is 880 GeV. However, the preference for lighter m_H is due to R_b and A_{LR}, both of which do not agree well with the Standard Model prediction.

[29] MATSUMOTO 95 fit to LEP, SLD, W mass, and various neutral current data available in the summer of 1994 plus $m_t = 180 \pm 13$ GeV from CDF/DØ, and the LEP direct limit $m_H > 63$ GeV. $\alpha_s(m_Z) = 0.124$ is used. Fixing $\alpha_s(m_Z) = 0.116$ lowers the upper limit to 440 GeV. Dependence on $\alpha(m_Z)$ is given in the paper.

[30] ELLIS 94 fit to LEP, SLD, W-mass, and neutrino data available in the summer of 1993. The fit to m_H, m_t, and α_s yields $m_t = 140^{+21}_{-22}$ GeV and $\alpha_s(m_Z) = 0.116^{+0.007}_{-0.006}$.

[31] ELLIS 94B fit to LEP, SLD, W mass, neutral current data available in the spring of 1994 plus $m_t = 167 \pm 12$ GeV determined from CDF/DØ $t\bar{t}$ direct searches. $\alpha_s(m_Z) = 0.118 \pm 0.007$ is used. The fit yields $m_t = 162 \pm 9$ GeV. A fit without the SLD data gives $m_H = 130^{+320}_{-90}$ GeV.

[32] GURTU 94 fit to LEP, SLD, W mass, neutral current data available in the spring of 1994 as well as $m_t = 174 \pm 16$ GeV. A fit without $\Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ gives $m_H = 120^{+364}_{-60}$ GeV.

[33] MONTAGNA 94 fit to LEP and SLD, W-mass data together with $m_t = 174 \pm 17$ GeV. Although the data favor smaller Higgs masses, the authors do not regard it significant.

[34] BLONDEL 93 perform two dimensional ($m_t - m_H$) fit to LEP electroweak data available in the spring of 1993. $\alpha_s = 0.117 \pm 0.005$ is used and $m_t > 108$ GeV, $m_H > 62.5$ GeV imposed. $m_{H^0} = 1$ TeV is compatible with the data within two standard deviations.

[35] ELLIS 93B fit to LEP and neutrino data available in the summer of 1993. m_t is adjusted to minimize χ^2 and $\alpha_s(m_Z) = 0.123 \pm 0.006$ is used. 95% CL limit for $m_H < 250$ GeV is claimed.

[36] NOVIKOV 93B use a subset of the most accurate and "gluon-free" data available in the spring of 1993. They use m_W, $\Gamma(\ell\ell)$, and $A^{\ell\ell}_{FB}$.

[37] DELAGUILA 92B perform two dimensional ($m_t - m_H$) fit to various LEP, neutrino, eH, and $p\bar{p}$ data available through 1991 with direct limits on m_t, m_H. The result $m_H = 65^{+245}_{-4}$ is not expected from the statistical sensitivity of the data but due to deviation of the data from the Standard Model expectation.

[38] ELLIS 92 result is from a fit to electroweak data from LEP and elsewhere. They also find $m_H < 160$ GeV at 68%CL and $0.5 < m_H < 1500$ GeV at 90%CL with m_t unconstrained.

[39] ELLIS 92E perform fit to electroweak data available in the spring of 1992. m_t is adjusted to minimize χ^2 and $\alpha_s(m_Z) = 0.118 \pm 0.008$ is used.

[40] RENTON 92 use electroweak data available in 1991 and require $m_H > 50$ GeV. The constraint $\alpha_s = 0.114 \pm 0.007$ was used.

[41] SCHAILE 92 performs fit to LEP electroweak data (as of summer 1991) as well as m_W (UA2/CDF) and νN (CDHS/CHARM). The fit with the constraint $m_H > 50$ GeV gives $m_H = 50^{+192}_{-0}$ GeV. However, the m_H dependence of the χ^2 is not consistent from that expected from the present statistics and the sensitivity to m_H arises from the fact that the measured values of g_A and A^b_{FB} deviate from the Standard Model expectation. Therefore, the result is not considered to be significant.

From Other Techniques

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[42] CASAS	95	THEO	Vacuum stability
		[43] ESPINOSA	95B	THEO	Vacuum metastability
		[44] ALTARELLI	94	THEO	Vacuum stability
none 0.001–0.072	95	[45] BARABASH	92	BDMP	$\eta' \to \eta H^0$
none 0.0012–0.052	90	DAVIER	89	BDMP	$e^- Z \to e H^0 Z$ ($H^0 \to e^+ e^-$)
none 0.010–0.10	90	[46] EGLI	89	CNTR	$\pi^+ \to e^+ \nu H^0$ ($H^0 \to e^+ e^-$)
		[47] LINDNER	89	THEO	Vacuum stability
none 0.015–0.04	90	[48] YEPES	89	RVUE	$\pi^\pm \to e^\pm \nu H^0$ ($H^0 \to e^+ e^-$)
		[49] DZHELYADIN	81		$\eta' \to \eta H^0$ ($H^0 \to \mu^+ \mu^-$)
		[50] WITTEN	81	COSM	
		[50] GUTH	80	COSM	
		[50] SHER	80	COSM	

[42] CASAS 95 require stability of the vacuum in the *minimal* Standard Model up to the scale Λ and find $m_H > 127.9 + 1.92(m_t - 174) - 4.25(\alpha_s(m_Z) - 0.124)/0.0006$ (units in GeV) for $\Lambda = 10^{19}$ GeV, and $m_H > 52$ GeV for $\Lambda = 1$ TeV, $m_t = 174$ GeV, $\alpha_s(m_Z) = 0.124$.

[43] ESPINOSA 95B require metastability of the vacuum in the *minimal* Standard Model up to the scale Λ and find $m_H > [2.278 - 4.654(\alpha_s(m_Z) - 0.124)]m_t - 277$ GeV for $\Lambda = 10^{19}$ GeV.

[44] ALTARELLI 94 require the stability of the vacuum in the *minimal* Standard Model and find $m_H > 72$ (135) GeV for the cut-off scale $\Lambda = 1$ TeV (10^{19} GeV), if $m_t = 174$ GeV and $\alpha_s(m_Z) = 0.118$. See paper for m_t, α_s, and Λ dependence of the result.

[45] BARABASH 92 is a beam dump experiment that searched for $H^0 \to e^+e^-$ and $\gamma\gamma$ produced via the decays $\pi \to e\nu_e H^0$, $K \to e\nu_e H^0$, $K \to \pi H^0$, and $\eta' \to \eta H^0$. The last process gives the best limit if the theoretical calculation by RUSKOV 87 is used.

[46] EGLI 89 give a limit for $B(\pi^+ \to e^+\nu H^0)\cdot B(H^0 \to e^+e^-)$ ranging from 10^{-9} to 10^{-11} for the mass range 10–110 MeV. The theoretical prediction they use is too large by a factor of 162/49 (see DAWSON 89, DAWSON 90, and CHENG 89). The lower limit given above is reevaluated by us.

[47] LINDNER 89 require vacuum stability and numerically solve the renormalization equations to two-loop order. If $m_{top} = 100, 110, 120$ GeV, then $m_{Higgs} > 20, 34, 50$ GeV. However, it is possible that the vacuum is not stable but is very long-lived.

[48] YEPES 89 reanalyzed a BNL beam-dump experiment (JACQUES 80) which looked for electron pairs in 7 foot BC downstream from the dump and found none.

[49] DZHELYADIN 81 obtained $B(\eta' \to \eta\mu^+\mu^-) < 1.5 \times 10^{-5}$ (CL = 90%), and argued that it excludes H^0 with the standard one-doublet-model couplings in $\mu^+\mu^-$ channel for $m_{H^0} = 0.25$–0.409 GeV. However, the number 0.409 is not well-determined due to theoretical uncertainties in $B(H^0 \to \mu^+\mu^-)$.

[50] Limits from cosmological considerations of SU(2)×U(1) symmetry-breaking phase transition occurring only after extreme supercooling, resulting in too high a ratio of entropy to baryon number. Limits apply to the standard one-doublet model H^0, with 'zero bare mass' whose physical mass is determined by the Coleman-Weinberg mechanism of dynamical symmetry breakdown. These limits depend on the mass of the top quark approximately according to $m_{H^0} > 10.4[1 - 4m_t^4/(2m_W^4 + m_Z^4)]^{1/2}$ GeV when $m_t < 80$ GeV. So for $m_t \approx 80$ GeV, there is no limit. If $m_t > 80$ GeV, then vacuum stability arguments may give bounds on m_H, see LINDNER 89 above.

H^0 (Higgs Boson) MASS LIMITS in Extended Higgs Models

The parameter x denotes the Higgs coupling to charge $-1/3$ quarks and charged leptons relative to the value in the standard one-Higgs-doublet model.

In order to prevent flavor-changing neutral currents in models with more than one Higgs doublet, only one of the Higgs doublets can couple to quarks of charge 2/3. The same requirement applies independently to charge $-1/3$ quarks and to leptons. Higgs couplings can be enhanced or suppressed.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[51] ABREU	95H	DLPH	$Z \to H^0 Z^*$, $H^0 A^0$
		[52] BRAHMACH...	93	RVUE	
		[53] BUSKULIC	93I	ALEP	$Z \to H^0 Z^*$
>65	95	[54] BUSKULIC	93I	ALEP	Invisible H^0
		[55] LOPEZ-FERN...	93	RVUE	
		[56] ADRIANI	92G	L3	$Z \to H^0 Z^*$
		[57] PICH	92	RVUE	Very light Higgs
> 3.57	95	[58] ACTON	91	OPAL	$Z \to H^0 Z^*$
		[59] DECAMP	91F	ALEP	$Z \to H^0 \ell^+ \ell^-$
		[60] DECAMP	91I	ALEP	Z decay
> 0.21	95	[61] AKRAWY	90P	OPAL	$Z \to H^0 Z^*$
		[62] DAVIER	89	BDMP	$e^- Z \to e H^0 Z$ ($H^0 \to e^+ e^-$)
		[63] SNYDER	89	MRK2	$B \to H^0 X$ ($H^0 \to e^+ e^-$)
none 0.6–6.2	90	[64] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=2
none 0.6–7.9	90	[64] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=4
none 3.7–5.6	90	[65] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=2
none 3.7–8.2	90	[65] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=4

[51] See Fig. 4 of ABREU 95H for the excluded region in the $m_{H^0} - m_{A^0}$ plane for general two-doublet models. For $\tan\beta > 1$, the region $m_{H^0} + m_{A^0} \lesssim 87$ GeV, $m_{H^0} < 47$ GeV is excluded at 95% CL.

[52] BRAHMACHARI 93 consider Higgs limit from Z decay when the Higgs decays to invisible modes. If H^0 coupling to Z is at least $1/\sqrt{2}$ of the Standard Model H^0, the DECAMP 92 limit of 48 GeV changes within ± 6 GeV for arbitrary $B(H^0 \to$ SM-like$) + B(H^0 \to$ invisible$) = 1$.

[53] See Fig. 1 of BUSKULIC 93I for the limit on ZZH^0 coupling for a general Higgs having a similar decay signature to Standard Model Higgs boson or decaying invisibly. If the decay rate for $Z \to H^0 Z^*$ is >10% of the minimal Standard Model rate, then $m_{H^0} > 40$ GeV. For the standard rate the limit is 58 GeV.

[54] BUSKULIC 93I limit for H^0 with the standard coupling to Z but decaying to weakly interacting particles.

[55] LOPEZ-FERNANDEZ 93 consider Higgs limit from Z decay when the Higgs decays to invisible modes. See Fig. 2 for excluded region in m_{H^0}-ZZH coupling plane with arbitrary $B(H^0 \to$ SM-like$) + B(H^0 \to$ invisible$) = 1$. $m_H > 50$ GeV is obtained if the H^0 coupling strength to the Z is greater than 0.2 times the Standard Model rate.

[56] See Fig. 1 of ADRIANI 92G for the limit on ZZH^0 coupling for a general Higgs having a similar decay signature to Standard Model Higgs boson. For most masses below 30 GeV, the rate for $Z \to H^0_1 Z^*$ is less than 10% of the Standard Model rate.

[57] PICH 92 analyse H^0 with $m_{H^0} < 2m_\mu$ in general two-doublet models. Excluded regions in the space of mass-mixing angles from LEP, beam dump, and $\pi^\pm$, η rare decays are shown in Figs. 3,4. The considered mass region is not totally excluded.

[58] ACTON 91 limit is valid for any H^0 having $\Gamma(Z \to H^0 Z^*)$ more than 0.24 (0.56) times that for the standard Higgs boson for Higgs masses below $2m_\mu$ ($2m_\tau$).

[59] DECAMP 91F search for $Z \to H^0 \ell^+ \ell^-$ where H^0 escapes before decaying. Combining this with DECAMP 90M and DECAMP 90N, they obtain $B(Z \to H^0 \ell^+ \ell^-)/B(Z \to \ell^+ \ell^-) < 2.5 \times 10^{-3}$ (95%CL) for $m_{H^0} < 60$ GeV.

[60] See Figs. 1, 3, 4, 5 of DECAMP 91I for excluded regions for the masses and mixing angles in general two-doublet models.

[61] AKRAWY 90P limit is valid for any H^0 having $\Gamma(Z \to H^0 Z^*)$ more than 0.57 times that for the Standard Higgs boson.

[62] DAVIER 89 give excluded region in m_{H^0}-x plane for m_{H^0} ranging from 1.2 MeV to 50 MeV.

[63] SNYDER 89 give limits on $B(B \to H^0 X)\cdot B(H^0 \to e^+e^-)$ for $100 < m_{H^0} < 200$ MeV, $c\tau < 24$ mm.

[64] First order QCD correction included with $\alpha_s \approx 0.2$. Their figure 4 shows the limits vs. x.

[65] ALBRECHT 85J found no mono-energetic photons in both $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays in the range 0.5 GeV $< E(\gamma) < 4.0$ GeV with typically BR< 0.01 for $\Upsilon(1S)$ and BR< 0.02 for $\Upsilon(2S)$ at 90% CL. These upper limits are 5–10 times the prediction of the standard Higgs-doublet model. The quoted 90% limit $B(\Upsilon(1S) \to H^0\gamma) < 1.5 \times 10^{-3}$ at $E(\gamma) = 1.07$ GeV contradicts previous Crystal Ball observation of $(4.7 \pm 1.1) \times 10^{-3}$; see their reference 3. Their figure 8a shows the upper limits of x^2 as a function of $E(\gamma)$ by assuming no QCD corrections. We used $m_{H^0} = m_\Upsilon (1 - 2E(\gamma)/m_\Upsilon)^{1/2}$.

H^0_1 (Higgs Boson) MASS LIMITS in Supersymmetric Models

The minimal supersymmetric model has two complex doublets of Higgs bosons. The resulting physical states are two scalars [H^0_1 and H^0_2, where we define $m_{H^0_1} < m_{H^0_2}$], a pseudoscalar (A^0), and a charged Higgs pair ($H^\pm$). H^0_1 and H^0_2 are also called h and H in the literature. There are two free parameters in the theory which can be chosen to be m_{A^0} and $\tan\beta = \nu_2/\nu_1$, the ratio of vacuum expectation values of the two Higgs doublets. Tree-level Higgs masses are constrained by the model to be $m_{H^0_1} \leq m_Z$, $m_{H^0_2} \geq m_Z$, $m_{A^0} \geq m_{H^0_1}$, and $m_{H^\pm} \geq m_W$. However, as described in the "Note on Supersymmetry," recent calculations of one-loop radiative corrections show that these relations may be violated. Many experimental analyses have not taken into account these corrections; footnotes indicate when these corrections are included. The results assume no invisible H^0 or A^0 decays.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>44	95	[66] ABREU	95H	DLPH	any $\tan\beta$
>44.5	95	[67] AKERS	94I	OPAL	$\tan\beta > 1$
>44	95	[68] BUSKULIC	93I	ALEP	$\tan\beta > 1$
>42	95	[69] ADRIANI	92G	L3	$1 < \tan\beta < 50$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[70] ROSIEK	95	RVUE	
>44.4	95	[71] ABREU	94O	DLPH	$m_{H^0_1} = m_{A^0}$, any $\tan\beta$
>34	95	[72] ABREU	92J	DLPH	$\tan\beta > 0.6$
>29	95	[72] ABREU	92J	DLPH	any $\tan\beta$
> 0.21	95	[73] ABREU	91B	DLPH	any $\tan\beta$
>28	95	[74] ABREU	91B	DLPH	any $\tan\beta$

none 3–38	95	[75] AKRAWY	91C	OPAL	$\tan\beta > 6$
none 3–22	95	[75] AKRAWY	91C	OPAL	$\tan\beta > 0.5$
		[76] BLUEMLEIN	91	BDMP	$pN \to H_1^0 X$ ($H_1^0 \to e^+e^-$, 2γ)
>41	95	[77] DECAMP	91I	ALEP	$\tan\beta > 1$
> 9	95	[78] ABREU	90E	DLPH	any $\tan\beta$
>13	95	[78] ABREU	90E	DLPH	$\tan\beta > 1$
>26	95	[79] ADEVA	90R	L3	$\tan\beta > 1$
none 0.05–3.1	95	[80] DECAMP	90E	ALEP	any $\tan\beta$
none 0.05–13	95	[80] DECAMP	90E	ALEP	$\tan\beta > 0.6$
none 0.006–20	95	[80] DECAMP	90E	ALEP	$\tan\beta > 2$
>37.1	95	[80] DECAMP	90E	ALEP	$\tan\beta > 6$
none 0.05–20	95	[81] DECAMP	90H	ALEP	$\tan\beta > 0.6$
none 0.006–21.4	95	[81] DECAMP	90H	ALEP	$\tan\beta > 2$
> 3.1	95	[82] DECAMP	90M	ALEP	any $\tan\beta$

[66] ABREU 95H search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$. Two-loop corrections are included with m_t=170 GeV, $m_{\tilde{t}}$=1 TeV. Including only one-loop corrections does not change the limit.

[67] AKERS 94I search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$. One-loop corrections are included with m_t <200 GeV, $m_{\tilde{t}}$ <1 TeV. See Fig. 10 for limits for $\tan\beta$ <1.

[68] BUSKULIC 93I search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$. One-loop corrections are included with any m_t, $m_{\tilde{t}} > m_t$.

[69] ADRIANI 92G search for $Z \to H_1^0 Z^*$, $Z \to H_1^0 A^0 \to 4b$, $bb\tau\tau$, 4τ, $6b$ (via $H^0 \to A^0 A^0$), and include constraints from $\Gamma(Z)$. One-loop corrections to the Higgs potential are included with 90<m_t <250 GeV, $m_t < m_{\tilde{t}}$ <1 TeV.

[70] ROSIEK 95 study the dependence of $m_{H_1^0}$ limit on various supersymmetry parameters. They argue that H_1^0 as light as 25 GeV is not excluded by ADRIANI 92G data in the region $m_{A^0} \sim 60$ GeV if $m_{\tilde{t}} \lesssim 200$ GeV and $\tilde{t}_L$-$\tilde{t}_R$ mixing is large.

[71] ABREU 94O study $H_1^0 A^0 \to$ four jets and combine with ABREU 94G analysis. The limit applies if the H_1^0-A^0 mass difference is <4 GeV.

[72] ABREU 92J searched for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$ with $H_1^0, A^0 \to \tau\tau$ or jet-jet. Small mass values are excluded by ABREU 91B.

[73] ABREU 91B result is based on negative search for $Z \to H_1^0 f\bar{f}$ and the limit on invisible Z width $\Gamma(Z \to H_1^0 A^0) < 39$ MeV (95%CL), assuming $m_{A^0} < m_{H_1^0}$.

[74] ABREU 91B result obtained by combining with analysis of ABREU 90I.

[75] AKRAWY 91C result from $Z \to H_1^0 A^0 \to$ 4jet or $\tau^+\tau^- jj$ or 4τ and $Z \to H_1^0 Z^*$ ($H_1^0 \to q\bar{q}$, $Z^* \to \nu\bar{\nu}$ or e^+e^- or $\mu^+\mu^-$). See paper for the excluded region for the case $\tan\beta < 1$. Although these limits do not take into account the one-loop radiative corrections, the authors have reported unpublished results including these corrections and showed that the excluded region becomes larger.

[76] BLUEMLEIN 91 excluded certain range of $\tan\beta$ for $m_{H_1^0} < 120$ MeV, $m_{A^0} < 80$ MeV.

[77] DECAMP 91I searched for $Z \to H_1^0 Z^*$, and $Z \to H_1^0 A^0 \to$ 4jets or $\tau\tau jj$ or $3A^0$. Their limits take into account the one-loop radiative corrections to the Higgs potential with varied top and squark masses.

[78] ABREU 90E searched for $Z \to H_1^0 A^0$ and $Z \to H_1^0 Z^*$. $m_{H_1^0} < 210$ MeV is not excluded by this analysis.

[79] ADEVA 90R result is from $Z \to H_1^0 A^0 \to$ 4jet or $\tau\tau jj$ or 4τ and $Z \to H_1^0 Z^*$. Some region of $m_{H_1^0} < 4$ GeV is not excluded by this analysis.

[80] DECAMP 90E look for $Z \to H_1^0 A^0$ as well as $Z \to H_1^0 \ell^+\ell^-$, $Z \to H_1^0 \nu\bar{\nu}$ with 18610 Z decays. Their search includes signatures in which H_1^0 and A^0 decay to $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, or $q\bar{q}$. See their figures of $m_{H_1^0}$ vs. $\tan\beta$.

[81] DECAMP 90H is similar to DECAMP 90E but with 25,000 Z decays.

[82] DECAMP 90M looked for $Z \to H^0 \ell\ell$, where H_1^0 decays outside the detector. This excludes a region in the ($m_{H_1^0}$, $\tan\beta$) plane centered at $m_{H_1^0}$ = 50 MeV, $\tan\beta$ = 0.5. This limit together with DECAMP 90E result excludes $m_{H_1^0}$ < 3 GeV for any $\tan\beta$.

A^0 (Pseudoscalar Higgs Boson) MASS LIMITS in Supersymmetric Models

Limits on the A^0 mass from e^+e^- collisions arise from direct searches in the $e^+e^- \to A^0 H_1^0$ channel and indirectly from the relations valid in the minimal supersymmetric model between m_{A^0} and $m_{H_1^0}$. As discussed in the "Note on Supersymmetry," at the one-loop level and in the simplest cases, these relations depend on the masses of the t quark and $\tilde{t}$ squarks. The limits are weaker for larger t and $\tilde{t}$ masses, while they increase with the inclusion of two-loop radiative corrections. Some specific examples of these dependences are provided in the footnotes to the listed papers.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>27	95	[83] ABREU	95H	DLPH	$\tan\beta$ >1, m_t = 170 GeV
>24.3	95	[84] AKERS	94I	OPAL	$\tan\beta$ >1, m_t <200 GeV
>21	95	[85] BUSKULIC	93I	ALEP	$\tan\beta$ >1, m_t = 140 GeV
>22	95	[86] ADRIANI	92G	L3	1<$\tan\beta$ <50, m_t <250 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>44.4	95	[87] ABREU	94O	DLPH	$m_{H_1^0} = m_{A^0}$, any $\tan\beta$
>44.5	95	[84] AKERS	94I	OPAL	$\tan\beta$ >1, $m_{H_1^0} = m_{A^0}$
		[88] ELLIS	93	RVUE	Electroweak
>34	95	[89] ABREU	92J	DLPH	$\tan\beta > 3$
> 0.21	95	[90] BUSKULIC	92	ALEP	$\tan\beta > 1$
none 3–40.5	95	[91] AKRAWY	91C	OPAL	$\tan\beta > 1$, if 3 GeV < $m_{H_1^0} < m_{A^0}$
>20	95	[92] DECAMP	91I	ALEP	$\tan\beta > 1$
>34	95	[93] ABREU	90E	DLPH	$\tan\beta > 1$, $m_{H_1^0} < m_{A^0}$
>12	95	[93] ABREU	90E	DLPH	$\tan\beta < 1$
>39	95	[94] ADEVA	90R	L3	$\tan\beta > 1$, $m_{H_1^0} < m_{A^0}$

[83] ABREU 95H search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$. One-loop corrections are included with m_t = 170 GeV, $m_{\tilde{t}}$ = 1 TeV. The limit becomes weak for larger m_t: at m_t = 190 GeV, the limit is 14 GeV. The limit at m_t = 170 GeV would increase to 39 GeV if two-loop radiative corrections were included. m_t and $m_{\tilde{t}}$ dependences are shown in Fig. 6.

[84] AKERS 94I search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$. One-loop corrections are included with m_t <200 GeV, $m_{\tilde{t}}$ <1 TeV. See Fig. 10 for limits for $\tan\beta$ <1.

[85] BUSKULIC 93I search for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$. One-loop corrections to the Higgs potential are included with any m_t, $m_{\tilde{t}} > m_t$. For m_t = 140 GeV and $m_{\tilde{t}}$ = 1 TeV, the limit is m_{A^0} >45 GeV. Assumes no invisible H^0 or A^0 decays.

[86] ADRIANI 92G search for $Z \to H_1^0 Z^*$, $Z \to H_1^0 A^0 \to 4b$, $bb\tau\tau$, 4τ, $6b$ (via $H^0 \to A^0 A^0$), and include constraints from $\Gamma(Z)$. One-loop corrections are included with 90<m_t <250 GeV, $m_t < m_{\tilde{t}}$ <1 TeV. The region m_{A^0} <11 GeV is allowed if 42<$m_{H_1^0}$ <62 GeV, but is excluded by other experiments.

[87] ABREU 94O study $H_1^0 A^0 \to$ four jets and combine with ABREU 94G analysis. The limit applies if the H_1^0-A^0 mass difference is <4 GeV.

[88] ELLIS 93 analyze possible constraints on the MSSM Higgs sector by electroweak precision measurements and find that m_{A^0} is not constrained by the electroweak data.

[89] ABREU 92J searched for $Z \to H_1^0 Z^*$ and $Z \to H_1^0 A^0$ with $H_1^0, A^0 \to \tau\tau$ or jet-jet. Small mass values are excluded by ABREU 91B.

[90] BUSKULIC 92 limit is from $\Gamma(Z)$, $Z \to H_1^0 Z^*$, and $Z \to H_1^0 A^0$. The limit is valid for any $m_{H_1^0}$ below the the theoretical limit $m_{H_1^0}$ <64 GeV which holds for $m_{A^0} \sim 0$ in the minimal supersymmetric model. One-loop radiative corrections are included.

[91] AKRAWY 91C result from $Z \to H_1^0 A^0 \to$ 4jet or $\tau^+\tau^- jj$ or 4τ. See paper for the excluded region for the case $\tan\beta < 1$.

[92] DECAMP 91I searched for $Z \to H_1^0 Z^*$, and $Z \to H_1^0 A^0 \to$ 4jets or $\tau\tau jj$ or $3A^0$. Their limits take into account the one-loop radiative corrections to the Higgs potential with varied top and squark masses. For m_t = 140 GeV and $m_{\tilde{q}}$ = 1 TeV, the limit is m_{A^0} > 31 GeV.

[93] ABREU 90E searched $Z \to H_1^0 A^0$ and $Z \to H_1^0 Z^*$. m_{A^0} < 210 MeV is not excluded by this analysis.

[94] ADEVA 90R result is from $Z \to H_1^0 A^0 \to$ 4jet or $\tau\tau jj$ or 4τ and $Z \to H_1^0 Z^*$. Some region of m_{A^0} < 5 GeV is not excluded by this analysis.

MASS LIMITS for Associated Higgs Production in e^+e^- Interactions

In multi-Higgs models, associated production of Higgs via virtual or real Z in e^+e^- annihilation, $e^+e^- \to H_1^0 H_2^0$, is possible if H_1^0 and H_2^0 have opposite CP eigenvalues. Limits are for the mass of the heavier Higgs H_2^0 in two-doublet models.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>53	95	[95] AKERS	94I	OPAL	$m_{H_1^0}$ < 12 GeV
		[96] ADRIANI	92G	L3	
>45	95	[97] DECAMP	90H	ALEP	$m_{H_1^0}$ < 20 GeV
>37.5	95	[97] DECAMP	90H	ALEP	$m_{H_1^0} < m_{H_2^0}$
none 5–45	95	[98] KOMAMIYA	90	MRK2	$m_{H_1^0}$ < 0.5 GeV, $H_2^0 \to q\bar{q}$ or $\tau^+\tau^-$
> 8	90	[99] KOMAMIYA	89	MRK2	$H_1^0 \to \mu^+\mu^-$, $H_2^0 \to q\bar{q}, \tau^+\tau^-$
>28	95	[100] LOW	89	AMY	$m_{H_1^0} \lesssim$ 20 MeV, $H_2^0 \to q\bar{q}$
none 2–9	90	[101] AKERLOF	85	HRS	$m_{H_1^0}$ = 0, $H_2^0 \to f\bar{f}$

none 4–10	90	[102] ASH	85C MAC	$m_{H_1^0}=0.2$ GeV, $H_2^0 \to \tau^+\tau^-$, $c\overline{c}$
none 1.3–24.7	95	[101] BARTEL	85L JADE	$m_{H_1^0}=0.2$ GeV, $H_2^0 \to f\overline{f}$ or $f\overline{f}H_1^0$
none 1.2–13.6	95	[101] BEHREND	85 CELL	$m_{H_1^0}=0$, $H_2^0 \to f\overline{f}$
none 1–11	90	[101] FELDMAN	85 MRK2	$m_{H_1^0}=0$, $H_2^0 \to f\overline{f}$
none 1–9	90	[101] FELDMAN	85 MRK2	$m_{H_1^0}=m_{H_2^0}$, $H_2^0 \to f\overline{f}$

[95] AKERS 94I search for $Z \to H_1^0 H_2^0$ with various decay modes. See Fig. 11 for the full excluded mass region in the general two-doublet model, from which the limit above is taken. In particular, for $m_{H_1^0}=m_{H_2^0}$ the limit becomes >38 GeV.

[96] ADRIANI 92G excluded regions of the $m_{H_1^0}-m_{A^0}$ plane for various decay modes with limits $B(Z \to H_1^0 H_2^0) <(2–20) \times 10^{-4}$ are shown in Figs. 2–5.

[97] DECAMP 90H search for $Z \to H_1^0 e^+e^-$, $H_1^0\mu^+\mu^-$, $H_1^0\tau^+\tau^-$, $H_1 q\overline{q}$, low multiplicity final states, τ-τ-jet-jet final states and 4-jet final states.

[98] KOMAMIYA 90 limits valid for $\cos^2(\alpha-\beta)\approx 1$. They also search for the cases $H_1^0 \to \mu^+\mu^-$, $\tau^+\tau^-$, and $H_2^0 \to H_1^0 H_1^0$. See their Fig. 2 for limits for these cases.

[99] KOMAMIYA 89 assume $B(H_1^0 \to \mu^+\mu^-) = 100$ %, $2m_\mu < m_{H_1^0} < m_\tau$. The limit is for maximal mixing. A limit of $m_{H_2^0} > 18$ GeV for the case $H_2^0 \to H_1^0 H_1^0$ ($H_1^0 \to \mu^+\mu^-$) is also given. From PEP at $E_{cm}=29$ GeV.

[100] LOW 89 assume that H_1^0 escapes the detector. The limit is for maximal mixing. A reduced limit of 24 GeV is obtained for the case $H_2^0 \to H_1^0 f\overline{f}$. Limits for a Higgs-triplet model are also discussed. $E_{cm}^{ee}=50$–60.8 GeV.

[101] The limit assumes maximal mixing and that H_1^0 escapes the detector.

[102] ASH 85 assumes that H_1^0 escapes undetected. The bound applies up to a mixing suppression factor of 5.

$H^\pm$ (Charged Higgs or Techni-pion) MASS LIMITS

Most of the following limits assume $B(H^+ \to \tau^+\nu) + B(H^+ \to c\overline{s}) = 1$. DECAMP 90I, BEHREND 87, and BARTEL 86 assume $B(H^+ \to \tau^+\nu) + B(H^+ \to c\overline{s}) + B(H^+ \to c\overline{b}) = 1$. All limits from Z decays as well as ADACHI 90B assume that H^+ has weak isospin $T_3=+1/2$. For a discussion of techni-particles, see EICHTEN 86.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>43.5	95	[103] ABREU	94O DLPH	$B(\tau\nu)=0$–1
>41	95	[104] ADRIANI	92G L3	$B(\tau\nu)=0$–1
>41.7	95	[105,106] DECAMP	92 ALEP	$B(\tau\nu)=0$–1
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[107] BUSKULIC	95 ALEP	$b \to \tau\nu_\tau X$
		[108] ABE	94H CDF	$t \to bH^+$, $H^+ \to \tau^+\nu_\tau$
		[109] ABE	94I CDF	$t \to bH^+$, $H^+ \to \tau^+\nu_\tau$
		[110] BARGER	93 RVUE	$b \to s\gamma$
		[111] BELANGER	93 RVUE	$b \to s\gamma$
		[110] HEWETT	93 RVUE	$b \to s\gamma$
		[112] ALITTI	92F UA2	$t \to bH^+$, $H^+ \to \tau\nu_\tau$
		[113] ALBAJAR	91B UA1	$t \to bH^+$, $H^+ \to \tau^+\nu$
none 8.0–20.2	95	[114] YUZUKI	91 VNS	$B(\ell\nu)=0$–1
>29	95	[105,115] ABREU	90B DLPH	$B(\tau\nu)=0$–1
>19	95	[105,116] ADACHI	90B TOPZ	$B(\tau\nu)=0$–1
>36.5	95	[105,117] ADEVA	90M L3	$B(\tau\nu)=0$–1
>35	95	[105,118] AKRAWY	90K OPAL	$B(\tau\nu)=0$–1
>35.4	95	[105,119] DECAMP	90I ALEP	$B(\tau\nu)=0$–1
none 10–20	95	[120] SMITH	90B AMY	$B(\tau\nu)>0.7$
>19	95	[119] BEHREND	87 CELL	$B(\tau\nu)=0$–1
>18	95	[121] BARTEL	86 JADE	$B(\tau\nu)=0.1$–1.0
>17	95	[121] ADEVA	85 MRKJ	$B(\tau\nu)=0.25$–1.0

[103] ABREU 94O study $H^+H^- \to c\overline{s}s\overline{c}$ (four-jet final states) and $H^+H^- \to \tau\nu_\tau\tau\nu_\tau$. Limit for $B(\tau\nu_\tau)=1$ is 45.4 GeV.

[104] ADRIANI 92G limit improves to 44 GeV if $B(\tau\nu_\tau) > 0.4$.

[105] Studied $H^+H^- \to (\tau\nu)+(\tau\nu)$, $H^+H^- \to (\tau\nu)$ + hadrons, $H^+H^- \to$ hadrons.

[106] DECAMP 92 limit improves to 45.3 GeV for $B(\tau\nu)=1$.

[107] BUSKULIC 95 give a limit $\tan\beta/m_{H^+} < 0.52$ GeV^{-1} (90%CL) for Type-II models from $b \to \tau\nu_\tau X$ branching ratio.

[108] ABE 94H search for $t\overline{t}$ production in $p\overline{p}$ collisions at $E_{cm}=1.8$ TeV, followed by the decay chain $t \to bH^+$, $H^+ \to \tau^+\nu_\tau$, τ decaying hadronically. The search is sensitive to the region $m_{H^+} < m_t - m_b < m_W$. See their Fig. 3 for the excluded region for $\tan\beta \geq 0.5$ and their Fig. 4 for that in the two-Higgs-doublet model.

[109] ABE 94I search for $t\overline{t}$ production in $p\overline{p}$ collisions at E_{cm}=1.8 TeV, followed by the decay chain $t \to bH^+$, $H^+ \to \tau^+\nu_\tau$, τ decaying leptonically. For $B(H^+ \to \tau\nu_\tau)$=1 (0.5), the region $m_{H^+} < m_t - m_b$, m_t <(95–110) GeV (70 GeV) is excluded at 95% CL. See Fig. 3 for the excluded parameter region in the two-Higgs-doublet model.

[110] HEWETT 93 and BARGER 93 analyze charged Higgs contribution to $b \to s\gamma$ in two-doublet models with the CLEO limit $B(b \to s\gamma) < 8.4 \times 10^{-4}$ (90% CL) and find lower limits on $m_{H^\pm}$ in the type of model (model II) in which different Higgs are responsible for up-type and down-type quark masses. HEWETT 93 give m_{H^+} >110 (70) GeV for m_t >150 (120) GeV using $m_b=5$ GeV. BARGER 93 give m_{H^+} >155 GeV for $m_t=150$ GeV using $m_b=4.25$ GeV. The authors employ leading logarithmic QCD corrections and emphasize that the limits are quite sensitve to m_b.

[111] BELANGER 93 make an analysis similar to BARGER 93 and HEWETT 93 with an improved CLEO limit $B(b \to s\gamma) < 5.4 \times 10^{-4}$ (95%CL). For the Type II model, the limit m_{H^+} >540 (300) GeV for m_t >150 (120) GeV is obtained. The authors employ leading logarithmic QCD corrections.

[112] ALITTI 92F search for $t \to bH^+$, $H^+ \to \tau\nu_\tau$ with τ decaying hadronically in $p\overline{p}$ collisions at $E_{cm}=630$ GeV. m_{H^+} between 40 and 65 GeV is excluded if $m_t - m_H = m_b + (\lesssim$ a few–10 GeV). See Figs. 5, 6 for the excluded region for $B(H^+ \to \tau\nu_\tau)$ = 1, 0.5.

[113] ALBAJAR 91B search for $W \to t\overline{b}$ and $t\overline{t}$ production in $p\overline{p}$ collisions with the decay chain $t \to H^+b$, $H^+ \to \tau^+\nu$, in single muon plus jets and dimuon channels. For $m_t=60$ GeV, m_{H^+} < 47 GeV is excluded at 95%CL if $\tan\beta > 2.3$. The search is restricted to small values of m_t, and no limit on m_{H^+} is obtained if $m_t > 61$ GeV. Note that existing limits on m_t are not valid if $t \to H^+b$.

[114] YUZUKI 91 assume photon exchange. The limit is valid for any decay mode $H^+ \to e\nu$, $\mu\nu$, $\tau\nu$, $q\overline{q}$ with five flavors. For $B(\ell\nu)=1$, the limit improves to 25.0 GeV.

[115] ABREU 90B limit improves to 36 GeV for $B(\tau\nu)=1$.

[116] ADACHI 90B limit improves to 22 GeV for $B(\tau\nu)=0.6$.

[117] ADEVA 90M limit improves to 42.5 GeV for $B(\tau\nu)=1$.

[118] AKRAWY 90K limit improves to 43 GeV for $B(\tau\nu)=1$.

[119] If $B(H^+ \to \tau^+\nu)=100$%, the DECAMP 90I limit improves to 43 GeV.

[120] SMITH 90B limit applies for $v_2/v_1 > 2$ in a model in which H_2 couples to u-type quarks and charged leptons.

[121] Studied $H^+H^- \to (\tau\nu)+(\tau\nu)$, $H^+H^- \to (\tau\nu)$ + hadrons. Search for muon opposite hadronic shower.

MASS LIMITS for $H^{\pm\pm}$ (doubly-charged Higgs boson)

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>45.6	95	[122] ACTON	92M OPAL	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[123] ASAKA	95 THEO	
>30.4	95	[124] ACTON	92M OPAL	$T_3(H^{++})=+1$
>25.5	95	[124] ACTON	92M OPAL	$T_3(H^{++})=0$
none 6.5–36.6	95	[125] SWARTZ	90 MRK2	$T_3(H^{++})=+1$
none 7.3–34.3	95	[125] SWARTZ	90 MRK2	$T_3(H^{++})=0$

[122] ACTON 92M limit assumes $H^{\pm\pm} \to \ell^\pm\ell^\pm$ or $H^{\pm\pm}$ does not decay in the detector. Thus the region $g_{\ell\ell} \approx 10^{-7}$ is not excluded.

[123] ASAKA 95 point out that H^{++} decays dominantly to four fermions in a large region of parameter space where the limit of ACTON 92M from the search of dilepton modes does not apply.

[124] ACTON 92M from $\Delta\Gamma_Z$ <40 MeV.

[125] SWARTZ 90 assume $H^{\pm\pm} \to \ell^\pm\ell^\pm$ (any flavor). The limits are valid for the Higgs-lepton coupling $g(H\ell\ell) \gtrsim 7.4 \times 10^{-7}/[m_H/\text{GeV}]^{1/2}$. The limits improve somewhat for ee and $\mu\mu$ decay modes.

H^0 and $H^\pm$ REFERENCES

ABREU	95H	ZPHY C67 69	+Adam, Adye, Agasi, Ajinenko, Aleksan+	(DELPHI Collab.)
ASAKA	95	PL B345 36	+Hikasa	(TOHOK)
BUSKULIC	95	PL B343 444	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
CASAS	95	PL B342 171	+Espinosa, Quiros	(MADE)
CHANKOWSKI	95	PL B356 307	+Pokorski	(WARS, MPIM)
ERLER	95	PR D52 441	+Langacker	(PENN)
ESPINOSA	95B	PL B353 257	+Quiros	(DESY, CERN)
MATSUMOTO	95	MPL A10 2553		(KEK)
ROSIEK	95	PL B341 419	+Sopczak	(IFIC, CERN)
ABE	94H	PRL 72 1977	+Albrow, Amidei, Anway-Wiese, Apollinari+	(CDF Collab.)
ABE	94I	PRL 73 2667	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABREU	94G	NP B421 3	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ABREU	94O	ZPHY C64 183	+Adam, Adye, Agasi, Ajinenko, Aleksan+	(DELPHI Collab.)
AKERS	94B	PL B327 397	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
AKERS	94I	ZPHY C64 1	+Alexander, Allison, Anderson, Arcelli, Asai+	(OPAL Collab.)
ALTARELLI	94	PL B337 141	+Isidori	(CERN, ROMA2, ROMAI)
ELLIS	94	PL B324 173	+Fogli, Lisi	(CERN, BARI)
ELLIS	94B	PL B333 118	+Fogli, Lisi	(CERN, BARI)
GURTU	94	MPL A9 3301		(TATA)
MONTAGNA	94	PL B335 484	+Nicrosini, Passarino, Piccinini	(INFN, PAVI, CERN, TORI)
ADRIANI	93C	PL B303 391	+Aguilar-Benitez, Ahlen, Alcaraz, Aloiso+	(L3 Collab.)
BARGER	93	PRL 70 1368	+Berger, Phillips	(WISC, RAL)
BELANGER	93	PR D48 5419	+Geng, Turcotte	(MONT, ISU, AMES)
BLONDEL	93	PL B311 346	+Verzegnassi	(EPOL, TRSTT, TRSTI)
BRAHMACH...	93	PR D48 4224	Brahmachari, Joshipura, Rindani+	(AHMED, TATA, CERN)
BUSKULIC	93H	PL B313 299	+De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
BUSKULIC	93I	PL B313 312	+De Bonis, Decamp, Ghez, Goy, Lees+	(ALEPH Collab.)
ELLIS	93	NP B393 3	+Fogli, Lisi	(CERN, BARI)
ELLIS	93B	PL B318 148	+Fogli, Lisi	(CERN, BARI)
GROSS	93	IJMP A8 407	+Yepes	(CERN)
HEWETT	93	PRL 70 1045		(ANL, OREG)
LOPEZ-FERN...	93	PL B312 240	Lopez-Fernandez, Romao+	(CERN, LISB, VALE)
NOVIKOV	93B	PL B308 123	+Okun, Vysotsky, Yurov	(SERP, CERN)
ABREU	92D	ZPHY C53 555	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ABREU	92J	NP B373 3	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ACTON	92M	PL B295 347	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ADEVA	92B	PL B283 454	+Adriani, Aguilar-Benitez, Ahlen, Akbari+	(L3 Collab.)
ADRIANI	92F	PL B292 472	+Aguilar-Benitez, Ahlen, Akbari, Alcarez+	(L3 Collab.)
ADRIANI	92G	PL B294 457	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
Also	93B	ZPHY C57 355	Adriani, Aguilar-Benitez, Ahlen, Alcaraz+	(L3 Collab.)
ALITTI	92F	PL B280 137	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
BARABASH	92	PL B295 154	+Baranov+	(JINR, CERN, SERP, BUDA, BERL)
Also	92B	SJNP 55 1810	Barabash+	(JINR, CERN, SERP, BUDA, BERL)
		Translated from YAF 55 3247.		

BUSKULIC 92 PL B285 309 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
DECAMP 92 PRPL 216 253 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
DELAGUILA 92B NP B381 451 del Aguila, Martinez, Quiros (GRAN, CERN)
ELLIS 92 PL B274 456 +Fogli, Lisi (CERN, BARI)
ELLIS 92E PL B292 427 +Fogli, Lisi (CERN, BARI)
PICH 92 NP B388 31 +Prades, Yepes (CERN, CPPM)
RENTON 92 ZPHY C56 355 (OXF)
SCHAILE 92 ZPHY C54 387 (FREIE)
ABREU 91B ZPHY C51 25 +Adam, Adami, Adye, Akesson+ (DELPHI Collab.)
ACTON 91 PL B268 122 +Alexander, Allison, Allport+ (OPAL Collab.)
ADEVA 91 PL B257 450 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 91D PL B262 155 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
AKRAWY 91 PL B253 511 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 91C ZPHY C49 1 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALBAJAR 91B PL B257 459 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
BLUEMLEIN 91 ZPHY C51 341 +Brunner, Grabosch+ (BERL, BUDA, JINR, SERP)
DECAMP 91F PL B262 139 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
DECAMP 91I PL B265 475 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
YUZUKI 91 PL B267 309 +Haba, Abe, Amako, Arai, Asano+ (VENUS Collab.)
ABE 90E PR D41 1717 +Amidei, Appollinari, Atac, Auchincloss+ (CDF Collab.)
ABREU 90B PL B241 449 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ABREU 90C NP B342 1 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ABREU 90E PL B245 276 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ABREU 90I HEP-90 Singapore unpub. +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
CERN-PPE/90-163
ADACHI 90B PL B240 513 +Aihara, Doeser, Enomoto+ (TOPAZ Collab.)
ADEVA 90H PL B248 203 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 90M PL B252 511 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 90N PL B252 518 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 90R PL B251 311 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
AKRAWY 90C PL B236 224 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90K PL B242 299 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 90P PL B251 211 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
DAWSON 90 PR D41 2844 +Gunion, Haber (BNL, UCD, UCSC)
DECAMP 90 PL B236 233 +Deschizeaux, Lees, Minard, Crespo+ (ALEPH Collab.)
DECAMP 90E PL B237 291 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
DECAMP 90H PL B241 141 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
DECAMP 90I PL B241 623 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
DECAMP 90M PL B245 289 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
DECAMP 90N PL B246 306 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
KOMAMIYA 90 PRL 64 2881 +Abrams, Adolphsen, Averill, Ballam+ (Mark II Collab.)
SMITH 90B PR D42 949 +McNeil, Breedon, Kim, Ko+ (AMY Collab.)
SWARTZ 90 PRL 64 2877 +Abrams, Adolphsen, Averill, Ballam+ (Mark II Collab.)
CAHN 89 RPP 52 389
CHENG 89 PR D40 2980 +Yu (AST)
DAVIER 89 PL B229 150 +Nguyen Ngoc (LALO)
DAWSON 89 PL B222 143 (BNL)
EGLI 89 PL B222 533 +Engfer, Grab, Hermes, Kraus+ (SINDRUM Collab.)
KOMAMIYA 89 PR D40 721 +Fordham, Abrams, Adolphsen, Akerlof+ (Mark II Collab.)
LINDNER 89 PL B228 139 +Sher, Zaglauer (FNAL, WUSL)
LOW 89 PL B228 548 +Xu, Abashian, Gotow, Hu, Mattson+ (AMY Collab.)
SHER 89 PRPL 179 273
SNYDER 89 PL B229 169 +Murray, Abrams, Adolphsen, Akerlof+ (Mark II Collab.)
YEPES 89 PL B227 182 (MCGI)
BEHREND 87 PL B193 376 +Buerger, Criegee, Dainton+ (CELLO Collab.)
FRANZINI 87 PR D35 2883 +Son, Tuts, Youssef, Zhao+ (CUSB Collab.)
RUSKOV 87 PL B187 165 (SOFI)
BARTEL 86 ZPHY C31 359 +Becker, Felst, Haidt+ (JADE Collab.)
EICHTEN 86 PR D34 1547 +Hinchliffe, Lane, Quigg+ (FNAL, LBL, OSU)
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
AKERLOF 85 PL 156B 271 +Bonvicini, Chapman, Errede+ (HRS Collab.)
ALBRECHT 85J ZPHY C29 167 +Binder, Harder+ (ARGUS Collab.)
ASH 85 PRL 55 1831 +Band, Blume, Camporesi+ (MAC Collab.)
ASH 85C PRL 54 2477 +Band, Blume, Camporesi+ (MAC Collab.)
BARTEL 85L PL 155B 288 +Becker, Cords, Felst, Hagiwara+ (JADE Collab.)
BEHREND 85 PL 161B 182 +Burger, Criegee, Fenner+ (CELLO Collab.)
FELDMAN 85 PRL 54 2289 +Abrams, Amidei, Baden+ (Mark II Collab.)
DZHELYADIN 81 PL 105B 239 +Golovkin, Konstantinov, Kubarovski+ (SERP)
WITTEN 81 NP B177 477 (HARV)
GUTH 80 PRL 45 1131 +Weinberg (SLAC)
JACQUES 80 PR D21 1206 +Kalelkar, Miller, Plano+ (RUTG, STEV, COLU)
SHER 80 PR D22 2989 (UCSC)
Also 83 ANP 148 95 Flores, Sher (UCSC, UCI)

Heavy Bosons Other Than Higgs Bosons, Searches for

We list here various limits on charged and neutral heavy vector bosons (other than W's and Z's), heavy scalar bosons (other than Higgs bosons), vector or scalar leptoquarks, and axigluons.

W_R (Right-Handed W Boson) MASS LIMITS

Assuming a light right-handed neutrino, except for BEALL 82, LANGACKER 89B, and COLANGELO 91. $g_R = g_L$ assumed. [Limits in the section MASS LIMITS for W' below are also valid for W_R if $m_{\nu_R} \ll m_{W_R}$.] Some limits assume manifest left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maskawa matrices. For a comprehensive review, see LANGACKER 89B. Limits on the W_L-W_R mixing angle ζ are found in the next section. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 406	90	[1] JODIDIO	86	ELEC	Any ζ
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 281	90	[2] KUZNETSOV	95	CNTR	Polarized neutron decay
> 282	90	[3] KUZNETSOV	94B	CNTR	Polarized neutron decay
> 439	90	[4] BHATTACH...	93	RVUE	Z-Z' mixing
> 250	90	[5] SEVERIJNS	93	CNTR	β^+ decay
		[6] IMAZATO	92	CNTR	K^+ decay
> 475	90	[7] POLAK	92B	RVUE	μ decay
> 240	90	[8] AQUINO	91	RVUE	Neutron decay
> 496	90	[8] AQUINO	91	RVUE	Neutron and muon decay
> 700		[9] COLANGELO	91	THEO	$m_{K^0_L} - m_{K^0_S}$
> 477	90	[10] POLAK	91	RVUE	μ decay
[none 540–23000]		[11] BARBIERI	89B	ASTR	SN 1987A; light ν_R
> 300	90	[12] LANGACKER	89B	RVUE	General
> 160	90	[13] BALKE	88	CNTR	$\mu \to e\nu\overline{\nu}$
> 482	90	[1] JODIDIO	86	ELEC	$\zeta = 0$
> 800		MOHAPATRA	86	RVUE	$SU(2)_L \times SU(2)_R \times U(1)$
> 400	95	[14] STOKER	85	ELEC	Any ζ
> 475	95	[14] STOKER	85	ELEC	ζ <0.041
		[15] BERGSMA	83	CHRM	$\nu_\mu e \to \mu \nu_e$
> 380	90	[16] CARR	83	ELEC	μ^+ decay
>1600		[17] BEALL	82	THEO	$m_{K^0_L} - m_{K^0_S}$
[> 4000]		STEIGMAN	79	COSM	Nucleosynthesis; light ν_R

[1] JODIDIO 86 is the same TRIUMF experiment as STOKER 85 (and CARR 83); however, it uses a different technique. The results given here are combined results of the two techniques. The technique here involves precise measurement of the end-point e^+ spectrum in the decay of the highly polarized μ^+.

[2] KUZNETSOV 95 limit is from measurements of the asymmetry $\langle \vec{p}_\nu \cdot \sigma_n \rangle$ in the β decay of polarized neutrons. Zero mixing assumed. See also KUZNETSOV 94B.

[3] KUZNETSOV 94B limit is from measurements of the asymmetry $\langle \vec{p}_\nu \cdot \sigma_n \rangle$ in the β decay of polarized neutrons. Zero mixing assumed.

[4] BHATTACHARYYA 93 uses Z-Z' mixing limit from LEP '90 data, assuming a specific Higgs sector of $SU(2)_L \times SU(2)_R \times U(1)$ gauge model. The limit is for m_t=200 GeV and slightly improves for smaller m_t.

[5] SEVERIJNS 93 measured polarization-asymmetry correlation in $^{107}\text{In}\ \beta^+$ decay. The listed limit assumes zero L-R mixing. Value quoted here is from SEVERIJNS 94 erratum.

[6] IMAZATO 92 measure positron asymmetry in $K^+ \to \mu^+ \nu_\mu$ decay and obtain $\xi P_\mu > 0.990$ (90%CL). If W_R couples to $u\overline{s}$ with full weak strength (V^R_{us}=1), the result corresponds to m_{W_R} >653 GeV. See their Fig. 4 for m_{W_R} limits for general $|V^R_{us}|^2 = 1 - |V^R_{ud}|^2$.

[7] POLAK 92B limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming ζ=0. Supersedes POLAK 91.

[8] AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right symmetry assumed. Stronger of the two limits also includes muon decay results.

[9] COLANGELO 91 limit uses hadronic matrix elements evaluated by QCD sum rule and is less restrictive than BEALL 82 limit which uses vacuum saturation approximation. Manifest left-right symmetry assumed.

[10] POLAK 91 limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming ζ=0. Superseded by POLAK 92B.

[11] BARBIERI 89B limit holds for $m_{\nu_R} \leq 10$ MeV.

[12] LANGACKER 89B limit is for any ν_R mass (either Dirac or Majorana) and for a general class of right-handed quark mixing matrices.

[13] BALKE 88 limit is for $m_{\nu_{eR}} = 0$ and $m_{\nu_{\mu R}} \leq 50$ MeV. Limits come from precise measurements of the muon decay asymmetry as a function of the positron energy.

[14] STOKER 85 is same TRIUMF experiment as CARR 83. Here they measure the decay e^+ spectrum asymmetry above 46 MeV/c using a muon-spin-rotation technique. Assumed a light right-handed neutrino. Quoted limits are from combining with CARR 83.

[15] BERGSMA 83 set limit $m_{W_2}/m_{W_1} > 1.9$ at CL = 90%.

[16] CARR 83 is TRIUMF experiment with a highly polarized μ^+ beam. Looked for deviation from $V-A$ at the high momentum end of the decay e^+ energy spectrum. Limit from previous world-average muon polarization parameter is m_{W_R} >240 GeV. Assumes a light right-handed neutrino.

[17] BEALL 82 limit is obtained assuming that W_R contribution to K^0_L-K^0_S mass difference is smaller than the standard one, neglecting the top quark contributions. Manifest left-right symmetry assumed.

Limit on W_L-W_R Mixing Angle ζ

Lighter mass eigenstate $W_1 = W_L \cos\zeta - W_R \sin\zeta$. Light ν_R assumed unless noted. Values in brackets are from cosmological and astrophysical considerations.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.04	90	[18] MISHRA	92	CCFR	νN scattering
−0.0006 to 0.0028	90	[19] AQUINO	91	RVUE	
[none 0.00001–0.02]		[20] BARBIERI	89B	ASTR	SN 1987A
< 0.040	90	[21] JODIDIO	86	ELEC	μ decay
−0.056 to 0.040	90	[21] JODIDIO	86	ELEC	μ decay

[18] MISHRA 92 limit is from the absence of extra large-x, large-y $\overline{\nu}_\mu N \to \overline{\nu}_\mu X$ events at Tevatron, assuming left-handed ν and right-handed $\overline{\nu}$ in the neutrino beam. The result gives $\zeta^2(1-2m^2_{W_1}/m^2_{W_2})$< 0.0015. The limit is independent of ν_R mass.

[19] AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right asymmetry is assumed.

[20] BARBIERI 89B limit holds for $m_{\nu_R} \leq 10$ MeV.

[21] First JODIDIO 86 result assumes m_{W_R}=∞, second is for unconstrained m_{W_R}.

MASS LIMITS for W' (A Heavy Charged Vector Boson Other Than W) in Hadron Collider Experiments

Couplings of W' to quarks and leptons are taken to be identical with those of W. The following limits are obtained from $p\overline{p} \to W'X$ with W' decaying to the mode indicated in the comments. New decay channels (*e.g.*, $W' \to WZ$ are assumed to be suppressed. Experiments other than ABE 95M, ABACHI 95E, and ABE 91F assume that the $t\overline{b}$ channel is not open.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>652	95	[22] ABE	95M	CDF	$W' \to e\nu_e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>610	95	[23] ABACHI	95E	D0	$W' \to e\nu_e$ and $W' \to \tau\nu_\tau \to e\nu\nu\overline{\nu}$
>251	90	[24] ALITTI	93	UA2	$W' \to q\overline{q}$
none 260–600	95	[25] RIZZO	93	RVUE	$W' \to q\overline{q}$
>520	95	[26] ABE	91F	CDF	$W' \to e\nu, \mu\nu$
none 101–158	90	[27] ALITTI	91	UA2	$W' \to q\overline{q}$
>220	90	[28] ALBAJAR	89	UA1	$W' \to e\nu$
>209	90	[29] ANSARI	87D	UA2	$W' \to e\nu$
>210	90	[30] ARNISON	86B	UA1	$W' \to e\nu$
>170	90	[31] ARNISON	83D	UA1	$W' \to e\nu$

[22] ABE 95M assume that the decay $W' \to WZ$ is suppressed and the (right-handed) neutrino is light, noninteracting, and stable. If m_ν=60 GeV, for example, the effect on the mass limit is neglibible.

[23] ABACHI 95E assume that the decay $W' \to WZ$ is suppressed and that the neutrino from W' decay is stable and has a mass significantly less $m_{W'}$.

[24] ALITTI 93 search for resonances in the two-jet invariant mass. The limit assumes $\Gamma(W')/m_{W'} = \Gamma(W)/m_W$ and $B(W' \to jj) = 2/3$. This corresponds to W_R with $m_{\nu_R} > m_{W_R}$ (no leptonic decay) and $W_R \to t\overline{b}$ allowed. See their Fig. 4 for limits in the $m_{W'}$–$B(q\overline{q})$ plane.

[25] RIZZO 93 analyses CDF limit on possible two-jet resonances. The limit is sensitive to the inclusion of the assumed K factor.

[26] ABE 91F assume leptonic branching ratio of 1/12 for each lepton flavor. The limit from the $e\nu$ ($\mu\nu$) mode alone is 490 (435) GeV. These limits apply to W_R if $m_{\nu_R} \lesssim 15$ GeV and ν_R does not decay in the detector. Cross section limit $\sigma \cdot B < (1\text{–}10)$ pb is given for $m_{W'} = 100$–550 GeV; see Fig. 2.

[27] ALITTI 91 search is based on two-jet invariant mass spectrum, assuming $B(W' \to q\overline{q}) = 67.6\%$. Limit on $\sigma \cdot B$ as a function of two-jet mass is given in Fig. 7.

[28] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(W')\, B(e\nu) < 4.1$ pb (90% CL).

[29] See Fig. 5 of ANSARI 87D for the excluded region in the $m_{W'}$–$[(g_{W'q})^2\, B(W' \to e\overline{\nu})]$ plane. Note that the quantity $(g_{W'q})^2\, B(W' \to e\overline{\nu})$ is normalized to unity for the standard W couplings.

[30] ARNISON 86B find no excess at large p_T in 148 $W \to e\nu$ events. Set limit $\sigma \times B(e\nu)$ <10 pb at CL = 90% at $E_{\rm cm}$ = 546 and 630 GeV.

[31] ARNISON 83D find among 47 $W \to e\nu$ candidates no event with excess p_T. Also set $\sigma \times B(e\nu)$ <30 pb with CL = 90% at $E_{\rm cm}$ = 540 GeV.

MASS LIMITS for Z' (Heavy Neutral Vector Boson Other Than Z)

THE Z' SEARCHES

The mass bounds depend on the gauge group and the gauge coupling of a Z' boson. The limits listed below are not exhaustive but include only typical Z' bosons that appear frequently in the literature. The following notations are used for these Z' bosons.

$Z'_{\rm SM}$: $Z'_{\rm SM}$ is a clone of the Z and is introduced as a convenient way to gauge the limits rather than with a theoretical motivation. It is assumed to have exactly the same couplings as the Z but a different mass.

Left-right symmetric bosons: Z_{LR} is the extra neutral boson which appears in left-right symmetric models with the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ or $SU(2)_L \times U(1)_R \times U(1)_{B-L}$, where $U(1)_R$ is the third component of $SU(2)_R$ and the weak hypercharge $Y = T_{3R} + \frac{1}{2}(B-L)$. The Z_{LR} couples to $\alpha T_{3R} - (1/2\alpha)(B-L)$ with the coupling strength g' (the weak hypercharge gauge coupling). The parameter α is model dependent. For left-right symmetric coupling $g_L = g_R$, $\alpha = (1-2\sin^2\theta_W)^{1/2}/\sin\theta_W \approx 1.53$, which is used for the limits in the listing unless noted. Another typical case $\alpha = (2/3)^{1/2}$ is identical to Z_χ (discussed below) with the coupling $g_\chi = g'$.

E_6 bosons: Two new neutral gauge bosons appear in E_6 models. One is contained in the SO(10) subgroup and the other is not:

$$E_6 \longrightarrow SO(10) \times U(1)_\psi ,$$

$$SO(10) \longrightarrow SU(5) \times U(1)_\chi .$$

One Z' is assumed to be relatively light, which in general is a linear combination of the two:

$$Z_\beta = Z_\chi \cos\beta + Z_\psi \sin\beta .$$

The gauge quantum numbers of the ordinary quarks and leptons are shown in the table:

f	T_{3R}	Y	$B-L$	$\sqrt{24}Q_\chi$	$\sqrt{\frac{72}{5}}Q_\psi$	Q_η
ν_L, e^-_L	0	$-\frac{1}{2}$	-1	$+3$	$+1$	$+\frac{1}{6}$
ν_R	$+\frac{1}{2}$	0	-1	$+5$	-1	$+\frac{5}{6}$
e^-_R	$-\frac{1}{2}$	-1	-1	$+1$	-1	$+\frac{1}{3}$
u_L, d_L	0	$+\frac{1}{6}$	$+\frac{1}{3}$	-1	$+1$	$-\frac{1}{3}$
u_R	$+\frac{1}{2}$	$+\frac{2}{3}$	$+\frac{1}{3}$	$+1$	-1	$+\frac{1}{3}$
d_R	$-\frac{1}{2}$	$-\frac{1}{3}$	$+\frac{1}{3}$	-3	-1	$-\frac{1}{6}$

In particular, the χ charge is related to others by $\sqrt{24}Q_\chi = 4Y - 5(B-L)$. Also notice that the Z_ψ coupling is pure axial for all quarks and leptons.

Another typical case Z_η is defined as

$$Z_\eta = \sqrt{\tfrac{3}{8}}Z_\chi - \sqrt{\tfrac{5}{8}}Z_\psi ,$$

which appears in a superstring-motivated model.

A reference gauge coupling for these bosons is $g' = e/\cos\theta_W$, which is predicted if there is no intermediate symmetry breaking scale.

In general, these Z' models require the existence of a set of new fermions (belonging to the 27 representation of E_6) to cancel gauge anomalies, and possibly superpartners. An exception is Z_χ, for which only right-handed neutrinos are necessary. For the direct limits from hadron colliders, it is often assumed that these new fermions are heavy and are not produced in the decay of the Z'.

Limits for Z'_{SM}

Z'_{SM} is assumed to have couplings with quarks and leptons which are identical to those of Z.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>505	95	[32] ABE	95 CDF	$p\overline{p}$; $Z'_{SM} \to e^+e^-$
>779	95	[33,34] LANGACKER	92B RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>398	95	[35] VILAIN	94B CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
>237	90	[36] ALITTI	93 UA2	$p\overline{p}$; $Z'_{SM} \to q\overline{q}$
>119	90	[37] ALLEN	93 CALO	$\nu e \to \nu e$
none 490–560	95	[38] RIZZO	93 RVUE	$p\overline{p}$; $Z'_{SM} \to q\overline{q}$
>412	95	ABE	92B CDF	$p\overline{p}$; $Z'_{SM} \to e^+e^-$, $\mu^+\mu^-$
>387	95	[39] ABE	91D CDF	$p\overline{p}$; $Z'_{SM} \to e^+e^-$
>307	90	[40] GEIREGAT	91 CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
>426	90	[41] ABE	90F VNS	e^+e^-
>208	90	[42] HAGIWARA	90 RVUE	e^+e^-
>173	90	[43] ALBAJAR	89 UA1	$p\overline{p}$; $Z'_{SM} \to e^+e^-$
>180	90	[44] ANSARI	87D UA2	$p\overline{p}$; $Z'_{SM} \to e^+e^-$
>160	90	[45] ARNISON	86B UA1	$p\overline{p}$; $Z'_{SM} \to e^+e^-$

[32] ABE 95 limit is obtained assuming that Z' decays to known fermions only.

[33] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. m_t >89 GeV used.

[34] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.0086 < \theta < 0.0005$.

[35] VILAIN 94B assume m_t = 150 GeV.

[36] ALITTI 93 search for resonances in the two-jet invariant mass. The limit assumes $B(Z' \to q\overline{q})$=0.7. See their Fig. 5 for limits in the $m_{Z'}$–$B(q\overline{q})$ plane.

[37] ALLEN 93 limit is from total cross section for $\nu e \to \nu e$, where $\nu = \nu_e, \nu_\mu, \overline{\nu}_\mu$.

[38] RIZZO 93 analyses CDF limit on possible two-jet resonances. The limit is sensitive to the inclusion of the assumed K factor.

[39] ABE 91D give $\sigma(Z')\cdot B(e^+e^-) <$ 1.31 pb (95%CL) for $m_{Z'} >$ 200 GeV at E_{cm} = 1.8 TeV. Limits ranging from 2 to 30 pb are given for $m_{Z'}$ = 100–200 GeV.

[40] GEIREGAT 91 limit is from comparison of g_V^e from $\nu_\mu e$ scattering with $\Gamma(Z \to ee)$ from LEP. Zero mixing assumed.

[41] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$. They fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.

[42] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.

[43] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(Z')$ $B(ee) <$ 4.2 pb (90% CL).

[44] See Fig. 5 of ANSARI 87D for the excluded region in the $m_{Z'}$–$[(g_{Z'q})^2\ B(Z' \to e^+e^-)]$ plane. Note that the quantity $(g_{Z'q})^2 B(Z' \to e^+e^-)$ is normalized to unity for the standard Z couplings.

[45] ARNISON 86B find no excess e^+e^- pairs among 13 pairs from Z. Set limit $\sigma \times B(e^+e^-)$ <13 pb at CL = 90% at E_{cm} = 546 and 630 GeV.

Limits for Z_{LR}

Z_{LR} is the extra neutral boson in left-right symmetric models. $g_L = g_R$ is assumed unless noted. Values in parentheses assume stronger constraint on the Higgs sector, usually motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>445	95	[46] ABE	95 CDF	$p\overline{p}$; $Z'_{LR} \to e^+e^-$
>389	95	[47,48] LANGACKER	92B RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>253	95	[49] VILAIN	94B CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
>130	95	[50] ADRIANI	93D L3	Z parameters
(> 1500)	90	[51] ALTARELLI	93B RVUE	Z parameters
none 490–560	95	[52] RIZZO	93 RVUE	$p\overline{p}$; $Z_{LR} \to q\overline{q}$
>310	95	[53] ABE	92B CDF	$p\overline{p}$
>230	95	[54] ABE	92B CDF	$p\overline{p}$
(> 900)	90	[55] DELAGUILA	92 RVUE	
(> 1400)		[56] LAYSSAC	92B RVUE	Z parameters
(> 564)	90	[57] POLAK	92 RVUE	μ decay
>474	90	[58] POLAK	92B RVUE	Electroweak
(> 1340)		[59] RENTON	92 RVUE	
(> 800)	90	[60] ALTARELLI	91B RVUE	Z parameters
(> 795)	90	[61] DELAGUILA	91 RVUE	
>382	90	[62] POLAK	91 RVUE	Electroweak
[> 2000]		WALKER	91 COSM	Nucleosynthesis; light ν_R
[> 500]		[63] GRIFOLS	90 ASTR	SN 1987A; light ν_R
(> 460)	90	[64] HE	90B RVUE	
[> 2400–6800]		[65] BARBIERI	89B ASTR	SN 1987A; light ν_R
>189		[66] DELAGUILA	89 RVUE	$p\overline{p}$
[> 10000]		RAFFELT	88 ASTR	SN 1987A; light ν_R
>325	90	[67] AMALDI	87 RVUE	
>278	90	[68] DURKIN	86 RVUE	
>150	95	[69] ADEVA	85B MRKJ	$e^+e^- \to \mu^+\mu^-$

[46] ABE 95 limit is obtained assuming that Z' decays to known fermions only. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[47] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. m_t >89 GeV used.

[48] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.0025 < \theta < 0.0083$.

[49] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[50] ADRIANI 93D give limits on the Z-Z' mixing $-0.002 < \theta < 0.015$ assuming the ABE 92B mass limit.

[51] ALTARELLI 93B limit is from LEP data available in summer '93 and is for m_t = 110 GeV. m_H = 100 GeV and α_s = 0.118 assumed. The limit improves for larger m_t (see their Fig. 5). The 90%CL limit on the Z-Z' mixing angle is in Table 4.

[52] RIZZO 93 analyses CDF limit on possible two-jet resonances. The limit is sensitive to the inclusion of the assumed K factor.

[53] These limits assume that Z' decays to known fermions only.

[54] These limits assume that Z' decays to all E_6 fermions and their superpartners.

[55] See Fig. 7b and 8 in DELAGUILA 92 for the allowed region in $m_{Z'}$-mixing plane and $m_{Z'} - m_t$ plane from electroweak fit including '90 LEP data.

[56] LAYSSAC 92B limit is from LEP data available spring '92. Specific Higgs sector is assumed. See also LAYSSAC 92.

[57] POLAK 92 limit is from m_{W_R} >477 GeV, which is derived from muon decay parameters assuming light ν_R. Specific Higgs sector is assumed.

[58] POLAK 92B limit is from a simultaneous fit to charged and neutral sector in $SU(2)_L \times SU(2)_R \times U(1)$ model using Z parameters, m_W, and low-energy neutral current data as of 1991. Light ν_R assumed and m_t=m_H=100 GeV used. Supersedes POLAK 91.

[59] RENTON 92 limits use LEP data taken up to '90 as well as m_W, νN, and atomic parity violation data. Specific Higgs structure is assumed.

[60] ALTARELLI 91B is based on Z mass, widths, and A_{FB}. The limits are for superstring motivated models with extra assumption on the Higgs sector. $m_t >$ 90 GeV and $m_{H^0} <$ 1 TeV assumed. For large m_t, the bound improves drastically. Bounds for Z-Z' mixing angle and Z mass shift without this model assumption are also given in the paper.

[61] DELAGUILA 91 bounds have extra assumption of superstring motivated Higgs sector. From νN neutral current data with $m_Z = 91.10 \pm 0.04$ GeV, $m_t >$ 77 GeV, $m_{H^0} <$ 1 TeV assumed.

[62] POLAK 91 limit is from a simultaneous fit to charged and neutral sector in $SU(2)_L \times SU(2)_R \times U(1)$ model using m_W, m_Z, and low-energy neutral current data as of 1990. Light ν_R assumed and m_t=m_H=100 GeV used. Superseded by POLAK 92B.

[63] GRIFOLS 90 limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also GRIFOLS 90D, RIZZO 91.

[64] HE 90B model assumes a specific Higgs sector. Neutral current data of COSTA 88 as well as m_Z is used. g_R is left free in the fit.

[65] BARBIERI 89B limit holds for $m_{\nu_R} \leq$ 10 MeV.

[66] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \to Z')\cdot B(Z' \to e^+e^-) <$ 1.8 pb at CERN $p\overline{p}$ collider.

[67] A wide range of neutral current data as of 1986 are used in the fit.

[68] A wide range of neutral current data as of 1985 are used in the fit.

[69] ADEVA 85B measure asymmetry of μ-pair production, following formalism of RIZZO 81.

Limits for Z_χ

Z_χ is the extra neutral boson in $SO(10) \to SU(5) \times U(1)_\chi$. $g_\chi = e/\cos\theta_W$ is assumed unless otherwise stated. We list limits with the assumption $\rho = 1$ but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>425	95	[70] ABE	95 CDF	$p\overline{p}$; $Z'_\chi \to e^+e^-$
>321	95	[71,72] LANGACKER	92B RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>147	95	[73] ABREU	95M DLPH	Z parameters and $e^+e^- \to \mu^+\mu^-(n\gamma)$
		[74] NARDI	95 RVUE	Z parameters
		[75] BUSKULIC	94 ALEP	Z parameters
>262	95	[76] VILAIN	94B CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
>117	95	[77] ADRIANI	93D L3	Z parameters
(>900)	90	[78] ALTARELLI	93B RVUE	Z parameters
>340	95	[79] ABE	92B CDF	$p\overline{p}$
>280	95	[80] ABE	92B CDF	$p\overline{p}$
(>650)	90	[81] DELAGUILA	92 RVUE	
(>760)		[82] LAYSSAC	92B RVUE	Z parameters
>148	95	[83] LEIKE	92 RVUE	Z parameters
(>700)		[84] RENTON	92 RVUE	
(> 500)	90	[85] ALTARELLI	91B RVUE	Z parameters
(> 570)		[86] BUCHMUEL...	91 RVUE	Z parameters
(> 555)	90	[87] DELAGUILA	91 RVUE	
[>1470]		[88] FARAGGI	91 COSM	Nucleosynthesis; light ν_R

>320	90	[89] GONZALEZ-G..91		RVUE	
>221		[90] MAHANTHAP..91		RVUE	Cs
>231	90	[91,92] ABE	90F	VNS	e^+e^-
>206	90	[92,93] ABE	90F	RVUE	e^+e^-, $\nu_\mu e$
>335		[94] BARGER	90B	RVUE	$p\overline{p}$
(> 650)	90	[95] GLASHOW	90	RVUE	
[> 1140]		[96] GONZALEZ-G..90D		COSM	Nucleosynthesis; light ν_R
[> 2100]		[97] GRIFOLS	90	ASTR	SN 1987A; light ν_R
none <150 or > 363	90	[98] HAGIWARA	90	RVUE	e^+e^-
>177		[99] DELAGUILA	89	RVUE	$p\overline{p}$
>280	95	[100] DORENBOS...	89	CHRM	$g_\chi = g_Z$
>352	90	[101] COSTA	88	RVUE	
>170	90	[102] ELLIS	88	RVUE	$p\overline{p}$
>273	90	[101] AMALDI	87	RVUE	
>266	90	[103] MARCIANO	87	RVUE	
>283	90	[104] DURKIN	86	RVUE	

[70] ABE 95 limit is obtained assuming that Z' decays to known fermions only. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[71] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. m_t >89 GeV used.

[72] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.0048 < \theta < 0.0097$.

[73] ABREU 95M limit is for α_s=0.123, m_t=150 GeV, and m_H=300 GeV. For the limit contour in the mass-mixing plane, see their Fig. 13.

[74] NARDI 95 give 90%CL limits on Z-Z' mixing $-0.0032 < \theta < 0.0031$ for $M_{Z'}$ >500 GeV, m_t=170 GeV, m_H=250 GeV, α_s=0.12. The bound is relaxed under the simultaneous presence of the mixing of the known fermions with new heavy states, $-0.0032 < \theta < 0.0079$.

[75] BUSKULIC 94 give 95%CL limits on the Z-Z' mixing $-0.0091 < \theta < 0.0023$.

[76] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[77] ADRIANI 93D give limits on the Z-Z' mixing $-0.004 < \theta < 0.015$ assuming the ABE 92B mass limit.

[78] ALTARELLI 93B limit is from LEP data available in summer '93 and is for m_t = 110 GeV. m_H = 100 GeV and α_s = 0.118 assumed. The limit improves for larger m_t (see their Fig. 5). The 90%CL limit on the Z-Z' mixing angle is in their Fig. 2.

[79] These limits assume that Z' decays to known fermions only.

[80] These limits assume that Z' decays to all E_6 fermions and their superpartners.

[81] See Fig. 7a and 8 in DELAGUILA 92 for the allowed region in $m_{Z'}$-mixing plane and $m_{Z'} - m_t$ plane from electroweak fit including '90 LEP data.

[82] LAYSSAC 92B limit is from LEP data available spring '92. Specific Higgs sector is assumed. See also LAYSSAC 92.

[83] LEIKE 92 is based on '90 LEP data published in LEP 92.

[84] RENTON 92 limits use LEP data taken up to '90 as well as m_W, νN, and atomic parity violation data. Specific Higgs structure is assumed.

[85] ALTARELLI 91B is based on Z mass, widths, and A_{FB}. The limits are for superstring motivated models with extra assumption on the Higgs sector. m_t > 90 GeV and m_{H^0} < 1 TeV assumed. For large m_t, the bound improves drastically. Bounds for Z-Z' mixing angle and Z mass shift without this model assumption are also given in the paper.

[86] BUCHMUELLER 91 limit is from LEP data. Specific assumption is made for the Higgs sector.

[87] DELAGUILA 91 bounds have extra assumption of superstring motivated Higgs sector. From νN neutral current data with m_Z = 91.10 ± 0.04 GeV, m_t > 77 GeV, m_{H^0} < 1 TeV assumed.

[88] FARAGGI 91 limit assumes the nucleosynthesis bound on the effective number of neutrinos ΔN_ν < 0.5 and is valid for m_{ν_R} < 1 MeV.

[89] GONZALEZ-GARCIA 91 limit is based on low-energy neutral current data, Z mass and widths, m_W from ABE 90G. 100 < m_t < 200 GeV, m_{H^0} = 100 GeV assumed. Dependence on m_t is shown in Fig. 7.

[90] MAHANTHAPPA 91 limit is from atomic parity violation in Cs with m_W, m_Z.

[91] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$.

[92] ABE 90F fix m_W = 80.49 ± 0.43 ± 0.24 GeV and m_Z = 91.13 ± 0.03 GeV.

[93] e^+e^- data for R, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below Z as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.

[94] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \to Z')\cdot B(Z' \to e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for Z' decay.

[95] GLASHOW 90 model assumes a specific Higgs sector. See GLASHOW 90B.

[96] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos (δN_ν < 1) constrains Z' masses if ν_R is light ($\lesssim$ 1 MeV).

[97] GRIFOLS 90 limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also GRIFOLS 90D, RIZZO 91.

[98] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries. The upper mass limit disappears at 2.7 s.d.

[99] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \to Z')\cdot B(Z' \to e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.

[100] DORENBOSCH 89 obtain the limit $(g_\chi/g_Z)^2 \cdot (m_Z/m_{Z_\chi})^2 < 0.11$ at 95% CL from the processes $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ and $\nu_\mu e \to \nu_\mu e$.

[101] A wide range of neutral current data as of 1986 are used in the fit.

[102] Z' mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z' decays only into light quarks and leptons.

[103] MARCIANO 87 limit from unitarity of Cabibbo-Kobayashi-Maskawa matrix.

[104] A wide range of neutral current data as of 1985 are used in the fit.

Limits for Z_ψ

Z_ψ is the extra neutral boson in $E_6 \to SO(10) \times U(1)_\psi$. $g_\psi = e/\cos\theta_W$ is assumed unless otherwise stated. We list limits with the assumption $\rho = 1$ but with no further constraints on the Higgs sector. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>415	95	[105] ABE	95	CDF	$p\overline{p}$; $Z'_\psi \to e^+e^-$
>160	95	[106,107] LANGACKER	92B	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>105	95	[108] ABREU	95M	DLPH	Z parameters and $e^+e^- \to \mu^+\mu^-(n\gamma)$
		[109] NARDI	95	RVUE	Z parameters
>135	95	[110] VILAIN	94B	CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
>118	95	[111] ADRIANI	93D	L3	Z parameters
>320	95	[112] ABE	92B	CDF	$p\overline{p}$
>180	95	[113] ABE	92B	CDF	$p\overline{p}$
>122	95	[114] LEIKE	92	RVUE	Z parameters
>105	90	[115,116] ABE	90F	VNS	e^+e^-
>146	90	[116,117] ABE	90F	RVUE	e^+e^-, $\nu_\mu e$
>320		[118] BARGER	90B	RVUE	$p\overline{p}$
[> 160]		[119] GONZALEZ-G..90D		COSM	Nucleosynthesis; light ν_R
[> 2000]		[120] GRIFOLS	90D	ASTR	SN 1987A; light ν_R
>136	90	[121] HAGIWARA	90	RVUE	e^+e^-
>154	90	[122] AMALDI	87	RVUE	
>146	90	[123] DURKIN	86	RVUE	

[105] ABE 95 limit is obtained assuming that Z' decays to known fermions only. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[106] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. m_t >89 GeV used.

[107] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.0025 < \theta < 0.013$.

[108] ABREU 95M limit is for α_s=0.123, m_t=150 GeV, and m_H=300 GeV. For the limit contour in the mass-mixing plane, see their Fig. 13.

[109] NARDI 95 give 90%CL limits on Z-Z' mixing $-0.0056 < \theta < 0.0055$ for $M_{Z'}$ >500 GeV, m_t=170 GeV, m_H=250 GeV, α_s=0.12. The bound is relaxed under the simultaneous presence of the mixing of the known fermions with new heavy states, $-0.0066 < \theta < 0.0071$.

[110] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[111] ADRIANI 93D give limits on the Z-Z' mixing $-0.003 < \theta < 0.020$ assuming the ABE 92B mass limit.

[112] These limits assume that Z' decays to known fermions only.

[113] These limits assume that Z' decays to all E_6 fermions and their superpartners.

[114] LEIKE 92 is based on '90 LEP data published in LEP 92.

[115] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$.

[116] ABE 90F fix m_W = 80.49 ± 0.43 ± 0.24 GeV and m_Z = 91.13 ± 0.03 GeV.

[117] e^+e^- data for R, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below Z as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.

[118] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \to Z')\cdot B(Z' \to e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for Z' decay.

[119] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos (δN_ν < 1) constrains Z' masses if ν_R is light ($\lesssim$ 1 MeV).

[120] GRIFOLS 90D limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also RIZZO 91.

[121] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.

[122] A wide range of neutral current data as of 1986 are used in the fit.

[123] A wide range of neutral current data as of 1985 are used in the fit.

Limits for Z_η

Z_η is the extra neutral boson in E_6 models, corresponding to $Q_\eta = \sqrt{3/8}\, Q_\chi - \sqrt{5/8}\, Q_\psi$. $g_\eta = e/\cos\theta_W$ is assumed unless otherwise stated. We list limits with the assumption $\rho = 1$ but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>440	95	[124] ABE	95	CDF	$p\overline{p}$; $Z'_\eta \to e^+e^-$
>182	95	[125,126] LANGACKER	92B	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>109	95	[127] ABREU	95M	DLPH	Z parameters and $e^+e^- \to \mu^+\mu^-(n\gamma)$
		[128] NARDI	95	RVUE	Z parameters
>100	95	[129] VILAIN	94B	CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
>100	95	[130] ADRIANI	93D	L3	Z parameters
(>500)	90	[131] ALTARELLI	93B	RVUE	Z parameters
>340	95	[132] ABE	92B	CDF	$p\overline{p}$
>230	95	[133] ABE	92B	CDF	$p\overline{p}$
(>450)	90	[134] DELAGUILA	92	RVUE	
(>315)		[135] LAYSSAC	92B	RVUE	Z parameters
>118	95	[136] LEIKE	92	RVUE	Z parameters
(>470)		[137] RENTON	92	RVUE	
(> 300)	90	[138] ALTARELLI	91B	RVUE	Z parameters
>120	90	[139] GONZALEZ-G..91		RVUE	
>125	90	[140,141] ABE	90F	VNS	e^+e^-

>115	90	[141,142] ABE	90F	RVUE	e^+e^-, $\nu_\mu e$
>340		[143] BARGER	90B	RVUE	$p\overline{p}$
[> 820]		[144] GONZALEZ-G..	90D	COSM	Nucleosynthesis; light ν_R
[> 3300]		[145] GRIFOLS	90	ASTR	SN 1987A; light ν_R
>100	90	[146] HAGIWARA	90	RVUE	e^+e^-
[> 1040]		[144] LOPEZ	90	COSM	Nucleosynthesis; light ν_R
>173		[147] DELAGUILA	89	RVUE	$p\overline{p}$
>129	90	[148] COSTA	88	RVUE	
>156	90	[149] ELLIS	88	RVUE	
>167	90	[150] ELLIS	88	RVUE	$p\overline{p}$
>111	90	[148] AMALDI	87	RVUE	
>143	90	[151] BARGER	86B	RVUE	$p\overline{p}$
>130	90	[152] DURKIN	86	RVUE	
[> 760]		[144] ELLIS	86	COSM	Nucleosynthesis; light ν_R
[> 500]		[144] STEIGMAN	86	COSM	Nucleosynthesis; light ν_R

[124] ABE 95 limit is obtained assuming that Z' decays to known fermions only. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[125] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. $m_t > 89$ GeV used.

[126] LANGACKER 92B give 95%CL limits on the Z-Z' mixing $-0.038 < \theta < 0.002$.

[127] ABREU 95M limit is for α_s=0.123, m_t=150 GeV, and m_H=300 GeV. For the limit contour in the mass-mixing plane, see their Fig. 13.

[128] NARDI 95 give 90%CL limits on Z-Z' mixing $-0.0087 < \theta < 0.0075$ for $M_{Z'} > 500$ GeV, m_t=170 GeV, m_H=250 GeV, α_s=0.12. The bound is relaxed under the simultaneous presence of the mixing of the known fermions with new heavy states, $-0.0087 < \theta < 0.010$.

[129] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[130] ADRIANI 93D give limits on the Z-Z' mixing $-0.029 < \theta < 0.010$ assuming the ABE 92B mass limit.

[131] ALTARELLI 93B limit is from LEP data available in summer '93 and is for m_t = 110 GeV. m_H = 100 GeV and α_s = 0.118 assumed. The 90%CL limit on the Z-Z' mixing angle is in Fig. 2.

[132] These limits assume that Z' decays to known fermions only.

[133] These limits assume that Z' decays to all E_6 fermions and their superpartners.

[134] See Fig. 7d in DELAGUILA 92 for the allowed region in $m_{Z'}$-mixing plane from electroweak fit including '90 LEP data.

[135] LAYSSAC 92B limit is from LEP data available spring '92. Specific Higgs sector is assumed. See also LAYSSAC 92.

[136] LEIKE 92 is based on '90 LEP data published in LEP 92.

[137] RENTON 92 limits use LEP data taken up to '90 as well as m_W, νN, and atomic parity violation data. Specific Higgs structure is assumed.

[138] ALTARELLI 91B is based on Z mass, widths, and A_{FB}. The limits are for superstring motivated models with extra assumption on the Higgs sector. m_t > 90 GeV and m_{H^0} < 1 TeV assumed. For large m_t, the bound improves drastically. Bounds for Z-Z' mixing angle and Z mass shift without this model assumption are also given in the paper.

[139] GONZALEZ-GARCIA 91 limit is based on low-energy neutral current data, LEP Z mass and widths, m_W from ABE 90G. 100 $< m_t <$ 200 GeV, m_{H^0} = 100 GeV assumed. Dependence on m_t is shown in Fig. 8.

[140] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$.

[141] ABE 90F fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.

[142] e^+e^- data for R, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below Z as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.

[143] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for Z' decay.

[144] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) constrains Z' masses if ν_R is light ($\lesssim$ 1 MeV).

[145] GRIFOLS 90 limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also GRIFOLS 90D, RIZZO 91.

[146] HAGIWARA 90 perform a fit to e^+e^- data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.

[147] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \rightarrow Z')\cdot B(Z' \rightarrow e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.

[148] A wide range of neutral current data as of 1986 are used in the fit.

[149] Z_η mass limits obtained by combining constraints from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider and the global analysis of neutral current data by COSTA 88. Least favorable spectrum of three (E_6 27) generations of particles and their superpartners are assumed.

[150] Z' mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z' decays only into light quarks and leptons.

[151] BARGER 86B limit is based on UA1/UA2 limit on $p\overline{p} \rightarrow Z'$, $Z' \rightarrow e^+e^-$ (Lepton Photon Symp., Kyoto, '85). Extra decay channels for Z' are assumed not be open.

[152] A wide range of neutral current data as of 1985 are used in the fit.

Limits for other Z'

$Z_\beta = Z_\chi \cos\beta + Z_\psi \sin\beta$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[153] DELAGUILA	92	RVUE	
>360		[154] ALTARELLI	91	RVUE	Z_β with $\tan\beta = \sqrt{3/5}$; Cs
>190		[155] MAHANTHAP..	91	RVUE	Z_β with $\tan\beta = \sqrt{3/5}$; Cs
		[156] GRIFOLS	90C	RVUE	
		[157] DELAGUILA	89	RVUE	$p\overline{p}$
>180	90	[158,159] COSTA	88	RVUE	Z_β with $\tan\beta = \sqrt{15}$
>158	90	[160] ELLIS	88	RVUE	Z_β ($\tan\beta = \sqrt{15}$), $p\overline{p}$

[153] Fig. 7c and 7e in DELAGUILA 92 give limits for $\tan\beta = -1/\sqrt{15}$ and $\sqrt{15}$ from electroweak fit including '90 LEP data.

[154] ALTARELLI 91 limit is from atomic parity violation in Cs together with LEP, CDF data. Z-Z' mixing is assumed to be zero to set the limit.

[155] MAHANTHAPPA 91 limit is from atomic parity violation in Cs with m_W, m_Z. See Table III of MAHANTHAPPA 91 (corrected in erratum) for limits on various Z' models.

[156] GRIFOLS 90C obtains a limit for Z' mass as a function of mixing angle β (his $\theta = \beta - \pi/2$), which is derived from a LAMPF experiment on $\sigma(\nu_e e)$ (ALLEN 90). The result is shown in Fig. 1.

[157] See Table I of DELAGUILA 89 for limits on various Z' models.

[158] $g_\beta = e/\cos\theta_W$ and $\rho = 1$ assumed.

[159] A wide range of neutral current data as of 1986 are used in the fit.

[160] Z' mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when Z' decays only into light quarks and leptons.

MASS LIMITS for Leptoquarks from Pair Production

These limits rely only on the color or electroweak charge of the leptoquark.

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
> 97	95		[161] ABACHI	95G	D0	Second generation
> 96	95		[162] ABE	95U	CDF	Second generation
>116	95		[163] ABACHI	94B	D0	First generation
> 80	95		[164] ABE	93I	CDF	First generation
> 45.5	95		[165,166] ABREU	93J	DLPH	First + second generation
> 44.4	95		[167] ADRIANI	93M	L3	First generation
> 44.6	95		[168] ADRIANI	93M	L3	Third generation
> 44	95		[167] DECAMP	92	ALEP	First or second generation
> 45	95		[167] DECAMP	92	ALEP	Third generation
> 44.2	95		[167] ALEXANDER	91	OPAL	First or second generation
> 41.4	95		[167] ALEXANDER	91	OPAL	Third generation
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 44.5	95		[167] ADRIANI	93M	L3	Second generation
> 42.1	95		[169] ABREU	92F	DLPH	Second generation
> 74	95		[170] ALITTI	92E	UA2	First generation
> 43.2	95		[167] ADEVA	91B	L3	First generation
> 43.4	95		[167] ADEVA	91B	L3	Second generation
none 8.9–22.6	95		[171] KIM	90	AMY	First generation
none 10.2–23.2	95		[171] KIM	90	AMY	Second generation
none 5–20.8	95		[172] BARTEL	87B	JADE	
none 7–20.5	95	2	[173] BEHREND	86B	CELL	

[161] ABACHI 95G search for scalar leptoquarks using $\mu\mu$+jets and $\mu\nu_\mu$+jets events in $p\overline{p}$ collisions at E_{cm} = 1.8 TeV. The limit is for B(μq) = B(νq) = 0.5 and improves to >119 GeV for B(μq) = 1.

[162] ABE 95U search for scalar leptoquarks of charge Q=2/3 and $-1/3$ using $\mu\mu jj$ events in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. The limit is for B(μq)=B(νq)=0.5 and improves to > 131 GeV for B(μq)=1.

[163] ABACHI 94B search for $eejj$ and $e\nu jj$ events in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. ABACHI 94B obtain the limit >120 GeV for B(eq)=B(νq)=0.5 and >133 GeV for B(eq)=1. A change in the DØ luminosity monitor constant reduces the first bound to >116 GeV quoted above (see FERMILAB-TM-1911). This limit does not depend on the electroweak quantum numbers of the leptoquark.

[164] ABE 93I search for $\ell\ell jj$ events in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. The limit is for B(eq) = B(νq) = 0.5 and improves to >113 GeV for B(eq) = 1. This limit does not depend on electroweak quantum numbers of the leptoquark.

[165] Limit is for charge $-1/3$ isospin-0 leptoquark with B(ℓq) = 2/3.

[166] First and second generation leptoquarks are assumed to be degenerate. The limit is slightly lower for each generation.

[167] Limits are for charge $-1/3$, isospin-0 scalar leptoquarks decaying to $\ell^- q$ or νq with any branching ratio. See paper for limits for other charge-isospin assignments of leptoquarks.

[168] ADRIANI 93M limit for charge $-1/3$, isospin-0 leptoquark decaying to τb.

[169] ABREU 92F limit is for charge $-1/3$ isosin-0 leptoquark with B(μq)=2/3. If first and second generation leptoquarks are degenerate, the limit is 43.0 GeV, and for a charge 2/3 second generation leptoquark 43.4 GeV. Cross-section limit for pair production of states decaying to ℓq is given in the paper.

[170] ALITTI 92E search for $\ell\ell jj$ and $\ell\nu jj$ events in $p\overline{p}$ collisions at E_{cm}=630 GeV. The limit is for B(eq) = 1 and is reduced to 67 GeV for B(eq) = B(νq) = 0.5. This limit does not depend on electroweak quantum numbers of the leptoquark.

[171] KIM 90 assume pair production of charge 2/3 scalar-leptoquark via photon exchange. The decay of the first (second) generation leptoquark is assumed to be any mixture of de^+ and $u\overline{\nu}$ ($s\mu^+$ and $c\overline{\nu}$). See paper for limits for specific branching ratios.

[172] BARTEL 87B limit is valid when a pair of charge 2/3 spinless leptoquarks X is produced with point coupling, and when they decay under the constraint B(X $\rightarrow c\overline{\nu}_\mu$) + B(X $\rightarrow s\mu^+$) = 1.

[173] BEHREND 86B assumed that a charge 2/3 spinless leptoquark, χ, decays either into $s\mu^+$ or $c\overline{\nu}$: B($\chi \rightarrow s\mu^+$) + B($\chi \rightarrow c\overline{\nu}$) = 1.

MASS LIMITS for Leptoquarks from Single Production

These limits depend on the q-ℓ-leptoquark coupling g_{LQ}. It is often assumed that $g^2_{LQ}/4\pi$=1/137. Limits shown are for a scalar, weak isoscalar, charge $-1/3$ leptoquark.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>230	95	[174] AHMED	94B	H1	First generation
> 73	95	[175] ABREU	93J	DLPH	Second generation

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 65	95	[175] ABREU	93J	DLPH	First generation
>181	95	[176] ABT	93	H1	First generation
>168	95	[177] DERRICK	93	ZEUS	First generation

[174] AHMED 94B limit is for the left-handed leptoquark decaying to eq and νq with $B(eq) = B(\nu q)=1/2$. Electromagnetic coupling strength is assumed for the scalar leptoquark interaction. For limits on states with different quantum numbers and the limits in the coupling-mass plane, see their Table 2 and Fig. 6.

[175] Limit from single production in Z decay. The limit is for a leptoquark coupling of electromagnetic strength and assumes $B(\ell q) = 2/3$. The limit is 77 GeV if first and second leptoquarks are degenerate.

[176] ABT 93 search for single leptoquark production in ep collisions with the decays eq and νq. The limit is for a leptoquark coupling of electromagnetic strength and assumes $B(eq) = B(\nu q) = 1/2$. The limit for $B(eq) = 1$ is 178 GeV. For limits on states with different quantum numbers, see their Fig. 2. ABT 93 superseded by AHMED 94B.

[177] DERRICK 93 search for single leptoquark production in ep collisions with the decay eq and νq. The limit is for leptoquark coupling of electromagnetic strength and assumes $B(eq) = B(\nu q) = 1/2$. The limit for $B(eq) = 1$ is 176 GeV. For limits on states with different quantum numbers, see their Table 3.

Indirect Limits for Leptoquarks

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 0.31	95	[178] AID	95	H1	First generation
		[179] MIZUKOSHI	95	RVUE	Third generation leptoquark
> 0.3	95	[180] BHATTACH...	94	RVUE	Spin-0 leptoquark coupled to $\overline{e}_R t_L$
		[181] DAVIDSON	94	RVUE	
> 18		[182] KUZNETSOV	94	RVUE	Pati-Salam type
> 0.43	95	[183] LEURER	94	RVUE	First generation spin-1 leptoquark
> 0.44	95	[183] LEURER	94B	RVUE	First generation spin-0 leptoquark
		[184] MAHANTA	94	RVUE	P and T violation
>350		[185] DESHPANDE	83	RVUE	Pati-Salam X-boson
> 1		[186] SHANKER	82	RVUE	Nonchiral spin-0 leptoquark
>125		[186] SHANKER	82	RVUE	Nonchiral spin-1 leptoquark

[178] AID 95 limit is for the weak isotriplet spin-1 leptoquark with the electromagnetic coupling strength. For the limits of leptoquarks with different quantum number, see their Table 2. AID 95 limits are from the measurements of the Q^2 spectrum measurement of $ep \to eX$.

[179] MIZUKOSHI 95 calculate the one-loop radiative correction to the Z-physics parameters in various leptoquark models. See their Fig. 4 for the exclusion plot of third generation leptoquark models in mass-coupling plane.

[180] BHATTACHARYYA 94 limit is from one-loop radiative correction to the leptonic decay width of the Z. m_H=250 GeV, $\alpha_s(m_Z)$=0.12, m_t=180 GeV, and the electroweak strength of leptoquark coupling are assumed. For leptoquark coupled to $\overline{e}_L t_R$, $\overline{\mu} t$, and $\overline{\tau} t$, see Fig. 2 in BHATTACHARYYA 94B erratum and Fig. 3.

[181] DAVIDSON 94 gives an extensive list of the bounds on leptoquark-induced four-fermion insteractions from π, K, D, B, μ, τ decays and meson mixings, *etc.* See Table 15 of DAVIDSON 94 for detail.

[182] KUZNETSOV 94 gives mixing independent bound of the Pati-Salam leptoquark from the cosmological limit on $\pi^0 \to \overline{\nu}\nu$.

[183] LEURER 94, LEURER 94B limits are obtained from atomic parity violation and apply to any chiral leptoquark which couples to the first generation with electromagnetic strength. For a nonchiral leptoquark, universality in $\pi_{\ell 2}$ decay provides a much more stringent bound. See also SHANKER 82.

[184] MAHANTA 94 gives bounds of P- and T-violating scalar-leptoquark couplings from atomic and molecular experiments.

[185] DESHPANDE 83 used upper limit on $K^0_L \to \mu e$ decay with renormalization-group equations to estimate coupling at the heavy boson mass. See also DIMOPOULOS 81.

[186] From $(\pi \to e\nu)/(\pi \to \mu\nu)$ ratio. SHANKER 82 assumes the leptoquark induced four-fermion coupling $4g^2/M^2$ $(\overline{\nu}_{eL}\, u_R)$ $(\overline{d}_L\, e_R)$with g=0.004 for spin-0 leptoquark and g^2/M^2 $(\overline{\nu}_{eL}\, \gamma_\mu u_L)$ $(\overline{d}_R\, \gamma^\mu e_R)$ with $g\simeq$ 0.6 for spin-1 leptoquark.

MASS LIMITS for Diquarks

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 15–31.7	95	[187] ABREU	94O	DLPH	SUSY E_6 diquark

[187] ABREU 94O limit is from $e^+e^- \to \overline{c}\overline{s}cs$. Range extends up to 43 GeV if diquarks are degenerate in mass.

MASS LIMITS for g_A (axigluon)

Axigluons are massive color-octet gauge bosons in chiral color models and have axial-vector coupling to quarks with the same coupling strength as gluons.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 200–870	95	[188] ABE	95N	CDF	$p\overline{p} \to g_A X$, $g_A \to q\overline{q}$
none 240–640	95	[189] ABE	93G	CDF	$p\overline{p} \to g_A X$, $g_A \to$ 2jets
>50	95	[190] CUYPERS	91	RVUE	$\sigma(e^+e^- \to$ hadrons)
none 120–210	95	[191] ABE	90H	CDF	$p\overline{p} \to g_A X$, $g_A \to$ 2jets
>29		[192] ROBINETT	89	THEO	Partial-wave unitarity
none 150–310	95	[193] ALBAJAR	88B	UA1	$p\overline{p} \to g_A X$, $g_A \to$ 2jets
>20		BERGSTROM	88	RVUE	$p\overline{p} \to \Upsilon X$ via $g_A g$
> 9		[194] CUYPERS	88	RVUE	Υ decay
>25		[195] DONCHESKI	88B	RVUE	Υ decay

[188] ABE 95N assume axigluons decaying to quarks in the Standard Model only.

[189] ABE 93G assume $\Gamma(g_A) = N\alpha_s m_{g_A}/6$ with $N = 10$.

[190] CUYPERS 91 compare α_s measured in Υ decay and that from R at PEP/PETRA energies.

[191] ABE 90H assumes $\Gamma(g_A) = N\alpha_s m_{g_A}/6$ with $N = 5$ $(\Gamma(g_A) = 0.09 m_{g_A})$. For $N = 10$, the excluded region is reduced to 120–150 GeV.

[192] ROBINETT 89 result demands partial-wave unitarity of $J = 0$ $t\overline{t} \to t\overline{t}$ scattering amplitude and derives a limit $m_{g_A} > 0.5\ m_t$. Assumes $m_t > 56$ GeV.

[193] ALBAJAR 88B result is from the nonobservation of a peak in two-jet invariant mass distribution. $\Gamma(g_A) < 0.4\ m_{g_A}$ assumed. See also BAGGER 88.

[194] CUYPERS 88 requires $\Gamma(\Upsilon \to g g_A) < \Gamma(\Upsilon \to ggg)$. A similar result is obtained by DONCHESKI 88.

[195] DONCHESKI 88B requires $\Gamma(\Upsilon \to g q\overline{q})/\Gamma(\Upsilon \to ggg) < 0.25$, where the former decay proceeds via axigluon exchange. A more conservative estimate of < 0.5 leads to $m_{g_A} > 21$ GeV.

X^0 (Heavy Boson) Searches in Z Decays

Searches for radiative transition of Z to a lighter spin-0 state X^0 decaying to hadrons, a lepton pair, or a photon pair as shown in the comments. The limits are for the product of branching ratios.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[196] ACTON	93E	OPAL	$X^0 \to \gamma\gamma$
		[197] ABREU	92D	DLPH	$X^0 \to$ hadrons
		[198] ADRIANI	92F	L3	$X^0 \to$ hadrons
		[199] ACTON	91	OPAL	$X^0 \to$ anything
$<1.1 \times 10^{-4}$	95	[200] ACTON	91B	OPAL	$X^0 \to e^+e^-$
$<9 \times 10^{-5}$	95	[200] ACTON	91B	OPAL	$X^0 \to \mu^+\mu^-$
$<1.1 \times 10^{-4}$	95	[200] ACTON	91B	OPAL	$X^0 \to \tau^+\tau^-$
$<2.8 \times 10^{-4}$	95	[201] ADEVA	91D	L3	$X^0 \to e^+e^-$
$<2.3 \times 10^{-4}$	95	[201] ADEVA	91D	L3	$X^0 \to \mu^+\mu^-$
$<4.7 \times 10^{-4}$	95	[202] ADEVA	91D	L3	$X^0 \to$ hadrons
$<8 \times 10^{-4}$	95	[203] AKRAWY	90J	OPAL	$X^0 \to$ hadrons

[196] ACTON 93E give $\sigma(e^+e^- \to X^0\gamma)\cdot B(X^0 \to \gamma\gamma) < 0.4$ pb (95%CL) for m_{X^0}=60 ± 2.5 GeV. If the process occurs via s-channel γ exchange, the limit translates to $\Gamma(X^0)\cdot B(X^0 \to \gamma\gamma)^2$ <20 MeV for $m_{X^0} = 60 \pm 1$ GeV.

[197] ABREU 92D give $\sigma_Z \cdot B(Z \to \gamma X^0) \cdot B(X^0 \to$ hadrons) <(3–10) pb for m_{X^0} = 10–78 GeV. A very similar limit is obtained for spin-1 X^0.

[198] ADRIANI 92F search for isolated γ in hadronic Z decays. The limit $\sigma_Z \cdot B(Z \to \gamma X^0) \cdot B(X^0 \to$ hadrons) <(2–10) pb (95%CL) is given for m_{X^0} = 25–85 GeV.

[199] ACTON 91 searches for $Z \to Z^* X^0$, $Z^* \to e^+e^-$, $\mu^+\mu^-$, or $\nu\overline{\nu}$. Excludes any new scalar X^0 with $m_{X^0} < 9.5$ GeV/c if it has the same coupling to ZZ^* as the MSM Higgs boson.

[200] ACTON 91B limits are for m_{X^0} = 60–85 GeV.

[201] ADEVA 91D limits are for m_{X^0} = 30–89 GeV.

[202] ADEVA 91D limits are for m_{X^0} = 30–86 GeV.

[203] AKRAWY 90J give $\Gamma(Z \to \gamma X^0)\cdot B(X^0 \to$ hadrons) < 1.9 MeV (95%CL) for m_{X^0} = 32–80 GeV. We divide by $\Gamma(Z) = 2.5$ GeV to get product of branching ratios. For nonresonant transitions, the limit is $B(Z \to \gamma q\overline{q}) < 8.2$ MeV assuming three-body phase space distribution.

MASS LIMITS for a Heavy Neutral Boson Coupling to e^+e^-

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 55–61		[204] ODAKA	89	VNS	$\Gamma(X^0 \to e^+e^-) \cdot B(X^0 \to \text{hadrons}) \gtrsim 0.2$ MeV
>45	95	[205] DERRICK	86	HRS	$\Gamma(X^0 \to e^+e^-)$=6 MeV
>46.6	95	[206] ADEVA	85	MRKJ	$\Gamma(X^0 \to e^+e^-)$=10 keV
>48	95	[206] ADEVA	85	MRKJ	$\Gamma(X^0 \to e^+e^-)$=4 MeV
		[207] BERGER	85B	PLUT	
none 39.8–45.5		[208] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+e^-)$=10 keV
>47.8	95	[208] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+e^-)$=4 MeV
none 39.8–45.2		[208] BEHREND	84C	CELL	
>47	95	[208] BEHREND	84C	CELL	$\Gamma(X^0 \to e^+e^-)$=4 MeV

[204] ODAKA 89 looked for a narrow or wide scalar resonance in $e^+e^- \to$ hadrons at E_{cm} = 55.0–60.8 GeV.

[205] DERRICK 86 found no deviation from the Standard Model Bhabha scattering at E_{cm}= 29 GeV and set limits on the possible scalar boson e^+e^- coupling. See their figure 4 for excluded region in the $\Gamma(X^0 \to e^+e^-)$-m_{X^0} plane. Electronic chiral invariance requires a parity doublet of X^0, in which case the limit applies for $\Gamma(X^0 \to e^+e^-)$ = 3 MeV.

[206] ADEVA 85 first limit is from 2γ, $\mu^+\mu^-$, hadrons assuming X^0 is a scalar. Second limit is from e^+e^- channel. E_{cm} = 40–47 GeV. Supersedes ADEVA 84.

[207] BERGER 85B looked for effect of spin-0 boson exchange in $e^+e^- \to e^+e^-$ and $\mu^+\mu^-$ at E_{cm} = 34.7 GeV. See Fig. 5 for excluded region in the $m_{X^0} - \Gamma(X^0)$ plane.

[208] ADEVA 84 and BEHREND 84C have E_{cm} = 39.8–45.5 GeV. MARK-J searched X^0 in $e^+e^- \to$ hadrons, 2γ, $\mu^+\mu^-$, e^+e^- and CELLO in the same channels plus τ pair. No narrow or broad X^0 is found in the energy range. They also searched for the effect of X^0 with $m_X > E_{cm}$. The second limits are from Bhabha data and for spin-0 singlet. The same limits apply for $\Gamma(X^0 \to e^+e^-)$ = 2 MeV if X^0 is a spin-0 doublet. The second limit of BEHREND 84C was read off from their figure 2. The original papers also list limits in other channels.

Search for X^0 Resonance in e^+e^- Collisions

The limit is for $\Gamma(X^0 \to e^+e^-) \cdot B(X^0 \to f)$, where f is the specified final state. Spin 0 is assumed for X^0.

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<10^3$	95	[209] ABE	93C	VNS	$\Gamma(ee)$
<(0.4–10)	95	[210] ABE	93C	VNS	$f = \gamma\gamma$
<(0.3–5)	95	[211,212] ABE	93D	TOPZ	$f = \gamma\gamma$
<(2–12)	95	[211,212] ABE	93D	TOPZ	f = hadrons
<(4–200)	95	[212,213] ABE	93D	TOPZ	$f = ee$
<(0.1–6)	95	[212,213] ABE	93D	TOPZ	$f = \mu\mu$
<(0.5–8)	90	[214] STERNER	93	AMY	$f = \gamma\gamma$

[209] Limit is for $\Gamma(X^0 \to e^+e^-)$ m_{X^0} = 56–63.5 GeV for $\Gamma(X^0)$ = 0.5 GeV.

[210] Limit is for m_{X^0} = 56–61.5 GeV and is valid for $\Gamma(X^0) \ll$ 100 MeV. See their Fig. 5 for limits for Γ = 1,2 GeV.

[211] Limit is for m_{X^0} = 57.2–60 GeV.

[212] Limit is valid for $\Gamma(X^0) \ll$ 100 MeV. See paper for limits for Γ = 1 GeV and those for J = 2 resonances.

[213] Limit is for m_{X^0} = 56.6–60 GeV.

[214] STERNER 93 limit is for m_{X^0} = 57–59.6 GeV and is valid for $\Gamma(X^0)$<100 MeV. See their Fig. 2 for limits for Γ = 1,3 GeV.

Search for X^0 Resonance in Two-Photon Process

The limit is for $\Gamma(X^0) \cdot B(X^0 \to \gamma\gamma)^2$. Spin 0 is assumed for X^0.

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.6	95	[215] ACTON	93E	OPAL	m_{X^0}=60 ± 1 GeV
<2.9	95	BUSKULIC	93F	ALEP	$m_{X^0} \sim$ 60 GeV

[215] ACTON 93E limit for a J = 2 resonance is 0.8 MeV.

Search for X^0 Resonance in $Z \to f\overline{f}X^0$

The limit is for $B(Z \to f\overline{f}X^0) \cdot B(X^0 \to F)$ where f is a fermion and F is the specified final state. Spin 0 is assumed for X^0.

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6.8 \times 10^{-6}$	95	[216] ACTON	93E	OPAL	f=e,μ,τ; F=$\gamma\gamma$
$<5.5 \times 10^{-6}$	95	[216] ACTON	93E	OPAL	f=q; F=$\gamma\gamma$
$<3.1 \times 10^{-6}$	95	[216] ACTON	93E	OPAL	f=ν; F=$\gamma\gamma$
$<6.5 \times 10^{-6}$	95	[216] ACTON	93E	OPAL	f=e,μ; F=$\ell\overline{\ell}$, $q\overline{q}$, $\nu\overline{\nu}$
$<7.1 \times 10^{-6}$	95	[216] BUSKULIC	93F	ALEP	f=e,μ; F=$\ell\overline{\ell}$, $q\overline{q}$, $\nu\overline{\nu}$
		[217] ADRIANI	92F	L3	f=q; F=$\gamma\gamma$

[216] Limit is for m_{X^0} around 60 GeV.

[217] ADRIANI 92F give $\sigma_Z \cdot B(Z \to q\overline{q}X^0) \cdot B(X^0 \to \gamma\gamma)$<(0.75–1.5) pb (95%CL) for m_{X^0} = 10–70 GeV. The limit is 1 pb at 60 GeV.

Heavy Particle Production in Quarkonium Decays

Limits are for branching ratios to modes shown.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.5 \times 10^{-5}$	90	[218] BALEST	95	CLE2	$\Upsilon(1S) \to X^0\gamma$, m_{X^0} < 5 GeV
$< 3 \times 10^{-5}$–6×10^{-3}	90	[219] BALEST	95	CLE2	$\Upsilon(1S) \to X^0\overline{X}^0\gamma$, m_{X^0} < 3.9 GeV
$<5.6 \times 10^{-5}$	90	[220] ANTREASYAN	90C	CBAL	$\Upsilon(1S) \to X^0\gamma$, m_{X^0} < 7.2 GeV
		[221] ALBRECHT	89	ARG	

[218] BALEST 95 two-body limit is for pseudoscalar X^0. The limit becomes < 10^{-4} for m_{X^0} < 7.7 GeV.

[219] BALEST 95 three-body limit is for phase-space photon energy distribution and angular distribution same as for $\Upsilon \to gg\gamma$.

[220] ANTREASYAN 90C assume that X^0 does not decay in the detector.

[221] ALBRECHT 89 give limits for $B(\Upsilon(1S), \Upsilon(2S) \to X^0\gamma) \cdot B(X^0 \to \pi^+\pi^-, K^+K^-, p\overline{p})$ for m_{X^0} < 3.5 GeV.

REFERENCES FOR Searches for Heavy Bosons Other Than Higgs Bosons

ABACHI	95E	PL B358 405	+Abbott, Abolins, Acharya, Adam, Adams+	(D0 Collab.)
ABACHI	95G	PRL 75 3618	+Abbott, Abolins, Acharya, Adam, Adams+	(D0 Collab.)
ABE	95	PR D51 R949	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABE	95M	PRL 74 2900	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABE	95N	PRL 74 3538	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ABE	95U	PRL 75 1012	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ABREU	95M	ZPHY C65 603	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
AID	95	PL B353 578	+Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
BALEST	95	PR D51 2053	+Cho, Ford, Johnson+	(CLEO Collab.)
KUZNETSOV	95	PRL 75 794	+Serebrov, Stepanenko+	(PNPI, KIAE, HARV, NIST)
MIZUKOSHI	95	NP B444 20	+Eboli, Gonzalez-Garcia	(SPAUL, CERN)
NARDI	95	PL B344 225	+Roulet, Tommasini	(MICH, CERN)
ABACHI	94B	PRL 72 965	+Abbott, Abolins, Acharya, Adam+	(D0 Collab.)
ABREU	94O	ZPHY C64 183	+Adam, Adye, Agasi, Ajinenko, Aleksan+	(DELPHI Collab.)
AHMED	94B	ZPHY C64 545	+Aid, Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
BHATTACH...	94	PL B336 100	Bhattacharyya, Ellis, Sridhar	(CERN)
Also	94B	PL B338 522 (erratum)	Bhattacharyya, Ellis, Sridhar	(CERN)
BHATTACH...	94B	PL B338 522 (erratum)	Bhattacharyya, Ellis, Sridhar	(CERN)
BUSKULIC	94	ZPHY C62 539	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
DAVIDSON	94	ZPHY C61 613	+Bailey, Campbell	(CFPA, TNTO, ALBE)
KUZNETSOV	94	PL B329 295	+Mikheev	(YARO)
KUZNETSOV	94B	JETPL 60 315	+Serebrov, Stepanenko+	(PNPI, KIAE, HARV, NIST)
		Translated from ZETFP 60 311.		
LEURER	94	PR D50 536		(REHO)
LEURER	94B	PR D49 333		(REHO)
Also	93	PRL 71 1324	Leurer	(REHO)
MAHANTA	94	PL B337 128		(MEHTA)
SEVERIJNS	94	PRL 73 611 (erratum)	+	(LOUV, WISC, LEUV, ETH, MASA)
VILAIN	94B	PL B332 465	+Wilquet, Beyer, Flegel, Grote+	(CHARM II Collab.)
ABE	93C	PL B302 119	+Amako, Arai, Arima, Asano, Chiba+	(VENUS Collab.)
ABE	93D	PL B304 373	+Adachi, Awa, Aoki, Belusevic, Emi+	(TOPAZ Collab.)
ABE	93G	PRL 71 2542	+Albrow, Akimoto, Amidei, Anway-Wiese+	(CDF Collab.)
ABE	93I	PR D48 R3939	+Albrow, Amidei, Anway-Wiese, Apollinari+	(CDF Collab.)
ABREU	93J	PL B316 620	+Adam, Adye, Agasi, Aleksan, Alekseev+	(DELPHI Collab.)
ABT	93	NP B396 3	+Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
ACTON	93E	PL B311 391	+Akers, Alexander+	(OPAL Collab.)
ADRIANI	93D	PL B306 187	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ALITTI	93	NP B400 3	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALLEN	93	PR D47 11	+Chen, Doe, Hausammann+	(UCI, LANL, ANL, UMD)
ALTARELLI	93B	PL B318 139	+Casalbuoni+	(CERN, FIRZ, GEVA, PADO)
BHATTACH...	93	PR D47 R3693	Bhattacharyya+	(CALC, JADA, ICTP, AHMED, BOSE)
BUSKULIC	93F	PL B308 425	+De Bonis, Decamp, Chez, Goy, Lees+	(ALEPH Collab.)
DERRICK	93	PL B306 173	+Krakauer, Magill, Musgrave, Repond+	(ZEUS Collab.)
RIZZO	93	PR D48 4470		(ANL)
SEVERIJNS	93	PRL 70 4047	+Gimeno-Nogues+	(LOUV, WISC, LEUV, ETH, MASA)
Also	94	PRL 73 611 (erratum)	Severijns+	(LOUV, WISC, LEUV, ETH, MASA)
STERNER	93	PL B303 385	+Abashian, Gotow, Haim, Mattson, Morgan+	(AMY Collab.)
ABE	92B	PRL 68 1463	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	92D	ZPHY C53 555	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ABREU	92F	PL B275 222	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ADRIANI	92F	PL B292 472	+Aguilar-Benitez, Ahlen, Akbari, Alcarez+	(L3 Collab.)
ALITTI	92E	PL B274 507	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
DECAMP	92	PRPL 216 253	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
DELAGUILA	92	NP B372 3	del Aguila+	(CERN, GRAN, MPIM, BRUXT, MADE)
Also	91C	NP B361 45	del Aguila, Moreno, Quiros	(BARC, MADE)
IMAZATO	92	PRL 69 877	+Kawashima, Tanaka+	(KEK, INUS, TOKY, TOKMS)
LANGACKER	92B	PR D45 278	+Luo	(PENN)
LAYSSAC	92	ZPHY C53 97	+Renard, Verzegnassi	(MONP, LAPP)
LAYSSAC	92B	PL B287 267	+Renard, Verzegnassi	(MONP, TRSTT)
LEIKE	92	PL B291 187	+Riemann, Riemann	(BERL, CERN)
LEP	92	PL B276 247	+ALEPH, DELPHI, L3, OPAL	(LEP Collabs.)
MISHRA	92	PRL 68 3499	+Leung, Arroyo+	(COLU, CHIC, FNAL, ROCH, WISC)
POLAK	92	PL B276 492	+Zralek	(SILES)
POLAK	92B	PR D46 3871	+Zralek	(SILES)
RENTON	92	ZPHY C56 355		(OXF)
ABE	91D	PRL 67 2418	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	91F	PRL 67 2609	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ACTON	91	PL B268 122	+Alexander, Allison, Allport+	(OPAL Collab.)
ACTON	91B	PL B273 338	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ADEVA	91B	PL B261 169	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	91D	PL B262 155	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ALEXANDER	91	PL B263 123	+Allison, Allport, Anderson, Arcelli+	(OPAL Collab.)
ALITTI	91	ZPHY C49 17	+Ansari, Ansorge, Autiero, Bareyre+	(UA2 Collab.)
ALTARELLI	91	PL B261 146	+Casalbuoni, De Curtis+	(CERN, FIRZ, GEVA)
ALTARELLI	91B	PL B263 459	+Casalbuoni, De Curtis+	(CERN, FIRZ, GEVA)
Also	90	PL B245 669	Altarelli, Casalbuoni, Feruglio, Gatto	(CERN, LECE, GEVA)
AQUINO	91	PL B261 280	+Fernandez, Garcia	(CINV, PUEB)
BUCHMUEL...	91	PL B267 395	Buchmueller, Greub, Minkowski	(DESY, BERN)
COLANGELO	91	PL B253 154	+Nardulli	(BARI)
CUYPERS	91	PL B259 173	+Falk, Frampton	(DURH, HARV, UNCCH)
DELAGUILA	91	PL B254 497	del Aguila, Moreno, Quiros	(BARC, MADE, CERN)
FARAGGI	91	MPL A6 61	+Nanopoulos	(TAMU)
GEIREGAT	91	PL B259 499	+Vilain, Wilquet, Binder, Burkard+	(CHARM II Collab.)
GONZALEZ-G...	91	PL B259 365	Gonzalez-Garcia, Valle	(VALE)
Also	90C	NP B345 312	Gonzalez-Garcia, Valle	(VALE)
MAHANTHAP...	91	PR D43 3093	Mahanthappa, Mohapatra	(COLO)
Also	91B	PR D44 1616 erratum	Mahanthappa, Mohapatra	(COLO)

POLAK	91	NP B363 385	+Zralek	(SILES)
RIZZO	91	PR D44 202		(WISC, ISU)
WALKER	91	APJ 376 51	+Steigman, Schramm, Olive+	(HSCA, OSU, CHIC, MINN)
ABE	90F	PL B246 297	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ABE	90G	PRL 65 2243	+Amidei, Apollinari, Atac+	(CDF Collab.)
ABE	90H	PR D41 1722	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
AKRAWY	90J	PL B246 285	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALLEN	90	PRL 64 1330	+Chen, Doe+	(UCI, LASL, UMD)
ANTREASYAN	90C	PL B251 204	+Bartels, Besset, Bieler, Bienlein+	(Crystal Ball Collab.)
BARGER	90B	PR D42 152	+Hewett, Rizzo	(WISC, ISU)
GLASHOW	90	PR D42 3224	+Sarid	(HARV)
GLASHOW	90B	PRL 64 725	+Sarid	(HARV)
GONZALEZ-G...	90D	PL B240 163	Gonzalez-Garcia, Valle	(VALE)
GRIFOLS	90	NP B331 244	+Masso	(BARC)
GRIFOLS	90C	MPL A5 2657		(BARC)
GRIFOLS	90D	PR D42 3293	+Masso, Rizzo	(BARC, CERN, WISC, ISU)
HAGIWARA	90	PR D41 815	+Najima, Sakuda, Terunuma	(KEK, DURH, YCC, HIRO)
HE	90B	PL B240 441	+Joshi, Volkas	(MELB)
Also	90C	PL B244 580 erratum	He, Joshi, Volkas	(MELB)
KIM	90	PL B240 243	+Breedon, Ko, Lander, Maeshima, Malchow+	(AMY Collab.)
LOPEZ	90	PL B241 392	+Nanopoulos	(TAMU)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
ALBRECHT	89	ZPHY C42 349	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
BARBIERI	89B	PR D39 1229	+Mohapatra	(PISA, UMD)
DELAGUILA	89	PR D40 2481	del Aguila, Moreno, Quiros	(BARC, MADE)
Also	90B	PR D41 134	del Aguila, Moreno, Quiros	(BARC, MADE)
Also	90C	PR D42 262 erratum	del Aguila, Moreno, Quiros	(BARC, MADE)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
GEIREGAT	89	PL B232 539	+Vilain, Wilquet, Bergsma, Binder+	(CHARM II Collab.)
LANGACKER	89B	PR D40 1569	+Uma Sankar	(PENN)
ODAKA	89	JPSJ 58 3037	+Kondo, Abe, Amako+	(VENUS Collab.)
ROBINETT	89	PR D39 834		(PSU)
ALBAJAR	88B	PL B209 127	+Albrow, Allkofer, Astbury, Aubert+	(UA1 Collab.)
BAGGER	88	PR D37 1188	+Schmidt, King	(HARV, BOST)
BALKE	88	PR D37 587	+Gidal, Jodidio+	(LBL, UCB, COLO, NWES, TRIU)
BERGSTROM	88	PL B212 386		(STOH)
COSTA	88	NP B297 244	+Ellis, Fogli+	(PADO, CERN, BARI, WISC, LBL)
CUYPERS	88	PRL 60 1237	+Frampton	(UNCCH)
DONCHESKI	88	PL B206 137	+Grotch, Robinett	(PSU)
DONCHESKI	88B	PR D38 412	+Grotch, Robinett	(PSU)
ELLIS	88	PL B202 417	Ellis, Franzini, Zwirner	(CERN, UCB, LBL)
RAFFELT	88	PRL 60 1793	+Seckel	(UCB, LLL, UCSC)
AMALDI	87	PR D36 1385	+Bohm, Durkin, Langacker+	(CERN, AACH3, OSU+)
ANSARI	87D	PL B195 613	+Bagnaia, Banner+	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	+Becker, Felst+	(JADE Collab.)
MARCIANO	87	PR D35 1672	+Sirlin	(BNL, NYU)
ARNISON	86B	EPL 1 327	+Albrow, Allkofer+	(UA1 Collab.)
BARGER	86B	PRL 56 30	+Deshpande, Whisnant	(WISC, OREG, FSU)
BEHREND	86B	PL B178 452	+Buerger, Criegee, Fenner, Field+	(CELLO Collab.)
DERRICK	86	PL 166B 463	+Gan, Kooijman, Loos+	(HRS Collab.)
Also	86B	PR D34 3286	Derrick, Gan, Kooijman, Loos, Musgrave+	(HRS Collab.)
DURKIN	86	PL 166B 436	+Langacker	(PENN)
ELLIS	86	PL 167B 457	+Enqvist, Nanopoulos, Sarkar	(CERN, OXFTP)
JODIDIO	86	PR D34 1967	+Balke, Carr, Gidal, Shinsky+	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	Jodidio, Balke, Carr+	(LBL, NWES, TRIU)
MOHAPATRA	86	PR D34 909		(UMD)
STEIGMAN	86	PL B176 33	+Olive, Schramm, Turner	(BART, MINN+)
ADEVA	85	PL 152B 439	+Becker, Becker-Szendy+	(Mark-J Collab.)
ADEVA	85B	PRL 55 665	+Becker, Becker-Szendy+	(Mark-J Collab.)
BERGER	85B	ZPHY C27 341	+Deuter, Genzel, Lackas, Pielorz+	(PLUTO Collab.)
STOKER	85	PRL 54 1887	+Balke, Carr, Gidal+	(LBL, NWES, TRIU)
ADEVA	84	PRL 53 134	+Barber, Becker, Berdugo+	(Mark-J Collab.)
BEHREND	84C	PL 140B 130	+Burger, Criegee, Fenner+	(CELLO Collab.)
ARNISON	83D	PL 129B 273	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BERGSMA	83	PL 122B 465	+Dorenbosch, Jonker+	(CHARM Collab.)
CARR	83	PRL 51 627	+Gidal, Gobbi, Jodidio, Oram+	(LBL, NWES, TRIU)
DESHPANDE	83	PR D27 1193	+Johnson	(OREG)
BEALL	82	PRL 48 848	+Bander, Soni	(UCI, UCLA)
SHANKER	82	NP B204 375		(TRIU)
DIMOPOUL...	81	NP B182 77	Dimopoulos, Raby, Kane	(STAN, MICH)
RIZZO	81	PR D24 704	+Senjanovic	(BNL)
STEIGMAN	79	PRL 43 239	+Olive, Schramm	(BART, EFI)

Axions (A^0) and Other Very Light Bosons, Searches for

AXIONS AND OTHER VERY LIGHT BOSONS

In this section we list limits for very light neutral (pseudo) scalar bosons that couple weakly to stable matter. These have been proposed to solve a variety of mostly theoretical concerns. Typical examples are pseudo-Goldstone bosons like axions (A^0) [1], familons [2], and Majorons [3,4], associated, respectively, with spontaneously broken Peccei-Quinn [5], family, and lepton-number symmetries.

In QCD, SU(3) gauge invariance does not forbid a term $\theta(g_s^2/32\pi^2)F^{\mu\nu a}\widetilde{F}^a_{\mu\nu}$ in Lagrangian. However, CP invariance is broken if $\theta \neq 0$ or π, and the parameter θ has to be small $\lesssim 10^{-9}$ in order not to generate too large elecric dilopole moment of neutron. This is called strong CP problem. Peccei-Quinn symmetry gives a natural solution to the strong CP problem. The axion mass and its coupling to stable particles are inversely proportional to the scale of Peccei-Quinn symmetry breaking, f_A. The original axion model [1,5] assumed $f_A \sim v$, where $v = (\sqrt{2}G_F)^{-1/2} = 247$ GeV is the scale of the electroweak symmetry breaking, and had two Higgs doublets as minimal ingredients. By requiring tree-level flavor conservation, the axion mass and its couplings were completely fixed in terms of one parameter, the ratio of the vacuum expectation values of the two Higgs fields. The result of extensive experimental searches for such an axion have been negative [6].

Observation of a narrow-peak structure in positron spectra from heavy ion collisions [7] suggested a particle of mass 1.8 MeV that decays into e^+e^-. Variants of the original axion model, which keep $f_A \sim v$, but drop the constraints of tree-level flavor conservation, were proposed [8]. Extensive searches for this particle, A^0(1.8 MeV), ended up with another negative result [9].

Another way to save the Peccei-Quinn idea is to introduce a new scale $f_A \gg v$. Then the A^0 mass becomes smaller and its coupling weaker, thus one can easily avoid all the existing experimental limits; such models are called invisible axion models [10,11]. See the note on Invisible Axions later in this section.

Familons arise when there is a global horizontal symmetry (a symmetry which interchanges different generations) broken spontaneously. They could be either scalars or pseudoscalars. An SU(3) horizontal symmetry among three generations is non-anomalous and hence the familons are exactly massless. In this case, familons are scalars. If one has larger horizontal symmetries with separate groups of left-handed and right-handed fields, one also has pseudo-scalar familons. Some of them have flavor-off-diagonal couplings such as $\partial_\mu\phi_F\bar{d}\gamma^\mu s/F$ or $\partial_\mu\phi_F\bar{e}\gamma^\mu\mu/F$, and the decay constant F can be different for individual operators. The decay constants have lower bounds constrained by flavor-changing processes. For instance, $B(K^+ \to \pi^+\phi_F) < 1.7 \times 10^{-9}$ [12] gives $F_{K\pi} > 1.3 \times 10^{11}$ GeV [2].

If there is a global lepton number symmetry and if it breaks spontaneously, there is a Majoron. The triplet Majoron model [4] has a weak-triplet Higgs boson, and the Majoron couples to Z. The original version is now excluded by the invisible Z decay width. The model would remain viable if there were an additional singlet Higgs boson and if the Majoron were mainly a singlet [13]. In the singlet Majoron model [3], lepton number symmetry is broken by a weak-singlet scalar field, and there are right-handed neutrinos that acquire Majorana masses. The left-handed neutrino masses are generated by a "seesaw" mechanism [14]. The scale of lepton number breaking can be much higher than the electroweak scale in this case. Astrophysical constraints require the decay constant to be $\gtrsim 10^9$ GeV [15].

Other light bosons (scalar, pseudoscalar or vector) are constrained by "fifth force" experiments. For a compilation of constraints, see [16].

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A^0 (Axion) MASS LIMITS from Astrophysics and Cosmology

These bounds depend on model-dependent assumptions (i.e. — on a combination of axion parameters).

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.2	BARROSO	82	ASTR	Standard Axion
>0.25	[1] RAFFELT	82	ASTR	Standard Axion
>0.2	[2] DICUS	78C	ASTR	Standard Axion
	MIKAELIAN	78	ASTR	Stellar emission
>0.3	[2] SATO	78	ASTR	Standard Axion
>0.2	VYSOTSKII	78	ASTR	Standard Axion

[1] Lower bound from 5.5 MeV γ-ray line from the sun.

[2] Lower bound from requiring the red giants' stellar evolution not be disrupted by axion emission.

A^0 (Axion) and Other Light Boson (X^0) Searches in Stable Particle Decays

Limits are for branching ratios.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<6 \times 10^{-5}$	90		[3] AMSLER	94B	CBAR	$\pi^0 \to \gamma X^0$, m_{X^0}=65–125 MeV
$<6 \times 10^{-5}$	90		[3] AMSLER	94B	CBAR	$\eta \to \gamma X^0$, m_{X^0}=200–525 MeV
<0.007	90		[4] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=25 MeV
<0.002	90		[4] MEIJERDREES	94	CNTR	$\pi^0 \to \gamma X^0$, m_{X^0}=100 MeV
$<1.7 \times 10^{-9}$	90		[5] ATIYA	93	B787	$K^+ \to \pi^+ A^0$
$<2 \times 10^{-7}$	90		[6] ATIYA	93B	B787	$K^+ \to \pi^+ A^0$
$<3 \times 10^{-13}$			[7] NG	93	COSM	$\pi^0 \to \gamma X^0$
$<1.1 \times 10^{-8}$	90		[8] ALLIEGRO	92	SPEC	$K^+ \to \pi^+ A^0$ ($A^0 \to e^+ e^-$)
$<5 \times 10^{-4}$	90		[9] ATIYA	92	B787	$\pi^0 \to \gamma X^0$
$<4 \times 10^{-6}$	90		[10] MEIJERDREES	92	SPEC	$\pi^0 \to \gamma X^0$, $X^0 \to e^+ e^-$, m_{X^0}= 100 MeV
$<1 \times 10^{-7}$	90		[11] ATIYA	90B	B787	$K^+ \to \pi^+ A^0$, ($A^0 \to \gamma\gamma$)
$<1.3 \times 10^{-8}$	90		[12] KORENCHE...	87	SPEC	$\pi^+ \to e^+ \nu A^0$ ($A^0 \to e^+ e^-$)
$<1 \times 10^{-9}$	90	0	[13] EICHLER	86	SPEC	Stopped $\pi^+ \to e^+ \nu A^0$
$<2 \times 10^{-5}$	90		[14] YAMAZAKI	84	SPEC	For 160<m<260 MeV
$<(1.5–4) \times 10^{-6}$	90		[14] YAMAZAKI	84	SPEC	K decay, $m_{A^0} \ll$ 100 MeV
		0	[15] ASANO	82	CNTR	Stopped $K^+ \to \pi^+ A^0$
		0	[16] ASANO	81B	CNTR	Stopped $K^+ \to \pi^+ A^0$
			[17] ZHITNITSKII	79		Heavy axion

[3] AMSLER 94B looked for a peak in missing-mass distribution.

[4] The MEIJERDREES 94 limit is based on inclusive photon spectrum and is independent of X^0 decay modes. It applies to $\tau(X^0) > 10^{-23}$ sec.

[5] ATIYA 93 looked for a peak in missing mass distribution. The limit is for massless stable A^0 particles and extends to m_{A^0}=80 MeV at the same level. See paper for dependence on finite lifetime.

[6] ATIYA 93B looked for a peak in missing mass distribution. The bound applies for stable A^0 of m_{A^0}=150–250 MeV, and the limit becomes stronger (10^{-8}) for m_{A^0}=180–240 MeV.

[7] NG 93 studied the production of X^0 via $\gamma\gamma \to \pi^0 \to \gamma X^0$ in the early universe at $T \simeq 1$ MeV. The bound on extra neutrinos from nucleosynthesis $\Delta N_\nu < 0.3$ (WALKER 91) is employed. It applies to $m_{X^0} \ll 1$ MeV in order to be relativistic down to nucleosynthesis temperature. See paper for heavier X^0.

[8] ALLIEGRO 92 limit applies for m_{A^0}=150–340 MeV and is the branching ratio times the decay probability. Limit is $< 1.5 \times 10^{-8}$ at 99%CL.

[9] ATIYA 92 looked for a peak in missing mass distribution. The limit applies to m_{X^0}=0–130 MeV in the narrow resonance limit. See paper for the dependence on lifetime. Covariance requires X^0 to be a vector particle.

[10] MEIJERDREES 92 limit applies for $\tau_{X^0} = 10^{-23}$–10^{-11} sec. Limits between 2×10^{-4} and 4×10^{-6} are obtained for m_{X^0} = 25–120 MeV. Angular momentum conservation requires that X^0 has spin ≥ 1.

[11] ATIYA 90B limit is for $B(K^+ \to \pi^+ A^0) \cdot B(A^0 \to \gamma\gamma)$ and applies for m_{A^0} = 50 MeV, $\tau_{A^0} < 10^{-10}$ s. Limits are also provided for $0 < m_{A^0} < 100$ MeV, $\tau_{A^0} < 10^{-8}$ s.

[12] KORENCHENKO 87 limit assumes m_{A^0} = 1.7 MeV, $\tau_{A^0} \lesssim 10^{-12}$ s, and $B(A^0 \to e^+ e^-) = 1$.

[13] EICHLER 86 looked for $\pi^+ \to e^+ \nu A^0$ followed by $A^0 \to e^+ e^-$. Limits on the branching fraction depend on the mass and and lifetime of A^0. The quoted limits are valid when $\tau(A^0) \gtrsim 3. \times 10^{-10}$s if the decays are kinematically allowed.

[14] YAMAZAKI 84 looked for a discrete line in $K^+ \to \pi^+$X. Sensitive to wide mass range (5–300 MeV), independent of whether X decays promptly or not.

[15] ASANO 82 at KEK set limits for $B(K^+ \to \pi^+ A^0)$ for m_{A^0} <100 MeV as BR $< 4. \times 10^{-8}$ for $\tau(A^0 \to n\gamma\text{'s}) > 1. \times 10^{-9}$ s, BR $< 1.4 \times 10^{-6}$ for $\tau < 1. \times 10^{-9}$s.

[16] ASANO 81B is KEK experiment. Set $B(K^+ \to \pi^+ A^0) < 3.8 \times 10^{-8}$ at CL = 90%.

[17] ZHITNITSKII 79 argue that a heavy axion predicted by YANG 78 (3 <m <40 MeV) contradicts experimental muon anomalous magnetic moments.

A^0 (Axion) Searches in Quarkonium Decays

Decay or transition of quarkonium. Limits are for branching ratio.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.3 \times 10^{-5}$	90		[18] BALEST	95	CLEO	$\Upsilon(1S) \to A^0\gamma$
$<4.0 \times 10^{-5}$	90		ANTREASYAN	90C	CBAL	$\Upsilon(1S) \to A^0\gamma$
			[19] ANTREASYAN	90C	RVUE	
$<5 \times 10^{-5}$	90		[20] DRUZHININ	87	ND	$\phi \to A^0\gamma$ ($A^0 \to e^+ e^-$)
$<2 \times 10^{-3}$	90		[21] DRUZHININ	87	ND	$\phi \to A^0\gamma$ ($A^0 \to \gamma\gamma$)
$<7 \times 10^{-6}$	90		[22] DRUZHININ	87	ND	$\phi \to A^0\gamma$ ($A^0 \to$ missing)
$<3.1 \times 10^{-4}$	90	0	[23] ALBRECHT	86D	ARG	$\Upsilon(1S) \to A^0\gamma$ ($A^0 \to e^+ e^-$)
$<4 \times 10^{-4}$	90	0	[23] ALBRECHT	86D	ARG	$\Upsilon(1S) \to A^0\gamma$ ($A^0 \to \mu^+\mu^-$, $\pi^+\pi^-$, K^+K^-)
$<8 \times 10^{-4}$	90	1	[24] ALBRECHT	86D	ARG	$\Upsilon(1S) \to A^0\gamma$

$<1.3 \times 10^{-3}$	90	0	[25] ALBRECHT 86D	ARG	$\Upsilon(1S) \rightarrow A^0\gamma$ ($A^0 \rightarrow e^+e^-, \gamma\gamma$)
$<2. \times 10^{-3}$	90		[26] BOWCOCK 86	CLEO	$\Upsilon(2S) \rightarrow \Upsilon(1S) \rightarrow A^0$
$<5. \times 10^{-3}$	90		[27] MAGERAS 86	CUSB	$\Upsilon(1S) \rightarrow A^0\gamma$
$<3. \times 10^{-4}$	90		[28] ALAM 83	CLEO	$\Upsilon(1S) \rightarrow A^0\gamma$
$<9.1 \times 10^{-4}$	90		[29] NICZYPORUK 83	LENA	$\Upsilon(1S) \rightarrow A^0\gamma$
$<1.4 \times 10^{-5}$	90		[30] EDWARDS 82	CBAL	$J/\psi \rightarrow A^0\gamma$
$<3.5 \times 10^{-4}$	90		[31] SIVERTZ 82	CUSB	$\Upsilon(1S) \rightarrow A^0\gamma$
$<1.2 \times 10^{-4}$	90		[31] SIVERTZ 82	CUSB	$\Upsilon(3S) \rightarrow A^0\gamma$

[18] BALEST 95 looked for a monochromatic γ from $\Upsilon(1S)$ decay. The bound is for $m_{A^0} <$ 5.0 GeV. See Fig. 7 in the paper for bounds for heavier m_{A^0}. They also quote a bound on branching ratios 10^{-3}–10^{-5} of three-body decay $\gamma X \overline{X}$ for $0 < m_X < 3.1$ GeV.

[19] The combined limit of ANTREASYAN 90C and EDWARDS 82 excludes standard axion with $m_{A^0} < 2m_e$ at 90% CL as long as $C_\Upsilon C_{J/\psi} > 0.09$, where C_V ($V = \Upsilon$, J/ψ) is the reduction factor for $\Gamma(V \rightarrow A^0\gamma)$ due to QCD and/or relativistic corrections. The same data excludes $0.02 < x < 260$ (90% CL) if $C_\Upsilon = C_{J/\psi} = 0.5$, and further combining with ALBRECHT 86D result excludes $5 \times 10^{-5} < x < 260$. x is the ratio of the vacuum expectation values of the two Higgs fields. These limits use conventional assumption $\Gamma(A^0 \rightarrow ee) \propto x^{-2}$. The alternative assumption $\Gamma(A^0 \rightarrow ee) \propto x^2$ gives a somewhat different excluded region $0.00075 < x < 44$.

[20] The first DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} < 3 \times 10^{-13}$ s/MeV and $m_{A^0} < 20$ MeV.

[21] The second DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} < 5 \times 10^{-13}$ s/MeV and $m_{A^0} < 20$ MeV.

[22] The third DRUZHININ 87 limit is valid when $\tau_{A^0}/m_{A^0} > 7 \times 10^{-12}$ s/MeV and $m_{A^0} < 200$ MeV.

[23] $\tau_{A^0} < 1 \times 10^{-13}$s and $m_{A^0} < 1.5$ GeV. Applies for $A^0 \rightarrow \gamma\gamma$ when $m_{A^0} < 100$ MeV.

[24] $\tau_{A^0} > 1 \times 10^{-7}$s.

[25] Independent of τ_{A^0}.

[26] BOWCOCK 86 looked for A^0 that decays into e^+e^- in the cascade decay $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \rightarrow A^0\gamma$. The limit for $B(\Upsilon(1S) \rightarrow A^0\gamma)B(A^0 \rightarrow e^+e^-)$ depends on m_{A^0} and τ_{A^0}. The quoted limit for m_{A^0}=1.8 MeV is at $\tau_{A^0} \sim 2. \times 10^{-12}$s, where the limit is the worst. The same limit $2. \times 10^{-3}$ applies for all lifetimes for masses $2m_e < m_{A^0} < 2m_\mu$ when the results of this experiment are combined with the results of ALAM 83.

[27] MAGERAS 86 looked for $\Upsilon(1S) \rightarrow \gamma A^0$ ($A^0 \rightarrow e^+e^-$). The quoted branching fraction limit is for $m_{A^0} = 1.7$ MeV, at $\tau(A^0) \sim 4. \times 10^{-13}$s where the limit is the worst.

[28] ALAM 83 is at CESR. This limit combined with limit for $B(J/\psi \rightarrow A^0\gamma)$ (EDWARDS 82) excludes standard axion.

[29] NICZYPORUK 83 is DESY-DORIS experiment. This limit together with lower limit 9.2×10^{-4} of $B(\Upsilon \rightarrow A^0\gamma)$ derived from $B(J/\psi(1S) \rightarrow A^0\gamma)$ limit (EDWARDS 82) excludes standard axion.

[30] EDWARDS 82 looked for $J/\psi \rightarrow \gamma A^0$ decays by looking for events with a single γ [of energy $\sim 1/2$ the $J/\psi(1S)$ mass], plus nothing else in the detector. The limit is inconsistent with the axion interpretation of the FAISSNER 81B result.

[31] SIVERTZ 82 is CESR experiment. Looked for $\Upsilon \rightarrow \gamma A^0$, A^0 undetected. Limit for $1S$ ($3S$) is valid for m_{A^0} <7 GeV (4 GeV).

A^0 (Axion) Searches in Positronium Decays

Decay or transition of positronium. Limits are for branching ratio.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-4}$	90	MAENO 95	CNTR	o-Ps $\rightarrow A^0\gamma$ m_{A^0}=850–1013 keV
$<3.0 \times 10^{-3}$	90	[32] ASAI 94	CNTR	o-Ps $\rightarrow A^0\gamma$ m_{A^0}=30–500 keV
$<2.8 \times 10^{-5}$	90	[33] AKOPYAN 91	CNTR	o-Ps $\rightarrow A^0\gamma$ ($A^0 \rightarrow \gamma\gamma$), $m_{A^0} <$ 30 keV
$<1.1 \times 10^{-6}$	90	[34] ASAI 91	CNTR	o-Ps $\rightarrow A^0\gamma$, $m_{A^0} <$ 800 keV
$<3.8 \times 10^{-4}$	90	GNINENKO 90	CNTR	o-Ps $\rightarrow A^0\gamma$, $m_{A^0} <$ 30 keV
$<(1\text{–}5) \times 10^{-4}$	95	[35] TSUCHIAKI 90	CNTR	o-Ps $\rightarrow A^0\gamma$, m_{A^0} = 300–900 keV
$<6.4 \times 10^{-5}$	90	[36] ORITO 89	CNTR	o-Ps $\rightarrow A^0\gamma$, $m_{A^0} <$ 30 keV
		[37] AMALDI 85	CNTR	Ortho-positronium
		[38] CARBONI 83	CNTR	Ortho-positronium

[32] The ASAI 94 limit is based on inclusive photon spectrum and is independent of A^0 decay modes.

[33] The AKOPYAN 91 limit applies for a short-lived A^0 with $\tau_{A^0} < 10^{-13}\, m_{A^0}$ [keV] s.

[34] ASAI 91 limit translates to $g^2_{A^0 e^+ e^-}/4\pi < 1.1 \times 10^{-11}$ (90%CL) for $m_{A^0} < 800$ keV.

[35] The TSUCHIAKI 90 limit is based on inclusive photon spectrum and is independent of A^0 decay modes.

[36] ORITO 89 limit translates to $g^2_{A^0 ee}/4\pi < 6.2 \times 10^{-10}$. Somewhat more sensitive limits are obtained for larger m_{A^0}: $B < 7.6 \times 10^{-6}$ at 100 keV.

[37] AMALDI 85 set limits $B(A^0\gamma)$ / $B(\gamma\gamma\gamma) < (1\text{–}5) \times 10^{-6}$ for m_{A^0} = 900–100 keV which are about 1/10 of the CARBONI 83 limits.

[38] CARBONI 83 looked for orthopositronium $\rightarrow A^0\gamma$. Set limit for A^0 electron coupling squared, $g(eeA^0)^2/(4\pi) < 6. \times 10^{-10}$–$7. \times 10^{-9}$ for m_{A^0} from 150–900 keV (CL = 99.7%). This is about 1/10 of the bound from g−2 experiments.

A^0 (Axion) Search in Photoproduction

VALUE	DOCUMENT ID	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •		
	[39] BASSOMPIE... 95	$m_{A^0} = 1.8 \pm 0.2$ MeV

[39] BASSOMPIERRE 95 is an extension of BASSOMPIERRE 93. They looked for a peak in the invariant mass of e^+e^- pairs in the region $m_{e^+e^-} = 1.8 \pm 0.2$ MeV. They obtained bounds on the production rate A^0 for $\tau(A^0) = 10^{-18}$–10^{-9} sec. They also found an excess of events in the range $m_{e^+e^-}$ = 2.1–3.5 MeV.

A^0 (Axion) Production in Hadron Collisions

Limits are for $\sigma(A^0)$ / $\sigma(\pi^0)$.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
			[40] BLUEMLEIN 92	BDMP	$A^0 N_Z \rightarrow \ell^+\ell^- N_Z$
			[41] MEIJERDREES 92	SPEC	$\pi^- p \rightarrow nA^0$, $A^0 \rightarrow e^+e^-$
			[42] BLUEMLEIN 91	BDMP	$A^0 \rightarrow e^+e^-$, 2γ
			[43] FAISSNER 89	OSPK	Beam dump, $A^0 \rightarrow e^+e^-$
			[44] DEBOER 88	RVUE	$A^0 \rightarrow e^+e^-$
			[45] EL-NADI 88	EMUL	$A^0 \rightarrow e^+e^-$
			[46] FAISSNER 88	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			[47] BADIER 86	BDMP	$A^0 \rightarrow e^+e^-$
$<2. \times 10^{-11}$	90	0	[48] BERGSMA 85	CHRM	CERN beam dump
$<1. \times 10^{-13}$	90	0	[48] BERGSMA 85	CHRM	CERN beam dump
		24	[49] FAISSNER 83	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
			[50] FAISSNER 83B	RVUE	LAMPF beam dump
			[51] FRANK 83B	RVUE	LAMPF beam dump
			[52] HOFFMAN 83	CNTR	$\pi p \rightarrow nA^0$ ($A^0 \rightarrow e^+e^-$)
			[53] FETSCHER 82	RVUE	See FAISSNER 81B
		12	[54] FAISSNER 81	OSPK	CERN PS ν wideband
		15	[55] FAISSNER 81B	OSPK	Beam dump, $A^0 \rightarrow 2\gamma$
		8	[56] KIM 81	OSPK	26 GeV $pN \rightarrow A^0 X$
		0	[57] FAISSNER 80	OSPK	Beam dump, $A^0 \rightarrow e^+e^-$
$<1. \times 10^{-8}$	90		[58] JACQUES 80	HLBC	28 GeV protons
$<1. \times 10^{-14}$	90		[58] JACQUES 80	HLBC	Beam dump
			[59] SOUKAS 80	CALO	28 GeV p beam dump
			[60] BECHIS 79	CNTR	
$<1. \times 10^{-8}$	90		[61] COTEUS 79	OSPK	Beam dump
$<1. \times 10^{-3}$	95		[62] DISHAW 79	CALO	400 GeV pp
$<1. \times 10^{-8}$	90		ALIBRAN 78	HYBR	Beam dump
$<6. \times 10^{-9}$	95		ASRATYAN 78B	CALO	Beam dump
$<1.5 \times 10^{-8}$	90		[63] BELLOTTI 78	HLBC	Beam dump
$<5.4 \times 10^{-14}$	90		[63] BELLOTTI 78	HLBC	m_{A^0}=1.5 MeV
$<4.1 \times 10^{-9}$	90		[63] BELLOTTI 78	HLBC	m_{A^0}=1 MeV
$<1. \times 10^{-8}$	90		[64] BOSETTI 78B	HYBR	Beam dump
			[65] DONNELLY 78		
$<0.5 \times 10^{-8}$	90		HANSL 78D	WIRE	Beam dump
			[66] MICELMAC... 78		
			[67] VYSOTSKII 78		

[40] BLUEMLEIN 92 is a proton beam dump experiment at Serpukhov with a secondary target to induce Bethe-Heitler production of e^+e^- or $\mu^+\mu^-$ from the produce A^0. See Fig. 5 for the excluded region in m_{A^0}-x plane. For the standard axion, $0.3 < x < 25$ is excluded at 95% CL. If combined with BLUEMLEIN 91, $0.008 < x < 32$ is excluded.

[41] MEIJERDREES 92 give $\Gamma(\pi^- p \rightarrow nA^0) \cdot B(A^0 \rightarrow e^+e^-)/\Gamma(\pi^- p \rightarrow \text{all}) < 10^{-5}$ (90% CL) for m_{A^0} = 100 MeV, $\tau_{A^0} = 10^{-11}$–10^{-23} sec. Limits ranging from 2.5×10^{-3} to 10^{-7} are given for m_{A^0} = 25–136 MeV.

[42] BLUEMLEIN 91 is a proton beam dump experiment at Serpukhov. No candidate event for $A^0 \rightarrow e^+e^-$, 2γ are found. Fig. 6 gives the excluded region in m_{A^0}-x plane ($x = \tan\beta = v_2/v_1$). Standard axion is excluded for $0.2 < m_{A^0} < 3.2$ MeV for most $x > 1$, 0.2–11 MeV for most $x < 1$.

[43] FAISSNER 89 searched for $A^0 \rightarrow e^+e^-$ in a proton beam dump experiment at SIN. No excess of events was observed over the background. A standard axion with mass $2m_e$–20 MeV is excluded. Lower limit on f_{A^0} of $\simeq 10^4$ GeV is given for $m_{A^0} = 2m_e$–20 MeV.

[44] DEBOER 88 reanalyze EL-NADI 88 data and claim evidence for three distinct states with mass $\sim$ 1.1, $\sim$ 2.1, and $\sim$ 9 MeV, lifetimes 10^{-16}–10^{-15} s decaying to e^+e^- and note the similarity of the data with those of a cosmic-ray experiment by Bristol group (B.M. Anand, Proc. of the Royal Society of London, Section A **A22** 183 (1953)). For a criticism see PERKINS 89, who suggests that the events are compatible with π^0 Dalitz decay. DEBOER 89B is a reply which contests the criticism.

[45] EL-NADI 88 claim the existence of a neutral particle decaying into e^+e^- with mass 1.60 ± 0.59 MeV, lifetime $(0.15 \pm 0.01) \times 10^{-14}$ s, which is produced in heavy ion interactions with emulsion nuclei at $\sim$ 4 GeV/c/nucleon.

[46] FAISSNER 88 is a proton beam dump experiment at SIN. They found no candidate event for $A^0 \rightarrow \gamma\gamma$. A standard axion decaying to 2γ is excluded except for a region $x \simeq 1$. Lower limit on f_{A^0} of 10^2–10^3 GeV is given for m_{A^0} = 0.1–1 MeV.

[47] BADIER 86 did not find long-lived A^0 in 300 GeV π^- Beam Dump Experiment that decays into e^+e^- in the mass range m_{A^0} = (20–200) MeV, which excludes the A^0 decay constant $f(A^0)$ in the interval (60–600) GeV. See their figure 6 for excluded region on $f(A^0)$-m_{A^0} plane.

[48] BERGSMA 85 look for $A^0 \rightarrow 2\gamma$, e^+e^-, $\mu^+\mu^-$. First limit above is for m_{A^0} = 1 MeV; second is for 200 MeV. See their figure 4 for excluded region on $f_{A^0}-m_{A^0}$ plane, where f_{A^0} is A^0 decay constant. For Peccei-Quinn PECCEI 77 A^0, m_{A^0} <180 keV and τ >0.037 s. (CL = 90%). For the axion of FAISSNER 81B at 250 keV, BERGSMA 85 expect 15 events but observe zero.

[49] FAISSNER 83 observed 19 1-γ and 12 2-γ events where a background of 4.8 and 2.3 respectively is expected. A small-angle peak is observed even if iron wall is set in front of the decay region.

[50] FAISSNER 83B extrapolate SIN γ signal to LAMPF ν experimental condition. Resulting 370 γ's are not at variance with LAMPF upper limit of 450 γ's. Derived from LAMPF limit that $[d\sigma(A^0)/d\omega$ at $90^\circ] m_{A^0}/\tau_{A^0} < 14 \times 10^{-35}$ cm^2 sr^{-1} MeV ms^{-1}. See comment on FRANK 83B.

[51] FRANK 83B stress the importance of LAMPF data bins with negative net signal. By statistical analysis say that LAMPF and SIN-A0 are at variance when extrapolation by phase-space model is done. They find LAMPF upper limit is 248 not 450 γ's. See comment on FAISSNER 83B.

[52] HOFFMAN 83 set CL = 90% limit $d\sigma/dt$ B$(e^+e^-) < 3.5 \times 10^{-32}$ cm^2/GeV^2 for 140 $< m_{A^0}$ <160 MeV. Limit assumes $\tau(A^0) < 10^{-9}$ s.

[53] FETSCHER 82 reanalyzes SIN beam-dump data of FAISSNER 81. Claims no evidence for axion since 2-γ peak rate remarkably decreases if iron wall is set in front of the decay region.

[54] FAISSNER 81 see excess μe events. Suggest axion interactions.

[55] FAISSNER 81B is SIN 590 MeV proton beam dump. Observed 14.5 ± 5.0 events of 2γ decay of long-lived neutral penetrating particle with $m_{2\gamma} \lesssim 1$ MeV. Axion interpretation with η-A^0 mixing gives m_{A^0} = 250 ± 25 keV, $\tau_{(2\gamma)} = (7.3 \pm 3.7) \times 10^{-3}$ s from above rate. See critical remarks below in comments of FETSCHER 82, FAISSNER 83, FAISSNER 83B, FRANK 83B, and BERGSMA 85. Also see in the next subsection ALEKSEEV 82, CAVAIGNAC 83, and ANANEV 85.

[56] KIM 81 analyzed 8 candidates for $A^0 \rightarrow 2\gamma$ obtained by Aachen-Padova experiment at CERN with 26 GeV protons on Be. Estimated axion mass is about 300 keV and lifetime is (0.86∼ 5.6) × 10^{-3} s depending on models. Faissner (private communication), says axion production underestimated and mass overestimated. Correct value around 200 keV.

[57] FAISSNER 80 is SIN beam dump experiment with 590 MeV protons looking for $A^0 \rightarrow e^+e^-$ decay. Assuming $A^0/\pi^0 = 5.5 \times 10^{-7}$, obtained decay rate limit 20/(A^0 mass) MeV/s (CL = 90%), which is about 10^{-7} below theory and interpreted as upper limit to $m_{A^0} < 2m_{e^-}$.

[58] JACQUES 80 is a BNL beam dump experiment. First limit above comes from nonobservation of excess neutral-current-type events $[\sigma(\text{production})\sigma(\text{interactaction}) < 7. \times 10^{-68}$ cm^4, CL = 90%]. Second limit is from nonobservation of axion decays into 2γ's or e^+e^-, and for axion mass a few MeV.

[59] SOUKAS 80 at BNL observed no excess of neutral-current-type events in beam dump.

[60] BECHIS 79 looked for the axion production in low energy electron Bremsstrahlung and the subsequent decay into either 2γ or e^+e^-. No signal found. CL = 90% limits for model parameter(s) are given.

[61] COTEUS 79 is a beam dump experiment at BNL.

[62] DISHAW 79 is a calorimetric experiment and looks for low energy tail of energy distributions due to energy lost to weakly interacting particles.

[63] BELLOTTI 78 first value comes from search for $A^0 \rightarrow e^+e^-$. Second value comes from search for $A^0 \rightarrow 2\gamma$, assuming mass $< 2m_{e^-}$. For any mass satisfying this, limit is above value×(mass^{-4}). Third value uses data of PL 60B 401 and quotes σ(production)σ(interaction) $< 10^{-67}$ cm^4.

[64] BOSETTI 78B quotes σ(production)σ(interaction) $< 2. \times 10^{-67}$ cm^4.

[65] DONNELLY 78 examines data from reactor neutrino experiments of REINES 76 and GURR 74 as well as SLAC beam dump experiment. Evidence is negative.

[66] MICELMACHER 78 finds no evidence of axion existence in reactor experiments of REINES 76 and GURR 74. (See reference under DONNELLY 78 below).

[67] VYSOTSKII 78 derived lower limit for the axion mass 25 keV from luminosity of the sun and 200 keV from red supergiants.

A^0 (Axion) Searches in Reactor Experiments

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[68] ALTMANN	95	CNTR	Reactor; $A^0 \rightarrow e^+e^-$
	[69] KETOV	86	SPEC	Reactor, $A^0 \rightarrow \gamma\gamma$
	[70] KOCH	86	SPEC	Reactor; $A^0 \rightarrow \gamma\gamma$
	[71] DATAR	82	CNTR	Light water reactor
	[72] VUILLEUMIER	81	CNTR	Reactor, $A^0 \rightarrow 2\gamma$

[68] ALTMANN 95 looked for A^0 decaying into e^+e^- from the Bugey 5 nuclear reactor. They obtain an upper limit on the A^0 production rate of $\omega(A^0)/\omega(\gamma) \times B(A^0 \rightarrow e^+e^-) < 10^{-16}$ for m_{A^0} = 1.5 MeV at 90% CL. The limit is weaker for heavier A^0. In the case of a standard axion, this limit excludes a mass in the range $2m_e < m_{A^0} < 4.8$ MeV at 90% CL. See Fig. 5 of their paper for exclusion limits of axion-like resonances Z^0 in the (m_{X^0},f_{X^0}) plane.

[69] KETOV 86 searched for A^0 at the Rovno nuclear power plant. They found an upper limit on the A^0 production probability of 0.8 $[100 \text{ keV}/m_{A^0}]^6 \times 10^{-6}$ per fission. In the standard axion model, this corresponds to m_{A^0} >150 keV. Not valid for $m_{A^0} \gtrsim$ 1 MeV.

[70] KOCH 86 searched for $A^0 \rightarrow \gamma\gamma$ at nuclear power reactor Biblis A. They found an upper limit on the A^0 production rate of $\omega(A^0)/\omega(\gamma(M1)) < 1.5 \times 10^{-10}$ (CL=95%). Standard axion with m_{A^0} = 250 keV gives 10^{-5} for the ratio. Not valid for m_{A^0} >1022 keV.

[71] DATAR 82 looked for $A^0 \rightarrow 2\gamma$ in neutron capture ($np \rightarrow dA^0$) at Tarapur 500 MW reactor. Sensitive to sum of $I = 0$ and $I = 1$ amplitudes. With ZEHNDER 81 $[(I = 0) - (I = 1)]$ result, assert nonexistence of standard A^0.

[72] VUILLEUMIER 81 is at Grenoble reactor. Set limit m_{A^0} <280 keV.

A^0 (Axion) and Other Light Boson (X^0) Searches in Nuclear Transitions

Limits are for branching ratio.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 5.5 \times 10^{-10}$	95		[73] TSUNODA	95	CNTR	^{252}Cf fission, $A^0 \rightarrow ee$
$< 1.2 \times 10^{-6}$	95		[74] MINOWA	93	CNTR	^{139}La* $\rightarrow$ ^{139}LaA^0
$< 2 \times 10^{-4}$	90		[75] HICKS	92	CNTR	^{35}S decay, $A^0 \rightarrow \gamma\gamma$
$< 1.5 \times 10^{-9}$	95		[76] ASANUMA	90	CNTR	^{241}Am decay
$<(0.4–10) \times 10^{-3}$	95		[77] DEBOER	90	CNTR	^{8}Be* $\rightarrow$ ^{8}BeA^0, $A^0 \rightarrow e^+e^-$
$<(0.2–1) \times 10^{-3}$	90		[78] BINI	89	CNTR	^{16}O* $\rightarrow$ ^{16}OX^0, $X^0 \rightarrow e^+e^-$
			[79] AVIGNONE	88	CNTR	Cu* $\rightarrow$ CuA^0 ($A^0 \rightarrow 2\gamma$, $A^0 e \rightarrow \gamma e$, $A^0 Z \rightarrow \gamma Z$)
$< 1.5 \times 10^{-4}$	90		[80] DATAR	88	CNTR	^{12}C* $\rightarrow$ ^{12}CA^0, $A^0 \rightarrow e^+e^-$
$< 5 \times 10^{-3}$	90		[81] DEBOER	88C	CNTR	^{16}O* $\rightarrow$ ^{16}OX^0, $X^0 \rightarrow e^+e^-$
$< 3.4 \times 10^{-5}$	95		[82] DOEHNER	88	SPEC	^{2}H*, $A^0 \rightarrow e^+e^-$
$< 4 \times 10^{-4}$	95		[83] SAVAGE	88	CNTR	Nuclear decay (isovector)
$< 3 \times 10^{-3}$	95		[83] SAVAGE	88	CNTR	Nuclear decay (isoscalar)
< 0.106	90		[84] HALLIN	86	SPEC	^{6}Li isovector decay
<10.8	90		[84] HALLIN	86	SPEC	^{10}B isoscalar decays
< 2.2	90		[84] HALLIN	86	SPEC	^{14}N isoscalar decays
$< 4 \times 10^{-4}$	90	0	[85] SAVAGE	86B	CNTR	^{14}N*
			[86] ANANEV	85	CNTR	Li*, deut* $A^0 \rightarrow 2\gamma$
			[87] CAVAIGNAC	83	CNTR	^{97}Nb*, deut* transition $A^0 \rightarrow 2\gamma$
			[88] ALEKSEEV	82B	CNTR	Li*, deut* transition $A^0 \rightarrow 2\gamma$
			[89] LEHMANN	82	CNTR	Cu* $\rightarrow$ CuA^0 ($A^0 \rightarrow 2\gamma$)
		0	[90] ZEHNDER	82	CNTR	Li*, Nb* decay, n-capt.
		0	[91] ZEHNDER	81	CNTR	Ba* $\rightarrow$ BaA^0 ($A^0 \rightarrow 2\gamma$)
			[92] CALAPRICE	79		Carbon

[73] TSUNODA 95 looked for axion emission when ^{252}Cf undergoes a spontaneous fission, with the axion decaying into e^+e^-. The bound is for m_{A^0}=40 MeV. It improves to 2.5×10^{-5} for m_{A^0}=200 MeV.

[74] MINOWA 93 studied chain process, ^{139}Ce $\rightarrow$ ^{139}La* by electron capture and M1 transition of ^{139}La* to the ground state. It does not assume decay modes of A^0. The bound applies for $m_{A^0} < 166$ keV.

[75] HICKS 92 bound is applicable for $\tau_{X^0} < 4 \times 10^{-11}$ sec.

[76] The ASANUMA 90 limit is for the branching fraction of X^0 emission per ^{241}Am α decay and valid for $\tau_{X^0} < 3 \times 10^{-11}$ s.

[77] The DEBOER 90 limit is for the branching ratio ^{8}Be* (18.15 MeV, 1^+) $\rightarrow$ ^{8}BeA^0, $A^0 \rightarrow e^+e^-$ for the mass range m_{A^0} = 4–15 MeV.

[78] The BINI 89 limit is for the branching fraction of ^{16}O*(6.05 MeV, 0^+) $\rightarrow$ ^{16}OX^0, $X^0 \rightarrow e^+e^-$ for m_X = 1.5–3.1 MeV. $\tau_{X^0} \lesssim 10^{-11}$ s is assumed. The spin-parity of X is restricted to 0^+ or 1^-.

[79] AVIGNONE 88 looked for the 1115 keV transition C* $\rightarrow$ CuA^0, either from $A^0 \rightarrow 2\gamma$ in-flight decay or from the secondary A^0 interactions by Compton and by Primakoff processes. Limits for axion parameters are obtained for $m_{A^0} < 1.1$ MeV.

[80] DATAR 88 rule out light pseudoscalar particle emission through its decay $A^0 \rightarrow e^+e^-$ in the mass range 1.02–2.5 MeV and lifetime range 10^{-13}–10^{-8} s. The above limit is for $\tau = 5 \times 10^{-13}$ s and m = 1.7 MeV; see the paper for the τ-m dependence of the limit.

[81] The limit is for the branching fraction of ^{16}O*(6.05 MeV, 0^+) $\rightarrow$ ^{16}OX^0, $X^0 \rightarrow e^+e^-$ against internal pair conversion for m_{X^0} = 1.7 MeV and $\tau_{X^0} < 10^{-11}$ s. Similar limits are obtained for m_{X^0} = 1.3–3.2 MeV. The spin parity of X^0 must be either 0^+ or 1^-. The limit at 1.7 MeV is translated into a limit for the X^0-nucleon coupling constant: $g^2_{X^0 NN}/4\pi < 2.3 \times 10^{-9}$.

[82] The DOEHNER 88 limit is for m_{A^0} = 1.7 MeV, $\tau(A^0) < 10^{-10}$ s. Limits less than 10^{-4} are obtained for m_{A^0} = 1.2–2.2 MeV.

[83] SAVAGE 88 looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N, 17.64 MeV state $J^P = 1^+$ in ^{8}Be, and the 18.15 MeV state $J^P = 1^+$ in ^{8}Be. This experiment constrains the isovector coupling of A^0 to hadrons, if m_{A^0} = (1.1 $\rightarrow$ 2.2) MeV and the isoscalar coupling of A^0 to hadrons, if m_{A^0} = (1.1 $\rightarrow$ 2.6) MeV. Both limits are valid only if $\tau(A^0) \lesssim 1 \times 10^{-11}$ s.

[84] Limits are for $\Gamma(A^0(1.8 \text{ MeV}))/\Gamma(\pi M1)$; i.e., for 1.8 MeV axion emission normalized to the rate for internal emission of e^+e^- pairs. Valid for $\tau_{A^0} < 2 \times 10^{-11}$s. ^{6}Li isovector decay data strongly disfavor PECCEI 86 model I, whereas the ^{10}B and ^{14}N isoscalar decay data strongly reject PECCEI 86 model II and III.

[85] SAVAGE 86B looked for A^0 that decays into e^+e^- in the decay of the 9.17 MeV $J^P = 2^+$ state in ^{14}N. Limit on the branching fraction is valid if $\tau_{A^0} \lesssim 1. \times 10^{-11}$s for m_{A^0} = (1.1–1.7) MeV. This experiment constrains the iso-vector coupling of A^0 to hadrons.
[86] ANANEV 85 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% masses below 470 keV (Li* decay) and below $2m_e$ for deuteron* decay.
[87] CAVAIGNAC 83 at Bugey reactor exclude axion at any $m_{^{97}\text{Nb}^*\text{decay}}$ and axion with m_{A^0} between 275 and 288 keV (deuteron* decay).
[88] ALEKSEEV 82 with IBR-2 pulsed reactor exclude standard A^0 at CL = 95% mass-ranges m_{A^0} <400 keV (Li* decay) and 330 keV $< m_{A^0} <$2.2 MeV. (deuteron* decay).
[89] LEHMANN 82 obtained $A^0 \rightarrow 2\gamma$ rate $< 6.2 \times 10^{-5}$/s (CL = 95%) excluding m_{A^0} between 100 and 1000 keV.
[90] ZEHNDER 82 used Goesgen 2.8GW light-water reactor to check A^0 production. No 2γ peak in Li*, Nb* decay (both single p transition) nor in n capture (combined with previous Ba* negative result) rules out standard A^0. Set limit m_{A^0} <60 keV for any A^0.
[91] ZEHNDER 81 looked for Ba* $\rightarrow A^0$Ba transition with $A^0 \rightarrow 2\gamma$. Obtained 2γ coincidence rate $< 2.2 \times 10^{-5}$/s (CL = 95%) excluding m_{A^0} >160 keV (or 200 keV depending on Higgs mixing). However, see BARROSO 81.
[92] CALAPRICE 79 saw no axion emission from excited states of carbon. Sensitive to axion mass between 1 and 15 MeV.

A^0 (Axion) Limits from Its Electron Coupling

Limits are for $\tau(A^0 \rightarrow e^+e^-)$.

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 4×10^{-16}–4.5×10^{-12}	90	[93] BROSS	91	BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
		[94] GUO	90	BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
		[95] BJORKEN	88	CALO	$A \rightarrow e^+e^-$ or 2γ
		[96] BLINOV	88	MD1	$ee \rightarrow eeA^0$ ($A^0 \rightarrow ee$)
none 1×10^{-14}–1×10^{-10}	90	[97] RIORDAN	87	BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
none 1×10^{-14}–1×10^{-11}	90	[98] BROWN	86	BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
none 6×10^{-14}–9×10^{-11}	95	[99] DAVIER	86	BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)
none 3×10^{-13}–1×10^{-7}	90	[100] KONAKA	86	BDMP	$eN \rightarrow eA^0N$ ($A^0 \rightarrow ee$)

[93] The listed BROSS 91 limit is for m_{A^0} = 1.14 MeV. B($A^0 \rightarrow e^+e^-$) = 1 assumed. Excluded domain in the τ_{A^0}–m_{A^0} plane extends up to $m_{A^0} \approx$ 7 MeV (see Fig. 5). Combining with electron $g-2$ constraint, axions coupling only to e^+e^- ruled out for m_{A^0} < 4.8 MeV (90%CL).
[94] GUO 90 use the same apparatus as BROWN 86 and improve the previous limit in the shorter lifetime region. Combined with $g-2$ constraint, axions coupling only to e^+e^- are ruled out for m_{A^0} < 2.7 MeV (90% CL).
[95] BJORKEN 88 reports limits on axion parameters (f_A, m_A, τ_A) for m_{A^0} < 200 MeV from electron beam-dump experiment with production via Primakoff photoproduction, bremsstrahlung from electrons, and resonant annihilation of positrons on atomic electrons.
[96] BLINOV 88 assume zero spin, m = 1.8 MeV and lifetime < 5×10^{-12} s and find $\Gamma(A^0 \rightarrow \gamma\gamma)$B($A^0 \rightarrow e^+e^-$) < 2 eV (CL=90%).
[97] Assumes $A^0\gamma\gamma$ coupling is small and hence Primakoff production is small. Their figure 2 shows limits on axions for m_{A^0} < 15 MeV.
[98] Uses electrons in hadronic showers from an incident 800 GeV proton beam. Limits for m_{A^0} < 15 MeV are shown in their figure 3.
[99] m_{A^0} = 1.8 MeV assumed. The excluded domain in the τ_{A^0}–m_{A^0} plane extends up to $m_{A^0} \approx$ 14 MeV, see their figure 4.
[100] The limits are obtained from their figure 3. Also given is the limit on the $A^0\gamma\gamma$–$A^0e^+e^-$ coupling plane by assuming Primakoff production.

Search for A^0 (Axion) Resonance in Bhabha Scattering

The limit is for $\Gamma(A^0)[\text{B}(A^0 \rightarrow e^+e^-)]^2$.

VALUE (10^{-3} eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.3	97	[101] HALLIN	92	CNTR	m_{A^0} = 1.75–1.88 MeV
none 0.0016–0.47	90	[102] HENDERSON	92C	CNTR	m_{A^0}= 1.5–1.86 MeV
< 2.0	90	[103] WU	92	CNTR	m_{A^0}= 1.56–1.86 MeV
< 0.013	95	TSERTOS	91	CNTR	m_{A^0} = 1.832 MeV
none 0.19–3.3	95	[104] WIDMANN	91	CNTR	m_{A^0}= 1.78–1.92 MeV
< 5	97	BAUER	90	CNTR	m_{A^0} = 1.832 MeV
none 0.09–1.5	95	[105] JUDGE	90	CNTR	m_{A^0} = 1.832 MeV, elastic
< 1.9	97	[106] TSERTOS	89	CNTR	m_{A^0} = 1.82 MeV
<(10–40)	97	[106] TSERTOS	89	CNTR	m_{A^0} = 1.51–1.65 MeV
<(1–2.5)	97	[106] TSERTOS	89	CNTR	m_{A^0} = 1.80–1.86 MeV
< 31	95	LORENZ	88	CNTR	m_{A^0} = 1.646 MeV
< 94	95	LORENZ	88	CNTR	m_{A^0} = 1.726 MeV
< 23	95	LORENZ	88	CNTR	m_{A^0} = 1.782 MeV
< 19	95	LORENZ	88	CNTR	m_{A^0} = 1.837 MeV
< 3.8	97	[107] TSERTOS	88	CNTR	m_{A^0} = 1.832 MeV
		[108] VANKLINKEN	88	CNTR	
		[109] MAIER	87	CNTR	
<2500	90	MILLS	87	CNTR	m_{A^0} = 1.8 MeV
		[110] VONWIMMER...	87	CNTR	

[101] HALLIN 92 quote limits on lifetime, 8×10^{-14}–5×10^{-13} sec depending on mass, assuming B($A^0 \rightarrow e^+e^-$) = 100%. They say that TSERTOS 91 overstated their sensitivity by a factor of 3.
[102] HENDERSON 92C exclude axion with lifetime τ_{A^0}=1.4×10^{-12}–4.0×10^{-10} s, assuming B($A^0 \rightarrow e^+e^-$)=100%. HENDERSON 92C also exclude a vector boson with τ=1.4×10^{-12}–6.0×10^{-10} s.
[103] WU 92 quote limits on lifetime > 3.3×10^{-13} s assuming B($A^0 \rightarrow e^+e^-$)=100%. They say that TSERTOS 89 overestimate the limit by a factor of $\pi/2$. WU 92 also quote a bound for vector boson, τ> 8.2×10^{-13} s.
[104] WIDMANN 91 bound applies exclusively to the case B($A^0 \rightarrow e^+e^-$)=1, since the detection efficiency varies substantially as $\Gamma(A^0)_{\text{total}}$ changes. See their Fig. 6.
[105] JUDGE 90 excludes an elastic pseudoscalar e^+e^- resonance for 4.5×10^{-13} s < $\tau(A^0)$ < 7.5×10^{-12} s (95% CL) at m_{A^0} = 1.832 MeV. Comparable limits can be set for m_{A^0} = 1.776–1.856 MeV.
[106] See also TSERTOS 88B in references.
[107] The upper limit listed in TSERTOS 88 is too large by a factor of 4. See TSERTOS 88B, footnote 3.
[108] VANKLINKEN 88 looked for relatively long-lived resonance (τ = 10^{-10}–10^{-12} s). The sensitivity is not sufficient to exclude such a narrow resonance.
[109] MAIER 87 obtained limits $R\Gamma \lesssim$ 60 eV (100 eV) at $m_{A^0} \simeq$ 1.64 MeV (1.83 MeV) for energy resolution $\Delta E_{\text{cm}} \simeq$ 3 keV, where R is the resonance cross section normalized to that of Bhabha scattering, and $\Gamma = \Gamma^2_{ee}/\Gamma_{\text{total}}$. For a discussion implying that $\Delta E_{\text{cm}} \simeq$ 10 keV, see TSERTOS 89.
[110] VONWIMMERSPERG 87 measured Bhabha scattering for E_{cm} = 1.37–1.86 MeV and found a possible peak at 1.73 with $\int \sigma dE_{\text{cm}}$ = 14.5 ± 6.8 keV·b. For a comment and a reply, see VANKLINKEN 88B and VONWIMMERSPERG 88. Also see CONNELL 88.

Search for A^0 (Axion) Resonance in $e^+e^- \rightarrow \gamma\gamma$

The limit is for $\Gamma(A^0 \rightarrow e^+e^-)\cdot\Gamma(A^0 \rightarrow \gamma\gamma)/\Gamma_{\text{total}}$

VALUE (10^{-3} eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.18	95	VO	94	CNTR	m_{A^0}=1.1 MeV
< 1.5	95	VO	94	CNTR	m_{A^0}=1.4 MeV
<12	95	VO	94	CNTR	m_{A^0}=1.7 MeV
< 6.6	95	[111] TRZASKA	91	CNTR	m_{A^0} = 1.8 MeV
< 4.4	95	WIDMANN	91	CNTR	m_{A^0}= 1.78–1.92 MeV
		[112] FOX	89	CNTR	
< 0.11	95	[113] MINOWA	89	CNTR	m_{A^0} = 1.062 MeV
<33	97	CONNELL	88	CNTR	m_{A^0} = 1.580 MeV
<42	97	CONNELL	88	CNTR	m_{A^0} = 1.642 MeV
<73	97	CONNELL	88	CNTR	m_{A^0} = 1.782 MeV
<79	97	CONNELL	88	CNTR	m_{A^0} = 1.832 MeV

[111] TRZASKA 91 also give limits in the range (6.6–30) $\times 10^{-3}$ eV (95%CL) for m_{A^0} = 1.6–2.0 MeV.
[112] FOX 89 measured positron annihilation with an electron in the source material into two photons and found no signal at 1.062 MeV (< 9×10^{-5} of two-photon annihilation at rest).
[113] Similar limits are obtained for m_{A^0} = 1.045–1.085 MeV.

Search for X^0 (Light Boson) Resonance in $e^+e^- \rightarrow \gamma\gamma\gamma$

The limit is for $\Gamma(X^0 \rightarrow e^+e^-)\cdot\Gamma(X^0 \rightarrow \gamma\gamma\gamma)/\Gamma_{\text{total}}$. C invariance forbids spin-0 X^0 coupling to both e^+e^- and $\gamma\gamma\gamma$.

VALUE (10^{-3} eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.2	95	[114] VO	94	CNTR	m_{X^0}=1.1–1.9 MeV
< 1.0	95	[115] VO	94	CNTR	m_{X^0}=1.1 MeV
< 2.5	95	[115] VO	94	CNTR	m_{X^0}=1.4 MeV
<120	95	[115] VO	94	CNTR	m_{X^0}=1.7 MeV
< 3.8	95	[116] SKALSEY	92	CNTR	m_{X^0}= 1.5 MeV

[114] VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying at rest. The precise limits depend on m_{X^0}. See Fig. 2(b) in paper.
[115] VO 94 looked for $X^0 \rightarrow \gamma\gamma\gamma$ decaying in flight.
[116] SKALSEY 92 also give limits 4.3 for m_{X^0} = 1.54 and 7.5 for 1.64 MeV. The spin of X^0 is assumed to be one.

Light Boson (X^0) Search in Nonresonant $e^+ e^-$ Annihilation at Rest

Limits are for the ratio of $n\gamma + X^0$ production relative to $\gamma\gamma$.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4	68	[117] SKALSEY	95	CNTR	γX^0
<40	68	[118] SKALSEY	95	RVUE	γX^0
< 0.18	90	[119] ADACHI	94	CNTR	$\gamma\gamma X^0$, $X^0 \to \gamma\gamma$
< 0.26	90	[120] ADACHI	94	CNTR	$\gamma\gamma X^0$, $X^0 \to \gamma\gamma$
< 0.33	90	[121] ADACHI	94	CNTR	γX^0, $X^0 \to \gamma\gamma\gamma$

[117] SKALSEY 95 looked for a monochromatic γ without an accompanying γ in $e^+ e^-$ annihilation. The bound applies for scalar and vector X^0 with $C = -1$ and $m_{X^0} =$ 100–1000 keV.

[118] SKALSEY 95 reinterpreted the bound on γA^0 decay of o-Ps by ASAI 91 where 3% of delayed annihilations are not from $^3S_1$ states. The bound applies for scalar and vector X^0 with $C = -1$ and $m_{X^0} =$ 0–800 keV.

[119] ADACHI 94 looked for a peak in the $\gamma\gamma$ invariant mass distribution in $\gamma\gamma\gamma\gamma$ production from $e^+ e^-$ annihilation. The bound applies for $m_{X^0} =$ 70–800 keV.

[120] ADACHI 94 looked for a peak in the missing-mass mass distribution in $\gamma\gamma$ channel, using $\gamma\gamma\gamma\gamma$ production from $e^+ e^-$ annihilation. The bound applies for m_{X^0} <800 keV.

[121] ADACHI 94 looked for a peak in the missing mass distribution in $\gamma\gamma\gamma$ channel, using $\gamma\gamma\gamma\gamma$ production from $e^+ e^-$ annihilation. The bound applies for $m_{X^0} =$ 200–900 keV.

Searches for Goldstone Bosons (X^0)

(Including Horizontal Bosons and Majorons.) Limits are for branching ratios.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[122] BOBRAKOV	91		Electron quasi-magnetic interaction
$<3.3 \times 10^{-2}$	95		[123] ALBRECHT	90E	ARG	$\tau \to \mu X^0$. Familon
$<1.8 \times 10^{-2}$	95		[123] ALBRECHT	90E	ARG	$\tau \to e X^0$. Familon
$<6.4 \times 10^{-9}$	90		[124] ATIYA	90	B787	$K^+ \to \pi^+ X^0$. Familon
$<1.1 \times 10^{-9}$	90		[125] BOLTON	88	CBOX	$\mu^+ \to e^+ \gamma X^0$. Familon
			[126] CHANDA	88	ASTR	Sun, Majoron
			[127] CHOI	88	ASTR	Majoron, SN 1987A
$<5 \times 10^{-6}$	90		[128] PICCIOTTO	88	CNTR	$\pi \to e\nu X^0$, Majoron
$<1.3 \times 10^{-9}$	90		[129] GOLDMAN	87	CNTR	$\mu \to e\gamma X^0$. Familon
$<3 \times 10^{-4}$	90		[130] BRYMAN	86B	RVUE	$\mu \to e X^0$. Familon
$<1. \times 10^{-10}$	90	0	[131] EICHLER	86	SPEC	$\mu^+ \to e^+ X^0$. Familon
$<2.6 \times 10^{-6}$	90		[132] JODIDIO	86	SPEC	$\mu^+ \to e^+ X^0$. Familon
			[133] BALTRUSAIT...	85	MRK3	$\tau \to \ell X^0$. Familon
			[134] DICUS	83	COSM	$\nu(\text{hvy}) \to \nu(\text{light}) X^0$

[122] BOBRAKOV 91 searched for anomalous magnetic interactions between polarized electrons expected from the exchange of a massless pseudoscalar boson (arion). A limit $x_e^2 < 2 \times 10^{-4}$ (95%CL) is found for the effective anomalous magneton parametrized as $x_e (G_F/8\pi\sqrt{2})^{1/2}$.

[123] ALBRECHT 90E limits are for $B(\tau \to \ell X^0)/B(\tau \to \ell\nu\overline{\nu})$. Valid for $m_{X^0} < 100$ MeV. The limits rise to 7.1% (for μ), 5.0% (for e) for $m_{X^0} = 500$ MeV.

[124] ATIYA 90 limit is for $m_{X^0} = 0$. The limit $B < 1 \times 10^{-8}$ holds for $m_{X^0} < 95$ MeV. For the reduction of the limit due to finite lifetime of X^0, see their Fig. 3.

[125] BOLTON 88 limit corresponds to $F > 3.1 \times 10^9$ GeV, which does not depend on the chirality property of the coupling.

[126] CHANDA 88 find $v_T < 10$ MeV for the weak-triplet Higgs vev. in Gelmini-Roncadelli model, and $v_S > 5.8 \times 10^6$ GeV in the singlet Majoron model.

[127] CHOI 88 used the observed neutrino flux from the supernova SN 1987A to exclude the neutrino Majoron Yukawa coupling h in the range $2 \times 10^{-5} < h < 3 \times 10^{-4}$ for the interaction $L_{int} = \frac{1}{2} i h \overline{\psi}_\nu^c \gamma_5 \psi_\nu \phi_X$. For several families of neutrinos, the limit applies for $(\Sigma h_i^4)^{1/4}$.

[128] PICCIOTTO 88 limit applies when $m_{X^0} < 55$ MeV and $\tau_{X^0} > 2$ns, and it decreases to 4×10^{-7} at $m_{X^0} = 125$ MeV, beyond which no limit is obtained.

[129] GOLDMAN 87 limit corresponds to $F > 2.9 \times 10^9$ GeV for the family symmetry breaking scale from the Lagrangian $L_{int} = (1/F) \overline{\psi}_\mu \gamma^\mu (a + b\gamma_5) \psi_e \partial_\mu \phi_{X^0}$ with $a^2 + b^2 = 1$. This is not as sensitive as the limit $F > 9.9 \times 10^9$ GeV derived from the search for $\mu^+ \to e^+ X^0$ by JODIDIO 86, but does not depend on the chirality property of the coupling.

[130] Limits are for $\Gamma(\mu \to e X^0)/\Gamma(\mu \to e\nu\overline{\nu})$. Valid when $m_{X^0} =$ 0–93.4, 98.1–103.5 MeV.

[131] EICHLER 86 looked for $\mu^+ \to e^+ X^0$ followed by $X^0 \to e^+ e^-$. Limits on the branching fraction depend on the mass and and lifetime of X^0. The quoted limits are valid when $\tau_{X^0} \lesssim 3. \times 10^{-10}$ s if the decays are kinematically allowed.

[132] JODIDIO 86 corresponds to $F > 9.9 \times 10^9$ GeV for the family symmetry breaking scale with the parity-conserving effective Lagrangian $L_{int} = (1/F) \overline{\psi}_\mu \gamma^\mu \psi_e \partial^\mu \phi_{X^0}$.

[133] BALTRUSAITIS 85 search for light Goldstone boson(X^0) of broken U(1). CL = 95% limits are $B(\tau \to \mu^+ X^0)/B(\tau \to \mu^+ \nu\nu) <0.125$ and $B(\tau \to e^+ X^0)/B(\tau \to e^+ \nu\nu) <0.04$. Inferred limit for the symmetry breaking scale is $m >3000$ TeV.

[134] The primordial heavy neutrino must decay into ν and familon, f_A, early so that the red-shifted decay products are below critical density, see their table. In addition, $K \to \pi f_A$ and $\mu \to e f_A$ are unseen. Combining these excludes $m_{\text{heavy}\nu}$ between 5×10^{-5} and 5×10^{-4} MeV (μ decay) and $m_{\text{heavy}\nu}$ between 5×10^{-5} and 0.1 MeV (K-decay).

Majoron Searches in Neutrinoless Double β Decay

Limits are for the half-life of neutrinoless $\beta\beta$ decay with a Majoron emission. Previous indications for neutrinoless double beta decay with majoron emission have been superseded. No experiment currently claims any such evidence. For a review, see DOI 88.

VALUE (years)	CL%	DOCUMENT ID		TECN	COMMENT
> 7.2 × 10^{24}	90	[135] BERNATOW...	92	CNTR	^{128}Te
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$> 1.7 \times 10^{22}$	90	BECK	93	CNTR	^{76}Ge
$> 7.9 \times 10^{20}$	68	[136] TANAKA	93	SPEC	^{100}Mo
$> 1.9 \times 10^{20}$	68	BARABASH	89	CNTR	^{136}Xe
$> 1.0 \times 10^{21}$	90	FISHER	89	CNTR	^{76}Ge
$> 3.3 \times 10^{20}$	90	ALSTON-...	88	CNTR	^{100}Mo
$(6 \pm 1) \times 10^{20}$		AVIGNONE	87	CNTR	^{76}Ge
$> 1.4 \times 10^{21}$	90	CALDWELL	87	CNTR	^{76}Ge
$> 4.4 \times 10^{20}$	90	ELLIOTT	87	SPEC	^{82}Se
$> 1.2 \times 10^{21}$	90	FISHER	87	CNTR	^{76}Ge
		[137] VERGADOS	82	CNTR	

[135] BERNATOWICZ 92 studied double-β decays of ^{128}Te and ^{130}Te, and found the ratio $\tau(^{130}\text{Te})/\tau(^{128}\text{Te}) = (3.52 \pm 0.11) \times 10^{-4}$ in agreement with relatively stable theoretical predictions. The bound is based on the requirement that Majoron-emitting decay cannot be larger than the observed double-beta rate of ^{128}Te of $(7.7 \pm 0.4) \times 10^{24}$ year. We calculated 90% CL limit as $(7.7 - 1.28 \times 0.4 = 7.2) \times 10^{24}$.

[136] TANAKA 93 also quote limit 5.3×10^{19} years on two Majoron emission.

[137] VERGADOS 82 sets limit $g_H < 4 \times 10^{-3}$ for (dimensionless) lepton-number violating coupling, g_H, of scalar boson (Majoron) to neutrinos, from analysis of data on double β decay of ^{48}Ca.

INVISIBLE A^0 (AXION)

As discussed in the note on "Axions and Other Light Bosons," the so-called invisible axion models decouple the scale of the Peccei–Quinn symmetry breaking from the electroweak scale, and avoid the constraints from negative accelerator searches for the axion. Two classes of models are discussed commonly in the literature. One introduces new heavy quarks that carry Peccei–Quinn charge while the usual quarks and leptons do not (KSVZ axions or "hadronic" axions) [1]. The other does not need additional quarks but requires two Higgs doublets, and all quarks and leptons carry Peccei–Quinn charges (DFSZ axions or "GUT" axions) [2]. All models contain at least one electroweak singlet scalar boson that acquires an expectation value and breaks the Peccei–Quinn symmetry.

The common property of all axion models is the effective coupling

$$\mathcal{L} = \left(\theta_{eff} - \frac{\phi_A}{f_A} \right) \frac{g_s^2}{32\pi^2} \, F^{\mu\nu a} \widetilde{F}^a_{\mu\nu} \; , \qquad (1)$$

where ϕ_A is the axion field, θ_{eff} is the effective QCD vacuum angle after the diagonalization of the quark masses, g_s the QCD coupling constant, $F^{\mu\nu a}$ the gluon field strength and $\widetilde{F}^a_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma a}$. It is often convenient to *define* the axion decay constant f_A with this Lagrangian [3]. The QCD instanton effect induces a potential for ϕ_A whose minimum is at $\phi_A = \theta_{eff} f_A$, cancelling θ_{eff} and solving the strong CP problem. The mass of the axion is related to f_A by

$$m_A = 0.62 \times 10^{-3} \text{eV} \; \times (10^{10} \text{GeV}/f_A) \; . \qquad (2)$$

The constraints on the axion mass from various experiments, astrophysics, and cosmology are derived from the interactions of the axion with either photons, electrons, or nucleons. We use the following notation for their coupling constants $G_{A\gamma\gamma}$ and G_{Aff},

$$\mathcal{L}_{A\gamma\gamma} = -\frac{1}{4} G_{A\gamma\gamma} \phi_A \, F^{\mu\nu} \widetilde{F}_{\mu\nu} = G_{A\gamma\gamma} \; \phi_A \boldsymbol{E} \cdot \boldsymbol{B} \; , \qquad (3)$$

$$\mathcal{L}_{Aff} = G_{Aff} \, \partial_\mu \phi_A \, \overline{f} \gamma^\mu \gamma_5 \, f \; , \qquad (4)$$

for $f = e, p, n$. The relations of these coupling constants to f_A (and m_A) are model dependent, and are listed in Table 1.

Table 1: The coupling constants of the axion to the matter particles in DFSZ and KSVZ models, taken from Ref. [5] where the results of Ref. [6] were used. These dimensionless coupling constants are related to those in the Lagrangian by $G_{Aii} = c_i/2f_A$ for $i = \gamma, e, p, n$. The parameter β is an arbitrary angle whose tangent is defined by the ratio between the expectation values of the two Higgs doublets in the DFSZ model. A rational number E/N in the KSVZ model depends on the number of new quarks and their charges. The coupling to nucleons are subject to certain ambiguities in hadronic matrix elements [4] that are not shown here. All entries have small uncertainties from the current quark masses.

	DFSZ	KSVZ
c_γ	0.0017	$0.0023(E/N - 1.92)$
c_e	$(1/3)\cos^2\beta$	0
c_p	$-0.10 - 0.45\cos^2\beta$	-0.39
c_n	$-0.18 + 0.39\cos^2\beta$	$+0.04$

For illustrative purposes, we depict various constraints on f_A (and m_A) for the case of the KSVZ model in Fig. 1, using only representative constraints. What follows is a brief discussion of each of the constraints shown in the figure. The bounds on the DFSZ axion are similar.

Astrophysics puts a lower bound on f_A, because a small f_A leads to a large coupling of the axion to nucleons, electrons, and photons and thus to a large "exotic" energy-loss rate. In horizontal-branch (HB) stars, the Primakoff process $\gamma + ({}^4He, e^-) \to ({}^4He, e^-) + A^0$ would be the dominant axionic energy-loss mechanism. It would accelerate the consumption of nuclear fuel and thus shorten the helium-burning lifetime of these stars. The observable number fraction of HB stars in globular clusters would be significantly reduced relative to theoretical expectations unless $G_{A\gamma\gamma} < 0.6 \times 10^{-10}$ GeV^{-1} [5]. The duration of the neutrino burst from supernova (SN) 1987A observed at the Kamiokande and IMB detectors was consistent with expectations, while axion emission would have cooled the core and shortened the burst duration [7]. The dominant emission process is axion bremsstrahlung in nucleon-nucleon collisions, a process that needs to be calculated in a hot and dense nuclear medium where many-body effects are important. Early calculations overestimated the emission rate to some extent. A more realistic treatment leads to a somewhat diminished limit of about $f_A > 0.6 \times 10^9$ GeV [8], [9], although the treatment of many-body effects in this result is still under study. The cooling argument does not exclude $f_A \lesssim 0.6 \times 10^6$ GeV; in this range of f_A, the axions produced in the SN core are trapped [10]. Still, $f_A \lesssim 0.3 \times 10^6$ GeV is excluded because the trapped axions result in a burst similar to that of the neutrinos and can produce signals in water

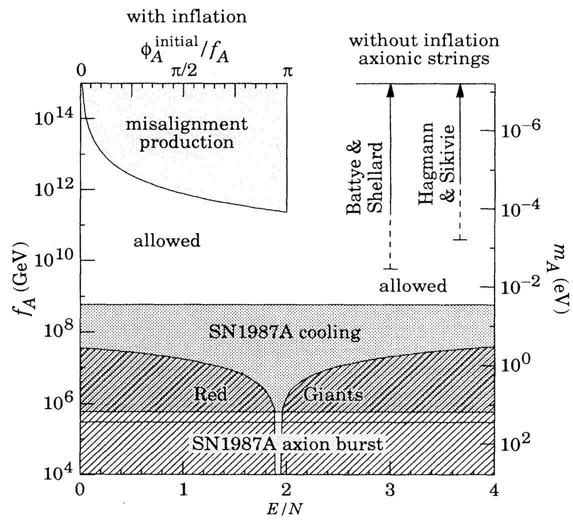

Figure 1: An illustration of the astrophysical and cosmological constraints on the axion decay constant f_A (and equivalently on m_A) in the KSVZ model. The constraint on the DSFZ model is similar except for the small window at $f_A \sim 10^6$ GeV, and one needs inflation. Shaded regions are excluded based on the arguments given in the text, though both sides have large uncertainties. The lower bound on f_A from red giants depends on the parameter E/N. All the other constraints do not. If there is inflation, there is an upper bound on f_A from misalignment production, which depends on the initial value of the axion field $\phi_A^{\rm initial}$ after inflation is over. If there is not, cosmic strings generated by Peccei–Quinn symmetry breaking produce axions, which contribute to the present mass density. Estimates of the resulting mass density vary. Here, upper bounds on f_A from two groups are shown, each of them with rather large ambiguity shown by dashed lines.

Cherenkov detectors [11]. For KSVZ axions with $E/N \approx 2$, there exists an apparent small window between these two SN arguments.

Cosmology usually puts an upper bound on f_A, because the predicted cosmic mass density in axions is proportional to $f_A^{1.175}$. The DFSZ model and the KSVZ model with more than one new quark leads to domain walls that have to be diluted away by inflation. On the other hand, the axion field does not know during inflation where the true minimum of its potential is, and is "misaligned" [12]. It begins a coherent oscillation from its misaligned initial value after the QCD phase transition and contributes to the present energy density [13] as $\Omega_a h^2 \simeq 0.2(f_A/10^{12}\ \text{GeV})^{1.175}(\phi_A^{\rm initial}/2\pi f_A)^2 \leq 1$ for a small misalignment $\phi_A^{\rm initial}/f_A \lesssim 1$. The KSVZ model with a single new quark does not produce domain walls and does not need inflation. Without inflation, there are cosmic strings created at the time of the Peccei–Quinn symmetry breaking, that emit axions and eventually decay (or collapse). There is an ongoing controversy on the estimate of the relic energy density of the emitted axions [14]. Furthermore, cosmological bounds change if there is additional entropy production [15] or a dissipation of the coherent oscillation into lighter particles [16].

It has been widely argued that a fundmental theory will not possess global symmetries; gravity, for example, is expected to violate them. Global symmetries such as baryon number typically arise as an indirect consequence of gauge symmetries and renormalizability (accidental symmetry). It has been noted [17] that the Peccei-Quinn symmetry, from this perspective, must also arise as an accidental one and must hold to an extraordinary degree of accuracy in order to solve the strong CP problem. See, for example, Ref. [17] for a possible resolution to this problem; string theory also provides sufficiently good symmetries (see for a review, [18]).

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Invisible A^0 (Axion) MASS LIMITS from Astrophysics and Cosmology

$v_1 = v_2$ is usually assumed (v_i = vacuum expectation values). For a review of these limits, see RAFFELT 90C and TURNER 90. In the comment lines below, D and K refer to DFSZ and KSVZ axion types, discussed in the above minireview.

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.018	[138] RAFFELT	95	ASTR	D, red giant
< 0.010	[139] ALTHERR	94	ASTR	D, red giants, white dwarfs
< 0.01	WANG	92	ASTR	D, white dwarf
< 0.03	WANG	92C	ASTR	D, C-O burning
none 3–8	[140] BERSHADY	91	ASTR	D, K, intergalactic light
<10	[141] KIM	91C	COSM	D, K, mass density of the universe, supersymmetry
	[142] RAFFELT	91B	ASTR	D,K, SN 1987A
$< 1 \times 10^{-3}$	[143] RESSELL	91	ASTR	K, intergalactic light
none 10^{-3}–3	BURROWS	90	ASTR	D,K, SN 1987A
	[144] ENGEL	90	ASTR	D,K, SN 1987A
< 0.02	[145] RAFFELT	90D	ASTR	D, red giant
$< 1 \times 10^{-3}$	[146] BURROWS	89	ASTR	D,K, SN 1987A
$<(1.4–10) \times 10^{-3}$	[147] ERICSON	89	ASTR	D,K, SN 1987A
$< 3.6 \times 10^{-4}$	[148] MAYLE	89	ASTR	D,K, SN 1987A
<12	CHANDA	88	ASTR	D, Sun
$< 1 \times 10^{-3}$	RAFFELT	88	ASTR	D,K, SN 1987A
	[149] RAFFELT	88B	ASTR	red giant
< 0.07	FRIEMAN	87	ASTR	D, red giant
< 0.7	[150] RAFFELT	87	ASTR	K, red giant
$< 2–5$	TURNER	87	COSM	K, thermal production
< 0.01	[151] DEARBORN	86	ASTR	D, red giant
< 0.06	RAFFELT	86	ASTR	D, red giant
< 0.7	[152] RAFFELT	86	ASTR	K, red giant
< 0.03	RAFFELT	86B	ASTR	D, white dwarf
< 1	[153] KAPLAN	85	ASTR	K, red giant
$< 0.003–0.02$	IWAMOTO	84	ASTR	D, K, neutron star
$> 1 \times 10^{-5}$	ABBOTT	83	COSM	D,K, mass density of the universe
$> 1 \times 10^{-5}$	DINE	83	COSM	D,K, mass density of the universe
< 0.04	ELLIS	83B	ASTR	D, red giant
$> 1 \times 10^{-5}$	PRESKILL	83	COSM	D,K, mass density of the universe
< 0.1	BARROSO	82	ASTR	D, red giant
< 1	[154] FUKUGITA	82	ASTR	D, stellar cooling
< 0.07	FUKUGITA	82B	ASTR	D, red giant

[138] RAFFELT 95 reexamined the constraints on axion emission from red giants due to the axion-electron coupling. They improve on DEARBORN 86 by taking into proper account degeneracy effects in the bremsstrahlung rate. The limit comes from requiring the red giant core mass at helium ignition not to exceed its standard value by more than 5% (0.025 solar masses).

[139] ALTHERR 94 bound is on the axion-electron coupling $g_{ae} < 1.5 \times 10^{-13}$, from energy loss via axion emission.

[140] BERSHADY 91 searched for a line at wave length from 3100–8300 Å expected from 2γ decays of relic thermal axions in intergalactic light of three rich clusters of galaxies.

[141] KIM 91C argues that the bound from the mass density of the universe will change drastically for the supersymmetric models due to the entropy production of saxion (scalar component in the axionic chiral multiplet) decay. Note that it is an *upperbound* rather than a lowerbound.

[142] RAFFELT 91B argue that previous SN 1987A bounds must be relaxed due to corrections to nucleon bremsstrahlung processes.

[143] RESSELL 91 uses absence of any intracluster line emission to set limit.

[144] ENGEL 90 rule out $10^{-10} \lesssim g_{AN} \lesssim 10^{-3}$, which for a hadronic axion with EMC motivated axion-nucleon couplings corresponds to 2.5×10^{-3} eV $\lesssim m_{A^0} \lesssim 2.5 \times 10^4$ eV. The constraint is loose in the middle of the range, i.e. for $g_{AN} \sim 10^{-6}$.
[145] RAFFELT 90D is a re-analysis of DEARBORN 86.
[146] The region $m_{A^0} \gtrsim 2$ eV is also allowed.
[147] ERICSON 89 considered various nuclear corrections to axion emission in a supernova core, and found a reduction of the previous limit (MAYLE 88) by a large factor.
[148] MAYLE 89 limit based on naive quark model couplings of axion to nucleons. Limit based on couplings motivated by EMC measurements is 2–4 times weaker. The limit from axion-electron coupling is weak: see HATSUDA 88B.
[149] RAFFELT 88B derives a limit for the energy generation rate by exotic processes in helium-burning stars $\epsilon < 100$ erg g^{-1} s^{-1}, which gives a firmer basis for the axion limits based on red giant cooling.
[150] RAFFELT 87 also gives a limit $g_{A\gamma} < 1 \times 10^{-10}$ GeV^{-1}.
[151] DEARBORN 86 also gives a limit $g_{A\gamma} < 1.4 \times 10^{-11}$ GeV^{-1}.
[152] RAFFELT 86 gives a limit $g_{A\gamma} < 1.1\times10^{-10}$ GeV^{-1} from red giants and $< 2.4\times10^{-9}$ GeV^{-1} from the sun.
[153] KAPLAN 85 says $m_{A^0} < 23$ eV is allowed for a special choice of model parameters.
[154] FUKUGITA 82 gives a limit $g_{A\gamma} < 2.3 \times 10^{-10}$ GeV^{-1}.

Search for Relic Invisible Axions

Limits are for $[G_{A\gamma\gamma}/m_{A^0}]^2 \rho_A$ where $G_{A\gamma\gamma}$ denotes the axion two-photon coupling, $L_{\rm int} = \frac{G_{A\gamma\gamma}}{4} \phi_A F_{\mu\nu} \tilde{F}^{\mu\nu} = G_{A\gamma\gamma} \phi_A \mathbf{E} \cdot \mathbf{B}$, and ρ_A is the axion energy density near the earth.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-41}$		[155] HAGMANN	90	CNTR	$m_{A^0} = (5.4\text{–}5.9)10^{-6}$ eV
$<1.3 \times 10^{-42}$	95	[156] WUENSCH	89	CNTR	$m_{A^0} = (4.5\text{–}10.2)10^{-6}$ eV
$<2 \times 10^{-41}$	95	[156] WUENSCH	89	CNTR	$m_{A^0} = (11.3\text{–}16.3)10^{-6}$ eV

[155] HAGMANN 90 experiment is based on the proposal of SIKIVIE 83.
[156] WUENSCH 89 looks for condensed axions near the earth that could be converted to photons in the presence of an intense electromagetic field via the Primakoff effect, following the proposal of SIKIVIE 83. The theoretical prediction with $[G_{A\gamma\gamma}/m_{A^0}]^2 = 2 \times 10^{-14}$ MeV^{-4} (the three generation DFSZ model) and $\rho_A = 300$ MeV/cm^3 that makes up galactic halos gives $(G_{A\gamma\gamma}/m_{A^0})^2\ \rho_A = 4\times10^{-44}$. Note that our definition of $G_{A\gamma\gamma}$ is $(1/4\pi)$ smaller than that of WUENSCH 89.

Invisible A^0 (Axion) Limits from Photon Coupling

Limits are for the axion-two-photon coupling $G_{A\gamma\gamma}$ defined by $L = G_{A\gamma\gamma} \phi_A \mathbf{E} \cdot \mathbf{B}$. Related limits from astrophysics can be found in the "Invisible A^0 (Axion) Mass Limits from Astrophysics and Cosmology" section.

VALUE (GeV^{-1})	CL%	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3.6 \times 10^{-7}$	95	[157] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, optical rotation
$<6.7 \times 10^{-7}$	95	[158] CAMERON	93	$m_{A^0} < 10^{-3}$ eV, photon regeneration
$<3.6 \times 10^{-9}$	99.7	[159] LAZARUS	92	$m_{A^0} < 0.03$ eV
$<7.7 \times 10^{-9}$	99.7	[159] LAZARUS	92	$m_{A^0} = 0.03\text{–}0.11$ eV
$<7.7 \times 10^{-7}$	99	[160] RUOSO	92	$m_{A^0} < 10^{-3}$ eV
$<2.5 \times 10^{-6}$		[161] SEMERTZIDIS	90	$m_{A^0} < 7 \times 10^{-4}$ eV

[157] Experiment based on proposal by MAIANI 86.
[158] Experiment based on proposal by VANBIBBER 87.
[159] LAZARUS 92 experiment is based on proposal found in VANBIBBER 89.
[160] RUOSO 92 experiment is based on the proposal by VANBIBBER 87.
[161] SEMERTZIDIS 90 experiment is based on the proposal of MAIANI 86. The limit is obtained by taking the noise amplitude as the upper limit. Limits extend to $m_{A^0} = 4 \times 10^{-3}$ where $G_{A\gamma\gamma} < 1 \times 10^{-4}$ GeV^{-1}.

Limit on Invisible A^0 (Axion) Electron Coupling

The limit is for $G_{Aee} \partial_\mu \phi_A \bar{e} \gamma^\mu \gamma_5 e$ in GeV^{-1}, or equivalenty, the dipole-dipole potential $\frac{G^2_{Aee}}{4\pi} ((\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) - 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{n})(\boldsymbol{\sigma}_2 \cdot \boldsymbol{n}))/r^3$ where $\boldsymbol{n} = \boldsymbol{r}/r$.

The limits below apply to invisible axion of $m_A \leq 10^{-6}$ eV.

VALUE (GeV^{-1})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.3 \times 10^{-5}$	66	[162] NI	94		Induced magnetism
$<6.7 \times 10^{-5}$	66	[162] CHUI	93		Induced magnetism
$<3.6 \times 10^{-4}$	66	[163] PAN	92		Torsion pendulum
$<2.7 \times 10^{-5}$	95	[162] BOBRAKOV	91		Induced magnetism
$<1.9 \times 10^{-3}$	66	[164] WINELAND	91	NMR	
$<8.9 \times 10^{-4}$	66	[163] RITTER	90		Torsion pendulum
$<6.6 \times 10^{-5}$	95	[162] VOROBYOV	88		Induced magnetism

[162] These experiments measured induced magnetization of a bulk material by the spin-dependent potential generated from other bulk material with aligned electron spins, where the magnetic field is shielded with superconductor.
[163] These experiments used a torsion pendulum to measure the potential between two bulk matter objects where the spins are polarized but without a net magnetic field in either of them.
[164] WINELAND 91 looked for an effect of bulk matter with aligned electron spins on atomic hyperfine splitting using nuclear magnetic resonance.

REFERENCES FOR Searches for Axions (A^0) and Other Very Light Bosons

ALTMANN 95 ZPHY C68 221 +Declais, v. Feilitzsch+ (MUNT, LAPP, CPPM)
BALEST 95 PR D51 2053 +Cho, Ford, Johnson+ (CLEO Collab.)
BASSOMPIE... 95 PL B355 584 Bassompierre, Bologna+ (LAPP, LCGT, LYON)
MAENO 95 PL B351 574 +Fujikawa, Kataoka, Nishihara+ (TOKY)
RAFFELT 95 PR D51 1495 +Weiss (MPIM, MPIA)
SKALSEY 95 PR D51 6292 +Conti (MICH)
TSUNODA 95 EPL 30 273 +Nakamura, Orito, Minowa (TOKY)
ADACHI 94 PR A49 3201 +Chiba, Hirose, Nagayama+ (TMU)
ALTHERR 94 ASP 2 175 +Petitgirard, del Rio Gaztelurrutia (CERN, LAPP, DFAB)
AMSLER 94B PL B333 271 +Armstrong, Ould-Saada+ (Crystal Barrel Collab.)
ASAI 94 PL B323 90 +Shigekuni, Sanuki, Orito (TOKY)
MEIJERDREES 94 PR D49 4937 Meijer Drees, Waltham+ (BRCO, OREG, TRIU)
NI 94 Physica B194 153 +Chui, Pan, Cheng (NTHU)
VO 94 PR C49 1551 +Kelly, Wohn, Hill+ (ISU, LBL, LLNL, UCD)
ATIYA 93 PRL 70 2521 +Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
Also 93C PRL 71 305 (erratum) Atiya, Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
ATIYA 93B PR D48 R1 +Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
BASSOMPIE... 93 EPL 22 239 Bassompierre, Bologna+ (LAPP, TORI, LYON)
BECK 93 PRL 70 2853 +Bensch, Bockholt, Heusser, Hirsch+(MPIH, KIAE, SASSO)
CAMERON 93 PR D47 3707 +Cantatore, Melissinos+ (ROCH, BNL, FNAL, TRST)
CHUI 93 PRL 71 3247 +Ni (NTHU)
MINOWA 93 PRL 71 4120 +Inoue, Asanuma, Imamura (TOKY)
NG 93 PR D48 2941 (AST)
TANAKA 93 PR D48 5412 +Ejiri (OSAK)
ALLIEGRO 92 PRL 68 278 +Campagnari+ (BNL, FNAL, PSI, WASH, YALE)
ATIYA 92 PRL 69 733 +Chiang, Frank, Haggerty, Ito+ (BNL, LANL, PRIN, TRIU)
BERNATOW... 92 PRL 69 2341 Bernatowicz, Brannon, Brazzle, Cowsik+ (WUSL, TATA)
BLUEMLEIN 92 IJMP A7 3835 +Brunner, Grabosch+ (BERL, BUDA, JINR, SERP)
HALLIN 92 PR D45 3955 +Calaprice, McPherson, Saettler (PRIN)
HENDERSON 92C PRL 69 1733 +Asoka-Kumar, Greenberg, Lynn+ (YALE, BNL)
HICKS 92 PL B276 423 +Alburger (OHIO, BNL)
LAZARUS 92 PRL 69 2333 +Smith, Cameron, Melissinos+ (BNL, ROCH, FNAL)
MEIJERDREES 92 PRL 68 3845 Meijer Drees, Waltham+ (SINDRUM I Collab.)
PAN 92 MPL 7 1287 +Ni, Chen (NTHU)
RUOSO 92 ZPHY C56 505 +Cameron, Cantatore+ (ROCH, BNL, FNAL, TRST)
SKALSEY 92 PRL 68 456 +Kolata (MICH, NDAM)
WANG 92 MPL A7 1497 (ILL)
WANG 92C PL B291 97 (ILL)
WU 92 PRL 69 1729 +Asoka-Kumar, Greenberg, Henderson+(BNL, YALE, CUNY)
AKOPYAN 91 PL B272 443 +Atoyan, Gninenko, Sukhov (INRM)
ASAI 91 PRL 66 2440 +Orito, Yoshimura, Haga (ICEPP)
BERSHADY 91 PRL 66 1398 +Ressell, Turner (CHIC, FNAL, EFI)
BLUEMLEIN 91 ZPHY C51 341 +Brunner, Grabosch+ (BERL, BUDA, JINR, SERP)
BOBRAKOV 91 JETPL 53 294 +Borisov, Lasakov, Serebrov, Tal'daev, Trofimova (PNPI)
Translated from ZETFP 53 283.
BROSS 91 PRL 67 2942 +Crisler, Pordes, Volk, Errede, Wrbanek (FNAL, ILL)
KIM 91C PRL 67 3465 (SEOUL)
RAFFELT 91B PRL 67 2605 +Seckel (MPIM, BART)
RESSELL 91 PR D44 3001 (CHIC, FNAL)
TRZASKA 91 PL B269 54 +Dejbakhsh, Dutta, Li, Cormier (TAMU)
TSERTOS 91 PL B266 259 +Kienle, Judge, Schreckenbach (ILLG, GSI)
WALKER 91 APJ 376 51 +Steigman, Schramm, Olive+ (HSCA, OSU, CHIC, MINN)
WIDMANN 91 ZPHY A340 209 +Bauer, Connell, Maier, Major+ (STUT, GSI, STUTM)
WINELAND 91 PRL 67 1735 +Bollinger, Heinzen, Itano, Raizen (NBSB)
ALBRECHT 90E PL B246 278 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
ANTREASYAN 90C PL B251 204 +Bartels, Besset, Bieler, Bienlein+ (Crystal Ball Collab.)
ASANUMA 90 PL B237 588 +Minowa, Tsukamoto, Orito, Tsunoda (TOKY)
ATIYA 90 PRL 64 21 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
ATIYA 90B PRL 65 1188 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
BAUER 90 NIM B50 300 +Briggmann, Carstanjen, Connell, et al (STUT, VILL, GSI)
BURROWS 90 PR D42 3297 +Ressell, Turner (ARIZ, CHIC, FNAL)
DEBOER 90 JPG 16 L1 de Boer, Lehmann, Steyaert (LOUV)
ENGEL 90 PRL 65 960 +Seckel, Hayes (BART, LANL)
GNINENKO 90 PL B237 287 +Klubakov, Poblaguev, Postoev (INRM)
GUO 90 PR D41 2924 +Kaplan, Alde+ (NIU, LANL, FNAL, CASE, TEXA)
HAGMANN 90 PR D42 1297 +Sikivie, Sullivan, Tanner (FLOR)
JUDGE 90 PRL 65 972 +Krusche, Schreckenbach, Tsertos, Kienle (ILLG, GSI)
RAFFELT 90C PRPL 198 1 (MPIM)
RAFFELT 90D PR D41 1324 (MPIM)
RITTER 90 PR D42 977 +Goldblum, Ni, Gillies, Speake (VIRG)
SEMERTZIDIS 90 PRL 64 2988 +Cameron, Cantatore+ (ROCH, BNL, FNAL, TRST)
TSUCHIAKI 90 PL B236 81 +Orito, Yoshida, Minowa (ICEPP)
TURNER 90 PRPL 197 67 (FNAL)
BARABASH 89 PL B223 273 +Kuzminov, Lobashev, Novikov+ (ITEP, INRM)
BINI 89 PL B221 99 +Fazzini, Giannatiempo, Poggi, Sona+(FIRZ, CERN, AARH)
BURROWS 89 PR D39 1020 +Turner, Brinkmann (ARIZ, CHIC, FNAL, BOCH)
Also 88 PRL 60 1797 Turner (FNAL, EFI)
DEBOER 89B PRL 62 2639 de Boer, van Dantzig (ANIK)
ERICSON 89 PL B219 507 +Mathiot (CERN, IPN)
FAISSNER 89 ZPHY C44 557 +Heinrigs, Preussger, Reitz, Samm+ (AACH3, BERL, PSI)
FISHER 89 PL B218 257 +Boehm, Bovet, Egger+ (CIT, NEUC, PSI)
FOX 89 PR C39 288 +Kemper, Cottle, Zingarelli (FSU)
MAYLE 89 PL B219 515 +Wilson, Ellis+ (LLL, CERN, MINN, FNAL, CHIC, OSU)
Also 88 PL B203 188 Mayle, Wilson+ (LLL, CERN, MINN, FNAL, CHIC, OSU)
MINOWA 89 PRL 62 1091 +Orito, Tlsuchiaki, Tlsukamoto (ICEPP)
ORITO 89 PRL 63 597 +Yoshimura, Haga, Minowa, Tsuchiaki (ICEPP)
PERKINS 89 PRL 62 2638 (OXF)
TSERTOS 89 PR D40 1397 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
VANBIBBER 89 PR D39 2089 Van Bibber, McIntyre, Morris, Raffelt (LLL, TAMU, LBL)
WUENSCH 89 PR D40 3153 +De Panfilis-Wuensch, Semertzidis+ (ROCH, BNL, FNAL)
Also 87 PRL 59 839 De Panfilis, Melissinos, Moskowitz+ (ROCH, BNL, FNAL)
ALSTON-... 88 PRL 60 1928 Alston-Garnjost, Dougherty+ (LBL, MTHO, UNM)
AVIGNONE 88 PR D37 618 +Baktash, Barker, Calaprice+(PRIN, SCUC, ORNL, WASH)
BJORKEN 88 PR D38 3375 +Ecklund, Nelson, Abashian+ (FNAL, SLAC, VPI)
BLINOV 88 SJNP 47 563 +Bondar, Bukin, Vorobyev, Groshev+ (NOVO)
Translated from YAF 47 889.
BOLTON 88 PR D38 2077 +Cooper, Frank, Hallin+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 56 2461 Bolton, Bowman, Cooper+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 57 3241 Grosnick, Wright, Bolton+ (CHIC, LANL, STAN, TEMP)
CHANDA 88 PR D37 2714 +Nieves, Pal (UMD, UPR, MASA)
CHOI 88 PR D37 3225 +Kim, Kim, Lam (JHU)
CONNELL 88 PRL 60 2242 +Fearick, Hoernle, Sideras-Haddad, Sellschop (WITW)
DATAR 88 PR C37 250 +Fortier, Gales, Hourani+ (IPN)
DEBOER 88 PRL 61 1274 de Boer, van Dantzig (ANIK)
Also 89 PRL 62 2644 erratum de Boer, van Dantzig (ANIK)
Also 89 PRL 62 2638 Perkins (OXF)
Also 89B PRL 62 2639 de Boer, van Dantzig (ANIK)
DEBOER 88C JPG 14 L131 de Boer, Deutsch, Lehmann, Prieels, Steyaert (LOUV)

DOEHNER 88 PR D38 2722 +Last, Arnold, Freedman, Dubbers (HEIDP, ANL, ILLG)
DOI 88 PR D37 2575 +Kotani, Takasugi (OSAK)
EL-NADI 88 PRL 61 1271 +Badawy (CAIR)
FAISSNER 88 ZPHY C37 231 +Heinrigs, Preussger, Reitz, Samm+ (AACH3, BERL, SIN)
HATSUDA 88B PL B203 469 +Yoshimura (KEK)
LORENZ 88 PL B214 10 +Mageras, Stiegler, Huszar (MPIM, PSI)
MAYLE 88 PL B203 188 +Wilson+ (LLL, CERN, MINN, FNAL, CHIC, OSU)
PICCIOTTO 88 PR D37 1131 +Ahmad, Britton, Bryman, Clifford+ (TRIU, CNRC)
RAFFELT 88 PRL 60 1793 +Seckel (UCB, LLL, UCSC)
RAFFELT 88B PR D37 549 +Dearborn (UCB, LLL)
SAVAGE 88 PR D37 1134 +Filippone, Mitchell (CIT)
TSERTOS 88 PL B207 273 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
TSERTOS 88B ZPHY A331 103 +Kozhuharov, Armbruster, Kienle+ (GSI, ILLG)
VANKLINKEN 88 PL B205 223 van Klinken, Meiring, de Boer, Schaafsma+ (GRON, GSI)
VANKLINKEN 88B PRL 60 2442 van Klinken (GRON)
VONWIMMER...88 PRL 60 2443 von Wimmersperg (BNL)
VOROBYOV 88 PL B208 146 +Gitarts (NOVO)
AVIGNONE 87 AIP Conf. 1987 +Brodzinski, Miley, Reeves (SCUC, PNL)
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CALDWELL 87 PRL 59 419 +Eisberg, Grumm, Witherell+ (UCSB, LBL)
DRUZHININ 87 ZPHY C37 1 +Dubrovin, Eidelman, Golubev+ (NOVO)
ELLIOTT 87 PRL 59 1649 +Hahn, Moe (UCI)
FISHER 87 PL B192 460 +Boehm, Bovet, Egger+ (CIT, NEUC, SIN)
FRIEMAN 87 PR D36 2201 +Dimopoulos, Turner (SLAC, STAN, FNAL, EFI)
GOLDMAN 87 PR D36 1543 +Hallin, Hoffman+ (LANL, CHIC, STAN, TEMP)
KORENCHE... 87 SJNP 46 192 Korenchenko, Kostin, Mzhaviya+ (JINR)
Translated from YAF 46 313.
MAIER 87 ZPHY A326 527 +Bauer, Briggmann, Carstanjen+ (STUT, GSI)
MILLS 87 PR D36 707 +Levy (BELL)
RAFFELT 87 PR D36 2211 +Dearborn (LLL, UCB)
RIORDAN 87 PRL 59 755 +Krasny, Lang, Barbaro, Bodek+ (ROCH, CIT+)
TURNER 87 PRL 59 2489 (FNAL, EFI)
VANBIBBER 87 PRL 59 759 Van Bibber, Dagdeviren, Koonin+(LLL, CIT, MIT, STAN)
VONWIMMER...87 PRL 59 266 von Wimmersperg, Connell, Hoernle, Sideras-Haddad(WITW)
ALBRECHT 86D PL B179 403 +Binder, Boeckmann+ (ARGUS Collab.)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BOWCOCK 86 PRL 56 2676 +Giles, Hassard, Kinoshita+ (CLEO Collab.)
BROWN 86 PRL 57 2101 + (FNAL, WASH, KYOT, KEK, COLU, STON, SACL)
BRYMAN 86B PRL 57 2787 +Clifford (TRIU)
DAVIER 86 PL B180 295 +Jeanjean, Nguyen Ngoc (LALO)
DEARBORN 86 PRL 56 26 +Schramm, Steigman (LLL, CHIC, FNAL, BART)
EICHLER 86 PL B175 101 +Felawka, Kraus, Niebuhr+ (SINDRUM Collab.)
HALLIN 86 PRL 57 2105 +Calparice, Dunford, McDonald (PRIN)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
KETOV 86 JETPL 44 146 +Klimov, Nikolaev, Mikaelyan+ (KIAE)
Translated from ZETFP 44 114.
KOCH 86 NC 96A 182 +Schult (JULI)
KONAKA 86 PRL 57 659 +Imai, Kobayashi, Masaike, Miyake+ (KYOT, KEK)
MAGERAS 86 PRL 56 2672 +Franzini, Tuts, Youssef+ (MPIM, COLU, STON)
MAIANI 86 PL B175 359 +Petronzio, Zavattini (CERN)
PECCEI 86 PL B172 435 +Wu, Yanagida (DESY)
RAFFELT 86 PR D33 897 (MPIM)
RAFFELT 86B PL 166B 402 (MPIM)
SAVAGE 86B PRL 57 178 +McKeown, Filippone, Mitchell (CIT)
AMALDI 85 PL 153B 444 +Carboni, Jonson, Thun (CERN)
ANANEV 85 SJNP 41 585 +Kalinina, Lushchikov, Olshevskii+ (JINR)
Translated from YAF 41 912.
BALTRUSAIT... 85 PRL 55 1842 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BERGSMA 85 PL 157B 458 +Dorenbosch, Allaby, Amaldi+ (CHARM Collab.)
KAPLAN 85 NP B260 215 (HARV)
IWAMOTO 84 PRL 53 1198 (UCSB, WUSL)
YAMAZAKI 84 PRL 52 1089 +Ishikawa, Taniguchi, Yamanaka+ (INUS, KEK)
ABBOTT 83 PL 120B 133 +Sikivie (BRAN, FLOR)
ALAM 83 PR D27 1665 + (VAND, CORN, ITHA, HARV, OHIO, ROCH+)
CARBONI 83 PL 123B 349 +Dahme (CERN, MUNI)
CAVAIGNAC 83 PL 121B 193 +Hoummada, Koang, Ost+ (ISNG, LAPP)
DICUS 83 PR D28 1778 +Teplitz (TEXA, UMD)
DINE 83 PL 120B 137 +Fischler (IAS, PENN)
ELLIS 83B NP B223 252 +Olive (CERN)
FAISSNER 83 PR D28 1198 +Heinrigs, Preussger, Samm (AACH)
FAISSNER 83B PR D28 1787 +Frenzel, Heinrigs, Preussger+ (AACH3)
FRANK 83B PR D28 1790 + (LANL, YALE, LBL, MIT, SACL, SIN, CNRC, BERN)
HOFFMAN 83 PR D28 660 +Frank, Mischke, Moir, Schardt (LANL, ARZS)
NICZYPORUK 83 ZPHY C17 197 +Jakubowski, Zeludziewicz+ (LENA Collab.)
PRESKILL 83 PL 120B 127 +Wise, Wilczek (HARV, UCSBT)
SIKIVIE 83 PRL 51 1415 (FLOR)
Also 84 PRL 52 695 erratum Sikivie (FLOR)
ALEKSEEV 82 JETP 55 591 +Kartamyshev, Makarin+ (KIAE)
Translated from ZETF 82 1007.
ALEKSEEV 82B JETPL 36 116 +Kalinina, Kruglov, Kulikov+ (MOSU, JINR)
Translated from ZETFP 36 94.
ASANO 82 PL 113B 195 +Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
BARROSO 82 PL 116B 247 +Branco (LISB)
DATAR 82 PL 114B 63 +Baba, Betigeri, Singh (BHAB)
EDWARDS 82 PRL 48 903 +Partridge, Peck, Porter+ (Crystal Ball Collab.)
FETSCHER 82 JPG 8 L147 (ETH)
FUKUGITA 82 PRL 48 1522 +Watamura, Yoshimura (KEK)
FUKUGITA 82B PR D26 1840 +Watamura, Yoshimura (KEK)
LEHMANN 82 PL 115B 270 +Lesquoy, Muller, Zylberajch (SACL)
RAFFELT 82 PL 119B 323 +Stodolsky (MPIM)
SIVERTZ 82 PR D26 717 +Lee-Franzini, Horstkotte+ (CUSB Collab.)
VERGADOS 82 PL 109B 96 (CERN)
ZEHNDER 82 PL 110B 419 +Gabathuler, Vuilleumier (ETH, SIN, CIT)
ASANO 81B PL 107B 159 +Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
BARROSO 81 PL 106B 91 +Mukhopadhyay (SIN)
FAISSNER 81 ZPHY C10 95 +Frenzel, Grimm, Hansl, Hoffman+ (AACH3)
FAISSNER 81B PL 103B 234 +Frenzel, Heinrigs, Preussger+ (AACH3)
KIM 81 PL 105B 55 +Stamm (AACH3)
VUILLEUMIER 81 PL 101B 341 +Boehm, Hahn, Kwon+ (CIT, MUNI)
ZEHNDER 81 PL 104B 494 (ETH)
FAISSNER 80 PL 96B 201 +Frenzel, Heinrigs, Preussger, Samm+ (AACH3)
JACQUES 80 PR D21 1206 +Kalelkar, Miller, Plano+ (RUTG, STEV, COLU)
SOUKAS 80 PRL 44 564 +Wanderer, Weng+ (BNL, HARV, ORNL, PENN)
BECHIS 79 PRL 42 1511 +Dombeck+ (UMD, COLU, AFRR)
CALAPRICE 79 PR D20 2708 +Dunford, Kouzes, Miller+ (PRIN)
COTEUS 79 PRL 42 1438 +Diesburg, Fine, Lee, Sokolsky+ (COLU, ILL, BNL)
DISHAW 79 PL 85B 142 +Diamant-Berger, Faessler, Liu+ (SLAC, CIT)
ZHITNITSKII 79 SJNP 29 517 +Skovpen (NOVO)
Translated from YAF 29 1001.
ALIBRAN 78 PL 74B 134 +Armenise, Arnold, Bartley (Gargamelle Collab.)
ASRATYAN 78B PL 79B 497 +Epstein, Fakhrutdinov+ (ITEP, SERP)
BELLOTTI 78 PL 76B 223 +Fiorini, Zanotti (MILA)
BOSETTI 78B PL 74B 143 +Deden, Deutschmann, Fritze+ (BEBC Collab.)
DICUS 78C PR D18 1829 +Kolb, Teplitz, Wagoner (TEXA, VPI, STAN)
DONNELLY 78 PR D18 1607 +Freedman, Lytel, Peccei, Schwartz (STAN)
Also 76 PRL 37 315 Reines, Gurr, Sobel (UCI)
Also 74 PRL 33 179 Gurr, Reines, Sobel (UCI)
HANSL 78D PL 74B 139 +Holder, Knobloch, May, Paar+ (CDHS Collab.)
MICELMAC... 78 LNC 21 441 Micelmacher, Pontecorvo (JINR)
MIKAELIAN 78 PR D18 3605 (FNAL, NWES)
SATO 78 PTP 60 1942 (KYOT)
VYSOTSKII 78 JETPL 27 502 +Zeldovich, Khlopov, Chechetkin (ASCI)
Translated from ZETFP 27 533.
YANG 78 PRL 41 523 (MASA)
PECCEI 77 PR D16 1791 +Quinn (STAN, SLAC)
Also 77B PRL 38 1440 Peccei, Quinn (STAN, SLAC)
REINES 76 PRL 37 315 +Gurr, Sobel (UCI)
GURR 74 PRL 33 179 +Reines, Sobel (UCI)
ANAND 53 PRSL A22 183

OTHER RELATED PAPERS

SREDNICKI 85 NP B260 689 (UCSB)
BARDEEN 78 PL 74B 229 +Tye (FNAL)

LEPTONS

Notes in the Lepton Listings

LEPTONS

e

$J = \frac{1}{2}$

e MASS

The mass is known much more precisely in u (atomic mass units) than in MeV (see the footnote). The conversion from u to MeV, $1\,u = 931.49432 \pm 0.00028$ MeV, involves the relatively poorly known electronic charge.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.51099907±0.00000015	[1] FARNHAM	95	CNTR	Penning
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.51099906±0.00000015	[2] COHEN	87	RVUE	1986 CODATA value
0.5110034 ±0.0000014	COHEN	73	RVUE	1973 CODATA value

[1] FARNHAM 95 compares cyclotron frequency of trapped electrons with that of a single trapped $^{12}C^{+6}$ ion. The result is $m_e = 0.0005485799111(12)$ u, where the figure in parenthesis is the 1σ uncertainty in the last digit. The uncertainty after conversion to MeV is dominated by the uncertainty in the electron charge.

[2] COHEN 87 (1986 CODATA) value in atomic mass units is 0.000548579903(13). See footnote on FARNHAM 95.

$(m_{e^+} - m_{e^-})\,/\,m_{\rm average}$

A test of *CPT* invariance.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4 \times 10^{-8}$	90	CHU	84	CNTR	Positronium spectroscopy

$\lvert q_{e^+} + q_{e^-}\rvert / e$

A test of *CPT* invariance. See also similar tests involving the proton.

VALUE	DOCUMENT ID		TECN	COMMENT
$< 4 \times 10^{-8}$	[3] HUGHES	92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<10^{-18}$	[4] MUELLER	92	THEO	Vacuum polarization

[3] HUGHES 92 uses recent measurements of Rydberg-energy and cyclotron-frequency ratios.

[4] MUELLER 92 argues that an inequality of the charge magnitudes would, through higher-order vacuum polarization, contribute to the net charge of atoms.

e MAGNETIC MOMENT ANOMALY

$\mu_e/\mu_B - 1 = (g-2)/2$

For the most accurate theoretical calculation, see KINOSHITA 81.

Some older results have been omitted.

VALUE (units 10^{-6})	DOCUMENT ID		TECN	CHG	COMMENT
1159.652193 ±0.000010	[5] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1159.6521884±0.0000043	VANDYCK	87	MRS	−	Single electron
1159.6521879±0.0000043	VANDYCK	87	MRS	+	Single positron
1159.652200 ±0.000040	VANDYCK	86	MRS	−	Single electron
1159.652222 ±0.000050	SCHWINBERG	81	MRS	+	Single positron

[5] The COHEN 87 value assumes the $g/2$ values for e^+ and e^- are equal, as required by *CPT*.

$(g_{e^+} - g_{e^-})\,/\,g_{\rm average}$

A test of *CPT* invariance.

VALUE (units 10^{-12})	CL%	DOCUMENT ID		TECN	COMMENT
− 0.5± 2.1		[6] VANDYCK	87	MRS	Penning trap
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 12	95	[7] VASSERMAN	87	CNTR	Assumes $m_{e^+} = m_{e^-}$
22 ±64		SCHWINBERG	81	MRS	Penning trap

[6] VANDYCK 87 measured $(g_-/g_+)-1$ and we converted it.

[7] VASSERMAN 87 measured $(g_+ - g_-)/(g-2)$. We multiplied by $(g-2)/g = 1.2 \times 10^{-3}$.

e ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-26} ecm)	CL%	DOCUMENT ID		TECN	COMMENT
− 0.27± 0.83		[8] ABDULLAH	90	MRS	^{205}Tl beams
• • • We do not use the following data for averages, fits, limits, etc. • • •					
− 14 ± 24		CHO	89	NMR	Tl F molecules
− 1.5 ± 5.5 ±1.5		MURTHY	89		Cesium, no *B* field
− 50 ±110		LAMOREAUX	87	NMR	^{199}Hg
190 ±340	90	SANDARS	75	MRS	Thallium
70 ±220	90	PLAYER	70	MRS	Xenon
< 300	90	WEISSKOPF	68	MRS	Cesium

[8] ABDULLAH 90 uses the relativistic enhancement of a valence electron's electric dipole moment in a high-Z atom.

e MEAN LIFE / BRANCHING FRACTION

A test of charge conservation. See the "Note on Testing Charge Conservation and the Pauli Exclusion Principle" following this section in our 1992 edition (Physical Review **D45,** 1 June, Part II (1992), p. VI.10). We use the best "disappearance" limit for the Summary Tables. The best limit for the specific channel $e^- \to \nu\gamma$ is much better.

Note that we use the mean life rather than what is often reported, the half life.

VALUE (yr)	CL%	DOCUMENT ID		TECN	COMMENT
$>4.3 \times 10^{23}$	68	AHARONOV	95B	CNTR	Ge K-shll disappearance
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>3.7 \times 10^{25}$	68	AHARONOV	95B	CNTR	$e^- \to \nu\gamma$
$>2.35 \times 10^{25}$	68	BALYSH	93	CNTR	$e^- \to \nu\gamma$, ^{76}Ge detector
$>2.7 \times 10^{23}$	68	REUSSER	91	CNTR	Ge K-shell disappearance
$>1.5 \times 10^{25}$	68	AVIGNONE	86	CNTR	$e^- \to \nu\gamma$
$>1 \times 10^{39}$		[9] ORITO	85	ASTR	Astrophysical argument
$>3 \times 10^{23}$	68	BELLOTTI	83B	CNTR	$e^- \to \nu\gamma$
$>2 \times 10^{22}$	68	BELLOTTI	83B	CNTR	Ge K-shell disappearance

[9] ORITO 85 assumes that electromagnetic forces extend out to large enough distances and that the age of our galaxy is 10^{10} years.

e REFERENCES

AHARONOV	95B	PR D52 3785	+Avignon, Brodzinski, Collar+	(SCUC, PNL, ZAGR, TELA)
Also	95	PL B353 168	Aharonov, Avignone+	(SCUC, PNL, ZAGR, TELA)
FARNHAM	95	PRL 75 3598	+Van Dyck, Schwinberg	(WASH)
BALYSH	93	PL B298 278	+Beck, Belyaev, Bensch+	(KIAE, MPIH, SASSO)
HUGHES	92	PRL 69 578	+Deutch	(LANL, AARH)
MUELLER	92	PRL 69 3432	+Thoma	(DUKE)
PDG	92	PR D45, 1 June, Part II	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
REUSSER	91	PL B255 143	+Treichel, Boehm, Broggini+	(NEUC, CIT, PSI)
ABDULLAH	90	PRL 65 2347	+Carlberg, Commins, Gould, Ross	(LBL, UCB)
CHO	89	PRL 63 2559	+Sangster, Hinds	(YALE)
MURTHY	89	PRL 63 965	+Krause, Li, Hunter	(AMHT)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
LAMOREAUX	87	PRL 59 2275	+Jacobs, Heckel, Raab, Fortson	(WASH)
VANDYCK	87	PRL 59 26	Van Dyck, Schwinberg, Dehmelt	(WASH)
VASSERMAN	87	PL B198 302	+Vorobyov, Gluskin+	(NOVO)
Also	87B	PL B187 172	Vasserman, Vorobyov, Gluskin+	(NOVO)
AVIGNONE	86	PR D34 97	+Brodzinski, Hensley, Miley, Reeves+	(PNL, SCUC)
VANDYCK	86	PR D34 722	Van Dyck, Schwinberg, Dehmelt	(WASH)
ORITO	85	PRL 54 2457	+Yoshimura	(TOKY, KEK)
CHU	84	PRL 52 1689	+Mills, Hall	(BELL, NBS, COLO)
BELLOTTI	83B	PL 124B 435	+Corti, Fiorini, Liguori, Pullia+	(MILA)
KINOSHITA	81	PRL 47 1573	+Lindquist	(CORN)
SCHWINBERG	81	PRL 47 1679	+Van Dyck, Dehmelt	(WASH)
SANDARS	75	PR A11 473	+Sternheimer	(OXF, BNL)
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
PLAYER	70	JPB 3 1620	+Sandars	(OXF)
WEISSKOPF	68	PRL 21 1645	+Carrico, Gould, Lipworth+	(BRAN)

μ

$J = \frac{1}{2}$

μ MASS

The mass is known more precisely in u (atomic mass units) than in MeV (see the footnote to COHEN 87). The conversion from u to MeV, 1 u = 931.49432 ± 0.00028 MeV, involves the relatively poorly known electronic charge.

Where m_μ/m_e was measured, we have used the 1986 CODATA value for m_e = 0.51099906 ± 0.00000015 MeV.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
105.658389±0.000034	[1] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105.65841 ±0.00033	[2] BELTRAMI	86	SPEC	−	Muonic atoms
105.658432±0.000064	[3] KLEMPT	82	CNTR	+	Incl. in MARIAM 82
105.658386±0.000044	[4] MARIAM	82	CNTR	+	
105.65856 ±0.00015	[5] CASPERSON	77	CNTR	+	
105.65836 ±0.00026	[6] CROWE	72	CNTR		
105.65865 ±0.00044	[7] CRANE	71	CNTR		

[1] The mass is known more precisely in u: m = 0.113428913 ± 0.000000017 u. COHEN 87 makes use of the other entries below.

[2] BELTRAMI 86 gives m_μ/m_e = 206.76830(64).

[3] KLEMPT 82 gives m_μ/m_e = 206.76835(11).

[4] MARIAM 82 gives m_μ/m_e = 206.768259(62).

[5] CASPERSON 77 gives m_μ/m_e = 206.76859(29).

[6] CROWE 72 gives m_μ/m_e = 206.7682(5).

[7] CRANE 71 gives m_μ/m_e = 206.76878(85).

μ MEAN LIFE τ

Measurements with an error > 0.001 × 10^{-6} s have been omitted.

VALUE (10^{-6} s)	DOCUMENT ID		TECN	CHG
2.19703 ±0.00004 OUR AVERAGE				
2.197078±0.000073	BARDIN	84	CNTR	+
2.197025±0.000155	BARDIN	84	CNTR	−
2.19695 ±0.00006	GIOVANETTI	84	CNTR	+
2.19711 ±0.00008	BALANDIN	74	CNTR	+
2.1973 ±0.0003	DUCLOS	73	CNTR	+

$\tau_{\mu^+}/\tau_{\mu^-}$ MEAN LIFE RATIO

A test of *CPT* invariance.

VALUE	DOCUMENT ID		TECN	COMMENT
1.000024±0.000078	BARDIN	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0008 ±0.0010	BAILEY	79	CNTR	Storage ring
1.000 ±0.001	MEYER	63	CNTR	Mean life μ^+/μ^-

$(\tau_{\mu^+} - \tau_{\mu^-}) / \tau_{\text{average}}$

A test of *CPT* invariance. Calculated from the mean-life ratio, above.

VALUE	DOCUMENT ID
(2±8) × 10^{-5} OUR EVALUATION	

μ MAGNETIC MOMENT ANOMALY

$\mu_\mu/(e\hbar/2m_\mu)-1 = (g_\mu-2)/2$

For reviews of theory and experiments, see HUGHES 85, KINOSHITA 84, COMBLEY 81, FARLEY 79, and CALMET 77.

VALUE (units 10^{-6})	DOCUMENT ID		TECN	CHG	COMMENT
1165.9230±0.0084	COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1165.910 ±0.011	[8] BAILEY	79	CNTR	+	Storage ring
1165.937 ±0.012	[8] BAILEY	79	CNTR	−	Storage ring
1165.923 ±0.0085	[8] BAILEY	79	CNTR	±	Storage ring
1165.922 ±0.009	[8] BAILEY	77	CNTR	±	Storage ring
1166.16 ±0.31	BAILEY	68	CNTR	±	Storage rings
1162.0 ±5.0	CHARPAK	62	CNTR	+	

[8] BAILEY 79 is final result. Includes BAILEY 77 data. We use μ/p magnetic moment ratio = 3.1833452 and recalculate the BAILEY 79 values. Third BAILEY 79 result is first two combined.

$(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-8})	DOCUMENT ID	
−2.6±1.6	BAILEY	79

μ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-19} ecm)	DOCUMENT ID		TECN	CHG	COMMENT
3.7±3.4	[9] BAILEY	78	CNTR	±	Storage ring
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.6±4.5	BAILEY	78	CNTR	+	Storage rings
0.8±4.3	BAILEY	78	CNTR	−	Storage rings

[9] This is the combination of the two BAILEY 78 results given below.

μ/p MAGNETIC MOMENT RATIO

This ratio is used to obtain a precise value of the muon mass. Measurements with an error > 0.00001 have been omitted.

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
3.18334547±0.00000047	[10] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.1833441 ±0.0000017	KLEMPT	82	CNTR	+	Precession strob
3.1833461 ±0.0000011	MARIAM	82	CNTR	+	HFS splitting
3.1833448 ±0.0000029	CAMANI	78	CNTR	+	See KLEMPT 82
3.1833403 ±0.0000044	CASPERSON	77	CNTR	+	HFS splitting
3.1833402 ±0.0000072	COHEN	73	RVUE		1973 CODATA value
3.1833467 ±0.0000082	CROWE	72	CNTR	+	Precession phase

[10] COHEN 87 (1986 CODATA) value was fitted using their own selection of the following data. Because their value is from a multiparameter fit, correlations with other quantities may be important and one cannot arrive at this result by any average of these data alone.

μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode			Fraction (Γ_i/Γ)		Confidence level
Γ_1	$e^-\overline{\nu}_e\nu_\mu$			≈ 100%		
Γ_2	$e^-\overline{\nu}_e\nu_\mu\gamma$		[a]	(1.4±0.4) %		
Γ_3	$e^-\overline{\nu}_e\nu_\mu e^+e^-$		[b]	(3.4±0.4) × 10^{-5}		
	Lepton Family number (*LF*) violating modes					
Γ_4	$e^-\nu_e\overline{\nu}_\mu$	*LF*	[c]	< 1.2	%	90%
Γ_5	$e^-\gamma$	*LF*		< 4.9	× 10^{-11}	90%
Γ_6	$e^-e^+e^-$	*LF*		< 1.0	× 10^{-12}	90%
Γ_7	$e^-2\gamma$	*LF*		< 7.2	× 10^{-11}	90%

[a] This only includes events with the γ energy > 10 MeV. Since the $e^-\overline{\nu}_e\nu_\mu$ and $e^-\overline{\nu}_e\nu_\mu\gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

[b] See the Particle Listings below for the energy limits used in this measurement.

[c] A test of additive vs. multiplicative lepton family number conservation.

μ^- BRANCHING RATIOS

$\Gamma(e^-\overline{\nu}_e\nu_\mu\gamma)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.014 ±0.004		CRITTENDEN	61	CNTR	γ KE > 10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	862	BOGART	67	CNTR	γ KE > 14.5 MeV
0.0033±0.0013		CRITTENDEN	61	CNTR	γ KE > 20 MeV
	27	ASHKIN	59	CNTR	

$\Gamma(e^-\overline{\nu}_e\nu_\mu e^+e^-)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.4±0.2±0.3	7443	[11] BERTL	85	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.2±1.5	7	[12] CRITTENDEN	61	HLBC	+	$E(e^+e^-)$>10 MeV
2	1	[13] GUREVICH	60	EMUL	+	
1.5±1.0	3	[14] LEE	59	HBC	+	

[11] BERTL 85 has transverse momentum cut p_T > 17 MeV/c. Systematic error was increased by us.

[12] CRITTENDEN 61 count only those decays where total energy of either (e^+, e^-) combination is >10 MeV.

[13] GUREVICH 60 interpret their event as either virtual or real photon conversion. e^+ and e^- energies not measured.

[14] In the three LEE 59 events, the sum of energies E(e^+) + E(e^-) + E(e^+) was 51 MeV, 55 MeV, and 33 MeV.

$\Gamma(e^- \nu_e \overline{\nu}_\mu)/\Gamma_{total}$ — Γ_4/Γ

Forbidden by the additive conservation law for lepton family number. A multiplicative law predicts this branching ratio to be 1/2. For a review see NEMETHY 81.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 0.012	90	FREEDMAN	93	CNTR	+	ν oscillation search
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.018	90	KRAKAUER	91B	CALO	+	
< 0.05	90	[15] BERGSMA	83	CALO		$\overline{\nu}_\mu e \to \mu^- \overline{\nu}_e$
< 0.09	90	JONKER	80	CALO		See BERGSMA 83
-0.001 ± 0.061		WILLIS	80	CNTR	+	
0.13 ± 0.15		BLIETSCHAU	78	HLBC	±	Avg. of 4 values
< 0.25	90	EICHTEN	73	HLBC	+	

[15] BERGSMA 83 gives a limit on the inverse muon decay cross-section ratio $\sigma(\overline{\nu}_\mu e^- \to \mu^- \overline{\nu}_e)/\sigma(\nu_\mu e^- \to \mu^- \nu_e)$, which is essentially equivalent to $\Gamma(e^- \nu_e \overline{\nu}_\mu)/\Gamma_{total}$ for small values like that quoted.

$\Gamma(e^- \gamma)/\Gamma_{total}$ — Γ_5/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 4.9	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<100	90	AZUELOS	83	CNTR	+	TRIUMF
< 17	90	KINNISON	82	SPEC	+	LAMPF
<100	90	SCHAAF	80	ELEC	+	SIN

$\Gamma(e^- e^+ e^-)/\Gamma_{total}$ — Γ_6/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-12})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 1.0	90	[16] BELLGARDT	88	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 36	90	BARANOV	91	SPEC	+	ARES
< 35	90	BOLTON	88	CBOX	+	LAMPF
< 2.4	90	[16] BERTL	85	SPEC	+	SINDRUM
<160	90	[16] BERTL	84	SPEC	+	SINDRUM
<130	90	[16] BOLTON	84	CNTR		LAMPF

[16] These experiments assume a constant matrix element.

$\Gamma(e^- 2\gamma)/\Gamma_{total}$ — Γ_7/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 7.2	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 840	90	[17] AZUELOS	83	CNTR	+	TRIUMF
<5000	90	[18] BOWMAN	78	CNTR		DEPOMMIER 77 data

[17] AZUELOS 83 uses the phase space distribution of BOWMAN 78.

[18] BOWMAN 78 assumes an interaction Lagrangian local on the scale of the inverse μ mass.

LIMIT ON $\mu^- \to e^-$ CONVERSION

Forbidden by lepton family number conservation.

$\sigma(\mu^- {}^{32}S \to e^- {}^{32}S) / \sigma(\mu^- {}^{32}S \to \nu_\mu {}^{32}P^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7 \times 10^{-11}$	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-10}$	90	BADERT...	77	STRC	SIN

$\sigma(\mu^- Cu \to e^- Cu) / \sigma(\mu^- Cu \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.6 \times 10^{-8}$	90	BRYMAN	72	SPEC

$\sigma(\mu^- Ti \to e^- Ti) / \sigma(\mu^- Ti \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.3 \times 10^{-12}$	90	[19] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.6 \times 10^{-12}$	90	AHMAD	88	TPC	TRIUMF
$<1.6 \times 10^{-11}$	90	BRYMAN	85	TPC	TRIUMF

[19] DOHMEN 93 assumes $\mu^- \to e^-$ conversion leaves the nucleus in its ground state, a process enhanced by coherence and expected to dominate.

$\sigma(\mu^- Pb \to e^- Pb) / \sigma(\mu^- Pb \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.6 \times 10^{-11}$	90	HONECKER	96	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.9 \times 10^{-10}$	90	AHMAD	88	TPC	TRIUMF

LIMIT ON $\mu^- \to e^+$ CONVERSION

Forbidden by total lepton number conservation.

$\sigma(\mu^- {}^{32}S \to e^+ {}^{32}Si^*) / \sigma(\mu^- {}^{32}S \to \nu_\mu {}^{32}P^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<9 \times 10^{-10}$	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.5 \times 10^{-9}$	90	BADERT...	78	STRC	SIN

$\sigma(\mu^- {}^{127}I \to e^+ {}^{127}Sb^*) / \sigma(\mu^- {}^{127}I \to \text{anything})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3 \times 10^{-10}$	90	[20] ABELA	80	CNTR	Radiochemical tech.

[20] ABELA 80 is upper limit for $\mu^- e^+$ conversion leading to particle-stable states of ^{127}Sb. Limit for total conversion rate is higher by a factor less than 4 (G. Backenstoss, private communication).

$\sigma(\mu^- Cu \to e^+ Co) / \sigma(\mu^- Cu \to \nu_\mu Ni)$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.6 \times 10^{-8}$	90	BRYMAN	72	SPEC
$<2.2 \times 10^{-7}$	90	CONFORTO	62	OSPK

$\sigma(\mu^- Ti \to e^+ Ca) / \sigma(\mu^- Ti \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<8.9 \times 10^{-11}$	90	[21] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.3 \times 10^{-12}$	90	[22] DOHMEN	93	SPEC	SINDRUM II
$<1.7 \times 10^{-10}$	90	[23] AHMAD	88	TPC	TRIUMF

[21] This DOHMEN 93 limit assumes a giant resonance excitation of the daughter Ca nucleus (mean energy and width both 20 MeV).

[22] This DOHMEN 93 limit assumes the daughter Ca nucleus is left in the ground state. However, the probability of this is unknown.

[23] Assuming a giant-resonance-excitation model.

LIMIT ON MUONIUM → ANTIMUONIUM CONVERSION

Forbidden by lepton family number conservation.

$R_g = G_C \,/\, G_F$

The effective Lagrangian for the $\mu^+ e^- \to \mu^- e^+$ conversion is assumed to be

$$\mathcal{L} = 2^{-1/2}\, G_C\, [\overline{\psi}_\mu \gamma_\lambda (1 - \gamma_5)\, \psi_e]\, [\overline{\psi}_\mu \gamma_\lambda (1 - \gamma_5)\, \psi_e] + \text{h.c.}$$

The experimental result is then an upper limit on G_C/G_F, where G_F is the Fermi coupling constant.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 0.13	90		GORDEEV	93	SPEC		JINR phasotron
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 0.14	90	1	[24] GORDEEV	94	SPEC	+	JINR phasotron
< 6.9	90		NI	93	CBOX		LAMPF
< 0.16	90		MATTHIAS	91	SPEC		LAMPF
< 0.29	90		HUBER	90B	CNTR		TRIUMF
< 0.88	90		HUBER	88	CNTR		See HUBER 90B
< 7.5	90		NI	87	CBOX		See NI 93
<20	95		BEER	86	CNTR		TRIUMF
<42	95		MARSHALL	82	CNTR		

[24] GORDEEV 94 quote limits on both $f = G_{M\overline{M}}/G_F$ and on the probability $W_{M\overline{M}} < 5.1 \times 10^{-7}$ (90% CL). Final results are based on the full data set.

MUON DECAY PARAMETERS

(by W. Fetscher and H.-J. Gerber, ETH Zürich)

All measurements in direct muon decay, $\mu^- \to e^- + 2$ neutrals, and its inverse, $\nu_\mu + e^- \to \mu^- +$ neutral, are successfully described by the "$V{-}A$ interaction," which is a particular case of a local, derivative-free, lepton-number-conserving, four-fermion interaction [1]. The matrix element is given below. The $V{-}A$ form and the nature of the neutrals (ν_μ and $\overline{\nu}_e$), and hence the doublet assignments $(\nu_e\ e^-)_L$ and $(\nu_\mu\ \mu^-)_L$, can be determined from experiments [2,3].

All results in direct muon decay (energy spectra, polarizations, and angular distributions) and in inverse muon decay (the reaction cross section) at energies well below $m_W c^2$ may be parametrized in terms of amplitudes $g^{\gamma}_{\varepsilon\mu}$ and the Fermi coupling constant G_F, using the matrix element

$$\frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T\\ \varepsilon,\mu=R,L}} g^{\gamma}_{\varepsilon\mu} \langle \overline{e}_\varepsilon \,|\, \Gamma^\gamma \,|\, (\nu_e)_n \rangle \, \langle (\overline{\nu}_\mu)_m \,|\, \Gamma_\gamma \,|\, \mu_\mu \rangle \ . \qquad (1)$$

We use the notation of Fetscher *et al.* [2], who in turn use the sign conventions and definitions of Scheck [4]. Here $\gamma = S, V, T$ indicate a scalar, vector, or tensor interaction; and ε, $\mu = R, L$ indicate a right- or left-handed chirality of the electron or muon. The chiralities n and m of the ν_e and $\overline{\nu}_\mu$ are then determined by the values of γ, ε, and μ. The particles are represented by fields of definite chirality [5].

As shown by Langacker and London [6], explicit lepton-number nonconservation still leads to a matrix element equivalent to Eq. (1). They conclude that it is not possible, even in principle, to test lepton-number conservation in (leptonic) muon decay if the final neutrinos are massless and are not observed.

The ten complex amplitudes $g^{\gamma}_{\varepsilon\mu}$ (g^T_{RR} and g^T_{LL} are identically zero) and G_F constitute 19 independent (real) parameters to be determined by experiment. The $V{-}A$ interaction corresponds to the single amplitude g^V_{LL} being unity and all the others being zero.

C. Jarlskog [7] has noted that certain experiments observing the decay electron are especially informative if they yield the $V{-}A$ values. Indeed, all (direct) muon decay experiments are compatible with an arbitrary mix of the scalar and vector amplitudes g^S_{LL} and g^V_{LL}—in the extreme, even with the purely scalar $g^S_{LL} = 2$, $g^V_{LL} = 0$. The decision in favor of $V{-}A$ comes from the quantitative observation of inverse muon decay, which would be forbidden for pure g^S_{LL} [2].

The differential decay probability to obtain an $e^\pm$ with (reduced) energy between x and $x + dx$, emitted in the direction $\hat{z}$ at an angle between θ and $\theta + d\theta$ with respect to the muon polarization vector $\vec{P}_\mu$, and with its spin pointing in the arbitrary direction $\hat{\zeta}$, is given by

$$\frac{d^2\Gamma}{dx\, d\cos\theta} = \frac{m_\mu}{4\pi^3} W^4_{e\mu} G^2_F \sqrt{x^2 - x_0^2} \times \Big(F_{IS}(x) \pm P_\mu \cos\theta\, F_{AS}(x)\Big) \times [1 + \vec{P}_e(x,\theta)\cdot\hat{\zeta}] \ .$$

Here $W_{e\mu} = \max(E_e) = (m^2_\mu + m^2_e)/2m_\mu$ is the maximum $e^\pm$ energy, $x = E_e/W_{e\mu}$ is the reduced energy, and $x_0 = m_e/W_{e\mu} = 9.67 \times 10^{-3}$. The quantity $P_\mu = |\vec{P}_\mu| \cdot \hat{\zeta}$ has the significance of the direction in which a perfect polarization-sensitive electron detector would be most sensitive. The isotropic part of the spectrum, $F_{IS}(x)$, the anisotropic part, $F_{AS}(x)$, and the electron polarization, $\vec{P}_e(x,\theta)$, depend on bilinear combinations—called decay parameters—of the coupling constants $g^{\gamma}_{\varepsilon\mu}$. Neglecting possible nonzero neutrino masses, we have, in terms of the decay parameters ρ, η, ξ, δ, etc.,

$$F_{IS}(x) = x(1-x) + \tfrac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta\, x_0(1-x)$$

$$F_{AS}(x) = \tfrac{1}{3}\xi\sqrt{x^2 - x_0^2} \times \Big[1 - x + \tfrac{2}{3}\delta\Big(4x - 3 - (\sqrt{1 - x_0^2} - 1)\Big)\Big]$$

$$\vec{P}_e(x,\theta) = P_{T_1}\,\hat{x} + P_{T_2}\,\hat{y} + P_L\,\hat{z} \ .$$

Here $\hat{x}$, $\hat{y}$, and $\hat{z}$ are orthogonal unit vectors defined as follows:

$\hat{z}$	is along the e momentum
$\hat{y} = [\hat{z} \times \vec{P}_\mu]/\lvert[\hat{z} \times \vec{P}_\mu]\rvert$	is transverse to the e momentum and perpendicular to the "decay plane"
$\hat{x} = \hat{y} \times \hat{z}$	is transverse to the e momentum and in the "decay plane."

The components of $\vec{P}_e$ then are given by

$$P_{T_1}(x,\theta) = P_\mu \sin\theta\, F_{T_1}(x) \Big/ \Big(F_{IS}(x) \pm P_\mu \cos\theta\, F_{AS}(x)\Big)$$

$$P_{T_2}(x,\theta) = P_\mu \sin\theta\, F_{T_2}(x) \Big/ \Big(F_{IS}(x) \pm P_\mu \cos\theta\, F_{AS}(x)\Big)$$

$$P_L(x,\theta) = \pm F_{IP}(x) + P_\mu \cos\theta \times F_{AP}(x) \Big/ \Big(F_{IS}(x) \pm P_\mu \cos\theta\, F_{AS}(x)\Big) \ ,$$

where

$$F_{T_1}(x) = \tfrac{1}{12}\Big\{-2\Big[\xi'' + 12(\rho - \tfrac{3}{4})\Big](1-x)x_0 - 3\eta(x^2 - x_0^2) + \eta''(-3x^2 + 4x - x_0^2)\Big\}$$

$$F_{T_2}(x) = \tfrac{1}{3}\sqrt{x^2 - x_0^2}\Big\{3\frac{\alpha'}{A}(1-x) + 2\frac{\beta'}{A}\sqrt{1 - x_0^2}\Big\}$$

$$F_{IP}(x) = \tfrac{1}{54}\sqrt{x^2 - x_0^2}\Big\{9\xi'\Big(-2x + 2 + \sqrt{1 - x_0^2}\Big) + 4\xi(\delta - \tfrac{3}{4})\Big(4x - 4 + \sqrt{1 - x_0^2}\Big)\Big\}$$

$$F_{AP}(x) = \tfrac{1}{6}\Big\{\xi''(2x^2 - x - x_0^2) + 4(\rho - \tfrac{3}{4})(4x^2 - 3x - x_0^2) + 2\eta''(1-x)x_0\Big\} \ .$$

For the experimental values of the decay parameters ρ, ξ, ξ', ξ'', δ, η, η'', α/A, β/A, α'/A, β'/A, which are not all independent, see the Data Listings below. Experiments in the past have also been analyzed using the parameters a, b, c, a', b', c', α/A, β/A, α'/A, β'/A (and $\eta = (\alpha - 2\beta)/2A$), as defined by Kinoshita and Sirlin [8]. They serve as a model-independent summary of all possible measurements on the decay electron (see Listings below). The relations between the two sets of parameters are

$$\rho - \frac{3}{4} = \frac{3}{4}(-a + 2c)/A ,$$
$$\eta = (\alpha - 2\beta)/A ,$$
$$\eta'' = (3\alpha + 2\beta)/A ,$$
$$\delta - \frac{3}{4} = \frac{9}{4} \cdot \frac{(a' - 2c')/A}{1 - [a + 3a' + 4(b + b') + 6c - 14c']/A} ,$$
$$1 - \xi\frac{\delta}{\rho} = 4\frac{[(b + b') + 2(c - c')]/A}{1 - (a - 2c)/A} ,$$
$$1 - \xi' = [(a + a') + 4(b + b') + 6(c + c')]/A ,$$
$$1 - \xi'' = (-2a + 20c)/A ,$$

where

$$A = a + 4b + 6c .$$

The relations to the coupling constants are:

$$a = 16(|g^V_{RL}|^2 + |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 + |g^S_{LR} + 6g^T_{LR}|^2 ,$$
$$a' = 16(|g^V_{RL}|^2 - |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 - |g^S_{LR} + 6g^T_{LR}|^2 ,$$
$$\alpha = 8\,\mathrm{Re}\left[g^V_{RL}(g^S_{LR} + 6g^T_{LR})^* + g^V_{LR}(g^S_{RL} + 6g^T_{RL})^*\right] ,$$
$$\alpha' = 8\,\mathrm{Im}\left[-g^V_{LR}(g^S_{RL} + 6g^T_{RL})^* - g^V_{RL}(g^S_{LR} + 6g^T_{LR})^*\right] ,$$
$$b = 4(|g^V_{RR}|^2 + |g^V_{LL}|^2) + |g^S_{RR}|^2 + |g^S_{LL}|^2 ,$$
$$b' = 4(|g^V_{RR}|^2 - |g^V_{LL}|^2) + |g^S_{RR}|^2 - |g^S_{LL}|^2 ,$$
$$\beta = -4\,\mathrm{Re}\left[g^V_{RR}(g^S_{LL})^* + g^V_{LL}(g^S_{RR})^*\right] ,$$
$$\beta' = 4\,\mathrm{Im}\left[g^V_{RR}(g^S_{LL})^* - g^V_{LL}(g^S_{RR})^*\right] ,$$
$$c = \tfrac{1}{2}\left[|g^S_{RL} - 2g^T_{RL}|^2 + |g^S_{LR} - 2g^T_{LR}|^2\right] ,$$
$$c' = \tfrac{1}{2}\left[|g^S_{RL} - 2g^T_{RL}|^2 - |g^S_{LR} - 2g^T_{LR}|^2\right] .$$

If also the electron mass is neglected, the energy and angular distribution of the electron in the rest frame of a polarized muon ($\mu^\mp$) is given by the Michel spectrum:

$$d^2\Gamma \sim \left\{3(1 - x) + \frac{2\rho}{3}(4x - 3) \mp\xi\,\cos\theta[1 - x + \frac{2\delta}{3}(4x - 3)]\right\} x^2 dx\, d(\cos\theta) .$$

Here θ is the angle between the electron momentum and the muon spin, and $x \equiv 2E_e/m_\mu$. For pure $V{-}A$ coupling, we obtain $\rho = \xi\delta = 3/4$, $\xi = 1$, and the differential decay rate is

$$d^2\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}\,[3 - 2x \pm \cos\theta(1 - 2x)]\, x^2 dx\, d(\cos\theta) .$$

Here the coefficient in front of the square bracket is the total decay rate.

In order to determine the amplitudes $g^\gamma_{\varepsilon\mu}$ uniquely from experiment, Fetscher *et al.* [2] introduced four probabilities $Q_{\varepsilon\mu}(\varepsilon, \mu = R, L)$ for the decay of a μ-handed muon into an ε-handed electron and showed that there exist upper bounds on Q_{RR}, Q_{LR}, and Q_{RL}, and a lower bound on Q_{LL}. These probabilities are given in terms of the $g^\gamma_{\varepsilon\mu}$'s by

$$Q_{\varepsilon\mu} = \frac{1}{4}|g^S_{\varepsilon\mu}|^2 + |g^V_{\varepsilon\mu}|^2 + 3(1 - \delta_{\varepsilon\mu})|g^T_{\varepsilon\mu}|^2 , \qquad (2)$$

where $\delta_{\varepsilon\mu} = 1$ for $\varepsilon = \mu$ and $\delta_{\varepsilon\mu} = 0$ for $\varepsilon \neq \mu$. They are related to the parameters a, b, c, a', b', and c' by

$$Q_{RR} = 2(b + b')/A ,$$
$$Q_{LR} = [(a - a') + 6(c - c')]/2A ,$$
$$Q_{RL} = [(a + a') + 6(c + c')]/2A ,$$
$$Q_{LL} = 2(b - b')/A ,$$

with $A = 16$. In the pure $V{-}A$ theory, $Q_{LL} = 1$ and the others are zero.

Since the upper bounds on Q_{RR}, Q_{LR}, and Q_{RL} are found to be small, and since the helicity of the ν_μ in pion decay is known from experiment [9,10] to very high precision to be -1 [11], the cross section S of *inverse* muon decay, normalized to the $V{-}A$ value, yields [2]

$$|g^S_{LL}|^2 \leq 4(1 - S) \qquad (3)$$

and

$$|g^V_{LL}|^2 = S . \qquad (4)$$

Thus the Standard Model assumption of a pure $V{-}A$ leptonic charged weak interaction for e and μ is confirmed (within errors) by experiments at energies far below the mass of the $W^\pm$: Eq. (4) gives a lower limit for $V{-}A$, and Eqs. (2) and (3) give upper limits for the other four-fermion interactions. The existence of such upper limits may also be seen from $Q_{RR}+Q_{RL} = (1-\xi')/2$ and $Q_{RR}+Q_{LR} = \frac{1}{2}(1+\xi/3-16\xi\delta/9)$. Table 1 gives the current experimental limits on the magnitudes of the $g^\gamma_{\varepsilon\mu}$'s.

Table 1. Ninety-percent confidence level experimental limits for the coupling constants $g^\gamma_{\varepsilon\mu}$. The limits on $|g^S_{LL}|$ and $|g^V_{LL}|$ are from Ref. 12, and the others are from Ref. 13. The experimental uncertainty on the muon polarization in pion decay is included.

$\lvert g^S_{RR}\rvert < 0.066$	$\lvert g^V_{RR}\rvert < 0.033$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125$	$\lvert g^V_{LR}\rvert < 0.060$	$\lvert g^T_{LR}\rvert < 0.036$
$\lvert g^S_{RL}\rvert < 0.424$	$\lvert g^V_{RL}\rvert < 0.110$	$\lvert g^T_{RL}\rvert < 0.122$
$\lvert g^S_{LL}\rvert < 0.55$	$\lvert g^V_{LL}\rvert > 0.96$	$\lvert g^T_{LL}\rvert \equiv 0$

Limits on the "charge retention" coordinates, as used in the older literature (*e.g.*, Ref. 14), are given by Burkard *et al.* [15].

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μ DECAY PARAMETERS

ρ PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7518±0.0026		DERENZO	69	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.762 ±0.008	170k	[25] FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.760 ±0.009	280k	[25] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.7503±0.0026	800k	[25] PEOPLES	66	ASPK	+	20–53 MeV e^+

[25] η constrained = 0. These values incorporated into a two parameter fit to ρ and η by DERENZO 69.

η PARAMETER

($V-A$) theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.007±0.013 OUR AVERAGE						
−0.007±0.013	5.3M	[26] BURKARD	85B	FIT	+	9–53 MeV e^+
−0.12 ±0.21	6346	DERENZO	69	HBC	+	1.6–6.8 MeV e^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.012±0.015±0.003	5.3M	[27] BURKARD	85B	CNTR	+	9–53 MeV e^+
0.011±0.081±0.026	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+
−0.7 ±0.5	170k	[28] FRYBERGER	68	ASPK	+	25–53 MeV e^+
−0.7 ±0.6	280k	[28] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.05 ±0.5	800k	[28] PEOPLES	66	ASPK	+	20–53 MeV e^+
−2.0 ±0.9	9213	[29] PLANO	60	HBC	+	Whole spectrum

[26] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[27] $\alpha = \alpha' = 0$ assumed.
[28] ρ constrained = 0.75.
[29] Two parameter fit to ρ and η; PLANO 60 discounts value for η.

δ PARAMETER

($V-A$) theory predicts $\delta = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7486±0.0026±0.0028		[30] BALKE	88	SPEC	+	Surface μ^+'s
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		[31] VOSSLER	69			
0.752 ±0.009	490k	FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.782 ±0.031		KRUGER	61			
0.78 ±0.05	8354	PLANO	60	HBC	+	Whole spectrum

[30] BALKE 88 uses $\rho = 0.752 \pm 0.003$.
[31] VOSSLER 69 has measured the asymmetry below 10 MeV. See comments about radiative corrections in VOSSLER 69.

$|(\xi$ PARAMETER)×(μ LONGITUDINAL POLARIZATION)$|$

($V-A$) theory predicts $\xi = 1$, longitudinal polarization = 1.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.0027±0.0079±0.0030		BELTRAMI	87	CNTR		SIN, π decay in flight
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.0013±0.0030±0.0053		[32] IMAZATO	92	SPEC	+	$K^+ \to \mu^+ \nu_\mu$
0.975 ±0.015		AKHMANOV	68	EMUL		140 kG
0.975 ±0.030	66k	GUREVICH	64	EMUL		See AKHMANOV 68
0.903 ±0.027		[33] ALI-ZADE	61	EMUL	+	27 kG
0.93 ±0.06	8354	PLANO	60	HBC	+	8.8 kG
0.97 ±0.05	9k	BARDON	59	CNTR		Bromoform target

[32] The corresponding 90% confidence limit from IMAZATO 92 is $|\xi P_\mu| > 0.990$. This measurement is of K^+ decay, not π^+ decay, so we do not include it in an average, nor do we yet set up a separate data block for K results.
[33] Depolarization by medium not known sufficiently well.

ξ × (μ LONGITUDINAL POLARIZATION) × δ / ρ

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
>0.99682	90	[34] JODIDIO	86	SPEC	+	TRIUMF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.9966	90	[35] STOKER	85	SPEC	+	μ-spin rotation
>0.9959	90	CARR	83	SPEC	+	11 kG

[34] JODIDIO 86 includes data from CARR 83 and STOKER 85. The value here is from the erratum.
[35] STOKER 85 find $(\xi P_\mu \delta/\rho)$ >0.9955 and >0.9966, where the first limit is from new μ spin-rotation data and the second is from combination with CARR 83 data. In $V-A$ theory, $(\delta/\rho) = 1.0$.

ξ' = LONGITUDINAL POLARIZATION OF e^+

($V-A$) theory predicts the longitudinal polarization = ± 1 for $e^\pm$, respectively. We have flipped the sign for e^- so our programs can average.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.00 ±0.04 OUR AVERAGE						
0.998±0.045	1M	BURKARD	85	CNTR	+	Bhabha + annihil
0.89 ±0.28	29k	SCHWARTZ	67	OSPK	−	Moller scattering
0.94 ±0.38		BLOOM	64	CNTR	+	Brems. transmiss.
1.04 ±0.18		DUCLOS	64	CNTR	+	Bhabha scattering
1.05 ±0.30		BUHLER	63	CNTR	+	Annihilation

ξ'' PARAMETER

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.65±0.36	326k	[36] BURKARD	85	CNTR	+	Bhabha + annihil

[36] BURKARD 85 measure $(\xi''-\xi\xi')/\xi$ and ξ' and set $\xi = 1$.

TRANSVERSE e^+ POLARIZATION IN PLANE OF μ SPIN, e^+ MOMENTUM

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.016±0.021±0.01	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

TRANSVERSE e^+ POLARIZATION NORMAL TO PLANE OF μ SPIN, e^+ MOMENTUM

Zero if T invariance holds.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.007±0.022±0.007	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

α/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.4± 4.3		[37] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
15 ±50 ±14	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[37] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

α'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
− 0.2± 4.3		[38] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−47 ±50 ±14	5.3M	[39] BURKARD	85B	CNTR	+	9–53 MeV e^+

[38] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[39] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

β/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.9± 6.2		[40] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2 ±17 ±6	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[40] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

β'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.5± 6.3		[41] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
17 ±17 ±6	5.3M	[42] BURKARD	85B	CNTR	+	9–53 MeV e^+

[41] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

[42] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

a/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<15.9	90	[43] BURKARD	85B	FIT

[43] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

a'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.3±4.1	[44] BURKARD	85B	FIT

[44] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$(b'+b)/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.04	90	[45] BURKARD	85B	FIT

[45] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.4	90	[46] BURKARD	85B	FIT

[46] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.5±2.0	[47] BURKARD	85B	FIT

[47] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$\bar{\eta}$ PARAMETER

($V-A$) theory predicts $\bar{\eta}=0$. $\bar{\eta}$ affects spectrum of radiative muon decay.

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.02 ±0.08 OUR AVERAGE					
−0.014±0.090	EICHENBER...	84	ELEC	+	ρ free
+0.09 ±0.14	BOGART	67	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.035±0.098	EICHENBER...	84	ELEC	+	ρ=0.75 assumed

μ REFERENCES

HONECKER 96 PRL 76 200 +Dohmen, Haan, Junker+ (SINDRUM II Collab.)
GORDEEV 94 JETPL 59 589 +Kiselev, Aleshin+ (PNPI, JINR)
Translated from ZETFP 59 565.
DOHMEN 93 PL B317 631 +Groth, Heer+ (PSI SINDRUM-II Collab.)
FREEDMAN 93 PR D47 811 +Fujikawa, Napolitano, Nelson+ (LAMPF E645 Collab.)
GORDEEV 93 JETPL 57 270 +Savchenko, Abazov+ (PNPI, JINR)
Translated from ZETFP 57 262.
NI 93 PR D48 1976 +Arnold, Chmely+ (LAMPF Crystal-Box Collab.)
IMAZATO 92 PRL 69 877 +Kawashima, Tanaka+ (KEK, INUS, TOKY, TOKMS)
BARANOV 91 SJNP 53 802 +Vanko, Glazov, Evtukhovich+ (JINR)
Translated from YAF 53 1302.
KRAKAUER 91B PL B263 534 +Talaga, Allen, Chen, Doe+ (UMD, UCI, LANL)
MATTHIAS 91 PRL 66 2716 +Ahn+ (YALE, HEIDP, WILL, GSI, VILL, BNL)
Also 91B PRL 67 932 erratum Matthias, Ahn+ (YALE, HEIDP, WILL, GSI, VILL, BNL)
HUBER 90B PR D41 2709 + (WYOM, VICT, ARIZ, ROCH, TRIU, SFRA, BRCO)
AHMAD 88 PR D38 2102 +Azuelos+ (TRIU, VICT, VPI, BRCO, MONT, CNRC)
Also 87 PRL 59 970 Ahmad+ (TRIU, VPI, VICT, BRCO, MONT, CNRC)
BALKE 88 PR D37 587 +Gidal, Jodidio+ (LBL, UCB, COLO, NWES, TRIU)
BELLGARDT 88 NP B299 1 +Otter, Eichler+ (SINDRUM Collab.)
BOLTON 88 PR D38 2077 +Cooper, Frank, Hallin+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 56 2461 Bolton, Bowman, Cooper+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 57 3241 Grosnick, Wright, Bolton+ (CHIC, LANL, STAN, TEMP)
HUBER 88 PRL 61 2189 +Beer+ (WYOM, VICT, ARIZ, ROCH, TRIU, BRCO)
BELTRAMI 87 PL B194 326 +Burkard, Von Dincklage+ (ETH, SIN, MANZ)
COHEN 87 RMP 59 1121 +Taylor (RISC, NBS)
NI 87 PRL 59 2716 +Arnold, Chmely+ (YALE, LANL, WILL, MISS, HEIDP)
BEER 86 PRL 57 671 +Marshall, Mason+ (VICT, TRIU, WYOM)
BELTRAMI 86 NP A451 679 +Aas, Beer, Dechambrier, Goudsmit+ (ETH, FRIB)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
BERTL 85 NP B260 1 +Egli, Eichler+ (SINDRUM Collab.)
BRYMAN 85 PRL 55 465 + (TRIU, CNRC, BRCO, LANL, CHIC, CARL+)
BURKARD 85 PL 150B 242 +Corriveau, Egger+ (ETH, SIN, MANZ)
BURKARD 85B PL 160B 343 +Corriveau, Egger+ (ETH, SIN, MANZ)
Also 81B PR D24 2004 Corriveau, Egger, Fetscher+ (ETH, SIN, MANZ)
Also 83B PL 129B 260 Corriveau, Egger, Fetscher+ (ETH, SIN, MANZ)
HUGHES 85 CNPP 14 341 +Kinoshita (YALE, CORN)
STOKER 85 PRL 54 1887 +Balke, Carr, Gidal+ (LBL, NWES, TRIU)
BARDIN 84 PL 137B 135 +Duclos, Magnon+ (SACL, CERN, BGNA, FIRZ)
BERTL 84 PL 140B 299 +Eichler, Felawka+ (SINDRUM Collab.)
BOLTON 84 PRL 53 1415 +Bowman, Carlini+ (LANL, CHIC, STAN, TEMP)
EICHENBER... 84 NP A412 523 Eichenberger, Engfer, VanderSchaff (ZURI)
GIOVANETTI 84 PR D29 343 +Dey, Eckhause, Hart+ (WILL)
KINOSHITA 84 PRL 52 717 +Nizic, Okamoto (CORN)
AZUELOS 83 PRL 51 164 +Depommier, Leroy, Martin+ (MONT, TRIU, BRCO)
Also 77 PRL 39 1113 Depommier+ (MONT, BRCO, TRIU, VICT, MELB)
BERGSMA 83 PL 122B 465 +Dorenbosch, Jonker+ (CHARM Collab.)
CARR 83 PRL 51 627 +Gidal, Gobbi, Jodidio, Oram+ (LBL, NWES, TRIU)
KINNISON 82 PR D25 2846 +Anderson, Matis, Wright+ (EFI, STAN, LANL)
Also 79 PRL 42 556 Bowman, Cooper, Hamm+ (LASL, EFI, STAN)
KLEMPT 82 PR D25 652 +Schulze, Wolf, Camani, Gygax+ (MANZ, ETH)
MARIAM 82 PRL 49 993 +Beer, Bolton, Egan, Gardner+ (YALE, HEIDH, BERN)
MARSHALL 82 PR D25 1174 +Warren, Oram, Kiefl (BRCO)
COMBLEY 81 PRPL 68 93 +Farley, Picasso (SHEF, RMCS, CERN)
NEMETHY 81 CNPP 10 147 +Hughes (LBL, YALE)
ABELA 80 PL 95B 318 +Backenstoss, Simons, Wuest+ (BASL, KARLK, KARLE)
BADERT... 80 LNC 28 401 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
Also 82 NP A377 406 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
JONKER 80 PL 93B 203 +Panman, Udo, Allaby+ (CHARM Collab.)
SCHAAF 80 NP A340 249 +Engfer, Povel, Dey+ (ZURI, ETH, SIN)
Also 77 PL 72B 183 Povel, Dey, Walter, Pfeiffer+ (ZURI, ETH, SIN)
WILLIS 80 PRL 44 522 +Hughes+ (YALE, LBL, LASL, SACL, SIN, CNRC+)
Also 80B PRL 45 1370 Willis+ (YALE, LBL, LASL, SACL, SIN, CNRC+)
BAILEY 79 NP B150 1 (CERN, DARE, MANZ)
FARLEY 79 ARNPS 29 243 +Picasso (RMCS, CERN)
BADERT... 78 PL 79B 371 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
BAILEY 78 JPG 4 345 (DARE, BERN, SHEF, MANZ, RMCS, CERN, BIRM)
Also 79 NP B150 1 Bailey (CERN, DARE, MANZ)
BLIETSCHAU 78 NP B133 205 +Deden, Hasert, Krenz+ (Gargamelle Collab.)
BOWMAN 78 PRL 41 442 +Cheng, Li, Matis (LASL, IAS, CMU, EFI)
CAMANI 78 PL 77B 326 +Gygax, Klempt, Schenck, Schulze+ (ETH, MANZ)
BADERT... 77 PRL 39 1385 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
BAILEY 77 PL 67B 225 + (CERN Muon Storage Ring Collab.)
Also 77C PL 68B 191 Bailey+ (CERN, DARE, BERN, SHEF, MANZ+)
Also 75 PL 55B 420 Bailey+ (CERN Muon Storage Ring Collab., BIRM)
CALMET 77 RMP 49 21 +Narison, Perrottet+ (CPPM)
CASPERSON 77 PRL 38 956 +Crane+ (BERN, HEIDH, LASL, WYOM, YALE)
DEPOMMIER 77 PRL 39 1113 + (MONT, BRCO, TRIU, VICT, MELB)
BALANDIN 74 JETP 40 811 +Grebenyuk, Zinov, Konin, Ponomarev (JINR)
Translated from ZETF 67 1631.
COHEN 73 JPCRD 2 663 +Taylor (RISC, NBS)
DUCLOS 73 PL 47B 491 +Magnon, Picard (SACL)
EICHTEN 73 PL 46B 281 +Deden, Hasert, Krenz+ (Gargamelle Collab.)
BRYMAN 72 PRL 28 1469 +Blecher, Gotow, Powers (VPI)
CROWE 72 PR D5 2145 +Hague, Rothberg, Schenck+ (LBL, WASH)
CRANE 71 PRL 27 474 +Casperson, Crane, Egan, Hughes+ (YALE)
DERENZO 69 PR 181 1854 (EFI)
VOSSLER 69 NC 63A 423 (EFI)
AKHMANOV 68 SJNP 6 230 +Gurevich, Dobretsov, Makarina+ (KIAE)
Translated from YAF 6 316.
BAILEY 68 PL 28B 287 +Bartl, VonBochmann, Brown, Farley+ (CERN)
Also 72 NC 9A 369 Bailey, Bartl, VonBochmann, Brown+ (CERN)
FRYBERGER 68 PR 166 1379 (EFI)
BOGART 67 PR 156 1405 +Dicapua, Nemethy, Strelzoff (COLU)
SCHWARTZ 67 PR 162 1306 (EFI)
SHERWOOD 67 PR 156 1475 (EFI)
PEOPLES 66 Nevis 147 unpub. (COLU)
BLOOM 64 PL 8 87 +Dick, Feuvrais, Henry, Macq, Spighel (CERN)
DUCLOS 64 PL 9 62 +Heintze, DeRujula, Soergel (CERN)
GUREVICH 64 PL 11 185 +Makarina+ (KIAE)
BUHLER 63 PL 7 368 +Cabibbo, Fidecaro, Massam, Muller+ (CERN)
MEYER 63 PR 132 2693 +Anderson, Bleser, Lederman+ (COLU)
CHARPAK 62 PL 1 16 +Farley, Garwin+ (CERN)
CONFORTO 62 NC 26 261 +Conversi, Dilella+ (INFN, ROMA, CERN)
ALI-ZADE 61 JETP 13 313 +Gurevich, Nikolski
Translated from ZETF 40 452.
CRITTENDEN 61 PR 121 1823 +Walker, Ballam (WISC, MSU)
KRUGER 61 UCRL 9322 unpub. (LRL)
GUREVICH 60 JETP 10 225 +Nikolski, Surkova (ITEP)
Translated from ZETF 37 318.
PLANO 60 PR 119 1400 (COLU)
ASHKIN 59 NC 14 1266 +Fazzini, Fidecaro, Lipman, Merrison+ (CERN)
BARDON 59 PRL 2 56 +Berley, Lederman (COLU)
LEE 59 PRL 3 55 +Samios (COLU)

τ

$J = \frac{1}{2}$

τ discovery paper was PERL 75. $e^+e^- \rightarrow \tau^+\tau^-$ cross-section threshold behavior and magnitude are consistent with pointlike spin-1/2 Dirac particle. BRANDELIK 78 ruled out pointlike spin-0 or spin-1 particle. FELDMAN 78 ruled out $J = 3/2$. KIRKBY 79 also ruled out J=integer, $J = 3/2$.

τ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
$1777.00^{+0.30}_{-0.27}$ OUR AVERAGE				
$1776.96^{+0.18}_{-0.21}{}^{+0.25}_{-0.17}$	65	[1] BAI 96	BES	E^{ee}_{cm}= 3.54–3.57 GeV
1777.8 ±0.7 ±1.7	35k	[2] BALEST 93	CLEO	E^{ee}_{cm}= 10.6 GeV
1776.3 ±2.4 ±1.4	11k	[3] ALBRECHT 92M	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
$1783\ ^{+3}_{-4}$	692	[4] BACINO 78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1776.9\ ^{+0.4}_{-0.5}$ ±0.2	14	[5] BAI 92	BES	Repl. by BAI 96

[1] BAI 96 fit $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ at different energies near threshold.

[2] BALEST 93 fit spectra of minimum kinematically allowed τ mass in events of the type $e^+e^- \rightarrow \tau^+\tau^- \rightarrow (\pi^+ n\pi^0\nu_\tau)(\pi^- m\pi^0\nu_\tau)$ $n \leq 2$, $m \leq 2$, $1 \leq n+m \leq 3$. If $m_{\nu_\tau} \neq 0$, result increases by $(m^2_{\nu_\tau}/1100$ MeV).

[3] ALBRECHT 92M fit τ pseudomass spectrum in $\tau^- \rightarrow 2\pi^-\pi^+\nu_\tau$ decays. Result assumes m_{ν_τ}=0.

[4] BACINO 78B value comes from $e^\pm X^\mp$ threshold. Published mass 1782 MeV increased by 1 MeV using the high precision $\psi(2S)$ mass measurement of ZHOLENTZ 80 to eliminate the absolute SPEAR energy calibration uncertainty.

[5] BAI 92 fit $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ near threshold using $e\mu$ events.

τ MEAN LIFE

A consistent treatment of systematic biases (see WASSERBAECH 93) yields a correction of −0.03 fs on the average. In addition, BATTLE 92 assumes an obsolete value of the τ mass; the correction to be applied to the average is −0.01 fs. These corrections do not change the result within rounding errors, so that OUR EVALUATION is equal to OUR AVERAGE.

VALUE (10^{-15} s)	EVTS	DOCUMENT ID	TECN	COMMENT
291.0± 1.5 OUR EVALUATION				
291.0± 1.5 OUR AVERAGE				
291.4± 3.0		ABREU 96B	DLPH	1991–1993 LEP runs
289.2± 1.7± 1.2		ALEXANDER 96E	OPAL	1990–1994 LEP runs
293.7± 2.7± 1.6	42k	BUSKULIC 96B	ALEP	1989–1992 LEP runs
297 ± 9 ± 5	1671	ABE 95Y	SLD	1992–1993 SLC runs
293 ± 9 ±12	5743	ADRIANI 93M	L3	1991 LEP run
304 ± 14 ± 7	4100	BATTLE 92	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
309 ± 23 ±30	2817	ADEVA 91F	L3	1990 LEP run
301 ± 29	3780	KLEINWORT 89	JADE	E^{ee}_{cm}= 35–46 GeV
288 ± 16 ±17	807	AMIDEI 88	MRK2	E^{ee}_{cm}= 29 GeV
306 ± 20 ±14	695	BRAUNSCH... 88C	TASS	E^{ee}_{cm}= 36 GeV
299 ± 15 ±10	1311	ABACHI 87C	HRS	E^{ee}_{cm}= 29 GeV
295 ± 14 ±11	5696	ALBRECHT 87P	ARG	E^{ee}_{cm}= 9.3–10.6 GeV
309 ± 17 ± 7	3788	BAND 87B	MAC	E^{ee}_{cm}= 29 GeV
325 ± 14 ±18	8470	BEBEK 87C	CLEO	E^{ee}_{cm}= 10.5 GeV
490 ±200	121	FORD 82	MAC	E^{ee}_{cm}= 29 GeV

τ MAGNETIC MOMENT ANOMALY

$\mu_\tau/(e\hbar/2m_\tau)-1 = (g_\tau-2)/2$

For a theoretical calculation $[(g_\tau-2)/2 = 11773(3) \times 10^{-7}]$, see SAMUEL 91B.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	95	[6] ESCRIBANO 93	RVUE	$Z \rightarrow \tau^+\tau^-$ at LEP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.12	90	GRIFOLS 91	RVUE	$Z \rightarrow \tau\tau\gamma$ at LEP
<0.023	95	[7] SILVERMAN 83	RVUE	$e^+e^- \rightarrow \tau^+\tau^-$ at PETRA

[6] ESCRIBANO 93 limit derived from $\Gamma(Z \rightarrow \tau^+\tau^-)$, and is on the absolute value of the magnetic moment anomaly.

[7] SILVERMAN 83 limit is derived from $e^+e^- \rightarrow \tau^+\tau^-$ total cross-section measurements for q^2 up to $(37\ \text{GeV})^2$.

τ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both T invariance and P invariance.

VALUE (ecm)	CL%	DOCUMENT ID	TECN	COMMENT
<5 × 10^{-17}	95	[8] ESCRIBANO 93	RVUE	$Z \rightarrow \tau^+\tau^-$ at LEP
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<7 × 10^{-16}	90	GRIFOLS 91	RVUE	$Z \rightarrow \tau\tau\gamma$ at LEP
<1.6 × 10^{-16}	90	DELAGUILA 90	RVUE	$e^+e^- \rightarrow \tau^+\tau^-$ E^{ee}_{cm}= 35 GeV

[8] ESCRIBANO 93 limit derived from $\Gamma(Z \rightarrow \tau^+\tau^-)$, and is on the absolute value of the electric dipole moment.

τ WEAK DIPOLE MOMENT (d^w_τ)

A nonzero value is forbidden by CP invariance.

Re(d^w_τ)

VALUE (ecm)	CL%	DOCUMENT ID	TECN	COMMENT
<0.78 × 10^{-17}	95	[9] AKERS 95F	OPAL	1991–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.5 × 10^{-17}	95	[9] BUSKULIC 95C	ALEP	1990–1992 LEP runs
<7.0 × 10^{-17}	95	[9] ACTON 92F	OPAL	$Z \rightarrow \tau^+\tau^-$ at LEP
<3.7 × 10^{-17}	95	[9] BUSKULIC 92J	ALEP	Repl. by BUSKULIC 95C

[9] Limit is on the absolute value of the real part of the weak dipole moment, and applies for $q^2 = m^2_Z$.

Im(d^w_τ)

VALUE (ecm)	CL%	DOCUMENT ID	TECN	COMMENT
<4.5 × 10^{-17}	95	[10] AKERS 95F	OPAL	1991–1993 LEP runs

[10] Limit is on the absolute value of the imaginary part of the weak dipole moment, and applies for $q^2 = m^2_Z$.

τ^- DECAY MODES

τ^+ modes are charge conjugates of the modes below. "$h^\pm$" stands for $\pi^\pm$ or $K^\pm$. "ℓ" stands for e or μ. "Neutral" means neutral hadron whose decay products include γ's and/or π^0's.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Modes with one charged particle			
Γ_1	particle$^-$ ≥ 0 neutrals ≥ $0K^0_L\nu_\tau$ ("1-prong")		(84.96± 0.14) %	S=1.3
Γ_2	particle$^-$ ≥ 0 neutrals ≥ $0K^0\nu_\tau$		(85.53± 0.14) %	S=1.3
Γ_3	$\mu^-\overline{\nu}_\mu\nu_\tau$	[a]	(17.35± 0.10) %	
Γ_4	$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$ (E_γ > 37 MeV)		(2.3 ± 1.0) × 10^{-3}	
Γ_5	$e^-\overline{\nu}_e\nu_\tau$	[a]	(17.83± 0.08) %	
Γ_6	h^- ≥ 0 neutrals ≥ $0K^0_L\ \nu_\tau$		(49.78± 0.17) %	S=1.2
Γ_7	h^- ≥ $0K^0_L\ \nu_\tau$		(12.51± 0.13) %	S=1.1
Γ_8	$h^-\nu_\tau$		(12.03± 0.14) %	S=1.1
Γ_9	$\pi^-\nu_\tau$	[a]	(11.31± 0.15) %	S=1.1
Γ_{10}	$K^-\nu_\tau$	[a]	(7.1 ± 0.5) × 10^{-3}	
Γ_{11}	h^- ≥ $1\pi^0\nu_\tau$		(36.97± 0.18) %	S=1.1
Γ_{12}	$h^-\pi^0\nu_\tau$		(25.76± 0.15) %	S=1.1
Γ_{13}	$\pi^-\pi^0\nu_\tau$	[a]	(25.24± 0.16) %	S=1.1
Γ_{14}	$\pi^-\pi^0$non-$\rho(770)\nu_\tau$		(3.0 ± 3.2) × 10^{-3}	
Γ_{15}	$K^-\pi^0\nu_\tau$	[a]	(5.2 ± 0.5) × 10^{-3}	
Γ_{16}	h^- ≥ $2\pi^0\nu_\tau$		(10.95± 0.16) %	S=1.1
Γ_{17}	$h^-2\pi^0\nu_\tau$		(9.50± 0.14) %	S=1.1
Γ_{18}	$h^-2\pi^0\nu_\tau$(ex.K^0)		(9.35± 0.14) %	S=1.1
Γ_{19}	$\pi^-2\pi^0\nu_\tau$(ex.K^0)	[a]	(9.27± 0.14) %	S=1.1
Γ_{20}	$K^-2\pi^0\nu_\tau$(ex.K^0)	[a]	(8.1 ± 2.7) × 10^{-4}	
Γ_{21}	h^- ≥ $3\pi^0\nu_\tau$		(1.46± 0.11) %	S=1.1
Γ_{22}	$h^-3\pi^0\nu_\tau$		(1.28± 0.10) %	
Γ_{23}	$\pi^-3\pi^0\nu_\tau$(ex.K^0)	[a]	(1.14± 0.14) %	
Γ_{24}	$K^-3\pi^0\nu_\tau$(ex.K^0)	[a]	($5.0\ ^{+10.0}_{-3.3}$) × 10^{-4}	
Γ_{25}	$h^-4\pi^0\nu_\tau$(ex.K^0)		(1.8 ± 0.6) × 10^{-3}	
Γ_{26}	$h^-4\pi^0\nu_\tau$(ex.K^0,η)	[a]	(1.2 ± 0.6) × 10^{-3}	
Γ_{27}	K^- ≥ 1 (π^0 or K^0) ν_τ		(9.4 ± 1.0) × 10^{-3}	

Modes with K^0's

Γ_{28}	$h^- \overline{K}^0 \geq 0$ neutrals $\geq 0 K_L^0 \nu_\tau$		(1.54 ± 0.10) %	S=1.3
Γ_{29}	$h^- \overline{K}^0 \nu_\tau$		(9.2 ± 0.8) $\times 10^{-3}$	S=1.3
Γ_{30}	$\pi^- \overline{K}^0 \nu_\tau$	[a]	(7.7 ± 0.8) $\times 10^{-3}$	S=1.3
Γ_{31}	$\pi^- \overline{K}^0$ (non-$K^*(892)^-$) ν_τ		< 1.7 $\times 10^{-3}$	CL=95%
Γ_{32}	$K^- K^0 \nu_\tau$	[a]	(1.55 ± 0.28) $\times 10^{-3}$	
Γ_{33}	$h^- \overline{K}^0 \pi^0 \nu_\tau$		(5.5 ± 0.5) $\times 10^{-3}$	
Γ_{34}	$\pi^- \overline{K}^0 \pi^0 \nu_\tau$	[a]	(4.1 ± 0.6) $\times 10^{-3}$	
Γ_{35}	$K^- K^0 \pi^0 \nu_\tau$	[a]	(1.38 ± 0.32) $\times 10^{-3}$	
Γ_{36}	$h^- K_S^0 K_S^0 \nu_\tau$		(2.5 ± 0.6) $\times 10^{-4}$	
Γ_{37}	$\pi^- K^0 \overline{K}^0 \nu_\tau$	[a]	(1.01 ± 0.23) $\times 10^{-3}$	
Γ_{38}	$K^- K^0 \geq 0$ neutrals ν_τ		(2.9 ± 0.4) $\times 10^{-3}$	
Γ_{39}	$K^- \geq 0\pi^0 \geq 0K^0\ \nu_\tau$		(1.65 ± 0.10) %	
Γ_{40}	K^0 (particles)$^-$ ν_τ		(1.58 ± 0.10) %	S=1.2
Γ_{41}	$K^0 h^+ h^- h^- \geq 0$ neut. ν_τ		< 1.7 $\times 10^{-3}$	CL=95%

Modes with three charged particles

Γ_{42}	$h^- h^- h^+ \geq$ 0neut. ν_τ ("3-prong")		(14.91 ± 0.14) %	S=1.3
Γ_{43}	$h^- h^- h^+ \geq 0$ neutrals ν_τ (ex. $K_S^0 \to \pi^+\pi^-$)		(14.36 ± 0.14) %	S=1.3
Γ_{44}	$\pi^- \pi^+ \pi^- \geq 0$ neutrals ν_τ		(14.09 ± 0.31) %	
Γ_{45}	$h^- h^- h^+ \nu_\tau$		(9.80 ± 0.10) %	S=1.1
Γ_{46}	$h^- h^- h^+ \nu_\tau$ (ex.K^0)		(9.48 ± 0.10) %	S=1.1
Γ_{47}	$h^- h^- h^+ \nu_\tau$ (ex.K^0,ω)	[a]	(9.44 ± 0.10) %	S=1.1
Γ_{48}	$h^- h^- h^+ \geq 1$ neutrals ν_τ		(5.08 ± 0.11) %	S=1.2
Γ_{49}	$h^- h^- h^+ \geq 1$ neutrals ν_τ (ex. $K_S^0 \to \pi^+\pi^-$)		(4.88 ± 0.11) %	S=1.2
Γ_{50}	$h^- h^- h^+ \pi^0 \nu_\tau$		(4.44 ± 0.09) %	S=1.1
Γ_{51}	$h^- h^- h^+ \pi^0 \nu_\tau$ (ex.K^0)		(4.25 ± 0.09) %	S=1.1
Γ_{52}	$h^- h^- h^+ \pi^0 \nu_\tau$ (ex. K^0, ω)	[a]	(2.55 ± 0.09) %	
Γ_{53}	$h^- (\rho\pi)^0 \nu_\tau$		(2.84 ± 0.34) %	
Γ_{54}	$(a_1(1260) h)^- \nu_\tau$		< 2.0 %	CL=95%
Γ_{55}	$h^- \rho \pi^0 \nu_\tau$		(1.33 ± 0.20) %	
Γ_{56}	$h^- \rho^+ h^- \nu_\tau$		(4.4 ± 2.2) $\times 10^{-3}$	
Γ_{57}	$h^- \rho^- h^+ \nu_\tau$		(1.15 ± 0.23) %	
Γ_{58}	$h^- h^- h^+ 2\pi^0 \nu_\tau$		(5.2 ± 0.5) $\times 10^{-3}$	
Γ_{59}	$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0)		(5.1 ± 0.5) $\times 10^{-3}$	
Γ_{60}	$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0,ω,η)	[a]	(1.0 ± 0.4) $\times 10^{-3}$	
Γ_{61}	$h^- h^- h^+ \geq 3\pi^0 \nu_\tau$	[a]	(1.1 ± 0.6) $\times 10^{-3}$	
Γ_{62}	$K^- h^+ h^- \geq 0$ neutrals ν_τ		< 6 $\times 10^{-3}$	CL=90%
Γ_{63}	$K^- \pi^+ \pi^- \geq 0$ neut. ν_τ		(3.9 $^{+1.9}_{-1.6}$) $\times 10^{-3}$	S=1.5
Γ_{64}	$K^- \pi^+ K^- \geq 0$ neut. ν_τ		< 9 $\times 10^{-4}$	CL=95%
Γ_{65}	$K^- K^+ \pi^- \geq 0$ neut. ν_τ		(1.5 $^{+0.9}_{-0.8}$) $\times 10^{-3}$	
Γ_{66}	$K^- K^+ \pi^- \nu_\tau$		(2.2 $^{+1.8}_{-1.2}$) $\times 10^{-3}$	
Γ_{67}	$\phi \pi^- \nu_\tau$		< 3.5 $\times 10^{-4}$	CL=90%
Γ_{68}	$K^- K^+ K^- \geq 0$ neut. ν_τ		< 2.1 $\times 10^{-3}$	CL=95%
Γ_{69}	$\pi^- K^+ \pi^- \geq 0$ neut. ν_τ		< 2.5 $\times 10^{-3}$	CL=95%
Γ_{70}	$e^- e^- e^+ \overline{\nu}_e \nu_\tau$		(2.8 ± 1.5) $\times 10^{-5}$	
Γ_{71}	$\mu^- e^- e^+ \overline{\nu}_\mu \nu_\tau$		< 3.6 $\times 10^{-5}$	CL=90%

Modes with five charged particles

Γ_{72}	$3h^- 2h^+ \geq 0$ neutrals ν_τ (ex. $K_S^0 \to \pi^-\pi^+$) ("5-prong")		(9.7 ± 0.7) $\times 10^{-4}$	
Γ_{73}	$3h^- 2h^+ \nu_\tau$ (ex.K^0)	[a]	(7.5 ± 0.7) $\times 10^{-4}$	
Γ_{74}	$3h^- 2h^+ \pi^0 \nu_\tau$ (ex.K^0)	[a]	(2.2 ± 0.5) $\times 10^{-4}$	
Γ_{75}	$3h^- 2h^+ 2\pi^0 \nu_\tau$		< 1.1 $\times 10^{-4}$	CL=90%

Miscellaneous other allowed modes

Γ_{76}	$(5\pi)^- \nu_\tau$		(3.3 ± 0.7) $\times 10^{-3}$	
Γ_{77}	$4h^- 3h^+ \geq 0$ neutrals ν_τ ("7-prong")		< 1.9 $\times 10^{-4}$	CL=90%
Γ_{78}	$K^*(892)^- \geq 0(h^0 \neq K_S^0)\nu_\tau$		(1.94 ± 0.31) %	
Γ_{79}	$K^*(892)^- \geq 0$ neutrals ν_τ		(1.33 ± 0.13) %	
Γ_{80}	$K^*(892)^- \nu_\tau$		(1.28 ± 0.08) %	
Γ_{81}	$K^*(892)^0 K^- \geq 0$ neutrals ν_τ		(3.2 ± 1.4) $\times 10^{-3}$	
Γ_{82}	$K^*(892)^0 K^- \nu_\tau$		(2.0 ± 0.6) $\times 10^{-3}$	
Γ_{83}	$\overline{K}^*(892)^0 \pi^- \geq 0$ neutrals ν_τ		(3.8 ± 1.7) $\times 10^{-3}$	
Γ_{84}	$\overline{K}^*(892)^0 \pi^- \nu_\tau$		(2.5 ± 1.1) $\times 10^{-3}$	
Γ_{85}	$K_1(1270)^- \nu_\tau$		(4 ± 4) $\times 10^{-3}$	
Γ_{86}	$K_1(1400)^- \nu_\tau$		(8 ± 4) $\times 10^{-3}$	
Γ_{87}	$K_2^*(1430)^- \nu_\tau$		< 3 $\times 10^{-3}$	CL=95%
Γ_{88}	$a_0(980)^- \geq 0$ neutrals ν_τ			
Γ_{89}	$\eta \pi^- \nu_\tau$		< 1.4 $\times 10^{-4}$	CL=95%
Γ_{90}	$\eta \pi^- \pi^0 \nu_\tau$	[a]	(1.71 ± 0.28) $\times 10^{-3}$	
Γ_{91}	$\eta \pi^- \pi^0 \pi^0 \nu_\tau$		< 4.3 $\times 10^{-4}$	CL=95%
Γ_{92}	$\eta K^- \nu_\tau$		(2.6 ± 0.7) $\times 10^{-4}$	
Γ_{93}	$\eta \pi^+ \pi^- \pi^- \geq 0$ neutrals ν_τ		< 3 $\times 10^{-3}$	CL=90%
Γ_{94}	$\eta \eta \pi^- \nu_\tau$		< 1.1 $\times 10^{-4}$	CL=95%
Γ_{95}	$\eta \eta \pi^- \pi^0 \nu_\tau$		< 2.0 $\times 10^{-4}$	CL=95%
Γ_{96}	$h^- \omega \geq 0$ neutrals ν_τ		(2.32 ± 0.11) %	
Γ_{97}	$h^- \omega \nu_\tau$	[a]	(1.91 ± 0.09) %	
Γ_{98}	$h^- \omega \pi^0 \nu_\tau$	[a]	(4.1 ± 0.6) $\times 10^{-3}$	

Lepton Family number (LF), Lepton number (L), or Baryon number (B) violating modes
(In the modes below, ℓ means a sum over e and μ modes)

L means lepton number violation (*e.g.* $\tau^- \to e^+\pi^-\pi^-$). Following common usage, LF means lepton family violation *and not* lepton number violation (*e.g.* $\tau^- \to e^-\pi^+\pi^-$).

Γ_{99}	$e^- \gamma$	LF	< 1.1	$\times 10^{-4}$	CL=90%
Γ_{100}	$\mu^- \gamma$	LF	< 4.2	$\times 10^{-6}$	CL=90%
Γ_{101}	$e^- \pi^0$	LF	< 1.4	$\times 10^{-4}$	CL=90%
Γ_{102}	$\mu^- \pi^0$	LF	< 4.4	$\times 10^{-5}$	CL=90%
Γ_{103}	$e^- K^0$	LF	< 1.3	$\times 10^{-3}$	CL=90%
Γ_{104}	$\mu^- K^0$	LF	< 1.0	$\times 10^{-3}$	CL=90%
Γ_{105}	$e^- \eta$	LF	< 6.3	$\times 10^{-5}$	CL=90%
Γ_{106}	$\mu^- \eta$	LF	< 7.3	$\times 10^{-5}$	CL=90%
Γ_{107}	$e^- \rho^0$	LF	< 4.2	$\times 10^{-6}$	CL=90%
Γ_{108}	$\mu^- \rho^0$	LF	< 5.7	$\times 10^{-6}$	CL=90%
Γ_{109}	$e^- K^*(892)^0$	LF	< 6.3	$\times 10^{-6}$	CL=90%
Γ_{110}	$\mu^- K^*(892)^0$	LF	< 9.4	$\times 10^{-6}$	CL=90%
Γ_{111}	$\pi^- \gamma$	L	< 2.8	$\times 10^{-4}$	CL=90%
Γ_{112}	$\pi^- \pi^0$	L	< 3.7	$\times 10^{-4}$	CL=90%
Γ_{113}	$e^- e^+ e^-$	LF	< 3.3	$\times 10^{-6}$	CL=90%
Γ_{114}	$e^- \mu^+ \mu^-$	LF	< 3.6	$\times 10^{-6}$	CL=90%
Γ_{115}	$e^+ \mu^- \mu^-$	LF	< 3.5	$\times 10^{-6}$	CL=90%
Γ_{116}	$\mu^- e^+ e^-$	LF	< 3.4	$\times 10^{-6}$	CL=90%
Γ_{117}	$\mu^+ e^- e^-$	L	< 3.4	$\times 10^{-6}$	CL=90%
Γ_{118}	$\mu^- \mu^+ \mu^-$	LF	< 1.9	$\times 10^{-6}$	CL=90%
Γ_{119}	$e^- \pi^+ \pi^-$	LF	< 4.4	$\times 10^{-6}$	CL=90%
Γ_{120}	$e^+ \pi^- \pi^-$	L	< 4.4	$\times 10^{-6}$	CL=90%
Γ_{121}	$\mu^- \pi^+ \pi^-$	LF	< 7.4	$\times 10^{-6}$	CL=90%
Γ_{122}	$\mu^+ \pi^- \pi^-$	L	< 6.9	$\times 10^{-6}$	CL=90%
Γ_{123}	$e^- \pi^+ K^-$	LF	< 7.7	$\times 10^{-6}$	CL=90%
Γ_{124}	$e^- \pi^- K^+$	LF	< 4.6	$\times 10^{-6}$	CL=90%
Γ_{125}	$e^+ \pi^- K^-$	L	< 4.5	$\times 10^{-6}$	CL=90%
Γ_{126}	$\mu^- \pi^+ K^-$	LF	< 8.7	$\times 10^{-6}$	CL=90%
Γ_{127}	$\mu^- \pi^- K^+$	LF	< 1.5	$\times 10^{-5}$	CL=90%
Γ_{128}	$\mu^+ \pi^- K^-$	L	< 2.0	$\times 10^{-5}$	CL=90%
Γ_{129}	$\overline{p} \gamma$	L,B	< 2.9	$\times 10^{-4}$	CL=90%
Γ_{130}	$\overline{p} \pi^0$	L,B	< 6.6	$\times 10^{-4}$	CL=90%
Γ_{131}	$\overline{p} \eta$	L,B	< 1.30	$\times 10^{-3}$	CL=90%
Γ_{132}	$e^- \overline{K}^*(892)^0$	LF	< 1.1	$\times 10^{-5}$	CL=90%
Γ_{133}	$\mu^- \overline{K}^*(892)^0$	LF	< 8.7	$\times 10^{-6}$	CL=90%
Γ_{134}	e^- light boson	LF	< 2.7	$\times 10^{-3}$	CL=95%
Γ_{135}	μ^- light boson	LF	< 5	$\times 10^{-3}$	CL=95%

[a] Basis mode for the τ.

CONSTRAINED FIT INFORMATION

An overall fit to 57 branching ratios uses 128 measurements and one constraint to determine 25 parameters. The overall fit has a $\chi^2 = 115.2$ for 104 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_5	−7									
x_9	−11	−9								
x_{10}	0	0	−31							
x_{13}	−15	−12	−20	2						
x_{15}	0	0	2	−7	−35					
x_{19}	−14	−12	−16	1	−21	1				
x_{20}	0	0	1	−3	1	−4	−19			
x_{23}	−6	−5	−13	13	−14	16	−12	8		
x_{24}	0	0	7	−19	8	−23	2	−11	−71	
x_{26}	−4	−4	−6	0	−8	0	−7	0	−3	0
x_{30}	−1	−1	−27	1	−2	1	−9	0	−2	2
x_{32}	0	0	−5	−3	1	−4	−1	−2	8	−11
x_{34}	−2	−2	−3	1	−4	2	−4	1	−10	4
x_{35}	−1	0	1	−4	1	−4	0	−2	7	−12
x_{37}	−1	−1	−5	0	−2	0	−2	0	−1	0
x_{47}	−8	−7	−6	0	−14	0	−12	0	−6	0
x_{52}	−3	−3	−5	0	−6	0	−6	0	−2	0
x_{60}	−1	−1	−1	0	−2	0	−1	0	−1	0
x_{61}	−4	−3	−5	0	−7	0	−6	0	−3	0
x_{73}	0	0	−1	0	−1	0	−1	0	0	0
x_{74}	0	0	0	0	0	0	0	0	0	0
x_{90}	−1	−1	−1	0	−2	0	−2	0	−1	0
x_{97}	−3	−3	−5	0	−6	0	−6	0	−2	0
x_{98}	−3	−3	−4	0	−5	0	−5	0	−2	0
	x_3	x_5	x_9	x_{10}	x_{13}	x_{15}	x_{19}	x_{20}	x_{23}	x_{24}

x_{30}	0									
x_{32}	0	−15								
x_{34}	−1	−3	0							
x_{35}	0	0	−2	−35						
x_{37}	−1	−1	0	−1	0					
x_{47}	−4	−17	−4	−2	0	−1				
x_{52}	−2	0	0	−8	−2	−1	−5			
x_{60}	2	0	0	0	0	0	0	0		
x_{61}	−2	0	0	0	0	−1	−6	−8	−1	
x_{73}	0	0	0	0	0	0	0	0	0	0
x_{74}	0	0	0	0	0	0	0	0	0	0
x_{90}	−16	0	0	0	0	0	−1	−1	−16	−1
x_{97}	−2	0	0	−6	−2	−1	−7	−43	−1	−7
x_{98}	−2	0	0	0	0	0	0	−4	−49	−3
	x_{26}	x_{30}	x_{32}	x_{34}	x_{35}	x_{37}	x_{47}	x_{52}	x_{60}	x_{61}

x_{74}	−24			
x_{90}	0	0		
x_{97}	0	0	−1	
x_{98}	0	0	0	−2
	x_{73}	x_{74}	x_{90}	x_{97}

τ BRANCHING FRACTIONS

(by K.G. Hayes, Hillsdale College)

Significant improvements in experimental measurements of τ branching fractions have been made since the 1994 edition of these Listings. Measurements of many new branching fractions of 1-prong τ decays containing charged and/or neutral kaons have been published [1–6]. Other new high-precision measurements of other τ branching fractions have also appeared, including many by the ALEPH collaboration [6] that are more precise than the 1994 world averages. Consequently, there are many new branching fractions in the Listings. The number of conventional τ-decay modes has increased from 59 in the 1994 edition to 98 in the current edition, and most τ branching fractions now have an absolute uncertainty in the range of 0.1 to 0.2%, with improvements over the 1994 edition typically being a factor of two or more.

Our goal for internal consistency of the τ Listings is now at the 0.1% level. To add correctly a new experimental measurement of a branching fraction to the Listings, we must understand and account for the experimenter's definition of both the signal and any background corrections to it at the 0.1% level or better. This requires that many details be considered. Some examples are: (a) is $K_S^0 \to \pi^+\pi^-$ considered to be 0-prong or 2-prong; (b) are K_L^0's included or excluded in a decay mode definition; (c) are $K_S^0 \to 2\pi^0$ decays background or signal; (d) how are photons from the decays of η and ω treated; (e) have particle ID requirements been applied to any charged prongs (either through direct detection or indirectly via cuts on invariant mass distributions); and (f) exactly what is meant by the word "neutral" in a decay mode definition?

The τ Listings have been updated in several ways to accommodate the new measurements and the need for higher precision. To help make explicit how the signal and background are defined, we have developed new notation for listing decay modes. First, invisible K_L^0's are never implicitly included in any decay mode (this is a change from previous editions). Second, for decay modes where contributions from an intermediate state are excluded, a list is appended to the decay mode which explicitly gives the excluded intermediate states. For this edition, the only intermediate states whose decays are excluded from some branching fractions are K^0, η, and ω. If there is no ambiguity as to which intermediate state decay modes are excluded, just the name of the intermediate state is given. Otherwise, the excluded intermediate state decay mode is explicitly listed. The list is appended to the decay mode using the notation "(ex. ⟨list of excluded intermediate states⟩)." For example, listed in Table 1 are a few decay modes from the current Listings and their fitted branching fractions:

One inconsistency that has existed in the data for several decay modes was the different manner in which experimenters treated $K_S^0 \to \pi^+\pi^-$ decays. Some chose to treat the pions as

Table 1: Examples of τ-decay modes and their fitted branching fractions.

particle$^-$ ≥ 0 neutrals ≥ 0 K_L^0 ν_τ	$(84.96 \pm 0.14)\%$
particle$^-$ ≥ 0 neutrals ≥ 0 K^0 ν_τ	$(85.53 \pm 0.14)\%$
$h^-h^-h^+ \geq 0$ neutrals ν_τ	$(14.91 \pm 0.14)\%$
$h^-h^-h^+ \geq 0$ neutrals ν_τ (ex. $K_S^0 \to \pi^+\pi^-$)	$(14.36 \pm 0.14)\%$
$h^-h^-h^+\pi^0\nu_\tau$	$(4.44 \pm 0.09)\%$
$h^-h^-h^+\pi^0\nu_\tau$ (ex. K^0)	$(4.25 \pm 0.09)\%$
$h^-h^-h^+\pi^0\nu_\tau$ (ex. K^0, ω)	$(2.55 \pm 0.09)\%$

charged prongs from the τ decay, while others rejected them as secondary tracks similar to electrons from photon conversion. To complicate the situation, some experimental papers make no mention as to how these decays were treated, even though different choices can affect some branching fractions by as much as 0.5%, as illustrated in the examples above.

In our definition of τ-decay modes, we treat pions from $K_S^0 \to \pi^+\pi^-$ as charged prongs from the τ decay. To correct branching fraction measurements for different choices, good knowledge of τ branching fractions for decays containing K^0's is necessary, but until this edition experimental knowledge was meager. In the 1994 edition, the only branching fraction measurement of a τ decay mode containing a K^0 (apart from K^0's used to reconstruct the K*(892)) was the measurement, based on 44 detected decays, of B($\tau^- \to K^0$ $h^- \geq 0$ neutrals ν_τ) = $(1.3 \pm 0.3)\%$ by the HRS collaboration [7]. For this edition, there are 12 new measurements, based on more than 1800 detected decays, of τ-decay modes containing K^0's. Consequently, sufficient information now exists, and we have reduced the inconsistency in branching fraction data by moving data to newly defined decay modes consistent with the way $K_S^0 \to \pi^+\pi^-$ decays were treated. Because of time limitations, we did this only for the most precise data.

To make best use of the new data, we have expanded the number of basis modes used in the constrained fit to branching fraction data from 12 in the 1994 edition to 25 in 1996. Consequently, the vast majority of branching fractions listed in the Summary Table are fit results (not averages) which is a significant change from previous editions. The only branching fractions which are not fit results are those which are either upper limits, 3-prong modes where one or more charged particles are identified, or modes containing resonances that are not included in the basis modes.

Selection of the basis modes was determined by several criteria. The basis modes must form an exclusive set whose branching fractions sum exactly to one. All measured branching fractions which contribute to the fit must be expressible in terms of a sum over basis mode branching fractions with accurately known coefficients, and all basis modes (except possibly one) must be constrained by one or more measured branching fractions. It is desirable to include a sufficient number of modes so that the largest number of branching fraction measurements can be included in the constrained fit. Finally, any modes necessary to satisfy the accuracy requirement must be included. The selected basis modes are listed in Table 2. The coefficients used to define a particular τ branching fraction in terms of the sum over basis mode branching fractions appear in the Listings immediately below each branching fraction header.

Table 2: Basis modes used in the 1994 and 1996 constrained fit to τ branching fraction data.

RPP94	RPP96
$e^-\overline{\nu}_e\nu_\tau$	*$e^-\overline{\nu}_e\nu_\tau$
$\mu^-\overline{\nu}_\mu\nu_\tau$	*$\mu^-\overline{\nu}_\mu\nu_\tau$
$\pi^-\nu_\tau$	*$\pi^-\nu_\tau$
$\pi^-\pi^0\nu_\tau$	*$\pi^-\pi^0\nu_\tau$
$h^-2\pi^0\nu_\tau$	$\pi^-2\pi^0\nu_\tau$(ex. K^0)
$h^-3\pi^0\nu_\tau$	$\pi^-3\pi^0\nu_\tau$(ex. K^0)
$h^-4\pi^0\nu_\tau$	$h^-4\pi^0\nu_\tau$(ex. K^0, η)
$K^-\nu_\tau$	*$K^-\nu_\tau$
—	$K^-\pi^0\nu_\tau$
—	$K^-2\pi^0\nu_\tau$(ex. K^0)
—	$K^-3\pi^0\nu_\tau$(ex. K^0)
—	$\pi^-\overline{K}^0\nu_\tau$
—	$\pi^-\overline{K}^0\pi^0\nu_\tau$
—	$\pi^-K^0\overline{K}^0\nu_\tau$
—	$K^-K^0\nu_\tau$
—	$K^-K^0\pi^0\nu_\tau$
$K^*(892)^-\nu_\tau$	—
$h^-h^-h^+\nu_\tau$	$h^-h^-h^+\nu_\tau$ (ex. K^0, ω)
$h^-h^-h^+ \geq 1$ neut. ν_τ	$h^-h^-h^+\pi^0\nu_\tau$ (ex. K^0, ω)
—	$h^-h^-h^+2\pi^0\nu_\tau$ (ex. K^0, ω, η)
—	$h^-h^-h^+ \geq 3\pi^0\nu_\tau$
$3h^-2h^+ \geq 0$ neut. ν_τ	$3h^-2h^+\nu_\tau$ (ex. K^0)
—	$3h^-2h^+\pi^0\nu_\tau$(ex. K^0)
—	$h^-\omega\nu_\tau$
—	$h^-\omega\pi^0\nu_\tau$
—	$\pi^-\eta\pi^0\nu_\tau$

* Unchanged from RPP94.

In selecting the basis modes, various choices and assumptions were made. For example, we have assumed that branching fractions for the following τ-decay modes are small relative to 0.1%: $\tau^- \to \pi^-\overline{K}^0 \geq 2\pi^0\nu_\tau$, $\tau^- \to \pi^-K^0\overline{K}^0 \geq 1\pi^0\nu_\tau$, $\tau^- \to h^-h^-h^+ \geq 1$ $K^0 \geq 0\pi^0\nu_\tau$, and $\tau^- \to h^- \geq 5\pi^0\nu_\tau$. Experimental upper limits on branching fractions exist for some of these modes, and comparison of measured inclusive and exclusive branching fractions allow limits to be determined for the others. The modes $\tau^- \to h^-\omega\nu_\tau$, $\tau^- \to h^-\omega\pi^0\nu_\tau$, and $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ must be included in the basis set since their combined branching fraction to final states containing photons not from π^0's is about 0.3%. We have not included in the basis set the mode $\tau^- \to K^*(892)^-\nu_\tau$. The branching fraction for this mode is usually determined from the branching fraction for either $\tau^- \to \pi^-\overline{K}^0\nu_\tau$ or $\tau^- \to K^-\pi^0\nu_\tau$ assuming these decays all originate in $\tau^- \to K^*(892)^-\nu_\tau$, but these two methods give values for B($\tau^- \rightarrow K^*(892)^- \nu_\tau$) that are inconsistent at the 2.5 σ level irrespective of whether the world average or fit values are used.

The constrained fit to branching fractions assumes all input data are uncorrelated, and data which are very highly correlated are not used in the fit. For the next edition, we plan to enhance the fitting procedure so that data correlations can be properly included. To minimize the effects of older experiments which often have larger systematic errors, we have excluded from the fit 27 older measurements in decay modes which contain at least several of the newer data of much higher precision. As a rule, we exclude those experiments with large errors which together would contribute no more than 5% of the weight in the average.

The precise new measurements have significantly reduced the uncertainties on most fitted branching fractions. Also, some problems in the data noted in the 1994 edition now have reduced significance. Table 3 lists several important hadronic branching fractions that had fit values in both the 1994 and 1996 editions. The reduction of the scale factors for most of these branching fractions illustrates the internal consistency of the new data. Note the significant change in B($h^-h^-h^+\nu_\tau$ (ex. K^0)).

Table 3: Fit branching ratios (%) and scale factors for a sample of τ hadronic decays.

Mode	1994 Fit	Scale	1996 Fit	Scale
$\pi^-\nu_\tau$	11.7 ± 0.4	1.3	11.31 ± 0.15	1.1
$K^-\nu_\tau$	0.67 ± 0.23	1.3	0.71 ± 0.05	1.0
$h^-\pi^0\nu_\tau$	25.7 ± 0.4	1.7	25.76 ± 0.15	1.1
$h^-2\pi^0\nu_\tau$	9.6 ± 0.4	1.5	9.50 ± 0.14	1.1
$h^-3\pi^0\nu_\tau$	1.28 ± 0.24	1.7	1.28 ± 0.10	1.0
$h^-h^-h^+\nu_\tau$ (ex. K^0)	8.42 ± 0.31	1.3	9.48 ± 0.10	1.1
$h^-h^-h^+ \geq 1$ neutrals ν_τ	5.63 ± 0.30	1.2	5.08 ± 0.11	1.2

Other evidence for the improved internal consistency is the decrease in the difference between the fitted and average values for the leptonic branching fractions. In previous editions, the data exhibited a "deficit" in 1-prong exclusive branching fractions for which the fit compensated by systematically increasing all 1-prong fit branching fractions above their average values. Table 4 compares the average and fit values for $B_e \equiv$ B($\tau^- \rightarrow e^- \overline{\nu}_e\nu_\tau$) and $B_\mu \equiv$ B($\tau^- \rightarrow \mu^- \overline{\nu}_\mu\nu_\tau$) for the 1994 and 1996 editions.

Table 4: Fit and average branching fractions for $\tau^- \rightarrow e^- \overline{\nu}_e\nu_\tau$ and $\tau^- \rightarrow \mu^- \overline{\nu}_\mu\nu_\tau$.

Branching Fraction (%)		1994	1996
B_e	Fit	18.01 ± 0.18	17.83 ± 0.08
B_e	Average	17.90 ± 0.17	17.80 ± 0.08
B_μ	Fit	17.65 ± 0.24	17.35 ± 0.10
B_μ	Average	17.44 ± 0.23	17.30 ± 0.10

The charged-prong topological branching fractions changed significantly from their 1994 values. Although only two measurements of charged prong topological branching fractions have been published since the 1994 edition (both of B($h^-h^-h^+ \geq 0$ neutrals ν_τ (ex. $K_S^0 \rightarrow \pi^+\pi^-$))), some new measurements of other modes influenced the fitted value of the topological branching fractions. The improved consistency of our treatment of $K_S^0 \rightarrow \pi^+\pi^-$ decays also influenced the results. Table 5 compares the average and fit values for $B_1 \equiv$ B(particle$^- \geq 0$ neutrals ≥ 0 K_L^0 ν_τ) and $B_3 \equiv$ B($h^-h^-h^+ \geq 0$ neutrals ν_τ) for the 1994 and 1996 editions. Although the fit and average values for B_1 and B_3 were very similar in 1994, the new fit values differ significantly from their averages. As the averages of these two modes are formed from older measurements (1992 or earlier), the precise new measurements lead to charged prong topological branching fractions which are significantly different from the older values.

Table 5: Fit and average branching fractions for B_1 and B_3.

Branching Fraction (%)		1994	1996
B_1	Fit	85.49 ± 0.24	84.96 ± 0.14
B_1	Average	85.46 ± 0.30	85.90 ± 0.30
B_3	Fit	14.38 ± 0.24	14.91 ± 0.14
B_3	Average	14.32 ± 0.27	14.01 ± 0.29

Conclusions: The precision of τ branching fraction measurements has increased significantly since the 1994 edition. Measurements of new 1-prong decay modes containing charged and/or neutral kaons have allowed a large expansion in the number of basis modes used in the constrained fit to τ branching fractions. Ambiguities and inconsistencies in the Listings caused by the lack of data on 1-prong modes containing neutral kaons have been significantly reduced. The new level of precision requires experimenters to be especially clear in describing their definition of signal and background in measurements of τ branching fractions. Future measurements of the charged and neutral kaon content in 3-prong τ decays will allow similar improvements in the understanding of those decay modes.

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τ^- BRANCHING RATIOS

$\Gamma(\text{particle}^- \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau(\text{"1-prong"}))/\Gamma_{\text{total}}$ — Γ_1/Γ

$\Gamma_1/\Gamma = (\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{30}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{35}+0.4316\Gamma_{37}+0.708\Gamma_{90}+0.085\Gamma_{97}+0.085\Gamma_{98})/\Gamma$

The charged particle here can be e, μ, or hadron. In many analyses, the sum of the topological branching fractions (1, 3, and 5 prongs) is constrained to be unity. Since the 5-prong fraction is very small, the measured 1-prong and 3-prong fractions are highly correlated and cannot be treated as independent quantities in our overall fit. We arbitrarily choose to use the 3-prong fraction in our fit, and leave the 1-prong fraction out. We do, however, use these 1-prong measurements in our average below. The measurements used only for the average are marked "avg," whereas "f&a" marks a result used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
84.96±0.14 OUR FIT	Error includes scale factor of 1.3.				
85.90±0.30 OUR AVERAGE	Error includes scale factor of 1.2.				
85.6 ±0.6 ±0.3	avg	3300	[11] ADEVA 91F	L3	E^{ee}_{cm}= 88.3–94.3 GeV
86.4 ±0.3 ±0.3	avg		ABACHI 89B	HRS	E^{ee}_{cm}= 29 GeV
84.9 ±0.4 ±0.3	avg		BEHREND 89B	CELL	E^{ee}_{cm}= 14–47 GeV
84.7 ±0.8 ±0.6	avg		[12] AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV
87.2 ±0.5 ±0.8	avg		SCHMIDKE 86	MRK2	E^{ee}_{cm}= 29 GeV
84.7 ±1.1 $^{+1.6}_{-1.3}$	avg	169	[13] ALTHOFF 85	TASS	E^{ee}_{cm}= 34.5 GeV
86.1 ±0.5 ±0.9	avg		BARTEL 85F	JADE	E^{ee}_{cm}= 34.6 GeV
86.7 ±0.3 ±0.6	avg		FERNANDEZ 85	MAC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
87.1 ±1.0 ±0.7			[14] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
87.8 ±1.3 ±3.9			[15] BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV

[11] Not independent of ADEVA 91F $\Gamma(h^- h^- h^+ \geq 0\text{neut. } \nu_\tau(\text{"3-prong"}))/\Gamma_{\text{total}}$ value.
[12] Not independent of AIHARA 87B $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$, and $\Gamma(h^- \geq 0\text{ neutrals} \geq 0K^0_L\ \nu_\tau)/\Gamma_{\text{total}}$ values.
[13] Not independent of ALTHOFF 85 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(h^- \geq 0\text{ neutrals} \geq 0K^0_L\ \nu_\tau)/\Gamma_{\text{total}}$, and $\Gamma(h^- h^- h^+ \geq 0\text{neut. } \nu_\tau(\text{"3-prong"}))/\Gamma_{\text{total}}$ values.
[14] Not independent of SCHMIDKE 86 value (also not independent of BURCHAT 87 value for $\Gamma(h^- h^- h^+ \geq 0\text{neut. } \nu_\tau(\text{"3-prong"}))/\Gamma_{\text{total}}$.
[15] Not independent of (1-prong + $0\pi^0$) and (1-prong + $\geq 1\pi^0$) values.

$\Gamma(\text{particle}^- \geq 0\text{ neutrals} \geq 0K^0\nu_\tau)/\Gamma_{\text{total}}$ — Γ_2/Γ

$\Gamma_2/\Gamma = (\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+\Gamma_{30}+\Gamma_{32}+\Gamma_{34}+\Gamma_{35}+\Gamma_{37}+0.708\Gamma_{90}+0.085\Gamma_{97}+0.085\Gamma_{98})/\Gamma$

VALUE (%)		DOCUMENT ID	TECN	COMMENT
85.53±0.14 OUR FIT	Error includes scale factor of 1.3.			
84.59±0.33 OUR AVERAGE				
84.48±0.27±0.23	avg	ACTON 92H	OPAL	1990–1991 LEP runs
85.45$^{+0.69}_{-0.73}$±0.65	f&a	DECAMP 92C	ALEP	1989–1990 LEP runs

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$ — Γ_3/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

To minimize the effect of experiments with large systematic errors, we exclude experiments which together would contribute 5% of the weight in the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
17.35±0.10 OUR FIT					
17.30±0.10 OUR AVERAGE					
17.31±0.11±0.05	f&a	20.7k	BUSKULIC 96C	ALEP	1991–1993 LEP runs
17.02±0.19±0.24	f&a	6586	ABREU 95T	DLPH	1991–1992 LEP runs
17.36±0.27	f&a	7941	AKERS 95I	OPAL	1990–1992 LEP runs
17.6 ±0.4 ±0.4	f&a	2148	ADRIANI 93M	L3	E^{ee}_{cm}= 88–94 GeV
17.2 ±0.4 ±0.5	avg		[16] ALBRECHT 92D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
17.35±0.41±0.37	f&a		DECAMP 92C	ALEP	1989–1990 LEP runs
17.7 ±0.8 ±0.4	f&a	568	BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
17.4 ±1.0	f&a	2197	ADEVA 88	MRKJ	E^{ee}_{cm}= 14–16 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
17.7 ±1.2 ±0.7			AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV
18.3 ±0.9 ±0.8			BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
18.6 ±0.8 ±0.7		558	[17] BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
12.9 ±1.7 $^{+0.7}_{-0.5}$			ALTHOFF 85	TASS	E^{ee}_{cm}= 34.5 GeV
18.0 ±0.9 ±0.5		473	[17] ASH 85B	MAC	E^{ee}_{cm}= 29 GeV
18.0 ±1.0 ±0.6			[18] BALTRUSAIT...85	MRK3	E^{ee}_{cm}= 3.77 GeV
19.4 ±1.6 ±1.7		153	BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV
17.6 ±2.6 ±2.1		47	BEHREND 83C	CELL	E^{ee}_{cm}= 34 GeV
17.8 ±2.0 ±1.8			BERGER 81B	PLUT	E^{ee}_{cm}= 9–32 GeV

[16] Not independent of ALBRECHT 92D $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ and $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$.
[17] Modified using $B(e^-\overline{\nu}_e\nu_\tau)$/B("1 prong") and B("1 prong") ,= 0.855.
[18] Error correlated with BALTRUSAITIS 85 $e\nu\overline{\nu}$ value.

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(\text{particle}^- \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau(\text{"1-prong"}))$ — Γ_3/Γ_1

$\Gamma_3/\Gamma_1 = \Gamma_3/(\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{30}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{35}+0.4316\Gamma_{37}+0.708\Gamma_{90}+0.085\Gamma_{97}+0.085\Gamma_{98})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.2042±0.0011 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.217 ±0.009 ±0.008		BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
0.211 ±0.010 ±0.006	390	ASH 85B	MAC	E^{ee}_{cm}= 29 GeV

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)$ — Γ_4/Γ_3

$E_\gamma > 37$ MeV.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.013±0.006	10	[19] WU 90	MRK2	E^{ee}_{cm}= 29 GeV

[19] Requirements on detected γ's correspond to a τ rest frame energy cutoff $E_\gamma > 37$ MeV.

$\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$ — Γ_5/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

To minimize the effect of experiments with large systematic errors, we exclude experiments which together would contribute 5% of the weight in the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
17.83±0.08 OUR FIT					
17.80±0.08 OUR AVERAGE					
17.78±0.10±0.09	f&a	25.3k	ALEXANDER 96D	OPAL	1991–1994 LEP runs
17.79±0.12±0.06	f&a	20.6k	BUSKULIC 96C	ALEP	1991–1993 LEP runs
17.51±0.23±0.31	f&a	5059	ABREU 95T	DLPH	1991–1992 LEP runs
17.9 ±0.4 ±0.4	f&a	2892	ADRIANI 93M	L3	E^{ee}_{cm}= 88–94 GeV
17.97±0.14±0.23	f&a	3970	AKERIB 92	CLEO	E^{ee}_{cm}= 10.6 GeV
17.3 ±0.4 ±0.5	avg		[20] ALBRECHT 92D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
19.1 ±0.4 ±0.6	avg	2960	[21] AMMAR 92	CLEO	E^{ee}_{cm}= 10.5–10.9 GeV
18.09±0.45±0.45	f&a		DECAMP 92C	ALEP	1989–1990 LEP runs
17.0 ±0.5 ±0.6	f&a	1.7k	ABACHI 90	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
18.4 ±0.8 ±0.4		644	BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
16.3 ±0.3 ±3.2			JANSSEN 89	CBAL	E^{ee}_{cm}= 9.4–10.6 GeV
18.4 ±1.2 ±1.0			AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV
19.1 ±0.8 ±1.1			BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
16.8 ±0.7 ±0.9		515	[21] BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
20.4 ±3.0 $^{+1.4}_{-0.9}$			ALTHOFF 85	TASS	E^{ee}_{cm}= 34.5 GeV
17.8 ±0.9 ±0.6		390	[21] ASH 85B	MAC	E^{ee}_{cm}= 29 GeV
18.2 ±0.7 ±0.5			[22] BALTRUSAIT...85	MRK3	E^{ee}_{cm}= 3.77 GeV
13.0 ±1.9 ±2.9			BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV
18.3 ±2.4 ±1.9		60	BEHREND 83C	CELL	E^{ee}_{cm}= 34 GeV
16.0 ±1.3		459	[23] BACINO 78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV

[20] Not independent of ALBRECHT 92D $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ and $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$.
[21] Modified using $B(e^-\overline{\nu}_e\nu_\tau)$/B("1 prong") and B("1 prong") ,= 0.855.
[22] Error correlated with BALTRUSAITIS 85 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$.
[23] BACINO 78B value comes from fit to events with $e^\pm$ and one other nonelectron charged prong.

$\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma(\text{particle}^- \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau(\text{"1-prong"}))$ — Γ_5/Γ_1

$\Gamma_5/\Gamma_1 = \Gamma_5/(\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{30}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{35}+0.4316\Gamma_{37}+0.708\Gamma_{90}+0.085\Gamma_{97}+0.085\Gamma_{98})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.2099±0.0010 OUR FIT	Error includes scale factor of 1.1.			
0.2231±0.0044±0.0073	2856	AMMAR 92	CLEO	E^{ee}_{cm}= 10.5–10.9 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.196 ±0.008 ±0.010		BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
0.208 ±0.010 ±0.007	390	ASH 85B	MAC	E^{ee}_{cm}= 29 GeV

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{\text{total}}$ — $\Gamma_3\Gamma_5/\Gamma^2$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.03094±0.00022 OUR FIT				
0.0306 ±0.0005 ±0.0013	3230	ALBRECHT 93G	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0288 ±0.0017 ±0.0019		ASH 85B	MAC	E^{ee}_{cm}= 29 GeV

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ — Γ_3/Γ_5

Predicted to be 1 for sequential lepton, 1/2 for para-electron, and 2 for para-muon. Para-electron also ruled out by HEILE 78.

VALUE	DOCUMENT ID	TECN	COMMENT
0.973±0.007 OUR FIT			
0.997±0.035±0.040	ALBRECHT 92D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$\Gamma(h^- \geq 0\,\text{neutrals} \geq 0K^0_L\,\nu_\tau)/\Gamma_{\text{total}}$ $\quad\Gamma_6/\Gamma$

$\Gamma_6/\Gamma = (\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{30}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{35}+0.4316\Gamma_{37}+0.708\Gamma_{90}+0.085\Gamma_{97}+0.085\Gamma_{98})/\Gamma$

VALUE (%)		DOCUMENT ID	TECN	COMMENT
49.78±0.17 OUR FIT	Error includes scale factor of 1.2.			
48.6 ±1.2 ±0.9	**avg**	[24] AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV

[24] Not independent of AIHARA 87B $e\nu\overline{\nu}$, $\mu\nu\overline{\nu}$, and $\pi^+ 2\pi^-(\geq 0\pi^0)\nu$ values.

$\Gamma(h^- \geq 0K^0_L\,\nu_\tau)/\Gamma_{\text{total}}$ $\quad\Gamma_7/\Gamma$

$\Gamma_7/\Gamma = (\Gamma_9+\Gamma_{10}+\frac{1}{2}\Gamma_{30}+\frac{1}{2}\Gamma_{32}+\frac{1}{4}\Gamma_{37})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
12.51±0.13 OUR FIT	Error includes scale factor of 1.1.				
12.44±0.14 OUR AVERAGE					
12.44±0.11±0.11	f&a	15k	[25] BUSKULIC 96	ALEP	1991–1993 LEP run
12.47±0.26±0.43	f&a	2967	[26] ACCIARRI 95	L3	1992 LEP run
12.4 ±0.7 ±0.7	f&a	283	[27] ABREU 92N	DLPH	1990 LEP run
12.98±0.44±0.33	f&a		[28] DECAMP 92C	ALEP	1989–1990 LEP runs
12.1 ±0.7 ±0.5	f&a	309	ALEXANDER 91D	OPAL	1990 LEP run
12.3 ±0.9 ±0.5	f&a	1338	BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
11.3 ±0.5 ±0.8	avg	798	[29] FORD 87	MAC	E^{ee}_{cm}= 29 GeV
12.3 ±0.6 ±1.1	avg	328	[30] BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
11.1 ±1.1 ±1.4			[31] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
13.0 ±2.0 ±4.0			BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV
11.2 ±1.7 ±1.2		34	[32] BEHREND 83C	CELL	E^{ee}_{cm}= 34 GeV

[25] BUSKULIC 96 quote 11.78 ± 0.11 ± 0.13 We add 0.66 to undo their correction for unseen K^0_L and modify the systematic error accordingly.
[26] ACCIARRI 95 with 0.65% added to remove their correction for $\pi^- K^0_L$ backgrounds.
[27] ABREU 92N with 0.5% added to remove their correction for $K^*(892)^-$ backgrounds.
[28] DECAMP 92C quote $B(h^- \geq 0K^0_L \geq 0(K^0_S \to \pi^+\pi^-)\,\nu_\tau) = 13.32 \pm 0.44 \pm 0.33$. We subtract 0.35 to correct for their inclusion of the K^0_S decays.
[29] FORD 87 result for $B(\pi^-\nu_\tau)$ with 0.67% added to remove their K^- correction and adjusted for 1992 B("1 prong").
[30] BARTEL 86D result for $B(\pi^-\nu_\tau)$ with 0.59% added to remove their K^- correction and adjusted for 1992 B("1 prong").
[31] BURCHAT 87 with 1.1% added to remove their correction for K^- and $K^*(892)^-$ backgrounds.
[32] BEHREND 83C quote $B(\pi^-\nu_\tau) = 9.9 \pm 1.7 \pm 1.3$ after subtracting 1.3 ± 0.5 to correct for $B(K^-\nu_\tau)$.

$\Gamma(h^- \geq 0K^0_L\,\nu_\tau)/\Gamma(\text{particle}^- \geq 0\,\text{neutrals} \geq 0K^0_L\nu_\tau(\text{"1-prong"}))$ $\quad\Gamma_7/\Gamma_1$

$\Gamma_7/\Gamma_1 = (\Gamma_9+\Gamma_{10}+\frac{1}{2}\Gamma_{30}+\frac{1}{2}\Gamma_{32}+\frac{1}{4}\Gamma_{37})/(\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{30}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{35}+0.4316\Gamma_{37}+0.708\Gamma_{90}+0.085\Gamma_{97}+0.085\Gamma_{98})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.1473±0.0015 OUR FIT	Error includes scale factor of 1.1.			
0.135 ±0.009 OUR AVERAGE				
0.131 ±0.006 ±0.009	798	[33] FORD 87	MAC	E^{ee}_{cm}= 29 GeV
0.143 ±0.007 ±0.013	328	[34] BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV

[33] FORD 87 result divided by 0.865, their assumed value for B("1 prong").
[34] BARTEL 86D result with 0.6% added to remove their K^- correction and then divided by 0.866, their assumed value for B("1 prong").

$\Gamma(h^- \geq 0K^0_L\,\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ $\quad\Gamma_7/\Gamma_5$

$\Gamma_7/\Gamma_5 = (\Gamma_9+\Gamma_{10}+\frac{1}{2}\Gamma_{30}+\frac{1}{2}\Gamma_{32}+\frac{1}{4}\Gamma_{37})/\Gamma_5$

VALUE	DOCUMENT ID	TECN	COMMENT
0.702±0.008 OUR FIT	Error includes scale factor of 1.1.		
0.678±0.037±0.044	ALBRECHT 92D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.647±0.039±0.061	[35] BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV

[35] Combined result of BARTEL 86D $e\nu\overline{\nu}$, $\mu\nu\overline{\nu}$, and $\pi^-\nu$ assuming $B(\mu\nu\overline{\nu})/B(e\nu\overline{\nu}) = 0.973$.

$\Gamma(h^-\nu_\tau)/\Gamma_{\text{total}}$ $\quad\Gamma_8/\Gamma = (\Gamma_9+\Gamma_{10})/\Gamma$

VALUE	DOCUMENT ID
0.1203±0.0014 OUR FIT	Error includes scale factor of 1.1.

$\Gamma(\pi^-\nu_\tau)/\Gamma_{\text{total}}$ $\quad\Gamma_9/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
11.31±0.15 OUR FIT	Error includes scale factor of 1.1.				
11.07±0.18 OUR AVERAGE					
11.06±0.11±0.14	avg		[36] BUSKULIC 96	ALEP	LEP 1991–1993 data
11.7 ±0.4 ±1.8	f&a	1138	BLOCKER 82D	MRK2	E^{ee}_{cm}= 3.5–6.7 GeV

[36] Not independent of BUSKULIC 96 $B(h^-\nu_\tau)$ and $B(K^-\nu_\tau)$ values.

$\Gamma(K^-\nu_\tau)/\Gamma_{\text{total}}$ $\quad\Gamma_{10}/\Gamma$

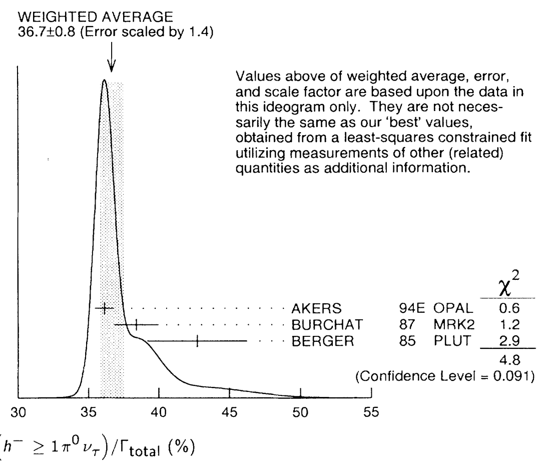
VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.71±0.05 OUR FIT				
0.71±0.05 OUR AVERAGE				
0.72±0.04±0.04	728	BUSKULIC 96	ALEP	LEP 1991–1993 data
0.85±0.18	27	ABREU 94K	DLPH	LEP 1992 Z data
0.66±0.07±0.09	99	BATTLE 94	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
0.59±0.18	16	MILLS 84	DLCO	E^{ee}_{cm}= 29 GeV
1.3 ±0.5	15	BLOCKER 82B	MRK2	E^{ee}_{cm}= 3.9–6.7 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.64±0.05±0.05	336	BUSKULIC 94E	ALEP	Repl. by BUSKULIC 96

$\Gamma(h^- \geq 1\pi^0\nu_\tau)/\Gamma_{\text{total}}$ $\quad\Gamma_{11}/\Gamma$

$\Gamma_{11}/\Gamma = (\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.157\Gamma_{30}+0.157\Gamma_{32}+0.157\Gamma_{34}+0.157\Gamma_{35}+0.0246\Gamma_{37}+0.708\Gamma_{90}+0.085\Gamma_{97}+0.085\Gamma_{98})/\Gamma$

VALUE (%)	DOCUMENT ID	TECN	COMMENT
36.97±0.18 OUR FIT	Error includes scale factor of 1.1.		
36.7 ±0.8 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.		
36.14±0.33±0.58	AKERS 94E	OPAL	1991–1992 LEP runs
38.4 ±1.2 ±1.0	[37] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
42.7 ±2.0 ±2.9	BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV

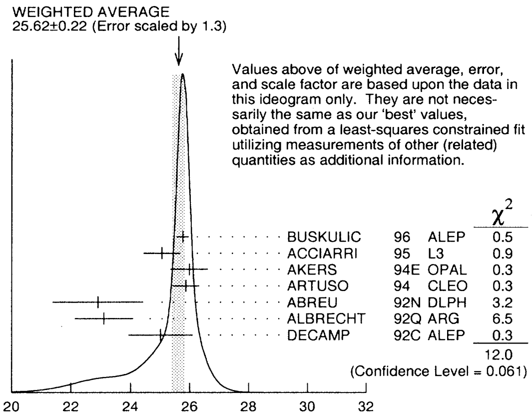
[37] BURCHAT 87 quote for $B(\pi^\pm \geq 1\,\text{neutral}\,\nu_\tau) = 0.378 \pm 0.012 \pm 0.010$. We add 0.006 to account for contribution from $(K^{*-}\nu_\tau)$ which they fixed at BR = 0.013.



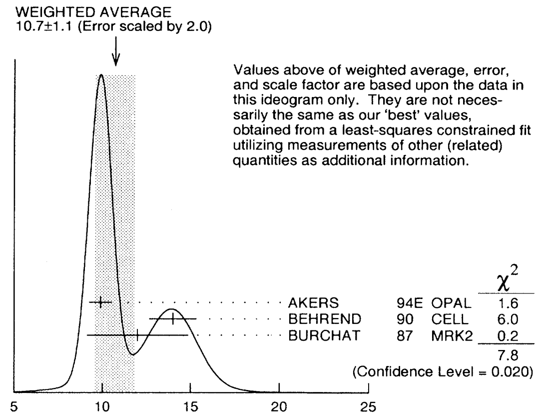
$\Gamma(h^-\pi^0\nu_\tau)/\Gamma_{\text{total}}$ $\quad\Gamma_{12}/\Gamma = (\Gamma_{13}+\Gamma_{15})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
25.76±0.15 OUR FIT	Error includes scale factor of 1.1.			
25.62±0.22 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.			
25.76±0.15±0.13	31k	BUSKULIC 96	ALEP	LEP 1991–1993 data
25.05±0.35±0.50	6613	ACCIARRI 95	L3	1992 LEP run
25.98±0.36±0.52		[38] AKERS 94E	OPAL	1991–1992 LEP runs
25.87±0.12±0.42	51k	[39] ARTUSO 94	CLEO	E^{ee}_{cm}= 10.6 GeV
22.9 ±0.8 ±1.3	283	[40] ABREU 92N	DLPH	E^{ee}_{cm}= 88.2–94.2 GeV
23.1 ±0.4 ±0.9	1249	[41] ALBRECHT 92Q	ARG	E^{ee}_{cm}= 10 GeV
25.02±0.64±0.88	1849	DECAMP 92C	ALEP	1989–1990 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
22.0 ±0.8 ±1.9	779	ANTREASYAN 91	CBAL	E^{ee}_{cm}= 9.4–10.6 GeV
22.6 ±1.5 ±0.7	1101	BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
23.1 ±1.9 ±1.6		BEHREND 84	CELL	E^{ee}_{cm}= 14,22 GeV

[38] AKERS 94E quote $(26.25 \pm 0.36 \pm 0.52) \times 10^{-2}$; we subtract 0.27% from their number to correct for $\tau^- \to h^- K^0_L \nu_\tau$.
[39] ARTUSO 94 reports the combined result from three independent methods, one of which (23% of the $\tau^- \to h^-\pi^0\nu_\tau$) is normalized to the inclusive one-prong branching fraction, taken as 0.854 ± 0.004. Renormalization to the present value causes negligible change.
[40] ABREU 92N with 0.5% added to remove their correction for $K^*(892)^-$ backgrounds.
[41] ALBRECHT 92Q with 0.5% added to remove their correction for $\tau^- \to K^*(892)^-\nu_\tau$ background.



$\Gamma(h^-\pi^0\nu_\tau)/\Gamma_{total}$ (%)



$\Gamma(h^- \geq 2\pi^0\nu_\tau)/\Gamma_{total}$ (%)

$\Gamma(\pi^-\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{13}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
25.24±0.16 OUR FIT	Error includes scale factor of 1.1.					
25.31±0.18 OUR AVERAGE						
25.30±0.15±0.13	avg		[42] BUSKULIC	96	ALEP	LEP 1991–1993 data
25.36±0.44	avg		[43] ARTUSO	94	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
21.5 ±0.4 ±1.9		4400	[44,45] ALBRECHT	88L	ARG	E^{ee}_{cm}= 10 GeV
23.0 ±1.3 ±1.7		582	ADLER	87B	MRK3	E^{ee}_{cm}= 3.77 GeV
25.8 ±1.7 ±2.5			[46] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
22.3 ±0.6 ±1.4		629	[45] YELTON	86	MRK2	E^{ee}_{cm}= 29 GeV

[42] Not independent of BUSKULIC 96 B($h^-\pi^0\nu_\tau$) and B($K^-\pi^0\nu_\tau$) values.
[43] Not independent of ARTUSO 94 B($h^-\pi^0\nu_\tau$) and BATTLE 94 B($K^-\pi^0\nu_\tau$) values.
[44] The authors divide by ($\Gamma_3 + \Gamma_5 + \Gamma_9 + \Gamma_{10}$)/Γ = 0.467 to obtain this result.
[45] Experiment had no hadron identification. Kaon corrections were made, but insufficient information is given to permit their removal.
[46] BURCHAT 87 value is not independent of YELTON 86 value. Nonresonant decays included.

$\Gamma(\pi^-\pi^0\ \text{non-}\rho(770)\nu_\tau)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (%)	DOCUMENT ID		TECN	COMMENT
0.3 ±0.1 ±0.3	[47] BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV

[47] BEHREND 84 assume a flat nonresonant mass distribution down to the $\rho(770)$ mass, using events with mass above 1300 to set the level.

$\Gamma(K^-\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.52±0.05 OUR FIT					
0.52±0.06 OUR AVERAGE					
0.52±0.04±0.05	395	BUSKULIC	96	ALEP	LEP 1991–1993 data
0.51±0.10±0.07	37	BATTLE	94	CLEO	$E^{ee}_{cm}\approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.53±0.05±0.07	220	BUSKULIC	94E	ALEP	Repl. by BUSKULIC 96

$\Gamma(h^- \geq 2\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{16}/Γ

$\Gamma_{16}/\Gamma = (\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.157\Gamma_{30}+0.157\Gamma_{32}+0.157\Gamma_{34}+0.157\Gamma_{35}+0.0246\Gamma_{37}+0.319\Gamma_{90})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
10.95±0.16 OUR FIT	Error includes scale factor of 1.1.					
10.7 ±1.1 OUR AVERAGE	Error includes scale factor of 2.0. See the ideogram below.					
9.89±0.34±0.55	avg		[48] AKERS	94E	OPAL	1991–1992 LEP runs
14.0 ±1.2 ±0.6	f&a	938	BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
12.0 ±1.4 ±2.5	f&a		[49] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
13.9 ±2.0 $^{+1.9}_{-2.2}$			[50] AIHARA	86E	TPC	E^{ee}_{cm}= 29 GeV

[48] AKERS 94E not independent of AKERS 94E B($h^- \geq 1\pi^0\nu_\tau$) and B($h^-\pi^0\nu_\tau$) measurements.
[49] Error correlated with BURCHAT 87 Γ($\rho^-\nu_e$)/Γ(total) value.
[50] AIHARA 86E (TPC) quote B($2\pi^0\pi^-\nu_\tau$) + 1.6B($3\pi^0\pi^-\nu_\tau$) + 1.1B($\pi^0\eta\pi^-\nu_\tau$).

$\Gamma(h^-2\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{17}/Γ

$\Gamma_{17}/\Gamma = (\Gamma_{19}+\Gamma_{20}+0.157\Gamma_{30}+0.157\Gamma_{32})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
9.50±0.14 OUR FIT	Error includes scale factor of 1.1.				
9.48±0.13±0.10	12k	[51] BUSKULIC	96	ALEP	LEP 1991–1993 data

[51] BUSKULIC 96 quote 9.29 ± 0.13 ± 0.10. We add 0.19 to undo their correction for $\tau^- \to h^- K^0 \nu_\tau$.

$\Gamma(h^-2\pi^0\nu_\tau(\text{ex.}K^0))/\Gamma_{total}$ — Γ_{18}/Γ

$\Gamma_{18}/\Gamma = (\Gamma_{19}+\Gamma_{20})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. f&a marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
9.35±0.14 OUR FIT	Error includes scale factor of 1.1.					
8.95±0.33 OUR AVERAGE	Error includes scale factor of 1.1.					
8.88±0.37±0.42	f&a	1060	ACCIARRI	95	L3	1992 LEP run
8.96±0.16±0.44	avg		[52] PROCARIO	93	CLEO	$E^{ee}_{cm}\approx$ 10.6 GeV
10.38±0.66±0.82	f&a	809	[53] DECAMP	92C	ALEP	1989–1990 LEP runs
5.7 ±0.5 $^{+1.7}_{-1.0}$	f&a	133	[54] ANTREASYAN	91	CBAL	E^{ee}_{cm}= 9.4–10.6 GeV
10.0 ±1.5 ±1.1	f&a	333	[55] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
8.7 ±0.4 ±1.1	f&a	815	[56] BAND	87	MAC	E^{ee}_{cm}= 29 GeV
6.0 ±3.0 ±1.8	f&a		BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
6.2 ±0.6 ±1.2			[57] GAN	87	MRK2	E^{ee}_{cm}= 29 GeV

[52] PROCARIO 93 entry is obtained from B($h^-2\pi^0\nu_\tau$)/B($h^-\pi^0\nu_\tau$) using ARTUSO 94 result for B($h^-\pi^0\nu_\tau$).
[53] We subtract 0.0015 to account for $\tau^- \to K^*(892)^-\nu_\tau$ contribution.
[54] ANTREASYAN 91 subtract 0.001 to account for the $\tau^- \to K^*(892)^-\nu_\tau$ contribution.
[55] BEHREND 90 subtract 0.002 to account for the $\tau^- \to K^*(892)^-\nu_\tau$ contribution.
[56] BAND 87 assume B($\pi^-3\pi^0\nu_\tau$) = 0.01 and B($\pi^-\pi^0\eta\nu_\tau$) = 0.005.
[57] GAN 87 analysis use photon multiplicity distribution.

$\Gamma(h^-2\pi^0\nu_\tau(\text{ex.}K^0))/\Gamma(h^-\pi^0\nu_\tau)$ — Γ_{18}/Γ_{12}

$\Gamma_{18}/\Gamma_{12} = (\Gamma_{19}+\Gamma_{20})/(\Gamma_{13}+\Gamma_{15})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.363±0.006 OUR FIT	Error includes scale factor of 1.1.			
0.342±0.006±0.016	[58] PROCARIO	93	CLEO	$E^{ee}_{cm}\approx$ 10.6 GeV

[58] PROCARIO 93 quote 0.345 ± 0.006 ± 0.016 after correction for 2 kaon backgrounds assuming B($K^{*-}\nu_\tau$)=1.42 ± 0.18% and B($h^-K^0\pi^0\nu_\tau$)=0.48 ± 0.48%. We multiply by 0.990 ± 0.010 to remove these corrections to B($h^-\pi^0\nu_\tau$).

$\Gamma(\pi^-2\pi^0\nu_\tau(\text{ex.}K^0))/\Gamma_{total}$ — Γ_{19}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		DOCUMENT ID		TECN	COMMENT
9.27±0.14 OUR FIT	Error includes scale factor of 1.1.				
9.21±0.13±0.11	**avg**	[59] BUSKULIC	96	ALEP	LEP 1991–1993 data

[59] Not independent of BUSKULIC 96 B($h^-2\pi^0\nu_\tau$(ex. K^0)) and B($K^-2\pi^0\nu_\tau$(ex. K^0)) values.

$\Gamma(K^- 2\pi^0 \nu_\tau (\text{ex.} K^0))/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.081±0.027 OUR FIT				
0.081±0.027 OUR AVERAGE				
0.08 ±0.02 ±0.02	59	BUSKULIC 96	ALEP	LEP 1991–1993 data
0.09 ±0.10 ±0.03	3	[60] BATTLE 94	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04 ±0.03 ±0.02	11	BUSKULIC 94E	ALEP	Repl. by BUSKULIC 96

[60] BATTLE 94 quote $0.14 \pm 0.10 \pm 0.03$ or < 0.3% at 90% CL. We subtract (0.05 ± 0.02)% to account for $\tau^- \to K^- (K^0 \to \pi^0 \pi^0) \nu_\tau$ background.

$\Gamma(h^- \geq 3\pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{21}/Γ

$\Gamma_{21}/\Gamma = (\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.157\Gamma_{34}+0.157\Gamma_{35}+0.0246\Gamma_{37}+0.319\Gamma_{90})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
1.46±0.11 OUR FIT Error includes scale factor of 1.1.					
1.8 ±0.6 OUR AVERAGE Error includes scale factor of 1.1.					
1.53±0.40±0.46	f&a	186	DECAMP 92C	ALEP	1989–1990 LEP runs
3.2 ±1.0 ±1.0	avg		[61] BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV

[61] Not independent of BEHREND 90 $\Gamma(h^- \geq 2\pi^0 \nu_\tau)/\Gamma_{total}$ and $\Gamma(h^- 2\pi^0 \nu_\tau)/\Gamma_{total}$ values.

$\Gamma(h^- 3\pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{22}/Γ

$\Gamma_{22}/\Gamma = (\Gamma_{23}+\Gamma_{24}+0.157\Gamma_{34}+0.157\Gamma_{35})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
1.28±0.10 OUR FIT					
1.22±0.10 OUR AVERAGE					
1.24±0.09±0.11	f&a	2.3k	[62] BUSKULIC 96	ALEP	LEP 1991–1993 data
1.70±0.24±0.38	f&a	293	ACCIARRI 95	L3	1992 LEP run
1.15±0.08±0.13	avg		[63] PROCARIO 93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.0\ ^{+1.4}_{-0.1}\ ^{+1.1}_{-0.1}$			[64] GAN 87	MRK2	E^{ee}_{cm}= 29 GeV

[62] BUSKULIC 96 quote $B(h^- 3\pi^0 \nu_\tau (\text{ex. } K^0)) = 1.17 \pm 0.09 \pm 0.11$. We add 0.07 to remove their correction for K^0 backgrounds.

[63] PROCARIO 93 entry is obtained from $B(h^- 3\pi^0 \nu_\tau)/B(h^- \pi^0 \nu_\tau)$ using ARTUSO 94 result for $B(h^- \pi^0 \nu_\tau)$.

[64] Highly correlated with GAN 87 $\Gamma(\eta \pi^- \pi^0 \nu_\tau)/\Gamma_{total}$ value. Authors quote $B(\pi^\pm 3\pi^0 \nu_\tau) + 0.67 B(\pi^\pm \eta \pi^0 \nu_\tau) = 0.047 \pm 0.010 \pm 0.011$.

$\Gamma(h^- 3\pi^0 \nu_\tau)/\Gamma(h^- \pi^0 \nu_\tau)$ — Γ_{22}/Γ_{12}

$\Gamma_{22}/\Gamma_{12} = (\Gamma_{23}+\Gamma_{24}+0.157\Gamma_{34}+0.157\Gamma_{35})/(\Gamma_{13}+\Gamma_{15})$

VALUE	DOCUMENT ID	TECN	COMMENT
0.050±0.004 OUR FIT			
0.044±0.003±0.005	[65] PROCARIO 93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[65] PROCARIO 93 quote $0.041 \pm 0.003 \pm 0.005$ after correction for 2 kaon backgrounds assuming $B(K^{*-} \nu_\tau)$=1.42 ± 0.18% and $B(h^- K^0 \pi^0 \nu_\tau)$=0.48 ± 0.48%. We add 0.003 ± 0.003 and multiply the sum by 0.990 ± 0.010 to remove these corrections.

$\Gamma(\pi^- 3\pi^0 \nu_\tau (\text{ex.} K^0))/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (%)	DOCUMENT ID
1.14±0.14 OUR FIT	

$\Gamma(K^- 3\pi^0 \nu_\tau (\text{ex.} K^0))/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.050^{+0.100}_{-0.033}}$ **OUR FIT**			
0.05 ±0.13	[66] BUSKULIC 94E	ALEP	1991-1992 LEP runs

[66] BUSKULIC 94E quote $B(K^- \geq 0\pi^0 \geq 0K^0 \nu_\tau) - [B(K^- \nu_\tau) + B(K^- \pi^0 \nu_\tau) + B(K^- K^0 \nu_\tau) + B(K^- \pi^0 \pi^0 \nu_\tau) + B(K^- \pi^0 K^0 \nu_\tau)] = 0.05 \pm 0.13$% accounting for common systematic errors in BUSKULIC 94E and BUSKULIC 94F measurements of these modes. We assume $B(K^- \geq 2K^0 \nu_\tau)$ and $B(K^- \geq 4\pi^0 \nu_\tau)$ are negligible.

$\Gamma(h^- 4\pi^0 \nu_\tau (\text{ex.} K^0))/\Gamma_{total}$ — Γ_{25}/Γ

$\Gamma_{25}/\Gamma = (\Gamma_{26}+0.319\Gamma_{90})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.18±0.06 OUR FIT				
0.16±0.06 OUR AVERAGE				
0.16±0.04±0.09	232	[67] BUSKULIC 96	ALEP	LEP 1991–1993 data
0.16±0.05±0.05		[68] PROCARIO 93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[67] BUSKULIC 96 quote result for $\tau^- \to h^- \geq 4\pi^0 \nu_\tau$. We assume $B(h^- \geq 5\pi^0 \nu_\tau)$ is negligible.

[68] PROCARIO 93 quotes $B(h^- 4\pi^0 \nu_\tau)/B(h^- \pi^0 \nu_\tau) = 0.006 \pm 0.002 \pm 0.002$. We multiply by the ARTUSO 94 result for $B(h^- \pi^0 \nu_\tau)$ to obtain $B(h^- 4\pi^0 \nu_\tau)$. PROCARIO 93 assume $B(h^- \geq 5\ \pi^0 \nu_\tau)$ is small and do not correct for it.

$\Gamma(h^- 4\pi^0 \nu_\tau (\text{ex.} K^0, \eta))/\Gamma_{total}$ — Γ_{26}/Γ

VALUE (%)	DOCUMENT ID
0.12±0.06 OUR FIT	

$\Gamma(K^- \geq 1 (\pi^0 \text{ or } K^0)\ \nu_\tau)/\Gamma_{total}$ — Γ_{27}/Γ

$\Gamma_{27}/\Gamma = (\Gamma_{15}+\Gamma_{20}+\Gamma_{24}+\Gamma_{32}+\Gamma_{35})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.94±0.10 OUR FIT					
0.76±0.23 OUR AVERAGE					
0.69±0.25	avg		[69] ABREU 94K	DLPH	LEP 1992 Z data
$1.2\ \pm 0.5\ ^{+0.2}_{-0.4}$	f&a	9	AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV

[69] Not independent of ABREU 94K $B(K^- \nu_\tau)$ and $B(K^- \geq 0\ \text{neutrals}\ \nu_\tau)$ measurements.

$\Gamma(h^- \overline{K}^0 \geq 0\ \text{neutrals} \geq 0 K^0_L \nu_\tau)/\Gamma_{total}$ — Γ_{28}/Γ

$\Gamma_{28}/\Gamma = (\Gamma_{30}+\Gamma_{32}+\Gamma_{34}+\Gamma_{35}+0.657\Gamma_{37})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
1.54±0.10 OUR FIT Error includes scale factor of 1.3.				
1.3 ±0.3	44	TSCHIRHART 88	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(h^- \overline{K}^0 \nu_\tau)/\Gamma_{total}$ — $\Gamma_{29}/\Gamma = (\Gamma_{30}+\Gamma_{32})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.92 ±0.08 OUR FIT Error includes scale factor of 1.3.				
0.855±0.036±0.073	1242	COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(\pi^- \overline{K}^0 \nu_\tau)/\Gamma_{total}$ — Γ_{30}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.77 ±0.08 OUR FIT Error includes scale factor of 1.3.					
0.76 ±0.06 OUR AVERAGE					
0.79 ±0.10 ±0.09	f&a	98	BUSKULIC 96	ALEP	LEP 1991–1993 data
0.704±0.041±0.072	avg		[70] COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
0.95 ±0.15 ±0.06	f&a		[71] ACCIARRI 95F	L3	1991–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.88 ±0.14 ±0.09		53	BUSKULIC 94F	ALEP	Repl. by BUSKULIC 96

[70] Not independent of COAN 96 $B(h^- K^0 \nu_\tau)$ and $B(K^- K^0 \nu_\tau)$ measurements.

[71] ACCIARRI 95F do not identify π^-/K^- and assume $B(K^- K^0 \nu_\tau) = (0.29 \pm 0.12)$%.

$\Gamma(\pi^- \overline{K}^0 (\text{non-} K^*(892)^-) \nu_\tau)/\Gamma_{total}$ — Γ_{31}/Γ

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
<0.17	95	ACCIARRI 95F	L3	1991–1993 LEP runs

$\Gamma(K^- K^0 \nu_\tau)/\Gamma_{total}$ — Γ_{32}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.155±0.028 OUR FIT				
0.162±0.032 OUR AVERAGE Error includes scale factor of 1.1.				
0.26 ±0.09 ±0.02	13	BUSKULIC 96	ALEP	LEP 1991–1993 data
0.151±0.021±0.022	111	COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29 ±0.12 ±0.03	8	BUSKULIC 94F	ALEP	Repl. by BUSKULIC 96

$\Gamma(h^- \overline{K}^0 \pi^0 \nu_\tau)/\Gamma_{total}$ — $\Gamma_{33}/\Gamma = (\Gamma_{34}+\Gamma_{35})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.55 ±0.05 OUR FIT				
0.562±0.050±0.048	264	COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(\pi^- \overline{K}^0 \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{34}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.41 ±0.06 OUR FIT					
0.39 ±0.06 OUR AVERAGE					
0.32 ±0.11 ±0.05	f&a	23	BUSKULIC 96	ALEP	LEP 1991–1993 data
0.417±0.058±0.044	avg		[72] COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
0.41 ±0.12 ±0.03	f&a		[73] ACCIARRI 95F	L3	1991–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.33 ±0.14 ±0.07		9	BUSKULIC 94F	ALEP	Repl. by BUSKULIC 96

[72] Not independent of COAN 96 $B(h^- K^0 \pi^0 \nu_\tau)$ and $B(K^- K^0 \pi^0 \nu_\tau)$ measurements.

[73] ACCIARRI 95F do not identify π^-/K^- and assume $B(K^- K^0 \pi^0 \nu_\tau) = (0.05 \pm 0.05)$%.

$\Gamma(K^- K^0 \pi^0 \nu_\tau)/\Gamma_{total}$ Γ_{35}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.138±0.032 OUR FIT					
0.130±0.034 OUR AVERAGE					
0.10 ±0.05 ±0.03	5	BUSKULIC	96	ALEP	LEP 1991–1993 data
0.145±0.036±0.020	32	COAN	96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.05 ±0.05 ±0.01	1	BUSKULIC	94F	ALEP	Repl. by BUSKULIC 96

$\Gamma(h^- K^0_S K^0_S \nu_\tau)/\Gamma_{total}$ $\Gamma_{36}/\Gamma = \frac{1}{4}\Gamma_{37}/\Gamma$

Bose-Einstein correlations might make the mixing fraction different than 1/4.

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.025±0.006 OUR FIT					
0.023±0.005±0.003	42	COAN	96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(\pi^- K^0 \overline{K}^0 \nu_\tau)/\Gamma_{total}$ Γ_{37}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
0.101±0.023 OUR FIT						
0.099±0.023 OUR AVERAGE						
0.092±0.020±0.012	avg	42	[74] COAN	96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
0.31 ±0.12 ±0.04	f&a		ACCIARRI	95F	L3	1991–1993 LEP runs

[74] We multiply the COAN 96 measurement $B(h^- K^0_S K^0_S \nu_\tau) = (0.023 \pm 0.005 \pm 0.003)$% by 4 to obtain the listed value. This factor of 1/4 is uncertain, and might be as large as 1/2, due to Bose-Einstein correlations and the resonant parentage of this state.

$\Gamma(K^- K^0 \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ $\Gamma_{38}/\Gamma = (\Gamma_{32}+\Gamma_{35})/\Gamma$

VALUE (%)	DOCUMENT ID
0.29±0.04 OUR FIT	

$\Gamma(K^- \geq 0\pi^0 \geq 0K^0 \nu_\tau)/\Gamma_{total}$ Γ_{39}/Γ

$\Gamma_{39}/\Gamma = (\Gamma_{10}+\Gamma_{15}+\Gamma_{20}+\Gamma_{24}+\Gamma_{32}+\Gamma_{35})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
1.65±0.10 OUR FIT						
1.69±0.07 OUR AVERAGE						
1.70±0.05±0.06	avg	1610	[75] BUSKULIC	96	ALEP	LEP 1991–1993 data
1.54±0.24	f&a		ABREU	94K	DLPH	LEP 1992 Z data
1.70±0.12±0.19	f&a	202	[76] BATTLE	94	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
1.6 ±0.4 ±0.2	f&a	35	AIHARA	87B	TPC	E^{ee}_{cm}= 29 GeV
1.71±0.29	f&a	53	MILLS	84	DLCO	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.60±0.07±0.12		967	[77] BUSKULIC	94E	ALEP	Repl. by BUSKULIC 96

[75] Not independent of BUSKULIC 96 $B(K^- \nu_\tau)$, $B(K^- \pi^0 \nu_\tau)$, $B(K^- 2\pi^0 \nu_\tau)$, $B(K^- K^0 \nu_\tau)$, and $B(K^- K^0 \pi^0 \nu_\tau)$ values.

[76] BATTLE 94 quote 1.60 ± 0.12 ± 0.19. We add 0.10 ± 0.02 to correct for their rejection of $K^0_S \to \pi^+\pi^-$ decays.

[77] Not independent of BUSKULIC 94E $B(K^- \nu_\tau)$, $B(K^- \pi^0 \nu_\tau)$, $B(K^- 2\pi^0 \nu_\tau)$, $B(K^- K^0 \nu_\tau)$, and $B(K^- K^0 \pi^0 \nu_\tau)$ values.

$\Gamma(K^0(\text{particles})^- \nu_\tau)/\Gamma_{total}$ Γ_{40}/Γ

$\Gamma_{40}/\Gamma = (\Gamma_{30}+\Gamma_{32}+\Gamma_{34}+\Gamma_{35}+\Gamma_{37})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.58±0.10 OUR FIT Error includes scale factor of 1.2.					
1.94±0.18±0.12	141	[78] AKERS	94G	OPAL	E^{ee}_{cm}= 88–94 GeV

[78] AKERS 94G measure $\Gamma(K^0_S(\text{particles})^- \nu_\tau)/\Gamma_{total} = 0.97 \pm 0.09 \pm 0.06$.

$\Gamma(K^0 h^+ h^- h^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ Γ_{41}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.17	95	TSCHIRHART	88	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.27	90	BELTRAMI	85	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(h^- h^- h^+ \geq 0\text{neut. } \nu_\tau (\text{"3-prong"}))/\Gamma_{total}$ Γ_{42}/Γ

$\Gamma_{42}/\Gamma = (0.3431\Gamma_{30}+0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{35}+0.4508\Gamma_{37}+\Gamma_{47}+\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+0.285\Gamma_{90}+0.9101\Gamma_{97}+0.9101\Gamma_{98})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
14.91± 0.14 OUR FIT Error includes scale factor of 1.3.						
14.01± 0.29 OUR AVERAGE Error includes scale factor of 1.2.						
14.4 ± 0.6 ±0.3	f&a		ADEVA	91F	L3	E^{ee}_{cm}= 88.3–94.3 GeV
13.5 ± 0.3 ±0.3	f&a		ABACHI	89B	HRS	E^{ee}_{cm}= 29 GeV
15.0 ± 0.4 ±0.3	f&a		BEHREND	89B	CELL	E^{ee}_{cm}= 14–47 GeV
15.1 ± 0.8 ±0.6	f&a		AIHARA	87B	TPC	E^{ee}_{cm}= 29 GeV
12.8 ± 0.5 ±0.8	f&a	1420	SCHMIDKE	86	MRK2	E^{ee}_{cm}= 29 GeV
15.3 ± 1.1 $^{+1.3}_{-1.6}$	f&a	367	ALTHOFF	85	TASS	E^{ee}_{cm}= 34.5 GeV
13.6 ± 0.5 ±0.8	f&a		BARTEL	85F	JADE	E^{ee}_{cm}= 34.6 GeV
13.3 ± 0.3 ±0.6	f&a		FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
12.8 ± 1.0 ±0.7			[79] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
12.1 ± 0.5 ±1.2			RUCKSTUHL	86	DLCO	E^{ee}_{cm}= 29 GeV
12.2 ± 1.3 ±3.9			[80] BERGER	85	PLUT	E^{ee}_{cm}= 34.6 GeV
24 ± 6		35	BRANDELIK	80	TASS	E^{ee}_{cm}= 30 GeV
32 ± 5		692	[81] BACINO	78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV
35 ±11			[81] BRANDELIK	78	DASP	Assumes $V-A$ decay
18 ± 6.5		33	[81] JAROS	78	MRK1	E^{ee}_{cm} > 6 GeV

[79] BURCHAT 87 value is not independent of SCHMIDKE 86 value.

[80] Not independent of BERGER 85 $\Gamma(\mu^- \overline{\nu}_\mu \nu_\tau)/\Gamma_{total}$, $\Gamma(e^- \overline{\nu}_e \nu_\tau)/\Gamma_{total}$, $\Gamma(h^- \geq 1\pi^0 \nu_\tau)/\Gamma_{total}$, and $\Gamma(h^- \geq 0K^0_L \nu_\tau)/\Gamma_{total}$, and therefore not used in the fit.

[81] Low energy experiments are not in average or fit because the systematic errors in background subtraction are judged to be large.

$\Gamma(h^- h^- h^+ \geq 0 \text{ neutrals } \nu_\tau (\text{ex. } K^0_S \to \pi^+\pi^-))/\Gamma_{total}$ Γ_{43}/Γ

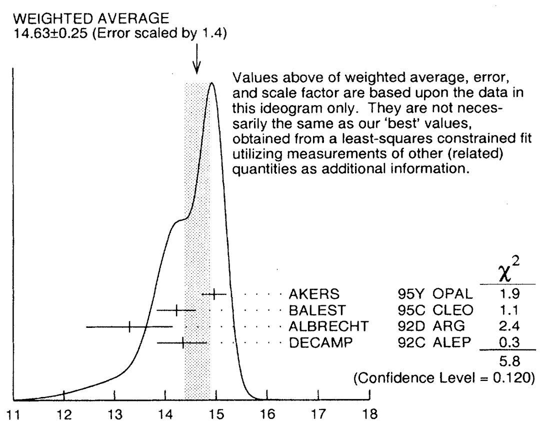
$\Gamma_{43}/\Gamma = (\Gamma_{47}+\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+0.285\Gamma_{90}+0.9101\Gamma_{97}+0.9101\Gamma_{98})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
14.36±0.14 OUR FIT Error includes scale factor of 1.3.						
14.63±0.25 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.						
14.96±0.09±0.22	f&a	10.4k	AKERS	95Y	OPAL	1991–1994 LEP runs
14.22±0.10±0.37	avg		[82] BALEST	95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
13.3 ±0.3 ±0.8	f&a		[83] ALBRECHT	92D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
14.35$^{+0.40}_{-0.45}$±0.24	f&a		DECAMP	92C	ALEP	1989–1990 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •						
15.26±0.26±0.22			ACTON	92H	OPAL	Repl. by AKERS 95Y

[82] Not independent of BALEST 95C $B(h^- h^- h^+ \nu_\tau)$ and $B(h^- h^- h^+ \pi^0 \nu_\tau)$ values, and BORTOLETTO 93 $B(h^- h^- h^+ 2\pi^0 \nu_\tau)/B(h^- h^- h^+ \geq 0 \text{ neutrals } \nu_\tau)$ value.

[83] This ALBRECHT 92D value is not independent of their $\Gamma(\mu^- \overline{\nu}_\mu \nu_\tau)\Gamma(e^- \overline{\nu}_e \nu_\tau)/\Gamma^2_{total}$ value.



$\Gamma(h^- h^- h^+ \geq 0 \text{ neutrals } \nu_\tau (\text{ex. } K^0_S \to \pi^+\pi^-))/\Gamma_{total}$ (%)

$\Gamma(\pi^-\pi^+\pi^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma(h^- h^- h^+ \geq 0\text{neut. } \nu_\tau (\text{"3-prong"}))$ Γ_{44}/Γ_{42}

$\Gamma_{44}/\Gamma_{42} = \Gamma_{44}/(0.3431\Gamma_{30}+0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{35}+0.4508\Gamma_{37}+\Gamma_{47}+\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+0.285\Gamma_{90}+0.9101\Gamma_{97}+0.9101\Gamma_{98})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.945±0.019	490	[84] BAUER	94	TPC	E^{ee}_{cm}= 29 GeV

[84] BAUER 94 quote $B(\pi^-\pi^+\pi^- \geq 0 \text{ neutrals } \nu_\tau) = 0.1329 \pm 0.0027$. We divide by 0.1406, their assumed value for B("3prong").

$\Gamma(h^- h^- h^+ \nu_\tau)/\Gamma_{total}$ Γ_{45}/Γ

$\Gamma_{45}/\Gamma = (0.3431\Gamma_{30}+0.3431\Gamma_{32}+\Gamma_{47}+0.0221\Gamma_{97})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
9.80±0.10 OUR FIT Error includes scale factor of 1.1.						
9.80±0.18 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.						
9.92±0.10±0.09	f&a	11.2k	[85] BUSKULIC	96	ALEP	LEP 1991–1993 data
9.49±0.36±0.63	f&a		DECAMP	92C	ALEP	1989–1990 LEP runs
8.7 ±0.7 ±0.3	f&a	694	[86] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
7.8 ±0.5 ±0.8	f&a	890	SCHMIDKE	86	MRK2	E^{ee}_{cm}= 29 GeV
8.4 ±0.4 ±0.7	avg	1255	[87] FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

7.0 ±0.3 ±0.7	1566	[88] BAND	87	MAC	E^{ee}_{cm}= 29 GeV
6.7 ±0.8 ±0.9		[89] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
6.4 ±0.4 ±0.9		[87] RUCKSTUHL	86	DLCO	E^{ee}_{cm}= 29 GeV
9.7 ±2.0 ±1.3		BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV

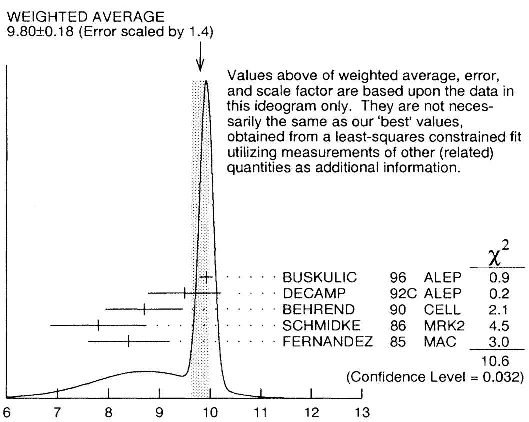
[85] BUSKULIC 96 quote $B(h^- h^- h^+ \nu_\tau (\text{ex. } K^0))$ = 9.50 ± 0.10 ± 0.11. We add 0.42 to remove their K^0 correction and reduce the systematic error accordingly.

[86] BEHREND 90 subtract 0.3% to account for the $\tau^- \rightarrow K^*(892)^- \nu_\tau$ contribution to measured events.

[87] Value obtained by multiplying paper's $R = B(h^- h^- h^+ \nu_\tau)/B(\text{3-prong})$ by B(3-prong) = 0.143 and subtracting 0.3% for $K^*(892)$ background.

[88] BAND 87 subtract for charged kaon modes; not independent of FERNANDEZ 85 value.

[89] BURCHAT 87 value is not independent of SCHMIDKE 86 value.



$\Gamma(h^- h^- h^+ \nu_\tau)/\Gamma_{\text{total}}$ (%)

$\Gamma(h^- h^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \geq \text{0neut. } \nu_\tau (\text{"3-prong"}))$ — Γ_{45}/Γ_{42}

$\Gamma_{45}/\Gamma_{42} = (0.3431\Gamma_{30}+0.3431\Gamma_{32}+\Gamma_{47}+0.0221\Gamma_{97})/(0.3431\Gamma_{30}+0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{35}+0.4508\Gamma_{37}+\Gamma_{47}+\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+0.285\Gamma_{90}+0.9101\Gamma_{98})$

This branching fractions is not independent of values for $\Gamma(h^- h^- h^+ \nu_\tau)/\Gamma_{\text{total}}$ and $\Gamma(h^- h^- h^+ \geq \text{0neut. } \nu_\tau (\text{"3-prong"}))/\Gamma_{\text{total}}$.

VALUE	DOCUMENT ID		TECN	COMMENT
0.744±0.007 OUR FIT				
0.61 ±0.03 ±0.05	FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.47 ±0.03 ±0.06	RUCKSTUHL	86	DLCO	E^{ee}_{cm}= 29 GeV

$\Gamma(h^- h^- h^+ \nu_\tau (\text{ex.} K^0))/\Gamma_{\text{total}}$ — Γ_{46}/Γ

$\Gamma_{46}/\Gamma = (\Gamma_{47}+0.0221\Gamma_{97})/\Gamma$

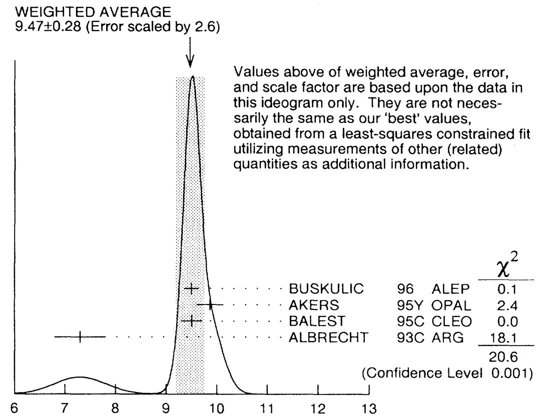
Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
9.48±0.10 OUR FIT Error includes scale factor of 1.1.						
9.47±0.28 OUR AVERAGE Error includes scale factor of 2.6. See the ideogram below.						
9.50±0.10±0.11	avg	11.2k	[90] BUSKULIC	96	ALEP	LEP 1991–1993 data
9.87±0.10±0.24	avg		[91] AKERS	95Y	OPAL	1991–1994 LEP runs
9.51±0.07±0.20	f&a	37.7k	BALEST	95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
7.3 ±0.1 ±0.5	avg		[92] ALBRECHT	93C	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[90] Not independent of BUSKULIC 96 $B(h^- h^- h^+ \nu_\tau)$ value.

[91] Not independent of AKERS 95Y $B(h^- h^- h^+ \geq 0 \text{ neutrals} \nu_\tau (\text{ex. } K^0_S \rightarrow \pi^+\pi^-))$ and $B(h^- h^- h^+ \nu_\tau (\text{ex. } K^0))/B(h^- h^- h^+ \geq 0 \text{ neutrals} \nu_\tau (\text{ex. } K^0_S \rightarrow \pi^+\pi^-))$ values.

[92] ALBRECHT 93C value with 0.5 ± 0.3% added to remove their corrections for charged-kaon backgrounds.



$\Gamma(h^- h^- h^+ \nu_\tau (\text{ex.} K^0))/\Gamma_{\text{total}}$ (%)

$\Gamma(h^- h^- h^+ \nu_\tau (\text{ex.} K^0)) \times \Gamma(\text{particle}^- \geq 0 \text{ neutrals} \geq 0 K^0_L \nu_\tau (\text{"1-prong"}))/\Gamma^2_{\text{total}}$ — $\Gamma_{46}\Gamma_1/\Gamma^2$

$\Gamma_{46}\Gamma_1/\Gamma^2 = (\Gamma_{47}+0.0221\Gamma_{97})(\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{20}+\Gamma_{23}+\Gamma_{24}+\Gamma_{26}+0.6569\Gamma_{30}+0.6569\Gamma_{32}+0.6569\Gamma_{34}+0.6569\Gamma_{35}+0.4316\Gamma_{37}+0.708\Gamma_{90}+0.085\Gamma_{97})/\Gamma^2$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0805±0.0008 OUR FIT Error includes scale factor of 1.1.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.063 ±0.001 ±0.004	7.5k	[93] ALBRECHT	93C	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[93] ALBRECHT 93C quote $B(\pi^- \pi^- \pi^+ \nu_\tau)$ = 6.8 ± 0.1 ± 0.5%. We add 0.5 ± 0.3% to remove their correction for charged kaon backgrounds, then multiply by 0.8613, their assumed value for B("1-prong").

$\Gamma(h^- h^- h^+ \nu_\tau (\text{ex.} K^0))/\Gamma(h^- h^- h^+ \geq 0 \text{ neutrals } \nu_\tau (\text{ex. } K^0_S \rightarrow \pi^+\pi^-))$ — Γ_{46}/Γ_{43}

$\Gamma_{46}/\Gamma_{43} = (\Gamma_{47}+0.0221\Gamma_{97})/(\Gamma_{47}+\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+0.285\Gamma_{90}+0.9101\Gamma_{97}+0.9101\Gamma_{98})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.660±0.006 OUR FIT Error includes scale factor of 1.1.				
0.660±0.004±0.014	AKERS	95Y	OPAL	1991–1994 LEP runs

$\Gamma(h^- h^- h^+ \nu_\tau (\text{ex.} K^0,\omega))/\Gamma_{\text{total}}$ — Γ_{47}/Γ

VALUE (%)	DOCUMENT ID
9.44±0.10 OUR FIT Error includes scale factor of 1.1.	

$\Gamma(h^- h^- h^+ \geq 1 \text{ neutrals } \nu_\tau)/\Gamma_{\text{total}}$ — Γ_{48}/Γ

$\Gamma_{48}/\Gamma = (0.3431\Gamma_{34}+0.3431\Gamma_{35}+0.1077\Gamma_{37}+\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+0.285\Gamma_{90}+0.888\Gamma_{97}+0.9101\Gamma_{98})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
5.08±0.11 OUR FIT Error includes scale factor of 1.2.						
5.2 ±0.4 OUR AVERAGE						
5.6 ±0.7 ±0.3	avg	352	[94] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
4.2 ±0.5 ±0.9	f&a	203	[95] ALBRECHT	87L	ARG	E^{ee}_{cm}= 10 GeV
4.7 ±0.5 ±0.8	avg	530	[96] SCHMIDKE	86	MRK2	E^{ee}_{cm}= 29 GeV
5.6 ±0.4 ±0.7	avg		[97] FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV
6.2 ±2.3 ±1.7	f&a		BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
6.1 ±0.8 ±0.9			[98] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
7.6 ±0.4 ±0.9			[97,99] RUCKSTUHL	86	DLCO	E^{ee}_{cm}= 29 GeV

[94] BEHREND 90 value is not independent of BEHREND 90 $B(3h\nu_\tau \geq 1 \text{ neutrals})$ + B(5-prong).

[95] ALBRECHT 87L measure the product of branching ratios $B(3\pi^\pm \pi^0 \nu_\tau)\ B((e\bar{\nu} \text{ or } \mu\bar{\nu} \text{ or } \pi \text{ or } K \text{ or } \rho)\nu_\tau)$ = 0.029 and use the PDG 86 values for the second branching ratio which sum to 0.69 ± 0.03 to get the quoted value.

[96] Not independent of SCHMIDKE 86 $h^- h^- h^+ \nu_\tau$ and $h^- h^- h^+ (\geq 0\pi^0)\nu_\tau$ values.

[97] Value obtained using paper's $R = B(h^- h^- h^+ \nu_\tau)/B(\text{3-prong})$ and current B(3-prong) = 0.143.

[98] BURCHAT 87 value is not independent of SCHMIDKE 86 value.

[99] Contributions from kaons and from $>1\pi^0$ are subtracted. Not independent of (3-prong + $0\pi^0$) and (3-prong + $\geq 0\pi^0$) values.

$\Gamma(h^- h^- h^+ \geq 1 \text{ neutrals } \nu_\tau (\text{ex. } K^0_S \to \pi^+\pi^-))/\Gamma_{total}$ — Γ_{49}/Γ

$\Gamma_{49}/\Gamma = (\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+0.285\Gamma_{90}+0.888\Gamma_{97}+0.9101\Gamma_{98})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
4.88±0.11 OUR FIT	Error includes scale factor of 1.2.					
5.07±0.24 OUR AVERAGE						
5.09±0.10±0.23	avg		[100] AKERS	95Y	OPAL	1991–1994 LEP runs
4.95±0.29±0.65	f&a	570	DECAMP	92C	ALEP	1989–1990 LEP runs

[100] Not independent of AKERS 95Y B($h^- h^- h^+ \geq 0$ neutralsν_τ(ex. $K^0_S \to \pi^+\pi^-$)) and B($h^- h^- h^+ \geq 0$ neutralsν_τ(ex. K^0))/B($h^- h^- h^+ \geq 0$ neutralsν_τ(ex. $K^0_S \to \pi^+\pi^-$)) values.

$\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{50}/Γ

$\Gamma_{50}/\Gamma = (0.3431\Gamma_{34}+0.3431\Gamma_{35}+\Gamma_{52}+0.888\Gamma_{97}+0.0221\Gamma_{98})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
4.44±0.09 OUR FIT	Error includes scale factor of 1.1.				
4.45±0.09±0.07	6.1k	[101] BUSKULIC	96	ALEP	LEP 1991–1993 data

[101] BUSKULIC 96 quote B($h^- h^- h^+ \pi^0 \nu_\tau$(ex. K^0)) = 4.30 ± 0.09 ± 0.09. We add 0.15 to remove their K^0 correction and reduce the systematic error accordingly.

$\Gamma(h^- h^- h^+ \pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ — Γ_{51}/Γ

$\Gamma_{51}/\Gamma = (\Gamma_{52}+0.888\Gamma_{97}+0.0221\Gamma_{98})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
4.25±0.09 OUR FIT	Error includes scale factor of 1.1.				
4.23±0.06±0.22	7.2k	BALEST	95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(h^- h^- h^+ \pi^0 \nu_\tau (\text{ex. } K^0, \omega))/\Gamma_{total}$ — Γ_{52}/Γ

VALUE (%)	DOCUMENT ID
2.55±0.09 OUR FIT	

$\Gamma(h^- (\rho\pi)^0 \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{53}/Γ_{50}

$\Gamma_{53}/\Gamma_{50} = (\Gamma_{55}+\Gamma_{56}+\Gamma_{57})/\Gamma_{50}$

VALUE	DOCUMENT ID		TECN	COMMENT
0.64±0.07±0.03	[102] ALBRECHT	91D	ARG	E^{ee}_{cm} = 9.4–10.6 GeV

[102] ALBRECHT 91D not independent of their $\Gamma(h^- \rho^+ h^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, $\Gamma(h^- \rho^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, and $\Gamma(h^- \rho\pi^0 \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ values.

$\Gamma((a_1(1260) h)^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{54}/Γ_{50}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.44	95	[103] ALBRECHT	91D	ARG	E^{ee}_{cm} = 9.4–10.6 GeV

[103] ALBRECHT 91D not independent of their $\Gamma(h^- \omega \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau(\text{ex.}K^0))$, $\Gamma(h^- \rho\pi^0 \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, $\Gamma(h^- \rho^+ h^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$, and $\Gamma(h^- \rho^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ values.

$\Gamma(h^- \rho\pi^0 \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{55}/Γ_{50}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.30±0.04±0.02	393	ALBRECHT	91D	ARG	E^{ee}_{cm} = 9.4–10.6 GeV

$\Gamma(h^- \rho^+ h^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{56}/Γ_{50}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.10±0.03±0.04	142	ALBRECHT	91D	ARG	E^{ee}_{cm} = 9.4–10.6 GeV

$\Gamma(h^- \rho^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — Γ_{57}/Γ_{50}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.26±0.05±0.01	370	ALBRECHT	91D	ARG	E^{ee}_{cm} = 9.4–10.6 GeV

$[\Gamma(h^- \rho^+ h^- \nu_\tau) + \Gamma(h^- \rho^- h^+ \nu_\tau)]/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ — $(\Gamma_{56}+\Gamma_{57})/\Gamma_{50}$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.33±0.06±0.01	475	[104] ALBRECHT	91D	ARG	E^{ee}_{cm} = 9.4–10.6 GeV

[104] ALBRECHT 91D not independent of their $\Gamma(h^- \rho^+ h^- \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ and $\Gamma(h^- \rho^- h^+ \nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ values.

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{58}/Γ

$\Gamma_{58}/\Gamma = (0.1077\Gamma_{37}+\Gamma_{60}+0.236\Gamma_{90}+0.888\Gamma_{98})/\Gamma$

VALUE (%)	DOCUMENT ID
0.52±0.05 OUR FIT	

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ — Γ_{59}/Γ

$\Gamma_{59}/\Gamma = (\Gamma_{60}+0.236\Gamma_{90}+0.888\Gamma_{98})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.51±0.05 OUR FIT					
0.50±0.07±0.07	1.8k	BUSKULIC	96	ALEP	LEP 1991–1993 data

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma(h^- h^- h^+ \geq 0\text{neut. } \nu_\tau (\text{"3-prong"}))$ — Γ_{59}/Γ_{42}

$\Gamma_{59}/\Gamma_{42} = (\Gamma_{60}+0.236\Gamma_{90}+0.888\Gamma_{98})/(0.3431\Gamma_{30}+0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{35}+0.4508\Gamma_{37}+\Gamma_{47}+\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+0.285\Gamma_{90}+0.9101\Gamma_{97}+0.9101\Gamma_{98})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0341±0.0031 OUR FIT					
0.034 ±0.002 ±0.003	668	BORTOLETTO	93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau (\text{ex.}K^0,\omega,\eta))/\Gamma_{total}$ — Γ_{60}/Γ

VALUE (%)	DOCUMENT ID
0.10±0.04 OUR FIT	

$\Gamma(h^- h^- h^+ \geq 3\pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{61}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.11±0.06 OUR FIT					
0.11±0.04±0.05	440	BUSKULIC	96	ALEP	LEP 1991–1993 data

$\Gamma(K^- h^+ h^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ — Γ_{62}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.6	90	AIHARA	84C	TPC	E^{ee}_{cm} = 29 GeV

$\Gamma(K^- \pi^+ \pi^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ — Γ_{63}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.39^{+0.19}_{-0.16}$ OUR AVERAGE	Error includes scale factor of 1.5.				
$0.58^{+0.15}_{-0.13}$±0.12	20	[105] BAUER	94	TPC	E^{ee}_{cm} = 29 GeV
$0.22^{+0.16}_{-0.13}$±0.05	9	[106] MILLS	85	DLCO	E^{ee}_{cm} = 29 GeV

[105] We multiply 0.58% by 0.20, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

[106] Error correlated with MILLS 85 ($KK\pi\nu$) value. We multiply 0.22% by 0.23, the relative systematic error quoted by MILLS 85, to obtain obtain the systematic error.

$\Gamma(K^- \pi^+ K^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ — Γ_{64}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.09	95	BAUER	94	TPC	E^{ee}_{cm} = 29 GeV

$\Gamma(K^- K^+ \pi^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ — Γ_{65}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.15^{+0.09}_{-0.07}$±0.03	4	[107] BAUER	94	TPC	E^{ee}_{cm} = 29 GeV

[107] We multiply 0.15% by 0.20, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

$\Gamma(K^- K^+ \pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{66}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.22^{+0.17}_{-0.11}$±0.05	9	[108] MILLS	85	DLCO	E^{ee}_{cm} = 29 GeV

[108] Error correlated with MILLS 85 ($K\pi\pi\pi^0\nu$) value. We multiply 0.22% by 0.23, the relative systematic error quoted by MILLS 85, to obtain obtain the systematic error.

$\Gamma(\phi\pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{67}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.5 × 10^{-4}	90	ALBRECHT	95H	ARG	E^{ee}_{cm} = 9.4–10.6 GeV

$\Gamma(K^- K^+ K^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ — Γ_{68}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.21	95	BAUER	94	TPC	E^{ee}_{cm} = 29 GeV

$\Gamma(\pi^- K^+ \pi^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ — Γ_{69}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.25	95	BAUER	94	TPC	E^{ee}_{cm} = 29 GeV

$\Gamma(e^- e^- e^+ \overline{\nu}_e \nu_\tau)/\Gamma_{total}$ — Γ_{70}/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
2.8±1.4±0.4	5	ALAM	96	CLEO	E^{ee}_{cm} = 10.6 GeV

$\Gamma(\mu^- e^- e^+ \overline{\nu}_\mu \nu_\tau)/\Gamma_{total}$ — Γ_{71}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<3.6	90	ALAM	96	CLEO	E^{ee}_{cm} = 10.6 GeV

$\Gamma(3h^- 2h^+ \geq 0 \text{ neutrals } \nu_\tau (\text{ex. } K^0_S \to \pi^-\pi^+)(\text{"5-prong"}))/\Gamma_{total}$ — Γ_{72}/Γ

$\Gamma_{72}/\Gamma = (\Gamma_{73}+\Gamma_{74})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.097±0.007 OUR FIT					
0.102±0.011 OUR AVERAGE					
0.097±0.005±0.011	419	GIBAUT	94B	CLEO	E^{ee}_{cm} = 10.6 GeV
0.26 ±0.06 ±0.05		ACTON	92H	OPAL	E^{ee}_{cm} = 88.2–94.2 GeV
0.10 $^{+0.05}_{-0.04}$ ±0.03		DECAMP	92C	ALEP	1989–1990 LEP runs
0.102±0.029	13	BYLSMA	87	HRS	E^{ee}_{cm} = 29 GeV
0.16 ±0.08 ±0.04	4	BURCHAT	85	MRK2	E^{ee}_{cm} = 29 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.16 \pm 0.13 \pm 0.04$		BEHREND	89B	CELL	E^{ee}_{cm}= 14–47 GeV
$0.3 \pm 0.1 \pm 0.2$		BARTEL	85F	JADE	E^{ee}_{cm}= 34.6 GeV
0.13 ± 0.04	10	BELTRAMI	85	HRS	Repl. by BYLSMA 87
1.0 ± 0.4	10	BEHREND	82	CELL	Repl. by BEHREND 89B

$[\Gamma(h^- h^- h^+ \geq 1\,\text{neutrals}\,\nu_\tau) + \Gamma(3h^- 2h^+ \geq 0\,\text{neutrals}\,\nu_\tau$ (ex. $K^0_S \to \pi^-\pi^+$)("5-prong"))$]/\Gamma_{total}$ — $(\Gamma_{48}+\Gamma_{72})/\Gamma$

$(\Gamma_{48}+\Gamma_{72})/\Gamma = (0.3431\Gamma_{34}+0.3431\Gamma_{35}+0.4507\Gamma_{37}+0.1177\Gamma_{37}+\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+\Gamma_{73}+\Gamma_{74}+0.29\Gamma_{90}+0.888\Gamma_{97}+0.9101\Gamma_{98})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
5.21±0.11 OUR FIT	Error includes scale factor of 1.2.				
5.4 ±0.5 OUR AVERAGE					
$5.05 \pm 0.29 \pm 0.65$	570	DECAMP	92C	ALEP	1989–1990 LEP runs
$5.8 \pm 0.7 \pm 0.2$	352	[109] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV

[109] BEHREND 90 not independent of their $\Gamma(h^- h^- h^+ \geq 1\,\text{neutrals}\,\nu_\tau)/\Gamma_{total}$ measurement.

$\Gamma(3h^- 2h^+ \nu_\tau\,(\text{ex.}K^0))/\Gamma_{total}$ — Γ_{73}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.075±0.007 OUR FIT					
0.073±0.008 OUR AVERAGE					
$0.080 \pm 0.011 \pm 0.013$	58	BUSKULIC	96	ALEP	LEP 1991–1993 data
$0.077 \pm 0.005 \pm 0.009$	295	GIBAUT	94B	CLEO	E^{ee}_{cm}= 10.6 GeV
$0.064 \pm 0.023 \pm 0.01$	12	ALBRECHT	88B	ARG	E^{ee}_{cm}= 10 GeV
0.051 ± 0.020	7	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.067 ± 0.030	5	[110] BELTRAMI	85	HRS	Repl. by BYLSMA 87

[110] The error quoted is statistical only.

$\Gamma(3h^- 2h^+ \pi^0 \nu_\tau\,(\text{ex.}K^0))/\Gamma_{total}$ — Γ_{74}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.022±0.005 OUR FIT					
0.021±0.005 OUR AVERAGE					
$0.018 \pm 0.007 \pm 0.012$	18	BUSKULIC	96	ALEP	LEP 1991–1993 data
$0.019 \pm 0.004 \pm 0.004$	31	GIBAUT	94B	CLEO	E^{ee}_{cm}= 10.6 GeV
0.051 ± 0.022	6	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.067 ± 0.030	5	[111] BELTRAMI	85	HRS	Repl. by BYLSMA 87

[111] The error quoted is statistical only.

$\Gamma(3h^- 2h^+ 2\pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{75}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	GIBAUT	94B	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma((5\pi)^- \nu_\tau)/\Gamma_{total}$ — Γ_{76}/Γ

$\Gamma_{76}/\Gamma = (\Gamma_{26}+\frac{1}{4}\Gamma_{37}+\Gamma_{60}+\Gamma_{73})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		DOCUMENT ID		TECN	COMMENT
0.33±0.07 OUR FIT					
0.61±0.06±0.08	avg	[112] GIBAUT	94B	CLEO	E^{ee}_{cm}= 10.6 GeV

[112] Not independent of GIBAUT 94B $B(3h^- 2h^+ \nu_\tau)$, PROCARIO 93 $B(h^- 4\pi^0 \nu_\tau)$, and BORTOLETTO 93 $B(2h^- h^+ 2\pi^0 \nu_\tau)/B(\text{"3prong"})$ measurements. Result is corrected for η contributions.

$\Gamma(4h^- 3h^+ \geq 0\,\text{neutrals}\,\nu_\tau\,(\text{"7-prong"}))/\Gamma_{total}$ — Γ_{77}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.019	90	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(K^*(892)^- \geq 0(h^0 \neq K^0_S)\nu_\tau)/\Gamma_{total}$ — Γ_{78}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.94±0.27±0.15	74	AKERS	94G	OPAL	E^{ee}_{cm}= 88–94 GeV

$\Gamma(K^*(892)^- \geq 0\,\text{neutrals}\,\nu_\tau)/\Gamma_{total}$ — Γ_{79}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.33±0.13 OUR AVERAGE					
$1.19 \pm 0.15^{+0.13}_{-0.18}$	104	ALBRECHT	95H	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
$1.43 \pm 0.11 \pm 0.13$	475	[113] GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV

[113] GOLDBERG 90 estimates that 10% of observed $K^*(892)$ are accompanied by a π^0.

$\Gamma(K^*(892)^- \nu_\tau)/\Gamma_{total}$ — Γ_{80}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.28±0.08 OUR AVERAGE					
$1.39 \pm 0.09 \pm 0.10$		[114] BUSKULIC	96	ALEP	LEP 1991–1993 data
1.11 ± 0.12		[115] COAN	96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
$1.42 \pm 0.22 \pm 0.09$		[116] ACCIARRI	95F	L3	1991–1993 LEP runs
$1.23 \pm 0.21^{+0.11}_{-0.21}$	54	[117] ALBRECHT	88L	ARG	E^{ee}_{cm}= 10 GeV
$1.9 \pm 0.3 \pm 0.4$	44	[118] TSCHIRHART	88	HRS	E^{ee}_{cm}= 29 GeV
$1.5 \pm 0.4 \pm 0.4$	15	[119] AIHARA	87C	TPC	E^{ee}_{cm}= 29 GeV
$1.3 \pm 0.3 \pm 0.3$	31	YELTON	86	MRK2	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.45 \pm 0.13 \pm 0.11$	273	[120] BUSKULIC	94F	ALEP	Repl. by BUSKULIC 96
1.7 ± 0.7	11	DORFAN	81	MRK2	E^{ee}_{cm}= 4.2–6.7 GeV

[114] Not independent of BUSKULIC 96 $B(\pi^- \overline{K}^0 \nu_\tau)$ and $B(K^- \pi^0 \nu_\tau)$ measurements.

[115] Not independent of COAN 96 $B(\pi^- \overline{K}^0 \nu_\tau)$ and BATTLE 94 $B(K^- \pi^0 \nu_\tau)$ measurements. $K\pi$ final states are consistent with and assumed to originate from $K^*(892)^-$ production.

[116] This result is obtained from their $B(\pi^- \overline{K}^0 \nu_\tau)$ assuming all those decays originate in $K^*(892)^-$ decays.

[117] The authors divide by $\Gamma_1/\Gamma = 0.865$ to obtain this result.

[118] Not independent of TSCHIRHART 88 $\Gamma(\tau^- \to h^- \overline{K}^0 \geq 0\,\text{neutrals} \geq 0 K^0_L \nu_\tau)/\Gamma(\text{total})$.

[119] Decay π^- identified in this experiment, is assumed in the others.

[120] BUSKULIC 94F obtain this result from BUSKULIC 94F $B(\overline{K}^0 \pi^- \nu_\tau)$ and BUSKULIC 94E $B(K^- \pi^0 \nu_\tau)$ assuming all of those decays originate in $K^*(892)^-$ decays.

$\Gamma(K^*(892)^- \nu_\tau)/\Gamma(\pi^- \pi^0 \nu_\tau)$ — Γ_{80}/Γ_{13}

VALUE	DOCUMENT ID		TECN	COMMENT
0.075±0.027	[121] ABREU	94K	DLPH	LEP 1992 Z data

[121] ABREU 94K quote $B(\tau^- \to K^*(892)^- \nu_\tau)B(K^*(892)^- \to K^- \pi^0)/B(\tau^- \to \rho^- \nu_\tau) = 0.025 \pm 0.009$. We divide by $B(K^*(892)^- \to K^- \pi^0) = 0.333$ to obtain this result.

$\Gamma(K^*(892)^0 K^- \geq 0\,\text{neutrals}\,\nu_\tau)/\Gamma_{total}$ — Γ_{81}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.32±0.08±0.12	119	GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV

$\Gamma(K^*(892)^0 K^- \nu_\tau)/\Gamma_{total}$ — Γ_{82}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.20±0.05±0.04	47	ALBRECHT	95H	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$\Gamma(\overline{K}^*(892)^0 \pi^- \geq 0\,\text{neutrals}\,\nu_\tau)/\Gamma_{total}$ — Γ_{83}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.38±0.11±0.13	105	GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV

$\Gamma(\overline{K}^*(892)^0 \pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{84}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.10±0.05	27	ALBRECHT	95H	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$\Gamma(K_1(1270)^- \nu_\tau)/\Gamma_{total}$ — Γ_{85}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.41^{+0.41}_{-0.35} \pm 0.10}$	5	[122] BAUER	94	TPC	E^{ee}_{cm}= 29 GeV

[122] We multiply 0.41% by 0.25, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

$\Gamma(K_1(1400)^- \nu_\tau)/\Gamma_{total}$ — Γ_{86}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.76^{+0.40}_{-0.33} \pm 0.20}$	11	[123] BAUER	94	TPC	E^{ee}_{cm}= 29 GeV

[123] We multiply 0.76% by 0.25, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

$[\Gamma(K_1(1270)^- \nu_\tau) + \Gamma(K_1(1400)^- \nu_\tau)]/\Gamma_{total}$ — $(\Gamma_{85}+\Gamma_{86})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{1.17^{+0.41}_{-0.37} \pm 0.29}$	16	[124] BAUER	94	TPC	E^{ee}_{cm}= 29 GeV

[124] We multiply 1.17% by 0.25, the relative systematic error quoted by BAUER 94, to obtain the systematic error. Not independent of BAUER 94 $B(K_1(1270)^- \nu_\tau)$ and BAUER 94 $B(K_1(1400)^- \nu_\tau)$ measurements.

$\Gamma(K^*_2(1430)^- \nu_\tau)/\Gamma_{total}$ — Γ_{87}/Γ

VALUE (%)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.3	95		TSCHIRHART	88	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.33	95		[125] ACCIARRI	95F	L3	1991–1993 LEP runs
<0.9	95	0	DORFAN	81	MRK2	E^{ee}_{cm}= 4.2–6.7 GeV

[125] ACCIARRI 95F quote $B(\tau^- \to K^*(1430)^- \to \pi^- \overline{K}^0 \nu_\tau) < 0.11\%$. We divide by $B(K^*(1430)^- \to \pi^- \overline{K}^0) = 0.33$ to obtain the limit shown.

$\Gamma(a_0(980)^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total} \times B(a_0(980) \to K^0 K^-)$ — $\Gamma_{88}/\Gamma \times B$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.8 × 10^{-4}	90	GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV

$\Gamma(\eta\pi^-\nu_\tau)/\Gamma_{total}$ — Γ_{89}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 1.4	95	0	BARTELT	96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 3.4	95		ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
< 90	95		ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV
<140	90		BEHREND	88	CELL	E^{ee}_{cm}= 14–46.8 GeV
<180	95		BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV
<250	90	0	COFFMAN	87	MRK3	E^{ee}_{cm}= 3.77 GeV
510 ±100±120		65	DERRICK	87	HRS	E^{ee}_{cm}= 29 GeV
<100	95		GAN	87B	MRK2	E^{ee}_{cm}= 29 GeV

$\Gamma(\eta\pi^-\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{90}/Γ

VALUE (%)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.171±0.028 OUR FIT						
0.17 ±0.02 ±0.02		125	ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.10	95		ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV
<2.10	95		BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV
4.20 $^{+0.70}_{-1.20}$ ±1.60			126 GAN	87	MRK2	E^{ee}_{cm}= 29 GeV

126 Highly correlated with GAN 87 $\Gamma(\pi^- 3\pi^0 \nu_\tau)/\Gamma(\text{total})$ value.

$\Gamma(\eta\pi^-\pi^0\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{91}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 4.3	95	ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<120	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(\eta K^-\nu_\tau)/\Gamma_{total}$ — Γ_{92}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.6±0.5±0.5		85	BARTELT	96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<4.7	95		ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(\eta\pi^+\pi^-\pi^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ — Γ_{93}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.3	90	ABACHI	87B	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(\eta\eta\pi^-\nu_\tau)/\Gamma_{total}$ — Γ_{94}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 1.1	95	ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<83	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(\eta\eta\pi^-\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{95}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 2.0	95	ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<90	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(h^-\omega \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ — Γ_{96}/Γ

$\Gamma_{96}/\Gamma = (\Gamma_{97}+\Gamma_{98})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
2.32±0.11 OUR FIT						
1.65±0.3 ±0.2	**avg**	1513	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(h^-\omega\nu_\tau)/\Gamma_{total}$ — Γ_{97}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
1.91±0.09 OUR FIT						
1.93±0.13 OUR AVERAGE						
1.95±0.07±0.11	avg	2223	127 BALEST	95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
1.60±0.27±0.41	f&a	139	BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV

127 Not independent of BALEST 95C $B(\tau^- \to h^-\omega\nu_\tau)/B(\tau^- \to h^-h^-h^+\pi^0\nu_\tau)$ value.

$[\Gamma(h^-\rho\pi^0\nu_\tau)+\Gamma(h^-\rho^+h^-\nu_\tau)+\Gamma(h^-\rho^-h^+\nu_\tau)+\Gamma(h^-\omega\nu_\tau)]/\Gamma(h^-h^-h^+\pi^0\nu_\tau)$ — $(\Gamma_{55}+\Gamma_{56}+\Gamma_{57}+\Gamma_{97})/\Gamma_{50}$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
>0.81	95	128 ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

128 ALBRECHT 91D not independent of their $\Gamma(h^-\omega\nu_\tau)/\Gamma(h^-h^-h^+\pi^0\nu_\tau\,(\text{ex.}K^0))$, $\Gamma(h^-\rho\pi^0\nu_\tau)/\Gamma(h^-h^-h^+\pi^0\nu_\tau)$, $\Gamma(h^-\rho^+h^-\nu_\tau)/\Gamma(h^-h^-h^+\pi^0\nu_\tau)$, and $\Gamma(h^-\rho^-h^+\nu_\tau)/\Gamma(h^-h^-h^+\pi^0\nu_\tau)$ values.

$\Gamma(h^-\omega\nu_\tau)/\Gamma(h^-h^-h^+\pi^0\nu_\tau\,(\text{ex.}K^0))$ — Γ_{97}/Γ_{51}

$\Gamma_{97}/\Gamma_{51} = \Gamma_{97}/(\Gamma_{52}+0.888\Gamma_{97}+0.0221\Gamma_{98})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.448±0.019 OUR FIT					
0.453±0.019 OUR AVERAGE					
0.431±0.033	2350	129 BUSKULIC	96	ALEP	LEP 1991–1993 data
0.464±0.016±0.017	2223	130 BALEST	95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.37 ±0.05 ±0.02	458	131 ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

129 BUSKULIC 96 quote the fraction of $\tau \to h^-h^-h^+\pi^0\nu_\tau$ (ex. K^0) decays which originate in a $h^-\omega$ final state = 0.383 ± 0.029. We divide this by the $\omega(782) \to \pi^+\pi^-\pi^0$ branching fraction (0.888).

130 BALEST 95C quote the fraction of $\tau^- \to h^-h^-h^+\pi^0\nu_\tau$ (ex. K^0) decays which originate in a $h^-\omega$ final state equals 0.412 ± 0.014 ± 0.015. We divide this by the $\omega(782) \to \pi^+\pi^-\pi^0$ branching fraction (0.888).

131 ALBRECHT 91D quote the fraction of $\tau^- \to h^-h^-h^+\pi^0\nu_\tau$ decays which originate in a $\pi^-\omega$ final state equals 0.33 ± 0.04 ± 0.02. We divide this by the $\omega(782) \to \pi^+\pi^-\pi^0$ branching fraction (0.888).

$\Gamma(h^-\omega\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{98}/Γ

VALUE (%)	DOCUMENT ID
0.41±0.06 OUR FIT	

$\Gamma(h^-\omega\pi^0\nu_\tau)/\Gamma(h^-h^-h^+ \geq 0\text{neut. } \nu_\tau\,(\text{"3-prong"}))$ — Γ_{98}/Γ_{42}

$\Gamma_{98}/\Gamma_{42} = \Gamma_{98}/(0.3431\Gamma_{30}+0.3431\Gamma_{32}+0.3431\Gamma_{34}+0.3431\Gamma_{35}+0.4508\Gamma_{37}+\Gamma_{47}+\Gamma_{52}+\Gamma_{60}+\Gamma_{61}+0.285\Gamma_{90}+0.9101\Gamma_{97}+0.9101\Gamma_{98})$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		EVTS	DOCUMENT ID		TECN	COMMENT
0.028±0.004 OUR FIT						
0.028±0.003±0.003	**avg**	430	132 BORTOLETTO	93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

132 Not independent of BORTOLETTO 93 $\Gamma(\tau^- \to h^-\omega\pi^0\nu_\tau)/\Gamma(\tau^- \to h^-h^-h^+2\pi^0\nu_\tau\,(\text{ex.}K^0))$ value.

$\Gamma(h^-\omega\pi^0\nu_\tau)/\Gamma(h^-h^-h^+2\pi^0\nu_\tau\,(\text{ex.}K^0))$ — Γ_{98}/Γ_{59}

$\Gamma_{98}/\Gamma_{59} = \Gamma_{98}/(\Gamma_{60}+0.236\Gamma_{90}+0.888\Gamma_{98})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.81±0.08 OUR FIT				
0.81±0.06±0.06	BORTOLETTO	93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(e^-\gamma)/\Gamma_{total}$ — Γ_{99}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10^{-4}	90	ABREU	95U	DLPH	1990–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.2 × 10^{-4}	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
<2.0 × 10^{-4}	90	KEH	88	CBAL	E^{ee}_{cm}= 10 GeV
<6.4 × 10^{-4}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(\mu^-\gamma)/\Gamma_{total}$ — Γ_{100}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 0.42 × 10^{-5}	90	BEAN	93	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 6.2 × 10^{-5}	90	ABREU	95U	DLPH	1990–1993 LEP runs
< 3.4 × 10^{-5}	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
<55 × 10^{-5}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^-\pi^0)/\Gamma_{total}$ — Γ_{101}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 14 × 10^{-5}	90	KEH	88	CBAL	E^{ee}_{cm}= 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 17 × 10^{-5}	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
<210 × 10^{-5}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(\mu^-\pi^0)/\Gamma_{total}$ — Γ_{102}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 4.4 × 10^{-5}	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<82 × 10^{-5}	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

$\Gamma(e^- K^0)/\Gamma_{total}$ Γ_{103}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.3 × 10⁻³	90	HAYES	82	MRK2	E^{ee}_{cm} = 3.8–6.8 GeV

$\Gamma(\mu^- K^0)/\Gamma_{total}$ Γ_{104}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.0 \times 10^{-3}$	90	HAYES	82	MRK2	E^{ee}_{cm} = 3.8–6.8 GeV

$\Gamma(e^- \eta)/\Gamma_{total}$ Γ_{105}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 6.3 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<24 \times 10^{-5}$	90	KEH	88	CBAL	E^{ee}_{cm} = 10 GeV

$\Gamma(\mu^- \eta)/\Gamma_{total}$ Γ_{106}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.3 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV

$\Gamma(e^- \rho^0)/\Gamma_{total}$ Γ_{107}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 0.42 \times 10^{-5}$	90	[133] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 1.9 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$<37 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm} = 3.8–6.8 GeV

[133] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \rho^0)/\Gamma_{total}$ Γ_{108}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 0.57 \times 10^{-5}$	90	[134] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 2.9 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$<44 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm} = 3.8–6.8 GeV

[134] BARTELT 94 assume phase space decays.

$\Gamma(e^- K^*(892)^0)/\Gamma_{total}$ Γ_{109}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<0.63 \times 10^{-5}$	90	[135] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.8 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV

[135] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- K^*(892)^0)/\Gamma_{total}$ Γ_{110}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<0.94 \times 10^{-5}$	90	[136] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.5 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV

[136] BARTELT 94 assume phase space decays.

$\Gamma(\pi^- \gamma)/\Gamma_{total}$ Γ_{111}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<28 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV

$\Gamma(\pi^- \pi^0)/\Gamma_{total}$ Γ_{112}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<37 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV

$\Gamma(e^- e^+ e^-)/\Gamma_{total}$ Γ_{113}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 0.33 \times 10^{-5}$	90	[137] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 1.3 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$< 2.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm} = 10.4–10.9
$<40 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm} = 3.8–6.8 GeV

[137] BARTELT 94 assume phase space decays.

$\Gamma(e^- \mu^+ \mu^-)/\Gamma_{total}$ Γ_{114}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 0.36 \times 10^{-5}$	90	[138] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 1.9 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$< 2.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm} = 10.4–10.9
$<33 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm} = 3.8–6.8 GeV

[138] BARTELT 94 assume phase space decays.

$\Gamma(e^+ \mu^- \mu^-)/\Gamma_{total}$ Γ_{115}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<0.35 \times 10^{-5}$	90	[139] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.8 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$<1.6 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm} = 10.4–10.9

[139] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- e^+ e^-)/\Gamma_{total}$ Γ_{116}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 0.34 \times 10^{-5}$	90	[140] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 1.4 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$< 2.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm} = 10.4–10.9
$<44 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm} = 3.8–6.8 GeV

[140] BARTELT 94 assume phase space decays.

$\Gamma(\mu^+ e^- e^-)/\Gamma_{total}$ Γ_{117}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<0.34 \times 10^{-5}$	90	[141] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.4 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$<1.6 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm} = 10.4–10.9

[141] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \mu^+ \mu^-)/\Gamma_{total}$ Γ_{118}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 0.19 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 0.43 \times 10^{-5}$	90	[142] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
$< 1.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm} = 10.4–10.9
$<49 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm} = 3.8–6.8 GeV

[142] BARTELT 94 assume phase space decays.

$\Gamma(e^- \pi^+ \pi^-)/\Gamma_{total}$ Γ_{119}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<0.44 \times 10^{-5}$	90	[143] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.7 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$<6.0 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm} = 10.4–10.9

[143] BARTELT 94 assume phase space decays.

$\Gamma(e^+ \pi^- \pi^-)/\Gamma_{total}$ Γ_{120}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<0.44 \times 10^{-5}$	90	[144] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.8 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$<1.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm} = 10.4–10.9

[144] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \pi^+ \pi^-)/\Gamma_{total}$ Γ_{121}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<0.74 \times 10^{-5}$	90	[145] BARTELT	94	CLEO	E^{ee}_{cm} = 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.6 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm} = 10 GeV
$<3.9 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm} = 10.4–10.9

[145] BARTELT 94 assume phase space decays.

$\Gamma(\mu^+\pi^-\pi^-)/\Gamma_{\rm total}$ — Γ_{122}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.69 × 10⁻⁵	90	[146] BARTELT	94	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.3 × 10⁻⁵	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
<3.9 × 10⁻⁵	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[146] BARTELT 94 assume phase space decays.

$\Gamma(e^-\pi^+K^-)/\Gamma_{\rm total}$ — Γ_{123}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.77 × 10⁻⁵	90	[147] BARTELT	94	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.9 × 10⁻⁵	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
<5.8 × 10⁻⁵	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[147] BARTELT 94 assume phase space decays.

$\Gamma(e^-\pi^-K^+)/\Gamma_{\rm total}$ — Γ_{124}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.46 × 10⁻⁵	90	[148] BARTELT	94	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5.8 × 10⁻⁵	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[148] BARTELT 94 assume phase space decays.

$\Gamma(e^+\pi^-K^-)/\Gamma_{\rm total}$ — Γ_{125}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.45 × 10⁻⁵	90	[149] BARTELT	94	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.0 × 10⁻⁵	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
<4.9 × 10⁻⁵	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[149] BARTELT 94 assume phase space decays.

$\Gamma(\mu^-\pi^+K^-)/\Gamma_{\rm total}$ — Γ_{126}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 0.87 × 10⁻⁵	90	[150] BARTELT	94	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<11 × 10⁻⁵	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
< 7.7 × 10⁻⁵	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[150] BARTELT 94 assume phase space decays.

$\Gamma(\mu^-\pi^-K^+)/\Gamma_{\rm total}$ — Γ_{127}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.5 × 10⁻⁵	90	[151] BARTELT	94	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7.7 × 10⁻⁵	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[151] BARTELT 94 assume phase space decays.

$\Gamma(\mu^+\pi^-K^-)/\Gamma_{\rm total}$ — Γ_{128}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.0 × 10⁻⁵	90	[152] BARTELT	94	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5.8 × 10⁻⁵	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV
<4.0 × 10⁻⁵	90	BOWCOCK	90	CLEO	$E^{ee}_{\rm cm}$= 10.4–10.9

[152] BARTELT 94 assume phase space decays.

$\Gamma(\overline{p}\gamma)/\Gamma_{\rm total}$ — Γ_{129}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<29 × 10⁻⁵	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV

$\Gamma(\overline{p}\pi^0)/\Gamma_{\rm total}$ — Γ_{130}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<66 × 10⁻⁵	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV

$\Gamma(\overline{p}\eta)/\Gamma_{\rm total}$ — Γ_{131}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<130 × 10⁻⁵	90	ALBRECHT	92K	ARG	$E^{ee}_{\rm cm}$= 10 GeV

$\Gamma(e^-\overline{K}^*(892)^0)/\Gamma_{\rm total}$ — Γ_{132}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10⁻⁵	90	[153] BARTELT	94	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[153] BARTELT 94 assume phase space decays.

$\Gamma(\mu^-\overline{K}^*(892)^0)/\Gamma_{\rm total}$ — Γ_{133}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.87 × 10⁻⁵	90	[154] BARTELT	94	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[154] BARTELT 94 assume phase space decays.

$\Gamma(e^-\text{ light boson})/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ — Γ_{134}/Γ_5

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	95	[155] ALBRECHT	95G	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.018	95	[156] ALBRECHT	90E	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
<0.040	95	[157] BALTRUSAIT...85		MRK3	$E^{ee}_{\rm cm}$= 3.77 GeV

[155] ALBRECHT 95G limit holds for bosons with mass < 0.4 GeV. The limit rises to 0.036 for a mass of 1.0 GeV, then falls to 0.006 at the upper mass limit of 1.6 GeV.

[156] ALBRECHT 90E limit applies for spinless boson with mass < 100 MeV, and rises to 0.050 for mass = 500 MeV.

[157] BALTRUSAITIS 85 limit applies for spinless boson with mass < 100 MeV.

$\Gamma(\mu^-\text{ light boson})/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ — Γ_{135}/Γ_5

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.026	95	[158] ALBRECHT	95G	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.033	95	[159] ALBRECHT	90E	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
<0.125	95	[160] BALTRUSAIT...85		MRK3	$E^{ee}_{\rm cm}$= 3.77 GeV

[158] ALBRECHT 95G limit holds for bosons with mass < 1.3 GeV. The limit rises to 0.034 for a mass of 1.4 GeV, then falls to 0.003 at the upper mass limit of 1.6 GeV.

[159] ALBRECHT 90E limit applies for spinless boson with mass < 100 MeV, and rises to 0.071 for mass = 500 MeV.

[160] BALTRUSAITIS 85 limit applies for spinless boson with mass < 100 MeV.

τ-DECAY PARAMETERS

Neglecting radiative corrections and terms proportional to m_ℓ^2/m_τ^2, the energy spectrum of the charged decay lepton ℓ in the τ rest frame is given by

$$\frac{d^2\Gamma_{\tau\to\ell\nu\overline{\nu}}}{d\Omega\, dx} \propto x^2 \times\left\{12(1-x)+\rho_\tau\left(\frac{32}{3}x-8\right)+24\eta_\tau\frac{m_\ell}{m_\tau}\frac{(1-x)}{x} -P_\tau\,\xi_\tau\cos\theta\left[4(1-x)+\delta_\tau\left(\frac{32}{3}x-8\right)\right]\right\}\,. \tag{1}$$

Here $x = 2E_\ell/m_\tau$ is the scaled lepton energy, P_τ is the τ polarization, and θ is the angle between the τ spin and the lepton momentum. With unpolarized τ's or integrating over the full θ range, the spectrum depends only on ρ_τ and η_τ. Measurements of the other two Michel parameters, ξ_τ and δ_τ, require polarized τ's. The Standard Model predicitions for ρ_τ, η_τ, ξ_τ and δ_τ are $\frac{3}{4}$, 0, 1 and $\frac{3}{4}$. Where possible, we give separately the parameters for $\tau^-\to e^-\nu_\tau\overline{\nu}_e$ and $\tau^-\to\mu^-\nu_\tau\overline{\nu}_\mu$, to avoid assumptions about universality. Listings labelled "(e or μ)" contain either the results assuming lepton universality if quoted by the experiments or repeat the results from the "e" or "μ" section.

Hadronic two-body decays $\tau\to\nu_\tau h$, $h=\pi$, ρ, a_1, …, can under minimal assumptions be written

$$\frac{1}{\Gamma}\frac{d\Gamma}{dz} = f_h(z) + P_\tau\,\xi_h\,g_h(z)\;, \tag{2}$$

where the kinematic functions f_h, g_h and the definition of the variable z depend on the spin of the hadron h. For the simple case $h=\pi$, one has $z = E_\pi/E_\tau$, $f(z)=1$, and $g(z)=2z-1$. The parameter ξ_h is predicted to be unity and can be identified with twice the negative ν_τ helicity. Again ξ_h is listed, when available, separately for each hadron and averaged over all hadronic decays modes.

ρ^τ(e or μ) PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.742±0.027 OUR AVERAGE					
0.738±0.038		[161] ALBRECHT	95C	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
0.751±0.039±0.022		BUSKULIC	95D	ALEP	1990–1992 LEP runs
0.79 ±0.10 ±0.10	3732	FORD	87B	MAC	E^{ee}_{cm}= 29 GeV
0.71 ±0.09 ±0.03	1426	BEHRENDS	85	CLEO	e^+e^- near $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.732±0.034±0.020	8.2k	[162] ALBRECHT	95	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
0.742±0.035±0.020	8000	ALBRECHT	90E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[161] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E.
[162] Value is from a simultaneous fit for the ρ^τ and η^τ decay parameters to the lepton energy spectrum. Not independent of ALBRECHT 90E ρ^τ(e or μ) value which assumes η^τ=0. Result is strongly correlated with ALBRECHT 95C.

ρ^τ(e) PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.736±0.028 OUR AVERAGE					
0.735±0.036±0.020	4.7k	[163] ALBRECHT	95	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
0.793±0.050±0.025		BUSKULIC	95D	ALEP	1990–1992 LEP runs
0.79 ±0.08 ±0.06	3230	[164] ALBRECHT	93G	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
0.64 ±0.06 ±0.07	2753	JANSSEN	89	CBAL	E^{ee}_{cm}= 9.4–10.6 GeV
0.62 ±0.17 ±0.14	1823	FORD	87B	MAC	E^{ee}_{cm}= 29 GeV
0.60 ±0.13	699	BEHRENDS	85	CLEO	e^+e^- near $\Upsilon(4S)$
0.72 ±0.10 ±0.11	594	BACINO	79B	DLCO	E^{ee}_{cm}= 3.5–7.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.747±0.045±0.028	5106	ALBRECHT	90E	ARG	Repl. by ALBRECHT 95

[163] ALBRECHT 95 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(h^+h^-h^+(\pi^0)\overline{\nu}_\tau)$ and their charged conjugates.
[164] ALBRECHT 93G use tau pair events of the type $\tau^-\tau^+ \to (\mu^-\overline{\nu}_\mu\nu_\tau)(e^+\nu_e\overline{\nu}_\tau)$ and their charged conjugates.

$\rho^\tau(\mu)$ PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.74 ±0.04 OUR AVERAGE					
0.693±0.057±0.028		BUSKULIC	95D	ALEP	1990–1992 LEP runs
0.76 ±0.07 ±0.08	3230	ALBRECHT	93G	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
0.734±0.055±0.027	3041	ALBRECHT	90E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
0.89 ±0.14 ±0.08	1909	FORD	87B	MAC	E^{ee}_{cm}= 29 GeV
0.81 ±0.13	727	BEHRENDS	85	CLEO	e^+e^- near $\Upsilon(4S)$

ξ^τ(e or μ) PARAMETER

($V-A$) theory predicts $\xi = 1$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.03±0.12 OUR AVERAGE					
0.97±0.14		[165] ALBRECHT	95C	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
1.18±0.15±0.16		BUSKULIC	95D	ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.90±0.15±0.10	3230	[166] ALBRECHT	93G	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[165] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E. ALBRECHT 95C uses events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(h^+h^-h^+\overline{\nu}_\tau)$ and their charged conjugates.
[166] ALBRECHT 93G measurement determines $|\xi^\tau|$ for the case $\xi^\tau(e) = \xi^\tau(\mu)$, but the authors point out that other LEP experiments determine the sign to be positive.

ξ^τ(e) PARAMETER

($V-A$) theory predicts $\xi = 1$.

VALUE	DOCUMENT ID		TECN	COMMENT
1.03±0.23±0.09	BUSKULIC	95D	ALEP	1990–1992 LEP runs

$\xi^\tau(\mu)$ PARAMETER

($V-A$) theory predicts $\xi = 1$.

VALUE	DOCUMENT ID		TECN	COMMENT
1.23±0.22±0.10	BUSKULIC	95D	ALEP	1990–1992 LEP runs

η^τ(e or μ) PARAMETER

($V-A$) theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.01±0.14 OUR AVERAGE					
0.03±0.18±0.12	8.2k	ALBRECHT	95	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
−0.04±0.15±0.11		BUSKULIC	95D	ALEP	1990–1992 LEP runs

$\eta^\tau(\mu)$ PARAMETER

($V-A$) theory predicts $\eta = 0$.

VALUE	DOCUMENT ID		TECN	COMMENT
−0.24±0.23±0.18	BUSKULIC	95D	ALEP	1990–1992 LEP runs

$(\delta\xi)^\tau$(e or μ) PARAMETER

($V-A$) theory predicts $(\delta\xi) = 0.75$.

VALUE	DOCUMENT ID		TECN	COMMENT
0.76±0.11 OUR AVERAGE Error includes scale factor of 1.3.				
0.65±0.12	[167] ALBRECHT	95C	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
0.88±0.11±0.07	BUSKULIC	95D	ALEP	1990–1992 LEP runs

[167] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E. ALBRECHT 95C uses events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(h^+h^-h^+\overline{\nu}_\tau)$ and their charged conjugates.

$(\delta\xi)^\tau$(e) PARAMETER

($V-A$) theory predicts $(\delta\xi) = 0.75$.

VALUE	DOCUMENT ID		TECN	COMMENT
1.11±0.17±0.07	BUSKULIC	95D	ALEP	1990–1992 LEP runs

$(\delta\xi)^\tau(\mu)$ PARAMETER

($V-A$) theory predicts $(\delta\xi) = 0.75$.

VALUE	DOCUMENT ID		TECN	COMMENT
0.71±0.14±0.06	BUSKULIC	95D	ALEP	1990–1992 LEP runs

$\xi^\tau(\pi)$ PARAMETER

($V-A$) theory predicts $\xi^\tau(\pi) = 1$.

VALUE	DOCUMENT ID		TECN	COMMENT
0.987±0.057±0.027	BUSKULIC	95D	ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.95 ±0.11 ±0.05	[168] BUSKULIC	94D	ALEP	1990+1991 LEP run

[168] Superseded by BUSKULIC 95D.

$\xi^\tau(\rho)$ PARAMETER

($V-A$) theory predicts $\xi^\tau(\rho) = 1$.

VALUE	DOCUMENT ID		TECN	COMMENT
1.045±0.058±0.032	BUSKULIC	95D	ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.03 ±0.11 ±0.05	[169] BUSKULIC	94D	ALEP	1990+1991 LEP run

[169] Superseded by BUSKULIC 95D.

$\xi^\tau(a_1)$ PARAMETER

($V-A$) theory predicts $\xi^\tau(a_1) = 1$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.01 ±0.04 OUR AVERAGE					
$1.08\ ^{+0.46}_{-0.41}\ ^{+0.14}_{-0.25}$	2.6k	[170] AKERS	95P	OPAL	1992 + 1993 runs
1.017±0.039		ALBRECHT	95C	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
0.937±0.116±0.064		BUSKULIC	95D	ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.022±0.028±0.030	1.7k	[171] ALBRECHT	94E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
$1.25\ \pm0.23\ ^{+0.15}_{-0.08}$	7.5k	ALBRECHT	93C	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[170] AKERS 95P obtain this result with a model independent fit to the hadronic structure functions. Fitting with the model of Kuhn and Santamaria (ZPHY **C48**, 445 (1990)) gives $0.87 \pm 0.27^{+0.05}_{-0.06}$, and with the model of of Isgur *et al.* (PR **D39**,1357 (1989)) they obtain $1.10 \pm 0.31^{+0.13}_{-0.14}$.
[171] ALBRECHT 94E measure the square of this quantity and use the sign determined by ALBRECHT 90I to obtain the quoted result. Replaced by ALBRECHT 95C.

ξ^τ(all hadronic modes) PARAMETER

($V-A$) theory predicts $\xi^\tau = 1$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.011±0.027 OUR AVERAGE					
$1.08\ ^{+0.46}_{-0.41}\ ^{+0.14}_{-0.25}$	2.6k	[172] AKERS	95P	OPAL	1992 + 1993 runs
1.017±0.039		[173] ALBRECHT	95C	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
1.006±0.032±0.019		[174] BUSKULIC	95D	ALEP	1990–1992 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.022±0.028±0.030	1.7k	[175] ALBRECHT	94E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
0.99 ±0.07 ±0.04		[176] BUSKULIC	94D	ALEP	1990+1991 LEP run
$1.25\ \pm0.23\ ^{+0.15}_{-0.08}$	7.5k	[177] ALBRECHT	93C	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[172] AKERS 95P use $\tau \to a_1\nu_\tau$ decays.
[173] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E.
[174] BUSKULIC 95D use $\tau \to \pi\nu_\tau$, $\tau \to \rho\nu_\tau$, and $\tau \to a_1\nu_\tau$ decays.
[175] ALBRECHT 94E measure the square of this quantity and use the sign determined by ALBRECHT 90I to obtain the quoted result. Uses $\tau \to a_1\nu_\tau$ decays. Replaced by ALBRECHT 95C.
[176] BUSKULIC 94D use $\tau \to \pi\nu_\tau$ and $\tau \to \rho\nu_\tau$ decays. Superseded by BUSKULIC 95D.
[177] Uses $\tau \to a_1\nu_\tau$ decays. Replaced by ALBRECHT 95C.

τ REFERENCES

ABREU	96B	PL B365 448	+Adam, Adye, Agasi+	(DELPHI Collab.)
ALAM	96	PRL 76 2637	+Kim, Ling, Mahmood, O'Neill+	(CLEO Collab.)
ALEXANDER	96D	PL B369 163	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
ALEXANDER	96E	PL B373 341	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BAI	96	PR D53 20	+Bardon, Becker-Szendy, Blum+	(BES Collab.)
BARTELT	96	PRL 76 4119	+Csorna, Jain, Marka+	(CLEO Collab.)
BUSKULIC	96	ZPHY C (to be publ.)	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
CERN-PPE/95-140				
BUSKULIC	96B	ZPHY C70 549	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	96C	ZPHY C70 561	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
COAN	96	PR D53 6037	+Dominick, Fadeyev, Korolkov+	(CLEO Collab.)
ABE·	95Y	PR D52 4828	+Abt, Ahn, Akagi, Allen+	(SLD Collab.)
ABREU	95T	PL B357 715	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ABREU	95U	PL B359 411	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACCIARRI	95	PL B345 93	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	95F	PL B352 487	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
AKERS	95F	ZPHY C66 31	+Alexander, Allison, Ametewee+	(OPAL Collab.)
AKERS	95I	ZPHY C66 543	+Alexander, Allison, Ametewee+	(OPAL Collab.)
AKERS	95P	ZPHY C67 45	+Alexander, Allison, Ametewee+	(OPAL Collab.)
AKERS	95Y	ZPHY C68 555	+Alexander, Allison, Altekamp+	(OPAL Collab.)
ALBRECHT	95	PL B341 441	+Hamacher, Hofmann, Kirchhoff+	(ARGUS Collab.)
ALBRECHT	95C	PL B349 576	+Hamacher, Hofmann, Kirchoff+	(ARGUS Collab.)
ALBRECHT	95G	ZPHY C68 25	+Hamacher, Hofmann, Kirchhoff+	(ARGUS Collab.)
ALBRECHT	95H	ZPHY C68 215	+Hamacher, Hofmann, Kirchhoff+	(ARGUS Collab.)
BALEST	95C	PRL 75 3809	+Cho, Ford, Lohner+	(CLEO Collab.)
BUSKULIC	95C	PL B346 371	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	95D	PL B346 379	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
Also	95P	PL B363 265 erratum		
ABREU	94K	PL B334 435	+Adam, Adye, Agasi+	(DELPHI Collab.)
AKERS	94E	PL B328 207	+Alexander, Allison, Anderson+	(OPAL Collab.)
AKERS	94G	PL B339 278	+Alexander, Allison, Anderson+	(OPAL Collab.)
ALBRECHT	94E	PL B337 383	+Hamacher, Hofmann+	(ARGUS Collab.)
ARTUSO	94	PRL 72 3762	+Goldberg, He, Horwitz+	(CLEO Collab.)
BARTELT	94	PRL 73 1890	+Csorna, Egyed, Jain+	(CLEO Collab.)
BATTLE	94	PRL 73 1079	+Ernst, Kwon, Roberts+	(CLEO Collab.)
BAUER	94	PR D50 R13	+Belcinski, Berg, Bingham+	(TPC/2gamma Collab.)
BUSKULIC	94D	PL B321 168	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	94E	PL B332 209	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	94F	PL B332 219	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
GIBAUT	94B	PRL 73 934	+Kinoshita, Barish, Chadha+	(CLEO Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ALBRECHT	93C	ZPHY C58 61	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALBRECHT	93G	PL B316 608	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
BALEST	93	PR D47 R3671	+Daoudi, Ford, Johnson+	(CLEO Collab.)
BEAN	93	PRL 70 138	+Gronberg, Kutschke+	(CLEO Collab.)
BORTOLETTO	93	PRL 71 1791	+Brown, Fast, McIlwain+	(CLEO Collab.)
ESCRIBANO	93	PL B301 419	+Masso	(BARC)
PROCARIO	93	PRL 70 1207	+Yang, Balest, Cho+	(CLEO Collab.)
WASSERBAECH	93	PR D48 4216		(FSUSC)
ABREU	92N	ZPHY C55 555	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACTON	92F	PL B281 405	+Alexander, Allison, Allport+	(OPAL Collab.)
ACTON	92H	PL B288 373	+Allison, Allport+	(OPAL Collab.)
AKERIB	92	PRL 69 3610	+Barish, Chadha, Cowen+	(CLEO Collab.)
Also	93B	PRL 71 3395 (erratum)	Akerib, Barish, Chadha, Cowen+	(CLEO Collab.)
ALBRECHT	92D	ZPHY C53 367	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALBRECHT	92K	ZPHY C55 179	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALBRECHT	92M	PL B292 221	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	92Q	ZPHY C56 339	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
AMMAR	92	PR D45 3976	+Baringer, Coppage, Davis+	(CLEO Collab.)
ARTUSO	92	PRL 69 3278	+Goldberg, Horwitz, Kennett+	(CLEO Collab.)
BAI	92	PRL 69 3021	+Bardon, Becker-Szendy, Burnett+	(BES Collab.)
BATTLE	92	PL B291 488	+Ernst, Kroha, Roberts+	(CLEO Collab.)
BUSKULIC	92J	PL B297 459	+Decamp, Goy, Lees+	(ALEPH Collab.)
DECAMP	92C	ZPHY C54 211	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
ADEVA	91F	PL B265 451	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
ALBRECHT	91D	PL B260 259	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALEXANDER	91D	PL B266 201	+Allison, Allport, Anderson+	(OPAL Collab.)
ANTREASYAN	91	PL B259 216	+Bartels, Besset, Bieler+	(Crystal Ball Collab.)
GRIFOLS	91	PL B255 611	+Mendez	(BARC)
SAMUEL	91B	PRL 67 668	+Li, Mendel	(OKSU, WONT)
Also	92B	PRL 69 995	Samuel, Li, Mendel	(OKSU, WONT)
Erratum.				
ABACHI	90	PR D41 1414	+Derrick, Kooijman, Musgrave+	(HRS Collab.)
ALBRECHT	90E	PL B246 278	+Ehrlichmann, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	90I	PL B250 164	+Ehrlichmann, Harder, Krueger+	(ARGUS Collab.)
BEHREND	90	ZPHY C46 537	+Criegee, Field, Franke+	(CELLO Collab.)
BOWCOCK	90	PR D41 805	+Kinoshita, Pipkin, Procario+	(CLEO Collab.)
DELAGUILA	90	PL B252 116	+Sher	(BARC, WILL)
GOLDBERG	90	PL B251 223	+Haupt, Horwitz, Jain+	(CLEO Collab.)
WU	90	PR D41 2339	+Hayes, Perl, Barklow+	(Mark II Collab.)
ABACHI	89B	PR D40 902	+Derrick, Kooijman, Musgrave+	(HRS Collab.)
BEHREND	89B	PL B222 163	+Criegee, Dainton, Field, Franke+	(CELLO Collab.)
JANSSEN	89	PL B228 273	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
KLEINWORT	89	ZPHY C42 7	+Allison, Ambrus, Barlow+	(JADE Collab.)
ADEVA	88	PR D38 2665	+Anderhub, Ansari, Becker+	(Mark-J Collab.)
ALBRECHT	88B	PL B202 149	+Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	88L	ZPHY C41 1	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ALBRECHT	88M	ZPHY C41 405	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
AMIDEI	88	PR D37 1750	+Trilling, Abrams, Baden+	(Mark II Collab.)
BEHREND	88	PL B200 226	+Criegee, Dainton, Field+	(CELLO Collab.)
BRAUNSCH...	88C	ZPHY C39 331	Braunschweig, Kirschfink, Martyn+	(TASSO Collab.)
KEH	88	PL B212 123	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
TSCHIRHART	88	PL B205 407	+Abachi, Akerlof, Baringer+	(HRS Collab.)
ABACHI	87B	PL B197 291	+Baringer, Bylsma, De Bonte+	(HRS Collab.)
ABACHI	87C	PRL 59 2519	+Akerlof, Baringer, Blockus+	(HRS Collab.)
ADLER	87B	PRL 59 1527	+Becker, Blaylock, Bolton+	(Mark III Collab.)
AIHARA	87B	PR D35 1553	+Alston-Garnjost, Avery+	(TPC Collab.)
AIHARA	87C	PRL 59 751	+Alston-Garnjost, Avery+	(TPC Collab.)
ALBRECHT	87L	PL B185 223	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
ALBRECHT	87P	PL B199 580	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
BAND	87	PL B198 297	+Camporesi, Chadwick, Delfino+	(MAC Collab.)
BAND	87B	PRL 59 415	+Bosman, Camporesi, Chadwick+	(MAC Collab.)
BARINGER	87	PRL 59 1993	+McIlwain, Miller, Shibata+	(CLEO Collab.)
BEBEK	87C	PR D36 690	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
BURCHAT	87	PR D35 27	+Feldman, Barklow, Boyarski+	(Mark II Collab.)
BYLSMA	87	PR D35 2269	+Abachi, Baringer, DeBonte+	(HRS Collab.)
COFFMAN	87	PR D36 2185	+Dubois, Eigen, Hauser+	(Mark III Collab.)
DERRICK	87	PL B189 260	+Kooijman, Loos, Musgrave+	(HRS Collab.)
FORD	87	PR D35 408	+Qi, Read, Smith+	(MAC Collab.)
FORD	87B	PR D36 1971	+Qi, Read, Smith+	(MAC Collab.)
GAN	87	PRL 59 411	+Abrams, Amidei, Baden+	(Mark II Collab.)
GAN	87B	PL B197 561	+Abrams, Amidei, Baden+	(Mark II Collab.)
AIHARA	86E	PRL 57 1836	+Alston-Garnjost, Avery+	(TPC Collab.)
BARTEL	86D	PL B182 216	+Becker, Felst, Haidt, Knies+	(JADE Collab.)
PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
RUCKSTUHL	86	PRL 56 2132	+Stroynowski, Atwood, Barish+	(DELCO Collab.)
SCHMIDKE	86	PRL 57 527	+Abrams, Matteuzzi, Amidei+	(Mark II Collab.)
YELTON	86	PRL 56 812	+Dorfan, Abrams, Amidei+	(Mark II Collab.)
ALTHOFF	85	ZPHY C26 521	+Braunschweig, Kirschfink+	(TASSO Collab.)
ASH	85B	PRL 55 2118	+Band, Blume, Camporesi+	(MAC Collab.)
BALTRUSAIT...	85	PRL 55 1842	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BARTEL	85F	PL 161B 188	+Becker, Cords, Felst+	(JADE Collab.)
BEHRENDS	85	PR D32 2468	+Gentile, Guida, Guida, Morrow+	(CLEO Collab.)
BELTRAMI	85	PRL 54 1775	+Bylsma, DeBonte, Gan+	(HRS Collab.)
BERGER	85	ZPHY C28 1	+Genzel, Lackas, Pielorz+	(PLUTO Collab.)
BURCHAT	85	PRL 54 2489	+Schmidke, Yelton, Abrams+	(Mark II Collab.)
FERNANDEZ	85	PRL 54 1624	+Ford, Qi, Read+	(MAC Collab.)
MILLS	85	PRL 54 624	+Pal, Atwood, Baillon+	(DELCO Collab.)
AIHARA	84C	PR D30 2436	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
BEHREND	84	ZPHY C23 103	+Fenner, Schachter, Schroder+	(CELLO Collab.)
MILLS	84	PRL 52 1944	+Ruckstuhl, Atwood, Baillon+	(DELCO Collab.)
BEHREND	83C	PL 127B 270	+Chen, Fenner, Gumpel+	(CELLO Collab.)
SILVERMAN	83	PR D27 1196	+Shaw	(UCI)
BEHREND	82	PL 114B 282	+Chen, Fenner, Field+	(CELLO Collab.)
BLOCKER	82B	PRL 48 1586	+Abrams, Alam, Blondel+	(Mark II Collab.)
BLOCKER	82D	PL 109B 119	+Dorfan, Abrams, Alam+	(Mark II Collab.) J
FORD	82	PRL 49 106	+Smith, Allaby, Ash	(MAC Collab.)
HAYES	82	PR D25 2869	+Perl, Alam, Boyarski+	(Mark II Collab.)
BERGER	81B	PL 99B 489	+Genzel, Grigull, Lackas+	(PLUTO Collab.)
DORFAN	81	PRL 46 215	+Blocker, Abrams, Alam+	(Mark II Collab.)
BRANDELIK	80	PL 92B 199	+Braunschweig, Gather+	(TASSO Collab.)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814	Zholentz, Kurdadze, Lelchuk+	(NOVO)
		Translated from YAF 34 1471.		
BACINO	79B	PRL 42 749	+Ferguson, Nodulman, Slater+	(DELCO Collab.)
KIRKBY	79	SLAC-PUB-2419		(SLAC) J
Batavia Lepton Photon Conference.				
BACINO	78B	PRL 41 13	+Ferguson, Nodulman, Slater+	(DELCO Collab.) J
Also	78	Tokyo Conf. 249	Kirz	(STON)
Also	80	PL 96B 214	Zholentz, Kurdadze, Lelchuk, Mishnev+	(NOVO)
BRANDELIK	78	PL 73B 109	+Braunschweig, Martyn, Sander+	(DASP Collab.) J
FELDMAN	78	Tokyo Conf. 777		(SLAC) J
HEILE	78	NP B138 189	+Perl, Abrams, Alam, Boyarski+	(SLAC, LBL)
JAROS	78	PRL 40 1120	+Abrams, Alam+	(SLAC, LBL, NWES, HAWA)
PERL	75	PRL 35 1489	+Abrams, Boyarski, Breidenbach+	(LBL, SLAC)

OTHER RELATED PAPERS

WEINSTEIN	93	ARNPS 43 457	+Stroynowski	(CIT, SMU)
PERL	92	RPP 55 653		(SLAC)
PICH	90	MPL A5 1995		(VALE)
BARISH	88	PRPL 157 1	+Stroynowski	(CIT)
GAN	88	IJMP A3 531	+Perl	(SLAC)
HAYES	88	PR D38 3351	+Perl	(SLAC)
PERL	80	ARNPS 30 299		(SLAC)

Heavy Charged Lepton Searches

Charged Heavy Lepton MASS LIMITS

Sequential Charged Heavy Lepton ($L^{\pm}$) MASS LIMITS

These experiments assumed that a fourth generation $L^{\pm}$ decayed to a fourth generation ν_L (or L^0) where ν_L was stable. New data show that stable ν_L have $m_{\nu_L} > 42.7$ GeV so that the above assumption is not valid for any mass limit ≤ 42.7 GeV. One can instead assume that $L^{\pm}$ decays via mixing to ν_e, ν_μ and/or ν_τ, and in that context the limits below are meaningful.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>42.8	95	ADEVA	90S	L3	Dirac
>44.3	95	AKRAWY	90G	OPAL	
>42.7	95	DECAMP	90F	ALEP	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 10–225		[1] AHMED	94	CNTR	H1 Collab. at HERA
none 12.6–29.6	95	KIM	91B	AMY	Massless ν assumed
none 0.5–10	95	[2] RILES	90	MRK2	For $(m_{L^-} - m_{L^0}) >$ 0.25–0.4 GeV
> 8		[3] STOKER	89	MRK2	For $(m_{L^+} - m_{L^0})$= 0.4 GeV
>12		[3] STOKER	89	MRK2	For m_{L^0}=0.9 GeV
none 18.4–27.6	95	[4] ABE	88	VNS	
>25.5	95	[5] ADACHI	88B	TOPZ	
none 1.5–22.0	95	BEHREND	88C	CELL	
>41	90	[6] ALBAJAR	87B	UA1	
>22.5	95	[7] ADEVA	85	MRKJ	
>18.0	95	[8] BARTEL	83	JADE	
none 4–14.5	95	[9] BERGER	81B	PLUT	
>15.5	95	[10] BRANDELIK	81	TASS	
>13.		[11] AZIMOV	80		
>16.	95	[12] BARBER	80B	CNTR	
> 0.490		[13] ROTHE	69	RVUE	

[1] The AHMED 94 limits are from a search for neutral and charged sequential heavy leptons at HERA via the decay channels $L^- \to e\gamma$, $L^- \to \nu W^-$, $L^- \to eZ$; and $L^0 \to \nu\gamma$, $L^0 \to e^- W^+$, $L^- \to \nu Z$, where the W decays to $\ell\nu_\ell$, or to jets, and Z decays to $\ell^+\ell^-$ or jets.

[2] RILES 90 limits were the result of a special analysis of the data in the case where the mass difference $m_{L^-} - m_{L^0}$ was allowed to be quite small, where L^0 denotes the neutrino into which the sequential charged lepton decays. With a slightly reduced $m_{L^{\pm}}$ range, the mass difference extends to about 4 GeV.

[3] STOKER 89 (Mark II at PEP) gives bounds on charged heavy lepton (L^+) mass for the generalized case in which the corresponding neutral heavy lepton (L^0) in the SU(2) doublet is not of negligible mass.

[4] ABE 88 search for L^+ and $L^- \to$ hadrons looking for acoplanar jets. The bound is valid for $m_\nu < 10$ GeV.

[5] ADACHI 88B search for hadronic decays giving acoplanar events with large missing energy. $E_{cm}^{ee} = 52$ GeV.

[6] Assumes associated neutrino is approximately massless.

[7] ADEVA 85 analyze one-isolated-muon data and sensitive to τ <10 nanosec. Assume B(lepton) = 0.30. E_{cm} = 40–47 GeV.

[8] BARTEL 83 limit is from PETRA e^+e^- experiment with average E_{cm} = 34.2 GeV.

[9] BERGER 81B is DESY DORIS and PETRA experiment. Looking for $e^+e^- \to L^+L^-$.

[10] BRANDELIK 81 is DESY-PETRA experiment. Looking for $e^+e^- \to L^+L^-$.

[11] AZIMOV 80 estimated probabilities for $M + N$ type events in $e^+e^- \to L^+L^-$ deducing semi-hadronic decay multiplicities of L from e^+e^- annihilation data at $E_{cm} = (2/3)m_L$. Obtained above limit comparing these with e^+e^- data (BRANDELIK 80).

[12] BARBER 80B looked for $e^+e^- \to L^+L^-$, $L \to \nu_L^{\mp} X$ with MARK-J at DESY-PETRA.

[13] ROTHE 69 examines previous data on μ pair production and π and K decays.

Stable Charged Heavy Lepton ($L^{\pm}$) MASS LIMITS

VALUE (GeV)	CL%	DOCUMENT ID		TECN
>42.8 (CL = 95%) OUR LIMIT				
>28.2	95	[14] ADACHI	90C	TOPZ
none 18.5–42.8	95	AKRAWY	90O	OPAL
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>26.5	95	DECAMP	90F	ALEP
none m_μ–36.3	95	SODERSTROM	90	MRK2

[14] ADACHI 90C put lower limits on the mass of stable charged particles with electric charge Q satisying $2/3 < Q/e < 4/3$ and with spin 0 or 1/2. We list here the special case for a stable charged heavy lepton.

Charged Long-Lived Heavy Lepton MASS LIMITS

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.1	0	[15] ANSORGE	73B	HBC	−	Long-lived
none 0.55–4.5		[16] BUSHNIN	73	CNTR	−	Long-lived
none 0.2–0.92		[17] BARNA	68	CNTR	−	Long-lived
none 0.97–1.03		[17] BARNA	68	CNTR	−	Long-lived

[15] ANSORGE 73B looks for electron pair production and electron-like Bremsstrahlung.

[16] BUSHNIN 73 is SERPUKOV 70 GeV p experiment. Masses assume mean life above 7×10^{-10} and 3×10^{-8} respectively. Calculated from cross section (see "Charged Quasi-Stable Lepton Production Differential Cross Section" below) and 30 GeV muon pair production data.

[17] BARNA 68 is SLAC photoproduction experiment.

Doubly-Charged Heavy Lepton MASS LIMITS

VALUE (GeV)	CL%	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 1–9 GeV	90	[18] CLARK	81	SPEC	++

[18] CLARK 81 is FNAL experiment with 209 GeV muons. Bounds apply to μ_P which couples with full weak strength to muon. See also section on "Doubly-Charged Lepton Produciton Cross Section."

Doubly-Charged Lepton Production Cross Section (μN Scattering)

VALUE (cm^2)	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6. \times 10^{-38}$	0	[19] CLARK	81	SPEC	++

[19] CLARK 81 is FNAL experiment with 209 GeV muon. Looked for μ^+ nucleon $\to \overline{\mu}_P^0 X$, $\overline{\mu}_P^0 \to \mu^+\mu^-\overline{\nu}_\mu$ and $\mu^+ n \to \mu_P^{++} X$, $\mu_P^{++} \to 2\mu^+\nu_\mu$. Above limits are for $\sigma\times$BR taken from their mass-dependence plot figure 2.

REFERENCES FOR Heavy Charged Lepton Searches

AHMED 94 PL B340 205 + (H1 Collab.)
KIM 91B IJMP A6 2583 +Smith, Breedon, Ko+ (AMY Collab.)
ADACHI 90C PL B244 352 +Aihara, Doser, Enomoto+ (TOPAZ Collab.)
ADEVA 90S PL B251 321 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
AKRAWY 90G PL B240 250 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90O PL B252 290 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
DECAMP 90F PL B236 511 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
RILES 90 PR D42 1 +Perl, Barklow+ (Mark II Collab.)
SODERSTROM 90 PRL 64 2980 +McKenna, Abrams, Adolphsen, Averill+ (Mark II Collab.)
STOKER 89 PR D39 1811 +Perl, Abrams+ (Mark II Collab.)
ABE 88 PRL 61 915 +Amako, Arai, Asano, Chiba (VENUS Collab.)
ADACHI 88B PR D37 1339 +Aihara, Dijkstra, Enomoto+ (TOPAZ Collab.)
BEHREND 88C ZPHY C41 7 +Buerger, Criegee, Dainton+ (CELLO Collab.)
ALBAJAR 87B PL B185 241 +Albrow, Allkofer, Arnison+ (UA1 Collab.)
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
Also 84C PRPL 109 131 Adeva, Barber, Becker+ (Mark-J Collab.)
BARTEL 83 PL 123B 353 +Cords, Dietrich, Eichler+ (JADE Collab.)
BERGER 81B PL 99B 489 +Genzel, Grigull, Lackas+ (PLUTO Collab.)
BRANDELIK 81 PL 99B 163 +Braunschweig, Gather+ (TASSO Collab.)
CLARK 81 PRL 46 299 +Johnson, Kerth, Loken+ (UCB, LBL, FNAL, PRIN)
Also 82 PR D25 2762 Smith, Clark, Johnson, Kerth+ (LBL, FNAL, PRIN)
AZIMOV 80 JETPL 32 664 +Khoze (PNPI)
Translated from ZETFP 32 677.
BARBER 80B PRL 45 1904 +Becker, Bei, Berghoff+ (Mark-J Collab.)
BRANDELIK 80 PL 92B 199 +Braunschweig, Gather+ (TASSO Collab.)
ANSORGE 73B PR D7 26 +Baker, Krzesinski, Neale, Rushbrooke+ (CAVE)
BUSHNIN 73 NP B58 476 +Dunaitzev, Golovkin, Kubarovsky+ (SERP)
Also 72 PL 42B 136 Golovkin, Grachev, Shodyrev+ (SERP)
ROTHE 69 NP B10 241 +Wolsky (PENN)
BARNA 68 PR 173 1391 +Cox, Martin, Perl, Tan, Toner, Zipf+ (SLAC, STAN)

OTHER RELATED PAPERS

PERL 81 SLAC-PUB-2752 (SLAC)
Physics in Collision Conference.

NEUTRINOS

(by R.E. Shrock, State Univ. of New York, Stony Brook)

In addition to the ν_e, ν_μ, and ν_τ sections, the *Review of Particle Physics* includes sections on "Number of Light Neutrino Types," "Heavy Lepton Searches," and "Searches for Massive Neutrinos and Lepton Mixing."

Neutrino experiments are notoriously difficult, owing to the basic property that neutrinos are neutral, weakly interacting particles. Over the years, many experimental claims pertaining to neutrino properties have been refuted by subsequent data. The *Review of Particle Physics* is an archival compendium which includes references to older papers, even experimental claims which have now been ruled out. It will be clear from the various listings which experiments have later been refuted.

In view of the continuing unsettled nature of data pertaining to various neutrino properties, it is perhaps well to record some of the definite accomplishments in the history of the subject. Neutrinos were first proposed in 1930 by Pauli, to explain the observed continuous electron energy distribution in nuclear beta decay [1]. Tentative evidence for the observation of the electron (anti)neutrino was reported in 1953, and definite evidence in 1956, by Cowan, Reines, and coworkers, using the reaction $\overline{\nu}_e p \to e^+ n$ with $\overline{\nu}_e$'s from reactor fluxes [2]. The separate identity of ν_e and ν_μ was demonstrated experimentally in 1962 by Lederman, Schwartz, Steinberger, and coworkers in a Brookhaven experiment [3]. Neutrinos from the sun were first observed by R. Davis and coworkers via the reaction $\nu_e\ {}^{37}\text{Cl} \to e^-\ {}^{37}\text{Ar}$, using an underground radiochemical experiment (which began operation in the late 1960's) in the Homestake Gold Mine [4]. Although we tabulate here only experiments with results pertaining to neutrino properties, it should be recalled that neutrino reactions played a crucial role in confirming the now-Standard Model when in 1973 neutral weak currents were first observed by the CERN Gargamelle bubble chamber experiment via the reactions $\nu_\mu e \to \nu_\mu e$ and $\nu_\mu(\overline{\nu}_\mu) + N \to \nu_\mu(\overline{\nu}_\mu)$ *hadrons* [6]. Neutrino reactions have also provided an important input to the measurement of the weak mixing angle θ_W. The discovery of the τ lepton by Perl *et al.* at SPEAR in 1975 and the study of its decay implied the existence of the third neutrino, ν_τ [7]. The precise measurement of the width of the Z at LEP and SLC has shown that there are only three species of neutrinos (in the usual electroweak doublets) with masses $< m_Z/2$ [8].

The theoretical perspective concerning neutrino masses has changed considerably over the past 20 years. Before that time, a standard view was that there was no theoretical reason for neutrinos to have masses, which was in accord with the striking fact that the upper limits on their masses were much smaller than those of the associated charged leptons. It was also noted that experimental data were consistent with the "laws" of lepton family number and total lepton number conservation. (Some early discussions of of neutrino oscillations and lepton mixing are given in Refs. 9 and 10). In the literature through the 1970's one often finds statements asserting that in the standard SU(2) $\times$ U(1) electroweak theory (without electroweak-singlet neutrinos) the known neutrinos (in electroweak-doublets) are massless. This is true if one pretends that the Standard Model is applicable to arbitrarily high energies and requires the exact absence of any nonrenormalizable, higher-dimension operators in this theory. However, a more modern view is that the Standard Model is an effective field theory, which is a good description of nature only up to some energy scale where new physics occurs. Clearly a strict upper bound on this scale is given by the Planck mass, $\overline{M}_{Pl} \equiv \sqrt{\hbar c/(8\pi G_N)} = 2.4 \times 10^{18}$ GeV, since quantum gravity is not included in the Standard Model. However, there are strong arguments that new physics beyond the Standard Model actually occurs at a much lower scale, of order a TeV. This new physics may be able to be included in a generalization of the Standard Model which remains perturbative, as in supersymmetric extensions, or may be nonperturbative, as in dynamical electroweak symmetry breaking schemes. It has been appreciated that renormalizability and, in particular, the great success of the Standard Model with its exclusion of any higher-dimension nonrenormalizable operators, may well be due only to the fact that the electroweak scale v_{EW} is considerably smaller than the scale of new physics. A summary of this modern view is given, *e.g.*, in Ref. 11.

Once one includes higher-dimension operators in the Lagrangian, nonzero neutrino masses can easily occur. The sizes of these masses reflect the scale(s) of the new physics. For example, given only the known left-handed neutrino fields of the Standard Model, there would be a gauge-invariant dimension-5 operator

$$\mathcal{O} = \frac{1}{M_X} \sum_{a,b} h_{a,b}(\epsilon_{ik}\epsilon_{jm} + \epsilon_{im}\epsilon_{jk}) \left[\mathcal{L}_{La}^{Ti} C \mathcal{L}_{Lb}^{j}\right] \phi^k \phi^m + h.c. \quad (1)$$

where $\mathcal{L}_{La} = (\nu_{\ell_a}, \ell_a)_L^T$ is the left-handed, $I = 1/2$, $Y = -1$ lepton doublet with generation index a (a = 1, 2, or 3), where $\ell_a = e, \mu, \tau$, for $a = 1, 2, 3$, and M_X denotes a generic mass scale characterizing the origin of this term. This operator involves a symmetric, $I = 1$ combination of the two $I = 1/2$ lepton doublets, contracted with an $I = 1$ combination of the two Higgs doublets. The term arising from the vacuum expectation values (vev's) of the Higgs doublets yields a (left-handed) Majorana neutrino mass term (symmetric in generation indices). If $M_X >> v_{EW}$, where $v_{EW} = 2^{-1/4} G_F^{-1/2} = 246$ GeV is the electroweak symmetry breaking scale, this would explain the smallness of the resultant neutrino masses.

Because of the hierarchy problem plaguing the Higgs sector of the Standard Model, many physicists have concluded that either this sector is stabilized against large radiative corrections by supersymmetry, or the electroweak symmetry breaking originates not from the vacuum expectation value of a pointlike Higgs field, but instead dynamically, from the condensation of bilinear products of fermion fields without any fundamental Higgs field. In supersymmetric extensions of the Standard Model, one again finds dimension-5 operators analogous to

Eq. (1). In approaches based on dynamical electroweak symmetry breaking, one can also get neutrino mass terms arising from higher-dimension multifermion operators.

In contrast to the higher-dimension operator (1), which involves only the known neutrinos, together with the hypothetical Higgs field of the Standard Model (or its supersymmetric extensions), another mechanism makes use only of renormalizable, dimension-4 operators, but requires the existence of electroweak-singlet neutrino fields. As will be discussed below, this mechanism produces light neutrino masses of order $m_\nu \sim M_D^2/M_R$, where M_D denotes a generic Dirac neutrino mass and M_R denotes a generic electroweak-singlet Majorana neutrino mass. Since the mass scale of the electroweak singlet neutrino mass term is naturally $>> v_{EW}$, this again yields, albeit for a different reason, very small m_ν [12].

In turn, a natural concomitant of (nondegenerate) neutrino masses is lepton mixing, which is thus also a general expectation. The lepton-mixing angles are functions of ratios of elements of neutrino-matrix elements and of charged lepton mass matrix elements, and even though left-handed neutrino masses are small, some of these ratios could, in principle, be $\mathcal{O}(1)$, which raises the issue of why such effects have not been seen. This question was answered as follows: a set of conditions for natural suppression of observable lepton flavor violation were formulated, and it was shown that the Standard Model (generalized to include nonzero m_ν) satisfies these [13]. This explains why the "law" of lepton family number conservation is obeyed to such high accuracy.

After these theoretical points, let us return to a description of the quantities upon which various experiments put limits. As an aid to understanding the limits on neutrino masses and lepton mixing, we recall that, in contrast to other particles in this *Review*, the neutrinos ν_e, ν_μ, and ν_τ are defined as weak eigenstates (the weak $I_3 = 1/2$ components of the $SU(2)_L$ lepton doublets) which couple with unit strength to e, μ, and τ, respectively. These neutrino weak eigenstates are not, in general, states of definite mass. If one assumes that neutrinos are massless, and hence degenerate, then it is possible to define the weak eigenstates to be simultaneously mass eigenstates. However, in the general case of possibly massive (nondegenerate) neutrinos, the weak eigenstates have no well-defined masses, but instead are linear combinations of mass eigenstates. Let us denote the charged leptons as the set $\{\ell_a\}$, $a = 1, \ldots, n$, where $n \geq 3$, with $\ell_1 = e$, $\ell_2 = \mu$, and $\ell_3 = \tau$. From the LEP measurement of the Z width (see section on "Number of Light Neutrinos"), one knows that there are only three neutrinos which couple to the Z in the usual way and have masses $m_\nu < m_Z/2$. Of course, this measurement does not preclude the existence of electroweak-singlet neutrinos. The left-handed components of the weak eigenstates of the neutrinos, $(\nu_{\ell_a})_L$ can be expressed in terms of mass eigenstates by the transformation

$$(\nu_{\ell_a})_L = \sum_j U_{aj} (\nu_j)_L \tag{2}$$

where the $\{\nu_j\}$ denote these mass eigenstates. The mass eigenstates are, in general, linear combinations of the known $I = 1/2$, $I_3 = 1/2$ neutrinos from electroweak doublets, and, in addition, possible electroweak-singlet neutrinos (sometimes called "sterile" neutrinos). The ordering of the mass eigenbasis can be defined so that U is as nearly diagonal as possible, *i.e.* (with no sum on j) $|U_{jj}| \geq |U_{jk}|$, $k \neq j$. Of course, this does not imply that $m(\nu_j) > m(\nu_k)$ for $j > k$.

Thus, as was noted in Ref. 14, decays such as $^3\text{H} \to {}^3\text{He}\, e^- \,\overline{\nu}_e$ and $\pi^+ \to \mu^+\nu_\mu$, which have been used to set the best bounds on the respective neutrino masses, really consist of sums of the separate decay modes $^3\text{H} \to {}^3\text{He}\, e^- \,\overline{\nu}_j$ and $\pi^+ \to \mu^+\nu_k$, where the ν_j and ν_k are mass eigenstates, and the indices j and k range over all of the values allowed by phase space in these respective decays. The coupling strengths for the jth mode in $^3\text{H}\beta$ decay and the kth mode in $\pi^+_{\mu 2}$ decay are given, respectively, by $|U_{1j}|^2$ and $|U_{2k}|^2$. In general, these modes are incoherent, although in the limit in which the ν_j all become degenerate they would become coherent. There are, in addition certain kinematic factors depending on the m_{ν_j} which enter in determining the branching ratio for a given decay mode. Assuming that the off-diagonal elements of the lepton mixing matrix U are small relative to the diagonal elements, the dominantly coupled decays are the ones with coupling strength $|U_{aj}|^2$, $a = j$, *i.e.*, $^3\text{H} \to {}^3\text{He}\, e^- \,\overline{\nu}_1$ and $\pi^+ \to \mu^+\nu_2$.

Hence, it follows that the neutrino mass limits quoted in the literature for "m_{ν_e}," "m_{ν_μ}," and "m_{ν_τ}" should really be interpreted as limits on the corresponding mass eigenstates [14,15]. Specifically, a bound on "m_{ν_e}" from a study of tritium β decay, for example, really constitutes a weighted limit on each of the mass eigenstates ν_j in the weak eigenstate ν_e which are kinematically allowed to occur in tritium decay and which are coupled with strength $|U_{1j}|^2$ sufficiently large to make a significant contribution to the observed spectrum. It is thus certainly a limit on ν_1, since this is, by the definition, of the order of the mass eigenbasis, the dominantly coupled neutrino. If lepton mixing is hierarchical, as quark mixing is known to be, *i.e.*, if $|U_{jj}|^2 \gg |U_{jk}|^2$, $j \neq k$, then ν_1 is the only mass eigenstate significantly constrained by a bound on "m_{ν_e}." Furthermore, strictly speaking, a neutrino mass limit cannot be stated in isolation; it always contains some implicit dependence on the relevant lepton-mixing angles. This dependence is fortunately relatively unimportant for the dominantly coupled decay modes, *i.e.*, $e\overline{\nu}_1$, $\mu\overline{\nu}_2$, and $\tau\overline{\nu}_3$ and hence the mass limits on "m_{ν_e}," "m_{ν_μ}," and "m_{ν_τ}" can be reinterpreted as being limits on m_{ν_j}, $j = 1$, 2, and 3, respectively.

There are three general types of (Lorentz-invariant) neutrino mass terms: Dirac masses of the form $m_D \overline{\nu}_L \chi_R + h.c.$, left-handed Majorana masses of the form $m_L \overline{\nu}_L \nu_R^c + h.c. = m_L^* \nu_L^T C \nu_L + h.c.$ and right-handed Majorana masses of the form $m_R \overline{\chi}_L^c \chi_R + h.c. = m_R \chi_R^T C \chi_R + h.c.$, where C is the Dirac charge conjugation matrix. Clearly, Dirac and right-handed Majorana mass terms require the existence of electroweak-singlet neutrinos. Our notation χ_R follows the usual practice of calling these "right-handed neutrino singlets", although since they are singlets, it is a convention whether one writes them as χ_R or $\chi'_L = (\chi_R)^c$. It is not known whether such electroweak-singlet neutrinos actually exist. Dirac mass terms conserve total lepton number $L_{\rm tot}$, while Majorana mass terms violate $L_{\rm tot}$. In the standard electroweak theory, extended to include massive neutrinos, (i) a Dirac mass term transforms as a weak $I = 1/2$ operator, and is coupled to the $I = 1/2$ Higgs to make an SU(2) × U(1) singlet operator; (ii) a Majorana mass term involving the $I = 1/2$ left-handed neutrinos transforms as $I = 1$ and must be coupled to an operator with $I = 1$ (and $Y = 2$) to make a gauge-invariant singlet; (iii) a Majorana mass term involving the SU(2) × U(1) singlet neutral leptons, conventionally considered to be right-handed, is a singlet; it could be present as a bare mass term or couple to some other singlet operator. Note that in the minimal supersymmetric Standard Model (MSSM), which has two Higgs doublets, of hypercharge $Y = 1$ and $Y = -1$, the Dirac neutrino mass term arises from the cubic chiral superfield terms $\epsilon_{ij} \sum_{a,b} \hat{L}^i_a \hat{\chi}^c_b \hat{H}^j_u$ (all chiral superfields are taken as left-handed), where $\hat{H}_u$ is the same Higgs that gives mass to the $Q = 2/3$ quarks. The Dirac neutrino mass terms are thus proportional to $\sin\beta$, where $\tan\beta = v_u/v_d$ is the ratio of the vacuum expectation values of the two Higgs in the MSSM.

In general, in the Standard Model, in addition to the three known left-handed $I = 1/2$ lepton doublets, there could be some number n_s of electroweak-singlet neutrinos. In a compact notation, one can then denote ν_L as the 3-component vector of left-handed $I = 1/2$ neutrinos and χ_R to be the n_s-dimensional vector of electroweak-singlet singlets, taken to be right-handed. The general neutrino mass term in the Lagrangian is then given by

$$-\mathcal{L}_m = \frac{1}{2}(\overline{\nu}_L, \overline{\chi}^c_L) \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu^c_R \\ \chi_R \end{pmatrix} + h.c. \qquad (3)$$

where M_L is the 3 × 3 left-handed Majorana-mass matrix, M_R is a $n_s \times n_s$ right-handed Majorana-mass matrix, and M_D is the 3-row by n_s-column Dirac-mass matrix. In general, all of these mass matrices are complex. The anticommutativity of fermion fields and the property that $C\gamma_\mu C^{-1} = -{\gamma_\mu}^T$ together imply that the Majorana mass matrices are symmetric: $M_L = {M_L}^T, M_R = {M_R}^T$. The diagonalization of the full $(3 + n_s) \times (3 + n_s)$ mass matrix in Eq. (2) yields $3 + n_s$ mass eigenstates, which are, in general, of Majorana type. Since Majorana mass terms violate total lepton number, one sees from a general viewpoint that one does not expect conservation of total lepton number. In particular, the dimension-5 operators discussed above give rise to left-handed Majorana neutrino mass terms and violate total lepton number. Dirac-neutrinos can be constructed from two Majorana-neutrino mass eigenstates whose masses are equal in magnitude [16]. For this reason, Dirac neutrino masses may be considered to be a special (degenerate) case of Majorana neutrino masses, and the latter may be regarded as the generic case. From the transformation which diagonalizes the neutrino mass matrix, together with the transformation which diagonalizes the charged lepton mass matrix (where, of course, only Dirac masses are allowed by electric-charge conservation), one constructs the lepton-mixing matrix U. In general, since U is not the identity, neutrino masses naturally give rise to lepton family number violation.

In supersymmetric extensions of the Standard Model, the neutrinos could, *a priori*, mix with the neutralinos (higgsinos and neutral gauginos). However, the usual R parity which is invoked to forbid unacceptably rapid proton decay also prevents such mixing between neutrinos and neutralinos.

In addition to mass and lifetime limits, this *Review* includes limits on various other possible properties, including electric charge, the CPT-violating difference $m_{\nu_1} - m_{\overline{\nu}_1}$, and a magnetic dipole moment. These are of interest because a massless purely chiral Dirac neutrino cannot have a magnetic (or electric) dipole moment. In the standard electroweak theory, extended to allow for Dirac neutrino masses, the neutrino magnetic dipole moment is nonzero and given [13,17], as

$$\mu_{\nu_j} = \frac{3eG_F m_{\nu_j}}{8\pi^2\sqrt{2}} = 3.2 \times 10^{-19}(m_{\nu_j}/1 \text{ eV})\mu_B \qquad (4)$$

where G_F is the Fermi constant and $\mu_B = e/2m_e$ is the Bohr magneton. The neutrino electric dipole moment violates both time-reversal invariance and parity; although it is nonzero in general, it is quite small (see, *e.g.* Ref. 18). Again, however, we note that Dirac neutrinos should be regarded as a special case; the generic case is Majorana neutrinos. Because of the properties

$$C\Gamma C^{-1} = -\Gamma \ , \qquad \Gamma = \sigma_{\alpha\beta} \ , \sigma_{\alpha\beta}\gamma_5 \qquad (5)$$

it follows that the operator products which define the magnetic and electric dipole moments are of the respective forms

$$(\overline{\nu}_i \sigma_{\alpha\beta} \nu_j - \ \overline{\nu}_j \sigma_{\alpha\beta} \nu_i) F^{\alpha\beta} \qquad (6)$$

and

$$(\overline{\nu}_i \sigma_{\alpha\beta} \gamma_5 \nu_j - \overline{\nu}_j \sigma_{\alpha\beta} \gamma_5 \nu_i) F^{\alpha\beta} \qquad (7)$$

(where $F^{\alpha\beta}$ is the electromagnetic field strength tensor). Hence, if ν_i is a Majorana neutrino (mass eigenstate), its magnetic and electric dipole elements vanish identically. Although only the diagonal magnetic and electric dipole moments are static properties of a given neutrino mass eigenstate, transition magnetic and electric dipole moments may exist, in general, for both Dirac and Majorana neutrinos.

Occasionally, one also finds references to the "neutrino charge radius" in the literature. This is defined via the Taylor series expansion of the generalized vector Dirac form factor multiplying γ_μ in the electromagnetic current matrix element: $F_1^V(q^2) = F_1^V(0) + q^2 \, dF_1^V/dq^2|_{q^2=0} + \mathcal{O}[(q^2)^2]$, where q denotes the 4-momentum of the photon [see, *e.g.* Ref. 13 Eq. (2.20)]. The electric charge is $Q = F^V(0) = 0$ for a neutrino, and the charge radius is given by $\langle r^2 \rangle = (1/6)(F_1^V)'(0)$. However, since this is multiplied by q^2 in the Taylor series expansion, it never occurs for a real photon, where $q^2 = 0$, and hence is not an S-matrix element, *i.e.*, not a physical quantity. In a gauge theory, this is manifested in the fact that the charge radius is gauge-dependent.

If one considers the possibility of nonzero masses for neutrinos, for consistency one must then also consider the leptonic mixing which would in general occur concomitantly. Accordingly, this *Review* devotes a section to correlated bounds on neutrino masses and lepton mixing angles. These can be divided into two types. First, there are those due to decays involving neutrinos in the final state, which must be recognized to have the possible multimode structure pointed out above. In the two most sensitive cases suggested as tests for neutrino masses and mixing, one obtains a limit on m_{ν_j} and $|U_{aj}|^2$ individually for each j. The peak-search test proposed in Ref. 14 was applied to existing data in that paper and a subsequent one [15]; it was applied in new experiments on 2-body leptonic decays of K^+ and π^+ by several groups at SIN (PSI), KEK, and TRIUMF. The results are catalogued in corresponding subsections on limits on $|U_{1j}|^2$ and $|U_{2j}|^2$. The kink-search test was also applied by a number of groups. The experimental situation, which was controversial for many years, has recently been clarified (see below).

Second, there are those due to processes involving the propagation and subsequent interaction of neutrinos. The latter are often called neutrino-oscillation limits, although this term is strictly correct only if the differences in neutrino masses are sufficiently small relative to their momenta that the propagation is effectively coherent in a quantum mechanical sense; otherwise, the individual ν_j from a given decay such as $\pi_{\mu 2}$ or $K_{\mu 2}$ propagate in a measurably incoherent manner, and there is no oscillation. Experimentalists usually present their results in terms of a simplifying model in which mixing is assumed to occur only between two neutrino species. The relevant transformation equation becomes

$$\begin{pmatrix} \nu_{\ell_a} \\ \nu_{\ell_b} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix} \tag{8}$$

where ν_{ℓ_a} are the neutrino weak eigenstates, with $\nu_{\ell_1} = \nu_e$, *etc.*, and ν_i are neutrino mass eigenstates. A given decay, such as $\pi^+ \to \mu^+\nu_\mu$, produces, at time $t = 0$, the neutrino mass eigenstates which are contained in the weak eigenstate ν_μ and are kinematically allowed to occur as decay products. Each mass eigenstate picks up a phase as it propagates, so that at time t, the jth eigenstate, as a quantum-mechanical state, has acquired a phase $\exp(-iE_j t)$, where E_j denotes its energy. Strictly speaking, E_j must be considered to be complex, since a massive neutrino will, in general, decay. Indeed such neutrino decays have been searched for in various experiments (see Listings). In the present discussion, we shall neglect this; for the ranges of neutrino masses of relevance to terrestrial neutrino oscillation experiments, such decays should have a negligible effect on the observed oscillations. (Indeed, the observation of neutrinos at about the expected rate from the 1987 supernova places significant lower bounds on neutrino lifetimes.) According to basic quantum mechanics, one cannot measure the energies E_j or momenta $p_j = \sqrt{E_j^2 - m_{\nu_j^2}}$ to arbitrary precision; rather, $\Delta E_j \Delta t_j \gtrsim \hbar/2$ and $\Delta(p_x)_j \Delta x_j \gtrsim \hbar/2$. Correspondingly, the neutrinos actually propagate as wavepackets. As noted above, if the mass differences $|m_{\nu_j} - m_{\nu_k}|$ are sufficiently small relative to the energies $E_j \simeq E_k$, then the resultant velocities are sufficiently close that these wavepackets will continue to maintain a high degree of overlap during the relevant time that they propagate in the experiment, and hence the individual mass eigenstates will remain effectively coherent in the quantum mechanical sense. Their propagation may then be characterized by a single momentum p. Now assume that, after having propagated for a time t (and hence, for $1 - v/c \ll 1$, a distance $L = ct$), the neutrino(s) scatter via a charged current weak interaction. This again projects out the weak interaction eigenstates. In particular, because of the different phases which the mass eigenstates pick up during the propagation, a neutrino which is emitted as ν_{ℓ_a} has a nonzero probability to produce a ℓ_b:

$$P = |\langle \nu_{\ell_b}(t)|\nu_{\ell_a}(0)\rangle|^2 = \sin^2(2\theta)\sin^2\Big(\frac{\Delta m^2 L}{4E}\Big) \tag{9}$$

where

$$\Delta m^2 = m_{\nu_i}^2 - m_{\nu_j}^2 \tag{10}$$

Numerically, $\Delta m^2 L/(4E) = (1.266932...)\Delta m^2 L/E$, where Δm^2 is measured in eV^2, L in m, and E in MeV (or L in km, E in GeV). Thus, neutrino oscillation experiments cannot measure individual neutrino masses, but only differences of masses squared, and indeed these are generally weighted in a more complicated way by lepton mixing matrix coefficients for the general case where there is mixing among more than just two species. Experimental results are presented as allowed regions on a plot, the axes of which are $|\Delta m^2|$ and $\sin^2 2\theta$. These are often summarized in terms of the upper limit on Δm^2 (the absolute value is usually suppressed in the notation) for maximal mixing, $\sin^2 2\theta = 1$, and the upper limit on $\sin^2 2\theta$ for "large" Δm^2, *i.e.*, sufficiently large $|\Delta m^2|$ that the detector averages over many cycles of oscillation (or there ceases to be any coherence). A more complete discussion is given in the "Note on Neutrino Oscillation Experiments" just before the tables reporting such results.

An important type of experiment is the search for neutrinoless double-β decay, which tests for total lepton number violation such as would result for Majorana-neutrino masses. This process takes place when a nucleus with Z protons and $A = ZN$ nucleons decays according to $(Z, A) \to (Z+2, A)e^-e^-$, violating total lepton number by two units. In the case of neutrinos with masses which are sufficiently light, an upper limit on neutrinoless double-β decay yields a correlated upper limit on the quantity

$$\overline{m} = \left| \sum_j U_{1j}^2 m_{\nu_j} \right| \ . \tag{11}$$

Cancellations may occur in the sum, since U_{1j} is, in general, complex. The situation is explored further in the minireview by Petr Vogel which prefaces the double-β decay sections. See Ref. 19 for some recent reviews of searches for neutrinoless double-β decay.

A brief summary of the current experimental situation follows (see previous editions for discussions of various positive claims for neutrino masses and mixing, and their refutations).

1. There is no evidence at present from direct searches for nonzero neutrino masses. These include the endpoint of the Kurie plot in nuclear beta decay for $m(\nu_e)$, $\pi^+ \rightarrow \mu^+\nu_\mu$ for $m(\nu_\mu)$, and certain τ decays for $m(\nu_\tau)$ (where, as discussed above, the limits actually apply to the respective mass eigenstates ν_1, ν_2, and ν_3 in these three weak eigenstates).

2. There are no indications of any positive neutrino masses from any of the peak search experiments in π or K decay, or from any experiments on neutrino decays.

3. There are no indications of any positive neutrino masses from nuclear beta decay spectra. The 7-year controversy over the claim by Simpson, Hime, and others of a 17 keV neutrino is finally over, with retractions by these authors of their original claims after very strong refutations by a number of high-sensitivity experiments.

4. A number of positive claims for neutrino oscillations in reactor and accelerator neutrino experiments have either been refuted or retracted, or both (see previous editions for details). However, in one analysis, the LSND (Liquid Scintillator Neutrino Detector) group at Los Alamos has reported evidence for the neutrino oscillation $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ [20]. A dissenting analysis of the data by a member of the collaboration reports no evidence for neutrino oscillations [21]. More recently, the LSND group has increased its data sample and strengthened its evidence for neutrino osciallations [22].

5. There is no indication of Majorana neutrino masses from searches for neutrinoless double-β decay.

6. Several experiments have reported evidence for atmospheric neutrino oscillations. Other experiments report results consistent with no such oscillations. This situation is unsettled at present.

7. It is generally acknowledged that the strongest indirect evidence for neutrino masses and mixing is the observed deficit in the solar neutrino flux. The current situation is reviewed by K. Nakamura as a preface to the Solar Neutrino Listings.

For some recent reviews on neutrino physics and further references to the original literature, see Refs. 23–28.

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ν_e

$J = \frac{1}{2}$

Not in general a mass eigenstate. See note on neutrino properties above.

These limits apply to ν_1, the primary mass eigenstate in ν_e. They would also apply to any other ν_j which mixes strongly in ν_e and has sufficiently small mass that it can occur in the respective decay. The neutrino mass may be of a Dirac or Majorana type; the former conserves total lepton number while the latter violates it. Either would violate lepton family number, since nothing forces the neutrino mass eigenstates to coincide with the neutrino interaction eigenstates. For limits on a Majorana ν_e mass, see the section on "Searches for Massive Neutrinos and Lepton Mixing," part (C), entitled "Searches for Neutrinoless Double-β Decay."

The square of the neutrino mass $m^2_{\nu_e}$ is measured in tritium beta decay experiments by fitting the shape of the beta spectrum near the endpoint; results are given in one of the tables in this section. In many experiments, it has been found to be significantly negative. In the 1994 edition of this *Review*, it was noted that the combined probability of a positive result was 3.5%. The problem has been exacerbated by the precise and careful experiments reported in two new papers (BELESEV 95 and STOEFFL 95). Both groups conclude that unknown effects cause the accumulation of events in the electron spectrum near its end point. If the fitting hypothesis does not account for this, unphysical values for $m^2_{\nu_e}$ are obtained. BELESEV 95 obtain their value for $m^2_{\nu_e}$ and limit for m_{ν_e} (4.35 eV at 95% CL) under the assumption that a certain narrow region is free of both high-energy and low-energy anomalies. Including the endpoint accumulation (they find no low-energy anomaly), STOEFFL 95 find a value for $m^2_{\nu_e}$ which is more than 5 standard deviations negative, and report a Bayesian limit of 7 eV for m_{ν_e} which is obtained by setting $m^2_{\nu_e} = 0$. Given the status of the tritium results, we find no clear way to set a meaningful limit on m_{ν_e}. On the other hand, a mass as large as 10–15 eV would probably cause detectable spectrum distortions near the endpoint.

The spread of arrival times of the neutrinos from SN 1987A, coupled with the measured neutrino energies, should provide a simple time-of-flight limit on m_{ν_e}. This statement, clothed in various degrees of sophistication, has been the basis for a very large number of papers. The LOREDO 89 limit (23 eV) is among the most conservative and involves few assumptions; as such, it is probably a safe limit. We list this limit below as "used," but conclude that a limit about half this size is justified by the tritium decay experiments.

ν_e MASS

Most of the data from which these limits are derived are from β^- decay experiments in which a $\overline{\nu}_e$ is produced, so that they really apply to $m_{\overline{\nu}_1}$. Assuming *CPT* invariance, a limit on $m_{\overline{\nu}_1}$ is the same as a limit on m_{ν_1}. Results from studies of electron capture transitions, given below "$m_{\nu_1} - m_{\overline{\nu}_1}$", give limits on m_{ν_1} itself. OUR EVALUATION of the present status of the tritium decay experiments is discussed in the above minireview.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
< 15	**OUR EVALUATION**				
< 23		LOREDO	89	ASTR	SN 1987A
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.35	95	[1] BELESEV	95	SPEC	^{3}H β decay
< 12.4	95	[2] CHING	95	SPEC	^{3}Hβ decay
< 92	95	[3] HIDDEMANN	95	SPEC	^{3}H β decay
$15\ ^{+32}_{-15}$		HIDDEMANN	95	SPEC	^{3}H β decay
< 19.6	95	KERNAN	95	ASTR	SN 1987A
< 7.0	95	[4] STOEFFL	95	SPEC	^{3}H β decay
<460	68	[5] YASUMI	94	CNTR	e capture in ^{163}Ho
< 7.2	95	[6] WEINHEIMER	93	SPEC	^{3}H β decay
< 11.7	95	[7] HOLZSCHUH	92B	SPEC	^{3}H β decay
< 13.1	95	[8] KAWAKAMI	91	SPEC	^{3}H β decay
< 9.3	95	[9] ROBERTSON	91	SPEC	^{3}H β decay
< 14	95	AVIGNONE	90	ASTR	SN 1987A
< 16		SPERGEL	88	ASTR	SN 1987A
17 to 40		[10] BORIS	87	SPEC	$\overline{\nu}_e$, ^{3}Hβ decay

[1] BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. A fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly) plus a monochromatic line 7–15 eV below the endpoint yields $m^2_\nu = -4.1 \pm 10.9$ eV^2, leading to this Bayesian limit.
[2] CHING 95 quotes results previously given by SUN 93; no experimental details are given. A possible explanation for consistently negative values of m^2_ν is given.
[3] HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. Bayesian limit calculated from the weighted mean $m^2_\nu = 221 \pm 4244$ eV^2 from the two runs listed below.
[4] STOEFFL 95 (LLNL) result is the Bayesian limit obtained from the m^2_ν errors given below but with m^2_ν set equal to 0. The anomalous endpoint accumulation leads to a value of m^2_ν which is negative by more than 5 standard deviations.
[5] The YASUMI 94 (KEK) limit results from their measurement $m_\nu = 110^{+350}_{-110}$ eV.
[6] WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium β spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.
[7] HOLZSCHUH 92B (Zurich) result is obtained from the measurement $m^2_\nu = -24 \pm 48 \pm 61$ (1σ errors), in eV^2, using the PDG prescription for conversion to a limit in m_ν.
[8] KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid. This result is the Bayesian limit obtained from the m^2_ν limit with the errors combined in quadrature. This was also done in ROBERTSON 91, although the authors report a different procedure.
[9] ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that m_ν lies between 17 and 40 eV. However, the probability of a positive m^2 is only 3% if statistical and systematic error are combined in quadrature.
[10] See also comment in BORIS 87B and erratum in BORIS 88.

ν_e MASS SQUARED

The tritium experiments actually measure mass squared. A combined limit on mass must therefore be obtained from the weighted average of the results shown here. The recent results are in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88, erratum)] that m_{ν_1} lies between 17 and 40 eV. The BORIS 87 result is excluded because of the controversy over the possibly large unreported systematic errors; see BERGKVIST 85B, BERGKVIST 86, SIMPSON 84, and REDONDO 89. However, the average for the new experiments given below implies only a 3.5% probability that m^2 is positive. See HOLZSCHUH 92 for a review of the recent direct m_{ν_1} measurements.

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
− 27± 20	**OUR AVERAGE**	Error includes scale factor of 4.2. See the ideogram below.			
− 22± 4.8		[11] BELESEV	95	SPEC	^{3}H β decay
−130± 20 ±15	95	[12] STOEFFL	95	SPEC	^{3}H β decay
− 31± 75 ±48		[13] SUN	93	SPEC	^{3}Hβ decay
− 39± 34 ±15		[14] WEINHEIMER	93	SPEC	^{3}H β decay
− 24± 48 ±61		[15] HOLZSCHUH	92B	SPEC	^{3}H β decay
− 65± 85 ±65		[16] KAWAKAMI	91	SPEC	^{3}H β decay
−147± 68 ±41		[17] ROBERTSON	91	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
129±6010		[18] HIDDEMANN	95	SPEC	^{3}H β decay
313±5994		[18] HIDDEMANN	95	SPEC	^{3}H β decay

[11] BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. This value comes from a fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly), including the effects of an apparent peak 7–15 eV below the endpoint.

[12] STOEFFL 95 (LLNL) uses a gaseous source of molecular tritium. An anomalous pileup of events at the endpoint leads to the negative value for m_ν^2. The authors acknowledge that "the negative value for the best fit of m_ν^2 has no physical meaning" and discuss possible explanations for this effect.

[13] SUN 93 uses a tritiated hydrocarbon source. See also CHING 95.

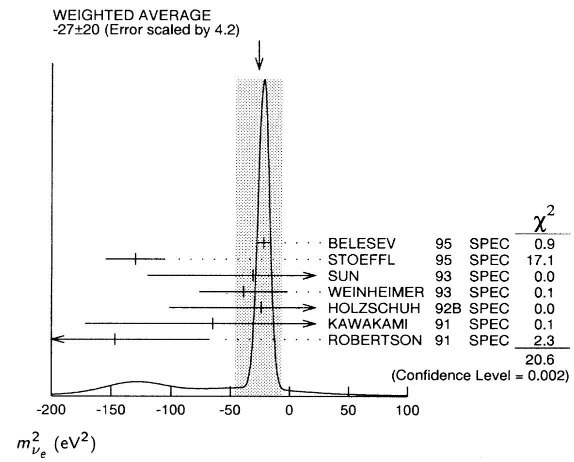
[14] WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium β spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.

[15] HOLZSCHUH 92B (Zurich) source is a monolayer of tritiated hydrocarbon.

[16] KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid.

[17] ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that m_ν lies between 17 and 40 eV. However, the probability of a positive m_ν^2 is only 3% if statistical and systematic error are combined in quadrature.

[18] HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. They quote measurements from two data sets.



$m_{\nu_1} - m_{\overline{\nu}_1}$

These are measurement of m_{ν_1} (in contrast to $m_{\overline{\nu}_1}$, given above). The masses can be different for a Dirac neutrino in the absense of CPT invariance. The test is not very strong.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
< 225	95	SPRINGER	87	CNTR	ν, ^{163}Ho
< 550	68	YASUMI	86	CNTR	ν, ^{163}Ho
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.5×10^5	90	CLARK	74	ASPK	K_{e3} decay
<4100	67	BECK	68	CNTR	ν, ^{22}Na

ν_1 CHARGE

VALUE (units: electron charge)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-15}$	[19] BARBIELLINI	87	ASTR	SN 1987A
$<1 \times 10^{-13}$	BERNSTEIN	63	ASTR	Solar energy losses

[19] Precise limit depends on assumptions about the intergalactic or galactic magnetic fields and about the direct distance and time through the field.

ν_1 MEAN LIFE

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[20] COWSIK	89	ASTR	m_ν = 1–50 MeV
		[21] RAFFELT	89	RVUE	$\overline{\nu}$ (Dirac, Majorana)
		[22] RAFFELT	89B	ASTR	
>278	90	[23] LOSECCO	87B	IMB	
> 1.1×10^{25}		[24] HENRY	81	ASTR	m_ν= 16–20 eV
> 10^{22}–10^{23}		[25] KIMBLE	81	ASTR	m_ν= 10–100 eV

[20] COWSIK 89 use observations of supernova SN 1987A to set the limit for the lifetime of a neutrino with $1 < m < 50$ MeV decaying through $\nu_H \to \nu_1 ee$ to be $\tau > 4 \times 10^{15}$ exp($-m$/5 MeV) s.

[21] RAFFELT 89 uses KYULDJIEV 84 to obtain $\tau m^3 > 3 \times 10^{18}$ s eV^3 (based on $\overline{\nu}_e e^-$ cross sections). The bound is not valid if electric and magnetic transition moments are equal for Dirac neutrinos.

[22] RAFFELT 89B analyze stellar evolution and exclude the region $3 \times 10^{12} < \tau m^3 < 3 \times 10^{21}$ s eV^3.

[23] LOSECCO 87B assumes observed rate of 2.1 SNU (solar neutrino units) comes from sun while 7.0 ± 3.0 is theory.

[24] HENRY 81 uses UV flux from clusters of galaxies to find limit for radiative decay.

[25] KIMBLE 81 uses extreme UV flux limits.

ν_1 (MEAN LIFE) / MASS

VALUE (s/eV)	CL%	DOCUMENT ID		TECN	COMMENT
>300	90	[26] REINES	74	CNTR	$\overline{\nu}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 2.8×10^{15}		[27,28] BLUDMAN	92	ASTR	$m_\nu < 50$ eV
> 6.4	90	[29] KRAKAUER	91	CNTR	$\overline{\nu}$ at LAMPF
> 6.3×10^{15}		[28,30] CHUPP	89	ASTR	$m_\nu < 20$ eV
> 1.7×10^{15}		[28] KOLB	89	ASTR	$m_\nu < 20$ eV
> 8.3×10^{14}		[31] VONFEILIT...	88	ASTR	
> 22	68	[32] OBERAUER	87		$\overline{\nu}_R$ (Dirac)
> 38	68	[32] OBERAUER	87		$\overline{\nu}$ (Majorana)
> 59	68	[32] OBERAUER	87		$\overline{\nu}_L$ (Dirac)
> 30	68	KETOV	86	CNTR	$\overline{\nu}$ (Dirac)
> 20	68	KETOV	86	CNTR	$\overline{\nu}$ (Majorana)
> 7×10^9		[33] RAFFELT	85	ASTR	
> 2×10^{21}		[34] STECKER	80	ASTR	m_ν= 10–100 eV

[26] REINES 74 looked for ν_e of nonzero mass decaying to a neutral of lesser mass + γ. Used liquid scintillator detector near fission reactor. Finds lab lifetime 6. × 10^7 s or more. Above value of (mean life)/mass assumes average effective neutrino energy of 0.2 MeV. To obtain the limit 6. × 10^7 s REINES 74 assumed that the full $\overline{\nu}_e$ reactor flux could be responsible for yielding decays with photon energies in the interval 0.1 MeV – 0.5 MeV. This represents some overestimate so their lower limit is an over-estimate of the lab lifetime (P. Vogel, private communication, 1984).

[27] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.

[28] Nonobservation of γ's in coincidence with ν's from SN 1987A.

[29] KRAKAUER 91 quotes the limit $\tau/m_{\nu_1} > (0.3a^2 + 9.8a + 15.9)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ $a = 0$ for a Majorana neutrino, but can vary from -1 to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $a = -1$).

[30] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.

[31] Model-dependent theoretical analysis of SN 1987A neutrinos.

[32] OBERAUER 87 bounds are from comparison of observed and expected rate of reactor neutrinos.

[33] RAFFELT 85 limit is from solar x- and γ-ray fluxes.

[34] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

$|(v - c)/c|$ ($v \equiv \nu_1$ VELOCITY)

Expected to be zero for massless neutrino, but tests also whether photons and neutrinos have the same limiting velocity in vacuum.

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	COMMENT
<1	17	[35] STODOLSKY	88	ASTR	SN 1987A

[35] STODOLSKY 88 result based on <10 hr between $\overline{\nu}_e$ detection in IMB and KAMI detectors and beginning of light signal. Inclusion of the problematic 5 neutrino events from FREJ (four hours later) does not change the result.

ν_1 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.20 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_{\nu_1} < 7.3$ eV, it follows that for the extended standard electroweak theory, $\mu(\nu_1) < 2.3 \times 10^{-18}\ \mu_B$. Current experiments are not yet challenging this limit. There is considerable controversy over the validity of many of the claimed upper limits on the magnetic moment from the astrophysical data. For example, VOLOSHIN 90 states that "in connection with the astrophysical limits on μ_ν, ... there is by now a general consensus that contrary to the initial claims (BARBIERI 88, LATTIMER 88, GOLDMAN 88, NOTZOLD 88), essentially no better than quoted limits (from previous constraints) can be derived from detection of the neutrino flux from the supernova SN1987A." See VOLOSHIN 88 and VOLOSHIN 88C.

VALUE ($10^{-10}\ \mu_B$)	CL%	DOCUMENT ID		TECN	COMMENT
< 1.8	90	[36] DERBIN	94	CNTR	Reactor $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.003–0.0005		[37] GOYAL	95		SN 1987A
< 7.7	95	MOURAO	92	ASTR	HOME/KAM2 ν rates
< 2.4	90	[38] VIDYAKIN	92	CNTR	Reactor $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$
<10.8	90	[39] KRAKAUER	90	CNTR	LAMPF $\nu_e e \rightarrow \nu_e e$
< 0.02	95	[40] RAFFELT	90	ASTR	Red giant luminosity
< 0.1		[41] RAFFELT	89B	ASTR	Cooling helium stars
< 0.02–0.08		[41,42,43] BARBIERI	88	ASTR	SN 1987A
		[44] FUKUGITA	88	COSM	Primordial magn. fields
< 0.01		[42,43,45] GOLDMAN	88	ASTR	SN 1987A
< 0.005		[41,43] LATTIMER	88	ASTR	SN 1987A
≤ 0.015		[41,43] NOETZOLD	88	ASTR	SN 1987A
≤ .3		[41] RAFFELT	88B	ASTR	He burning stars
< 0.11		[41] FUKUGITA	87	ASTR	Cooling helium stars
< 0.4		LYNN	81	ASTR	
< 0.1–0.2		MORGAN	81	COSM	^{4}He abundance
< 0.85		BEG	78	ASTR	Stellar plasmons
< 0.6		[46] SUTHERLAND	76	ASTR	Red giants + degen. dwarfs
< 1		BERNSTEIN	63	ASTR	Cooling white dwarfs
<14		COWAN	57	CNTR	Reactor $\overline{\nu}_e$

[36] DERBIN 94 supersedes DERBIN 93.

[37] GOYAL 95 assume that helicity flip via μ_ν would result in faster cooling and hence shorter burst from SN1987A. Limit is based on the assumed presence of a pion condensate or quark core in the remanant.

[38] VIDYAKIN 92 limit is from a $e\overline{\nu}_e$ elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was 1/10. The limit uses $\sin^2\theta_W = 0.23$ as input.

[39] KRAKAUER 90 experiment fully reported in ALLEN 93.

[40] RAFFELT 90 limit applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.

[41] Significant dependence on details of stellar models.

[42] A limit of 10^{-13} is obtained with even more model-dependence.

[43] These papers have assumed that the right-handed neutrino is inert; see BARBIERI 88B.

[44] FUKUGITA 88 find magnetic dipole moments of any two neutrino species are bounded by $\mu < 10^{-16}\ [10^{-9}\ G/B_0]$ where B_0 is the present-day intergalactic field strength.

[45] Some dependence on details of stellar models.

[46] We obtain above limit from SUTHERLAND 76 using their limit $f < 1/3$.

NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

We report limits on the so-called neutrino charge radius squared in this section. This quantity is not an observable, physical quantity and this is reflected in the fact that it is gauge dependent (see LEE 77C). It is not necessarily positive. A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

VALUE (10^{-32} cm^2)	CL%	DOCUMENT ID		TECN	COMMENT
0.9±2.7		ALLEN	93	CNTR	LAMPF $\nu_e e \rightarrow \nu_e e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.3	95	MOURAO	92	ASTR	HOME/KAM2 ν rates
<7.3	90	[47] VIDYAKIN	92	CNTR	Reactor $\overline{\nu}_e e \rightarrow \overline{\nu}_e e$
1.1±2.3		ALLEN	91	CNTR	Repl. by ALLEN 93
		[48] GRIFOLS	89B	ASTR	SN 1987A

[47] VIDYAKIN 92 limit is from a $e\overline{\nu}_e$ elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was 1/10. The limit uses $\sin^2\theta_W = 0.23$ as input.

[48] GRIFOLS 89B sets a limit of $\langle r^2 \rangle < 0.2 \times 10^{-32}$ cm^2 for right-handed neutrinos.

ν_e REFERENCES

BELESEV	95	PL B350 263	+Bleule, Geraskin, Golubev+	(INRM, KIAE)
CHING	95	IJMP A10 2841	+Ho, Liang, Mao, Chen, Sun	(CST, BEIJT, CIAE)
GOYAL	95	PL B346 312	+Dutta, Choudhury	(DELH)
HIDDEMANN	95	JP G21 639	+Daniel, Schwentker	(MUNT)
KERNAN	95	NP B437 243	+Krauss	(CASE)
STOEFFL	95	PRL 75 3237	+Decman	(LLNL)
DERBIN	94	PAN 57 222		(PNPI)
		Translated from YAF 57 236.		
YASUMI	94	PL B334 229	+Maezawa, Shima, Inagaki+	(KEK, TSUK, KYOT+)
ALLEN	93	PR D47 11	+Chen, Doe, Hausammann+	(UCI, LANL, ANL, UMD)
DERBIN	93	JETPL 57 768	+Chernyi, Popeko, Muratova+	(PNPI)
		Translated from ZETFP 57 755.		
SUN	93	CJNP 15 261	+Liang, Chen, Si+	(CIAE, CST, BEIJT)
WEINHEIMER	93	PL B300 210	+Przyrembel, Backe+	(MANZ)
BLUDMAN	92	PR D45 4720		(CFPA)
HOLZSCHUH	92	RPP 55 1035		(ZURI)
HOLZSCHUH	92B	PL B287 381	+Fritschi, Kuendig	(ZURI)
MOURAO	92	PL B285 364	+Pulido, Ralston	(LISB, LISBT, CERN, KANS)
VIDYAKIN	92	JETPL 55 206	+Vyrodov, Gurevich, Koslov+	(KIAE)
		Translated from ZETFP 55 212.		
ALLEN	91	PR D43 R1	+Chen, Doe, Hausammann	(UCI, LANL, UMD)
KAWAKAMI	91	PL B256 105	+Kato, Ohshima+	(INUS, TOHOK, TINT, KOBE, KEK)
KRAKAUER	91	PR D44 R6	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
ROBERTSON	91	PRL 67 957	+Bowles, Stephenson, Wark, Wilkerson, Knapp	(LASL, LLL)
AVIGNONE	90	PR D41 682	+Collar	(SCUC)
KRAKAUER	90	PL B252 177	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
RAFFELT	90	PRL 64 2856		(MPIM)
VOLOSHIN	90	NP B (Proc. Suppl) 19 433		(ITEP)
Neutrino 90 Conference				
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
COWSIK	89	PL B218 91	+Schramm, Hoflich	(WUSL, TATA, CHIC, MPIM)
GRIFOLS	89B	PR D40 3819	+Masso	(BARC)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
LOREDO	89	ANYAS 571 601	+Lamb	(CHIC)
RAFFELT	89	PR D39 2066		(PRIN, UCB)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
REDONDO	89	PR C40 368	+Robertson	(LANL)
BARBIERI	88	PRL 61 27	+Mohapatra	(PISA, UMD)
BARBIERI	88B	PL B213 69	+Mohapatra, Yanagida	(PISA, UMD, MICH)
BORIS	88	PRL 61 245 erratum	+Golutvin, Laptin+	(ITEP, ASCI)
FUKUGITA	88	PRL 60 879	+Notzold, Raffelt, Silk	(KYOTY, MPIM, UCB)
GOLDMAN	88	PRL 60 1789	+Aharanov, Alexander, Nussinov	(TELA)
LATTIMER	88	PRL 61 23	+Cooperstein	(STON, BNL)
Also	88B	PRL 61 2633 erratum	Lattimer, Cooperstein	(STON, BNL)
NOETZOLD	88	PR D38 1658		(MPIM)
NOTZOLD	88	PR D38 1658		(MPIM)
RAFFELT	88B	PR D37 549	+Dearborn	(UCB, LLL)
SPERGEL	88	PL B200 366	+Bahcall	(IAS)
STODOLSKY	88	PL B201 353		(MPIM)
VOLOSHIN	88	PL B209 360		(ITEP)
Also	88B	JETPL 47 501	Voloshin	(ITEP)
		Translated from ZETFP 47 421.		
VOLOSHIN	88C	JETPL 68 690		(ITEP)
VONFEILIT...	88	PL B200 580	Von Feilitzsch, Oberauer	(MUNT)
BARBIELLINI	87	Nature 329 21	+Cocconi	(CERN)
BORIS	87	PRL 58 2019	+Golutvin, Laptin+	(ITEP, ASCI)
Also	88	PRL 61 245 erratum	Boris, Golutvin, Laptin+	(ITEP, ASCI)
BORIS	87B	JETPL 45 333	+Golutvin, Laptin+	(ITEP)
		Translated from ZETFP 45 267.		
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOTY, TOKY)
LOSECCO	87B	PR D35 2073	+Bionta, Blewitt, Bratton+	(IMB Collab.)
OBERAUER	87	PL B198 113	+von Feilitzsch, Mossbauer	(MUNT)
SPRINGER	87	PR A35 679	+Bennet, Baisden+	(LLNL)
BERGKVIST	86	Moriond Conf., Vol. M48, 465		(STOH)
KETOV	86	JETPL 44 146	+Klimov, Nikolaev, Mikaelyan+	(KIAE)
		Translated from ZETFP 44 114.		
YASUMI	86	PL B181 169	+Ando+	(KEK, OSAK, TOHOK, TSUK, KYOT, INUS+)
BERGKVIST	85B	PL 159B 408		(STOH)
RAFFELT	85	PR D31 3002		(MPIM)
KYULDJIEV	84	NP B243 387		(SOFI)
SIMPSON	84	PR D30 1110		(GUEL)
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
LYNN	81	PR D23 2151		(COLU)
MORGAN	81	PL 102B 247	Morgan	(SUSS)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
LUBIMOV	80	PL 94B 266	+Novikov, Nozik, Tretyakov, Kosik	(ITEP)
Also	80	SJNP 32 154	Kozik, Lubimov, Novikov+	(ITEP)
		Translated from YAF 32 301.		
Also	81	JETP 54 616	Lubimov, Novikov, Nozik+	(ITEP)
		Translated from ZETF 81 1158.		
STECKER	80	PRL 45 1460		(NASA)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
LEE	77C	PR D16 1444	+Shrock	(STON)
SUTHERLAND	76	PR D13 2700	+Ng, Flowers+	(PENN, COLU, NYU)
CLARK	74	PR D9 533	+Elioff, Frisch, Johnson, Kerth, Shen+	(LBL)
REINES	74	PRL 32 180	+Sobel, Gurr	(UCI)
Also	78	Private Comm.	Barnes	(PURD)
BECK	68	ZPHY 216 229	+Daniel	(MPIH)
BERNSTEIN	63	PR 132 1227	+Ruderman, Feinberg	(NYU, COLU)
COWAN	57	PR 107 528	+Reines	(LANL)

ν_μ

$J = \frac{1}{2}$

Not in general a mass eigenstate. See note on neutrinos in the ν_e section above.

ν_μ MASS

Applies to ν_2, the primary mass eigenstate in ν_μ. Would also apply to any other ν_j which mixes strongly in ν_μ and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for $j \geq 3$, given the ν_e mass limit above.) Results based upon an obselete pion mass are no longer shown; they were in any cass less restrive than ASSAMAGAN 96.

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<0.17	90	[1] ASSAMAGAN	96	SPEC	$m^2 = -0.016 \pm 0.023$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15		[2] DOLGOV	95	COSM	Nucleosynthesis
<0.48		[3] ENQVIST	93	COSM	Nucleosynthesis
<0.003		[4,5] MAYLE	93	ASTR	SN 1987A cooling
< 0.025–0.030		[5,6] BURROWS	92	ASTR	SN 1987A cooling
<0.3		[7] FULLER	91	COSM	Nucleosynthesis
<0.42		[7] LAM	91	COSM	Nucleosynthesis
< 0.028–0.15		[8] NATALE	91	ASTR	SN 1987A
<0.028		[5] GANDHI	90	ASTR	SN 1987A
<0.014		[5,9] GRIFOLS	90B	ASTR	SN 1987A
<0.06		[5,10] GAEMERS	89		SN 1987A
<0.50	90	[11] ANDERHUB	82	SPEC	$m^2 = -0.14 \pm 0.20$
<0.65	90	CLARK	74	ASPK	$K_{\mu 3}$ decay

[1] ASSAMAGAN 96 measurement of p_μ from $\pi^+ \rightarrow \mu^+ \nu_\mu$ at rest combined with JECKELMANN 94 Solution B pion mass yields $m^2_\nu = -0.016 \pm 0.023$ with corresponding Bayesian limit listed above. If Solution A is used, $m_2 = -0.143 \pm 0.024$ MeV^2. Replaces ASSAMAGAN 94.

[2] DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below T_{QCD} for wrong-helicity Divac neutrinos (ENQVIST 93, FULLER 91) to set more stringent limits.

[3] ENQVIST 93 bases limit on the fact that thermalized wrong-helicity Dirac neutrinos would speed up expansion of early universe, thus reducing the primordial abundance. FULLER 91 exploits the same mechanism but in the older calculation obtains a larger production rate for these states, and hence a lower limit. Neutrino lifetime assumed to exceed nucleosynthesis time, ~ 1 s.

[4] MAYLE 93 recalculates cooling rate enhancement by escape of wrong-helicity Dirac neutrinos using the Livermore Supernova Explosion Code, obtains more restrictive result than the "very conservative" BURROWS 92 limit because of higher core temperature.

[5] There would be an increased cooling rate if Dirac neutrino mass is included; this does not apply for Majorana neutrinos. Limit is on $\sqrt{m^2_{\nu_\mu} + m^2_{\nu_\tau}}$, and error becomes very large if ν_τ is nonrelativistic, which occurs near the lab limit of 31 MeV. RAJPOOT 93 notes that limit could be evaded with new physics.

[6] BURROWS 92 limit for Dirac neutrinos only.

[7] Assumes neutrino lifetime >1 s. For Dirac neutrinos only. See also ENQVIST 93.

[8] NATALE 91 published result multiplied by $\sqrt{8}\sqrt{4}$ at the advice of the author.

[9] GRIFOLS 90B estimated error is a factor of 3.

[10] GAEMERS 89 published result (< 0.03) corrected via the GANDHI 91 erratum.

[11] ANDERHUB 82 kinematics is insensitive to the pion mass.

$m_{\nu_2} - m_{\overline{\nu}_2}$

Test of *CPT* for a Dirac neutrino. (Not a very strong test.)

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.45	90	CLARK	74	ASPK	$K_{\mu 3}$ decay

ν_2 (MEAN LIFE) / MASS

These limits often apply to ν_τ (ν_3) also.

VALUE (s/eV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
>15.4	90		[12] KRAKAUER	91	CNTR	ν_μ, $\overline{\nu}_\mu$ at LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 2.8 $\times 10^{15}$			[13,14] BLUDMAN	92	ASTR	$m_\nu < 50$ eV
none 10^{-12} – 5×10^4			[15] DODELSON	92	ASTR	m_ν=1–300 keV
> 6.3 $\times 10^{15}$			[14,16] CHUPP	89	ASTR	$m_\nu < 20$ eV
> 1.7 $\times 10^{15}$			[14] KOLB	89	ASTR	$m_\nu < 20$ eV
> 3.3 $\times 10^{14}$			[17,18] VONFEILIT...	88	ASTR	
> 0.11	90	0	[19] FRANK	81	CNTR	$\nu\overline{\nu}$ LAMPF
			[20] HENRY	81	ASTR	m_ν= 16–20 eV
			[21] KIMBLE	81	ASTR	m_ν= 10–100 eV
			[22] REPHAELI	81	ASTR	m_ν= 30–150 eV
			[23] DERUJULA	80	ASTR	m_ν= 10–100 eV
> 2 $\times 10^{21}$			[24] STECKER	80	ASTR	m_ν= 10–100 eV
> 1.0 $\times 10^{-2}$	90	0	[19] BLIETSCHAU	78	HLBC	ν_μ, CERN GGM
> 1.7 $\times 10^{-2}$	90	0	[19] BLIETSCHAU	78	HLBC	$\overline{\nu}_\mu$, CERN GGM
> 2.2 $\times 10^{-3}$	90	0	[19] BARNES	77	DBC	ν, ANL 12-ft
> 3. $\times 10^{-3}$	90	0	[19] BELLOTTI	76	HLBC	ν, CERN GGM
> 1.3 $\times 10^{-2}$	90	1	[19] BELLOTTI	76	HLBC	$\overline{\nu}$, CERN GGM

[12] KRAKAUER 91 quotes the limit $\tau/m_{\nu_1} > (0.75a^2 + 21.65a + 26.3)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ The parameter $a = 0$ for a Majorana neutrino, but can vary from -1 to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $a = -1$).

[13] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.

[14] Nonobservation of γ's in coincidence with ν's from SN 1987A. Results should be divided by the $\tau_\nu \rightarrow \gamma X$ branching ratio.

[15] DODELSON 92 range is for wrong-helicity keV mass Dirac ν's from the core of neutron star in SN 1987A decaying to ν's that would have interacted in KAM2 or IMB detectors.

[16] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.

[17] Model-dependent theoretical analysis of SN 1987A neutrinos.

[18] Limit applies to ν_τ also.

[19] These experiments look for $\nu_\mu \rightarrow \nu_e \gamma$ or $\overline{\nu}_\mu \rightarrow \overline{\nu}_e \gamma$.

[20] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.

[21] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–10^{23} s.

[22] REPHAELI 81 consider ν decay γ effect on neutral H in early universe; based on M31 HI concludes $\tau > 10^{24}$ s.

[23] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.

[24] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

$|(v - c)/c|$ ($v \equiv \nu_2$ VELOCITY)

Expected to be zero for massless neutrino, but also tests whether photons and neutrinos have the same limiting velocity in vacuum.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<0.4	95	9800	KALBFLEISCH	79	SPEC		
<2.0	99	77	ALSPECTOR	76	SPEC	0	>5 GeV ν
<4.0	99	26	ALSPECTOR	76	SPEC	0	<5 GeV ν

ν_2 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.2 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_{\nu_2} < 0.17$ MeV, it follows that for the extended standard electroweak theory, $\mu(\nu_2) < 0.51 \times 10^{-13}\ \mu_B$.

VALUE ($10^{-10}\ \mu_B$)	CL%	DOCUMENT ID		TECN	COMMENT
< 8.5	90	AHRENS	90	CNTR	$\nu_\mu e \rightarrow \nu_\mu e$
< 7.4	90	[25] KRAKAUER	90	CNTR	LAMPF (ν_μ, $\overline{\nu}_\mu$)e elast.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 30	90	VILAIN	95B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$
<100	95	[26] DORENBOS...	91	CHRM	$\nu_\mu e \rightarrow \nu_\mu e$
< 0.02	95	[27] RAFFELT	90	ASTR	Red giant luminosity
< 0.1		[28] RAFFELT	89B	ASTR	Cooling helium stars
< 0.11		[28,29] FUKUGITA	87	ASTR	Cooling helium stars
< 0.0006		[30] NUSSINOV	87	ASTR	Cosmic EM backgrounds
< 0.4		LYNN	81	ASTR	
< 0.85		[29] BEG	78	ASTR	Stellar plasmons
< 81		[31] KIM	74	RVUE	$\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
< 1		[32] BERNSTEIN	63	ASTR	Cooling white dwarfs

[25] KRAKAUER 90 experiment fully reported in ALLEN 93.

[26] DORENBOSCH 91 corrects an incorrect statement in DORENBOSCH 89 that the ν_2 magnetic moment is $< 1 \times 10^{-9}$ at the 95%CL. DORENBOSCH 89 measures both $\nu_\mu e$ and $\overline{\nu}_\mu e$ elastic scattering and assume $\mu(\nu_\mu) = \mu(\overline{\nu}_\mu)$.

[27] RAFFELT 90 limit applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.

[28] Significant dependence on details of stellar properties.

[29] If $m_{\nu_2} < 10$ keV.

[30] For $m_{\nu_2} = 8$–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\mu \rightarrow \nu_e$ and obtain $< 3 \times 10^{-15}$ for $m_{\nu_2} > 16$ eV and $< 6 \times 10^{-14}$ for $m_{\nu_2} > 4$ eV.

[31] KIM 74 is a theoretical analysis of $\overline{\nu}_\mu$ reaction data.

[32] If $m_{\nu_2} < 1$ keV.

NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

We report limits on the so-called neutrino charge radius squared in this section. This quantity is not an observable, physical quantity and this is reflected in the fact that it is gauge dependent (see LEE 77C). It is not necessarily positive. A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

VALUE (10^{-32} cm^2)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< \lvert 0.6 \rvert$	90	VILAIN	95B	CHM2	$\nu_\mu e$ elas scat
-1.1 ± 1.0		[33] AHRENS	90	CNTR	$\nu_\mu e$ elas scat
-0.3 ± 1.5		[33] DORENBOS...	89	CHRM	$\nu_\mu e$ elas scat

[33] Result is obtained from reanalysis given in ALLEN 91, followed by our reduction to obtain 1 σ errors.

ν_μ REFERENCES

ASSAMAGAN	96	PR D53 6065	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
DOLGOV	95	PR D51 4129	+Kainulainen, Rothstein	(MICH, MINN, CERN)
VILAIN	95B	PL B345 115	+Wilquet, Beyer+	(CHARM II Collab.)
ASSAMAGAN	94	PL B335 231	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
JECKELMANN	94	PL B335 326	+Goudsmit, Leisi	(WABRN, VILL)
ALLEN	93	PR D47 11	+Chen, Doe, Hausammann+	(UCI, LANL, ANL, UMD)
DOLGOV	93	PRL 71 476	+Rothstein	(MICH)
ENQVIST	93	PL B301 376	+Uibo	(NORD)
MAYLE	93	PL B317 119	+Schramm, Turner, Wilson	(LLNL, CHIC)
RAJPOOT	93	MPL A8 1179		(CSULB)
BLUDMAN	92	PR D45 4720		(CFPA)
BURROWS	92	PRL 68 3834	+Gandhi, Turner	(ARIZ, CHIC)
DODELSON	92	PRL 68 2572	+Frieman, Turner	(FNAL, CHIC)
ALLEN	91	PR D43 R1	+Chen, Doe, Hausammann	(UCI, LANL, UMD)
DORENBOS...	91	ZPHY C51 142	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
FULLER	91	PR D43 3136	+Malaney	(UCSD)
GANDHI	91	PL B261 519E (erratum)	+Burrows	(ARIZ)
KRAKAUER	91	PR D44 R6	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
LAM	91	PR D44 3345	+Ng	(AST)
NATALE	91	PL B258 227		(SPIFT)
AHRENS	90	PR D41 3297	+	(BNL, BROW, HIRO, KEK, OSAK, PENN, STON)
GANDHI	90	PL B246 149	+Burrows	(ARIZ)
Also	91	PL B261 519E (erratum)	Gandhi, Burrows	(ARIZ)
GRIFOLS	90B	PL B242 77	+Masso	(BARC, CERN)
KRAKAUER	90	PL B252 177	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
RAFFELT	90	PRL 64 2856		(MPIM)
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
GAEMERS	89	PR D40 309	+Gandhi, Lattimer	(ANIK, STON)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
VONFEILIT...	88	PL B200 580	Von Feilitzsch, Oberauer	(MUNT)
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOTY, TOKY)
NUSSINOV	87	PR D36 2278	+Rephaeli	(TELA)
ANDERHUB	82	PL 114B 76	+Boecklin, Hofer, Kottmann+	(ETH, SIN)
FRANK	81	PR D24 2001	+Burman+	(LASL, YALE, MIT, SACL, SIN+)
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
LYNN	81	PR D23 2151		(COLU)
REPHAELI	81	PL 106B 73	+Szalay	(UCSB, CHIC)
DERUJULA	80	PRL 45 942	+Glashow	(MIT, HARV)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
STECKER	80	PRL 45 1460		(NASA)
KALBFLEISCH	79	PRL 43 1361	+Baggett, Fowler+	(FNAL, PURD, BELL)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
BLIETSCHAU	78	NP B133 205	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
BARNES	77	PRL 38 1049	+Carmony, Dauwe, Fernandez+	(PURD, ANL)
LEE	77C	PR D16 1444	+Shrock	(STON)
ALSPECTOR	76	PRL 36 837	+	(BNL, PURD, CIT, FNAL, ROCK)
BELLOTTI	76	LNC 17 553	+Cavalli, Fiorini, Rollier	(MILA)
CLARK	74	PR D9 533	+Elioff, Frisch, Johnson, Kerth, Shen+	(LBL)
KIM	74	PR D9 3050	+Mather, Okubo	(ROCH)
BERNSTEIN	63	PR 132 1227	+Ruderman, Feinberg	(NYU, COLU)

ν_τ

$J = \frac{1}{2}$

Existence indirectly established from τ decay data combined with ν reaction data. See for example FELDMAN 81. ALBRECHT 92Q rules out $J = 3/2$ by establishing that the ρ^- is not in a pure $H_\rho = -1$ helicity state in $\tau^- \to \rho^- \nu_\tau$.

Not in general a mass eigenstate. See note on neutrinos in the ν_e section above.

ν_τ MASS

Applies to ν_3, the primary mass eigenstate in ν_τ. Would also apply to any other ν_j which mixes strongly in ν_τ and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for a hypothetical $j \geq 4$, given the ν_e and ν_μ mass limits above.) See also the Listings in the Neutrino Bounds from Astrophysics and Cosmology section.

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<24	95	25	[1] BUSKULIC	95H	ALEP	1991–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<74	95		[2] AKERS	95D	OPAL	$Z \to \tau^+\tau^-$ at LEP
< 0.19			[3] DOLGOV	95	COSM	Nucleosynthesis
< 3			[4] SIGL	95	ASTR	SN 1987A
< 0.4 or > 30			[5] DODELSON	94	COSM	Nucleosynthesis
< 0.1 or > 50			[6] KAWASAKI	94	COSM	Nucleosynthesis
<75	95		[7] BALEST	93	CLEO	$E^{ee}_{cm} = 10.6$ GeV
<32.6	95	113	[8] CINABRO	93	CLEO	$E^{ee}_{cm} \approx 10.6$ GeV
< 0.3 or > 35			[9] DOLGOV	93	COSM	Nucleosynthesis
< 0.74			[10] ENQVIST	93	COSM	Nucleosynthesis
< 0.003			[11,12] MAYLE	93	ASTR	SN 1987A cooling
<31	95	19	[13] ALBRECHT	92M	ARG	$E^{ee}_{cm} = 9.4$–10.6 GeV
< 0.025–0.030			[12,14] BURROWS	92	ASTR	SN 1987A cooling
< 0.3			[15] FULLER	91	COSM	Nucleosynthesis
< 0.5 or > 25			[16] KOLB	91	COSM	Nucleosynthesis
< 0.42			[15] LAM	91	COSM	Nucleosynthesis
< 0.028–0.15			[17] NATALE	91	ASTR	SN 1987A
< 0.028			[12] GANDHI	90	ASTR	SN 1987A
< 0.014 or > 34			[12,18] GRIFOLS	90B	ASTR	SN 1987A
< 0.06			[12,19] GAEMERS	89		SN 1987A

[1] BUSKULIC 95H bound comes from a two-dimensional fit of the visible energy and invariant mass distribution of $\tau \to 5\pi(\pi^0)\nu_\tau$ decays.

[2] AKERS 95D bound comes from analysis of $\tau^- \to 3\pi^- 2\pi^+ \nu_\tau$ decay mode.

[3] DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below T_{QCD} for wrong-helicity Divac neutrinos (ENQVIST 93, FULLER 91) to set more stringent limits.

[4] SIGL 95 exclude massive Dirac or Majorana neutrinos with lifetimes between 10^{-3} and 10^8 seconds if the decay products are predominantly γ or e^+e^-.

[5] DODELSON 94 calculate constraints on ν_τ mass and lifetime from nucleosynthesis for 4 generic decay modes. Limits depend strongly on decay mode. Quoted limit is valid for all decay modes of Majorana neutrinos with lifetime greater than about 300 s. For Dirac neutrinos limits change to < 0.3 or > 33.

[6] KAWASAKI 94 excluded region is for Majorana neutrino with lifetime >1000 s. Other limits are given as a function of ν_τ lifetime for decays of the type $\nu_\tau \to \nu_\mu \phi$ where ϕ is a Nambu-Goldstone boson.

[7] BALEST 93 derive limit by comparing their m_τ measurement (which depends on m_{ν_τ}) to BAI 92 and BACINO 78B m_τ threshold measurements.

[8] CINABRO 93 bound comes from analysis of $\tau^- \to 3\pi^- 2\pi^+ \nu_\tau$ and $\tau^- \to 2\pi^- \pi^+ 2\pi^0 \nu_\tau$ decay modes.

[9] DOLGOV 93 assumes neutrino lifetime >100 s. For Majorana neutrinos, the low mass limit is 0.5 MeV. KAWANO 92 points out that these bounds can be overcome for a Dirac neutrino if it possesses a magnetic moment.

[10] ENQVIST 93 bases limit on the fact that thermalized wrong-helicity Dirac neutrinos would speed up expansion of early universe, thus reducing the primordial abundance. FULLER 91 exploits the same mechanism but in the older calculation obtains a larger production rate for these states, and hence a lower limit. Neutrino lifetime assumed to exceed nucleosynthesis time, ~ 1 s.

[11] MAYLE 93 recalculates cooling rate enhancement by escape of wrong-helicity Dirac neutrinos using the Livermore Supernova Explosion Code, obtains more restrictive result than the "very conservative" BURROWS 92 limit because of higher core temperature.

[12] There would be an increased SN 1987A cooling rate if Dirac neutrino mass is included; this does not apply for Majorana neutrinos. Limit is on $\sqrt{m^2_{\nu_\mu} + m^2_{\nu_\tau}}$, and error becomes very large if ν_τ is nonrelativistic, which occurs near the lab limit of 31 MeV. RAJPOOT 93 notes that limit could be evaded with new physics.

[13] ALBRECHT 92M reports measurement of a slightly lower τ mass, which has the effect of reducing the ν_τ mass reported in ALBRECHT 88B. Bound is from analysis of $\tau^- \to 3\pi^- 2\pi^+ \nu_\tau$ mode.

[14] BURROWS 92 limit for Dirac neutrinos only.

[15] Assumes neutrino lifetime >1 s. For Dirac neutrinos. See also ENQVIST 93.

[16] KOLB 91 exclusion region is for Dirac neutrino with lifetime >1 s; other limits are given.

[17] NATALE 91 published result multiplied by $\sqrt{8}\sqrt{4}$ at the advice of the author.

[18] GRIFOLS 90B estimated error is a factor of 3.

[19] GAEMERS 89 published result (< 0.03) corrected via the GANDHI 91 erratum.

ν_3 (MEAN LIFE) / MASS

These limits often apply to ν_μ (ν_2) also.

VALUE (s/eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>1 \times 10^{14}$	[20] SIGL	95	ASTR	$m_\nu >$ few MeV
$>2.8 \times 10^{15}$	[21,22] BLUDMAN	92	ASTR	$m_\nu < 50$ eV
$< 10^{-12}$ or $> 5 \times 10^4$	[23] DODELSON	92	ASTR	m_ν=1–300 keV
	[24] GRANEK	91	COSM	Decaying L^0
	[25] WALKER	90	ASTR	$m_\nu = 0.03 - \sim 2$ MeV
$>6.3 \times 10^{15}$	[22,26] CHUPP	89	ASTR	$m_\nu < 20$ eV
$>1.7 \times 10^{15}$	[22] KOLB	89	ASTR	$m_\nu < 20$ eV
	[27] TERASAWA	88	COSM	$m_\mu = 30$–70 MeV
	[28] KAWASAKI	86	COSM	$m_\nu >10$ MeV
	[29] LINDLEY	85	COSM	$m_\nu > 10$ MeV
	[30] BINETRUY	84	COSM	$m_\nu \sim 1$ MeV
	[31] SARKAR	84	COSM	$m_\nu = 10$–100 MeV
	[32] HENRY	81	ASTR	$m_\nu = 16$–20 eV
	[33] KIMBLE	81	ASTR	$m_\nu = 10$–100 eV
	[34] REPHAELI	81	ASTR	$m_\nu = 30$–150 eV
	[35] DERUJULA	80	ASTR	$m_\nu = 10$–100 eV
$>2 \times 10^{21}$	[36] STECKER	80	ASTR	$m_\nu = 10$–100 eV
	[37] DICUS	78	COSM	$m_\nu = 0.5$–30 MeV
$<3 \times 10^{-11}$	[38] FALK	78	ASTR	$m_\nu <10$ MeV
	[39] COWSIK	77	ASTR	

[20] SIGL 95 exclude 1 s $\lesssim \tau \lesssim 10^8$ s for MeV-mass τ nuetrinos from SN 1987A decaying radiatively, and eliminates the lower limit using other published results.

[21] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.

[22] Nonobservation of γ's in coincidence with ν's from SN 1987A. Results should be divided by the $\tau_\nu \to \gamma X$ branching ratio.

[23] DODELSON 92 range is for wrong-helicity keV mass Dirac ν's from the core of neutron star in SN 1987A decaying to ν's that would have interacted in KAM2 or IMB detectors.

[24] GRANEK 91 considers heavy neutrino decays to $\gamma\nu_L$ and $3\nu_L$, where m_{ν_L} <100 keV. Lifetime is calculated as a function of heavy neutrino mass, branching ratio into $\gamma\nu_L$, and m_{ν_L}.

[25] WALKER 90 uses SN 1987A γ flux limits after 289 days to find $m_\tau > 1.1 \times 10^{15}$ eV s.

[26] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.

[27] TERASAWA 88 finds only $10^2 < \tau < 10^4$ allowed for 30–70 MeV ν's from primordal nucleosynthesis.

[28] KAWASAKI 86 concludes that light elements in primordal nucleosynthesis would be destroyed by radiative decay of neutrinos with 10 MeV$<m_\nu<$1 GeV unless $\tau \lesssim 10^4$ s.

[29] LINDLEY 85 considers destruction of cosmologically-produced light elements, and finds $\tau < 2 \times 10^3$ s for 10 MeV $<m_\nu<$100 MeV. See also LINDLEY 79.

[30] BINETRUY 84 finds $\tau < 10^8$ s for neutrinos in a radiation-dominated universe.

[31] SARKAR 84 finds $\tau <$ 20 s at m_ν=10 MeV, with higher limits for other m_ν, and claims that all masses between 1 MeV and 50 MeV are ruled out.

[32] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.

[33] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–10^{23} s.

[34] REPHAELI 81 consider ν decay γ effect on neutral H in early universe; based on M31 HI concludes $\tau > 10^{24}$ s.

[35] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.

[36] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

[37] DICUS 78 considers effect of ν decay photons on light-element production, and finds lifetime must be less than "hours." See also DICUS 77.

[38] FALK 78 finds lifetime constraints based on supernova energetics.

[39] COWSIK 77 considers varity of scenarios. For neutrinos produced in the big bang, present limits on optical photon flux require $\tau > 10^{23}$ s for $m_\nu \sim 1$ eV. See also COWSIK 79 and GOLDMAN 79.

ν_3 MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.20 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound m_{ν_3} < 35 MeV, it follows that for the extended standard electroweak theory, $\mu(\nu_3) < 1.1 \times 10^{-11}\ \mu_B$.

VALUE (μ_B)	CL%	DOCUMENT ID		TECN	COMMENT
<5.4 × 10⁻⁷ → **$<5.4 \times 10^{-7}$**	90	[40] COOPER-...	92	BEBC	$\nu_\tau e^- \to \nu_\tau e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.1 \times 10^{-6}$	90	ACCIARRI	95D	L3	$e^+e^- \to \nu\overline{\nu}\gamma$ at LEP
$<5.5 \times 10^{-6}$	90	GOULD	94	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$ at LEP
$\gtrsim 10^{-8}$		[41] KAWANO	92	ASTR	Primodial ^{4}He abundance
$<5.6 \times 10^{-6}$	90	DESHPANDE	91	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$
$<2 \times 10^{-12}$	95	[42] RAFFELT	90	ASTR	Red giant luminosity
$<1 \times 10^{-11}$		[43] RAFFELT	89B	ASTR	Cooling helium stars
$<4. \times 10^{-6}$	90	[44] GROTCH	88	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$
$<1.1 \times 10^{-11}$		[43,45] FUKUGITA	87	ASTR	Cooling helium stars
$<6 \times 10^{-14}$		[46] NUSSINOV	87	ASTR	Cosmic EM backgrounds
$<8.5 \times 10^{-11}$		[45] BEG	78	ASTR	Stellar plasmons

[40] COOPER-SARKAR 92 assume $f_{D_s}/f_\pi = 2$ and D_s, $\overline{D}_s$ production cross section = 2.6 μb to calculate ν_τ flux.

[41] KAWANO 92 lower limit is that needed to circumvent ^{4}He production if m_{ν_τ} is between 5 and $\sim$ 30 MeV/c^2.

[42] RAFFELT 90 limit valid if m_{ν_3} < 5 keV. It applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.

[43] Significant dependence on details of stellar properties.

[44] GROTCH 88 combined data from MAC, ASP, CELLO, and Mark J.

[45] If m_{ν_3} < 10 keV.

[46] For m_{ν_3} = 8–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\tau \to \nu_e$ and obtain $< 3 \times 10^{-15}$ for m_{ν_3} < 16 eV and $< 6 \times 10^{-14}$ for m_{ν_3} > 4 eV.

ν_3 CHARGE

VALUE (units: electron charge)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4 \times 10^{-4}$	[47] BABU	94	RVUE	BEBC beam dump
$<3 \times 10^{-4}$	[48] DAVIDSON	91	RVUE	SLAC electron beam dump

[47] BABU 94 use COOPER-SARKAR 92 limit on ν_3 magnetic moment to derive quoted result.

[48] DAVIDSON 91 use data from early SLAC electron beam dump experiment to derive charge limit as a function of neutrino mass.

LIMIT ON ν_τ PRODUCTION IN BEAM DUMP EXPERIMENT

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[49] DORENBOS...	88	CHRM
	[50] BOFILL	87	CNTR
	[51] TALEBZADEH	87	BEBC
	[52] USHIDA	86C	EMUL
	[53] ASRATYAN	81	HLBC
	[54] FRITZE	80	BEBC

[49] DORENBOSCH 88 is CERN SPS beam dump experiment with the CHARM detector. $\nu_\tau + \overline{\nu}_\tau$ flux is <21% of the total prompt flux at 90% CL.

[50] BOFILL 87 is a Fermilab narrow-band ν beam with a fine-grained neutrino detector.

[51] TALEBZADEH 87 is a CERN SPS beam dump experiment with the BEBC detector. Mixing probability $P(\nu_e \to \nu_\tau)$ <18% at 90% CL.

[52] USHIDA 86C is a Fermilab wide-band ν beam with a hybrid emulsion spectrometer. Mixing probabilities $P(\nu_e \to \nu_\tau) < 7.3\%$ and $P(\nu_\mu \to \nu_\tau) < 0.2\%$ at 90% CL.

[53] ASRATYAN 81 is a Fermilab wide-band $\overline{\nu}$ beam with a 15 foot bubble chamber. Mixing probability $P(\overline{\nu}_\mu \to \overline{\nu}_\tau) < 2.2\%$ at 90% CL.

[54] FRITZE 80 is CERN SPS experiment with BEBC. Neutral-current/charged-current ratio corresponds to R = (prompt-ν_τ-induced events)/(all prompt-ν events) <0.1. Mixing probability $P(\nu_e \to \nu_\tau)$ <0.35 at CL = 90%.

ν_τ REFERENCES

ACCIARRI	95D	PL B346 190	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
AKERS	95D	ZPHY C65 183	+Alexander, Allison, Anderson+	(OPAL Collab.)
BUSKULIC	95H	PL B349 585	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
DOLGOV	95	PR D51 4129	+Kainulainen, Rothstein	(MICH, MINN, CERN)
SIGL	95	PR D51 1499	+Turner	(FNAL, EFI)
BABU	94	PL B321 140	+Gould, Rothstein	(BART, JHU, MICH)
DODELSON	94	PR D49 5068	+Gyuk, Turner	(FNAL, CHIC, EFI)
GOULD	94	PL B333 545	+Rothstein	(JHU, MICH)
KAWASAKI	94	NP B419 105	+Kernan, Kang+	(OSU)
BALEST	93	PR D47 R3671	+Daoudi, Ford, Johnson+	(CLEO Collab.)
CINABRO	93	PRL 70 3700	+Henderson, Kinoshita+	(CLEO Collab.)
DOLGOV	93	PRL 71 476	+Rothstein	(MICH)
ENQVIST	93	PL B301 376	+Uibo	(NORD)
MAYLE	93	PL B317 119	+Schramm, Turner, Wilson	(LLNL, CHIC)
RAJPOOT	93	MPL A8 1179		(CSULB)
ALBRECHT	92M	PL B292 221	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	92Q	ZPHY C56 339	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
BAI	92	PRL 69 3021	+Bardon, Becker-Szendy, Burnett+	(BES Collab.)
BLUDMAN	92	PR D45 4720		(CFPA)
BURROWS	92	PRL 68 3834	+Gandhi, Turner	(ARIZ, CHIC)
COOPER-...	92	PL B280 153	Cooper-Sarkar, Sarkar, Guy, Venus+	(BEBC WA66 Collab.)
DODELSON	92	PRL 68 2572	+Frieman, Turner	(FNAL, CHIC)
KAWANO	92	PL B275 487	+Fuller, Malaney, Savage	(CIT, UCSD, LLL, RUTG)
DAVIDSON	91	PR D43 2314	+Campbell, Bailey	(ALBE, TNTO)
DESHPANDE	91	PR D43 943	+Sarma	(OREG, TATA)
FULLER	91	PR D43 3136	+Malaney	(UCSD)
GANDHI	91	PL B261 519E (erratum)	+Burrows	(ARIZ)
GRANEK	91	IJMP A6 2387	+McKellar	(MELB)
KOLB	91	PRL 67 533	+Turner, Chakravorty, Schramm	(FNAL, CHIC)
LAM	91	PR D44 3345	+Ng	(AST)
NATALE	91	PL B258 227		(SPIFT)
GANDHI	90	PL B246 149	+Burrows	(ARIZ)
Also	91	PL B261 519E (erratum)	Gandhi, Burrows	(ARIZ)
GRIFOLS	90B	PL B242 77	+Masso	(BARC, CERN)
RAFFELT	90	PRL 64 2856		(MPIM)
WALKER	90	PR D41 689		(HARV)
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
GAEMERS	89	PR D40 309	+Gandhi, Lattimer	(ANIK, STON)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
ALBRECHT	88B	PL B202 149	+Binder, Boeckmann+	(ARGUS Collab.)
DORENBOS...	88	ZPHY C40 497	Dorenbosch, Allaby, Amaldi, Barbiellini+	(CHARM Collab.)
GROTCH	88	ZPHY C39 553	+Robinett	(PSU)
TERASAWA	88	NP B302 697	+Kawasaki, Sato	(TOKY)
BOFILL	87	PR D36 3309	+Busza, Eldridge+	(MIT, FNAL, MSU)
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOTY, TOKY)
NUSSINOV	87	PR D36 2278	+Rephaeli	(TELA)
TALEBZADEH	87	NP B291 503	+Guy, Venus+	(BEBC WA66 Collab.)
KAWASAKI	86	PL B178 71	+Terasawa, Sato	(TOKY)
USHIDA	86C	PRL 57 2897	+Kondo, Tasaka, Park, Song+	(FNAL E531 Collab.)
LINDLEY	85	APJ 294 1		(FNAL)
BINETRUY	84	PL 134B 174	+Girardi, Salati	(LAPP)
SARKAR	84	PL 148B 347	+Cooper	(OXF, CERN)
ASRATYAN	81	PL 105B 301	+Efremenko, Fedotov+	(ITEP, FNAL, SERP, MICH)
FELDMAN	81	SLAC-PUB-2839		(SLAC, STAN)
Santa Cruz APS.				
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
REPHAELI	81	PL 106B 73	+Szalay	(UCSB, CHIC)
DERUJULA	80	PRL 45 942	+Glashow	(MIT, HARV)
FRITZE	80	PL 96B 427		(AACH3, BONN, CERN, LOIC, OXF, SACL)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
STECKER	80	PRL 45 1460		(NASA)
COWSIK	79	PR D19 2219		(TATA)
GOLDMAN	79	PR D19 2215	+Stephenson	(LASL)
LINDLEY	79	MNRAS 188 15P		(SUSS)
BACINO	78B	PRL 41 13	+Ferguson, Nodulman, Slater+	(DELCO Collab.)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
DICUS	78	PR D17 1529	+Kolb, Teplitz, Wagoner	(TEXA, VPI, STAN)
FALK	78	PL 79B 511	+Schramm	(CHIC)
COWSIK	77	PRL 39 784		(MPIM, TATA)
DICUS	77	PRL 39 168	+Kolb, Teplitz	(TEXA, VPI)

OTHER RELATED PAPERS

WEINSTEIN	93	ARNPS 43 457	+Stroynowski	(CIT, SMU)

Number of Light Neutrino Types

The neutrinos referred to in this section are those of the Standard SU(2)×U(1) Electroweak Model possibly extended to allow nonzero neutrino masses. Light neutrinos are those with $m_\nu < m_Z/2$. The limits are on the number of neutrino families or species, including ν_e, ν_μ, ν_τ

THE NUMBER OF LIGHT NEUTRINO TYPES FROM COLLIDER EXPERIMENTS

(by Dean Karlen, Carleton University)

The most precise measurements of the number of light neutrino types, N_ν, come from studies of Z production in e^+e^- collisions. At the time of this report, the most recent combined analysis of the four LEP experiments [1] included nearly 8 million visible Z decays. The invisible partial width, $\Gamma_{\rm inv}$, is determined from these data by subtracting the measured visible partial widths, corresponding to Z decays into quarks and charged leptons, from the total Z width. The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model. In order to reduce the model dependence, the Standard Model value for the ratio of the neutrino to charged leptonic partial widths, $(\Gamma_\nu/\Gamma_\ell)_{\rm SM} = 1.992$, is used instead of $(\Gamma_\nu)_{\rm SM}$ to determine the number of light neutrino types:

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM}$$

The combined LEP result is $N_\nu = 2.991 \pm 0.016$.

In the past, when only small samples of Z decays had been recorded by the LEP experiments and by the Mark II at SLC, the uncertainty in N_ν was reduced by using Standard Model fits to the measured hadronic cross sections at several center-of-mass energies near the Z resonance. Since this method is much more dependent on the Standard Model, the approach described above is favored.

Before the advent of the SLC and LEP, limits on the number of neutrino generations were placed by experiments at lower-energy e^+e^- colliders by measuring the cross section of the process $e^+e^- \rightarrow \nu\overline{\nu}\gamma$. The ASP, CELLO, MAC, MARK J, and VENUS experiments observed a total of 3.9 events above background [2], leading to a 95% CL limit of $N_\nu < 4.8$. This process has a much larger cross section at center-of-mass energies near the Z mass and has been measured at LEP by the ALEPH, L3, and OPAL experiments [3]. Each experiment has observed several hundred of these events, and the combined result is $N_\nu = 3.09 \pm 0.13$.

Experiments at $p\overline{p}$ colliders also placed limits on N_ν by determining the total Z width from the observed ratio of $W^\pm \rightarrow \ell^\pm\nu$ to $Z \rightarrow \ell^+\ell^-$ events [4]. This involved a calculation that assumed Standard Model values for the total W width and the ratio of W and Z leptonic partial widths, and used an estimate of the ratio of Z to W production cross sections. Now that the Z width is very precisely known from the LEP experiments, the approach is now one of those used to determine the W width.

References

1. The LEP Electroweak Working Group, CERN/PPE/95-172.
2. C. Hearty *et al.*, Phys. Rev. **D39**, 3207 (1989);
   H.J Behrend *et al.*, Phys. Lett. **B215**, 186 (1988);
   W.T. Ford *et al.*, Phys. Rev. **D33**, 3472 (1986);
   H. Wu, Ph.D. Thesis, Univ. Hamburg (1986);
   K. Abe *et al.*, Phys. Lett. **B232**, 431 (1989).
3. R. Akers *et al.*, Z. Phys. **C65**, 47 (1995);
   D. Buskulic *et al.*, Phys. Lett. **B313**, 520 (1993);
   O. Adriani *et al.*, Phys. Lett. **B292**, 463 (1992);
   B. Adeva *et al.*, Phys. Lett. **B275**, 209 (1992);
   M.Z. Akrawy *et al.*, Z. Phys. **C50**, 373 (1991).
4. C. Albajar *et al.*, Phys. Lett. **B198**, 271 (1987);
   R. Ansari *et al.*, Phys. Lett. **B186**, 440 (1987).

Number from e^+e^- Colliders

Number of Light ν Types

Our evaluation uses the invisible and leptonic widths of the Z boson from our combined fit shown in the Particle Listings for the Z Boson, and the Standard Model value Γ_ν/Γ_ℓ = 1.992 ± 0.003.

VALUE	DOCUMENT ID		TECN
2.991±0.016 OUR EVALUATION	1995 combined fit to all LEP data.		
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.00 ±0.05	[1] LEP	92	RVUE

[1] Simultaneous fits to all measured cross section data from all four LEP experiments.

Number of Light ν Types from Direct Measurement of Invisible Z Width

In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+e^- \rightarrow \nu\overline{\nu}\gamma$. All are obtained from LEP runs in the $E^{ee}_{\rm cm}$ range 88–94 GeV.

VALUE	DOCUMENT ID		TECN	COMMENT
3.09±0.13 OUR AVERAGE				
3.23±0.16±0.10	AKERS	95C	OPAL	1990–1992 LEP runs
2.68±0.20±0.20	BUSKULIC	93L	ALEP	1990–1991 LEP runs
3.24±0.46±0.22	ADEVA	92	L3	1990 LEP run
3.14±0.24±0.12	ADRIANI	92E	L3	1991 LEP run
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.0 ±0.4 ±0.2	AKRAWY	91D	OPAL	Repl. by AKERS 95C

Limits from Astrophysics and Cosmology

Number of Light ν Types

("light" means < about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90.

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
< 3.6	[2] OLIVE	95	COSM
< 3.1	OLIVE	95B	COSM
< 3.04	KERNAN	94	COSM
< 3.3	WALKER	91	COSM
< 3.4	OLIVE	90	COSM
< 5.2	ELLIS	86	COSM
< 4	STEIGMAN	86	COSM
< 4	YANG	84	COSM
< 4	YANG	79	COSM
< 7	STEIGMAN	77	COSM
	PEEBLES	71	COSM
<16	[3] SHVARTSMAN	69	COSM
	HOYLE	64	COSM

[2] OLIVE 95 limit assumes the existence of at least three (massless) neutrinos.
[3] SHVARTSMAN 69 limit inferred from his equations.

Number Coupling with Less Than Full Weak Strength

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<20	[4] OLIVE	81C	COSM
<20	[4] STEIGMAN	79	COSM

[4] Limit varies with strength of coupling. See also WALKER 91.

REFERENCES FOR Limits on Number of Light Neutrino Types

AKERS 95C ZPHY C65 47 +Alexander, Allison+ (OPAL Collab.)
OLIVE 95 PL B354 357 +Steigman (MINN, OSU)
OLIVE 95B APJS 97 49 +Steigman (MINN, OSU)
KERNAN 94 PRL 72 3309 +Krauss (CASE)
BUSKULIC 93L PL B313 520 +De Bonis, Decamp+ (ALEPH Collab.)
ADEVA 92 PL B275 209 +Adriani, Aguilar-Benitez+ (L3 Collab.)
ADRIANI 92E PL B292 463 +Aguilar-Benitez, Ahlen, Akbari, Alcaraz+ (L3 Collab.)
LEP 92 PL B276 247 +ALEPH, DELPHI, L3, OPAL (LEP Collabs.)
AKRAWY 91D ZPHY C50 373 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
WALKER 91 APJ 376 51 +Steigman, Schramm, Olive+ (HSCA, OSU, CHIC, MINN)
DENEGRI 90 RMP 62 1 +Sadoulet, Spiro (CERN, UCB, SACL)
OLIVE 90 PL B236 454 +Schramm, Steigman, Walker (MINN, CHIC, OSU, HARV)
ELLIS 86 PL 167B 457 +Enqvist, Nanopoulos, Sarkar (CERN, OXFTP)
STEIGMAN 86 PL B176 33 +Olive, Schramm, Turner (BART, MINN+)
YANG 84 APJ 281 493 +Turner, Steigman, Schramm, Olive (CHIC, BART)
OLIVE 81 APJ 246 557 +Schramm, Steigman, Turner, Yang+ (CHIC, BART)
OLIVE 81C NP B180 497 +Schramm, Steigman (EFI, BART)
STEIGMAN 79 PRL 43 239 +Olive, Schramm (BART, EFI)
YANG 79 APJ 227 697 +Schramm, Steigman, Rood (CHIC, YALE, VIRG)
STEIGMAN 77 PL 66B 202 +Schramm, Gunn (YALE, CHIC, CIT)
PEEBLES 71 Physical Cosmology (PRIN)
Princeton Univ. Press (1971)
SHVARTSMAN 69 JETPL 9 184 (MOSU)
Translated from ZETFP 9 315.
HOYLE 64 Nature 203 1108 +Tayler (CAMB)

Massive Neutrinos and Lepton Mixing, Searches for

Searches for massive neutral leptons and the effects of nonzero neutrino masses are listed here. These results are divided into the following main sections:

A. Heavy neutral lepton mass limits;
B. Sum of neutrino masses;
C. Searches for neutrinoless double-β decay (see the note by P. Vogel on "Searches for neutrinoless double-β decay" preceding this section);
D. Other bounds from nuclear and particle decays;
E. Bounds from particle decays;
F. Solar ν experiments (see the note on "Solar Neutrinos" by K. Nakamura preceding this section);
G. Astrophysical neutrino observations;
H. Reactor $\overline{\nu}_e$ disappearance experiments;
I. Accelerator neutrino appearance experiments;
J. Disappearance experiments with accelerator and radioactive source neutrinos.

Direct searches for masses of dominantly coupled neutrinos are listed in the appropriate section on ν_e, ν_μ, or ν_τ. Searches for massive charged leptons are given elsewhere, and searches for the mixing of $(\mu^- e^+)$ and $(\mu^+ e^-)$ are given in the muon listings.

Discussion of the ν_e and ν_μ mass limits and the theory of mixing are given in the note on "Neutrinos" by R.E. Shrock in the ν_e section near the beginning of these Particle Listings. Several reviews are also listed there.

Most of the results of the present section are correlated upper bounds on mixing matrix coefficients U_{aj} versus neutrino mass. In some of these cases (*e.g.* accelerator neutrino oscillation experiments), results are presented assuming that mixing occurs only between two neutrino species. In this case limits or results can be shown as allowed regions on a plot of $|\Delta m^2|$ as a function of $\sin^2 2\theta$, where $\Delta m^2 = m^2_{\nu_i} - m^2_{\nu_j}$. Although there are three flavors, data are usually analyzed assuming an oscillation between just two of them, *e.g.*, $\nu_\tau \leftrightarrow \nu_e$. The same remark applies to lepton-number violating mixing between two states, *e.g.*, $\nu_e \leftrightarrow \overline{\nu}_\mu$ or $\nu_\mu \leftrightarrow \overline{\nu}_\mu$. However, in a comprehensive analysis of all current data on limits on (or positive reports of) neutrino oscillations, one should use a three-generation mixing framework.

The simplest situation occurs in an "appearance" experiment, where one searches for interactions by neutrinos of a variety not expected in the beam. An example is the search for $\overline{\nu}_e$ interactions in a beam of neutrinos from the π^+ decay chain, which (among other possibilities) might be taken as evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$. For oscillation between two states, the probability that the "wrong" state will appear is given by Eq. 5 in Shrock's "Note on Neutrinos" at the beginning of the Quark and Lepton Particle Listings. For our present purposes, this may be rewritten as

$$P = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E) \ , \qquad (1)$$

where L is the distance from the neutrino's production point to its interaction point, and E is its energy. In the above, $|\Delta m^2|$ is in eV^2 and L/E is in km/GeV or m/MeV. Since in a real experiment L and E have some spread, one must average P over the appropriate distributions. As an example, let us make the somewhat unrealistic assumption that $b \equiv 1.27L/E$ has a Gaussian distribution with standard deviation σ_b about a central value b_0. Then:

$$\langle P \rangle = \tfrac{1}{2} \sin^2 2\theta [1 - \cos(2b_0 \Delta m^2) \exp(-2\sigma_b^2 (\Delta m^2)^2)] \qquad (2)$$

The value of $\langle P \rangle$ is set by the experiment. For example, if 230 interactions of the expected flavor are detected and none of the wrong flavor are seen, then $P = 0.010$ at the 90% CL. We can then solve the above expression for $\sin^2 2\theta$ as a function of $|\Delta m^2|$. This function is shown in Fig. 1 for the parameter assumptions given in the caption. Note that:

(a) since the fast oscillations are completely washed out by the resolution for large $|\Delta m^2|$, $\sin^2 2\theta = 2\,\langle P \rangle$ in this region;
(b) the maximum excursion to the left is to approximately $\langle P \rangle$, and it occurs at $|\Delta m^2| = \pi/2b_0$ eV^2;
(c) for large $\sin^2 2\theta$, $\Delta m^2 \propto (\sin^2 2\theta)^{-1/2}$; and
(d) the intercept at $\sin^2 2\theta = 1$ is at $\sqrt{\langle P \rangle}/b_0$.

The intercept for large $|\Delta m^2|$ is just a measure of running time and backgrounds, while the intercept at $\sin^2 2\theta = 1$ also depends on the mean value of L/E. The wiggles depend on the experimental resolution, but aside from such details the two intercepts completely describe the exclusion region: For large $|\Delta m^2|$, $\sin^2 2\theta$ is constant, and for large $\sin^2 2\theta$ the constant slope is known. For these reasons, it is (nearly) sufficient to summarize the results of an experiment by stating the two intercepts, as is done in the following tables. The reader is referred to the original papers for the two-dimensional plots expressing the actual limits.

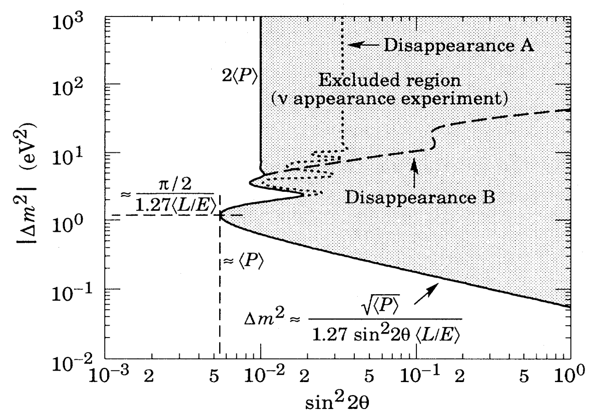


Figure 1: Neutrino oscillation parameter ranges excluded by a toy experiment in which one searches for the appearance of neutrinos not expected in the beam. The probability of appearance, in this case 0.5% at some specified CL, is set by the number of right-flavor events observed and/or information about the flux and cross sections. Here it is assumed that $\langle L/E \rangle = 1$ km GeV^{-1}, and that the distribution of L/E is Gaussian with a 20% standard deviation. The wiggle structure is determined by the resolution function, and the intercepts are determined by the appearance probability and $\langle L/E \rangle$. The leftmost excursion relative to the high-$|\Delta m^2|$ limit and the slope of the lower part of the curve are independent of the experiment. In a disappearance experiment, high-$|\Delta m^2|$ sensitivity is lost unless the incident flux is known. These two possibilities are shown qualitatively by the dashed lines marked "Disappearance A" and "Disappearance B."

If a positive effect is claimed, then the excluded region becomes an included region. This is the case for the HIRATA 92 analysis of $R(\mu/e)$ for atmospheric neutrinos.

In a "disappearance" experiment, one looks for the attenuation of the beam neutrinos (for example, ν_k) by mixing with at least one other neutrino eigenstate. (We label such experiments as $\nu_k \not\to \nu_k$.) These experiments fall into two general classes:

(a) Those in which the beam neutrino flux is known, from theory or other measurements. In the high-$|\Delta m^2|$ region, where the oscillation length is small compared to the size of the apparatus, the oscillations are in both directions and the beam intensity is reduced by a factor of two (for two-component mixing). In this case, indicated qualitatively by the "Disappearance A" curve in Fig. 1. sensitivity is maintained for large $|\Delta m^2|$, but with no simple rule relating this asymptote to the maximum excursion to the left. An example is provided by the VUILLEUMIER 82 measurements at the Gösgen reactor.

(b) Those in which the intensity must be measured in the apparatus itself (two detectors, or a "long" detector). Then above some minimum $|\Delta m^2|$ the equilibrium is established upstream, and there is no change in intensity over the length of the apparatus. As a result, sensitivity is lost at high $|\Delta m^2|$, as is qualitatively indicated by the curve "Disappearance B" in Fig. 1. See, for example, DYDAK 84.

Finally, there are more complicated cases, such as in the HIRATA 92B analysis of the Kamiokande II solar neutrino data in terms of the MSW parameters. An irregular region on the $|\Delta m^2|$ vs $\sin^2 2\theta$ is excluded for a combination of physical reasons. It is difficult to represent adequately these graphical data within the strictures of our tables.

(A) Heavy neutral leptons

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m <$ 2400 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
>44.1	95	ALEXANDER	91F	OPAL	Dirac
>37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
>42.8	95	[1] ADEVA	90S	L3	Dirac
>34.8	95	[1] ADEVA	90S	L3	Majorana
>42.7	95	DECAMP	90F	ALEP	Dirac

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2 \times 10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1 \times 10^{-10}$ for $m_{L^0} = 40$ GeV.

Neutral Heavy Lepton MASS LIMITS

Limits apply only to heavy lepton type given in comment at right of data Listings. See review above for description of types.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
none 2.5–50	95	[2] ADRIANI	92I	L3	$\lvert U_{\tau \text{ or } \mu}\rvert^2 < 3 \times 10^{-4}$
none 4–50	95	[2] ADRIANI	92I	L3	$\lvert U_\tau\rvert^2 < 3 \times 10^{-4}$
>46.4	95	[3] ADEVA	90S	L3	Dirac
>45.1	95	[3] ADEVA	90S	L3	Majorana
>46.5	95	[4] AKRAWY	90L	OPAL	Coupling to e or μ
>45.7	95	[4] AKRAWY	90L	OPAL	Coupling to τ
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>44.5	95	[5] ABREU	92B	DLPH	Dirac
>39.0	95	[5] ABREU	92B	DLPH	Majorana
>41	95	[6,7] BURCHAT	90	MRK2	Dirac, $\lvert U_{\ell j}\rvert^2 > 10^{-10}$
>19.6	95	[6,7] BURCHAT	90	MRK2	Dirac, all $\lvert U_{\ell j}\rvert^2$
none 25–45.7	95	[6,8] DECAMP	90F	ALEP	Dirac $\lvert U_{\ell j}\rvert^2 > 10^{-13}$
none 8.2–26.5	95	[9] SHAW	89	AMY	Dirac L^0, $\lvert U_{ej}\rvert^2 > 10^{-6}$
none 8.3–22.4	95	[9] SHAW	89	AMY	Majorana L^0, $\lvert U_{ej}\rvert^2 > 10^{-6}$
none 8.1–24.9	95	[9] SHAW	89	AMY	Majorana L^0, $\lvert U_{\mu j}\rvert^2 > 10^{-6}$
none 1.8–6.7	90	[10] AKERLOF	88	HRS	$\lvert U_{ej}\rvert^2=1$
none 1.8–6.4	90	[10] AKERLOF	88	HRS	$\lvert U_{\mu j}\rvert^2=1$
none 2.5–6.3	80	[10] AKERLOF	88	HRS	$\lvert U_{\tau j}\rvert^2=1$
none 0.25–14	90	[11] MISHRA	87	CNTR	$\lvert U_{\mu j}\rvert^2=1.$
none 0.25–10	90	[11] MISHRA	87	CNTR	$\lvert U_{\mu j}\rvert^2=0.1$
none 0.25–7.7	90	[11] MISHRA	87	CNTR	$\lvert U_{\mu j}\rvert^2=0.03$
none 1.–2.	90	[12] WENDT	87	MRK2	$\lvert U_{e \text{ or } \mu j}\rvert^2=0.1$
none 2.2–4.	90	[12] WENDT	87	MRK2	$\lvert U_{e \text{ or } \mu j}\rvert^2=0.001$
none 2.3–3.	90	[12] WENDT	87	MRK2	$\lvert U_{\tau j}\rvert^2=0.1$
none 3.2–4.8	90	[12] WENDT	87	MRK2	$\lvert U_{\tau j}\rvert^2=0.001$
none 0.3–0.9	90	[13] BADIER	86	CNTR	$\lvert U_{ej}\rvert^2=0.8$
none 0.33–2.0	90	[13] BADIER	86	CNTR	$\lvert U_{ej}\rvert^2=0.03$
none 0.6–0.7	90	[13] BADIER	86	CNTR	$\lvert U_{\mu j}\rvert^2=0.8$
none 0.6–2.0	90	[13] BADIER	86	CNTR	$\lvert U_{\mu j}\rvert^2=0.01–0.001$
> 1.2		MEYER	77	MRK1	Neutral

[2] ADRIANI 92I is a search for isosinglet heavy lepton N_ℓ which might be produced from $Z \to \nu_\ell N_\ell$, then decay via a number of different channels. Limits are weaker for decay lengths longer than about 1 m.

[3] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2\times10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1\times10^{-10}$ for $m_{L^0} = 40$ GeV.

[4] AKRAWY 90L limits valid if coupling strength is greater than a mass-dependent value, e.g., 4.9×10^{-7} at $m_{L^0} = 20$ GeV, 3.5×10^{-8} at 30 GeV, 4×10^{-9} at 40 GeV.

[5] ABREU 92B limit is for mixing matrix element ≈ 1 for coupling to e or μ. Reduced somewhat for coupling to τ, increased somewhat for smaller mixing matrix element. Replaces ABREU 91F.

[6] Limits apply for $\ell = e$, μ, or τ and for $V-A$ decays of Dirac neutrinos.

[7] BURCHAT 90 searched for Z decay to unstable L^0 pairs at SLC. It includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[8] For $25 < m_{L^0} < 42.7$ GeV, DECAMP 90F exclude an L^0 for all values of $|U_{\ell j}|^2$.

[9] SHAW 89 also excludes the mass region from 8.0 to 27.2 GeV for Dirac L^0 and from 8.1 to 23.6 GeV for Majorana L^0 with equal full-strength couplings to e and μ. SHAW 89 also gives correlated bounds on lepton mixing.

[10] AKERLOF 88 is PEP e^+e^- experiment at $E_{cm} = 29$ GeV. The L^0 is assumed to decay via $V-A$ to e or μ or τ plus a virtual W.

[11] MISHRA 87 is Fermilab neutrino experiment looking for either dimuon or double vertex events (hence long-lived).

[12] WENDT 87 is MARK-II search at PEP for heavy ν with decay length 1–20 cm (hence long-lived).

[13] BADIER 86 is a search for a long-lived penetrating sequential lepton produced in π^- – nucleon collisions with lifetimes in the range from $5 \times 10^{-7} - 5 \times 10^{-11}$ s and decaying into at least two charged particles. U_{ej} and U_{mj} are mixing angles to ν_e and ν_μ. See also the BADIER 86 entry in the section "Searches for Massive Neutrinos and Lepton Mixing".

Astrophysical Limits on Neutrino MASS for $m_\nu > 1$ GeV

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 60–115		[14] FARGION	95	ASTR	Dirac
none 26–4700		[15] BECK	94	COSM	Dirac
none 6 – hundreds		[16,17] MORI	92B	KAM2	Dirac neutrino
none 24 – hundreds		[16,17] MORI	92B	KAM2	Majorana neutrino
none 10–2400	90	[18] REUSSER	91	CNTR	HPGe search
none 3–100	90	SATO	91	KAM2	Kamiokande II
		[19] ENQVIST	89	COSM	
none 12–1400		[15] CALDWELL	88	COSM	Dirac ν
none 4–16	90	[15,16] OLIVE	88	COSM	Dirac ν
none 4–35	90	OLIVE	88	COSM	Majorana ν
>4.2 to 4.7		SREDNICKI	88	COSM	Dirac ν
>5.3 to 7.4		SREDNICKI	88	COSM	Majorana ν
none 20–1000	95	[15] AHLEN	87	COSM	Dirac ν
>4.1		GRIEST	87	COSM	Dirac ν

[14] FARGION 95 bound is sensitive to assumed ν concentration in the Galaxy. See also KONOPLICH 94.

[15] These results assume that neutrinos make up dark matter in the galactic halo.

[16] Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.

[17] MORI 92B results assume that neutrinos make up dark matter in the galactic halo. Limits based on annihilations in earth are also given.

[18] REUSSER 91 uses existing $\beta\beta$ detector (see FISHER 89) to search for CDM Dirac neutrinos.

[19] ENQVIST 89 argue that there is no cosmological upper bound on heavy neutrinos.

(B) Sum of neutrino masses

The limits on low mass ($m_\nu \lesssim 1$ MeV) neutrinos apply to $m_{\rm tot}$ given by

$$m_{\rm tot} = \sum_\nu (g_\nu/2) m_\nu \ ,$$

where g_ν is the number of spin degrees of freedom for ν plus $\overline{\nu}$: $g_\nu = 4$ for neutrinos with Dirac masses; $g_\nu = 2$ for Majorana neutrinos. The limits on high mass ($m_\nu > 1$ MeV) neutrinos apply separately to each neutrino type.

Limit on Total ν MASS, $m_{\rm tot}$

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to $m_{\rm tot}$. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<180	SZALAY	74	COSM
<132	COWSIK	72	COSM
<280	MARX	72	COSM
<400	GERSHTEIN	66	COSM

Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<100–200	[20] OLIVE	82	COSM	Dirac ν
<200–2000	[20] OLIVE	82	COSM	Majorana ν

[20] Depending on interaction strength G_R where $G_R < G_F$.

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 10	[21] OLIVE	82	COSM	G_R/G_F <0.1
>100	[21] OLIVE	82	COSM	G_R/G_F <0.01

[21] These results apply to heavy Majorana neutrinos and are summarized by the equation: $m_\nu > 1.2$ GeV (G_F/G_R). The bound saturates, and if G_R is too small no mass range is allowed.

(C) Searches for neutrinoless double-β decay

LIMITS FROM NEUTRINOLESS $\beta\beta$ DECAY

(Revised 1995 by Petr Vogel, Caltech)

Limits on an effective Majorana neutrino mass and a lepton-number violating current admixture can be obtained from lifetime limits on $0\nu\beta\beta$ nuclear decay. The derived quantities are model-dependent, so the half-life measurements are given first. Where possible we list the references for the matrix elements used in the subsequent analysis. Since rates for the more conventional $2\nu\beta\beta$ decay serve to calibrate the theory, results for this process are also given. As an indication of the spread among different ways of evaluating the matrix elements, we show in Fig. 1 some representative examples for the most popular nuclei. For further calculations, see, *e.g.,* Ref. 1.

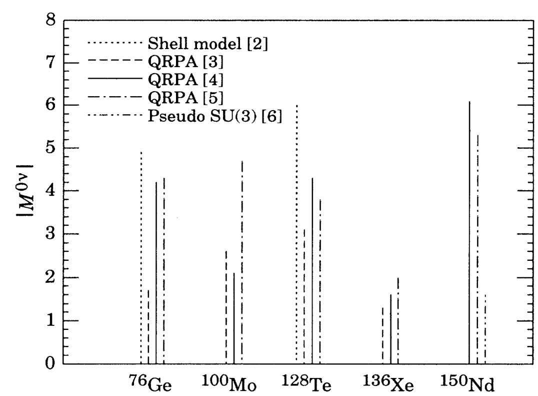


Figure 1: Nuclear matrix elements for $0\nu\beta\beta$ decay calculated by a subset of different methods and different authors for the most popular double-beta decay candidate nuclei. Recalculated from the published half-lives using consistent phase-space factors and $g_A = 1.25$. The QRPA [3] value is for $\alpha' = -390$ MeV fm^3.

To define the limits on lepton-number violating right-handed current admixtures, we display the relevant part of a phenomenological current-current weak interaction Hamiltonian:

$$H_W = (G_F/\sqrt{2}) \times (J_L \cdot j_L^\dagger + \kappa J_R \cdot j_L^\dagger + \eta J_L \cdot j_R^\dagger + \lambda J_R \cdot j_R^\dagger) + \text{h.c.}$$

where $j_L^\mu = \bar{e}_L \gamma^\mu \nu_{eL}$, $j_R^\mu = \bar{e}_R \gamma^\mu \nu_{eR}$, and J_L^μ and J_R^μ are left-handed and right-handed hadronic weak currents. Experiments are not sensitive to κ, but quote limits on quantities proportional to η and λ.* In analogy to $\langle m_\nu \rangle$ (see Eq. 11 in the "Note on Neutrinos" at the beginning of the Neutrino Particle Listings), the quantities extracted from experiments are $\langle \eta \rangle = \eta \sum U_{1j} V_{1j}$ and $\langle \lambda \rangle = \lambda \sum U_{1j} V_{1j}$, where V_{ij} is a matrix analogous to U_{ij} (see Eq. 2 in the "Note on Neutrinos"), but describing the mixing among right-handed neutrinos. The quantities $\langle \eta \rangle$ and $\langle \lambda \rangle$ therefore vanish for massless or unmixed neutrinos. Also, as in the case of $\langle m_\nu \rangle$, cancellations are possible in $\langle \eta \rangle$ and $\langle \lambda \rangle$. The limits on $\langle \eta \rangle$ are of order 10^{-8} while the limits on $\langle \lambda \rangle$ are of order 10^{-6}. The reader is warned that a number of earlier experiments did not distinguish between η and λ. Because of evolving reporting conventions and matrix element calculations, we have not tabulated the admixture parameters for experiments published earlier than 1989.

See the section on Majoron searches for additional limits set by these experiments.

Footnotes and References

* We have previously used a less accepted but more explicit notation in which $\eta_{RL} \equiv \kappa$, $\eta_{LR} \equiv \eta$, and $\eta_{RR} \equiv \lambda$.

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4. A. Staudt, K. Muto, and H.V. Klapdor-Kleingrothaus, Europhys. Lett. **13**, 31 (1990).
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Half-life Measurements and Limits for Double β Decay

In all cases of double beta decay, (Z,A) $\to$ (Z+2,A) + $2\beta^-$ + (0 or 2)$\overline{\nu}_e$.

$t_{1/2}(10^{21}$ yr)	CL%	ISOTOPE		TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$0.036^{+0.006}_{-0.005} \pm 0.003$		^{116}Cd	2ν	$0^+ \to 0^+$	NEMO	[22] ARNOLD	95
>5600	90	^{76}Ge	0ν	$0^+ \to 0^+$	Enriched HPGe	BALYSH	95
$0.61^{+0.18}_{-0.11}$		^{100}Mo	2ν	$0^+ \to 0^+$	γ in HPGe	[23] BARABASH	95
$>$ 0.00013	99	^{160}Gd	2ν	$0^+ \to 0^+$	Gd_2SiO_5:Ce scint	[24] BURACHAS	95
$>$ 0.00012	99	^{160}Gd	2ν	$0^+ \to 2^+$	Gd_2SiO_5:Ce scint	[24] BURACHAS	95
$>$ 0.014	90	^{160}Gd	0ν	$0^+ \to 0^+$	Gd_2SiO_5:Ce scint	[24] BURACHAS	95
$>$ 0.013	90	^{160}Gd	0ν	$0^+ \to 2^+$	Gd_2SiO_5:Ce scint	[24] BURACHAS	95
$(9.5 \pm 0.4 \pm 0.9)$E18		^{100}Mo	2ν		NEMO 2	DASSIE	95
$>$ 6.4	90	^{100}Mo	0ν	$0^+ \to 0^+$	NEMO 2	DASSIE	95
$>$ 0.8	90	^{100}Mo	0ν	$0^+ \to 2^+_1$	NEMO 2	DASSIE	95
$>$ 0.6	90	^{100}Mo	0ν	$0^+ \to 0^+_1$	NEMO 2	DASSIE	95
$0.026^{+0.009}_{-0.005}$		^{116}Cd	2ν	$0^+ \to 0^+$	ELEGANT IV	EJIRI	95
$>$ 2.9	90	^{116}Cd	0ν	$0^+ \to 0^+$	ELEGANT IV	EJIRI	95
$>$ 29	90	^{116}Cd	0ν	$0^+ \to 0^+$	$^{116}CdWO_4$ scint	[25] GEORGADZE	95
$>$ 0.3	68	^{160}Gd	0ν		Gd_2SiO_5: Ce scint	KOBAYASHI	95
$>$ 18	90	^{130}Te	0ν	$0^+ \to 0^+$	Bolometer	[26] ALESSAND...	94
$>$ 0.041	90	^{96}Zr	$0\nu+2\nu$	$0^+ \to 2^+_1$	γ in HPGe	ARPESELLA	94
$>$ 0.033	90	^{96}Zr	$0\nu+2\nu$	$0^+ \to 0^+_1$	γ in HPGe	ARPESELLA	94
$>$ 0.024	90	^{96}Zr	$0\nu+2\nu$	$0^+ \to 2^+_2$	γ in HPGe	ARPESELLA	94
$>$ 0.031	90	^{96}Zr	$0\nu+2\nu$	$0^+ \to 2^+_3$	γ in HPGe	ARPESELLA	94
$1.42 \pm 0.03 \pm 0.13$		^{76}Ge	2ν		Enriched HPGe	BALYSH	94
$>$ 2.37	90	^{116}Cd	$0\nu+2\nu$	$0^+ \to 2^+$	γ in HPGe	[27] PIEPKE	94
$>$ 2.05	90	^{116}Cd	$0\nu+2\nu$	$0^+ \to 0^+_1$	γ in HPGe	[27] PIEPKE	94
$>$ 2.05	90	^{116}Cd	$0\nu+2\nu$	$0^+ \to 0^+_2$	γ in HPGe	[27] PIEPKE	94
$>$ 44	68	^{100}Mo	0ν	$0^+ \to 0^+$	Si(Li)	ALSTON-...	93
$0.017^{+0.010}_{-0.005} \pm 0.0035$		^{150}Nd	2ν	$0^+ \to 0^+$	TPC	ARTEMEV	93
0.039 ± 0.009		^{96}Mo	$0\nu+2\nu$		Geochem	KAWASHIMA	93
$>$ 340	90	^{136}Xe	0ν	$0^+ \to 0^+$	TPC	[28] VUILLEUMIER	93
$>$ 260	90	^{136}Xe	0ν	$0^+ \to 0^+$	TPC	[29] VUILLEUMIER	93
$>$ 0.21	90	^{136}Xe	2ν	$0^+ \to 0^+$	TPC	VUILLEUMIER	93
$>$ 0.093	90	^{136}Xe	2ν	$0^+ \to 0^+$	Drift chamber	ARTEMJEV	92
$>$1400	90	^{76}Ge	0ν	$0^+ \to 0^+$	Enriched HPGe	BALYSH	92
$>$ 430	90	^{76}Ge	0ν	$0^+ \to 2^+$	Enriched HPGe	BALYSH	92
2.7 ± 0.1		^{130}Te			Geochem	BERNATOW...	92
7200 ± 400		^{128}Te			Geochem	[30] BERNATOW...	92
$>$ 0.5	90	^{100}Mo	$0\nu+2\nu$	$0^+ \to 2^+_1$	γ in HPGe	[31] BLUM	92
$>$ 0.9	90	^{100}Mo	$0\nu+2\nu$	$0^+ \to 0^+_1$	γ in HPGe	[31] BLUM	92
$>$ 0.6	90	^{100}Mo	$0\nu+2\nu$	$0^+ \to 2^+_2$	γ in HPGe	[31] BLUM	92
$>$ 27	68	^{82}Se	0ν	$0^+ \to 0^+$	TPC	ELLIOTT	92
$0.108^{+0.026}_{-0.006}$		^{82}Se	2ν	$0^+ \to 0^+$	TPC	ELLIOTT	92
$>$ 0.15	68	^{100}Mo	2ν	$0^+ \to 2^+_1$	Spect	[32] KUDOMI	92
$>$ 1.1	68	^{100}Mo	0ν	$0^+ \to 2^+_1$	Spect	[32] KUDOMI	92
$>$ 0.08	68	^{100}Mo	2ν	$0^+ \to 0^+_1$	Spect	[32] KUDOMI	92
$>$ 0.56	68	^{100}Mo	0ν	$0^+ \to 0^+_1$	Spect	[32] KUDOMI	92
$>$ 0.051	68	^{100}Mo	2ν	$0^+ \to 4^+_1$	Spect	[32] KUDOMI	92
$>$ 0.63	68	^{100}Mo	0ν	$0^+ \to 4^+_1$	Spect	[32] KUDOMI	92
$>$ 0.065	68	^{100}Mo	2ν	$0^+ \to 2^+_2$	Spect	[32] KUDOMI	92
$>$ 0.12	68	^{100}Mo	0ν	$0^+ \to 2^+_2$	Spect	[32] KUDOMI	92
$>$ 330	90	^{76}Ge	0ν	$0^+ \to 0^+$	HPGe	[33] REUSSER	92
$>$ 65	90	^{76}Ge	0ν	$0^+ \to 2^+$	HPGe	[33] REUSSER	92
$0.92^{+0.07}_{-0.04}$		^{76}Ge	2ν	$0^+ \to 0^+$	Enriched HPGe	[34] AVIGNONE	91
$>$ 12	95	^{136}Xe	0ν	$0^+ \to 0^+$	Prop cntr	[28,35] BELLOTTI	91
$>$ 10	95	^{136}Xe	0ν	$0^+ \to 0^+$	Prop cntr	[29,35] BELLOTTI	91
$>$ 3.3	95	^{136}Xe	0ν	$0^+ \to 2^+$	Prop cntr	[35] BELLOTTI	91
$>$ 0.16	95	^{136}Xe	2ν		Prop cntr	BELLOTTI	91
$>$ 4.7	68	^{100}Mo	0ν		Spect	EJIRI	91
$0.0115^{+0.0030}_{-0.0020}$		^{100}Mo	2ν		Spect	EJIRI	91
2.0 ± 0.6		^{238}U			Radiochem	[36] TURKEVICH	91
$>$ 9.5	76	^{48}Ca	0ν		CaF_2 scint.	YOU	91
$>$ 0.14	68	^{100}Mo	$0\nu+2\nu$	$0^+ \to 2^+$	γ in HPGe	BARABASH	90
$>$ 0.042	68	^{100}Mo	$0\nu+2\nu$	$0^+ \to 0^+_1$	γ in HPGe	BARABASH	90
$>$ 0.17	68	^{116}Cd	$0\nu+2\nu$	$0^+ \to 2^+$	γ in HPGe	BARABASH	90
$1.12^{+0.48}_{-0.26}$		^{76}Ge	2ν	$0^+ \to 0^+$	HPGe	[37] MILEY	90
$>$1300	68	^{76}Ge	0ν	$0^+ \to 0^+$	Enriched Ge(Li)	[38] VASENKO	90
0.9 ± 0.1		^{76}Ge	2ν		Enriched Ge(Li)	VASENKO	90
$>$ 0.40	68	^{100}Mo	0ν	$0^+ \to 2^+$	Si(Li)	ALSTON-...	89
$>$ 3.3	68	^{136}Xe	0ν	$0^+ \to 0^+$	Ion chamber	[28] BARABASH	89
$>$ 2.9	68	^{136}Xe	0ν	$0^+ \to 0^+$	Ion chamber	[29] BARABASH	89
$>$ 1.5	68	^{136}Xe	0ν	$0^+ \to 2^+$	Ion chamber	BARABASH	89
$>$ 0.084	68	^{136}Xe	2ν	$0^+ \to 0^+$	Ion chamber	BARABASH	89
$>$ 1.3	68	^{116}Cd	0ν		$^{116}CdWO_4$ scint	DANEVICH	89
$>$ 60	68	^{76}Ge	0ν	$0^+ \to 2^+$	HPGe	[39] MORALES	88
$>$ 4.7	68	^{128}Te		$0^+ \to 2^+$	Ge(Li)	[24] BELLOTTI	87
$>$ 4.5	68	^{130}Te		$0^+ \to 2^+$	Ge(Li)	[24] BELLOTTI	87
$>$ 500	68	^{76}Ge	0ν	$0^+ \to 0^+$	HPGe	CALDWELL	87
$>$ 330	68	^{76}Ge	0ν	$0^+ \to 0^+$	HPGe	BELLOTTI	86
$>$ 27	68	^{76}Ge	0ν	$0^+ \to 2^+$	HPGe	BELLOTTI	86
$>$ 2.3	68	^{76}Ge	0ν		Ge(Li)	[40] HUBERT	85
$>$ 17	90	^{76}Ge	0ν		Intrinsic Ge	AVIGNONE	83
$>$ 800	95	^{128}Te			Geochem	[41] KIRSTEN	83
2.60 ± 0.28		^{130}Te			Geochem	[41] KIRSTEN	83

[22] ARNOLD 95 final result, $(0.0375^{+0.0035}_{-0.0021}) \times 10^{21}$ y, has been submitted for publication to Z. Phys.

[23] BARABASH 95 cannot distinguish 0ν and 2ν, but it is inferred indirectly that the 0ν mode accounts for less than 0.026% of their event sample. They also note that their result disagrees with the previous experiment by the NEMO group (BLUM 92, but also see DASSIE 95).

[24] BELLOTTI 87 searches for γ rays for 2^+ state decays in corresponding Xe isotopes. Limit for ^{130}Te case argues for dominant $0^+ \to 0^+$ transition in known decay of this isotope.

[25] GEORGADZE 95 result for this and other modes are also give in DANEVICH 95. Result for 2ν decay omitted because of authors' caveats.

[26] ALESSANDRELLO 94 state that their present limit excludes a significant contribution from the 0ν channel of ^{130}Te even if the large lifetime obtained in the geochemical experiment of BERNATOWICZ 92 is assumed.

[27] In PIEPKE 94, the studied excited states of ^{116}Sn have energies above the ground state of 1.2935 MeV for the 2^+ state, 1.7568 MeV for the 0^+_1 state, and 2.0273 for the 0^+_2 state.
[28] Limit in the case of a transition induced by a Majorana mass.
[29] Limit for lepton-number violating right-handed current-induced (RHC) decay.
[30] BERNATOWICZ 92 finds ^{128}Te/^{130}Te activity ratio from slope of ^{128}Xe/^{132}Xe vs ^{130}Xe/^{132}Xe ratios during extraction, and normalizes to lead-dated ages for the ^{130}Te lifetime. The authors state that their results imply that "(a) the double beta decay of ^{128}Te has been firmly established and its half-life has been determined ... without any ambiguity due to trapped Xe interferences... (b) Theoretical calculations ... underestimate the [long half-lives of ^{128}Te ^{130}Te] by 1 or 2 orders of magnitude, pointing to a real supression in the 2ν decay rate of these isotopes. (c) Despite [this], most $\beta\beta$-models predict a *ratio* of 2ν decay widths ... in fair agreement with observation." Further details of the experiment are given in BERNATOWICZ 93. Our listed half-life has been revised downward from the published value by the authors, on the basis of reevaluated cosmic-ray ^{128}Xe production corrections.
[31] BLUM 92 reports lifetime limits for the decay of ^{100}Mo to several excited states of ^{100}Ru. Limits for decay to the 0^+_1 state are about 30% higher if decay to the 2^+ states are assumed negligible. Uses 99.5% enriched ^{100}Mo.
[32] KUDOMI 92 reports lifetime limits for 0ν and 2ν decays to four excited states of the daughter ^{100}Ru. The limits were obtained from searches for the two individual electrons in coincidence with photons from the decays of the excited states. The experiment was performed in the Kamioka underground laboratory. See EJIRI 91 for the group's ground-state transition measurement.
[33] REUSSER 92 contains the final results for the search for neutrinoless double beta decay of ^{76}Ge in the Gotthard tunnel underground laboratory. Supersedes FISHER 89.
[34] AVIGNONE 91 reports confirmation of the MILEY 90 and VASENKO 90 observations of $2\nu\beta\beta$ decay of ^{76}Ge. Error is 2σ.
[35] BELLOTTI 91 uses difference between natural and enriched ^{136}Xe runs to obtain $\beta\beta 0\nu$ limits, leading to "less stringent, but safer limits."
[36] TURKEVICH 91 observes activity in old U sample. The authors compare their results with theoretical calculations. They state "Using the phase-space factors of Boehm and Vogel (BOEHM 87) leads to matrix element values for the ^{238}U transition in the same range as deduced for ^{130}Te and ^{76}Ge. On the other hand, the latest theoretical estimates (STAUDT 90) give an upper limit that is 10 times lower. This large discrepancy implies either a defect in the calculations or the presence of a faster path than the standard two-neutrino mode in this case." See BOEHM 87 and STAUDT 90.
[37] MILEY 90 claims only "suggestive evidence" for the decay. Error is 2σ.
[38] VASENKO 90 limit based on background statistics. Maximum likelihood solution is >2000.
[39] MORALES 88 notes a 2.5 sigma coincidence rate between electrons with energy 1483.7 ± 0.5 keV in the Ge detector and photons with energy 558 ± 15 keV in the NaI detector, close to the region where neutrinoless $0^+ \rightarrow 2^+$ ^{76}Ge decay should be expected. However, a further study reported in MORALES 91 rejects this peak at the 95% CL.
[40] HUBERT 85 gives lifetime limits on neutrinoless double β decay of ^{76}Ge to excited states of ^{76}Se.
[41] KIRSTEN 83 reports "2σ" error. References are given to earlier determinations of the ^{130}Te lifetime.

$\langle m_\nu \rangle$, The Effective Weighted Sum of Majorana Neutrino Masses Contributing to Neutrinoless Double β Decay

$\langle m_\nu \rangle = |\Sigma\ U^2_{1j} m_{\nu_j}|$, where the sum goes from 1 to n and where n = number of neutrino generations, and ν_j is a Majorana neutrino. Note that U^2_{1j}, not $|U_{1j}|^2$, occurs in the sum. The possibility of cancellations has been stressed.

VALUE (eV)	CL%	ISOTOPE		TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 0.65	90	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Enriched HPGe	BALYSH	95
< 4.1	90	^{116}Cd	0ν		^{116}CdWO$_4$ scint	[42] DANEVICH	95
< 6.6	68	^{100}Mo	0ν	$0^+ \rightarrow 0^+$	Si(Li)	[43] ALSTON-...	93
< 2.8–4.3	90	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	TPC	[44] VUILLEUMIER	93
< 1.5	90	^{76}Ge			Enriched HPGe	[45] BALYSH	92
< 1.1–1.5		^{128}Te			Geochem	[46] BERNATOW...	92
< 5	68	^{82}Se			TPC	[47] ELLIOTT	92
< 1.9–6.7	68	^{76}Ge		$0^+ \rightarrow 0^+$	HPGe	[48] REUSSER	92
< 11–30	95	^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop cntr	[49] BELLOTTI	91
< 3.3–5.0		^{136}Xe	0ν	$0^+ \rightarrow 0^+$	TPC	[50] WONG	91
< 8.3	76	^{48}Ca	0ν		CaF$_2$ scint.	YOU	91
< 1.4–8	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Enriched Ge(Li)	[51] VASENKO	90
<4.3–28		^{136}Xe	0ν	$0^+ \rightarrow 0^+$	Prop chamber	[52] BELLOTTI	89
<12	68	^{116}Cd	0ν		^{116}CdWO$_4$ scint	[53] DANEVICH	89
< 1.8		^{76}Ge	0ν	$0^+ \rightarrow 0^+$	HPGe	[54] CALDWELL	87
< 2.7	68	^{76}Ge	0ν	$0^+ \rightarrow 0^+$	HPGe	BELLOTTI	86
<20	68	^{76}Ge	0ν		Ge(Li)	[55] HUBERT	85
<22		^{76}Ge	0ν	$0^+ \rightarrow 0^+$	Ge	FORSTER	84
<10	90	^{76}Ge	0ν		Intrinsic Ge	AVIGNONE	83
< 5.6	95	^{128}Te			Geochem	KIRSTEN	83

[42] DANEVICH 95 is identical to GEORGADZE 95.
[43] ALSTON-GARNJOST 93 use the "conservative matrix elements of Engel *et al.* (ENGEL 88).
[44] VUILLEUMIER 93 mass range from parameter range in the Caltech calculations (ENGEL 88). On the basis of these calculations, the BALYSH 92 mass range would be < 2.2–4.4 eV.
[45] BALYSH 92 uses the MUTO 89 matrix elements.
[46] BERNATOWICZ 92 finds these majoron mass limits assuming that the measured geochemical decay width is a limit on the 0ν decay width. The range is the range found using matrix elements from HAXTON 84, TOMODA 87, and SUHONEN 91. Further details of the experiment are given in BERNATOWICZ 93.
[47] ELLIOTT 92 uses the matrix elements of HAXTON 84.
[48] REUSSER 92 contains the final results for the search for neutrinoless double beta decay of ^{76}Ge in the Gotthard tunnel underground laboratory. Range comes from range of nuclear matrix elements used to relate neutrino mass to lifetime limit (ENGEL 88, HAXTON 84, and MUTO 89).
[49] BELLOTTI 91 range of limits comes from range of theoretical calculations considered. Analysis uses difference between natural and enriched ^{136}Xe runs to obtain the $\beta\beta 0\nu$ limits, leading to "less stringent, but safer limits."
[50] WONG 91 uses the quasiparticle random phase approximation of ENGEL 88 to extract the above limit for the case of a transition caused by a Majorana neutrino mass.
[51] VASENKO 90 range comes from range of nuclear matrix elements of HAXTON 84, ENGEL 88. On the basis of the MUTO 89 matrix element, the limit will be < 1.3 eV.
[52] BELLOTTI 89 gives model-dependent upper bounds on Majorana neutrino masses and on the admixture of right-handed lepton-number-violating currents.
[53] DANEVICH 89 uses calculations of GROTZ 86.
[54] CALDWELL 87 least stringent limit (using HAXTON 84) is listed. Limits given using other nuclear matrix element calculations are 1.5 eV and 0.7 eV.
[55] HUBERT 85 limit is obtained from analysis of data using theoretical calculations by HAXTON 81, HAXTON 82.

Limits on Lepton-Number Violating ($V+A$) Current Admixture

For reasons given in the discussion at the beginning of this section, we list only results from 1989 and later. $\langle \lambda \rangle = \lambda \sum U_{1j} V_{1j}$ and $\langle \eta \rangle = \eta \sum U_{1j} V_{1j}$, where the sum is over the number of neutrino generations. This sum vanishes for massless or unmixed neutrinos.

$\langle \lambda \rangle$ (10^{-6})	CL%	$\langle \eta \rangle$ (10^{-8})	CL%	ISOTOPE	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<5.3	90	<5.9	90	^{116}Cd	^{116}CdWO$_4$ scint	[56] DANEVICH	95
<2.3	90	<1.5	90	^{76}Ge	Enriched HPGe	[57] BALYSH	92
		<5.3		^{128}Te	Geochem	[58] BERNATOW...	92
<3.6	68	<2.2	68	^{76}Ge	HPGe	[59] REUSSER	92
<9	68	<8	68	^{76}Ge	Ion chamber	BELLOTTI	89

[56] DANEVICH 95 is identical to GEORGADZE 95.
[57] BALYSH 92 uses the MUTO 89 matrix elements.
[58] BERNATOWICZ 92 takes the measured geochemical decay width as a limit on the 0ν width, and uses the SUHONEN 91 coefficients to obtain the least restrictive limit on η. Further details of the experiment are given in BERNATOWICZ 93.
[59] REUSSER 92 uses the MUTO 89 matrix elements for this reduction.

(D) Other bounds from nuclear and particle decays

Limits on $|U_{1J}|^2$ as Function of m_{ν_J}

Peak and kink search tests

Limits on $|U_{1j}|^2$ as function of m_{ν_j}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1 × 10^{-7}	90	[60] BRITTON	92B	CNTR	50 MeV < m_{ν_j} < 130 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5 × 10^{-6}	90	DELEENER-...	91		m_{ν_j} = 20 MeV
<5 × 10^{-7}	90	DELEENER-...	91		m_{ν_j} = 40 MeV
<3 × 10^{-7}	90	DELEENER-...	91		m_{ν_j} = 60 MeV
<1 × 10^{-6}	90	DELEENER-...	91		m_{ν_j} = 80 MeV
<1 × 10^{-6}	90	DELEENER-...	91		m_{ν_j} = 100 MeV
<5 × 10^{-7}	90	AZUELOS	86	CNTR	m_{ν_j}=60 MeV
<2 × 10^{-7}	90	AZUELOS	86	CNTR	m_{ν_j}=80 MeV
<3 × 10^{-7}	90	AZUELOS	86	CNTR	m_{ν_j}=100 MeV
<1 × 10^{-6}	90	AZUELOS	86	CNTR	m_{ν_j}=120 MeV
<2 × 10^{-7}	90	AZUELOS	86	CNTR	m_{ν_j}=130 MeV
<8 × 10^{-6}		DELEENER-...	86	CNTR	m_{ν_j}=20 MeV
<4 × 10^{-7}		DELEENER-...	86	CNTR	m_{ν_j}=60 MeV
<2 × 10^{-6}		DELEENER-...	86	CNTR	m_{ν_j}=100 MeV
<7 × 10^{-6}		DELEENER-...	86	CNTR	m_{ν_j}=120 MeV
<1 × 10^{-4}	90	[61] BRYMAN	83B	CNTR	m_{ν_j}=5 MeV
<1.5 × 10^{-6}	90	BRYMAN	83B	CNTR	m_{ν_j}=53 MeV
<1 × 10^{-5}	90	BRYMAN	83B	CNTR	m_{ν_j}=70 MeV
<1 × 10^{-4}	90	BRYMAN	83B	CNTR	m_{ν_j}=130 MeV
<1 × 10^{-4}	68	[62] SHROCK	81	THEO	m_{ν_j}=10 MeV
<5 × 10^{-6}	68	[62] SHROCK	81	THEO	m_{ν_j}=60 MeV
<1 × 10^{-5}	68	[63] SHROCK	80	THEO	m_{ν_j}=80 MeV
<3 × 10^{-6}	68	[63] SHROCK	80	THEO	m_{ν_j}=160 MeV

[60] BRITTON 92B is from a search for additional peaks in the e^+ spectrum from $\pi^+ \rightarrow e^+ \nu_e$ decay at TRIUMF. See also BRITTON 92.
[61] BRYMAN 83B obtain upper limits from both direct peak search and analysis of B($\pi \rightarrow e\nu$)/B($\pi \rightarrow \mu\nu$). Latter limits are not listed, except for this entry (i.e. — we list the most stringent limits for given mass).
[62] Analysis of $(\pi^+ \rightarrow e^+ \nu_e)/(\pi^+ \rightarrow \mu^+ \nu_\mu)$ and $(K^+ \rightarrow e^+ \nu_e)/(K^+ \rightarrow \mu^+ \nu_\mu)$ decay ratios.
[63] Analysis of $(K^+ \rightarrow e^+ \nu_e)$ spectrum.

Kink search in nuclear β decay

High-sensitivity follow-up experiments show that indications for a neutrino with mass 17 keV (Simpson, Hime, and others) were not valid. Accordingly, we no longer list the experiments by these authors and some others which made positive claims of 17 keV neutrino emission. Complete listings are given in the 1994 edition (Physical Review **D50** 1173 (1994)). Limits on $|U_{1j}|^2$ as a function of m_{ν_j}.

VALUE (units 10^{-3})	CL%	m_{ν_j} (keV)	ISOTOPE	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 1 \times 10^{-2}$	95	1	^{3}H	SPEC	[64] HIDDEMANN	95
$< 6 \times 10^{-3}$	95	2	^{3}H	SPEC	[64] HIDDEMANN	95
$< 2 \times 10^{-3}$	95	3	^{3}H	SPEC	[64] HIDDEMANN	95
$< 2 \times 10^{-3}$	95	4	^{3}H	SPEC	[64] HIDDEMANN	95
$0.3 \pm 1.5 \pm 0.8$		17	^{35}S	Mag spect	[65] BERMAN	93
$<$ 2.8	99	17	^{3}H	Prop chamber	[66] KALBFLEISCH	93
$<$ 1	99	14.4–15.2	^{3}H	Prop chamber	[66] KALBFLEISCH	93
$<$ 0.7	99	16.3–16.6	^{3}H	Prop chamber	[66] KALBFLEISCH	93
$<$ 2	95	13–40	^{35}S	Si(Li)	[67] MORTARA	93
$<$ 0.73	95	17	^{63}Ni	Mag spect	OHSHIMA	93
$<$ 1.5	95	10.5–25.0	^{63}Ni	Mag spect	[68] OHSHIMA	93
$<$ 6	95	5–25	^{55}Fe	IBEC in Ge	[69] WIETFELDT	93
$<$ 2	90	17	^{35}S	Mag spect.	[70] CHEN	92
$<$ 0.95	95	17	^{63}Ni	Mag spect	[71] KAWAKAMI	92
$<$ 1.0	95	10–24	^{63}Ni	Mag spect	KAWAKAMI	92
$<$ 10	90	16–35	^{125}I	IBEC; γ det	[72] BORGE	86
$<$ 7.5	99	5–50	^{35}S	Mag spect	ALTZITZOG...	85
$<$ 8	90	80	^{35}S	Mag spect	[73] APALIKOV	85
$<$ 1.5	90	60	^{35}S	Mag spect	APALIKOV	85
$<$ 8	90	30	^{35}S	Mag spect	APALIKOV	85
$<$ 3	90	17	^{35}S	Mag spect	APALIKOV	85
$<$ 45	90	4	^{35}S	Mag spect	APALIKOV	85
$<$ 10	90	5–30	^{35}S	Si(Li)	DATAR	85
$<$ 3.0	90	5–50		Mag spect	MARKEY	85
$<$ 0.62	90	48	^{35}S	Si(Li)	OHI	85
$<$ 0.90	90	30	^{35}S	Si(Li)	OHI	85
$<$ 1.30	90	20	^{35}S	Si(Li)	OHI	85
$<$ 1.50	90	17	^{35}S	Si(Li)	OHI	85
$<$ 3.30	90	10	^{35}S	Si(Li)	OHI	85
$<$ 25	90	30	^{64}Cu	Mag spect	[74] SCHRECK...	83
$<$ 4	90	140	^{64}Cu	Mag spect	[74] SCHRECK...	83
$<$ 8	90	440	^{64}Cu	Mag spect	[74] SCHRECK...	83
$<$ 1	95	0.1			[75] SIMPSON	81B
$<$ 4	95× 1010^3				[75] SIMPSON	81B
$<$100	90	0.1–3000		THEO	[76] SHROCK	80
$<$ 0.1	68	80		THEO	[77] SHROCK	80

[64] In the beta spectrum from tritium β decay nonvanishing or mixed $m_{\overline{\nu}_1}$ state in the mass region 0.01–4 keV. For m_{ν_j} <1 keV, their upper limit on $|U_{1j}|^2$ becomes less

[65] BERMAN 93 uses an iron-free intermediate-image magnetic spectrometer to measure ^{35}Sβ decay over a large portion of the spectrum. Paper reports (0.01 ± 0.15)%; above result revised by author on basis of analysis refinements.

[66] KALBFLEISCH 93 extends the 17 keV neutrino search of BAHRAN 92, using an improved proportional chamber to which a small amount of ^{3}H is added. Systematics are significantly reduced, allowing for an improved upper limit. The authors give a 99% confidence limit on $|U_{1j}|^2$ as a function of m_{ν_j} in the range from 13.5 keV to 17.5 keV. Typical upper limits are listed above. They report that this experiment in combination with BAHRAN 92 gives an upper limit of 2.4×10^{-3} at the 99% CL. See also the related papers BAHRAN 93, BAHRAN 93B, and BAHRAN 95 on theoretical aspects of beta spectra and fitting methods for heavy neutrinos.

[67] MORTARA 93 limit is from study using a high-resolution solid-state detector with a superconducting solenoid. The authors note that "The sensitivity to neutrino mass is verified by measurement with a mixed source of ^{35}S and ^{14}C, which artificially produces a distortion in the beta spectrum similar to that expected from the massive neutrino."

[68] OHSHIMA 93 is the full data analysis from this experiment. The above limit on the mixing strength for a 17 keV neutrino is obtained from the measurement $|U_{1j}|^2 = (-0.11 \pm 0.33 \pm 0.30) \times 10^{-3}$ by taking zero as the best estimate and ignoring physical boundaries; see discussion in HOLZSCHUH 92B for a comparison of methods. An earlier report of this experiment was given in KAWAKAMI 92.

[69] WIETFELDT 93 is an extension of the NORMAN 91 experiment. However, whereas NORMAN 91 reported indications for the emission of a neutrino with mass $m_{\nu_j} = 21 \pm 2$ keV and coupling strength $= 0.0085 \pm 0.0045$, the present experiment states that "We find no evidence for emission of a neutrino in the mass range 5–25 keV. In particular, a 17 keV neutrino with $\sin^2\theta$ ($|U_{1j}|^2$ in our notation) $= 0.008$ is excluded at the 7σ level." The listed limits can be obtained from the paper's Fig. 4. The authors acknowledge that this conclusion contradicts the one reported in NORMAN 91, based on a smaller data sample. In further tests, WIETFELDT 95 have shown that "the observed distortion was most likely caused by systematic effects... A new measurement with a smaller data sample shows no sign of this distortion."

[70] CHEN 92 is a continuation and improvement of the Boehm *et al.* Caltech iron-free magnetic spectrometer experiment searching for emission of massive neutrinos in ^{35}S decay (MARKEY 85). The upper limit on $|U_{1j}|^2$ for $m_{\nu_j} = 17$ keV comes from the measurement $|U_{1j}|^2 = (-0.5 \pm 1.4) \times 10^{-3}$. The authors state that their results "rule out, at the 6σ level, a 17 keV neutrino admixed at 0.85% (*i.e.* with $|U_{1j}|^2 = 0.85 \times 10^{-2}$," the level claimed by Hime and Jelly in HIME 91. They also state that "our data show no evidence for a heavy neutrino with a mass between 12 and 22 keV" with substantial admixture in the weak admixture in the weak eigenstate ν_e; see their Fig. 4 for a graphical set of measured values of $|U_{1j}|^2$ for various hypothetical values of m_{ν_j} in this range.

[71] KAWAKAMI 92 experiment final results are given in OHSHIMA 93. The upper limit is improved to 0.73×10^{-3}, based on $|U_{1j}|^2 = (-0.11 \pm 0.33 \pm 0.30) \times 10^{-3}$. Ohshima notes that the result is 22σ away from the value $|U_{1j}|^2 = 1\%$.

[72] BORGE 86 results originally presented as evidence against the SIMPSON 85 claim of a 17 keV antineutrino emitted with $|U_{1j}|^2 = 0.03$ in ^{3}H decay.

[73] This limit was taken from the figure 3 of APALIKOV 85; the text gives a more restrictive limit of 1.7×10^{-3} at CL = 90%.

[74] SCHRECKENBACH 83 is a combined measurement of the β^+ and β^- spectrum.

[75] Application of kink search test to tritium β decay Kurie plot.

[76] SHROCK 80 was a retroactive analysis of data on several superallowed β decays to search for kinks in the Kurie plot.

[77] Application of test to search for kinks in β decay Kurie plots.

Searches for Decays of Massive ν

Limits on $|U_{1j}|^2$ as function of m_{ν_j}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-5}$	90	[78] BARANOV	93		m_{ν_j}= 100 MeV
$<1 \times 10^{-6}$	90	[78] BARANOV	93		m_{ν_j}= 200 MeV
$<3 \times 10^{-7}$	90	[78] BARANOV	93		m_{ν_j}= 300 MeV
$<2 \times 10^{-7}$	90	[78] BARANOV	93		m_{ν_j}= 400 MeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	m_{ν_j} = 20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	m_{ν_j} = 40 GeV
all values ruled out	95	[79] BURCHAT	90	MRK2	m_{ν_j} < 19.6 GeV
$<1 \times 10^{-10}$	95	[79] BURCHAT	90	MRK2	m_{ν_j} = 22 GeV
$<1 \times 10^{-11}$	95	[79] BURCHAT	90	MRK2	m_{ν_j} = 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_j}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_j}= 42.7–45.7 GeV
$<5 \times 10^{-3}$	90	AKERLOF	88	HRS	m_{ν_j}=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF	88	HRS	m_{ν_j}=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF	88	HRS	m_{ν_j}=6 GeV
$<1.2 \times 10^{-7}$	90	BERNARDI	88	CNTR	m_{ν_j}=100 MeV
$<1 \times 10^{-8}$	90	BERNARDI	88	CNTR	m_{ν_j}=200 MeV
$<2.4 \times 10^{-9}$	90	BERNARDI	88	CNTR	m_{ν_j}=300 MeV
$<2.1 \times 10^{-9}$	90	BERNARDI	88	CNTR	m_{ν_j}=400 MeV
$<2 \times 10^{-2}$	68	[80] OBERAUER	87		m_{ν_j}=1.5 MeV
$<8 \times 10^{-4}$	68	[80] OBERAUER	87		m_{ν_j}=4.0 MeV
$<8 \times 10^{-3}$	90	BADIER	86	CNTR	m_{ν_j}=400 MeV
$<8 \times 10^{-5}$	90	BADIER	86	CNTR	m_{ν_j}=1.7 GeV
$<8 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_j}=100 MeV
$<4 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_j}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_j}=400 MeV
$<3 \times 10^{-5}$	90	DORENBOS...	86	CNTR	m_{ν_j}=150 MeV
$<1 \times 10^{-6}$	90	DORENBOS...	86	CNTR	m_{ν_j}=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS...	86	CNTR	m_{ν_j}=1.6 GeV
$<7 \times 10^{-7}$	90	[81] COOPER-...	85	HLBC	m_{ν_j}=0.4 GeV
$<8 \times 10^{-8}$	90	[81] COOPER-...	85	HLBC	m_{ν_j}=1.5 GeV
$<1 \times 10^{-2}$	90	[82] BERGSMA	83B	CNTR	m_{ν_j}=10 MeV
$<1 \times 10^{-5}$	90	[82] BERGSMA	83B	CNTR	m_{ν_j}=110 MeV
$<6 \times 10^{-7}$	90	[82] BERGSMA	83B	CNTR	m_{ν_j}=410 MeV
$<1 \times 10^{-5}$	90	GRONAU	83		m_{ν_j}=160 MeV
$<1 \times 10^{-6}$	90	GRONAU	83		m_{ν_j}=480 MeV

[78] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron. The limits are not as good as those achieved earlier by BERGSMA 83 and BERNARDI 86, BERNARDI 88.

[79] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[80] OBERAUER 87 bounds from search for $\nu \rightarrow \nu' ee$ decay mode using reactor (anti)neutrinos.

[81] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, j is not equal to 3, i.e. ν_j cannot be the dominant mass eigenstate in ν_τ since m_{ν_3} <70 MeV (ALBRECHT 85I). Also, of course, j is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

[82] BERGSMA 83B also quote limits on $|U_{13}|^2$ where the index 3 refers to the mass eigenstate dominantly coupled to the τ. Those limits were based on assumptions about the D_s mass and $D_s \rightarrow \tau \nu_\tau$ branching ratio which are no longer valid. See COOPER-SARKAR 85.

Limits on $|U_{2J}|^2$ as Function of m_{ν_J}

Peak search test

Limits on $|U_{2j}|^2$ as function of m_{ν_j}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>10^{-16}$		[83] ARMBRUSTER 95	KARM	$m_{\nu_x} = 33.9$ MeV
$< 4 \times 10^{-7}$	95	[84] BILGER 95	LEPS	$m_{\overline{\nu}_x} = 33.9$ MeV
$< 7 \times 10^{-8}$	95	[84] BILGER 95	LEPS	$m_{\nu_x} = 33.9$ MeV
$< 2.6 \times 10^{-8}$	95	[84] DAUM 95B	TOF	$m_{\nu_x} = 33.9$ MeV
$< 2 \times 10^{-2}$	90	DAUM 87		m_{ν_j}=1 MeV
$< 1 \times 10^{-3}$	90	DAUM 87		m_{ν_j}=2 MeV
$< 6 \times 10^{-5}$	90	DAUM 87		3 MeV $< m_{\nu_j} <$ 19.5 MeV
$< 3 \times 10^{-2}$	90	[85] MINEHART 84		m_{ν_j}=2 MeV
$< 1 \times 10^{-3}$	90	[85] MINEHART 84		m_{ν_j}=4 MeV
$< 3 \times 10^{-4}$	90	[85] MINEHART 84		m_{ν_j}=10 MeV
$< 5 \times 10^{-6}$	90	[86] HAYANO 82		m_{ν_j}=330 MeV
$< 1 \times 10^{-4}$	90	[86] HAYANO 82		m_{ν_j}=70 MeV
$< 9 \times 10^{-7}$	90	[86] HAYANO 82		m_{ν_j}=250 MeV
$< 1 \times 10^{-1}$	90	[85] ABELA 81		m_{ν_j}=4 MeV
$< 7 \times 10^{-5}$	90	[85] ABELA 81		m_{ν_j}=10.5 MeV
$< 2 \times 10^{-4}$	90	[85] ABELA 81		m_{ν_j}=11.5 MeV
$< 2 \times 10^{-5}$	90	[85] ABELA 81		m_{ν_j}=16–30 MeV
$< 2 \times 10^{-5}$	95	[86] ASANO 81		m_{ν_j}=170 MeV
$< 3 \times 10^{-6}$	95	[86] ASANO 81		m_{ν_j}=210 MeV
$< 3 \times 10^{-6}$	95	[86] ASANO 81		m_{ν_j}=230 MeV
$< 6 \times 10^{-6}$	95	[87] ASANO 81		m_{ν_j}=240 MeV
$< 5 \times 10^{-7}$	95	[87] ASANO 81		m_{ν_j}=280 MeV
$< 6 \times 10^{-6}$	95	[87] ASANO 81		m_{ν_j}=300 MeV
$< 1 \times 10^{-2}$	95	[85] CALAPRICE 81		m_{ν_j}=7 MeV
$< 3 \times 10^{-3}$	95	[85] CALAPRICE 81		m_{ν_j}=33 MeV
$< 1 \times 10^{-4}$	68	[88] SHROCK 81	THEO	m_{ν_j}=13 MeV
$< 3 \times 10^{-5}$	68	[88] SHROCK 81	THEO	m_{ν_j}=33 MeV
$< 6 \times 10^{-3}$	68	[89] SHROCK 81	THEO	m_{ν_j}=80 MeV
$< 5 \times 10^{-3}$	68	[89] SHROCK 81	THEO	m_{ν_j}=120 MeV

[83] ARMBRUSTER 95 study the reactions $^{12}C(\nu_e,e^-)\,^{12}N$ and $^{12}C(\nu,\nu')\,^{12}C^*$ induced by neutrinos from π^+ and μ^+ decay at the ISIS neutron spallation source at the Rutherford-Appleton laboratory. An anomaly in the time distribution can be interpreted as the decay $\pi^+ \rightarrow \mu^+ \nu_x$, where ν_x is a neutral weakly interacting particle with mass $\approx$ 33.9 MeV and spin 1/2. The lower limit to the branching ratio is a function of the lifetime of the new massive neutral particle, and reaches a minimum of a few $\times 10^{-16}$ for $\tau_x \sim 5$ s.

[84] From experiments of π^+ and π^- decay in flight at PSI, to check the claim of the KARMEN Collaboration quoted above (ARMBRUSTER 95).

[85] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[86] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[87] Analysis of experiment on $K^+ \rightarrow \mu^+ \nu_\mu \nu_x \overline{\nu}_x$ decay.

[88] Analysis of magnetic spectrometer experiment, bubble chamber experiment, and emulsion experiment on $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay.

[89] Analysis of magnetic spectrometer experiment on $K \rightarrow \mu, \nu_\mu$ decay.

Peak Search in Muon Capture

Limits on $|U_{2j}|^2$ as function of m_{ν_j}

VALUE	DOCUMENT ID	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •		
$<1 \times 10^{-1}$	DEUTSCH 83	m_{ν_j}=45 MeV
$<7 \times 10^{-3}$	DEUTSCH 83	m_{ν_j}=70 MeV
$<1 \times 10^{-1}$	DEUTSCH 83	m_{ν_j}=85 MeV

Searches for Decays of Massive ν

Limits on $|U_{2j}|^2$ as function of m_{ν_j}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3 \times 10^{-6}$	90	GALLAS 95	CNTR	m_{ν_j} = 1 GeV
$<3 \times 10^{-5}$	90	[90] VILAIN 95C	CHM2	m_{ν_j} = 2 GeV
$<6.2 \times 10^{-8}$	95	ADEVA 90S	L3	m_{ν_j} = 20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA 90S	L3	m_{ν_j} = 40 GeV
all values ruled out	95	[91] BURCHAT 90	MRK2	$m_{\nu_j} <$ 19.6 GeV
$<1 \times 10^{-10}$	95	[91] BURCHAT 90	MRK2	m_{ν_j} = 22 GeV
$<1 \times 10^{-11}$	95	[91] BURCHAT 90	MRK2	m_{ν_j} = 41 GeV
all values ruled out	95	DECAMP 90F	ALEP	m_{ν_j}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP 90F	ALEP	m_{ν_j}= 42.7–45.7 GeV
$<5 \times 10^{-4}$	90	[92] KOPEIKIN 90	CNTR	m_{ν_j} = 5.2 MeV
$<5 \times 10^{-3}$	90	AKERLOF 88	HRS	m_{ν_j}=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF 88	HRS	m_{ν_j}=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF 88	HRS	m_{ν_j}=6 GeV
$<1 \times 10^{-7}$	90	BERNARDI 88	CNTR	m_{ν_j}=200 MeV
$<3 \times 10^{-9}$	90	BERNARDI 88	CNTR	m_{ν_j}=300 MeV
$<4 \times 10^{-4}$	90	[93] MISHRA 87	CNTR	m_{ν_j}=1.5 GeV
$<4 \times 10^{-3}$	90	[93] MISHRA 87	CNTR	m_{ν_j}=2.5 GeV
$<0.9 \times 10^{-2}$	90	[93] MISHRA 87	CNTR	m_{ν_j}=5 GeV
<0.1	90	[93] MISHRA 87	CNTR	m_{ν_j}=10 GeV
$<8 \times 10^{-4}$	90	BADIER 86	CNTR	m_{ν_j}=600 MeV
$<1.2 \times 10^{-5}$	90	BADIER 86	CNTR	m_{ν_j}=1.7 GeV
$<3 \times 10^{-8}$	90	BERNARDI 86	CNTR	m_{ν_j}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI 86	CNTR	m_{ν_j}=350 MeV
$<1 \times 10^{-6}$	90	DORENBOS... 86	CNTR	m_{ν_j}=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS... 86	CNTR	m_{ν_j}=1600 MeV
$<0.8 \times 10^{-5}$	90	[94] COOPER-... 85	HLBC	m_{ν_j}=0.4 GeV
$<1.0 \times 10^{-7}$	90	[94] COOPER-... 85	HLBC	m_{ν_j}=1.5 GeV

[90] VILAIN 95C is a search for the decays of heavy isosinglet neutrinos produced by neutral current neutrino interactions. Limits were quoted for masses in the range from 0.3 to 24 GeV. The best limit is listed above.

[91] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[92] KOPEIKIN 90 find no m_{ν_j} in the interval 1–6.3 MeV at 90%CL for maximal mixing.

[93] See also limits on $|U_{3j}|$ from WENDT 87.

[94] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, j is not equal to 3, i.e. ν_j cannot be the dominant mass eigenstate in ν_τ since m_{ν_3} <70 MeV (ALBRECHT 85I). Also, of course, j is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

Limits on $|U_{3J}|^2$ as a Function of m_{ν_J}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<6 \times 10^{-4}$	90	[95] HAGNER 95	WIRE	m_{ν_j} = 2 MeV
$<2.5 \times 10^{-4}$	90	[95] HAGNER 95	WIRE	m_{ν_j} = 4 MeV
$<3.1 \times 10^{-4}$	90	[95] HAGNER 95	WIRE	m_{ν_j} = 6 MeV
$<2 \times 10^{-3}$	90	[95] HAGNER 95	WIRE	m_{ν_j} = 8 MeV
$<6.2 \times 10^{-8}$	95	ADEVA 90S	L3	m_{ν_j} = 20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA 90S	L3	m_{ν_j} = 40 GeV
all values ruled out	95	[96] BURCHAT 90	MRK2	$m_{\nu_j} <$ 19.6 GeV
$<1 \times 10^{-10}$	95	[96] BURCHAT 90	MRK2	m_{ν_j} = 22 GeV
$<1 \times 10^{-11}$	95	[96] BURCHAT 90	MRK2	m_{ν_j} = 41 GeV
all values ruled out	95	DECAMP 90F	ALEP	m_{ν_j}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP 90F	ALEP	m_{ν_j}= 42.7–45.7 GeV
$<5 \times 10^{-2}$	80	AKERLOF 88	HRS	m_{ν_j}=2.5 GeV
$<9 \times 10^{-5}$	80	AKERLOF 88	HRS	m_{ν_j}=4.5 GeV

[95] HAGNER 95 is a search at the Bugey reactor for the neutrino decay $\nu_e \rightarrow \nu_j e^+ e^-$. Upper limits were obtained for m_{ν_3} in the range from 1 to 9.5 MeV.

[96] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

Limits on $|U_{aJ}|^2$

Where a = 1, 2 from ρ parameter in μ decay.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-2}$	68	SHROCK	81B	THEO	m_{ν_j}=10 MeV
$<2 \times 10^{-3}$	68	SHROCK	81B	THEO	m_{ν_j}=40 MeV
$<4 \times 10^{-2}$	68	SHROCK	81B	THEO	m_{ν_j}=70 MeV

Limits on $|U_{1J} \times U_{2J}|$ as Function of m_{ν_J}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3 \times 10^{-5}$	90	[97] BARANOV	93		m_{ν_j}= 80 MeV
$<3 \times 10^{-6}$	90	[97] BARANOV	93		m_{ν_j}= 160 MeV
$<6 \times 10^{-7}$	90	[97] BARANOV	93		m_{ν_j}= 240 MeV
$<2 \times 10^{-7}$	90	[97] BARANOV	93		m_{ν_j}= 320 MeV
$<9 \times 10^{-5}$	90	BERNARDI	86	CNTR	m_{ν_j}=25 MeV
$<3.6 \times 10^{-7}$	90	BERNARDI	86	CNTR	m_{ν_j}=100 MeV
$<3 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_j}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_j}=350 MeV
$<1 \times 10^{-2}$	90	BERGSMA	83B	CNTR	m_{ν_j}=10 MeV
$<1 \times 10^{-5}$	90	BERGSMA	83B	CNTR	m_{ν_j}=140 MeV
$<7 \times 10^{-7}$	90	BERGSMA	83B	CNTR	m_{ν_j}=370 MeV

[97] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron.

SOLAR NEUTRINOS

(by K. Nakamura, KEK, National Laboratory for High-Energy Physics, Japan)

The Sun is a main-sequence star at a stage of stable hydrogen burning. It produces an intense flux of electron neutrinos as a consequence of nuclear fusion reactions which generate solar energy, and whose combined effect is

$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + 26.73\ \text{MeV} - E_\nu\ , \qquad (1)$$

where E_ν represents the energy taken away by neutrinos, with an average value being $\langle E_\nu \rangle \sim 0.6$ MeV. Each neutrino-producing reaction and the resulting flux predicted by the two recent standard solar model (SSM) calculations [1,2] are listed in Table 1. Figure 1 shows the energy spectra of solar neutrinos from these reactions quoted from the SSM calculation by Bahcall and Ulrich [3]. All SSM calculations give essentially the same results for the same input parameters and physics. The Bahcall and Pinsonneault model [1] and the Turck-Chièze and Lopes model [2] listed in Table 1 differ primarily in that Bahcall and Pinsonneault include helium diffusion [4].

Observations of solar neutrinos directly addresses the SSM and, more generally, the theory of stellar structure and evolution which is the basis of the SSM. The Sun as a well defined neutrino source also provides extremely important opportunities to investigate nontrivial neutrino properties such as nonzero mass and mixing, because of the wide range of matter density and the very long distance from the Sun to the Earth. In fact, the currently available solar-neutrino data seem to require such neutrino properties, if one tries to understand them consistently.

At present, four solar-neutrino experiments are taking data. Three of them are radiochemical experiments using ^{37}Cl (Homestake in USA) or ^{71}Ga (GALLEX at Gran Sasso in Italy and SAGE at Baksan in Russia) to capture neutrinos: $^{37}\text{Cl}\ \nu_e \rightarrow {}^{37}\text{Ar}\ e^-$ (threshold 814 keV) or $^{71}\text{Ga}\ \nu_e \rightarrow {}^{71}\text{Ge}\ e^-$

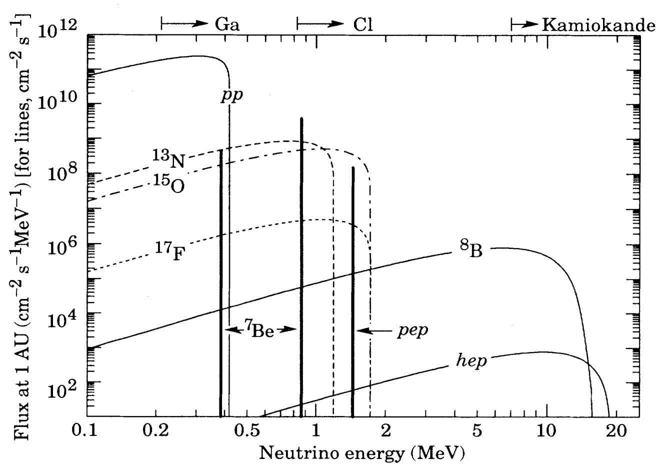

Figure 1: The solar neutrino spectrum predicted by the standard solar model. The neutrino fluxes from continuum sources are given in units of number $\text{cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}$ at one astronomical unit, and the line fluxes are given in number $\text{cm}^{-2}\text{s}^{-1}$. Spectra for the *pp* chain are shown by solid lines, and those for the CNO chain by dotted or dashed lines. (Courtesy of J.N. Bahcall, 1995.)

Table 1: Neutrino-producing reactions in the Sun (the first column) and their abbreviations (second column). The neutrino fluxes predicted by Bahcall and Pinsonneault (B-P) [1] and by Turck-Chièze and Lopes (T-C-L) [2] are listed in the third and fourth columns, respectively. The errors associated with the B-P calculation are "theoretical" 3 standard deviations according to the authors.

Reaction	Abbr.	B-P	T-C-L
$pp \rightarrow d\, e^+\, \nu$	*pp*	$6.00(1 \pm 0.02)$E10	6.02E10
$pe^-p \rightarrow d\, \nu$	*pep*	$1.43(1 \pm 0.04)$E8	1.3E8
$^3\text{He}\ p \rightarrow {}^4\ \text{He}\ e^+\nu$	*hep*	1.23E3	
$^7\text{Be}\ e^- \rightarrow {}^7\ \text{Li}\ \nu + (\gamma)$	^{7}Be	$4.89(1 \pm 0.18)$E9	4.33E9
$^8\text{B} \rightarrow {}^8\text{B}^*\ e^+\nu$	^{8}B	$5.69(1 \pm 0.43)$E6	4.43E9
$^{13}\text{N} \rightarrow {}^{13}\text{C}\ e^+\nu$	^{13}N	$4.92(1 \pm 0.51)$E8	3.83E8
$^{15}\text{O} \rightarrow {}^{15}\text{N}\ e^+\nu$	^{15}O	$4.26(1 \pm 0.58)$E8	3.15E8
$^{17}\text{F} \rightarrow {}^{17}\text{O}\ e^+\nu$	^{17}F	$5.39(1 \pm 0.48)$E6	

(threshold 233 keV). The produced ^{37}Ar and ^{71}Ge are both radioactive nuclei with half lives ($\tau_{1/2}$) of 34.8 days and 11.43 days, respectively. After an exposure of the detector for two to three times $\tau_{1/2}$, the reaction products are extracted and introduced into a low-background proportional counter, and are counted for a sufficiently long period to determine the exponentially decaying signal and a constant background. In the chlorine experiment, the dominant contribution comes from ^{8}B neutrinos, but ^{7}Be, *pep*, ^{13}N, and ^{15}O neutrinos also contribute. At present, the most abundant *pp* neutrinos can be detected only in gallium experiments. Even so, almost half of the capture rate in these experiments is due to other solar neutrinos.

The fourth is a real-time experiment utilizing νe scattering in a large water-Čerenkov detector (Kamiokande in Japan). This experiment takes advantage of the directional correlation between the incoming neutrino and the recoil electron. This feature greatly helps the clear separation of the solar-neutrino signal from the background. Due to its high threshold (7 MeV at present), Kamiokande observes pure ^{8}B solar neutrinos (*hep* neutrinos have too small a flux to be observed in the present generation of solar neutrino experiments.)

Solar neutrinos were first observed in the Homestake chlorine experiment around 1970. From the very beginning, it was recognized that the observed capture rate was significantly smaller than the SSM prediction. This deficit has been called "the solar-neutrino problem." The Kamiokande-II Collaboration started observing the ^{8}B solar neutrinos at the beginning of 1987. Because of the strong directional correlation of νe scattering, this result gave the first direct evidence that the Sun emits neutrinos (no directional information is available in radiochemical solar-neutrino experiments.) The observed solar-neutrino flux was also significantly less than the SSM prediction. In addition, Kamiokande-II obtained the energy spectrum of recoil electrons and the fluxes separately measured in the day time and nighttime. GALLEX presented the first evidence of *pp* solar-neutrino observation in 1992. Here also, the observed capture rate is significantly less than the SSM prediction. SAGE, after initial confusion which is ascribed to statistics by the group, observes a similar capture rate to that of GALLEX. The most recent results on the average capture rates or flux from these experiments [5–8] are compared with the recent SSM calculations [1,2] in Table 2.

Table 2: Recent results from the four solar-neutrino experiments. For Homestake [5], GALLEX [6], and SAGE [7], the data are capture rates given in SNU (Solar Neutrino Units; 1 SNU = 10^{-36} capture per atom per second). For Kamiokande [8], the datum is ^{8}B solar-neutrino flux given in units of 10^6 cm^{-2} s^{-1}. The first errors are statistical and the second errors are systematic. The SSM predictions by Bahcall and Pinsonneault (B-P) [1] and by Turck-Chièze and Lopes (T-C-L) [2] are listed in the third and fourth columns, respectively. The errors associated with the B-P calculation are "theoretical" 3 standard deviations according to the authors.

Experiment	Data	B-P	T-C-L
Homestake	$2.55 \pm 0.17 \pm 0.18$	8.0 ± 3.0	6.4
GALLEX	$79 \pm 10 \pm 6$	131.5^{+21}_{-17}	122.5
SAGE	73^{+18+5}_{-16-7}	131.5^{+21}_{-17}	122.5
Kamiokande	$2.89^{+0.22}_{-0.21} \pm 0.35$	5.7 ± 2.4	4.4

There was a controversy concerning whether the ^{37}Cl capture rate showed time variation, anticorrelated with the sunspot numbers which represent the 11-year solar-activity cycle. However, more than 7 years of the Kamiokande-II solar-neutrino observation does not show evidence for a statistically significant correlation or anticorrelation between the solar-neutrino flux and sunspot number.

All results from the present solar-neutrino experiments indicate significantly less flux than expected from the SSM calculations. Is there any possible consistent explanation of all the results of solar-neutrino observations in the framework of the standard solar model? This is difficult because the Homestake result and the Kamiokande result, taken at face value, are mutually inconsistent if one assumes standard neutrino spectra. That is, with the reduction factor of the ^{8}B solar-neutrino flux as determined from the Kamiokande result, the Homestake ^{37}Cl capture rate would be oversaturated, and there would be no room to accommodate the ^{7}Be solar neutrinos. Several authors made more elaborate analyses using the constraint of observed solar luminosity, and found that not only the SSM but also nonstandard solar models are incompatible with the observed data. Now it is a common understanding that the solar-neutrino problem is not only the deficit of the ^{8}B solar-neutrino flux, but also the deficit of ^{7}Be solar-neutrino flux. The latter problem stems from the incompatibility between the Homestake and Kamiokande results and this makes astrophysical solutions untenable. There is another solar-neutrino problem concerning the low gallium capture rate observed by GALLEX and SAGE.

In view of the above situation, it is attractive to invoke nontrivial neutrino properties. Neutrino oscillation in matter (MSW mechanism) is particularly attractive in explaining all the experimental data on the average solar-neutrino flux consistently, without any a priori assumptions or fine tuning. Several authors made extensive MSW analyses using all the existing data and ended up with similar results. For example, Hata and Langacker [9] analyzed the solar-neutrino data as of mid-1993. They obtained solutions for various standard and nonstandard solar models taking the Earth effect and the Kamiokande day-night data into account. Assuming the Bahcall-Pinsonneault SSM [1], the small-mixing solution ($\Delta m^2 \sim 6 \times 10^{-6}$ eV^2 and $\sin^2 2\theta \sim 7 \times 10^{-3}$) gives an excellent fit to the data, but the large-mixing solution ($\Delta m^2 \sim 9 \times 10^{-6}$ eV^2 and $\sin^2 2\theta \sim 0.6$) is marginally allowed at 90% confidence level.

Assuming that the solution to the solar-neutrino problem be provided by some nontrivial neutrino properties, how can one discriminate various scenarios? There are at least two very important things to do experimentally. One is the measurement of energy spectrum of the solar neutrinos and the other is the measurement of the solar-neutrino flux by utilizing neutral-current reactions. Two high-statistics solar-neutrino experiments which are under construction, SuperKamiokande and Sudbury Neutrino Observatory (SNO) are expected to provide such results within a few years. A 50 kton water-Čerenkov detector, SuperKamiokande is sensitive to the solar-neutrino spectrum through measurement of recoil electron energy. SNO will use 1,000 tons of heavy water (D_2O) to measure solar neutrinos through both inverse beta decay ($\nu_e d \rightarrow e^- pp$) and neutral current interactions ($\nu_x d \rightarrow \nu_x pn$). In addition, νe scattering events will also be measured. The Borexino experiment with 300 tons of ultra-pure liquid scintillator is approved for the Gran Sasso. The primary purpose of this experiment is the measurement of the ^{7}Be solar neutrino flux, where possible deficit is now a key question, by lowering the detection threshold for the recoil electrons to 250 keV. It is hoped that these experiments will finally provide the key to solving the solar-neutrino problem.

References

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(E) Solar ν Experiments

VALUE	DOCUMENT ID		TECN	COMMENT
$77.1 \pm 8.5^{+4.4}_{-5.4}$ SNU	[98] ANSELMANN	95B	GALX	^{71}Ga $\rightarrow$ ^{71}Ge
$73^{+18}_{-16}{}^{+5}_{-7}$ SNU	[99] ABDURASHI...	94	SAGE	^{71}Ga $\rightarrow$ ^{71}Ge
$(0.46 \pm 0.05 \pm 0.06)\times$SSM	[100] HIRATA	90	KAM2	Water Cerenkov
2.33 ± 0.25 SNU	[101] DAVIS	89	HOME	^{37}CL radiochemical
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[102] ACKER	94	THEO	Solar ν decay
	[103] BAHCALL	94	THEO	
	[104] BAHCALL	93		
	[105] HAMPEL	93	RVUE	
6.4 ± 1.4 SNU	[106] TURCK-CHI...	93B	THEO	^{37}CL radiochemical
$(4.4 \pm 1.1) \times 10^{-6}$ cm^{-2}s^{-1}	[106] TURCK-CHI...	93B	THEO	Water Cerenkov, $E \geq 7.5$ MeV
123 ± 7 SNU	[106] TURCK-CHI...	93B	THEO	^{71}Ga $\rightarrow$ ^{71}Ge
8.0 ± 3.0 SNU	[107] BAHCALL	92		^{37}Cl prediction
132^{+21}_{-17} SNU	[107] BAHCALL	92		^{71}Ga prediction
	[108] GARCIA	91	CNTR	Nuclear physics
	[109] HIRATA	91	KAM2	
	[110] FILIPPONE	90	THY	
	[111] HIRATA	90B	KAM2	
7.9 ± 2.6 SNU	[112] BAHCALL	88	THEO	^{37}Cl prediction; total theor. range
132^{+20}_{-17} SNU	[112] BAHCALL	88	THEO	^{71}Ga prediction; total theor. range
5.8 ± 1.3 SNU	TURCK-CHI...	88	THEO	^{37}Cl prediction
125 ± 5 SNU	TURCK-CHI...	88	THEO	^{71}Ga prediction
5.6 SNU	[110] FILIPPONE	83	THEO	^{37}Cl prediction
7.6 ± 3.3 SNU	[113] BAHCALL	82		^{37}Cl prediction
106^{+13}_{-8} SNU	[113] BAHCALL	82		^{71}Ga prediction
7.0 ± 3.0 SNU	FILIPPONE	82	THEO	^{37}Cl prediction
6.9 ± 1.0 SNU	FOWLER	82	THEO	^{37}Cl prediction
7.3 SNU	BAHCALL	80	THEO	^{37}CL prediction

See also the reviews by BAHCALL 92, DAVIS 89, and ACKER 94. The latter rules out neutrino decay as a solution to the solar neutrino problem at better than 98% using the existing solar neutrino data as of mid-1993.

[98] ANSELMANN 95B result is for a total of 39 completed runs (GALLEX I and GALLEX II combined), which updates the ANSELMANN 94 result. The total run data, covering the period 14 May 1991 through 22 June 1994, are consistent with a ^{71}Ge production rate constant in time. The results are strengthened by a calibration run using a strong ^{51}Cr source (ANSELMANN 95), where the (measured)/(expected) Cr-induced ^{71}Ge rate was found to be 1.04 ± 0.12.

[99] ABDURASHITOV 94 result is for a total of 15 runs from January 1990 through May 1992, using 30 tons of metallic gallium for the first 7 runs, increased to 57 tons for the rest of 8 runs. The first 5 runs in 1990 yielded $40^{+31}_{-38}{}^{+5}_{-7}$ SNU which updates the ABAZOV 91B result.

[100] HIRATA 90 data consists of 1040 days with threshold $E_e > 9.3$ MeV (first 450 days) or $E_e > 7.5$ MeV. "The total data sample is also analyzed for short-term variations; within the statistical error, no significant variation is observed." The flux is scaled by the value relative to the standard solar model (SSM) prediction. A theoretical flux of $(5.8 \pm 2.1) \times 10^6$ cm^{-2} s^{-1} is cited, with the central value corresponding to 7.9 SNU for ^{37}Cl experiment (but see TURCK-CHIEZE 93B and other theoretical calculations.) The analysis is more fully reported in HIRATA 91B. Earlier analyses were reported by HIRATA 91 and HIRATA 90B.

[101] DAVIS 89 is the average from the ^{37}CL experiment at the Homestake Mine (HOME) from 1970–1988. Earlier averages are given in the references therein.

[102] ACKER 94 rules out neutrino decay as a solution to the solar neutrino problem at better than 98% CL, using the existing solar neutrino data as of mid-1993.

[103] BAHCALL 94 argues that there are really two solar neutrino problems: (1) incompatibility of the chlorine (Homestake) and Kamiokande experiments, (2) deficiency of the observed solar neutrino flux in the gallium experiments.

[104] BAHCALL 93 is a study of 1000 solar models in which each input parameter is chosen from a normal distribution with the appropriate mean and error. It is concluded that "Even if one abuses the solar models by artifically imposing consistency with the Kamiokande experiment, the resulting predictions of all 1000 of the 'fudged' solar models are inconsistent with the result of the chlorine experiment."

[105] HAMPEL 93, by a member of the GALLEX collaboration, is a discussion of possible scenarios to explain the combined solar neutrino experimental data.

[106] TURCK-CHIEZE 93B proposes new results on the solar neutrino predictions and acoustic mode frequencies. See also TURCK-CHIEZE 93 for an extensive review (233 pages, 524 references) concerning the solar interior. Table 17 provides a particularly useful comparison of experiment and theory as of mid-1993.

[107] BAHCALL 92 is an extensive discussion of theoretical neutrino flux calculations with predicted event rates for various different solar neutrino detectors. "The quoted errors represent the total theoretical range and include the effects on the model predictions of 3σ errors in measured input parameters."

[108] GARCIA 91 reports a new study of ^{37}Caβ decays, with the result that the BAHCALL 88 SSM prediction for ^{37}Cl should be increased from 7.9 to 8.1 SNU.

[109] HIRATA 91 reports a search for day-night and semi-annual variations in the solar neutrino flux observed in the Kamiokande II Detector. The sample is the same 1040 day counting period used for HIRATA 90 and HIRATA 90B. "Within statistical error, no such short-time variations were observed." This result was used to constrain neutrino oscillation parameters, in the framework of oscillations between two mass eigenstates. "A region defined by $\sin^2 2\theta > 0.02$ and 2×10^{-6} eV^2 $< \Delta(m^2) < 1 \times 10^{-5}$ eV^2 is excluded at the 90% CL without any assumptions on the absolute value of the expected solar neutrino flux."

[110] In a later unbiased analysis, FILIPPONE 90 show that the hypothesis of a time-independent ^{37}Cl neutrino capture rate is marginally rejected, having only 2% probability. However, it is disturbing that we are not able to find a simple hypothesis of time variation that would describe the data well. A capture rate anticorrelated with sunspot number, although more probable than the constant rate hypothesis, has a probablity of only 6%. One possible explanation of these results is simply the poor statistics of the ^{37}Cl experiment."

[111] HIRATA 90B gives an analysis of the implications of these data for allowed values of $\Delta(m^2)$ and $\sin^2 2\theta$ describing neutrino mixing between two mass eigenstates, in the model of resonant (MSW) neutrino oscillations. The possibility of regeneration as the neutrinos pass through the earth is neglected. Two limits are given, the first from the measured event rate alone, and the second from the combination of the measured event rate and the recoil electron energy spectrum. The latter "disfavor the region of adiabatic solutions $\Delta(m^2) \sim 1.3 \times 10^{-4}$ eV^2 and $7.2 \times 10^{-4} < \sin^2 2\theta < 6.3 \times 10^{-3}$ at 90%CL." The allowed regions in $\sin^2 2\theta$ vs. $\Delta(m^2)$ are given graphically; see Figs. 2(a) and 2(b) in the paper.

[112] BAHCALL 88 "total theoretical range is calculated by evaluating the 3σ uncertainties for all measured input parameters and using the full spread in calculated values for input quantitites that cannot be measured; the uncertainties from different quantities are combined quadratically." (Quotation from BAHCALL 89, p. 301.)

[113] BAHCALL 82 quotes "effective 3σ errors." First extensive discussion of formal uncertainties in the problem.

(F) Astrophysical neutrino observations

Neutrinos and antineutrinos produced in the atmosphere induce μ-like and e-like events in underground detectors. The ratio of the numbers of the two kinds of events is defined as μ/e. It has the advantage that that systematic effects, such as flux uncertainty, tend to cancel, for both experimental and theoretical values of the ratio. The "ratio of the ratios" of experimental to theoretical μ/e, $R(\mu/e)$, is reported below. If the actual value is not unity, the value obtained in a given experiment may depend on the experimental conditions.

$R(\mu/e)$ = (Measured Ratio μ/e) / (Expected Ratio μ/e)

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.00 \pm 0.15 \pm 0.08$	[114] DAUM	95	FREJ	Calorimeter
$0.60^{+0.06}_{-0.05} \pm 0.05$	[115] FUKUDA	94	KAM2	sub-GeV
$0.57^{+0.08}_{-0.07} \pm 0.07$	[116] FUKUDA	94	KAM2	multi-Gev
	[117] BECKER-SZ...	92B	IMB	Water Cerenkov

[114] DAUM 95 results are based on an exposure of 2.0 kton yr which includes the data used by BERGER 90B. This ratio is for the contained and semicontained events. DAUM 95 also report $R(\mu/e) = 0.99 \pm 0.13 \pm 0.08$ for the total neutrino induced data sample which includes upward going stopping muons and horizontal muons in addition to the contained and semicontained events.

[115] FUKUDA 94 result is based on an exposure of 7.7 kton yr and updates the HIRATA 92 result. The analyzed data sample consists of fully contained e-like events with $0.1 < p_e < 1.33$ GeV/c and fully-contained μ-like events with $0.2 < p_\mu < 1.5$ GeV/c.

[116] FUKUDA 94 analyzed the data sample consisting of fully contained events with visible energy > 1.33 GeV and partially contained μ-like events.

[117] BECKER-SZENDY 92B reports the fraction of nonshowering events (mostly muons from atmospheric neutrinos) as $0.36 \pm 0.02 \pm 0.02$, as compared with expected fraction $0.51 \pm 0.01 \pm 0.05$. After cutting the energy range to the KAM2 limits, BEIER 92 finds $R(\mu/e)$ very close to the KAM2 value.

$R(\nu_\mu)$ = (Measured Flux of ν_μ) / (Expected Flux of ν_μ)

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.73\pm0.09\pm0.06$	[118] AHLEN	95	MCRO	Streamer tubes
	[119] CASPER	91	IMB	Water Cherenkov
	[120] AGLIETTA	89	NUSX	
0.95 ± 0.22	[121] BOLIEV	81		Baksan
0.62 ± 0.17	CROUCH	78		Case Western/UCI

[118] AHLEN 95 result is for all nadir angles. The lower cutoff on the muon energy is 1 GeV. The errors are statistical / systematic. The Monte Carlo flux error is ±0.12.
[119] CASPER 91 correlates showering/nonshowering signature of single-ring events with parent atmospheric-neutrino flavor. They find nonshowering ($\approx \nu_\mu$ induced) fraction is $0.41 \pm 0.03 \pm 0.02$, as compared with expected 0.51 ± 0.05 (syst).
[120] AGLIETTA 89 finds no evidence for any anomaly in the neutrino flux. They define ρ = (measured number of ν_e's)/(measured number of ν_μ's). They report $\rho(\text{measured})=\rho(\text{expected}) = 0.96^{+0.32}_{-0.28}$.
[121] From this data BOLIEV 81 obtain the limit $\Delta(m^2) \leq 6 \times 10^{-3}$ eV^2 for maximal mixing, $\nu_\mu \not\to \nu_\mu$ type oscillation.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\nu_e \leftrightarrow \nu_\mu$)

For a review see BAHCALL 89.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.55	90	[122] FUKUDA	94	KAM2	$\Delta(m^2) = 0.007$–0.08 eV^2
>0.33	90	[123] HIRATA	92	KAM2	$\Delta(m^2) > 0.004$ eV^2
<0.47	90	[124] BERGER	90B	FREJ	$\Delta(m^2) > 1$ eV^2
<0.14	90	LOSECCO	87	IMB	$\Delta(m^2)= 0.00011$ eV^2

[122] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.
[123] HIRATA 92 states that the allowed region for $\nu_e \leftrightarrow \nu_\mu$ conflicts with the constraints from the solar neutrino data (HIRATA 90B).
[124] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_e \leftrightarrow \nu_\mu$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$700 < \Delta(m^2) < 7000$	90	[125] FUKUDA	94	KAM2
<150	90	[126] BERGER	90B	FREJ

[125] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.
[126] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\overline{\nu}_e \leftrightarrow \overline{\nu}_\mu$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.9	99	[127] SMIRNOV	94	THEO	$\Delta(m^2) > 3 \times 10^{-4}$ eV^2
<0.7	99	[127] SMIRNOV	94	THEO	$\Delta(m^2) < 10^{-11}$ eV^2

[127] SMIRNOV 94 analyzed the data from SN 1987A using stellar-collapse models. They also give less stringent upper limits on $\sin^2 2\theta$ for $10^{-11} < \Delta(m^2) < 3 \times 10^{-7}$ eV^2 and $10^{-5} < \Delta(m^2) < 3 \times 10^{-4}$ eV^2. The same results apply to $\overline{\nu}_e \leftrightarrow \overline{\nu}_\tau$, ν_μ, and ν_τ.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.65	90	[128] FUKUDA	94	KAM2	$\Delta(m^2) = 0.005$–0.03 eV^2
>0.5	90	[129] BECKER-SZ...	92	IMB	$\Delta(m^2)= 1$–2×10^{-4} eV^2
<0.6	90	[130] BERGER	90B	FREJ	$\Delta(m^2) > 1$ eV^2

[128] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.
[129] BECKER-SZENDY 92 uses upward-going muons to search for atmospheric ν_μ oscillations. The fraction of muons which stop in the detector is used to search for deviations in the expected spectrum. No evidence for oscillations is found.
[130] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$500 < \Delta(m^2) < 2500$	90	[131] FUKUDA	94	KAM2
<350	90	[132] BERGER	90B	FREJ

[131] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.
[132] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antinuetrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \to \nu_s$)

ν_s means ν_τ or any sterile (noninteracting) ν.

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3000 (or <550)	90	[133] OYAMA	89		Kamiokande II
< 4.2 or > 54.	90	BIONTA	88	IMB	Flux has ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$

[133] OYAMA 89 gives a range of limits, depending on assumptions in their analysis. They argue that the region $\Delta(m^2) = (100$–$1000) \times 10^{-5}$ eV^2 is not ruled out by any data for large mixing.

(G) Reactor $\overline{\nu}_e$ disappearance experiments

In most cases, the reaction $\overline{\nu}_e p \to e^+ n$ is observed at different distances from one or more reactors in a complex.

Events (Observed/Expected) from Reactor $\overline{\nu}_e$ Experiments

VALUE	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$1.05 \pm0.02 \pm0.05$	VUILLEUMIER	82	Gösgen reactor
$0.955\pm0.035\pm0.110$	[134] KWON	81	$\overline{\nu}_e p \to e^+ n$
0.89 ± 0.15	[134] BOEHM	80	$\overline{\nu}_e p \to e^+ n$
0.38 ± 0.21	[135,136] REINES	80	
0.40 ± 0.22	[135,136] REINES	80	

[134] KWON 81 represents an analysis of a larger set of data from the same experiment as BOEHM 80.
[135] REINES 80 involves comparison of neutral- and charged-current reactions $\overline{\nu}_e d \to n p \overline{\nu}_e$ and $\overline{\nu}_e d \to n n e^+$ respectively. Combined analysis of reactor $\overline{\nu}_e$ experiments was performed by SILVERMAN 81.
[136] The two REINES 80 values correspond to the calculated $\overline{\nu}_e$ fluxes of AVIGNONE 80 and DAVIS 79 respectively.

$\overline{\nu}_e \not\to \overline{\nu}_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.0075	90	[137] VIDYAKIN	94		Krasnoyark reactors
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.01	90	[138] ACHKAR	95	CNTR	Bugey reactor
<0.0083	90	[137] VIDYAKIN	90		Krasnoyark reactors
<0.04	90	[139] AFONIN	88	CNTR	Rovno reactor
<0.014	68	[140] VIDYAKIN	87		$\overline{\nu}_e p \to e^+ n$
<0.019	90	[141] ZACEK	86		Gösgen reactor
<0.02	90	[142] ZACEK	85		Gösgen reactor
<0.016	90	[143] GABATHULER	84		Gösgen reactor

[137] VIDYAKIN 94 bound is for L=57.0 m, 57.6 m, and 231.4 m. Supersedes VIDYAKIN 90.
[138] ACHKAR 95 bound is for L=15, 40, and 95 m.
[139] AFONIN 86 and AFONIN 87 also give limits on $\sin^2(2\theta)$ for intermediate values of $\Delta(m^2)$. (See also KETOV 92). Supersedes AFONIN 87, AFONIN 86, AFONIN 85, AFONIN 83, and BELENKII 83.
[140] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.
[141] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m.
[142] See the comment for ZACEK 85 in the section on $\sin^2(2\theta)$ below.
[143] This bound comes from a combination of the VUILLEUMIER 82 data at distance 37.9 m and new data at 45.9 m.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[144] ACHKAR	95	CNTR	For $\Delta(m^2) = 0.6$ eV^2
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.087	68	[145] VYRODOV	95	CNTR	For $\Delta(m^2) > 2$ eV^2
<0.15	90	[146] VIDYAKIN	94		For $\Delta(m^2) > 5.0 \times 10^{-2}$ eV^2
<0.2	90	[147] AFONIN	88	CNTR	$\overline{\nu}_e p \to e^+ n$
<0.14	68	[148] VIDYAKIN	87		$\overline{\nu}_e p \to e^+ n$
<0.21	90	[149] ZACEK	86		$\overline{\nu}_e p \to e^+ n$
<0.19	90	[150] ZACEK	85		Gösgen reactor
<0.16	90	[151] GABATHULER	84		$\overline{\nu}_e p \to e^+ n$

[144] ACHKAR 95 bound is from data for L=15, 40, and 95 m distance from the Bugey reactor.
[145] The VYRODOV 95 bound is from data for L=15 m distance from the Bugey-5 reactor.
[146] The VIDYAKIN 94 bound is from data for L=57.0 m, 57.6 m, and 231.4 m from three reactors in the Krasnoyark Reactor complex.
[147] Several different methods of data analysis are used in AFONIN 88. We quote the most stringent limits. Different upper limits on $\sin^2 2\theta$ apply at intermediate values of $\Delta(m^2)$. Supersedes AFONIN 87, AFONIN 85, and BELENKII 83.
[148] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.
[149] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m distance from Gosgen reactor.
[150] ZACEK 85 gives two sets of bounds depending on what assumptions are used in the data analysis. The bounds in figure 3(a) of ZACEK 85 are progressively poorer for large $\Delta(m^2)$ whereas those of figure 3(b) approach a constant. We list the latter. Both sets of bounds use combination of data from 37.9, 45.9, and 64.7m distance from reactor. ZACEK 85 states "Our experiment excludes this area (the oscillation parameter region allowed by the Bugey data, CAVAIGNAC 84) almost completely, thus disproving the indications of neutrino oscillations of CAVAIGNAC 84 with a high degree of confidence."
[151] This bound comes from a combination of the VUILLEUMIER 82 data at distance 37.9m from Gosgen reactor and new data at 45.9m.

$\Delta(m^2)$ for given $\sin^2(2\theta)$

VALUE (eV^2)	DOCUMENT ID		COMMENT
0.2 ±0.1	[152] CAVAIGNAC	84	$\overline{\nu}_e p \to e^+ n$

[152] $\sin^2(2\theta) = 0.25 \pm 0.1$. These are from best fit to data; see CAVAIGNAC 84 for plot of allowed regions in these variables. These data from Bugey reactor.

(H) Accelerator neutrino appearance experiments

—— $\nu_e \to \nu_\tau$ ——

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 9	90	USHIDA	86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<44	90	TALEBZADEH	87	HLBC	BEBC

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.25	90	[153] USHIDA	86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.36	90	TALEBZADEH	87	HLBC	BEBC

[153] USHIDA 86C published result is $\sin^2 2\theta < 0.12$. The quoted result is corrected for a numerical mistake incurred in calculating the expected number of ν_e CC events, normalized to the total number of neutrino interactions (3886) rather than to the total number of ν_μ CC events (1870).

—— $\overline{\nu}_e \to \overline{\nu}_\tau$ ——

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.7	90	[154] FRITZE	80	HYBR	BEBC CERN SPS

[154] Authors give P($\nu_e \to \nu_\tau$) <0.35, equivalent to above limit.

—— $\nu_\mu \to \nu_e$ ——

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.09	90	ANGELINI	86	HLBC	BEBC CERN PS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.9	90	VILAIN	94C	CHM2	CERN SPS
<0.1	90	BLUMENFELD	89	CNTR	
<1.3	90	AMMOSOV	88	HLBC	SKAT at Serpukhov
<0.19	90	BERGSMA	88	CHRM	
		[155] LOVERRE	88	RVUE	
<2.4	90	AHRENS	87	CNTR	BNL AGS
<1.8	90	BOFILL	87	CNTR	FNAL
<2.2	90	[156] BRUCKER	86	HLBC	15-ft FNAL
<0.43	90	AHRENS	85	CNTR	BNL AGS E734
<0.20	90	BERGSMA	84	CHRM	
<1.7	90	ARMENISE	81	HLBC	GGM CERN PS
<0.6	90	BAKER	81	HLBC	15-ft FNAL
<1.7	90	ERRIQUEZ	81	HLBC	BEBC CERN PS
<1.2	95	BLIETSCHAU	78	HLBC	GGM CERN PS
<1.2	95	BELLOTTI	76	HLBC	GGM CERN PS

[155] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.
[156] 15ft bubble chamber at FNAL.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
< 2.5	90	AMMOSOV	88	HLBC	SKAT at Serpukhov
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 9.4	90	VILAIN	94C	CHM2	CERN SPS
< 5.6	90	[157] VILAIN	94C	CHM2	CERN SPS
< 16	90	BLUMENFELD	89	CNTR	
< 8	90	BERGSMA	88	CHRM	$\Delta(m^2) \geq 30$ eV^2
		[158] LOVERRE	88	RVUE	
< 10	90	AHRENS	87	CNTR	BNL AGS
< 15	90	BOFILL	87	CNTR	FNAL
< 20	90	[159] ANGELINI	86	HLBC	BEBC CERN PS
20 to 40		[160] BERNARDI	86B	CNTR	$\Delta(m^2)$=5–10
< 11	90	[161] BRUCKER	86	HLBC	15-ft FNAL
< 3.4	90	AHRENS	85	CNTR	BNL AGS E734
<240	90	BERGSMA	84	CHRM	
< 10	90	ARMENISE	81	HLBC	GGM CERN PS
< 6	90	BAKER	81	HLBC	15-ft FNAL
< 10	90	ERRIQUEZ	81	HLBC	BEBC CERN PS
< 4	95	BLIETSCHAU	78	HLBC	GGM CERN PS
< 10	95	BELLOTTI	76	HLBC	GGM CERN PS

[157] VILAIN 94C limit derived by combining the ν_μ and $\overline{\nu}_\mu$ data assuming *CP* conservation.
[158] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.
[159] ANGELINI 86 limit reaches 13×10^{-3} at $\Delta(m^2) \approx 2$ eV^2.
[160] BERNARDI 86B is a typical fit to the data, assuming mixing between two species. As the authors state, this result is in conflict with earlier upper bounds on this type of neutrino oscillations.
[161] 15ft bubble chamber at FNAL.

—— $\overline{\nu}_\mu \to \overline{\nu}_e$ ——

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.14	90		[162] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.075±0.030		9	[163] ATHANASSO...	95		
<0.07	90		[164] HILL	95		
<0.9	90		VILAIN	94C	CHM2	CERN SPS
<3.1	90		BOFILL	87	CNTR	FNAL
<2.4	90		TAYLOR	83	HLBC	15-ft FNAL
<0.91	90		[165] NEMETHY	81B	CNTR	LAMPF
<1	95		BLIETSCHAU	78	HLBC	GGM CERN PS

[162] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$. FREEDMAN 93 replaces DURKIN 88.
[163] ATHANASSOPOULOS 95 error corresponds to the 2σ band in the plot, and is corrected for the 20% systematic error. The expected background is 2.1 ± 0.3 events. Corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$. For a different interpretation, see HILL 95. Preprint ATHANASSOPOULOS 96 reports strengthened conclusions based on an excess of 52 events.
[164] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \to \overline{\nu}_e$ and obtains only upper limits.
[165] In reaction $\overline{\nu}_e p \to e^+ n$.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.004	95		BLIETSCHAU	78	HLBC	GGM CERN PS
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.007±0.005		9	[166] ATHANASSO...	95		
<0.006	90		[167] HILL	95		
<4.8	90		VILAIN	94C	CHM2	CERN SPS
<5.6	90		[168] VILAIN	94C	CHM2	CERN SPS
<0.024	90		[169] FREEDMAN	93	CNTR	LAMPF
<0.04	90		BOFILL	87	CNTR	FNAL
<0.013	90		TAYLOR	83	HLBC	15-ft FNAL
<0.2	90		[170] NEMETHY	81B	CNTR	LAMPF

[166] ATHANASSOPOULOS 95 error corresponds to the 2σ band in the plot, and is corrected for the 20% systematic error. The expected background is 2.1 ± 0.3 events. Corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$. For a different interpretation, see HILL 95. Preprint ATHANASSOPOULOS 96 reports strengthened conclusions based on an excess of 52 events.
[167] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \to \overline{\nu}_e$ and obtains only upper limits.
[168] VILAIN 94C limit derived by combining the ν_μ and $\overline{\nu}_\mu$ data assuming *CP* conservation.
[169] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$. FREEDMAN 93 replaces DURKIN 88.
[170] In reaction $\overline{\nu}_e p \to e^+ n$.

—— $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$ ——

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.075	90	BORODOV...	92	CNTR	BNL E776

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<3	90	BORODOV...	92	CNTR	BNL E776
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.8	90	[171] MCFARLAND	95	CCFR	FNAL

[171] MCFARLAND 95 state that "This result is the most stringent to date for 250< $\Delta(m^2)$ <450 ev^2 and also excludes at 90%CL much of the high $\Delta(m^2)$ region favored by the recent LSND observation." See ATHANASSOPOULOS 95 and ATHANASSOPOULOS 96.

—— $\nu_\mu \to \nu_\tau$ ——

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.9	90	USHIDA	86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.4	90	MCFARLAND	95	CCFR	FNAL
< 4.5	90	BATUSOV	90B	EMUL	FNAL
<10.2	90	BOFILL	87	CNTR	FNAL
< 6.3	90	BRUCKER	86	HLBC	15-ft FNAL
< 4.6	90	ARMENISE	81	HLBC	GGM CERN SPS
< 3	90	BAKER	81	HLBC	15-ft FNAL
< 6	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
< 3	90	USHIDA	81	EMUL	FNAL

See key on page 199

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	90	USHIDA	86C	EMUL	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0081	90	MCFARLAND	95	CCFR	FNAL
<0.06	90	BATUSOV	90B	EMUL	FNAL
<0.34	90	BOFILL	87	CNTR	FNAL
<0.088	90	BRUCKER	86	HLBC	15-ft FNAL
<0.11	90	BALLAGH	84	HLBC	15-ft FNAL
<0.017	90	ARMENISE	81	HLBC	GGM CERN SPS
<0.06	90	BAKER	81	HLBC	15-ft FNAL
<0.05	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
<0.013	90	USHIDA	81	EMUL	FNAL

$\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<2.2	90	ASRATYAN	81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4	90	MCFARLAND	95	CCFR	FNAL
<6.5	90	BOFILL	87	CNTR	FNAL
<7.4	90	TAYLOR	83	HLBC	15-ft FNAL

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.4 × 10^{-2}	90	ASRATYAN	81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0081	90	MCFARLAND	95	CCFR	FNAL
<0.15	90	BOFILL	87	CNTR	FNAL
<8.8 × 10^{-2}	90	TAYLOR	83	HLBC	15-ft FNAL

$\nu_\mu(\overline{\nu}_\mu) \rightarrow \nu_\tau(\overline{\nu}_\tau)$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	[172] GRUWE	93	CHM2	CERN SPS

[172] GRUWE 93 is a search using the CHARM II detector in the CERN SPS wide-band neutrino beam for $\nu_\mu \rightarrow \nu_\tau$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$ oscillations signalled by quasi-elastic ν_τ and $\overline{\nu}_\tau$ interactions followed by the decay $\tau \rightarrow \nu_\tau \pi$. The maximum sensitivity in $\sin^2 2\theta$ ($< 6.4 \times 10^{-3}$ at the 90% CL) is reached for $\Delta(m^2) \simeq 50$ eV^2.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<8	90	[173] GRUWE	93	CHM2	CERN SPS

[173] GRUWE 93 is a search using the CHARM II detector in the CERN SPS wide-band neutrino beam for $\nu_\mu \rightarrow \nu_\tau$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$ oscillations signalled by quasi-elastic ν_τ and $\overline{\nu}_\tau$ interactions followed by the decay $\tau \rightarrow \nu_\tau \pi$. The maximum sensitivity in $\sin^2 2\theta$ ($< 6.4 \times 10^{-3}$ at the 90% CL) is reached for $\Delta(m^2) \simeq 50$ eV^2.

$\nu_e \rightarrow (\overline{\nu}_e)_L$

This is a limit on lepton family-number violation and total lepton-number violation. $(\overline{\nu}_e)_L$ denotes a hypothetical left-handed $\overline{\nu}_e$. The bound is quoted in terms of $\Delta\,(m^2)$, $\sin(2\theta)$, and α, where α denotes the fractional admixture of $(V+A)$ charged current.

$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.14	90	[174] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7	90	[175] COOPER	82	HLBC	BEBC CERN SPS

[174] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$.

[175] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.032	90	[176] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	[177] COOPER	82	HLBC	BEBC CERN SPS

[176] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$.

[177] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\nu_\mu \rightarrow (\overline{\nu}_e)_L$

See note above for $\nu_e \rightarrow (\overline{\nu}_e)_L$ limit

$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.16	90	[178] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.7	90	[179] COOPER	82	HLBC	BEBC CERN SPS

[178] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. The limit on $\Delta(m^2)$ is better than the CERN BEBC experiment, but the limit on $\sin^2\theta$ is almost a factor of 100 less sensitive.

[179] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.001	90	[180] COOPER	82	HLBC	BEBC CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.07	90	[181] FREEDMAN	93	CNTR	LAMPF

[180] COOPER 82 states that existing bounds on V+A currents require α to be small.

[181] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. The limit on $\Delta(m^2)$ is better than the CERN BEBC experiment, but the limit on $\sin^2\theta$

(I) Disappearance experiments with accelerator & radioactive source neutrinos

$\nu_e \not\rightarrow \nu_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.17	90	[182] BAHCALL	95	THEO	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<14.9	90	BRUCKER	86	HLBC	15-ft FNAL
< 8	90	BAKER	81	HLBC	15-ft FNAL
<56	90	DEDEN	81	HLBC	BEBC CERN SPS
<10	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
<2.3 OR >8	90	NEMETHY	81B	CNTR	LAMPF

[182] BAHCALL 95 analyzed the GALLEX ^{51}Cr source experiment (ANSELMANN 95). They also gave a 95% CL limit of < 0.19 eV^2.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7 × 10^{-2}	90	[183] ERRIQUEZ	81	HLBC	BEBC CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.38	90	[184] BAHCALL	95	THEO	^{51}Cr source
<0.54	90	BRUCKER	86	HLBC	15-ft FNAL
<0.6	90	BAKER	81	HLBC	15-ft FNAL
<0.3	90	[183] DEDEN	81	HLBC	BEBC CERN SPS

[183] Obtained from a Gaussian centered in the unphysical region.

[184] BAHCALL 95 analyzed the GALLEX ^{51}Cr calibration source experiment (ANSELMANN 95). They also gave a 95% CL limit of < 0.45.

$\nu_\mu \not\rightarrow \nu_\mu$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

These experiments also allow sufficiently large $\Delta(m^2)$.

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.23 OR >1500 OUR LIMIT					
<0.23 OR >100	90	DYDAK	84	CNTR	
<13 OR >1500	90	STOCKDALE	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.29 OR >22	90	BERGSMA	88	CHRM	
<7	90	BELIKOV	85	CNTR	Serpukhov
<8.0 OR >1250	90	STOCKDALE	85	CNTR	
<0.29 OR >22	90	BERGSMA	84	CHRM	
<8.0	90	BELIKOV	83	CNTR	

$\sin^2(2\theta)$ for $\Delta(m^2) = 100$eV^2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[185] STOCKDALE	85	CNTR	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.17	90	[186] BERGSMA	88	CHRM	
<0.07	90	[187] BELIKOV	85	CNTR	Serpukhov
<0.27	90	[186] BERGSMA	84	CHRM	CERN PS
<0.1	90	[188] DYDAK	84	CNTR	CERN PS
<0.02	90	[189] STOCKDALE	84	CNTR	FNAL
<0.1	90	[190] BELIKOV	83	CNTR	Serpukhov

[185] This bound applies for $\Delta(m^2) = 100$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $8 < \Delta(m^2) < 1250$ eV^2.

[186] This bound applies for $\Delta(m^2) = 0.7$–$9.$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.28 < \Delta(m^2) < 22$ eV^2.

[187] This bound applies for a wide range of $\Delta(m^2) > 7$ eV^2. For some values of $\Delta(m^2)$, the value is less stringent; the least restrictive, nontrivial bound occurs approximately at $\Delta(m^2) = 300$ eV^2 where $\sin^2(2\theta) < 0.13$ at CL = 90%.
[188] This bound applies for $\Delta(m^2) = 1.$–$10.$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.23 < \Delta(m^2) < 90$ eV^2.
[189] This bound applies for $\Delta(m^2) = 110$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $13 < \Delta(m^2) < 1500$ eV^2.
[190] Bound holds for $\Delta(m^2) = 20$–1000 eV^2.

$\overline{\nu}_\mu \not\to \overline{\nu}_\mu$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID	TECN
<7 OR >1200 OUR LIMIT			
<7 OR >1200	90	STOCKDALE 85	CNTR

$\sin^2(2\theta)$ for 190 eV^2 < $\Delta(m^2)$ < 320 eV^2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.02	90	[191] STOCKDALE 85	CNTR	FNAL

[191] This bound applies for $\Delta(m^2)$ between 190 and 320 or = 530 eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $7 < \Delta(m^2) < 1200$ eV^2.

REFERENCES FOR Searches for Massive Neutrinos and Lepton Mixing

ATHANASSO... 96 PR D (subm.) Athanassopoulos, Auerbach, Burman, Cohen+(LSND Collab.)
nucl-ex/9605001
ACHKAR 95 NP B434 503 +Aleksan+ (SING, SACLD, CPPM, CDEF, LAPP)
AHLEN 95 PL B357 481 +Ambrosio, Antolini, Auriemma+ (MACRO Collab.)
ANSELMANN 95 PL B342 440 +Fockenbrock, Hampel, Heusser+ (GALLEX Collab.)
ANSELMANN 95B PL B357 237 +Hampel, Heusser, Kike+ (GALLEX Collab.)
ARMBRUSTER 95 PL B348 19 +Blair, Bodmann, Booth+ (KARMEN Collab.)
ARNOLD 95 JETPL 61 170 +Caurier, Guyonnet, Linck+ (NEMO Collab.)
Translated from ZETFP 61 168.
ATHANASSO... 95 PRL 75 2650 Athanassopoulos, Auerbach+ (LSND Collab.)
BAHCALL 95 PL B348 121 +Krastev, Lisi (IAS)
BAHRAN 95 PL B354 481 +Kalbfleisch (OKLA)
BALYSH 95 PL B356 450 +Beck, Belyaev+ (MPIH, KIAE, SASSO)
BARABASH 95 PL B345 408 +Avignone+ (ITEP, SCUC, PNL, MINN, LEBD)
BILGER 95 PL B363 41 +Clement, Denig, Fohl+ (TUBIN, KARLE, PSI)
BURACHAS 95 PAN 58 153 +Danevich, Zdesenko, Kobychev+ (KIEV)
Translated from YAF 58 195.
DANEVICH 95 PL B344 72 +Georgadze, Kobychev, Kropivyansky+ (KIEV)
DASSIE 95 PR D51 2090 +Eschbach, Hubert, Isaac, Isac+ (NEMO Collab.)
DAUM 95 ZPHY C66 417 +Rhode, Bareyre, Barloutaud+ (FREJUS Collab.)
DAUM 95B PL B361 179 +Frosch, Hajdas, Janousch+ (PSI, VIRG)
EJIRI 95 JPSJ 64 339 +Fushmii, Hazama, Kawasaki+ (OSAK, KIEV)
FARGION 95 PR D52 1828 +Khlopov, Konplich, Mignani (ROMA, KIAM, MPEI)
GALLAS 95 PR D52 6 +Abolins, Brock, Cobau+ (MSU, FNAL, MIT, FLOR)
GEORGADZE 95 PAN 58 1093
Translated from YAF 58 1170.
HAGNER 95 PR D52 1343 +Altmann, Feilitzsch, Oberauer+ (MUNT, LAPP, CPPM)
HIDDEMANN 95 JP G21 639 +Daniel, Schwentker (MUNT)
HILL 95 PRL 75 2654 (PENN)
KOBAYASHI 95 NP A586 457 +Kobayashi (KEK, SAGA)
MCFARLAND 95 PRL 75 3993 +Naples, Arroyo, Auchinchloss+ (CCFR Collab.)
VILAIN 95C PL B351 387 +Wilquet, Petrak+ (CHARM II Collab.)
Also 95 PL B343 453 Vilain, Wilquet+ (CHARM II Collab.)
VYRODOV 95 JETPL 61 163 +Kozlov, Martem'yanov, Machulin+ (KIAE, LAPP, CDEF)
Translated from ZETFP 61 161.
WIETFELDT 95 PR C52 1028 +Norman+ (LBL, UCB, SPAUL, IND, TENN)
ABDURASHI... 94 PL B328 234 Abdurashitov, Faizov, Gavrin, Gusev+ (SAGE Collab.)
ACKER 94 PL B320 320 +Pakvasa (HAWA)
ALESSAND... 94 PL B335 519 Alessandrello, Brofferio, ..., Fiorini+ (MILA)
ANSELMANN 94 PL B327 377 +Hampel, Heusser, Kiko, Kirsten+ (GALLEX Collab.)
ARPESELLA 94 EPL 27 29 +Barabash, Bellotti+ (SASSO, ITEP, MOSU, MILA, LEBD)
BAHCALL 94 PL B338 276 (IAS)
BALYSH 94 PL B322 176 +Beck, Belyaev, Bensch+ (MPIH, KIAE, SASSO)
BECK 94 PL B336 141 +Bensch, Bockholt+ (MPIH, KIAE, SASSO)
FUKUDA 94 PL B335 237 +Hayakawa, Inoue, Ishida+ (Kamiokande Collab.)
KONOPLICH 94 PAN 57 425 +Khlopov (MPEI)
PDG 94 PR D50 1173 Montanet+ (CERN, LBL, BOST, IFIC+)
PIEPKE 94 NP A577 493 +..., Klapdor-Kleingrothaus+ (MPIH, ITEP)
SMIRNOV 94 PR D49 1389 +Spergel, Bahcall (IAS, ICTP, INRM, PRIN)
VIDYAKIN 94 JETPL 59 390 +Vyrodov, Kozlov+ (KIAE)
Translated from ZETFP 59 364.
VILAIN 94C ZPHY C64 539 +Wilquet, Beyer+ (CHARM II Collab.)
ALSTON-... 93 PRL 71 831 Alston-Garnjost+ (LBL, MTHO, UNM, INEL)
ARTEMEV 93 JETPL 58 262 +Brakhman, Zeldofich, Karelin+ (ITEP, INRM)
Translated from ZETFP 58 256.
BAHCALL 93 PR D47 1298 +Bethe (IAS, CORN)
BAHRAN 93 PR D47 R754 +Kalbfleisch (OKLA)
BAHRAN 93B PR D47 R759 +Kalbfleisch (OKLA)
BARANOV 93 PL B302 336 +Batusov, Bunyatov, Klimov+ (JINR, SERP, BUDA)
BERMAN 93 PR C48 R1 +Pitt, Calaprice, Lowry (PRIN)
BERNATOW... 93 PR C47 806 Bernatowicz, Brazzle, Cowsik+ (WUSL, TATA)
FREEDMAN 93 PR D47 811 +Fujikawa, Napolitano, Nelson+ (LAMPF E645 Collab.)
GRUWE 93 PL B309 463 +Mommaert, Vilain, Wilquet+ (CHARM II Collab.)
HAMPEL 93 JPG 19 S209 (MPIH)
KALBFLEISCH 93 PL B303 355 +Bahran (OKLA)
KAWASHIMA 93 PR C47 R2452 +Takahashi, Masuda (TOKYC, RIKEN)
MORTARA 93 PRL 70 394 +Ahmad, Coulter, Freedman+ (ANL, LBL, UCB)
OHSHIMA 93 PR D47 4840 + (KEK, TUAT, RIKEN, SCUC, ROCH, TSUK, INUS)
TURCK-CHI... 93 PRPL 230 57 Turck-Chieze+ (SACLD, USC, NICEA, NICEO, MEUD)
TURCK-CHI... 93B APJ 408 347 Turck-Chieze, Lopez (SACLD)
VUILLEUMIER 93 PR D48 1009 +Busto, Farine, Jorgens+ (NEUC, CIT, VILL)
WIETFELDT 93 PRL 70 1759 +Chan, da Cruz, Garcia+ (LBL, UCB, SPAUL)
ABREU 92B PL B274 230 +Adams, Adami, Adye+ (DELPHI Collab.)
ADRIANI 92I PL B295 371 +Aguilar-Benitez, Ahlen, Akbari, Alcaraz+ (L3 Collab.)
ARTEMJEV 92 PL B280 159 +Brakchman, Ivanovsky, Karelin+ (ITEP)
BAHCALL 92 RMP 64 885 +Pinsonneault (IAS, YALE)
BAHRAN 92 PL B291 336 +Kalbfleisch (OKLA)
BALYSH 92 PL B283 32 +Belyaev, Bockholt, Demehin+ (MPIH, KIAE, SASSO)
BECKER-SZ... 92 PRL 69 1010 Becker-Szendy, Bratton, Casper, Dye+ (IMB Collab.)
BECKER-SZ... 92B PR D46 3720 Becker-Szendy, Bratton, Casper, Dye+ (IMB Collab.)
BEIER 92 PL B283 446 +Frank, Frati, Kim, Mann+ (KAM2 Collab.)
Also 94 PTRSL A346 63 Beier, Frank (PENN)
BERNATOW... 92 PRL 69 2341 Bernatowicz, Brannon, Brazzle, Cowsik+ (WUSL, TATA)
BLUM 92 PL B275 506 +Busto, Campagne, Dassie, Hubert+ (NEMO Collab.)
BORODOV... 92 PRL 68 274 Borodovsky, Chi, Ho, Kondakis, Lee+ (COLU, JHU, ILL)
BRITTON 92 PRL 68 3000 +Ahmad, Bryman, Burnham+ (TRIU, CARL)
Also 94 PR D49 28 Britton, Ahmad, Bryman+ (TRIU, CARL)
BRITTON 92B PR D46 R885 +Ahmad, Bryman+ (TRIU, CARL)
CHEN 92 PRL 69 3151 +Imel, Radcliffe, Henrickson, Boehm (CIT)
ELLIOTT 92 PR C46 1535 +Hahn, Moe+ (UCI)
HIRATA 92 PL B280 146 +Inoue, Ishida+ (Kamiokande II Collab.)
HOLZSCHUH 92B PL B287 381 +Fritschi, Kuendig (ZURI)
KAWAKAMI 92 PL B287 45 + (INUS, KEK, SCUC, TUAT, RIKEN, ROCH, TSUK)
KETOV 92 JETPL 55 564 +Machulin, Mikaelyan+ (KIAE)
Translated from ZETFP 55 544.
KUDOMI 92 PR C46 R2132 +Ejiri, Nagata, Okada, Shibata+ (OSAK, INUS)
MORI 92B PL B289 463 +Hikasa, Nojiri, Oyama+ (KAM2 Collab.)
REUSSER 92 PR D45 2548 Reussser, Treichel, Boehm+ (CIT, NEUC, VILL)
ABAZOV 91B PRL 67 3332 +Anosov, Faizov+ (SAGE Collab.)
ABREU 91F NP B367 511 +Adam, Adami, Adye, Akesson+ (DELPHI Collab.)
ALEXANDER 91F ZPHY C52 175 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)
AVIGNONE 91 PL B256 559 +Brodzinski, Guerard+ (SCUC, PNL, ITEP, YERE)
BELLOTTI 91 PL B266 193 +Cremonesi, Fiorini, Gervasio+ (MILA, INFN)
CASPER 91 PRL 66 2561 +Becker-Szendy, Bratton, Cady+ (IMB Collab.)
DELEENER-... 91 PR D43 3611 De Leener-Rosier, Deutsch+ (LOUV, ZURI, LAUS)
EJIRI 91 PL B258 17 +Fushimi, Kamada, Kinoshita+ (OSAK)
GARCIA 91 PRL 67 3654 +Adelberger, Magnus, Swanson+ (WASH, CERN, LBL)
HIME 91 PL B257 441 +Jelley (OXF)
HIRATA 91 PRL 66 9 +Inoue, Kajita, Kihara+ (Kamiokande II Collab.)
HIRATA 91B PR D44 2241
MORALES 91 NC 104A 1581 +Morales, Nunez-Lagos, Puimedon+ (ZARA)
NORMAN 91 JPG 17 S291 +Sur, Lesko+ (LBL)
REUSSER 91 PL B255 143 +Treichel, Boehm, Broggini+ (NEUC, CIT, PSI)
SATO 91 PR D44 2220 +Hirata, Kajita, Kifune, Kihara+ (Kamioka Collab.)
SUHONEN 91 NP A535 509 +Khadkikar, Faessler (JYV, AHMED, TUBIN)
TURKEVICH 91 PRL 67 3211 +Economou, Cowan (CHIC, LANL)
WONG 91 PRL 67 1218 +Boehm, Fisher, Gabathuler+ (CIT, VILL, NEUC)
YOU 91 PL B265 53 +Zhu, Lu+ (BHEP, CAST+)
ADEVA 90S PL B251 321 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
AKRAWY 90L PL B247 448 +Alexander, Allison, Allport+ (OPAL Collab.)
BARABASH 90 PL B249 186 +Kopylov, Cherehovsky (ITEP, INRM)
BATUSOV 90B ZPHY C48 209 +Bunyatov, Kuznetsov, Pozharova+ (JINR, ITEP, SERP)
BERGER 90B PL B245 305 +Froehlich, Moench, Nisius+ (FREJUS Collab.)
BURCHAT 90 PR D41 3542 +King, Abrams, Adolphsen+ (Mark II Collab.)
DECAMP 90F PL B236 511 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
FILIPPONE 90 PL B246 546 +Vogel (CIT)
HIRATA 90 PRL 65 1297 +Inoue, Kajita+ (Kamiokande II Collab.)
HIRATA 90B PRL 65 1301 +Inoue, Kajita+ (Kamiokande II Collab.)
JUNG 90 PRL 64 1091 +Van Kooten, Abrams, Adolphsen+ (Mark II Collab.)
KOPEIKIN 90 JETPL 51 86 +Mikazlyan, Fayans (KIAE)
Translated from ZETFP 51 75.
MILEY 90 PRL 65 3092 +Avignone, Brodzinski, Collar, Reeves (SCUC, PNL)
STAUDT 90 EPL 13 31 +Muto, Klapdor-Kleingrothaus (MPIH)
VASENKO 90 MPL A5 1299 +Kirpichnikov, Kuznetsov, Starostin (ITEP, YERE)
VIDYAKIN 90 JETP 71 424 +Vyrodov, Gurevich, Koslov+ (KIAE)
Translated from ZETF 98 764.
ABRAMS 89C PRL 63 2447 +Adolphsen, Averill, Ballam+ (Mark II Collab.)
AGLIETTA 89 EPL 8 611 +Battistoni, Bellotti+ (FREJUS Collab.)
ALSTON-... 89 PRL 63 1671 Alston-Garnjost, Dougherty+ (LBL, MTHO, UNM, INEL)
BAHCALL 89 Neutrino Astrophysics, Cambridge Univ. Press (IAS)
BARABASH 89 PL B223 273 +Kuzminov, Lobashev, Novikov+ (ITEP, INRM)
BELLOTTI 89 PL B221 209 +Cremonesi, Fiorini, Gervasio+ (MILA)
BLUMENFELD 89 PRL 62 2237 +Chi, Chichura, Chien+ (COLU, ILL, JHU)
DANEVICH 89 JETPL 49 476 +Zdesenko, Nikolaiko, Tretyak (UZINR)
Translated from ZETFP 49 417.
DAVIS 89 ARNPS 39 467 +Mann, Wolfenstein (BNL, PENN, CMU)
ENQVIST 89 NP B317 647 +Kainulainen, Maalampi (HELS)
FISHER 89 PL B218 257 +Boehm, Bovet, Egger+ (CIT, NEUC, PSI)
MUTO 89 ZPHY A334 187 +Bender, Klapdor (TINT, MPIH)
OYAMA 89 PR D39 1481 +Hirata, Kajita, Kifune+ (Kamiokande II Collab.)
SHAW 89 PRL 63 1342 +Blanis, Bodek, Budd+ (AMY Collab.)
AFONIN 88 JETP 67 213 +Ketov, Kopeikin, Mikaelyan+ (KIAE)
Translated from ZETF 94 1, issue 2.
AKERLOF 88 PR D37 577 +Chapman, Errede, Ken+ (HRS Collab.)
AMMOSOV 88 ZPHY C40 487 +Belikov+ (SKAT Collab.)
BAHCALL 88 RMP 60 297 +Ulrich (IAS, UCLA)
BERGSMA 88 ZPHY C40 171 +Dorenbosch, Nieuwenhuis+ (CHARM Collab.)
BERNARDI 88 PL B203 332 +Carugno, Chauveau+ (PARIN, CERN, INFN, ATEN)
BIONTA 88 PR D38 768 +Blewitt, Bratton, Casper+ (IMB Collab.)
CALDWELL 88 PRL 61 510 +Eisberg, Grumm, Witherell+ (UCSB, UCB, LBL)
DURKIN 88 PRL 61 1811 +Harper, Ling+ (OSU, ANL, CIT, LBL, LSU, LANL)
ENGEL 88 PR C37 731 +Vogel, Zimbene
LOVERRE 88 PL B206 711 (INFN)
MORALES 88 NC 100A 525 +Morales, Nunez-Lagos, Puimedon+ (ZARA)
OLIVE 88 PL B205 553 +Srednicki (MINN, UCSB)
SREDNICKI 88 NP B310 693 +Watkins, Olive (MINN, UCSB)
TURCK-CHI... 88 APJ 335 415 Turck-Chieze, Cahen, Casse, Doom (SACL, BRUX)
AFONIN 87 JETPL 45 257 +Bogatov, Vershinskii+ (KIAE)
Translated from ZETFP 45 201.
AHLEN 87 PL B195 603 +Avignone, Brodzinski+ (BOST, SCUC, HARV, CHIC)
AHRENS 87 PR D36 702 + (BNL, BROW, UCI, HIRO, KEK, OSAK, PENN, STON)
BELLOTTI 87 EPL 3 889 +Cattadori, Cremonesi, Fiorini+ (MILA)
BOEHM 87 Massive Neutrinos +Vogel (CIT)
Cambridge Univ. Press, Cambridge
BOFILL 87 PR D36 3309 +Busza, Eldridge+ (MIT, FNAL, MSU)
CALDWELL 87 PRL 59 419 +Eisberg, Grumm, Witherell+ (UCSB, LBL)
DAUM 87 PR D36 2624 +Kettle, Jost+ (SIN, VIRG)
GRIEST 87 NP B283 681 +Seckel (UCSC, CERN)
Also 88 NP B296 1034 erratum Griest, Seckel (UCSC, CERN)
LOSECCO 87 PL B184 305 +Bionta, Blewitt, Bratton+ (IMB Collab.)
MISHRA 87 PRL 59 1397 +Auchincloss+ (COLU, CIT, FNAL, CHIC, ROCH)
OBERAUER 87 PL B198 113 +von Feilitzsch, Mossbauer (MUNT)
TALEBZADEH 87 NP B291 503 +Guy, Venus+ (BEBC WA66 Collab.)
TOMODA 87 PL B199 475 +Faessler (TUBIN)
VIDYAKIN 87 JETP 66 243 +Vyrodov, Gurevich, Kozlov+ (KIAE)
Translated from ZETF 93 424.
WENDT 87 PRL 58 1810 +Abrams, Amidei, Baden+ (Mark II Collab.)
AFONIN 86 JETPL 44 142 +Bogatov, Borovoi, Vershinskii+ (KIAE)
Translated from ZETFP 44 111.
ANGELINI 86 PL B179 307 +Apostolakis, Baldini+ (PISA, ATHU, PADO, WISC)
AZUELOS 86 PRL 56 2241 +Britton, Bryman+ (TRIU, CNRC)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BELLOTTI 86 NC 95A 1 +Cremonesi, Fiorini, Liguori+ (MILA)
BERNARDI 86 PL 166B 479 +Carugno+ (CURIN, INFN, CDEF, ATEN, CERN)
BERNARDI 86B PL B181 173 +Carugno+ (CURIN, INFN, CDEF, ATEN, CERN)
BORGE 86 PS 34 591 +DeRujula, Hansen, Jonson+ (ISOLDE Collab.)
BRUCKER 86 PR D34 2183 +Jacques, Kalelkar, Koller+ (RUTG, BNL, COLU)
DELEENER-... 86 PL B177 228 DeLeener-Rosier, Deutsch+ (LOUV, ZURI, LAUS)
DORENBOS... 86 PL 166B 473 Dorenbosch, Allaby, Amaldi+ (CHARM Collab.)
GROTZ 86 NC C9 535 +Klapdor (MPIH)
USHIDA 86C PRL 57 2897 +Kondo, Tasaka, Park, Song+ (FNAL E531 Collab.)
ZACEK 86 PR D34 2621 +Feilitzsch+ (CIT-SIN-TUM Collab.)
AFONIN 85 JETPL 41 435 +Borovoi, Dobrynin+ (KIAE)
Translated from ZETFP 41 355.
Also 85B JETPL 42 285 Afonin, Bogatov, Borovoi, Dobrynin+ (KIAE)
Translated from ZETFP 42 230.
AHRENS 85 PR D31 2732 +Aronson+ (BNL, BROW, KEK, OSAK, PENN+)
ALBRECHT 85I PL 163B 404 +Binder, Drescher, Schubert+ (ARGUS Collab.)
ALTZITZOG... 85 PRL 55 799 Altzitzoglou, Calaprice, Dewey+ (PRIN)
APALIKOV 85 JETPL 42 289 +Boris, Golutvin, Laptin, Lubimov+ (ITEP)
Translated from ZETFP 42 233.
BELIKOV 85 SJNP 41 589 +Volkov, Kochetkov, Mukhin+ (SERP)
Translated from YAF 41 919.

COOPER-... 85 PL 160B 207 Cooper-Sarkar+ (CERN, LOIC, OXF, SACL+)

COWSIK 85 PL 151B 62 (TATA)

DATAR 85 Nature 318 547 +Baba, Bhattacherjee, Bhuinya, Roy (BHAB, TATA)

HUBERT 85 NC 85A 19 +Leccia, Dassie, Mennrath+ (BCEN, ZARA)

MARKEY 85 PR C32 2215 +Boehm (CIT)

OHI 85 PL 160B 322 +Nakajima, Tamura+ (TOKY, INUS, KEK)

SIMPSON 85 PRL 54 1891 (GUEL)

STOCKDALE 85 ZPHY C27 53 +Bodek+ (ROCH, CHIC, COLU, FNAL)

ZACEK 85 PL 164B 193 +Zacek, Boehm+ (MUNI, CIT, SIN)

BALLAGH 84 PR D30 2271 +Bingham+ (UCB, LBL, FNAL, HAWA, WASH, WISC)

BERGSMA 84 PL 142B 103 +Dorenbosch, Allaby, Abt+ (CHARM Collab.)

CAVAIGNAC 84 PL 148B 387 +Hoummada, Koang+ (ISNG, LAPP)

DYDAK 84 PL 134B 281 +Feldman+ (CERN, DORT, HEIDH, SACL, WARS)

FORSTER 84 PL 138B 301 +Kwon, Markey, Boehm, Henrikson (CIT)

FREESE 84 NP B233 167 +Schramm (CHIC, FNAL)

GABATHULER 84 PL 138B 449 +Boehm+ (CIT, SIN, MUNI)

HAXTON 84 PPNP 12 409 +Stevenson

MINEHART 84 PRL 52 804 +Ziock, Marshall, Stephens, Daum+ (VIRG, SIN)

SCHRAMM 84 PL 141B 337 +Steigman (FNAL, BART)

STOCKDALE 84 PRL 52 1384 +Bodek+ (ROCH, CHIC, COLU, FNAL)

AFONIN 83 JETPL 38 436 +Bogatov, Borovoi, Vershinskii+ (KIAE)
Translated from ZETFP 38 361.

AVIGNONE 83 PRL 50 721 +Brodzinski, Brown, Evans, Hensley+ (SCUC, PNL)

BELENKII 83 JETPL 38 493 +Dobrynin, Zemlyakov, Mikaelyan+ (KIAE)
Translated from ZETFP 38 406.

BELIKOV 83 JETPL 38 661 +Volkov, Kochetkov, Mukhin, Sviridov+ (SERP)
Translated from ZETFP 38 547.

BERGSMA 83 PL 122B 465 +Dorenbosch, Jonker+ (CHARM Collab.)

BERGSMA 83B PL 128B 361 +Dorenbosch+ (CHARM Collab.)

BRYMAN 83B PRL 50 1546 +Dubois, Numao, Olaniya, Olin+ (TRIU, CNRC)

Also 83 PRL 50 7 Bryman, Dubois, Numao, Olaniya+ (TRIU, CNRC)

DEUTSCH 83 PR D27 1644 +Lebrun, Prieels (LOUV)

FILIPPONE 83 PRL 50 412 +Elwyn, Davids+ (ANL, CHIC, VALP)

GRONAU 83 PR D28 2762 (HAIF)

KIRSTEN 83 PRL 50 474 +Richter, Jessberger (MPIH)

Also 83B ZPHY 16 189 Kirsten, Richter, Jessberger (MPIH)

SCHRECK... 83 PL 129B 265 Schreckenbach, Colvin+ (ISNG, ILLG)

TAYLOR 83 PR D28 2705 +Cence, Harris, Jones+ (HAWA, LBL, FNAL)

BAHCALL 82 RMP 54 767 +Huebner, Lubow+ (IAS, LANL, HPC, YALE, UCLA)

COOPER 82 PL 112B 97 +Guy, Michette, Tyndel, Venus (RL)

FILIPPONE 82 APJ 253 393 +Schramm (ANL, EFI)

FOWLER 82 A.I.P. 96 80 (CIT)

HAXTON 82 PR D25 2360 +Stephenson, Strottman (LANL, PURD)

HAYANO 82 PRL 49 1305 +Taniguchi, Yamanaka+ (TOKY, KEK, TSUK)

OLIVE 82 PR D25 213 +Turner (CHIC, UCSB)

VUILLEUMIER 82 PL 114B 298 +Boehm, Egger+ (CIT, SIN, MUNI)

ABELA 81 PL 105B 263 +Daum, Eaton, Frosch, Jost, Kettle, Steiner (SIN)

ARMENISE 81 PL 100B 182 +Fogli-Muciaccia+ (BARI, CERN, MILA, LALO)

ASANO 81 PL 104B 84 +Hayano, Kikutani, Kurokawa+(KEK, TOKY, INUS, OSAK)

Also 81 PR D24 1232 Shrock (STON)

ASRATYAN 81 PL 105B 301 +Efremenko, Fedotov+ (ITEP, FNAL, SERP, MICH)

BAKER 81 PRL 47 1576 +Connolly, Kahn, Kirk, Murtagh+ (BNL, COLU)

Also 78 PRL 40 144 Cnops, Connolly, Kahn, Kirk+ (BNL, COLU)

BERNSTEIN 81 PL 101B 39 +Feinberg (STEV, COLU)

BOLIEV 81 SJNP 34 787 +Butkevich, Zakidyshev, Makoev+ (INRM)
Translated from YAF 34 1418.

CALAPRICE 81 PL 106B 175 +Schreiber, Schneider+ (PRIN, IND)

DEDEN 81 PL 98B 310 +Grassler, Boeckmann, Mermikides+ (BEBC Collab.)

ERRIQUEZ 81 PL 102B 73 +Natali+ (BARI, BIRM, BRUX, EPOL, RHEL, SACL+)

HAXTON 81 PRL 47 153 +Stephenson, Strottman (PURD, LASL)

KWON 81 PR D24 1097 +Boehm, Hahn, Henrikson+ (CIT, ISNG, MUNI)

NEMETHY 81B PR D23 262 + (YALE, LBL, LASL, MIT, SACL, SIN, CNRC, BERN)

SHROCK 81 PR D24 1232 (STON)

SHROCK 81B PR D24 1275 (STON)

SILVERMAN 81 PRL 46 467 +Soni (UCI, UCLA)

SIMPSON 81B PR D24 2971 (GUEL)

USHIDA 81 PRL 47 1694 + (AICH, FNAL, KOBE, SEOU, MCGI, NAGO, OSU+)

AVIGNONE 80 PR C22 594 +Greenwood (SCUC)

BAHCALL 80 PRL 45 945 +Lubow, Huebner+ (IAS, LASL, YALE, LLL, UCLA)

Also 76 Science 191 264 Bahcall, Davis (IAS, BNL)

BOEHM 80 PL 97B 310 +Cavaignac, Feilitzsch+ (ILLG, CIT, ISNG, MUNI)

FRITZE 80 PL 96B 427 (AACH3, BONN, CERN, LOIC, OXF, SACL)

REINES 80 PRL 45 1307 +Sobel, Pasierb (UCI)

Also 59 PR 113 273 Reines, Cowan (LASL)

Also 66 PR 142 852 Nezrick, Reines (CASE)

Also 76 PRL 37 315 Reines, Gurr, Sobel (UCI)

SHROCK 80 PL 96B 159 (STON)

DAVIS 79 PR C19 2259 +Vogel, Mann, Schenter (CIT)

BLIETSCHAU 78 NP B133 205 +Deden, Hasert, Krenz+ (Gargamelle Collab.)

CROUCH 78 PR D18 2239 +Landecker, Lathrop, Reines+ (CASE, UCI, WITW)

MEYER 77 PL 70B 469 +Nguyen, Abrams+ (SLAC, LBL, NWES, HAWA)

VYSOTSKY 77 JETPL 26 188 +Dolgov, Zeldovich (ITEP)
Translated from ZETFP 26 200.

BELLOTTI 76 LNC 17 553 +Cavalli, Fiorini, Rollier (MILA)

SZALAY 76 AA 49 437 +Marx (EOTV)

SZALAY 74 APAH 35 8 +Marx (EOTV)

COWSIK 72 PRL 29 669 +McClelland (UCB)

MARX 72 Nu Conf. Budapest +Szalay (EOTV)

GERSHTEIN 66 JETPL 4 120 +Zeldovich (KIAM)
Translated from ZETFP 4 189.

QUARKS

Notes in the Quark Listings

QUARKS

QUARK MASSES

(by A. Manohar, University of California, San Diego)

A. Introduction

This note discusses some of the theoretical issues involved in the determination of quark masses. Unlike the leptons, quarks are confined inside hadrons and are not observed as physical particles. Quark masses cannot be measured directly, but must be determined indirectly through their influence on hadron properties. As a result, the values of the quark masses depend on precisely how they are defined; there is no one definition that is the obvious choice. Though one often speaks loosely of quark masses as one would of the electron or muon mass, any careful statement of a quark mass value must make reference to a particular computational scheme that is used to extract the mass from observations. It is important to keep this scheme dependence in mind when using the quark mass values tabulated in the data listings.

The simplest way to define the mass of a quark is by making a fit of the hadron mass spectrum to a nonrelativistic quark model. The quark masses are defined as the values obtained from the fit. The resulting masses only make sense in the limited context of a particular quark model. They depend on the phenomenological potential used, and on how relativistic effects are modelled. The quark masses used in potential models also cannot be connected with the quark mass parameters in the QCD Lagrangian. Fortunately, there exist other definitions of the quark mass that have a more general significance, though they also depend on the method of calculation. The purpose of this review is to explain the most important such definitions and their interrelations.

B. Mass parameters and the QCD Lagrangian

The QCD Lagrangian for N_F quark flavors is

$$\mathcal{L} = \sum_{k=1}^{N_F} \overline{q}_k \left(i \not{D} - m_k \right) q_k - \tfrac{1}{4} G_{\mu\nu} G^{\mu\nu} \ , \qquad (1)$$

where $\not{D} = \left(\partial_\mu - igA_\mu\right)\gamma^\mu$ is the gauge covariant derivative, A_μ is the gluon field, $G_{\mu\nu}$ is the gluon field strength, m_k is the mass parameter of the k^{th} quark, and q_k is the quark Dirac field. The QCD Lagrangian Eq. (1) gives finite scattering amplitudes after renormalization, a procedure that invokes a subtraction scheme to render the amplitudes finite, and requires the introduction of a dimensionful scale parameter μ. The mass parameters in the QCD Lagrangian Eq. (1) depend on the renormalization scheme used to define the theory, and also on the scale parameter μ. The most commonly used renormalization scheme for QCD perturbation theory is the $\overline{\text{MS}}$ scheme.

The QCD Lagrangian has a chiral symmetry in the limit that the quark masses vanish. This symmetry is spontaneously broken by dynamical chiral symmetry breaking, and explicitly broken by the quark masses. The nonperturbative scale of dynamical chiral symmetry breaking, Λ_χ, is around 1 GeV. It is conventional to call quarks heavy if $m > \Lambda_\chi$, so that explicit chiral symmetry breaking dominates, and light if $m < \Lambda_\chi$, so that spontaneous chiral symmetry breaking dominates. The c, b, and t quarks are heavy, and the u, d and s quarks are light. The computations for light quarks involve an expansion in m_q/Λ_χ about the limit $m_q = 0$, whereas for heavy quarks, they involve an expansion in Λ_χ/m_q about $m_q = \infty$. The corrections are largest for the s and c quarks, which are the heaviest light quark and the lightest heavy quark, respectively.

At high energies or short distances, nonperturbative effects such as chiral symmetry breaking are unimportant, and one can in principle analyze mass-dependent effects using QCD perturbation theory to extract the quark mass values. The QCD computations are conventionally performed using the $\overline{\text{MS}}$ scheme at a scale $\mu \gg \Lambda_\chi$, and give the $\overline{\text{MS}}$ "running" mass $\overline{m}(\mu)$. The μ dependence of $\overline{m}(\mu)$ at short distances can be calculated using the renormalization group equations.

For heavy quarks, one can obtain useful information on the quark masses by studying the spectrum and decays of hadrons containing heavy quarks. One method of calculation uses the heavy quark effective theory (HQET), which defines a HQET quark mass m_Q. Other commonly used definitions of heavy quark masses such as the pole mass are discussed in Sec. C. QCD perturbation theory at the heavy quark scale $\mu = m_Q$ can be used to relate the various heavy quark masses to the $\overline{\text{MS}}$ mass $\overline{m}(\mu)$, and to each other.

For light quarks, one can obtain useful information on the quark mass ratios by studying the properties of the light pseudoscalar mesons using chiral perturbation theory, which utilizes the symmetries of the QCD Lagrangian Eq. (1). The quark mass ratios determined using chiral perturbation theory are those in a subtraction scheme that is independent of the quark masses themselves, such as the $\overline{\text{MS}}$ scheme.

A more detailed discussion of the masses for heavy and light quarks is given in the next two sections. The $\overline{\text{MS}}$ scheme applies to both heavy and light quarks. It is also commonly used for predictions of quark masses in unified theories, and for computing radiative corrections in the Standard Model. For this reason, we use the $\overline{\text{MS}}$ scheme as the standard scheme in reporting quark masses. One can easily convert the $\overline{\text{MS}}$ masses into other schemes using the formulæ given in this review.

C. Heavy quarks

The commonly used definitions of the quark mass for heavy quarks are the pole mass, the $\overline{\text{MS}}$ mass, the Georgi-Politzer mass, the potential model mass used in ψ and Υ spectroscopy, and the HQET mass.

The strong interaction coupling constant at the heavy quark scale is small, and one can compute the heavy quark propagator using QCD perturbation theory. For an observable particle such as the electron, the position of the pole in the propagator is the definition of the particle mass. In QCD this definition of the quark mass is known as the pole mass m_P, and is independent of the renormalization scheme used. It is known that the on-shell quark propagator has no infrared divergences in perturbation theory [1], so this provides a perturbative definition of the quark mass. The pole mass cannot be used to arbitrarily high accuracy because of nonperturbative infrared effects in QCD. The full quark propagator has no pole because the quarks are confined, so that the pole mass cannot be defined outside of perturbation theory.

The $\overline{\rm MS}$ running mass $\overline{m}(\mu)$ is defined by regulating the QCD theory using dimensional regularization, and subtracting the divergences using the modified minimal subtraction scheme. The $\overline{\rm MS}$ scheme is particularly convenient for Feynman diagram computations, and is the most commonly used subtraction scheme.

The Georgi-Politzer mass $\widehat{m}$ is defined using the momentum space subtraction scheme at the spacelike point $-p^2 = \widehat{m}^2$ [2]. A generalization of the Georgi-Politzer mass that is often used in computations involving QCD sum rules [3] is $\widehat{m}(\xi)$, defined at the subtraction point $p^2 = -(\xi + 1)m_P^2$. QCD sum rules are discussed in more detail in the next section on light quark masses.

Lattice gauge theory calculations can be used to obtain heavy quark masses from ψ and Υ spectroscopy. The quark masses are obtained by comparing a nonperturbative computation of the meson spectrum with the experimental data. The lattice quark mass values can then be converted into quark mass values in the continuum QCD Lagrangian Eq. (1) using lattice perturbation theory at a scale given by the inverse lattice spacing. A recent computation determines the b-quark pole mass to be 5.0 ± 0.2 GeV, and the $\overline{\rm MS}$ mass to be 4.0 ± 0.1 GeV [4].

Potential model calculations of the hadron spectrum also involve the heavy quark mass. There is no way to relate the quark mass as defined in a potential model to the quark mass parameter of the QCD Lagrangian, or to the pole mass. Even in the heavy quark limit, the two masses can differ by nonperturbative effects of order $\Lambda_{\rm QCD}$. There is also no reason why the potential model quark mass should be independent of the particular form of the potential used.

Recent work on the heavy quark effective theory [5–9] has provided a definition of the quark mass for a heavy quark that is valid when one includes nonperturbative effects and will be called the HQET mass m_Q. The HQET mass is particularly useful in the analysis of the $1/m_Q$ corrections in HQET. The HQET mass agrees with the pole mass to all orders in perturbation theory when only one quark flavor is present, but differs from the pole mass at order α_s^2 when there are additional flavors [10]. Physical quantities such as hadron masses can in principle be computed in the heavy quark effective theory in terms of the HQET mass m_Q. The computations cannot be done analytically in practice because of nonperturbative effects in QCD, which also prevent a direct extraction of the quark masses from the original QCD Lagrangian, Eq. (1). Nevertheless, for heavy quarks, it is possible to parametrize the nonperturbative effects to a given order in the $1/m_Q$ expansion in terms of a few unknown constants that can be obtained from experiment. For example, the B and D meson masses in the heavy quark effective theory are given in terms of a single nonperturbative parameter $\overline{\Lambda}$,

$$M(B) = m_b + \overline{\Lambda} + \mathcal{O}\left(\frac{\overline{\Lambda}^2}{m_b}\right) ,$$

$$M(D) = m_c + \overline{\Lambda} + \mathcal{O}\left(\frac{\overline{\Lambda}^2}{m_c}\right) . \tag{2}$$

This allows one to determine the mass difference $m_b - m_c = M(B) - M(D) = 3.4$ GeV up to corrections of order $\overline{\Lambda}^2/m_b - \overline{\Lambda}^2/m_c$. The extraction of the individual quark masses m_b and m_c requires some knowledge of $\overline{\Lambda}$. An estimate of $\overline{\Lambda}$ using QCD sum rules gives $\overline{\Lambda} = 0.57 \pm 0.07$ GeV [11]. The HQET masses with this value of $\overline{\Lambda}$ are $m_b = 4.74 \pm 0.14$ GeV and $m_c = 1.4 \pm 0.2$ GeV, where the spin averaged meson masses $(3M(B^*) + M(B))/4$ and $(3M(D^*) + M(D))/4$ have been used to eliminate the spin-dependent $\mathcal{O}(\overline{\Lambda}^2/m_Q)$ correction terms. The errors reflect the uncertainty in $\overline{\Lambda}$ and the unknown spin-averaged $\mathcal{O}(\overline{\Lambda}^2/m_Q)$ correction. The errors do not include any theoretical uncertainty in the QCD sum rules, which could be large. A quark model estimate suggests that $\overline{\Lambda}$ is the constituent quark mass (≈ 350 MeV), which differs significantly from the sum rule estimate. In HQET, the $1/m_Q$ corrections to heavy meson decay form-factors are also given in terms of $\overline{\Lambda}$. Thus an accurate enough measurement of these form-factors could be used to extract $\overline{\Lambda}$ directly from experiment, which then determines the quark masses up to corrections of order $1/m_Q$.

The quark mass m_Q of HQET can be related to other quark mass parameters using QCD perturbation theory at the scale m_Q. The relation between m_Q and $\widehat{m}(\xi)$ at one loop is [12]

$$m_Q = \widehat{m}(\xi)\left[1 + \frac{\widehat{\alpha}_s(\xi)}{\pi}\frac{\xi+2}{\xi+1}\log(\xi+2)\right] , \tag{3}$$

where $\widehat{\alpha}_s(\xi)$ is the strong interaction coupling constant in the momentum space subtraction scheme. The relation between m_Q and the $\overline{\rm MS}$ mass $\overline{m}$ is known to two loops [13],

$$m_Q = \overline{m}(m_Q)\left[1 + \frac{4\overline{\alpha}_s(m_Q)}{3\pi} + \left(16.11 - 1.04\sum_k\left(1 - \frac{m_{Q_k}}{m_Q}\right)\right)\left(\frac{\overline{\alpha}_s(m_Q)}{\pi}\right)^2\right] , \tag{4}$$

where $\overline{\alpha}_s(\mu)$ is the strong interaction coupling constants in the $\overline{\rm MS}$ scheme, and the sum on k extends over all flavors Q_k lighter than Q. For the b-quark, Eq. (4) reads

$$m_b = \overline{m}_b(m_b)\left[1 + 0.09 + 0.06\right] , \tag{5}$$

where the contributions from the different orders in α_s are shown explicitly. The two loop correction is comparable in size and has the same sign as the one loop term. There is presumably an error of order 0.05 in the relation between m_b and $\overline{m}_b(m_b)$ from the uncalculated higher order terms.

D. Light quarks

For light quarks, one can use the techniques of chiral perturbation theory to extract quark mass ratios. The light quark part of the QCD Lagrangian Eq. (1) has a chiral symmetry in the limit that the light quark masses are set to zero, under which left- and right-handed quarks transform independently. The mass term explicitly breaks the chiral symmetry, since it couples the left- and right-handed quarks to each other. A systematic analysis of this explicit chiral symmetry breaking provides some information on the light quark masses.

It is convenient to think of the three light quarks u, d and s as a three component column vector Ψ, and to write the mass term for the light quarks as

$$\overline{\Psi} M \Psi = \overline{\Psi}_L M \Psi_R + \overline{\Psi}_R M \Psi_L, \tag{6}$$

where M is the quark mass matrix M,

$$M = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}. \tag{7}$$

The mass term $\overline{\Psi} M \Psi$ is the only term in the QCD Lagrangian that mixes left- and right-handed quarks. In the limit that $M \to 0$, there is an independent SU(3) flavor symmetry for the left- and right-handed quarks. This $G_\chi = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ chiral symmetry of the QCD Lagrangian is spontaneously broken, which leads to eight massless Goldstone bosons, the π's, K's, and η, in the limit $M \to 0$. The symmetry G_χ is only an approximate symmetry, since it is explicitly broken by the quark mass matrix M. The Goldstone bosons acquire masses which can be computed in a systematic expansion in M in terms of certain unknown nonperturbative parameters of the theory. For example, to first order in M one finds that [14,15]

$$\begin{aligned} m_{\pi^0}^2 &= B\,(m_u + m_d)\ , \\ m_{\pi^\pm}^2 &= B\,(m_u + m_d) + \Delta_{em}\ , \\ m_{K^0}^2 = m_{\overline{K}^0}^2 &= B\,(m_d + m_s)\ , \\ m_{K^\pm}^2 &= B\,(m_u + m_s) + \Delta_{em}\ , \\ m_\eta^2 &= \frac{1}{3} B\,(m_u + m_d + 4m_s)\ , \end{aligned} \tag{8}$$

with two unknown parameters B and Δ_{em}, the electromagnetic mass difference. From Eq. (8), one can determine the quark mass ratios [14]

$$\begin{aligned} \frac{m_u}{m_d} &= \frac{2m_{\pi^0}^2 - m_{\pi^+}^2 + m_{K^+}^2 - m_{K^0}^2}{m_{K^0}^2 - m_{K^+}^2 + m_{\pi^+}^2} = 0.56\ , \\ \frac{m_s}{m_d} &= \frac{m_{K^0}^2 + m_{K^+}^2 - m_{\pi^+}^2}{m_{K^0}^2 + m_{\pi^+}^2 - m_{K^+}^2} = 20.1\ , \end{aligned} \tag{9}$$

to lowest order in chiral perturbation theory. The error on these numbers is the size of the second-order corrections, which are discussed at the end of this section. Chiral perturbation theory cannot determine the overall scale of the quark masses, since it uses only the symmetry properties of M, and any multiple of M has the same G_χ transformation law as M. This can be seen from Eq. (8), where all quark masses occur only in the form Bm, so that B and m cannot be determined separately.

The mass parameters in the QCD Lagrangian have a scale dependence due to radiative corrections, and are renormalization scheme dependent. Since the mass ratios extracted using chiral perturbation theory use the symmetry transformation property of M under the chiral symmetry G_χ, it is important to use a renormalization scheme for QCD that does not change this transformation law. Any quark mass independent subtraction scheme such as $\overline{\mathrm{MS}}$ is suitable. The ratios of quark masses are scale independent in such a scheme.

The absolute normalization of the quark masses can be determined by using methods that go beyond chiral perturbation theory, such as QCD sum rules [3]. Typically, one writes a sum rule for a quantity such as B in terms of a spectral integral over all states with certain quantum numbers. This spectral integral is then evaluated by assuming it is dominated by one (or two) of the lowest resonances, and using the experimentally measured resonance parameters [16]. There are many subtleties involved, which cannot be discussed here [16].

Another method for determining the absolute normalization of the quark masses, is to assume that the strange quark mass is equal to the SU(3) mass splitting in the baryon multiplets [14,16]. There is an uncertainty in this method since in the baryon octet one can use either the Σ–N or the Λ–N mass difference, which differ by about 75 MeV, to estimate the strange quark mass. But more importantly, there is no way to relate this normalization to any more fundamental definition of quark masses.

One can extend the chiral perturbation expansion Eq. (8) to second order in the quark masses M to get a more accurate determination of the quark mass ratios. There is a subtlety that arises at second order [17], because

$$M\left(M^\dagger M\right)^{-1} \det M^\dagger \tag{10}$$

transforms in the same way under G_χ as M. One can make the replacement $M \to M(\lambda) = M + \lambda M\left(M^\dagger M\right)^{-1} \det M^\dagger$ in all formulæ,

$$\begin{aligned} M(\lambda) &= \mathrm{diag}\left(m_u(\lambda)\,,\ m_d(\lambda)\,,\ m_s(\lambda)\right) \\ &= \mathrm{diag}\left(m_u + \lambda m_d m_s\,,\ m_d + \lambda m_u m_s\,,\ m_s + \lambda m_u m_d\right)\ , \end{aligned} \tag{11}$$

so it is not possible to determine λ by fitting to data. One can only determine the ratios $m_i(\lambda)/m_j(\lambda)$ using second-order chiral perturbation theory, not the desired ratios $m_i/m_j = m_i(\lambda = 0)/m_j(\lambda = 0)$.

Dimensional analysis can be used to estimate [18] that second-order corrections in chiral perturbation theory due to the strange quark mass are of order $\lambda m_s \sim 0.25$. The ambiguity due to the redefinition Eq. (11) (which corresponds to a second-order correction) can produce a sizeable uncertainty in the ratio m_u/m_d. The lowest-order value $m_u/m_d = 0.56$ gets corrections of order $\lambda m_s(m_d/m_u - m_u/m_d) \sim 30\%$, whereas m_s/m_d gets a smaller correction of order $\lambda m_s(m_u/m_d - m_u m_d/m_s^2) \sim 15\%$. A more quantitative discussion of second-order effects can be found in Refs. 17,19,20. Since the second-order terms have a single parameter ambiguity, the value of m_u/m_d is related to the value of m_s/m_d.

The ratio m_u/m_d is of great interest since there is no strong CP problem if $m_u = 0$. To determine m_u/m_d requires fixing λ in the mass redefinition Eq. (11). There has been considerable effort to determine the chiral Lagrangian parameters accurately enough to determine m_u/m_d, for example from the analysis of the decays $\psi' \to \psi + \pi^0, \eta$, the decay $\eta \to 3\pi$, using sum rules, and from the heavy meson mass spectrum [16,21–24]. A recent paper giving a critique of these estimates is Ref. 25.

Eventually, lattice gauge theory methods will be accurate enough to be able to compute meson masses directly from the QCD Lagrangian Eq. (1), and thus determine the light quark masses. For a reliable determination of quark masses, these computations will have to be done with dynamical fermions, and with a small enough lattice spacing that one can accurately compute the relation between lattice and continuum Lagrangians.

The quark masses for light quarks discussed so far are often referred to as current quark masses. Nonrelativistic quark models use constituent quark masses, which are of order 350 MeV for the u and d quarks. Constituent quark masses model the effects of dynamical chiral symmetry breaking, and are not related to the quark mass parameters m_k of the QCD Lagrangian Eq. (1). Constituent masses are only defined in the context of a particular hadronic model.

E. Numerical values and caveats

The quark masses in the particle data listings have been obtained by using the wide variety of theoretical methods outlined above. Each method involves its own set of approximations and errors. In most cases, the errors are a best guess at the size of neglected higher-order corrections. The expansion parameter for the approximations is not much smaller than unity (for example it is $m_K^2/\Lambda_\chi^2 \approx 0.25$ for the chiral expansion), so an unexpectedly large coefficient in a neglected higher-order term could significantly alter the results. It is also important to note that the quark mass values can be significantly different in the different schemes. For example, assuming that the b-quark pole mass is 5.0 GeV, and $\overline{\alpha}_s(m_b) \approx 0.22$ gives the $\overline{\rm MS}$ b-quark mass $\overline{m}_b(\mu = m_b) = 4.6$ GeV using the one-loop term in Eq. (4), and $\overline{m}_b(\mu = m_b) = 4.3$ GeV including the one-loop and two-loop terms. The heavy quark masses obtained using HQET, QCD sum rules, or lattice gauge theory are consistent with each other if they are all converted into the same scheme. When using the data listings, it is important to remember that the numerical value for a quark mass is meaningless without specifying the particular scheme in which it was obtained. All non-$\overline{\rm MS}$ quark masses have been converted to $\overline{\rm MS}$ values in the data listings using one-loop formulæ, unless an explicit two-loop conversion is given by the authors in the original article.

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u

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 2 to 8 MeV   Charge = $\frac{2}{3}\,e$ $I_z = +\frac{1}{2}$

m_u/m_d = 0.25 to 0.70

d

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 5 to 15 MeV   Charge = $-\frac{1}{3}\,e$ $I_z = -\frac{1}{2}$

m_s/m_d = 17 to 25

s

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 100 to 300 MeV   Charge = $-\frac{1}{3}\,e$ Strangeness = −1

$(m_s - (m_u + m_d)/2)/(m_d - m_u)$ = 34 to 51

LIGHT QUARKS (*u*, *d*, *s*)

OMITTED FROM SUMMARY TABLE

u-QUARK MASS

The *u*-, *d*-, and *s*-quark masses are estimates of so-called "current-quark masses," in a mass- independent subtraction scheme such as $\overline{\rm MS}$ at a scale $\mu \approx 1$ GeV. The ratios m_u/m_d and m_s/m_d are extracted from pion and kaon masses using chiral symmetry. The estimates of *d* and *u* masses are not without controversy and remain under active investigation. Within the literature there are even suggestions that the *u* quark could be essentially massless. The *s*-quark mass is estimated from SU(3) splittings in hadron masses.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2 to 8 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.3±1.5	[1] JAMIN	95	THEO	Assumes $\overline{\rm MS}$ scheme
4 ±1	[2] NARISON	95C	THEO	Assumes $\overline{\rm MS}$ scheme
	[3] CHOI	92B	THEO	
5.8	[4] BARDUCCI	88	THEO	
5.1±1.5	[5] GASSER	82	THEO	
1.8±0.7	[6] PAGELS	80	THEO	
5.6±2.9	[7] PAGELS	80	THEO	
4.2	[8] WEINBERG	77	THEO	
4	[9] GASSER	75	THEO	

[1] JAMIN 95 uses QCD sum rules at next-to-leading order.
[2] NARISON 95C determines the $\overline{\rm MS}$ mass at 1 GeV.
[3] CHOI 92B argues that $m_u = 0$ is okay based on instanton contributions to the chiral coefficients. Disagrees with DONOGHUE 92 and DONOGHUE 92B.
[4] BARDUCCI 88 renormalized quark mass at 1 GeV. Uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$.
[5] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. The renormalization scale is 1 GeV.
[6] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\rangle$.
[7] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\overline{q}q\rangle$ correlation function.
[8] WEINBERG 77 assumes that the baryon SU(3) splittings are equal to m_s.
[9] GASSER 75 uses inelastic electron scattering and SU(6).

d-QUARK MASS

See the comment for the *u* quark above.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
5 to 15 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[10] BIJNENS	95	THEO	
9.4±1.5	[11] JAMIN	95	THEO	Assumes $\overline{\rm MS}$ scheme
10 ±1	[12] NARISON	95C	THEO	Assumes $\overline{\rm MS}$ scheme
	[13] ADAMI	93	THEO	
	[14] NEFKENS	92	THEO	
8.4	[15] BARDUCCI	88	THEO	
	[16] DOMINGUEZ	87	THEO	
	[17] KREMER	84	THEO	
8.9±2.6	[18] GASSER	82	THEO	
4.3±0.7	[19] PAGELS	80	THEO	
14.6±5.7	[20] PAGELS	80	THEO	
7.5	[21] WEINBERG	77	THEO	
6	[22] GASSER	75	THEO	

[10] BIJNENS 95 determines $m_{\overline{u}}+m_{\overline{d}}$ (1 GeV) = 12 ± 2.5 MeV using finite energy sum rules.
[11] JAMIN 95 uses QCD sum rules at next-to-leading order.
[12] NARISON 95C determines the $\overline{\rm MS}$ mass at 1 GeV.
[13] ADAMI 93 obtain $m_d - m_u$=3 ± 1 MeV at μ=0.5 GeV using isospin-violating effects in QCD sum rules.
[14] NEFKENS 92 results for $m_d - m_u$ are 3.1 ± 0.4 MeV from meson masses and 3.6 ± 0.4 MeV from baryon masses.
[15] BARDUCCI 88 renormalized quark mass at 1 GeV. Uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$.
[16] DOMINGUEZ 87 uses QCD sum rules to obtain m_u+m_d = 15.5 ± 2.0 MeV and $m_d - m_u$ = 6 ± 1.5 MeV.
[17] KREMER 84 obtain m_u+m_d=21 ± 2 MeV at Q^2 = 1 GeV^2 using SVZ values for quark condensates; they obtain m_u+m_d=35 ± 3 MeV at Q^2 = 1 GeV^2 using factorization values for quark condensates.
[18] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. The renormalization scale is 1 GeV.
[19] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\rangle$.
[20] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\overline{q}q\rangle$ correlation function.
[21] WEINBERG 77 assumes that the baryon SU(3) splittings are equal to m_s.
[22] GASSER 75 uses inelastic electron scattering and SU(6).

s-QUARK MASS

See the comment for the *u* quark above.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 300 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
171± 15	[23] CHETYRKIN	95	THEO	Assumes $\overline{\rm MS}$ scheme
189± 32	[24] JAMIN	95	THEO	Assumes $\overline{\rm MS}$ scheme
197± 29	[25] NARISON	95C	THEO	Assumes $\overline{\rm MS}$ scheme
	[26] NEFKENS	92	THEO	
194± 4	[27] DOMINGUEZ	91	THEO	
118	[28] BARDUCCI	88	THEO	
	[29] KREMER	84	THEO	
175± 55	[30] GASSER	82	THEO	
>300	[31] PENSO	82B	THEO	
112± 66	[32] PAGELS	80	THEO	
378±220	[33] PAGELS	80	THEO	
150	[34] WEINBERG	77	THEO	
135	[35] GASSER	75	THEO	

[23] $\overline{\rm MS}$ mass at 1 GeV. CHETYRKIN 95 uses QCD sum rules at next-to-leading order.
[24] JAMIN 95 uses QCD sum rules at next-to-leading order.
[25] NARISON 95C determines the $\overline{\rm MS}$ mass at 1 GeV.
[26] NEFKENS 92 results for $m_s-(m_u+m_d)/2$ are 111 ± 10 MeV from meson masses and 163 ± 15 MeV from baryon masses.
[27] DOMINGUEZ 91 uses QCD sum rules with $\Lambda_{\rm QCD}$ = 100–200 MeV and the SVZ value for the gluon condensate. The renormalization point is 1 GeV.
[28] BARDUCCI 88 renormalized quark mass at 1 GeV. Uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$.
[29] KREMER 84 obtain m_u+m_s=245 ± 10 MeV at Q^2 = 1 GeV^2 using SVZ values for quark condensates; they obtain m_u+m_s=270 ± 10 MeV at Q^2 = 1 GeV^2 using factorization values for quark condensates.
[30] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. The renormalization scale is 1 GeV.
[31] PENSO 82 uses SVZ sum rules to put a lower bound on the strange quark mass.
[32] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\rangle$.
[33] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\overline{q}q\rangle$ correlation function.
[34] WEINBERG 77 assumes that the baryon SU(3) splittings are equal to m_s.
[35] GASSER 75 is based on SU(6).

LIGHT QUARK MASS RATIOS

u/*d* MASS RATIO

VALUE	DOCUMENT ID		TECN
0.25 to 0.70 OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.3	[36] CHOI	92	THEO
0.26	[37] DONOGHUE	92	THEO
0.30±0.07	[38] DONOGHUE	92B	THEO
0.66	[39] GERARD	90	THEO
0.4 to 0.65	[40] LEUTWYLER	90B	THEO
0.05 to 0.78	[41] MALTMAN	90	THEO
0.0 to 0.56	[42] CHOI	89B	THEO
0.0 to 0.8	[43] KAPLAN	86	THEO
0.57±0.04	[44] GASSER	82	THEO
0.38±0.13	[45] LANGACKER	79	THEO
0.47±0.11	[46] LANGACKER	79B	THEO
0.56	[47] WEINBERG	77	THEO

[36] CHOI 92 result obtained from the decays $\psi(2S) \rightarrow J/\psi(1S)\pi$ and $\psi(2S) \rightarrow J/\psi(1S)\eta$, and a dilute instanton gas estimate of some unknown matrix elements.
[37] DONOGHUE 92 result is from a combined analysis of meson masses, $\eta \rightarrow 3\pi$ using second-order chiral perturbation theory including nonanalytic terms, and $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$.
[38] DONOGHUE 92B computes quark mass ratios using $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$, and an estimate of L_{14} using Weinberg sum rules.
[39] GERARD 90 uses large N and η-η' mixing.
[40] LEUTWYLER 90B determines quark mass ratios using second-order chiral perturbation theory for the meson and baryon masses, including nonanalytic corrections. Also uses Weinberg sum rules to determine L_7.

[41] MALTMAN 90 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Uses a criterion of "maximum reasonableness" that certain coefficients which are expected to be of order one are ≤ 3.
[42] CHOI 89 uses second-order chiral perturbation theory and a dilute instanton gas estimate of second-order coefficients in the chiral lagrangian.
[43] KAPLAN 86 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Assumes that less than 30% of the mass squared of the pion is due to second-order corrections.
[44] GASSER 82 uses chiral perturbation theory for the meson and baryon masses.
[45] LANGACKER 79 result is from a fit to the meson and baryon mass spectrum, and the decay $\eta \rightarrow 3\pi$. The electromagnetic contribution is taken from Socolow rather than from Dashen's formula.
[46] LANGACKER 79B result uses LANGACKER 79 and also ρ-ω mixing.
[47] WEINBERG 77 uses lowest-order chiral perturbation theory for the meson and baryon masses and Dashen's formula for the electromagnetic mass differences.

s/d MASS RATIO

VALUE	DOCUMENT ID		TECN
17 to 25 OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
21	[48] DONOGHUE	92	THEO
18	[49] GERARD	90	THEO
18 to 23	[50] LEUTWYLER	90B	THEO
15 to 26	[51] KAPLAN	86	THEO
19.6±1.5	[52] GASSER	82	THEO
22 ±5	[53] LANGACKER	79	THEO
24 ±4	[54] LANGACKER	79B	THEO
20	[55] WEINBERG	77	THEO

[48] DONOGHUE 92 result is from a combined analysis of meson masses, $\eta \rightarrow 3\pi$ using second-order chiral perturbation theory including nonanalytic terms, and $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$.
[49] GERARD 90 uses large N and η-η' mixing.
[50] LEUTWYLER 90B determines quark mass ratios using second-order chiral perturbation theory for the meson and baryon masses, including nonanalytic corrections. Also uses Weinberg sum rules to determine L_7.
[51] KAPLAN 86 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Assumes that less than 30% of the mass squared of the pion is due to second-order corrections.
[52] GASSER 82 uses chiral perturbation theory for the meson and baryon masses.
[53] LANGACKER 79 result is from a fit to the meson and baryon mass spectrum, and the decay $\eta \rightarrow 3\pi$. The electromagnetic contribution is taken from Socolow rather than from Dashen's formula.
[54] LANGACKER 79B result uses LANGACKER 79 and also ρ-ω mixing.
[55] WEINBERG 77 uses lowest-order chiral perturbation theory for the meson and baryon masses and Dashen's formula for the electromagnetic mass differences.

$(m_s - m)/(m_d - m_u)$ MASS RATIO

$m \equiv (m_u + m_d)/2$

VALUE	DOCUMENT ID		TECN
34 to 51 OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
36 ±5	[56] NEFKENS	92	THEO
45 ±3	[57] NEFKENS	92	THEO
38 ±9	[58] AMETLLER	84	THEO
43.5±2.2	GASSER	82	THEO
34 to 51	GASSER	81	THEO
48 ±7	MINKOWSKI	80	THEO

[56] NEFKENS 92 result is from an analysis of meson masses, mixing, and decay.
[57] NEFKENS 92 result is from an analysis of of baryon masses.
[58] AMETLLER 84 uses $\eta \rightarrow \pi^+\pi^-\pi^0$ and ρ dominance.

LIGHT QUARKS (u, d, s) REFERENCES

BIJNENS	95	PL B348 226	+Prades, de Rafael	(NORD, BOHR, CPPM)
CHETYRKIN	95	PR D51 5090	+Dominguez, Pirjol, Schilcher	(INRM, CAPE, MANZ)
JAMIN	95	ZPHY C66 633	+Munz	(HEIDT, MUNT)
NARISON	95C	PL B358 113		(MONP)
ADAMI	93	PR D48 2304	+Drukarev, Ioffe	(CIT, ITEP, PNPI)
CHOI	92	PL B292 159		(UCSD)
CHOI	92B	NP B383 58		(UCSD)
DONOGHUE	92	PRL 69 3444	+Holstein, Wyler	(MASA, ZURI)
DONOGHUE	92B	PR D45 892	+Wyler	(MASA, ZURI, UCSBT)
NEFKENS	92	CNPP 20 221	+Miller, Slaus	(UCLA, WASH, ZAGR)
DOMINGUEZ	91	PL B253 241	+van Gend, Paver	(CAPE, TRST, INFN)
GERARD	90	MPL A5 391		(MPIM)
LEUTWYLER	90B	NP B337 108		(BERN)
MALTMAN	90	PL B234 158	+Goldman, Stephenson Jr.	(YORKC, LANL)
CHOI	89	PRL 62 849		
CHOI	89B	PR D40 890	+Kim	(CMU, JHU)
BARDUCCI	88	PR D38 238	+Casalbuoni, De Curtis+	(FIRZ, INFN, LECE, GEVA)
Also	87	PL B193 305	Barducci, Casalbuoni+	(FIRZ, INFN, LECE, GEVA)
DOMINGUEZ	87	ANP 174 372	+de Rafael	(ICTP, MARS, WIEN)
KAPLAN	86	PRL 56 2004	+Manohar	(HARV)
AMETLLER	84	PR D30 674	+Ayala, Bramon	(BARC)
KREMER	84	PL 143B 476	+Papadopoulos, Schilcher	(MANZ)
GASSER	82	PRPL 87 77	+Leutwyler	(BERN)
PENSO	82	NC 68A 213	+Penso, Truong	(ROMA, EPOL)
PENSO	82B	NC 72A 113	+Verzegnassi	(ROMA, INFN, TRST, SISSA)
GASSER	81	ANP 136 62		(BERN)
MINKOWSKI	80	NP B164 25	+Zepeda	(BERN)
PAGELS	80	PR D22 2876	+Stokar	(ROCK)
LANGACKER	79	PR D19 2070	+Pagels	(DESY, PRIN)
LANGACKER	79B	PR D20 2983		(PENN)
WEINBERG	77	ANYAS 38 185		(HARV)
GASSER	75	NP B94 269	+Leutwyler	(BERN)

c

$I(J^P) = 0(\frac{1}{2}^+)$

Charge $= \frac{2}{3}\,e$ Charm $= +1$

c-QUARK MASS

The c-quark mass is estimated from charmonium and D masses. It corresponds to the "running" mass in the $\overline{MS}$ scheme. We have converted masses in other schemes to the $\overline{MS}$ scheme using one-loop QCD pertubation theory with $\alpha_s(\mu{=}m_c) = 0.39$. The range 1.0–1.6 GeV for the $\overline{MS}$ mass corresponds to 1.2–1.9 GeV for the pole mass (see the "Note on Quark Masses").

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
1.0 to 1.6 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.22±0.06	[1] DOMINGUEZ	94	THEO	Assumes $\overline{MS}$ scheme
≥ 1.23	[2] LIGETI	94	THEO	Assumes $\overline{MS}$ scheme
≥ 1.25	[3] LUKE	94	THEO	Assumes $\overline{MS}$ scheme
1.23±0.04	[4] NARISON	94	THEO	Assumes $\overline{MS}$ scheme
1.31±0.03	[5] TITARD	94	THEO	Assumes $\overline{MS}$ scheme
$1.5\ ^{+0.2}_{-0.1}\ \pm0.2$	[6] ALVAREZ	93	THEO	
1.27±0.02	[7] NARISON	89	THEO	
1.25±0.05	[8] NARISON	87	THEO	
1.27±0.05	[9] GASSER	82	THEO	

[1] DOMINGUEZ 94 uses QCD sum rules for $J/\psi(1S)$ system and finds a pole mass of 1.46 ± 0.07 GeV.
[2] LIGETI 94 computes lower bound of 1.43 GeV on pole mass using HQET, and experimental data on inclusive B and D decays.
[3] LUKE 94 computes lower bound of 1.46 GeV on pole mass using HQET, and experimental data on inclusive B and D decays.
[4] NARISON 94 uses spectral sum rules to two loops, and $J/\psi(1S)$ and Υ systems.
[5] TITARD 94 uses one-loop computation of the quark potential with nonperturbative gluon condensate effects to fit $J/\psi(1S)$ and Υ states.
[6] ALVAREZ 93 method is to fit the measured x_F and p_T^2 charm photoproduction distributions to the theoretical predictions of ELLIS 89C.
[7] NARISON 89 determines the Georgi-Politzer mass at $p^2 = -m^2$ to be 1.26 ± 0.02 GeV using QCD sum rules.
[8] NARISON 87 computes pole mass of 1.46 ± 0.05 GeV using QCD sum rules, with $\Lambda(\overline{MS}) = 180 \pm 80$ MeV.
[9] GASSER 82 uses SVZ sum rules. The renormalization point is μ = quark mass.

c-QUARK REFERENCES

DOMINGUEZ	94	PL B333 184	+Gluckman, Paver	(CAPE, TRST, INFN)
LIGETI	94	PR D49 R4331	+Nir	(REHO)
LUKE	94	PL B321 88	+Savage	(TNTO, UCSD, CMU)
NARISON	94	PL B341 73		(CERN, MONP)
TITARD	94	PR D49 6007	+Yndurain	(MICH, MADU)
ALVAREZ	93	ZPHY C60 53	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ELLIS	89C	NP B312 551	+Nason	(FNAL, ETH)
NARISON	89	PL B216 191		(ICTP)
NARISON	87	PL B197 405		(CERN)
GASSER	82	PRPL 87 77	+Leutwyler	(BERN)

b

$I(J^P) = 0(\frac{1}{2}^+)$

Charge $= -\frac{1}{3}\,e$ Bottom $= -1$

b-QUARK MASS

The b-quark mass is estimated from bottomonium and B masses. It corresponds to the "running" mass in the $\overline{MS}$ scheme. We have converted masses in other schemes to the $\overline{MS}$ scheme using one-loop QCD pertubation theory with $\alpha_s(\mu{=}m_b) = 0.22$. The range 4.1–4.5 GeV for the $\overline{MS}$ mass corresponds to 4.5–4.9 GeV for the pole mass (see the "Note on Quark Masses").

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
4.1 to 4.5 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.22 ±0.05	[1] NARISON	95B	THEO	Assumes $\overline{MS}$ scheme
4.415±0.006	[2] VOLOSHIN	95	THEO	Assumes $\overline{MS}$ scheme
4.0 ±0.1	[3] DAVIES	94	THEO	Assumes $\overline{MS}$ scheme
≥ 4.26	[4] LIGETI	94	THEO	Assumes $\overline{MS}$ scheme
≥ 4.2	[5] LUKE	94	THEO	Assumes $\overline{MS}$ scheme
4.23 ±0.04	[6] NARISON	94	THEO	Assumes $\overline{MS}$ scheme
4.397±0.025	[7] TITARD	94	THEO	Assumes $\overline{MS}$ scheme
4.32 ±0.05	[8] DOMINGUEZ	92	THEO	
4.24 ±0.05	[9] NARISON	89	THEO	
4.18 ±0.02	[10] REINDERS	88	THEO	
4.30 ±0.13	[11] NARISON	87	THEO	
4.25 ±0.1	[12] GASSER	82	THEO	

[1] NARISON 95B uses finite energy sum rules to two-loop accuracy to determine a b-quark pole mass of 4.61 ± 0.05 GeV.
[2] VOLOSHIN 95 result was converted from a pole mass of 4827 ± 7 MeV using the one-loop formula. Pole mass was extracted using moments of the total cross section for $e^+e^- \rightarrow b$hadrons.

[3] DAVIES 94 uses lattice computation of Υ spectroscopy. They also quote a value of 5.0 ± 0.2 GeV for the b-quark pole mass. The numerical computation includes quark vacuum polarization (unquenched); they find that the masses are independent of n_f to within their errors. Their error for the pole mass is larger than the error for the $\overline{\rm MS}$ mass, because both are computed from the bare lattice quark mass, and the conversion for the pole mass is less accurate.

[4] LIGETI 94 computes lower bound of 4.66 GeV on pole mass using HQET, and experimental data on inclusive B and D decays.

[5] LUKE 94 computes lower bound of 4.60 GeV on pole mass using HQET, and experimental data on inclusive B and D decays.

[6] NARISON 94 uses spectral sum rules to two loops, and $J/\psi(1S)$ and Υ systems.

[7] TITARD 94 uses one-loop computation of the quark potential with nonperturbative gluon condensate effects to fit $J/\psi(1S)$ and Υ states.

[8] DOMINGUEZ 92 determines pole mass to be 4.72 ± 0.05 using next-to-leading order in $1/m$ in moment sum rule.

[9] NARISON 89 determines the Georgi-Politzer mass at $p^2 = -m^2$ to be 4.23 ± 0.05 GeV using QCD sum rules.

[10] REINDERS 88 determines the Georgi-Politzer mass at $p^2 = -m^2$ to be 4.17 ± 0.02 using moments of $\overline{b}\gamma^\mu b$. This technique leads to a value for the mass of the B meson of 5.25 ± 0.15 GeV.

[11] NARISON 87 determines the pole mass to be 4.70 ± 0.14 using QCD sum rules, with $\Lambda(\overline{\rm MS}) = 180 \pm 80$ MeV.

[12] GASSER 82 uses SVZ sum rules. The renormalization point is μ = quark mass.

$m_b - m_c$ MASS DIFFERENCE

The mass difference $m_b - m_c$ in the HQET scheme is 3.4 ± 0.2 GeV (see the "Note on Quark Masses").

VALUE (GeV)	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •		
≥ 3.29	[13] GROSSE	78

[13] GROSSE 78 obtain $(m_b - m_c) \geq 3.29$ GeV based on eigenvalue inequalities in potential models.

b-QUARK REFERENCES

NARISON	95B	PL B352 122		(MONP)
VOLOSHIN	95	IJMP A10 2865		(MINN)
DAVIES	94	PRL 73 2654	+Hornbostel+	(GLAS, SMU, CORN, EDIN, OSU, FSU)
LIGETI	94	PR D49 R4331	+Nir	(REHO)
LUKE	94	PL B321 88	+Savage	(TNTO, UCSD, CMU)
NARISON	94	PL B341 73		(CERN, MONP)
TITARD	94	PR D49 6007	+Yndurain	(MICH, MADU)
DOMINGUEZ	92	PL B293 197	+Paver	(CAPE, TRST, INFN)
NARISON	89	PL B216 191		(ICTP)
REINDERS	88	PR D38 947		(BONN)
NARISON	87	PL B197 405		(CERN)
GASSER	82	PRPL 87 77	+Leutwyler	(BERN)
GROSSE	78	PL 79B 103	+Martin	(CERN)

t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge = $\frac{2}{3}\,e$ Top = +1

THE TOP QUARK

(by M. Mangano at CERN and T. Trippe at LBNL)

A. Introduction: The top quark is the $Q = 2/3$, $T_3 = +1/2$ member of the weak-isospin doublet containing the bottom quark (see our review on the "Standard Model of Electroweak Interactions" for more information). The existence of a sixth quark has been expected since the discovery of the bottom quark itself and has become an absolute theoretical necessity within the Standard Model (SM) after the measurement of the $T_3 = -1/2$ weak isospin of the bottom quark [1]. While models with additional quarks but quantum numbers different from the top quark have been constructed, the simplest hypothesis that the weak doublet containing the bottom be completed into a family structure similar to the first two generations has always been the most appealing. This idea has finally been confirmed with the recent announcement of the top discovery by the CDF and DØ experiments at the Fermilab 1.8 TeV Tevatron proton-antiproton collider.

We start this note by presenting a brief historical survey of top searches. Then we discuss in more detail the essential features of top production and decay properties which were exploited to perform the discovery. Finally, we discuss the experimental and theoretical issues involved in the determination of its parameters (mass, production cross section, decay branching ratios, *etc.*) and conclude with the prospects for future improvements.

B. Some history: The first expectations for the value of the top mass used a naive extrapolation of the up- to down-type quark mass ratios in the first two generations, leading to values in the range of 10–20 GeV. Direct searches for $t\overline{t}$ pair production in e^+e^- collisions in this mass range were performed beginning in the late 70's at DESY and SLAC (see the compilation of limits in our 1990 edition [2]). These searches looked for a sudden increase in the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ or for anomalies in the distributions of thrust and acoplanarity in hadronic events. The lower limit on the top mass was increased to 30 GeV and then to approximately 46 GeV between the end of the 80's and the beginning of the 90's, when the more powerful Tristan, SLC and LEP e^+e^- colliders began operations (see the t-Quark Particle Listings in the current edition).

In parallel to the searches in e^+e^- collisions, direct searches were performed during the 80's by the UA1 and UA2 experiments at the CERN $S\overline{p}pS$ proton-antiproton collider, $\sqrt{s} = 630$ GeV. At this energy, and at the available luminosities, the CERN experiments were sensitive to top mass values not exceeding 70 GeV, the top quark being mostly produced via an intermediate on-shell W, decaying to $t\overline{b}$. A top quark with mass below the Wb threshold was then expected to undergo a 3-body weak decay to a $bf\overline{f}'$ final state, with $f\overline{f}'$ being a weak isospin doublet such as $\nu_\ell\overline{\ell}$ or $u\overline{d}$.

Because of the overwhelming QCD background to the detection of the purely hadronic final states, the experiments looked for final states including a high momentum isolated lepton, missing transverse energy ($\not\!\!E_T$), and one or more jets. No evidence for top production was obtained (see the t-Quark Particle Listings in the current edition for the references): the 95% CL mass limits went from 41 GeV (UA1, 1988), to 60 GeV (UA1, 1990), to 69 GeV (UA2, 1990). The first limits from CDF at the Fermilab Tevatron also appeared in 1990: $m_t > 72$ GeV from searches in the $e\mu$ final states, and $m_t > 77$ GeV from searches in the e plus jets and missing $\not\!\!E_T$ final states.

Further indications of a large top mass had come from the measurement of a significant B^0–$\overline{B}^0$ mixing, performed in 1986 by UA1 and Argus.

Mass limits independent of the decay mode were also set in the range $m_t > 40$ GeV via the determination of the W boson width, from the measurement in hadronic collisions of the ratio $\sigma(W \to \ell\nu_\ell)/\sigma(Z \to \ell^+\ell^-)$. With the advent of high-precision electroweak data (from deep-inelastic scattering, M_W, atomic parity violation and, most importantly, from the study of the Z-boson couplings at SLC and LEP), global fits of the SM parameters have become possible, and have provided significant indirect constraints on the value of the top mass, once more indicating a large value (see our review "Standard

Model of Electroweak Interactions" in the current edition for more information).

In this edition we have shortened the Particle Listings of indirect top mass limits by omitting superseded limits and reviews published before 1994. For more complete listings see our 1994 edition [3].

C. Top quark searches at the Tevatron: The first direct limits on the top mass exceeding the threshold for the decay into real W and a bottom quark came in the early 90's from the Fermilab Tevatron collider: $m_t > 91$ GeV (CDF, 1992) and $m_t > 131$ GeV (D0, 1994).

At the Tevatron energy, 1.8 TeV, a top quark above the W mass is dominantly produced in pairs from pure QCD processes: $q\overline{q} \to t\overline{t}$ and $gg \to t\overline{t}$. For a top mass around 100 GeV, the production cross section is expected to be of the order of 100 pb and is evenly shared between the two above channels. At 150 (175, 200) GeV the cross section is about 10 (5, 2.5) pb, with approximately 80% (90%, 95%) of it due to the light quark annihilation.

For masses above the Wb threshold, and neglecting terms of order m_b^2/m_t^2, the top quark decay width is predicted in the SM to be [4]:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}(1-\frac{M_W^2}{m_t^2})^2(1+2\frac{M_W^2}{m_t^2})[1-\frac{2\alpha_s}{3\pi}(\frac{2\pi^2}{3}-\frac{5}{2})].$$

The use of G_F in this equation accounts for the largest part of the 1-loop electroweak radiative corrections, providing an expression accurate to better than 2%. The width values increase from 302 MeV (for $m_t = 120$ GeV) to 1.04 GeV ($m_t = 160$ GeV) and 2.23 GeV ($m_t = 200$ GeV). With such a correspondingly short lifetime, the top quark is expected to decay before top-favoured hadrons or $t\overline{t}$ quarkonium bound states can form.

The top quark decay is expected to be largely dominated by the Wb final state. The Ws and Wd final states are suppressed relatively to Wb by the square of the CKM matrix elements V_{ts} and V_{td}, whose values can be estimated under the assumption of unitarity of the three-generation CKM matrix to be less than 0.046 and 0.014, respectively (see our review "The Cabibbo-Kobayashi-Maskawa Mixing Matrix" in the current edition for more information).

Typical final states therefore belong to three classes:

A. $t\overline{t} \to W\,b\,W\,\overline{b} \to q\,\overline{q}'\,b\,q''\,\overline{q}'''\,\overline{b}$,

B. $t\overline{t} \to W\,b\,W\,\overline{b} \to q\,\overline{q}'\,b\,\ell\,\overline{\nu}_\ell\,\overline{b}$,

C. $t\overline{t} \to W\,b\,W\,\overline{b} \to \overline{\ell}\,\nu_\ell\,b\,\ell'\,\overline{\nu}_{\ell'}\,\overline{b}$.

The final state quarks emit radiation and evolve into jets of hadrons. The precise number of jets reconstructed by the detectors varies event by event, as it depends on the decay kinematics, as well as on the precise definition of jet used in the analysis. The neutrinos are reconstructed via the large imbalance in detected transverse momentum of the event (missing E_T).

The $t\overline{t}$ production signature is by itself quite clear in all possible decay channels, due to the many kinematical constraints imposed by the sequential decay via a real W. However, the combination of the limited experimental resolution and of the large cross section for the production of 6 jets in the QCD continuum (several nb) make the search in the purely hadronic channel very difficult. Since the detection of τ leptons has small efficiency, studies have therefore mostly concentrated on final states where one (or both) W decays to either an electron or a muon. Potential physics backgrounds still exist, mainly due to associated production of one (or two) W and several jets, with the W decaying leptonically. The gain in the S/B ratio is by an approximate factor of 10 for each W which is required to decay leptonically.

The theoretical estimates of the physics backgrounds have large uncertainties, since only leading order QCD calculations are available for most of the relevant processes (W+3 and 4 jets, or WW+2 jets). While this limitation is known to affect the estimates of the overall production rates, it is believed that the LO determination of the event kinematics and of the fraction of W plus multi-jet events containing b quarks is rather accurate. In particular, one expects the E_T spectrum of these jets to fall rather steeply, the jet direction to point preferentially at small angles from the beams, and the fraction of events with b quarks to be of the order of few percent. In the case of the top signal, *vice versa*, the b fraction is $\sim 100\%$ and the jets are rather energetic, since they come from the decay of a massive object. It is therefore possible to improve the S/B ratio by either requiring the presence of a b quark, or by selecting very energetic and central kinematical configurations.

A detailed study of control samples with features similar to those of the relevant backgrounds, but free from possible top contamination (*e.g.*, a sample of Z plus multi-jet events), is required to provide a reliable check on the background estimates.

D. Top observation at CDF and DØ: The CDF experiment and the DØ experiment independently observed the production and decay of the top quark at the Fermilab Tevatron collider in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV.

The CDF experiment published the first direct experimental evidence for the top quark in 1994 [5]. They found 12 events consistent with top, containing 6 silicon vertex tags, 7 low-p_T lepton tags, and 3 dilepton events (these categories are discussed below in more detail) with estimated backgrounds of 2.3 ± 0.3, 3.1 ± 0.3, and $0.56^{+0.25}_{-0.13}$ respectively. The combined excess signal was inconsistent with backgrounds by 2.8 σ, not enough to firmly establish the existence of the top quark. Interpreting the excess events as top, they found a $t\overline{t}$ production cross section of $13.9^{+6.1}_{-4.8}$ pb, larger than the expected QCD cross section discussed below. A mass analysis of seven of these events yielded $m_t = 174 \pm 10^{+13}_{-12}$ GeV. A sample of events selected according to the expected kinematical properties of top provided additional support for the top interpretation [6].

The DØ experiment [7] found nine top candidates in their data taken during the same Tevatron run with an estimated background of 3.8 ± 0.9. They found a probability of 2.7% that this yield was consistent with backgrounds, corresponding to a 1.9 σ effect. If they assumed that the observed excess was top production, they obtained a $t\bar{t}$ production cross section of 8.2 ± 5.1 pb at $m_t = 180$ GeV.

After accumulating more than three times the amount of data, both CDF and DØ reported in 1995 [8,9] that they had conclusively observed the top quark.

The CDF experiment [8] observed top signals in two classes of events: $\ell\ell + jets$ events, which have two high-p_T leptons (e or μ) of opposite charge, large missing E_T, and at least two jets; and $\ell + jets/b$-tag events, which have one high-p_T lepton, large missing E_T, and at least three jets, of which at least one is tagged as a b jet. They tagged b jets by finding secondary vertices from b-quark decay with their silicon vertex detector or by finding low-p_T leptons from semileptonic b decay.

In 67 pb^{-1} integrated luminosity, CDF observed 37 $\ell + jets/b$-tag) events containing 27 secondary vertex b tags and 23 low-p_T lepton b tags with estimated backgrounds of 6.7 ± 2.1 and 15.4 ± 2.0 respectively. They also observed 6 $\ell\ell$ events with an estimated background of 1.3 ± 0.3 events. The combined excess signal observed in these three categories is inconsistent with the background prediction by 4.8 σ.

The DØ experiment [9] observed top signals in three classes of events: $\ell\ell + jets$ events, $\ell + jets$ events, and $\ell + jets/b$-tag events. These classes differ from those of CDF in the details of their selection cuts, but the main differences are that DØ imposes topological cuts, includes $\ell + jets$ events without a b tag if they have at least four jets, and uses soft-muon b tagging only. The topological cuts, mainly H_T, which is the scalar sum of transverse energies of the jets (and, in dilepton events, the leading electron), are very effective since the top quark is heavy, and hence top events are more spherical than background events and are produced more centrally in the detector.

In an integrated luminosity of approximately 50 pb^{-1} DØ observed 3 $\ell\ell + jets$ events, 8 $\ell + jets$ events, and 6 $\ell + jets/b$-tag events, a total of 17 top candidates. The total estimated background in these events is 3.8 ± 0.6 events. The excess signal is inconsistent with the background prediction by 4.6 σ.

E. Measured top properties: CDF and DØ both measured the top mass using single lepton events with four or more jets. Each event was subjected to a two-constraint kinematic fit to the hypothesis $t\bar{t} \to W^+ b W^- \bar{b} \to \ell \nu_\ell q \bar{q}' b \bar{b}$, assuming that the four highest E_T jets were the $t\bar{t}$ daughters. All permutations of these jets were tried, with the restriction that b-tagged jets were assigned to b quarks in the fit.

CDF found that of their 37 $\ell + jets/b$-tag events, 19 events had four or more jets. Of these 19, $6.9^{+2.5}_{-1.9}$ were expected to be background. A fit to the mass distribution of the 19 events by the sum of the expected distributions for the $W + jets$ background and a top quark yielded $m_t = 176 \pm 8 \pm 10$ GeV where the second error is the estimated systematic uncertainty.

DØ found that of their 14 $\ell + jets$ (with and without b-tags) events, 11 had four or more jets and passed the fit. To increase the statistics and reduce mass biases, the H_T requirement was removed, yielding 27 $\ell + 4jets$ events, of which 24 passed the fit. A fit of the mass distribution to top and background contributions yielded $m_t = 199^{+19}_{-21} \pm 22$ GeV, where the second error is the estimated systematic error.

Preliminary results for the top mass based on the full (Run Ia+Ib) data set have been presented by CDF and DØ at conferences in early 1996 and are given in Table 1. Since these are preliminary results, we do not average them or include them in the data listings or summary tables.

Table 1: Preliminary top masses presented at conferences in early 1996. See for example Ref. 10 for CDF results and Ref. 11 for DØ results.

top quark mass	Expt.	Channel
$175.6 \pm 5.7 \pm 7.1$ GeV	CDF	lepton + jets
$159^{+24}_{-22} \pm 17$ GeV	CDF	dilepton
$187 \pm 8 \pm 12$ GeV	CDF	hadronic
$170 \pm 15 \pm 10$ GeV	DØ	lepton + jets
$158 \pm 24 \pm 10$ GeV	DØ	$e\mu$

The current average of the CDF and DØ published results is $m_t = 180 \pm 12$ GeV, where statistical and systematic errors have been combined in quadrature and where CDF and DØ systematic errors have been assumed to be independent.

Given the experimental technique used to extract the top mass, this value should be taken as representing the top *pole mass* (see our review "Note on Quark Masses" in the current edition).

The extraction of the value of the top mass from the analyses described requires, in addition to an understanding of the absolute energy calibration and resolution of the detectors, also an *a priori* knowledge of the structure of the final state. Given the hardness of a $t\bar{t}$ production process, jets can in fact arise not only from the top decays, but also from the initial state gluon radiation. Furthermore, quarks from the top decays can radiate additional jets. The presence of these additional jets will affect the shape of the mass spectrum, depending on the details of how the samples used for the mass determination were defined. QCD calculations used to model top production and decay are expected to be rather reliable, but residual uncertainties remain and are accounted for in the overall systematic error on the top mass.

CDF [8] and DØ [9] determined the $t\bar{t}$ cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV from their numbers of top candidates, their estimated background, their $t\bar{t}$ acceptance, and their integrated luminosity. The evaluation was done under the assumption of SM decays $t \to Wb$, with unity branching ratio. Based on their number of secondary-vertex b-tagged events, CDF determined the $t\bar{t}$ cross section to be $6.8^{+3.6}_{-2.4}$ pb at $m_t = 175$ GeV. The next-to-leading-order QCD prediction [12], allowing for a variation of the renormalization and factorization scales μ in the range $0.5 < \mu/m_t < 2$ and using the MRSA set of parton densities [13], gives $4.3 < \sigma_{t\bar{t}}(\text{pb}) < 5.0$ at $m_t = 175$ GeV.

Based on their 17 top candidates, DØ determined the $t\bar{t}$ cross section to be 6.4 ± 2.2 pb at their central mass value of 199 GeV or 8.2 ± 2.9 pb at 180 GeV. The QCD predictions are: $2.0 < \sigma_{t\bar{t}}(\text{pb}) < 2.4$ ($m_t = 199$ GeV), and $3.6 < \sigma_{t\bar{t}}(\text{pb}) < 4.3$ ($m_t = 180$ GeV).

More recent preliminary values of the $t\bar{t}$ cross section were given at early 1996 conferences CDF found $7.5^{+1.9}_{-1.7}$ pb at 175 GeV [14] and DØ found 5.2 ± 1.8 pb at 170 GeV [15].

The measurement of other properties of the top quark has just started. CDF reported the first direct measurement of the $t \to Wb$ branching ratio [16]. Their preliminary result, obtained by comparing the number of events with 1 and 2 tagged-b jets and using the known tagging efficiency, is: $R = \text{B}(t \to Wb)/\sum_{q=d,s,b} \text{B}(t \to Wq) = 0.87^{+0.13+0.13}_{-0.30-0.11}$.

F. The future: With the discovery of the top quark, future studies will follow two main tracks. Theoretically, it is hoped that the large top mass, and the tantalizing coincidence between its current value and the fundamental scale of the electroweak symmetry breaking, will lead to some understanding of the structure of fermion masses and of the symmetry breaking mechanism itself. Experimentally, the work will concentrate on reducing the errors on the mass and cross section determinations and on the measurement of more specific properties of the top quark, namely its decay branching ratios and its couplings. With a smaller error on the top mass, and with yet improved measurements of the electroweak parameters, it will be possible to get important constraints on the value of the Higgs mass. Current global fits performed within the SM and its minimal supersymmetric extension, provide indications for a relatively light Higgs (see the "H^0 Indirect Mass Limits from Electroweak Analysis" in the Particle Listings of the current edition), possibly within the range of the upcoming LEP2 experiments.

The current Tevatron data, once fully analysed, should allow the first determination of limits on rare top decay modes, such as $t \to \gamma c$ or $t \to Zc$. Studies of the decay angular distributions will allow a first direct analysis of the $V - A$ nature of the Wtb coupling, as well as providing direct information on the relative coupling of longitudinal and transverse W bosons to the top. In the SM, the fraction of decays to transversely polarized W bosons is expected to be $1/(1 + m_t^2/2M_W^2)$ (29% for $m_t = 180$ GeV). Deviations from this value would challenge the Higgs mechanism of spontaneous symmetry breaking.

Over the longer term, a direct measurement of the Wtb coupling constant will be possible when enough data will be accumulated to detect the less frequent single-top production processes, such as $q\bar{q}' \to W^* \to t\bar{b}$ and $qb \to q't$ via W exchange.

A precise determination of the top production cross section will test the current theoretical understanding of the production mechanisms. The current state of the art amounts to complete calculations at the next-to-leading order in QCD [12], as well as efforts to resum classes of potentially large logarithmic corrections coming from multiple soft gluon emission in the intial state [17]. A precise understanding of top production at the Tevatron is important for the extrapolation to the higher energies of future colliders, like the LHC, where the expected large cross section will enable more extensive studies.

Discrepancies in rate between theory and data, on the other hand, would be more exciting and might indicate the presence of exotic production channels, as predicted in some models. In this case, one should also expect a modification of kinematical distributions such as the invariant mass of the top pair or the top quark transverse momentum.

As discussed in the previous sections, some of the current uncertainty in the determination of the top mass from the reconstruction of its final state jets arises from theoretical uncertainties in the modeling of the radiation in these very hard events. The current data, once fully analyzed, will presumably help improve our theoretical understanding. At the same time, the larger samples that will become available in the future will allow more strict selection criteria, leading to purer samples of top quarks. For example, requesting the presence of two secondary-vertex b tags in the event, in addition to two and only two central jets of high-E_T, should largely reduce the possibility of erroneously including jets not coming from the top decays into the mass reconstruction. This will significantly improve the mass resolution and will make it less sensitive to the theoretical uncertainties.

Finally, the large mass of the top quark leaves open the possibility of top decays into yet unobserved particles beyond the SM. For example, current limits on the masses of a charged Higgs (H^+) or of a supersymmetric scalar top quark ($\tilde{t}$) and neutralino ($\widetilde{\chi}^0$), cannot exclude the existence of decays such as $t \to H^+b$ or $t \to \tilde{t}\widetilde{\chi}^0$. The first channel, in particular, has been used extensively in the past in direct top searches (see the Particle Listings in the current edition). Both these exotic modes are currently under investigation at CDF and DØ.

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t-Quark Mass in $p\overline{p}$ Collisions

The *t* quark has now been observed. Its mass is sufficiently high that decay is expected to occur before hadronization.

Preliminary results for the top mass based on the full (Run Ia+Ib) data set have been presented by CDF and DØ at conferences in early 1996:

$m_t = 175.6 \pm 5.7 \pm 7.1$ GeV	CDF	lepton + jets
$m_t = 159^{+24}_{-22} \pm 17$ GeV	CDF	dilepton
$m_t = 187 \pm 8 \pm 12$ GeV	CDF	hadronic
$m_t = 170 \pm 15 \pm 10$ GeV	DØ	lepton + jets
$m_t = 158 \pm 24 \pm 10$ GeV	DØ	$e\mu$

Because of the high current interest, we mention these preliminary results here but do not average them or include them in the Listings or Tables. See the note on the top quark for references.

Search limits, which are now primarily of historical interest, are based on the assumption that no nonstandard decay modes such as $t \to bH^+$ are available, except as noted in the comments.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
180±12 OUR AVERAGE					
$199^{+19}_{-21} \pm 22$		[1] ABACHI	95	D0	ℓ + jet
$176 \pm 8 \pm 10$		[2] ABE	95F	CDF	ℓ + b-jet
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[3] ABACHI	95B	D0	$\ell\ell$ + jets, ℓ + jets
>128	95	[4] ABACHI	95F	D0	$\ell\ell$ + jets, ℓ + jets
		[5] ABE	95O	CDF	
		[6] ABE	95V	CDF	
		[7] ABE,F	95	CDF	$W + \geq 4$ jets
>131	95	[8] ABACHI	94	D0	$\ell\ell$ + jets, ℓ + jets
$174 \pm 10^{+13}_{-12}$		[9] ABE	94E	CDF	ℓ + b-jet
>118	95	[9] ABE	94E	CDF	$\ell\ell$
		[10] ABE	94H	CDF	$t \to bH^+$, $H^+ \to \tau^+\nu_\tau$
		[11] ABE	94I	CDF	$t \to bH^+$, $H^+ \to \tau^+\nu_\tau$
> 91	95	[12] ABE	92	CDF	$\ell\ell$, ℓ + b-jet
		[13] ALITTI	92F	UA2	$t \to bH^+$, $H^+ \to \tau^+\nu_\tau$
> 60	95	[14] ALBAJAR	91B	UA1	$t \to bH^+$, $H^+ \to \tau^+\nu_\tau$
		[15] BAER	91B	RVUE	$t \to \widetilde{t}_1 \widetilde{\chi}^0_1$
> 72	95	[16] ABE	90B	CDF	$e + \mu$
> 77	95	[17] ABE	90C	CDF	e + jets + missing E_T
> 69	95	[18] AKESSON	90	UA2	e + jets + missing E_T
> 60	95	ALBAJAR	90B	UA1	e or μ + jets, $\mu\mu$ + jet
		[19] BARGER	90E	RVUE	$t \to bH^+$
> 41	95	[20] ALBAJAR	88	UA1	e or μ + jets

[1] ABACHI 95 search for $\ell\ell$+jets ($e\mu$, ee, and $\mu\mu$) and ℓ+jets (ℓ=e or μ). The ℓ+jets search is done in two ways, using either topological cuts or requiring μ tagging. They observe 17 (3 $\ell\ell$, 6 ℓ+b-jets, and 8 ℓ+jets topological) events with an expected background of 3.8 ± 0.6. These seven analysis channels combine to give a 4.6 standard deviation effect. The mass fit is from 24 ℓ+4-jet events obtained with looser cuts.

[2] ABE 95F search for $\ell\ell$ (ee, $e\mu$, and $\mu\mu$) final states and ℓ + b-jet final states. They find 37 ℓ + b-jet candidates containing 27 secondary vertex tags and 23 lepton tags with expected backgrounds of 6.7 ± 2.1 and 15.4 ± 2.0 respectively. They find 6 $\ell\ell$ events with an expected background of 1.3 ± 0.3 These three observations combine to give a 4.8 standard deviation effect. The mass fit is from 19 ℓ+4-jet events with a b-tag. The shape of the mass distribution is consistant with top and this increases the significance of the effect to 5.0σ.

[3] ABACHI 95B searched for dilepton channels $e\mu$+ jets, ee+ jets, $\mu\mu$+ jets, and singleletpon channels e+ jets and μ+ jets with and without b tagging. They found 9 events where 3.8 ± 0.9 events are expected from background. Based on an integrated luminosity of $13.5 \pm 1.6\text{pb}^{-1}$. These analyses combine to give a 1.9 standard deviation effect. Assuming that the observed excess signal is due to top quark production, the cross section is 8.2 ± 5.1 pb for $m_t = 180$ GeV.

[4] ABACHI 95F searched for dilepton channels $e\mu$+ jets, ee+ jets, $\mu\mu$+ jets, and singlelepton channels e + jets and μ + jets with and without b tagging. The lower mass bound supersedes that of ABACHI 94 and is weaker as a result of a recalibration of the integrated luminosity. Assuming that the observed excess signal is due to top quark production, the cross section is 8.2 ± 5.1 pb (9.2 ± 5.7 pb) for $m_t = 180$ GeV (160 GeV).

[5] ABE 95O find evidence for top production in the jet E_T distributions of $W + \geq 3$ jet events, based on an integrated luminosity of 19.3pb^{-1}. The observed distributions are consistent with $m_t = 170$ GeV. Supersed by ABE 95V.

[6] ABE 95V find evidence for top production in the jet E_T distributions of $W + \geq 3$ jet events, based on an integrated luminosity of 67pb^{-1}.

[7] ABE,F 95 compared the total transverse energy distribution of the $W + \geq 4$-jet data with that expected from all known backgrounds and found 3.8σ deviation in the shape. The distribution agrees well with a linear combination of background and $t\overline{t}$ events, the agreement being best for $m_t = 180$ GeV.

[8] ABACHI 94 search for $e\mu$ + jets, ee + jets, e + jets, and μ + jets. Production cross section with soft-gluon resummation of LAENEN 94 is used. The limit decreases to >122 GeV if $\mathcal{O}(\alpha_s{}^3)$ cross section is employed for comparison with ABE 92. Superseded by ABACHI 95F.

[9] ABE 94E search for ee, $e\mu$, and $\mu\mu$ dilepton final states and single lepton + b-jet final states. They observe a total of 15 top topology tags (12 events of which three are doubly tagged) with an expected background of $5.96^{+0.49}_{-0.44}$. The mass determination is from 7 single-lepton + b-jet events which have four jets. Their $\ell\ell$ limit uses the production cross section with soft gluon resummation from LAENEN 94. Superseded by ABE 95F.

[10] ABE 94H searched for $t \to bH^+$, $H^+ \to \tau^+\nu_\tau$ with τ decaying hadronically. The search was done in the region 45 GeV $< m_{H^+} < m_t - m_b$ and 55 GeV $< m_t < m_W + m_b$. See their Fig. 3 for the 95% CL excluded regions in the (m_{H^+},m_t) plane for $B(H^+ \to \tau^+\nu_\tau) = 1$, 0.75, and 0.5.

[11] ABE 94I searched for $t \to bH^+$, $H^+ \to \tau^+\nu_\tau$, $\tau^+ \to \ell^+\nu_\ell\overline{\nu}_\tau$. The search was done in the region 45 GeV $< m_{H^+} < m_t - m_b$ and 62 GeV $< m_t <$ 110 GeV. See their Fig. 2 for the 95% CL excluded regions in the (m_{H^+},m_t) plane for $B(H^+ \to \tau^+\nu_\tau)$ = 1, 0.75, and 0.5. The entire region of the plane is excluded for $B(H^+ \to \tau^+\nu_\tau)$ > 0.75 when $m_t < m_W + m_b$.

[12] ABE 92 search for ee, $e\mu$, $\mu\mu$ dilepton final states and (e or μ) plus a b-quark jet. The b jet is tagged by a soft muon. The 90%CL limit is 95 GeV. Superseded by ABE 94E $\ell\ell$ limit.

[13] ALITTI 92F search for $t \to bH^+$, $H^+ \to \tau^+\nu_\tau$ with τ^+ decaying hadronically. m_t between 50 and 70 GeV is excluded if $m_t - m_{H^+} = m_b$+($\lesssim$ a few–10 GeV). See their Figs. 5,6 for the excluded region for $B(H^+ \to \tau^+\nu_\tau) = 1$, 0.5.

[14] ALBAJAR 91B searched for the decay $t \to H^+ b$ using single muon and dimuon events and assuming $B(H^+ \to \tau^+\nu) \geq 0.95$. The limit holds for $m_{H^+} \lesssim m_t - m_b -$ (3–6) GeV.

[15] BAER 91B argue that a top quark as light as 60 GeV (65 GeV, if the minimal SUSY framework is assumed) may have escaped detection at CDF if a supersymmetric decay mode is open.

[16] ABE 90B exclude the region 28–72 GeV.

[17] ABE 90C cannot exclude m_t < 40 GeV, but this region is ruled out by other experiments. They study events with an energetic electron, missing transverse energy and two or more jets. Only the $t\overline{t}$ contribution (not $W \to tb$) is relevant for these masses. See also ABE 91.

[18] AKESSON 90 searched for events having an electron with p_T > 12 GeV, missing momentum > 15 GeV, and a jet with E_T > 10 GeV, $|\eta|$ < 2.2, and excluded m_t between 30 and 69 GeV.

[19] BARGER 90E claim that ABE 90C data exclude most regions of two-Higgs-doublet models with m_t < 80 GeV even if $t \to bH^+$ decay is allowed.

[20] ALBAJAR 88 value quoted here is revised using the full $\mathcal{O}(\alpha_s^3)$ cross section of ALTARELLI 88. Superseded by ALBAJAR 90B.

Indirect t-Quark Mass from Standard Model Electroweak Fit

"OUR EVALUATION" below is from the fit to electroweak data described in the "Standard Model of Electroweak Interactions" section of this Review. This fit result does not include direct measurements of m_t. The second error corresponds to m_H=300^{+700}_{-240} GeV.

The RVUE values are based on the data described in the footnotes. RVUE's published before 1994 and superseded analyses are now omitted. For more complete listings of earlier results, see the 1994 edition (Physical Review **D50** 1173 (1994)).

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
$179\pm\ 8^{+17}_{-20}$ OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$175\pm11^{+17}_{-19}$	[21] ERLER	95	RVUE	Z parameters, m_W, low energy
$180\pm 9^{+19}_{-21}\mp 2.6\pm 4.8$	[22] MATSUMOTO	95	RVUE	
$157^{+36}_{-48}{}^{+19}_{-20}$	[23] ABREU	94	DLPH	Z parameters
$158^{+32}_{-40}\pm19$	[24] ACCIARRI	94	L3	Z parameters
$132^{+41}_{-48}{}^{+24}_{-18}$	[25] AKERS	94	OPAL	Z parameters
$190^{+39}_{-48}{}^{+12}_{-14}$	[26] ARROYO	94	CCFR	ν_μ iron scattering
$184^{+25}_{-29}{}^{+17}_{-18}$	[27] BUSKULIC	94	ALEP	Z parameters
153 ± 15	[28] ELLIS	94B	RVUE	Electroweak
$177\pm\ 9^{+16}_{-20}$	[29] GURTU	94	RVUE	Electroweak
$174^{+11}_{-13}{}^{+17}_{-18}$	[30] MONTAGNA	94	RVUE	Electroweak
$171\pm12^{+15}_{-21}$	[31] NOVIKOV	94B	RVUE	Electroweak
160^{+50}_{-60}	[32] ALITTI	92B	UA2	m_W, m_Z

[21] ERLER 95 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding $\alpha_s(m_Z)$ = 0.127(5)(2).
[22] MATSUMOTO 95 result is from fit with free m_t to Z parameters, M_W, and low-energy neutral-current data. The second error is for $m_H = 300^{+700}_{-240}$ GeV, the third error is for $\alpha_s(m_Z) = 0.116 \pm 0.005$, the fourth error is for $\delta\alpha_{had} = 0.0283 \pm 0.0007$.
[23] ABREU 94 value is for $\alpha_s(m_Z)$ constrained to 0.123 ± 0.005. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.
[24] ACCIARRI 94 value is for $\alpha_s(m_Z)$ constrained to 0.124 ± 0.006. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.
[25] AKERS 94 result is from fit with free α_s. The second error corresponds to m_H=300^{+700}_{-240} GeV. The 95%CL limit is m_t <210 GeV.
[26] ARROYO 94 measures the ratio of the neutral-current and charged-current deep inelastic scattering of ν_μ on an iron target. By assuming the SM electroweak correction, they obtain $1-m_W^2/m_Z^2 = 0.2218\pm0.0059$, yielding the quoted m_t value. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.
[27] BUSKULIC 94 result is from fit with free α_s. The second error is from m_H=300^{+700}_{-240} GeV.
[28] ELLIS 94B result is fit to electroweak data available in spring 1994, including the 1994 A_{LR} data from SLD. m_t and m_H are two free parameters of the fit for $\alpha_s(m_Z)$ = 0.118 ± 0.007 yielding m_t above, and $m_H = 35^{+70}_{-22}$ GeV. ELLIS 94B also give results for fits including constraints from CDF's direct measurement of m_t and CDF's and DØ 's production cross-section measurements. Fits excluding the A_{LR} data from SLD are also given.
[29] GURTU 94 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z)$ = $0.125 \pm 0.005^{+0.003}_{-0.001}$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Uses LEP, M_W, νN, and SLD electroweak data available in spring 1994.
[30] MONTAGNA 94 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z) = 0.124$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Errors in $\alpha(m_Z)$ and m_b are taken into account in the fit. Uses LEP, SLC, and M_W/M_Z data available in spring 1994.
[31] NOVIKOV 94B result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z) = 0.125 \pm 0.005 \pm 0.002$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Uses LEP and CDF electroweak data available in spring 1994.
[32] ALITTI 92B assume m_H = 100 GeV. The 95%CL limit is m_t < 250 GeV for m_H < 1 TeV.

MASS LIMITS for t Quark or Hadron Independent of t Decay Mode

These limits are derived from $\Gamma(W)$ values shown in the W width section. Independent of the top decay mode, any W decay to $t\bar{b}$ would increase the total width of the W boson. Since the discovery of top, this section is of historical interest only.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>62	95	[33] ABE	95W	CDF	$E_{cm}^{p\bar{p}}$= 1800 GeV
>62	95	[34] ABE	94B	CDF	$E_{cm}^{p\bar{p}}$= 1800 GeV
>45	95	[35] ABE	92I	CDF	$E_{cm}^{p\bar{p}}$= 1800 GeV
>53	95	[36] ALITTI	92	UA2	$E_{cm}^{p\bar{p}}$= 630 GeV
>55	95	[37] ALITTI	92	RVUE	
>43	95	[38] ABE	91C	CDF	$E_{cm}^{p\bar{p}}$= 1800 GeV
>38	90	[39] ALBAJAR	91	UA1	$E_{cm}^{p\bar{p}}$= 630 GeV
>51	90	[40] ALBAJAR	91	RVUE	$\Gamma(W)$

[33] ABE 95W result is from $\Gamma(W \rightarrow e\nu_e)/\Gamma(W) = 0.1094 \pm 0.0033(\text{stat})\pm0.0031(\text{syst.})$. In addition they obtain $\Gamma(W) = 2.064 \pm 0.060(\text{stat})\pm0.059(\text{syst.})$.
[34] ABE 94B result is from $\Gamma(W) = 2.063 \pm 0.061 \pm 0.060$ GeV. Superseded by ABE 95W.
[35] ABE 92I data include both e and μ final states. The result is derived from $\Gamma(W)$=2.16 ± 0.17 GeV. At 90%CL, the limit is >49 GeV.
[36] ALITTI 92 result is derived from $\Gamma(W) = 2.10 \pm 0.16$ GeV.
[37] Limit is from combined data of ALBAJAR 91, ALITTI 92, and ABE 90: $\Gamma(W)$ = 2.15 ± 0.11 GeV.
[38] ABE 91C result is derived from $\Gamma(W) = 2.12 \pm 0.20$ GeV. At 90%CL, the limit is > 48 GeV.
[39] ALBAJAR 91 result is derived from $\Gamma(W) = 2.18^{+0.26}_{-0.24} \pm 0.04$ GeV.
[40] Limit is from combined data of ALBAJAR 91, ALITTI 90C, and ABE 90.

MASS LIMITS for Top Hadrons in e^+e^- Collisions

The last column specifies measured quantities: S = Sphericity, T = Thrust.

For limits prior to 1987, see our 1990 edition, Physics Letters **B239**, p. VII.167 (1990). Since the discovery of top, this section is of historical interest only.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[41] ADRIANI	93G	L3	Quarkonium
>41.8	95	ADRIANI	93M	L3	$\Gamma(Z)$
>43	95	[42] ABREU	91F	DLPH	$\Gamma(Z)$
>30.2	95	ABE	90D	VNS	Event shape
>44.5	95	[42] ABREU	90D	DLPH	Event shape
>44.0	95	[42,43] ABREU	90D	DLPH	$t \rightarrow bH^+$, $H^+ \rightarrow c\bar{s}$, $\tau^+\nu$
>33.5	95	[44] ABREU	90D	DLPH	$\Gamma(Z \rightarrow$ hadrons)
>44.5	95	[45] AKRAWY	90B	OPAL	Acoplanarity
>44.3	95	[46] AKRAWY	90B	OPAL	$t \rightarrow bH^+$, $H^+ \rightarrow c\bar{s}$, $\tau\nu$
>45.8	95	[42] DECAMP	90F	ALEP	isolated charged particle and aplanarity
>40.7	95	[47] ABRAMS	89C	MRK2	Event shape
>42.5	95	ABRAMS	89C	MRK2	$t \rightarrow bH^+$, $H^+ \rightarrow c\bar{s}$
>29.9	95	[48] ADACHI	89C	TOPZ	μ
>29.9	95	[49] ENO	89	AMY	μ, e
>25.8	95	[50] ADACHI	88	TOPZ	R, T, Acoplanarity
>25.9	95	[51] IGARASHI	88	AMY	T + (μ,e)
>25.9	95	[52] SAGAWA	88	AMY	R, T
none E_{cm}=50	95	[53] ABE	87	VNS	R, T, Acoplanarity
>25.5	95	[54] YOSHIDA	87	VNS	R, T, Acoplanarity

[41] ADRIANI 93G search for vector quarkonium states near Z and give limit on quarkonium-Z mixing parameter δm^2 <(10–30) GeV^2 (95%CL) for the mass 88–94.5 GeV. Using Richardson potential, a 1S toponium state is excluded for the mass range 87.9–88.7, 89.1–94.3 GeV. This range is very sensitive to the potential choice.
[42] Search was near the Z peak at LEP.
[43] Assumed $m_{H^+} < m_t - 6$ GeV.
[44] Superseded by ABREU 91F.
[45] AKRAWY 90B search was restricted to data near the Z peak at E_{cm} = 91.26 GeV at LEP. The excluded region is between 23.4 and 44.5 GeV if no H^+ decays exist.
[46] AKRAWY 90B limit applies for any H^+ branching ratio B($c\bar{s}$). Limit increases to 45.2 GeV if B($c\bar{s}$) = 1. The lower end of the excluded region is m_{H^+} + 5 GeV.
[47] The ABRAMS 89C limit from an isolated track search is 40.0 GeV.
[48] ADACHI 89C search was at E_{cm} = 56.5–60.8 GeV at TRISTAN using multi-hadron events accompanying muons.
[49] ENO 89 search at E_{cm} = 50–60.8 GeV at TRISTAN.
[50] ADACHI 88 set limit σ(top) < 8.2 pb at CL=95% for top-flavored-hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark-parton model cross-section formula with first-order QCD corrections near the threshold, the above limit leads to a lower mass limit of 25.8 GeV at 95% confidence level for top quarks.
[51] IGARASHI 88 searches for leptons in low-thrust events and gives $\Delta R(t)$ < 0.15 (95% CL) at E_{cm} = 50–52 GeV.
[52] SAGAWA 88 set limit σ(top) < 6.1 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark parton model cross-section formula near threshold, the above limit leads to lower mass bounds of 25.9 GeV for charge 2/3 quarks.
[53] ABE 87 set limit σ(top) < 16 pb at CL=95% for top-flavored hadron production, which should be compared with the full top-quark production cross section of 45.9 pb.
[54] YOSHIDA 87 set limit σ(top) < 17 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. This limit should be compared with the full top-quark production cross section of 34 pb, which takes into account the effect of weak neutral current but neglects its axial-vector coupling contribution expected to be suppressed near threshold. After considering the radiative effects, top quarks of mass below 25.5 GeV can be excluded by the above limit.

t-Quark REFERENCES

ABACHI	95	PRL 74 2632	+Abbott, Abolins, Acharya, Adam+	(D0 Collab.)
ABACHI	95B	PRL 74 2422	+Abbott, Abolins, Acharya, Adam, Adams+	(D0 Collab.)
ABACHI	95F	PR D52 4877	+Abbott, Abolins, Acharya, Adam, Adams+	(D0 Collab.)
ABE	95F	PRL 74 2626	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABE	95O	PR D51 4623	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ABE	95V	PR D52 R2605	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABE	95W	PR D52 2624	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ABE,F	95	PRL 75 3997	Abe, Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ERLER	95	PR D52 441	+Langacker	(PENN)
MATSUMOTO	95	MPL A10 2553		(KEK)
ABACHI	94	PRL 72 2138	+Abbott, Abolins, Acharya, Adam+	(D0 Collab.)
ABE	94B	PRL 73 220	+Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ABE	94E	PR D50 2966	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
Also	94F	PRL 73 225	Abe, Albrow, Amidei, Antos, Anway-Weise+	(CDF Collab.)
ABE	94H	PRL 72 1977	+Albrow, Amidei, Anway-Wiese, Apollinari+	(CDF Collab.)
ABE	94I	PRL 73 2667	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABREU	94	NP B418 403	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	94	ZPHY C62 551	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
AKERS	94	ZPHY C61 19	+Alexander, Allison+	(OPAL Collab.)
ARROYO	94	PRL 72 3452	+King, Bachman+	(COLU, CHIC, FNAL, ROCH, WISC)
BUSKULIC	94	ZPHY C62 539	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
ELLIS	94B	PL B333 118	+Fogli, Lisi	(CERN, BARI)
GURTU	94	MPL A9 3301		(TATA)
LAENEN	94	PL B321 254	+Smith, van Neerven	(FNAL, UTRE, LEID)
MONTAGNA	94	PL B335 484	+Nicrosini, Passarino, Piccinini	(INFN, PAVI, CERN, TORI)
NOVIKOV	94B	MPL A9 2641	+Okun, Rozanov, Vysotsky	(GUEL, CERN, ITEP)
PDG	94	PR D50 1173	Montanet+	(CERN, LBL, BOST, IFIC+)
ADRIANI	93G	PL B313 326	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ABE	92	PRL 68 447	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
Also	92G	PR D45 3921	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	92I	PRL 69 28	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALITTI	92	PL B276 365	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92B	PL B276 354	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92F	PL B280 137	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ABE	91	PR D43 664	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	91C	PR D44 29	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	91F	NP B367 511	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ALBAJAR	91	PL B253 503	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
ALBAJAR	91B	PL B257 459	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
BAER	91B	PR D44 725	+Drees, Godbole+	(FSU, DESY, BOMB, UCD, HAWA)
ABE	90	PRL 64 152	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90B	PRL 64 147	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90C	PRL 64 142	+Amidei, Apollinari, Atac+	(CDF Collab.)
Also	91	PR D43 664	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90D	PL B234 382	+Amako, Arai, Asano+	(VENUS Collab.)
ABREU	90D	PL B242 536	+Adam, Adami, Adye, Alekseev, Allaby+	(DELPHI Collab.)
AKESSON	90	ZPHY C46 179	+Alitti, Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
AKRAWY	90B	PL B236 364	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALBAJAR	90B	ZPHY C48 1	+Albrow, Allkofer, Andrieu, Ankoviak+	(UA1 Collab.)
ALITTI	90C	ZPHY C47 11	+Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
BARGER	90E	PR D41 3421	+Hewett, Phillips	(WISC, RAL)
DECAMP	90F	PL B236 511	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
ABRAMS	89C	PRL 63 2447	+Adolphsen, Averill, Ballam+	(Mark II Collab.)
ADACHI	89C	PL B229 427	+Aihara, Doser, Enomoto, Fujii+	(TOPAZ Collab.)
ENO	89	PRL 63 1910	+Auchincloss, Blanis, Bodek, Budd+	(AMY Collab.)
ADACHI	88	PRL 60 97	+Aihara, Dijkstra+	(TOPAZ Collab.)
ALBAJAR	88	ZPHY C37 505	+Albrow, Allkofer+	(UA1 Collab.)
ALTARELLI	88	NP B308 724	+Diemoz, Martinelli, Nason	(CERN, ROMA, ETH)
IGARASHI	88	PRL 60 2359	+Myung, Chiba, Hanaoka+	(AMY Collab.)
SAGAWA	88	PRL 60 93	+Mori, Abe+	(AMY Collab.)
ABE	87	JPSJ 56 3763	+Amako, Arai+	(VENUS Collab.)
YOSHIDA	87	PL B198 570	+Chiba, Endo+	(VENUS Collab.)

b′ (4th Generation) Quark, Searches for

MASS LIMITS for b′ (4th Generation) Quark or Hadron in $p\overline{p}$ Collisions

These experiments (except for MUKHOPADHYAYA 93) assume that no two-body modes such as $b' \to b\gamma$, $b' \to bg$, or $b' \to cH^+$ are available.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>85	95	[1] ABE	92	CDF	$\ell\ell$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>75	95	[2] MUKHOPAD...	93	RVUE	FCNC
>72	95	[3] ABE	90B	CDF	$e + \mu$
>54	95	[4] AKESSON	90	UA2	e + jets + missing E_T
>43	95	[5] ALBAJAR	90B	UA1	μ + jets
>34	95	[6] ALBAJAR	88	UA1	e or μ + jets

[1] ABE 92 dilepton analysis limit of >85 GeV at CL=95% also applies to b' quarks, as discussed in ABE 90B.

[2] MUKHOPADHYAYA 93 analyze CDF dilepton data of ABE 92G in terms of a new quark decaying via flavor-changing neutral current. The above limit assumes $B(b' \to b\ell^+\ell^-)$=1%. For an exotic quark decaying only via virtual Z [$B(b\ell^+\ell^-) = 3\%$], the limit is 85 GeV.

[3] ABE 90B exclude the region 28–72 GeV.

[4] AKESSON 90 searched for events having an electron with $p_T > 12$ GeV, missing momentum > 15 GeV, and a jet with $E_T > 10$ GeV, $|\eta| < 2.2$, and excluded $m_{b'}$ between 30 and 69 GeV.

[5] For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.

[6] ALBAJAR 88 study events at E_{cm} = 546 and 630 GeV with a muon or isolated electron, accompanied by one or more jets and find agreement with Monte Carlo predictions for the production of charm and bottom, without the need for a new quark. The lower mass limit is obtained by using a conservative estimate for the $b'\overline{b}'$ production cross section and by assuming that it cannot be produced in W decays. The value quoted here is revised using the full $O(\alpha_s^3)$ cross section of ALTARELLI 88.

MASS LIMITS for b′ (4th Generation) Quark or Hadron in e^+e^- Collisions

Search for hadrons containing a fourth-generation −1/3 quark denoted b'.

The last column specifies the assumption for the decay mode (CC denotes the conventional charged-current decay) and the event signature which is looked for.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>46.0	95	[7] DECAMP	90F	ALEP	any decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[8] ADRIANI	93G	L3	Quarkonium
>44.7	95	ADRIANI	93M	L3	$\Gamma(Z)$
>45	95	ABREU	91F	DLPH	$\Gamma(Z)$
none 19.4–28.2	95	ABE	90D	VNS	Any decay; event shape
>45.0	95	ABREU	90D	DLPH	$B(CC) = 1$; event shape
>44.5	95	[9] ABREU	90D	DLPH	$b' \to cH^-$, $H^- \to \overline{c}s$, $\tau^-\nu$
>40.5	95	[10] ABREU	90D	DLPH	$\Gamma(Z \to$ hadrons)
>28.3	95	ADACHI	90	TOPZ	B(FCNC)=100%; isol. γ or 4 jets
>41.4	95	[11] AKRAWY	90B	OPAL	Any decay; acoplanarity
>45.2	95	[11] AKRAWY	90B	OPAL	$B(CC) = 1$; acoplanarity
>46	95	[12] AKRAWY	90J	OPAL	$b' \to \gamma$ + any
>27.5	95	[13] ABE	89E	VNS	$B(CC)$ =1; μ, e
none 11.4–27.3	95	[14] ABE	89G	VNS	$B(b' \to b\gamma) > 10\%$; isolated γ
>44.7	95	[15] ABRAMS	89C	MRK2	$B(CC)$= 100%; isol. track
>42.7	95	[15] ABRAMS	89C	MRK2	$B(bg)$= 100%; event shape
>42.0	95	[15] ABRAMS	89C	MRK2	Any decay; event shape
>28.4	95	[16,17] ADACHI	89C	TOPZ	$B(CC)$ =1; μ
>28.8	95	[18] ENO	89	AMY	$B(CC) \gtrsim 90\%$; μ, e
>27.2	95	[18,19] ENO	89	AMY	any decay; event shape
>29.0	95	[18] ENO	89	AMY	$B(b' \to bg) \gtrsim 85\%$; event shape
>24.4	95	[20] IGARASHI	88	AMY	μ,e
>23.8	95	[21] SAGAWA	88	AMY	event shape
>22.7	95	[22] ADEVA	86	MRKJ	μ
>21		[23] ALTHOFF	84C	TASS	R, event shape
>19		[24] ALTHOFF	84I	TASS	Aplanarity

[7] DECAMP 90F looked for isolated charged particles, for isolated photons, and for four-jet final states. The modes $b' \to bg$ for $B(b' \to bg) > 65\%$ $b' \to b\gamma$ for $B(b' \to b\gamma) > 5\%$ are excluded. Charged Higgs decay were not discussed.

[8] ADRIANI 93G search for vector quarkonium states near Z and give limit on quarkonium-Z mixing parameter $\delta m^2 <$(10–30) GeV^2 (95%CL) for the mass 88–94.5 GeV. Using Richardson potential, a 1S ($b'\overline{b}'$) state is excluded for the mass range 87.7–94.7 GeV. This range depends on the potential choice.

[9] ABREU 90D assumed $m_{H^-} < m_{b'} - 3$ GeV.

[10] Superseded by ABREU 91F.

[11] AKRAWY 90B search was restricted to data near the Z peak at E_{cm} = 91.26 GeV at LEP. The excluded region is between 23.6 and 41.4 GeV if no H^+ decays exist. For charged Higgs decays the excluded regions are between (m_{H^+} + 1.5 GeV) and 45.5 GeV.

[12] AKRAWY 90J search for isolated photons in hadronic Z decay and derive $B(Z \to b'\overline{b}')\cdot B(b' \to \gamma X)/B(Z \to \text{hadrons}) < 2.2 \times 10^{-3}$. Mass limit assumes $B(b' \to \gamma X) > 10\%$.

[13] ABE 89E search at E_{cm} = 56–57 GeV at TRISTAN for multihadron events with a spherical shape (using thrust and acoplanarity) or containing isolated leptons.

[14] ABE 89G search was at E_{cm} = 55–60.8 GeV at TRISTAN.

[15] If the photonic decay mode is large ($B(b' \to b\gamma) > 25\%$), the ABRAMS 89C limit is 45.4 GeV. The limit for for Higgs decay ($b' \to cH^-$, $H^- \to \overline{c}s$) is 45.2 GeV.

[16] ADACHI 89C search was at E_{cm} = 56.5–60.8 GeV at TRISTAN using multi-hadron events accompanying muons.

[17] ADACHI 89C also gives limits for any mixture of CC and bg decays.

[18] ENO 89 search at E_{cm} = 50–60.8 at TRISTAN.

[19] ENO 89 considers arbitrary mixture of the charged current, bg, and $b\gamma$ decays.

[20] IGARASHI 88 searches for leptons in low-thrust events and gives $\Delta R(b') < 0.26$ (95% CL) assuming charged current decay, which translates to $m_{b'} > 24.4$ GeV.

[21] SAGAWA 88 set limit σ(top) < 6.1 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark parton model cross-section formula near threshold, the above limit leads to lower mass bounds of 23.8 GeV for charge −1/3 quarks.

[22] ADEVA 86 give 95%CL upper bound on an excess of the normalized cross section, ΔR, as a function of the minimum c.m. energy (see their figure 3). Production of a pair of 1/3 charge quarks is excluded up to E_{cm} = 45.4 GeV.

[23] ALTHOFF 84C narrow state search sets limit $\Gamma(e^+e^-)$B(hadrons) <2.4 keV CL = 95% and heavy charge 1/3 quark pair production m >21 GeV, CL = 95%.

[24] ALTHOFF 84I exclude heavy quark pair production for 7 < m <19 GeV (1/3 charge) using aplanarity distributions (CL = 95%).

REFERENCES FOR Searches for (Fourth Generation) b' Quark

ADRIANI	93G	PL B313 326	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
MUKHOPAD...	93	PR D48 2105	Mukhopadhyaya, Roy	(TATA)
ABE	92	PRL 68 447	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
Also	92G	PR D45 3921	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	92G	PR D45 3921	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	91F	NP B367 511	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ABE	90B	PRL 64 147	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90D	PL B234 382	+Amako, Arai, Asano+	(VENUS Collab.)
ABREU	90D	PL B242 536	+Adam, Adami, Adye, Alekseev, Allaby+	(DELPHI Collab.)
ADACHI	90	PL B234 197	+Aihara, Doser, Enomoto+	(TOPAZ Collab.)
AKESSON	90	ZPHY C46 179	+Alitti, Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
AKRAWY	90B	PL B236 364	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90J	PL B246 285	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALBAJAR	90B	ZPHY C48 1	+Albrow, Allkofer, Andrieu, Ankoviak+	(UA1 Collab.)
DECAMP	90F	PL B236 511	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
ABE	89E	PR D39 3524	+Amako, Arai, Asano, Chiba, Chiba+	(VENUS Collab.)
ABE	89G	PRL 63 1776	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ABRAMS	89C	PRL 63 2447	+Adolphsen, Averill, Ballam+	(Mark II Collab.)
ADACHI	89C	PL B229 427	+Aihara, Doser, Enomoto, Fujii+	(TOPAZ Collab.)
ENO	89	PRL 63 1910	+Auchincloss, Blanis, Bodek, Budd+	(AMY Collab.)
ALBAJAR	88	ZPHY C37 505	+Albrow, Allkofer+	(UA1 Collab.)
ALTARELLI	88	NP B308 724	+Diemoz, Martinelli, Nason	(CERN, ROMA, ETH)
IGARASHI	88	PRL 60 2359	+Myung, Chiba, Hanaoka+	(AMY Collab.)
SAGAWA	88	PRL 60 93	+Mori, Abe+	(AMY Collab.)
ADEVA	86	PR D34 681	+Ansari, Becker, Becker-Szendy+	(Mark-J Collab.)
ALTHOFF	84C	PL 138B 441	+Braunschweig, Kirschfink+	(TASSO Collab.)
ALTHOFF	84I	ZPHY C22 307	+Braunschweig, Kirschfink+	(TASSO Collab.)

Free Quark Searches

FREE QUARK SEARCHES

The basis for much of the theory of particle scattering and hadron spectroscopy is the construction of the hadrons from a set of fractionally charged constituents (quarks). A central but unproven hypothesis of this theory, Quantum Chromodynamics, is that quarks cannot be observed as free particles but are confined to mesons and baryons.

Experiments show that it is at best difficult to "unglue" quarks. Accelerator searches at increasing energies have produced no evidence for free quarks, while only a few cosmic-ray and matter searches have produced uncorroborated events.

This compilation is only a guide to the literature, since the quoted experimental limits are often only indicative. Reviews can be found in Refs. 1–3.

References

1. P.F. Smith, Ann. Rev. Nucl. and Part. Sci. **39**, 73 (1989).
2. L. Lyons, Phys. Reports **129**, 225 (1985).
3. M. Marinelli and G. Morpurgo, Phys. Reports **85**, 161 (1982).

Quark Production Cross Section — Accelerator Searches

X-SECT (cm^2)	CHG (e/3)	MASS (GeV)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<2.E−35	+2	250	1800	$p\overline{p}$	0	[1] ABE	92J	CDF
<1.E−35	+4	250	1800	$p\overline{p}$	0	[1] ABE	92J	CDF
<3.8E−28			14.5A	^{28}Si–Pb	0	[2] HE	91	PLAS
<3.2E−28			14.5A	^{28}Si–Cu	0	[2] HE	91	PLAS
<1.E−40	±1,2	<10		$p,\nu,\overline{\nu}$	0	BERGSMA	84B	CHRM
<1.E−36	±1,2	<9	200	μ	0	AUBERT	83C	SPEC
<2.E−10	±2,4	1–3	200	p	0	[3] BUSSIERE	80	CNTR
<5.E−38	+1,2	>5	300	p	0	[4,5] STEVENSON	79	CNTR
<1.E−33	±1	<20	52	pp	0	BASILE	78	SPEC
<9.E−39	±1,2	<6	400	p	0	[4] ANTREASYAN	77	SPEC
<8.E−35	+1,2	<20	52	pp	0	[6] FABJAN	75	CNTR
<5.E−38	−1,2	4–9	200	p	0	NASH	74	CNTR
<1.E−32	+2,4	4–24	52	pp	0	ALPER	73	SPEC
<5.E−31	+1,2,4	<12	300	p	0	LEIPUNER	73	CNTR
<6.E−34	±1,2	<13	52	pp	0	BOTT	72	CNTR
<1.E−36	−4	4	70	p	0	ANTIPOV	71	CNTR
<1.E−35	±1,2	2	28	p	0	[7] ALLABY	69B	CNTR
<4.E−37	−2	<5	70	p	0	[3] ANTIPOV	69	CNTR
<3.E−37	−1,2	2–5	70	p	0	[7] ANTIPOV	69B	CNTR
<1.E−35	+1,2	<7	30	p	0	DORFAN	65	CNTR
<2.E−35	−2	< 2.5–5	30	p	0	[8] FRANZINI	65B	CNTR
<5.E−35	+1,2	<2.2	21	p	0	BINGHAM	64	HLBC
<1.E−32	+1,2	<4.0	28	p	0	BLUM	64	HBC
<1.E−35	+1,2	<2.5	31	p	0	[8] HAGOPIAN	64	HBC
<1.E−34	+1	<2	28	p	0	LEIPUNER	64	CNTR
<1.E−33	+1,2	<2.4	24	p	0	MORRISON	64	HBC

[1] ABE 92J flux limits decrease as the mass increases from 50 to 500 GeV.
[2] HE 91 limits are for charges of the form $N \pm 1/3$ from 23/3 to 38/3.
[3] Hadronic or leptonic quarks.
[4] Cross section cm^2/GeV^2.
[5] 3×10^{-5} <lifetime $< 1 \times 10^{-3}$ s.
[6] Includes BOTT 72 results.
[7] Assumes isotropic cm production.
[8] Cross section inferred from flux.

Quark Differential Production Cross Section — Accelerator Searches

X-SECT (cm^{2}sr^{-1}GeV^{-1})	CHG e/3	MASS (GeV)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<4.E−36	−2,4	1.5–6	70	p	0	BALDIN	76	CNTR
<2.E−33	±4	5–20	52	pp	0	ALBROW	75	SPEC
<5.E−34	<7	7–15	44	pp	0	JOVANOV...	75	CNTR
<5.E−35			20	γ	0	[9] GALIK	74	CNTR
<9.E−35	−1,2		200	p	0	NASH	74	CNTR
<4.E−36	−4	2.3–2.7	70	p	0	ANTIPOV	71	CNTR
<3.E−35	±1,2	<2.7	27	p	0	ALLABY	69B	CNTR
<7.E−38	−1,2	<2.5	70	p	0	ANTIPOV	69B	CNTR

[9] Cross section in cm^2/sr/equivalent quanta.

Quark Flux — Accelerator Searches

The definition of FLUX depends on the experiment

(a) is the ratio of measured free quarks to predicted free quarks if there is no "confinement."
(b) is the probability of fractional charge on nuclear fragments.
(c) is the 90%CL upper limit on fractionally-charged particles produced per interaction.
(d) is quarks per collision.
(e) is inclusive quark-production cross-section ratio to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.
(f) is quark flux per charged particle.
(g) is the flux per ν-event.
(h) is quark yield per π^- yield.
(i) is 2-body exclusive quark-production cross-section ratio to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.

FLUX		CHG (e/3)	MASS (GeV)	ENRGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<0.94E−4	e	±2	2–30	88–94	e^+e^-	0	AKERS	95R	OPAL
<1.7E−4	e	±2	30–40	88–94	e^+e^-	0	AKERS	95R	OPAL
<3.6E−4	e	±4	5–30	88–94	e^+e^-	0	AKERS	95R	OPAL
<1.9E−4	e	±4	30–45	88–94	e^+e^-	0	AKERS	95R	OPAL
<2.E−3	e	+1	5–40	88–94	e^+e^-	0	[10] BUSKULIC	93C	ALEP
<6.E−4	e	+2	5–30	88–94	e^+e^-	0	[10] BUSKULIC	93C	ALEP
<1.2E−3	e	+4	15–40	88–94	e^+e^-	0	[10] BUSKULIC	93C	ALEP
<3.6E−4	i	+4	5.0–10.2	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<3.6E−4	i	+4	16.5–26.0	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<6.9E−4	i	+4	26.0–33.3	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<9.1E−4	i	+4	33.3–38.6	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<1.1E−3	i	+4	38.6–44.9	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
	b	4,5,7,8		2.1A	^{16}O	0,2,0,6	[11] GHOSH	92	EMUL
<6.4E−5	g	1			$\nu,\overline{\nu}$	1	[12] BASILE	91	CNTR
<3.7E−5	g	2			$\nu,\overline{\nu}$	0	[12] BASILE	91	CNTR
<3.9E−5	g	1			$\nu,\overline{\nu}$	1	[13] BASILE	91	CNTR
<2.8E−5	g	2			$\nu,\overline{\nu}$	0	[13] BASILE	91	CNTR
<1.9E−4	c			14.5A	^{28}Si–Pb	0	[14] HE	91	PLAS
<3.9E−4	c			14.5A	^{28}Si–Cu	0	[14] HE	91	PLAS
<1.E−9	c	±1,2,4		14.5A	^{16}O–Ar	0	MATIS	91	MDRP
<5.1E−10	c	±1,2,4		14.5A	^{16}O–Hg	0	MATIS	91	MDRP
<8.1E−9	c	±1,2,4		14.5A	Si–Hg	0	MATIS	91	MDRP
<1.7E−6	c	±1,2,4		60A	^{16}O–Hg	0	MATIS	91	MDRP
<3.5E−7	c	±1,2,4		200A	^{16}O–Hg	0	MATIS	91	MDRP
<1.3E−6	c	±1,2,4		200A	S–Hg	0	MATIS	91	MDRP
<5E−2	e	2	19–27	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<5E−2	e	4	<24	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<1.E−4	e	+2	<3.5	10	e^+e^-	0	BOWCOCK	89B	CLEO
<1.E−6	d	±1,2		60	^{16}O–Hg	0	CALLOWAY	89	MDRP
<3.5E−7	d	±1,2		200	^{16}O–Hg	0	CALLOWAY	89	MDRP
<1.3E−6	d	±1,2		200	S–Hg	0	CALLOWAY	89	MDRP
<1.2E−10	d	±1	1	800	p–Hg	0	MATIS	89	MDRP
<1.1E−10	d	±2	1	800	p–Hg	0	MATIS	89	MDRP
<1.2E−10	d	±1	1	800	p–N_2	0	MATIS	89	MDRP
<7.7E−11	d	±2	1	800	p–N_2	0	MATIS	89	MDRP
<6.E−9	h	−5	0.9–2.3	12	p	0	NAKAMURA	89	SPEC
<5.E−5	g	1,2	<0.5		$\nu,\overline{\nu}d$	0	ALLASIA	88	BEBC
<3.E−4	b	See note		14.5	^{16}O–Pb	0	[15] HOFFMANN	88	PLAS
<2.E−4	b	See note		200	^{16}O–Pb	0	[16] HOFFMANN	88	PLAS
<2.E−4	a	±1,2	<300	320	$\overline{p}p$	0	LYONS	87	MLEV
<1.E−9	c	±1,2,4,5		14.5	^{16}O–Hg	0	SHAW	87	MDRP

<3.E−3	d	−1,2,3,4,6	<5	2	Si–Si	0	[17] ABACHI 86C	CNTR
<1.E−4	e	±1,2,4	<4	10	e^+e^-	0	ALBRECHT 85G	ARG
<6.E−5	b	±1,2	1	540	$p\overline{p}$	0	BANNER 85	UA2
<5.E−3	e	−4	1–8	29	e^+e^-	0	AIHARA 84	TPC
<1.E−2	e	±1,2	1–13	29	e^+e^-	0	AIHARA 84B	TPC
<2.E−4	b	±1		72	^{40}Ar	0	[18] BARWICK 84	CNTR
<1.E−4	e	±2	<0.4	1.4	e^+e^-	0	BONDAR 84	OLYA
<5.E−1	e	±1,2	<13	29	e^+e^-	0	GURYN 84	CNTR
<3.E−3	b	±1,2	<2	540	$p\overline{p}$	0	BANNER 83	CNTR
<1.E−4	b	±1,2		106	^{56}Fe	0	LINDGREN 83	CNTR
<3.E−3	b	$>\|\pm 0.1\|$		74	^{40}Ar	0	[18] PRICE 83	PLAS
<1.E−2	e	±1,2	<14	29	e^+e^-	0	MARINI 82B	CNTR
<8.E−2	e	±1,2	<12	29	e^+e^-	0	ROSS 82	CNTR
<3.E−4	e	±2	1.8–2	7	e^+e^-	0	WEISS 81	MRK2
<5.E−2	e	+1,2,4,5	2–12	27	e^+e^-	0	BARTEL 80	JADE
<2.E−5	g	1,2			ν	0	[12,13] BASILE 80	CNTR
<3.E−10	f	±2,4	1–3	200	p	0	[19] BOZZOLI 79	CNTR
<6.E−11	f	±1	<21	52	pp	0	BASILE 78	SPEC
<5.E−3	g				ν_μ	0	BASILE 78B	CNTR
<2.E−9	f	±1	<26	62	pp	0	BASILE 77	SPEC
<7.E−10	f	+1,2	<20	52	p	0	[20] FABJAN 75	CNTR
		+1,2	>4.5		γ	0	[12,13] GALIK 74	CNTR
		+1,2	>1.5	12	e^-	0	[12,13] BELLAMY 68	CNTR
		+1,2	>0.9		γ	0	[13] BATHOW 67	CNTR
		+1,2	>0.9	6	γ	0	[13] FOSS 67	CNTR

[10] BUSKULIC 93C limits for inclusive quark production are more conservative if the ALEPH hadronic fragmentation function is assumed.
[11] GHOSH 92 reports measurement of spallation fragment charge based on ionization in emulsion. Out of 650 measured tracks, 2 were consistent with charge $5e/3$, and 4 with $7e/3$.
[12] Hadronic quark.
[13] Leptonic quark.
[14] HE 91 limits are for charges of the form $N\pm1/3$ from 23/3 to 38/3, and correspond to cross-section limits of 380μb (Pb) and 320μb (Cu).
[15] The limits apply to projectile fragment charges of 17, 19, 20, 22, 23 in units of $e/3$.
[16] The limits apply to projectile fragment charges of 16, 17, 19, 20, 22, 23 in units of $e/3$.
[17] Flux limits and mass range depend on charge.
[18] Bound to nuclei.
[19] Quark lifetimes $> 1 \times 10^{-8}$ s.
[20] One candidate m <0.17 GeV.

Quark Flux — Cosmic Ray Searches

Shielding values followed with an asterisk indicate altitude in km. Shielding values not followed with an asterisk indicate sea level in kg/cm^2.

FLUX ($cm^{-2}sr^{-1}s^{-1}$)	CHG ($e/3$)	MASS (GeV)	SHIELDING	EVTS	DOCUMENT ID	TECN
<2.1E−15	±1			0	MORI 91	KAM2
<2.3E−15	±2			0	MORI 91	KAM2
<2.E−10	±1, 2		0.3	0	WADA 88	CNTR
	±4		0.3	12	[21] WADA 88	CNTR
	±4		0.3	9	[22] WADA 86	CNTR
<1.E−12	±2,3/2		−70.	0	[23] KAWAGOE 84B	PLAS
<9.E−10	±1,2		0.3	0	WADA 84B	CNTR
<4.E−9	±4		0.3	7	WADA 84B	CNTR
<2.E−12	±1,2,3		−0.3 *	0	MASHIMO 83	CNTR
<3.E−10	±1,2		0.3	0	MARINI 82	CNTR
<2.E−11	±1,2			0	MASHIMO 82	CNTR
<8.E−10	±1,2		0.3	0	[23] NAPOLITANO 82	CNTR
				3	[24] YOCK 78	CNTR
<1.E−9				0	[25] BRIATORE 76	ELEC
<2.E−11	+1			0	[26] HAZEN 75	CC
<2.E−10	+1,2			0	KRISOR 75	CNTR
<1.E−7	+1,2			0	[26,27] CLARK 74B	CC
<3.E−10	+1	>20		0	KIFUNE 74	CNTR
<8.E−11	+1			0	[26] ASHTON 73	CNTR
<2.E−8	+1,2			0	HICKS 73B	CNTR
<5.E−10	+4		2.8 *	0	BEAUCHAMP 72	CNTR
<1.E−10	+1,2			0	[26] BOHM 72B	CNTR
<1.E−10	+1,2		2.8 *	0	COX 72	ELEC
<3.E−10	+2			0	CROUCH 72	CNTR
<3.E−8			7	0	[25] DARDO 72	CNTR
<4.E−9	+1			0	[26] EVANS 72	CC
<2.E−9		>10		0	[25] TONWAR 72	CNTR
<2.E−10	+1		2.8 *	0	CHIN 71	CNTR
<3.E−10	+1,2			0	[26] CLARK 71B	CC
<1.E−10	+1,2			0	[26] HAZEN 71	CC
<5.E−10	+1,2		3.5 *	0	BOSIA 70	CNTR
	+1,2	<6.5		1	[26] CHU 70	HLBC
<2.E−9	+1			0	FAISSNER 70B	CNTR
<2.E−10	+1,2		0.8 *	0	KRIDER 70	CNTR
<5.E−11	+2			4	CAIRNS 69	CC
<8.E−10	+1,2	<10		0	FUKUSHIMA 69	CNTR
	+2			1	[26,28] MCCUSKER 69	CC
<1.E−10		>5	1.7,3.6	0	[25] BJORNBOE 68	CNTR
<1.E−8	±1,2,4		6.3,.2 *	0	[23] BRIATORE 68	CNTR
<3.E−8		>2		0	FRANZINI 68	CNTR
<9.E−11	±1,2			0	GARMIRE 68	CNTR
<4.E−10	±1			0	HANAYAMA 68	CNTR
<3.E−8		>15		0	KASHA 68	OSPK
<2.E−10	+2			0	KASHA 68B	CNTR
<2.E−10	+4			0	KASHA 68C	CNTR
<2.E−10	+2		6	0	BARTON 67	CNTR
<2.E−7	+4		0.008,0.5 *	0	BUHLER 67	CNTR
<5.E−10	1,2		0.008,0.5 *	0	BUHLER 67B	CNTR
<4.E−10	+1,2			0	GOMEZ 67	CNTR
<2.E−9	+2			0	KASHA 67	CNTR
<2.E−10	+2		220	0	BARTON 66	CNTR
<2.E−9	+1,2		0.5 *	0	BUHLER 66	CNTR
<3.E−9	+1,2			0	KASHA 66	CNTR
<2.E−9	+1,2			0	LAMB 66	CNTR
<2.E−8	+1,2	>7	2.8 *	0	DELISE 65	CNTR
<5.E−8	+2	>2.5	0.5 *	0	MASSAM 65	CNTR
<2.E−8	+1		2.5 *	0	BOWEN 64	CNTR
<2.E−7	+1		0.8	0	SUNYAR 64	CNTR

[21] Distribution in celestial sphere was described as anisotropic.
[22] With telescope axis at zenith angle 40° to the south.
[23] Leptonic quarks.
[24] Lifetime $> 10^{-8}$ s; charge ±0.70, 0.68, 0.42; and mass >4.4, 4.8, and 20 GeV, respectively.
[25] Time delayed air shower search.
[26] Prompt air shower search.
[27] Also $e/4$ and $e/6$ charges.
[28] No events in subsequent experiments.

Quark Density — Matter Searches

For a recent review, see SMITH 89.

QUARKS/ NUCLEON	CHG ($e/3$)	MASS (GeV)	MATERIAL/METHOD	EVTS	DOCUMENT ID
<8.E−22	+2		Si/infrared photoionization	0	PERERA 93
<5.E−27	±1,2		sea water/levitation	0	HOMER 92
<4.E−20	±1,2		meteorites/mag. levitation	0	JONES 89
<1.E−19	±1,2		various/spectrometer	0	MILNER 87
<5.E−22	±1,2		W/levitation	0	SMITH 87
<3.E−20	+1,2		org liq/droplet tower	0	VANPOLEN 87
<6.E−20	−1,2		org liq/droplet tower	0	VANPOLEN 87
<3.E−21	±1		Hg drops-untreated	0	SAVAGE 86
<3.E−22	±1,2		levitated niobium	0	SMITH 86
<2.E−26	±1,2		^{4}He/levitation	0	SMITH 86B
<2.E−20	>±1	0.2–250	niobium+tungs/ion	0	MILNER 85
<1.E−21	±1		levitated niobium	0	SMITH 85
	+1,2	<100	niobium/mass spec	0	KUTSCHERA 84
<5.E−22			levitated steel	0	MARINELLI 84
<9.E−20	± <13		water/oil drop	0	JOYCE 83
<2.E−21	$>\|\pm 1/2\|$		levitated steel	0	LIEBOWITZ 83
<1.E−19	±1,2		photo ion spec	0	VANDESTEEG 83
<2.E−20			mercury/oil drop	0	[29] HODGES 81
1.E−20	+1		levitated niobium	4	[30] LARUE 81
1.E−20	−1		levitated niobium	4	[30] LARUE 81
<1.E−21			levitated steel	0	MARINELLI 80B
<6.E−16			helium/mass spec	0	BOYD 79
1.E−20	+1		levitated niobium	2	[30] LARUE 79
<4.E−28			earth+/ion beam	0	OGOROD... 79
<5.E−15	+1		tungs./mass spec	0	BOYD 78
<5.E−16	+3	<1.7	hydrogen/mass spec	0	BOYD 78B
<1.E−21	±2,4		water/ion beam	0	LUND 78
<6.E−15	>1/2		levitated tungsten	0	PUTT 78
<1.E−22			metals/mass spec	0	SCHIFFER 78
<5.E−15			levitated tungsten ox	0	BLAND 77
<3.E−21			levitated iron	0	GALLINARO 77
2.E−21	−1		levitated niobium	1	[30] LARUE 77
4.E−21	+1		levitated niobium	2	[30] LARUE 77
<1.E−13	+3	<7.7	hydrogen/mass spec	0	MULLER 77
<5.E−27			water+/ion beam	0	OGOROD... 77
<1.E−21			lunar+/ion spec	0	STEVENS 76
<1.E−15	+1	<60	oxygen+/ion spec	0	ELBERT 70
<5.E−19			levitated graphite	0	MORPURGO 70
<5.E−23			water+/atom beam	0	COOK 69
<1.E−17	±1,2		levitated graphite	0	BRAGINSK 68
<1.E−17			water+/uv spec	0	RANK 68
<3.E−19	±1		levitated iron	0	STOVER 67
<1.E−10			sun/uv spec	0	[31] BENNETT 66
<1.E−17	+1,2		meteorites+/ion beam	0	CHUPKA 66
<1.E−16	±1		levitated graphite	0	GALLINARO 66
<1.E−22			argon/electrometer	0	HILLAS 59
	−2		levitated oil	0	MILLIKAN 10

[29] Also set limits for $Q = \pm e/6$.
[30] Note that in PHILLIPS 88 these authors report a subtle magnetic effect which could account for the apparent fractional charges.
[31] Limit inferred by JONES 77B.

REFERENCES FOR Free Quark Searches

AKERS 95R ZPHY C67 203 +Alexander, Allison, Ametewee, Anderson+ (OPAL Collab.)
BUSKULIC 93C PL B303 198 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
PERERA 93 PRL 70 1053 +Betarbet, Byungsung, Coon (PITT)
ABE 92J PR D46 R1889 +Amidei, Anway-Weiss+ (CDF Collab.)
GHOSH 92 NC 105A 99 +Roy, Ghosh, Ghosh, Basu (JADA, BANGB)
HOMER 92 ZPHY C55 549 +Smith, Lewin, Robertson+ (RAL, SHMP, LOQM)
BASILE 91 NC 104A 405 +Berbiers, Cara Romeo+ (BGNA, INFN, CERN, PLRM+)
HE 91 PR C44 1672 +Price (UCB)
MATIS 91 NP A525 513c +Pugh, Alba, Bland, Calloway+ (LBL, SFSU, UCI, LANL)
MORI 91 PR D43 2843 +Oyama, Suzuki, Takahashi+ (Kamiokande II Collab.)
ADACHI 90C PL B244 352 +Aihara, Doser, Enomoto+ (TOPAZ Collab.)
BOWCOCK 89B PR D40 263 +Kinoshita, Mauskopf, Pipkin+ (CLEO Collab.)
CALLOWAY 89 PL B232 549 +Alba, Bland, Dickson, Hodges+ (SFSU, UCI, LBL, LANL)
JONES 89 ZPHY C43 349 +Smith, Homer, Lewin, Walford (LOIC, RAL)
MATIS 89 PR D39 1851 +Pugh, Bland, Calloway+ (LBL, SFSU, UCI, FNAL, LANL)
NAKAMURA 89 PR D39 1261 +Kobayashi, Konaka, Imai, Masaike+ (KYOT, TMTC)
SMITH 89 ARNPS 39 73 (RAL)
ALLASIA 88 PR D37 219 +Angelini, Baldini+ (WA25 Collab.)
HOFFMANN 88 PL B200 583 +Brechtmann, Heinrich, Benton (SIEG, USF)
PHILLIPS 88 NIM A264 125 +Fairbank, Navarro (STAN)
WADA 88 NC 11C 229 +Yamashita, Yamamoto (OKAY)
LYONS 87 ZPHY C36 363 +Smith, Homer, Lewin, Walford+ (OXF, RAL, LOIC)
MILNER 87 PR D36 37 +Cooper, Chang, Wilson, Labrenz, McKeown (CIT)
SHAW 87 PR D36 3533 +Matis, Pugh, Slansky+ (UCI, LBL, LANL, SFSU)
SMITH 87 PL B197 447 +Homer, Lewin, Walford, Jones (RAL, LOIC)
VANPOLEN 87 PR D36 1983 +Hagstrom, Hirsch (ANL, LBL)
ABACHI 86C PR D33 2733 +Shor, Barasch, Carroll+ (UCLA, LBL, UCD)
SAVAGE 86 PL 167B 481 +Bland, Hodges, Huntington, Joyce+ (SFSU)
SMITH 86 PL B171 129 +Homer, Lewin, Walford, Jones (RAL, LOIC)
SMITH 86B PL B181 407 +Homer, Lewin, Walford, Jones (RAL, LOIC)
WADA 86 NC 9C 358 (OKAY)
ALBRECHT 85G PL 156B 134 +Binder, Harder, Hasemann+ (ARGUS Collab.)
BANNER 85 PL 156B 129 +Bloch, Borer, Borghini+ (UA2 Collab.)
MILNER 85 PRL 54 1472 +Cooper, Chang, Wilson, Labrenz, McKeown (CIT)
SMITH 85 PL 153B 188 +Homer, Lewin, Walford, Jones (RAL, LOIC)
AIHARA 84 PRL 52 168 +Alston-Garnjost, Badtke, Bakker+ (TPC Collab.)
AIHARA 84B PRL 52 2332 +Alston-Garnjost, Badtke, Bakker+ (TPC Collab.)
BARWICK 84 PR D30 691 +Musser, Stevenson (UCB)
BERGSMA 84B ZPHY C24 217 +Allaby, Abt, Gemanov+ (CHARM Collab.)
BONDAR 84 JETPL 40 1265 +Kurdadze, Lelchuk, Panin, Sidorov+ (NOVO)
Translated from ZETFP 40 440.
GURYN 84 PL 139B 313 +Parker, Fries+ (FRAS, LBL, NWES, STAN, HAWA)
KAWAGOE 84B LNC 41 604 +Mashimo, Nakamura, Nozaki, Orito (TOKY)
KUTSCHERA 84 PR D29 791 +Schiffer, Frekers+ (ANL, FNAL)
MARINELLI 84 PL 137B 439 +Morpurgo (GENO)
WADA 84B LNC 40 329 +Yamashita, Yamamoto (OKAY)
AUBERT 83C PL 133B 461 +Bassompierre, Becks, Best+ (EMC Collab.)
BANNER 83 PL 121B 187 +Bloch, Bonaudi, Borer+ (UA2 Collab.)
JOYCE 83 PRL 51 731 +Abrams, Bland, Johnson, Lindgren+ (SFSU)
LIEBOWITZ 83 PRL 50 1640 +Binder, Ziock (VIRG)
LINDGREN 83 PRL 51 1621 +Joyce+ (SFSU, UCR, UCI, SLAC, LBL, LANL)
MASHIMO 83 PL 128B 327 +Orito, Kawagoe, Nakamura, Nozaki (ICEPP)
PRICE 83 PRL 50 566 +Tincknell, Tarle, Ahlen, Frankel+ (UCB)
VANDESTEEG 83 PRL 50 1234 +Jongbloets, Wyder (NIJM)
MARINI 82 PR D26 1777 +Peruzzi, Piccolo+ (FRAS, LBL, NWES, STAN, HAWA)
MARINI 82B PRL 48 1649 +Peruzzi, Piccolo+ (FRAS, LBL, NWES, STAN, HAWA)
MASHIMO 82 JPSJ 51 3067 +Kawagoe, Koshiba (INUS)
NAPOLITANO 82 PR D25 2837 +Besset+ (STAN, FRAS, LBL, NWES, HAWA)
ROSS 82 PL 118B 199 +Ronga, Besset+ (FRAS, LBL, NWES, STAN, HAWA)
HODGES 81 PRL 47 1651 +Abrams, Baden, Bland, Joyce+ (UCR, SFSU)
LARUE 81 PRL 46 967 +Phillips, Fairbank (STAN)
WEISS 81 PL 101B 439 +Abrams, Alam, Blocker+ (SLAC, LBL, UCB)
BARTEL 80 ZPHY C6 295 +Canzler, Lords, Drumm+ (JADE Collab.)
BASILE 80 LNC 29 251 +Berbiers+ (BGNA, CERN, FRAS, ROMA, BARI)
BUSSIERE 80 NP B174 1 +Giacomelli, Lesquoy+ (BGNA, SACL, LAPP)
MARINELLI 80B PL 94B 433 +Morpurgo (GENO)
Also 80 PL 94B 427 Marinelli, Morpurgo (GENO)
BOYD 79 PRL 43 1288 +Blatt, Donoghue, Dries, Hausman, Suiter (OSU)
BOZZOLI 79 NP B159 363 +Bussiere, Giacomelli+ (BGNA, LAPP, SACL, CERN)
LARUE 79 PRL 42 142 +Fairbank, Phillips (STAN)
Also 79B PRL 42 1019 Larue, Fairbank, Phillips
OGOROD... 79 JETP 49 953 Ogorodnikov, Samoilov, Solntsev (KIAE)
Translated from ZETF 76 1881.
STEVENSON 79 PR D20 82 (LBL)
BASILE 78 NC 45A 171 +Cara-Romeo, Cifarelli, Contin+ (CERN, BGNA)
BASILE 78B NC 45A 281 +Cara-Romeo, Cifarelli, Contin+ (CERN, BGNA)
BOYD 78 PRL 40 216 +Elmore, Melissinos, Sugarbaker (ROCH)
BOYD 78B PL 72B 484 +Elmore, Nitz, Olsen, Sugarbaker, Warren+ (ROCH)
LUND 78 RA 25 75 +Brandt, Fares (MARB)
PUTT 78 PR D17 1466 +Yock (AUCK)
SCHIFFER 78 PR D17 2241 +Renner, Gemmell, Mooring (CHIC, ANL)
YOCK 78 PR D18 641 (AUCK)
ANTREASYAN 77 PRL 39 513 +Cocconi, Cronin, Frisch+ (EFI, PRIN)
BASILE 77 NC 40A 41 +Romeo, Cifarelli, Giusti+ (CERN, BGNA)
BLAND 77 PRL 39 369 +Bocobo, Eubank, Royer (SFSU)
GALLINARO 77 PRL 38 1255 +Marinelli, Morpurgo (GENO)
JONES 77B RMP 69 717
LARUE 77 PRL 38 1011 +Fairbank, Hebard (STAN)
MULLER 77 Science 521 +Alvarez, Holley, Stephenson (LBL)
OGOROD... 77 JETP 45 857 Ogorodnikov, Samoilov, Solntsev (KIAE)
Translated from ZETF 72 1633.
BALDIN 76 SJNP 22 264 +Vertogradov, Vishnevsky, Grishkevich+ (JINR)
Translated from YAF 22 512.
BRIATORE 76 NC 31A 553 +Dardo, Piazzoli, Mannocchi+ (LCGT, FRAS, FREIB)
STEVENS 76 PR D14 716 +Schiffer, Chupka (ANL)
ALBROW 75 NP B97 189 +Barber+ (CERN, DARE, FOM, LANC, MCHS, UTRE)
FABJAN 75 NP B101 349 +Gruhn, Peak, Sauli, Caldwell+ (CERN, MPIM)
HAZEN 75 NP B95 189 +Hodson, Winterstein, Green, Kass+ (MICH, LEED)
JOVANOV... 75 PL 56B 105 Jovanovich+ (MANI, AACH, CERN, GENO, HARV+)
KRISOR 75 NC 27A 132 (AACH3)
CLARK 74B PR D10 2721 +Finn, Hansen, Smith (LLL)
GALIK 74 PR D9 1856 +Jordan, Richter, Seppi, Siemann+ (SLAC, FNAL)
KIFUNE 74 JPSJ 36 629 +Hieda, Kurokawa, Tsunemoto+ (TOKY, KEK)
NASH 74 PRL 32 858 +Yamanouchi, Nease, Sculli (FNAL, CORN, NYU)
ALPER 73 PL 46B 265 + (CERN, LIVP, LUND, BOHR, RHEL, STOH, BERG+)
ASHTON 73 JPA 6 577 +Cooper, Parvaresh, Saleh (DURH)
HICKS 73B NC 14A 65 +Flint, Standil (MANI)
LEIPUNER 73 PRL 31 1226 +Larsen, Sessoms, Smith, Williams+ (BNL, YALE)
BEAUCHAMP 72 PR D6 1211 +Bowen, Cox, Kalbach (ARIZ)
BOHM 72B PRL 28 326 +Diemont, Faissner, Fasold, Krisor+ (AACH)
BOTT 72 PL 40B 693 +Caldwell, Fabjan, Gruhn, Peak+ (CERN, MPIM)
COX 72 PR D6 1203 +Beauchamp, Bowen, Kalbach (ARIZ)
CROUCH 72 PR D5 2667 +Mori, Smith (CASE)
DARDO 72 NC 9A 319 +Navarra, Penengo, Sitte (TORI)
EVANS 72 PRSE A70 143 +Fancey, Muir, Watson (EDIN, LEED)
TONWAR 72 JPA 5 569 +Naranan, Sreekantan (TATA)
ANTIPOV 71 NP B27 374 +Kachanov, Kutjin, Landsberg, Lebedev+ (SERP)
CHIN 71 NC 2A 419 +Hanayama, Hara, Higashi, Tsuji (OSAK)
CLARK 71B PRL 27 51 +Ernst, Finn, Griffin, Hansen, Smith+ (LLL, LBL)
HAZEN 71 PRL 26 582 (MICH)
BOSIA 70 NC 66A 167 +Briatore (TORI)
CHU 70 PRL 24 917 +Kim, Beam, Kwak (OSU, ROSE, KANS)
Also 70B PRL 25 550 Allison, Derrick, Hunt, Simpson, Voyvodic (ANL)
ELBERT 70 NP B20 217 +Erwin, Herb, Nielsen, Petrilak, Weinberg (WISC)
FAISSNER 70B PRL 24 1357 +Holder, Krisor, Mason, Sawaf, Umbach (AACH3)
KRIDER 70 PR D1 835 +Bowen, Kalbach (ARIZ)
MORPURGO 70 NIM 79 95 +Gallinaro, Palmieri (GENO)
ALLABY 69B NC 64A 75 +Bianchini, Diddens, Dobinson, Hartung+ (CERN)
ANTIPOV 69 PL 29B 245 +Karpov, Khromov, Landsberg, Lapshin+ (SERP)
ANTIPOV 69B PL 30B 576 +Bolotov, Devishev, Devisheva, Isakov+ (SERP)
CAIRNS 69 PR 186 1394 +McCkusker, Peak, Woolcott (SYDN)
COOK 69 PR 188 2092 +Depasquali, Frauenfelder, Peacock+ (ILL)
FUKUSHIMA 69 PR 178 2058 +Kifune, Kondo, Koshiba+ (TOKY)
MCCUSKER 69 PRL 23 658 +Cairns (SYDN)
BELLAMY 68 PR 166 1391 +Hofstadter, Lakin, Perl, Toner (STAN, SLAC)
BJORNBOE 68 NC B53 241 +Damgard, Hansen+ (BOHR, TATA, BERN, BERG)
BRAGINSK 68 JETP 27 51 +Zeldovich, Martynov, Migulin (MOSU)
Translated from ZETF 54 91.
BRIATORE 68 NC 57A 850 +Castagnoli, Bollini, Massam+ (TORI, CERN, BGNA)
FRANZINI 68 PRL 21 1013 +Shulman (COLU)
GARMIRE 68 PR 166 166 +Leong, Sreekantan (MIT)
HANAYAMA 68 CJP 46 S734 +Hara, Higashi, Kitamura, Miono+ (OSAK)
KASHA 68 PR 172 1297 +Stefanski (BNL, YALE)
KASHA 68B PRL 20 217 +Larsen, Leipuner, Adair (BNL, YALE)
KASHA 68C CJP 46 S730 +Larsen, Leipuner, Adair (BNL, YALE)
RANK 68 PR 176 1635 (MICH)
BARTON 67 PRSL 90 87 (NPOL)
BATHOW 67 PL 25B 163 +Freytag, Schulz, Tesch (DESY)
BUHLER 67 NC 49A 209 +Fortunato, Massam, Zichichi (CERN, BGNA)
BUHLER 67B NC 51A 837 +Dalpiaz, Massam, Zichichi (CERN, BGNA, STRB)
FOSS 67 PL 25B 166 +Garelick, Homma, Lobar, Osborne, Uglum (MIT)
GOMEZ 67 PRL 18 1022 +Kobrak, Moline, Mullins, Orth, VanPutten+ (CIT)
KASHA 67 PR 154 1263 +Leipuner, Wangler, Alspector, Adair (BNL, YALE)
STOVER 67 PR 164 1599 +Moran, Trischka (SYRA)
BARTON 66 PL 21 360 +Stockel (NPOL)
BENNETT 66 PRL 17 1196 (YALE)
BUHLER 66 NC 45A 520 +Fortunato, Massam, Muller+ (CERN, BGNA, STRB)
CHUPKA 66 PRL 17 60 +Schiffer, Stevens (ANL)
GALLINARO 66 PL 23 609 +Morpurgo (GENO)
KASHA 66 PR 150 1140 +Leipuner, Adair (BNL, YALE)
LAMB 66 PRL 17 1068 +Lundy, Novey, Yovanovitch (ANL)
DELISE 65 PR 140B 458 +Bowen (ARIZ)
DORFAN 65 PRL 14 999 +Eades, Lederman, Lee, Ting (COLU)
FRANZINI 65B PRL 14 196 +Leontic, Rahm, Samios, Schwartz (BNL, COLU)
MASSAM 65 NC 40A 589 +Muller, Zichichi (CERN)
BINGHAM 64 PL 9 201 +Dickinson, Diebold, Koch, Leith+ (CERN, EPOL)
BLUM 64 PRL 13 353A +Brandt, Cocconi, Czyzewski, Danysz+ (CERN)
BOWEN 64 PRL 13 728 +Delise, Kalbach, Mortara (ARIZ)
HAGOPIAN 64 PRL 13 280 +Selove, Ehrlich, Leboy, Lanza+ (PENN, BNL)
LEIPUNER 64 PRL 12 423 +Chu, Larsen, Adair (BNL, YALE)
MORRISON 64 PL 9 199 (CERN)
SUNYAR 64 PR 136B 1157 +Schwarzschild, Connors (BNL)
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MILLIKAN 10 Phil Mag 19 209 (CHIC)

OTHER RELATED PAPERS

LYONS 85 PRPL C129 225 (OXF)
Review
MARINELLI 82 PRPL 85 161 +Morpurgo (GENO)
Review

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

OTHER LIGHT UNFLAVORED ($S = C = B = 0$)

STRANGE MESONS ($S = \pm1, C = B = 0$)

(continued on the next page)

• Indicates the particle is in the Meson Summary Table

CHARMED MESONS ($C = \pm1$)

CHARMED, STRANGE MESONS ($C = S = \pm1$)

BOTTOM MESONS ($B = \pm1$)

BOTTOM, STRANGE MESONS ($B = \pm1$, $S = \mp1$)

$c\overline{c}$ MESONS

$b\overline{b}$ MESONS

NON-$q\overline{q}$ CANDIDATES

• Indicates the particle is in the Meson Summary Table

Notes in the Meson Listings

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u}+d\overline{d}) + c_2(s\overline{s})$

PSEUDOSCALAR-MESON DECAY CONSTANTS

(by M. Suzuki, LBNL)

Charged mesons

The decay constant f_P for a charged pseudoscalar meson P is defined by

$$\langle 0|A_\mu(0)|P(\mathbf{q})\rangle = i f_P\, q_\mu \ ,$$

where A_μ is the axial-vector part of the charged weak current after a Cabibbo-Kobayashi-Maskawa mixing-matrix element $V_{qq'}$ has been removed. The state vector is normalized by $\langle P(\mathbf{q})|P(\mathbf{q'})\rangle = (2\pi)^3\, 2E_q\, \delta(\mathbf{q}-\mathbf{q'})$, and its phase is chosen to make f_P real and positive. Note, however, that in many theoretical papers our $f_P/\sqrt{2}$ is denoted by f_P.

In determining f_P experimentally, radiative corrections must be taken into account. Since the photon-loop correction introduces an infrared divergence that is canceled by soft-photon emission, we can determine f_P only from the combined rate for $P^\pm \to \ell^\pm\nu_\ell$ and $P^\pm \to \ell^\pm\nu_\ell\gamma$. This rate is given by

$$\Gamma\,(P \to \ell\nu_\ell + \ell\nu_\ell\gamma) = \frac{G_F^2|V_{qq'}{}^2|}{8\pi} f_P^2\, m_\ell^2\, m_P \left(1-\frac{m_\ell^2}{m_P^2}\right)^2 [1+\mathcal{O}(\alpha)] \ .$$

Radiative corrections include inner bremsstrahlung, which is independent of the structure of the meson [1–3], and also a structure-dependent term [4,5]. After radiative corrections are made, there are ambiguities in extracting f_P from experimental measurements. In fact, the definition of f_P is no longer unique.

It is desirable to define f_P such that it depends only on the properties of the pseudoscalar meson, not on the final decay products. The short-distance corrections to the fundamental electroweak constants like $G_F|V_{qq'}|$ should be separated out. Following Marciano and Sirlin [6], we define f_P with the following form for the $\mathcal{O}(\alpha)$ corrections:

$$1+\mathcal{O}(\alpha) = \left[1+\frac{2\alpha}{\pi}\ln\Big(\frac{m_Z}{m_\rho}\Big)\right]\left[1+\frac{\alpha}{\pi}F(x)\right]$$
$$\times\left\{1-\frac{\alpha}{\pi}\left[\frac{3}{2}\ln\Big(\frac{m_\rho}{m_P}\Big)+C_1+C_2\frac{m_\ell^2}{m_\rho^2}\ln\left(\frac{m_\rho^2}{m_\ell^2}\right)+C_3\frac{m_\ell^2}{m_\rho^2}+\ldots\right]\right\} \ .$$

Here

$$F(x) = 3\ln x + \frac{13-19x^2}{8(1-x^2)} - \frac{8-5x^2}{2(1-x^2)^2}\,x^2\ln x$$
$$-2\Big(\frac{1+x^2}{1-x^2}\ln x + 1\Big)\ln(1-x^2) + 2\Big(\frac{1+x^2}{1-x^2}\Big)L(1-x^2) \ ,$$

with

$$x \equiv m_\ell/m_P \ , \qquad L(z) \equiv \int_0^z \frac{\ln(1-t)}{t}\,dt \ .$$

The first bracket in the expression for $1+\mathcal{O}(\alpha)$ is the short-distance electroweak correction. The QCD correction reduces this factor by 0.00033. The second bracket together with the term $-(3\alpha/2\pi)\ln(m_\rho/m_P)$ in the third bracket corresponds to the radiative corrections to the point-like pion decay ($\Lambda_{\text{cutoff}} \approx m_\rho$) [2]. The rest of the corrections in the third bracket are expanded in powers of m_ℓ/m_ρ. The expansion coefficients C_1, C_2, and C_3 depend on the hadronic structure of the pseudoscalar meson and in most cases cannot be computed accurately. In particular, C_1 absorbs the uncertainty in the matching energy scale between short- and long-distance strong interactions and thus is the main source of uncertainty in determining f_{π^+} accurately.

With the experimental value for the decay $\pi \to \mu\nu_\mu + \mu\nu_\mu\gamma$, one obtains

$$f_{\pi^+} = 130.7 \pm 0.1 \pm 0.36 \text{ MeV} \ ,$$

where the first error comes from the experimental uncertainty on $|V_{ud}|$ and the second comes from the uncertainty on C_1 ($= 0 \pm 0.24$) [6]. Similarly, one obtains from the decay $K \to \mu\nu_\mu + \mu\nu_\mu\gamma$ the decay constant

$$f_{K^+} = 159.8 \pm 1.4 \pm 0.44 \text{ MeV} \ ,$$

where the first error is due to the uncertainty on $|V_{us}|$.

For the heavy pseudoscalar mesons, uncertainties in the experimental values for the decay rates are much larger than the radiative corrections. For the D^+, only an upper bound can be obtained from the published data:

$$f_{D^+} < 310 \text{ MeV (CL = 90\%)} \ .$$

Three groups have measured the $D_s^+ \to \mu^+\nu_\mu$ branching fraction, leading to the following values of the decay constant:

$$f_{D_s^+} = 232 \pm 45 \pm 20 \pm 48 \text{ MeV} \quad [7] \ ,$$
$$f_{D_s^+} = 344 \pm 37 \pm 52 \pm 42 \text{ MeV} \quad [8] \ ,$$
$$f_{D_s^+} = 430^{+150}_{-130} \pm 40 \text{ MeV} \quad [9] \ ,$$

where the first errors are statistical, the second errors are systematic, and the third errors are uncertainties involved in extracting the branching fraction $\text{B}(D_s^+ \to \mu^+\nu_\mu)$. We must wait for more data before drawing a conclusion on $f_{D_s^+}$.

There have been many attempts to extract f_P from spectroscopy and nonleptonic decays using theoretical models. Since it is difficult to estimate uncertainties for them, we have listed here only values of decay constants that are obtained directly from the observation of $P^\pm \to \ell^\pm\nu_\ell$.

Light neutral mesons

The decay constants for the light neutral pseudoscalar mesons π^0, η, and η' are defined by

$$\langle 0|A_\mu(0)|P^0(\mathbf{q})\rangle = i(f_P/\sqrt{2})q_\mu \ ,$$

where A_μ is a neutral axial-vector current of octet or singlet. Values of f_P can be obtained from the two-photon decay $P^0 \rightarrow \gamma\gamma$, since in the $m_P = 0$ limit the decay matrix element is determined by the Adler-Bell-Jackiw anomaly [10,11]. However, large uncertainties enter values of f_P through extrapolation to the physical mass and, in the case of η and η', through the mixing angle, too.

The CELLO Collaboration has obtained the values [12]

$$f_{\pi^0} = 119 \pm 4 \text{ MeV}$$

$$f_\eta \ = 133 \pm 10 \text{ MeV}$$

$$f_{\eta'} \ = 126 \pm 7 \text{ MeV} \ ,$$

while the TPC/2γ Collaboration has obtained [13]

$$f_\eta = 129 \pm 8 \text{ MeV}$$

$$f_{\eta'} = 110 \pm 7 \text{ MeV} \ .$$

(We have multiplied the published values by $\sqrt{2}$ to be in accord with our definition of f_P.)

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$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

$\pi^{\pm}$ MASS

The most accurate charged pion mass measurements are based upon x-ray wavelength measurements for transitions in π^--mesonic atoms. The observed line is the blend of three components, corresponding to different K-shell occupancies. JECKELMANN 94 revisits the occupancy question, with the conclusion that two sets of occupancy ratios, resulting in two different pion masses (Solutions A and B), are equally probable. We choose the higher Solution B since only this solution is consistent with a positive mass-squared for the muon neutrino, given the precise muon momentum measurements now available (DAUM 91, ASSAMAGAN 94, and ASSAMAGAN 96) for the decay of pions at rest. Earlier mass determinations with pi-mesonic atoms may have used incorrect K-shell screening corrections.

Measurements with an error of > 0.005 MeV have been omitted from this Listing.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
139.56995±0.00035 OUR FIT					
139.56995±0.00035	[1] JECKELMANN	94	CNTR	−	π^- atom, Soln. B
• • • We do not use the following data for averages, fits, limits, etc. • • •					
139.57022±0.00014	[2] ASSAMAGAN	96	SPEC	+	$\pi^+ \rightarrow \mu^+\nu_\mu$
139.56782±0.00037	[3] JECKELMANN	94	CNTR	−	π^- atom, Soln. A
139.56996±0.00067	[4] DAUM	91	SPEC	+	$\pi^+ \rightarrow \mu^+\nu$
139.56752±0.00037	[5] JECKELMANN	86B	CNTR	−	Mesonic atoms
139.5704 ±0.0011	[4] ABELA	84	SPEC	+	See DAUM 91
139.5664 ±0.0009	[6] LU	80	CNTR	−	Mesonic atoms
139.5686 ±0.0020	CARTER	76	CNTR	−	Mesonic atoms
139.5660 ±0.0024	[6,7] MARUSHEN...	76	CNTR	−	Mesonic atoms

[1] JECKELMANN 94 Solution B (dominant 2-electron K-shell occupancy), chosen for consistency with positive $m^2_{\nu_\mu}$.

[2] ASSAMAGAN 96 measures the μ^+ momentum p_μ in $\pi^+ \rightarrow \mu^+\nu_\mu$ decay at rest to be 29.79200 ± 0.00011 MeV/c. Combined with the μ^+ mass and the assumption $m_{\nu_\mu} = 0$, this gives the π^+ mass above; if $m_{\nu_\mu} > 0$, m_{π^+} given above is a lower limit. Combined instead with m_μ and (assuming *CPT*) the π^- mass of JECKELMANN 94, p_μ gives an upper limit on m_{ν_μ} (see the ν_μ).

[3] JECKELMANN 94 Solution A (small 2-electron K-shell occupancy) in combination with either the DAUM 91 or ASSAMAGAN 94 pion decay muon momentum measurement yields a significantly negative $m^2_{\nu_\mu}$. It is accordingly not used in our fits.

[4] The DAUM 91 value includes the ABELA 84 result. The value is based on a measurement of the μ^+ momentum for π^+ decay at rest, $p_\mu = 29.79179 \pm 0.00053$ MeV, uses $m_\mu = 105.658389 \pm 0.000034$ MeV, and assumes that $m_{\nu_\mu} = 0$. The last assumption means that in fact the value is a lower limit.

[5] JECKELMANN 86B gives $m_\pi/m_e = 273.12677(71)$. We use $m_e = 0.51099906(15)$ MeV from COHEN 87. The authors note that two solutions for the probability distribution of K-shell occupancy fit equally well, and use other data to choose the lower of the two possible $\pi^{\pm}$ masses.

[6] These values are scaled with a new wavelength-energy conversion factor $V\lambda = 1.23984244(37) \times 10^{-6}$ eV m from COHEN 87. The LU 80 screening correction relies upon a theoretical calculation of inner-shell refilling rates.

[7] This MARUSHENKO 76 value used at the authors' request to use the accepted set of calibration γ energies. Error increased from 0.0017 MeV to include QED calculation error of 0.0017 MeV (12 ppm).

$m_{\pi^+} - m_{\mu^+}$

Measurements with an error > 0.05 MeV have been omitted from this Listing.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
33.91157±0.00067		[8] DAUM	91	SPEC	+	$\pi^+ \rightarrow \mu^+\nu$
33.9111 ±0.0011		ABELA	84	SPEC		See DAUM 91
33.925 ±0.025		BOOTH	70	CNTR	+	Magnetic spect.
33.881 ±0.035	145	HYMAN	67	HEBC	+	K^- He

[8] The DAUM 91 value assumes that $m_{\nu_\mu} = 0$ and uses our $m_\mu = 105.658389 \pm 0.000034$ MeV.

$(m_{\pi^+} - m_{\pi^-}) \ / \ m_{\text{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*
2±5	AYRES	71	CNTR

$\pi^{\pm}$ MEAN LIFE

Measurements with an error $> 0.02 \times 10^{-8}$ s have been omitted.

VALUE (10^{-8} s)	DOCUMENT ID		TECN	CHG	COMMENT
2.6033 ±0.0005 OUR AVERAGE	Error includes scale factor of 1.2.				
2.60361±0.00052	[9] KOPTEV	95	SPEC	+	Surface μ^+'s
2.60231±0.00050±0.00084	NUMAO	95	SPEC	+	Surface μ^+'s
2.609 ±0.008	DUNAITSEV	73	CNTR	+	
2.602 ±0.004	AYRES	71	CNTR	±	
2.604 ±0.005	NORDBERG	67	CNTR	+	
2.602 ±0.004	ECKHAUSE	65	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.640 ±0.008	[10] KINSEY	66	CNTR	+	

[9] KOPTEV 95 combines the statistical and systematic errors; the statistical error dominates.
[10] Systematic errors in the calibration of this experiment are discussed by NORDBERG 67.

$(\tau_{\pi^+} - \tau_{\pi^-}) / \tau_{\text{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-4})	DOCUMENT ID		TECN
5.5± 7.1	AYRES	71	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−14 ±29	PETRUKHIN	68	CNTR
40 ±70	BARDON	66	CNTR
23 ±40	[11] LOBKOWICZ	66	CNTR

[11] This is the most conservative value given by LOBKOWICZ 66.

π^+ DECAY MODES

π^- modes are charge conjugates of the modes below.

	Mode			Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\mu^+\nu_\mu$		[a]	(99.98770±0.00004) %	
Γ_2	$\mu^+\nu_\mu\gamma$		[b]	(1.24 ±0.25) $\times 10^{-4}$	
Γ_3	$e^+\nu_e$		[a]	(1.230 ±0.004) $\times 10^{-4}$	
Γ_4	$e^+\nu_e\gamma$		[b]	(1.61 ±0.23) $\times 10^{-7}$	
Γ_5	$e^+\nu_e\pi^0$			(1.025 ±0.034) $\times 10^{-8}$	
Γ_6	$e^+\nu_e e^+ e^-$			(3.2 ±0.5) $\times 10^{-9}$	
Γ_7	$e^+\nu_e\nu\overline{\nu}$			< 5 $\times 10^{-6}$	90%
	Lepton Family number (*LF*) or Lepton number (*L*) violating modes				
Γ_8	$\mu^+\overline{\nu}_e$	*L*	[c]	< 1.5 $\times 10^{-3}$	90%
Γ_9	$\mu^+\nu_e$	*LF*	[c]	< 8.0 $\times 10^{-3}$	90%
Γ_{10}	$\mu^- e^+ e^+ \nu$	*LF*		< 1.6 $\times 10^{-6}$	90%

[a] Measurements of $\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ always include decays with γ's, and measurements of $\Gamma(e^+\nu_e\gamma)$ and $\Gamma(\mu^+\nu_\mu\gamma)$ never include low-energy γ's. Therefore, since no clean separation is possible, we consider the modes with γ's to be subreactions of the modes without them, and let $[\Gamma(e^+\nu_e) + \Gamma(\mu^+\nu_\mu)]/\Gamma_{\text{total}} = 100\%$.

[b] See the Particle Listings below for the energy limits used in this measurement; low-energy γ's are not included.

[c] Derived from an analysis of neutrino-oscillation experiments.

π^+ BRANCHING RATIOS

$\Gamma(e^+\nu_e)/\Gamma_{\text{total}}$ — Γ_3/Γ

See note [a] in the list of π^+ decay modes just above, and see also the next block of data.

VALUE (units 10^{-4})	DOCUMENT ID
1.230±0.004 OUR EVALUATION	

$[\Gamma(e^+\nu_e) + \Gamma(e^+\nu_e\gamma)]/[\Gamma(\mu^+\nu_\mu) + \Gamma(\mu^+\nu_\mu\gamma)]$ — $(\Gamma_3+\Gamma_4)/(\Gamma_1+\Gamma_2)$

See note [a] in the list of π^+ decay modes above. See NUMAO 92 for a discussion of e-μ universality.

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.230 ±0.004 OUR AVERAGE					
1.2346±0.0035±0.0036	120k	CZAPEK	93	CALO	Stopping π^+
1.2265±0.0034±0.0044	190k	BRITTON	92	CNTR	Stopping π^+
1.218 ±0.014	32k	BRYMAN	86	CNTR	Stopping π^+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.273 ±0.028	11k	[12] DICAPUA	64	CNTR	
1.21 ±0.07		ANDERSON	60	SPEC	

[12] DICAPUA 64 has been updated using the current mean life.

$\Gamma(\mu^+\nu_\mu\gamma)/\Gamma_{\text{total}}$ — Γ_2/Γ

Note that measurements here do not cover the full kinematic range.

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.24±0.25	26	CASTAGNOLI	58	EMUL	$KE_\mu < 3.38$ MeV

$\Gamma(e^+\nu_e\gamma)/\Gamma_{\text{total}}$ — Γ_4/Γ

Note that measurements here do not cover the full kinematic range.

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	COMMENT
16.1±2.3		[13] BOLOTOV	90B	SPEC	17 GeV $\pi^- \to e^-\overline{\nu}_e\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.6±0.7	226	[14] STETZ	78	SPEC	$P_e > 56$ MeV/c
3.0	143	DEPOMMIER	63B	CNTR	$(KE)_{e^+\gamma} > 48$ MeV

[13] BOLOTOV 90B is for $E_\gamma > 21$ MeV, $E_e > 70 - 0.8\,E_\gamma$.
[14] STETZ 78 is for an $e^-\gamma$ opening angle $> 132°$. Obtains 3.7 when using same cutoffs as DEPOMMIER 63B.

$\Gamma(e^+\nu_e\pi^0)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.025±0.034 OUR AVERAGE						
1.026±0.039	1224	[15] MCFARLANE	85	CNTR	+	Decay in flight
1.00 $^{+0.08}_{-0.10}$	332	DEPOMMIER	68	CNTR	+	
1.07 ±0.21	38	[16] BACASTOW	65	OSPK	+	
1.10 ±0.26		[16] BERTRAM	65	OSPK	+	
1.1 ±0.2	43	[16] DUNAITSEV	65	CNTR	+	
0.97 ±0.20	36	[16] BARTLETT	64	OSPK	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.15 ±0.22	52	[16] DEPOMMIER	63	CNTR	+	See DEPOMMIER 68

[15] MCFARLANE 85 combines a measured rate (0.394 ± 0.015)/s with 1982 PDG mean life.
[16] DEPOMMIER 68 says the result of DEPOMMIER 63 is at least 10% too large because of a systematic error in the π^0 detection efficiency, and that this may be true of all the previous measurements (also V. Soergel, private communication, 1972).

$\Gamma(e^+\nu_e e^+ e^-)/\Gamma(\mu^+\nu_\mu)$ — Γ_6/Γ_1

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
3.2 ±0.5 ±0.2		98	EGLI	89	SPEC	Uses R_{PCAC} = 0.068 ± 0.004
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.46±0.16±0.07		7	[17] BARANOV	92	SPEC	Stopped π^+
< 4.8	90		KORENCHE...	76B	SPEC	
<34	90		KORENCHE...	71	OSPK	

[17] This measurement by BARANOV 92 is of the structure-dependent part of the decay. The value depends on values assumed for ratios of form factors.

$\Gamma(e^+\nu_e\nu\overline{\nu})/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
<5	90	PICCIOTTO	88	SPEC

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{\text{total}}$ — Γ_8/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\mu^+\nu_e)/\Gamma_{\text{total}}$ — Γ_9/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<8.0	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\mu^- e^+ e^+ \nu)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	CHG
<1.6	90	BARANOV	91B	SPEC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7.7	90	KORENCHE...	87	SPEC	+

π^+ — POLARIZATION OF EMITTED μ^+

$\pi^+ \to \mu^+\nu$

Tests the Lorentz structure of leptonic charged weak interactions.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<(−0.9959)	90	[18] FETSCHER	84	RVUE	+	
−0.99±0.16		[19] ABELA	83	SPEC	−	μ *X*-rays

[18] FETSCHER 84 uses only the measurement of CARR 83.
[19] Sign of measurement reversed in ABELA 83 to compare with μ^+ measurements.

$\pi^{\pm} \to \ell^{\pm}\nu\gamma$ AND $K^{\pm} \to \ell^{\pm}\nu\gamma$ FORM FACTORS

(by H.S. Pruys, Zürich University)

In the radiative decays $\pi^{\pm} \to \ell^{\pm}\nu\gamma$ and $K^{\pm} \to \ell^{\pm}\nu\gamma$, where ℓ is an e or a μ and γ is a real or virtual photon (e^+e^- pair), both the vector and the axial-vector weak hadronic currents contribute to the decay amplitude. Each current gives a structure-dependent term (SD_V and SD_A) from virtual hadronic states, and the axial-vector current also gives a contribution from inner bremsstrahlung (IB) from the lepton and meson. The IB amplitudes are determined by the meson decay constants f_π and f_K [1]. The SD_V and SD_A amplitudes are parameterized in terms of the vector form factor F_V and the axial-vector form factors F_A and R [1–4]:

$$M(\mathrm{SD}_V) = \frac{-eG_F\,V_{qq'}}{\sqrt{2}\,m_P}\epsilon^{\mu}\,\ell^{\nu}\,F_V\,\epsilon_{\mu\nu\sigma\tau}\,k^{\sigma}\,q^{\tau} ,$$

$$M(\mathrm{SD}_A) = \frac{-ie\,G_F V_{qq'}}{\sqrt{2}\,m_P}\,\epsilon^{\mu}\,\ell^{\nu}\,\{F_A\,[(s-t)g_{\mu\nu} - q_{\mu}\,k_{\nu}] + R\,t\,g_{\mu\nu}\} .$$

Here $V_{qq'}$ is the Cabibbo-Kobayashi-Maskawa mixing-matrix element; ϵ^{μ} is the polarization vector of the photon (or the effective vertex, $\epsilon^{\mu} = (e/t)\overline{u}(p_-)\gamma^{\mu}v(p_+)$, of the e^+e^- pair); $\ell^{\nu} = \overline{u}(p_{\nu})\gamma^{\nu}(1-\gamma_5)v(p_{\ell})$ is the lepton-neutrino current; q and k are the meson and photon four-momenta, with $s = q\cdot k$ and $t = k^2(=(p_+ + p_-)^2)$; and P stands for π or K. In the analysis of data, the s and t dependence of the form factors is neglected, which is a good approximation for pions [2] but not for kaons [4]. The pion vector form factor F_V^{π} is related via CVC to the π^0 lifetime, $|F_V^{\pi}| = (1/\alpha)\sqrt{2\Gamma_{\pi^0}/\pi m_{\pi^0}}$ [1]. PCAC relates R to the electromagnetic radius of the meson [2,4], $R^P = \frac{1}{3}m_P f_P\langle r_P^2\rangle$. The calculation of the other form factors, F_A^{π}, F_V^K, and F_A^K, is model dependent [1,4].

When the photon is real, the partial decay rate can be given analytically [1,5]:

$$\frac{d^2\Gamma_{P\to\ell\nu\gamma}}{dxdy} = \frac{d^2\,(\Gamma_{\mathrm{IB}} + \Gamma_{\mathrm{SD}} + \Gamma_{\mathrm{INT}})}{dxdy} ,$$

where $\Gamma_{\mathrm{IB}}, \Gamma_{\mathrm{SD}}$, and Γ_{INT} are the contributions from inner bremsstrahlung, structure-dependent radiation, and their interference, and the Γ_{SD} term is given by

$$\frac{d^2\Gamma_{\mathrm{SD}}}{dxdy} = \frac{\alpha}{8\pi}\Gamma_{P\to\ell\nu}\,\frac{1}{r(1-r)^2}\left(\frac{m_P}{f_P}\right)^2 \times \left[(F_V + F_A)^2\,\mathrm{SD}^+ + (F_V - F_A)^2\,\mathrm{SD}^-\right] .$$

Here

$$\mathrm{SD}^+ = (x+y-1-r)\,[(x+y-1)(1-x) - r] ,$$

$$\mathrm{SD}^- = (1-y+r)\,[(1-x)(1-y) + r] ,$$

where $x = 2E_{\gamma}/m_P$, $y = 2E_{\ell}/m_P$, and $r = (m_{\ell}/m_P)^2$.

In $\pi^{\pm} \to e^{\pm}\nu\gamma$ and $K^{\pm} \to e^{\pm}\nu\gamma$ decays, the interference terms are small, and thus only the absolute values $|F_A + F_V|$ and $|F_A - F_V|$ can be obtained. In $K^{\pm} \to \mu^{\pm}\nu\gamma$ decay, the interference term is important, and thus the signs of F_V and F_A can be obtained. In $\pi^{\pm} \to \mu^{\pm}\nu\gamma$ decay, bremsstrahlung completely dominates. In $\pi^{\pm} \to e^{\pm}\nu e^+e^-$ and $K^{\pm} \to \ell^{\pm}\nu e^+e^-$ decays, all three form factors, F_V, F_A, and R, can be determined.

We give the $\pi^{\pm}$ form factors F_V, F_A, and R in the Listings below. In the $K^{\pm}$ Listings, we give the sum $F_A + F_V$ and difference $F_A - F_V$.

The electroweak decays of the pseudoscalar mesons are investigated to learn something about the unknown hadronic structure of these mesons, assuming a standard $V - A$ structure of the weak leptonic current. The experiments are quite difficult, and it is not meaningful to analyse the results using parameters for both the hadronic structure (decay constants, form factors) and the leptonic weak current (*e.g.*, to add pseudoscalar or tensor couplings to the $V - A$ coupling). Deviations from the $V - A$ interactions are much better studied in purely leptonic systems such as muon decay.

References

1. D.A. Bryman *et al.*, Phys. Reports **88**, 151 (1982). See also our note on "Pseudoscalar-Meson Decay Constants," above.
2. A. Kersch and F. Scheck, Nucl. Phys. **B263**, 475 (1986).
3. W.T. Chu *et al.*, Phys. Rev. **166**, 1577 (1968).
4. D.Yu. Bardin and E.A. Ivanov, Sov. J. Nucl. Phys. **7**, 286 (1976).
5. S.G. Brown and S.A. Bludman, Phys. Rev. **136**, B1160 (1964).

$\pi^{\pm}$ FORM FACTORS

F_V, VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.017±0.008 OUR AVERAGE					
0.014±0.009		[20] BOLOTOV	90B	SPEC	17 GeV $\pi^- \to e^-\overline{\nu}_e\gamma$
$0.023^{+0.015}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \to e^+\nu_e e^+e^-$

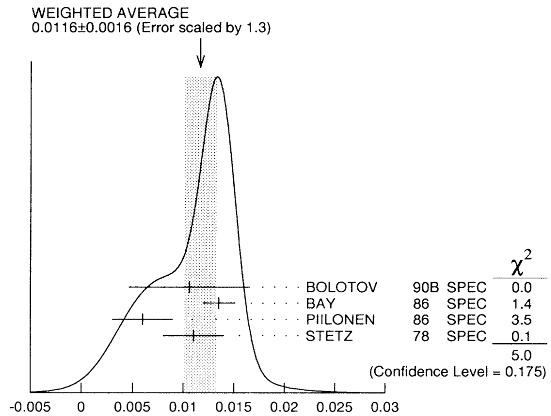
[20] BOLOTOV 90B only determines the absolute value.

F_A, AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0116±0.0016 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
0.0106±0.0060		[21] BOLOTOV	90B	SPEC	17 GeV $\pi^- \to e^-\overline{\nu}_e\gamma$
0.0135±0.0016		[21] BAY	86	SPEC	$\pi^+ \to e^+\nu\gamma$
0.006 ±0.003		[21] PIILONEN	86	SPEC	$\pi^+ \to e^+\nu\gamma$
0.011 ±0.003		[21,22] STETZ	78	SPEC	$\pi^+ \to e^+\nu\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.021^{+0.011}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \to e^+\nu_e e^+e^-$

[21] Using the vector form factor from CVC prediction $F_V = 0.0259 \pm 0.0005$. Only the absolute value of F_A is determined.

[22] The result of STETZ 78 has a two-fold ambiguity. We take the solution compatible with later determinations.



R, SECOND AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.059^{+0.009}_{-0.008}$	98	EGLI	89	SPEC	$\pi^+ \to e^+ \nu_e e^+ e^-$

$\pi^{\pm}$ REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition Physics Letters **B204** (1988).

ASSAMAGAN	96	PR D53 6065	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
KOPTEV	95	JETPL 61 877	+Mikirtych'yants, Shcherbakov+	(PNPI)
		Translated from ZETFP 61 865.		
NUMAO	95	PR D52 4855	+Macdonald, Marshall, Olin, Fujiwara	(TRIU, BRCO)
ASSAMAGAN	94	PL B335 231	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
JECKELMANN	94	PL B335 326	+Goudsmit, Leisi	(WABRN, VILL)
CZAPEK	93	PRL 70 17	+Federspiel, Flueckiger, Frei+	(BERN, VILL)
BARANOV	92	SJNP 55 1644	+Vanko, Glazov, Evtukhovich+	(JINR)
		Translated from YAF 55 2940.		
BRITTON	92	PRL 68 3000	+Ahmad, Bryman, Burnham+	(TRIU, CARL)
Also	94	PR D49 28	Britton, Ahmad, Bryman+	(TRIU, CARL)
NUMAO	92	MPL A7 3357		(TRIU)
BARANOV	91B	SJNP 54 790	+Kisel, Korenchenko, Kuchinskii+	(JINR)
		Translated from YAF 54 1298.		
DAUM	91	PL B265 425	+Frosch, Herter, Janousch, Kettle	(VILL)
BOLOTOV	90B	PL B243 308	+Gninenko, Djilkibaev, Isakov+	(INRM)
EGLI	89	PL B222 533	+Engfer, Grab, Hermes, Kraus+	(SINDRUM Collab.)
Also	86	PL B175 97	Egli, Engfer, Grab, Hermes+	(AACH3, ETH, SIN, ZURI)
PDG	88	PL B204	Yost, Barnett+	(LBL+)
PICCIOTTO	88	PR D37 1131	+Ahmad, Britton, Bryman, Clifford+	(TRIU, CNRC)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
KORENCHE...	87	SJNP 46 192	Korenchenko, Kostin, Mzhaviya+	(JINR)
		Translated from YAF 46 313.		
BAY	86	PL B174 445	+Ruegger, Gabioud, Joseph, Loude+	(LAUS, ZURI)
BRYMAN	86	PR D33 1211	+Dubois, Macdonald, Numao+	(TRIU, CNRC)
Also	83	PRL 50 7	Bryman, Dubois, Numao, Olaniya+	(TRIU, CNRC)
JECKELMANN	86B	NP A457 709	+Beer, Chambrier, Elsenhans+	(ETH, FRIB)
Also	86	PRL 56 1444	Jeckelmann, Nakada, Beer+	(ETH, FRIB)
PIILONEN	86	PRL 57 1402	+Bolton, Cooper, Frank+	(LANL, TEMP, CHIC)
MCFARLANE	85	PR D32 547	+Auerbach, Gaille+	(TEMP, LANL)
ABELA	84	PL 146B 431	+Daum, Eaton, Frosch, Jost, Kettle+	(SIN)
Also	78	PL 74B 126	Daum, Eaton, Frosch, Hirschmann+	(SIN)
Also	79	PR D20 2692	Daum, Eaton, Frosch, Hirschmann+	(SIN)
FETSCHER	84	PL 140B 117		(ETH)
ABELA	83	NP A395 413	+Backenstoss, Kunold, Simons+	(BASL, KARLK, KARLE)
CARR	83	PRL 51 627	+Gidal, Gobbi, Jodidio, Oram+	(LBL, NWES, TRIU)
COOPER	82	PL 112B 97	+Guy, Michette, Tyndel, Venus	(RL)
LU	80	PRL 45 1066	+Delker, Dugan, Wu, Caffrey+	(YALE, COLU, JHU)
STETZ	78	NP B138 285	+Carroll, Ortendahl, Perez-Mendez+	(LBL, UCLA)
CARTER	76	PRL 37 1380	+Dixit, Sundaresan+	(CARL, CNRC, CHIC, CIT)
KORENCHE...	76B	JETP 44 35	Korenchenko, Kostin, Micelmacher+	(JINR)
		Translated from ZETF 71 69.		
MARUSHEN...	76	JETPL 23 72	Marushenko, Mezentsev, Petrunin+	(PNPI)
		Translated from ZETFP 23 80.		
Also	76	Private Comm.	Shafer	(FNAL)
Also	78	Private Comm.	Smirnov	(PNPI)
DUNAITSEV	73	SJNP 16 292	+Prokoshkin, Razuvaev+	(SERP)
		Translated from YAF 16 524.		
AYRES	71	PR D3 1051	+Cormack, Greenberg, Kenney+	(LRL, UCSB)
Also	67	PR 157 1288	Ayres, Caldwell, Greenberg, Kenney, Kurz+	(LRL)
Also	68	PRL 21 261	Ayres, Cormack, Greenberg+	(LRL, UCSB)
Also	69	Thesis UCRL 18369	Ayres	(LRL)
Also	69	PRL 23 1267	Greenberg, Ayres, Cormack+	(LRL, UCSB)
KORENCHE...	71	SJNP 13 189	Korenchenko, Kostin, Micelmacher+	(JINR)
		Translated from YAF 13 339.		
BOOTH	70	PL 32B 723	+Johnson, Williams, Wormald	(LIVP)
DEPOMMIER	68	NP B4 189	+Duclos, Heintze, Kleinknecht+	(CERN)
PETRUKHIN	68	JINR P1 3862	+Rykalin, Khazins, Cisek	(JINR)
HYMAN	67	PL 25B 376	+Loken, Pewitt, McKenzie+	(ANL, CMU, NWES)
NORDBERG	67	PL 24B 594	+Lobkowicz, Burman	(ROCH)
BARDON	66	PRL 16 775	+Dore, Dorfan, Krieger+	(COLU)
KINSEY	66	PR 144 1132	+Lobkowicz, Nordberg	(ROCH)
LOBKOWICZ	66	PRL 17 548	+Melissinos, Nagashima+	(ROCH, BNL)
BACASTOW	65	PR 139B 407	+Ghesquiere, Wiegand, Larsen	(LRL, SLAC)
BERTRAM	65	PR 139B 617	+Meyer, Carrigan+	(MICH, CMU)
DUNAITSEV	65	JETP 20 58	+Petrukhin, Prokoshkin+	(JINR)
		Translated from ZETF 47 84.		
ECKHAUSE	65	PL 19 348	+Harris, Shuler+	(WILL)
BARTLETT	64	PR 136B 1452	+Devons, Meyer, Rosen	(COLU)
DICAPUA	64	PR 133B 1333	+Garland, Pondrom, Strelzoff	(COLU)
Also	86	Private Comm.	Pondrom	(WISC)
DEPOMMIER	63	PL 5 61	+Heintze, Rubbia, Soergel	(CERN)
DEPOMMIER	63B	PL 7 285	+Heintze, Rubbia, Soergel	(CERN)
ANDERSON	60	PR 119 2050	+Fujii, Miller+	(EFI)
CASTAGNOLI	58	PR 112 1779	+Muchnik	(ROMA)

π^0

$I^G(J^{PC}) = 1^-(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

π^0 MASS

The value is calculated from $m_{\pi^\pm}$ and $(m_{\pi^\pm} - m_{\pi^0})$. See notes under the $\pi^\pm$ Mass Listings concerning recent revision of the charged pion mass.

VALUE (MeV)	DOCUMENT ID
134.9764±0.0006 OUR FIT	

$m_{\pi^\pm} - m_{\pi^0}$

Measurements with an error > 0.01 MeV have been omitted.

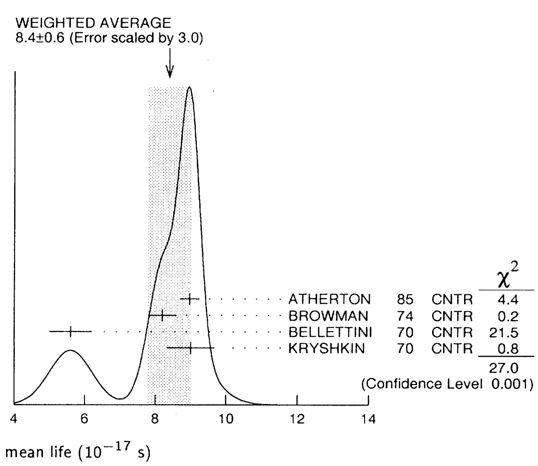
VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4.5936 ±0.0005 OUR FIT				
4.5936 ±0.0005 OUR AVERAGE				
4.59364±0.00048	CRAWFORD	91	CNTR	$\pi^- p \to \pi^0 n$, n TOF
4.5930 ±0.0013	CRAWFORD	86	CNTR	$\pi^- p \to \pi^0 n$, n TOF
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.59366±0.00048	CRAWFORD	88B	CNTR	See CRAWFORD 91
4.6034 ±0.0052	VASILEVSKY	66	CNTR	
4.6056 ±0.0055	CZIRR	63	CNTR	

π^0 MEAN LIFE

Measurements with an error > 1×10^{-17} s have been omitted.

VALUE (10^{-17} s)	EVTS	DOCUMENT ID		TECN	COMMENT
8.4 ±0.6 OUR AVERAGE	Error includes scale factor of 3.0. See the ideogram below.				
8.97±0.22±0.17		ATHERTON	85	CNTR	
8.2 ±0.4		[1] BROWMAN	74	CNTR	Primakoff effect
5.6 ±0.6		BELLETTINI	70	CNTR	Primakoff effect
9 ±0.68		KRYSHKIN	70	CNTR	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.4 ±0.5 ±0.5	1182	[2] WILLIAMS	88	CBAL	$e^+e^- \to e^+e^-\pi^0$

[1] BROWMAN 74 gives a π^0 width $\Gamma = 8.02 \pm 0.42$ eV. The mean life is $\hbar/\Gamma$.
[2] WILLIAMS 88 gives $\Gamma(\gamma\gamma) = 7.7 \pm 0.5 \pm 0.5$ eV. We give here $\tau = \hbar/\Gamma(\text{total})$.



π^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	2γ	(98.798±0.032) %	S=1.1
Γ_2	$e^+e^-\gamma$	(1.198±0.032) %	S=1.1
Γ_3	γ positronium	(1.82 ±0.29) $\times 10^{-9}$	
Γ_4	$e^+e^+e^-e^-$	(3.14 ±0.30) $\times 10^{-5}$	
Γ_5	e^+e^-	(7.5 ±2.0) $\times 10^{-8}$	
Γ_6	4γ	< 2 $\times 10^{-8}$	CL=90%
Γ_7	$\nu\overline{\nu}$	[a] < 8.3 $\times 10^{-7}$	CL=90%
Γ_8	$\nu_e\overline{\nu}_e$	< 1.7 $\times 10^{-6}$	CL=90%
Γ_9	$\nu_\mu\overline{\nu}_\mu$	< 3.1 $\times 10^{-6}$	CL=90%
Γ_{10}	$\nu_\tau\overline{\nu}_\tau$	< 2.1 $\times 10^{-6}$	CL=90%

Charge conjugation (*C*) or Lepton Family number (*LF*) violating modes

Γ_{11}	3γ	*C*	< 3.1	$\times 10^{-8}$	CL=90%
Γ_{12}	$\mu^+ e^-$				
Γ_{13}	$\mu^+ e^- + e^- \mu^+$	*LF*	< 1.72	$\times 10^{-8}$	CL=90%

[*a*] Astrophysical and cosmological arguments give limits of order 10^{-13}; see the Particle Listings below.

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 4 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 1.9 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100	
x_4	−1	0
	x_1	x_2

π^0 BRANCHING RATIOS

$\Gamma(e^+e^-\gamma)/\Gamma(2\gamma)$ Γ_2/Γ_1

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.213±0.033 OUR FIT	Error includes scale factor of 1.1.				
1.213±0.030 OUR AVERAGE					
1.25 ±0.04		SCHARDT	81	SPEC	$\pi^- p \to n\pi^0$
1.166±0.047	3071	[3] SAMIOS	61	HBC	$\pi^- p \to n\pi^0$
1.17 ±0.15	27	BUDAGOV	60	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.196		JOSEPH	60	THEO	QED calculation

[3] SAMIOS 61 value uses a Panofsky ratio = 1.62.

$\Gamma(\gamma\,\text{positronium})/\Gamma(2\gamma)$ Γ_3/Γ_1

VALUE (units 10^{-9})	EVTS	DOCUMENT ID		TECN	COMMENT
1.84±0.29	277	AFANASYEV	90	CNTR	*p*C 70 GeV

$\Gamma(e^+e^+e^-e^-)/\Gamma(2\gamma)$ Γ_4/Γ_1

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN
3.18±0.30 OUR FIT				
3.18±0.30	146	[4] SAMIOS	62B	HBC

[4] SAMIOS 62B value uses a Panofsky ratio = 1.62.

$\Gamma(e^+e^-)/\Gamma_{total}$ Γ_5/Γ

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	COMMENT
7.5±2.0 OUR AVERAGE					
6.9±2.3±0.6	21	[5] DESHPANDE	93	SPEC	$K^+ \to \pi^+\pi^0$
$8.8^{+4.5}_{-3.2}$±0.6	8	[6] MCFARLAND	93	SPEC	$K^0_L \to 3\pi^0$ in flight

[5] The DESHPANDE 93 result with bremsstrahlung radiative corrections is (8.0 ± 2.6 ± 0.6) × 10^{-8}.
[6] The MCFARLAND 93 result with radiative corrections and excluding $[m_{ee}/m_{\pi^0}]^2 <$ 0.95 is $(7.6^{+3.9}_{-2.8} \pm 0.5) \times 10^{-8}$.

$\Gamma(e^+e^-)/\Gamma(2\gamma)$ Γ_5/Γ_1

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	90		NIEBUHR	89	SPEC	$\pi^- p \to \pi^0 n$ at rest
<5.3	90		ZEPHAT	87	SPEC	$\pi^- p \to \pi^0 n$ 0.3 GeV/*c*
1.7 ±0.6 ±0.3		59	FRANK	83	SPEC	$\pi^- p \to n\pi^0$
1.8 ±0.6		58	MISCHKE	82	SPEC	See FRANK 83
$2.23^{+2.40}_{-1.10}$	90	8	FISCHER	78B	SPRK	$K^+ \to \pi^+\pi^0$

$\Gamma(4\gamma)/\Gamma_{total}$ Γ_6/Γ

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 2	90		MCDONOUGH	88	CBOX	$\pi^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<160	90		BOLOTOV	86C	CALO	
<440	90	0	AUERBACH	80	CNTR	

$\Gamma(\nu\overline{\nu})/\Gamma_{total}$ Γ_7/Γ

The astrophysical and cosmological limits are many orders of magnitude lower, but we use the best laboratory limit for the Summary Tables.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.83	90		[7] ATIYA	91	B787	$K^+ \to \pi^+\nu\nu'$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 2.9 × 10^{-7}			[8] LAM	91		Cosmological limit
< 3.2 × 10^{-7}			[9] NATALE	91		SN 1987A
< 6.5	90		DORENBOS...	88	CHRM	Beam dump, prompt ν
<24	90	0	[7] HERCZEG	81	RVUE	$K^+ \to \pi^+\nu\nu'$

[7] This limit applies to all possible $\nu\nu'$ states as well as to other massless, weakly interacting states.
[8] LAM 91 considers the production of right-handed neutrinos produced from the cosmic thermal background at the temperature of about the pion mass through the reaction $\gamma\gamma \to \pi^0 \to \nu\overline{\nu}$.
[9] NATALE 91 considers the excess energy-loss rate from SN 1987A if the process $\gamma\gamma \to \pi^0 \to \nu\overline{\nu}$ occurs, permitted if the neutrinos have a right-handed component. As pointed out in LAM 91 (and confirmed by Natale), there is a factor 4 error in the NATALE 91 published result (0.8 × 10^{-7}).

$\Gamma(\nu_e\overline{\nu}_e)/\Gamma_{total}$ Γ_8/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
<1.7	90	DORENBOS...	88	CHRM	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.1	90	[10] HOFFMAN	88	RVUE	Beam dump, prompt ν

[10] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\mu\overline{\nu}_\mu)/\Gamma_{total}$ Γ_9/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
<3.1	90	[11] HOFFMAN	88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7.8	90	DORENBOS...	88	CHRM	Beam dump, prompt ν

[11] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\tau\overline{\nu}_\tau)/\Gamma_{total}$ Γ_{10}/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
<2.1	90	[12] HOFFMAN	88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.1	90	DORENBOS...	88	CHRM	Beam dump, prompt ν

[12] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(3\gamma)/\Gamma_{total}$ Γ_{11}/Γ

Forbidden by *C* invariance.

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 3.1	90		MCDONOUGH	88	CBOX	$\pi^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 38	90	0	HIGHLAND	80	CNTR	
<150	90	0	AUERBACH	78	CNTR	
<490	90	0	[13] DUCLOS	65	CNTR	
<490	90		[13] KUTIN	65	CNTR	

[13] These experiments give $B(3\gamma/2\gamma) <$ 5.0 × 10^{-6}.

$\Gamma(\mu^+e^-)/\Gamma_{total}$ Γ_{12}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-9})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<16	90	LEE	90	SPEC	$K^+ \to \pi^+\mu^+e^-$
<78	90	CAMPAGNARI	88	SPEC	See LEE 90

$[\Gamma(\mu^+e^-) + \Gamma(e^-\mu^+)]/\Gamma_{total}$ Γ_{13}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-9})	CL%	DOCUMENT ID		TECN	COMMENT
< 17.2	90	KROLAK	94	E799	In $K^0_L \to 3\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<140		HERCZEG	84	RVUE	$K^+ \to \pi^+\mu e$
< 2 × 10^{-6}		HERCZEG	84	THEO	$\mu^- \to e^-$ conversion
< 70	90	BRYMAN	82	RVUE	$K^+ \to \pi^+\mu e$

π^0 ELECTROMAGNETIC FORM FACTOR

The amplitude for the process $\pi^0 \to e^+e^-\gamma$ contains a form factor $F(x)$ at the $\pi^0\gamma\gamma$ vertex, where $x = [m_{e^+e^-}/m_{\pi^0}]^2$. The parameter *a* in the linear expansion $F(x) = 1 + ax$ is listed below.

All the measurements except that of BEHREND 91 are in the time-like region of momentum transfer.

LINEAR COEFFICIENT OF π^0 ELECTROMAGNETIC FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.032 ±0.004 OUR AVERAGE					
+0.026 ±0.024 ±0.048	7548	FARZANPAY	92	SPEC	$\pi^- p \to \pi^0 n$ at rest
+0.025 ±0.014 ±0.026	54k	MEIJERDREES	92B	SPEC	$\pi^- p \to \pi^0 n$ at rest
+0.0326±0.0026±0.0026	127	[14] BEHREND	91	CELL	$e^+e^- \to e^+e^-\pi^0$
−0.11 ±0.03 ±0.08	32k	FONVIEILLE	89	SPEC	Radiation corr.

• • • We do not use the following data for averages, fits, limits, etc. • • •

0.12	$^{+0.05}_{-0.04}$		[15] TUPPER	83	THEO	FISCHER 78 data
+0.10	±0.03	31k	[16] FISCHER	78	SPEC	Radiation corr.
+0.01	±0.11	2200	DEVONS	69	OSPK	No radiation corr.
−0.15	±0.10	7676	KOBRAK	61	HBC	No radiation corr.
−0.24	±0.16	3071	SAMIOS	61	HBC	No radiation corr.

[14] BEHREND 91 estimates that their systematic error is of the same order of magnitude as their statistical error, and so we have included a systematic error of this magnitude. The value of *a* is obtained by extrapolation from the region of large space-like momentum transfer assuming vector dominance.

[15] TUPPER 83 is a theoretical analysis of FISCHER 78 including 2-photon exchange in the corrections.

[16] The FISCHER 78 error is statistical only. The result without radiation corrections is +0.05 ± 0.03.

π^0 REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition Physics Letters **B204** (1988).

KROLAK	94	PL B320 407	+Briere, Cheu, Harris+	(FNAL E799 Collab.)
DESHPANDE	93	PRL 71 27	+Alliegro, Chaloupka+	(BNL E851 Collab.)
MCFARLAND	93	PRL 71 31	+Briere, Cheu, Harris+	(FNAL E799 Collab.)
FARZANPAY	92	PL B278 413	+	(ORST, TRIU, BRCO, QUKI, LBL, BIRM, OXF)
MEIJERDREES	92B	PR D45 1439	Meijer Drees, Waltham+	(PSI SINDRUM-I Collab.)
ATIYA	91	PRL 66 2189	+Chiang, Frank, Haggerty+	(BNL, LANL, PRIN, TRIU)
BEHREND	91	ZPHY C49 401	+Criegee, Field, Franke+	(CELLO Collab.)
CRAWFORD	91	PR D43 46	+Daum, Frosch, Jost, Kettle+	(VILL, VIRG)
LAM	91	PR D44 3345	+Ng	(AST)
NATALE	91	PL B258 227		(SPIFT)
AFANASYEV	90	PL B236 116	+Chvyrov, Karpukhin+	(JINR, MOSU, SERP)
Also	90B	SJNP 51 664	Afanasyev, Gorchakov, Karpukhin, Komarov+	(JINR)
		Translated from YAF 51 1040.		
LEE	90	PRL 64 165	+Alliegro, Campagnari+	(BNL, FNAL, VILL, WASH, YALE)
FONVIEILLE	89	PL B233 65	+Bensayah, Berthot, Bertin+	(CLER, LYON, SACL)
NIEBUHR	89	PR D40 2796	+Eichler, Felawka, Kozlowski+	(SINDRUM Collab.)
CAMPAGNARI	88	PRL 61 2062	+Alliegro, Chaloupka+	(BNL, FNAL, PSI, WASH, YALE)
CRAWFORD	88B	PL B213 391	+Daum, Frosch, Jost, Kettle, Marshall+	(PSI, VIRG)
DORENBOS...	88	ZPHY C40 497	Dorenbosch, Allaby, Amaldi, Barbiellini+	(CHARM Collab.)
HOFFMAN	88	PL B208 149		(LANL)
MCDONOUGH	88	PR D38 2121	+Highland, McFarlane, Bolton+	(TEMP, LANL, CHIC)
PDG	88	PL B204	Yost, Barnett+	(LBL+)
WILLIAMS	88	PR D38 1365	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
ZEPHAT	87	JPG 13 1375	+Playfer, van Doesburg, Bressani+	(OMICRON Collab.)
BOLOTOV	86C	JETPL 43 520	+Gninenko, Dzhilkibaev, Isakov	(INRM)
		Translated from ZETFP 43 405.		
CRAWFORD	86	PRL 56 1043	+Daum, Frosch, Jost, Kettle+	(SIN, VIRG)
ATHERTON	85	PL 158B 81	+Bovet, Coet+	(CERN, ISU, LUND, CURIN, EFI)
HERCZEG	84	PR D29 1954	+Hoffman	(LANL)
FRANK	83	PR D28 423	+Hoffman, Mischke, Moir+	(LANL, ARZS)
TUPPER	83	PR D28 2905	+Grose, Samuel	(OKSU)
BRYMAN	82	PR D26 2538		(TRIU)
MISCHKE	82	PRL 48 1153	+Frank, Hoffman, Moir, Sarracino+	(LANL, ARZS)
HERCZEG	81	PL 100B 347	+Hoffman	(LANL)
SCHARDT	81	PR D23 639	+Frank, Hoffmann, Mischke, Moir+	(ARZS, LANL)
AUERBACH	80	PL 90B 317	+Haik, Highland, McFarlane, Macek+	(TEMP, LASL)
HIGHLAND	80	PRL 44 628	+Auerbach, Haik, McFarlane, Macek+	(TEMP, LASL)
AUERBACH	78	PRL 41 275	+Highland, Johnson+	(TEMP, LASL)
FISCHER	78	PL 73B 359	+Extermann, Guisan, Mermod+	(GEVA, SACL)
FISCHER	78B	PL 73B 364	+Extermann, Guisan, Mermod+	(GEVA, SACL)
BROWMAN	74	PRL 33 1400	+Dewire, Gittelman, Hanson+	(CORN, BING)
BELLETTINI	70	NC 66A 243	+Bemporad, Lubelsmey+	(PISA, BONN)
KRYSHKIN	70	JETP 30 1037	+Sterligov, Usov	(TMSK)
		Translated from ZETF 57 1917.		
DEVONS	69	PR 184 1356	+Nemethy, Nissim-Sabat, Capua+	(COLU, ROMA)
VASILEVSKY	66	PL 23 281	+Vishnyakov, Dunaitsev+	(JINR)
DUCLOS	65	PL 19 253	+Freytag, Heintze+	(CERN, HEID)
KUTIN	65	JETPL 2 243	+Petrukhin, Prokoshkin	(JINR)
		Translated from unknown journal.		
CZIRR	63	PR 130 341		(LRL)
SAMIOS	62B	PR 126 1844	+Plano, Prodell+	(COLU, BNL)
KOBRAK	61	NC 20 1115		(EFI)
SAMIOS	61	PR 121 275		(COLU, BNL)
BUDAGOV	60	JETP 11 755	+Viktor, Dzhelepov, Ermolov+	(JINR)
		Translated from ZETF 38 1047.		
JOSEPH	60	NC 16 997		(EFI)

η

$I^G(J^{PC}) = 0^+(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

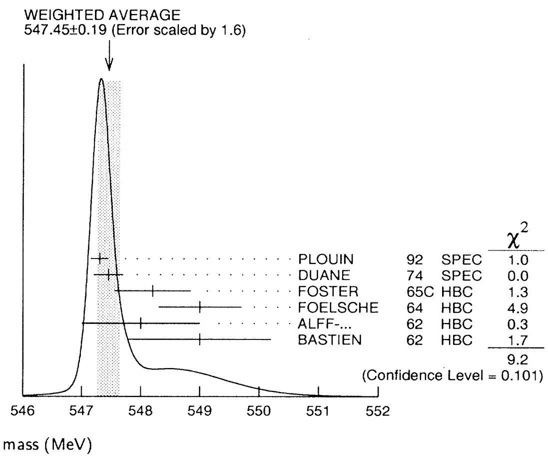
η MASS

Measurements with an error ≥ 2 MeV are omitted from the average.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
547.45±0.19 OUR AVERAGE		Error includes scale factor of 1.6. See the ideogram below.			
547.30±0.15		PLOUIN	92	SPEC	$dp \to \eta\,^3$He
547.45±0.25		DUANE	74	SPEC	$\pi^- p \to n$ neutrals
548.2 ±0.65		FOSTER	65C	HBC	
549.0 ±0.7	148	FOELSCHE	64	HBC	
548.0 ±1.0	91	ALFF-...	62	HBC	
549.0 ±1.2	53	BASTIEN	62	HBC	

• • • We do not use the following data for averages, fits, limits, etc. • • •

555.0 ±2.0	250	JAMES	66	HBC	
552.0 ±3.0	325	KRAEMER	64	DBC	
549.3 ±2.9		DELCOURT	63	CNTR	
546.0 ±4.0	35	PICKUP	62	HBC	



η WIDTH

This is the partial decay rate $\Gamma(\eta \to \gamma\gamma)$ divided by the fitted branching fraction for that mode. See the "Note on the Decay Width $\Gamma(\eta \to \gamma\gamma)$" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1451.

VALUE (keV)	*DOCUMENT ID*
1.18±0.11 OUR FIT	Error includes scale factor of 1.8.

η DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	neutral modes		(71.4 ±0.6) %	S=1.3
Γ_2	2γ	[a]	(39.25±0.31) %	S=1.3
Γ_3	$3\pi^0$		(32.1 ±0.4) %	S=1.2
Γ_4	$\pi^0 2\gamma$		(7.1 ±1.4) × 10^{-4}	
Γ_5	other neutral modes		< 2.8 %	CL=90%
Γ_6	charged modes		(28.6 ±0.6) %	S=1.3
Γ_7	$\pi^+\pi^-\pi^0$		(23.2 ±0.5) %	S=1.3
Γ_8	$\pi^+\pi^-\gamma$		(4.78±0.12) %	S=1.2
Γ_9	$e^+e^-\gamma$		(4.9 ±1.1) × 10^{-3}	
Γ_{10}	$\mu^+\mu^-\gamma$		(3.1 ±0.4) × 10^{-4}	
Γ_{11}	e^+e^-		< 3 × 10^{-4}	CL=90%
Γ_{12}	$\mu^+\mu^-$		(5.8 ±0.8) × 10^{-6}	
Γ_{13}	$\pi^+\pi^-e^+e^-$		(1.3 $^{+1.2}_{-0.8}$) × 10^{-3}	
Γ_{14}	$\pi^+\pi^-2\gamma$		< 2.1 × 10^{-3}	
Γ_{15}	$\pi^+\pi^-\pi^0\gamma$		< 6 × 10^{-4}	CL=90%
Γ_{16}	$\pi^0\mu^+\mu^-\gamma$		< 3 × 10^{-6}	CL=90%

Charge conjugation (*C*), Parity (*P*), or Charge conjugation × Parity (*CP*) violating modes

Γ_{17}	$\pi^+\pi^-$	*P,CP*		< 1.5 × 10^{-3}	
Γ_{18}	3γ	*C*		< 5 × 10^{-4}	CL=95%
Γ_{19}	$\pi^0e^+e^-$	*C*	[b]	< 4 × 10^{-5}	CL=90%
Γ_{20}	$\pi^0\mu^+\mu^-$	*C*	[b]	< 5 × 10^{-6}	CL=90%

[*a*] See the "Note on the Decay Width $\Gamma(\eta \to \gamma\gamma)$" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1451.

[*b*] *C* parity forbids this to occur as a single-photon process.

CONSTRAINED FIT INFORMATION

An overall fit to a decay rate and 15 branching ratios uses 43 measurements and one constraint to determine 9 parameters. The overall fit has a $\chi^2 = 33.2$ for 35 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	45							
x_4	3	2						
x_7	−78	−83	−5					
x_8	−65	−70	−4	74				
x_9	−9	−10	−1	−8	−7			
x_{10}	0	0	0	−1	0	0		
x_{13}	−3	−4	0	−16	−12	−2	0	
Γ	−9	−4	0	7	6	1	0	0
	x_2	x_3	x_4	x_7	x_8	x_9	x_{10}	x_{13}

	Mode	Rate (keV)	Scale factor
Γ_2	2γ	[a] 0.46 ±0.04	1.8
Γ_3	$3\pi^0$	0.380 ±0.035	1.8
Γ_4	$\pi^0 2\gamma$	(8.4 ±1.9) × 10^{-4}	1.1
Γ_7	$\pi^+\pi^-\pi^0$	0.274 ±0.026	1.8
Γ_8	$\pi^+\pi^-\gamma$	0.057 ±0.005	1.7
Γ_9	$e^+e^-\gamma$	0.0058±0.0014	
Γ_{10}	$\mu^+\mu^-\gamma$	(3.7 ±0.6) × 10^{-4}	1.1
Γ_{13}	$\pi^+\pi^-e^+e^-$	$0.0015^{+0.0015}_{-0.0009}$	

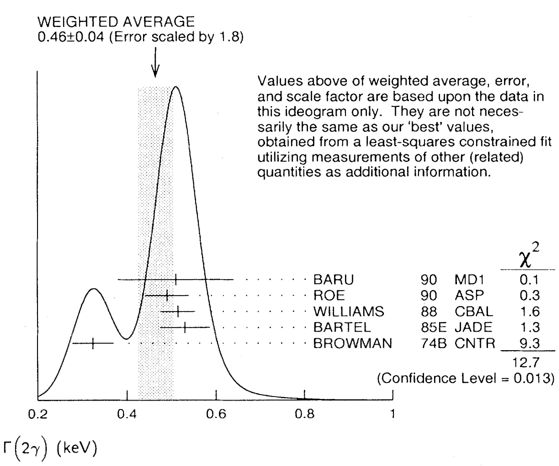
η DECAY RATES

$\Gamma(2\gamma)$ — Γ_2

See the "Note on the Decay Width $\Gamma(\eta \to \gamma\gamma)$," in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1451.

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
0.46 ±0.04 OUR FIT		Error includes scale factor of 1.8.		
0.46 ±0.04 OUR AVERAGE		Error includes scale factor of 1.8. See the ideogram below.		
0.51 ±0.12 ±0.05	36	BARU 90	MD1	$e^+e^- \to e^+e^-\eta$
0.490±0.010±0.048	2287	ROE 90	ASP	$e^+e^- \to e^+e^-\eta$
0.514±0.017±0.035	1295	WILLIAMS 88	CBAL	$e^+e^- \to e^+e^-\eta$
0.53 ±0.04 ±0.04		BARTEL 85E	JADE	$e^+e^- \to e^+e^-\eta$
0.324±0.046		BROWMAN 74B	CNTR	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.64 ±0.14 ±0.13		AIHARA 86	TPC	$e^+e^- \to e^+e^-\eta$
0.56 ±0.16	56	WEINSTEIN 83	CBAL	$e^+e^- \to e^+e^-\eta$
1.00 ±0.22		[1] BEMPORAD 67	CNTR	Primakoff effect

[1] BEMPORAD 67 gives $\Gamma(2\gamma) = 1.21 \pm 0.26$ keV assuming $\Gamma(2\gamma)/\Gamma(\text{total}) = 0.314$. Bemporad private communication gives $\Gamma(2\gamma)^2/\Gamma(\text{total}) = 0.380 \pm 0.083$. We evaluate this using $\Gamma(2\gamma)/\Gamma(\text{total}) = 0.38 \pm 0.01$. Not included in average because the uncertainty resulting from the separation of the coulomb and nuclear amplitudes has apparently been underestimated.



η BRANCHING RATIOS

$\Gamma(\text{neutral modes})/\Gamma_{total}$ — $\Gamma_1/\Gamma = (\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.714±0.006 OUR FIT		Error includes scale factor of 1.3.		
0.705±0.008	16k	BASILE 71D	CNTR	MM spectrometer
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.79 ±0.08		BUNIATOV 67	OSPK	

$\Gamma(2\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.3925±0.0031 OUR FIT		Error includes scale factor of 1.3.		
0.3949±0.0017±0.0030	65k	ABEGG 96	SPEC	$pd \to {}^3\text{He}\eta$

$\Gamma(2\gamma)/\Gamma(\text{neutral modes})$ — $\Gamma_2/\Gamma_1 = \Gamma_2/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.5497±0.0027 OUR FIT		Error includes scale factor of 1.1.		
0.549 ±0.004 OUR AVERAGE				
0.549 ±0.004		ALDE 84	GAM2	
0.535 ±0.018		BUTTRAM 70	OSPK	
0.59 ±0.033		BUNIATOV 67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.52 ±0.09	88	ABROSIMOV 80	HLBC	
0.60 ±0.14	113	KENDALL 74	OSPK	
0.57 ±0.09		STRUGALSKI 71	HLBC	
0.579 ±0.052		FELDMAN 67	OSPK	
0.416 ±0.044		DIGIUGNO 66	CNTR	Error doubled
0.44 ±0.07		GRUNHAUS 66	OSPK	
0.39 ±0.06		[2] JONES 66	CNTR	

[2] This result from combining cross sections from two different experiments.

$\Gamma(3\pi^0)/\Gamma(\text{neutral modes})$ — $\Gamma_3/\Gamma_1 = \Gamma_3/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.4493±0.0027 OUR FIT		Error includes scale factor of 1.1.		
0.450 ±0.004 OUR AVERAGE				
0.450 ±0.004		ALDE 84	GAM2	
0.439 ±0.024		BUTTRAM 70	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44 ±0.08	75	ABROSIMOV 80	HLBC	
0.32 ±0.09		STRUGALSKI 71	HLBC	
0.41 ±0.033		BUNIATOV 67	OSPK	Not indep. of $\Gamma(2\gamma)/\Gamma(\text{neutral modes})$
0.177 ±0.035		FELDMAN 67	OSPK	
0.209 ±0.054		DIGIUGNO 66	CNTR	Error doubled
0.29 ±0.10		GRUNHAUS 66	OSPK	

$\Gamma(3\pi^0)/\Gamma(2\gamma)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
0.817±0.009 OUR FIT	Error includes scale factor of 1.1.		
0.841±0.030 OUR AVERAGE			
0.841±0.034	AMSLER 93	CBAR	$\bar{p}p \to \pi^+\pi^-\eta$ at rest
0.91 ±0.14	COX 70B	HBC	
0.75 ±0.09	DEVONS 70	OSPK	
0.88 ±0.16	BALTAY 67D	DBC	
1.1 ±0.2	CENCE 67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.822±0.009	[3] ALDE 84	GAM2	
1.25 ±0.39	BACCI 63	CNTR	Inverse BR reported

[3] This result is not independent of other ALDE 84 results in this Listing, and so is omitted from the fit and average.

$\Gamma(\pi^0 2\gamma)/\Gamma(\text{neutral modes})$ — $\Gamma_4/\Gamma_1 = \Gamma_4/(\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID	TECN
(1.00 ±0.20) × 10^{-3} OUR FIT		
0.0010 ±0.0002	ALDE 84	GAM2

$\Gamma(\pi^0 2\gamma)/\Gamma_{total}$ — Γ_4/Γ

These results are summarized in the review by LANDSBERG 85.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
7.1±1.4 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
9.5±2.3		70	BINON 82	GAM2	See ALDE 84
<30	90	0	DAVYDOV 81	GAM2	$\pi^-p \to \eta n$

$\Gamma(\text{neutral modes})/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^+\pi^-\gamma) + \Gamma(e^+e^-\gamma)]$ — $\Gamma_1/(\Gamma_7+\Gamma_8+\Gamma_9) = (\Gamma_2+\Gamma_3+\Gamma_4)/(\Gamma_7+\Gamma_8+\Gamma_9)$

VALUE	EVTS	DOCUMENT ID	TECN
2.51±0.07 OUR FIT		Error includes scale factor of 1.4.	
2.64±0.23		BALTAY 67B	DBC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.5 ±1.0	280	[4] JAMES 66	HBC
3.20±1.26	53	[4] BASTIEN 62	HBC
2.5 ±1.0	10	[4] PICKUP 62	HBC

[4] These experiments are not used in the averages as they do not separate clearly $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ from each other. The reported values thus probably contain some unknown fraction of $\eta \to \pi^+\pi^-\gamma$.

$\Gamma(2\gamma)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^+\pi^-\gamma)+\Gamma(e^+e^-\gamma)]$ — $\Gamma_2/(\Gamma_7+\Gamma_8+\Gamma_9)$

VALUE	EVTS	DOCUMENT ID	TECN
1.38±0.04 OUR FIT Error includes scale factor of 1.3.			
1.1 ±0.4 OUR AVERAGE			
1.51±0.93	75	KENDALL 74	OSPK
0.99±0.48		CRAWFORD 63	HBC

$\Gamma(\text{neutral modes})/\Gamma(\pi^+\pi^-\pi^0)$ — $\Gamma_1/\Gamma_7 = (\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma_7$

VALUE	EVTS	DOCUMENT ID	TECN
3.08±0.09 OUR FIT Error includes scale factor of 1.4.			
3.26±0.30 OUR AVERAGE			
2.54±1.89	74	KENDALL 74	OSPK
3.4 ±1.1	29	AGUILAR-... 72B	HBC
2.83±0.80	70	[5] BLOODWO... 72B	HBC
3.6 ±0.6	244	FLATTE 67B	HBC
2.89±0.56		ALFF-... 66	HBC
3.6 ±0.8	50	KRAEMER 64	DBC
3.8 ±1.1		PAULI 64	DBC

[5] Error increased from published value 0.5 by Bloodworth (private communication).

$\Gamma(2\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_2/Γ_7

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.69±0.05 OUR FIT Error includes scale factor of 1.3.				
1.75±0.13 OUR AVERAGE				
1.78±0.10±0.13	1077	AMSLER 95	CBAR	$\overline{p}p \to \pi^+\pi^-\eta$ at rest
1.72±0.25	401	BAGLIN 69	HLBC	
1.61±0.39		FOSTER 65	HBC	

$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_3/Γ_7

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.39±0.04 OUR FIT Error includes scale factor of 1.3.				
1.34±0.10 OUR AVERAGE Error includes scale factor of 1.2.				
1.44±0.09±0.10	1627	AMSLER 95	CBAR	$\overline{p}p \to \pi^+\pi^-\eta$ at rest
$1.50^{+0.15}_{-0.29}$	199	BAGLIN 69	HLBC	
$1.47^{+0.20}_{-0.17}$		BULLOCK 68	HLBC	
1.3 ±0.4		BAGLIN 67B	HLBC	
0.90±0.24		FOSTER 65	HBC	
2.0 ±1.0		FOELSCHE 64	HBC	
0.83±0.32		CRAWFORD 63	HBC	

$\Gamma(\text{other neutral modes})/\Gamma_{\text{total}}$ — Γ_5/Γ

These are neutral modes other than $\gamma\gamma$, $3\pi^0$, and $\pi^0\gamma\gamma$; nearly any such mode one can think of would violate P, or C, or both.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.028	90	ABEGG 96	SPEC	$pd \to {}^3\text{He}\eta$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_8/Γ_7

VALUE	EVTS	DOCUMENT ID	TECN
0.207±0.004 OUR FIT Error includes scale factor of 1.1.			
0.207±0.004 OUR AVERAGE Error includes scale factor of 1.1.			
0.209±0.004	18k	THALER 73	ASPK
0.201±0.006	7250	GORMLEY 70	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.28 ±0.04		BALTAY 67B	DBC
0.25 ±0.035		LITCHFIELD 67	DBC
0.30 ±0.06		CRAWFORD 66	HBC
0.196±0.041		FOSTER 65C	HBC

$\Gamma(e^+e^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_9/Γ_7

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
2.1±0.5 OUR FIT				
2.1±0.5	80	JANE 75B	OSPK	See the erratum

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
3.1±0.4 OUR FIT				
3.1±0.4	600	DZHELYADIN 80	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.5±0.75	100	BUSHNIN 78	SPEC	See DZHELYADIN 80

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<3	90	DAVIES 74	RVUE	Uses ESTEN 67

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
5.8±0.8 OUR AVERAGE					
5.7±0.7±0.5		114	ABEGG 94	SPEC	$pd \to \eta^3\text{He}$
6.5±2.1		27	DZHELYADIN 80B	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$5.6^{+0.6}_{-0.7}$±0.5		100	KESSLER 93	SPEC	See ABEGG 94
<20	95	0	WEHMANN 68	OSPK	

$\Gamma(\mu^+\mu^-)/\Gamma(2\gamma)$ — Γ_{12}/Γ_2

VALUE (units 10^{-5})	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
5.9±2.2	HYAMS 69	OSPK

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma(\pi^+\pi^-\gamma)$ — Γ_{13}/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN
$0.027^{+0.026}_{-0.017}$ OUR FIT			
0.026±0.026	1	GROSSMAN 66	HBC

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE (units 10^{-2})	DOCUMENT ID	TECN
$0.13^{+0.12}_{-0.08}$ OUR FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •		
<0.7	RITTENBERG 65	HBC

$\Gamma(\pi^+\pi^-2\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{14}/Γ_7

VALUE	CL%	DOCUMENT ID	TECN
<0.009		PRICE 67	HBC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.016	95	BALTAY 67B	DBC

$\Gamma(\pi^+\pi^-\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{15}/Γ_7

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID	TECN
<0.24	90	0	THALER 73	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.7	90		ARNOLD 68	HLBC
<1.6	95		BALTAY 67B	DBC
<7.0			FLATTE 67	HBC
<0.9			PRICE 67	HBC

$\Gamma(\pi^0\mu^+\mu^-\gamma)/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN	COMMENT
<3	90	DZHELYADIN 81	SPEC	$\pi^- p \to \eta n$

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{17}/Γ

Forbidden by P and CP invariance.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
<0.15	0	THALER 73	ASPK

$\Gamma(3\gamma)/\Gamma(\text{neutral modes})$ — $\Gamma_{18}/\Gamma_1 = \Gamma_{18}/(\Gamma_2+\Gamma_3+\Gamma_4)$

Forbidden by C invariance.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN
<7	95	ALDE 84	GAM2

$\Gamma(\pi^0e^+e^-)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{19}/Γ_7

C parity forbids this to occur as a single-photon process.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN
< 1.9	90		JANE 75	OSPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 42	90		BAGLIN 67	HLBC
< 16	90	0	BILLING 67	HLBC
< 77		0	FOSTER 65B	HBC
<110			PRICE 65	HBC

$\Gamma(\pi^0e^+e^-)/\Gamma_{\text{total}}$ — Γ_{19}/Γ

C parity forbids this to occur as a single-photon process.

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.016	90	0	MARTYNOV 76	HLBC
<0.084	90		BAZIN 68	DBC
<0.7			RITTENBERG 65	HBC

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{20}/Γ

C parity forbids this to occur as a single-photon process.

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<0.05	90	DZHELYADIN 81	SPEC	$\pi^- p \to \eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5		WEHMANN 68	OSPK	

η C-NONCONSERVING DECAY PARAMETERS

$\pi^+\pi^-\pi^0$ LEFT-RIGHT ASYMMETRY PARAMETER

Measurements with an error $> 1.0 \times 10^{-2}$ have been omitted.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN
0.09±0.17 OUR AVERAGE			
0.28±0.26	165k	JANE 74	OSPK
−0.05±0.22	220k	LAYTER 72	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.5 ±0.5	37k	[6] GORMLEY 68C	ASPK

[6] The GORMLEY 68C asymmetry is probably due to unmeasured (**E** × **B**) spark chamber effects. New experiments with (**E** × **B**) controls don't observe an asymmetry.

$\pi^+\pi^-\pi^0$ SEXTANT ASYMMETRY PARAMETER

Measurements with an error $> 2.0 \times 10^{-2}$ have been omitted.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
0.18±0.16 OUR AVERAGE				
0.20±0.25	165k	JANE	74	OSPK
0.10±0.22	220k	LAYTER	72	ASPK
0.5 ±0.5	37k	GORMLEY	68C	WIRE

$\pi^+\pi^-\pi^0$ QUADRANT ASYMMETRY PARAMETER

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
−0.17±0.17 OUR AVERAGE				
−0.30±0.25	165k	JANE	74	OSPK
−0.07±0.22	220k	LAYTER	72	ASPK

$\pi^+\pi^-\gamma$ LEFT-RIGHT ASYMMETRY PARAMETER

Measurements with an error $> 2.0 \times 10^{-2}$ have been omitted.

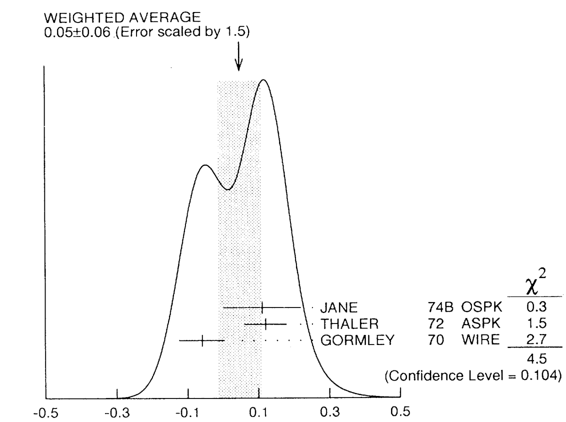
VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
0.9 ±0.4 OUR AVERAGE				
1.2 ±0.6	35k	JANE	74B	OSPK
0.5 ±0.6	36k	THALER	72	ASPK
1.22±1.56	7257	GORMLEY	70	ASPK

$\pi^+\pi^-\gamma$ PARAMETER β (*D*-wave)

Sensitive to a *D*-wave contribution: $dN/d\cos\theta = \sin^2\theta\ (1 + \beta\ \cos^2\theta)$

VALUE	EVTS	DOCUMENT ID		TECN
0.05 ±0.06 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.			
0.11 ±0.11	35k	JANE	74B	OSPK
0.12 ±0.06		[7] THALER	72	ASPK
−0.060±0.065	7250	GORMLEY	70	WIRE

[7] The authors don't believe this indicates *D*-wave because the dependence of β on the γ energy is inconsistent with theoretical prediction. A $\cos^2\theta$ dependence may also come from *P*- and *F*-wave interference.



$\eta \rightarrow \pi^+\pi^-\gamma$ parameter β (*D*-wave)

ENERGY DEPENDENCE OF $\eta \rightarrow \pi^+\pi^-\pi^0$ DALITZ PLOT

See the "Note on η Decay Parameters" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1454. The following experiments fit to one or more of the coefficients *a*, *b*, *c*, *d*, or *e* for $|\text{matrix element}|^2 = 1 + ay + by^2 + cx + dx^2 + exy$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	1077	[8] AMSLER	95	CBAR	$\bar{p}p \rightarrow \pi^+\pi^-\eta$ at rest
	81k	LAYTER	73	ASPK	
	220k	LAYTER	72	ASPK	
	1138	CARPENTER	70	HBC	
	349	DANBURG	70	DBC	
	7250	GORMLEY	70	WIRE	
	526	BAGLIN	69	HLBC	
	7170	CNOPS	68	OSPK	
	37k	GORMLEY	68C	WIRE	
	1300	CLPWY	66	HBC	
	705	LARRIBE	66	HBC	

[8] AMSLER 95 fits to $(1+ay+by^2)$ and obtains $a=-0.94 \pm 0.15$ and $b=0.11 \pm 0.27$.

α PARAMETER FOR $\eta \rightarrow 3\pi^0$

See the "Note on η Decay Parameters" in our 1994 edition, Phys. Rev. **D50**, 1 August 1994, Part I, p. 1454. The value here is of α in $|\text{matrix element}|^2 = 1 + 2\alpha z$.

VALUE	EVTS	DOCUMENT ID		TECN
−0.022±0.023	50k	ALDE	84	GAM2
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.32 ±0.37	192	BAGLIN	70	HLBC

η REFERENCES

ABEGG 96 PR D53 11 +Abela, Boudard+ (Saclay SPES2 Collab.)
AMSLER 95 PL B346 203 +Armstrong, Heinsius+ (Crystal Barrel Collab.)
ABEGG 94 PR D50 92 +Baldisseri, Boudard+ (SPES-II Collab.)
AMSLER 93 ZPHY C58 175 +Armstrong, Merkel+ (Crystal Barrel Collab.)
KESSLER 93 PRL 70 892 +Abegg, Baldisseri+ (SPES-II Collab.)
PLOUIN 92 PL B276 526 + (SACL, EPOL, IPN, SACL, GWU, UCLA, BGUN, LOUC)
BARU 90 ZPHY C48 581 +Blinov, Blinov+ (MD-1 Collab.)
ROE 90 PR D41 17 +Bartha, Burke, Garbincius+ (ASP Collab.)
PDG 88 PL B204 Yost, Barnett+ (LBL+)
WILLIAMS 88 PR D38 1365 +Antreasyan, Bartels, Besset+ (Crystal Ball Collab.)
AIHARA 86 PR D33 844 +Alston-Garnjost+ (TPC-2γ Collab.)
BARTEL 85E PL 160B 421 +Becker, Cords, Felst+ (JADE Collab.)
LANDSBERG 85 PRPL 128 310 (SERP)
ALDE 84 ZPHY C25 225 +Binon, Bricman, Donskov+ (SERP, BELG, LAPP)
Also 84B SJNP 40 918 Alde, Binon, Bricman+ (SERP, BELG, LAPP)
Translated from YAF 40 1447.
WEINSTEIN 83 PR D28 2896 +Antreasyan, Gu, Kollman+ (Crystal Ball Collab.)
BINON 82 SJNP 36 391 +Bricman, Gouanere+ (SERP, BELG, LAPP, CERN)
Translated from YAF 36 670.
Also 82B NC 71A 497 Binon, Bricman+ (SERP, BELG, LAPP, CERN)
DAVYDOV 81 LNC 32 45 +Donskov, Inyakin+ (SERP, BELG, LAPP, CERN)
Also 81B SJNP 33 825 Davydov, Binon+ (SERP, BELG, LAPP, CERN)
Translated from YAF 33 1534.
DZHELYADIN 81 PL 105B 239 +Golovkin, Konstantinov, Kubarovski+ (SERP)
Also 81C SJNP 33 822 Dzhelyadin, Viktorov, Golovkin+ (SERP)
Translated from YAF 33 1529.
ABROSIMOV 80 SJNP 31 195 +Ilina, Niszcz, Okhrimenko+ (JINR)
Translated from YAF 31 371.
DZHELYADIN 80 PL 94B 548 +Viktorov, Golovkin+ (SERP)
Also 80C SJNP 32 516 Dzhelyadin, Golovkin, Kachanov+ (SERP)
Translated from YAF 32 998.
DZHELYADIN 80B PL 97B 471 +Viktorov, Golovkin+ (SERP)
Also 80D SJNP 32 518 Dzhelyadin, Golovkin, Kachanov+ (SERP)
Translated from YAF 32 1002.
BUSHNIN 78 PL 79B 147 +Dzhelyadin, Golovkin, Gritsuk+ (SERP)
Also 78B SJNP 28 775 Bushnin, Golovkin, Gritsuk, Dzhelyadin+ (SERP)
Translated from YAF 28 1507.
MARTYNOV 76 SJNP 23 48 +Saltykov, Tarasov, Uzhinskii (JINR)
Translated from YAF 23 93.
JANE 75 PL 59B 99 +Grannis, Jones, Lipman, Owen+ (RHEL, LOWC)
JANE 75B PL 59B 103 +Grannis, Jones, Lipman, Owen+ (RHEL, LOWC)
Also 78B PL 73B 503 Jane
Erratum in private communication.
BROWMAN 74B PRL 32 1067 +Dewire, Gittelman, Hanson, Loh+ (CORN, BING)
DAVIES 74 NC 24A 324 +Guy, Zia (BIRM, RHEL, SHMP)
DUANE 74 PRL 32 425 +Binnie, Camilleri, Carr+ (LOIC, SHMP)
JANE 74 PL 48B 260 +Jones, Lipman, Owen+ (RHEL, LOWC, SUSS)
JANE 74B PL 48B 265 +Jones, Lipman, Owen+ (RHEL, LOWC, SUSS)
KENDALL 74 NC 21A 387 +Lanou, Massimo, Shapiro+ (BROW, BARI, MIT)
LAYTER 73 PR D7 2565 +Appel, Kotlewski, Lee, Stein, Thaler (COLU)
THALER 73 PR D7 2569 +Appel, Kotlewski, Layter, Lee, Stein (COLU)
AGUILAR-... 72B PR D6 29 Aguilar-Benitez, Chung, Eisner, Samios (BNL)
BLOODWO... 72B NP B39 525 Bloodworth, Jackson, Prentice, Yoon (TNTO)
LAYTER 72 PRL 29 316 +Appel, Kotlewski, Lee, Stein, Thaler (COLU)
THALER 72 PRL 29 313 +Appel, Kotlewski, Layter, Lee, Stein (COLU)
BASILE 71D NC 3A 796 +Bollini, Dalpiaz, Frabetti+ (CERN, BGNA, STRB)
STRUGALSKI 71 NP B27 429 +Chuvilo, Gemesy, Ivanovskaya+ (JINR)
BAGLIN 70 NP B22 66 +Bezaguet, Degrange+ (EPOL, MADR, STRB)
BUTTRAM 70 PRL 25 1358 +Kreisler, Mischke (PRIN)
CARPENTER 70 PR D1 1303 +Binkley, Chapman, Cox, Dagan+ (DUKE)
COX 70B PRL 24 534 +Fortney, Golson (DUKE)
DANBURG 70 PR D2 2564 +Abolins, Dahl, Davies, Hoch, Kirz+ (LRL)
DEVONS 70 PR D1 1936 +Grunhaus, Kozlowski, Nemethy+ (COLU, SYRA)
GORMLEY 70 PR D2 501 +Hyman, Lee, Nash, Peoples+ (COLU, BNL)
Also 70B Thesis Nevis 181 Gormley (COLU)
BAGLIN 69 PL 29B 445 +Bezaguet+ (EPOL, UCB, MADR, STRB)
Also 70 NP B22 66 Baglin, Bezaguet, Degrange+ (EPOL, MADR, STRB)
HYAMS 69 PL 29B 128 +Koch, Potter, VonLindern+ (CERN, MPIM)
ARNOLD 68 PL 27B 466 +Paty, Baglin, Bingham+ (STRB, MADR, EPOL, UCB)
BAZIN 68 PRL 20 895 +Goshaw, Zacher+ (PRIN, QUKI)
BULLOCK 68 PL 27B 402 +Esten, Fleming, Govan, Henderson+ (LOUC)
CNOPS 68 PRL 21 1609 +Hough, Cohn+ (BNL, ORNL, UCND, TENN, PENN)
GORMLEY 68C PRL 21 402 +Hyman, Lee, Nash, Peoples+ (COLU, BNL)
WEHMANN 68 PRL 20 748 +Engels+ (HARV, CASE, SLAC, CORN, MCGI)
BAGLIN 67 PL 24B 637 +Bezaguet, Degrange+ (EPOL, UCB)
BAGLIN 67B BAPS 12 567 +Bezaguet, Degrange+ (EPOL, UCB)
BALTAY 67B PRL 19 1498 +Franzini, Kim, Newman+ (COLU, STON)
BALTAY 67D PRL 19 1495 +Franzini, Kim, Newman+ (COLU, BRAN)
BEMPORAD 67 PL 25B 380 +Braccini, Foa, Lubelsmey+ (PISA, BONN)
Also 67 Private Comm. Ion
BILLING 67 PL 25B 435 +Bullock, Esten, Govan+ (LOUC, OXF)
BUNIATOV 67 PL 25B 560 +Zavattini, Deinet+ (CERN, KARL)
CENCE 67 PRL 19 1393 +Peterson, Stenger, Chiu+ (HAWA, LRL)
ESTEN 67 PL 24B 115 +Govan, Knight, Miller, Tovey+ (LOUC, OXF)
FELDMAN 67 PRL 18 868 +Frati, Gleeson, Halpern+ (PENN)
FLATTE 67 PRL 18 976 (LRL)
FLATTE 67B PR 163 1441 +Wohl (LRL)
LITCHFIELD 67 PL 24B 486 +Rangan, Segar, Smith+ (RHEL, SACL)
PRICE 67 PRL 18 1207 +Crawford (LRL)
ALFF-... 66 PR 145 1072 Alff-Steinberger, Berley+ (COLU, RUTG)
CLPWY 66 PR 149 1044 (SCUC, LRL, PURD, WISC, YALE)
CRAWFORD 66 PRL 16 333 +Price (LRL)
DIGIUGNO 66 PRL 16 767 +Giorgi, Silvestri+ (NAPL, TRST, FRAS)
GROSSMAN 66 PR 146 993 +Price, Crawford (LRL)
GRUNHAUS 66 Thesis (COLU)
JAMES 66 PR 142 896 +Kraybill (YALE, BNL)
JONES 66 PL 23 597 +Binnie, Duane, Horsey, Mason+ (LOIC, RHEL)
LARRIBE 66 PL 23 600 +Leveque, Muller, Pauli+ (SACL, RHEL)
FOSTER 65 PR 138B 652 +Peters, Meer, Loeffler+ (WISC, PURD)
FOSTER 65B Athens Conf. +Good, Meer (WISC)
FOSTER 65C Thesis (WISC)
PRICE 65 PRL 15 123 +Crawford (LRL)
RITTENBERG 65 PRL 15 556 +Kalbfleisch (LRL, BNL)
FOELSCHE 64 PR 134B 1138 +Kraybill (YALE)
KRAEMER 64 PR 136B 496 +Madansky, Fields+ (JHU, NWES, WOOD)
PAULI 64 PL 13 351 +Muller (SACL)
BACCI 63 PRL 11 37 +Penso, Salvini+ (ROMA, FRAS)
CRAWFORD 63 PRL 10 546 +Lloyd, Fowler (LRL, DUKE)
Also 66B PRL 16 907 Crawford, Lloyd, Fowler (LRL, DUKE)
DELCOURT 63 PL 7 215 +Lefrancois, Perez-y-Jorba+ (ORSAY)
ALFF-... 62 PRL 9 322 Alff-Steinberger, Berley, Colley+ (COLU, RUTG)
BASTIEN 62 PRL 8 114 +Berge, Dahl, Ferro-Luzzi+ (LRL)
PICKUP 62 PRL 8 329 +Robinson, Salant (CNRC, BNL)

$f_0(400\text{–}1200)$ or σ

$I^G(J^{PC}) = 0^+(0^{++})$

See "Note on scalar mesons" under $f_0(1370)$.

$f_0(400\text{–}1200)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{\mathrm{pole}}})$.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(400–1200)–i(300–500) OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$470 - i250$	[1,2] TORNQVIST 96	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}, K\pi, \eta\pi$
$\sim (1100 - i300)$	AMSLER 95B	CBAR	$\overline{p}p \rightarrow 3\pi^0$
$400 - i500$	[2,3] AMSLER 95D	CBAR	$\overline{p}p \rightarrow 3\pi^0$
$1100 - i137$	[2,4] AMSLER 95D	CBAR	$\overline{p}p \rightarrow 3\pi^0$
$387 - i305$	[2,5] JANSSEN 95	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}$
$525 - i269$	[6] ACHASOV 94	RVUE	$\pi\pi \rightarrow \pi\pi$
$370 - i356$	[7] ZOU 94B	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}$
$408 - i342$	[2,7] ZOU 93	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}$
$870 - i370$	[2,8] AU 87	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}$
$750 \pm 50 - i(450 \pm 50)$	[9] ESTABROOKS 79	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}$
$660 \pm 100 - i(320 \pm 70)$	PROTOPOP... 73	HBC	$\pi\pi \rightarrow \pi\pi, K\overline{K}$
$650 - i370$	[10] BASDEVANT 72	RVUE	$\pi\pi \rightarrow \pi\pi$

[1] Uses data from BEIER 72B, OCHS 73, HYAMS 73, GRAYER 74, ROSSELET 77, CASON 83, ASTON 88, and ARMSTRONG 91B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.
[2] Demonstrates explicitly that $f_0(400\text{–}1200)$ and $f_0(1370)$ are two different poles.
[3] Coupled channel analysis of $\overline{p}p \rightarrow 3\pi^0$, $\pi^0\eta\eta$ and $\pi^0\pi^0\eta$ on sheet II.
[4] Coupled channel analysis of $\overline{p}p \rightarrow 3\pi^0$, $\pi^0\eta\eta$ and $\pi^0\pi^0\eta$ on sheet III.
[5] Analysis of data from FALVARD 88.
[6] Analysis of data from OCHS 73, ESTABROOKS 75, ROSSELET 77, and MUKHIN 80.
[7] Analysis of data from OCHS 73, GRAYER 74, and ROSSELET 77.
[8] Analysis of data from OCHS 73, GRAYER 74, BECKER 79, and CASON 83.
[9] Analysis of data from APEL 73, GRAYER 74, CASON 76, PAWLICKI 77. Includes spread and errors of 4 solutions.
[10] Analysis of data from BATON 70, BENSINGER 71, COLTON 71, BAILLON 72, PROTOPOPESCU 73, and WALKER 67.

$f_0(400\text{–}1200)$ BREIT-WIGNER MASS OR K-MATRIX POLE PARAMETERS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(400–1200) OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
761 ± 12	[11] SVEC 96	RVUE	6–17 $\pi N_{\mathrm{polar}} \rightarrow \pi^+\pi^- N$
~ 860	[12] TORNQVIST 96	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}, K\pi, \eta\pi$
1165 ± 50	[13,14] ANISOVICH 95	RVUE	$\pi^- p \rightarrow \pi^0\pi^0 n$, $\overline{p}p \rightarrow \pi^0\pi^0\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$
~ 1000	[15] ACHASOV 94	RVUE	$\pi\pi \rightarrow \pi\pi$
414 ± 20	[11] AUGUSTIN 89	DM2	

[11] Breit-Wigner fit to S-wave intensity measured in $\pi N \rightarrow \pi^-\pi^+ N$ on polarized targets. The fit does not include $f_0(980)$.
[12] Uses data from ASTON 88, OCHS 73, HYAMS 73, ARMSTRONG 91B, GRAYER 74, CASON 83, ROSSELET 77, and BEIER 72B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.
[13] Uses $\pi^0\pi^0$ data from ANISOVICH 94, AMSLER 94D, and ALDE 95B, $\pi^+\pi^-$ data from OCHS 73, GRAYER 74 and ROSSELET 77, and $\eta\eta$ data fromANISOVICH 94.
[14] The pole is on Sheet III. Demonstrates explicitly that $f_0(400\text{–}1200)$ and $f_0(1370)$ are two different poles.
[15] Analysis of data from OCHS 73, ESTABROOKS 75, ROSSELET 77, and MUKHIN 80.

$f_0(400\text{–}1200)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(600–1000) OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
290 ± 54	[16] SVEC 96	RVUE	6–17 $\pi N_{\mathrm{polar}} \rightarrow \pi^+\pi^- N$
~ 880	[17] TORNQVIST 96	RVUE	$\pi\pi \rightarrow \pi\pi, K\overline{K}, K\pi, \eta\pi$
460 ± 40	[18,19] ANISOVICH 95	RVUE	$\pi^- p \rightarrow \pi^0\pi^0 n$, $\overline{p}p \rightarrow \pi^0\pi^0\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$
~ 3200	[20] ACHASOV 94	RVUE	$\pi\pi \rightarrow \pi\pi$
494 ± 58	[16] AUGUSTIN 89	DM2	

[16] Breit-Wigner fit to S-wave intensity measured in $\pi N \rightarrow \pi^-\pi^+ N$ on polarized targets. The fit does not include $f_0(980)$.
[17] Uses data from ASTON 88, OCHS 73, HYAMS 73, ARMSTRONG 91B, GRAYER 74, CASON 83, ROSSELET 77, and BEIER 72B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.
[18] Uses $\pi^0\pi^0$ data from ANISOVICH 94, AMSLER 94D, and ALDE 95B, $\pi^+\pi^-$ data from OCHS 73, GRAYER 74 and ROSSELET 77, and $\eta\eta$ data fromANISOVICH 94.
[19] The pole is on Sheet III. Demonstrates explicitly that $f_0(400\text{–}1200)$ and $f_0(1370)$ are two different poles.
[20] Analysis of data from OCHS 73, ESTABROOKS 75, ROSSELET 77, and MUKHIN 80.

$f_0(400\text{–}1200)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	dominant
Γ_2	$\gamma\gamma$	seen

$f_0(400\text{–}1200)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_2

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
seen	[21] MORGAN 90	RVUE	$\gamma\gamma \rightarrow \pi^+\pi^-, \pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
10 ± 6	COURAU 86	DM1	$e^+e^- \rightarrow \pi^+\pi^- e^+e^-$

[21] Analysis of data from BOYER 90 and MARSISKE 90.

$f_0(400\text{–}1200)$ REFERENCES

SVEC	96	PR D53 2343		(MCGI)
TORNQVIST	96	PRL 76 1575	+Roos	(HELS)
ALDE	95B	ZPHY C66 375	+Binon, Boutemeur+	(GAMS Collab.)
AMSLER	95B	PL B342 433	+Armstrong, Brose+	(Crystal Barrel Collab.)
AMSLER	95D	PL B355 425	+Armstrong, Spanier+	(Crystal Barrel Collab.)
ANISOVICH	95	PL B355 363	+Kondashov+	(PNPI, SERP)
JANSSEN	95	PR D52 2690	+Pearce, Holinde, Speth	(STON, ADLD, JULI)
ACHASOV	94	PR D49 5779	+Shestakov	(NOVM)
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.)
ANISOVICH	94	PL B323 233	+Armstrong+	(Crystal Barrel Collab.)
ZOU	94B	PR D50 591	+Bugg	(LOQM)
ZOU	93	PR D48 R3948	+Bugg	(LOQM)
ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
BOYER	90	PR D42 1350	+Butler+	(Mark II Collab.)
MARSISKE	90	PR D41 3324	+Antreasyan+	(Crystal Ball Collab.)
MORGAN	90	ZPHY C48 623	+Pennington	(RAL, DURH)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)
COURAU	86	NP B271 1	+Falvard, Haissinski, Jousset, Michel+	(CLER, LALO)
CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
MUKHIN	80	JETPL 32 601	+Patarakin+	
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
ESTABROOKS	79	PR D19 2678		(CARL)
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL) IJ
ROSSELET	77	PR D15 574	+Extermann, Fischer, Guisan+	(GEVA, SACL)
CASON	76	PRL 36 1485	+Polychronakos, Bishop, Biswas+	(NDAM, ANL) IJ
ESTABROOKS	75	NP B95 322	+Martin	(DURH)
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)
APEL	73	PL 41B 542	+Auslander, Muller+	(KARL, PISA)
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
OCHS	73	Thesis		(MPIM, MUNI)
PROTOPOP...	73	PR D7 1279	Protopopescu, Alston-Garnjost, Galtieri, Flatte+	(LBL)
BAILLON	72	PL 38B 555	+Carnegie, Kluge, Leith, Lynch, Ratcliff+	(SLAC)
BASDEVANT	72	PL 41B 178	+Froggatt, Petersen	(CERN)
BEIER	72B	PRL 29 511	+Buchholtz, Mann+	(PENN)
BENSINGER	71	PL 36B 134	+Erwin, Thompson, Walker	(WISC)
COLTON	71	PR D3 2028	+Malamud, Schlein+	(LBL, FNAL, UCLA, HAWA)
BATON	70	PL 33B 528	+Laurens, Reignier	(SACL)
WALKER	67	RMP 39 695		(WISC)

OTHER RELATED PAPERS

AMSLER	96	PR D53 295	+Close	(ZURI, RAL)
AMSLER	95C	PL B353 571	+Armstrong, Hackman+	(Crystal Barrel Collab.)
ANTINORI	95	PL B353 589	+Barberis, Bayes+	(ATHU, BARI, BIRM, CERN, JINR)
TORNQVIST	95	ZPHY C68 647		(HELS)
AMSLER	94	PL B322 431	+Armstrong, Meyer+	(Crystal Barrel Collab.)
ADAMO	93	NP A558 13C	+Agnello+	(OBELIX Collab.)
GASPERO	93	NP A562 407		(ROMAI)
MORGAN	93	PR D48 1185	+Pennington	(RAL, DURH)
Also	93C	NC A Conf. Suppl.	Morgan	(RAL)
SVEC	92	PR D45 55	+de Lesquen, van Rossum	(MCGI, SACL)
SVEC	92B	PR D45 1518	+de Lesquen, van Rossum	(MCGI, SACL)
SVEC	92C	PR D46 949	+de Lesquen, van Rossum	(MCGI, SACL)
WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)
ACHASOV	84	ZPHY C22 53	+Devyanin, Shestakov	(NOVM)
BINON	83	NC 78A 313	+Donskov, Duteil+	(BELG, LAPP, SERP, CERN)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
TORNQVIST	82	PRL 49 624		(HELS)
COHEN	80	PR D22 2595	+Ayres, Diebold, Kramer, Pawlicki+	(ANL) IJP
BECKER	79B	NP B150 301	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL) IJP
WETZEL	76	NP B115 208	+Freudenreich, Beusch+	(ETH, CERN, LOIC)

$\rho(770)$

$I^G(J^{PC}) = 1^+(1^{--})$

THE $\rho(770)$

Because of its large width, determination of the parameters of the $\rho(770)$ is beset with many difficulties. In physical-region fits, the line shape does not correspond to a relativistic Breit-Wigner function with a P-wave width, but requires some additional shape parameter. This dependence on parametrization was demonstrated long ago by PISUT 68, who showed that the mass was consistent with values between 761 MeV and 783 MeV to within two standard deviations. When mass values are quoted, as below, with one-standard-deviation errors, the conflicts between them are evident.

The same model dependence afflicts any other source of the resonance parameters, such as the energy dependence of the phase shift δ_1^1 or the pole position. It is therefore not surprising that a recent study of $\rho(770)$ dominance in the decays of the η and η' reveals the need for specific dynamical effects in addition to the $\rho(770)$ pole (BENAYOUN 93).

Recently LAFFERTY 93 has demonstrated that Bose-Einstein correlations are another source of shifts in the $\rho(770)$ line shape.

$\rho(770)$ MASS

We no longer list S-wave Breit-Wigner fits, or data with high combinatorial background.

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
768.5±0.6 OUR AVERAGE	Includes data from the 3 datablocks that follow this one. Error includes scale factor of 1.2.

CHARGED ONLY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
766.9±1.2 OUR AVERAGE						
768 ±9		AGUILAR-...	91	EHS		400 pp
767 ±3	2935	[2] CAPRARO	87	SPEC	−	200 $\pi^- \text{Cu} \rightarrow \pi^- \pi^0 \text{Cu}$
761 ±5	967	[2] CAPRARO	87	SPEC	−	200 $\pi^- \text{Pb} \rightarrow \pi^- \pi^0 \text{Pb}$
771 ±4		HUSTON	86	SPEC	+	202 $\pi^+ A \rightarrow \pi^+ \pi^0 A$
766 ±7	6500	[3] BYERLY	73	OSPK	−	5 $\pi^- p$
766.8±1.5	9650	[4] PISUT	68	RVUE	−	1.7–3.2 $\pi^- p$, t <10
767 ±6	900	[2] EISNER	67	HBC	−	4.2 $\pi^- p$, t <10

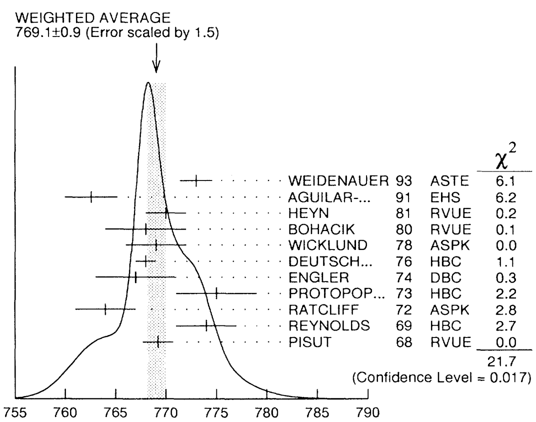
NEUTRAL ONLY, PHOTOPRODUCED

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
768.1± 1.3 OUR AVERAGE						
767.6± 2.7		BARTALUCCI	78	CNTR	0	$\gamma p \rightarrow e^+ e^- p$
775 ± 5		GLADDING	73	CNTR	0	2.9–4.7 γp
767 ± 4	1930	BALLAM	72	HBC	0	2.8 γp
770 ± 4	2430	BALLAM	72	HBC	0	4.7 γp
765 ±10		ALVENSLEBEN	70	CNTR	0	γA, t <0.01
767.7± 1.9	140k	BIGGS	70	CNTR	0	<4.1 $\gamma C \rightarrow \pi^+ \pi^- C$
765 ± 5	4000	ASBURY	67B	CNTR	0	γ + Pb

NEUTRAL ONLY, OTHER REACTIONS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
769.1±0.9 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.					
773 ±1.6		WEIDENAUER	93	ASTE		$\bar{p}p \rightarrow \pi^+ \pi^- \omega$
762.6±2.6		AGUILAR-...	91	EHS		400 pp
770 ±2		[5] HEYN	81	RVUE		Pion form factor
768 ±4		[6,7] BOHACIK	80	RVUE	0	
769 ±3		[3] WICKLUND	78	ASPK	0	3,4,6 $\pi^\pm N$
768 ±1	76000	DEUTSCH...	76	HBC	0	16 $\pi^+ p$
767 ±4	4100	ENGLER	74	DBC	0	6 $\pi^+ n \rightarrow \pi^+ \pi^- p$
775 ±4	32000	[6] PROTOPOP...	73	HBC	0	7.1 $\pi^+ p$, t <0.4
764 ±3	6800	RATCLIFF	72	ASPK	0	15 $\pi^- p$, t <0.3
774 ±3	1700	REYNOLDS	69	HBC	0	2.26 $\pi^- p$
769.2±1.5	13300	[8] PISUT	68	RVUE	0	1.7–3.2 $\pi^- p$, t <10
• • • We do not use the following data for averages, fits, limits, etc. • • •						
757.5±1.5		[1] BERNICHA	94	RVUE		$e^+ e^- \rightarrow \pi^+ \pi^-$
761.1±2.9		DUBNICKA	89	RVUE		π form factor
768 ±1		[9] GESHKENBEIN	89	RVUE		π form factor
775.9±1.1		[10] BARKOV	85	OLYA	0	$e^+ e^- \rightarrow \pi^+ \pi^-$
777.4±2.0		[11] CHABAUD	83	ASPK	0	17 $\pi^- p$ polarized
769.5±0.7		[6,7] LANG	79	RVUE	0	
770 ±9		[7] ESTABROOKS	74	RVUE	0	17 $\pi^- p \rightarrow \pi^+ \pi^-$.
773.5±1.7	11200	[2] JACOBS	72	HBC	0	2.8 $\pi^- p$
775 ±3	2250	HYAMS	68	OSPK	0	11.2 $\pi^- p$

[1] Applying the S-matrix formalism to the BARKOV 85 data.



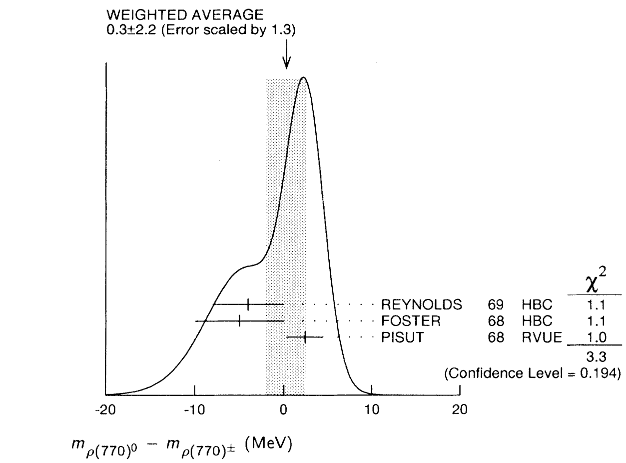
$\rho(770)^0$ mass (MeV)

[2] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[3] Phase shift analysis. Systematic errors added corresponding to spread of different fits.
[4] From fit of 3-parameter relativistic P-wave Breit-Wigner to total mass distribution. Includes BATON 68, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65 and CARMONY 64.
[5] HEYN 81 includes all spacelike and timelike F_π values until 1978.
[6] From pole extrapolation.
[7] From phase shift analysis of GRAYER 74 data.
[8] Includes MALAMUD 69, ARMENISE 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, GOLDHABER 64, ABOLINS 63.
[9] Includes BARKOV 85 data. Model-dependent width definition.
[10] From the Gounaris-Sakurai parametrization of the pion form factor.
[11] From fit of 3-parameter relativistic Breit-Wigner to helicity-zero part of P-wave intensity. CHABAUD 83 includes data of GRAYER 74.

$m_{\rho(770)^0} - m_{\rho(770)^\pm}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.3±2.2 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.					
−4 ±4	3000	[12] REYNOLDS	69	HBC	−0	2.26 $\pi^- p$
−5 ±5	3600	[12] FOSTER	68	HBC	±0	0.0 $\bar{p}p$
2.4±2.1	22950	[13] PISUT	68	RVUE		$\pi N \rightarrow \rho N$

[12] From quoted masses of charged and neutral modes.
[13] Includes MALAMUD 69, ARMENISE 68, BATON 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65, CARMONY 64, GOLDHABER 64, ABOLINS 63.



ρ(770) RANGE PARAMETER

The range parameter R enters an energy-dependent correction to the width, of the form $(1 + q_r^2 R^2) / (1 + q^2 R^2)$, where q is the momentum of one of the pions in the $\pi\pi$ rest system. At resonance, $q = q_r$.

VALUE (GeV^{-1})	DOCUMENT ID		TECN	CHG	COMMENT
$5.3^{+0.9}_{-0.7}$	CHABAUD	83	ASPK	0	17 $\pi^- p$ polarized

ρ(770) WIDTH

We no longer list S-wave Breit-Wigner fits, or data with high combinatorial background.

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
150.7±1.2 OUR AVERAGE	Includes data from the 3 datablocks that follow this one.

CHARGED ONLY

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
149.1± 2.9 OUR FIT						
149.1± 2.9 OUR AVERAGE						
155 ±11	2935	[15] CAPRARO	87	SPEC	−	200 π^- Cu → $\pi^-\pi^0$ Cu
154 ±20	967	[15] CAPRARO	87	SPEC	−	200 π^- Pb → $\pi^-\pi^0$ Pb
150 ± 5		HUSTON	86	SPEC	+	202 π^+ A → $\pi^+\pi^0$ A
146 ±12	6500	[16] BYERLY	73	OSPK	−	5 $\pi^- p$
148.2± 4.1	9650	[17] PISUT	68	RVUE	−	1.7–3.2 $\pi^- p$, t <10
146 ±13	900	EISNER	67	HBC	−	4.2 $\pi^- p$, t <10

NEUTRAL ONLY, PHOTOPRODUCED

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
150.9± 3.0		BARTALUCCI	78	CNTR	0	$\gamma p \to e^+e^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
147 ±11		GLADDING	73	CNTR	0	2.9–4.7 γp
155 ±12	2430	BALLAM	72	HBC	0	4.7 γp
145 ±13	1930	BALLAM	72	HBC	0	2.8 γp
140 ± 5		ALVENSLEBEN	70	CNTR	0	γA, t <0.01
146.1± 2.9	140k	BIGGS	70	CNTR	0	<4.1 γC → $\pi^+\pi^-$ C
160 ±10		LANZEROTTI	68	CNTR	0	γp
130 ± 5	4000	ASBURY	67B	CNTR	0	γ + Pb

NEUTRAL ONLY, OTHER REACTIONS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
151.0± 2.0 OUR FIT	Error includes scale factor of 1.3.					
151.0± 1.7 OUR AVERAGE	Error includes scale factor of 1.1.					
145.7± 5.3		WEIDENAUER	93	ASTE		$\bar{p}p \to \pi^+\pi^-\omega$
144.9± 3.7		DUBNICKA	89	RVUE		π form factor
148 ± 6		[18,19] BOHACIK	80	RVUE	0	
152 ± 9		[16] WICKLUND	78	ASPK	0	3,4,6 $\pi^\pm pN$
154 ± 2	76000	DEUTSCH...	76	HBC	0	16 $\pi^+ p$
157 ± 8	6800	RATCLIFF	72	ASPK	0	15 $\pi^- p$, t <0.3
143 ± 8	1700	REYNOLDS	69	HBC	0	2.26 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
142.5± 3.5		[14] BERNICHA	94	RVUE		$e^+e^- \to \pi^+\pi^-$
138 ± 1		[20] GESHKENBEIN	89	RVUE		π form factor
150.5± 3.0		[21] BARKOV	85	OLYA	0	$e^+e^- \to \pi^+\pi^-$
$160.0^{+4.1}_{-4.0}$		[22] CHABAUD	83	ASPK	0	17 $\pi^- p$ polarized
155 ± 1		[23] HEYN	81	RVUE	0	π form factor
148.0± 1.3		[18,19] LANG	79	RVUE	0	
146 ±14	4100	ENGLER	74	DBC	0	6 $\pi^+ n \to \pi^+\pi^- p$
143 ±13		[19] ESTABROOKS	74	RVUE	0	17 $\pi^- p \to \pi^+\pi^- n$
160 ±10	32000	[18] PROTOPOP...	73	HBC	0	7.1 $\pi^+ p$, t <0.4
145 ±12	2250	[15] HYAMS	68	OSPK	0	11.2 $\pi^- p$
163 ±15	13300	[24] PISUT	68	RVUE	0	1.7–3.2 $\pi^- p$, t <10

[14] Applying the S-matrix formalism to the BARKOV 85 data.
[15] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[16] Phase shift analysis. Systematic errors added corresponding to spread of different fits.
[17] From fit of 3-parameter relativistic P-wave Breit-Wigner to total mass distribution. Includes BATON 68, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, BLIEDEN 65 and CARMONY 64.
[18] From pole extrapolation.
[19] From phase shift analysis of GRAYER 74 data.
[20] Includes BARKOV 85 data. Model-dependent width definition.
[21] From the Gounaris-Sakurai parametrization of the pion form factor.
[22] From fit of 3-parameter relativistic Breit-Wigner to helicity-zero part of P-wave intensity. CHABAUD 83 includes data of GRAYER 74.
[23] HEYN 81 includes all spacelike and timelike F_π values until 1978.
[24] Includes MALAMUD 69, ARMENISE 68, BACON 67, HUWE 67, MILLER 67B, ALFF-STEINBERGER 66, HAGOPIAN 66, HAGOPIAN 66B, JACOBS 66B, JAMES 66, WEST 66, GOLDHABER 64, ABOLINS 63.

ρ(770) DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi\pi$		~ 100 %	
	ρ(770)$^\pm$ decays			
Γ_2	$\pi^\pm\pi^0$		~ 100 %	
Γ_3	$\pi^\pm\gamma$		(4.5 ±0.5) × 10^{-4}	S=2.2
Γ_4	$\pi^\pm\eta$		< 6 × 10^{-3}	CL=84%
Γ_5	$\pi^\pm\pi^+\pi^-\pi^0$		< 2.0 × 10^{-3}	CL=84%
	ρ(770)^0 decays			
Γ_6	$\pi^+\pi^-$		~ 100 %	
Γ_7	$\pi^+\pi^-\gamma$		(9.9 ±1.6) × 10^{-3}	
Γ_8	$\pi^0\gamma$		(7.9 ±2.0) × 10^{-4}	
Γ_9	$\eta\gamma$		(3.8 ±0.7) × 10^{-4}	
Γ_{10}	$\mu^+\mu^-$	[a]	(4.60±0.28) × 10^{-5}	
Γ_{11}	e^+e^-	[a]	(4.48±0.22) × 10^{-5}	
Γ_{12}	$\pi^+\pi^-\pi^0$		< 1.2 × 10^{-4}	CL=90%
Γ_{13}	$\pi^+\pi^-\pi^+\pi^-$		< 2 × 10^{-4}	CL=90%
Γ_{14}	$\pi^+\pi^-\pi^0\pi^0$		< 4 × 10^{-5}	CL=90%

[a] The e^+e^- branching fraction is from $e^+e^- \to \pi^+\pi^-$ experiments only. The $\omega\rho$ interference is then due to $\omega\rho$ mixing only, and is expected to be small. If $e\mu$ universality holds, $\Gamma(\rho^0 \to \mu^+\mu^-) = \Gamma(\rho^0 \to e^+e^-) \times 0.99785$.

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 9 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 10.2$ for 7 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−100	
Γ	18	−18
	x_2	x_3

	Mode	Rate (MeV)	Scale factor
Γ_2	$\pi^\pm\pi^0$	149.1 ±2.9	
Γ_3	$\pi^\pm\gamma$	0.068±0.007	2.3

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and a branching ratio uses 9 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 = 7.8$ for 6 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta p_i \delta p_j \rangle / (\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i / \Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

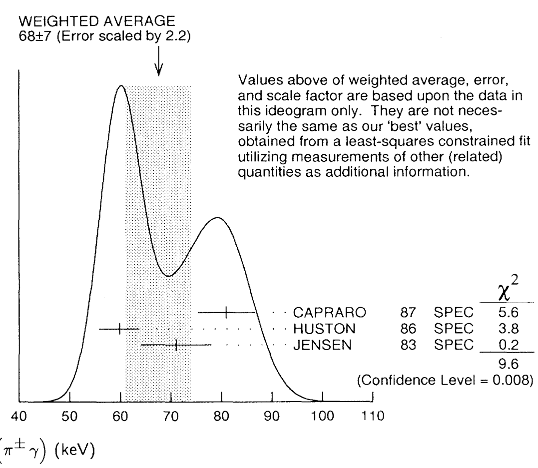
x_{10}	−79		
x_{11}	−61	0	
Γ	16	0	−27
	x_6	x_{10}	x_{11}

	Mode	Rate (MeV)	Scale factor
Γ_6	$\pi^+\pi^-$	151.0 ±2.0	1.3
Γ_{10}	$\mu^+\mu^-$	[a] 0.0069 ±0.0004	
Γ_{11}	e^+e^-	[a] 0.00677±0.00032	

$\rho(770)$ PARTIAL WIDTHS

$\Gamma(\pi^\pm\gamma)$ — Γ_3

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
68 ±7 OUR FIT Error includes scale factor of 2.3.					
68 ±7 OUR AVERAGE Error includes scale factor of 2.2. See the ideogram below.					
81 ±4 ±4	CAPRARO	87	SPEC	−	200 $\pi^- A \to \pi^-\pi^0 A$
59.8±4.0	HUSTON	86	SPEC	+	202 $\pi^+ A \to \pi^+\pi^0 A$
71 ±7	JENSEN	83	SPEC	−	156–260 $\pi^- A \to \pi^-\pi^0 A$



$\Gamma(e^+e^-)$ — Γ_{11}

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
6.77±0.32 OUR FIT				
6.77±0.10±0.30	BARKOV	85	OLYA	$e^+e^- \to \pi^+\pi^-$

$\Gamma(\pi^0\gamma)$ — Γ_8

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
121±31	DOLINSKY	89	ND	$e^+e^- \to \pi^0\gamma$

$\Gamma(\eta\gamma)$ — Γ_9

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
62±17	[25] DOLINSKY	89	ND	$e^+e^- \to \eta\gamma$
111±22	[26] DOLINSKY	89	ND	$e^+e^- \to \eta\gamma$

[25] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero. Also much favored by the ALDE 93 model-independent measurement of $B(\omega \to \eta\gamma)$.
[26] Solution corresponding to destructive ρ-ω interference.

$\rho(770)$ BRANCHING RATIOS

$\Gamma(\pi^\pm\eta)/\Gamma(\pi\pi)$ — Γ_4/Γ_1

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<60	84	FERBEL	66	HBC	±	$\pi^\pm p$ above 2.5

$\Gamma(\pi^\pm\pi^+\pi^-\pi^0)/\Gamma(\pi\pi)$ — Γ_5/Γ_1

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<20	84	FERBEL	66	HBC	±	$\pi^\pm p$ above 2.5
• • • We do not use the following data for averages, fits, limits, etc. • • •						
35±40		JAMES	66	HBC	+	2.1 $\pi^+ p$

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ — Γ_{10}/Γ_6

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
4.60±0.28 OUR FIT				
4.6 ±0.2 ±0.2	ANTIPOV	89	SIGM	$\pi^- Cu \to \mu^+\mu^-\pi^- Cu$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$8.2^{+1.6}_{-3.6}$	[27] ROTHWELL	69	CNTR	Photoproduction
5.6 ±1.5	[28] WEHMANN	69	OSPK	12 π^- C, Fe
$9.7^{+3.1}_{-3.3}$	[29] HYAMS	67	OSPK	11 π^- Li, H

[27] Possibly large ρ-ω interference leads us to increase the minus error.
[28] Result contains 11 ± 11% correction using SU(3) for central value. The error on the correction takes account of possible ρ-ω interference and the upper limit agrees with the upper limit of $\omega \to \mu^+\mu^-$ from this experiment.
[29] HYAMS 67's mass resolution is 20 MeV. The ω region was excluded.

$\Gamma(e^+e^-)/\Gamma(\pi\pi)$ — Γ_{11}/Γ_1

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
0.41±0.05	BENAKSAS	72	OSPK	e^+e^-

$\Gamma(\eta\gamma)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	CHG	COMMENT
3.8±0.7 OUR AVERAGE					
4.0±1.1	[30] DOLINSKY	89	ND		$e^+e^- \to \eta\gamma$
3.6±0.9	[30] ANDREWS	77	CNTR	0	6.7–10 γ Cu
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.3±1.5	[31] DOLINSKY	89	ND		$e^+e^- \to \eta\gamma$
5.4±1.1	[31] ANDREWS	77	CNTR	0	6.7–10 γ Cu

[30] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative phase of zero. Also much favored by the ALDE 93 model-independent measurement of $B(\omega \to \eta\gamma)$.
[31] Solution corresponding to destructive ω-ρ interference.

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2	90	KURDADZE	88	OLYA	$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma(\pi\pi)$ — Γ_{13}/Γ_1

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<15	90	ERBE	69	HBC	0	2.5–5.8 γp
<20		CHUNG	68	HBC	0	3.2,4.2 $\pi^- p$
<20	90	HUSON	68	HLBC	0	16.0 $\pi^- p$
<80		JAMES	66	HBC	0	2.1 $\pi^+ p$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<1.2	90	VASSERMAN	88B	ND	$e^+e^- \to \pi^+\pi^-\pi^0$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma(\pi\pi)$ — Γ_{12}/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 0.01		BRAMON	86	RVUE	0	$J/\psi \to \omega\pi^0$
<0.01	84	[32] ABRAMS	71	HBC	0	3.7 $\pi^+ p$

[32] Model dependent, assumes I = 1, 2, or 3 for the 3π system.

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.4	90	AULCHENKO	87C	ND	0	$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2	90	KURDADZE	86	OLYA	0	$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{total}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.0099±0.0016		[33] DOLINSKY	91	ND	$e^+e^- \to \pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0111±0.0014		[34] VASSERMAN	88	ND	$e^+e^- \to \pi^+\pi^-\gamma$
<0.005	90	[35] VASSERMAN	88	ND	$e^+e^- \to \pi^+\pi^-\gamma$

[33] Bremsstrahlung from a decay pion and for photon energy above 50 MeV.
[34] Superseded by DOLINSKY 91.
[35] Structure radiation due to quark rearrangement in the decay.

$\Gamma(\pi^0\gamma)/\Gamma_{total}$ Γ_8/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
7.9±2.0	DOLINSKY	89	ND	$e^+e^- \to \pi^0\gamma$

$\rho(770)$ REFERENCES

BERNICHA 94 PR D50 4454 +Lopez Castro, Pestieau (LOUV, CINV)
ALDE 93 PAN 56 1229 +Binon+ (SERP, LAPP, LANL, BELG, BRUX, CERN)
Translated from YAF 56 137.
WEIDENAUER 93 ZPHY C59 387 +Duch+ (ASTERIX Collab.)
AGUILAR-... 91 ZPHY C50 405 Aguilar-Benitez, Allison, Batalor+ (LEBC-EHS Collab.)
DOLINSKY 91 PRPL 202 99 +Druzhinin, Dubrovin+ (NOVO)
ANTIPOV 89 ZPHY C42 185 +Batarin+ (SERP, JINR, BGNA, MILA, TBIL)
DOLINSKY 89 ZPHY C42 511 +Druzhinin, Dubrovin, Golubev+ (NOVO)
DUBNICKA 89 JPG 15 1349 +Martinovic+ (JINR, SLOV)
GESHKENBEIN 89 ZPHY 45 351 (ITEP)
KURDADZE 88 JETPL 47 512 +Leltchouk, Pakhtusova, Sidorov+ (NOVO)
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VASSERMAN 88 SJNP 47 1035 +Golubev, Dolinsky+ (NOVO)
Translated from YAF 47 1635.
VASSERMAN 88B SJNP 48 480 +Golubev, Dolinsky+ (NOVO)
Translated from YAF 48 753.
AULCHENKO 87C IYF 87-90 Preprint +Dolinsky, Druzhinin+ (NOVO)
CAPRARO 87 NP B288 659 +Levy+ (CLER, FRAS, MILA, PISA, LCGT, TRST+)
BRAMON 86 PL B173 97 +Casulleras (BARC)
HUSTON 86 PR 33 3199 +Berg, Collick, Jonckheere+ (ROCH, FNAL, MINN)
KURDADZE 86 JETPL 43 643 +Lelchuk, Pakhtusova, Sidorov, Skrinskii+ (NOVO)
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BARKOV 85 NP B256 365 +Chilingarov, Eidelman, Khazin, Lelchuk+ (NOVO)
CHABAUD 83 NP B223 1 +Gorlich, Cerrada+ (CERN, CRAC, MPIM)
JENSEN 83 PR D27 26 +Berg, Biel, Collick+ (ROCH, FNAL, MINN)
HEYN 81 ZPHY C7 169 +Lang (GRAZ)
BOHACIK 80 PR D21 1342 +Kuhnelt (SLOV, WIEN)
LANG 79 PR D19 956 +Mas-Parareda (GRAZ)
BARTALUCCI 78 NC 44A 587 +Basini, Bertolucci+ (DESY, FRAS)
WICKLUND 78 PR D17 1197 +Ayres, Diebold, Greene, Kramer, Pawlicki (ANL)
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DEUTSCH... 76 NP B103 426 Deutschmann+ (AACH3, BERL, BONN, CERN+)
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BYERLY 73 PR D7 637 +Anthony, Coffin, Meanley, Meyer, Rice+ (MICH)
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BENAKSAS 72 PL 39B 289 +Cosme, Jean-Marie, Jullian, Laplanche+ (ORSAY)
JACOBS 72 PR D6 1291 (SACL)
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REYNOLDS 69 PR 184 1424 +Albright, Bradley, Brucker, Harms+ (FSU)
ROTHWELL 69 PRL 23 1521 +Chase, Earles, Gettner, Glass, Weinstein+ (NEAS)
WEHMANN 69 PR 178 2095 + (HARV, CASE, SLAC, CORN, MCGI)
ARMENISE 68 NC 54A 999 +Ghidini, Forino+ (BARI, BGNA, FIRZ, ORSAY)
BATON 68 PR 176 1574 +Laurens (SACL)
CHUNG 68 PR 165 1491 +Dahl, Kirz, Miller (LRL)
FOSTER 68 NP B6 107 +Gavillet, Labrosse, Montanet+ (CERN, CDEF)
HUSON 68 PL 28B 208 +Lubatti, Six, Veillet+ (ORSAY, MILA, UCLA)
HYAMS 68 NP B7 1 +Koch, Potter, Wilson, VonLindern+ (CERN, MPIM)
LANZEROTTI 68 PR 166 1365 +Blumenthal, Ehn, Faissler+ (HARV)
PISUT 68 NP B6 325 +Roos (CERN)
ASBURY 67B PRL 19 865 +Becker, Bertram, Joos, Jordan+ (DESY, COLU)
BACON 67 PR 157 1263 +Fickinger, Hill, Hopkins, Robinson+ (BNL)
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ALFF-... 66 PR 145 1072 Alff-Steinberger, Berley+ (COLU, RUTG)
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JACOBS 66B UCRL 16877 (LRL)
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WEST 66 PR 149 1089 +Boyd, Erwin, Walker (WISC)
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LAFFERTY 93 ZPHY C60 659 (MCHS)
KAMAL 92 PL B284 421 +Xu (ALBE)
ERKAL 85 ZPHY C29 485 +Olsson (WISC)
RYBICKI 85 ZPHY C28 65 +Sakrejda (CRAC)
KURDADZE 83 JETPL 37 733 +Lelchuk, Pakhtusova+ (NOVO)
Translated from ZETFP 37 613.
ALEKSEEV 82 JETP 55 591 +Kartamyshev, Makarin+ (KIAE)
Translated from ZETF 82 1007.
KENNEY 62 PR 126 736 +Shephard, Gall (KNTY)
SAMIOS 62 PRL 9 139 +Bachman, Lea+ (BNL, CUNY, COLU, KNTY)
XUONG 62 PR 128 1849 +Lynch (LRL)
ANDERSON 61 PRL 6 365 +Bang, Burke, Carmony, Schmitz (LRL)
ERWIN 61 PRL 6 628 +March, Walker, West (WISC)

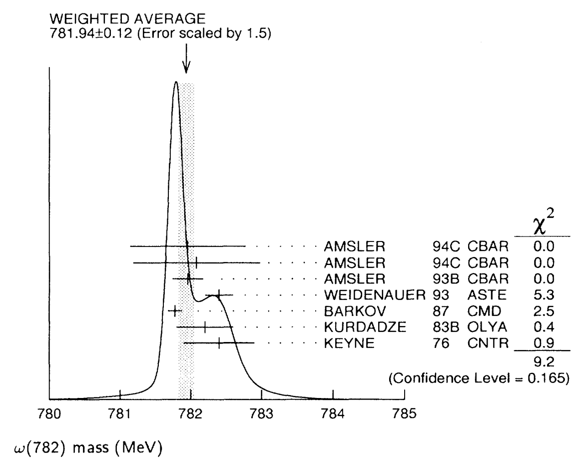
$\omega(782)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\omega(782)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
781.94±0.12 OUR AVERAGE	Error includes scale factor of 1.5. See the ideogram below.				
781.96±0.17±0.80	11k	AMSLER	94C	CBAR	0.0 $\bar{p}p \to \omega\pi^0\pi^0$
782.08±0.36±0.82	3463	AMSLER	94C	CBAR	0.0 $\bar{p}p \to \omega\eta\pi^0$
781.96±0.13±0.17	15k	AMSLER	93B	CBAR	0.0 $\bar{p}p \to \omega\pi^0\pi^0$
782.4 ±0.2	270k	WEIDENAUER	93	ASTE	$\bar{p}p \to 2\pi^+2\pi^-\pi^0$
781.78±0.10		BARKOV	87	CMD	$e^+e^- \to \pi^+\pi^-\pi^0$
782.2 ±0.4	1488	KURDADZE	83B	OLYA	$e^+e^- \to \pi^+\pi^-\pi^0$
782.4 ±0.5	7000	[1] KEYNE	76	CNTR	$\pi^-p \to \omega n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
783.3 ±0.4		CORDIER	80	WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
782.5 ±0.8	33260	ROOS	80	RVUE	0.0–3.6 $\bar{p}p$
782.6 ±0.8	3000	BENKHEIRI	79	OMEG	9–12 $\pi^\pm p$
781.8 ±0.6	1430	COOPER	78B	HBC	0.7–0.8 $\bar{p}p \to 5\pi$
782.7 ±0.9	535	VANAPEL...	78	HBC	7.2 $\bar{p}p \to \bar{p}p\omega$
783.5 ±0.8	2100	GESSAROLI	77	HBC	11 $\pi^-p \to \omega n$
782.5 ±0.8	418	AGUILAR-...	72B	HBC	3.9,4.6 K^-p
783.4 ±1.0	248	BIZZARRI	71	HBC	0.0 $p\bar{p} \to K^+K^-\omega$
781.0 ±0.6	510	BIZZARRI	71	HBC	0.0 $p\bar{p} \to K_1K_1\omega$
783.7 ±1.0	3583	[2] COYNE	71	HBC	3.7 $\pi^+p \to p\pi^+\pi^+\pi^-\pi^0$
784.1 ±1.2	750	ABRAMOVI...	70	HBC	3.9 π^-p
783.2 ±1.6		[3] BIGGS	70B	CNTR	<4.1 $\gamma C \to \pi^+\pi^-C$
782.4 ±0.5	2400	BIZZARRI	69	HBC	0.0 $\bar{p}p$

[1] Observed by threshold-crossing technique. Mass resolution = 4.8 MeV FWHM.
[2] From best-resolution sample of COYNE 71.
[3] From ω-ρ interference in the $\pi^+\pi^-$ mass spectrum assuming ω width 12.6 MeV.



$\omega(782)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
8.43±0.10 OUR AVERAGE					
8.4 ±0.1		[4] AULCHENKO	87	ND	$e^+e^- \to \pi^+\pi^-\pi^0$
8.30±0.40		BARKOV	87	CMD	$e^+e^- \to \pi^+\pi^-\pi^0$
9.8 ±0.9	1488	KURDADZE	83B	OLYA	$e^+e^- \to \pi^+\pi^-\pi^0$
9.0 ±0.8		CORDIER	80	WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
9.1 ±0.8		BENAKSAS	72B	OSPK	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
12 ±2	1430	COOPER	78B	HBC	0.7–0.8 $\bar{p}p \to 5\pi$
9.4 ±2.5	2100	GESSAROLI	77	HBC	11 $\pi^-p \to \omega n$
10.22±0.43	20000	[5] KEYNE	76	CNTR	$\pi^-p \to \omega n$
13.3 ±2	418	AGUILAR-...	72B	HBC	3.9,4.6 K^-p
10.5 ±1.5		BORENSTEIN	72	HBC	2.18 K^-p
7.70±0.9 ±1.15	940	BROWN	72	MMS	2.5 $\pi^-p \to n$MM
10.3 ±1.4	510	BIZZARRI	71	HBC	0.0 $p\bar{p} \to K_1K_1\omega$
12.8 ±3.0	248	BIZZARRI	71	HBC	0.0 $p\bar{p} \to K^+K^-\omega$
9.5 ±1.0	3583	COYNE	71	HBC	3.7 $\pi^+p \to p\pi^+\pi^+\pi^-\pi^0$

[4] Relativistic Breit-Wigner includes radiative corrections.
[5] Observed by threshold-crossing technique. Mass resolution = 4.8 MeV FWHM.

$\omega(782)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\pi^+\pi^-\pi^0$	(88.8 ± 0.7) %	
Γ_2	$\pi^0\gamma$	(8.5 ± 0.5) %	
Γ_3	$\pi^+\pi^-$	(2.21 ± 0.30) %	
Γ_4	neutrals (excluding $\pi^0\gamma$)	$(5.3\ ^{+8.7}_{-3.5}) \times 10^{-3}$	
Γ_5	$\eta\gamma$	$(8.3 \pm 2.1) \times 10^{-4}$	
Γ_6	$\pi^0 e^+ e^-$	$(5.9 \pm 1.9) \times 10^{-4}$	
Γ_7	$\pi^0\mu^+\mu^-$	$(9.6 \pm 2.3) \times 10^{-5}$	
Γ_8	e^+e^-	$(7.15 \pm 0.19) \times 10^{-5}$	
Γ_9	$\pi^+\pi^-\pi^0\pi^0$	< 2 %	90%
Γ_{10}	$\pi^+\pi^-\gamma$	$< 3.6 \times 10^{-3}$	95%
Γ_{11}	$\pi^+\pi^-\pi^+\pi^-$	$< 1 \times 10^{-3}$	90%
Γ_{12}	$\pi^0\pi^0\gamma$	$(7.2 \pm 2.5) \times 10^{-5}$	
Γ_{13}	$\mu^+\mu^-$	$< 1.8 \times 10^{-4}$	90%
Γ_{14}	3γ	$< 2 \times 10^{-4}$	90%

Charge conjugation (C)

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_{15}	$\eta\pi^0$	C	$< 1 \times 10^{-3}$	90%
Γ_{16}	$3\pi^0$	C	$< 3 \times 10^{-4}$	90%

CONSTRAINED FIT INFORMATION

An overall fit to 6 branching ratios uses 20 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 10.3 for 17 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	13		
x_3	−39	−5	
x_4	−74	−68	−1
	x_1	x_2	x_3

$\omega(782)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_8

VALUE (keV)	DOCUMENT ID
0.60±0.02 OUR EVALUATION	

$\omega(782)$ BRANCHING RATIOS

$\Gamma(\text{neutrals})/\Gamma(\pi^+\pi^-\pi^0)$ — $(\Gamma_2+\Gamma_4)/\Gamma_1$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.102±0.008 OUR FIT					
$0.103^{+0.011}_{-0.010}$ OUR AVERAGE					
0.15 ±0.04	46	AGUILAR-...	72B	HBC	3.9,4.6 K^-p
0.10 ±0.03	19	BARASH	67B	HBC	0.0 $\overline{p}p$
0.134±0.026	850	DIGIUGNO	66B	CNTR	1.4 π^-p
0.097±0.016	348	FLATTE	66	HBC	1.4 – 1.7 $K^-p \to \Lambda$MM
$0.06\ ^{+0.05}_{-0.02}$		JAMES	66	HBC	2.1 π^+p
0.08 ±0.03	35	KRAEMER	64	DBC	1.2 π^+d
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.11 ±0.02	20	BUSCHBECK	63	HBC	1.5 K^-p

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_3/Γ_1

See also $\Gamma(\pi^+\pi^-)/\Gamma_{\rm total}$.

VALUE	DOCUMENT ID		TECN	COMMENT
0.0249±0.0035 OUR FIT				
0.026 ±0.005 OUR AVERAGE				
$0.021\ ^{+0.028}_{-0.009}$	[6] RATCLIFF	72	ASPK	15 $\pi^-p \to n2\pi$
0.028 ±0.006	BEHREND	71	ASPK	Photoproduction
$0.022\ ^{+0.009}_{-0.01}$	[7] ROOS	70	RVUE	

[6] Significant interference effect observed. NB of $\omega \to 3\pi$ comes from an extrapolation.
[7] ROOS 70 combines ABRAMOVICH 70 and BIZZARRI 70.

$\Gamma(\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.096±0.006 OUR FIT				
0.096±0.006 OUR AVERAGE				
0.099±0.007	DOLINSKY	89	ND	$e^+e^- \to \pi^0\gamma$
0.084±0.013	KEYNE	76	CNTR	$\pi^-p \to \omega n$
0.109±0.025	BENAKSAS	72C	OSPK	e^+e^-
0.081±0.020	BALDIN	71	HLBC	2.9 π^+p
0.13 ±0.04	JACQUET	69B	HLBC	

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{10}/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.066	90	KALBFLEISCH	75	HBC	2.18 $K^-p \to \Lambda\pi^+\pi^-\gamma$
<0.05	90	FLATTE	66	HBC	1.2 – 1.7 $K^-p \to \Lambda\pi^+\pi^-\gamma$

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{\rm total}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0036	95	WEIDENAUER	90	ASTE	$p\overline{p} \to \pi^+\pi^-\pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.004	95	BITYUKOV	88B	SPEC	32 $\pi^-p \to \pi^+\pi^-\gamma X$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{\rm total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1 \times 10^{-3}$	90	KURDADZE	88	OLYA	$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{\rm total}$ — Γ_9/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
<2	90	KURDADZE	86	OLYA	$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{13}/Γ_1

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.2	90	WILSON	69	OSPK	12 π^-C $\to$ Fe
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.7	74	FLATTE	66	HBC	1.2 – 1.7 $K^-p \to \Lambda\mu^+\mu^-$
<1.2		BARBARO-...	65	HBC	2.7 K^-p

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\pi^0\gamma)$ — Γ_{12}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.00085±0.00029		40 ± 14	ALDE	94B	GAM2	$38\pi^-p \to \pi^0\pi^0\gamma n$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.005	90		DOLINSKY	89	ND	$e^+e^- \to \pi^0\pi^0\gamma$
< 0.18	95		KEYNE	76	CNTR	$\pi^-p \to \omega n$
< 0.15	90		BENAKSAS	72C	OSPK	e^+e^-
< 0.14			BALDIN	71	HLBC	2.9 π^+p
< 0.1	90		BARMIN	64	HLBC	1.3–2.8 π^-p

$\Gamma(\eta\pi^0)/\Gamma_{\rm total}$ — Γ_{15}/Γ

Violates C conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.001	90	ALDE	94B	GAM2	$38\pi^-p \to \eta\pi^0 n$

$[\Gamma(\eta\gamma) + \Gamma(\eta\pi^0)]/\Gamma(\pi^+\pi^-\pi^0)$ — $(\Gamma_5+\Gamma_{15})/\Gamma_1$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.016	90	[8] FLATTE	66	HBC	1.2 – 1.7 $K^-p \to \Lambda\pi^+\pi^-$MM
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.045	95	JACQUET	69B	HLBC	

[8] Restated by us using BR($\eta \to$ $charged modes$)=(29.2)%.

$\Gamma(\text{neutrals})/\Gamma(\text{charged particles})$ — $(\Gamma_2+\Gamma_4)/(\Gamma_1+\Gamma_3)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.099±0.008 OUR FIT				
0.124±0.021	FELDMAN	67C	OSPK	1.2 π^-p

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{12}/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.00045	90	DOLINSKY	89	ND	$e^+e^- \to \pi^0\pi^0\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.08	95	JACQUET	69B	HLBC	

$\Gamma(\eta\gamma)/\Gamma(\pi^0\gamma)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.0098±0.0024	[9] ALDE	93	GAM2	$38\pi^-p \to \omega n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.0082±0.0033	[10] DOLINSKY	89	ND	$e^+e^- \to \eta\gamma$
0.039 ±0.007	[11] DOLINSKY	89	ND	e^+e^-
0.010 ±0.045	APEL	72B	OSPK	4–8 $\pi^-p \to n3\gamma$

[9] Model independent determination.
[10] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.
[11] Solution corresponding to destructive ρ-ω interference.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\rm total}$ — Γ_7/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
0.96±0.23	DZHELYADIN	81B	CNTR	25–33 $\pi^-p \to \omega n$

$\Gamma(\pi^0 e^+ e^-)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
5.9±1.9	43	DOLINSKY 88	ND	$e^+e^- \to \pi^0 e^+ e^-$

$\Gamma(e^+ e^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
0.715±0.019 OUR AVERAGE				
0.714±0.036		DOLINSKY 89	ND	$e^+e^- \to \pi^+\pi^-\pi^0$
0.72 ±0.03		BARKOV 87	CMD	$e^+e^- \to \pi^+\pi^-\pi^0$
0.66 ±0.05		KURDADZE 84	OLYA	$e^+e^- \to$ hadrons
0.675±0.069		CORDIER 80	WIRE	$e^+e^- \to 3\pi$
0.83 ±0.10		BENAKSAS 72B	OSPK	$e^+e^- \to 3\pi$
0.77 ±0.06		[12] AUGUSTIN 69D	OSPK	$e^+e^- \to 2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.64 ±0.04	1488	[13] KURDADZE 83B	OLYA	$e^+e^- \to \pi^+\pi^-\pi^0$
0.65 ±0.13	33	[14] ASTVACAT... 68	OSPK	Assume SU(3)+mixing

[12] Rescaled by us to correspond to ω width 8.4 MeV.
[13] Superseded by KURDADZE 84.
[14] Not resolved from ρ decay. Error statistical only.

$\Gamma(\text{neutrals})/\Gamma_{total}$ — $(\Gamma_2+\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.090±0.006 OUR FIT				
0.081±0.011 OUR AVERAGE				
0.075±0.025		BIZZARRI 71	HBC	0.0 $p\bar{p}$
0.079±0.019		DEINET 69B	OSPK	1.5 $\pi^- p$
0.084±0.015		BOLLINI 68C	CNTR	2.1 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.073±0.018	42	BASILE 72B	CNTR	1.67 $\pi^- p$

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_3/Γ

See also $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$.

VALUE	DOCUMENT ID	TECN	COMMENT
0.0221±0.0030 OUR FIT			
0.021 ±0.004 OUR AVERAGE			
0.023 ±0.005	BARKOV 85	OLYA	e^+e^-
$0.016^{+0.009}_{-0.007}$	QUENZER 78	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.010 ±0.001	[15] WICKLUND 78	ASPK	3,4,6 $\pi^\pm N$
0.0122±0.0030	ALVENSLEBEN71C	CNTR	Photoproduction
$0.013^{+0.012}_{-0.009}$	MOFFEIT 71	HBC	2.8,4.7 γp
$0.0080^{+0.0028}_{-0.002}$	[16] BIGGS 70B	CNTR	$4.2\gamma C \to \pi^+\pi^- C$

[15] From a model-dependent analysis assuming complete coherence.
[16] Re-evaluated under $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ by BEHREND 71 using more accurate $\omega \to \rho$ photoproduction cross-section ratio.

$\Gamma(\pi^0\pi^0\gamma)/\Gamma(\text{neutrals})$ — $\Gamma_{12}/(\Gamma_2+\Gamma_4)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.07		[17] DAKIN 72	OSPK	1.4 $\pi^- p \to n$MM
<0.19	90	DEINET 69B	OSPK	

[17] See $\Gamma(\pi^0\gamma)/\Gamma(\text{neutrals})$.

$\Gamma(\pi^0\gamma)/\Gamma(\text{neutrals})$ — $\Gamma_2/(\Gamma_2+\Gamma_4)$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.78±0.07		[18] DAKIN 72	OSPK	1.4 $\pi^- p \to n$MM
>0.81	90	DEINET 69B	OSPK	

[18] Error statistical only. Authors obtain good fit also assuming $\pi^0\gamma$ as the only neutral decay.

$\Gamma(\eta\gamma)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
8.3±2.1	[19] ALDE 93	GAM2	$38\pi^- p \to \omega n$
7.3±2.9	[20] DOLINSKY 89	ND	$e^+e^- \to \eta\gamma$
35 ±5	[21] DOLINSKY 89	ND	$e^+e^- \to \eta\gamma$
$3.0^{+2.5}_{-1.8}$	[20] ANDREWS 77	CNTR	6.7–10 γCu
29.0±7.0	[21] ANDREWS 77	CNTR	6.7–10 γCu

[19] Model independent determination.
[20] Solution corresponding to constructive ω-ρ interference. The quark model predicts a relative decay phase of zero.
[21] Solution corresponding to destructive ω-ρ interference.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma(\mu^+\mu^-)$ — Γ_7/Γ_{13}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.2±0.6	30	[22] DZHELYADIN 79	CNTR	25–33 $\pi^- p$

[22] Superseded by DZHELYADIN 81B result above.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.8942±0.0062	DOLINSKY 89	ND	$e^+e^- \to \pi^+\pi^-\pi^0$

$\Gamma(3\pi^0)/\Gamma_{total}$ — Γ_{16}/Γ

Violates C conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0003	90	PROKOSHKIN 95	GAM2	$38\ \pi^- p \to 3\pi^0 n$

$\Gamma(3\gamma)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0002	90	PROKOSHKIN 95	GAM2	$38\ \pi^- p \to 3\gamma n$

$\omega(782)$ REFERENCES

PROKOSHKIN 95 SPD 342 273 +Samoilenko (SERP)
Translated from DANS 342 610.
ALDE 94B PL B340 122 +Binon, Bouteumeur+ (SERP, BELG, LANL, LAPP, MONT)
AMSLER 94C PL B327 425 +Armstrong, Ravndal+ (Crystal Barrel Collab.)
ALDE 93 PAN 56 1229 +Binon+ (SERP, LAPP, LANL, BELG, BRUX, CERN)
Translated from YAF 56 137.
Also 94 ZPHY C61 35 Alde, Binon+ (SERP, LAPP, LANL, BELG, BRUX, CERN)
AMSLER 93B PL B311 362 +Armstrong, v.Dombrowski+ (Crystal Barrel Collab.)
WEIDENAUER 93 ZPHY C59 387 +Duch+ (ASTERIX Collab.)
WEIDENAUER 90 ZPHY C47 353 +Duch, Heel, Kalinowsky+ (ASTERIX Collab.)
DOLINSKY 89 ZPHY C42 511 +Druzhinin, Dubrovin, Golubev+ (NOVO)
BITYUKOV 88B SJNP 47 800 +Borisov, Viktorov, Golovkin+ (SERP)
Translated from YAF 47 1258.
DOLINSKY 88 SJNP 48 277 +Druzhinin, Dubrovin, Golubev+ (NOVO)
Translated from YAF 48 442.
KURDADZE 88 JETPL 47 512 +Leltchouk, Pakhtusova, Sidorov+ (NOVO)
Translated from ZETFP 47 432.
AULCHENKO 87 PL B186 432 +Dolinsky, Druzhinin, Dubrovin+ (NOVO)
BARKOV 87 JETPL 46 164 +Vasserman, Vorobev, Ivanov (NOVO)
Translated from ZETFP 46 132.
KURDADZE 86 JETPL 43 643 +Lelchuk, Pakhtusova, Sidorov, Skrinskii+ (NOVO)
Translated from ZETFP 43 497.
BARKOV 85 NP B256 365 +Chilingarov, Eidelman, Khazin, Lelchuk+ (NOVO)
KURDADZE 84 IYF 84-7 Preprint +Leltchouk, Pakhtusova, Sidorov+ (NOVO)
KURDADZE 83B JETPL 36 274 +Pakhtusova, Sidorov+ (NOVO)
Translated from ZETFP 36 221.
DZHELYADIN 81B PL 102B 296 +Golovkin, Konstantinov+ (SERP)
CORDIER 80 NP B172 13 +Delcourt, Eschstruth, Fulda+ (LALO)
ROOS 80 LNC 27 321 +Pellinen (HELS)
BENKHEIRI 79 NP B150 268 +Eisenstein+ (EPOL, CERN, CDEF, LALO)
DZHELYADIN 79 PL 84B 143 +Golovkin, Gritsuk+ (SERP)
COOPER 78B NP B146 1 +Ganguli+ (TATA, CERN, CDEF, MADR)
QUENZER 78 PL 76B 512 +Ribes, Rumpf, Bertrand, Bizot, Chase+ (LALO)
VANAPEL... 78 NP B133 245 VanApeldoorn, Grundeman, Harting+ (ZEEM)
WICKLUND 78 PR D17 1197 +Ayres, Diebold, Greene, Kramer, Pawlicki (ANL)
ANDREWS 77 PRL 38 198 +Fukushima, Harvey, Lobkowicz, May+ (ROCH)
GESSAROLI 77 NP B126 382 + (BGNA, FIRZ, GENO, MILA, OXF, PAVI)
KEYNE 76 PR D14 28 +Binnie, Carr, Debenham, Garbutt+ (LOIC, SHMP)
Also 73B PR D8 2789 Binnie, Carr, Debenham, Duane+ (LOIC, SHMP)
KALBFLEISCH 75 PR D11 987 +Strand, Chapman (BNL, MICH)
AGUILAR-... 72B PR D6 29 Aguilar-Benitez, Chung, Eisner, Samios (BNL)
APEL 72B PL 41B 234 +Auslander, Muller, Bertolucci+ (KARLK, KARLE, PISA)
BASILE 72B Phil. Conf. 153 +Bollini, Broglin, Dalpiaz, Frabetti+ (CERN)
BENAKSAS 72B PL 42B 507 +Cosme, Jean-Marie, Jullian (ORSAY)
BENAKSAS 72C PL 42B 511 +Cosme, Jean-Marie, Jullian, Laplanche+ (ORSAY)
BORENSTEIN 72 PR D5 1559 +Danburg, Kalbfleisch+ (BNL, MICH)
BROWN 72 PL 42B 117 +Downing, Holloway, Huld, Bernstein+ (ILL, ILLC)
DAKIN 72 PR D6 2321 +Hauser, Kreisler, Mischke (PRIN)
RATCLIFF 72 PL 38B 345 +Bulos, Carnegie, Kluge, Leith, Lynch+ (SLAC)
ALVENSLEBEN 71C PRL 27 888 +Becker, Busza, Chen, Cohen+ (DESY)
BALDIN 71 SJNP 13 758 +Yergakov, Trebukhovsky, Shishov (ITEP)
Translated from YAF 13 1318.
BEHREND 71 PRL 27 61 +Lee, Nordberg, Wehmann+ (ROCH, CORN, FNAL)
BIZZARRI 71 NP B27 140 +Montanet, Nilsson, D'Andlau+ (CERN, CDEF)
COYNE 71 NP B32 333 +Butler, Fang-Landau, MacNaughton (LRL)
MOFFEIT 71 NP B29 349 +Bingham, Fretter+ (LRL, UCB, SLAC, TUFTS)
ABRAMOVI... 70 NP B20 209 Abramovich, Blumenfeld, Bruyant+ (CERN)
BIGGS 70B PRL 24 1201 +Clifft, Gabathuler, Kitching, Rand (DARE)
BIZZARRI 70 PRL 25 1385 +Ciapetti, Dore, Gaspero, Guidoni+ (ROMA, SYRA)
ROOS 70 DNPL/R7 173 (CERN)
Proc. Daresbury Study Weekend No. 1.
AUGUSTIN 69D PL 28B 513 +Benaksas, Buon, Gracco, Haissinski+ (ORSAY)
BIZZARRI 69 NP B14 169 +Foster, Gavillet, Montanet+ (CERN, CDEF)
DEINET 69B PL 30B 426 +Menzione, Muller, Buniatov+ (KARL, CERN)
JACQUET 69B NC 63A 743 +Nguyen-Khac, Haatuft, Halsteinslid (EPOL, BERG)
WILSON 69 Private Comm. (HARV)
Also 69 PR 178 2095 Wehmann+ (HARV, CASE, SLAC, CORN, MCGI)
ASTVACAT... 68 PL 27B 45 Astvacaturov, Azimov, Baldin+ (JINR, MOSU)
BOLLINI 68C NC 56A 531 +Buhler, Dalpiaz, Massam+ (CERN, BGNA, STRB)
BARASH 67B PR 156 1399 +Kirsch, Miller, Tan (COLU)
FELDMAN 67C PR 159 1219 +Frati, Gleeson, Halpern, Nussbaum+ (PENN)
DIGIUGNO 66B NC 44A 1272 +Peruzzi, Troise+ (NAPL, FRAS, TRST)
FLATTE 66 PR 145 1050 +Huwe, Murray, Button-Shafer, Solmitz+ (LRL)
JAMES 66 PR 142 896 +Kraybill (YALE, BNL)
BARBARO-... 65 PRL 14 279 Barbaro-Galtieri, Tripp (LRL)
BARMIN 64 JETP 18 1289 +Dolgolenko, Krestnikov+ (ITEP)
Translated from ZETF 45 1879.
KRAEMER 64 PR 136B 496 +Madansky, Fields+ (JHU, NWES, WOOD)
BUSCHBECK 63 Siena Conf. 1 166 +Czapp+ (VIEN, CERN, ANIK)

OTHER RELATED PAPERS

DOLINSKY 86 PL B174 453 +Druzhinin, Dubrovin, Eidelman+ (NOVO)
KURDADZE 83 JETPL 37 733 +Lelchuk, Pakhtusova+ (NOVO)
Translated from ZETFP 37 613.
ALFF-... 62B PRL 9 325 Alff-Steinberger, Berley, Colley+ (COLU, RUTG)
ARMENTEROS 62 CERN Conf. 90 +Budde+ (CERN, CDEF, EPOL)
STEVENSON 62 PR 125 687 +Alvarez, Maglich, Rosenfeld (LRL)
MAGLICH 61 PRL 7 178 +Alvarez, Rosenfeld, Stevenson (LRL)
PEVSNER 61 PRL 7 421 +Kraemer, Nussbaum, Richardson+ (JHU)
XUONG 61 PRL 7 327 +Lynch (LRL)

$\eta'(958)$

$I^G(J^{PC}) = 0^+(0^{-+})$

$\eta'(958)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
957.77±0.14 OUR AVERAGE					
959 ±1	630	BELADIDZE	92C	VES	$36\ \pi^- \text{Be} \to \pi^- \eta' \eta \text{Be}$
958 ±1	340	ARMSTRONG	91B	OMEG	$300\ pp \to pp\eta\pi^+\pi^-$
958.2 ±0.4	622	AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
957.8 ±0.2	2420	AUGUSTIN	90	DM2	$J/\psi \to \gamma\gamma\pi^+\pi^-$
956.3 ±1.0	143	GIDAL	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
957.46±0.33		DUANE	74	MMS	$\pi^- p \to n\text{MM}$
958.2 ±0.5	1414	DANBURG	73	HBC	$2.2\ K^- p \to \Lambda X^0$
958 ±1	400	JACOBS	73	HBC	$2.9\ K^- p \to \Lambda X^0$
956.1 ±1.1	3415	BASILE	71	CNTR	$1.6\ \pi^- p \to n X^0$
957.4 ±1.4	535	BASILE	71	CNTR	$1.6\ \pi^- p \to n X^0$
957 ±1		RITTENBERG	69	HBC	1.7–2.7 $K^- p$

$\eta'(958)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.201±0.016 OUR FIT	Error includes scale factor of 1.3.					
0.28 ±0.10	1000	BINNIE	79	MMS	0	$\pi^- p \to n\text{MM}$

$\eta'(958)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-\eta$	(43.7 ±1.5) %	S=1.1
Γ_2	$\rho^0\gamma$	(30.2 ±1.3) %	S=1.1
Γ_3	$\pi^0\pi^0\eta$	(20.8 ±1.3) %	S=1.2
Γ_4	$\omega\gamma$	(3.02±0.30) %	
Γ_5	$\gamma\gamma$	(2.12±0.13) %	S=1.2
Γ_6	$3\pi^0$	(1.55±0.26) × 10^{-3}	
Γ_7	$\mu^+\mu^-\gamma$	(1.04±0.26) × 10^{-4}	
Γ_8	$\pi^+\pi^-\pi^0$	< 5 %	CL=90%
Γ_9	$\pi^0\rho^0$	< 4 %	CL=90%
Γ_{10}	$\pi^+\pi^-$	< 2 %	CL=90%
Γ_{11}	$\pi^0 e^+e^-$	< 1.3 %	CL=90%
Γ_{12}	ηe^+e^-	< 1.1 %	CL=90%
Γ_{13}	$\pi^+\pi^+\pi^-\pi^-$	< 1 %	CL=90%
Γ_{14}	$\pi^+\pi^+\pi^-\pi^-$ neutrals	< 1 %	CL=95%
Γ_{15}	$\pi^+\pi^+\pi^-\pi^-\pi^0$	< 1 %	CL=90%
Γ_{16}	6π	< 1 %	CL=90%
Γ_{17}	$\pi^+\pi^- e^+e^-$	< 6 × 10^{-3}	CL=90%
Γ_{18}	$\pi^0\pi^0$	< 9 × 10^{-4}	CL=90%
Γ_{19}	$\pi^0\gamma\gamma$	< 8 × 10^{-4}	CL=90%
Γ_{20}	$4\pi^0$	< 5 × 10^{-4}	CL=90%
Γ_{21}	3γ	< 1.0 × 10^{-4}	CL=90%
Γ_{22}	$\mu^+\mu^-\pi^0$	< 6.0 × 10^{-5}	CL=90%
Γ_{23}	$\mu^+\mu^-\eta$	< 1.5 × 10^{-5}	CL=90%
Γ_{24}	$\pi^+\pi^-\gamma$ (including $\rho^0\gamma$)		
Γ_{25}	e^+e^-	< 2.1 × 10^{-7}	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, 2 combinations of partial widths obtained from integrated cross section, and 16 branching ratios uses 45 measurements and one constraint to determine 7 parameters. The overall fit has a $\chi^2 = 33.4$ for 39 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−49					
x_3	−63	−35				
x_4	−27	−25	34			
x_5	−22	−13	27	8		
x_6	−23	−13	36	12	10	
Γ	35	−11	−21	−3	−83	−7
	x_1	x_2	x_3	x_4	x_5	x_6

	Mode	Rate (MeV)	Scale factor
Γ_1	$\pi^+\pi^-\eta$	0.088 ±0.009	1.2
Γ_2	$\rho^0\gamma$	0.061 ±0.005	1.3
Γ_3	$\pi^0\pi^0\eta$	0.042 ±0.004	1.5
Γ_4	$\omega\gamma$	0.0061 ±0.0008	1.2
Γ_5	$\gamma\gamma$	0.00426±0.00019	1.1
Γ_6	$3\pi^0$	(3.1 ±0.6) × 10^{-4}	1.1

$\eta'(958)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_5

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
4.26±0.19 OUR FIT	Error includes scale factor of 1.1.				
4.34±0.25 OUR AVERAGE					
4.53±0.29±0.51	266	KARCH	92	CBAL	$e^+e^- \to e^+e^-\eta\pi^0\pi^0$
3.62±0.14±0.48		BEHREND [1]	91	CELL	$e^+e^- \to e^+e^-\eta'(958)$
4.6 ±1.1 ±0.6	23	BARU	90	MD1	$e^+e^- \to e^+e^-\pi^+\pi^-\gamma$
4.57±0.25±0.44		BUTLER	90	MRK2	$e^+e^- \to e^+e^-\eta'(958)$
4.94±0.23±0.72	547	ROE [2]	90	ASP	$e^+e^- \to e^+e^-2\gamma$
3.8 ±0.7 ±0.6	34	AIHARA	88C	TPC	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
4.8 ±0.5 ±0.5	136	WILLIAMS [2]	88	CBAL	$e^+e^- \to e^+e^-2\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.7 ±0.6 ±0.9	143	GIDAL [3]	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
4.0 ±0.9		BARTEL [4]	85E	JADE	$e^+e^- \to e^+e^-2\gamma$

[1] Using B($\eta' \to \rho(770)\gamma$) = (30.1 ± 1.4)%.
[2] Using B($\eta' \to \gamma\gamma$) = (2.17 ± 0.17)%.
[3] Superseded by BUTLER 90.
[4] Systematic error not evaluated.

$\eta'(958)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

This combination of a partial width with the partial width into $\gamma\gamma$ and with the total width is obtained from the integrated cross section into channel(i) in the $\gamma\gamma$ annihilation.

$\Gamma(\gamma\gamma) \times \Gamma(\rho^0\gamma)/\Gamma_{\text{total}}$ — $\Gamma_5\Gamma_2/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID	TECN	COMMENT
1.29±0.06 OUR FIT	Error includes scale factor of 1.2.			
1.26±0.07 OUR AVERAGE	Error includes scale factor of 1.2.			
1.09±0.04±0.13		BEHREND 91	CELL	$e^+e^- \to e^+e^-\rho(770)^0\gamma$
1.35±0.09±0.21		AIHARA 87	TPC	$e^+e^- \to e^+e^-\rho\gamma$
1.13±0.04±0.13	867	ALBRECHT 87B	ARG	$e^+e^- \to e^+e^-\rho\gamma$
1.53±0.09±0.21		ALTHOFF 84E	TASS	$e^+e^- \to e^+e^-\rho\gamma$
1.14±0.08±0.11	243	BERGER 84B	PLUT	$e^+e^- \to e^+e^-\rho\gamma$
1.73±0.34±0.35	95	JENNI 83	MRK2	$e^+e^- \to e^+e^-\rho\gamma$
1.49±0.13±0.027	213	BARTEL 82B	JADE	$e^+e^- \to e^+e^-\rho\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.85±0.31±0.24	43	BEHREND 83B	CELL	$e^+e^- \to e^+e^-\rho\gamma$

$\Gamma(\gamma\gamma) \times \Gamma(\pi^0\pi^0\eta)/\Gamma_{\text{total}}$ — $\Gamma_5\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.88±0.07 OUR FIT	Error includes scale factor of 1.1.		
0.93±0.06±0.11	[5] KARCH 92	CBAL	$e^+e^- \to e^+e^-\eta\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.95±0.05±0.08	[6] KARCH 90	CBAL	$e^+e^- \to e^+e^-\eta\pi^0\pi^0$
1.00±0.08±0.10	[5,6] ANTREASYAN 87	CBAL	$e^+e^- \to e^+e^-\eta\pi^0\pi^0$

[5] Using BR($\eta \to 2\gamma$)=(38.9 ± 0.5)%.
[6] Superseded by KARCH 92.

$\eta'(958)$ α PARAMETER

$|\text{MATRIX ELEMENT}|^2 = (1 + \alpha y)^2 + cx^2$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.058±0.013	[7] ALDE 86	GAM2	$38\ \pi^- p \to n\eta 2\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.08 ±0.03	[7] KALBFLEISCH 74	RVUE	$\eta' \to \eta\pi^+\pi^-$

[7] May not necessarily be the same for $\eta' \to \eta\pi^+\pi^-$ and $\eta' \to \eta\pi^0\pi^0$.

$\eta'(958)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-\eta(\text{neutral decay}))/\Gamma_{\text{total}}$ — $0.709\Gamma_1/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.310±0.011 OUR FIT	Error includes scale factor of 1.1.			
0.314±0.026	281	RITTENBERG 69	HBC	1.7–2.7 $K^- p$

$\Gamma(\pi^+\pi^-\text{neutrals})/\Gamma_{\text{total}}$ — $(0.709\Gamma_1+0.291\Gamma_3+0.9\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.398±0.009 OUR FIT	Error includes scale factor of 1.1.			
0.36 ±0.05 OUR AVERAGE				
0.4 ±0.1	39	LONDON 66	HBC	2.24 $K^- p \to \Lambda\pi^+\pi^-$ neutrals
0.35 ±0.06	33	BADIER 65B	HBC	3 $K^- p$

$\Gamma(\pi^+\pi^-\eta(\text{charged decay}))/\Gamma_{\text{total}}$ — $0.291\Gamma_1/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.127±0.004 OUR FIT	Error includes scale factor of 1.1.			
0.116±0.013 OUR AVERAGE				
0.123±0.014	107	RITTENBERG 69	HBC	1.7–2.7 $K^- p$
0.10 ±0.04	10	LONDON 66	HBC	2.24 $K^- p \to \Lambda\pi^+\pi^-\pi^+\pi^-\pi^0$
0.07 ±0.04	7	BADIER 65B	HBC	3 $K^- p$

$[\Gamma(\pi^0\pi^0\eta(\text{charged decay})) + \Gamma(\omega(\text{charged decay})\gamma)]/\Gamma_{\text{total}}$ — $(0.291\Gamma_3+0.9\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.088±0.005 OUR FIT	Error includes scale factor of 1.2.			
0.045±0.029	42	RITTENBERG 69	HBC	1.7–2.7 $K^- p$

$\Gamma(\text{neutrals})/\Gamma_{\text{total}}$ — $(0.709\Gamma_3+0.09\Gamma_4+\Gamma_5)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.171±0.009 OUR FIT	Error includes scale factor of 1.2.			
0.187±0.017 OUR AVERAGE				
0.185±0.022	535	BASILE 71	CNTR	1.6 $\pi^- p \to nX^0$
0.189±0.026	123	RITTENBERG 69	HBC	1.7–2.7 $K^- p$

$\Gamma(\rho^0\gamma)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.302±0.013 OUR FIT	Error includes scale factor of 1.1.			
0.319±0.030 OUR AVERAGE				
0.329±0.033	298	RITTENBERG 69	HBC	1.7–2.7 $K^- p$
0.2 ±0.1	20	LONDON 66	HBC	2.24 $K^- p \to \Lambda\pi^+\pi^-\gamma$
0.34 ±0.09	35	BADIER 65B	HBC	3 $K^- p$

$\Gamma(\rho^0\gamma)/\Gamma(\pi\pi\eta)$ — $\Gamma_2/(\Gamma_1+\Gamma_3)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.468±0.029 OUR FIT	Error includes scale factor of 1.1.		
0.31 ±0.15	DAVIS 68	HBC	5.5 $K^- p$

$\Gamma(\pi^0 e^+e^-)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.013	90	RITTENBERG 65	HBC	2.7 $K^- p$

$\Gamma(\eta e^+e^-)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.011	90	RITTENBERG 65	HBC	2.7 $K^- p$

$\Gamma(\pi^0\rho^0)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.04	90	RITTENBERG 65	HBC	2.7 $K^- p$

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{\text{total}}$ — Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.006	90	RITTENBERG 65	HBC	2.7 $K^- p$

$\Gamma(6\pi)/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	90	LONDON 66	HBC	Compilation

$\Gamma(\omega\gamma)/\Gamma(\pi^+\pi^-\eta)$ — Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.069±0.008 OUR FIT	Error includes scale factor of 1.1.			
0.068±0.013	68	ZANFINO 77	ASPK	8.4 $\pi^- p$

$\Gamma(\rho^0\gamma)/[\Gamma(\pi^+\pi^-\eta) + \Gamma(\pi^0\pi^0\eta) + \Gamma(\omega\gamma)]$ — $\Gamma_2/(\Gamma_1+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.447±0.028 OUR FIT	Error includes scale factor of 1.1.		
0.25 ±0.14	DAUBER 64	HBC	1.95 $K^- p$

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0212±0.0013 OUR FIT	Error includes scale factor of 1.2.			
0.0196±0.0015 OUR AVERAGE				
0.0200±0.0018		[8] STANTON 80	SPEC	8.45 $\pi^- p \to n\pi^+\pi^- 2\gamma$
0.025 ±0.007		DUANE 74	MMS	$\pi^- p \to n$MM
0.0171±0.0033	68	DALPIAZ 72	CNTR	1.6 $\pi^- p \to nX^0$
0.020 $^{+0.008}_{-0.006}$	31	HARVEY 71	OSPK	3.65 $\pi^- p \to nX^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.018 ±0.002	6000	[9] APEL 79	NICE	15–40 $\pi^- p \to n2\gamma$

[8] Includes APEL 79 result.
[9] Data is included in STANTON 80 evaluation.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ — Γ_{25}/Γ

VALUE (units 10^{-7})	CL%	DOCUMENT ID	TECN	COMMENT
<2.1	90	VOROBYEV 88	ND	$e^+e^- \to \pi^+\pi^-\eta$

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.02	90	RITTENBERG 69	HBC	1.7–2.7 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.08	95	DANBURG 73	HBC	2.2 $K^- p \to \Lambda X^0$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.05	90	RITTENBERG 69	HBC	1.7–2.7 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.09	95	DANBURG 73	HBC	2.2 $K^- p \to \Lambda X^0$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\text{neutrals})/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	95	DANBURG 73	HBC	2.2 $K^- p \to \Lambda X^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.01	90	RITTENBERG 69	HBC	1.7–2.7 $K^- p$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	90	RITTENBERG 69	HBC	1.7–2.7 $K^- p$

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.01	90	RITTENBERG 69	HBC	1.7–2.7 $K^- p$

$\Gamma(\rho^0\gamma)/\Gamma(\pi^+\pi^-\gamma(\text{including}\,\rho^0\gamma))$ — Γ_2/Γ_{24}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.15 ± 0.10	473	DANBURG	73	HBC	$2.2\ K^- p \to \Lambda X^0$
1.01 ± 0.15	137	JACOBS	73	HBC	$2.9\ K^- p \to \Lambda X^0$
0.94 ± 0.20		AGUILAR-...	70D	HBC	3.9–$4.6\ K^- p$

$\Gamma(\pi^0\pi^0\eta(3\pi^0\,\text{decay}))/\Gamma_{\text{total}}$ — $0.319\Gamma_3/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.066 ± 0.004 OUR FIT	Error includes scale factor of 1.2.				
$0.11\ \pm0.06$	4	BENSINGER	70	DBC	$2.2\ \pi^+ d$

$\Gamma(\rho^0\gamma)/\Gamma(\pi^+\pi^-\eta(\text{neutral decay}))$ — $\Gamma_2/0.709\Gamma_1$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.97 ± 0.07 OUR FIT	Error includes scale factor of 1.1.				
1.01 ± 0.09 OUR AVERAGE					
1.07 ± 0.17		BELADIDZE	92C	VES	$36\ \pi^-\text{Be} \to \pi^-\eta'\eta\text{Be}$
0.92 ± 0.14	473	DANBURG	73	HBC	$2.2\ K^- p \to \Lambda X^0$
1.11 ± 0.18	192	JACOBS	73	HBC	$2.9\ K^- p \to \Lambda X^0$

$\Gamma(\gamma\gamma)/\Gamma(\pi^0\pi^0\eta(\text{neutral decay}))$ — $\Gamma_5/0.709\Gamma_3$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.144 ± 0.010 OUR FIT	Error includes scale factor of 1.6.				
0.188 ± 0.058	16	APEL	72	OSPK	$3.8\ \pi^- p \to n X^0$

$\Gamma(\mu^+\mu^-\gamma)/\Gamma(\gamma\gamma)$ — Γ_7/Γ_5

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.9 ± 1.2	33	VIKTOROV	80	CNTR	$25,33\ \pi^- p \to 2\mu\gamma$

$\Gamma(\mu^+\mu^-\eta)/\Gamma_{\text{total}}$ — Γ_{23}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	DZHELYADIN	81	CNTR	$30\ \pi^- p \to \eta' n$

$\Gamma(\mu^+\mu^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{22}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<6.0	90	DZHELYADIN	81	CNTR	$30\ \pi^- p \to \eta' n$

$\Gamma(3\pi^0)/\Gamma(\pi^0\pi^0\eta)$ — Γ_6/Γ_3

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
74±12 OUR FIT				
74±12 OUR AVERAGE				
74 ± 15	ALDE	87B	GAM2	$38\ \pi^- p \to n 6\gamma$
75 ± 18	BINON	84	GAM2	30–$40\ \pi^- p \to n 6\gamma$

$\Gamma(\gamma\gamma)/\Gamma(\pi^0\pi^0\eta)$ — Γ_5/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.102 ± 0.007 OUR FIT Error includes scale factor of 1.6.				
0.105 ± 0.010 OUR AVERAGE Error includes scale factor of 1.9.				
0.091 ± 0.009	AMSLER	93	CBAR	$0.0\ \bar{p}p$
$0.112\pm0.002\pm0.006$	ALDE	87B	GAM2	$38\ \pi^- p \to n 2\gamma$

$\Gamma(\omega\gamma)/\Gamma(\pi^0\pi^0\eta)$ — Γ_4/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.145 ± 0.014 OUR FIT				
0.147 ± 0.016	ALDE	87B	GAM2	$38\ \pi^- p \to n 4\gamma$

$\Gamma(3\gamma)/\Gamma(\pi^0\pi^0\eta)$ — Γ_{21}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<4.6	90	ALDE	87B	GAM2	$38\ \pi^- p \to n 3\gamma$

$\Gamma(\pi^0\gamma\gamma)/\Gamma(\pi^0\pi^0\eta)$ — Γ_{19}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<37	90	ALDE	87B	GAM2	$38\ \pi^- p \to n 4\gamma$

$\Gamma(\pi^0\pi^0)/\Gamma(\pi^0\pi^0\eta)$ — Γ_{18}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<45	90	ALDE	87B	GAM2	$38\ \pi^- p \to n 4\gamma$

$\Gamma(4\pi^0)/\Gamma(\pi^0\pi^0\eta)$ — Γ_{20}/Γ_3

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<23	90	ALDE	87B	GAM2	$38\ \pi^- p \to n 8\gamma$

$\eta'(958)$ C-NONCONSERVING DECAY PARAMETER

See the note on η decay parameters in the Stable Particle Particle Listings for definition of this parameter.

DECAY ASYMMETRY PARAMETER FOR $\pi^+\pi^-\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$-0.01\ \pm0.04$ OUR AVERAGE					
-0.019 ± 0.056		AIHARA	87	TPC	$2\gamma \to \pi^+\pi^-\gamma$
-0.069 ± 0.078	295	GRIGORIAN	75	STRC	$2.1\ \pi^- p$
$0.00\ \pm0.10$	103	KALBFLEISCH	75	HBC	$2.18\ K^- p \to \Lambda\pi^+\pi^-\gamma$
$0.07\ \pm0.08$	152	RITTENBERG	65	HBC	2.1–$2.7\ K^- p$

$\eta'(958)$ REFERENCES

AMSLER 93 ZPHY C58 175 +Armstrong, Merkel+ (Crystal Barrel Collab.)
BELADIDZE 92C SJNP 55 1535 +Bityukov, Borisov (SERP, TBIL)
Translated from YAF 55 2748.
KARCH 92 ZPHY C54 33 +Antreasyan, Bartels+ (Crystal Ball Collab.)
ARMSTRONG 91B ZPHY C52 389 +Barnes+ (ATHU, BARI, BIRM, CERN, CDEF)
BEHREND 91 ZPHY C49 401 +Criegee, Field, Franke+ (CELLO Collab.)
AUGUSTIN 90 PR D42 10 +Cosme+ (DM2 Collab.)
BARU 90 ZPHY C48 581 +Blinov, Blinov+ (MD-1 Collab.)
BUTLER 90 PR D42 1368 +Boyer+ (Mark II Collab.)
KARCH 90 PL B249 353 +Antreasyan, Bartels+ (Crystal Ball Collab.)
ROE 90 PR D41 17 +Bartha, Burke, Garbincius+ (ASP Collab.)
AIHARA 88C PR D38 1 +Alston-Garnjost+ (TPC-2γ Collab.)
VOROBYEV 88 SJNP 48 273 +Golubev, Dolinsky, Druzhinin+ (NOVO)
Translated from YAF 48 436.
WILLIAMS 88 PR D38 1365 +Antreasyan, Bartels, Besset+ (Crystal Ball Collab.)
AIHARA 87 PR D35 2650 +Alston-Garnjost+ (TPC-2γ Collab.) JP
ALBRECHT 87B PL B199 457 +Andam, Binder+ (ARGUS Collab.)
ALDE 87B ZPHY C36 603 +Binon, Bricman+ (LANL, BELG, SERP, LAPP)
ANTREASYAN 87 PR D36 2633 +Bartels, Besset+ (Crystal Ball Collab.)
GIDAL 87 PRL 59 2012 +Boyer, Butler, Cords, Abrams+ (LBL, SLAC, HARV)
ALDE 86 PL B177 115 +Binon, Bricman+ (SERP, BELG, LANL, LAPP)
BARTEL 85E PL 160B 421 +Becker, Cords, Felst+ (JADE Collab.)
ALTHOFF 84E PL 147B 487 +Braunschweig, Kirschfink, Luebelsmeyer+ (TASSO Collab.)
BERGER 84B PL 142B 125 (PLUTO Collab.)
BINON 84 PL 140B 264 +Donskov, Duteil+ (SERP, BELG, LAPP, CERN)
BEHREND 83B PL 125B 518 +D'Agostini+ (CELLO Collab.)
Also 82C PL 114B 378 Behrend, Chen, Fenner, Field+ (CELLO Collab.)
JENNI 83 PR D27 1031 +Burke, Telnov, Abrams, Blocker+ (SLAC, LBL)
BARTEL 82B PL 113B 190 +Cords+ (JADE Collab.)
DZHELYADIN 81 PL 105B 239 +Golovkin, Konstantinov, Kubarovski+ (SERP)
STANTON 80 PL 92 B 353 +Edwards, Legacey+ (OSU, CARL, MCGI, TNTO)
VIKTOROV 80 SJNP 32 520 +Golovkin, Dzhelyadin, Zaitsev, Mukhin+ (SERP)
Translated from YAF 32 1005.
APEL 79 PL 83B 131 +Augenstein, Bertolucci(KARLK, KARLE, PISA, SERP, WIEN)
BINNIE 79 PL 83B 141 +Carr, Debenham, Jones, Karami, Keyne+ (LOIC)
ZANFINO 77 PRL 38 930 +Brockman+ (CARL, MCGI, OHIO, TNTO)
GRIGORIAN 75 NP B91 232 +Ladage, Mellema, Rudnick+ (UCLA)
KALBFLEISCH 75 PR D11 987 +Strand, Chapman (BNL, MICH)
DUANE 74 PRL 32 425 +Binnie, Camilleri, Carr+ (LOIC, SHMP)
KALBFLEISCH 74 PR D10 916 (BNL)
DANBURG 73 PR D8 3744 +Kalbfleisch, Borenstein, Chapman+ (BNL, MICH) JP
JACOBS 73 PR D8 18 +Chang, Gauthier+ (BRAN, UMD, SYRA, TUFTS) JP
APEL 72 PL 40B 680 +Auslander, Muller, Bertolucci+ (KARLK, KARLE, PISA)
DALPIAZ 72 PL 42B 377 +Frabetti, Massam, Navarria, Zichichi (CERN)
BASILE 71 NC 3A 371 +Bollini, Dalpiaz, Frabetti+ (CERN, BGNA, STRB)
HARVEY 71 PRL 27 885 +Marquit, Peterson, Rhoades+ (MINN, MICH)
AGUILAR-... 70D PRL 25 1635 Aguilar-Benitez, Bassano, Samios, Barnes+ (BNL)
BENSINGER 70 PL 33B 505 +Erwin, Thompson, Walker (WISC)
RITTENBERG 69 Thesis UCRL 18863 (LRL) I
DAVIS 68 PL 27B 532 +Ammar, Mott, Dagan, Derrick+ (NWES, ANL)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA) IJP
BADIER 65B PL 17 337 +Demoulin, Barloutaud+ (EPOL, SACL, AMST)
RITTENBERG 65 PRL 15 556 +Kalbfleisch (LRL, BNL)
DAUBER 64 PRL 13 449 +Slater, Smith, Stork, Ticho (UCLA) JP
Also 64B Dubna Conf. 1 418 Dauber, Slater, Smith, Stork, Ticho (UCLA)

OTHER RELATED PAPERS

GENOVESE 94 ZPHY C61 425 +Lichtenberg, Pedrazzi (TORI, IND)
BENAYOUN 93 ZPHY 58 31 +Feindt, Girone+ (CDEF, CERN, BARI)
KAMAL 92 PL B284 421 +Xu (ALBE)
BICKERSTAFF 82 ZPHY C16 171 +McKellar (MELB)
KIENZLE 65 PL 19 438 +Maglich, Levrat, Lefebvres+ (CERN)
TRILLING 65 PL 19 427 +Brown, Goldhaber, Kadyk, Scanio (LRL)
GOLDBERG 64 PRL 12 546 +Gundzik, Lichtman, Connolly, Hart+ (SYRA, BNL)
GOLDBERG 64B PRL 13 249 +Gundzik, Leitner, Connolly, Hart+ (SYRA, BNL)
KALBFLEISCH 64 PRL 12 527 +Alvarez, Barbaro-Galtieri+ (LRL) JP
KALBFLEISCH 64B PRL 13 349 +Dahl, Rittenberg (LRL) JP

$f_0(980)$

$I^G(J^{PC}) = 0^+(0^{++})$

See also the minireview on scalar mesons under $f_0(1370)$ and on the non-$q\bar{q}$ candidates. (See the index for the page number.)

$f_0(980)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
980 ±10 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1006		TORNQVIST	96	RVUE	$\pi\pi \to \pi\pi, K\bar{K}, K\pi, \eta\pi$
997 ± 5	3k	[1] ALDE	95B	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
960 ±10	10k	[2] ALDE	95B	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
994 ± 5		AMSLER	95B	CBAR	$0.0\ \bar{p}p \to 3\pi^0$
~ 996		[3] AMSLER	95D	CBAR	$0.0\ \bar{p}p \to \pi^0\pi^0\pi^0, \pi^0\eta\eta, \pi^0\pi^0\eta$
987 ± 6		[4] ANISOVICH	95	RVUE	
1015		JANSSEN	95	RVUE	$\pi\pi \to \pi\pi, K\bar{K}$
983		[5] BUGG	94	RVUE	$\bar{p}p \to \eta 2\pi^0$
988		[6] ZOU	94B	RVUE	
988 ±10		[7] MORGAN	93	RVUE	$\pi\pi(K\bar{K}) \to \pi\pi(K\bar{K}), J/\psi \to \phi\pi\pi(K\bar{K}), D_s \to \pi(\pi\pi)$
971.1± 4.0		[8] AGUILAR-...	91	EHS	$400\ pp$
979 ± 4		[9] ARMSTRONG	91	OMEG	$300\ pp \to pp\pi\pi, ppK\bar{K}$

VALUE	DOCUMENT ID		TECN	COMMENT
956 ±12	BREAKSTONE	90	SFM	$pp \to pp\pi^+\pi^-$
959.4± 6.5	[8] AUGUSTIN	89	DM2	$J/\psi \to \omega\pi^+\pi^-$
978 ± 9	[8] ABACHI	86B	HRS	$e^+e^- \to \pi^+\pi^- X$
$985.0^{+9.0}_{-39.0}$	ETKIN	82B	MPS	$23\ \pi^- p \to n 2K^0_S$
974 ± 4	[9] GIDAL	81	MRK2	$J/\psi \to \pi^+\pi^- X$
975	[10] ACHASOV	80	RVUE	
986 ±10	[9] AGUILAR-...	78	HBC	$0.7\ \overline{p}p \to K^0_S K^0_S$
969 ± 5	[9] LEEPER	77	ASPK	$2\text{–}2.4\ \pi^- p \to \pi^+\pi^- n,\ K^+K^- n$
987 ± 7	[9] BINNIE	73	CNTR	$\pi^- p \to n MM$
1012 ± 6	[11] GRAYER	73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
1007 ±20	[11] HYAMS	73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
997 ± 6	[11] PROTOPOP...	73	HBC	$7\ \pi^+ p \to \pi^+ p \pi^+\pi^-$

[1] At high $|t|$.
[2] At low $|t|$.
[3] On sheet II in a 4-pole solution, the other poles are found on sheet III at (953−55*i*) MeV and on sheet IV at (938−35*i*) MeV.
[4] Combined fit of ALDE 95B, ANISOVICH 94, AMSLER 94D.
[5] On sheet II in a 2 pole solution. The other pole is found on sheet III at (996−103*i*) MeV.
[6] On sheet II in a 2 pole solution. The other pole is found on sheet III at (797−185*i*) MeV and can be interpreted as a shadow pole.
[7] On sheet II in a 2 pole solution. The other pole is found on sheet III at (978−28*i*) MeV.
[8] From invariant mass fit.
[9] From coupled channel analysis.
[10] Coupled channel analysis with finite width corrections.
[11] Included in AGUILAR-BENITEZ 78 fit.

$f_0(980)$ WIDTH

Width determination very model dependent. Peak width is about 50 MeV, but decay width can be much larger.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
40 to 100 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
34		TORNQVIST	96	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
48 ± 10	3k	[12] ALDE	95B	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
95 ± 20	10k	[13] ALDE	95B	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
26 ± 10		AMSLER	95B	CBAR	$0.0\ \overline{p}p \to 3\pi^0$
~ 112		[14] AMSLER	95D	CBAR	$0.0\ \overline{p}p \to \pi^0\pi^0\pi^0, \pi^0\eta\eta, \pi^0\pi^0\eta$
80 ± 12		[15] ANISOVICH	95	RVUE	
30		JANSSEN	95	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
74		[16] BUGG	94	RVUE	$\overline{p}p \to \eta 2\pi^0$
46		[17] ZOU	94B	RVUE	
48 ± 12		[18] MORGAN	93	RVUE	$\pi\pi(K\overline{K}) \to \pi\pi(K\overline{K}), J/\psi \to \phi\pi\pi(K\overline{K}), D_s \to \pi(\pi\pi)$
37.4± 10.6		[19] AGUILAR-...	91	EHS	$400\ pp$
72 ± 8		[20] ARMSTRONG	91	OMEG	$300\ pp \to pp\pi\pi, ppK\overline{K}$
110 ± 30		BREAKSTONE	90	SFM	$pp \to pp\pi^+\pi^-$
29 ± 13		[19] ABACHI	86B	HRS	$e^+e^- \to \pi^+\pi^- X$
120 ±281 ±20		ETKIN	82B	MPS	$23\ \pi^- p \to n 2K^0_S$
28 ± 10		[20] GIDAL	81	MRK2	$J/\psi \to \pi^+\pi^- X$
70 to 300		[21] ACHASOV	80	RVUE	
100 ± 80		[22] AGUILAR-...	78	HBC	$0.7\ \overline{p}p \to K^0_S K^0_S$
30 ± 8		[20] LEEPER	77	ASPK	$2\text{–}2.4\ \pi^- p \to \pi^+\pi^- n,\ K^+K^- n$
48 ± 14		[20] BINNIE	73	CNTR	$\pi^- p \to n MM$
32 ± 10		[23] GRAYER	73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
30 ± 10		[23] HYAMS	73	ASPK	$17\ \pi^- p \to \pi^+\pi^- n$
54 ± 16		[23] PROTOPOP...	73	HBC	$7\ \pi^+ p \to \pi^+ p \pi^+\pi^-$

[12] At high $|t|$.
[13] At low $|t|$.
[14] On sheet II in a 4-pole solution, the other poles are found on sheet III at (953−55*i*) MeV and on sheet IV at (938−35*i*) MeV.
[15] Combined fit of ALDE 95B, ANISOVICH 94.
[16] On sheet II in a 2 pole solution. The other pole is found on sheet III at (996−103*i*) MeV.
[17] On sheet II in a 2 pole solution. The other pole is found on sheet III at (797−185*i*) MeV and can be interpreted as a shadow pole.
[18] On sheet II in a 2 pole solution. The other pole is found on sheet III at (978−28*i*) MeV.
[19] From invariant mass fit.
[20] From coupled channel analysis.
[21] Coupled channel analysis with finite width corrections.
[22] From coupled channel fit to the HYAMS 73 and PROTOPOPESCU 73 data. With a simultaneous fit to the $\pi\pi$ phase-shifts, inelasticity and to the $K^0_S K^0_S$ invariant mass.
[23] Included in AGUILAR-BENITEZ 78 fit.

$f_0(980)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\pi\pi$	(78.1 ±2.4) %	
Γ_2	$K\overline{K}$	(21.9 ±2.4) %	
Γ_3	$\gamma\gamma$	(1.19±0.33) × 10^{-5}	
Γ_4	e^+e^-	< 3 × 10^{-7}	90%

CONSTRAINED FIT INFORMATION

An overall fit to a branching ratio uses 3 measurements and one constraint to determine 2 parameters. The overall fit has a $\chi^2 =$ 2.0 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100
	x_1

$f_0(980)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_3

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
0.56±0.11 OUR AVERAGE					
0.63±0.14		[24] MORGAN	90	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$
0.42±0.06±0.18	60	[25] OEST	90	JADE	$e^+e^- \to e^+e^-\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.29±0.07±0.12		[26,27] BOYER	90	MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
0.31±0.14±0.09		[26,27] MARSISKE	90	CBAL	$e^+e^- \to e^+e^-\pi^0\pi^0$

[24] From amplitude analysis of BOYER 90 and MARSISKE 90, data corresponds to resonance parameters m = 989 MeV, Γ = 61 MeV.
[25] OEST 90 quote systematic errors $^{+0.08}_{-0.18}$. We use ±0.18.
[26] From analysis allowing arbitrary background unconstrained by unitarity.
[27] Data included in MORGAN 90 analysis.

$\Gamma(e^+e^-)$ — Γ_4

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<8.4	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\pi^0$

$f_0(980)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/[\Gamma(\pi\pi)+\Gamma(K\overline{K})]$ — $\Gamma_1/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.781±0.024 OUR FIT				
$0.781^{+0.027}_{-0.023}$ OUR AVERAGE				
0.67 ±0.09	[28] LOVERRE	80	HBC	$4\ \pi^- p \to n 2K^0_S$
$0.81\ ^{+0.09}_{-0.04}$	[28] CASON	78	STRC	$7\ \pi^- p \to n 2K^0_S$
0.78 ±0.03	[28] WETZEL	76	OSPK	$8.9\ \pi^- p \to n 2K^0_S$

[28] Measure $\pi\pi$ elasticity assuming two resonances coupled to the $\pi\pi$ and $K\overline{K}$ channels only.

$f_0(980)$ REFERENCES

TORNQVIST	96	PRL 76 1575	+Roos	(HELS)
ALDE	95B	ZPHY C66 375	+Binon, Bouteмeur+	(GAMS Collab.)
AMSLER	95B	PL B342 433	+Armstrong, Brose+	(Crystal Barrel Collab.)
AMSLER	95D	PL B355 425	+Armstrong, Spanier+	(Crystal Barrel Collab.)
ANISOVICH	95	PL B355 363	+Kondashov+	(PNPI, SERP)
JANSSEN	95	PR D52 2690	+Pearce, Holinde, Speth	(STON, ADLD, JULI)
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.)
ANISOVICH	94	PL B323 233	+Armstrong+	(Crystal Barrel Collab.)
BUGG	94	PR D50 4412	+Anisovich+	(LOQM)
ZOU	94B	PR D50 591	+Bugg	(LOQM)
MORGAN	93	PR D48 1185	+Pennington	(RAL, DURH)
AGUILAR-...	91	ZPHY C50 405	Aguilar-Benitez, Allison, Batalor+	(LEBC-EHS Collab.)
ARMSTRONG	91	ZPHY C51 351	+Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF)
BOYER	90	PR D42 1350	+Butler+	(Mark II Collab.)
BREAKSTONE	90	ZPHY C48 569	+	(ISU, BGNA, CERN, DORT, HEIDH, WARS)
MARSISKE	90	PR D41 3324	+Antreasyan+	(Crystal Ball Collab.)
MORGAN	90	ZPHY C48 623	+Pennington	(RAL, DURH)
OEST	90	ZPHY C47 343	+Olsson+	(JADE Collab.)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
VOROBYEV	88	SJNP 48 273	+Golubev, Dolinsky, Druzhinin+	(NOVO)
		Translated from YAF 48 436.		
ABACHI	86B	PRL 57 1990	+Derrick, Blockus+	(PURD, ANL, IND, MICH, LBL)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+	(SLAC, LBL)
ACHASOV	80	SJNP 32 566	+Devyanin, Shestakov	(NOVM)
		Translated from YAF 32 1098.		
LOVERRE	80	ZPHY C6 187	+Armenteros, Dionisi+	(CERN, CDEF, MADR, STOH) IJP
AGUILAR-...	78	NP B140 73	Aguilar-Benitez, Cerrada+	(MADR, BOMB, CERN+)
CASON	78	PRL 41 271	+Baumbaugh, Bishop, Biswas+	(NDAM, ANL)
LEEPER	77	PR D16 2054	+Buttram, Crawley, Duke, Lamb, Peterson	(ISU)
WETZEL	76	NP B115 208	+Freudenreich, Beusch+	(ETH, CERN, LOIC)
BINNIE	73	PRL 31 1534	+Carr, Debenham, Duane, Garbutt+	(LOIC, SHMP)
GRAYER	73	Tallahassee	+Hyams, Jones, Blum, Dietl, Koch+	(CERN, MPIM)
HYAMS	73	NP B64 134	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
PROTOPOP...	73	PR D7 1279	Protopopescu, Alston-Garnjost, Galtieri, Flatte+	(LBL)

OTHER RELATED PAPERS

AU	87	PR D35 1633	+Morgan, Pennington	(DURH, RAL)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
MENNESSIER	83	ZPHY C16 241		(MONP)
BARBER	82	ZPHY C12 1	+Dainton, Brodbeck, Brookes+	(DARE, LANC, SHEF)
ETKIN	82C	PR D25 2446	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
BIGI	62	CERN Conf. 247	+Brandt, Carrara+	(CERN)
BINGHAM	62	CERN Conf. 240	+Bloch+	(EPOL, CERN)
ERWIN	62	PRL 9 34	+Hoyer, March, Walker, Wangler	(WISC, BNL)
WANG	61	JETP 13 323 Translated from ZETF 40 464.	+Veksler, Vrana+	(JINR)

$a_0(980)$

$I^G(J^{PC}) = 1^-(0^{++})$

See our minireview on scalar mesons under $f_0(1370)$ and on the non-$q\overline{q}$ candidates.

$a_0(980)$ MASS

VALUE (MeV)	*DOCUMENT ID*
983.5±0.9 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

$\eta\pi$ FINAL STATE ONLY

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
983.7 ± 0.9 OUR AVERAGE						
984.45± 1.23±0.34		AMSLER	94C	CBAR		$0.0\ \overline{p}p \to \omega\eta\pi^0$
982 ± 2		[1] AMSLER	92	CBAR		$0.0\ \overline{p}p \to \eta\eta\pi^0$
984 ± 4	1040	[1] ARMSTRONG	91B	OMEG	±	$300\ pp \to pp\eta\pi^+\pi^-$
976 ± 6		ATKINSON	84E	OMEG	±	$25\text{–}55\ \gamma p \to \eta\pi n$
986 ± 3	500	[2] EVANGELISTA	81	OMEG	±	$12\ \pi^- p \to \eta\pi^+\pi^-\pi^- p$
990 ± 7	145	[2] GURTU	79	HBC	±	$4.2\ K^- p \to \Lambda\eta 2\pi$
977 ± 7		GRASSLER	77	HBC	−	$16\ \pi^\mp p \to p\eta 3\pi$
972 ±10	150	DEFOIX	72	HBC	±	$0.7\ \overline{p}p \to 7\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
987		TORNQVIST	96	RVUE		$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
991		JANSSEN	95	RVUE		$\eta\pi \to \eta\pi, K\overline{K}, K\pi, \eta\pi$
980 ±11	47	CONFORTO	78	OSPK	−	$4.5\ \pi^- p \to pX^-$
978 ±16	50	CORDEN	78	OMEG	±	$12\text{–}15\ \pi^- p \to n\eta 2\pi$
989 ± 4	70	WELLS	75	HBC	−	$3.1\text{–}6\ K^- p \to \Lambda\eta 2\pi$
970 ±15	20	BARNES	69C	HBC	−	$4\text{–}5\ K^- p \to \Lambda\eta 2\pi$
980 ±10		CAMPBELL	69	DBC	±	$2.7\ \pi^+ d$
980 ±10	15	MILLER	69B	HBC	−	$4.5\ K^- N \to \eta\pi\Lambda$
980 ±10	30	AMMAR	68	HBC	±	$5.5\ K^- p \to \Lambda\eta 2\pi$

[1] From a single Breit-Wigner fit.
[2] From $f_1(1285)$ decay.

$K\overline{K}$ ONLY

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
976 ± 6	316	DEBILLY	80	HBC	±	$1.2\text{–}2\ \overline{p}p \to f_1(1285)\omega$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1016 ±10	100	[3] ASTIER	67	HBC	±	$0.0\ \overline{p}p$
1003.3± 7.0	143	[4] ROSENFELD	65	RVUE	±	

[3] ASTIER 67 includes data of BARLOW 67, CONFORTO 67, ARMENTEROS 65.
[4] Plus systematic errors.

$a_0(980)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
50 to 100 OUR ESTIMATE		Width determination very model dependent. Peak width is about 60 MeV, but decay width can be much larger.				
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 100		TORNQVIST	96	RVUE		$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
202		JANSSEN	95	RVUE		$\eta\pi \to \eta\pi, K\overline{K}, K\pi, \eta\pi$
54.12± 0.34±0.12		AMSLER	94C	CBAR		$0.0\ \overline{p}p \to \omega\eta\pi^0$
54 ±10		[5] AMSLER	92	CBAR		$0.0\ \overline{p}p \to \eta\eta\pi^0$
95 ±14	1040	[5] ARMSTRONG	91B	OMEG	±	$300\ pp \to pp\eta\pi^+\pi^-$
62 ±15	500	[6] EVANGELISTA	81	OMEG	±	$12\ \pi^- p \to \eta\pi^+\pi^-\pi^- p$
60 ±20	145	[6] GURTU	79	HBC	±	$4.2\ K^- p \to \Lambda\eta 2\pi$
$60\ ^{+50}_{-30}$	47	CONFORTO	78	OSPK	−	$4.5\ \pi^- p \to pX^-$
$86.0\ ^{+60.0}_{-50.0}$	50	CORDEN	78	OMEG	±	$12\text{–}15\ \pi^- p \to n\eta 2\pi$
44 ±22		GRASSLER	77	HBC	−	$16\ \pi^\mp p \to p\eta 3\pi$
80 to 300		[7] FLATTE	76	RVUE	−	$4.2\ K^- p \to \Lambda\eta 2\pi$
$16.0\ ^{+25.0}_{-16.0}$	70	WELLS	75	HBC	−	$3.1\text{–}6\ K^- p \to \Lambda\eta 2\pi$
30 ± 5	150	DEFOIX	72	HBC	±	$0.7\ \overline{p}p \to 7\pi$
40 ±15		CAMPBELL	69	DBC	±	$2.7\ \pi^+ d$
60 ±30	15	MILLER	69B	HBC	−	$4.5\ K^- N \to \eta\pi\Lambda$
80 ±30	30	AMMAR	68	HBC	±	$5.5\ K^- p \to \Lambda\eta 2\pi$

[5] From a single Breit-Wigner fit.
[6] From $f_1(1285)$ decay.
[7] Using a two-channel resonance parametrization of GAY 76B data.

$K\overline{K}$ ONLY

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 25	100	[8] ASTIER	67	HBC	±
57±13	143	[9] ROSENFELD	65	RVUE	±

[8] ASTIER 67 includes data of BARLOW 67, CONFORTO 67, ARMENTEROS 65.
[9] Plus systematic errors.

$a_0(980)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi$	dominant
Γ_2	$K\overline{K}$	seen
Γ_3	$\rho\pi$	
Γ_4	$\pi\eta'(958)$	
Γ_5	$\gamma\gamma$	seen
Γ_6	e^+e^-	

$a_0(980)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_5/\Gamma$

VALUE (keV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{0.24^{+0.08}_{-0.07}}$ **OUR AVERAGE**					
0.28±0.04±0.10	44	OEST	90	JADE	$e^+e^- \to e^+e^-\pi^0\eta$
$0.19\pm0.07^{+0.10}_{-0.07}$		ANTREASYAN	86	CBAL	$e^+e^- \to e^+e^-\pi^0\eta$

$\Gamma(\eta\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_6/\Gamma$

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1.5	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\eta$

$a_0(980)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\eta\pi)$ — Γ_2/Γ_1

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.16±0.18	[10] BUGG	94	RVUE		$\overline{p}p \to \eta\eta\pi^0$
0.7 ±0.3	[11] CORDEN	78	OMEG		$12\text{–}15\ \pi^- p \to n\eta 2\pi$
0.25±0.08	[11] DEFOIX	72	HBC	±	$0.7\ \overline{p} \to 7\pi$

[10] BUGG 94 uses AMSLER 94C data. This is a ratio of couplings.
[11] From the decay of $f_1(1285)$.

$\Gamma(\rho\pi)/\Gamma(\eta\pi)$ — Γ_3/Γ_1

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.25	70	AMMAR	70	HBC	±	$4.1,5.5\ K^- p \to \Lambda\eta 2\pi$

$a_0(980)$ REFERENCES

TORNQVIST	96	PRL 76 1575	+Roos	(HELS)
JANSSEN	95	PR D52 2690	+Pearce, Holinde, Speth	(STON, ADLD, JULI)
AMSLER	94C	PL B327 425	+Armstrong, Ravndal+	(Crystal Barrel Collab.)
BUGG	94	PR D50 4412	+Anisovich+	(LOQM)
AMSLER	92	PL B291 347	+Augustin, Baker+	(Crystal Barrel Collab.)
ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
OEST	90	ZPHY C47 343	+Olsson+	(JADE Collab.)
VOROBYEV	88	SJNP 48 273 Translated from YAF 48 436.	+Golubev, Dolinsky, Druzhinin+	(NOVO)
ANTREASYAN	86	PR D33 1847	+Aschman, Besset, Bienlein+	(Crystal Ball Collab.)
ATKINSON	84E	PL 138B 459	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
DEBILLY	80	NP B176 1	+Briand, Duboc, Levy+	(CURIN, LAUS, NEUC, GLAS)
GURTU	79	NP B151 181	+Gavillet, Blokzijl+	(CERN, ZEEM, NIJM, OXF)
CONFORTO	78	LNC 23 419	+Conforto, Key+	(RHEL, TNTO, CHIC, FNAL+)
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
GRASSLER	77	NP B121 189	+	(AACH3, BERL, BONN, CERN, CRAC, HEIDH+)
FLATTE	76	PL 63B 224		(CERN)
GAY	76B	PL 63B 220	+Chaloupka, Blokzijl, Heinen+	(CERN, AMST, NIJM) JP
WELLS	75	NP B101 333	+Radojicic, Roscoe, Lyons	(OXF)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
AMMAR	70	PR D2 430	+Kropac, Davis+	(KANS, NWES, ANL, WISC)
BARNES	69C	PRL 23 610	+Chung, Eisner, Bassano, Goldberg+	(BNL, SYRA)
CAMPBELL	69	PRL 22 1204	+Lichtman, Loeffler+	(PURD)
MILLER	69B	PL 29B 255	+Kramer, Carmony+	(PURD)
Also	69	PR 188 2011	Yen, Ammann, Carmony, Elsner+	(PURD)
AMMAR	68	PRL 21 1832	+Davis, Kropac, Derrick, Fields+	(NWES, ANL)
ASTIER	67	PL 25B 294 Includes data of BARLOW 67, CONFORTO 67, and ARMENTEROS 65.	+Montanet, Baubillier, Duboc+	(CDEF, CERN, IRAD)
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
CONFORTO	67	NP B3 469	+Marechal+	(CERN, CDEF, IPNP, LIVP)
ARMENTEROS	65	PL 17 344	+Edwards, Jacobsen+	(CERN, CDEF)
ROSENFELD	65	Oxford Conf. 58		(LRL)

OTHER RELATED PAPERS

TORNQVIST	90	NPBPS 21,196		(HELS)
WEINSTEIN	89	UTPT 89 03	+Isgur	(TNTO)
ACHASOV	88B	ZPHY C41 309	+Shestakov	(NOVM)
WEINSTEIN	83B	PR D27 588	+Isgur	(TNTO)
TORNQVIST	82	PRL 49 624		(HELS)
BRAMON	80	PL 93B 65	+Masso	(BARC)
TURKOT	63	Siena Conf. 1 661	+Collins, Fujii, Kemp+	(BNL, PITT)

$\phi(1020)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\phi(1020)$ MASS

We average mass and width values only when the systematic errors have been evaluated.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1019.413±0.008 OUR AVERAGE					
1019.42 ±0.06	55600	AKHMETSHIN	95	CMD2	$e^+e^- \to$ hadrons
1019.7 ±0.3	2012	DAVENPORT	86	MPSF	400 $pA \to 4KX$
1019.411±0.008	642k	[1] DIJKSTRA	86	SPEC	100–200 $\pi^\pm$, $\bar{p}$, p, $K^\pm$, on Be
1019.7 ±0.1 ±0.1	5079	ALBRECHT	85D	ARG	10 $e^+e^- \to K^+K^-X$
1019.3 ±0.1	1500	ARENTON	82	AEMS	11.8 polar. $pp \to KK$
1019.67 ±0.17	25080	[2] PELLINEN	82	RVUE	
1019.54 ±0.12	1100	BARKOV	79B	EMUL	$e^+e^- \to K^+K^-$
1019.52 ±0.13	3681	BUKIN	78C	OLYA	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1019.8 ±0.7		ARMSTRONG	86	OMEG	85 $\pi^+/pp \to \pi^+/p4Kp$
1020.1 ±0.11	5526	[3] ATKINSON	86	OMEG	20–70 γp
1019.7 ±1.0		BEBEK	86	CLEO	$e^+e^- \to \Upsilon(4S)$
1020.9 ±0.2		[3] FRAME	86	OMEG	13 $K^+p \to \phi K^+p$
1021.0 ±0.2		[3] ARMSTRONG	83B	OMEG	18.5 $K^-p \to K^-K^+\Lambda$
1020.0 ±0.5		[3] ARMSTRONG	83B	OMEG	18.5 $K^-p \to K^-K^+\Lambda$
1019.7 ±0.3		[3] BARATE	83	GOLI	190 π^- Be $\to 2\mu X$
1019.8 ±0.2 ±0.5	766	IVANOV	81	OLYA	1–1.4 $e^+e^- \to K^+K^-$
1019.4 ±0.5	337	COOPER	78B	HBC	0.7–0.8 $\bar{p}p \to K^0_S K^0_L \pi^+\pi^-$
1020 ±1	383	[3] BALDI	77	CNTR	10 $\pi^-p \to \pi^-\phi p$
1018.9 ±0.6	800	COHEN	77	ASPK	6 $\pi^\pm N \to K^+K^-N$
1019.7 ±0.5	454	KALBFLEISCH	76	HBC	2.18 $K^-p \to \Lambda K\bar{K}$
1019.4 ±0.8	984	BESCH	74	CNTR	2 $\gamma p \to pK^+K^-$
1020.3 ±0.4	100	BALLAM	73	HBC	2.8–9.3 γp
1019.4 ±0.7		BINNIE	73B	CNTR	$\pi^-p \to \phi n$
1019.6 ±0.5	120	[4] AGUILAR-...	72B	HBC	3.9,4.6 $K^-p \to \Lambda K^+K^-$
1019.9 ±0.5	100	[4] AGUILAR-...	72B	HBC	3.9,4.6 $K^-p \to K^-pK^+K^-$
1020.4 ±0.5	131	COLLEY	72	HBC	10 $K^+p \to K^+p\phi$
1019.9 ±0.3	410	STOTTLE...	71	HBC	2.9 $K^-p \to \Sigma/\Lambda K\bar{K}$

[1] Weighted and scaled average of 12 measurements of DIJKSTRA 86.
[2] PELLINEN 82 review includes AKERLOF 77, DAUM 81, BALDI 77, AYRES 74, DE-GROOT 74.
[3] Systematic errors not evaluated.
[4] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$\phi(1020)$ WIDTH

We average mass and width values only when the systematic errors have been evalutated.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
4.43±0.05 OUR FIT					
4.43±0.05 OUR AVERAGE					
4.44±0.09	55600	AKHMETSHIN	95	CMD2	$e^+e^- \to$ hadrons
4.45±0.06	271k	DIJKSTRA	86	SPEC	100 π^- Be
4.5 ±0.7	1500	ARENTON	82	AEMS	11.8 polar. $pp \to KK$
4.2 ±0.6	766	[5] IVANOV	81	OLYA	1–1.4 $e^+e^- \to K^+K^-$
4.3 ±0.6		[5] CORDIER	80	WIRE	$e^+e^- \to \pi^+\pi^-\pi^0$
4.58±0.55	1100	[5] BARKOV	79B	EMUL	$e^+e^- \to K^+K^-$
4.36±0.29	3681	[5] BUKIN	78C	OLYA	$e^+e^- \to$ hadrons
4.4 ±0.6	984	[5] BESCH	74	CNTR	2 $\gamma p \to pK^+K^-$
4.67±0.72	681	[5] BALAKIN	71	OSPK	$e^+e^- \to$ hadrons
4.09±0.29		BIZOT	70	OSPK	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.08±0.14	13714	KURDADZE	84	OLYA	$e^+e^- \to$ hadrons
3.6 ±0.8	337	[5] COOPER	78B	HBC	0.7–0.8 $\bar{p}p \to K^0_S K^0_L \pi^+\pi^-$
4.5 ±0.50	1300	[5,6] AKERLOF	77	SPEC	400 $pA \to K^+K^-X$
4.5 ±0.8	500	[5,6] AYRES	74	ASPK	3–6 $\pi^-p \to K^+K^-n$, $K^-p \to K^+K^-\Lambda/\Sigma^0$
3.81±0.37		COSME	74B	OSPK	$e^+e^- \to K^0_L K^0_S$
3.8 ±0.7	454	[5] BORENSTEIN	72	HBC	2.18 $K^-p \to K\bar{K}n$

[5] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[6] Systematic errors not evaluated.

$\phi(1020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(49.1 ±0.6) %	S=1.2
Γ_2	$K^0_L K^0_S$	(34.1 ±0.5) %	S=1.1
Γ_3	$\rho\pi$	(12.9 ±0.7) %	
Γ_4	$\pi^+\pi^-\pi^0$	(2.7 ±0.9) %	S=1.1
Γ_5	$\eta\gamma$	(1.26±0.06) %	S=1.1
Γ_6	$\pi^0\gamma$	(1.31±0.13) $\times 10^{-3}$	
Γ_7	e^+e^-	(3.00±0.06) $\times 10^{-4}$	S=1.1
Γ_8	$\mu^+\mu^-$	(2.48±0.34) $\times 10^{-4}$	
Γ_9	ηe^+e^-	(1.3 $^{+0.8}_{-0.6}$) $\times 10^{-4}$	
Γ_{10}	$\pi^+\pi^-$	(8 $^{+5}_{-4}$) $\times 10^{-5}$	S=1.5
Γ_{11}	$\omega\gamma$	< 5 %	CL=84%
Γ_{12}	$\rho\gamma$	< 2 %	CL=84%
Γ_{13}	$\pi^+\pi^-\gamma$	< 7 $\times 10^{-3}$	CL=90%
Γ_{14}	$f_0(980)\gamma$		
Γ_{15}	$\pi^0\pi^0\gamma$	< 1 $\times 10^{-3}$	CL=90%
Γ_{16}	$\pi^+\pi^-\pi^+\pi^-$	< 8.7 $\times 10^{-4}$	CL=90%
Γ_{17}	$\eta'(958)\gamma$	< 4.1 $\times 10^{-4}$	CL=90%
Γ_{18}	$\pi^+\pi^+\pi^-\pi^-\pi^0$	< 1.5 $\times 10^{-4}$	CL=95%
Γ_{19}	$\pi^0e^+e^-$	< 1.2 $\times 10^{-4}$	CL=90%
Γ_{20}	$\pi^0\eta\gamma$		
Γ_{21}	$a_0(980)\gamma$	< 5 $\times 10^{-3}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and 9 branching ratios uses 43 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 = 28.9$ for 38 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−63				
x_3	0	0			
x_4	−34	−16	−81		
x_5	−5	−3	0	−1	
Γ	0	0	−20	16	0
	x_1	x_2	x_3	x_4	x_5

	Mode	Rate (MeV)	Scale factor
Γ_1	K^+K^-	2.18 ±0.04	1.1
Γ_2	$K^0_L K^0_S$	1.510 ±0.029	1.1
Γ_3	$\rho\pi$	0.570 ±0.030	
Γ_4	$\pi^+\pi^-\pi^0$	0.12 ±0.04	1.1
Γ_5	$\eta\gamma$	0.0561±0.0025	1.1

$\phi(1020)$ PARTIAL WIDTHS

$\Gamma(\rho\pi)$ — Γ_3

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
0.570±0.030 OUR FIT			
0.57 ±0.03	JULLIAN 76	OSPK	e^+e^-

$\Gamma(e^+e^-)$ — Γ_7

VALUE (keV)	DOCUMENT ID
1.37±0.05 OUR EVALUATION	

$\phi(1020)$ BRANCHING RATIOS

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.491±0.006 OUR FIT Error includes scale factor of 1.2.				
0.493±0.010 OUR AVERAGE				
0.492±0.012	2913	AKHMETSHIN 95	CMD2	$e^+e^- \to K^+K^-$
0.44 ±0.05	321	KALBFLEISCH 76	HBC	2.18 $K^-p \to \Lambda K^+K^-$
0.49 ±0.06	270	DEGROOT 74	HBC	4.2 $K^-p \to \Lambda\phi$
0.540±0.034	565	BALAKIN 71	OSPK	$e^+e^- \to K^+K^-$
0.486±0.044		CHATELUS 71	OSPK	e^+e^-
0.48 ±0.04	252	LINDSEY 66	HBC	2.1–2.7 $K^-p \to \Lambda K^+K^-$

$\Gamma(K^0_L K^0_S)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.341±0.005 OUR FIT Error includes scale factor of 1.1.				
0.334±0.007 OUR AVERAGE				
0.335±0.010	40644	AKHMETSHIN 95	CMD2	$e^+e^- \to K^0_L K^0_S$
0.326±0.035		DOLINSKY 91	ND	$e^+e^- \to K^0_L K^0_S$
0.310±0.024		DRUZHININ 84	ND	$e^+e^- \to K^0_L K^0_S$
0.338±0.010		KURDADZE 84	OLYA	$e^+e^- \to K^0_L K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.27 ±0.03	133	KALBFLEISCH 76	HBC	2.18 $K^-p \to \Lambda K^0_L K^0_S$
0.257±0.030	95	BALAKIN 71	OSPK	$e^+e^- \to K^0_L K^0_S$
0.40 ±0.04	167	LINDSEY 66	HBC	2.1–2.7 $K^-p \to \Lambda K^0_L K^0_S$

$[\Gamma(\rho\pi)+\Gamma(\pi^+\pi^-\pi^0)]/\Gamma_{total}$ — $(\Gamma_3+\Gamma_4)/\Gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.156±0.005 OUR FIT Error includes scale factor of 1.3.				
0.152±0.005 OUR AVERAGE Error includes scale factor of 1.2.				
0.161±0.008	11761	AKHMETSHIN 95	CMD2	$e^+e^- \to \pi^+\pi^-\pi^0$
0.143±0.007		DOLINSKY 91	ND	$e^+e^- \to \pi^+\pi^-\pi^0$
0.155±0.008		KURDADZE 84	OLYA	$e^+e^- \to \pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.139±0.007		[7] PARROUR 76B	OSPK	e^+e^-

[7] Using total width 4.1 MeV. The $\rho\pi$ to 3π mode is more than 80%. at the 90% confidence level.

$\Gamma(K^0_L K^0_S)/\Gamma(K\overline{K})$ — $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.409±0.006 OUR FIT Error includes scale factor of 1.1.				
0.45 ±0.04 OUR AVERAGE				
0.44 ±0.07		LONDON 66	HBC	2.24 $K^-p \to \Lambda K\overline{K}$
0.48 ±0.07	52	BADIER 65B	HBC	3 K^-p
0.40 ±0.10	34	SCHLEIN 63	HBC	1.95 $K^-p \to \Lambda K\overline{K}$

$[\Gamma(\rho\pi)+\Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K\overline{K})$ — $(\Gamma_3+\Gamma_4)/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID	TECN	COMMENT
0.187±0.007 OUR FIT Error includes scale factor of 1.3.			
0.24 ±0.04 OUR AVERAGE			
0.237±0.039	CERRADA 77B	HBC	4.2 $K^-p \to \Lambda 3\pi$
0.30 ±0.15	LONDON 66	HBC	2.24 $K^-p \to \Lambda\pi^+\pi^-\pi^0$

$[\Gamma(\rho\pi)+\Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K^0_L K^0_S)$ — $(\Gamma_3+\Gamma_4)/\Gamma_2$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.457±0.018 OUR FIT Error includes scale factor of 1.3.				
0.51 ±0.05 OUR AVERAGE				
0.56 ±0.07	3681	BUKIN 78C	OLYA	$e^+e^- \to K^0_L K^0_S$, $\pi^+\pi^-\pi^0$
0.47 ±0.06	516	COSME 74	OSPK	$e^+e^- \to \pi^+\pi^-\pi^0$

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
2.48±0.34 OUR AVERAGE			
2.69±0.46	[8] HAYES 71	CNTR	8.3,9.8 $\gamma C \to \mu^+\mu^- X$
2.17±0.60	[8] EARLES 70	CNTR	6.0 $\gamma C \to \mu^+\mu^- X$
2.34±1.01	MOY 69	CNTR	5.0 $\gamma C \to \mu^+\mu^- X$

[8] Neglecting interference between resonance and continuum.

$\Gamma(\eta\gamma)/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0126±0.0006 OUR FIT Error includes scale factor of 1.1.				
0.0126±0.0005 OUR AVERAGE Error includes scale factor of 1.1.				
0.0118±0.0011	279	AKHMETSHIN 95	CMD2	$e^+e^- \to \eta\gamma$
0.0130±0.0006		[9] DRUZHININ 84	ND	$e^+e^- \to 3\gamma$
0.014 ±0.002		[10] DRUZHININ 84	ND	$e^+e^- \to 6\gamma$
0.0088±0.0020	290	KURDADZE 83C	OLYA	$e^+e^- \to 3\gamma$
0.0135±0.0029		ANDREWS 77	CNTR	6.7–10 γ Cu
0.015 ±0.004	54	[9] COSME 76	OSPK	e^+e^-

[9] From 2γ decay mode of η.

[10] From $3\pi^0$ decay mode of η.

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.007	90	COSME 74	OSPK	$e^+e^- \to \pi^+\pi^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.06	90	KALBFLEISCH 75	HBC	2.18 $K^-p \to \Lambda\pi^+\pi^-\gamma$
<0.04	99	LINDSEY 65	HBC	2.1–2.7 $K^-p \to \Lambda\pi^+\pi^-$ neutrals

$\Gamma(\omega\gamma)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.05	84	LINDSEY 66	HBC	2.1–2.7 $K^-p \to \Lambda\pi^+\pi^-$ neutrals

$\Gamma(\rho\gamma)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.02	84	LINDSEY 66	HBC	2.1–2.7 $K^-p \to \Lambda\pi^+\pi^-$ neutrals

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
3.00±0.06 OUR AVERAGE Error includes scale factor of 1.1.				
2.88±0.09	55600	AKHMETSHIN 95	CMD2	$e^+e^- \to$ hadrons
3.05±0.12	13714	KURDADZE 84	OLYA	$e^+e^- \to$ hadrons
3.00±0.21	3681	BUKIN 78C	OLYA	$e^+e^- \to$ hadrons
3.10±0.14		[11] PARROUR 76	OSPK	e^+e^-
3.3 ±0.3		COSME 74	OSPK	$e^+e^- \to$ hadrons
2.81±0.25	681	BALAKIN 71	OSPK	$e^+e^- \to$ hadrons
3.50±0.27		CHATELUS 71	OSPK	e^+e^-

[11] Using total width 4.2 MeV. They detect 3π mode and observe significant interference with ω tail. This is accounted for in the result quoted above.

$\Gamma(\pi^0\gamma)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.31±0.13 OUR AVERAGE				
1.30±0.13		DRUZHININ 84	ND	$e^+e^- \to 3\gamma$
1.4 ±0.5	32	COSME 76	OSPK	e^+e^-

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
$0.8^{+0.5}_{-0.4}$ OUR AVERAGE Error includes scale factor of 1.5.				
$0.63^{+0.37}_{-0.28}$		[12] GOLUBEV 86	ND	$e^+e^- \to \pi^+\pi^-$
$1.94^{+1.03}_{-0.81}$		[12] VASSERMAN 81	OLYA	e^+e^-
<6.6	95	BUKIN 78B	OLYA	$e^+e^- \to \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.0	95	JULLIAN 76	OSPK	e^+e^-
<2.7	95	ALVENSLEBEN 72	CNTR	6.7 $\gamma C \to C\pi^+\pi^-$

[12] Using $\Gamma(e^+e^-)/\Gamma_{total} = 3.1 \times 10^{-4}$.

$\Gamma(K^0_L K^0_S)/\Gamma(K^+K^-)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.693±0.018 OUR FIT Error includes scale factor of 1.1.				
0.740±0.031 OUR AVERAGE				
0.70 ±0.06	2732	BUKIN 78C	OLYA	$e^+e^- \to K^0_L K^0_S$
0.82 ±0.08		LOSTY 78	HBC	4.2 $K^-p \to \phi$ hyperon
0.71 ±0.05		LAVEN 77	HBC	10 $K^-p \to K^+K^-\Lambda$
0.71 ±0.08		LYONS 77	HBC	3–4 $K^-p \to \Lambda\phi$
0.89 ±0.10	144	AGUILAR-... 72B	HBC	3.9,4.6 K^-p

$[\Gamma(\rho\pi)+\Gamma(\pi^+\pi^-\pi^0)]/\Gamma(K^+K^-)$ — $(\Gamma_3+\Gamma_4)/\Gamma_1$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.317±0.013 OUR FIT Error includes scale factor of 1.3.				
0.28 ±0.09	34	AGUILAR-... 72B	HBC	3.9,4.6 K^-p

$\Gamma(\eta e^+e^-)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID	TECN	COMMENT
$1.3^{+0.8}_{-0.6}$	7	GOLUBEV 85	ND	$e^+e^- \to \gamma\gamma e^+e^-$

$\Gamma(\eta'(958)\gamma)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<4.1	90	DRUZHININ	87	ND	$e^+e^- \to \gamma\eta\pi^+\pi^-$

$\Gamma(\pi^0\pi^0\gamma)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1	90	DRUZHININ	87	ND	$e^+e^- \to 5\gamma$

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	95	BARKOV	88	CMD	$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<8.7	90	CORDIER	79	WIRE	$e^+e^- \to 4\pi$

$\Gamma(f_0(980)\gamma)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2	90	[13] DRUZHININ	87	ND	$e^+e^- \to \pi^0\pi^0\gamma$

[13] Uses narrow width approximation which is questioned by ACHASOV 95

$\Gamma(\pi^0 e^+ e^-)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.2 \times 10^{-4}$	90	DOLINSKY	88	ND	$e^+e^- \to \pi^0 e^+e^-$

$\Gamma(\pi^0\eta\gamma)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.5	90	DOLINSKY	91	ND	$e^+e^- \to \pi^0\eta\gamma$

$\Gamma(a_0(980)\gamma)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	[14] DOLINSKY	91	ND	$e^+e^- \to \pi^0\eta\gamma$

[14] Uses narrow width approximation which is questioned by ACHASOV 95

$\phi(1020)$ REFERENCES

ACHASOV 95 PLB 363 106 +Gubin (NOVM)
AKHMETSHIN 95 PL B364 199 +Akesnov+ (NOVO, BOST, PITT, MINN, YALE)
DOLINSKY 91 PRPL 202 99 +Druzhinin, Dubrovin+ (NOVO)
BARKOV 88 SJNP 47 248 +Vasserman, Vorobyev, Ivanov+ (NOVO)
Translated from YAF 47 393.
DOLINSKY 88 SJNP 48 277 +Druzhinin, Dubrovin, Golubev+ (NOVO)
Translated from YAF 48 442.
DRUZHININ 87 ZPHY C37 1 +Dubrovin, Eidelman, Golubev+ (NOVO)
ARMSTRONG 86 PL 166B 245 +Bloodworth, Carney+ (ATHU, BARI, BIRM, CERN)
ATKINSON 86 ZPHY C30 521 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
BEBEK 86 PRL 56 1893 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
DAVENPORT 86 PR 33 2519 (TUFTS, ARIZ, FNAL, FSU, NDAM, VAND)
DIJKSTRA 86 ZPHY C31 375 +Bailey+ (ANIK, BRIS, CERN, CRAC, MPIM, RAL)
FRAME 86 NP B276 667 +Hughes, Lynch, Minto, McFadzean+ (GLAS)
GOLUBEV 86 SJNP 44 409 +Druzhinin, Ivanchenko, Perevedentsev+ (NOVO)
Translated from YAF 44 633.
ALBRECHT 85D PL 153B 343 +Drescher, Binder, Drews+ (ARGUS Collab.)
GOLUBEV 85 SJNP 41 756 +Druzhinin, Ivanchenko, Peryshkin+ (NOVO)
Translated from YAF 41 1183.
DRUZHININ 84 PL 144B 136 +Golubev, Ivanchenko, Peryshkin+ (NOVO)
KURDADZE 84 IYF 84-7 Preprint +Leltchouk, Pakhtusova, Sidorov+ (NOVO)
ARMSTRONG 83B NP B224 193 + (BARI, BIRM, CERN, MILA, CURIN+)
BARATE 83 PL 121B 449 +Bareyre, Bonamy+ (SACL, LOIC, SHMP, IND)
KURDADZE 83C JETPL 38 366 +Lelchuk, Root+ (NOVO)
Translated from ZETFP 38 306.
ARENTON 82 PR D25 2241 +Ayres, Diebold, May, Swallow+ (ANL, ILL)
PELLINEN 82 PS 25 599 +Roos (HELS)
DAUM 81 PL 100B 439 +Bardsley+ (AMST, BRIS, CERN, CRAC, MPIM+)
IVANOV 81 PL 107B 297 +Kurdadze, Lelchuk, Sidorov, Skrinsky+ (NOVO)
Also 82 Private Comm. Eidelman (NOVO)
VASSERMAN 81 PL 99B 62 +Kurdadze, Sidorov, Skrinsky+ (NOVO)
CORDIER 80 NP B172 13 +Delcourt, Eschstruth, Fulda+ (LALO)
BARKOV 79B IYF 79-93 Preprint +Zolotorev, Makarina, Mishakova+ (NOVO)
CORDIER 79 PL 81B 389 +Delcourt, Eschstruth, Fulda+ (LALO)
BUKIN 78B SJNP 27 521 +Kurdadze, Sidorov, Skrinsky+ (NOVO)
Translated from YAF 27 985.
BUKIN 78C SJNP 27 516 +Kurdadze, Serednyakov, Sidorov+ (NOVO)
Translated from YAF 27 976.
COOPER 78B NP B146 1 +Ganguli+ (TATA, CERN, CDEF, MADR)
LOSTY 78 NP B133 38 +Holmgren, Blokzijl+ (CERN, AMST, NIJM, OXF)
AKERLOF 77 PRL 39 861 +Alley, Bintinger, Ditzler+ (FNAL, MICH, PURD)
ANDREWS 77 PRL 38 198 +Fukushima, Harvey, Lobkowicz, May+ (ROCH)
BALDI 77 PL 68B 381 +Bohringer, Dorsaz, Hungerbuhler+ (GEVA)
CERRADA 77B NP B126 241 +Blockzijl, Heinen+ (AMST, CERN, NIJM, OXF)
COHEN 77 PRL 38 269 +Ayres, Diebold, Kramer, Pawlicki, Wicklund (ANL)
LAVEN 77 NP B127 43 +Otter, Klein+ (AACH3, BERL, CERN, LOIC, WIEN)
LYONS 77 NP B125 207 +Cooper, Clark (OXF)
COSME 76 PL 63B 352 +Courau, Dudelzak, Grelaud, Jean-Marie+ (ORSAY)
JULLIAN 76 Tbilisi 2 B19 (ORSAY)
KALBFLEISCH 76 PR D13 22 +Strand, Chapman (BNL, MICH)
PARROUR 76 PL 63B 357 +Grelaud, Cosme, Courau, Dudelzak+ (ORSAY)
PARROUR 76B PL 63B 362 +Grelaud, Cosme, Courau, Dudelzak+ (ORSAY)
KALBFLEISCH 75 PR D11 987 +Strand, Chapman (BNL, MICH)
AYRES 74 PRL 32 1463 +Diebold, Greene, Kramer, Levine+ (ANL)
BESCH 74 NP B70 257 +Hartmann, Kose, Krautschneider, Paul+ (BONN)
COSME 74 PL 48B 155 +Jean-Marie, Jullian, Laplanche+ (ORSAY)
COSME 74B PL 48B 159 +Jean-Marie, Jullian, Laplanche+ (ORSAY)
DEGROOT 74 NP B74 77 +Hoogland, Jongejans, Metzger+ (AMST, NIJM)
BALLAM 73 PR D7 3150 +Chadwick, Eisenberg, Bingham+ (SLAC, LBL)
BINNIE 73B PR D8 2789 +Carr, Debenham, Duane+ (LOIC, SHMP)
AGUILAR-... 72B PR D6 29 Aguilar-Benitez, Chung, Eisner, Samios (BNL)
ALVENSLEBEN 72 PRL 28 66 +Becker, Biggs, Binkley+ (MIT, DESY)
BORENSTEIN 72 PR D5 1559 +Danburg, Kalbfleisch+ (BNL, MICH)
COLLEY 72 NP B50 1 +Jobes, Riddiford, Griffiths+ (BIRM, GLAS)
BALAKIN 71 PL 34B 328 +Budker, Pakhtusova, Sidorov, Skrinsky+ (NOVO)
CHATELUS 71 Thesis LAL 1247 (STRB)
Also 70 PL 32 416 Bizot, Buon, Chatelus, Jeanjean+ (ORSAY)
HAYES 71 PR D4 899 +Imlay, Joseph, Keizer, Stein (CORN)
STOTTLE... 71 Thesis ORO 2504 170 Stottlemyer (UMD)
BIZOT 70 PL 32 416 +Buon, Chatelus, Jeanjean+ (ORSAY)
Also 69 Liverpool Sym. 69 Perez-y-Jorba
EARLES 70 PRL 25 1312 +Faissler, Gettner, Lutz, Moy, Tang+ (NEAS)
MOY 69 Thesis (NEAS)
LINDSEY 66 PR 147 913 +Smith (LRL)
LONDON 66 PR 143 1034 +Rau, Goldberg, Lichtman+ (BNL, SYRA) IGJPC
BADIER 65B PL 17 337 +Demoulin, Barloutaud+ (EPOL, SACL, AMST)
LINDSEY 65 PRL 15 221 +Smith (LRL)
LINDSEY 65 data included in LINDSEY 66.
SCHLEIN 63 PRL 10 368 +Slater, Smith, Stork, Ticho (UCLA) IGJP

OTHER RELATED PAPERS

KAMAL 92 PL B284 421 +Xu (ALBE)
GEORGIO... 85 PL 152B 428 Georgiopoulos+ (TUFTS, ARIZ, FNAL, FSU, NDAM+)
ARMENTEROS 63B Siena Conf. 2 70 +Edwards, Astier+ (CERN, CDEF)
GELFAND 63B PRL 11 438 +Miller, Nussbaum, Kirsch+ (COLU, RUTG)
BERTANZA 62 PRL 9 180 +Brisson, Connolly, Hart+ (BNL, SYRA)

$h_1(1170)$

$I^G(J^{PC}) = 0^-(1^{+-})$

$h_1(1170)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1170±20 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1168± 4	ANDO	92	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
1166± 5±3	[1] ANDO	92	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
1190±60	[2] DANKOWY...	81	SPEC	0	$8\ \pi p \to 3\pi n$

[1] Average and spread of values using 2 variants of the model of BOWLER 75.
[2] Uses the model of BOWLER 75.

$h_1(1170)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
360±40 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
345± 6	ANDO	92	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
375± 6±34	[3] ANDO	92	SPEC		$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$
320±50	[4] DANKOWY...	81	SPEC	0	$8\ \pi p \to 3\pi n$

[3] Average and spread of values using 2 variants of the model of BOWLER 75.
[4] Uses the model of BOWLER 75.

$h_1(1170)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen

$h_1(1170)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ATKINSON	84	OMEG	20–70 $\gamma p \to \pi^+\pi^-\pi^0 p$
seen	DANKOWY...	81	SPEC	$8\ \pi p \to 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	ANDO	92	SPEC	$8\ \pi^- p \to \pi^+\pi^-\pi^0 n$

$h_1(1170)$ REFERENCES

ANDO 92 PL B291 496 +Imai+ (KEK, KYOT, NIRS, SAGA, INUS, AKIT)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
DANKOWY... 81 PRL 46 580 Dankowych+ (TNTO, BNL, CARL, MCGI, OHIO)
BOWLER 75 NP B97 227 +Game, Aitchison, Dainton (OXFTP, DARE)

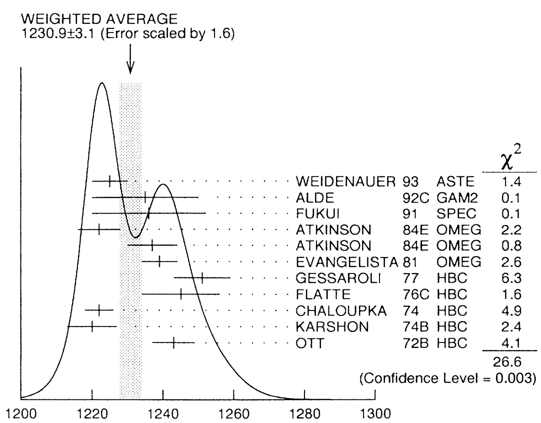
$b_1(1235)$

$I^G(J^{PC}) = 1^+(1^{+-})$

$b_1(1235)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1231 ±10 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.				
1230.9± 3.1 OUR AVERAGE		Error includes scale factor of 1.6. See the ideogram below.				
1225 ± 5		WEIDENAUER	93	ASTE		$\bar{p}p \to 2\pi^+2\pi^-\pi^0$
1235 ±15		ALDE	92C	GAM2		38,100 $\pi^- p \to \omega\pi^0 n$
1236 ±16		FUKUI	91	SPEC		8.95 $\pi^- p \to \omega\pi^0 n$
1222 ± 6		ATKINSON	84E	OMEG	±	25–55 $\gamma p \to \omega\pi X$
1237 ± 7		ATKINSON	84E	OMEG	0	25–55 $\gamma p \to \omega\pi X$
1239 ± 5		EVANGELISTA	81	OMEG	−	12 $\pi^- p \to \omega\pi p$
1251 ± 8	450	GESSAROLI	77	HBC	−	11 $\pi^- p \to \pi^-\omega p$
1245 ±11	890	FLATTE	76C	HBC	−	4.2 $K^- p \to \pi^-\omega\Sigma^+$
1222 ± 4	1400	CHALOUPKA	74	HBC	−	3.9 $\pi^- p$
1220 ± 7	600	KARSHON	74B	HBC	+	4.9 $\pi^+ p$
1243 ± 6	1163	[1] OTT	72B	HBC	+	7.1 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1311 ±10		[2] TAKAMATSU	90	SPEC	0	8 $\pi^- p \to \eta\rho n$
1190 ±10		AUGUSTIN	89	DM2	±	$e^+e^- \to 5\pi$
1213 ± 5		ATKINSON	84C	OMEG	0	20–70 γp
1271 ±11		COLLICK	84	SPEC	+	200 $\pi^+ Z \to Z\pi\omega$

[1] From fit of the mass spectrum.
[2] Breit–Wigner fitting of PWA of $\eta\pi\pi$ system.



$b_1(1235)$ mass (MeV)

$b_1(1235)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
142± 8 OUR AVERAGE		Error includes scale factor of 1.1.				
113±12		WEIDENAUER	93	ASTE		$\bar{p}p \to 2\pi^+2\pi^-\pi^0$
160±30		ALDE	92C	GAM2		38,100 $\pi^- p \to \omega\pi^0 n$
151±31		FUKUI	91	SPEC		8.95 $\pi^- p \to \omega\pi^0 n$
170±15		EVANGELISTA	81	OMEG	−	12 $\pi^- p \to \omega\pi p$
170±50	225	BALTAY	78B	HBC	+	15 $\pi^+ p \to p4\pi$
155±32	450	GESSAROLI	77	HBC	−	11 $\pi^- p \to \pi^-\omega p$
182±45	890	FLATTE	76C	HBC	−	4.2 $K^- p \to \pi^-\omega\Sigma^+$
135±20	1400	CHALOUPKA	74	HBC	−	3.9 $\pi^- p$
156±22	600	KARSHON	74B	HBC	+	4.9 $\pi^+ p$
134^{+23}_{-26}	1163	[3] OTT	72B	HBC	+	7.1 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
126±10		[4] TAKAMATSU	90	SPEC	0	8 $\pi^- p \to \eta\rho n$
210±19		AUGUSTIN	89	DM2	±	$e^+e^- \to 5\pi$
231±14		ATKINSON	84C	OMEG	0	20–70 γp
232±29		COLLICK	84	SPEC	+	200 $\pi^+ Z \to Z\pi\omega$

[3] From fit of the mass spectrum.
[4] Breit–Wigner fitting of PWA of $\eta\pi\pi$ system.

$b_1(1235)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\omega\pi$ [D/S amplitude ratio = 0.26 ± 0.04]	dominant	
Γ_2	$\pi^{\pm}\gamma$	$(1.6\pm0.4)\times10^{-3}$	
Γ_3	$\eta\rho$	seen	
Γ_4	$\pi^+\pi^+\pi^-\pi^0$	< 50 %	84%
Γ_5	$(K\overline{K})^{\pm}\pi^0$	< 8 %	90%
Γ_6	$K^0_S K^0_L \pi^{\pm}$	< 6 %	90%
Γ_7	$K^0_S K^0_S \pi^{\pm}$	< 2 %	90%
Γ_8	$\pi\phi$	< 1.5 %	84%

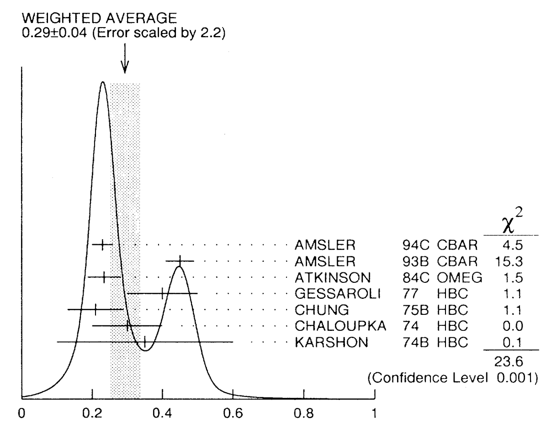
$b_1(1235)$ PARTIAL WIDTHS

$\Gamma(\pi^{\pm}\gamma)$ — Γ_2

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
230±60	COLLICK	84	SPEC	+	200 $\pi^+ Z \to Z\pi\omega$

$b_1(1235)$ D-wave/S-wave AMPLITUDE RATIO IN DECAY OF $b_1(1235) \to \omega\pi$

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.29 ±0.04 OUR AVERAGE		Error includes scale factor of 2.2. See the ideogram below.				
0.23 ±0.03		AMSLER	94C	CBAR		0.0 $\bar{p}p \to \omega\eta\pi^0$
0.45 ±0.04		AMSLER	93B	CBAR		0.0 $\bar{p}p \to \omega\pi^0\pi^0$
0.235±0.047		ATKINSON	84C	OMEG		20–70 γp
$0.4\ ^{+0.1}_{-0.1}$		GESSAROLI	77	HBC	−	11 $\pi^- p \to \pi^-\omega p$
0.21 ±0.08		CHUNG	75B	HBC	+	7.1 $\pi^+ p$
0.3 ±0.1		CHALOUPKA	74	HBC	−	3.9–7.5 $\pi^- p$
0.35 ±0.25	600	KARSHON	74B	HBC	+	4.9 $\pi^+ p$



$b_1(1235)$ D-wave/S-wave amplitude ratio in decay of $b_1(1235) \to \omega\pi$

$b_1(1235)$ BRANCHING RATIOS

$\Gamma(\eta\rho)/\Gamma(\omega\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	TAKAMATSU	90	SPEC	
<0.10	ATKINSON	84D	OMEG	20–70 γp

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(\omega\pi)$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.5	ABOLINS	63	HBC	+	3.5 $\pi^+ p$

$\Gamma((K\overline{K})^{\pm}\pi^0)/\Gamma(\omega\pi)$ — Γ_5/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.08	90	BALTAY	67	HBC	±	0.0 $\bar{p}p$

$\Gamma(K^0_S K^0_L \pi^{\pm})/\Gamma(\omega\pi)$ — Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.06	90	BALTAY	67	HBC	±	0.0 $\bar{p}p$

$\Gamma(K^0_S K^0_S \pi^{\pm})/\Gamma(\omega\pi)$ — Γ_7/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.02	90	BALTAY	67	HBC	±	0.0 $\bar{p}p$

$\Gamma(\pi\phi)/\Gamma(\omega\pi)$ — Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.015		DAHL	67	HBC		1.6–4.2 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.04	95	BIZZARRI	69	HBC	$\pm$	0.0 $\overline{p}p$

$b_1(1235)$ REFERENCES

AMSLER 94C PL B327 425 +Armstrong, Ravndal+ (Crystal Barrel Collab.)
AMSLER 93B PL B311 362 +Armstrong, v.Dombrowski+ (Crystal Barrel Collab.)
WEIDENAUER 93 ZPHY C59 387 +Duch+ (ASTERIX Collab.)
ALDE 92C ZPHY C54 553 +Bencheikh, Binon+ (BELG, SERP, KEK, LANL, LAPP)
FUKUI 91 PL B257 241 +Horikawa+ (SUGI, NAGO, KEK, KYOT, MIYA)
TAKAMATSU 90 Hadron 89 Conf. p 71 +Ando+ (KEK)
AUGUSTIN 89 NP B320 1 +Cosme (DM2 Collab.)
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+) JP
ATKINSON 84D NP B242 269 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON 84E PL 138B 459 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
COLLICK 84 PRL 53 2374 +Heppelmann, Berg+ (MINN, ROCH, FNAL)
EVANGELISTA 81 NP B178 197 + (BARI, BONN, CERN, DARE, LIVP+)
BALTAY 78B PR D17 62 +Cautis, Cohen, Csorna+ (COLU, BING)
GESSAROLI 77 NP B126 382 + (BGNA, FIRZ, GENO, MILA, OXF, PAVI) JP
FLATTE 76C PL 64B 225 +Gay, Blokzijl, Metzger+ (CERN, AMST, NIJM, OXF) JP
CHUNG 75B PR D11 2426 +Protopopescu, Lynch, Flatte+ (BNL, LBL, UCSC) JP
CHALOUPKA 74 PL 51B 407 +Ferrando, Losty, Montanet (CERN) JP
KARSHON 74B PR D10 3608 +Mikenberg, Eisenberg, Pitluck, Ronat+ (REHO) JP
OTT 72B Thesis LBL-1547 (LBL) JP
BIZZARRI 69 NP B14 169 +Foster, Gavillet, Montanet+ (CERN, CDEF)
BALTAY 67 PRL 18 93 +Franzini, Severiens, Yeh, Zanello (COLU)
DAHL 67 PR 163 1377 +Hardy, Hess, Kirz, Miller (LRL)
ABOLINS 63 PRL 11 381 +Lander, Mehlhop, Nguyen, Yager (UCSD)

OTHER RELATED PAPERS

BRAU 88 PR D37 2379 +Franek+ (SLAC Hybrid Facility Photon Collab.) JP
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+) JP
GOLDHABER 65 PRL 15 118 +Goldhaber, Kadyk, Shen (LRL)
CARMONY 64 PRL 12 254 +Lander, Rindfleisch, Xuong, Yager (UCB) JP
BONDAR 63B PL 5 209 +Dodd+ (AACH, BIRM, HAMB, LOIC, MPIM)

$a_1(1260)$

$I^G(J^{PC}) = 1^-(1^{++})$

THE $a_1(1260)$

The main experimental data on the $a_1(1260)$ may be grouped into two classes:

(1) Hadronic production: This comprises diffractive production with incident π^- (DAUM 80, 81B) and charge-exchange production with low-energy π^- (DANKOWYCH 81, ANDO 92). The 1980's experiments explain the $I^GLJ^P = 1^+S0^+$ data using a phenomenological amplitude consisting of a rescattered Deck amplitude plus a direct resonance-production term. They agree on an $a_1(1260)$ mass of about 1270 MeV and a width of 300-380 MeV. ANDO 92 finds rather lower values for the mass (1121 MeV) and width (239 MeV) in a partial-wave analysis based on the isobar model of the $\pi^+\pi^-\pi^0$ system. However, in this analysis, only Breit-Wigner terms were considered.

(2) τ decay: Five experiments have reported good data on $\tau \to a_1(1260)\nu_\tau \to \rho\pi\nu_\tau$ (RUCKSTUHL 86, SCHMIDKE 86, ALBRECHT 86B, BAND 87, and AKERS 95P). They are somewhat inconsistent concerning the $a_1(1260)$ mass, which can, however, be attributed to model-dependent systematic uncertainties (BOWLER 86, ALBRECHT 93C, AKERS 95P). They all find a width greater than 400 MeV.

The discrepancies between the early hadronic and τ decay results have stimulated several reanalyses. BOWLER 86, TORNQVIST 87, ISGUR 89, and IVANOV 91 have studied the process $\tau \to 3\pi\nu_\tau$. Despite quite different approaches, they all found a good overall description of the τ decay data with an $a_1(1260)$ mass near 1230 MeV, consistent with the hadronic data. However, their widths remain significantly higher (400-600 MeV) than those extracted from diffractive-hadronic data. This is also the case with the later OPAL experiment (AKERS 95P).

BOWLER 88 showed that good fits to both the hadronic and the τ-decay data could be obtained with a width of about 400 MeV. However, applying the same type of analysis to the ANDO 92 data, the low mass and narrow width they obtained with the Breit-Wigner PWA do not change appreciably.

CONDO 93 found no evidence for charge-exchange photoproduction of the $a_1(1260)$ (but found a clear signal of $a_2(1320)$ photoproduction). They show that this is consistent with either an extremely large $a_1(1260)$ hadronic width or with a small radiative width to $\pi\gamma$, which could be accommodated if the a_1 mass is somewhat below 1260 MeV.

$a_1(1260)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1230±40 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1266\pm14^{+12}_{-2}$	[1] AKERS	95P	OPAL		E^{ee}_{cm}= 88–94
$1202\pm9^{+9}_{-1}$	[2] AKERS	95P	OPAL		E^{ee}_{cm}= 88–94
1211 ± 7	ALBRECHT	93C	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1121 ± 8	[3] ANDO	92	SPEC		8 $\pi^- p \to \pi^+\pi^-\pi^0 n$
1242 ± 37	[4] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
1260 ± 14	[5] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
1250 ± 9	[6] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
1208 ± 15	ARMSTRONG	90	OMEG	0	300.0$pp \to pp\pi^+\pi^-\pi^0$
1220 ± 15	[7] ISGUR	89	RVUE		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1260 ± 25	[8] BOWLER	88	RVUE		
$1166\pm18\pm11$	BAND	87	MAC		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
$1164\pm41\pm23$	BAND	87	MAC		$\tau^+ \to \pi^+\pi^0\pi^0\nu$
1250 ± 40	[7] TORNQVIST	87	RVUE		
1046 ± 11	ALBRECHT	86B	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
$1056\pm20\pm15$	RUCKSTUHL	86	DLCO		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
$1194\pm14\pm10$	SCHMIDKE	86	MRK2		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
1240 ± 80	[9] DANKOWY...	81	SPEC	0	8.45 $\pi^- p \to n3\pi$
1280 ± 30	[9] DAUM	81B	CNTR		63,94 $\pi^- p \to p3\pi$
1041 ± 13	[10] GAVILLET	77	HBC	+	4.2 $K^- p \to \Sigma 3\pi$

[1] Uses the model of Kuhn and Santamaria.
[2] Uses the model of Isgur, Morningstar, and Reader.
[3] Average and spread of values using 2 variants of the model of BOWLER 75.
[4] Reanalysis of RUCKSTUHL 86.
[5] Reanalysis of SCHMIDKE 86.
[6] Reanalysis of ALBRECHT 86B.
[7] From a combined reanalysis of ALBRECHT 86B, SCHMIDKE 86, and RUCKSTUHL 86.
[8] From a combined reanalysis of ALBRECHT 86B and DAUM 81B.
[9] Uses the model of BOWLER 75.
[10] Produced in K^- backward scattering.

$a_1(1260)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
~ 400 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$610\pm49^{+53}_{-19}$	[11] AKERS	95P	OPAL		E^{ee}_{cm}= 88–94
$422\pm23^{+33}_{-4}$	[12] AKERS	95P	OPAL		E^{ee}_{cm}= 88–94
446 ± 21	ALBRECHT	93C	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
239 ± 11	ANDO	92	SPEC		8 $\pi^- p \to \pi^+\pi^-\pi^0 n$
$266\pm13\pm4$	[13] ANDO	92	SPEC		8 $\pi^- p \to \pi^+\pi^-\pi^0 n$
465^{+228}_{-143}	[14] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
298^{+40}_{-34}	[15] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
488 ± 32	[16] IVANOV	91	RVUE		$\tau \to \pi^+\pi^+\pi^-\nu$
430 ± 50	ARMSTRONG	90	OMEG	0	300.0$pp \to pp\pi^+\pi^-\pi^0$
420 ± 40	[17] ISGUR	89	RVUE		$\tau^+ \to \pi^+\pi^+\pi^-\nu$

396 ± 43	[18] BOWLER	88	RVUE		
$405\pm 75\pm 25$	BAND	87	MAC		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
$419\pm 108\pm 57$	BAND	87	MAC		$\tau^+ \to \pi^+\pi^0\pi^0\nu$
521 ± 27	ALBRECHT	86B	ARG		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
$476^{+132}_{-120}\pm 54$	RUCKSTUHL	86	DLCO		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
$462\pm 56\pm 30$	SCHMIDKE	86	MRK2		$\tau^+ \to \pi^+\pi^+\pi^-\nu$
380 ± 100	[19] DANKOWY...	81	SPEC	0	$8.45\ \pi^- p \to n 3\pi$
300 ± 50	[19] DAUM	81B	CNTR		$63,94\ \pi^- p \to p 3\pi$
230 ± 50	[20] GAVILLET	77	HBC	+	$4.2\ K^- p \to \Sigma 3\pi$

[11] Uses the model of Kuhn and Santamaria.
[12] Uses the model of Isgur, Morningstar, and Reader.
[13] Average and spread of values using 2 variants of the model of BOWLER 75.
[14] Reanalysis of RUCKSTUHL 86.
[15] Reanalysis of SCHMIDKE 86.
[16] Reanalysis of ALBRECHT 86B.
[17] From a combined reanalysis of ALBRECHT 86B, SCHMIDKE 86, and RUCKSTUHL 86.
[18] From a combined reanalysis of ALBRECHT 86B and DAUM 81B.
[19] Uses the model of BOWLER 75.
[20] Produced in K^- backward scattering.

$a_1(1260)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	dominant
Γ_2	$\pi\gamma$	seen
Γ_3	$\pi(\pi\pi)_{S\text{-wave}}$	
Γ_4	$K\overline{K}^*(892)$	possibly seen

$a_1(1260)$ PARTIAL WIDTHS

$\Gamma(\pi\gamma)$ Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
640±246	ZIELINSKI	84C	SPEC	$200\ \pi^+ Z \to Z 3\pi$

D-wave/*S*-wave AMPLITUDE RATIO IN DECAY OF $a_1(1260) \to \rho\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09 ±0.03 ±0.01	[21] AKERS	95P	OPAL	E^{ee}_{cm}= 88–94

[21] Uses the model of Isgur, Morningstar, and Reader.

$a_1(1260)$ BRANCHING RATIOS

$\Gamma(\pi(\pi\pi)_{S\text{-wave}})/\Gamma(\rho\pi)$ Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.003 ± 0.003	[22] LONGACRE	82	RVUE

[22] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from GAVILLET 77, DAUM 80, and DANKOWYCH 81.

$a_1(1260)$ REFERENCES

AKERS 95P ZPHY C67 45 +Alexander, Allison, Ametewee+ (OPAL Collab.)
ALBRECHT 93C ZPHY C58 61 +Ehrlichmann, Hamacher+ (ARGUS Collab.)
ANDO 92 PL B291 496 +Imai+ (KEK, KYOT, NIRS, SAGA, INUS, AKIT)
IVANOV 91 ZPHY C49 563 +Osipov, Volkov (JINR)
ARMSTRONG 90 ZPHY C48 213 +Benayoun, Beusch (WA76 Collab.)
ISGUR 89 PR D39 1357 +Morningstar, Reader (TNTO)
BOWLER 88 PL B209 99 (OXF)
BAND 87 PL B198 297 +Camporesi, Chadwick, Delfino+ (MAC Collab.)
TORNQVIST 87 ZPHY C36 695 (HELS)
ALBRECHT 86B ZPHY C33 7 +Donker, Gabriel, Edwards+ (ARGUS Collab.)
RUCKSTUHL 86 PRL 56 2132 +Stroynowski, Atwood, Barish+ (DELCO Collab.)
SCHMIDKE 86 PRL 57 527 +Abrams, Matteuzzi, Amidei+ (Mark II Collab.)
ZIELINSKI 84C PRL 52 1195 +Berg, Chandlee, Cihangir+ (ROCH, MINN, FNAL)
LONGACRE 82 PR D26 83 (BNL)
DANKOWY... 81 PRL 46 580 Dankowych+ (TNTO, BNL, CARL, MCGI, OHIO)
DAUM 81B NP B182 269 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
DAUM 80 PL 89B 281 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+) JP
GAVILLET 77 PL 69B 119 +Blockzijl, Engelen+ (AMST, CERN, NIJM, OXF) JP
BOWLER 75 NP B97 227 +Game, Aitchison, Dainton (OXFTP, DARE)

OTHER RELATED PAPERS

BOLONKIN 95 PAN 58 1535 +Vladimirskii, Erofeeva+ (ITEP)
Translated from YAF 58 1628.
WINGATE 95 PRL 74 4596 +De Grand (COLO, FSU)
IIZUKA 89 PR D39 3357 +Koibuchi, Masuda (NAGO, IBAR, TSUK)
TORNQVIST 87 ZPHY C36 695 (HELS)
BOWLER 86 PL B182 400 (OXF)
ADERHOLZ 64 PL 10 226 + (AACH3, BERL, BIRM, BONN, DESY, HAMB+)
GOLDHABER 64 PRL 12 336 +Brown, Kadyk, Shen+ (LRL, UCB)
LANDER 64 PRL 13 346A +Abolins, Carmony, Hendricks, Xuong+ (UCSD) JP
BELLINI 63 NC 29 896 +Fiorini, Herz, Negri, Ratti (MILA)

$f_2(1270)$

$I^G(J^{PC}) = 0^+(2^{++})$

$f_2(1270)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1275 ± 5 OUR ESTIMATE					
1274.8± 1.2 OUR AVERAGE					
1272 ± 8	200k	PROKOSHKIN	94	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
1269.7± 5.2	5730	AUGUSTIN	89	DM2	$e^+e^- \to 5\pi$
1283 ± 8	400	[1] ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
1274 ± 5		[1] AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1283 ± 6		[2] LONGACRE	86	MPS	$22\ \pi^- p \to n 2K^0_S$
1276 ± 7		COURAU	84	DLCO	$e^+e^- \to e^+e^-\pi^+\pi^-$
1273.3± 2.3		[3] CHABAUD	83	ASPK	$17\ \pi^- p$ polarized
1280 ± 4		[4] CASON	82	STRC	$8\ \pi^+ p \to \Delta^{++}\pi^0\pi^0$
1281 ± 7	11600	GIDAL	81	MRK2	J/ψ decay
1282 ± 5		[5] CORDEN	79	OMEG	$12–15\ \pi^- p \to n 2\pi$
1269 ± 4	10k	APEL	75	NICE	$40\ \pi^- p \to n 2\pi^0$
1272 ± 4	4600	ENGLER	74	DBC	$6\ \pi^+ n \to \pi^+\pi^- p$
1277 ± 4	5300	FLATTE	71	HBC	$7.0\ \pi^+ p$
1273 ± 8		[1] STUNTEBECK	70	HBC	$8\ \pi^- p$, $5.4\ \pi^+ d$
1265 ± 8		BOESEBECK	68	HBC	$8\ \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1281 ± 6		ADAMO	91	OBLX	$\overline{n} p \to \pi^+\pi^+\pi^-$
1262 ±11		AGUILAR-...	91	EHS	$400\ pp$
1275 ±10		AKER	91	CBAR	$0.0\ \overline{p} p \to 3\pi^0$
1220 ±10		BREAKSTONE	90	SFM	$pp \to pp\pi^+\pi^-$
1288 ±12		ABACHI	86B	HRS	$e^+e^- \to \pi^+\pi^- X$
1284 ±30	3k	BINON	83	GAM2	$38\ \pi^- p \to n 2\eta$
1280 ±20	3k	APEL	82	CNTR	$25\ \pi^- p \to n 2\pi^0$
1284 ±10	16000	DEUTSCH...	76	HBC	$16\ \pi^+ p$
1258 ±10	600	TAKAHASHI	72	HBC	$8\ \pi^- p \to n 2\pi$
1275 ±13		ARMENISE	70	HBC	$9\ \pi^+ n \to p\pi^+\pi^-$
1261 ± 5	1960	[1] ARMENISE	68	DBC	$5.1\ \pi^+ n \to p\pi^+ MM^-$
1270 ±10	360	[1] ARMENISE	68	DBC	$5.1\ \pi^+ n \to p\pi^0 MM$
1268 ± 6		[6] JOHNSON	68	HBC	$3.7–4.2\ \pi^- p$
1276 ±11		RABIN	67	HBC	$8.5\ \pi^+ p$

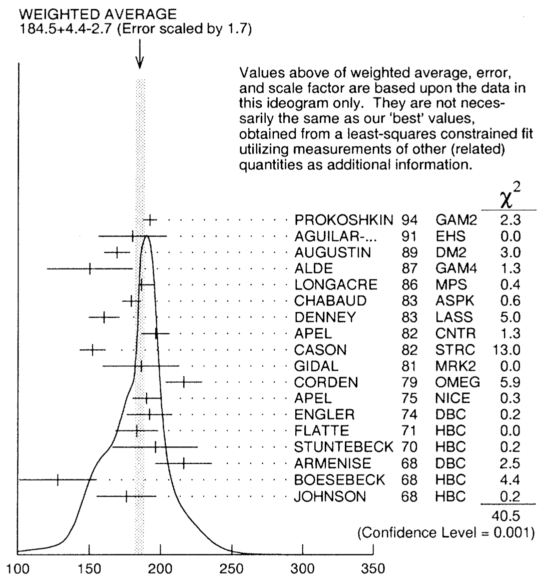
[1] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[2] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[3] From an energy-independent partial-wave analysis.
[4] From an amplitude analysis of the reaction $\pi^+\pi^- \to 2\pi^0$.
[5] From an amplitude analysis of $\pi^+\pi^- \to \pi^+\pi^-$ scattering data.
[6] JOHNSON 68 includes BONDAR 63, LEE 64, DERADO 65, EISNER 67.

$f_2(1270)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
185 ±20 OUR ESTIMATE					
185.4± 2.8 OUR FIT Error includes scale factor of 1.5.					
$184.5^{+4.4}_{-2.7}$ OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.					
192 ± 5	200k	PROKOSHKIN	94	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
180 ±24		AGUILAR-...	91	EHS	$400\ pp$
169 ± 9	5730	[7] AUGUSTIN	89	DM2	$e^+e^- \to 5\pi$
150 ±30	400	[7] ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$
186^{+9}_{-2}		[8] LONGACRE	86	MPS	$22\ \pi^- p \to n 2K^0_S$
$179.2^{+6.9}_{-6.6}$		[9] CHABAUD	83	ASPK	$17\ \pi^- p$ polarized
160 ±11		DENNEY	83	LASS	$10\ \pi^+ N$
196 ±10	3k	APEL	82	CNTR	$25\ \pi^- p \to n 2\pi^0$
152 ± 9		[10] CASON	82	STRC	$8\ \pi^+ p \to \Delta^{++}\pi^0\pi^0$
186 ±27	11600	GIDAL	81	MRK2	J/ψ decay
216 ±13		[11] CORDEN	79	OMEG	$12–15\ \pi^- p \to n 2\pi$
190 ±10	10k	APEL	75	NICE	$40\ \pi^- p \to n 2\pi^0$
192 ±16	4600	ENGLER	74	DBC	$6\ \pi^+ n \to \pi^+\pi^- p$
183 ±15	5300	FLATTE	71	HBC	$7\ \pi^+ p \to \Delta^{++} f_2$
196 ±30		[7] STUNTEBECK	70	HBC	$8\ \pi^- p$, $5.4\ \pi^+ d$
216 ±20	1960	[7] ARMENISE	68	DBC	$5.1\ \pi^+ n \to p\pi^+ MM^-$
128 ±27		[7] BOESEBECK	68	HBC	$8\ \pi^+ p$
176 ±21		[7,12] JOHNSON	68	HBC	$3.7–4.2\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
206 ±19		ADAMO	91	OBLX	$\overline{n} p \to \pi^+\pi^+\pi^-$
200 ±10		AKER	91	CBAR	$0.0\ \overline{p} p \to 3\pi^0$
240 ±40	3k	BINON	83	GAM2	$38\ \pi^- p \to n 2\eta$
187 ±30	650	[7] ANTIPOV	77	CIBS	$25\ \pi^- p \to p 3\pi$
225 ±38	16000	DEUTSCH...	76	HBC	$16\ \pi^+ p$
166 ±28	600	[7] TAKAHASHI	72	HBC	$8\ \pi^- p \to n 2\pi$
173 ±53		[7] ARMENISE	70	HBC	$9\ \pi^+ n \to p\pi^+\pi^-$
155 ±17		RABIN	67	HBC	$8.5\ \pi^+ p$

[7] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

[8] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[9] From an energy-independent partial-wave analysis.
[10] From an amplitude analysis of the reaction $\pi^+\pi^- \rightarrow 2\pi^0$.
[11] From an amplitude analysis of $\pi^+\pi^- \rightarrow \pi^+\pi^-$ scattering data.
[12] JOHNSON 68 includes BONDAR 63, LEE 64, DERADO 65, EISNER 67.



$f_2(1270)$ width (MeV)

$f_2(1270)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi\pi$	$(84.7\ ^{+2.6}_{-1.2})$ %	S=1.3
Γ_2	$\pi^+\pi^-2\pi^0$	$(7.2\ ^{+1.4}_{-2.9})$ %	S=1.3
Γ_3	$K\overline{K}$	$(4.6\ \pm0.5)$ %	S=2.8
Γ_4	$2\pi^+2\pi^-$	$(2.8\ \pm0.4)$ %	S=1.2
Γ_5	$\eta\eta$	$(4.5\ \pm1.0) \times 10^{-3}$	S=2.4
Γ_6	$4\pi^0$	$(3.0\ \pm1.0) \times 10^{-3}$	
Γ_7	$\gamma\gamma$	$(1.32^{+0.18}_{-0.16}) \times 10^{-5}$	
Γ_8	$\eta\pi\pi$	$< 8 \times 10^{-3}$	CL=95%
Γ_9	$K^0K^-\pi^+$ + c.c.	$< 3.4 \times 10^{-3}$	CL=95%
Γ_{10}	e^+e^-	$< 9 \times 10^{-9}$	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, 4 partial widths, a combination of partial widths obtained from integrated cross sections, and 6 branching ratios uses 38 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 69.8$ for 31 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i \delta p_j\rangle/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−92						
x_3	11	−38					
x_4	11	−36	1				
x_5	2	−9	0	0			
x_6	0	−7	0	0	0		
x_7	8	−3	−15	1	0	0	
Γ	−80	74	−12	−9	−3	0	−10
	x_1	x_2	x_3	x_4	x_5	x_6	x_7

	Mode	Rate (MeV)	Scale factor
Γ_1	$\pi\pi$	$156.9\ ^{+3.7}_{-1.3}$	
Γ_2	$\pi^+\pi^-2\pi^0$	$13.3\ ^{+2.8}_{-5.4}$	1.3
Γ_3	$K\overline{K}$	$8.6\ \pm0.8$	2.9
Γ_4	$2\pi^+2\pi^-$	$5.2\ \pm0.7$	1.2
Γ_5	$\eta\eta$	$0.83\ \pm0.18$	2.4
Γ_6	$4\pi^0$	$0.55\ \pm0.19$	
Γ_7	$\gamma\gamma$	$0.00244\ ^{+0.00032}_{-0.00029}$	

$f_2(1270)$ PARTIAL WIDTHS

$\Gamma(\pi\pi)$ — Γ_1

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
$156.9^{+3.7}_{-1.3}$ OUR FIT				
$157.0^{+6.0}_{-1.0}$	[13] LONGACRE	86	MPS	$22\ \pi^- p \rightarrow n 2K^0_S$

$\Gamma(K\overline{K})$ — Γ_3

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
8.6 ±0.8 OUR FIT Error includes scale factor of 2.9.				
$9.0\ ^{+0.7}_{-0.3}$	[13] LONGACRE	86	MPS	$22\ \pi^- p \rightarrow n 2K^0_S$

$\Gamma(\eta\eta)$ — Γ_5

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.83±0.18 OUR FIT Error includes scale factor of 2.4.				
1.0 ±0.1	[13] LONGACRE	86	MPS	$22\ \pi^- p \rightarrow n 2K^0_S$

$\Gamma(\gamma\gamma)$ — Γ_7

The value of this width depends on the theoretical model used. Unitarised models with scalars give values clustering around ≃ 2.6; without an *S*-wave contribution, values are systematically higher (typically around 3). Since it is used to average results obtained with variety of models, we prefer to quote our own estimate.

VALUE (keV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.8 ±0.4 OUR ESTIMATE					
$2.44^{+0.32}_{-0.29}$ OUR FIT					
$2.58\pm0.13^{+0.36}_{-0.27}$		[14] BEHREND	92	CELL	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$3.10\pm0.35\pm0.35$		[15] BLINOV	92	MD1	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
$2.27\pm0.47\pm0.11$		ADACHI	90D	TOPZ	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
$3.15\pm0.04\pm0.39$		BOYER	90	MRK2	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
$3.19\pm0.16^{+0.29}_{-0.28}$		MARSISKE	90	CBAL	$e^+e^- \rightarrow e^+e^-\pi^0\pi^0$
2.35 ± 0.65		[16] MORGAN	90	RVUE	$\gamma\gamma \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$
$3.19\pm0.09^{+0.22}_{-0.38}$	2177	OEST	90	JADE	$e^+e^- \rightarrow e^+e^-\pi^0\pi^0$
$3.2\ \pm0.1\ \pm0.4$		[17] AIHARA	86B	TPC	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
$2.5\ \pm0.1\ \pm0.5$		BEHREND	84B	CELL	$e^+e^- \rightarrow e^+e^-\pi^+\pi^-$
$2.85\pm0.25\pm0.5$		[18] BERGER	84	PLUT	$e^+e^- \rightarrow e^+e^-2\pi$

2.70±0.05±0.20	COURAU	84 DLCO	$e^+e^- \to e^+e^-\pi^+\pi^-$
2.52±0.13±0.38	[19] SMITH	84C MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
2.3 ±0.2 ±0.5	FRAZER	83 JADE	$e^+e^- \to e^+e^-\pi^+\pi^-$
2.7 ±0.2 ±0.6	EDWARDS	82F CBAL	$e^+e^- \to e^+e^-2\pi^0$
2.9 $^{+0.6}_{-0.4}$ ±0.6	[20] EDWARDS	82F CBAL	$e^+e^- \to e^+e^-2\pi^0$
3.2 ±0.2 ±0.6	BRANDELIK	81B TASS	$e^+e^- \to e^+e^-\pi^+\pi^-$
3.6 ±0.3 ±0.5	ROUSSARIE	81 MRK2	$e^+e^- \to e^+e^-\pi^+\pi^-$
2.3 ±0.8	[21] BERGER	80B PLUT	e^+e^-

$\Gamma(e^+e^-)$ Γ_{10}

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<1.7	90	VOROBYEV	88 ND	$e^+e^- \to \pi^0\pi^0$

[13] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[14] Using a unitarized model with scalars.
[15] Using the unitarized model of LYTH 85.
[16] Error includes spread of different solutions. Data of MARK2 and CRYSTAL BALL used in the analysis. Authors report strong correlations with $\gamma\gamma$ width of $f_0(1370)$: $\Gamma(f_2)$ + 1/4 $\Gamma(f^0)$ = 3.6 ± 0.3 KeV.
[17] Radiative corrections modify the partial widths; for instance the COURAU 84 value becomes 2.66 ± 0.21 in the calculation of LANDRO 86.
[18] Using the MENNESSIER 83 model.
[19] Superseded by BOYER 90.
[20] If helicity = 2 assumption is not made.
[21] Using mass, width and B($f_2(1270) \to 2\pi$) from PDG 78.

$f_2(1270)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ $\Gamma_3\Gamma_7/\Gamma$

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.113$^{+0.016}_{-0.015}$ OUR FIT Error includes scale factor of 1.1.			
0.091±0.007±0.027	[22] ALBRECHT	90G ARG	$e^+e^- \to e^+e^-K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.104±0.007±0.072	[23] ALBRECHT	90G ARG	$e^+e^- \to e^+e^-K^+K^-$

[22] Using an incoherent background.
[23] Using a coherent background.

$f_2(1270)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.847$^{+0.026}_{-0.012}$ OUR FIT Error includes scale factor of 1.3.				
0.837±0.020 OUR AVERAGE				
0.849±0.025		CHABAUD	83 ASPK	17 π^-p polarized
0.85 ±0.05	250	BEAUPRE	71 HBC	8 $\pi^+p \to \Delta^{++}f_2$
0.8 ±0.04	600	OH	70 HBC	1.26 $\pi^-p \to \pi^+\pi^-n$

$\Gamma(\pi^+\pi^-2\pi^0)/\Gamma(\pi\pi)$ Γ_2/Γ_1

Should be twice $\Gamma(2\pi^+2\pi^-)/\Gamma(\pi\pi)$ if decay is $\rho\rho$. (See ASCOLI 68D.)

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.085$^{+0.018}_{-0.036}$ OUR FIT Error includes scale factor of 1.3.				
0.15 ±0.06	600	EISENBERG	74 HBC	4.9 $\pi^+p \to \Delta^{++}f_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.07		EMMS	75D DBC	4 $\pi^+n \to pf_2$

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ Γ_3/Γ_1

We average only experiments which either take into account $f_2(1270)$-$a_2(1320)$ interference explicitly or demonstrate that $a_2(1320)$ production is negligible.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.055±0.006 OUR FIT Error includes scale factor of 2.8.				
0.040$^{+0.005}_{-0.006}$ OUR AVERAGE				
0.037$^{+0.008}_{-0.021}$		ETKIN	82B MPS	23 $\pi^-p \to n2K^0_S$
0.045±0.009		CHABAUD	81 ASPK	17 π^-p polarized
0.039±0.008		LOVERRE	80 HBC	4 $\pi^-p \to K\overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.036±0.005		[24] COSTA...	80 OMEG	1–2.2 $\pi^-p \to K^+K^-n$
0.030±0.005		[25] MARTIN	79 RVUE	
0.027±0.009		[26] POLYCHRO...	79 STRC	7 $\pi^-p \to n2K^0_S$
0.025±0.015		EMMS	75D DBC	4 $\pi^+n \to pf_2$
0.031±0.012	20	ADERHOLZ	69 HBC	8 $\pi^+p \to K^+K^-\pi^+p$

[24] Re-evaluated by CHABAUD 83.
[25] Includes PAWLICKI 77 data.
[26] Takes into account the $f_2(1270)$-$f_2'(1525)$ interference.

$\Gamma(2\pi^+2\pi^-)/\Gamma(\pi\pi)$ Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.033±0.005 OUR FIT Error includes scale factor of 1.2.				
0.033±0.004 OUR AVERAGE Error includes scale factor of 1.1.				
0.024±0.006	160	EMMS	75D DBC	4 $\pi^+n \to pf_2$
0.051±0.025	70	EISENBERG	74 HBC	4.9 $\pi^+p \to \Delta^{++}f_2$
0.043$^{+0.007}_{-0.011}$	285	LOUIE	74 HBC	3.9 $\pi^-p \to nf_2$
0.037±0.007	154	ANDERSON	73 DBC	6 $\pi^+n \to pf_2$
0.047±0.013		OH	70 HBC	1.26 $\pi^-p \to \pi^+\pi^-n$

$\Gamma(\eta\eta)/\Gamma_{total}$ Γ_5/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
4.5±1.0 OUR FIT Error includes scale factor of 2.4.			
3.1±0.8 OUR AVERAGE Error includes scale factor of 1.3.			
2.8±0.7	ALDE	86D GAM4	100 $\pi^-p \to 2\eta n$
5.2±1.7	BINON	83 GAM2	38 $\pi^-p \to 2\eta n$

$\Gamma(\eta\eta)/\Gamma(\pi\pi)$ Γ_5/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.05	95	EDWARDS	82F CBAL	$e^+e^- \to e^+e^-2\eta$
<0.016	95	EMMS	75D DBC	4 $\pi^+n \to pf_2$
<0.09	95	EISENBERG	74 HBC	4.9 $\pi^+p \to \Delta^{++}f_2$

$\Gamma(4\pi^0)/\Gamma_{total}$ Γ_6/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0030±0.0010 OUR FIT				
0.003 ±0.001	400±50	ALDE	87 GAM4	100 $\pi^-p \to 4\pi^0n$

$\Gamma(\eta\pi\pi)/\Gamma(\pi\pi)$ Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.010	95	EMMS	75D DBC	4 $\pi^+n \to pf_2$

$\Gamma(K^0K^-\pi^+ + \text{c.c.})/\Gamma(\pi\pi)$ Γ_9/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.004	95	EMMS	75D DBC	4 $\pi^+n \to pf_2$

$f_2(1270)$ REFERENCES

PROKOSHKIN 94 SPD 39 420 +Kondashov (SERP)
Translated from DANS 336 613.
BEHREND 92 ZPHY C56 381 (CELLO Collab.)
BLINOV 92 ZPHY C53 33 +Bondar, Bukin+ (NOVO)
ADAMO 91 Hadron 91 Conf. +Agnello, Balestra+ (OBELIX Collab.)
AGUILAR-... 91 ZPHY C50 405 Aguilar-Benitez, Allison, Batalor+ (LEBC-EHS Collab.)
AKER 91 PL B260 249 +Amsler, Peters+ (Crystal Barrel Collab.)
ADACHI 90D PL B234 185 +Doser+ (TOPAZ Collab.)
ALBRECHT 90G ZPHY C48 183 +Ehrlichmann, Harder+ (ARGUS Collab.)
BOYER 90 PR D42 1350 +Butler+ (Mark II Collab.)
BREAKSTONE 90 ZPHY C48 569 + (ISU, BGNA, CERN, DORT, HEIDH, WARS)
MARSISKE 90 PR D41 3324 +Antreasyan+ (Crystal Ball Collab.)
MORGAN 90 ZPHY C48 623 +Pennington (RAL, DURH)
OEST 90 ZPHY C47 343 +Olsson+ (JADE Collab.)
AUGUSTIN 89 NP B320 1 +Cosme (DM2 Collab.)
VOROBYEV 88 SJNP 48 273 +Golubev, Dolinsky, Druzhinin+ (NOVO)
Translated from YAF 48 436.
ALDE 87 PL B198 286 +Binon, Bricman+ (LANL, BRUX, SERP, LAPP)
AUGUSTIN 87 ZPHY C36 369 +Cosme+ (LALO, CLER, FRAS, PADO)
ABACHI 86B PRL 57 1990 +Derrick, Blockus+ (PURD, ANL, IND, MICH, LBL)
AIHARA 86B PRL 57 404 +Alston-Garnjost+ (TPC-2γ Collab.)
ALDE 86D NP B269 485 +Binon, Bricman+ (BELG, LAPP, SERP, CERN, LANL)
LANDRO 86 PL B172 445 +Mork, Olsen (UTRO)
LONGACRE 86 PL B177 223 +Etkin+ (BNL, BRAN, CUNY, DUKE, NDAM)
LYTH 85 JPG 11 459
BEHREND 84B ZPHY C23 223 +Fenner, Schachter, Schroeder+ (CELLO Collab.)
BERGER 84 ZPHY C26 199 +Klovning, Burger+ (PLUTO Collab.)
COURAU 84 PL 147B 227 +Johnson, Sherman, Atwood, Baillon+ (CIT, SLAC)
SMITH 84C PR D30 851 +Burke, Abrams, Blocker, Levi+ (SLAC, LBL, HARV)
BINON 83 NC 78A 313 +Donskov, Duteil+ (BELG, LAPP, SERP, CERN)
Also 83B SJNP 38 561 Binon, Gouanere+ (BELG, LAPP, SERP, CERN)
Translated from YAF 38 934.
CHABAUD 83 NP B223 1 +Gorlich, Cerrada+ (CERN, CRAC, MPIM)
DENNEY 83 PR D28 2726 +Cranley, Firestone, Chapman+ (IOWA, MICH)
FRAZER 83 Aachen Conf. (UCSD)
MENNESSIER 83 ZPHY C16 241 (MONP)
APEL 82 NP B201 197 +Augenstein+(KARLK, KARLE, PISA, SERP, WIEN, CERN)
CASON 82 PRL 48 1316 +Biswas, Baumbaugh, Bishop+ (NDAM, ANL)
EDWARDS 82F PL 110B 82 +Partridge, Peck+ (CIT, HARV, PRIN, STAN, SLAC)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)
BRANDELIK 81B ZPHY C10 117 +Boerner+ (TASSO Collab.)
CHABAUD 81 APP B12 575 +Niczyporuk, Becker+ (CERN, CRAC, MPIM)
GIDAL 81 PL 107B 153 +Goldhaber, Guy, Millikan, Abrams+ (SLAC, LBL)
ROUSSARIE 81 PL 105B 304 +Burke, Abrams, Alam+ (SLAC, LBL)
BERGER 80B PL 94B 254 +Genzer+ (PLUTO Collab.)
COSTA... 80 NP B175 402 Costa De Beauregard+ (BARI, BONN, CERN+)
LOVERRE 80 ZPHY C6 187 +Armenteros, Dionisi+ (CERN, CDEF, MADR, STOH)
CORDEN 79 NP B157 250 +Dowell, Garvey+ (BIRM, RHEL, TELA, LOWC)
MARTIN 79 NP B158 520 +Ozmutlu (DURH)
POLYCHRO... 79 PR D19 1317 Polychronakos, Cason, Bishop+ (NDAM, ANL)
PDG 78 PL 75B Bricman+
ANTIPOV 77 NP B119 45 +Busnello, Damgaard, Kienzle+ (SERP, GEVA)
PAWLICKI 77 PR D15 3196 +Ayres, Cohen, Diebold, Kramer, Wicklund (ANL)
DEUTSCH... 76 NP B103 426 Deutschmann+ (AACH3, BERL, BONN, CERN+)
APEL 75 PL 57B 398 +Augenstein+(KARLK, KARLE, PISA, SERP, WIEN, CERN)

EMMS 75D NP B96 155 +Kinson, Stacey, Votruba+ (BIRM, DURH, RHEL)
EISENBERG 74 PL 52B 239 +Engler, Haber, Karshon+ (REHO)
ENGLER 74 PR D10 2070 +Kraemer, Toaff, Weisser, Diaz+ (CMU, CASE)
LOUIE 74 PL 48B 385 +Alitti, Gandois, Chaloupka+ (SACL, CERN)
ANDERSON 73 PRL 31 562 +Engler, Kraemer, Toaff, Diaz+ (CMU, CASE)
TAKAHASHI 72 PR D6 1266 +Barish+ (TOHOK, PENN, NDAM, ANL)
BEAUPRE 71 NP B28 77 +Deutschmann, Graessler+ (AACH, BERL, CERN)
FLATTE 71 PL 34B 551 +Alston-Garnjost, Barbaro-Galtieri+ (LBL)
ARMENISE 70 LNC 4 199 +Ghidini, Foring, Cartacci+ (BARI, BGNA, FIRZ)
OH 70 PR D1 2494 +Garfinkel, Morse, Walker, Prentice (WISC, TNTO) JP
STUNTEBECK 70 PL 32B 391 +Kenney, Deery, Biswas, Cason+ (NDAM)
ADERHOLZ 69 NP B11 259 +Bartsch+ (AACH3, BERL, CERN, JAGL, WARS)
ARMENISE 68 NC 54A 999 +Ghidini, Forino+ (BARI, BGNA, FIRZ, ORSAY)
ASCOLI 68D PRL 21 1712 +Crawley, Mortara+ (ILL)
BOESEBECK 68 NP B4 501 +Deutschmann+ (AACH, BERL, CERN)
JOHNSON 68 PR 176 1651 +Poirier, Biswas, Gutay+ (NDAM, PURD, SLAC)
EISNER 67 PR 164 1699 +Johnson, Klein, Peters, Sahni, Yen+ (PURD)
RABIN 67 Thesis (RUTG)
DERADO 65 PRL 14 872 +Kenney, Poirier, Shephard (NDAM)
LEE 64 PRL 12 342 +Roe, Sinclair, VanderVelde (MICH)
BONDAR 63 PL 5 153 + (AACH, BIRM, BONN, DESY, LOIC, MPIM)

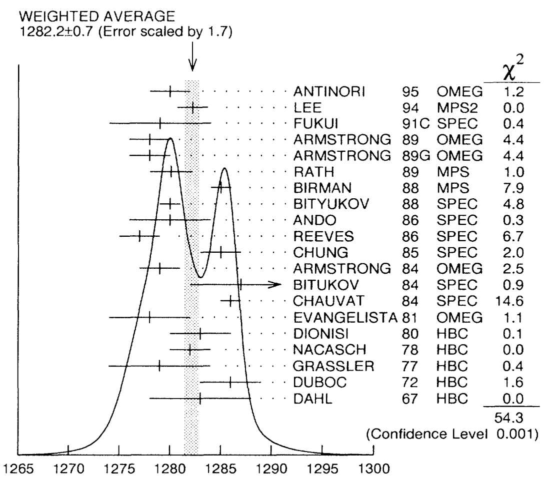
$f_1(1285)$

$I^G(J^{PC}) = 0^+(1^{++})$

$f_1(1285)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1282.2± 0.7 OUR AVERAGE		Error includes scale factor of 1.7. See the ideogram below.			
1280 ± 2		[1] ANTINORI 95	OMEG		300,450 $pp \to pp2(\pi^+\pi^-)$
1282.2± 1.5		LEE 94	MPS2		18 $\pi^- p \to K^+ \overline{K}^0 2\pi^- p$
1279 ± 5		FUKUI 91C	SPEC		8.95 $\pi^- p \to \eta\pi^+\pi^- n$
1278 ± 2	140	ARMSTRONG 89	OMEG		300 $pp \to K\overline{K}\pi pp$
1278 ± 2		ARMSTRONG 89G	OMEG		85 $\pi^+ p \to 4\pi\pi p$, $pp \to 4\pi pp$
1280.1± 2.1	60	RATH 89	MPS		21.4 $\pi^- p \to K^0_S K^0_S \pi^0 n$
1285 ± 1	4750	[2] BIRMAN 88	MPS		8 $\pi^- p \to K^+ \overline{K}^0 \pi^- n$
1280 ± 1	504	BITYUKOV 88	SPEC		32.5 $\pi^- p \to K^+ K^- \pi^0 n$
1280 ± 4		ANDO 86	SPEC		8 $\pi^- p \to n\eta\pi^+\pi^-$
1277 ± 2	420	REEVES 86	SPEC		6.6 $p\overline{p} \to K K \pi X$
1285 ± 2		CHUNG 85	SPEC		8 $\pi^- p \to N K \overline{K} \pi$
1279 ± 2	604	ARMSTRONG 84	OMEG		85 $\pi^+ p \to K\overline{K}\pi\pi p$, $pp \to K\overline{K}\pi pp$
1287 ± 5	353	BITUKOV 84	SPEC		32 $\pi^- p \to K^+ K^- \pi^0 n$
1286 ± 1		CHAUVAT 84	SPEC		ISR 31.5 pp
1278 ± 4		EVANGELISTA 81	OMEG		12 $\pi^- p \to \eta\pi^+\pi^-\pi^- p$
1283 ± 3	103	DIONISI 80	HBC		4 $\pi^- p \to K\overline{K}\pi n$
1282 ± 2	320	NACASCH 78	HBC		0.7,0.76 $\overline{p}p \to K\overline{K}3\pi$
1279 ± 5	210	GRASSLER 77	HBC		16 $\pi^{\mp} p$
1286 ± 3	180	DUBOC 72	HBC		1.2 $\overline{p}p \to 2K4\pi$
1283 ± 5		DAHL 67	HBC		1.6–4.2 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1270 ±10		AMELIN 95	VES		37 $\pi^- N \to \pi^-\pi^+\pi^-\gamma N$
1280 ± 2		ABATZIS 94	OMEG		450 $pp \to pp2(\pi^+\pi^-)$
1282 ± 4		ARMSTRONG 93C	SPEC		$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$
1270 ± 6 ±10		ARMSTRONG 92C	OMEG		300 $pp \to pp\pi^+\pi^-\gamma$
1264 ± 8		AUGUSTIN 90	DM2		$J/\psi \to \gamma\eta\pi^+\pi^-$
1284 ± 4		TAKAMATSU 90	SPEC	0	8 $\pi^- p \to K\overline{K}\pi n$
1281 ± 1		ARMSTRONG 89E	OMEG		300 $pp \to pp2(\pi^+\pi^-)$
1279 ± 6 ±10	16	BECKER 87	MRK3		$e^+e^- \to \phi K \overline{K} \pi$
1286 ± 9		GIDAL 87	MRK2		$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
~ 1279		[3] TORNQVIST 82B	RVUE		
1275 ± 6	31	BROMBERG 80	SPEC		100 $\pi^- p \to K\overline{K}\pi X$
1288 ± 9	200	GURTU 79	HBC		4.2 $K^- p \to n\eta 2\pi$
~ 1275.0	46	[4] STANTON 79	CNTR		8.5 $\pi^- p \to n 2\gamma 2\pi$
1271 ±10	34	CORDEN 78	OMEG		12–15 $\pi^- p \to K^+ K^- \pi n$
1295 ±12	85	CORDEN 78	OMEG		12–15 $\pi^- p \to n 5\pi$
1292 ±10	150	DEFOIX 72	HBC		0.7 $\overline{p}p \to 7\pi$
1280 ± 3	500	[5] THUN 72	MMS		13.4 $\pi^- p$
1303 ± 8		BARDADIN-... 71	HBC		8 $\pi^+ p \to p 6\pi$
1283 ± 6		BOESEBECK 71	HBC		16.0 $\pi p \to p 5\pi$
1270 ±10		CAMPBELL 69	DBC		2.7 $\pi^+ d$
1285 ± 7		LORSTAD 69	HBC		0.7 $\overline{p}p$, 4,5-body
1290 ± 7		D'ANDLAU 68	HBC		1.2 $\overline{p}p$, 5–6 body

[1] Supersedes ABATZIS 94, ARMSTRONG 89E.
[2] From partial wave analysis of $K^+ \overline{K}^0 \pi^-$ system.
[3] From a unitarized quark-model calculation.
[4] From phase shift analysis of $\eta\pi^+\pi^-$ system.
[5] Seen in the missing mass spectrum.



$f_1(1285)$ mass (MeV)

$f_1(1285)$ WIDTH

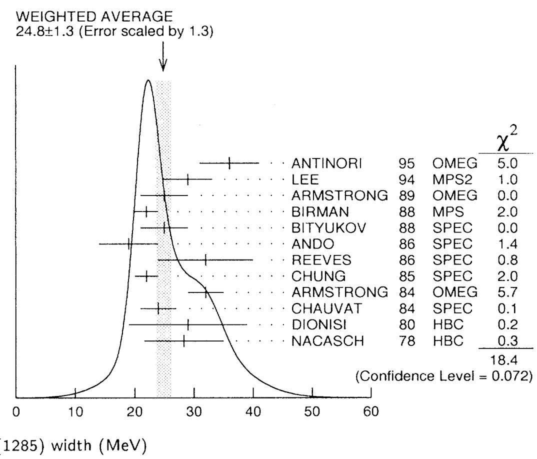
Only experiments giving width error less than 20 MeV are kept for averaging.

VALUE (MeV)	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
24.8± 1.3 OUR AVERAGE			Error includes scale factor of 1.3. See the ideogram below.			
36 ± 5			[6] ANTINORI 95	OMEG		300,450 $pp \to pp2(\pi^+\pi^-)$
29.0± 4.1			LEE 94	MPS2		18 $\pi^- p \to K^+ \overline{K}^0 2\pi^- p$
25 ± 4		140	ARMSTRONG 89	OMEG		300 $pp \to K\overline{K}\pi pp$
22 ± 2		4750	[7] BIRMAN 88	MPS		8 $\pi^- p \to K^+ \overline{K}^0 \pi^- n$
25 ± 4		504	BITYUKOV 88	SPEC		32.5 $\pi^- p \to K^+ K^- \pi^0 n$
19 ± 5			ANDO 86	SPEC		8 $\pi^- p \to n\eta\pi^+\pi^-$
32 ± 8		420	REEVES 86	SPEC		6.6 $p\overline{p} \to K K \pi X$
22 ± 2			CHUNG 85	SPEC		8 $\pi^- p \to N K \overline{K} \pi$
32 ± 3		604	ARMSTRONG 84	OMEG		85 $\pi^+ p \to K\overline{K}\pi\pi p$, $pp \to K\overline{K}\pi pp$
24 ± 3			CHAUVAT 84	SPEC		ISR 31.5 pp
29 ±10		103	DIONISI 80	HBC		4 $\pi^- p \to K\overline{K}\pi n$
28.3± 6.7		320	NACASCH 78	HBC		0.7,0.76 $\overline{p}p \to K\overline{K}3\pi$

• • • We do not use the following data for averages, fits, limits, etc. • • •

40 ± 5		ABATZIS	94	OMEG		450 $pp \to pp2(\pi^+\pi^-)$
44 ±20		AUGUSTIN	90	DM2		$J/\psi \to \gamma\eta\pi^+\pi^-$
22 ± 5		TAKAMATSU	90	SPEC	0	8 $\pi^- p \to K\overline{K}\pi n$
<20	90	TAKAMATSU	90	SPEC	0	8.95 $\pi^- p \to \eta\pi^+\pi^- n$
31 ± 5		ARMSTRONG	89E	OMEG		300 $pp \to pp2(\pi^+\pi^-)$
41 ±12		ARMSTRONG	89G	OMEG		85 $\pi^+ p \to 4\pi\pi p$, $pp \to 4\pi pp$
17.9±10.9	60	RATH	89	MPS		21.4 $\pi^- p \to K^0_S K^0_S \pi^0 n$
14 $^{+20}_{-14}$ ±10	16	BECKER	87	MRK3		$e^+e^- \to \phi K\overline{K}\pi$
26 ±12		EVANGELISTA	81	OMEG		12 $\pi^- p \to \eta\pi^+\pi^-\pi^- p$
25 ±15	200	GURTU	79	HBC		4.2 $K^- p \to n\eta 2\pi$
~ 10		[8] STANTON	79	CNTR		8.5 $\pi^- p \to n2\gamma 2\pi$
24 ±18	210	GRASSLER	77	HBC		16 $\pi^\mp p$
28 ± 5	150	[9] DEFOIX	72	HBC		0.7 $\overline{p}p \to 7\pi$
46 ± 9	180	[9] DUBOC	72	HBC		1.2 $\overline{p}p \to 2K4\pi$
37 ± 5	500	[10] THUN	72	MMS		13.4 $\pi^- p$
10 ±10		BOESEBECK	71	HBC		16.0 $\pi p \to p5\pi$
30 ±15		CAMPBELL	69	DBC		2.7 $\pi^+ d$
60 ±15		[9] LORSTAD	69	HBC		0.7 $\overline{p}p$, 4,5-body
35 ±10		[9] DAHL	67	HBC		1.6–4.2 $\pi^- p$

[6] Supersedes ABATZIS 94, ARMSTRONG 89E.
[7] From partial wave analysis of $K^+\overline{K}^0\pi^-$ system.
[8] From phase shift analysis of $\eta\pi^+\pi^-$ system.
[9] Resolution is not unfolded.
[10] Seen in the missing mass spectrum.



$f_1(1285)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	4π	(29 ± 6) %	
Γ_2	$\pi^0\pi^0\pi^+\pi^-$	(15 $^{+9}_{-8}$) %	S=1.1
Γ_3	$2\pi^+2\pi^-$	(15 ± 6) %	
Γ_4	$\rho^0\pi^+\pi^-$	dominates $2\pi^+ 2\pi^-$	
Γ_5	$4\pi^0$	< 7 × 10^{-4}	CL=90%
Γ_6	$\eta\pi\pi$	(54 ±15) %	
Γ_7	$a_0(980)\pi$ [ignoring $a_0(980) \to K\overline{K}$]	(44 ± 7) %	S=1.1
Γ_8	$\eta\pi\pi$ [excluding $a_0(980)\pi$]	(10 $^{+7}_{-6}$) %	S=1.1
Γ_9	$K\overline{K}\pi$	(9.7± 1.6) %	S=1.2
Γ_{10}	$K\overline{K}^*(892)$	not seen	
Γ_{11}	$\gamma\rho^0$	(6.6± 1.3) %	S=1.5
Γ_{12}	$\phi\gamma$	(8.0± 3.1) × 10^{-4}	
Γ_{13}	$\gamma\gamma^*$		
Γ_{14}	$\gamma\gamma$		

CONSTRAINED FIT INFORMATION

An overall fit to 7 branching ratios uses 13 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 =$ 11.4 for 8 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−87				
x_7	−33	13			
x_8	−4	−5	−78		
x_9	46	−19	−38	−12	
x_{11}	−59	45	30	−11	−41
	x_2	x_3	x_7	x_8	x_9

$f_1(1285)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_6\Gamma_{14}/\Gamma = (\Gamma_7+\Gamma_8)\Gamma_{14}/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
<0.62	95	GIDAL	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma^*)/\Gamma_{total}$ — $\Gamma_6\Gamma_{13}/\Gamma = (\Gamma_7+\Gamma_8)\Gamma_{13}/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
1.4 ±0.4 OUR AVERAGE Error includes scale factor of 1.4.					
1.18±0.25±0.20	26	[11,12] AIHARA	88B	TPC	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
2.30±0.61±0.42		[11,13] GIDAL	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$

[11] Assuming a ρ-pole form factor.
[12] Published value multiplied by $\eta\pi\pi$ branching ratio 0.49.
[13] Published value divided by 2 and multiplied by the $\eta\pi\pi$ branching ratio 0.49.

$f_1(1285)$ BRANCHING RATIOS

$\Gamma(K\overline{K}\pi)/\Gamma(4\pi)$ — $\Gamma_9/\Gamma_1 = \Gamma_9/(\Gamma_2+\Gamma_3)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.33±0.04 OUR FIT Error includes scale factor of 1.2.				
0.32±0.04 OUR AVERAGE Error includes scale factor of 1.2.				
0.28±0.05	[14] ARMSTRONG	89E	OMEG	300 $pp \to ppf_1(1285)$
0.37±0.03±0.05	[15] ARMSTRONG	89G	OMEG	85 $\pi p \to 4\pi X$

[14] Assuming $\rho\pi\pi$ and $a_0(980)\pi$ intermediate states.
[15] 4π consistent with being entirely $\rho\pi\pi$.

$\Gamma(K\overline{K}\pi)/\Gamma(\eta\pi\pi)$ — $\Gamma_9/\Gamma_6 = \Gamma_9/(\Gamma_7+\Gamma_8)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.04 OUR FIT Error includes scale factor of 1.1.				
0.23±0.06 OUR AVERAGE Error includes scale factor of 1.2.				
0.42±0.15	GURTU	79	HBC	4.2 $K^- p$
0.5 ±0.2	CORDEN	78	OMEG	12–15 $\pi^- p$
0.20±0.08	[16] DEFOIX	72	HBC	0.7 $\overline{p}p \to 7\pi$
0.16±0.08	CAMPBELL	69	DBC	2.7 $\pi^+ d$

[16] $K\overline{K}$ system characterized by the $I = 1$ threshold enhancement. (See under $a_0(980)$).

$\Gamma(a_0(980)\pi$ [ignoring $a_0(980) \to K\overline{K}$]$)/\Gamma(\eta\pi\pi)$ — $\Gamma_7/\Gamma_6 = \Gamma_7/(\Gamma_7+\Gamma_8)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.82±0.12 OUR FIT Error includes scale factor of 1.1.				
0.69$^{+0.13}_{-0.12}$ OUR AVERAGE				
0.72±0.15	GURTU	79	HBC	4.2 $K^- p$
0.6 $^{+0.3}_{-0.2}$	CORDEN	78	OMEG	12–15 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0 ±0.3	GRASSLER	77	HBC	16 $\pi^\mp p$

$\Gamma(4\pi)/\Gamma(\eta\pi\pi)$ — $\Gamma_1/\Gamma_6 = (\Gamma_2+\Gamma_3)/(\Gamma_7+\Gamma_8)$

VALUE	DOCUMENT ID		TECN	COMMENT
0.54±0.12 OUR FIT Error includes scale factor of 1.1.				
0.41±0.14 OUR AVERAGE				
0.37±0.11±0.11	BOLTON	92	MRK3	$J/\psi \to \gamma f_1(1285)$
0.64±0.40	GURTU	79	HBC	4.2 $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.93±0.30	[17] GRASSLER	77	HBC	16 $\pi^\mp p$

[17] Assuming $\rho\pi\pi$ and $a_0(980)\pi$ intermediate states.

$\Gamma(K\overline{K}^*(892))/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	NACASCH	78	HBC	0.7,0.76 $\overline{p}p \to K\overline{K}3\pi$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma(2\pi^+2\pi^-)$ — Γ_4/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0±0.4	GRASSLER	77	HBC	16 GeV $\pi^\pm p$

$\Gamma(4\pi^0)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<7	90	ALDE	87	GAM4	100 $\pi^- p \to 4\pi^0 n$

$\Gamma(\phi\gamma)/\Gamma(K\overline{K}\pi)$ — Γ_{12}/Γ_9

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.82±0.21±0.20		19	BITYUKOV	88	SPEC	32.5 $\pi^- p \to K^+ K^- \pi^0 n$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.93	95		AMELIN	95	VES	37 $\pi^- N \to \pi^-\pi^+\pi^-\gamma N$

$\Gamma(\gamma\rho^0)/\Gamma(K\overline{K}\pi)$ — Γ_{11}/Γ_9

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.035	90	[18] COFFMAN	90	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$

[18] Using B($J/\psi \to \gamma f_1(1285) \to \gamma\gamma\rho^0$)=0.25 × 10^{-4} and B($J/\psi \to \gamma f_1(1285) \to \gamma K\overline{K}\pi$)=< 0.72 × 10^{-3}.

$\Gamma(\gamma\rho^0)/\Gamma(2\pi^+2\pi^-)$ — Γ_{11}/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.45±0.18 OUR FIT				
0.45±0.18	[19] COFFMAN	90	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$

[19] Using B($J/\psi \to \gamma f_1(1285) \to \gamma\gamma\rho^0$)=0.25 × 10^{-4} and B($J/\psi \to \gamma f_1(1285) \to \gamma 2\pi^+ 2\pi^-$)=0.55 × 10^{-4} given by MIR 88.

$\Gamma(\gamma\rho^0)/\Gamma(a_0(980)\pi$ [ignoring $a_0(980) \to K\overline{K}$]$)$ — Γ_{11}/Γ_7

VALUE	DOCUMENT ID		TECN	COMMENT
0.15±0.04 OUR FIT Error includes scale factor of 1.6.				
0.10±0.03±0.02	[20] BURCHELL	91	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$

[20] Uses a result from COFFMAN 90, and includes an unknown branching ratio for $a_0(980) \to \eta\pi$.

$\Gamma(\gamma\rho^0)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.028±0.007±0.006		AMELIN	95	VES	37 $\pi^- N \to \pi^-\pi^+\pi^-\gamma N$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	95	BITYUKOV	91B	SPEC	32 $\pi^- p \to \pi^+\pi^-\gamma n$

$\Gamma(\eta\pi\pi)/\Gamma(\gamma\rho^0)$ — $\Gamma_6/\Gamma_{11} = (\Gamma_7+\Gamma_8)/\Gamma_{11}$

VALUE	DOCUMENT ID		TECN	COMMENT
8.2±1.6 OUR FIT Error includes scale factor of 1.8.				
7.5±1.0	[21] ARMSTRONG	92C	OMEG	300 $pp \to pp\pi^+\pi^-\gamma$, $pp\eta\pi^+\pi^-$

[21] Published value multiplied by 1.5.

$f_1(1285)$ REFERENCES

AMELIN 95 ZPHY C66 71 +Berdnikov+ (VES Collab.)
ANTINORI 95 PL B353 589 +Barberis, Bayes+ (ATHU, BARI, BIRM, CERN, JINR)
ABATZIS 94 PL B324 509 +Antinori, Barberis+ (ATHU, BARI, BIRM, CERN, JINR)
LEE 94 PL B323 227 +Chung, Kirk+ (BNL, IND, KYUN, MASD, RICE)
ARMSTRONG 93C PL B307 394 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
ARMSTRONG 92C ZPHY C54 371 +Barnes, Benayoun+ (ATHU, BARI, BIRM, CERN, CDEF)
BOLTON 92 PL B278 495 +Brown, Bunnell+ (Mark III Collab.)
BITYUKOV 91B SJNP 54 318 +Borisov, Viktorov+ (SERP)
Translated from YAF 54 529.
BURCHELL 91 NP B21 132 (suppl) (Mark III Collab.)
FUKUI 91C PL B267 293 + (SUGI, NAGO, KEK, KYOT, MIYA, AKIT)
AUGUSTIN 90 PR D42 10 +Cosme+ (DM2 Collab.)
COFFMAN 90 PR D41 1410 +De Jongh+ (Mark III Collab.)
TAKAMATSU 90 Hadron 89 Conf. p 71 +Ando+ (KEK)
ARMSTRONG 89 PL B221 216 +Benayoun+(CERN, CDEF, BIRM, BARI, ATHU, CURIN+) JPC
ARMSTRONG 89E PL B228 536 +Benayoun (ATHU, BARI, BIRM, CERN, CDEF, CURIN+)
ARMSTRONG 89G ZPHY C43 55 +Bloodworth+ (CERN, BIRM, BARI, ATHU, CURIN+)
RATH 89 PR D40 693 +Cason+ (NDAM, BRAN, BNL, CUNY, DUKE)
AIHARA 88B PL B209 107 +Alston-Garnjost+ (TPC-2γ Collab.)
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, MASD) JP
BITYUKOV 88 PL B203 327 +Borisov, Dorofeev+ (SERP)
MIR 88 Photon-Photon 88 Conf., 126 (Mark III Collab.)
ALDE 87 PL B198 286 +Binon, Bricman+ (LANL, BRUX, SERP, LAPP)
BECKER 87 PRL 59 186 +Blaylock, Bolton, Brown+ (Mark III Collab.)
GIDAL 87 PRL 59 2012 +Boyer, Butler, Cords, Abrams+ (LBL, SLAC, HARV)
ANDO 86 PRL 57 1296 +Imai+ (KEK, KYOT, NIRS, SAGA, INUS, TSUK+) IJP
REEVES 86 PR 34 1960 +Chung, Crittenden+ (FLOR, BNL, IND, MASD) JP
CHUNG 85 PRL 55 779 +Fernow, Boehnlein+ (BNL, FLOR, IND, MASD) JP
ARMSTRONG 84 PL 146B 273 +Bloodworth, Burns+ (ATHU, BARI, BIRM, CERN) JP
BITUKOV 84 PL 144B 133 +Dorofeev, Dzhelyadin, Golovkin, Kulik+ (SERP)
CHAUVAT 84 PL 148B 382 +Meritet, Bonino+ (CERN, CLER, UCLA, SACL)
TORNQVIST 82B NP B203 268 (HELS)
EVANGELISTA 81 NP B178 197 + (BARI, BONN, CERN, DARE, LIVP+)
BROMBERG 80 PR D22 1513 +Haggerty, Abrams, Dzierba (CIT, FNAL, ILLC, IND)
DIONISI 80 NP B169 1 +Gavillet+ (CERN, MADR, CDEF, STOH)
GURTU 79 NP B151 181 +Gavillet, Blokzijl+ (CERN, ZEEM, NIJM, OXF)
STANTON 79 PRL 42 346 +Brockman+ (OSU, CARL, MCGI, TNTO) JP
CORDEN 78 NP B144 253 +Corbett, Alexander+ (BIRM, RHEL, TELA, LOWC) JP
NACASCH 78 NP B135 203 +Defoix, Dobrzynski+ (PARIS, MADR, CERN)
GRASSLER 77 NP B121 189 + (AACH3, BERL, BONN, CERN, CRAC, HEIDH+)
DEFOIX 72 NP B44 125 +Nascimento, Bizzarri+ (CDEF, CERN)
DUBOC 72 NP B46 429 +Goldberg, Makowski, Donald+ (PARIS, LIVP)
THUN 72 PRL 28 1733 +Blieden, Finocchiaro, Bowen+ (STON, NEAS)
BARDADIN-... 71 PR D4 2711 Bardadin-Otwinowska, Hofmokl+ (WARS)
BOESEBECK 71 PL 34B 659 (AACH, BERL, BONN, CERN, CRAC, HEID, WARS)
CAMPBELL 69 PRL 22 1204 +Lichtman, Loeffler+ (PURD)
LORSTAD 69 NP B14 63 +D'Andlau, Astier+ (CDEF, CERN) JP
D'ANDLAU 68 NP B5 693 +Astier, Barlow+ (CDEF, CERN, IRAD, LIVP) IJP
DAHL 67 PR 163 1377 +Hardy, Hess, Kirz, Miller (LRL) IJP

OTHER RELATED PAPERS

AIHARA 88C PR D38 1 +Alston-Garnjost+ (TPC-2γ Collab.) JPC
ASTON 85 PR D32 2255 +Carnegie, Dunwoodie+ (SLAC, CARL, CNRC)
ATKINSON 84E PL 138B 459 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
GAVILLET 82 ZPHY C16 119 +Armenteros+ (CERN, CDEF, PADO, ROMA)
D'ANDLAU 65 PL 17 347 +Barlow, Adamson+ (CDEF, CERN, IRAD, LIVP)
MILLER 65 PRL 14 1074 +Chung, Dahl, Hess, Hardy, Kirz+ (LRL, UCB)

$\eta(1295)$

$I^G(J^{PC}) = 0^+(0^{-+})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$\eta(1295)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1295±4	FUKUI	91C	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1275	STANTON	79	CNTR	8.4 $\pi^- p \to n\eta 2\pi$

$\eta(1295)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
53±6	FUKUI	91C	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 70	STANTON	79	CNTR	8.4 $\pi^- p \to n\eta 2\pi$

$\eta(1295)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi^+\pi^-$	seen
Γ_2	$a_0(980)\pi$	seen
Γ_3	$\gamma\gamma$	

$\eta(1295)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(\eta\pi^+\pi^-) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.6	90	AIHARA	88C	TPC	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
<0.3		ANTREASYAN	87	CBAL	$e^+e^- \to e^+e^-\eta\pi\pi$

$\eta(1295)$ BRANCHING RATIOS

$\Gamma(a_0(980)\pi)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	BIRMAN	88	MPS	8 $\pi^- p \to K^+\overline{K}^0\pi^- n$
large	ANDO	86	SPEC	8 $\pi^- p \to n\eta\pi^+\pi^-$
large	STANTON	79	CNTR	8.4 $\pi^- p \to n\eta 2\pi$

$\eta(1295)$ REFERENCES

FUKUI 91C PL B267 293 + (SUGI, NAGO, KEK, KYOT, MIYA, AKIT)
AIHARA 88C PR D38 1 +Alston-Garnjost+ (TPC-2γ Collab.)
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, MASD) JP
ANTREASYAN 87 PR D36 2633 +Bartels, Besset+ (Crystal Ball Collab.)
ANDO 86 PRL 57 1296 +Imai+ (KEK, KYOT, NIRS, SAGA, INUS, TSUK+) IJP
STANTON 79 PRL 42 346 +Brockman+ (OSU, CARL, MCGI, TNTO) JP

$\pi(1300)$

$I^G(J^{PC}) = 1^-(0^{-+})$

$\pi(1300)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1300±100 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1190± 30	ZIELINSKI	84	SPEC	$200\ \pi^+ Z \to Z3\pi$
1240± 30	BELLINI	82	SPEC	$40\ \pi^- A \to A3\pi$
1273± 50	[1] AARON	81	RVUE	
1342± 20	BONESINI	81	OMEG	$12\ \pi^- p \to p3\pi$
~ 1400	DAUM	81B	SPEC	$63{,}94\ \pi^- p$

[1] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 to 600 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
440± 80	ZIELINSKI	84	SPEC	$200\ \pi^+ Z \to Z3\pi$
360±120	BELLINI	82	SPEC	$40\ \pi^- A \to A3\pi$
580±100	[2] AARON	81	RVUE	
220± 70	BONESINI	81	OMEG	$12\ \pi^- p \to p3\pi$
~ 600	DAUM	81B	SPEC	$63{,}94\ \pi^- p$

[2] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\pi(\pi\pi)_{S\text{-wave}}$	seen
Γ_3	$f_0(1370)\pi$	

$\pi(1300)$ BRANCHING RATIOS

$\Gamma(\pi(\pi\pi)_{S\text{-wave}})/\Gamma(\rho\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.12	[3] AARON	81	RVUE

[3] Uses multichannel Aitchison-Bowler model (BOWLER 75). Uses data from DAUM 80 and DANKOWYCH 81.

$\pi(1300)$ REFERENCES

ZIELINSKI	84	PR D30 1855	+Berg, Chandlee, Cihangir+	(ROCH, MINN, FNAL)
BELLINI	82	PRL 48 1697	+Frabetti, Ivanshin, Litkin+	(MILA, BGNA, JINR)
AARON	81	PR D24 1207	+Longacre	(NEAS, BNL)
BONESINI	81	PL 103B 75	+Donald+	(MILA, LIVP, DARE, CERN, BARI, BONN)
DANKOWY...	81	PRL 46 580	Dankowych+	(TNTO, BNL, CARL, MCGI, OHIO)
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
DAUM	80	PL 89B 281	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
BOWLER	75	NP B97 227	+Game, Aitchison, Dainton	(OXFTP, DARE)

$a_2(1320)$

$I^G(J^{PC}) = 1^-(2^{++})$

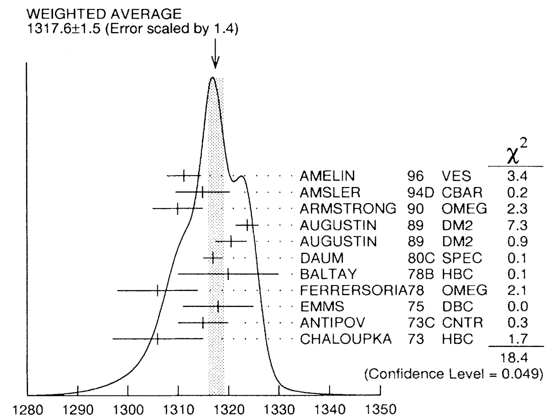
$a_2(1320)$ MASS

VALUE (MeV)	DOCUMENT ID
1318.1±0.7 OUR AVERAGE	Includes data from the 4 datablocks that follow this one. Error includes scale factor of 1.2.

3π MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
1317.6± 1.5 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.					
1311.3± 1.6±3.0	72400	AMELIN	96	VES		$36\ \pi^- p \to \pi^+\pi^-\pi^0 n$
1315 ± 5 ±2		[1] AMSLER	94D	CBAR		$0.0\ \bar{p}p \to \pi^0\pi^0\eta$
1310 ± 5		ARMSTRONG	90	OMEG	0	$300.0 pp \to pp\pi^+\pi^-\pi^0$
1323.8± 2.3	4022	AUGUSTIN	89	DM2	±	$J/\psi \to \rho^\pm a_2^\mp$
1320.6± 3.1	3562	AUGUSTIN	89	DM2	0	$J/\psi \to \rho^0 a_2^0$
1317 ± 2	25000	[2] DAUM	80C	SPEC	−	$63{,}94\ \pi^- p \to 3\pi p$
1320 ±10	1097	[2] BALTAY	78B	HBC	+0	$15\ \pi^+ p \to p4\pi$
1306 ± 8		FERRERSORIA	78	OMEG	−	$9\ \pi^- p \to p3\pi$
1318 ± 7	1600	[2] EMMS	75	DBC	0	$4\ \pi^+ n \to p(3\pi)^0$
1315 ± 5		[2] ANTIPOV	73C	CNTR	−	$25{,}40\ \pi^- p \to p\eta\pi^-$
1306 ± 9	1580	CHALOUPKA	73	HBC	−	$3.9\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1305 ±14		CONDO	93	SHF		$\gamma p \to \eta\pi^+\pi^+\pi^-$
1310 ± 2		[2] EVANGELISTA	81	OMEG	−	$12\ \pi^- p \to 3\pi p$
1343 ±11	490	BALTAY	78B	HBC	0	$15\ \pi^+ p \to \Delta 3\pi$
1309 ± 5	5000	BINNIE	71	MMS	−	$\pi^- p$ near a_2 threshold
1299 ± 6	28000	BOWEN	71	MMS	−	$5\ \pi^- p$
1300 ± 6	24000	BOWEN	71	MMS	+	$5\ \pi^+ p$
1309 ± 4	17000	BOWEN	71	MMS	−	$7\ \pi^- p$
1306 ± 4	941	ALSTON-...	70	HBC	+	$7.0\ \pi^+ p \to 3\pi p$

[1] The systematic error of 2 MeV corresponds to the spread of solutions.
[2] From a fit to $J^P = 2^+$ $\rho\pi$ partial wave.



$a_2(1320)$ mass, 3π mode (MeV)

$K^\pm K^0_S$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
1318.1± 0.7 OUR AVERAGE						
1319 ± 5	4700	[3,4] CLELAND	82B	SPEC	+	$50\ \pi^+ p \to K^0_S K^+ p$
1324 ± 6	5200	[3,4] CLELAND	82B	SPEC	−	$50\ \pi^- p \to K^0_S K^- p$
1320 ± 2	4000	CHABAUD	80	SPEC	−	$17\ \pi^- A \to K^0_S K^- A$
1312 ± 4	11000	CHABAUD	78	SPEC	−	$9.8\ \pi^- p \to K^- K^0_S p$
1316 ± 2	4730	CHABAUD	78	SPEC	−	$18.8\ \pi^- p \to K^- K^0_S p$
1318 ± 1		[3,5] MARTIN	78D	SPEC	−	$10\ \pi^- p \to K^0_S K^- p$
1320 ± 2	2724	MARGULIE	76	SPEC	−	$23\ \pi^- p \to K^- K^0_S p$
1313 ± 4	730	FOLEY	72	CNTR	−	$20.3\ \pi^- p \to K^- K^0_S p$
1319 ± 3	1500	[5] GRAYER	71	ASPK	−	$17.2\ \pi^- p \to K^- K^0_S p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1330 ±11	1000	[3,4] CLELAND	82B	SPEC	+	$30\ \pi^+ p \to K^0_S K^+ p$
1324 ± 5	350	HYAMS	78	ASPK	+	$12.7\ \pi^+ p \to K^+ K^0_S p$

[3] From a fit to $J^P = 2^+$ partial wave.
[4] Number of events evaluated by us.
[5] Systematic error in mass scale subtracted.

$\eta\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
1319.4±2.1 OUR AVERAGE						
1325.1±5.1		AOYAGI	93	BKEI		$\pi^- p \to \eta\pi^- p$
1317.7±1.4±2.0		BELADIDZE	93	VES		$37\pi^- N \to \eta\pi^- N$
1323 ±8	1000	[6] KEY	73	OSPK	−	$6\ \pi^- p \to p\pi^-\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1324 ±5		ARMSTRONG	93C	SPEC	0	$\bar{p}p \to \pi^0\eta\eta \to 6\gamma$
1336.2±1.7	2561	DELFOSSE	81	SPEC	+	$\pi^\pm p \to p\pi^\pm\eta$
1330.7±2.4	1653	DELFOSSE	81	SPEC	−	$\pi^\pm p \to p\pi^\pm\eta$
1324 ±8	6200	[6,7] CONFORTO	73	OSPK	−	$6\ \pi^- p \to p MM^-$

[6] Error includes 5 MeV systematic mass-scale error.
[7] Missing mass with enriched MMS $= \eta\pi^-$, $\eta = 2\gamma$.

$\eta'\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1327.0±10.7	BELADIDZE	93	VES	$37\pi^- N \to \eta'\pi^- N$

$a_2(1320)$ WIDTH

3π MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
105.5± 1.8 OUR AVERAGE						
103.0± 6.0±3.3	72400	AMELIN	96	VES		$36\ \pi^- p \to \pi^+\pi^-\pi^0 n$
112 ± 3 ±2		AMSLER [8]	94D	CBAR		$0.0\ \bar{p}p \to \pi^0\pi^0\eta$
120 ±10		ARMSTRONG	90	OMEG	0	$300.0 pp \to pp\pi^+\pi^-\pi^0$
107.0± 9.7	4022	AUGUSTIN	89	DM2	±	$J/\psi \to \rho^\pm a_2^\mp$
118.5±12.5	3562	AUGUSTIN	89	DM2	0	$J/\psi \to \rho^0 a_2^0$
97 ± 5		EVANGELISTA [9]	81	OMEG	−	$12\ \pi^- p \to 3\pi p$
96 ± 9	25000	DAUM [9]	80C	SPEC	−	$63{,}94\ \pi^- p \to 3\pi p$
110 ±15	1097	BALTAY [9]	78B	HBC	+0	$15\ \pi^+ p \to p 4\pi$
112 ±18	1600	EMMS [9]	75	DBC	0	$4\ \pi^+ n \to p(3\pi)^0$
122 ±14	1200	WAGNER [9,10]	75	HBC	0	$7\ \pi^+ p \to \Delta^{++}(3\pi)^0$
115 ±15		ANTIPOV [9]	73C	CNTR	−	$25{,}40\ \pi^- p \to p\eta\pi^-$
99 ±15	1580	CHALOUPKA	73	HBC	−	$3.9\ \pi^- p$
105 ± 5	28000	BOWEN	71	MMS	−	$5\ \pi^- p$
99 ± 5	24000	BOWEN	71	MMS	+	$5\ \pi^+ p$
103 ± 5	17000	BOWEN	71	MMS	−	$7\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
120 ±40		CONDO	93	SHF		$\gamma p \to \eta\pi^+\pi^+\pi^-$
115 ±14	490	BALTAY	78B	HBC	0	$15\ \pi^+ p \to \Delta 3\pi$
72 ±16	5000	BINNIE	71	MMS	−	$\pi^- p$ near a_2 threshold
79 ±12	941	ALSTON-...	70	HBC	+	$7.0\ \pi^+ p \to 3\pi p$

[8] The systematic error of 2 MeV corresponds to the spread of solutions.
[9] From a fit to $J^P = 2^+$ $\rho\pi$ partial wave.
[10] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$K^\pm K^0_S$ AND $\eta\pi$ MODES

VALUE (MeV)	DOCUMENT ID
107 ±5 OUR ESTIMATE	
109.8±2.0 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

$K^\pm K^0_S$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
109.8± 2.4 OUR AVERAGE						
112 ±20	4700	CLELAND [11,12]	82B	SPEC	+	$50\ \pi^+ p \to K^0_S K^+ p$
120 ±25	5200	CLELAND [11,12]	82B	SPEC	−	$50\ \pi^- p \to K^0_S K^- p$
106 ± 4	4000	CHABAUD	80	SPEC	−	$17\ \pi^- A \to K^0_S K^- A$
126 ±11	11000	CHABAUD	78	SPEC	−	$9.8\ \pi^- p \to K^- K^0_S p$
101 ± 8	4730	CHABAUD	78	SPEC	−	$18.8\ \pi^- p \to K^- K^0_S p$
113 ± 4		MARTIN [11,13]	78D	SPEC	−	$10\ \pi^- p \to K^0_S K^- p$
105 ± 8	2724	MARGULIE [13]	76	SPEC	−	$23\ \pi^- p \to K^- K^0_S p$
113 ±19	730	FOLEY	72	CNTR	−	$20.3\ \pi^- p \to K^- K^0_S p$
123 ±13	1500	GRAYER [13]	71	ASPK	−	$17.2\ \pi^- p \to K^- K^0_S p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
121 ±51	1000	CLELAND [11,12]	82B	SPEC	+	$30\ \pi^+ p \to K^0_S K^+ p$
110 ±18	350	HYAMS	78	ASPK	+	$12.7\ \pi^+ p \to K^+ K^0_S p$

[11] From a fit to $J^P = 2^+$ partial wave.
[12] Number of events evaluated by us.
[13] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$\eta\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.						
110.0± 3.5 OUR AVERAGE						
103 ± 6 ±3		BELADIDZE	93	VES		$37\pi^- N \to \eta\pi^- N$
112.2± 5.7	2561	DELFOSSE	81	SPEC	+	$\pi^\pm p \to p\pi^\pm\eta$
116.6± 7.7	1653	DELFOSSE	81	SPEC	−	$\pi^\pm p \to p\pi^\pm\eta$
108 ± 9	1000	KEY	73	OSPK	−	$6\ \pi^- p \to p\pi^-\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
118 ±10		ARMSTRONG	93C	SPEC	0	$\bar{p}p \to \pi^0\eta\eta \to 6\gamma$
104 ± 9	6200	CONFORTO [14]	73	OSPK	−	$6\ \pi^- p \to p\mathrm{MM}^-$

[14] Model dependent.

$\eta'\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
106±32	BELADIDZE	93	VES	$37\pi^- N \to \eta'\pi^- N$

$a_2(1320)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\rho\pi$	(70.1±2.7) %	S=1.2
Γ_2	$\eta\pi$	(14.5±1.2) %	
Γ_3	$\omega\pi\pi$	(10.6±3.2) %	S=1.3
Γ_4	$K\bar{K}$	(4.9±0.8) %	
Γ_5	$\eta'(958)\pi$	(5.7±1.1) × 10^{-3}	
Γ_6	$\pi^\pm\gamma$	(2.8±0.6) × 10^{-3}	
Γ_7	$\gamma\gamma$	(9.7±1.0) × 10^{-6}	
Γ_8	$\pi^+\pi^-\pi^-$	< 8 %	CL=90%
Γ_9	e^+e^-	< 2.3 × 10^{-7}	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 18 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 9.3 for 15 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	10		
x_3	−89	−46	
x_4	−1	−2	−24
	x_1	x_2	x_3

$a_2(1320)$ PARTIAL WIDTHS

$\Gamma(\pi^\pm\gamma)$ — Γ_6

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
295± 60	CIHANGIR	82	SPEC	+	$200\ \pi^+ A$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
461±110	MAY [14]	77	SPEC	±	$9.7\ \gamma A$

$\Gamma(\gamma\gamma)$ — Γ_7

VALUE (keV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.04±0.09 OUR AVERAGE						
1.26±0.26±0.18	36	BARU	90	MD1		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1.00±0.07±0.15	415	BEHREND	90C	CELL	0	$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1.03±0.13±0.21		BUTLER	90	MRK2		$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
1.01±0.14±0.22	85	OEST	90	JADE		$e^+e^- \to e^+e^-\pi^0\eta$
0.90±0.27±0.15	56	ALTHOFF [15]	86	TASS	0	$e^+e^- \to e^+e^- 3\pi$
1.14±0.20±0.26		ANTREASYAN [16]	86	CBAL	0	$e^+e^- \to e^+e^-\pi^0\eta$
1.06±0.18±0.19		BERGER	84C	PLUT	0	$e^+e^- \to e^+e^- 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$0.81\pm0.19^{+0.42}_{-0.11}$	35	BEHREND [15]	83B	CELL	0	$e^+e^- \to e^+e^- 3\pi$
0.84±0.07±0.15		FRAZER [15]	83	JADE	0	$e^+e^- \to e^+e^- 3\pi$
0.77±0.18±0.27	22	EDWARDS [16]	82F	CBAL	0	$e^+e^- \to e^+e^-\pi^0\eta$

[15] From $\rho\pi$ decay mode.
[16] From $\eta\pi^0$ decay mode.

$\Gamma(e^+e^-)$ — Γ_9

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<25	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\eta$

$a_2(1320)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\bar{K}) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_4\Gamma_7/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.126±0.007±0.028	ALBRECHT [17]	90G	ARG	$e^+e^- \to e^+e^- K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.081±0.006±0.027	ALBRECHT [18]	90G	ARG	$e^+e^- \to e^+e^- K^+K^-$

[17] Using an incoherent background.
[18] Using a coherent background.

$a_2(1320)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\rho\pi)$ — Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.070±0.012 OUR FIT					
0.078±0.017		CHABAUD 78	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.056±0.014	50	[19] CHALOUPKA 73	HBC	−	3.9 $\pi^- p$
0.097±0.018	113	[19] ALSTON-... 71	HBC	+	7.0 $\pi^+ p$
0.06 ±0.03		[19] ABRAMOVI... 70B	HBC	−	3.93 $\pi^- p$
0.054±0.022		[19] CHUNG 68	HBC	−	3.2 $\pi^- p$

[19] Included in CHABAUD 78 review.

$\Gamma(\eta\pi)/[\Gamma(\rho\pi)+\Gamma(\eta\pi)+\Gamma(K\overline{K})]$ — $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.162±0.012 OUR FIT					
0.140±0.028 OUR AVERAGE					
0.13 ±0.04		ESPIGAT 72	HBC	±	0.0 $\overline{p}p$
0.15 ±0.04	34	BARNHAM 71	HBC	+	3.7 $\pi^+ p$

$\Gamma(\eta\pi)/\Gamma(\rho\pi)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.207±0.018 OUR FIT					
0.213±0.020 OUR AVERAGE					
0.18 ±0.05		FORINO 76	HBC		11 $\pi^- p$
0.22 ±0.05	52	ANTIPOV 73	CNTR	−	40 $\pi^- p$
0.211±0.044	149	CHALOUPKA 73	HBC	−	3.9 $\pi^- p$
0.246±0.042	167	ALSTON-... 71	HBC	+	7.0 $\pi^+ p$
0.25 ±0.09	15	BOECKMANN 70	HBC	+	5.0 $\pi^+ p$
0.23 ±0.08	22	ASCOLI 68	HBC	−	5 $\pi^- p$
0.12 ±0.08		CHUNG 68	HBC	−	3.2 $\pi^- p$
0.22 ±0.09		CONTE 67	HBC	−	11.0 $\pi^- p$

$\Gamma(\eta'(958)\pi)/\Gamma_{total}$ — Γ_5/Γ

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.006	95	ALDE 92B	GAM2		38,100 $\pi^- p \to \eta' \pi^0 n$
<0.02	97	BARNHAM 71	HBC	+	3.7 $\pi^+ p$
0.004±0.004		BOESEBECK 68	HBC	+	8 $\pi^+ p$

$\Gamma(\eta'(958)\pi)/\Gamma(\rho\pi)$ — Γ_5/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.011	90	EISENSTEIN 73	HBC	−	5 $\pi^- p$
<0.04		ALSTON-... 71	HBC	+	7.0 $\pi^+ p$
$0.04\ ^{+0.03}_{-0.04}$		BOECKMANN 70	HBC	0	5.0 $\pi^+ p$

$\Gamma(K\overline{K})/[\Gamma(\rho\pi)+\Gamma(\eta\pi)+\Gamma(K\overline{K})]$ — $\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.054±0.009 OUR FIT					
0.048±0.012 OUR AVERAGE					
0.05 ±0.02		TOET 73	HBC	+	5 $\pi^+ p$
0.09 ±0.04		TOET 73	HBC	0	5 $\pi^+ p$
0.03 ±0.02	8	DAMERI 72	HBC	−	11 $\pi^- p$
0.06 ±0.03	17	BARNHAM 71	HBC	+	3.7 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.020±0.004		[20] ESPIGAT 72	HBC	±	0.0 $\overline{p}p$

[20] Not averaged because of discrepancy between masses from $K\overline{K}$ and $\rho\pi$ modes.

$\Gamma(\pi^+\pi^-\pi^-)/\Gamma(\rho\pi)$ — Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<0.12	90	ABRAMOVI... 70B	HBC	−	3.93 $\pi^- p$

$\Gamma(\pi^\pm\gamma)/\Gamma_{total}$ — Γ_6/Γ

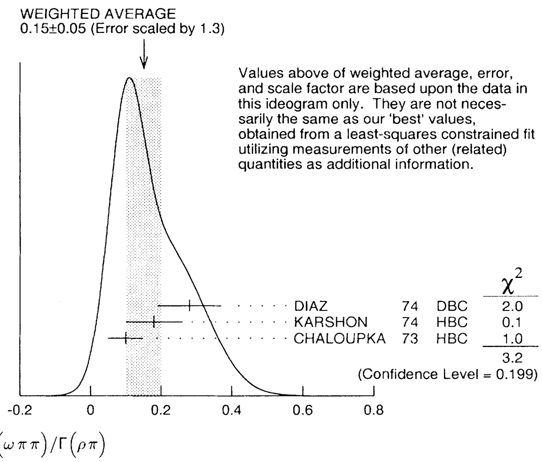
VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.005\ ^{+0.005}_{-0.003}$	[21] EISENBERG 72	HBC	4.3,5.25,7.5 γp

[21] Pion-exchange model used in this estimation.

$\Gamma(\omega\pi\pi)/\Gamma(\rho\pi)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.15±0.05 OUR FIT Error includes scale factor of 1.3.					
0.15±0.05 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
0.28±0.09	60	DIAZ 74	DBC	0	6 $\pi^+ n$
0.18±0.08		[22] KARSHON 74	HBC		Avg. of above two
0.10±0.05	279	CHALOUPKA 73	HBC	−	3.9 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.29±0.08	140	[22] KARSHON 74	HBC	0	4.9 $\pi^+ p$
0.10±0.04	60	[22] KARSHON 74	HBC	+	4.9 $\pi^+ p$
0.19±0.08		DEFOIX 73	HBC	0	0.7 $\overline{p}p$

[22] KARSHON 74 suggest an additional $I = 0$ state strongly coupled to $\omega\pi\pi$ which could explain discrepancies in branching ratios and masses. We use a central value and a systematic spread.



$\Gamma(\eta'(958)\pi)/\Gamma(\eta\pi)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
0.040±0.007 OUR AVERAGE			
0.047±0.010±0.004	[23] BELADIDZE 93	VES	$37\pi^- N \to a_2^- N$
0.034±0.008±0.005	BELADIDZE 92	VES	$36\pi^- C \to a_2^- C$

[23] Using $B(\eta' \to \pi^+\pi^-\eta) = 0.441$, $B(\eta \to \gamma\gamma) = 0.389$ and $B(\eta \to \pi^+\pi^-\pi^0) = 0.236$.

$a_2(1320)$ REFERENCES

AMELIN	96	ZPHY C70 71	+Berdnikov, Bityukov+	(SERP, TBIL)
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.)
AOYAGI	93	PL B314 246	+Fukui, Hasegawa+	(BKEI Collab.)
ARMSTRONG	93C	PL B307 394	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
BELADIDZE	93	PL 313 276	+Berdnikov, Bityukov+	(VES Collab.)
CONDO	93	PR D48 3045	+Handler, Bugg+	(SLAC Hybrid Collab.)
ALDE	92B	ZPHY C54 549	+Binon+	(SERP, BELG, LANL, LAPP, PISA, KEK)
BELADIDZE	92	ZPHY C54 235	+Bityukov, Borisov+	(VES Collab.)
ALBRECHT	90G	ZPHY C48 183	+Ehrlichmann, Harder+	(ARGUS Collab.)
ARMSTRONG	90	ZPHY C48 213	+Benayoun, Beusch	(WA76 Collab.)
BARU	90	ZPHY C48 581	+Blinov, Blinov+	(MD-1 Collab.)
BEHREND	90C	ZPHY C46 583	+Criegee+	(CELLO Collab.)
BUTLER	90	PR D42 1368	+Boyer+	(Mark II Collab.)
OEST	90	ZPHY C47 343	+Olsson+	(JADE Collab.)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
VOROBYEV	88	SJNP 48 273	+Golubev, Dolinsky, Druzhinin+	(NOVO)
		Translated from YAF 48 436.		
ALTHOFF	86	ZPHY C31 537	+Boch, Foster, Bernardi+	(TASSO Collab.)
ANTREASYAN	86	PR D33 1847	+Aschman, Besset, Bienlein+	(Crystal Ball Collab.)
BERGER	84C	PL 149B 427	+Klovning, Burger+	(PLUTO Collab.)
BEHREND	83B	PL 125B 518	+D'Agostini+	(CELLO Collab.)
FRAZER	83	Aachen Conf.		(UCSD)
CIHANGIR	82	PL 117B 123	+Berg, Biel, Chandlee+	(FNAL, MINN, ROCH)
CLELAND	82B	NP B208 228	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
EDWARDS	82F	PL 110B 82	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
DELFOSSE	81	NP B183 349	+Guisan, Martin, Muhlemann, Weill+	(GEVA, LAUS)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
CHABAUD	80	NP B175 189	+Hyams, Papadopoulou+	(CERN, MPIM, AMST)
DAUM	80C	PL 89B 276	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
BALTAY	78B	PR D17 62	+Cautis, Cohen, Csorna+	(COLU, BING)
CHABAUD	78	NP B145 349	+Hyams, Jones, Weilhammer, Blum+	(CERN, MPIM)
FERRERSORIA	78	PL 74B 287	+Treille+	(ORSAY, CERN, CDEF, EPOL)
HYAMS	78	NP B146 303	+Jones, Weilhammer, Blum+	(CERN, MPIM, ATEN)
MARTIN	78D	PL 74B 417	+Ozmutlu, Baldi, Bohringer, Dorsaz+	(DURH, GEVA) JP
MAY	77	PR D16 1983	+Abramson, Andrews, Busnello+	(ROCH, CORN)
FORINO	76	NC 35A 465	+Gessaroli+	(BGNA, FIRZ, GENO, MILA, OXF, PAVI)
MARGULIE	76	PR D14 667	+Kramer, Foley, Love, Lindenbaum+	(BNL, CUNY)
EMMS	75	PL 58B 117	+Jones, Kinson, Stacey, Bell+	(BIRM, DURH, RHEL) JP
WAGNER	75	PL 58B 201	+Tabak, Chew	(LBL) JP
DIAZ	74	PRL 32 260	+Dibianca, Fickinger, Anderson+	(CASE, CMU)
KARSHON	74	PRL 32 852	+Mikenberg, Pitluck, Eisenberg, Ronat+	(REHO)
ANTIPOV	73	NP B63 175	+Ascoli, Busnello, Focacci+	(CERN, SERP) JP
ANTIPOV	73C	NP B63 153	+Ascoli, Busnello, Focacci+	(CERN, SERP) JP
CHALOUPKA	73	PL 44B 211	+Dobrzynski, Ferrando, Losty+	(CERN)
CONFORTO	73	PL 45B 154	+Mobley, Key+	(EFI, FNAL, TNTO, WISC)
DEFOIX	73	PL 43B 141	+Dobrzynski, Espigat, Nascimento+	(CDEF)
EISENSTEIN	73	PR D7 278	+Schultz, Ascoli, Ioffredo+	(ILL)
KEY	73	PRL 30 503	+Conforto, Mobley+	(TNTO, EFI, FNAL, WISC)
TOET	73	NP B63 248	+Thuan, Major+	(NIJM, BONN, DURH, TORI)
DAMERI	72	NC 9A 1	+Borzatta, Goussu+	(GENO, MILA, SACL)
EISENBERG	72	PR D5 15	+Ballam, Dagan+	(REHO, SLAC, TELA)
ESPIGAT	72	NP B36 93	+Ghesquiere, Lillestol, Montanet	(CERN, CDEF)
FOLEY	72	PR D6 747	+Love, Ozaki, Platner, Lindenbaum+	(BNL, CUNY)
ALSTON-...	71	PL 34B 156	Alston-Garnjost, Barbaro, Buhl, Derenzo+	(LRL)

BARNHAM	71	PRL 26 1494	+Abrams, Butler, Coyne, Goldhaber, Hall+	(LBL)
BINNIE	71	PL 36B 257	+Camilleri, Duane, Faruqi, Burton+	(LOIC, SHMP)
BOWEN	71	PRL 26 1663	+Earles, Faissler, Blieden+	(NEAS, STON)
GRAYER	71	PL 34B 333	+Hyams, Jones, Schlein, Blum+	(CERN, MPIM)
ABRAMOVI...	70B	NP B23 466	Abramovich, Blumenfeld, Bruyant+	(CERN) JP
ALSTON-...	70	PL 33B 607	Alston-Garnjost, Barbaro, Buhl, Derenzo+	(LRL)
BOECKMANN	70	NP B16 221	+Major+	(BONN, DURH, NIJM, EPOL, TORI)
ASCOLI	68	PRL 20 1321	+Crawley, Mortara, Shapiro, Bridges+	(ILL) JP
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)
CHUNG	68	PR 165 1491	+Dahl, Kirz, Miller	(LRL)
CONTE	67	NC 51A 175	+Tomasini, Cords+	(GENO, HAMB, MILA, SACL)

OTHER RELATED PAPERS

JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
BEHREND	82C	PL 114B 378	+Chen, Fenner, Field+	(CELLO Collab.)
ABOLINS	65	Athens Conf.	+Carmony, Lander, Xuong, Yager	(UCSD) I
ADERHOLZ	65	PR 138B 897		(AACH3, BERL, BIRM, BONN, HAMB, LOIC, MPIM)
ALITTI	65	PL 15 69	+Baton, Deler, Crussard+	(SACL, BGNA) JP
CHUNG	65	PRL 15 325	+Dahl, Hardy, Hess, Jacobs, Kirz	(LRL)
FORINO	65B	PL 19 68	+Gessaroli+	(BGNA, BARI, FIRZ, ORSAY, SACL)
LEFEBVRES	65	PL 19 434	+Levrat+	(CERN Missing Mass Spect. Collab.)
SEIDLITZ	65	PRL 15 217	+Dahl, Miller	(LRL)
ADERHOLZ	64	PL 10 226	+	(AACH3, BERL, BIRM, BONN, DESY, HAMB+)
CHUNG	64	PRL 12 621	+Dahl, Hardy, Hess, Kalbfleisch, Kirz	(LRL)
GOLDHABER	64B	Dubna Conf. 1 480	+Goldhaber, O'Halloran, Shen	(LRL)
Also	64	PRL 12 336	Goldhaber, Brown, Kadyk, Shen+	(LRL, UCB)
LANDER	64	PRL 13 346A	+Abolins, Carmony, Hendricks, Xuong+	(UCSD)

$f_0(1370)$
was $f_0(1300)$

$I^G(J^{PC}) = 0^+(0^{++})$

NOTE ON SCALAR MESONS

The analysis of the scalar resonances in the $\pi\pi$ S-wave is notoriously difficult. In other partial waves, a resonance may be identified by the behavior of a single dominant channel across a mass range of a few hundred MeV. In contrast, the scalar waves couple strongly to more than one channel, and have overlapping and interfering broad resonances, often extending over more than 1 GeV. In addition, the $K\overline{K}$ and $\eta\eta$ thresholds produce sharp cusps in the partial waves. Thus, given experimental results in one channel, one can derive conclusions affecting the other scalar resonances. For this reason we discuss in this one Note all light scalars, organized in the Listings under the entries f_0(400-1200), $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $a_0(980)$, $a_0(1450)$, and $K_0^*(1430)$. This list is "minimal:" it does not necessarily exhaust the list of actual resonances.

The $I = 0$ states and the $\pi\pi$ S-wave: From the $\pi\pi$ threshold to about 1500 MeV, the claimed isoscalar resonances are found under four separate entries: f_0(400-1200), $f_0(980)$, $f_0(1370)$, and $f_0(1500)$. The data are obtained from resonance decays into the channels $\pi\pi$, $K\overline{K}$, $\eta\eta$, $\eta\eta'$, and 4π.

Below 1100 MeV, the essential contributions come from $\pi\pi$ and $K\overline{K}$ final states. The $\pi\pi$ phase shift δ_0^0 is well known to rise smoothly (GRAYER 74, ROSSELET 77) to 90° at around 900 MeV (HYAMS 73, CASON 76), then shows a rapid step of 180° near the $K\overline{K}$ threshold, due to the $f_0(980)$ resonance, which is superimposed over a large background. Above 1 GeV, the $\pi\pi$ phase shift continues to grow slowly, as expected for a very broad resonance. The $\pi\pi$ S-wave inelasticity is not accurately known, and the reported $\pi\pi \to K\overline{K}$ cross sections (WETZEL 76, POLYCHRONAKOS 79, COHEN 80, ETKIN 82B) may have large uncertainties.

In our editions from 1976 to 1994, this behavior of the phase shift was thought to be due mainly to the narrow $f_0(980)$ and the broad $f_0(1370)$, the latter variously named in earlier editions the $\epsilon(1200)$ and the f_0(1300-1400). It was, however, always uncertain whether there also exists a very broad structure mostly called σ in the literature. Before 1974, when the phase shift was known only up to about 900 MeV, one generally believed in a light σ (also called ϵ or η_{0+}) with a very large and uncertain width.

BECKER 79B excluded a narrow resonance behavior for δ_0^0 in their π^-p (polarized) $\to \pi^+\pi^-n$ data below 900 MeV. In contrast, SVEC 92, 96, using their data on π^+n (polarized) $\to \pi^+\pi^-p$ from 600 to 900 MeV, suggest a narrow scalar state at 750 MeV with a width of 100 to 200 MeV; the $f_0(980)$ was not included, which can explain the very narrow width obtained. Furthermore, the associated δ_0^0 values differ substantially from recent consensus and would reopen the old Up-Down ambiguity of the early 1970's (see our 1984 edition). Thus, the interpretation of SVEC 92 and others who claim a narrow σ must be treated with reservation, although, as SVEC 96 emphasize, the contribution from a_1 exchange in the $\pi N \to \pi\pi N$ processes has not been included in most analyses. New data resolving these important ambiguities would be most welcome. For further discussions of earlier analyses on the $\pi\pi$ S-wave, see our Notes in earlier editions and AU 87, MORGAN 93, and ZOU 93.

It has now become evident that the simplest understanding of the conventional $\pi\pi$ S-wave is obtained if one includes, in addition to the $f_0(980)$ and $f_0(1370)$ resonances, a very broad σ with a mass in the region 400-1200 MeV and a width exceeding 500 MeV (AU 87, MORGAN 93, ZOU 93, 94B, ACHASOV 94, TORNQVIST 95, 96, AMSLER 95B, AMSLER 95D, JANSSEN 95). The large spread in the resonance parameters obtained by these groups is due less to differences in the data used than to differences in the models employed. Important input in all analyses for the f_0(400-1200) are the standard $\pi\pi$ phase shifts below 1200 MeV, the same for all groups.

As to the $f_0(1370)$, all analyses of $\pi\pi$ and $K\overline{K}$ data claim a mainly elastic resonance around 1400 MeV. This still depends strongly on the standard $\pi\pi$ phase shift solution above 1100 MeV, and in particular on the small inelasticity of that solution, as mentioned above.

Above 1300 MeV, there is also evidence for a scalar–isoscalar resonance decaying to 4π. Whether this is the same resonance as the $f_0(1370)$ remains unsettled. There may be two resonances, one seen in elastic $\pi\pi$ scattering and coupling predominantly to $\pi\pi$, and another coupling mainly to 4π via $\rho\rho$ and two $\pi\pi$ S-waves. For now, we list both under the $f_0(1370)$. The 4π decay mode would, however, point to a large inelasticity. The information on the 4π channel comes mainly from the analysis of $\overline{p}n$ or $\overline{p}p \to 5\pi$ (GASPERO 93, ADAMO 93, AMSLER 94). AMSLER 94 finds a large production of a 0^{++} resonance decaying into 4π, mostly $\rho\rho$, with $M = 1374 \pm 38$ MeV and $\Gamma = 375 \pm 61$ MeV, and quotes a 4π:2π branching ratio of order 5:1.

Above the $f_0(1370)$ there is at least one resonance, the $f_0(1500)$, seen by the Crystal Barrel Collaboration (ANTINORI 95, AMSLER 95B, 95C). The $f_0(1590)$ of GAMS (BINON 83) in our 1994 edition is now listed under the same entry as the

$f_0(1500)$. For the determination of the resonance parameters, we use only the analyses in terms of T-matrix poles. See also our Note on Non-$q\overline{q}$ Mesons.

The $I = 1$ states: Two states are known, the $a_0(980)$ and the $a_0(1450)$ seen by the Crystal Barrel (AMSLER 94D). For a longer Note on the $a_0(980)$, see our 1994 edition, which includes comments on the nature of this resonance.

The most important fact about the $a_0(980)$ is that it lies very close to the $K\overline{K}$ threshold (like the $f_0(980)$); its shape, mass, and width are strongly distorted by this threshold. A naive Breit-Wigner fit to the resonance bump cannot reveal its true coupling constants to $\eta\pi$ and $K\overline{K}$. To obtain these, one must use a coupled-channel model with energy-dependent widths and mass-shift contributions. For the same reason, the branching ratios to $K\overline{K}$ and $\eta\pi$ are strongly energy dependent and one cannot use quoted width parameters in a naive way to determine the strength of the couplings.

Independently of any model about the nature of the $a_0(980)$ (or the $f_0(980)$), the $K\overline{K}$ component in the wave function of the state must be large. By general quantum mechanical arguments, any state (be it $q\overline{q}$ or whatever) that lies at the S-wave $K\overline{K}$ threshold and to which it couples strongly must have significant mixing with the $K\overline{K}$ continuum. Therefore, one cannot discuss the $a_0(980)$ (or the $f_0(980)$) without taking into account this large continuum component, *e.g.* when calculating $\gamma\gamma$ widths. The $\gamma\gamma$ width will always be suppressed by the $K\overline{K}$ component of the state.

The $I = 1/2$ sector: The $K_0^*(1430)$ (ASTON 88) is certainly the least controversial of the light scalar mesons. The phase shift rises smoothly from threshold, passes 90° at 1350 MeV, and then continues to rise to about 170° at 1600 MeV at the first important inelastic threshold, $K\eta'$. Thus, it behaves just as expected of a single broad, nearly elastic resonance. All analyses agree on a pole mass of about 1430 MeV and a width of about 300 MeV.

Interpretation of the nature of the scalars: Almost every model of the scalar states agrees that the $K_0^*(1430)$ is the 1^3P_0 quark model $s\overline{u}$ (or $s\overline{d}$) state. For the interpretation of the other light scalars, there are two main classes of models:

(i) The two states near the $K\overline{K}$ threshold, the $f_0(980)$ and the $a_0(980)$, are $K\overline{K}$ bound states (WEINSTEIN 89). The $f_0(1370)$ is the 1^3P_0 $u\overline{u} + d\overline{d}$ state, the $a_0(1450)$ is the $u\overline{d}$ state, and the mainly $s\overline{s}$ is still missing. The last is perhaps the state reported by LASS at 1525 MeV (ASTON 88D) or the $f_J(1710)$. The $f_0(400\text{-}1200)$ is then left as a background structure. The $f_0(1500)$ is too light and too narrow to be the second radially excited $u\overline{u} + d\overline{d}$ state, and it is not the missing $s\overline{s}$ state, due to its small $K\overline{K}$ branching ratio. A non-$q\overline{q}$ (gluonium) interpretation seems likely (AMSLER 96); see our Note on Non-$q\overline{q}$ Mesons.

(ii) Most, if not all, light scalars are different manifestations of the quark model $^3P_0$ $q\overline{q}$ states. The most economic model for this second alternative is that of TORNQVIST 82, 95, and 96, who fits the $f_0(400\text{-}1200)$, $f_0(980)$, $f_0(1370)$, $a_0(980)$, $a_0(1450)$, and $K_0^*(1430)$, as unitarized remnants of $q\overline{q}$ 1^3P_0 states with six parameters and theoretical constraints including flavor symmetry, the OZI rule, the equal-spacing rule for bare $q\overline{q}$ states, Adler zeroes, unitarity, and analyticity. Here the $f_0(400\text{-}1200)$ is at the same time the $u\overline{u} + d\overline{d}$ state, the chiral partner of the π, and the Higgs boson of QCD. The $f_0(980)$ and the $f_0(1370)$ are two different manifestations of the unitarized $s\overline{s}$ state, while the $a_0(980)$ and the $a_0(1450)$ are two manifestations of $u\overline{d}$. The interpretation of $f_0(1500)$ is in this scheme an open question.

For other models and more details discussing the interpretations of the scalar resonances, see AU 87, MORGAN 93, ZOU 93, 94B, and JANSSEN 95.

$f_0(1370)$ T-MATRIX POLE POSITION

Note that $\Gamma \approx 2\,\mathrm{Im}(\sqrt{s_{pole}})$.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
(1200–1500)−*i*(150–250) OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$(1330 \pm 50)-i(150 \pm 40)$	[1] AMSLER	95B	CBAR	$\overline{p}p \to 3\pi^0$
$(1360 \pm 35)-i(150\text{–}300)$	[1] AMSLER	95C	CBAR	$\overline{p}p \to \pi^0\eta\eta$
$1390 \pm 30 - i(190 \pm 40)$	[2] AMSLER	95D	CBAR	$\overline{p}p \to 3\pi^0, \pi^0\eta\eta, \pi^0\pi^0\eta$
$1346 - i249$	[3,4] JANSSEN	95	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
$1214 - i168$	[4,5] TORNQVIST	95	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
$1364 - i139$	AMSLER	94D	CBAR	$\overline{p}p \to \pi^0\pi^0\eta$
$(1365^{+20}_{-55})-i(134 \pm 35)$	ANISOVICH	94	CBAR	$\overline{p}p \to 3\pi^0, \pi^0\eta\eta$
$1340 \pm 40 - i(127^{+30}_{-20})$	[6] BUGG	94	RVUE	$\overline{p}p \to 3\pi^0, \eta\eta\pi^0, \eta\pi^0\pi^0$
$1515 - i214$	[4,7] ZOU	93	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$
$1420 - i220$	[8] AU	87	RVUE	$\pi\pi \to \pi\pi, K\overline{K}$

[1] Supersedes ANISOVICH 94.
[2] Coupled-channel analysis of $\overline{p}p \to 3\pi^0$, $\pi^0\eta\eta$, and $\pi^0\pi^0\eta$ on sheet IV. Demonstrates explicitly that $f_0(400\text{–}1200)$ and $f_0(1370)$ are two different poles.
[3] Analysis of data from FALVARD 88.
[4] The pole is on Sheet III. Demonstrates explicitly that $f_0(400\text{–}1200)$ and $f_0(1370)$ are two different poles.
[5] Uses data from BEIER 72B, OCHS 73, HYAMS 73, GRAYER 74, ROSSELET 77, CASON 83, ASTON 88, and ARMSTRONG 91B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.
[6] Reanalysis of ANISOVICH 94 data.
[7] Analysis of data from OCHS 73, GRAYER 74, and ROSSELET 77.
[8] Analysis of data from OCHS 73,GRAYER 74, BECKER 79, and CASON 83.

$f_0(1370)$ BREIT-WIGNER MASS OR K-MATRIX POLE PARAMETER

VALUE (MeV)	*DOCUMENT ID*
1200 to 1500 OUR ESTIMATE	

$\pi\pi$ MODE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1186	[9] TORNQVIST	95	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
1472 ± 12	ARMSTRONG	91	OMEG	$300\ pp \to pp\pi\pi, ppK\overline{K}$
1275 ± 20	BREAKSTONE	90	SFM	$62\ pp \to pp\pi^+\pi^-$
1420 ± 20	AKESSON	86	SPEC	$63\ pp \to pp\pi^+\pi^-$
1256	FROGGATT	77	RVUE	$\pi^+\pi^-$ channel

[9] Uses data from BEIER 72B, OCHS 73, HYAMS 73, GRAYER 74, ROSSELET 77, CASON 83, ASTON 88, and ARMSTRONG 91B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.

$K\overline{K}$ MODE

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1440 ± 20	CHEN	91	MRK3	$J/\psi \to \gamma\pi^+\pi^-, \gamma K\overline{K}$
1440 ± 50	BOLONKIN	88	SPEC	$40\ \pi^- p \to K_S^0 K_S^0 n$
1463 ± 9	ETKIN	82B	MPS	$23\ \pi^- p \to n2K_S^0$
1425 ± 15	WICKLUND	80	SPEC	$6\ \pi N \to K^+K^-N$
~ 1300	POLYCHRO...	79	STRC	$7\ \pi^- p \to n2K_S^0$

4π MODE $2(\pi\pi)_S+\rho\rho$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1374 ± 38	AMSLER	94	CBAR	$0.0\ \overline{p}p \to \pi^+\pi^-3\pi^0$
1345 ± 12	ADAMO	93	OBLX	$\overline{n}p \to 3\pi^+2\pi^-$
1386 ± 30	GASPERO	93	DBC	$0.0\ \overline{p}n \to 2\pi^+3\pi^-$

$\eta\eta$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1430	AMSLER	92	CBAR	$0.0\ \overline{p}p \to \pi^0\eta\eta$
1220 ± 40	ALDE	86D	GAM4	$100\ \pi^-p \to n2\eta$

$f_0(1370)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID
300 to 500 OUR ESTIMATE	

$\pi\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
350	[10] TORNQVIST	95	RVUE	$\pi\pi \to \pi\pi, K\overline{K}, K\pi, \eta\pi$
195 ± 33	ARMSTRONG	91	OMEG	$300\ pp \to pp\pi\pi, ppK\overline{K}$
285 ± 60	BREAKSTONE	90	SFM	$62\ pp \to pp\pi^+\pi^-$
460 ± 50	AKESSON	86	SPEC	$63\ pp \to pp\pi^+\pi^-$
~ 400	[11] FROGGATT	77	RVUE	$\pi^+\pi^-$ channel

[10] Uses data from BEIER 72B, OCHS 73, HYAMS 73, GRAYER 74, ROSSELET 77, CASON 83, ASTON 88, and ARMSTRONG 91B. Coupled channel analysis with flavor symmetry and all light two-pseudoscalars systems.
[11] Width defined as distance between 45 and 135° phase shift.

$K\overline{K}$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
160 ± 40	CHEN	91	MRK3	$J/\psi \to \gamma\pi^+\pi^-, \gamma K\overline{K}$
250 ± 80	BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_S K^0_S n$
118^{+138}_{-16}	ETKIN	82B	MPS	$23\ \pi^-p \to n2K^0_S$
160 ± 30	WICKLUND	80	SPEC	$6\ \pi N \to K^+K^-N$
~ 150	POLYCHRO...	79	STRC	$7\ \pi^-p \to n2K^0_S$

4π MODE $2(\pi\pi)_S+\rho\rho$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
375 ± 61	AMSLER	94	CBAR	$0.0\ \overline{p}p \to \pi^+\pi^-3\pi^0$
398 ± 26	ADAMO	93	OBLX	$\overline{n}p \to 3\pi^+2\pi^-$
310 ± 50	GASPERO	93	DBC	$0.0\ \overline{p}n \to 2\pi^+3\pi^-$

$\eta\eta$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
250	AMSLER	92	CBAR	$0.0\ \overline{p}p \to \pi^0\eta\eta$
320 ± 40	ALDE	86D	GAM4	$100\ \pi^-p \to n2\eta$

$f_0(1370)$ DECAY MODES

In two-particle decay modes the $\pi\pi$ decay is dominant. We include here the resonance observed in 4π under the same entry as the one decaying to 2 pseudoscalars. See also the minireview under non-$q\overline{q}$ candidates.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	seen
Γ_2	4π	seen
Γ_3	$4\pi^0$	
Γ_4	$2\pi^+2\pi^-$	seen
Γ_5	$\pi^+\pi^-2\pi^0$	seen
Γ_6	$\rho\rho$	
Γ_7	$2(\pi\pi)_S$	
Γ_8	$\eta\eta$	seen
Γ_9	$K\overline{K}$	seen
Γ_{10}	$\gamma\gamma$	seen
Γ_{11}	e^+e^-	not seen

$f_0(1370)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_{10}

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.4 ± 2.3	MORGAN	90	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$

$\Gamma(e^+e^-)$ — Γ_{11}

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<20	90	VOROBYEV	88	ND	$e^+e^- \to \pi^0\pi^0$

$f_0(1370)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.15	[12] AMSLER	94	CBAR	$\overline{p}p \to \pi^+\pi^-3\pi^0$
<0.20	GASPERO	93	DBC	$0.0\ \overline{p}n \to$ hadrons

[12] Using AMSLER 95B ($3\pi^0$).

$\Gamma(4\pi)/\Gamma_{total}$ — $\Gamma_2/\Gamma = (\Gamma_3+\Gamma_4+\Gamma_5)/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.80 ± 0.04	GASPERO	93	DBC	$0.0\ \overline{p}n \to$ hadrons

$\Gamma(2\pi^+2\pi^-)/\Gamma(4\pi)$ — $\Gamma_4/\Gamma_2 = \Gamma_4/(\Gamma_3+\Gamma_4+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.420 ± 0.014	[13] GASPERO	93	DBC	$0.0\ \overline{p}n \to 2\pi^+3\pi^-$

[13] Model-dependent evaluation.

$\Gamma(\pi^+\pi^-2\pi^0)/\Gamma(4\pi)$ — $\Gamma_5/\Gamma_2 = \Gamma_5/(\Gamma_3+\Gamma_4+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.512 ± 0.019	[14] GASPERO	93	DBC	$0.0\ \overline{p}n \to$ hadrons

[14] Model-dependent evaluation.

$\Gamma(\rho\rho)/\Gamma(2(\pi\pi)_S)$ — Γ_6/Γ_7

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.6\ \pm0.2$	AMSLER	94	CBAR	$\overline{p}p \to \pi^+\pi^-3\pi^0$
0.58 ± 0.16	GASPERO	93	DBC	$0.0\ \overline{p}n \to 2\pi^+3\pi^-$

$f_0(1370)$ REFERENCES

AMSLER 95B PL B342 433 +Armstrong, Brose+ (Crystal Barrel Collab.)
AMSLER 95C PL B353 571 +Armstrong, Hackman+ (Crystal Barrel Collab.)
AMSLER 95D PL B355 425 +Armstrong, Spanier+ (Crystal Barrel Collab.)
JANSSEN 95 PR D52 2690 +Pearce, Holinde, Speth (STON, ADLD, JULI)
TORNQVIST 95 ZPHY C68 647 (HELS)
AMSLER 94 PL B322 431 +Armstrong, Meyer+ (Crystal Barrel Collab.) JPC
AMSLER 94D PL B333 277 +Anisovich, Spanier+ (Crystal Barrel Collab.)
ANISOVICH 94 PL B323 233 +Armstrong+ (Crystal Barrel Collab.) JPC
BUGG 94 PR D50 4412 +Anisovich+ (LOQM)
ADAMO 93 NP A558 13C +Agnello+ (OBELIX Collab.) JPC
GASPERO 93 NP A562 407 (ROMAI) JPC
ZOU 93 PR D48 R3948 +Bugg (LOQM)
AMSLER 92 PL B291 347 +Augustin, Baker+ (Crystal Barrel Collab.)
ARMSTRONG 91 ZPHY C51 351 +Benayoun+ (ATHU, BARI, BIRM, CERN, CDEF)
ARMSTRONG 91B ZPHY C52 389 +Barnes+ (ATHU, BARI, BIRM, CERN, CDEF)
CHEN 91 Hadron 91 Conf. (Mark III Collab.)
SLAC-PUB-5669
BREAKSTONE 90 ZPHY C48 569 + (ISU, BGNA, CERN, DORT, HEIDH, WARS)
MORGAN 90 ZPHY C48 623 +Pennington (RAL, DURH)
ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, INUS)
BOLONKIN 88 NP B309 426 +Bloshenko, Gorin+ (ITEP, SERP)
FALVARD 88 PR D38 2706 +Ajaltouni+ (CLER, FRAS, LALO, PADO)
VOROBYEV 88 SJNP 48 273 +Golubev, Dolinsky, Druzhinin+ (NOVO)
Translated from YAF 48 436.
AU 87 PR D35 1633 +Morgan, Pennington (DURH, RAL)
AKESSON 86 NP B264 154 +Albrow, Almehed+ (Axial Field Spec. Collab.)
ALDE 86D NP B269 485 +Binon, Bricman+ (BELG, LAPP, SERP, CERN, LANL)
CASON 83 PR D28 1586 +Cannata, Baumbaugh, Bishop+ (NDAM, ANL)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)
WICKLUND 80 PRL 45 1469 +Ayres, Cohen, Diebold, Pawlicki (ANL)
BECKER 79 NP B151 46 +Blanar, Blum+ (MPIM, CERN, ZEEM, CRAC)
POLYCHRO... 79 PR D19 1317 Polychronakos, Cason, Bishop+ (NDAM, ANL)
FROGGATT 77 NP B129 89 +Petersen (GLAS, NORD)
ROSSELET 77 PR D15 574 +Extermann, Fischer, Guisan+ (GEVA, SACL)
GRAYER 74 NP B75 189 +Hyams, Blum, Dietl+ (CERN, MPIM)
HYAMS 73 NP B64 134 +Jones, Weilhammer, Blum, Dietl+ (CERN, MPIM)
OCHS 73 Thesis (MPIM, MUNI)
BEIER 72B PRL 29 511 +Buchholtz, Mann+ (PENN)

OTHER RELATED PAPERS

TORNQVIST 96 PRL 76 1575 +Roos (HELS)
LI 91 PR D43 2161 +Close, Barnes+ (TENN)
BIZZARRI 69 NP B14 169 +Foster, Gavillet, Montanet+ (CERN, CDEF)
BETTINI 66 NC 42A 695 +Cresti, Limentani, Bertanza, Bigi+ (PADO, PISA)

$h_1(1380)$

$I^G(J^{PC}) = ?^-(1^{+?})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K^0_S K^\pm \pi^\mp$ system. Evidence for $K^* \overline{K} + \overline{K}^* K$ decays (ASTON 88C). Needs confirmation.

$h_1(1380)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1380±20	ASTON	88C	LASS	11 $K^- p \rightarrow K^0_S K^\pm \pi^\mp \Lambda$

$h_1(1380)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80±30	ASTON	88C	LASS	11 $K^- p \rightarrow K^0_S K^\pm \pi^\mp \Lambda$

$h_1(1380)$ DECAY MODES

	Mode
Γ_1	$K \overline{K}^*(892)$ + c.c.

$h_1(1380)$ REFERENCES

ASTON 88C PL B201 573 +Awaji, Bienz+ (SLAC, NAGO, CINC, INUS)

$\hat{\rho}(1405)$

$I^G(J^{PC}) = 1^-(1^{-+})$

OMITTED FROM SUMMARY TABLE

Seen by ALDE 88B in $\pi^- p \rightarrow \eta \pi^0 n$ amplitude analysis. Not confirmed by reanalysis of PROKOSHKIN 95B.

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$\hat{\rho}(1405)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1406 ±20	[1] ALDE	88B	GAM4	0	100 $\pi^- p \rightarrow \eta \pi^0 n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1323.1± 4.6	AOYAGI	93	BKEI		$\pi^- p \rightarrow \eta \pi^- p$

[1] Seen in the P_0-wave intensity of the $\eta \pi^0$ system.

$\hat{\rho}(1405)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
180 ±20	[2] ALDE	88B	GAM4	0	100 $\pi^- p \rightarrow \eta \pi^0 n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
143.2±12.5	AOYAGI	93	BKEI		$\pi^- p \rightarrow \eta \pi^- p$

[2] Seen in the P_0-wave intensity of the $\eta \pi^0$ system.

$\hat{\rho}(1405)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta \pi^0$	possibly seen
Γ_2	$\eta \pi^-$	
Γ_3	$\rho \pi$	not seen
Γ_4	$\eta' \pi$	

$\hat{\rho}(1405)$ BRANCHING RATIOS

$\Gamma(\eta \pi^0)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
possibly seen	[3] ALDE	88B	GAM4	0	100 $\pi^- p \rightarrow \eta \pi^0 n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
not seen	PROKOSHKIN	95B	GAM4		100 $\pi^- p \rightarrow \eta \pi^0 n$
not seen	[4] BUGG	94	RVUE		$\overline{p} p \rightarrow \eta 2\pi^0$
not seen	[5] APEL	81	NICE	0	40 $\pi^- p \rightarrow \eta \pi^0 n$

[3] Seen in the P_0-wave intensity of the $\eta \pi^0$ system.
[4] Using Crystal Barrel data.
[5] A general fit allowing S, D, and P waves (including m=0) is not done because of limited statistics.

$\Gamma(\eta \pi^-)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
possibly seen	AOYAGI	93	BKEI	$\pi^- p \rightarrow \eta \pi^- p$

$\Gamma(\rho \pi)/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		COMMENT
not seen	[6] ZIELINSKI	86	200 π^+ Cu,Pb $\rightarrow \pi^+ \pi^+ \pi^- X$

[6] A general fit allowing S, D, and P waves (including m=0) is not done because of limited statistics.

$\Gamma(\eta' \pi)/\Gamma(\eta \pi^0)$ Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.80	95	BOUTEMEUR	90	GAM4	100 $\pi^- p \rightarrow 4\gamma n$

$\hat{\rho}(1405)$ REFERENCES

PROKOSHKIN 95B PAN 58 606 +Sadovski (SERP)
Translated from YAF 58 662.
BUGG 94 PR D50 4412 +Anisovich+ (LOQM)
AOYAGI 93 PL B314 246 +Fukui, Hasegawa+ (BKEI Collab.)
BOUTEMEUR 90 Hadron 89 Conf. p 119+Poulet (SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE 88B PL B205 397 +Binon, Boutemeur+ (SERP, BELG, LANL, LAPP) IGJPC
ZIELINSKI 86 Berkeley HEP 1 736 +Berg+ (ROCH, MINN, FNAL)
APEL 81 NP B193 269 +Augenstein, Bertolucci, Donskov+ (SERP, CERN)

OTHER RELATED PAPERS

PROKOSHKIN 95C PAN 58 853 +Sadovski (SERP)
Translated from YAF 58 921.
KALASHNIK... 94 ZPHY C62 323 Kalashnikova (ITEP)
IDDIR 88 PL B205 564 +Le Yaouanc, Ono+ (ORSAY, TOKY)
TUAN 88 PL B213 537 +Ferbel, Dalitz (HAWA, ROCH, OXFTP)
ZIELINSKI 87 ZPHY C34 255 (ROCH)

$f_1(1420)$

$I^G(J^{PC}) = 0^+(1^{++})$

See also minireview under non-$q\overline{q}$ candidates.

THE $f_1(1420)$

This particle is the axial-vector component of the old puzzling E/ι, which has caused much trouble.

In hadron-induced reactions, the $f_1(1420)$ is observed in centrally produced $K\overline{K}\pi$ systems obtained with π and p beams (DIONISI 80, ARMSTRONG 84, 89). A Dalitz-plot analysis gives its quantum numbers and the dominant decay mode. For instance, ARMSTRONG 89 finds that the signal is totally consistent with being an 1^{++} state with a dominant quasi-two-body S-wave decay into $K^*(892)\overline{K}$; furthermore, no 0^{-+} or 1^{+-} waves are required to fit the data. A G parity of $+1$ is suggested by the positive interference between the two overlapping $K^*(892)$ (ARMSTRONG 84). No significant signals in the $\eta\pi\pi$ or 4π decay modes are found in centrally produced 4π systems (ARMSTRONG 89G). All of this is in line with the previous observations made in $\overline{p}p$ annihilations.

In $\gamma\gamma$ fusion from e^+e^- annihilations, a signal at about 1420 MeV is seen only in single-tag events (AIHARA 86C, GIDAL 87B, BEHREND 89, HILL 89), where one of the two photons is off the mass shell; by contrast, it is totally absent in the untagged events where both photons are real and hence they cannot produce a spin-1 meson, because of the Yang-Landau theorem. This clearly implies $J = 1$ and $C = +1$. As for the parity, AIHARA 88B, 88C (same analysis as AIHARA 86C, with 25% more events) and BEHREND 89 all find angular distributions with positive parity preferred, but negative parity not excluded.

Although some uncertainties still remain, the state seen in hadronic interactions and that seen in spacelike virtual photon fusion from e^+e^- annihilations are often identified with one another since there are more similarities than differences. In particular, all experiments agree that this state appears only in $K^*(892)\overline{K}$. The same conclusions are obtained from partial wave analyses of $J/\psi(1S) \rightarrow \gamma K \overline{K} \pi$ (BAI 90C, AUGUSTIN 91).

BITYUKOV 88 studied the radiative decay $1^{++} \rightarrow \phi\gamma$. Since the ϕ is (almost) a pure $s\overline{s}$ state, the $\phi\gamma$ decay seems to be a good analyser to extract the $s\overline{s}$ component in the wave function of the decaying meson. Finding the $f_1(1285)$ but not the $f_1(1420)$, BITYUKOV 88 concludes that the $f_1(1420)$ cannot be the $s\overline{s}$ isoscalar member of the $q\overline{q}$ nonet containing the $f_1(1285)$. On the other hand, AIHARA 88C argues that, assuming they both belong to the same nonet and using several hypotheses, the octet-singlet mixing angle obtained is compatible with the $f_1(1420)$ being mostly $s\overline{s}$ and the $f_1(1285)$ being mostly $(u\overline{u}+d\overline{d})/\sqrt{2}$, although both require large admixtures of other $q\overline{q}$ components.

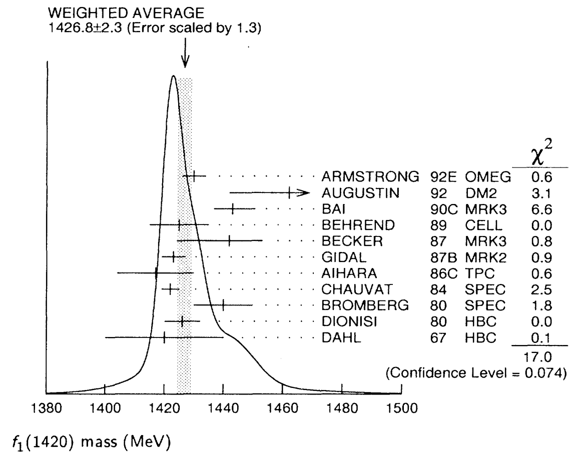
Arguments favoring the possibility the $f_1(1420)$ is a hybrid $q\overline{q}g$ meson or a four-quark state are put forward by ISHIDA 89 and by CALDWELL 90, respectively.

LONGACRE 90 argues that this particle is inconsistent with a QCD arrangement of quarks and gluons. He then develops a final-state rescattering mechanism with successive interactions between a K, a $\overline{K}$, and a π. The $f_1(1420)$ would then be a molecular state formed by the π orbiting in a P wave around an S-wave $K\overline{K}$ state.

$f_1(1420)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1426.8± 2.3 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.		
1430 ± 4		[1] ARMSTRONG 92E	OMEG	85,300 $\pi^+ p$, $pp \rightarrow \pi^+ p$, $pp(K\overline{K}\pi)$
1462 ±20		[2] AUGUSTIN 92	DM2	$J/\psi \rightarrow \gamma K \overline{K} \pi$
1443 $^{+7}_{-6}$ $^{+3}_{-2}$	1100	BAI 90C	MRK3	$J/\psi \rightarrow \gamma K^0_S K^{\pm}\pi^{\mp}$
1425 ±10	17	BEHREND 89	CELL	$\gamma\gamma \rightarrow K^0_S K^{\pm}\pi^{\mp}$
1442 ± 5 $^{+10}_{-17}$	111	BECKER 87	MRK3	e^+e^-, $\omega K \overline{K} \pi$
1423 ± 4		GIDAL 87B	MRK2	$e^+e^- \rightarrow e^+e^- K\overline{K}\pi$
1417 ±13	13	AIHARA 86C	TPC	$e^+e^- \rightarrow e^+e^- K\overline{K}\pi$
1422 ± 3		CHAUVAT 84	SPEC	ISR 31.5 pp
1440 ±10		[3] BROMBERG 80	SPEC	100 $\pi^- p \rightarrow K\overline{K}\pi X$
1426 ± 6	221	DIONISI 80	HBC	4 $\pi^- p \rightarrow K\overline{K}\pi n$
1420 ±20		DAHL 67	HBC	1.6–4.2 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1429 ± 3	389	ARMSTRONG 89	OMEG	300 $pp \rightarrow K\overline{K}\pi pp$
1425 ± 2	1520	ARMSTRONG 84	OMEG	85 $\pi^+ p$, $pp \rightarrow (\pi^+,p)(K\overline{K}\pi)p$

[1] This result supersedes ARMSTRONG 84, ARMSTRONG 89.
[2] From fit to the $K^*(892)K$ 1^{++} partial wave.
[3] Mass error increased to account for $a_0(980)$ mass cut uncertainties.



$f_1(1420)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
53± 5 OUR AVERAGE				
58±10		[4] ARMSTRONG 92E	OMEG	85,300 $\pi^+ p$, $pp \rightarrow \pi^+ p$, $pp(K\overline{K}\pi)$
129±41		[5] AUGUSTIN 92	DM2	$J/\psi \rightarrow \gamma K \overline{K} \pi$
68 $^{+29}_{-18}$ $^{+8}_{-9}$	1100	BAI 90C	MRK3	$J/\psi \rightarrow \gamma K^0_S K^{\pm}\pi^{\mp}$
42±22	17	BEHREND 89	CELL	$\gamma\gamma \rightarrow K^0_S K^{\pm}\pi^{\mp}$
40 $^{+17}_{-13}$ ±5	111	BECKER 87	MRK3	$e^+e^- \rightarrow \omega K \overline{K} \pi$
35 $^{+47}_{-20}$	13	AIHARA 86C	TPC	$e^+e^- \rightarrow e^+e^- K\overline{K}\pi$
47±10		CHAUVAT 84	SPEC	ISR 31.5 pp
62±14		BROMBERG 80	SPEC	100 $\pi^- p \rightarrow K\overline{K}\pi X$
40±15	221	DIONISI 80	HBC	4 $\pi^- p \rightarrow K\overline{K}\pi n$
60±20		DAHL 67	HBC	1.6–4.2 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
58± 8	389	ARMSTRONG 89	OMEG	300 $pp \rightarrow K\overline{K}\pi pp$
62± 5	1520	ARMSTRONG 84	OMEG	85 $\pi^+ p$, $pp \rightarrow (\pi^+,p)(K\overline{K}\pi)p$

[4] This result supersedes ARMSTRONG 84, ARMSTRONG 89.
[5] From fit to the $K^*(892)K$ 1^{++} partial wave.

$f_1(1420)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}\pi$	dominant
Γ_2	$\eta\pi\pi$	possibly seen
Γ_3	$a_0(980)\pi$	
Γ_4	$\pi\pi\rho$	
Γ_5	$K\overline{K}^*(892)$+ c.c.	
Γ_6	4π	
Γ_7	$\gamma\gamma^*$	
Γ_8	$\rho^0\gamma$	

$f_1(1420)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma^*)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
1.7±0.4 OUR AVERAGE				
3.0±0.9±0.7		[6,7] BEHREND 89	CELL	$e^+e^- \rightarrow e^+e^- K^0_S K\pi$
2.3 $^{+1.0}_{-0.9}$ ±0.8		HILL 89	JADE	$e^+e^- \rightarrow e^+e^- K^{\pm} K^0_S \pi^{\mp}$
1.3±0.5±0.3		AIHARA 88B	TPC	$e^+e^- \rightarrow e^+e^- K^{\pm} K^0_S \pi^{\mp}$
1.6±0.7±0.3		[6,8] GIDAL 87B	MRK2	$e^+e^- \rightarrow e^+e^- K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<8.0	95	JENNI 83	MRK2	$e^+e^- \rightarrow e^+e^- K\overline{K}\pi$

[6] Assume a ρ-pole form factor.
[7] A ϕ - pole form factor gives considerably smaller widths.
[8] Published value divided by 2.

$f_1(1420)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(K\overline{K}\pi)$ Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.76±0.06	BROMBERG	80	SPEC	$100\ \pi^- p \to K\overline{K}\pi X$
0.86±0.12	DIONISI	80	HBC	$4\ \pi^- p \to K\overline{K}\pi n$

$\Gamma(\pi\pi\rho)/\Gamma(K\overline{K}\pi)$ Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.3	95	CORDEN	78	OMEG	$12\text{–}15\ \pi^- p$
<2.0		DAHL	67	HBC	$1.6\text{–}4.2\ \pi^- p$

$\Gamma(\eta\pi\pi)/\Gamma(K\overline{K}\pi)$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	95	ARMSTRONG	91B	OMEG	$300\ pp \to pp\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.35±0.75		KOPKE	89	MRK3	$J/\psi \to \omega\eta\pi\pi(K\overline{K}\pi)$
<0.6	90	GIDAL	87	MRK2	$e^+e^- \to e^+e^-\eta\pi^+\pi^-$
<0.5	95	CORDEN	78	OMEG	$12\text{–}15\ \pi^- p$
1.5 ±0.8		DEFOIX	72	HBC	$0.7\ \overline{p}p$

$\Gamma(a_0(980)\pi)/\Gamma(\eta\pi\pi)$ Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen in either mode	ANDO	86	SPEC	$8\ \pi^- p$
not seen in either mode	CORDEN	78	OMEG	$12\text{–}15\ \pi^- p$
0.4±0.2	DEFOIX	72	HBC	$0.7\ \overline{p}p \to 7\pi$

$\Gamma(4\pi)/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ Γ_6/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.90	95	DIONISI	80	HBC	$4\ \pi^- p$

$\Gamma(K\overline{K}\pi)/[\Gamma(a_0(980)\pi)+\Gamma(K\overline{K}^*(892)+\text{c.c.})]$ $\Gamma_1/(\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.65±0.27	[9] DIONISI	80	HBC	$4\ \pi^- p$

[9] Calculated using $\Gamma(K\overline{K})/\Gamma(\eta\pi) = 0.24 \pm 0.07$ for $a_0(980)$ fractions.

$\Gamma(a_0(980)\pi)/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ Γ_3/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	68	ARMSTRONG	84	OMEG	$85\ \pi^+ p$

$\Gamma(4\pi)/\Gamma(K\overline{K}\pi)$ Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.62	95	ARMSTRONG	89G	OMEG	$85\ \pi p \to 4\pi X$

$\Gamma(\rho^0\gamma)/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	95	[10] ARMSTRONG	92C	SPEC	$300\ pp \to pp\pi^+\pi^-\gamma$

[10] Using the data on the $\overline{K}K\pi$ mode from ARMSTRONG 89.

$f_1(1420)$ REFERENCES

ARMSTRONG	92C	ZPHY C54 371	+Barnes, Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF)
ARMSTRONG	92E	ZPHY 56 29	+Benayoun+	(ATHU, BARI, BIRM, CERN, CDEF) JPC
AUGUSTIN	92	PR D46 1951	+Cosme	(DM2 Collab.)
ARMSTRONG	91B	ZPHY C52 389	+Barnes+	(ATHU, BARI, BIRM, CERN, CDEF)
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)
ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+) JPC
ARMSTRONG	89G	ZPHY C43 55	+Bloodworth+	(CERN, BIRM, BARI, ATHU, CURIN+)
BEHREND	89	ZPHY C42 367	+Criegee+	(CELLO Collab.)
HILL	89	ZPHY C42 355	+Olsson+	(JADE Collab.) JP
KOPKE	89	PRPL 174 67	+Wermes+	(CERN)
AIHARA	88B	PL B209 107	+Alston-Garnjost+	(TPC-2γ Collab.)
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.) JP
GIDAL	87	PRL 59 2012	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
GIDAL	87B	PRL 59 2016	+Boyer, Butler, Cords, Abrams+	(LBL, SLAC, HARV)
AIHARA	86C	PRL 57 2500	+Alston-Garnjost+	(TPC-2γ Collab.) JP
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, INUS, TSUK+)
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN) JP
CHAUVAT	84	PL 148B 382	+Meritet, Bonino+	(CERN, CLER, UCLA, SACL)
JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
BROMBERG	80	PR D22 1513	+Haggerty, Abrams, Dzierba	(CIT, FNAL, ILLC, IND)
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH) IJP
CORDEN	78	NP B144 253	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL) IJP
Also	65	PRL 14 1074	Miller, Chung, Dahl, Hess, Hardy, Kirz+	(LRL, UCB)

OTHER RELATED PAPERS

IIZUKA	91	PTP 86 885	+Koibuchi	(NAGO)
CALDWELL	90	Hadron 89 Conf. p 127		(UCSB)
ISHIDA	89	PTP 82 119	+Oda, Sawazaki, Yamada	(NIHO)
AIHARA	88C	PR D38 1	+Alston-Garnjost+	(TPC-2γ Collab.) JPC
BITYUKOV	88	PL B203 327	+Borisov, Dorofeev+	(SERP)
PROTOPOP...	87B	Hadron 87 Conf.	Protopopescu, Chung	(BNL)

$\omega(1420)$

$I^G(J^{PC}) = 0^-(1^{--})$

See also $\omega(1600)$.

$\omega(1420)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1419±31	315	[1] ANTONELLI	92	DM2	$1.34\text{–}2.4 e^+e^- \to \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1440±70		[2] CLEGG	94	RVUE	

[1] From a fit to two Breit-Wigner functions interfering between them and with the ω,ϕ tails with fixed (+,−,+) phases.

[2] Using data published by ANTONELLI 92.

$\omega(1420)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
174±59	315	[3] ANTONELLI	92	DM2	$1.34\text{–}2.4 e^+e^- \to \rho\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
240±70		[4] CLEGG	94	RVUE	

[3] From a fit to two Breit-Wigner functions interfering between them and with the ω,ϕ tails with fixed (+,−,+) phases.

[4] Using data published by ANTONELLI 92.

$\omega(1420)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	dominant
Γ_2	$\omega\pi\pi$	
Γ_3	e^+e^-	

$\omega(1420)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\rho\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (eV)	EVTS	DOCUMENT ID		TECN	COMMENT
81±31	315	[5] ANTONELLI	92	DM2	$1.34\text{–}2.4 e^+e^- \to \rho\pi$

[5] From a fit to two Breit-Wigner functions interfering between them and with the ω,ϕ tails with fixed (+,−,+) phases.

$\omega(1420)$ REFERENCES

CLEGG	94	ZPHY C62 455	+Donnachie	(LANC, MCHS)
ANTONELLI	92	ZPHY C56 15	+Baldini+	(DM2 Collab.)

OTHER RELATED PAPERS

ATKINSON	87	ZPHY C34 157	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN)
ATKINSON	84	NP B231 15	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON	83B	PL 127B 132	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)

$f_2(1430)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

This entry lists nearby peaks observed in the D wave of the $K\overline{K}$ and $\pi^+\pi^-$ systems. Needs confirmation.

$f_2(1430)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1430 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1421± 5	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1410±50	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
1436^{+26}_{-16}	DAUM	84	CNTR	$17\text{–}18\ \pi^- p \to K^+K^- n$
1412± 3	DAUM	84	CNTR	$63\ \pi^- p \to K^0_S K^0_S n$, $K^+K^- n$
1439^{+5}_{-6}	[1] BEUSCH	67	OSPK	$5,7,12\ \pi^- p \to K^0_S K^0_S n$

[1] Not seen by WETZEL 76.

$f_2(1430)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
30 ± 9	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
80 ± 40	AKESSON	86	SPEC	$pp \to pp\pi^+\pi^-$
81^{+56}_{-29}	DAUM	84	CNTR	$17\text{–}18\ \pi^- p \to K^+K^- n$
14 ± 6	DAUM	84	CNTR	$63\ \pi^- p \to K^0_S K^0_S n$, $K^+K^- n$
43^{+17}_{-18}	[2] BEUSCH	67	OSPK	$5,7,12\ \pi^- p \to K^0_S K^0_S n$

[2] Not seen by WETZEL 76.

$f_2(1430)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$
Γ_2	$\pi\pi$

$f_2(1430)$ REFERENCES

AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
AKESSON	86	NP B264 154	+Albrow, Almehed+	(Axial Field Spec. Collab.)
DAUM	84	ZPHY C23 339	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
WETZEL	76	NP B115 208	+Freudenreich, Beusch+	(ETH, CERN, LOIC)
BEUSCH	67	PL 25B 357	+Fischer, Gobbi, Astbury+	(ETH, CERN)

$\eta(1440)$

$I^G(J^{PC}) = 0^+(0^{-+})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

THE $\eta(1440)$

The first observation of a meson with $I^G J^{PC} = 0^+0^{-+}$ in the 1400-MeV mass region was made in $p\overline{p} \to K\overline{K}3\pi$ annihilations at rest (BAILLON 67). The $\eta(1440)$ was reported to decay into $K\overline{K}\pi$, equally through $a_0(980)\pi$ and $K^*(892)\overline{K}$.

The $\eta(1440)$ has since also been seen in a partial-wave analysis of the $K\overline{K}\pi$ system (CHUNG 85, BIRMAN 88), in 6-GeV $p\overline{p}$ annihilations (REEVES 86), and in nonperipherally selected $\pi^- p \to K^0_S K^0_S \pi^0 n$ (RATH 89). RATH 89 favors two η resonances in the 1410-1480 MeV region. This is also observed at LEAR in $\overline{p}p \to K\overline{K}3\pi$ annihilations at rest (BERTIN 95).

In a partial-wave analysis of $\pi^- p \to \eta\pi^+\pi^-$, FUKUI 91C confirms the decay $\eta(1440) \to a_0(980)\pi$. In $\overline{p}p \to \eta\pi\pi$ annihilations at rest, AMSLER 95F finds roughly equal contributions from $a_0(980)\pi$ and $\eta(\pi\pi)_S$.

Neither the $\eta(1440)$ nor the $f_1(1420)$ are observed in the $s\overline{s}$-enriched peripheral reaction $K^- p \to K\overline{K}\pi\Lambda$ at 11 GeV/c (ASTON 87), which speaks against an $s\overline{s}$ interpretation of either state. ARMSTRONG 84, 89, studying $K\overline{K}\pi$ central production in $\pi^+ p \to \pi^+(K\overline{K}\pi)p$ and $pp \to p(K\overline{K}\pi)p$ at 85 and 300 GeV/c, observed the $f_1(1420)$ but not the $\eta(1440)$.

The $\eta(1440)$ is also seen as a broad enhancement in $J/\psi(1S)$ radiative decay. BUGG 95 has reanalyzed the MARK-III data and finds a contribution to 4π in agreement with DM2 (BISELLO 89B). The $\eta\pi^+\pi^-$ channel peaks near 1400 MeV (AUGUSTIN 90, BOLTON 92B), in agreement with observations in $\overline{p}p$ annihilation at rest (AMSLER 95F). It has been shown (TOKI 87, BAI 90C) that two pseudoscalar resonances at $\approx$ 1420 and $\approx$ 1490 MeV, together with a 1^{++} around 1440 MeV, give a better description of the $K\overline{K}\pi$ data. These results, together with RATH 89 and BERTIN 95, suggest the existence of two overlapping pseudoscalar states, one around 1400 MeV decaying into both $K\overline{K}\pi$ and $\eta\pi\pi$, the other one around 1480 MeV decaying only to $K\overline{K}\pi$.

We continue to list under the $\eta(1440)$ all the results on the 0^{-+} system in the 1380-1490 MeV region, but there is probably more than one resonance present in the observations. It is thus difficult to give reliable $\overline{K}^*K$ or $a_0\pi$ branching ratios. The masses and widths are given separately according to the various decay modes. See also our Note on "Non-$q\overline{q}$ Mesons."

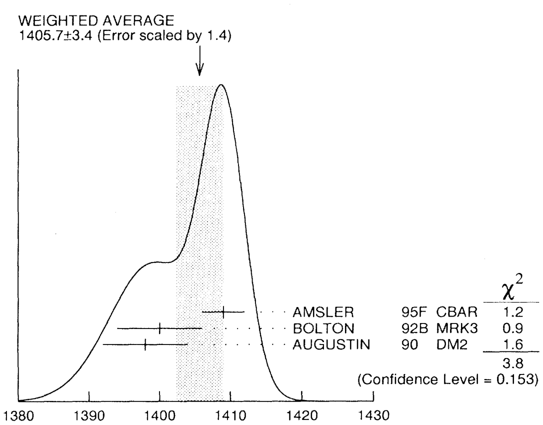
$\eta(1440)$ MASS

VALUE (MeV)	DOCUMENT ID
1415±10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\eta\pi\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1405.7± 3.4 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.			
1409 ± 3		AMSLER	95F	CBAR	$0\ \overline{p}p \to \pi^+\pi^-\pi^0\pi^0\eta$
1400 ± 6		[1] BOLTON	92B	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
1398 ± 6	261	[2] AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1385 ± 15		[1] BEHREND	92	CELL	$J/\psi \to \gamma\eta\pi^+\pi^-$
1388 ± 4		FUKUI	91C	SPEC	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$
1420 ± 5		ANDO	86	SPEC	$8\ \pi^- p \to n\eta\pi^+\pi^-$

[1] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[2] Best fit with a single Breit Wigner.



$\eta(1440)$ mass, $\eta\pi\pi$ mode (MeV)

$\pi\pi\gamma$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1401 ± 18	[3,4] AUGUSTIN	90	DM2	$J/\psi \to \pi^+\pi^-\gamma\gamma$
1440 ± 20	[4] COFFMAN	90	MRK3	$J/\psi \to \pi^+\pi^- 2\gamma$

[3] Best fit with a single Breit Wigner.
[4] This peak in the $\gamma\rho$ channel may not be related to the $\eta(1440)$.

4π MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1420 ± 20		BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1489 ± 12	3270	[5] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

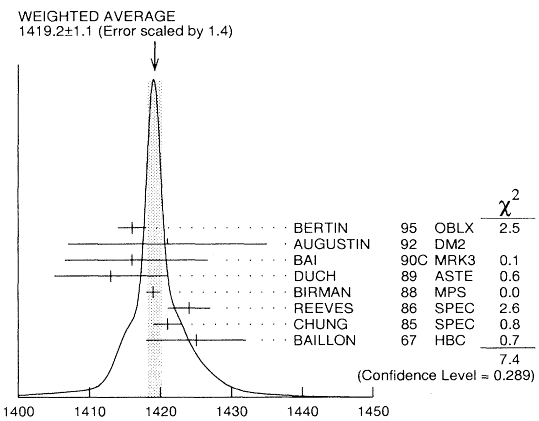
[5] Estimated by us from various fits.

$K\overline{K}\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1419.2± 1.1 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.			
1416 ± 2		[6] BERTIN	95	OBLX	$0\ \overline{p}p \to K\overline{K}\pi\pi\pi$
1421 ± 14		[7] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\overline{K}\pi$
$1416 \pm 8\ ^{+7}_{-5}$	700	[8] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
1413 ± 8	500	DUCH	89	ASTE	$\overline{p}p \to \pi^+\pi^- K^\pm\pi^\mp K^0$
1419 ± 1	8800	[9,10] BIRMAN	88	MPS	$8\ \pi^- p \to K^+\overline{K}^0\pi^- n$
1424 ± 3	620	[10,11] REEVES	86	SPEC	$6.6\ p\overline{p} \to K\overline{K}\pi X$
1421 ± 2		CHUNG	85	SPEC	$8\ \pi^- p \to K\overline{K}\pi n$
1425 ± 7	800	[10,12] BAILLON	67	HBC	$0.0\ \overline{p}p \to K\overline{K}\pi\pi\pi$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1460 ±10		[13] BERTIN	95	OBLX	$0\ \bar{p}p \to K\bar{K}\pi\pi\pi$
1459 ± 5		[9] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\bar{K}\pi$
1445 ± 8	693	[10] AUGUSTIN	90	DM2	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$
1433 ± 8	296	[10] AUGUSTIN	90	DM2	$J/\psi \to \gamma K^+ K^- \pi^0$
1490 $^{+14}_{-8}$ $^{+3}_{-16}$	1100	[7] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$
1443 ± 5		[7] TAKAMATSU	90	SPEC	$8\ \pi^- p \to nK^*(892)K$
1424 ± 4		TAKAMATSU	90	SPEC	$8\ \pi^- p \to nK^0_S K^\pm \pi^\mp$
1475 ± 4		[14] RATH	89	MPS	$21.4\ \pi^- p \to nK^0_S K^0_S \pi^0$
1452.8± 6.8	170	[10] RATH	89	MPS	$21.4\ \pi^- p \to K^0_S K^0_S \pi^0 n$
1412.8± 5.4		RATH	89	MPS	$21.4\ \pi^- p \to nK^0_S K^0_S \pi^0$
1454 ± 3		WISNIEWSKI	87	MRK3	$J/\psi \to K\bar{K}\pi\gamma$
1440 $^{+20}_{-15}$	174	EDWARDS	82E	CBAL	$J/\psi \to \gamma K^+ K^- \pi^0$
1440 $^{+10}_{-15}$		SCHARRE	80	MRK2	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$

[6] Decaying into $(K\bar{K})_S\pi$, $(K\pi)_S\bar{K}$, and $a_0(980)\pi$.
[7] From fit to the $K^*(892)K$ 0^{-+} partial wave.
[8] From fit to the $a_0(980)\pi$ 1^{++} partial wave. cannot rule out a $a_0(980)\pi$ 1^{++} partial wave.
[9] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[10] Best fit with a single Breit Wigner.
[11] From fit of the 0^{-+} partial wave , mainly $a_0(980)\pi$.
[12] From best fit of 0^{-+} partial wave , 50% $K^*(892)K$, 50% $a_0(980)\pi$.
[13] Decaying into $K^*(892)K$.
[14] From fit to the $a_0(980)\pi$ 0^{-+} partial wave , but $a_0(980)\pi$ 1^{++} cannot be excluded. The fit is also consistent with one resonance at 1453 MeV.



$\eta(1440)$ mass, $K\bar{K}\pi$ mode (MeV)

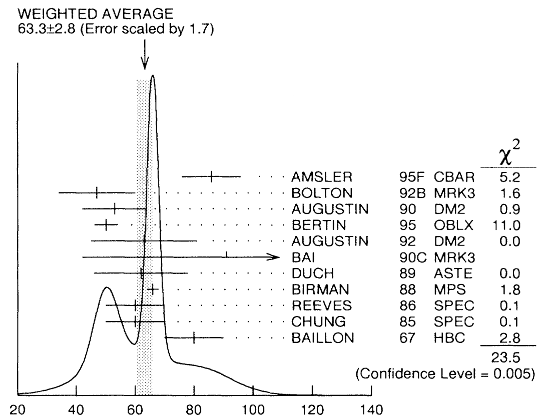
$\eta(1440)$ WIDTH

VALUE (MeV)	DOCUMENT ID
60±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\eta\pi\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
63.3± 2.8 OUR AVERAGE	Includes data from the datablock that follows this one. Error includes scale factor of 1.7. See the ideogram below.			
86 ±10	AMSLER	95F	CBAR	$0\ \bar{p}p \to \pi^+\pi^-\pi^0\pi^0\eta$
47 ±13	[15] BOLTON	92B	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
53 ±11	[16] AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 50	[16] BEHREND	92	CELL	$J/\psi \to \gamma\eta\pi^+\pi^-$
59 ± 4	FUKUI	91C	SPEC	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$
31 ± 7	ANDO	86	SPEC	$8\ \pi^- p \to n\eta\pi^+\pi^-$

[15] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[16] From $\eta\pi^+\pi^-$ mass distribution - mainly $a_0(980)\pi$ - no spin–parity determination available.



$\eta(1440)$ width $\eta\pi\pi$ mode (MeV)

$\pi\pi\gamma$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
174±44	AUGUSTIN	90	DM2	$J/\psi \to \pi^+\pi^-\gamma\gamma$
60±30	[17] COFFMAN	90	MRK3	$J/\psi \to \pi^+\pi^- 2\gamma$

[17] This peak in the $\gamma\rho$ channel may not be related to the $\eta(1440)$.

4π MODE

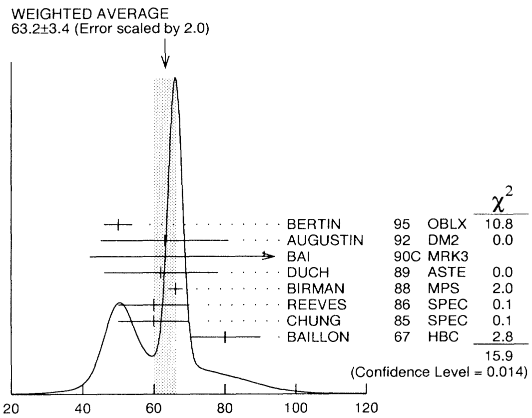
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
160±30		BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
144±13	3270	[18] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[18] Estimated by us from various fits.

$K\bar{K}\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.					
63.2± 3.4 OUR AVERAGE	Error includes scale factor of 2.0. See the ideogram below.				
50 ± 4		[19] BERTIN	95	OBLX	$0\ \bar{p}p \to K\bar{K}\pi\pi\pi$
63 ±18		AUGUSTIN	92	DM2	$J/\psi \to \gamma K\bar{K}\pi$
91 $^{+67}_{-31}$ $^{+15}_{-38}$		BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$
62 ±16	500	DUCH	89	ASTE	$\bar{p}p \to K\bar{K}\pi\pi\pi$
66 ± 2	8800	BIRMAN	88	MPS	$8\ \pi^- p \to K^+\bar{K}^0\pi^- n$
60 ±10	620	[20] REEVES	86	SPEC	$6.6\ p\bar{p} \to KK\pi X$
60 ±10		CHUNG	85	SPEC	$8\ \pi^- p \to K\bar{K}\pi n$
80 ±10	800	[21] BAILLON	67	HBC	$0.0\ \bar{p}p \to K\bar{K}\pi\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105 ±15		[22] BERTIN	95	OBLX	$0\ \bar{p}p \to K\bar{K}\pi\pi\pi$
75 ± 9		[23] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\bar{K}\pi$
75 ± 9	693	[23] AUGUSTIN	90	DM2	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$
93 ±14	296	AUGUSTIN	90	DM2	$J/\psi \to \gamma K^+ K^- \pi^0$
105 ±10	693	AUGUSTIN	90	DM2	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$
54 $^{+37}_{-21}$ $^{+13}_{-24}$		[24] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$
59 ± 4		[24] TAKAMATSU	90	SPEC	$9\ \pi^- p \to n\eta\pi^+\pi^-$
82 ± 8		TAKAMATSU	90	SPEC	$8\ \pi^- p \to nK^0_S K^\pm \pi^\mp$
57 ± 8		TAKAMATSU	90	SPEC	$8\ \pi^- p \to nK^*(892)K$
51 ±13		[25] RATH	89	MPS	$21.4\ \pi^- p \to nK^0_S K^0_S \pi^0$
99.9±11.4	170	[26] RATH	89	MPS	$21.4\ \pi^- p \to K^0_S K^0_S \pi^0 n$
19 ± 7		RATH	89	MPS	$21.4\ \pi^- p \to nK^0_S K^0_S \pi^0$
160 ±11		WISNIEWSKI	87	MRK3	$J/\psi \to K\bar{K}\pi\gamma$
55 $^{+20}_{-30}$	174	EDWARDS	82E	CBAL	$J/\psi \to \gamma K^+ K^- \pi^0$
50 $^{+30}_{-20}$		SCHARRE	80	MRK2	$J/\psi \to \gamma K^0_S K^\pm \pi^\mp$

[19] Decaying into $(K\bar{K})_S\pi$, $(K\pi)_S\bar{K}$, and $a_0(980)\pi$.
[20] From best fit to 0^{-+} partial wave , 50% $K^*(892)K$, 50% $a_0(980)\pi$.
[21] From fit to the 0^{-+} partial wave , mainly $a_0(980)\pi$.
[22] Decaying into $K^*(892)K$.
[23] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[24] From fit to the $K^*(892)K$ 0^{-+} partial wave.
[25] From fit to the $a_0(980)\pi$ 0^{-+} partial wave , but $a_0(980)\pi$ 1^{++} cannot be excluded. The fit is also consistent with one resonance at 1453 MeV.
[26] Best fit with a single Breit Wigner.



$\eta(1440)$ width $K\overline{K}\pi$ mode (MeV)

$\eta(1440)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}\pi$	seen
Γ_2	$\eta\pi\pi$	seen
Γ_3	$a_0(980)\pi$	seen
Γ_4	$\pi\pi\rho$	
Γ_5	$K\overline{K}^*(892)+$ c.c.	
Γ_6	4π	seen
Γ_7	$\gamma\gamma$	
Γ_8	$\rho^0\gamma$	

$\eta(1440)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_1\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
<1.2	95	BEHREND	89	CELL	$\gamma\gamma \to K^0_S K^\pm\pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	95	AIHARA	86D	TPC	$e^+e^- \to e^+e^- K^0_S K^\pm\pi^\mp$
<2.2	95	ALTHOFF	85B	TASS	$e^+e^- \to e^+e^- K\overline{K}\pi$
<8.0	95	JENNI	83	MRK2	$e^+e^- \to e^+e^- K\overline{K}\pi$

$\Gamma(\eta\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_2\Gamma_7/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.3	ANTREASYAN	87	CBAL	$e^+e^- \to e^+e^-\eta\pi\pi$

$\Gamma(\rho^0\gamma) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_8\Gamma_7/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5	95	ALTHOFF	84E	TASS	$e^+e^- \to e^+e^-\pi^+\pi^-\gamma$

$\eta(1440)$ BRANCHING RATIOS

$\Gamma(\eta\pi\pi)/\Gamma(K\overline{K}\pi)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.5	90	EDWARDS	83B	CBAL	$J/\psi \to \eta\pi\pi\gamma$
<1.1	90	SCHARRE	80	MRK2	$J/\psi \to \eta\pi\pi\gamma$
<1.5	95	FOSTER	68B	HBC	0.0 $\overline{p}p$

$\Gamma(a_0(980)\pi)/\Gamma(K\overline{K}\pi)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
~ 0.8	500	[27] DUCH	89	ASTE	$\overline{p}p \to \pi^+\pi^- K^\pm\pi^\mp K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 0.15		[27] BERTIN	95	OBLX	0 $\overline{p}p \to K\overline{K}\pi\pi\pi$
~ 0.75		[27] REEVES	86	SPEC	6.6 $p\overline{p} \to KK\pi X$

[27] Assuming that the $a_0(980)$ decays only into $K\overline{K}$.

$\Gamma(a_0(980)\pi)/\Gamma(\eta\pi\pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.56±0.04±0.03	[28] AMSLER	95F	CBAR	0 $\overline{p}p \to \pi^+\pi^-\pi^0\pi^0\eta$

[28] Assuming that the $a_0(980)$ decays only into $\eta\pi$.

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(K\overline{K}\pi)$ — Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.50±0.10	BAILLON	67	HBC	0.0 $\overline{p}p \to K\overline{K}\pi\pi\pi$

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/[\Gamma(a_0(980)\pi)+\Gamma(K\overline{K}^*(892)+\text{c.c.})]$ — $\Gamma_5/(\Gamma_3+\Gamma_5)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.25	90	EDWARDS	82E	CBAL	$J/\psi \to K^+K^-\pi^0\gamma$

$\Gamma(\rho^0\gamma)/\Gamma(K\overline{K}\pi)$ — Γ_8/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.0152±0.0038	[29] COFFMAN	90	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$

[29] Using B($J/\psi \to \gamma\eta(1440) \to \gamma K\overline{K}\pi$)=$4.2 \times 10^{-3}$ and B($J/\psi \to \gamma\eta(1440) \to \gamma\gamma\rho^0$)=$6.4 \times 10^{-5}$ and assuming that the $\gamma\rho^0$ signal does not come from the $f_1(1420)$.

$\eta(1440)$ REFERENCES

AMSLER	95F	PL B358 389	+Armstrong, Urner+	(Crystal Barrel Collab.)
BERTIN	95	PL B361 187	+Bruschi+	(OBELIX Collab.)
BUGG	95	PL B353 378	+Scott, Zoli+	(LOQM, PNPI, WASH)
AUGUSTIN	92	PR D46 1951	+Cosme	(DM2 Collab.)
BEHREND	92	ZPHY C56 381		(CELLO Collab.)
BOLTON	92B	PRL 69 1328	+Brown, Bunnell+	(Mark III Collab.)
FUKUI	91C	PL B267 293	+	(SUGI, NAGO, KEK, KYOT, MIYA, AKIT)
AUGUSTIN	90	PR D42 10	+Cosme+	(DM2 Collab.)
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)
COFFMAN	90	PR D41 1410	+De Jongh+	(Mark III Collab.)
TAKAMATSU	90	Hadron 89 Conf. p 71	+Ando+	(KEK)
BEHREND	89	ZPHY C42 367	+Criegee+	(CELLO Collab.)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
DUCH	89	ZPHY 45 223	+Heel, Bailey+	(ASTERIX Collab.) JP
RATH	89	PR D40 693	+Cason+	(NDAM, BRAN, BNL, CUNY, DUKE)
BIRMAN	88	PRL 61 1557	+Chung, Peaslee+	(BNL, FSU, IND, MASD) JP
ANTREASYAN	87	PR D36 2633	+Bartels, Besset+	(Crystal Ball Collab.)
WISNIEWSKI	87	Hadron 87 Conf.		(Mark III Collab.)
AIHARA	86D	PRL 57 51	+Alston-Garnjost+	(TPC-2γ Collab.)
ANDO	86	PRL 57 1296	+Imai+	(KEK, KYOT, NIRS, SAGA, INUS, TSUK+) IJP
REEVES	86	PR 34 1960	+Chung, Crittenden+	(FLOR, BNL, IND, MASD) JP
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
CHUNG	85	PRL 55 779	+Fernow, Boehnlein+	(BNL, FLOR, IND, MASD) JP
ALTHOFF	84E	PL 147B 487	+Braunschweig, Kirschfink, Luebelsmeyer+	(TASSO Collab.)
EDWARDS	83B	PRL 51 859	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
EDWARDS	82E	PRL 49 259	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
Also	83	PRL 50 219	Edwards, Partridge+	(CIT, HARV, PRIN, STAN+)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
FOSTER	68B	NP B8 174	+Gavillet, Labrosse, Montanet+	(CERN, CDEF)
BAILLON	67	NC 50A 393	+Edwards, D'Andlau, Astier+	(CERN, CDEF, IRAD)

OTHER RELATED PAPERS

GENOVESE	94	ZPHY C61 425	+Lichtenberg, Pedrazzi	(TORI, IND)
AHMAD	89	NP B (PROC.)8 50	+Amsler, Auld+	(ASTERIX Collab.)
ARMSTRONG	89	PL B221 216	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
ZIEMINSKA	88	AIP Conf.		(IND)
ARMSTRONG	87	ZPHY C34 23	+Bloodworth+	(CERN, BIRM, BARI, ATHU, CURIN+)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
PROTOPOP...	87B	Hadron 87 Conf.	Protopopescu, Chung	(BNL)
TOKI	87	Hadron 87 Conf.		(SLAC)
ARMSTRONG	84	PL 146B 273	+Bloodworth, Burns+	(ATHU, BARI, BIRM, CERN)
DIONISI	80	NP B169 1	+Gavillet+	(CERN, MADR, CDEF, STOH)
DEFOIX	72	NP B44 125	+Nascimento, Bizzarri+	(CDEF, CERN)
DUBOC	72	NP B46 429	+Goldberg, Makowski, Donald+	(PARIS, LIVP)
LORSTAD	69	NP B14 63	+D'Andlau, Astier+	(CDEF, CERN)

$a_0(1450)$

$I^G(J^{PC}) = 1^-(0^{++})$

OMITTED FROM SUMMARY TABLE

From a partial-wave analysis of the $\pi\eta$ system. Needs confirmation. See minireview on scalar mesons under $f_0(1370)$.

$a_0(1450)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1450±40	AMSLER	94D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1470±25	[1] AMSLER	95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
1435±40	BUGG	94	RVUE	$\overline{p}p \to \eta 2\pi^0$

[1] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.

$a_0(1450)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
270±40	AMSLER	94D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
265±30	[2] AMSLER	95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
270±40	BUGG	94	RVUE	$\overline{p}p \to \eta 2\pi^0$

[2] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.

$a_0(1450)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\eta$	seen

$a_0(1450)$ REFERENCES

AMSLER	95B	PL B342 433	+Armstrong, Brose+	(Crystal Barrel Collab.)
AMSLER	95C	PL B353 571	+Armstrong, Hackman+	(Crystal Barrel Collab.)
AMSLER	95D	PL B355 425	+Armstrong, Spanier+	(Crystal Barrel Collab.)
AMSLER	94D	PL B333 277	+Anisovich, Spanier+	(Crystal Barrel Collab.) IGJPC
BUGG	94	PR D50 4412	+Anisovich+	(LOQM)

$\rho(1450)$

$I^G(J^{PC}) = 1^+(1^{--})$

See the mini-review under the $\rho(1700)$.

$\rho(1450)$ MASS

VALUE (MeV)	DOCUMENT ID
1465±25 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
1449± 8 OUR AVERAGE	Includes data from the 4 datablocks that follow this one.

MIXED MODES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1265.5±75.3	DUBNICKA	89	RVUE	$e^+e^- \to \pi^+\pi^-$

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1470±20	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
1446±10	FUKUI	88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1424±25	BISELLO	89	DM2	$e^+e^- \to \pi^+\pi^-$

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
1463±25	[1] CLEGG	94	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1250	[2] ASTON	80C	OMEG	20–70 $\gamma p \to \omega\pi^0 p$
1290±40	[2] BARBER	80C	SPEC	3–5 $\gamma p \to \omega\pi^0 p$

[1] Using data from BISELLO 91B, DOLINSKY 86 and ALBRECHT 87L.
[2] Not separated from $b_1(1235)$, not pure $J^P = 1^-$ effect.

$\phi\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1480±40	[3] BITYUKOV	87	SPEC	0	32.5 $\pi^- p \to \phi\pi^0 n$

[3] See the minireview for $\rho(1700)$ and ACHASOV 88 for a non-exotic interpretation. DONNACHIE 91 suggests this is a different particle.

$\rho(1450)$ WIDTH

VALUE (MeV)	DOCUMENT ID
310±60 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\omega\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
311± 62	[4] CLEGG	94	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
300	[5] ASTON	80C	OMEG	20–70 $\gamma p \to \omega\pi^0 p$
320±100	[5] BARBER	80C	SPEC	3–5 $\gamma p \to \omega\pi^0 p$

[4] Using data from BISELLO 91B, DOLINSKY 86 and ALBRECHT 87L.
[5] Not separated from $b_1(1235)$, not pure $J^P = 1^-$ effect.

MIXED MODES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
391±70	DUBNICKA	89	RVUE	$e^+e^- \to \pi^+\pi^-$

$\eta\rho^0$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
230±30	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
60±15	FUKUI	88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

$\pi^+\pi^-$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
269±31	BISELLO	89	DM2	$e^+e^- \to \pi^+\pi^-$

$\phi\pi$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
130±60	[6] BITYUKOV	87	SPEC	0	32.5 $\pi^- p \to \phi\pi^0 n$

[6] See the minireview for $\rho(1700)$ and ACHASOV 88 for a non-exotic interpretation. DONNACHIE 91 suggests this is a different particle.

$\rho(1450)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\pi\pi$	seen	
Γ_2	4π	seen	
Γ_3	e^+e^-	seen	
Γ_4	$\eta\rho$	<4 %	
Γ_5	$\omega\pi$	<2.0 %	95%
Γ_6	$\phi\pi$	<1 %	
Γ_7	$K\overline{K}$	$<1.6 \times 10^{-3}$	95%

$\rho(1450)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.12	[7] DIEKMAN	88	RVUE	$e^+e^- \to \pi^+\pi^-$

[7] Using total width = 235 MeV.

$\Gamma(\eta\rho) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_4\Gamma_3/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
91±19	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$

$\Gamma(\phi\pi) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_6\Gamma_3/\Gamma$

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<70	90	[8] AULCHENKO	87B	ND	$e^+e^- \to K^0_S K^0_L \pi^0$

[8] Using mass 1480 ± 40 MeV and total width 130 ± 60 MeV of BITYUKOV 87.

$\rho(1450)$ BRANCHING RATIOS

$\Gamma(\eta\rho)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN
<0.04	DONNACHIE	87B	RVUE

$\Gamma(\phi\pi)/\Gamma(\omega\pi)$ — Γ_6/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
>0.5	95	BITYUKOV	87	SPEC	0	32.5 $\pi^- p \to \phi\pi^0 n$

$\Gamma(\omega\pi)/\Gamma(4\pi)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN
<0.14	CLEGG	88	RVUE

$\Gamma(\eta\rho)/\Gamma(\omega\pi)$ — Γ_4/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
~ 0.24	[9] DONNACHIE	91	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>2	FUKUI	91	SPEC	8.95 $\pi^- p \to \omega\pi^0 n$

$\Gamma(\omega\pi)/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN
~ 0.21	CLEGG	94	RVUE

$\Gamma(\pi\pi)/\Gamma(\omega\pi)$ — Γ_1/Γ_5

VALUE	DOCUMENT ID		TECN
~ 0.32	CLEGG	94	RVUE

$\Gamma(\phi\pi)/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN
<0.01	[9] DONNACHIE	91	RVUE

$\Gamma(K\overline{K})/\Gamma(\omega\pi)$ — Γ_7/Γ_5

VALUE	DOCUMENT ID	TECN
<0.08	[9] DONNACHIE 91	RVUE

[9] Using data from BISELLO 91B, DOLINSKY 86 and ALBRECHT 87L.

$\rho(1450)$ REFERENCES

CLEGG	94	ZPHY C62 455	+Donnachie	(LANC, MCHS)
BISELLO	91B	NP B21 111 (suppl)		(DM2 Collab.)
DONNACHIE	91	ZPHY C51 689	+Clegg	(MCHS, LANC)
FUKUI	91	PL B257 241	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
BISELLO	89	PL B220 321	+Busetto+	(DM2 Collab.)
DUBNICKA	89	JPG 15 1349	+Martinovic+	(JINR, SLOV)
ACHASOV	88	PL B207 199	+Kozhevnikov	(NOVM)
ANTONELLI	88	PL B212 133	+Baldini+	(DM2 Collab.)
CLEGG	88	ZPHY C40 313	+Donnachie	(MCHS, LANC)
DIEKMAN	88	PRPL 159 101		(BONN)
FUKUI	88	PL B202 441	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
ALBRECHT	87L	PL B185 223	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
AULCHENKO	87B	JETPL 45 145 Translated from ZETFP 45 118.	+Dolinsky, Druzhinin, Dubrovin+	(NOVO)
BITYUKOV	87	PL B188 383	+Dzhelyadin, Dorofeev, Golovkin+	(SERP)
DONNACHIE	87B	ZPHY C34 257	+Clegg	(MCHS, LANC)
DOLINSKY	86	PL B174 453	+Druzhinin, Dubrovin, Eidelman+	(NOVO)
ASTON	80C	PL 92B 211		(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BARBER	80C	ZPHY C4 169	+Dainton, Brodbeck, Brookes+	(DARE, LANC, SHEF)

OTHER RELATED PAPERS

MURADOV	94	PAN 57 864		(BAKU)
LANDSBERG	92	SJNP 55 1051 Translated from YAF 55 1896.		(SERP)
BRAU	88	PR D37 2379	+Franek+	(SLAC Hybrid Facility Photon Collab.)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
KURDADZE	86	JETPL 43 643 Translated from ZETFP 43 497.	+Lelchuk, Pakhtusova, Sidorov, Skrinskii+	(NOVO)
BARKOV	85	NP B256 365	+Chilingarov, Eidelman, Khazin, Lelchuk+	(NOVO)
BISELLO	85	LAL 85-15	+Augustin, Ajaltouni+	(PADO, LALO, CLER, FRAS)
ABE	84B	PRL 53 751	+Bacon, Ballam+	(SLAC Hybrid Facility Photon Collab.)
ATKINSON	84C	NP B243 1	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
CORDIER	82	PL 109B 129	+Bisello, Bizot, Buon, Delcourt	(LALO)
KILLIAN	80	PR D21 3005	+Treadwell, Ahrens, Berkelman, Cassel+	(CORN)
COSME	76	PL 63B 352	+Courau, Dudelzak, Grelaud, Jean-Marie+	(ORSAY)
BINGHAM	72B	PL 41B 635	+Rabin, Rosenfeld, Smadja+	(LBL, UCB, SLAC)
FRENKIEL	72	NP B47 61	+Ghesquiere, Lillestol, Chung+	(CDEF, CERN)
LAYSSAC	71	NC 6A 134	+Renard	(MONP)

$f_0(1500)$

was $f_0(1525)$ and $f_0(1590)$

$I^G(J^{PC}) = 0^+(0^{++})$

See also the mini-reviews on scalar mesons under $f_0(1370)$ and on non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_0(1500)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1503±11 OUR AVERAGE				
1500±15		[1] AMSLER 95B	CBAR	0.0 $\overline{p}p \to 3\pi^0$
1505±15		[2] AMSLER 95C	CBAR	0.0 $\overline{p}p \to \eta\eta\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1460±20	120	[3] AMELIN 96B	VES	37 $\pi^- A \to \eta\eta\pi^- A$
1500±10		[4] AMSLER 95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
1445± 5		[5] ANTINORI 95	OMEG	300,450 $pp \to pp2(\pi^+\pi^-)$
1497±30		[3] ANTINORI 95	OMEG	300,450 $pp \to pp\pi^+\pi^-$
~ 1505		BUGG 95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1446± 5		[3] ABATZIS 94	OMEG	450 $pp \to pp2(\pi^+\pi^-)$
1545±25		[3] AMSLER 94E	CBAR	0.0 $\overline{p}p \to \pi^0\eta\eta'$
1520±25		[6,7] ANISOVICH 94	CBAR	0.0 $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$
1505±20		[7,8] BUGG 94	RVUE	$\overline{p}p \to 3\pi^0$, $\eta\eta\pi^0$, $\eta\pi^0\pi^0$
1560±25		[3] AMSLER 92	CBAR	0.0 $\overline{p}p \to \pi^0\eta\eta$
1550±45±30		[3] BELADIDZE 92C	VES	36 $\pi^-\mathrm{Be} \to \pi^-\eta'\eta\mathrm{Be}$
1449± 4		[3] ARMSTRONG 89E	OMEG	300 $pp \to pp2(\pi^+\pi^-)$
1610±20		[3] ALDE 88	GAM4	300 $\pi^- N \to \pi^- N 2\eta$
~ 1525		ASTON 88D	LASS	11 $K^- p \to K^0_S K^0_S \Lambda$
1570±20	600	[3] ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$
1575±45		[9] ALDE 86D	GAM4	100 $\pi^- p \to 2\eta n$
1568±33		[3] BINON 84C	GAM2	38 $\pi^- p \to \eta\eta' n$
1592±25		[3] BINON 83	GAM2	38 $\pi^- p \to 2\eta n$
1525± 5		[3] GRAY 83	DBC	0.0 $\overline{p}N \to 3\pi$

[1] T-matrix pole, supersedes ANISOVICH 94.
[2] T-matrix pole, supersedes ANISOVICH 94 and AMSLER 92.
[3] Breit-Wigner mass.
[4] T-matrix pole. Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.
[5] Supersedes ABATZIS 94, ARMSTRONG 89E. Breit-Wigner mass.
[6] From a simultaneous analysis of the annihilations $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$.
[7] T-matrix pole.
[8] Reanalysis of ANISOVICH 94 data.
[9] From central value and spread of two solutions. Breit-Wigner mass.

$f_0(1500)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
120±19 OUR AVERAGE				
120±25		[10] AMSLER 95B	CBAR	0.0 $\overline{p}p \to 3\pi^0$
120±30		[11] AMSLER 95C	CBAR	0.0 $\overline{p}p \to \eta\eta\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
100±30	120	[12] AMELIN 96B	VES	37 $\pi^- A \to \eta\eta\pi^- A$
154±30		[13] AMSLER 95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
65±10		[14] ANTINORI 95	OMEG	300,450 $pp \to pp2(\pi^+\pi^-)$
199±30		[12] ANTINORI 95	OMEG	300,450 $pp \to pp\pi^+\pi^-$
56±12		[12] ABATZIS 94	OMEG	450 $pp \to pp2(\pi^+\pi^-)$
100±40		[12] AMSLER 94E	CBAR	0.0 $\overline{p}p \to \pi^0\eta\eta'$
148^{+20}_{-25}		[15,16] ANISOVICH 94	CBAR	0.0 $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$
150±20		[16,17] BUGG 94	RVUE	$\overline{p}p \to 3\pi^0$, $\eta\eta\pi^0$, $\eta\pi^0\pi^0$
245±50		[12] AMSLER 92	CBAR	0.0 $\overline{p}p \to \pi^0\eta\eta$
153±67±50		[12] BELADIDZE 92C	VES	36 $\pi^-\mathrm{Be} \to \pi^-\eta'\eta\mathrm{Be}$
78±18		[12] ARMSTRONG 89E	OMEG	300 $pp \to pp2(\pi^+\pi^-)$
170±40		[12] ALDE 88	GAM4	300 $\pi^- N \to \pi^- N 2\eta$
150±20	600	[12] ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$
265±65		[18] ALDE 86D	GAM4	100 $\pi^- p \to 2\eta n$
260±60		[12] BINON 84C	GAM2	38 $\pi^- p \to \eta\eta' n$
210±40		[12] BINON 83	GAM2	38 $\pi^- p \to 2\eta n$
101±13		[12] GRAY 83	DBC	0.0 $\overline{p}N \to 3\pi$

[10] T-matrix pole, supersedes ANISOVICH 94.
[11] T-matrix pole, supersedes ANISOVICH 94 and AMSLER 92.
[12] Breit-Wigner mass.
[13] T-matrix pole. Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.
[14] Supersedes ABATZIS 94, ARMSTRONG 89E. Breit-Wigner mass.
[15] From a simultaneous analysis of the annihilations $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$.
[16] T-matrix pole.
[17] Reanalysis of ANISOVICH 94 data.
[18] From central value and spread of two solutions. Breit-Wigner mass.

$f_0(1500)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\eta'(958)$	seen
Γ_2	$\eta\eta$	seen
Γ_3	$4\pi^0$	seen
Γ_4	$\pi^0\pi^0$	seen
Γ_5	$2\pi^+2\pi^-$	seen
Γ_6	$K\overline{K}$	

$f_0(1500)$ BRANCHING RATIOS

$\Gamma(\eta\eta'(958))/\Gamma(\eta\eta)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.29±0.10	[19] AMSLER 95C	CBAR	0.0 $\overline{p}p \to \eta\eta\pi^0$
2.7 ±0.8	BINON 84C	GAM2	38 $\pi^- p \to \eta\eta' n$

[19] Using AMSLER 94E ($\eta\eta'\pi^0$).

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
large	ALDE 88	GAM4	300 $\pi^- N \to \eta\eta\pi^- N$
large	BINON 83	GAM2	38 $\pi^- p \to 2\eta n$

$\Gamma(4\pi^0)/\Gamma(\eta\eta)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.8±0.3	ALDE 87	GAM4	100 $\pi^- p \to 4\pi^0 n$

$\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta)$ — Γ_4/Γ_2

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.45±0.61	[20] AMSLER 95C	CBAR	0.0 $\overline{p}p \to \eta\eta\pi^0$
2.12±0.81	[21] AMSLER 95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
<0.3	[22] BINON 83	GAM2	38 $\pi^- p \to 2\eta n$

[20] Using AMSLER 95B ($3\pi^0$).
[21] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.
[22] Superseded by PROKOSHKIN 90.

$\Gamma(K\overline{K})/\Gamma(\eta\eta)$ — Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.6		[23] BINON	83	GAM2	$38\ \pi^- p \to 2\eta n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.4	90	[24] PROKOSHKIN	91	GAM4	$300\ \pi^- p \to \pi^- p \eta\eta$

[23] Using ETKIN 82B and COHEN 80.
[24] Combining results of GAM4 with those of WA76 on $K\overline{K}$ central production.

$f_0(1500)$ REFERENCES

AMELIN 96B YAF 59 1021 +Berdnikov, Bityukov+ (SERP, TBIL)
AMSLER 95B PL B342 433 +Armstrong, Brose+ (Crystal Barrel Collab.)
AMSLER 95C PL B353 571 +Armstrong, Hackman+ (Crystal Barrel Collab.)
AMSLER 95D PL B355 425 +Armstrong, Spanier+ (Crystal Barrel Collab.)
ANTINORI 95 PL B353 589 +Barberis, Bayes+ (ATHU, BARI, BIRM, CERN, JINR)
BUGG 95 PL B353 378 +Scott, Zoli+ (LOQM, PNPI, WASH)
ABATZIS 94 PL B324 509 +Antinori, Barberis+ (ATHU, BARI, BIRM, CERN, JINR)
AMSLER 94D PL B333 277 +Anisovich, Spanier+ (Crystal Barrel Collab.)
AMSLER 94E PL B340 259 +Armstrong, Hackman+ (Crystal Barrel Collab.)
ANISOVICH 94 PL B323 233 +Armstrong+ (Crystal Barrel Collab.)
BUGG 94 PR D50 4412 +Anisovich+ (LOQM)
AMSLER 92 PL B291 347 +Augustin, Baker+ (Crystal Barrel Collab.)
BELADIDZE 92C SJNP 55 1535 +Bityukov, Borisov (SERP, TBIL)
Translated from YAF 55 2748.
PROKOSHKIN 91 SPD 36 155 (GAM2, GAM4 Collab.)
Translated from DANS 316 900.
PROKOSHKIN 90 Hadron 89 Conf. p 27 (SERP, BELG, LANL, LAPP, PISA, KEK)
ARMSTRONG 89E PL B228 536 +Benayoun (ATHU, BARI, BIRM, CERN, CDEF, CURIN+)
ALDE 88 PL B201 160 +Bellazzini, Binon+ (SERP, BELG, LANL, LAPP, PISA)
ASTON 88D NP B301 525 +Awaji, Bienz+ (SLAC, NAGO, CINC, INUS)
ALDE 87 PL B198 286 +Binon, Bricman+ (LANL, BRUX, SERP, LAPP)
ALDE 86D NP B269 485 +Binon, Bricman+ (BELG, LAPP, SERP, CERN, LANL)
BINON 84C NC 80A 363 +Bricman, Donskov+ (BELG, LAPP, SERP, CERN)
BINON 83 NC 78A 313 +Donskov, Duteil+ (BELG, LAPP, SERP, CERN)
Also 83B SJNP 38 561 Binon, Gouanere+ (BELG, LAPP, SERP, CERN)
Translated from YAF 38 934.
GRAY 83 PR D27 307 +Kalogeropoulos, Nandy, Roy, Zenone (SYRA)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)
COHEN 80 PR D22 2595 +Ayres, Diebold, Kramer, Pawlicki+ (ANL)

OTHER RELATED PAPERS

AMSLER 96 PR D53 295 +Close (ZURI, RAL)
AMSLER 95E PL B353 385 +Close (ZURI, RAL)
SLAUGHTER 88 MPL A3 1361 (LANL)

$f_1(1510)$

$I^G(J^{PC}) = 0^+(1^{++})$

$f_1(1510)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1512± 4	600	[1] BIRMAN	88	MPS	$8\ \pi^- p \to K^+ \overline{K}^0 \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1525		[2] BAUER	93B		$\gamma\gamma^* \to \pi^+\pi^-\pi^0\pi^0$
1530±10		ASTON	88C	LASS	$11\ K^- p \to K^0_S K^\pm \pi^\mp \Lambda$
1526± 6	271	GAVILLET	82	HBC	$4.2\ K^- p \to \Lambda K K \pi$

[1] From partial wave analysis of $K^+ \overline{K}^0 \pi^-$ state.
[2] Possibly a different resonance than that seen in $K\overline{K}\pi$, isospin and spin uncertain.

$f_1(1510)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
35±15	600	[3] BIRMAN	88	MPS	$8\ \pi^- p \to K^+ \overline{K}^0 \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
100±40		ASTON	88C	LASS	$11\ K^- p \to K^0_S K^\pm \pi^\mp \Lambda$
107±15	271	GAVILLET	82	HBC	$4.2\ K^- p \to \Lambda K K \pi$

[3] From partial wave analysis of $K^+ \overline{K}^0 \pi^-$ state.

$f_1(1510)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}^*(892)$+ c.c.	seen

$f_1(1510)$ REFERENCES

BAUER 93B PR D48 3976 +Belcinski, Berg, Bingham+ (SLAC)
ASTON 88C PL B201 573 +Awaji, Bienz+ (SLAC, NAGO, CINC, INUS) JP
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, MASD) JP
GAVILLET 82 ZPHY C16 119 +Armenteros+ (CERN, CDEF, PADO, ROMA)

$f_2'(1525)$

$I^G(J^{PC}) = 0^+(2^{++})$

$f_2'(1525)$ MASS

VALUE (MeV)	DOCUMENT ID
1525±5 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

PRODUCED BY PION BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1547^{+10}_{-2}		[1] LONGACRE	86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$
1496^{+9}_{-8}		[2] CHABAUD	81	ASPK	$6\ \pi^- p \to K^+ K^- n$
1497^{+8}_{-9}		CHABAUD	81	ASPK	$18.4\ \pi^- p \to K^+ K^- n$
1492±29		GORLICH	80	ASPK	$17\ \pi^- p$polarized $\to K^+ K^- n$
1502±25		[3] CORDEN	79	OMEG	$12–15\ \pi^- p \to \pi^+\pi^- n$
1480	14	CRENNELL	66	HBC	$6.0\ \pi^- p \to K^0_S K^0_S n$

PRODUCED BY $K^\pm$ BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1524.3± 1.4 OUR AVERAGE		Includes data from the datablock that follows this one.			
1526.8± 4.3		ASTON	88D	LASS	$11\ K^- p \to K^0_S K^0_S \Lambda$
1504 ±12		BOLONKIN	86	SPEC	$40\ K^- p \to K^0_S K^0_S Y$
1529 ± 3		ARMSTRONG	83B	OMEG	$18.5\ K^- p \to K^- K^+ \Lambda$
1521 ± 6	650	AGUILAR-...	81B	HBC	$4.2\ K^- p \to \Lambda K^+ K^-$
1521 ± 3	572	ALHARRAN	81	HBC	$8.25\ K^- p \to \Lambda K \overline{K}$
1522 ± 6	123	BARREIRO	77	HBC	$4.15\ K^- p \to \Lambda K^0_S K^0_S$
1528 ± 7	166	EVANGELISTA	77	OMEG	$10\ K^- p \to K^+ K^- (\Lambda, \Sigma)$
1527 ± 3	120	BRANDENB...	76C	ASPK	$13\ K^- p \to K^+ K^- (\Lambda, \Sigma)$
1519 ± 7	100	AGUILAR-...	72B	HBC	$3.9,4.6\ K^- p \to K\overline{K}(\Lambda, \Sigma)$

PRODUCED IN $e^+ e^-$ ANNIHILATION

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1520 ± 4 OUR AVERAGE				
1529 ±10	ACCIARRI	95J	L3	E^{ee}_{cm}= 88–94 GeV
1531.6±10.0	AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+ K^-$
1515 ± 5	[4] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$
1525 ±10 ±10	BALTRUSAIT...87		MRK3	$J/\psi \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1496 ± 2	[5] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$

[1] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[2] CHABAUD 81 is a reanalysis of PAWLICKI 77 data.
[3] From an amplitude analysis where the $f_2'(1525)$ width and elasticity are in complete disagreement with the values obtained from $K\overline{K}$ channel, making the solution dubious.
[4] From an analysis ignoring interference with $f_J(1710)$.
[5] From an analysis including interference with $f_J(1710)$.

$f_2'(1525)$ WIDTH

VALUE (MeV)	DOCUMENT ID		COMMENT
76±10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.		
73^{+6}_{-5} OUR FIT			
76±10	PDG	90	For fitting

PRODUCED BY PION BEAM

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
108^{+5}_{-2}	[6] LONGACRE	86	MPS	$22\ \pi^- p \to K^0_S K^0_S n$
69^{+22}_{-16}	[7] CHABAUD	81	ASPK	$6\ \pi^- p \to K^+ K^- n$
137^{+23}_{-21}	CHABAUD	81	ASPK	$18.4\ \pi^- p \to K^+ K^- n$
150^{+83}_{-50}	GORLICH	80	ASPK	$17\ \pi^- p$polarized $\to K^+ K^- n$
165±42	[8] CORDEN	79	OMEG	$12–15\ \pi^- p \to \pi^+\pi^- n$
92^{+39}_{-22}	[9] POLYCHRO...	79	STRC	$7\ \pi^- p \to n K^0_S K^0_S$

PRODUCED BY $K^{\pm}$ BEAM

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
77± 5 OUR AVERAGE	Includes data from the datablock that follows this one.				
90±12		ASTON	88D	LASS	11 $K^- p \to K_S^0 K_S^0 \Lambda$
73±18		BOLONKIN	86	SPEC	40 $K^- p \to K_S^0 K_S^0 Y$
83±15		ARMSTRONG	83B	OMEG	18.5 $K^- p \to K^- K^+ \Lambda$
85±16	650	AGUILAR-...	81B	HBC	4.2 $K^- p \to \Lambda K^+ K^-$
80^{+14}_{-11}	572	ALHARRAN	81	HBC	8.25 $K^- p \to \Lambda K \overline{K}$
72±25	166	EVANGELISTA	77	OMEG	10 $K^- p \to K^+ K^- (\Lambda, \Sigma)$
69±22	100	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p \to K \overline{K} (\Lambda, \Sigma)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
62^{+19}_{-14}	123	BARREIRO	77	HBC	4.15 $K^- p \to \Lambda K_S^0 K_S^0$
61± 8	120	BRANDENB...	76C	ASPK	13 $K^- p \to K^+ K^- (\Lambda, \Sigma)$

PRODUCED IN $e^+ e^-$ ANNIHILATION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
67± 9 OUR AVERAGE				
103±30	AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+ K^-$
62±10	[10] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$
85±35	BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
76±40	ACCIARRI	95J	L3	E_{cm}^{ee} = 88–94 GeV
100± 3	[11] FALVARD	88	DM2	$J/\psi \to \phi K^+ K^-$

[6] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.
[7] CHABAUD 81 is a reanalysis of PAWLICKI 77 data.
[8] From an amplitude analysis where the $f_2'(1525)$ width and elasticity are in complete disagreement with the values obtained from $K\overline{K}$ channel, making the solution dubious.
[9] From a fit to the D with $f_2(1270)$-$f_2'(1525)$ interference. Mass fixed at 1516 MeV.
[10] From an analysis ignoring interference with $f_J(1710)$.
[11] From an analysis including interference with $f_J(1710)$.

$f_2'(1525)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	(88.8 ±3.1) %
Γ_2	$\eta\eta$	(10.3 ±3.1) %
Γ_3	$\pi\pi$	(8.2 ±1.5) × 10^{-3}
Γ_4	$\gamma\gamma$	(1.32±0.21) × 10^{-6}
Γ_5	$K\overline{K}^*(892)$+ c.c.	
Γ_6	$\pi\pi\eta$	
Γ_7	$\pi K\overline{K}$	
Γ_8	$\pi^+\pi^+\pi^-\pi^-$	

CONSTRAINED FIT INFORMATION

An overall fit to the total width, 2 partial widths, a combination of partial widths obtained from integrated cross sections, and 3 branching ratios uses 14 measurements and one constraint to determine 5 parameters. The overall fit has a χ^2 = 11.4 for 10 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta p_i \delta p_j \rangle / (\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i / \Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100			
x_3	−3	−1		
x_4	−7	7	1	
Γ	−32	32	−1	−42
	x_1	x_2	x_3	x_4

	Mode	Rate (MeV)
Γ_1	$K\overline{K}$	$65\ ^{+5}_{-4}$
Γ_2	$\eta\eta$	7.6 ±2.6
Γ_3	$\pi\pi$	0.60±0.12
Γ_4	$\gamma\gamma$	(9.7 ±1.4) × 10^{-5}

$f_2'(1525)$ PARTIAL WIDTHS

$\Gamma(K\overline{K})$ — Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
65^{+5}_{-4} OUR FIT				
63^{+6}_{-5}	[12] LONGACRE	86	MPS	22 $\pi^- p \to K_S^0 K_S^0 n$

$\Gamma(\pi\pi)$ — Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.60±0.12 OUR FIT				
$1.4\ ^{+1.0}_{-0.5}$	[12] LONGACRE	86	MPS	22 $\pi^- p \to K_S^0 K_S^0 n$

$\Gamma(\eta\eta)$ — Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
7.6±2.5 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$24\ ^{+3}_{-1}$	[12] LONGACRE	86	MPS	22 $\pi^- p \to K_S^0 K_S^0 n$

[12] From a partial-wave analysis of data using a K-matrix formalism with 5 poles.

$f_2'(1525)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ — $\Gamma_1\Gamma_4/\Gamma$

VALUE (keV)		DOCUMENT ID		TECN	COMMENT
0.086 ±0.012 OUR FIT					
0.086 ±0.012 OUR AVERAGE					
0.093 ±0.018	±0.022	[13] ACCIARRI	95J	L3	E_{cm}^{ee} = 88–94 GeV
0.067 ±0.008	±0.015	[13] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^- K^+ K^-$
0.11 $^{+0.03}_{-0.02}$	±0.02	BEHREND	89C	CELL	$e^+e^- \to e^+e^- K_S^0 K_S^0$
0.10 $^{+0.04}_{-0.03}$	$^{+0.03}_{-0.02}$	BERGER	88	PLUT	$e^+e^- \to e^+e^- K_S^0 K_S^0$
0.12 ±0.07	±0.04	[13] AIHARA	86B	TPC	$e^+e^- \to e^+e^- K^+ K^-$
0.11 ±0.02	±0.04	[13] ALTHOFF	83	TASS	$e^+e^- \to e^+e^- K\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0314±0.0050	±0.0077	[14] ALBRECHT	90G	ARG	$e^+e^- \to e^+e^- K^+ K^-$

[13] Using an incoherent background.
[14] Using a coherent background.

$f_2'(1525)$ BRANCHING RATIOS

$\Gamma(\eta\eta)/\Gamma(K\overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.12±0.04 OUR FIT				
0.11±0.04	[15] PROKOSHKIN	91	GAM4	300 $\pi^- p \to \pi^- p \eta\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.50	BARNES	67	HBC	4.6,5.0 $K^- p$

[15] Combining results of GAM4 with those of WA76 on $K\overline{K}$ central production and results of CBAL, MRK3 and DM2 on $J/\psi \to \gamma\eta\eta$.

$\Gamma(\pi\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.0082±0.0016 OUR FIT					
0.0075±0.0016 OUR AVERAGE					
0.007 ±0.002		COSTA...	80	OMEG	10 $\pi^- p \to K^+ K^- n$
0.027 $^{+0.071}_{-0.013}$		[16] GORLICH	80	ASPK	17,18 $\pi^- p$
0.0075±0.0025		[16,17] MARTIN	79	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.06	95	AGUILAR-...	81B	HBC	4.2 $K^- p \to \Lambda K^+ K^-$
0.19 ±0.03		CORDEN	79	OMEG	12–15 $\pi^- p \to \pi^+\pi^- n$
<0.045	95	BARREIRO	77	HBC	4.15 $K^- p \to \Lambda K_S^0 K_S^0$
0.012 ±0.004		[16] PAWLICKI	77	SPEC	6 $\pi N \to K^+ K^- N$
<0.063	90	BRANDENB...	76C	ASPK	13 $K^- p \to K^+ K^- (\Lambda, \Sigma)$
<0.0086		[16] BEUSCH	75B	OSPK	8.9 $\pi^- p \to K^0 \overline{K}^0 n$

[16] Assuming that the $f_2'(1525)$ is produced by an one-pion exchange production mechanism.
[17] MARTIN 79 uses the PAWLICKI 77 data with different input value of the $f_2'(1525) \to K\overline{K}$ branching ratio.

$\Gamma(\pi\pi)/\Gamma(K\overline{K})$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.0092±0.0018 OUR FIT				
0.075 ±0.035	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$

$\Gamma(\pi\pi\eta)/\Gamma(K\overline{K})$ — Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.41	95	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$
<0.3	67	AMMAR	67	HBC	

$[\Gamma(K\overline{K}^*(892)+\text{c.c.})+\Gamma(\pi K\overline{K})]/\Gamma(K\overline{K})$ — $(\Gamma_5+\Gamma_7)/\Gamma_1$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.35	95	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$
<0.4	67	AMMAR	67	HBC	

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma(K\overline{K})$ — Γ_8/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.32	95	AGUILAR-...	72B	HBC	3.9,4.6 $K^- p$

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10±0.03	[18] PROKOSHKIN	91	GAM4	300 $\pi^- p \to \pi^- p\eta\eta$

[18] Combining results of GAM4 with those of WA76 on $K\overline{K}$ central production and results of CBAL, MRK3 and DM2 on $J/\psi \to \gamma\eta\eta$.

$f'_2(1525)$ REFERENCES

ACCIARRI	95J	PL B363 118	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
PROKOSHKIN	91	SPD 36 155		(GAM2, GAM4 Collab.)
		Translated from DANS 316 900.		
ALBRECHT	90G	ZPHY C48 183	+Ehrlichmann, Harder+	(ARGUS Collab.)
PDG	90	PL B239	Hernandez, Stone, Porter+	(IFIC, BOST, CIT+)
BEHREND	89C	ZPHY C43 91	+Criegee, Dainton+	(CELLO Collab.)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)
BERGER	88	ZPHY C37 329	+Genzel, Lackas+	(PLUTO Collab.)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
AIHARA	86B	PRL 57 404	+Alston-Garnjost+	(TPC-2γ Collab.)
BOLONKIN	86	SJNP 43 776	+Bloshenko+	(ITEP) JP
		Translated from YAF 43 1211.		
LONGACRE	86	PL B177 223	+Etkin+	(BNL, BRAN, CUNY, DUKE, NDAM)
ALTHOFF	83	PL 121B 216	+Brandelik, Boerner, Burkhardt+	(TASSO Collab.)
ARMSTRONG	83B	NP B224 193	+	(BARI, BIRM, CERN, MILA, CURIN+)
AGUILAR-...	81B	ZPHY C8 313	Aguilar-Benitez, Albajar+	(CERN, CDEF, MADR+)
ALHARRAN	81	NP B191 26	+Baubillier+	(BIRM, CERN, GLAS, MICH, CURIN)
CHABAUD	81	APP B12 575	+Niczyporuk, Becker+	(CERN, CRAC, MPIM)
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)
GORLICH	80	NP B174 16	+Niczyporuk+	(CRAC, MPIM, CERN, ZEEM)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
MARTIN	79	NP B158 520	+Ozmutlu	(DURH)
POLYCHRO...	79	PR D19 1317	Polychronakos, Cason, Bishop+	(NDAM, ANL)
BARREIRO	77	NP B121 237	+Diaz, Gay, Hemingway+	(CERN, AMST, NIJM, OXF)
EVANGELISTA	77	NP B127 384	+	(BARI, BONN, CERN, DARE, GLAS+)
PAWLICKI	77	PR D15 3196	+Ayres, Cohen, Diebold, Kramer, Wicklund	(ANL) IJP
BRANDENB...	76C	NP B104 413	Brandenburg, Carnegie, Cashmore+	(SLAC)
BEUSCH	75B	PL 60B 101	+Birman, Websdale, Wetzel	(CERN, ETH)
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
AMMAR	67	PRL 19 1071	+Davis, Hwang, Dagan, Derrick+	(NWES, ANL) JP
BARNES	67	PRL 19 964	+Dornan, Goldberg, Leitner+	(BNL, SYRA) IJPC
CRENNELL	66	PRL 16 1025	+Kalbfleisch, Lai, Scarr, Schumann+	(BNL) I

OTHER RELATED PAPERS

JENNI	83	PR D27 1031	+Burke, Telnov, Abrams, Blocker+	(SLAC, LBL)
ARMSTRONG	82	PL 110B 77	+Baubillier+	(BARI, BIRM, CERN, MILA, CURIN+)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
LUKE	82	DESY 82/073		(DESY)
ABRAMS	67B	PRL 18 620	+Kehoe, Glasser, Sechi-Zorn, Wolsky	(UMD)
BARNES	65	PRL 15 322	+Culwick, Guidoni, Kalbfleisch, Goz+	(BNL, SYRA)

$f_2(1565)$ was $f_2(1520)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Seen in antinucleon-nucleon annihilation at rest. See also minireview under non-$q\overline{q}$ candidates. Needs confirmation.

$f_2(1565)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1565±20	MAY	90	ASTE	$\overline{p}p \to \pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~1552	[1] AMSLER	95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
1598±72	BALOSHIN	95	SPEC	40 $\pi^- C \to K^0_S K^0_S X$
1566^{+80}_{-50}	[2] ANISOVICH	94	CBAR	0.0 $\overline{p}p \to 3\pi^0, \eta\eta\pi^0$
1502± 9	ADAMO	93	OBLX	$\overline{n}p \to \pi^+\pi^+\pi^-$
1488±10	[3] ARMSTRONG	93C	SPEC	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$
1508±10	[3] ARMSTRONG	93D	SPEC	$\overline{p}p \to 3\pi^0 \to 6\gamma$
1525±10	[3] ARMSTRONG	93D	SPEC	$\overline{p}p \to \eta\pi^0\pi^0 \to 6\gamma$
~1504	[4] WEIDENAUER	93	ASTE	0.0 $\overline{p}N \to 3\pi^-2\pi^+$
1540±15	[3] ADAMO	92	OBLX	$\overline{n}p \to \pi^+\pi^+\pi^-$
1515±10	[5] AKER	91	CBAR	0.0 $\overline{p}p \to 3\pi^0$
1477± 5	BRIDGES	86C	DBC	0.0 $\overline{p}N \to 3\pi^-2\pi^+$

[1] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.
[2] From a simultaneous analysis of the annihilations $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$ including AKER 91 data.
[3] J^P not determined, could be partly $f_0(1500)$.
[4] J^P not determined.
[5] Superseded by AMSLER 95B,

$f_2(1565)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
170± 40	MAY	90	ASTE	$\overline{p}p \to \pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~142	[6] AMSLER	95D	CBAR	0.0 $\overline{p}p \to \pi^0\pi^0\pi^0$, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$
263±101	BALOSHIN	95	SPEC	40 $\pi^- C \to K^0_S K^0_S X$
166^{+80}_{-20}	[7] ANISOVICH	94	CBAR	0.0 $\overline{p}p \to 3\pi^0, \eta\eta\pi^0$
130± 10	[8] ADAMO	93	OBLX	$\overline{n}p \to \pi^+\pi^+\pi^-$
148± 27	[9] ARMSTRONG	93C	SPEC	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$
103± 15	[9] ARMSTRONG	93D	SPEC	$\overline{p}p \to 3\pi^0 \to 6\gamma$
111± 10	[9] ARMSTRONG	93D	SPEC	$\overline{p}p \to \eta\pi^0\pi^0 \to 6\gamma$
~206	[10] WEIDENAUER	93	ASTE	0.0 $\overline{p}N \to 3\pi^-2\pi^+$
132± 37	[9] ADAMO	92	OBLX	$\overline{n}p \to \pi^+\pi^+\pi^-$
120± 10	[11] AKER	91	CBAR	0.0 $\overline{p}p \to 3\pi^0$
116± 9	BRIDGES	86C	DBC	0.0 $\overline{p}N \to 3\pi^-2\pi^+$

[6] Coupled-channel analysis of AMSLER 95B, AMSLER 95C, and AMSLER 94D.
[7] From a simultaneous analysis of the annihilations $\overline{p}p \to 3\pi^0, \pi^0\eta\eta$ including AKER 91 data.
[8] Supersedes ADAMO 92.
[9] J^P not determined, could be partly $f_0(1500)$.
[10] J^P not determined.
[11] Superseded by AMSLER 95B,

$f_2(1565)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-$	seen
Γ_2	$\rho^0\rho^0$	seen
Γ_3	$\pi^0\pi^0$	seen
Γ_4	$2\pi^+2\pi^-$	seen
Γ_5	$\eta\eta$	seen

$f_2(1565)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	[12] ANISOVICH	94B	RVUE	$\overline{p}p \to \pi^+\pi^-\pi^0$
seen	MAY	89	ASTE	$\overline{p}p \to \pi^+\pi^-\pi^0$

[12] ANISOVICH 94B is from a reanalysis of MAY 90.

$\Gamma(\pi^+\pi^-)/\Gamma(\rho^0\rho^0)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.042±0.013	BRIDGES	86B	DBC	$\overline{p}N \to 3\pi^-2\pi^+$

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AMSLER	95B	CBAR	0.0 $\bar{p}p \to 3\pi^0$

$\Gamma(\eta\eta)/\Gamma(\pi^0\pi^0)$ — Γ_5/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.024±0.005±0.012	[13] ARMSTRONG	93C	SPEC	$\bar{p}p \to \pi^0\eta\eta \to 6\gamma$

[13] J^P not determined, could be partly $f_0(1500)$.

$f_2(1565)$ REFERENCES

AMSLER 95B PL B342 433 +Armstrong, Brose+ (Crystal Barrel Collab.)
AMSLER 95C PL B353 571 +Armstrong, Hackman+ (Crystal Barrel Collab.)
AMSLER 95D PL B355 425 +Armstrong, Spanier+ (Crystal Barrel Collab.)
BALOSHIN 95 PAN 58 46 +Bolonkin, Vladimirskii+ (ITEP)
Translated from YAF 58 50.
AMSLER 94D PL B333 277 +Anisovich, Spanier+ (Crystal Barrel Collab.)
ANISOVICH 94 PL B323 233 +Armstrong+ (Crystal Barrel Collab.)
ANISOVICH 94B PR D50 1972 +Bugg+ (LOQM)
ADAMO 93 NP A558 13C +Agnello+ (OBELIX Collab.)
ARMSTRONG 93C PL B307 394 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
ARMSTRONG 93D PL B307 399 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
WEIDENAUER 93 ZPHY C59 387 +Duch+ (ASTERIX Collab.)
ADAMO 92 PL B287 368 +Agnello, Balestra+ (OBELIX Collab.)
AKER 91 PL B260 249 +Amsler, Peters+ (Crystal Barrel Collab.)
MAY 90 ZPHY C46 203 +Duch, Heel+ (ASTERIX Collab.)
MAY 89 PL B225 450 +Duch, Heel+ (ASTERIX Collab.) IJP
BRIDGES 86B PRL 56 215 +Daftari, Kalogeropoulos, Debbe+ (SYRA, CASE)
BRIDGES 86C PRL 57 1534 +Daftari, Kalogeropoulos+ (SYRA)

$\omega(1600)$

$I^G(J^{PC}) = 0^-(1^{--})$

See also $\omega(1420)$.

$\omega(1600)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1649±24 OUR AVERAGE	Error includes scale factor of 2.3.					
1609±20	315	[1] ANTONELLI	92	DM2		1.34–2.4 $e^+e^- \to \rho\pi$
1663±12	435	[2] ANTONELLI	92	DM2		1.34–2.4 $e^+e^- \to \omega\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1600±30		[1] CLEGG	94	RVUE		$e^+e^- \to \rho\pi$
1607±10		[2] CLEGG	94	RVUE		$e^+e^- \to \omega\pi\pi$
1635±35		[3] CLEGG	94	RVUE		$e^+e^- \to \rho\pi$
1625±21		[3] CLEGG	94	RVUE		$e^+e^- \to \omega\pi\pi$
1670±20		ATKINSON	83B	OMEG		20–70 $\gamma p \to 3\pi X$
1657±13		CORDIER	81	DM1		$e^+e^- \to \omega 2\pi$
1679±34	21	ESPOSITO	80	FRAM		$e^+e^- \to 3\pi$
1652±17		COSME	79	OSPK	0	$e^+e^- \to 3\pi$

[1] From a two Breit-Wigner fit.
[2] From a single Breit-Wigner plus background fit.
[3] From a single Breit-Wigner fit.

$\omega(1600)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
220±35 OUR AVERAGE	Error includes scale factor of 1.6.					
159±43	315	[4] ANTONELLI	92	DM2		1.34–2.4 $e^+e^- \to \rho\pi$
240±25	435	[5] ANTONELLI	92	DM2		1.34–2.4 $e^+e^- \to \omega\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
140±50		[4] CLEGG	94	RVUE		$e^+e^- \to \rho\pi$
86±20		[5] CLEGG	94	RVUE		$e^+e^- \to \omega\pi\pi$
350±80		[6] CLEGG	94	RVUE		$e^+e^- \to \rho\pi$
401±63		[6] CLEGG	94	RVUE		$e^+e^- \to \omega\pi\pi$
160±20		ATKINSON	83B	OMEG		20–70 $\gamma p \to 3\pi X$
136±46		CORDIER	81	DM1		$e^+e^- \to \omega 2\pi$
99±49	21	ESPOSITO	80	FRAM		$e^+e^- \to 3\pi$
42±17		COSME	79	OSPK	0	$e^+e^- \to 3\pi$

[4] From a two Breit-Wigner fit.
[5] From a single Breit-Wigner plus background fit.
[6] From a single Breit-Wigner fit.

$\omega(1600)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\omega\pi\pi$	seen
Γ_3	e^+e^-	seen

$\omega(1600)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\rho\pi) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (eV)	EVTS	DOCUMENT ID		TECN	COMMENT
134±14	435	[7] ANTONELLI	92	DM2	1.34–2.4 $e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
93±27	315	ANTONELLI	92	DM2	1.34–2.4 $e^+e^- \to \rho\pi$
96±35		DONNACHIE	89	RVUE	$e^+e^- \to \rho\pi$

[7] From a coupled fit of $\rho\pi$ and $\omega\pi\pi$ channels.

$\Gamma(\omega\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_2\Gamma_3/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
170±17	435	[8] ANTONELLI	92	DM2	1.34–2.4 $e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135±16	435	[9] ANTONELLI	92	DM2	1.34–2.4 $e^+e^- \to \omega\pi\pi$
56±31		DONNACHIE	89	RVUE	$e^+e^- \to \omega 2\pi$

[8] From a coupled fit of $\rho\pi$ and $\omega\pi\pi$ channels.
[9] From a single Breit-Wigner fit.

$\omega(1600)$ REFERENCES

CLEGG 94 ZPHY C62 455 +Donnachie (LANC, MCHS)
ANTONELLI 92 ZPHY C56 15 +Baldini+ (DM2 Collab.)
DONNACHIE 89 ZPHY C42 663 +Clegg (CERN, MCHS)
ATKINSON 83B PL 127B 132 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
CORDIER 81 PL 106B 155 +Bisello, Bizot, Buon, Delcourt, Mane (ORSAY)
ESPOSITO 80 LNC 28 195 +Marini, Patteri+ (FRAS, NAPL, PADO, ROMA)
COSME 79 NP B152 215 +Dudelzak, Grelaud, Jean-Marie, Jullian+ (IPN)

OTHER RELATED PAPERS

DOLINSKY 91 PRPL 202 99 +Druzhinin, Dubrovin+ (NOVO)
ATKINSON 87 ZPHY C34 157 + (BONN, CERN, GLAS, LANC, MCHS, CURIN)
ATKINSON 84 NP B231 15 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)

$X(1600)$

$I^G(J^{PC}) = 2^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Observed in the reaction $\gamma\gamma \to \rho\rho$ near threshold. See also minireview under non-$q\bar{q}$ candidates.

$X(1600)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1600±100	[1] ALBRECHT	91F	ARG	0	10.2 $e^+e^- \to e^+e^- 2(\pi^+\pi^-)$

[1] Our estimate.

$X(1600)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
400±200	[2] ALBRECHT	91F	ARG	0	10.2 $e^+e^- \to e^+e^- 2(\pi^+\pi^-)$

[2] Our estimate.

$X(1600)$ REFERENCES

ALBRECHT 91F ZPHY C50 1 +Appuan, Paulini, Funk+ (ARGUS Collab.)

OTHER RELATED PAPERS

ALBRECHT 89M PL B217 205 +Bockmann+ (ARGUS Collab.)
BEHREND 89D PL B218 494 +Criegee+ (CELLO Collab.)

$f_2(1640)$

$I^G(J^{PC}) = 0^+(2^{++})$

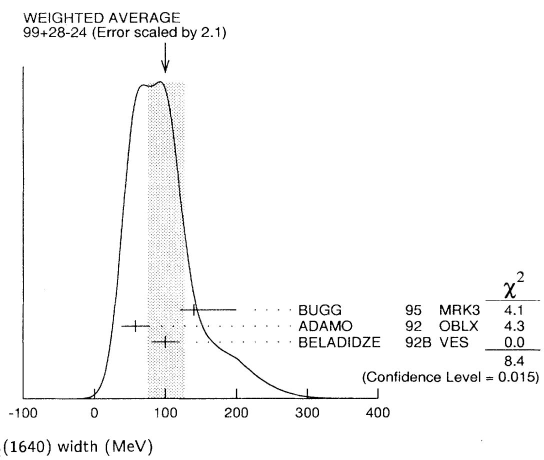
OMITTED FROM SUMMARY TABLE

$f_2(1640)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1638± 6 OUR AVERAGE	Error includes scale factor of 1.2.			
1620±16	BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1647± 7	ADAMO	92	OBLX	$\bar{n}p \to 3\pi^+2\pi^-$
1590±30	BELADIDZE	92B	VES	$36\ \pi^-p \to \omega\omega n$
1635± 7	ALDE	90	GAM2	$38\ \pi^-p \to \omega\omega n$

$f_2(1640)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
99^{+28}_{-24} OUR AVERAGE		Error includes scale factor of 2.1. See the ideogram below.			
140^{+60}_{-20}		BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
58±20		ADAMO	92	OBLX	$\bar{n}p \to 3\pi^+2\pi^-$
100±20		BELADIDZE	92B	VES	$36\ \pi^-p \to \omega\omega n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 70	90	ALDE	90	GAM2	$38\ \pi^-p \to \omega\omega n$



$f_2(1640)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\omega$	seen
Γ_2	4π	seen

$f_2(1640)$ REFERENCES

BUGG	95	PL B353 378	+Scott, Zoli+	(LOQM, PNPI, WASH) JP
ADAMO	92	PL B287 368	+Agnello, Balestra+	(OBELIX Collab.)
BELADIDZE	92B	ZPHY C54 367	+Bityukov, Borisov+	(VES Collab.)
ALDE	90	PL B241 600	+Binon+	(SERP, BELG, LANL, LAPP, PISA, KEK)

$\omega_3(1670)$

$I^G(J^{PC}) = 0^-(3^{--})$

$\omega_3(1670)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1667 ± 4 OUR AVERAGE					
1665.3± 5.2±4.5	23400	AMELIN	96	VES	$36\ \pi^-p \to \pi^+\pi^-\pi^0 n$
1685 ±20	60	BAUBILLIER	79	HBC	$8.2\ K^-p$ backward
1673 ±12	430	[1,2] BALTAY	78E	HBC	$15\ \pi^+p \to \Delta 3\pi$
1650 ±12		CORDEN	78B	OMEG	8–12 $\pi^-p \to N3\pi$
1669 ±11	600	[2] WAGNER	75	HBC	$7\ \pi^+p \to \Delta^{++}3\pi$
1678 ±14	500	DIAZ	74	DBC	$6\ \pi^+n \to p3\pi^0$
1660 ±13	200	DIAZ	74	DBC	$6\ \pi^+n \to p\omega\pi^0\pi^0$
1679 ±17	200	MATTHEWS	71D	DBC	$7.0\ \pi^+n \to p3\pi^0$
1670 ±20		KENYON	69	DBC	$8\ \pi^+n \to p3\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1700	110	[1] CERRADA	77B	HBC	$4.2\ K^-p \to \Lambda 3\pi$
1695 ±20		BARNES	69B	HBC	$4.6\ K^-p \to \omega 2\pi X$
1636 ±20		ARMENISE	68B	DBC	$5.1\ \pi^+n \to p3\pi^0$

[1] Phase rotation seen for $J^P = 3^-$ $\rho\pi$ wave.
[2] From a fit to $I(J^P) = 0(3^-)$ $\rho\pi$ partial wave.

$\omega_3(1670)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
168±10 OUR AVERAGE					
149±19±7	23400	AMELIN	96	VES	$36\ \pi^-p \to \pi^+\pi^-\pi^0 n$
160±80	60	[3] BAUBILLIER	79	HBC	$8.2\ K^-p$ backward
173±16	430	[4,5] BALTAY	78E	HBC	$15\ \pi^+p \to \Delta 3\pi$
253±39		CORDEN	78B	OMEG	8–12 $\pi^-p \to N3\pi$
173±28	600	[3,5] WAGNER	75	HBC	$7\ \pi^+p \to \Delta^{++}3\pi$
167±40	500	DIAZ	74	DBC	$6\ \pi^+n \to p3\pi^0$
122±39	200	DIAZ	74	DBC	$6\ \pi^+n \to p\omega\pi^0\pi^0$
155±40	200	[3] MATTHEWS	71D	DBC	$7.0\ \pi^+n \to p3\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
90±20		BARNES	69B	HBC	$4.6\ K^-p \to \omega 2\pi$
100±40		KENYON	69	DBC	$8\ \pi^+n \to p3\pi^0$
112±60		ARMENISE	68B	DBC	$5.1\ \pi^+n \to p3\pi^0$

[3] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[4] Phase rotation seen for $J^P = 3^-$ $\rho\pi$ wave.
[5] From a fit to $I(J^P) = 0(3^-)$ $\rho\pi$ partial wave.

$\omega_3(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi$	seen
Γ_2	$\omega\pi\pi$	seen
Γ_3	$b_1(1235)\pi$	possibly seen

$\omega_3(1670)$ BRANCHING RATIOS

$\Gamma(\omega\pi\pi)/\Gamma(\rho\pi)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.71±0.27	100	DIAZ	74	DBC	$6\ \pi^+n \to p5\pi^0$

$\Gamma(b_1(1235)\pi)/\Gamma(\rho\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
possibly seen	DIAZ	74	DBC	$6\ \pi^+n \to p5\pi^0$

$\Gamma(b_1(1235)\pi)/\Gamma(\omega\pi\pi)$ — Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.75	68	BAUBILLIER	79	HBC	$8.2\ K^-p$ backward

$\omega_3(1670)$ REFERENCES

AMELIN	96	ZPHY C70 71	+Berdnikov, Bityukov+	(SERP, TBIL)
BAUBILLIER	79	PL 89B 131	+	(BIRM, CERN, GLAS, MSU, ORSAY)
BALTAY	78E	PRL 40 87	+Cautis, Kalelkar	(COLU) JP
CORDEN	78B	NP B138 235	+Corbett, Alexander+	(BIRM, RHEL, TELA, LOWC)
CERRADA	77B	NP B126 241	+Blockzijl, Heinen+	(AMST, CERN, NIJM, OXF) JP
WAGNER	75	PL 58B 201	+Tabak, Chew	(LBL) JP
DIAZ	74	PRL 32 260	+Dibianca, Fickinger, Anderson+	(CASE, CMU)
MATTHEWS	71D	PR D3 2561	+Prentice, Yoon, Carroll+	(TNTO, WISC)
BARNES	69B	PRL 23 142	+Chung, Eisner, Flaminio+	(BNL)
KENYON	69	PRL 23 146	+Kinson, Scarr+	(BNL, UCND, ORNL)
ARMENISE	68B	PL 26B 336	+Forino, Cartacci+	(BARI, BGNA, FIRZ, ORSAY)

OTHER RELATED PAPERS

MATTHEWS	71	LNC 1 361	+Prentice, Yoon, Carroll+	(TNTO, WISC)
ARMENISE	70	LNC 4 199	+Ghidini, Foring, Cartacci+	(BARI, BGNA, FIRZ)

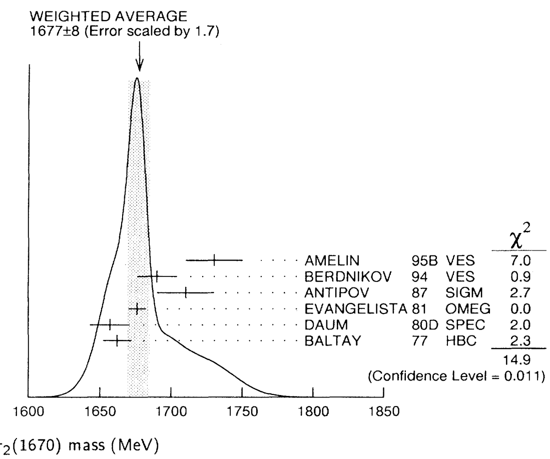
$\pi_2(1670)$

$I^G(J^{PC}) = 1^-(2^{-+})$

π_2(1670) MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1670±20 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.			
1677± 8 OUR AVERAGE		Error includes scale factor of 1.7. See the ideogram below.			
1730±20		[1] AMELIN	95B	VES	$36\ \pi^- A \to \pi^+\pi^-\pi^- A$
1690±14		[2] BERDNIKOV	94	VES	$37\ \pi^- A \to K^+K^-\pi^- A$
1710±20	700	ANTIPOV	87	SIGM −	$50\ \pi^- \text{Cu} \to \mu^+\mu^-\pi^- \text{Cu}$
1676± 6		[2] EVANGELISTA	81	OMEG −	$12\ \pi^- p \to 3\pi p$
1657±14		[2,3] DAUM	80D	SPEC −	$63–94\ \pi p \to 3\pi X$
1662±10	2000	[2] BALTAY	77	HBC +	$15\ \pi^+ p \to p 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1742±31±49		ANTREASYAN	90	CBAL	$e^+e^- \to e^+e^-\pi^0\pi^0\pi^0$
1710±20		[4] DAUM	81B	SPEC −	$63,94\ \pi^- p$
1640±10	575	KALELKAR	75	HBC +	$15\ \pi^+ p \to p\pi^+ f_2$
1660±10		[2] ASCOLI	73	HBC −	$5–25\ \pi^- p \to p\pi_2$

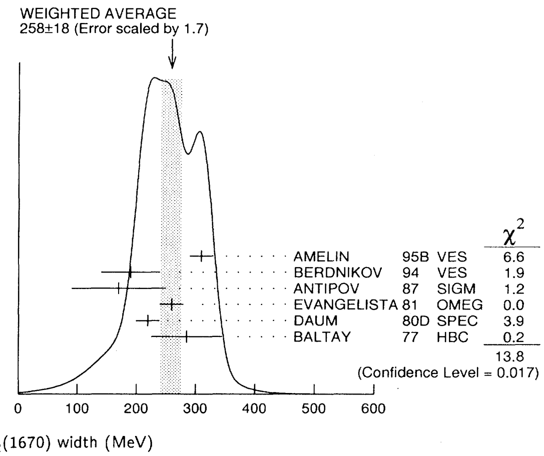
[1] From a fit to $J^{PC} = 2^{-+}$ $f_2(1270)\pi$, $f_0(1370)\pi$ waves.
[2] From a fit to $J^P = 2^-$ S-wave $f_2(1270)\pi$ partial wave.
[3] Clear phase rotation seen in 2^-S, 2^-P, 2^-D waves. We quote central value and spread of single-resonance fits to three channels.
[4] From a two-resonance fit to four 2^-0^+ waves. This should not be averaged with all the single resonance fits.



π_2(1670) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
258±18 OUR AVERAGE		Error includes scale factor of 1.7. See the ideogram below.			
310±20		[5] AMELIN	95B	VES	$36\ \pi^- A \to \pi^+\pi^-\pi^- A$
190±50		[6] BERDNIKOV	94	VES	$37\ \pi^- A \to K^+K^-\pi^- A$
170±80	700	ANTIPOV	87	SIGM −	$50\ \pi^- \text{Cu} \to \mu^+\mu^-\pi^- \text{Cu}$
260±20		[6] EVANGELISTA	81	OMEG −	$12\ \pi^- p \to 3\pi p$
219±20		[6,7] DAUM	80D	SPEC −	$63–94\ \pi p \to 3\pi X$
285±60	2000	[6] BALTAY	77	HBC +	$15\ \pi^+ p \to p 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
236±49±36		ANTREASYAN	90	CBAL	$e^+e^- \to e^+e^-\pi^0\pi^0\pi^0$
312±50		[8] DAUM	81B	SPEC −	$63,94\ \pi^- p$
240±30	575	KALELKAR	75	HBC +	$15\ \pi^+ p \to p\pi^+ f_2$
270±60		[6] ASCOLI	73	HBC −	$5–25\ \pi^- p \to p\pi_2$

[5] From a fit to $J^{PC} = 2^{-+}$ $f_2(1270)\pi$, $f_0(1370)\pi$ waves.
[6] From a fit to $J^P = 2^-$ $f_2(1270)\pi$ partial wave.
[7] Clear phase rotation seen in 2^-S, 2^-P, 2^-D waves. We quote central value and spread of single-resonance fits to three channels.
[8] From a two-resonance fit to four 2^-0^+ waves. This should not be averaged with all the single resonance fits.



π_2(1670) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	(95.8±1.4) %
Γ_2	$f_2(1270)\pi$	(56.2±3.2) %
Γ_3	$\rho\pi$	(31 ±4) %
Γ_4	$f_0(1370)\pi$	(8.7±3.4) %
Γ_5	$K\overline{K}^*(892)$+ c.c.	(4.2±1.4) %
Γ_6	$\gamma\gamma$	(5.2±1.1) $\times 10^{-6}$
Γ_7	$\eta\pi$	
Γ_8	$\pi^\pm 2\pi^+ 2\pi^-$	

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 6 measurements and one constraint to determine 4 parameters. The overall fit has a χ^2 = 1.9 for 3 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−53		
x_4	−29	−59	
x_5	−8	−21	−9
	x_2	x_3	x_4

π_2(1670) PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ Γ_6

VALUE (keV)	DOCUMENT ID	TECN	CHG	COMMENT
1.35±0.26 OUR AVERAGE				
1.41±0.23±0.28	ANTREASYAN 90	CBAL	0	$e^+e^- \to e^+e^-\pi^0\pi^0\pi^0$
1.3 ±0.3 ±0.2	[9] BEHREND 90C	CELL	0	$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.8 ±0.3 ±0.12	[10] BEHREND 90C	CELL	0	$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$

[9] Incoherent Ansatz.
[10] Constructive interference between $f_2(1270)$,$\rho\pi$ and background.

π_2(1670) BRANCHING RATIOS

$\Gamma(3\pi)/\Gamma_{\text{total}}$ $\Gamma_1/\Gamma = (\Gamma_2+\Gamma_3+\Gamma_4)/\Gamma$

VALUE	DOCUMENT ID
0.958±0.014 OUR FIT	

$\Gamma(\rho\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\frac{1}{2}\Gamma_3/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.29±0.04 OUR FIT				
0.29±0.05	[11] DAUM 81B	SPEC		$63,94\ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.3	BARTSCH 68	HBC	+	$8\ \pi^+ p \to 3\pi p$
<0.4	FERBEL 68	RVUE	±	

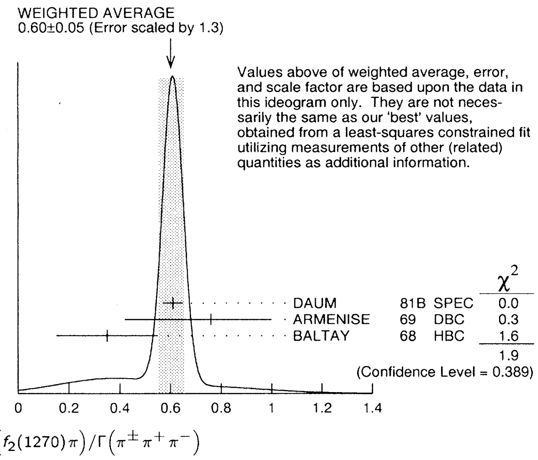
[11] From a two-resonance fit to four 2^-0^+ waves.

$\Gamma(f_2(1270)\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\quad 0.567\Gamma_2/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

(With $f_2(1270) \to \pi^+\pi^-$.)

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.604±0.035 OUR FIT					
0.60 ±0.05 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
0.61 ±0.04	[12] DAUM	81B	SPEC		63,94 $\pi^- p$
0.76 $^{+0.24}_{-0.34}$	ARMENISE	69	DBC	+	5.1 $\pi^+ d \to d3\pi$
0.35 ±0.20	BALTAY	68	HBC	+	7–8.5 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.59	BARTSCH	68	HBC	+	8 $\pi^+ p \to 3\pi p$

[12] From a two-resonance fit to four 2^-0^+ waves.



$\Gamma(\eta\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\quad \Gamma_7/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

(All η decays.)

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	BALTAY	68	HBC	+	7–8.5 $\pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.10	CRENNELL	70	HBC	−	6 $\pi^- p \to f_2\pi^- N$

$\Gamma(\pi^\pm 2\pi^+ 2\pi^-)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\quad \Gamma_8/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.10	CRENNELL	70	HBC	−	6 $\pi^- p \to f_2\pi^- N$
<0.1	BALTAY	68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(f_0(1370)\pi)/\Gamma(\pi^\pm\pi^+\pi^-)$ $\quad 0.624\Gamma_4/(0.567\Gamma_2+\frac{1}{2}\Gamma_3+0.624\Gamma_4)$

(With $f_0(1370) \to \pi^+\pi^-$.)

VALUE	DOCUMENT ID		TECN	COMMENT
0.10±0.04 OUR FIT				
0.10±0.05	[13] DAUM	81B	SPEC	63,94 $\pi^- p$

[13] From a two-resonance fit to four 2^-0^+ waves.

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(f_2(1270)\pi)$ $\quad \Gamma_5/\Gamma_2$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.075±0.025 OUR FIT					
0.075±0.025	[14] ARMSTRONG	82B	OMEG	−	16 $\pi^- p \to K^+K^-\pi^- p$

[14] From a partial-wave analysis of $K^+K^-\pi^-$ system.

D-wave/S-wave RATIO FOR $\pi_2(1670) \to f_2(1270)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22±0.10	[15] DAUM	81B	SPEC	63,94 $\pi^- p$

[15] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(1670)$ REFERENCES

AMELIN	95B	PL B356 595	+Berdnikov, Bityukov+	(SERP, TBIL)
BERDNIKOV	94	PL B337 219	+Bityukov+	(SERP, TBIL)
ANTREASYAN	90	ZPHY C48 561	+Bartels, Besset+	(Crystal Ball Collab.)
BEHREND	90C	ZPHY C46 583	+Criegee+	(CELLO Collab.)
ANTIPOV	87	EPL 4 403	+Batarin+	(SERP, JINR, INRM, TBIL, BGNA, MILA)
ARMSTRONG	82B	NP B202 1	+Baccari	(AACH3, BARI, BONN, CERN, GLAS+)
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
Also	81B	NP B186 594	Evangelista	
DAUM	80D	PL 89B 285	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+) JP
BALTAY	77	PRL 39 591	+Cautis, Kalelkar	(COLU) JP
KALELKAR	75	Thesis Nevis 207		(COLU)
ASCOLI	73	PR D7 669		(ILL, TNTO, GENO, HAMB, MILA, SACL) JP
CRENNELL	70	PRL 24 781	+Karshon, Lai, Scarr, Sims	(BNL)
ARMENISE	69	LNC 2 501	+Ghidini, Forino, Cartacci+	(BARI, BGNA, FIRZ)
BALTAY	68	PRL 20 887	+Kung, Yeh, Ferbel+	(COLU, ROCH, RUTG, YALE) I
BARTSCH	68	NP B7 345	+Keppel, Kraus+	(AACH, BERL, CERN) JP
FERBEL	68	Phil. Conf. 335		(ROCH)

OTHER RELATED PAPERS

CHEN	83B	PR D28 2304	+Fenker+	(ARIZ, FNAL, FLOR, NDAM, TUFTS+)
LEEDOM	83	PR D27 1426	+DeBonte, Gaidos, Key, Wong+	(PURD, TNTO)
BELLINI	82B	NP B199 1	+ (CERN, MILA, JINR, BGNA, HELS, PAVI, WARS+)	
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)
LEVRAT	66	PL 22 714	+Tolstrup+	(CERN Missing Mass Spect. Collab.)
LUBATTI	66	Thesis Berkeley		(LRL)
VETLITSKY	66	PL 21 579	+Guszavin, Kliger, Zolganov+	(ITEP)
FORINO	65B	PL 19 68	+Gessaroli+	(BGNA, BARI, FIRZ, ORSAY, SACL)

$\phi(1680)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\phi(1680)$ MASS

e^+e^- PRODUCTION

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1680±20 OUR ESTIMATE					
1681± 8 OUR AVERAGE					
1700±20		[1] CLEGG	94	RVUE	$e^+e^- \to K^+K^-$, $K^0_S K\pi$
1657±27	367	BISELLO	91C	DM2	$e^+e^- \to K^0_S K^\pm\pi^\mp$
1680±10		[2] BUON	82	DM1	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1655±17		[3] BISELLO	88B	DM2	$e^+e^- \to K^+K^-$
1677±12		[4] MANE	82	DM1	$e^+e^- \to K^0_S K\pi$

[1] Using BISELLO 88B and MANE 82 data.

PHOTOPRODUCTION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1726±22	BUSENITZ	89	TPS	$\gamma p \to K^+K^-X$
1760±20	ATKINSON	85C	OMEG	20–70 $\gamma p \to K\overline{K}X$
1690±10	ASTON	81F	OMEG	25–70 $\gamma p \to K^+K^-X$

[2] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^\pm\pi^\mp$. Assume mass 1570 MeV and width 510 MeV for ρ radial excitations, mass 1570 and width 500 MeV for ω radial excitation.

[3] From global fit including ρ, ω, ϕ and $\rho(1700)$ assume mass 1570 MeV and width 510 MeV for ρ radial excitation.

[4] Fit to one channel only, neglecting interference with ω, $\rho(1700)$.

$\phi(1680)$ WIDTH

e^+e^- PRODUCTION

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
150±50 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
300±60		[5] CLEGG	94	RVUE	$e^+e^- \to K^+K^-$, $K^0_S K\pi$
146±55	367	BISELLO	91C	DM2	$e^+e^- \to K^0_S K^\pm\pi^\mp$
207±45		[6] BISELLO	88B	DM2	$e^+e^- \to K^+K^-$
185±22		[7] BUON	82	DM1	$e^+e^- \to$ hadrons
102±36		[8] MANE	82	DM1	$e^+e^- \to K^0_S K\pi$

[5] Using BISELLO 88B and MANE 82 data.

PHOTOPRODUCTION

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
121±47	BUSENITZ	89	TPS	$\gamma p \to K^+K^-X$
80±40	ATKINSON	85C	OMEG	20–70 $\gamma p \to K\overline{K}X$
100±40	ASTON	81F	OMEG	25–70 $\gamma p \to K^+K^-X$

[6] From global fit including ρ, ω, ϕ and $\rho(1700)$ assume mass 1570 MeV and width 510 MeV for ρ radial excitation.

[7] From global fit of ρ, ω, ϕ and their radial excitations to channels $\omega\pi^+\pi^-$, K^+K^-, $K^0_S K^0_L$, $K^0_S K^\pm\pi^\mp$. Assume mass 1570 MeV and width 510 MeV for ρ radial excitations, mass 1570 and width 500 MeV for ω radial excitation.

[8] Fit to one channel only, neglecting interference with ω, $\rho(1700)$.

$\phi(1680)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}^*(892)+$ c.c.	dominant
Γ_2	$K^0_S K\pi$	seen
Γ_3	$K\overline{K}$	seen
Γ_4	e^+e^-	seen
Γ_5	$\omega\pi\pi$	not seen
Γ_6	$K^+K^-\pi^0$	

$\phi(1680)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel (I) in e^+e^- annihilation. We list only data that have not been used to determine the partial width $\Gamma(I)$ or the branching ratio $\Gamma(I)$/total.

$\Gamma(K\overline{K}^*(892)+\text{c.c.}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_4/\Gamma$

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.48±0.14	367	BISELLO	91C	DM2	$e^+e^- \to K^0_S K^\pm\pi^\mp$

$\phi(1680)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(K^0_S K\pi)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
dominant	MANE	82	DM1	$e^+e^- \to K^0_S K^\pm\pi^\mp$

$\Gamma(K\overline{K})/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.07 ±0.01	BUON	82	DM1	e^+e^-

$\Gamma(\omega\pi\pi)/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ — Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
<0.10	BUON	82	DM1	e^+e^-

$\phi(1680)$ REFERENCES

CLEGG	94	ZPHY C62 455	+Donnachie	(LANC, MCHS)
BISELLO	91C	ZPHY C52 227	+Busetto, Castro, Nigro, Pescara+	(DM2 Collab.)
BUSENITZ	89	PR D40 1	+Olszewski, Callahan+	(ILL, FNAL)
BISELLO	88B	ZPHY C39 13	+Busetto+	(PADO, CLER, FRAS, LALO)
ATKINSON	85C	ZPHY C27 233	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
BUON	82	PL 118B 221	+Bisello, Bizot, Cordier, Delcourt+	(LALO, MONP)
MANE	82	PL 112B 178	+Bisello, Bizot, Buon, Delcourt, Fayard+	(LALO)
ASTON	81F	PL 104B 231		(BONN, CERN, EPOL, GLAS, LANC, MCHS+)

OTHER RELATED PAPERS

ATKINSON	86C	ZPHY C30 541	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON	84	NP B231 15	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON	84B	NP B231 1	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON	83C	NP B229 269	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
CORDIER	81	PL 106B 155	+Bisello, Bizot, Buon, Delcourt, Mane	(ORSAY)
MANE	81	PL 99B 261	+Bisello, Bizot, Buon, Cordier, Delcourt	(ORSAY)
ASTON	80F	NP B174 269		(BONN, CERN, EPOL, GLAS, LANC, MCHS+)

$\rho_3(1690)$

$I^G(J^{PC}) = 1^+(3^{--})$

$\rho_3(1690)$ MASS

VALUE (MeV)	DOCUMENT ID
1691 ±5 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
1688.8±2.1 OUR AVERAGE	Includes data from the 5 datablocks that follow this one.

2π MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1686± 4 OUR AVERAGE						
1677±14		EVANGELISTA	81	OMEG	−	$12\ \pi^-p \to 2\pi p$
1679±11	476	BALTAY	78B	HBC	0	$15\ \pi^+p \to \pi^+\pi^-n$
1678±12	175	[1] ANTIPOV	77	CIBS	0	$25\ \pi^-p \to p3\pi$
1690± 7	600	[1] ENGLER	74	DBC	0	$6\ \pi^+n \to \pi^+\pi^-p$
1693± 8		[2] GRAYER	74	ASPK	0	$17\ \pi^-p \to \pi^+\pi^-n$
1678±12		MATTHEWS	71C	DBC	0	$7\ \pi^+N$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1734±10		[3] CORDEN	79	OMEG		$12\text{–}15\ \pi^-p \to n2\pi$
1692±12		[2,4] ESTABROOKS	75	RVUE		$17\ \pi^-p \to \pi^+\pi^-n$
1737±23		ARMENISE	70	DBC	0	$9\ \pi^+N$
1650±35	122	BARTSCH	70B	HBC	+	$8\ \pi^+p \to N2\pi$
1687±21		STUNTEBECK	70	HDBC	0	$8\ \pi^-p$, $5.4\ \pi^+d$
1683±13		ARMENISE	68	DBC	0	$5.1\ \pi^+d$
1670±30		GOLDBERG	65	HBC	0	$6\ \pi^+d$, $8\ \pi^-p$

[1] Mass errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[2] Uses same data as HYAMS 75.
[3] From a phase shift solution containing a $f_2'(1525)$ width two times larger than the $K\overline{K}$ result.
[4] From phase-shift analysis. Error takes account of spread of different phase-shift solutions.

$K\overline{K}$ AND $K\overline{K}\pi$ MODES

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1696± 4 OUR AVERAGE						
1699± 5		ALPER	80	CNTR	0	$62\ \pi^-p \to K^+K^-n$
1698±12	6k	[5,6] MARTIN	78D	SPEC		$10\ \pi p \to K^0_S K^-p$
1692± 6		BLUM	75	ASPK	0	$18.4\ \pi^-p \to nK^+K^-$
1690±16		ADERHOLZ	69	HBC	+	$8\ \pi^+p \to K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1694± 8		[7] COSTA...	80	OMEG		$10\ \pi^-p \to K^+K^-n$

[5] From a fit to $J^P = 3^-$ partial wave.
[6] Systematic error on mass scale subtracted.
[7] They cannot distinguish between $\rho_3(1690)$ and $\omega_3(1670)$.

$(4\pi)^\pm$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1686± 5 OUR AVERAGE Error includes scale factor of 1.1.						
1694± 6		[8] EVANGELISTA	81	OMEG	−	$12\ \pi^-p \to p4\pi$
1665±15	177	BALTAY	78B	HBC	+	$15\ \pi^+p \to p4\pi$
1670±10		THOMPSON	74	HBC	+	$13\ \pi^+p$
1687±20		CASON	73	HBC	−	$8{,}18.5\ \pi^-p$
1685±14		[9] CASON	73	HBC	−	$8{,}18.5\ \pi^-p$
1680±40	144	BARTSCH	70B	HBC	+	$8\ \pi^+p \to N4\pi$
1689±20	102	[9] BARTSCH	70B	HBC	+	$8\ \pi^+p \to N2\rho$
1705±21		CASO	70	HBC	−	$11.2\ \pi^-p \to n\rho 2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1718±10		[10] EVANGELISTA	81	OMEG	−	$12\ \pi^-p \to p4\pi$
1673± 9		[11] EVANGELISTA	81	OMEG	−	$12\ \pi^-p \to p4\pi$
1733± 9	66	[9] KLIGER	74	HBC	−	$4.5\ \pi^-p \to p4\pi$
1630±15		HOLMES	72	HBC	+	$10\text{–}12\ K^+p$
1720±15		BALTAY	68	HBC	+	$7,\ 8.5\ \pi^+p$

[8] From $\rho^-\rho^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[9] From $\rho^\pm\rho^0$ mode.
[10] From $a_2(1320)^-\pi^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[11] From $a_2(1320)^0\pi^-$ mode, not independent of the other two EVANGELISTA 81 entries.

$\omega\pi$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1681± 7 OUR AVERAGE					
1670±25	[12] ALDE	95	GAM2		$38\ \pi^-p \to \omega\pi^0 n$
1690±15	EVANGELISTA	81	OMEG	−	$12\ \pi^-p \to \omega\pi p$
1666±14	GESSAROLI	77	HBC		$11\ \pi^-p \to \omega\pi p$
1686± 9	THOMPSON	74	HBC	+	$13\ \pi^+p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1654±24	BARNHAM	70	HBC	+	$10\ K^+p \to \omega\pi X$

[12] Supersedes ALDE 92C.

$\eta\pi^+\pi^-$ MODE

(For difficulties with MMS experiments, see the $a_2(1320)$ mini-review in the 1973 edition.)

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1680±15	FUKUI	88	SPEC	0	$8.95\ \pi^-p \to \eta\pi^+\pi^-n$

• • • We do not use the following data for averages, fits, limits, etc. • • •

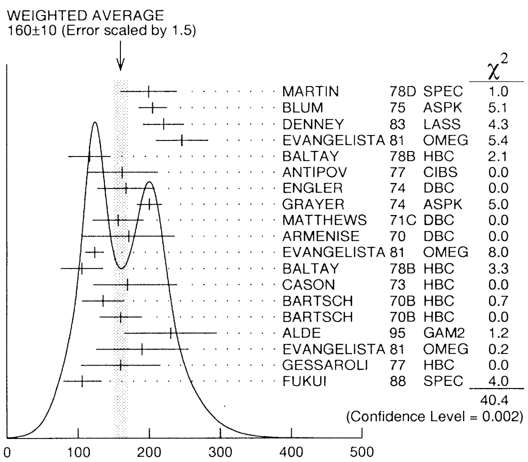
1700±47	[13] ANDERSON	69 MMS	−	16 $\pi^- p$ backward
1632±15	[13,14] FOCACCI	66 MMS	−	7–12 $\pi^- p \rightarrow p$MM
1700±15	[13,14] FOCACCI	66 MMS	−	7–12 $\pi^- p \rightarrow p$MM
1748±15	[13,14] FOCACCI	66 MMS	−	7–12 $\pi^- p \rightarrow p$MM

[13] Seen in 2.5–3 GeV/c $\overline{p}p$. $2\pi^+2\pi^-$, with 0, 1, 2 $\pi^+\pi^-$ pairs in ρ band not seen by OREN 74 (2.3 GeV/c $\overline{p}p$) with more statistics. (Jan. 1976)
[14] Not seen by BOWEN 72.

$\rho_3(1690)$ WIDTH

2π, $K\overline{K}$, AND $K\overline{K}\pi$ MODES

VALUE (MeV)	DOCUMENT ID
160±10 OUR AVERAGE	Includes data from the 5 datablocks that follow this one. Error includes scale factor of 1.5. See the ideogram below.



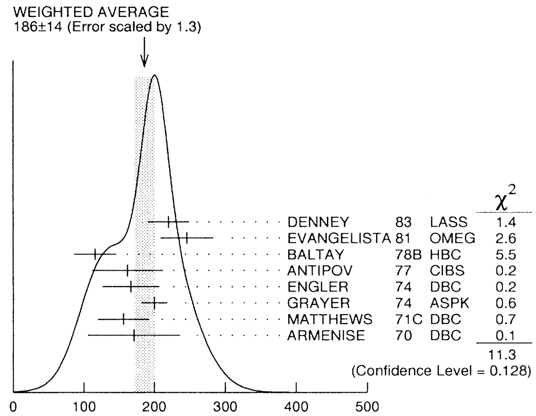
$\rho_3(1690)$ width, 2π, $K\overline{K}$, and $K\overline{K}\pi$ modes (MeV)

2π MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
186±14 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
220±29		DENNEY	83 LASS		10 $\pi^+ N$
246±37		EVANGELISTA 81	OMEG	−	12 $\pi^- p \rightarrow 2\pi p$
116±30	476	BALTAY	78B HBC	0	15 $\pi^+ p \rightarrow \pi^+\pi^- n$
162±50	175	[15] ANTIPOV	77 CIBS	0	25 $\pi^- p \rightarrow p 3\pi$
167±40	600	ENGLER	74 DBC	0	6 $\pi^+ n \rightarrow \pi^+\pi^- p$
200±18		[16] GRAYER	74 ASPK	0	17 $\pi^- p \rightarrow \pi^+\pi^- n$
156±36		MATTHEWS	71C DBC	0	7 $\pi^+ N$
171±65		ARMENISE	70 DBC	0	9 $\pi^+ d$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
322±35		[17] CORDEN	79 OMEG		12–15 $\pi^- p \rightarrow n 2\pi$
240±30		[16,18] ESTABROOKS	75 RVUE		17 $\pi^- p \rightarrow \pi^+\pi^- n$
180±30	122	BARTSCH	70B HBC	+	8 $\pi^+ p \rightarrow N 2\pi$
267^{+72}_{-46}		STUNTEBECK	70 HDBC	0	8 $\pi^- p$, 5.4 $\pi^+ d$
188±49		ARMENISE	68 DBC	0	5.1 $\pi^+ d$
180±40		GOLDBERG	65 HBC	0	6 $\pi^+ d$, 8 $\pi^- p$

[15] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[16] Uses same data as HYAMS 75 and BECKER 79.
[17] From a phase shift solution containing a $f_2'(1525)$ width two times larger than the $K\overline{K}$ result.
[18] From phase-shift analysis. Error takes account of spread of different phase-shift solutions.



$\rho_3(1690)$ width, 2π mode (MeV)

$K\overline{K}$ AND $K\overline{K}\pi$ MODES

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
204±18 OUR AVERAGE					
199±40	6000	[19] MARTIN	78D SPEC		10 $\pi p \rightarrow K^0_S K^- p$
205±20		BLUM	75 ASPK	0	18.4 $\pi^- p \rightarrow n K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
219± 4		ALPER	80 CNTR	0	62 $\pi^- p \rightarrow K^+ K^- n$
186±11		[20] COSTA...	80 OMEG		10 $\pi^- p \rightarrow K^+ K^- n$
112±60		ADERHOLZ	69 HBC	+	8 $\pi^+ p \rightarrow K\overline{K}\pi$

[19] From a fit to $J^P = 3^-$ partial wave.
[20] They cannot distinguish between $\rho_3(1690)$ and $\omega_3(1670)$.

$(4\pi)^{\pm}$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
129±10 OUR AVERAGE					
123±13		[21] EVANGELISTA	81 OMEG	−	12 $\pi^- p \rightarrow p 4\pi$
105±30	177	BALTAY	78B HBC	+	15 $\pi^+ p \rightarrow p 4\pi$
169^{+70}_{-48}		CASON	73 HBC	−	8,18.5 $\pi^- p$
135±30	144	BARTSCH	70B HBC	+	8 $\pi^+ p \rightarrow N 4\pi$
160±30	102	BARTSCH	70B HBC	+	8 $\pi^+ p \rightarrow N 2\rho$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
230±28		[22] EVANGELISTA	81 OMEG	−	12 $\pi^- p \rightarrow p 4\pi$
184±33		[23] EVANGELISTA	81 OMEG	−	12 $\pi^- p \rightarrow p 4\pi$
150	66	[24] KLIGER	74 HBC	−	4.5 $\pi^- p \rightarrow p 4\pi$
106±25		THOMPSON	74 HBC	+	13 $\pi^+ p$
125^{+83}_{-35}		[24] CASON	73 HBC	−	8,18.5 $\pi^- p$
130±30		HOLMES	72 HBC	+	10–12 $K^+ p$
180±30	90	[24] BARTSCH	70B HBC	+	8 $\pi^+ p \rightarrow N a_2 \pi$
100±35		BALTAY	68 HBC	+	7, 8.5 $\pi^+ p$

[21] From $\rho^- \rho^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[22] From $a_2(1320)^- \pi^0$ mode, not independent of the other two EVANGELISTA 81 entries.
[23] From $a_2(1320)^0 \pi^-$ mode, not independent of the other two EVANGELISTA 81 entries.
[24] From $\rho^{\pm} \rho^0$ mode.

$\omega\pi$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
190±40 OUR AVERAGE				
230±65	[25] ALDE	95 GAM2		38 $\pi^- p \rightarrow \omega \pi^0 n$
190±65	EVANGELISTA	81 OMEG	−	12 $\pi^- p \rightarrow \omega \pi p$
160±56	GESSAROLI	77 HBC		11 $\pi^- p \rightarrow \omega \pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
89±25	THOMPSON	74 HBC	+	13 $\pi^+ p$
130^{+73}_{-43}	BARNHAM	70 HBC	+	10 $K^+ p \rightarrow \omega \pi X$

[25] Supersedes ALDE 92C.

$\eta\pi^+\pi^-$ MODE

(For difficulties with MMS experiments, see the $a_2(1320)$ mini-review in the 1973 edition.)

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
The data in this block is included in the average printed for a previous datablock.				
106±27	FUKUI	88 SPEC	0	8.95 $\pi^- p \to \eta\pi^+\pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
195	[26] ANDERSON	69 MMS	−	16 $\pi^- p$ backward
< 21	[26,27] FOCACCI	66 MMS	−	7–12 $\pi^- p \to p$MM
< 30	[26,27] FOCACCI	66 MMS	−	7–12 $\pi^- p \to p$MM
< 38	[26,27] FOCACCI	66 MMS	−	7–12 $\pi^- p \to p$MM

[26] Seen in 2.5–3 GeV/c $\bar{p}p$. $2\pi^+2\pi^-$, with 0, 1, 2 $\pi^+\pi^-$ pairs in ρ^0 band not seen by OREN 74 (2.3 GeV/c $\bar{p}p$) with more statistics. (Jan. 1979)

[27] Not seen by BOWEN 72.

$\rho_3(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	4π	(71.1 ± 1.9) %	
Γ_2	$\pi^\pm\pi^+\pi^-\pi^0$	(67 ± 22) %	
Γ_3	$\pi\pi$	(23.6 ± 1.3) %	
Γ_4	$\omega\pi$	(16 ± 6) %	
Γ_5	$K\bar{K}\pi$	(3.8 ± 1.2) %	
Γ_6	$K\bar{K}$	(1.58 ± 0.26) %	1.2
Γ_7	$\eta\pi^+\pi^-$	seen	
Γ_8	$\pi\pi\rho$ Excluding 2ρ and $a_2(1320)\pi$.		
Γ_9	$a_2(1320)\pi$		
Γ_{10}	$\rho\rho$		
Γ_{11}	$\phi\pi$		
Γ_{12}	$\eta\pi$		
Γ_{13}	$\pi^\pm 2\pi^+ 2\pi^- \pi^0$		

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 10 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 14.7 for 7 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−77		
x_5	−74	17	
x_6	−15	2	0
	x_1	x_3	x_5

$\rho_3(1690)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.236±0.013 OUR FIT				
0.243±0.013 OUR AVERAGE				
$0.259^{+0.018}_{-0.019}$	BECKER	79 ASPK	0	17 $\pi^- p$ polarized
0.23 ±0.02	CORDEN	79 OMEG		12–15 $\pi^- p \to n2\pi$
0.22 ±0.04	[28] MATTHEWS	71C HDBC	0	7 $\pi^+ n \to \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.245±0.006	[29] ESTABROOKS	75 RVUE		17 $\pi^- p \to \pi^+\pi^- n$

[28] One-pion-exchange model used in this estimation.

[29] From phase-shift analysis of HYAMS 75 data.

$\Gamma(\pi\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_3/Γ_2

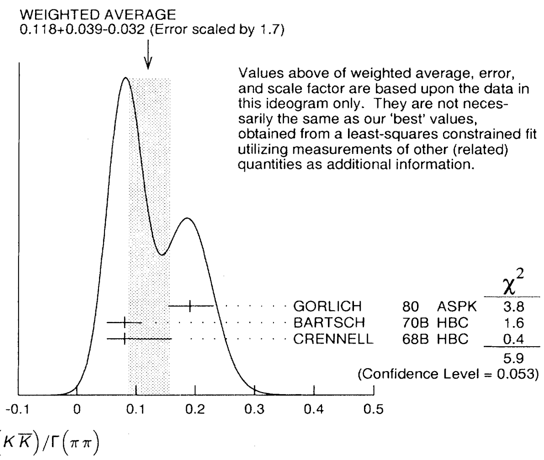
VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.35±0.11	CASON	73 HBC	−	8,18.5 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.2	HOLMES	72 HBC	+	10–12 $K^+ p$
<0.12	BALLAM	71B HBC	−	16 $\pi^- p$

$\Gamma(\pi\pi)/\Gamma(4\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.332±0.026 OUR FIT Error includes scale factor of 1.1.				
0.30 ±0.10	BALTAY	78B HBC	0	15 $\pi^+ p \to p4\pi$

$\Gamma(K\bar{K})/\Gamma(\pi\pi)$ — Γ_6/Γ_3

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.067±0.011 OUR FIT Error includes scale factor of 1.2.				
$\mathbf{0.118^{+0.039}_{-0.032}}$ **OUR AVERAGE** Error includes scale factor of 1.7. See the ideogram below.				
$0.191^{+0.040}_{-0.037}$	GORLICH	80 ASPK	0	17,18 $\pi^- p$ polarized
0.08 ±0.03	BARTSCH	70B HBC	+	8 $\pi^+ p$
$0.08^{+0.08}_{-0.03}$	CRENNELL	68B HBC		6.0 $\pi^- p$



$\Gamma(K\bar{K}\pi)/\Gamma(\pi\pi)$ — Γ_5/Γ_3

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.16±0.05 OUR FIT				
0.16±0.05	[30] BARTSCH	70B HBC	+	8 $\pi^+ p$

[30] Increased by us to correspond to B($\rho_3(1690) \to \pi\pi$)=0.24.

$[\Gamma(\pi\pi\rho) + \Gamma(a_2(1320)\pi) + \Gamma(\rho\rho)]/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — $(\Gamma_8+\Gamma_9+\Gamma_{10})/\Gamma_2$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.94±0.09 OUR AVERAGE				
0.96±0.21	BALTAY	78B HBC	+	15 $\pi^+ p \to p4\pi$
0.88±0.15	BALLAM	71B HBC	−	16 $\pi^- p$
1 ±0.15	BARTSCH	70B HBC	+	8 $\pi^+ p$
consistent with 1	CASO	68 HBC	−	11 $\pi^- p$

$\Gamma(\rho\rho)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_{10}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.12±0.11		BALTAY	78B HBC	+	15 $\pi^+ p \to p4\pi$
0.56	66	KLIGER	74 HBC	−	4.5 $\pi^- p \to p4\pi$
0.13±0.09		[31] THOMPSON	74 HBC	+	13 $\pi^+ p$
0.7 ±0.15		BARTSCH	70B HBC	+	8 $\pi^+ p$

[31] $\rho\rho$ and $a_2(1320)\pi$ modes are indistinguishable.

$\Gamma(\rho\rho)/[\Gamma(\pi\pi\rho) + \Gamma(a_2(1320)\pi) + \Gamma(\rho\rho)]$ — $\Gamma_{10}/(\Gamma_8+\Gamma_9+\Gamma_{10})$

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.48±0.16	CASO	68 HBC	−	11 $\pi^- p$

$\Gamma(a_2(1320)\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_9/Γ_2

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.66±0.08	BALTAY	78B HBC	+	15 $\pi^+ p \to p4\pi$
0.36±0.14	[32] THOMPSON	74 HBC	+	13 $\pi^+ p$
not seen	CASON	73 HBC	−	8,18.5 $\pi^- p$
0.6 ±0.15	BARTSCH	70B HBC	+	8 $\pi^+ p$
0.6	BALTAY	68 HBC	+	7,8.5 $\pi^+ p$

[32] $\rho\rho$ and $a_2(1320)\pi$ modes are indistinguishable.

$\Gamma(\omega\pi)/\Gamma(\pi^\pm\pi^+\pi^-\pi^0)$ — Γ_4/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
0.23±0.05 OUR AVERAGE Error includes scale factor of 1.2.					
0.33±0.07		THOMPSON	74 HBC	+	13 $\pi^+ p$
0.12±0.07		BALLAM	71B HBC	−	16 $\pi^- p$
0.25±0.10		BALTAY	68 HBC	+	7,8.5 $\pi^+ p$
0.25±0.10		JOHNSTON	68 HBC	−	7.0 $\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	95	BALTAY	78B HBC	+	15 $\pi^+ p \to p4\pi$
<0.09		KLIGER	74 HBC	−	4.5 $\pi^- p \to p4\pi$

$\Gamma(\phi\pi)/\Gamma(\pi^{\pm}\pi^{+}\pi^{-}\pi^{0})$ — Γ_{11}/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	BALTAY	68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(\pi^{\pm}2\pi^{+}2\pi^{-}\pi^{0})/\Gamma(\pi^{\pm}\pi^{+}\pi^{-}\pi^{0})$ — Γ_{13}/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15	BALTAY	68	HBC	+	7,8.5 $\pi^+ p$

$\Gamma(\eta\pi)/\Gamma(\pi^{\pm}\pi^{+}\pi^{-}\pi^{0})$ — Γ_{12}/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	THOMPSON	74	HBC	+	13 $\pi^+ p$

$\Gamma(K\overline{K})/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.0158±0.0026 OUR FIT Error includes scale factor of 1.2.					
0.0130±0.0024 OUR AVERAGE					
0.013 ±0.003	COSTA...	80	OMEG	0	10 $\pi^- p \to K^+ K^- n$
0.013 ±0.004	[33] MARTIN	78B	SPEC	−	10 $\pi p \to K^0_S K^- p$

[33] From $(\Gamma_3\Gamma_6)^{1/2} = 0.056 \pm 0.034$ assuming $B(\rho_3(1690) \to \pi\pi) = 0.24$.

$\Gamma(\omega\pi)/[\Gamma(\omega\pi)+\Gamma(\rho\rho)]$ — $\Gamma_4/(\Gamma_4+\Gamma_{10})$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.22±0.08	CASON	73	HBC	−	8,18.5 $\pi^- p$

$\Gamma(\eta\pi^{+}\pi^{-})/\Gamma_{total}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	FUKUI	88	SPEC	8.95 $\pi^- p \to \eta\pi^+\pi^- n$

$\rho_3(1690)$ REFERENCES

ALDE	95	ZPHY C66 379	+Binon, Bricman+	(GAMS Collab.) JP
ALDE	92C	ZPHY C54 553	+Bencheikh, Binon+	(BELG, SERP, KEK, LANL, LAPP)
FUKUI	88	PL B202 441	+Horikawa+	(SUGI, NAGO, KEK, KYOT, MIYA)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
EVANGELISTA	81	NP B178 197	+	(BARI, BONN, CERN, DARE, LIVP+)
ALPER	80	PL 94B 422	+Becker+	(AMST, CERN, CRAC, MPIM, OXF+)
COSTA...	80	NP B175 402	Costa De Beauregard+	(BARI, BONN, CERN+)
GORLICH	80	NP B174 16	+Niczyporuk+	(CRAC, MPIM, CERN, ZEEM)
BECKER	79	NP B151 46	+Blanar, Blum+	(MPIM, CERN, ZEEM, CRAC)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
BALTAY	78B	PR D17 62	+Cautis, Cohen, Csorna+	(COLU, BING)
MARTIN	78B	NP B140 158	+Ozmutlu, Baldi, Bohringer, Dorsaz+	(DURH, GEVA)
MARTIN	78D	PL 74B 417	+Ozmutlu, Baldi, Bohringer, Dorsaz+	(DURH, GEVA)
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)
GESSAROLI	77	NP B126 382	+	(BGNA, FIRZ, GENO, MILA, OXF, PAVI)
BLUM	75	PL 57B 403	+Chabaud, Dietl, Garelick, Grayer+	(CERN, MPIM) JP
ESTABROOKS	75	NP B95 322	+Martin	(DURH)
HYAMS	75	NP B100 205	+Jones, Weilhammer, Blum, Dietl+	(CERN, MPIM)
ENGLER	74	PR D10 2070	+Kraemer, Toaff, Weisser, Diaz+	(CMU, CASE)
GRAYER	74	NP B75 189	+Hyams, Blum, Dietl+	(CERN, MPIM)
KLIGER	74	SJNP 19 428 Translated from YAF 19 839.	+Beketov, Grechko, Guzhavin, Dubovikov+	(ITEP)
OREN	74	NP B71 189	+Cooper, Fields, Rhines, Allison+	(ANL, OXF)
THOMPSON	74	NP B69 220	+Gaidos, McIlwain, Miller, Mulera+	(PURD)
CASON	73	PR D7 1971	+Biswas, Kenney, Madden+	(NDAM)
BOWEN	72	PRL 29 890	+Earles, Faissler, Blieden+	(NEAS, STON)
HOLMES	72	PR D6 3336	+Ferbel, Slattery, Werner	(ROCH)
BALLAM	71B	PR D3 2606	+Chadwick, Guiragossian, Johnson+	(SLAC)
MATTHEWS	71C	NP B33 1	+Prentice, Yoon, Carroll+	(TNTO, WISC) JP
ARMENISE	70	LNC 4 199	+Ghidini, Foring, Cartacci+	(BARI, BGNA, FIRZ)
BARNHAM	70	PRL 24 1083	+Colley, Jobes, Kenyon, Pathak, Riddiford	(BIRM)
BARTSCH	70B	NP B22 109	+Kraus, Tsanos, Grote+	(AACH, BERL, CERN)
CASO	70	LNC 3 707	+Conte, Tomasini+	(GENO, HAMB, MILA, SACL)
STUNTEBECK	70	PL 32B 391	+Kenney, Deery, Biswas, Cason+	(NDAM)
ADERHOLZ	69	NP B11 259	+Bartsch+	(AACH3, BERL, CERN, JAGL, WARS)
ANDERSON	69	PRL 22 1390	+Collins+	(BNL, CMU)
ARMENISE	68	NC 54A 999	+Ghidini, Forino+	(BARI, BGNA, FIRZ, ORSAY) I
BALTAY	68	PRL 20 887	+Kung, Yeh, Ferbel+	(COLU, ROCH, RUTG, YALE) I
CASO	68	NC 54A 983	+Conte, Cords, Diaz+	(GENO, HAMB, MILA, SACL)
CRENNELL	68B	PL 28B 136	+Karshon, Lai, Scarr, Skillicorn	(BNL)
JOHNSTON	68	PRL 20 1414	+Prentice, Steenberg, Yoon	(TNTO, WISC) IJP
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)
GOLDBERG	65	PL 17 354	+	(CERN, EPOL, ORSAY, MILA, CEA, SACL)

OTHER RELATED PAPERS

BARNETT	83B	PL 120B 455	+Blockus, Burka, Chien, Christian+	(JHU)
EHRLICH	66	PR 152 1194	+Selove, Yuta	(PENN)
LEVRAT	66	PL 22 714	+Tolstrup+	(CERN Missing Mass Spect. Collab.)
SEGUINOT	66	PL 19 712	+Martin+	(CERN Missing Mass Spect. Collab.)
BELLINI	65	NC 40A 948	+DiCorato, Duimio, Fiorini	(MILA)
DEUTSCH...	65	PL 18 351	Deutschmann+	(AACH3, BERL, CERN)
FORINO	65	PL 19 65	+Gessaroli+	(BGNA, ORSAY, SACL)

$\rho(1700)$

$I^G(J^{PC}) = 1^+(1^{--})$

THE $\rho(1450)$ AND THE $\rho(1700)$

In our 1988 edition, we replaced the $\rho(1600)$ entry with two new ones, the $\rho(1450)$ and the $\rho(1700)$, because there was emerging evidence that the 1600-MeV region actually contains two ρ-like resonances. ERKAL 86 had pointed out this possibility with a theoretical analysis on the consistency of 2π and 4π electromagnetic form factors and the $\pi\pi$ scattering length. DONNACHIE 87, with a full analysis of data in the annihilation reactions $e^+e^- \to \pi^+\pi^-$, $2\pi^+2\pi^-$, and $\pi^+\pi^-\pi^0\pi^0$, and in the photoproduction reactions $\gamma p \to \pi^+\pi^- p$, $2\pi^+2\pi^- p$, and $\pi^+\pi^-\pi^0\pi^0 p$, had also argued that to obtain a consistent picture two resonances, whose masses and widths could be fixed reasonably well, were necessary. This picture was supported by the analysis of DONNACHIE 87B of $J^P = 1^-$ $\eta\rho^0$ mass spectra obtained in photoproduction and in e^+e^- annihilations; the analysis showed the need for a contribution from a ρ meson with a mass of about 1470 MeV, but could say little about a higher-mass resonance (actually the data could be explained without it). Confirmation of the decay $\rho(1450) \to \omega\pi$, and a tight constraint on the mass due to strong interference with the $\rho(770)$ tail, was found by DONNACHIE 91 in an analysis of $e^+e^- \to \omega\pi$.

The analysis of DONNACHIE 87 was extended by CLEGG 88 to include new data on 4π systems produced in e^+e^- annihilation and in τ decay (4π τ decays and 4π annihilation reactions can be related by the Conserved Vector Current assumption). These systems were successfully analyzed using interfering contributions from two ρ-like states, and from the tail of the $\rho(770)$ decaying into two-body states. While specific conclusions on $\rho(1450) \to 4\pi$ were obtained, the quality of the data used by CLEGG 88 prevented any conclusion on $\rho(1700) \to 4\pi$ decay.

An analysis by CLEGG 90 of 6π mass spectra from e^+e^- annihilation and from diffractive photoproduction provides evidence for two ρ mesons, at about 2.1 and 1.8 GeV, that decay strongly into 6π states. While the former is a candidate for a new resonance, the latter could be a manifestation of the $\rho(1700)$ distorted by threshold effects.

Independent evidence for two 1^- states is provided by KILLIAN 80 in 4π electroproduction at $\langle Q^2\rangle = 1$ (GeV/c)^2, and by FUKUI 88 in a high-statistics sample of the $\eta\pi\pi$ system in $\pi^- p$ charge exchange.

This picture with two overlapping resonances is supported by other data. BISELLO 89 measured the pion form factor in the interval 1.35-2.4 GeV with significant statistics (280 $e^+e^- \to \pi^+\pi^-$ events with very low background). A deep minimum is observed around 1.6 GeV, and the best fit to the form factor is obtained with the hypothesis of ρ-like resonances at 1420 and 1770 MeV with widths of about 250 MeV. ANTONELLI 88 found that the $e^+e^- \to \eta\pi^+\pi^-$ cross section (using three different η decay modes) is better fitted with two fully interfering Breit-Wigners, with parameters in fair agreement with those of DONNACHIE 87 and BISELLO 89.

These results (although ANTONELLI 88 is statistically less significant than BISELLO 89) have also resolved the disagreement between DONNACHIE 87 and FUKUI 88 on the $\rho(1450)$ width in favor of the DONNACHIE 87 value. From this point of view, BISELLO 89 and ANTONELLI 88 can be considered as solid confirmation of the $\rho(1450)$. For the possibility that its $\phi\pi$ mode actually contains two independent vector states, see LANDSBERG 92.

Several observations on the $\omega\pi$ system in the 1200-MeV region (FRENKIEL 72, COSME 76, BARBER 80C, ASTON 80C, ATKINSON 84C, BRAU 88, AMSLER 93B) may be interpreted in terms of either $J^P = 1^-$ $\rho(770) \to \pi\omega$ production (LAYSSAC 71) or $J^P = 1^+$ $b_1(1235)$ production (BRAU 88, AMSLER 93B). We argue that no special entry for a $\rho(1250)$ is needed. The LASS amplitude analysis (ASTON 91B) showing evidence for a $\rho(1270)$ is preliminary and needs confirmation. For completeness, these various observations are listed under the $\rho(1450)$.

ρ(1700) MASS

$\eta\rho^0$ AND $\pi^+\pi^-$ MODES

VALUE (MeV)	DOCUMENT ID
1700±20 OUR ESTIMATE	
1717±13 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 1.2.

$\eta\rho^0$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1740±20	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
1701±15	[1] FUKUI	88	SPEC	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$

[1] From a two Breit-Wigner fit.

$\pi^+\pi^-$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1730 ±30	CLEGG	94	RVUE	$e^+e^- \to \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1768 ±21	BISELLO	89	DM2	$e^+e^- \to \pi^+\pi^-$
1745.7±91.9	DUBNICKA	89	RVUE	$e^+e^- \to \pi^+\pi^-$
1546 ±26	GESHKENBEIN	89	RVUE	
1650	[2] ERKAL	85	RVUE	20–70 $\gamma p \to \gamma\pi$
1550 ±70	ABE	84B	HYBR	20 $\gamma p \to \pi^+\pi^- p$
1590 ±20	[3] ASTON	80	OMEG	20–70 $\gamma p \to p2\pi$
1600 ±10	[4] ATIYA	79B	SPEC	50 $\gamma C \to C2\pi$
1598 $^{+24}_{-22}$	BECKER	79	ASPK	17 $\pi^- p$ polarized
1659 ±25	[2] LANG	79	RVUE	
1575	[2] MARTIN	78C	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
1610 ±30	[2] FROGGATT	77	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
1590 ±20	[5] HYAMS	73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$

$K\overline{K}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1582±36	1600	CLELAND	82B	SPEC	±	50 $\pi p \to K^0_S K^\pm p$

$2(\pi^+\pi^-)$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1570± 20		[6] CORDIER	82	DM1	$e^+e^- \to 2(\pi^+\pi^-)$
1520± 30		[3] ASTON	81E	OMEG	20–70 $\gamma p \to p4\pi$
1654± 25		[7] DIBIANCA	81	DBC	$\pi^+ d \to pp2(\pi^+\pi^-)$
1666± 39		[6] BACCI	80	FRAG	$e^+e^- \to 2(\pi^+\pi^-)$
1780	34	KILLIAN	80	SPEC	11 $e^- p \to 2(\pi^+\pi^-)$
1500		[8] ATIYA	79B	SPEC	50 $\gamma C \to C4\pi^\pm$
1570± 60	65	[9] ALEXANDER	75	HBC	7.5 $\gamma p \to p4\pi$
1550± 60		[3] CONVERSI	74	OSPK	$e^+e^- \to 2(\pi^+\pi^-)$
1550± 50	160	SCHACHT	74	STRC	5.5–9 $\gamma p \to p4\pi$
1450±100	340	SCHACHT	74	STRC	9–18 $\gamma p \to p4\pi$
1430± 50	400	BINGHAM	72B	HBC	9.3 $\gamma p \to p4\pi$

$\pi^+\pi^-\pi^0\pi^0$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1660±30	ATKINSON	85B	OMEG	20–70 γp

$3(\pi^+\pi^-)$ AND $2(\pi^+\pi^-\pi^0)$ MODES

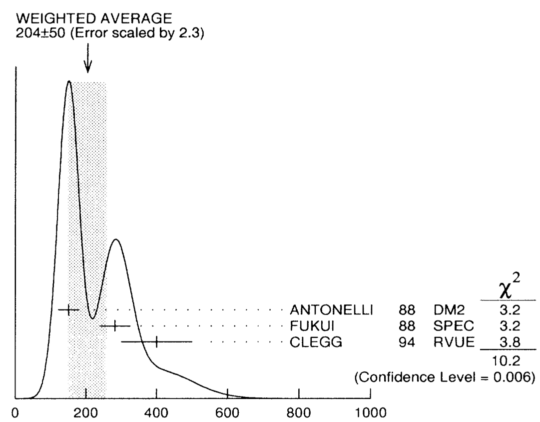
VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1783±15	CLEGG	90	RVUE	$e^+e^- \to 3(\pi^+\pi^-)2(\pi^+\pi^-\pi^0)$

[2] From phase shift analysis of HYAMS 73 data.
[3] Simple relativistic Breit-Wigner fit with constant width.
[4] An additional 40 MeV uncertainty in both the mass and width is present due to the choice of the background shape.
[5] Included in BECKER 79 analysis.
[6] Simple relativistic Breit-Wigner fit with model dependent width.
[7] One peak fit result.
[8] Parameters roughly estimated, not from a fit.
[9] Skew mass distribution compensated by Ross-Stodolsky factor.

ρ(1700) WIDTH

$\eta\rho^0$ AND $\pi^+\pi^-$ MODES

VALUE (MeV)	DOCUMENT ID
235±50 OUR ESTIMATE	
204±50 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 2.3. See the ideogram below.



$\rho(1700)$ width, $\eta\rho^0$ and $\pi^+\pi^-$ modes (MeV)

$\eta\rho^0$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150±30	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$
282±44	[10] FUKUI	88	SPEC	$8.95\ \pi^- p \to \eta\pi^+\pi^- n$

[10] From a two Breit-Wigner fit.

$\pi^+\pi^-$ MODE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
400 ±100	CLEGG	94	RVUE	$e^+e^- \to \pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
224 ± 22	BISELLO	89	DM2	$e^+e^- \to \pi^+\pi^-$
242.5±163.0	DUBNICKA	89	RVUE	$e^+e^- \to \pi^+\pi^-$
620 ± 60	GESHKENBEIN	89	RVUE	
<315	[11] ERKAL	85	RVUE	20–70 $\gamma p \to \gamma\pi$
280 $^{+30}_{-80}$	ABE	84B	HYBR	20 $\gamma p \to \pi^+\pi^- p$
230 ± 80	[12] ASTON	80	OMEG	20–70 $\gamma p \to p2\pi$
283 ± 14	[13] ATIYA	79B	SPEC	50 $\gamma C \to C2\pi$
175 $^{+98}_{-53}$	BECKER	79	ASPK	17 $\pi^- p$ polarized
232 ± 34	[11] LANG	79	RVUE	
340	[11] MARTIN	78C	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
300 ±100	[11] FROGGATT	77	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
180 ± 50	[14] HYAMS	73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$

$K\overline{K}$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
265±120	1600	CLELAND	82B	SPEC	±	50 $\pi p \to K^0_S K^\pm p$

$2(\pi^+\pi^-)$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
510 ± 40		CORDIER [15]	82	DM1	$e^+e^- \to 2(\pi^+\pi^-)$
400 ± 50		ASTON [12]	81E	OMEG	20–70 $\gamma p \to p4\pi$
400 ± 146		DIBIANCA [16]	81	DBC	$\pi^+ d \to pp2(\pi^+\pi^-)$
700 ± 160		BACCI [15]	80	FRAG	$e^+e^- \to 2(\pi^+\pi^-)$
100	34	KILLIAN	80	SPEC	11 $e^- p \to 2(\pi^+\pi^-)$
600		ATIYA [17]	79B	SPEC	50 γC $\to$ C$4\pi^\pm$
340 ± 160	65	ALEXANDER [18]	75	HBC	7.5 $\gamma p \to p4\pi$
360 ± 100		CONVERSI [12]	74	OSPK	$e^+e^- \to 2(\pi^+\pi^-)$
400 ± 120	160	SCHACHT [19]	74	STRC	5.5–9 $\gamma p \to p4\pi$
850 ± 200	340	SCHACHT [19]	74	STRC	9–18 $\gamma p \to p4\pi$
650 ± 100	400	BINGHAM	72B	HBC	9.3 $\gamma p \to p4\pi$

$\pi^+\pi^-\pi^0\pi^0$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
300 ± 50	ATKINSON	85B	OMEG	20–70 γp

$3(\pi^+\pi^-)$ AND $2(\pi^+\pi^-\pi^0)$ MODES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
285 ± 20	CLEGG	90	RVUE	$e^+e^- \to 3(\pi^+\pi^-)2(\pi^+\pi^-\pi^0)$

[11] From phase shift analysis of HYAMS 73 data.
[12] Simple relativistic Breit-Wigner fit with constant width.
[13] An additional 40 MeV uncertainty in both the mass and width is present due to the choice of the background shape.
[14] Included in BECKER 79 analysis.
[15] Simple relativistic Breit-Wigner fit with model-dependent width.
[16] One peak fit result.
[17] Parameters roughly estimated, not from a fit.
[18] Skew mass distribution compensated by Ross-Stodolsky factor.
[19] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$\rho(1700)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\rho\pi\pi$	dominant
Γ_2	$\rho^0\pi^+\pi^-$	large
Γ_3	$\rho^0\pi^0\pi^0$	
Γ_4	$\rho^\pm\pi^\mp\pi^0$	large
Γ_5	$2(\pi^+\pi^-)$	large
Γ_6	$\pi^+\pi^-$	seen
Γ_7	$K\overline{K}^*(892)+$ c.c.	seen
Γ_8	$\eta\rho$	seen
Γ_9	$K\overline{K}$	seen
Γ_{10}	e^+e^-	seen
Γ_{11}	$\rho^0\rho^0$	
Γ_{12}	$\pi\omega$	

$\rho(1700)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the cross-section into channel$_i$ in e^+e^- annihilation.

$\Gamma(2(\pi^+\pi^-)) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_5\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
2.83±0.42	BACCI	80	FRAG	$e^+e^- \to 2(\pi^+\pi^-)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$2.6\ \pm0.2$	DELCOURT	81B	DM1	$e^+e^- \to 2(\pi^+\pi^-)$

$\Gamma(\pi^+\pi^-) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_6\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.13	DIEKMAN [20]	88	RVUE	$e^+e^- \to \pi^+\pi^-$

[20] Using total width = 220 MeV.

$\Gamma(K\overline{K}^*(892)+\text{c.c.}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_7\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.305 ± 0.071	BIZOT [21]	80	DM1	e^+e^-

$\Gamma(\eta\rho) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_8\Gamma_{10}/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
7 ±3	ANTONELLI	88	DM2	$e^+e^- \to \eta\pi^+\pi^-$

$\Gamma(K\overline{K}) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_9\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.035 ± 0.029	BIZOT [21]	80	DM1	e^+e^-

$\Gamma(\rho\pi\pi) \times \Gamma(e^+e^-)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_{10}/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.510 ± 0.090	BIZOT [21]	80	DM1	e^+e^-

[21] Model dependent.

$\rho(1700)$ BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.287^{+0.043}_{-0.042}$	BECKER	79	ASPK	17 $\pi^- p$ polarized
0.15 to 0.30	MARTIN [22]	78C	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
<0.20	COSTA... [23]	77B	RVUE	$e^+e^- \to 2\pi, 4\pi$
$0.30\ \pm0.05$	FROGGATT [22]	77	RVUE	17 $\pi^- p \to \pi^+\pi^- n$
<0.15	EISENBERG [24]	73	HBC	5 $\pi^+ p \to \Delta^{++}2\pi$
$0.25\ \pm0.05$	HYAMS [25]	73	ASPK	17 $\pi^- p \to \pi^+\pi^- n$
$0.20\ \pm0.05$	MONTANET	73	HBC	0.0 $\overline{p}p$

[22] From phase shift analysis of HYAMS 73 data.
[23] Estimate using unitarity, time reversal invariance, Breit-Wigner.
[24] Estimated using one-pion-exchange model.
[25] Included in BECKER 79 analysis.

$\Gamma(\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-))$ — Γ_6/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.13 ± 0.05	ASTON	80	OMEG	20–70 $\gamma p \to p2\pi$
<0.14	DAVIER [26]	73	STRC	6–18 $\gamma p \to p4\pi$
<0.2	BINGHAM [27]	72B	HBC	9.3 $\gamma p \to p2\pi$

[26] Upper limit is estimate.
[27] 2σ upper limit.

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(2(\pi^+\pi^-))$ — Γ_7/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15 ± 0.03	DELCOURT [28]	81B	DM1	$e^+e^- \to \overline{K}K\pi$

[28] Assuming $\rho(1700)$ and ω radial excitations to be degenerate in mass.

$\Gamma(\eta\rho)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04		DONNACHIE	87B	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	58	ATKINSON	86B	OMEG	20–70 γp

$\Gamma(\eta\rho)/\Gamma(2(\pi^+\pi^-))$ — Γ_8/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.123 ± 0.027	DELCOURT	82	DM1	$e^+e^- \to \pi^+\pi^-$ MM
~ 0.1	ASTON	80	OMEG	20–70 γp

$\Gamma(\pi^+\pi^-\text{ neutrals})/\Gamma(2(\pi^+\pi^-))$ — $(\Gamma_3+\Gamma_4+0.709\Gamma_8)/\Gamma_5$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.6 ± 0.4	BALLAM [29]	74	HBC	9.3 γp

[29] Upper limit. Background not subtracted.

$\Gamma(K\overline{K})/\Gamma(2(\pi^+\pi^-))$ — Γ_9/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.015 ± 0.010		DELCOURT [30]	81B	DM1		$e^+e^- \to \overline{K}K$
<0.04	95	BINGHAM	72B	HBC	0	9.3 γp

[30] Assuming $\rho(1700)$ and ω radial excitations to be degenerate in mass.

$\Gamma(K\overline{K})/\Gamma(K\overline{K}^*(892)+\text{c.c.})$ — Γ_9/Γ_7

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.052 ± 0.026	BUON	82	DM1	$e^+e^- \to$ hadrons

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-))$ — Γ_2/Γ_5

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1.0		DELCOURT	81B	DM1	$e^+e^- \to 2(\pi^+\pi^-)$
$0.7\ \pm0.1$	500	SCHACHT	74	STRC	5.5–18 $\gamma p \to p4\pi$
0.80		BINGHAM [31]	72B	HBC	9.3 $\gamma p \to p4\pi$

[31] The $\pi\pi$ system is in S-wave.

$\Gamma(\rho^0\pi^0\pi^0)/\Gamma(\rho^\pm\pi^\mp\pi^0)$ — Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.10	ATKINSON	85B	OMEG		20–70 γp
<0.15	ATKINSON	82	OMEG	0	20–70 $\gamma p \to p4\pi$

$\rho(1700)$ REFERENCES

CLEGG 94 ZPHY C62 455 +Donnachie (LANC, MCHS)
CLEGG 90 ZPHY C45 677 +Donnachie (LANC, MCHS)
BISELLO 89 PL B220 321 +Busetto+ (DM2 Collab.)
DUBNICKA 89 JPG 15 1349 +Martinovic+ (JINR, SLOV)
GESHKENBEIN 89 ZPHY 45 351 (ITEP)
ANTONELLI 88 PL B212 133 +Baldini+ (DM2 Collab.)
DIEKMAN 88 PRPL 159 101 (BONN)
FUKUI 88 PL B202 441 +Horikawa+ (SUGI, NAGO, KEK, KYOT, MIYA)
DONNACHIE 87B ZPHY C34 257 +Clegg (MCHS, LANC)
ATKINSON 86B ZPHY C30 531 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON 85B ZPHY C26 499 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ERKAL 85 ZPHY C29 485 +Olsson (WISC)
ABE 84B PRL 53 751 +Bacon, Ballam+ (SLAC Hybrid Facility Photon Collab.)
ATKINSON 82 PL 108B 55 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
BUON 82 PL 118B 221 +Bisello, Bizot, Cordier, Delcourt+ (LALO, MONP)
CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
CORDIER 82 PL 109B 129 +Bisello, Bizot, Buon, Delcourt (LALO)
DELCOURT 82 PL 113B 93 +Bisello, Bizot, Buon, Cordier, Mane (LALO)
ASTON 81E NP B189 15 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
DELCOURT 81B Bonn Conf. 205 (ORSAY)
Also 82 PL 109B 129 Cordier, Bisello, Bizot, Buon, Delcourt (LALO)
DIBIANCA 81 PR D23 595 +Fickinger, Malko, Dado, Engler+ (CASE, CMU)
ASTON 80 PL 92B 215 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
BACCI 80 PL 95B 139 +DeZorzi, Penso, Baldini-Celio+ (ROMA, FRAS)
BIZOT 80 Madison Conf. 546 +Bisello, Buon, Cordier, Delcourt+ (LALO, MONP)
KILLIAN 80 PR D21 3005 +Treadwell, Ahrens, Berkelman, Cassel+ (CORN)
ATIYA 79B PRL 43 1691 +Holmes, Knapp, Lee, Seto+ (COLU, ILL, FNAL)
BECKER 79 NP B151 46 +Blanar, Blum+ (MPIM, CERN, ZEEM, CRAC)
LANG 79 PR D19 956 +Mas-Parareda (GRAZ)
MARTIN 78C ANP 114 1 +Pennington (CERN)
COSTA... 77B PL 71B 345 Costa De Beauregard, Pire, Truong (EPOL)
FROGGATT 77 NP B129 89 +Petersen (GLAS, NORD)
ALEXANDER 75 PL 57B 487 +Benary, Gandsman, Lissauer+ (TELA)
BALLAM 74 NP B76 375 +Chadwick, Bingham, Fretter+ (SLAC, LBL, MPIM)
CONVERSI 74 PL 52B 493 +Paoluzi, Ceradini, Grilli+ (ROMA, FRAS)
SCHACHT 74 NP B81 205 +Derado, Fries, Park, Yount (MPIM)
DAVIER 73 NP B58 31 +Derado, Fries, Liu, Mozley, Odian, Park+ (SLAC)
EISENBERG 73 PL 43B 149 +Karshon, Mikenberg, Pitluck+ (REHO)
HYAMS 73 NP B64 134 +Jones, Weilhammer, Blum, Dietl+ (CERN, MPIM)
MONTANET 73 Erice School 518 (CERN)
BINGHAM 72B PL 41B 635 +Rabin, Rosenfeld, Smadja+ (LBL, UCB, SLAC) IGJP

OTHER RELATED PAPERS

AMSLER 93B PL B311 362 +Armstrong, v.Dombrowski+ (Crystal Barrel Collab.)
LANDSBERG 92 SJNP 55 1051 (SERP)
Translated from YAF 55 1896.
ASTON 91B NPBPS 21 105 +Awaji, Bienz+ (LASS Collab.)
ACHASOV 88C PL B209 373 +Kozhevnikov (NOVM)
BRAU 88 PR D37 2379 +Franek+ (SLAC Hybrid Facility Photon Collab.) JP
CLEGG 88 ZPHY C40 313 +Donnachie (MCHS, LANC)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)
ERKAL 86 ZPHY C31 615 +Olsson (WISC)
BARKOV 85 NP B256 365 +Chilingarov, Eidelman, Khazin, Lelchuk+ (NOVO)
BISELLO 85 LAL 85-15 +Augustin, Ajaltouni+ (PADO, LALO, CLER, FRAS)
ATKINSON 84C NP B243 1 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+) JP
ATKINSON 83B PL 127B 132 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
ATKINSON 83C NP B229 269 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
AUGUSTIN 83 LAL 83-21 +Ayach, Bisello, Baldini+ (LALO, PADO, FRAS)
SHAMBROOM 82 PR D26 1 +Wilson, Anderson, Francis+ (HARV, EFI, ILL, OXF)
BARBER 80C ZPHY C4 169 +Dainton, Brodbeck, Brookes+ (DARE, LANC, SHEF)
KILLIAN 80 PR D21 3005 +Treadwell, Ahrens, Berkelman, Cassel+ (CORN)
COSME 76 PL 63B 352 +Courau, Dudelzak, Grelaud, Jean-Marie+ (ORSAY)
FRENKIEL 72 NP B47 61 +Ghesquiere, Lillestol, Chung+ (CDEF, CERN)
ALVENSLEBEN 71 PRL 26 273 +Becker, Bertram, Chen+ (DESY, MIT) G
BRAUN 71 NP B30 213 +Fridman, Gerber, Givernaud+ (STRB) G
BULOS 71 PRL 26 149 +Busza, Kehoe, Beniston+ (SLAC, UMD, IBM, LBL) G
LAYSSAC 71 NC 6A 134 +Renard (MONP)

$f_J(1710)$

$I^G(J^{PC}) = 0^+(\text{even}^{++})$

THE $f_J(1710)$

The $f_J(1710)$ is seen in the gluon-rich radiative decay $J/\psi(1S) \to \gamma f_J(1710)$; therefore $C = +1$. It decays into 2η and $K^0_S K^0_S$, which implies $I^G J^{PC} = 0^+(\text{even})^{++}$. In an amplitude analysis of the $K\overline{K}$ and $\pi^+\pi^-$ systems produced in $J/\psi(1S)$ radiative decay, CHEN 91 finds a large spin-0 component for this particle, but ARMSTRONG 89D favors spin 2 in central production. The spin is thus uncertain. This resonance is also observed in $K\overline{K}$ systems recoiling against a ϕ or an ω in hadronic $J/\psi(1S)$ decay. However, according to FALVARD 88, $J/\psi(1S) \to \omega f_J(1710)$ is rather controversial. The $f_J(1710)$ is not seen by DM2 (BISELLO 89B) in $J/\psi(1S) \to \gamma\rho^0\rho^0$, in agreement with the indication from MARK III (BALTRUSAITIS 86B) that the $\rho\rho$ enhancement in this region has $J^P = 0^-$, and hence is unrelated to the $f_J(1710)$. However, a reanalysis (BUGG 95) of the 4π channel from MARK III, including now two $\pi\pi$ S-waves in addition to $\rho\rho$, finds 0^{++}.

Clear evidence is seen in 300-GeV/c pp central production in both K^+K^- and $K^0_S K^0_S$ (ARMSTRONG 89D). Mass and width determinations are complicated because the spectra are dominated by overlap with the $f_2'(1525)$. The apparent large disagreement between the widths found by ARMSTRONG 89D in the two channels (≈ 180 MeV in K^+K^- and ≈ 100 MeV in $K^0_S K^0_S$) can be explained by the arbitrariness of the polynomial-exponential background shape, which leads to a large systematic error for the width. ARMSTRONG 93C also sees in $\eta\eta$ a broad peak at 1747 MeV, which may be the $f_J(1710)$. This resonance is not observed in the hypercharge-exchange reactions $K^-p \to K^0_S K^0_S \Lambda$ (ASTON 88D) and $K^-p \to K^0_S K^0_S Y^*$ (BOLONKIN 86).

A partial-wave analysis of the $\pi^-p \to K^0_S K^0_S$ system (BOLONKIN 88) finds a D_0 wave behavior ($J^{PC} = 2^{++}$) near 1700 MeV, but the width (≈ 30 MeV) is much narrower than that observed in $J/\psi(1S)$ decays and in hadroproduction.

Note that in our 1992 edition this particle was named the $f_2(1710)$. See also our Note on "Non-$q\overline{q}$ Mesons."

$f_J(1710)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1697± 4 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.			
1713±10	ARMSTRONG	89D	OMEG	300 $pp \to ppK^+K^-$
1706±10	ARMSTRONG	89D	OMEG	300 $pp \to ppK^0_S K^0_S$
1707±10	AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
1690± 4	[1] FALVARD	88	DM2	$J/\psi \to \phi K^+K^-$
1698±15	AUGUSTIN	87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
1720±10±10	BALTRUSAIT...	87	MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1768±14	BALOSHIN	95	SPEC	40 $\pi^- C \to K^0_S K^0_S X$
1750±15	[2] BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1748±10	ARMSTRONG	93C	SPEC	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$
~ 1750	BREAKSTONE	93	SFM	$pp \to pp\pi^+\pi^-\pi^+\pi^-$
1710±20	CHEN	91	MRK3	$J/\psi \to \gamma\pi^+\pi^-, \gamma K\overline{K}$
1700±15	BOLONKIN	88	SPEC	40 $\pi^-p \to K^0_S K^0_S n$
1720±60	BOLONKIN	88	SPEC	40 $\pi^-p \to K^0_S K^0_S n$
1638±10	[3] FALVARD	88	DM2	$J/\psi \to \phi K^+K^-$
$1730^{+\ 2}_{-10}$	[4,5] LONGACRE	86	MPS	22 $\pi^-p \to n2K^0_S$
1742±15	WILLIAMS	84	MPSF	200 $\pi^-N \to 2K^0_S X$
1670±50	BLOOM	83	CBAL	$J/\psi \to \gamma 2\eta$
1700±45	EDWARDS	83B	CBAL	$J/\psi \to \eta\gamma 2\pi$
1650±50	BURKE	82	MRK2	$J/\psi \to \gamma 2\rho$
1730±10±20	ETKIN	82C	MPS	23 $\pi^-p \to n2K^0_S$
1708±30	FRANKLIN	82	MRK2	$e^+e^- \to \gamma K^+K^-$

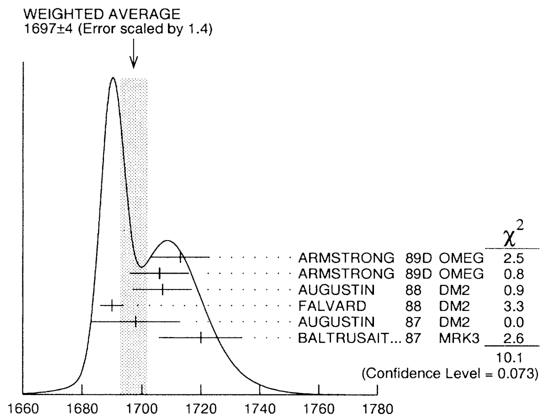
[1] From an analysis including interference with $f_2'(1525)$.

[2] From a fit to the 0^+ partial wave.

[3] From an analysis ignoring interference with $f_2'(1525)$.

[4] From a partial-wave analysis of data using a K-matrix formalism with 5 poles, but assuming spin 2.

[5] Fit with constrained inelasticity.

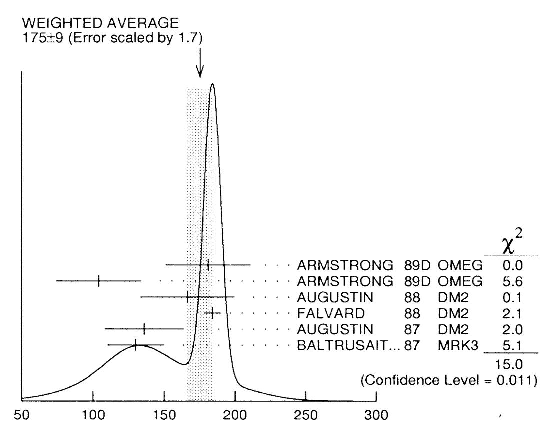


$f_J(1710)$ mass (MeV)

$f_J(1710)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
175 ± 9 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.		
181 ± 30	ARMSTRONG 89D	OMEG	300 $pp \to ppK^+K^-$
104 ± 30	ARMSTRONG 89D	OMEG	300 $pp \to ppK^0_S K^0_S$
166.4 ± 33.2	AUGUSTIN 88	DM2	$J/\psi \to \gamma K^+K^-$
184 ± 6	[6] FALVARD 88	DM2	$J/\psi \to \phi K^+K^-$
136 ± 28	AUGUSTIN 87	DM2	$J/\psi \to \gamma\pi^+\pi^-$
130 ± 20	BALTRUSAIT...87	MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
56 ± 19	BALOSHIN 95	SPEC	40 $\pi^- C \to K^0_S K^0_S X$
160 ± 40	[7] BUGG 95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
264 ± 25	ARMSTRONG 93C	SPEC	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$
200 to 300	BREAKSTONE 93	SFM	$pp \to pp\pi^+\pi^-\pi^+\pi^-$
186 ± 30	CHEN 91	MRK3	$J/\psi \to \gamma\pi^+\pi^-, \gamma K\overline{K}$
30 ± 20	BOLONKIN 88	SPEC	40 $\pi^- p \to K^0_S K^0_S n$
350 ± 150	BOLONKIN 88	SPEC	40 $\pi^- p \to K^0_S K^0_S n$
148 ± 17	[8] FALVARD 88	DM2	$J/\psi \to \phi K^+K^-$
122^{+74}_{-15}	[9,10] LONGACRE 86	MPS	22 $\pi^- p \to n2K^0_S$
57 ± 38	WILLIAMS 84	MPSF	200 $\pi^- N \to 2K^0_S X$
160 ± 80	BLOOM 83	CBAL	$J/\psi \to \gamma 2\eta$
520 ± 110	EDWARDS 83B	CBAL	$J/\psi \to \eta\gamma 2\pi$
200 ± 100	BURKE 82	MRK2	$J/\psi \to \gamma 2\rho$
$200.0^{+156.0}_{-9.0}$	[11] ETKIN 82B	MPS	23 $\pi^- p \to n2K^0_S$
156 ± 60	FRANKLIN 82	MRK2	$e^+e^- \to \gamma K^+K^-$

[6] From an analysis including interference with $f'_2(1525)$.
[7] From a fit to the 0^+ partial wave.
[8] From an analysis ignoring interference with $f'_2(1525)$.
[9] From a partial-wave analysis of data using a K-matrix formalism with 5 poles, but assuming spin 2.
[10] Fit with constrained inelasticity.
[11] From an amplitude analysis of the $K^0_S K^0_S$ system.



$f_J(1710)$ width (MeV)

$f_J(1710)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$\eta\eta$	seen
Γ_3	$\pi\pi$	seen
Γ_4	$\rho\rho$	
Γ_5	$\gamma\gamma$	

$f_J(1710)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_1\Gamma_5/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
<0.11	95	[12] BEHREND 89C	CELL	$\gamma\gamma \to K^0_S K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.48	95	ALBRECHT 90G	ARG	$\gamma\gamma \to K^+K^-$
<0.28	95	[12] ALTHOFF 85B	TASS	$\gamma\gamma \to K\overline{K}\pi$

[12] Assuming helicity 2.

$f_J(1710)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.38^{+0.09}_{-0.19}$	[13,14] LONGACRE 86	MPS	22 $\pi^- p \to n2K^0_S$

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
$0.18^{+0.03}_{-0.13}$	[13,14] LONGACRE 86	RVUE

$\Gamma(\pi\pi)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
$0.039^{+0.002}_{-0.024}$	[13,14] LONGACRE 86	RVUE

$\Gamma(\pi\pi)/\Gamma(K\overline{K})$ — Γ_3/Γ_1

VALUE	DOCUMENT ID	TECN	COMMENT
0.39±0.14	ARMSTRONG 91	OMEG	300 $pp \to pp\pi\pi$, $ppK\overline{K}$

$\Gamma(\eta\eta)/\Gamma(K\overline{K})$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.02	90	[15] PROKOSHKIN 91	GA24	300 $\pi^- p \to \pi^- p\eta\eta$

[13] From a partial-wave analysis of data using a K-matrix formalism with 5 poles, but assuming spin 2.
[14] Fit with constrained inelasticity.
[15] Combining results of GAM4 with those of ARMSTRONG 89D.

$f_J(1710)$ REFERENCES

BALOSHIN 95 PAN 58 46 +Bolonkin, Vladimirskii+ (ITEP)
Translated from YAF 58 50.
BUGG 95 PL B353 378 +Scott, Zoli+ (LOQM, PNPI, WASH)
ARMSTRONG 93C PL B307 394 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
BREAKSTONE 93 ZPHY C58 251 +Campanini+ (IOWA, CERN, DORT, HEIDH, WARS)
ARMSTRONG 91 ZPHY C51 351 +Benayoun+ (ATHU, BARI, BIRM, CERN, CDEF)
CHEN 91 Hadron 91 Conf. (Mark III Collab.)
SLAC-PUB-5669
PROKOSHKIN 91 SPD 36 155 (GAM2, GAM4 Collab.)
Translated from DANS 316 900.
ALBRECHT 90G ZPHY C48 183 +Ehrlichmann, Harder+ (ARGUS Collab.)
ARMSTRONG 89D PL B227 186 +Benayoun (ATHU, BARI, BIRM, CERN, CDEF)
BEHREND 89C ZPHY C43 91 +Criegee, Dainton+ (CELLO Collab.)
AUGUSTIN 88 PRL 60 2238 +Calcaterra+ (DM2 Collab.)
BOLONKIN 88 NP B309 426 +Bloshenko, Gorin+ (ITEP, SERP)
FALVARD 88 PR D38 2706 +Ajaltouni+ (CLER, FRAS, LALO, PADO)
AUGUSTIN 87 ZPHY C36 369 +Cosme+ (LALO, CLER, FRAS, PADO)
BALTRUSAIT... 87 PR D35 2077 Baltrusaitis, Coffman, Dubois+ (Mark III Collab.)
LONGACRE 86 PL B177 223 +Etkin+ (BNL, BRAN, CUNY, DUKE, NDAM)
ALTHOFF 85B ZPHY C29 189 +Braunschweig, Kirschfink+ (TASSO Collab.)
WILLIAMS 84 PR D30 877 +Diamond+ (VAND, NDAM, TUFTS, ARIZ, FNAL+)
BLOOM 83 ARNS 33 143 +Peck (SLAC, CIT)
EDWARDS 83B PRL 51 859 +Partridge, Peck+ (CIT, HARV, PRIN, STAN, SLAC)
BURKE 82 PRL 49 632 +Trilling, Abrams, Alam, Blocker+ (LBL, SLAC)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)
ETKIN 82C PR D25 2446 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)
FRANKLIN 82 SLAC-254 (SLAC)

OTHER RELATED PAPERS

BISELLO 89B PR D39 701 Busetto+ (DM2 Collab.)
ASTON 88D NP B301 525 +Awaji, Bienz+ (SLAC, NAGO, CINC, INUS)
AKESSON 86 NP B264 154 +Albrow, Almehed+ (Axial Field Spec. Collab.)
ARMSTRONG 86B PL 167B 133 +Bloodworth, Carney+ (ATHU, BARI, BIRM, CERN)
BALTRUSAIT... 86B PR D33 1222 Baltrusaitis, Coffman, Hauser+ (Mark III Collab.)
ALTHOFF 83 PL 121B 216 +Brandelik, Boerner, Burkhardt+ (TASSO Collab.)
BARNETT 83B PL 120B 455 +Blockus, Burka, Chien, Christian+ (JHU)
ALTHOFF 82 ZPHY C16 13 +Boerner, Burkhardt+ (TASSO Collab.)
BARNES 82 PL B116 365 +Close (RHEL)
BARNES 82B NP B198 360 +Close, Monaghan (RHEL, OXFTP)
TANIMOTO 82 PL 116B 198 (BIEL)

$X(1740)$

$I^G(J^{PC}) = 0^+(\text{even}\,{+}{+})$

OMITTED FROM SUMMARY TABLE

Seen as a narrow state decaying to $\eta\eta$. $J^P = 0^+$ or 2^+, needs confirmation.

X(1740) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1744±15	[1] ALDE	92D	GAM2	38 $\pi^- p \to \eta\eta N^*$

[1] ALDE 92D combines all the GAMS-2000 data.

X(1740) WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<80	90	[2] ALDE	92D	GAM2	38 $\pi^- p \to \eta\eta N^*$

[2] ALDE 92D combines all the GAMS-2000 data.

X(1740) DECAY MODES

	Mode
Γ_1	$\eta\eta$
Γ_2	$\pi^0\pi^0$
Γ_3	$\eta\eta'$

X(1740) BRANCHING RATIOS

$\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta)$ Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1	90	ALDE	92D	GAM2	38 $\pi^- p \to \eta\eta N^*$

$\Gamma(\eta\eta')/\Gamma(\eta\eta)$ Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1	90	ALDE	92D	GAM2	38 $\pi^- p \to \eta\eta N^*$

X(1740) REFERENCES

ALDE 92D PL B284 457 +Binon, Bricman+ (GAM2 Collab.)
Also 91 SJNP 54 451 Alde, Binon, Bricman+ (GAM2 Collab.)
Translated from YAF 54 745.

OTHER RELATED PAPERS

ALDE 86C PL B182 105 +Binon, Bricman+ (SERP, BELG, LANL, LAPP)

$\eta(1760)$

$I^G(J^{PC}) = 0^+(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen by DM2 in the $\rho\rho$ system BISELLO 89B. Structure in this region has been reported before in the same system BALTRUSAITIS 86B and in the $\omega\omega$ system BALTRUSAITIS 85C, BISELLO 87. Needs confirmation.

η(1760) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1760±11	320	[1] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[1] Estimated by us from various fits.

η(1760) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
60±16	320	[2] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[2] Estimated by us from various fits.

η(1760) REFERENCES

BISELLO 89B PR D39 701 Busetto+ (DM2 Collab.)
BISELLO 87 PL B192 239 +Ajaltouni, Baldini+ (PADO, CLER, FRAS, LALO)
BALTRUSAIT... 86B PR D33 1222 Baltrusaitis, Coffman, Hauser+ (Mark III Collab.)
BALTRUSAIT... 85C PRL 55 1723 Baltrusaitis+ (CIT, UCSC, ILL, SLAC, WASH)

$\pi(1800)$

was $\pi(1770)$ and $X(1830)$

$I^G(J^{PC}) = 1^-(0^{-+})$

OMITTED FROM SUMMARY TABLE

Needs confirmation. See also minireview under non-$q\overline{q}$ candidates.

π(1800) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1795±10 OUR ESTIMATE						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1840±10±10	1200	AMELIN	96B	VES	−	37 $\pi^- A \to \eta\eta\pi^- A$
1775± 7±10		[1] AMELIN	95B	VES	−	36 $\pi^- A \to \pi^+\pi^-\pi^- A$
1790±14		[2] BERDNIKOV	94	VES	−	37 $\pi^- A \to K^+K^-\pi^- A$
1873±33±20		BELADIDZE	92C	VES	−	36 π^- Be $\to \pi^-\eta'\eta$ Be
1814±10±23	426±57	BITYUKOV	91	VES	−	36 π^- C $\to \pi^-\eta\eta$ C
1770±30	1100	BELLINI	82	SPEC	−	40 π^- A $\to 3\pi$ A

[1] From a fit to $J^{PC} = 0^{-+}$ $f_0(980)\pi$, $f_0(1370)\pi$ waves.

[2] From a fit to $J^{PC} = 0^{-+}$ $K_0^*(1430)K^-$ and $f_0(980)\pi^-$ waves.

π(1800) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
212±37 OUR ESTIMATE						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
210±30±30	1200	AMELIN	96B	VES	−	37 $\pi^- A \to \eta\eta\pi^- A$
190±15±15		[3] AMELIN	95B	VES	−	36 $\pi^- A \to \pi^+\pi^-\pi^- A$
210±70		[4] BERDNIKOV	94	VES	−	37 $\pi^- A \to K^+K^-\pi^- A$
225±35±20		BELADIDZE	92C	VES	−	36 π^- Be $\to \pi^-\eta'\eta$ Be
205±18±32	426±57	BITYUKOV	91	VES	−	36 π^- C $\to \pi^-\eta\eta$ C
310±50	1100	BELLINI	82	SPEC	−	40 π^- A $\to 3\pi$ A

[3] From a fit to $J^{PC} = 0^{-+}$ $f_0(980)\pi$, $f_0(1370)\pi$ waves.

[4] From a fit to $J^{PC} = 0^{-+}$ $K_0^*(1430)K^-$ and $f_0(980)\pi^-$ waves.

π(1800) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+\pi^-\pi^-$	seen
Γ_2	$f_0(980)\pi^-$	seen
Γ_3	$f_0(1370)\pi^-$	seen
Γ_4	$\eta\eta\pi^-$	seen
Γ_5	$a_0(980)\eta$	seen
Γ_6	$f_0(1500)\pi^-$	seen
Γ_7	$\eta\eta'(958)\pi^-$	seen
Γ_8	$K_0^*(1430)K^-$	seen
Γ_9	$K^*(892)K^-$	not seen
Γ_{10}	$\rho\pi^-$	not seen

π(1800) BRANCHING RATIOS

$\Gamma(f_0(980)\pi^-)/\Gamma(f_0(1370)\pi^-)$ Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1.7±1.3	AMELIN	95B	VES	−	36 $\pi^- A \to \pi^+\pi^-\pi^- A$

$\Gamma(f_0(1370)\pi^-)/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	BELLINI	82	SPEC	−	40 π^- A $\to 3\pi$ A

$\Gamma(\eta\eta\pi^-)/\Gamma(\pi^+\pi^-\pi^-)$ Γ_4/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.5 ±0.1	1200	AMELIN	96B	VES	−	37 $\pi^- A \to \eta\eta\pi^- A$

$\Gamma(f_0(1500)\pi^-)/\Gamma(a_0(980)\eta)$ Γ_6/Γ_5

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.08 ±0.03	1200	[5] AMELIN	96B	VES	−	37 $\pi^- A \to \eta\eta\pi^- A$

[5] Assuming that $f_0(1500)$ decays only to $\eta\eta$ and $a_0(980)$ decays only to $\eta\pi$.

$\Gamma(\eta\eta'(958)\pi^-)/\Gamma(\eta\eta\pi^-)$ — Γ_7/Γ_4

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.29±0.06 OUR AVERAGE						
0.29±0.07		BELADIDZE	92C	VES	−	36 π^- Be → $\pi^-\eta'\eta$Be
0.3 ±0.1	426±57	BITYUKOV	91	VES	−	36 π^- C → $\pi^-\eta\eta$C

$\Gamma(K_0^*(1430)K^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	BERDNIKOV	94	VES	−	37 $\pi^- A \to K^+K^-\pi^- A$

$\Gamma(K^*(892)K^-)/\Gamma_{total}$ — Γ_9/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
not seen	BERDNIKOV	94	VES	−	37 $\pi^- A \to K^+K^-\pi^- A$

$\Gamma(\rho\pi^-)/\Gamma(f_0(980)\pi^-)$ — Γ_{10}/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.14	90	AMELIN	95B	VES	−	36 $\pi^- A \to \pi^+\pi^-\pi^- A$

$\Gamma(\rho\pi^-)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
not seen	BELLINI	82	SPEC	−	40 π^- A → 3πA

$\pi(1800)$ REFERENCES

AMELIN	96B	YAF 59 1021	+Berdnikov, Bityukov+	(SERP, TBIL) IGJPC
AMELIN	95B	PL B356 595	+Berdnikov, Bityukov+	(SERP, TBIL)
BERDNIKOV	94	PL B337 219	+Bityukov+	(SERP, TBIL)
BELADIDZE	92C	SJNP 55 1535 Translated from YAF 55 2748.	+Bityukov, Borisov	(SERP, TBIL)
BITYUKOV	91	PL B268 137	+Borisov+	(SERP, TBIL)
BELLINI	82	PRL 48 1697	+Frabetti, Ivanshin, Litkin+	(MILA, BGNA, JINR)

OTHER RELATED PAPERS

BORISOV	92	SJNP 55 1441 Translated from YAF 55 2583.	+Gershtein, Zaitsev	(SERP)

$X(1775)$

$I^G(J^{PC}) = 1^-(?^{-+})$

OMITTED FROM SUMMARY TABLE

$X(1775)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1776±13 OUR AVERAGE				
1763±20	CONDO	91	SHF	$\gamma p \to (p\pi^+)(\pi^+\pi^-\pi^-)$
1787±18	CONDO	91	SHF	$\gamma p \to n\pi^+\pi^+\pi^-$

$X(1775)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
155±40 OUR AVERAGE				
192±60	CONDO	91	SHF	$\gamma p \to (p\pi^+)(\pi^+\pi^-\pi^-)$
118±60	CONDO	91	SHF	$\gamma p \to n\pi^+\pi^+\pi^-$

$X(1775)$ DECAY MODES

	Mode
Γ_1	$\rho\pi$
Γ_2	$f_2(1270)\pi$

$X(1775)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma(f_2(1270)\pi)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
1.43±0.26 OUR AVERAGE				
1.3 ±0.3	CONDO	91	SHF	$\gamma p \to (p\pi^+)(\pi^+\pi^-\pi^-)$
1.8 ±0.5	CONDO	91	SHF	$\gamma p \to n\pi^+\pi^+\pi^-$

$X(1775)$ REFERENCES

CONDO	91	PR D43 2787	+Handler+	(SLAC Hybrid Collab.)

$f_2(1810)$

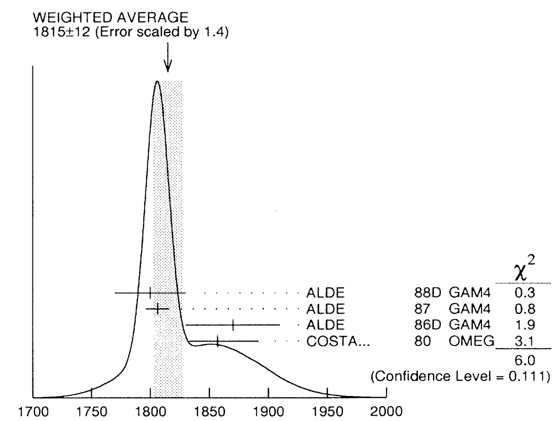
$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$f_2(1810)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1815±12 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.					
1800±30	40	ALDE	88D	GAM4	300 $\pi^- p \to \pi^- p 4\pi^0$
1806±10	1600	ALDE	87	GAM4	100 $\pi^- p \to 4\pi^0 n$
1870±40		ALDE [1]	86D	GAM4	100 $\pi^- p \to \eta\eta n$
1857^{+35}_{-24}		COSTA... [2]	80	OMEG	10 $\pi^- p \to K^+K^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1858^{+18}_{-71}		LONGACRE [3]	86	RVUE	Compilation
1799±15		CASON [4]	82	STRC	8 $\pi^+ p \to \Delta^{++}\pi^0\pi^0$

[1] Seen in only one solution.
[2] Error increased by spread of two solutions. Included in LONGACRE 86 global analysis.
[3] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.
[4] From an amplitude analysis of the reaction $\pi^+\pi^- \to 2\pi^0$. The resonance in the $2\pi^0$ final state not confirmed by PROKOSHKIN 94.

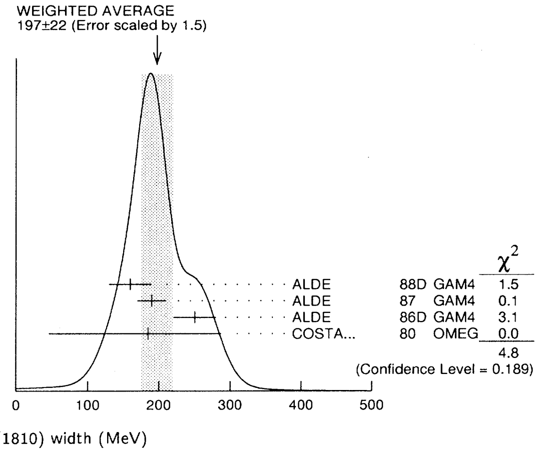


$f_2(1810)$ mass (MeV)

$f_2(1810)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
197± 22 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.					
160± 30	40	ALDE	88D	GAM4	300 $\pi^- p \to \pi^- p 4\pi^0$
190± 20	1600	ALDE	87	GAM4	100 $\pi^- p \to 4\pi^0 n$
250± 30		ALDE [5]	86D	GAM4	100 $\pi^- p \to \eta\eta n$
185^{+102}_{-139}		COSTA... [6]	80	OMEG	10 $\pi^- p \to K^+K^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
388^{+15}_{-21}		LONGACRE [7]	86	RVUE	Compilation
280^{+42}_{-35}		CASON [8]	82	STRC	8 $\pi^+ p \to \Delta^{++}\pi^0\pi^0$

[5] Seen in only one solution.
[6] Error increased by spread of two solutions. Included in LONGACRE 86 global analysis.
[7] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.
[8] From an amplitude analysis of the reaction $\pi^+\pi^- \to 2\pi^0$. The resonance in the $2\pi^0$ final state not confirmed by PROKOSHKIN 94.



$f_2(1810)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	
Γ_2	$\eta\eta$	
Γ_3	$4\pi^0$	seen
Γ_4	K^+K^-	

$f_2(1810)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	PROKOSHKIN	94	GAM2	$38\ \pi^- p \to \pi^0\pi^0 n$
$0.21^{+0.02}_{-0.03}$	[9] LONGACRE	86	RVUE	Compilation
0.44 ± 0.03	[10] CASON	82	STRC	$8\ \pi^+ p \to \Delta^{++}\pi^0\pi^0$

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.008^{+0.028}_{-0.003}$	[9] LONGACRE	86	RVUE	Compilation

$\Gamma(\pi\pi)/\Gamma(4\pi^0)$ — Γ_1/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.75	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(4\pi^0)/\Gamma(\eta\eta)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.8 ± 0.3	ALDE	87	GAM4	$100\ \pi^- p \to 4\pi^0 n$

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.003^{+0.019}_{-0.002}$	[9] LONGACRE	86	RVUE	Compilation
seen	COSTA...	80	OMEG	$10\ \pi^- p \to K^+K^- n$

[9] From a partial-wave analysis of data using a K-matrix formalism with 5 poles. Includes compilation of several other experiments.
[10] Included in LONGACRE 86 global analysis.

$f_2(1810)$ REFERENCES

PROKOSHKIN 94 SPD 39 420 +Kondashov (SERP)
Translated from DANS 336 613.
ALDE 88D SJNP 47 810 +Bellazzini, Binon+ (SERP, BELG, LANL, LAPP, PISA)
Translated from YAF 47 1273.
ALDE 87 PL B198 286 +Binon, Bricman+ (LANL, BRUX, SERP, LAPP)
ALDE 86D NP B269 485 +Binon, Bricman+ (BELG, LAPP, SERP, CERN, LANL)
LONGACRE 86 PL B177 223 +Etkin+ (BNL, BRAN, CUNY, DUKE, NDAM)
CASON 82 PRL 48 1316 +Biswas, Baumbaugh, Bishop+ (NDAM, ANL)
COSTA... 80 NP B175 402 Costa De Beauregard+ (BARI, BONN, CERN+)

OTHER RELATED PAPERS

AKER 91 PL B260 249 +Amsler, Peters+ (Crystal Barrel Collab.)
CASON 83 PR D28 1586 +Cannata, Baumbaugh, Bishop+ (NDAM, ANL)
ETKIN 82B PR D25 1786 +Foley, Lai+ (BNL, CUNY, TUFTS, VAND)

$\phi_3(1850)$

$I^G(J^{PC}) = 0^-(3^{--})$

$\phi_3(1850)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1854± 7 OUR AVERAGE					
1855 ± 10		ASTON	88E	LASS	$11\ K^- p \to K^-K^+\Lambda$, $K^0_S K^\pm\pi^\mp\Lambda$
1870^{+30}_{-20}	430	ARMSTRONG	82	OMEG	$18.5\ K^- p \to K^-K^+\Lambda$
1850 ± 10	123	ALHARRAN	81B	HBC	$8.25\ K^- p \to K\overline{K}\Lambda$

$\phi_3(1850)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
87^{+28}_{-23} OUR AVERAGE Error includes scale factor of 1.2.					
64 ± 31		ASTON	88E	LASS	$11\ K^- p \to K^-K^+\Lambda$, $K^0_S K^\pm\pi^\mp\Lambda$
160^{+90}_{-50}	430	ARMSTRONG	82	OMEG	$18.5\ K^- p \to K^-K^+\Lambda$
80^{+40}_{-30}	123	ALHARRAN	81B	HBC	$8.25\ K^- p \to K\overline{K}\Lambda$

$\phi_3(1850)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$K\overline{K}^*(892)$ + c.c.	seen

$\phi_3(1850)$ BRANCHING RATIOS

$\Gamma(K\overline{K}^*(892)+\text{c.c.})/\Gamma(K\overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
$0.55^{+0.85}_{-0.45}$	ASTON	88E	LASS	$11\ K^- p \to K^-K^+\Lambda$, $K^0_S K^\pm\pi^\mp\Lambda$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.8\ \pm0.4$	ALHARRAN	81B	HBC	$8.25\ K^- p \to K\overline{K}\pi\Lambda$

$\phi_3(1850)$ REFERENCES

ASTON 88E PL B208 324 +Awaji, Biewz+ (SLAC, NAGO, CINC, INUS) IGJPC
ARMSTRONG 82 PL 110B 77 +Baubillier+ (BARI, BIRM, CERN, MILA, CURIN+) JP
ALHARRAN 81B PL 101B 357 +Amirzadeh+ (BIRM, CERN, GLAS, MICH, CURIN)

OTHER RELATED PAPERS

CORDIER 82B PL 110B 335 +Bisello, Bizot, Buon, Delcourt, Fayard+ (LALO)
ASTON 80B PL 92B 219 (BONN, CERN, EPOL, GLAS, LANC, MCHS+)

$\eta_2(1870)$

$I^G(J^{PC}) = 0^+(2^{-+})$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$\eta_2(1870)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1881±32±40	26	KARCH	92	CBAL	$e^+e^- \to e^+e^-\eta\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1850 ± 50		FEINDT	91	CELL	$\gamma\gamma \to \eta\pi^+\pi^-$

$\eta_2(1870)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
221± 92±44	26	KARCH	92	CBAL	$e^+e^- \to e^+e^-\eta\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 360		FEINDT	91	CELL	$\gamma\gamma \to \eta\pi^+\pi^-$

$\eta_2(1870)$ DECAY MODES

	Mode
Γ_1	$\eta\pi\pi$
Γ_2	$a_2(1320)\pi$
Γ_3	$f_0(980)\pi^-$

$\eta_2(1870)$ REFERENCES

KARCH	92	ZPHY C54 33	+Antreasyan, Bartels+	(Crystal Ball Collab.)
FEINDT	91	Singapore Conf. 537		

OTHER RELATED PAPERS

KARCH	90	PL B249 353	+Antreasyan, Bartels+	(Crystal Ball Collab.)

X(1910)

$I^G(J^{PC}) = 0^+(?^{?+})$

OMITTED FROM SUMMARY TABLE

We list here two different peaks with close masses and widths seen in the mass distributions of $\omega\omega$ and $\eta\eta'$ final states. ALDE 91B argues that they are of different nature. See also minireview under non-$q\overline{q}$ candidates.

X(1910) MASS

VALUE (MeV)	DOCUMENT ID
1810 to 1920 OUR ESTIMATE	

X(1910) $\omega\omega$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1921± 8 OUR AVERAGE				
1920±10	[1] BELADIDZE	92B	VES	$36\ \pi^- p \rightarrow \omega\omega n$
1924±14	[1] ALDE	90	GAM2	$38\ \pi^- p \rightarrow \omega\omega n$

[1] $J^{PC} = 2^{++}$.

X(1910) $\eta\eta'$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1911±10	ALDE	91B	GAM2	$38\ \pi^- p \rightarrow \eta\eta' n$

X(1910) WIDTH

VALUE (MeV)	DOCUMENT ID
90 to 250 OUR ESTIMATE	

X(1910) $\omega\omega$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
90±19 OUR AVERAGE				
90±20	[2] BELADIDZE	92B	VES	$36\ \pi^- p \rightarrow \omega\omega n$
91±50	[2] ALDE	90	GAM2	$38\ \pi^- p \rightarrow \omega\omega n$

[2] $J^{PC} = 2^{++}$.

X(1910) $\eta\eta'$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
90±35	ALDE	91B	GAM2	$38\ \pi^- p \rightarrow \eta\eta' n$

X(1910) DECAY MODES

	Mode
Γ_1	$\pi^0\pi^0$
Γ_2	$K^0_S K^0_S$
Γ_3	$\eta\eta$
Γ_4	$\omega\omega$
Γ_5	$\eta\eta'$
Γ_6	$\eta'\eta'$

X(1910) BRANCHING RATIOS

$\Gamma(\omega\omega)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	ALDE	89B	GAM2	$38\ \pi^- p \rightarrow \omega\omega n$

$\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta')$ — Γ_1/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.1	ALDE	89	GAM2	$38\pi^- p \rightarrow \eta\eta' n$

$\Gamma(\eta\eta)/\Gamma(\eta\eta')$ — Γ_3/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	ALDE	91B	GAM2	$38\ \pi^- p \rightarrow \eta\eta' n$

$\Gamma(K^0_S K^0_S)/\Gamma(\eta\eta')$ — Γ_2/Γ_5

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.066	90	BALOSHIN	86	SPEC	$40\pi p \rightarrow K^0_S K^0_S n$

$\Gamma(\eta'\eta')/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
possibly seen	BELADIDZE	92D	VES	$37\ \pi^- p \rightarrow \eta'\eta' n$

X(1910) REFERENCES

BELADIDZE	92B	ZPHY C54 367	+Bityukov, Borisov+	(VES Collab.)
BELADIDZE	92D	ZPHY C57 13	+Berdnikov+	(VES Collab.)
ALDE	91B	SJNP 54 455	+Binon+	(SERP, BELG, LANL, LAPP, PISA, KEK)
		Translated from YAF 54 751.		
Also	92	PL B276 375	Alde, Binon+	(BELG, SERP, KEK, LANL, LAPP)
ALDE	90	PL B241 600	+Binon+	(SERP, BELG, LANL, LAPP, PISA, KEK)
ALDE	89	PL B216 447	+Binon, Bricman, Donskov+	(SERP, BELG, LANL, LAPP)
Also	88E	SJNP 48 1035	Alde, Binon, Bricman+	(BELG, SERP, LANL, LAPP)
		Translated from YAF 48 1724.		
ALDE	89B	PL B216 451	+Binon, Bricman+	(SERP, BELG, LANL, LAPP, TBIL)
BALOSHIN	86	SJNP 43 959	+Barkov, Bolonkin, Vladimirskii, Grigoriev+	(ITEP)
		Translated from YAF 43 1487.		

OTHER RELATED PAPERS

LEE	94	PL B323 227	+Chung, Kirk+	(BNL, IND, KYUN, MASD, RICE)

$f_2(1950)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$f_2(1950)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1950±15	[1] ASTON	91	LASS	0	$11\ K^- p \rightarrow \Lambda K \overline{K}\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1918±12	ANTINORI	95	OMEG		$300,450\ pp \rightarrow pp2(\pi^+\pi^-)$
~ 1996	HASAN	94	RVUE		$\overline{p}p \rightarrow \pi\pi$

[1] Cannot determine spin to be 2.

$f_2(1950)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
250±50	[2] ASTON	91	LASS	0	$11\ K^- p \rightarrow \Lambda K \overline{K}\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
390±60	ANTINORI	95	OMEG		$300,450\ pp \rightarrow pp2(\pi^+\pi^-)$
~ 134	HASAN	94	RVUE		$\overline{p}p \rightarrow \pi\pi$

[2] Cannot determine spin to be 2.

$f_2(1950)$ DECAY MODES

	Mode
Γ_1	$K^*(892)\overline{K}^*(892)$
Γ_2	$\pi^0\pi^0$
Γ_3	$\pi^+\pi^-\pi^+\pi^-$

$f_2(1950)$ BRANCHING RATIOS

$\Gamma(K^*(892)\overline{K}^*(892))/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	ASTON	91	LASS	0	$11\ K^- p \rightarrow \Lambda K \overline{K}\pi\pi$

$f_2(1950)$ REFERENCES

ANTINORI	95	PL B353 589	+Barberis, Bayes+	(ATHU, BARI, BIRM, CERN, JINR) JP
HASAN	94	PL B334 215	+Bugg	(LOQM)
ASTON	91	NP B21 5 (suppl)	+Awaji+	(LASS Collab.)

OTHER RELATED PAPERS

BIENZ	90	SLAC 369		(LASS Collab.)
ALBRECHT	88N	PL B212 528	+	(ARGUS Collab.)
ALBRECHT	87Q	PL B198 255	+Binder+	(ARGUS Collab.)
ARMSTRONG	87C	ZPHY C34 33	+Bloodworth+	(CERN, BIRM, BARI, ATHU, CURIN+)

$X(2000)$
was $a_3(2050)$

$I^G(J^{PC}) = 1^-(?^{?+})$

OMITTED FROM SUMMARY TABLE
BALTAY 77 favors $J^P = 3^+$. Needs confirmation.

$X(2000)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1964 ± 35		[1] ARMSTRONG	93D	SPEC		$\overline{p}p \to 3\pi^0 \to 6\gamma$
~ 2100		[1] ANTIPOV	77	CIBS	$-$	$25\ \pi^- p \to p\pi^-\rho_3$
2214 ± 15		BALTAY	77	HBC	0	$15\ \pi^- p \to \Delta^{++}3\pi$
2080 ± 40	208	KALELKAR	75	HBC	+	$15\ \pi^+ p \to p\pi^+\rho_3$

[1] Cannot determine spin to be 3.

$X(2000)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
225 ± 50		[2] ARMSTRONG	93D	SPEC		$\overline{p}p \to 3\pi^0 \to 6\gamma$
~ 500		[2] ANTIPOV	77	CIBS	$-$	$25\ \pi^- p \to p\pi^-\rho_3$
355 ± 21		BALTAY	77	HBC	0	$15\ \pi^- p \to \Delta^{++}3\pi$
340 ± 80	208	KALELKAR	75	HBC	+	$15\ \pi^+ p \to p\pi^+\rho_3$

[2] Cannot determine spin to be 3.

$X(2000)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	
Γ_2	$\rho_3(1690)\pi$	dominant

$X(2000)$ BRANCHING RATIOS

$\Gamma(\rho_3(1690)\pi)/\Gamma(3\pi)$ **Γ_2/Γ_1**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
dominant	KALELKAR	75	HBC	+	$15\ \pi^+ p \to p3\pi$

$X(2000)$ REFERENCES

ARMSTRONG 93D PL B307 399 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
ANTIPOV 77 NP B119 45 +Busnello, Damgaard, Kienzle+ (SERP, GEVA)
BALTAY 77 PRL 39 591 +Cautis, Kalelkar (COLU) JP
KALELKAR 75 Thesis Nevis 207 (COLU)

OTHER RELATED PAPERS

HARRIS 81 ZPHY C9 275 +Dunn, Lubatti, Moriyasu, Podolsky+ (SEAT, UCB)
HUSON 68 PL 28B 208 +Lubatti, Six, Veillet+ (ORSAY, MILA, UCLA)
DANYSZ 67B NC 51A 801 +French, Simak (CERN)

$f_2(2010)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2010)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$\mathbf{2011^{+62}_{-76}}$	[1] ETKIN	88	MPS	$22\ \pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1980 ± 20	[2] BOLONKIN	88	SPEC	$40\ \pi^- p \to K^0_S K^0_S n$
2050^{+90}_{-50}	ETKIN	85	MPS	$22\ \pi^- p \to 2\phi n$
2120^{+20}_{-120}	LINDENBAUM	84	RVUE	
2160 ± 50	ETKIN	82	MPS	$22\ \pi^- p \to 2\phi n$

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi$ 2^{++} S_2, D_2, and D_0 is 98^{+1}_{-3}, 0^{+1}_{-0}, and 2^{+2}_{-1}, respectively.
[2] Statistically very weak, only 1.4 s.d.

$f_2(2010)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$\mathbf{202^{+67}_{-62}}$	[3] ETKIN	88	MPS	$22\ \pi^- p \to \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
145 ± 50	[4] BOLONKIN	88	SPEC	$40\ \pi^- p \to K^0_S K^0_S n$
200^{+160}_{-50}	ETKIN	85	MPS	$22\ \pi^- p \to 2\phi n$
300^{+150}_{-50}	LINDENBAUM	84	RVUE	
310 ± 70	ETKIN	82	MPS	$22\ \pi^- p \to 2\phi n$

[3] Includes data of ETKIN 85.
[4] Statistically very weak, only 1.4 s.d.

$f_2(2010)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2010)$ REFERENCES

BOLONKIN 88 NP B309 426 +Bloshenko, Gorin+ (ITEP, SERP)
ETKIN 88 PL B201 568 +Foley, Lindenbaum+ (BNL, CUNY)
ETKIN 85 PL 165B 217 +Foley, Longacre, Lindenbaum+ (BNL, CUNY)
LINDENBAUM 84 CNPP 13 285 (CUNY)
ETKIN 82 PRL 49 1620 +Foley, Longacre, Lindenbaum+ (BNL, CUNY)
Also 83 Brighton Conf. 351 Lindenbaum (BNL, CUNY)

OTHER RELATED PAPERS

ARMSTRONG 89B PL B221 221 +Benayoun+(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
GREEN 86 PRL 56 1639 +Lai+ (FNAL, ARIZ, FSU, NDAM, TUFTS, VAND+)
BOOTH 84 NP B242 51 +Ballance, Carroll, Donald+ (LIVP, GLAS, CERN)

$a_4(2040)$

$I^G(J^{PC}) = 1^-(4^{++})$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$a_4(2040)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2037±26 OUR AVERAGE					
2040 ± 30	[1] CLELAND	82B	SPEC	$\pm$	$50\ \pi p \to K^0_S K^\pm p$
2030 ± 50	[2] CORDEN	78C	OMEG	0	$15\ \pi^- p \to 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1903 ± 10	[3] BALDI	78	SPEC	$-$	$10\ \pi^- p \to pK^0_S K^-$

[1] From an amplitude analysis.
[2] $J^P = 4^+$ is favored, though $J^P = 2^+$ cannot be excluded.
[3] From a fit to the Y^0_8 moment. Limited by phase space.

$a_4(2040)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
427±120 OUR AVERAGE					
380±150	[4] CLELAND	82B	SPEC	±	50 $\pi p \rightarrow K^0_S K^\pm p$
510±200	[5] CORDEN	78C	OMEG	0	15 $\pi^- p \rightarrow 3\pi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
166± 43	[6] BALDI	78	SPEC	−	10 $\pi^- p \rightarrow p K^0_S K^-$

[4] From an amplitude analysis.
[5] $J^P = 4^+$ is favored, though $J^P = 2^+$ cannot be excluded.
[6] From a fit to the Y^0_8 moment. Limited by phase space.

$a_4(2040)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\overline{K}$	seen
Γ_2	$\pi^+\pi^-\pi^0$	seen

$a_4(2040)$ BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	BALDI	78	SPEC	±	10 $\pi^- p \rightarrow K^0_S K^- p$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	CORDEN	78C	OMEG	0	15 $\pi^- p \rightarrow 3\pi n$

$a_4(2040)$ REFERENCES

CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
BALDI 78 PL 74B 413 +Bohringer, Dorsaz, Hungerbuhler+ (GEVA) JP
CORDEN 78C NP B136 77 +Dowell, Garvey+ (BIRM, RHEL, TELA, LOWC) JP

OTHER RELATED PAPERS

DELFOSSE 81 NP B183 349 +Guisan, Martin, Muhlemann, Weill+ (GEVA, LAUS)

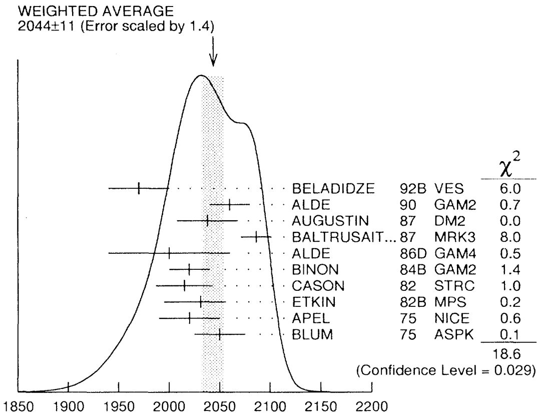
$f_4(2050)$

$I^G(J^{PC}) = 0^+(4^{++})$

$f_4(2050)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2044±11 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.				
1970±30		BELADIDZE	92B	VES	36 $\pi^- p \rightarrow \omega\omega n$
2060±20		ALDE	90	GAM2	38 $\pi^- p \rightarrow \omega\omega n$
2038±30		AUGUSTIN	87	DM2	$J/\psi \rightarrow \gamma\pi^+\pi^-$
2086±15		BALTRUSAIT...	87	MRK3	$J/\psi \rightarrow \gamma\pi^+\pi^-$
2000±60		ALDE	86D	GAM4	100 $\pi^- p \rightarrow n 2\eta$
2020±20	40k	[1] BINON	84B	GAM2	38 $\pi^- p \rightarrow n 2\pi^0$
2015±28		[2] CASON	82	STRC	8 $\pi^+ p \rightarrow \Delta^{++}\pi^0\pi^0$
2031^{+25}_{-36}		ETKIN	82B	MPS	23 $\pi^- p \rightarrow n 2K^0_S$
2020±30	700	APEL	75	NICE	40 $\pi^- p \rightarrow n 2\pi^0$
2050±25		BLUM	75	ASPK	18.4 $\pi^- p \rightarrow n K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1978± 5		[3] ALPER	80	CNTR	62 $\pi^- p \rightarrow K^+K^- n$
2040±10		[3] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p} n$
1935±13		[3] CORDEN	79	OMEG	12–15 $\pi^- p \rightarrow n 2\pi$
1988± 7		EVANGELISTA	79B	OMEG	10 $\pi^- p \rightarrow K^+K^- n$
1922±14		[4] ANTIPOV	77	CIBS	25 $\pi^- p \rightarrow p 3\pi$

[1] From a partial-wave analysis of the data.
[2] From an amplitude analysis of the reaction $\pi^+\pi^- \rightarrow 2\pi^0$.
[3] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.
[4] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.



$f_4(2050)$ mass (MeV)

$f_4(2050)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
208± 13 OUR AVERAGE	Error includes scale factor of 1.2.				
300± 50		BELADIDZE	92B	VES	36 $\pi^- p \rightarrow \omega\omega n$
170± 60		ALDE	90	GAM2	38 $\pi^- p \rightarrow \omega\omega n$
304± 60		AUGUSTIN	87	DM2	$J/\psi \rightarrow \gamma\pi^+\pi^-$
210± 63		BALTRUSAIT...	87	MRK3	$J/\psi \rightarrow \gamma\pi^+\pi^-$
400±100		ALDE	86D	GAM4	100 $\pi^- p \rightarrow n 2\eta$
240± 40	40k	[5] BINON	84B	GAM2	38 $\pi^- p \rightarrow n 2\pi^0$
190± 14		DENNEY	83	LASS	10 $\pi^+ n/\pi^+ p$
186^{+103}_{-58}		[6] CASON	82	STRC	8 $\pi^+ p \rightarrow \Delta^{++}\pi^0\pi^0$
305^{+36}_{-119}		ETKIN	82B	MPS	23 $\pi^- p \rightarrow n 2K^0_S$
180± 60	700	APEL	75	NICE	40 $\pi^- p \rightarrow n 2\pi^0$
225^{+120}_{-70}		BLUM	75	ASPK	18.4 $\pi^- p \rightarrow n K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
243± 16		[7] ALPER	80	CNTR	62 $\pi^- p \rightarrow K^+K^- n$
140± 15		[7] ROZANSKA	80	SPRK	18 $\pi^- p \rightarrow p\overline{p} n$
263± 57		[7] CORDEN	79	OMEG	12–15 $\pi^- p \rightarrow n 2\pi$
100± 28		EVANGELISTA	79B	OMEG	10 $\pi^- p \rightarrow K^+K^- n$
107± 56		[8] ANTIPOV	77	CIBS	25 $\pi^- p \rightarrow p 3\pi$

[5] From a partial-wave analysis of the data.
[6] From an amplitude analysis of the reaction $\pi^+\pi^- \rightarrow 2\pi^0$.
[7] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.
[8] Width errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.

$f_4(2050)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega\omega$	(26 ±6) %
Γ_2	$\pi\pi$	(17.0±1.5) %
Γ_3	$K\overline{K}$	($6.8^{+3.4}_{-1.8}$) $\times 10^{-3}$
Γ_4	$\eta\eta$	(2.1±0.8) $\times 10^{-3}$
Γ_5	$4\pi^0$	< 1.2 %
Γ_6	$\gamma\gamma$	

$f_4(2050)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ $\Gamma_3\Gamma_6/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.29	95	ALTHOFF	85B	TASS	$\gamma\gamma \rightarrow K\overline{K}\pi$

$\Gamma(\pi\pi) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ $\Gamma_2\Gamma_6/\Gamma$

VALUE (keV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.1	95	13 ± 4	OEST	90	JADE	$e^+e^- \rightarrow e^+e^-\pi^0\pi^0$

$f_4(2050)$ BRANCHING RATIOS

$\Gamma(\omega\omega)/\Gamma(\pi\pi)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
1.5 ±0.3	ALDE	90	GAM2	38 $\pi^- p \rightarrow \omega\omega n$

$\Gamma(\pi\pi)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.170±0.015 OUR AVERAGE				
0.18 ±0.03	[9] BINON	83C	GAM2	38 $\pi^- p \to n 4\gamma$
0.16 ±0.03	[9] CASON	82	STRC	8 $\pi^+ p \to \Delta^{++} \pi^0 \pi^0$
0.17 ±0.02	[9] CORDEN	79	OMEG	12–15 $\pi^- p \to n 2\pi$

[9] Assuming one pion exchange.

$\Gamma(K\overline{K})/\Gamma(\pi\pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.04 $^{+0.02}_{-0.01}$	ETKIN	82B	MPS	23 $\pi^- p \to n 2K^0_S$

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.1±0.8	ALDE	86D	GAM4	100 $\pi^- p \to n 4\gamma$

$\Gamma(4\pi^0)/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.012	ALDE	87	GAM4	100 $\pi^- p \to 4\pi^0 n$

$f_4(2050)$ REFERENCES

BELADIDZE	92B	ZPHY C54 367	+Bityukov, Borisov+	(VES Collab.)
ALDE	90	PL B241 600	+Binon+	(SERP, BELG, LANL, LAPP, PISA, KEK)
OEST	90	ZPHY C47 343	+Olsson+	(JADE Collab.)
ALDE	87	PL B198 286	+Binon, Bricman+	(LANL, BRUX, SERP, LAPP)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN, LANL)
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
BINON	84B	LNC 39 41	+Donskov, Duteil, Gouanere+	(SERP, BELG, LAPP)
BINON	83C	SJNP 38 723	+Gouanere, Donskov, Duteil+	(SERP, BRUX+)
		Translated from YAF 38 1199.		
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH)
CASON	82	PRL 48 1316	+Biswas, Baumbaugh, Bishop+	(NDAM, ANL)
ETKIN	82B	PR D25 1786	+Foley, Lai+	(BNL, CUNY, TUFTS, VAND)
ALPER	80	PL 94B 422	+Becker+	(AMST, CERN, CRAC, MPIM, OXF+)
ROZANSKA	80	NP B162 505	+Blum, Dietl, Grayer, Lorenz+	(MPIM, CERN)
CORDEN	79	NP B157 250	+Dowell, Garvey+	(BIRM, RHEL, TELA, LOWC) JP
EVANGELISTA	79B	NP B154 381	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
ANTIPOV	77	NP B119 45	+Busnello, Damgaard, Kienzle+	(SERP, GEVA)
APEL	75	PL 57B 398	+Augenstein+	(KARLK, KARLE, PISA, SERP, WIEN, CERN) JP
BLUM	75	PL 57B 403	+Chabaud, Dietl, Garelick, Grayer+	(CERN, MPIM) JP

OTHER RELATED PAPERS

CASON	83	PR D28 1586	+Cannata, Baumbaugh, Bishop+	(NDAM, ANL)
GOTTESMAN	80	PR D22 1503	+Jacobs+	(SYRA, BRAN, BNL, CINC)
WAGNER	74	London Conf. 2 27		(MPIM)

$\pi_2(2100)$

$I^G(J^{PC}) = 1^-(2^{-+})$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$\pi_2(2100)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2090± 29 OUR AVERAGE				
2090± 30	[1] AMELIN	95B	VES	36 $\pi^- A \to \pi^+\pi^-\pi^- A$
2100±150	[2] DAUM	81B	CNTR	63,94 $\pi^- p \to 3\pi X$

[1] From a fit to $J^{PC} = 2^{-+}$ $f_2(1270)\pi$, $(\pi\pi)_S\pi$ waves.
[2] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(2100)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
625± 50 OUR AVERAGE Error includes scale factor of 1.2.				
520±100	[3] AMELIN	95B	VES	36 $\pi^- A \to \pi^+\pi^-\pi^- A$
651± 50	[4] DAUM	81B	CNTR	63,94 $\pi^- p \to 3\pi X$

[3] From a fit to $J^{PC} = 2^{-+}$ $f_2(1270)\pi$, $(\pi\pi)_S\pi$ waves.
[4] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(2100)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	3π	seen
Γ_2	$\rho\pi$	seen
Γ_3	$f_2(1270)\pi$	seen
Γ_4	$(\pi\pi)_S\pi$	seen

$\pi_2(2100)$ BRANCHING RATIOS

$\Gamma(\rho\pi)/\Gamma(3\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.19±0.05	[5] DAUM	81B	CNTR	63,94 $\pi^- p$

$\Gamma(f_2(1270)\pi)/\Gamma(3\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.36±0.09	[5] DAUM	81B	CNTR	63,94 $\pi^- p$

$\Gamma((\pi\pi)_S\pi)/\Gamma(3\pi)$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.45±0.07	[5] DAUM	81B	CNTR	63,94 $\pi^- p$

D-wave/S-wave RATIO FOR $\pi_2(2100) \to f_2(1270)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
0.39±0.23	[5] DAUM	81B	CNTR	63,94 $\pi^- p$

[5] From a two-resonance fit to four 2^-0^+ waves.

$\pi_2(2100)$ REFERENCES

AMELIN	95B	PL B356 595	+Berdnikov, Bityukov+	(SERP, TBIL)
DAUM	81B	NP B182 269	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)

$f_2(2150)$

$I^G(J^{PC}) = 0^+(2^{++})$

OMITTED FROM SUMMARY TABLE
This entry was previously called T_0.

$f_2(2150)$ MASS

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2226	HASAN	94	RVUE	$\overline{p}p \to \pi\pi$
~ 2170	[1] MARTIN	80B	RVUE	
~ 2150	[1] MARTIN	80C	RVUE	
~ 2150	[2] DULUDE	78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$

[1] $I(J^P) = 0(2^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I^G(J^P) = 0^+(2^+)$ from partial-wave amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2190	[3] CUTTS	78B	CNTR		0.97–3 $\overline{p}p \to \overline{N}N$
2155±15	[3,4] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
2193± 2	[3,5] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel

[3] Isospins 0 and 1 not separated.
[4] From a fit to the total elastic cross section.
[5] Referred to as T or T region by ALSPECTOR 73.

$\eta\eta$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2175±20	PROKOSHKIN	95D	GAM4	300 $\pi^- N \to \pi^- N 2\eta$, 450 $pp \to pp 2\eta$
2130±35	SINGOVSKI	94	GAM4	450 $pp \to pp 2\eta$
2104±20	ARMSTRONG	93C	SPEC	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$

$f_2(2150)$ WIDTH

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
250 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 226	HASAN	94	RVUE	$\overline{p}p \to \pi\pi$
~ 250	[6] MARTIN	80B	RVUE	
~ 250	[6] MARTIN	80C	RVUE	
~ 250	[7] DULUDE	78B	OSPK	1–2 $\overline{p}p \to \pi^0\pi^0$

[6] $I(J^P) = 0(2^+)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[7] $I^G(J^P) = 0^+(2^+)$ from partial-wave amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135±75	[8,9] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
98± 8	[9] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel

[8] From a fit to the total elastic cross section.
[9] Isospins 0 and 1 not separated.

$\eta\eta$ MODE

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
150±35	PROKOSHKIN	95D	GAM4	300 $\pi^- N \to \pi^- N 2\eta$, 450 $pp \to pp 2\eta$
130±30	SINGOVSKI	94	GAM4	450 $pp \to pp 2\eta$
203±10	ARMSTRONG	93C	SPEC	$\overline{p}p \to \pi^0\eta\eta \to 6\gamma$

f_2(2150) DECAY MODES

	Mode
Γ_1	$\pi\pi$
Γ_2	$\eta\eta$
Γ_3	$K\overline{K}$

f_2(2150) BRANCHING RATIOS

$\Gamma(K\overline{K})/\Gamma(\eta\eta)$ — Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.1	95	[10] PROKOSHKIN 95D	GAM4	300 $\pi^- N \to \pi^- N 2\eta$, 450 $pp \to pp2\eta$

[10] Using data from ARMSTRONG 89D.

$\Gamma(\pi\pi)/\Gamma(\eta\eta)$ — Γ_1/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.33	95	[11] PROKOSHKIN 95D	GAM4	300 $\pi^- N \to \pi^- N 2\eta$, 450 $pp \to pp2\eta$

[11] Derived from a $\pi^0\pi^0/\eta\eta$ limit.

f_2(2150) REFERENCES

PROKOSHKIN	95D	SPD 40 495 Translated from DANS 344 469.		(SERP) IGJPC
HASAN	94	PL B334 215	+Bugg	(LOQM)
SINGOVSKI	94	NC 107 1911		(SERP)
ARMSTRONG	93C	PL B307 394	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
ARMSTRONG	89D	PL B227 186	+Benayoun	(ATHU, BARI, BIRM, CERN, CDEF)
MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
DULUDE	78B	PL 79B 335	+Lanou, Massimo, Peaslee+	(BROW, MIT, BARI) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)

OTHER RELATED PAPERS

FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)

$\rho(2150)$

$I^G(J^{PC}) = 1^+(1^{--})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $T_1(2190)$.

ρ(2150) MASS

$e^+e^- \to \pi^+\pi^-, K^+K^-, 6\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2149±17 OUR AVERAGE Includes data from the datablock that follows this one.				
2153±37	BIAGINI 91	RVUE		$e^+e^- \to \pi^+\pi^-, K^+K^-$
2110±50	[1] CLEGG 90	RVUE	0	$e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0)$

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 2191	HASAN 94	RVUE	$\overline{p}p \to \pi\pi$
~ 1988	HASAN 94	RVUE	$\overline{p}p \to \pi\pi$
~ 2170	[2] MARTIN 80B	RVUE	
~ 2100	[2] MARTIN 80C	RVUE	

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2190	[3] CUTTS 78B	CNTR		0.97–3 $\overline{p}p \to \overline{N}N$
2155±15	[3,4] COUPLAND 77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
2193± 2	[3,5] ALSPECTOR 73	CNTR		$\overline{p}p$ S channel
2190±10	[6] ABRAMS 70	CNTR		S channel $\overline{p}N$

$\pi^-p \to \omega\pi^0 n$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
2155±21 OUR AVERAGE			
2140±30	ALDE 95	GAM2	38 $\pi^-p \to \omega\pi^0 n$
2170±30	ALDE 92C	GAM4	100 $\pi^-p \to \omega\pi^0 n$

[1] Includes ATKINSON 85.
[2] $I(J^P) = 1(1^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[3] Isospins 0 and 1 not separated.
[4] From a fit to the total elastic cross section.
[5] Referred to as T or $\overline{T}$ region by ALSPECTOR 73.
[6] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

ρ(2150) WIDTH

$e^+e^- \to \pi^+\pi^-, K^+K^-, 6\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
363± 50 OUR AVERAGE Includes data from the datablock that follows this one.				
389± 79	BIAGINI 91	RVUE		$e^+e^- \to \pi^+\pi^-, K^+K^-$
410±100	[7] CLEGG 90	RVUE	0	$e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0)$

$\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 296	HASAN 94	RVUE	$\overline{p}p \to \pi\pi$
~ 244	HASAN 94	RVUE	$\overline{p}p \to \pi\pi$
~ 250	[8] MARTIN 80B	RVUE	
~ 200	[8] MARTIN 80C	RVUE	

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
135±75	[9,10] COUPLAND 77	CNTR	0	0.7–2.4 $\overline{p}p \to \overline{p}p$
98± 8	[10] ALSPECTOR 73	CNTR		$\overline{p}p$ S channel
~ 85	[11] ABRAMS 70	CNTR		S channel $\overline{p}N$

$\pi^-p \to \omega\pi^0 n$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
320±70	ALDE 95	GAM2	38 $\pi^-p \to \omega\pi^0 n$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 300	ALDE 92C	GAM4	100 $\pi^-p \to \omega\pi^0 n$

[7] Includes ATKINSON 85.
[8] $I(J^P) = 1(1^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[9] From a fit to the total elastic cross section.
[10] Isospins 0 and 1 not separated.
[11] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

ρ(2150) REFERENCES

ALDE	95	ZPHY C66 379	+Binon, Bricman+	(GAMS Collab.) JP
HASAN	94	PL B334 215	+Bugg	(LOQM)
ALDE	92C	ZPHY C54 553	+Bencheikh, Binon+	(BELG, SERP, KEK, LANL, LAPP)
BIAGINI	91	NC 104A 363	+Dubnicka+	(FRAS, PRAG)
CLEGG	90	ZPHY C45 677	+Donnachie	(LANC, MCHS)
ATKINSON	85	ZPHY C29 333	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
PEASLEE	75	PL 57B 189	+Demarzo, Guerriero+	(CANB, BARI, BROW, MIT)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)
COOPER	68	PRL 20 1059	+Hyman, Manner, Musgrave+	(ANL)

OTHER RELATED PAPERS

BRICMAN	69	PL 29B 451	+Ferro-Luzzi, Bizard+	(CERN, CAEN, SACL)
ABRAMS	67C	PRL 18 1209	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

$f_0(2200)$

$I^G(J^{PC}) = 0^+(0^{++})$

OMITTED FROM SUMMARY TABLE

Seen at DCI in the $K^0_S K^0_S$ system. Not seen in Υ radiative decays (BARU 89). Needs confirmation.

f_0(2200) MASS

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2197±17	[1] AUGUSTIN 88	DM2	0	$J/\psi \to \gamma K^0_S K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2122	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$
~ 2321	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$

[1] Cannot determine spin to be 0.

f_0(2200) WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
201±51	[2] AUGUSTIN 88	DM2	0	$J/\psi \to \gamma K^0_S K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 273	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$
~ 223	HASAN 94	RVUE		$\overline{p}p \to \pi\pi$

[2] Cannot determine spin to be 0.

f_0(2200) REFERENCES

HASAN	94	PL B334 215	+Bugg	(LOQM)
BARU	89	ZPHY C42 505	+Beilin, Blinov, Blinov+	(NOVO)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)

$f_J(2220)$ was $\xi(2220)$

$I^G(J^{PC}) = 0^+(2^{++}$ or $4^{++})$

OMITTED FROM SUMMARY TABLE

This state has been seen at SPEAR in the $K\overline{K}$ systems (K^+K^- and $K^0_S K^0_S$) produced in the radiative decay of $J/\psi(1S)$. Seen in $\eta\eta'$ (ALDE 86B), in $K^0_S K^0_S$ (ASTON 88D), and in K^+K^- (ASTON 88F). Not seen in Υ radiative decays (BARU 89) nor in B inclusive decay (BEHRENDS 84). Not seen in $\overline{p}p \to K^+K^-$ formation experiment (BARDIN 87,SCULLI 87) and $\overline{p}p \to K^0_S K^0_S$ formation experiment (BARNES 93). Not seen at DCI in either K^+K^- or $K^0_S K^0_S$ systems (AUGUSTIN 88). Needs confirmation.

$f_J(2220)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2225± 6 OUR AVERAGE					
$2209^{+17}_{-15}\pm10$		ASTON	88F	LASS	$11\ K^-p \to K^+K^-\Lambda$
2230±20		BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_S K^0_S n$
2220±10	41	[1] ALDE	86B	GA24	$38\text{–}100\ \pi p \to n\eta\eta'$
2230± 6±14	93	BALTRUSAIT..86D		MRK3	$e^+e^- \to \gamma K^+K^-$
2232± 7± 7	23	BALTRUSAIT..86D		MRK3	$e^+e^- \to \gamma K^0_S K^0_S$

[1] ALDE 86B uses data from both the GAMS-2000 and GAMS-4000 detectors.

$f_J(2220)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
38^{+15}_{-13} OUR AVERAGE					
60^{+107}_{-57}		ASTON	88F	LASS	$11\ K^-p \to K^+K^-\Lambda$
80± 30		BOLONKIN	88	SPEC	$40\ \pi^-p \to K^0_S K^0_S n$
$26^{+20}_{-16}\pm17$	93	BALTRUSAIT..86D		MRK3	$e^+e^- \to \gamma K^+K^-$
$18^{+23}_{-15}\pm10$	23	BALTRUSAIT..86D		MRK3	$e^+e^- \to \gamma K^0_S K^0_S$

$f_J(2220)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K\overline{K}$		
Γ_2	$p\overline{p}$	$<1.1\times10^{-3}$	99.7%
Γ_3	$\gamma\gamma$		
Γ_4	$\eta\eta'(958)$		

$f_J(2220)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}) \times \Gamma(\gamma\gamma)/\Gamma_{total}$ $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
<0.086	95	[2] ALBRECHT	90G	ARG	$\gamma\gamma \to K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.0	95	[3] ALTHOFF	85B	TASS	$\gamma\gamma,\ K\overline{K}\pi$

[2] Assuming $J^P = 2^+$.
[3] True for $J^P = 0^+$ and $J^P = 2^+$.

$f_J(2220)$ BRANCHING RATIOS

$\Gamma(p\overline{p})/\Gamma_{total}$ Γ_2/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.1	99.7	[4] BARNES	93	SPEC	$1.3\text{-}1.57\overline{p}p \to K^0_S K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.6	99.7	[4] BARDIN	87	CNTR	$1.3\text{-}1.5\overline{p}p \to K^+K^-$
<3.6	99.7	[4] SCULLI	87	CNTR	$1.29\text{-}1.55\overline{p}p \to K^+K^-$

[4] Assuming Γ = 30-35 MeV, $J^P = 2^+$ and B($f_J(2220) \to K\overline{K}$) = 10%.

$f_J(2220)$ REFERENCES

BARNES	93	PL B309 469	+Birien, Breunlich	(PS185 Collab.)
ALBRECHT	90G	ZPHY C48 183	+Ehrlichmann, Harder+	(ARGUS Collab.)
BARU	89	ZPHY C42 505	+Beilin, Blinov, Blinov+	(NOVO)
ASTON	88D	NP B301 525	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)
ASTON	88F	PL B215 199	+Awaji+	(SLAC, NAGO, CINC, INUS) JP
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)
BOLONKIN	88	NP B309 426	+Bloshenko, Gorin+	(ITEP, SERP)
BARDIN	87	PL B195 292	+Burgun+	(SACL, FERR, CERN, PADO, TORI)
SCULLI	87	PRL 58 1715	+Christenson, Kreiter, Nemethy, Yamin	(NYU, BNL)
ALDE	86B	PL B177 120	+Binon, Bricman+	(SERP, BELG, LANL, LAPP)
BALTRUSAIT...	86D	PRL 56 107	Baltrusaitis	(CIT, UCSC, ILL, SLAC, WASH)
ALTHOFF	85B	ZPHY C29 189	+Braunschweig, Kirschfink+	(TASSO Collab.)
BEHRENDS	84	PL 137B 277	+Chadwich, Chauveau, Gentile+	(CLEO Collab.)

OTHER RELATED PAPERS

BARDIN	87	PL B195 292	+Burgun+	(SACL, FERR, CERN, PADO, TORI)
YAOUANC	85	ZPHY C28 309	+Oliver, Pene, Raynal, Ono	(ORSAY, TOKY)
GODFREY	84	PL 141B 439	+Kokoski, Isgur	(TNTO)
SHATZ	84	PL 138B 209		(CIT)
WILLEY	84	PRL 52 585		(PITT)
EINSWEILER	83	Brighton Conf. 348		(Mark III Collab.)
HITLIN	83	Cornell Conf. 746		(CIT)

$\eta(2225)$

$I^G(J^{PC}) = 0^+(0^{-+})$

OMITTED FROM SUMMARY TABLE

Seen in $J/\psi \to \gamma\phi\phi$. Needs confirmation.

$\eta(2225)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2230±25±15	BAI	90B	MRK3	$J/\psi \to \gamma K^+K^-K^+K^-$
2214±20±13	BAI	90B	MRK3	$J/\psi \to \gamma K^+K^-K^0_S K^0_L$
~ 2220	BISELLO	86B	DM2	$J/\psi \to \gamma K^+K^-K^+K^-$

$\eta(2225)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$150^{+300}_{-60}\pm60$	BAI	90B	MRK3	$J/\psi \to \gamma K^+K^-K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 80	BISELLO	86B	DM2	$J/\psi \to \gamma K^+K^-K^+K^-$

$\eta(2225)$ REFERENCES

BAI	90B	PRL 65 1309	+Blaylock+	(Mark III Collab.)
BISELLO	86B	PL B179 294	+Busetto, Castro, Limentani+	(DM2 Collab.)

$\rho_3(2250)$

$I^G(J^{PC}) = 1^+(3^{--})$

OMITTED FROM SUMMARY TABLE

Contains results only from formation experiments. For production experiments see the $\overline{N}N(1100\text{–}3600)$ entry. See also $\rho(2150)$, $f_2(2150)$, $f_4(2300)$, $\rho_5(2350)$.

$\rho_3(2250)$ MASS

$\overline{p}p \to \pi\pi$ or $K\overline{K}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2232	HASAN	94	RVUE		$\overline{p}p \to \pi\pi$
~ 2007	HASAN	94	RVUE		$\overline{p}p \to \pi\pi$
~ 2250	[1] MARTIN	80B	RVUE		
~ 2300	[1] MARTIN	80C	RVUE		
~ 2140	[2] CARTER	78B	CNTR	0	$0.7\text{–}2.4\ \overline{p}p \to K^-K^+$
~ 2150	[3] CARTER	77	CNTR	0	$0.7\text{–}2.4\ \overline{p}p \to \pi\pi$

[1] $I(J^P) = 1(3^-)$ from simultaneous analysis of $p\overline{p} \to \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I = 0, 1$. $J^P = 3^-$ from Barrelet-zero analysis.
[3] $I(J^P) = 1(3^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2190	[4] CUTTS	78B	CNTR		$0.97\text{–}3\ \overline{p}p \to \overline{N}N$
2155±15	[4,5] COUPLAND	77	CNTR	0	$0.7\text{–}2.4\ \overline{p}p \to \overline{p}p$
2193± 2	[4,6] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
2190±10	[7] ABRAMS	70	CNTR		S channel $\overline{p}N$

[4] Isospins 0 and 1 not separated.
[5] From a fit to the total elastic cross section.
[6] Referred to as T or T region by ALSPECTOR 73.
[7] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho_3(2250)$ WIDTH

$\overline{p}p \rightarrow \pi\pi$ or $K\overline{K}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 220	HASAN	94	RVUE		$\overline{p}p \rightarrow \pi\pi$
~ 287	HASAN	94	RVUE		$\overline{p}p \rightarrow \pi\pi$
~ 250	[8] MARTIN	80B	RVUE		
~ 200	[8] MARTIN	80C	RVUE		
~ 150	[9] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow K^-K^+$
~ 200	[10] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

[8] $I(J^P) = 1(3^-)$ from simultaneous analysis of $p\overline{p} \rightarrow \pi^-\pi^+$ and $\pi^0\pi^0$.
[9] $I = 0, 1$. $J^P = 3^-$ from Barrelet-zero analysis.
[10] $I(J^P) = 1(3^-)$ from amplitude analysis.

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135±75	[11,12] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \overline{p}p$
98± 8	[12] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
~ 85	[13] ABRAMS	70	CNTR		S channel $\overline{p}N$

[11] From a fit to the total elastic cross section.
[12] Isospins 0 and 1 not separated.
[13] Seen as bump in $I = 1$ state. See also COOPER 68. PEASLEE 75 confirm $\overline{p}p$ results of ABRAMS 70, no narrow structure.

$\rho_3(2250)$ REFERENCES

HASAN	94	PL B334 215	+Bugg	(LOQM)
MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CARTER	78B	NP B141 467		(LOQM)
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
PEASLEE	75	PL 57B 189	+Demarzo, Guerriero+	(CANB, BARI, BROW, MIT)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)
COOPER	68	PRL 20 1059	+Hyman, Manner, Musgrave+	(ANL)

— OTHER RELATED PAPERS —

MARTIN	79B	PL 86B 93	+Pennington	(DURH)
CARTER	78	NP B132 176		(LOQM) JP
CARTER	77B	PL 67B 122		(LOQM) JP
CARTER	77C	NP B127 202	+Coupland, Atkinson+	(LOQM, DARE, RHEL)
MONTANET	77	Boston Conf. 260		(CERN)
ZEMANY	76	NP B103 537	+MingMa, Mountz, Smith	(MSU)
BERTANZA	74	NC 23A 209	+Bigi, Casali, Lariccia+	(PISA, PADO, TORI)
BETTINI	73	NC 15A 563	+Alston-Garnjost, Bigi+	(PADO, LBL, PISA, TORI)
DONNACHIE	73	LNC 7 285	+Thomas	(MCHS)
NICHOLSON	73	PR D7 2572	+Delorme, Carroll+	(CIT, ROCH, BNL)
FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
ABRAMS	67C	PRL 18 1209	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

$f_2(2300)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2300)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2297±28	[1] ETKIN	88	MPS	22 $\pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2231±10	BOOTH	86	OMEG	85 π^- Be $\rightarrow 2\phi$Be
2220^{+90}_{-20}	LINDENBAUM	84	RVUE	
2320±40	ETKIN	82	MPS	22 $\pi^- p \rightarrow 2\phi n$

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi$ 2^{++} S_2, D_2, and D_0 is 6^{+15}_{-5}, 25^{+18}_{-14}, and 69^{+16}_{-27}, respectively.

$f_2(2300)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
149±41	[2] ETKIN	88	MPS	22 $\pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
133±50	BOOTH	86	OMEG	85 π^- Be $\rightarrow 2\phi$Be
200±50	LINDENBAUM	84	RVUE	
220±70	ETKIN	82	MPS	22 $\pi^- p \rightarrow 2\phi n$

[2] Includes data of ETKIN 85.

$f_2(2300)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2300)$ REFERENCES

ETKIN	88	PL B201 568	+Foley, Lindenbaum+	(BNL, CUNY)
BOOTH	86	NP B273 677	+Carroll, Donald, Edwards+	(LIVP, GLAS, CERN)
ETKIN	85	PL 165B 217	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
LINDENBAUM	84	CNPP 13 285		(CUNY)
ETKIN	82	PRL 49 1620	+Foley, Longacre, Lindenbaum+	(BNL, CUNY)
Also	83	Brighton Conf. 351	Lindenbaum	(BNL, CUNY)

— OTHER RELATED PAPERS —

ARMSTRONG	89B	PL B221 221	+Benayoun+	(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFTS, VAND+)
BOOTH	84	NP B242 51	+Ballance, Carroll, Donald+	(LIVP, GLAS, CERN)

$f_4(2300)$

$I^G(J^{PC}) = 0^+(4^{++})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $U_0(2350)$. Contains results only from formation experiments. For production experiments see the $\overline{N}N(1100\text{–}3600)$ entry. See also $\rho(2150)$, $f_2(2150)$, $\rho_3(2250)$, $\rho_5(2350)$.

$f_4(2300)$ MASS

$\overline{p}p \rightarrow \pi\pi$ or $\overline{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2314	HASAN	94	RVUE	$\overline{p}p \rightarrow \pi\pi$
~ 2300	[1] MARTIN	80B	RVUE	
~ 2300	[1] MARTIN	80C	RVUE	
~ 2340	[2] CARTER	78B	CNTR	0.7–2.4 $\overline{p}p \rightarrow K^-K^+$
~ 2330	DULUDE	78B	OSPK	1–2 $\overline{p}p \rightarrow \pi^0\pi^0$
~ 2310	[3] CARTER	77	CNTR	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

[1] $I(J^P) = 0(4^+)$ from simultaneous analysis of $p\overline{p} \rightarrow \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I(J^P) = 0(4^+)$ from Barrelet-zero analysis.
[3] $I(J^P) = 0(4^+)$ from amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 2380	[4] CUTTS	78B	CNTR	0.97–3 $\overline{p}p \rightarrow \overline{N}N$
2345±15	[4,5] COUPLAND	77	CNTR	0.7–2.4 $\overline{p}p \rightarrow \overline{p}p$
2359± 2	[4,6] ALSPECTOR	73	CNTR	$\overline{p}p$ S channel
2375±10	ABRAMS	70	CNTR	S channel $\overline{N}N$

[4] Isospins 0 and 1 not separated.
[5] From a fit to the total elastic cross section.
[6] Referred to as U or U region by ALSPECTOR 73.

$f_4(2300)$ WIDTH

$\overline{p}p \rightarrow \pi\pi$ or $\overline{K}K$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 278	HASAN	94	RVUE	$\overline{p}p \rightarrow \pi\pi$
~ 200	[7] MARTIN	80C	RVUE	
~ 150	[8] CARTER	78B	CNTR	0.7–2.4 $\overline{p}p \rightarrow K^-K^+$
~ 210	[9] CARTER	77	CNTR	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

[7] $I(J^P) = 0(4^+)$ from simultaneous analysis of $p\overline{p} \rightarrow \pi^-\pi^+$ and $\pi^0\pi^0$.
[8] $I(J^P) = 0(4^+)$ from Barrelet-zero analysis.
[9] $I(J^P) = 0(4^+)$ from amplitude analysis.

S-CHANNEL $\overline{p}p$ or $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
135^{+150}_{-65}	[10,11] COUPLAND	77	CNTR	0.7–2.4 $\overline{p}p \rightarrow \overline{p}p$
165^{+18}_{-8}	[11] ALSPECTOR	73	CNTR	$\overline{p}p$ S channel
~ 190	ABRAMS	70	CNTR	S channel $\overline{N}N$

[10] From a fit to the total elastic cross section.
[11] Isospins 0 and 1 not separated.

$f_4(2300)$ REFERENCES

HASAN	94	PL B334 215	+Bugg	(LOQM)
MARTIN	80B	NP B176 355	+Morgan	(LOUC, RHEL) JP
MARTIN	80C	NP B169 216	+Pennington	(DURH) JP
CARTER	78B	NP B141 467		(LOQM)
CUTTS	78B	PR D17 16	+Good, Grannis, Green, Lee+	(STON, WISC)
DULUDE	78B	PL 79B 335	+Lanou, Massimo, Peaslee+	(BROW, MIT, BARI) JP
CARTER	77	PL 67B 117	+Coupland, Eisenhandler, Astbury+	(LOQM, RHEL) JP
COUPLAND	77	PL 71B 460	+Eisenhandler, Gibson, Astbury+	(LOQM, RHEL)
ALSPECTOR	73	PRL 30 511	+Cohen, Cvijanovich+	(RUTG, UPNJ)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL)

— OTHER RELATED PAPERS —

FIELDS	71	PRL 27 1749	+Cooper, Rhines, Allison	(ANL, OXF)
YOH	71	PRL 26 922	+Barish, Caroll, Lobkowicz+	(CIT, BNL, ROCH)
BRICMAN	69	PL 29B 451	+Ferro-Luzzi, Bizard+	(CERN, CAEN, SACL)

$f_2(2340)$

$I^G(J^{PC}) = 0^+(2^{++})$

See also the mini-review under non-$q\overline{q}$ candidates. (See the index for the page number.)

$f_2(2340)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2339±55	[1] ETKIN	88	MPS	$22\ \pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2392±10	BOOTH	86	OMEG	$85\ \pi^-\text{Be} \rightarrow 2\phi\text{Be}$
2360±20	LINDENBAUM	84	RVUE	

[1] Includes data of ETKIN 85. The percentage of the resonance going into $\phi\phi$ 2^{++} S_2, D_2, and D_0 is 37 ± 19, 4^{+12}_{-4}, and 59^{+21}_{-19}, respectively.

$f_2(2340)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$\mathbf{319^{+81}_{-69}}$	[2] ETKIN	88	MPS	$22\ \pi^- p \rightarrow \phi\phi n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
198± 50	BOOTH	86	OMEG	$85\ \pi^-\text{Be} \rightarrow 2\phi\text{Be}$
150^{+150}_{-50}	LINDENBAUM	84	RVUE	

[2] Includes data of ETKIN 85.

$f_2(2340)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\phi\phi$	seen

$f_2(2340)$ REFERENCES

ETKIN 88 PL B201 568 +Foley, Lindenbaum+ (BNL, CUNY)
BOOTH 86 NP B273 677 +Carroll, Donald, Edwards+ (LIVP, GLAS, CERN)
ETKIN 85 PL 165B 217 +Foley, Longacre, Lindenbaum+ (BNL, CUNY)
LINDENBAUM 84 CNPP 13 285 (CUNY)

OTHER RELATED PAPERS

ARMSTRONG 89B PL B221 221 +Benayoun+(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
GREEN 86 PRL 56 1639 +Lai+ (FNAL, ARIZ, FSU, NDAM, TUFTS, VAND+)
BOOTH 84 NP B242 51 +Ballance, Carroll, Donald+ (LIVP, GLAS, CERN)

$\rho_5(2350)$

$I^G(J^{PC}) = 1^+(5^{--})$

OMITTED FROM SUMMARY TABLE

This entry was previously called $U_1(2400)$. See also the $\overline{N}N(1100\text{–}3600)$ and $X(1900\text{–}3600)$ entries. See also $\rho(2150)$, $f_2(2150)$, $\rho_3(2250)$, $f_4(2300)$.

$\rho_5(2350)$ MASS

$\pi^- p \rightarrow \omega\pi^0 n$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2330±35	ALDE	95	GAM2	$38\ \pi^- p \rightarrow \omega\pi^0 n$

$\overline{p}p \rightarrow \pi\pi$ or $K\overline{K}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2303	HASAN	94	RVUE		$\overline{p}p \rightarrow \pi\pi$
~ 2300	[1] MARTIN	80B	RVUE		
~ 2250	[1] MARTIN	80C	RVUE		
~ 2500	[2] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow K^-K^+$
~ 2480	[3] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2380	[4] CUTTS	78B	CNTR		0.97–3 $\overline{p}p \rightarrow \overline{N}N$
2345±15	[4,5] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \overline{p}p$
2359± 2	[4,6] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
2350±10	[7] ABRAMS	70	CNTR		S channel $\overline{N}N$
2360±25	[8] OH	70B	HDBC	−0	$\overline{p}(pn)$, $K^*K2\pi$

[1] $I(J^P) = 1(5^-)$ from simultaneous analysis of $p\overline{p} \rightarrow \pi^-\pi^+$ and $\pi^0\pi^0$.
[2] $I = 0(1)$; $J^P = 5^-$ from Barrelet-zero analysis.
[3] $I(J^P) = 1(5^-)$ from amplitude analysis.
[4] Isospins 0 and 1 not separated.
[5] From a fit to the total elastic cross section.
[6] Referred to as U or U region by ALSPECTOR 73.
[7] For $I = 1$ $\overline{N}N$.
[8] No evidence for this bump seen in the $\overline{p}p$ data of CHAPMAN 71B. Narrow state not confirmed by OH 73 with more data.

$\rho_5(2350)$ WIDTH

$\pi^- p \rightarrow \omega\pi^0 n$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
400±100	ALDE	95	GAM2	$38\ \pi^- p \rightarrow \omega\pi^0 n$

$\overline{p}p \rightarrow \pi\pi$ or $K\overline{K}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 169	HASAN	94	RVUE		$\overline{p}p \rightarrow \pi\pi$
~ 250	[9] MARTIN	80B	RVUE		
~ 300	[9] MARTIN	80C	RVUE		
~ 150	[10] CARTER	78B	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow K^-K^+$
~ 210	[11] CARTER	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \pi\pi$

S-CHANNEL $\overline{N}N$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
135^{+150}_{-65}	[12,13] COUPLAND	77	CNTR	0	0.7–2.4 $\overline{p}p \rightarrow \overline{p}p$
165^{+18}_{-8}	[13] ALSPECTOR	73	CNTR		$\overline{p}p$ S channel
< 60	[14] OH	70B	HDBC	−0	$\overline{p}(pn)$, $K^*K2\pi$
~ 140	ABRAMS	67C	CNTR		S channel $\overline{p}N$

[9] $I(J^P) = 1(5^-)$ from simultaneous analysis of $p\overline{p} \rightarrow \pi^-\pi^+$ and $\pi^0\pi^0$.
[10] $I = 0(1)$; $J^P = 5^-$ from Barrelet-zero analysis.
[11] $I(J^P) = 1(5^-)$ from amplitude analysis.
[12] From a fit to the total elastic cross section.
[13] Isospins 0 and 1 not separated.
[14] No evidence for this bump seen in the $\overline{p}p$ data of CHAPMAN 71B. Narrow state not confirmed by OH 73 with more data.

$\rho_5(2350)$ REFERENCES

ALDE 95 ZPHY C66 379 +Binon, Bricman+ (GAMS Collab.) JP
HASAN 94 PL B334 215 +Bugg (LOQM)
MARTIN 80B NP B176 355 +Morgan (LOUC, RHEL) JP
MARTIN 80C NP B169 216 +Pennington (DURH) JP
CARTER 78B NP B141 467 (LOQM)
CUTTS 78B PR D17 16 +Good, Grannis, Green, Lee+ (STON, WISC)
CARTER 77 PL 67B 117 +Coupland, Eisenhandler, Astbury+ (LOQM, RHEL) JP
COUPLAND 77 PL 71B 460 +Eisenhandler, Gibson, Astbury+ (LOQM, RHEL)
ALSPECTOR 73 PRL 30 511 +Cohen, Cvijanovich+ (RUTG, UPNJ)
OH 73 NP B51 57 +Eastman, MingMa, Parker, Smith+ (MSU)
CHAPMAN 71B PR D4 1275 +Green, Lys, Murphy, Ring+ (MICH)
ABRAMS 70 PR D1 1917 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL)
OH 70B PRL 24 1257 +Parker, Eastman, Smith, Sprafka, Ma (MSU)
ABRAMS 67C PRL 18 1209 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL)

OTHER RELATED PAPERS

CASO 70 LNC 3 707 +Conte, Tomasini+ (GENO, HAMB, MILA, SACL)
BRICMAN 69 PL 29B 451 +Ferro-Luzzi, Bizard+ (CERN, CAEN, SACL)

$a_6(2450)$

$I^G(J^{PC}) = 1^-(6^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$a_6(2450)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2450±130	[1] CLELAND	82B	SPEC	±	$50\ \pi p \rightarrow K^0_S K^\pm p$

[1] From an amplitude analysis.

$a_6(2450)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
400±250	[2] CLELAND	82B	SPEC	±	$50\ \pi p \rightarrow K^0_S K^\pm p$

[2] From an amplitude analysis.

$a_6(2450)$ DECAY MODES

	Mode
Γ_1	$K\overline{K}$

$a_6(2450)$ REFERENCES

CLELAND 82B NP B208 228 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)

$f_6(2510)$

$I^G(J^{PC}) = 0^+(6^{++})$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$f_6(2510)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2510±30	BINON	84B	GAM2	38 $\pi^- p \to n 2\pi^0$

$f_6(2510)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
240±60	BINON	84B	GAM2	23 $\pi^- p \to n 2\pi^0$

$f_6(2510)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	(6.0±1.0) %

$f_6(2510)$ BRANCHING RATIOS

$\Gamma(\pi\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06 ±0.01	[1] BINON	83C	GAM2	38 $\pi^- p \to n 4\gamma$

[1] Assuming one pion exchange and using data of BOLOTOV 74.

$f_6(2510)$ REFERENCES

BINON 84B LNC 39 41 +Donskov, Duteil, Gouanere+ (SERP, BELG, LAPP) JP
BINON 83C SJNP 38 723 +Gouanere, Donskov, Duteil+ (SERP, BRUX+)
Translated from YAF 38 1199.
BOLOTOV 74 PL 52B 489 +Isakov, Kakauridze, Khaustov+ (SERP)

$X(3250)$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE
Narrow peak observed in several final states with hidden strangeness ($\Lambda\overline{p}K^+$, $\Lambda\overline{p}K^+\pi^\pm$, $K^0 p\overline{p}K^\pm$). Needs confirmation. See also under non-$q\overline{q}$ candidates. (See the index for the page number.)

$X(3250)$ MASS

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3250±8±20	[1] ALEEV	93	BIS2	$X(3250) \to \Lambda\overline{p}K^+$
3265±7±20	[1] ALEEV	93	BIS2	$X(3250) \to \overline{\Lambda}pK^-$

[1] Supersedes KEKELIDZE 90.

4-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3245±8±20	[1] ALEEV	93	BIS2	$X(3250) \to \Lambda\overline{p}K^+\pi^\pm$
3250±9±20	[1] ALEEV	93	BIS2	$X(3250) \to \overline{\Lambda}pK^-\pi^\mp$
3270±8±20	[1] ALEEV	93	BIS2	$X(3250) \to K^0_S p\overline{p}K^\pm$

$X(3250)$ WIDTH

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
45±18	[2] ALEEV	93	BIS2	$X(3250) \to \Lambda\overline{p}K^+$
40±18	[2] ALEEV	93	BIS2	$X(3250) \to \overline{\Lambda}pK^-$

[2] Supersedes KEKELIDZE 90.

4-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
25±11	[2] ALEEV	93	BIS2	$X(3250) \to \Lambda\overline{p}K^+\pi^\pm$
50±20	[2] ALEEV	93	BIS2	$X(3250) \to \overline{\Lambda}pK^-\pi^\mp$
25±11	[2] ALEEV	93	BIS2	$X(3250) \to K^0_S p\overline{p}K^\pm$

$X(3250)$ DECAY MODES

	Mode
Γ_1	$\Lambda\overline{p}K^+$
Γ_2	$\Lambda\overline{p}K^+\pi^\pm$
Γ_3	$K^0 p\overline{p}K^\pm$

$X(3250)$ REFERENCES

ALEEV 93 PAN 56 1358 +Balandin+ (BIS-2 Collab.)
Translated from YAF 56 100.
KEKELIDZE 90 Hadron 89 Conf. p 551+Aleev+ (BIS-2 Collab.)

OTHER LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

$e^+e^-(1100–2200)$

$I^G(J^{PC}) = ?^?(1^{--})$

OMITTED FROM SUMMARY TABLE

This entry contains unflavored vector mesons coupled to e^+e^- (photon) between the ϕ and $J/\psi(1S)$ mass regions. See also $\omega(1420)$, $\rho(1450)$, $\omega(1600)$, $\phi(1680)$, and $\rho(1700)$.

$e^+e^-(1100–2200)$ MASSES AND WIDTHS

We do not use the following data for averages, fits, limits, etc.

VALUE (MeV)	DOCUMENT ID
1100 to 2200 OUR LIMIT	

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$1097.0^{+16.0}_{-19.0}$	BARTALUCCI	79	OSPK	$7\ \gamma p \to e^+e^-p$
$31.0^{+24.0}_{-20.0}$	BARTALUCCI	79	OSPK	$7\ \gamma p \to e^+e^-p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1266.0 ± 5.0	BARTALUCCI	79	DASP	0	$7\ \gamma p \to e^+e^-p$
110.0 ± 35.0	BARTALUCCI	79	DASP	0	$7\ \gamma p \to e^+e^-p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 1830.0	PETERSON	78	SPEC	$\gamma p \to K^+K^-p$
~ 120.0	PETERSON	78	SPEC	$\gamma p \to K^+K^-p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 1820	[1] SPINETTI	79	RVUE	$e^+e^- \to 4\pi^\pm 2\gamma$
~ 30	[1] SPINETTI	79	RVUE	$e^+e^- \to 4\pi^\pm 2\gamma$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1870 ± 10	ANTONELLI	96	SPEC	$e^+e^- \to$ hadrons
10 ± 5	ANTONELLI	96	SPEC	$e^+e^- \to$ hadrons

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
~ 2130	[2] ESPOSITO	78	FRAM	$e^+e^- \to K^*(892)^+ \ldots$
~ 30	[2] ESPOSITO	78	FRAM	$e^+e^- \to K^*(892)^+ \ldots$

[1] Integrated cross section of BACCI 77, BARBIELLINI 77, ESPOSITO 77.
[2] Not seen by DELCOURT 79.

$e^+e^-(1100–2200)$ REFERENCES

ANTONELLI	96	PL B365 427	+Baldini, Bertani+	(FENICE Collab.)
BARTALUCCI	79	NC 49A 207	+Basini, Bertolucci+	(DESY, FRAS)
DELCOURT	79	PL 86B 395	+Derado, Bertrand, Bisello, Bizot, Buon+	(LALO)
SPINETTI	79	Batavia Conf. 506		(FRAS)
ESPOSITO	78	LNC 22 305	+Felicetti	(FRAS, NAPL, PADO, ROMA)
PETERSON	78	PR D18 3955	+Dixon, Ehrlich, Galik, Larson	(CORN, HARV)
BACCI	77	PL 68B 393	+DeZorzi, Penso, Stella, Baldini+	(ROMA, FRAS)
BARBIELLINI	77	PL 68B 397	+Barletta+	(FRAS, NAPL, PISA, SANI)
ESPOSITO	77	PL 68B 389	+Felicetti, Marini+	(FRAS, NAPL, PADO, ROMA)

OTHER RELATED PAPERS

BACCI	76	PL 64B 356	+Bidoli, Penso, Stella, Baldini+	(ROMA, FRAS)
BACCI	75	PL 58B 481	+Bidoli, Penso, Stella+	(ROMA, FRAS)

$\overline{N}N(1100–3600)$

OMITTED FROM SUMMARY TABLE

This entry contains various high mass, unflavored structures coupled to the baryon-antibaryon system, as well as quasi-nuclear bound states below threshold.

$\overline{N}N(1100–3600)$ MASSES AND WIDTHS

We do not use the following data for averages, fits, limits etc.

VALUE (MeV)	DOCUMENT ID
1100 to 3600 OUR LIMIT	

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1107 ± 4	DAFTARI	87	DBC	0	0. $\overline{p}n \to \rho^-\pi^+\pi^-$
$111 \pm 8 \pm 15$	DAFTARI	87	DBC	0	0. $\overline{p}n \to \rho^-\pi^+\pi^-$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1167 ± 7	[2] CHIBA	91	CNTR		$\overline{p}d \to \gamma X$
1191.0 ± 9.9	[2] CHIBA	87	CNTR	0	0. $\overline{p}p \to \gamma X$
1210 ± 5.0	[2,3,4,5] RICHTER	83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1325 ± 5	[2] CHIBA	91	CNTR		$\overline{p}d \to \gamma X$
1329.2 ± 7.6	[2] CHIBA	87	CNTR	0	0. $\overline{p}p \to \gamma X$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1390.9 ± 6.3	[2] CHIBA	87	CNTR	0	0. $\overline{p}p \to \gamma X$
1395	[2,4,5,6] PAVLOPO...	78	CNTR		Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
~ 1410	BETTINI	66	DBC	0	0. $\overline{p}N \to 5\pi$
~ 100	BETTINI	66	DBC	0	0. $\overline{p}N \to 5\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1468 ± 6	[7] BRIDGES	86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$
88 ± 18	[7] BRIDGES	86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1512 ± 7	[2] CHIBA	91	CNTR		$\overline{p}d \to \gamma X$
1523.8 ± 3.6	[2] CHIBA	87	CNTR	0	0. $\overline{p}p \to \gamma X$
1522 ± 7	[7] BRIDGES	86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+$
59 ± 12	[7] BRIDGES	86B	DBC	0	0. $\overline{p}N \to 2\pi^-\pi^+$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1577.8 ± 3.4	[2] CHIBA	87	CNTR	0	0. $\overline{p}p \to \gamma X$
1594 ± 9	[7] BRIDGES	86B	DBC	$-$	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$
81 ± 12	[7] BRIDGES	86B	DBC	$-$	0. $\overline{p}N \to 2\pi^-\pi^+\pi^0$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1633.6 ± 4.1	[2] CHIBA	87	CNTR	0	0. $\overline{p}p \to \gamma X$
$1637.1^{+5.6}_{-7.3}$	ADIELS	84	CNTR		$\overline{p}$He

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1638 ± 3.0	[2,3,4,5] RICHTER	83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$1644.0^{+5.6}_{-7.3}$	ADIELS	84	CNTR	$\overline{p}$He

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1646	[2,4,5,6] PAVLOPO...	78	CNTR	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$1687.1^{+5.0}_{-4.3}$	ADIELS	84	CNTR	$\overline{p}$He
1684	[2,4,5,6] PAVLOPO...	78	CNTR	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1693 ± 2	[2] CHIBA	91	CNTR		$\overline{p}d \to \gamma X$
1694 ± 2.0	[2,3,4,5] RICHTER	83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1713.0 ± 2.6	[2] CHIBA	87	CNTR	0	0. $\overline{p}p \to \gamma X$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1731.0 ± 1.5	[2] CHIBA	87	CNTR	0	0. $\overline{p}p \to \gamma X$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1771±1.0	[2,4,5,8] RICHTER 83	CNTR	0	Stopped $\overline{p}$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1856.6±5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$
20 ±5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1873±2.5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$
< 5	BRIDGES 86D	SPEC	0	0. $\overline{p}d \to \pi\pi N$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1897±17	[9] ABASHIAN 76	STRC	8 $\pi^- p \to p3\pi$
110±82	[9] ABASHIAN 76	STRC	8 $\pi^- p \to p3\pi$
1897± 1	KALOGERO... 75	DBC	$\overline{p}n$ annihilation near threshold
25± 6	KALOGERO... 75	DBC	$\overline{p}n$ annihilation near threshold

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 1920	[10] EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$
~ 190	EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$1937.3^{+1.3}_{-0.7}$		[11] FRANKLIN 87	SPEC		0.586 $\overline{p}p$
< 3.0		[11] FRANKLIN 87	SPEC		0.586 $\overline{p}p$
1930 ± 2		[12] ASTON 80D	OMEG		$\gamma p \to p\overline{p}X$
12 ± 7		[12] ASTON 80D	OMEG		$\gamma p \to p\overline{p}X$
1940 ± 1	36	DAUM 80E	CNTR	0	93 $pp \to \overline{p}pX$
~ 6.0		DAUM 80E	CNTR		93 $pp \to \overline{p}pX$
1949 ±10		[13] DEFOIX 80	HBC	0	$\overline{p}p \to 5\pi$
80 ±20		[13] DEFOIX 80	HBC	0	$\overline{p}p \to 5\pi$
1939 ± 2		[14] HAMILTON 80B	CNTR	0	S channel $\overline{p}p$
22 ± 6		[14] HAMILTON 80B	CNTR	0	S channel $\overline{p}p$
1935.5± 1.0		SAKAMOTO 79	HBC	0	0.37–0.73 $\overline{p}p$
2.8± 1.4		SAKAMOTO 79	HBC	0	0.37–0.73 $\overline{p}p$
1939 ± 3		BRUCKNER 77	SPEC	0	0.4–0.85 $\overline{p}p$
< 4.0		BRUCKNER 77	SPEC	0	0.4–0.85 $\overline{p}p$
1935.9± 1.0		[15] CHALOUPKA 76	HBC	0	$\overline{p}p$ total,elastic
$8.8^{+4.3}_{-3.2}$		[16] CHALOUPKA 76	HBC	0	$\overline{p}p$ total,elastic
1942 ± 5		[17] D'ANDLAU 75	HBC	0	0.175–0.750 $\overline{p}p$
57.5± 5		[18] D'ANDLAU 75	HBC	0	0.175–0.750 $\overline{p}p$
$1934.4^{+2.6}_{-1.4}$		[19] KALOGERO... 75	DBC	−	$\overline{p}N$ annihilation
11^{+11}_{-4}		[20] KALOGERO... 75	DBC	−	$\overline{p}N$ annihilation
1932 ± 2		[15] CARROLL 74	CNTR		S channel $\overline{p}p \to d$
9^{+4}_{-3}		[16] CARROLL 74	CNTR		S channel $\overline{p}p \to d$
1968		[21] BENVENUTI 71	HBC	0	0.1–0.8 $\overline{p}p$
35		[21] BENVENUTI 71	HBC	0	0.1–0.8 $\overline{p}p$
1940 ± 8		CLINE 70	HBC	0	0.25–0.74 $\overline{p}p$
49 ± 9		CLINE 70	HBC	0	0.25–0.74 $\overline{p}p$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1949±10	[22] DEFOIX 80	HBC	0	0.0–1.2 $\overline{p}p \to 5\pi$
80±20	[22] DEFOIX 80	HBC	0	0.0–1.2 $\overline{p}p \to 5\pi$

VALUE (MeV)	DOCUMENT ID	COMMENT
2011± 7	[23] FERRER 93	$\pi^- p \to pp\overline{p}\pi^-\pi^0$
25^{+10}_{-25}	FERRER 93	$\pi^- p \to pp\overline{p}\pi^-\pi^0$
2025	GIBBARD 79	$e^- p \to e^- pp\overline{p}$
< 30	GIBBARD 79	$e^- p \to e^- pp\overline{p}$
2020± 3	BENKHEIRI 77	$\pi^- p \to pp\overline{p}\pi^-$
24±12	BENKHEIRI 77	$\pi^- p \to pp\overline{p}\pi^-$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2022± 6	[24] AZOOZ 83	HYBR	+	6 $\overline{p}p \to p\overline{n}3\pi$
14±13	[24] AZOOZ 83	HYBR	+	6 $\overline{p}p \to p\overline{n}3\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2023± 5	BODENKAMP 83	SPEC	0	$\gamma p \to \overline{p}pp$
27±12	BODENKAMP 83	SPEC	0	$\gamma p \to \overline{p}pp$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2026± 5	[24] AZOOZ 83	HYBR	−	4 $\overline{p}p \to \overline{p}n3\pi$
20±11	[24] AZOOZ 83	HYBR	−	4 $\overline{p}p \to \overline{p}n3\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2080±10	[25] KREYMER 80	STRC	0	13 $\pi^- d \to p\overline{p}n(n)$
110±20	[25] KREYMER 80	STRC	0	13 $\pi^- d \to p\overline{p}n(n)$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2090±20	[26] KREYMER 80	STRC	13 $\pi^- d \to np\overline{p}\pi^- p$
170±50	[26] KREYMER 80	STRC	13 $\pi^- d \to np\overline{p}\pi^- p$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 2110	[27] EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$
~ 330	[27] EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2110±10	[28] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$
190±10	[28] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2141	[29] DONALD 73	HBC	0	$\overline{p}p$ S channel
14	[29] DONALD 73	HBC	0	$\overline{p}p$ S channel

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2180±10	[30] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$
270±10	[30] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2207±13	[31] ALLES-... 67B	HBC	0	5.7 $\overline{p}p$
62±52	[31] ALLES-... 67B	HBC	0	5.7 $\overline{p}p$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2210^{+79}_{-21}	EVANGELISTA 79B	OMEG	10 $\pi^- p \to K^+K^- n$
~ 203	EVANGELISTA 79B	OMEG	10 $\pi^- p \to K^+K^- n$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2231.9 ±0.1	[1] BARNES 94	SPEC	0–46 $\overline{p}p \to \overline{\Lambda}\Lambda$
0.59±0.25	[1] BARNES 94	SPEC	0–46 $\overline{p}p \to \overline{\Lambda}\Lambda$
~ 2229.2	CARBONELL 93	RVUE	$\overline{p}p \to \Lambda\overline{\Lambda}$
~ 1.8	CARBONELL 93	RVUE	$\overline{p}p \to \Lambda\overline{\Lambda}$

[1] Supersedes CARBONELL 93.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
~ 2260	[32] EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$
~ 440	[32] EVANGELISTA 79	OMEG	10,16 $\pi^- p \to \overline{p}p$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2307± 6	ALPER 80	CNTR	0	62 $\pi^- p \to K^+K^- n$
245±20	ALPER 80	CNTR	0	62 $\pi^- p \to K^+K^- n$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2380±10	[33] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$
380±20	[33] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2450±10	[34] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$
280±20	[34] ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2480±30	[35] CARTER 77	CNTR	0	0.7–2.4 $\overline{p}p \to \pi\pi$
210±25	[35] CARTER 77	CNTR	0	0.7–2.4 $\overline{p}p \to \pi\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
~ 2500	[36] CARTER 78B	CNTR	0	0.7–2.4 $\overline{p}p \to K^-K^+$
~ 150	[36] CARTER 78B	CNTR	0	0.7–2.4 $\overline{p}p \to K^-K^+$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2710±20	ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$
170±40	ROZANSKA 80	SPRK	18 $\pi^- p \to p\overline{p}n$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2850±5	[37] BRAUN 76	DBC	−	5.5 $\overline{p}d \to N\overline{N}\pi$
< 39	[37] BRAUN 76	DBC	−	5.5 $\overline{p}d \to N\overline{N}\pi$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
3370±10	[38] ALEXANDER 72	HBC	0	6.94 $\overline{p}p$
150±40	[38] ALEXANDER 72	HBC	0	6.94 $\overline{p}p$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
3600±20	[38] ALEXANDER 72	HBC	0	6.94 $\overline{p}p$
140±20	[38] ALEXANDER 72	HBC	0	6.94 $\overline{p}p$

[2] Not seen by GRAF 91.
[3] Not seen by CHIBA 88, ANGELOPOULOS 86, ADIELS 86.
[4] They looked for radiative transitions to bound $p\overline{p}$ states, mono-energetic γ rays detected.
[5] Observed widths consistent with experimental resolution.
[6] Not seen by ADIELS 86.
[7] From analysis of difference of π^- and π^+ spectra.
[8] Not seen by CHIBA 88, ANGELOPOULOS 86.
[9] Produced backwards.
[10] $I(J^P) = 1(1^-)$ from a mass dependent partial-wave analysis taking solution A.
[11] From reanalysis of data from JASTRZEMBSKI 81.
[12] Not seen by BUSENITZ 89.
[13] From energy dependence of 5π cross section. $I^G = 1^-$ from observation of $\omega\rho$ decay. $P = +$ and $J > 1$. $a_2(1320)\pi\pi$ also seen.
[14] $I = 0$ favored, $J = 0$ or 1, seen in total $\overline{p}p$ total cross section. Primarily from annihilation reactions. Not seen in $\overline{p}d$ total and annihilation cross sections.
[15] Narrow bump seen in total $\overline{p}p$, $\overline{p}d$ cross sections. Isospin uncertain. Not seen in $\overline{p}p$ charge exchange by ALSTON-GARNJOST 75, CHALOUPKA 76. Integrated cross section three times larger than BRUCKNER 77.
[16] Narrow bump seen in total $\overline{p}p$, $\overline{p}d$ cross sections. Isospin uncertain. Not seen in $\overline{p}p$ charge exchange by ALSTON-GARNJOST 75, CHALOUPKA 76. Integrated cross section three times larger than BRUCKNER 77. Not seen by CLOUGH 84.
[17] From energy dependence of far backward elastic scattering. Some indication of additional structure.
[18] From energy dependence of far backward elastic scattering. Some indication of additional structure.
[19] Not seen by ALBERI 79 with comparable statistics.
[20] Not seen by ALBERI 79 with comparable statistics.
[21] Seen as a bump in the $\overline{p}p \rightarrow K^0_S K^0_L$ cross section with $J^{PC} = 1^{--}$.
[22] Isospin 1 favored.
[23] Not seen by AJALTOUNI 82, ARMSTRONG 79.
[24] Not seen by BIONTA 80, CARROLL 80, HAMILTON 80, BANKS 81, CHUNG 81, BARNETT 83.
[25] Neutron spectator. See also $np\overline{p}\pi^-(p)$ channel following.
[26] Proton spectator. See also $p\overline{p}n(n)$ channel above.
[27] $I(J^P) = 1(3^-)$ from a mass dependent partial-wave analysis taking solution A.
[28] $I(J^P) = 1(3^-)$ from amplitude analysis assuming one-pion exchange.
[29] Seen in final state $\omega\pi^+\pi^-$.
[30] $I(J^P) = 0(2^+)$ from amplitude analysis assuming one-pion exchange.
[31] ALLES-BORELLI 67B see neutral mode only $\pi^+\pi^-\pi^0$.
[32] $I(J^P) = 0(4^+)$ from a mass dependent partial-wave analysis taking solution A.
[33] $I(J^P) = 0(4^+)$ from amplitude analysis assuming one-pion exchange.
[34] $I(J^P) = 1(5^-)$ from amplitude analysis assuming one-pion exchange.
[35] $I(J^P) = 1(5^-)$ from amplitude analysis of $\overline{p}p \rightarrow \pi\pi$.
[36] I=0,1 $J^P = 5^-$ from Barrelet-zero analysis.
[37] Decays to $\overline{N}N$ and $\overline{N}N\pi$. Not seen by BARNETT 83.
[38] Decays to $4\pi^+4\pi^-$.

$\overline{N}N$(1100–3600) REFERENCES

BARNES 94 PL B331 203 +Birien+ (PS185 Collab.)
CARBONELL 93 PL B306 407 +Protasov, Dalkarov (ISNG, LEBD)
FERRER 93 NP A558 191c +Grigonian (WA56 Collab.)
CHIBA 91 PR D44 1933 +Fujitani+ (FUKI, KEK, SANG, OSAK, TMU)
GRAF 91 PR D44 1945 +Fero, Gee+(UCI, PENN, NMSU, KARLK, KARLE, ATHU)
BUSENITZ 89 PR D40 1 +Olszewski, Callahan+ (ILL, FNAL)
CHIBA 88 PL B202 447 +Doi (FUKI, INUS, KEK, SANG, OSAK, TMU)
CHIBA 87 PR D36 3321 +Doi+ (FUKI, INUS, KEK, SANG, OSAK, TMU)
DAFTARI 87 PRL 58 859 +Gray, Kalogeropoulos, Roy (SYRA)
FRANKLIN 87 PL B184 81
ADIELS 86 PL B182 405 +Backenstoss+ (STOH, BASL, LASL, THES, CERN)
ANGELOPO... 86 PL B178 441 Angelopoulos+(ATHU, UCI, KARLK, KARLE, NMSU, PENN)
BRIDGES 86B PRL 56 215 +Daftari, Kalogeropoulos, Debbe+ (SYRA, CASE)
BRIDGES 86D PL B180 313 +Brown, Daftari+ (SYRA, BNL, CASE, UMD, COLU)
ADIELS 84 PL 138B 235 + (BASL, KARLK, KARLE, STOH, STRB, THES)
CLOUGH 84 PL 146B 299 +Beard, Bugg+ (SURR, LOQM, ANIK, TRST, GEVA)
AZOOZ 83 PL 122B 471 +Butterworth (LOIC, RHEL, SACL, SLAC, TOHOK+)
BARNETT 83 PR D27 493 +Blockus, Burka, Chien, Christian+ (JHU)
BODENKAMP 83 PL 133B 275 +Fries, Behrend, Fenner+ (KARLK, KARLE, DESY)
RICHTER 83 PL 126B 284 +Adiels (BASL, KARLK, KARLE, STOH, STRB, THES)
AJALTOUNI 82 NP B209 301 +Bachman+ (+, CERN, NEUC+)
BANKS 81 PL 100B 191 +Booth, Campbell, Armstrong+ (LIVP, CERN)
CHUNG 81 PRL 46 395 +Bensinger+ (BNL, BRAN, CINC, FSU, MASD)
JASTRZEM... 81 PR D23 2784 Jastrzembski, Mandelkern+ (TEMP, UCI, UNM)
ALPER 80 PL 94B 422 +Becker+ (AMST, CERN, CRAC, MPIM, OXF+)
ASTON 80D PL 93B 517 (BONN, CERN, EPOL, GLAS, LANC, MCHS, ORSAY+)
BIONTA 80 PRL 44 909 +Carroll, Edelstein+ (BNL, CMU, FNAL, MASD)
CARROLL 80 PRL 44 1572 +Chiang, Johnson, Cester, Webb+ (BNL, PRIN)
DAUM 80E PL 90B 475 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
DEFOIX 80 NP B162 12 +Dobrzynski, Angelini, Bigi+ (CDEF, PISA)
HAMILTON 80 PRL 44 1179 +Pun, Tripp, Lazarus+ (LBL, BNL, MTHO)
HAMILTON 80B PRL 44 1182 +Pun, Tripp, Lazarus+ (LBL, BNL, MTHO)
KREYMER 80 PR D22 36 +Baggett, Fieguth+ (IND, PURD, SLAC, VAND)
ROZANSKA 80 NP B162 505 +Blum, Dietl, Grayer, Lorenz+ (MPIM, CERN)
ALBERI 79 PL 83B 247 +Alvear, Castelli, Poropat+ (TRST, CERN, IFRJ)
ARMSTRONG 79 PL B85 304 +Baccari, Belletti, Booth+ (DESY, GLAS)
EVANGELISTA 79 NP B153 253 + (BARI, BONN, CERN, DARE, GLAS, LIVP+)
EVANGELISTA 79B NP B154 381 + (BARI, BONN, CERN, DARE, GLAS, LIVP+)
GIBBARD 79 PRL 42 1593 +Ahrens, Berkelman, Cassel, Day, Harding+ (CORN)
SAKAMOTO 79 NP B158 410 +Hashimoto, Sai, Yamamoto+ (INUS)
CARTER 78B NP B141 467 (LOQM)
PAVLOPO... 78 PL 72B 415 Pavlopoulos+(KARLK, KARLE, BASL, CERN, STOH, STRB)
BENKHEIRI 77 PL 68B 483 +Boucrot+ (CERN, CDEF, EPOL, LALO)
BRUCKNER 77 PL 67B 222 +Granz, Ingham, Kilian+ (MPIH, HEIDP, CERN)
CARTER 77 PL 67B 117 +Coupland, Eisenhandler, Astbury+ (LOQM, RHEL) JP
ABASHIAN 76 PR D13 5 +Watson, Gelfand, Buttram+ (ILL, ANL, CHIC, ISU)
BRAUN 76 PL 60B 481 +Brick, Fridman, Gerber, Juillot, Maurer+ (STRB)
CHALOUPKA 76 PL 61B 487 + (CERN, LIVP, MONS, PADO, ROMA, TRST)
ALSTON-... 75 PRL 35 1685 Alston-Garnjost, Kenney, Pollard, Ross, Tripp+(LBL, MTHO)
D'ANDLAU 75 PL 58B 223 +Cohen-Ganouna, Laloum, Lutz, Petri (CDEF, PISA)
KALOGERO... 75 PRL 34 1047 Kalogeropoulos, Tzanakos (SYRA)
CARROLL 74 PRL 32 247 +Chiang, Kycia, Li, Mazur, Michael+ (BNL)
DONALD 73 NP B61 333 +Edwards, Gibbins, Briand, Duboc+ (LIVP, PARIS)
ALEXANDER 72 NP B45 29 +Bar-Nir, Benary, Dagan+ (TELA)
BENVENUTI 71 PRL 27 283 +Cline, Rutz, Reeder, Scherer (WISC)
CLINE 70 Preprint +English, Reeder (WISC)
ALLES-... 67B NC 50A 776 Alles-Borelli, French, Frisk+ (CERN, BONN) G
BETTINI 66 NC 42A 695 +Cresti, Limentani, Bertanza, Bigi+ (PADO, PISA)

OTHER RELATED PAPERS

TANIMORI 90 PR D41 744 +Ishimoto+ (KEK, INUS, KYOT, TOHOK, HIRO)
LIU 87 PRL 58 2288 +Kiu, Li (STON)
ARMSTRONG 86C PL B175 383 +Chu, Clement, Elinon+ (BNL, HOUS, PENN, RICE)
BRIDGES 86 PRL 56 211 +Brown+ (BLSU, BNL, CASE, COLU, UMD, SYRA)
BRIDGES 86C PRL 57 1534 +Daftari, Kalogeropoulos+ (SYRA) JP
DOVER 86 PRL 57 1207 + (BNL) JP
ANGELOPO... 85 PL 159B 210 Angelopoulos+ (ATHU, UCI, UNM, PENN, TEMP)
BODENKAMP 85 NP B255 717 +Fries, Behrend, Hesse+ (KARLK, KARLE, DESY)
AZOOZ 84 NP B244 277 +Butterworth (LOIC, RHEL, SACL, SLAC, TOHOK+)

$X(1900\text{–}3600)$

OMITTED FROM SUMMARY TABLE

THE $X(1900\text{–}3600)$ REGION

This high-mass region is covered nearly continuously with evidence for peaks of various widths and decay modes. As no satisfactory grouping into particles is yet possible, we list together in order of increasing mass all the $Y=0$ bumps above 1900 MeV that are coupled neither to $\overline{N}N$ nor to e^+e^-.

X(1900–3600) MASSES AND WIDTHS

We do not use the following data for averages, fits, limits, etc.

VALUE (MeV)	DOCUMENT ID
1900 to 3600 OUR LIMIT	

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1870±40	[1] ALDE 86D	GAM4	0	100 $\pi^- p \rightarrow 2\eta X$
250±30	[1] ALDE 86D	GAM4	0	100 $\pi^- p \rightarrow 2\eta X$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1898±18	100	THOMPSON 74	HBC	+	13 $\pi^+ p \rightarrow 2\rho X$
108^{+41}_{-27}	100	THOMPSON 74	HBC	+	13 $\pi^+ p \rightarrow 2\rho X$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1900± 40	100	BOESEBECK 68	HBC	+	8 $\pi^+ p \rightarrow \pi^+\pi^0 X$
216±105	100	BOESEBECK 68	HBC	+	8 $\pi^+ p \rightarrow \pi^+\pi^0 X$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1929±14	[2] FOCACCI 66	MMS	−	3–12 $\pi^- p$
22± 2	[2] FOCACCI 66	MMS	−	3–12 $\pi^- p$

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
1970±10	CHLIAPNIK... 80	HBC	0	32 $K^+ p \rightarrow 2K^0_S 2\pi X$
40±20	CHLIAPNIK... 80	HBC	0	32 $K^+ p \rightarrow 2K^0_S 2\pi X$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1973±15	30	CASO 70	HBC	−	11.2 $\pi^- p \rightarrow \rho 2\pi$
80	30	CASO 70	HBC	−	11.2 $\pi^- p \rightarrow \rho 2\pi$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2070	50	TAKAHASHI 72	HBC	8 $\pi^- p \rightarrow N 2\pi$
160	50	TAKAHASHI 72	HBC	8 $\pi^- p \rightarrow N 2\pi$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
~ 2104		BUGG	95	MRK3		$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
2103 ± 50	586	[3] BISELLO	89B	DM2		$J/\psi \to 4\pi\gamma$
187 ± 75	586	[3] BISELLO	89B	DM2		$J/\psi \to 4\pi\gamma$
2100 ± 40		[4] ALDE	86D	GAM4	0	$100\ \pi^- p \to 2\eta X$
250 ± 40		[4] ALDE	86D	GAM4	0	$100\ \pi^- p \to 2\eta X$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2141 ± 12	389	GREEN	86	MPSF	$400\ pA \to 4KX$
49 ± 28	389	GREEN	86	MPSF	$400\ pA \to 4KX$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2190 ± 10	CLAYTON	67	HBC	$\pm$	$2.5\ \overline{p}p \to a_2, \omega$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2195 ± 15	[2] FOCACCI	66	MMS	$-$	$3\text{–}12\ \pi^- p$
39 ± 14	[2] FOCACCI	66	MMS	$-$	$3\text{–}12\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2207 ± 22	[5] CASO	70	HBC	$-$	$11.2\ \pi^- p$
130	[5] CASO	70	HBC	$-$	$11.2\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$2280\pm\ 50$	ATKINSON	85	OMEG	$20\text{–}70\ \gamma p \to p\omega\pi^+\pi^-\pi^0$
440 ± 110	ATKINSON	85	OMEG	$20\text{–}70\ \gamma p \to p\omega\pi^+\pi^-\pi^0$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2300 ± 100	ATKINSON	84F	OMEG	±0	$20\text{–}70\ \gamma p \to \rho f$
~ 250	ATKINSON	84F	OMEG	±0	$20\text{–}70\ \gamma p \to \rho f$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2330 ± 30	ATKINSON	88	OMEG	0	$25\text{–}50\ \gamma p \to \rho^{\pm}\rho^0\pi^{\mp}$
435 ± 75	ATKINSON	88	OMEG	0	$25\text{–}50\ \gamma p \to \rho^{\pm}\rho^0\pi^{\mp}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2340 ± 20	126	[6] BALTAY	75	HBC	$+$	$15\ \pi^+ p \to p5\pi$
180 ± 60	126	[6] BALTAY	75	HBC	$+$	$15\ \pi^+ p \to p5\pi$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2382 ± 24	[2] FOCACCI	66	MMS	$-$	$3\text{–}12\ \pi^- p$
$62\pm\ 6$	[2] FOCACCI	66	MMS	$-$	$3\text{–}12\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2500 ± 32	ANDERSON	69	MMS	$-$	$16\ \pi^- p$ backward
87	ANDERSON	69	MMS	$-$	$16\ \pi^- p$ backward

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2620 ± 20	550	BAUD	69	MMS	$-$	$8\text{–}10\ \pi^- p$
85 ± 30	550	BAUD	69	MMS	$-$	$8\text{–}10\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2676 ± 27	[5] CASO	70	HBC	$-$	$11.2\ \pi^- p$
150	[5] CASO	70	HBC	$-$	$11.2\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2747 ± 32	DENNEY	83	LASS	$10\ \pi^+ N$
195 ± 75	DENNEY	83	LASS	$10\ \pi^+ N$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2800 ± 20	640	BAUD	69	MMS	$-$	$8\text{–}10\ \pi^- p$
46 ± 10	640	BAUD	69	MMS	$-$	$8\text{–}10\ \pi^- p$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2820 ± 10	15	[7] SABAU	71	HBC	$+$	$8\ \pi^+ p$
50 ± 10	15	[7] SABAU	71	HBC	$+$	$8\ \pi^+ p$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2880 ± 20	230	BAUD	69	MMS	$-$	$8\text{–}10\ \pi^- p$
$<\ 15$	230	BAUD	69	MMS	$-$	$8\text{–}10\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3025 ± 20	BAUD	70	MMS	$-$	$10.5\text{–}13\ \pi^- p$
$\sim\ 25$	BAUD	70	MMS	$-$	$10.5\text{–}13\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3075 ± 20	BAUD	70	MMS	$-$	$10.5\text{–}13\ \pi^- p$
$\sim\ 25$	BAUD	70	MMS	$-$	$10.5\text{–}13\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3145 ± 20	BAUD	70	MMS	$-$	$10.5\text{–}15\ \pi^- p$
$<\ 10$	BAUD	70	MMS	$-$	$10.5\text{–}15\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3475 ± 20	BAUD	70	MMS	$-$	$14\text{–}15.5\ \pi^- p$
$\sim\ 30$	BAUD	70	MMS	$-$	$14\text{–}15.5\ \pi^- p$

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
3535 ± 20	BAUD	70	MMS	$-$	$14\text{–}15.5\ \pi^- p$
$\sim\ 30$	BAUD	70	MMS	$-$	$14\text{–}15.5\ \pi^- p$

[1] Seen in $J=2$ wave in one of the two ambiguous solutions.
[2] Not seen by ANTIPOV 72, who performed a similar experiment at 25 and 40 GeV/c.
[3] ASTON 81B sees no peak, has 850 events in Ajinenko+Barth bins. ARESTOV 80 sees no peak.
[4] Seen in $J=0$ wave in one of the two ambiguous solutions.
[5] Seen in $\rho^-\pi^+\pi^-$ (ω and η antiselected in 4π system).
[6] Dominant decay into $\rho^0\rho^0\pi^+$. BALTAY 78 finds confirmation in $2\pi^+\pi^-2\pi^0$ events which contain $\rho^+\rho^0\pi^0$ and $2\rho^+\pi^-$.
[7] Seen in $(K\overline{K}\pi\pi)$ mass distribution.

$X(1900\text{–}3600)$ REFERENCES

BUGG	95	PL B353 378	+Scott, Zoli+	(LOQM, PNPI, WASH)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
ATKINSON	88	ZPHY C38 535	+Axon+	(BONN, CERN, GLAS, LANC, MCHS, CURIN)
ALDE	86D	NP B269 485	+Binon, Bricman+	(BELG, LAPP, SERP, CERN, LANL)
GREEN	86	PRL 56 1639	+Lai+	(FNAL, ARIZ, FSU, NDAM, TUFTS, VAND+)
ATKINSON	85	ZPHY C29 333	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
ATKINSON	84F	NP B239 1	+	(BONN, CERN, GLAS, LANC, MCHS, IPNP+)
DENNEY	83	PR D28 2726	+Cranley, Firestone, Chapman+	(IOWA, MICH) J
ASTON	81B	NP B189 205	+	(BONN, CERN, EPOL, GLAS, LANC, MCHS+)
ARESTOV	80	IHEP 80-165	+Bogoljubski+	(SERP)
CHLIAPNIK...	80	ZPHY C3 285	Chliapnikov, Gerdyukov+	(SERP, BRUX, MONS)
BALTAY	78	PR D17 52	+Cautis, Cohen, Csorna, Kalelkar+	(COLU, BING)
BALTAY	75	PRL 35 891	+Cautis, Cohen, Kalelkar, Pisello+	(COLU, BING)
THOMPSON	74	NP B69 220	+Gaidos, McIlwain, Miller, Mulera+	(PURD)
ANTIPOV	72	PL 40 147	+Kienzle, Landsberg+	(SERP)
TAKAHASHI	72	PR D6 1266	+Barish+	(TOHOK, PENN, NDAM, ANL)
SABAU	71	LNC 1 514	+Uretsky	(BUCH, ANL)
BAUD	70	PL 31B 549	+Benz+	(CERN Boson Spectrometer Collab.)
CASO	70	LNC 3 707	+Conte, Tomasini+	(GENO, HAMB, MILA, SACL)
ANDERSON	69	PRL 22 1390	+Collins+	(BNL, CMU)
BAUD	69	PL 30B 129	+Benz+	(CERN Boson Spectrometer Collab.)
BOESEBECK	68	NP B4 501	+Deutschmann+	(AACH, BERL, CERN)
CLAYTON	67	Heidelberg Conf. 57	+Mason, Muirhead, Filippas+	(LIVP, ATHU)
FOCACCI	66	PRL 17 890	+Kienzle, Levrat, Maglich, Martin	(CERN)

OTHER RELATED PAPERS

ANTIPOV	72	PL 40 147	+Kienzle, Landsberg+	(SERP)
CHIKOVANI	66	PL 22 233	+Kienzle, Maglich+	(SERP)

STRANGE MESONS
($S = \pm 1$, $C = B = 0$)

$K^+ = u\overline{s}$, $K^0 = d\overline{s}$, $\overline{K}^0 = \overline{d}s$, $K^- = \overline{u}s$, similarly for K^*'s

$K^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

THE CHARGED KAON MASS

(by T.G. Trippe, Lawrence Berkeley National Laboratory)

The average of the six charged kaon mass measurements which we use in the Particle Listings is

$$m_{K^\pm} = 493.677 \pm 0.013 \text{ MeV (S = 2.4)} , \quad (1)$$

where the error has been increased by the scale factor S. The large scale factor indicates a serious disagreement between different input data. The average before scaling the error is

$$m_{K^\pm} = 493.677 \pm 0.005 \text{ MeV} ,$$
$$\chi^2 = 22.9 \text{ for 5 D.F., Prob. } = 0.04\% , \quad (2)$$

where the high χ^2 and correspondingly low χ^2 probability further quantify the disagreement.

The main disagreement is between the two most recent and precise results,

$$m_{K^\pm} = 493.696 \pm 0.007 \text{ MeV} \qquad \text{DENISOV 91}$$
$$m_{K^\pm} = 493.636 \pm 0.011 \text{ MeV (S = 1.5)} \quad \text{GALL 88}$$
$$\text{Average} = 493.679 \pm 0.006 \text{ MeV}$$
$$\chi^2 = 21.2 \text{ for 1 D.F., Prob. } = 0.0004\% , \quad (3)$$

both of which are measurements of x-ray energies from kaonic atoms. Comparing the average in Eq. (3) with the overall average in Eq. (2), it is clear that DENISOV 91 and GALL 88 dominate the overall average, and that their disagreement is responsible for most of the high χ^2.

The GALL 88 measurement was made using four different kaonic atom transitions, K^- Pb ($9 \to 8$), K^- Pb ($11 \to 10$), K^- W ($9 \to 8$), and K^- W ($11 \to 10$). The $m_{K^\pm}$ values they obtain from each of these transitions is shown in the Particle Listings and in Fig. 1. Their K^- Pb ($9 \to 8$) $m_{K^\pm}$is below and somewhat inconsistent with their other three transitions. The average of their four measurements is

$$m_{K^\pm} = 493.636 \pm 0.007 ,$$
$$\chi^2 = 7.0 \text{ for 3 D.F., Prob. } = 7.2\% . \quad (4)$$

This is a low but acceptable χ^2 probability so, to be conservative, GALL 88 scaled up the error on their average by S=1.5 to obtain their published error ± 0.011 shown in Eq. (3) above and used in the Particle Listings average.

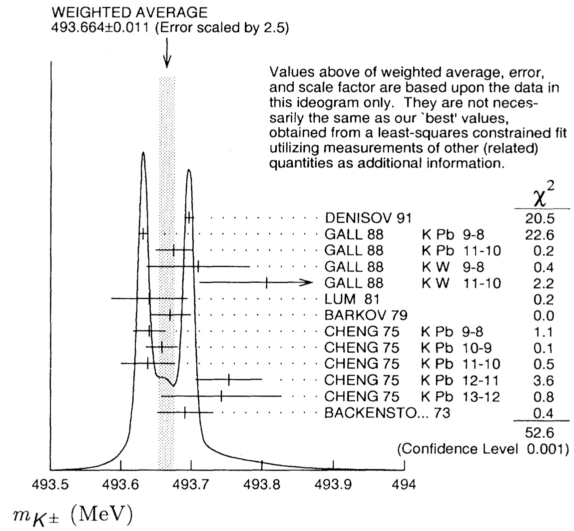


Figure 1: Ideogram of $m_{K^\pm}$ mass measurements. GALL 88 and CHENG 75 measurements are shown separately for each transition they measured.

The ideogram in Fig. 1 shows that the DENISOV 91 measurement and the GALL 88 K^- Pb ($9 \to 8$) measurement yield two well-separated peaks. One might suspect the GALL 88 K^- Pb ($9 \to 8$) measurement since it is responsible both for the internal inconsistency in the GALL 88 measurements and the disagreement with DENISOV 91.

To see if the disagreement could result from a systematic problem with the K^- Pb ($9 \to 8$) transition, we have separated the CHENG 75 data, which also used K^- Pb, into its separate transitions. Figure 1 shows that the CHENG 75 and GALL 88 K^- Pb ($9 \to 8$) values are consistent, suggesting the possibility of a common effect such as contaminant nuclear γ rays near the K^- Pb ($9 \to 8$) transition energy, although the CHENG 75 errors are too large to make a strong conclusion. The average of all 13 measurements has a χ^2 of 52.6 as shown in Fig. 1 and the first line of Table 1, yielding an unacceptable χ^2 probability of 0.00005%. The second line of Table 1 excludes both the GALL 88 and CHENG 75 measurements of the K^- Pb ($9 \to 8$) transition and yields a χ^2 probability of 43%. The third [fourth] line of Table 1 excludes only the GALL 88 K^- Pb ($9 \to 8$) [DENISOV 91] measurement and yields a χ^2 probability of 20% [8.6%]. Table 1 shows that removing both measurements of the K^- Pb ($9 \to 8$) transition produces the most consistent set of data, but that excluding only the GALL 88 K^- Pb ($9 \to 8$) transition or DENISOV 91 also produces acceptable probabilities.

Yu.M. Ivanov, representing DENISOV 91, has estimated corrections needed for the older experiments because of improved ^{192}Ir and ^{198}Au calibration γ-ray energies. He estimates

Table 1: $m_{K^\pm}$ averages for some combinations of Fig. 1 data.

$m_{K^\pm}$ (MeV)	χ^2	D.F.	Prob. (%)	Measurements used
493.664 ± 0.004	52.6	12	0.00005	all 13 measurements
493.690 ± 0.006	10.1	10	43	no K^- Pb(9→8)
493.687 ± 0.006	14.6	11	20	no GALL 88 K^- Pb(9→8)
493.642 ± 0.006	17.8	11	8.6	no DENISOV 91

that CHENG 75 and BACKENSTOSS 73 $m_{K^\pm}$ values could be raised by about 15 keV and 22 keV, respectively. With these estimated corrections, Table 1 becomes Table 2. The last line of Table 2 shows that if such corrections are assumed, then GALL 88 K^- Pb ($9 \to 8$) is inconsistent with the rest of the data even when DENISOV 91 is excluded. Yu.M. Ivanov warns that these are rough estimates. Accordingly, we do not use Table 2 to reject the GALL 88 K^- Pb ($9 \to 8$) transition, but we note that a future reanalysis of the CHENG 75 data could be useful because it might provide supporting evidence for such a rejection.

Table 2: $m_{K^\pm}$ averages for some combinations of Fig. 1 data after raising CHENG 75 and BACKENSTOSS 73 values by 0.015 and 0.022 MeV respectively.

$m_{K^\pm}$ (MeV)	χ^2	D.F.	Prob. (%)	Measurements used
493.666 ± 0.004	53.9	12	0.00003	all 13 measurements
493.693 ± 0.006	9.0	10	53	no K^- Pb(9→8)
493.690 ± 0.006	11.5	11	40	no GALL 88 K^- Pb(9→8)
493.645 ± 0.006	23.0	11	1.8	no DENISOV 91

The GALL 88 measurement uses a Ge semiconductor spectrometer which has a resolution of about 1 keV, so they run the risk of some contaminant nuclear γ rays. Studies of γ rays following stopped π^- and Σ^- absorption in nucleii (unpublished) do not show any evidence for contaminants according to GALL 88 spokesperson, B.L. Roberts. The DENISOV 91 measurement uses a crystal diffraction spectrometer with a resolution of 6.3 eV for radiation at 22.1 keV to measure the 4f-3d transition in K^- ^{12}C. The high resolution and the light nucleus reduce the probability for overlap by contaminant γ rays, compared with the measurement of GALL 88. The DENISOV 91 measurement is supported by their high-precision measurement of the 4d-2p transition energy in π^- ^{12}C, which is good agreement with the calculated energy.

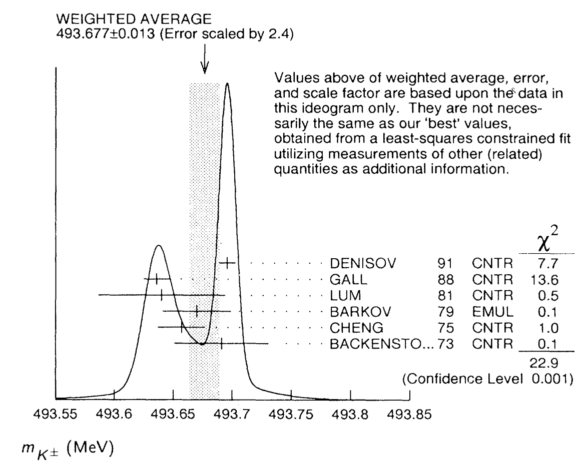
While we suspect that the GALL 88 K^- Pb ($9 \to 8$) measurements could be the problem, we are unable to find clear grounds for rejecting it. Therefore, we retain their measurement in the average and accept the large scale factor until further information can be obtained from new measurements and/or from reanalysis of GALL 88 and CHENG 75 data.

We thank B.L. Roberts (Boston Univ.) and Yu.M. Ivanov (Petersburg Nuclear Physics Inst.) for their extensive help in understanding this problem.

$K^{\pm}$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
493.677±0.016 OUR FIT	Error includes scale factor of 2.8.				
493.677±0.013 OUR AVERAGE	Error includes scale factor of 2.4. See the ideogram below.				
493.696±0.007	[1] DENISOV	91	CNTR	−	Kaonic atoms
493.636±0.011	[2] GALL	88	CNTR	−	Kaonic atoms
493.640±0.054	LUM	81	CNTR	−	Kaonic atoms
493.670±0.029	BARKOV	79	EMUL	±	$e^+e^- \to K^+K^-$
493.657±0.020	[2] CHENG	75	CNTR	−	Kaonic atoms
493.691±0.040	BACKENSTO...	73	CNTR	−	Kaonic atoms
• • • We do not use the following data for averages, fits, limits, etc. • • •					
493.631±0.007	GALL	88	CNTR	−	K^- Pb (9→ 8)
493.675±0.026	GALL	88	CNTR	−	K^- Pb (11→ 10)
493.709±0.073	GALL	88	CNTR	−	K^- W (9→ 8)
493.806±0.095	GALL	88	CNTR	−	K^- W (11→ 10)
493.640±0.022±0.008	[3] CHENG	75	CNTR	−	K^- Pb (9→ 8)
493.658±0.019±0.012	[3] CHENG	75	CNTR	−	K^- Pb (10→ 9)
493.638±0.035±0.016	[3] CHENG	75	CNTR	−	K^- Pb (11→ 10)
493.753±0.042±0.021	[3] CHENG	75	CNTR	−	K^- Pb (12→ 11)
493.742±0.081±0.027	[3] CHENG	75	CNTR	−	K^- Pb (13→ 12)
493.662±0.19	KUNSELMAN	74	CNTR	−	Kaonic atoms
493.78 ±0.17	GREINER	65	EMUL	+	
493.7 ±0.3	BARKAS	63	EMUL	−	
493.9 ±0.2	COHEN	57	RVUE	+	

[1] Error increased from 0.0059 based on the error analysis in IVANOV 92.
[2] This value is the authors' combination of all of the separate transitions listed for this paper.
[3] The CHENG 75 values for separate transitions were calculated from their Table 7 transition energies. The first error includes a 20% systematic error in the noncircular contaminant shift. The second error is due to a ±5 eV uncertainty in the theoretical transition energies.



$m_{K^+} - m_{K^-}$

Test of *CPT*.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG
−0.032±0.090	1.5M	[4] FORD	72	ASPK	±

[4] FORD 72 uses $m_{\pi^+} - m_{\pi^-} = +28 \pm 70$ keV.

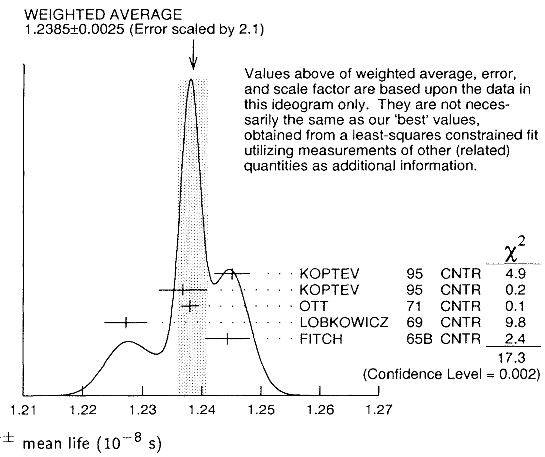
$K^{\pm}$ MEAN LIFE

VALUE (10^{-8} s)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.2386±0.0024 OUR FIT	Error includes scale factor of 2.0.					
1.2385±0.0025 OUR AVERAGE	Error includes scale factor of 2.1. See the ideogram below.					
1.2451±0.0030	250k	KOPTEV	95	CNTR		K at rest, U target
1.2368±0.0041	150k	KOPTEV	95	CNTR		K at rest, Cu target
1.2380±0.0016	3M	OTT	71	CNTR	+	K at rest
1.2272±0.0036		LOBKOWICZ	69	CNTR	+	K in flight
1.2443±0.0038		FITCH	65B	CNTR	+	K at rest

• • • We do not use the following data for averages, fits, limits, etc. • • •

1.2415 ± 0.0024	400k	[5] KOPTEV	95	CNTR		K at rest
1.221 ± 0.011		FORD	67	CNTR	$\pm$	
1.231 ± 0.011		BOYARSKI	62	CNTR	$+$	
$1.25\ ^{+0.22}_{-0.17}$		BARKAS	61	EMUL		
$1.27\ ^{+0.36}_{-0.23}$	51	BHOWMIK	61	EMUL		
1.31 ± 0.08	293	NORDIN	61	HBC	$-$	
1.24 ± 0.07		NORDIN	61	RVUE	$-$	
1.38 ± 0.24	33	FREDEN	60B	EMUL		
1.21 ± 0.06		BURROWES	59	CNTR		
1.60 ± 0.3	52	EISENBERG	58	EMUL		
$0.95\ ^{+0.36}_{-0.25}$		ILOFF	56	EMUL		

[5] KOPTEV 95 report this weighted average of their U-target and Cu-target results, where they have weighted by $1/\sigma$ rather than $1/\sigma^2$.



$(\tau_{K^+} - \tau_{K^-}) / \tau_{\text{average}}$

This quantity is a measure of *CPT* invariance in weak interactions.

VALUE (%)	DOCUMENT ID		TECN
0.11 ±0.09 OUR AVERAGE	Error includes scale factor of 1.2.		
0.090 ± 0.078	LOBKOWICZ	69	CNTR
0.47 ± 0.30	FORD	67	CNTR

RARE KAON DECAYS

(by L. Littenberg, BNL and G. Valencia, Iowa State University)

A. Introduction: There are several recent reviews on rare kaon decays and related topics [1–13]. The current activity in rare kaon decays can be divided roughly into four categories:

1. Searches for explicit violations of the Standard Model
2. Measurements of Standard Model parameters
3. Searches for CP violation
4. Studies of strong interactions at low energy.

The paradigm of Category 1 is the lepton flavor violating decay $K_L \to \mu e$. Category 2 includes processes such as $K^+ \to \pi^+\nu\overline{\nu}$, which is sensitive to $|V_{td}|$. Much of the interest in Category 3 is focussed on the decays $K_L \to \pi^0\ell\overline{\ell}$, where $\ell \equiv e, \mu, \nu$. Category 4 includes reactions like $K^+ \to \pi^+\ell^+\ell^-$ which constitute a testing ground for the ideas of chiral perturbation theory. Other reactions of this type are $K_L \to \pi^0\gamma\gamma$, which also scales a CP-conserving background to CP violation in $K_L \to \pi^0\ell^+\ell^-$ and $K_L \to \gamma\ell^+\ell^-$, which could possibly shed light on long distance contributions to $K_L \to \mu^+\mu^-$.

B. Explicit violations of the Standard Model: Most of the activity here is in searches for lepton flavor violation (LFV). This is motivated by the fact that many extensions of the minimal Standard Model violate lepton flavor and by the potential to access very high scales. For example, the tree-level exchange of a LFV vector boson of mass M_X that couples to left-handed fermions with electroweak strength and without mixing angles yields $\text{B}(K_L \to \mu e) = 3.3\times10^{-11}(91\ \text{TeV}/M_X)^4$ [7]. This simple dimensional analysis may be used to read from Table 1 that the reaction $K_L \to \mu e$ is already probing scales of nearly 100 TeV. Table 1 summarizes the present experimental situation vis a vis LFV, along with the expected near-future progress. The decays $K_L \to \mu^\pm e^\mp$ and $K^+ \to \pi^+e^\mp\mu^\pm$ (or $K_L \to \pi^0 e^\mp\mu^\pm$) provide complementary information on potential family number violating interactions since the former is sensitive to axial-vector (or pseudoscalar) couplings and the latter is sensitive to vector (or scalar) couplings.

Table 1: Searches for lepton flavor violation in K decay

Mode	90% CL upper limit	Exp't	Yr./Ref.	(Near-) future aim
$K^+ \to \pi^+ e\mu$	2.1E-10	BNL-777	90/14	3E-12 (BNL-865)
$K_L \to \mu e$	3.3E-11	BNL-791	93/15	2E-12 (BNL-871)
$K_L \to \pi^0 \mu e$	3.5E-9	FNAL-799	94/16	E-11 (FNAL799II)

Another forbidden decay currently being pursued is $K^+ \to \pi^+X^0$, where X^0 is a very light, noninteracting particle (*e.g.* hyperphoton, axion, familon, etc.). The published upper limit on this process [17] is 1.7×10^{-9}, but recently this has been improved to 5.2×10^{-10} [18]. Data already collected by BNL-787 are expected to yield another substantial factor in sensitivity to this process.

C. Measurements of Standard Model parameters: Until recently searches for $K^+ \to \pi^+\nu\overline{\nu}$ have been motivated by the possibility of observing non-SM physics because the sensitivity attained was far short of the SM prediction for this decay [19] and long-distance contributions were known to be negligible [3,20]. However, BNL-787 is approaching the sensitivity at which the observation of an event could no longer be unambiguously attributed to non-SM physics. The published 90% c.l. upper limit [17] is 5.2×10^{-9}, but this has been recently improved to 2.4×10^{-9} [18], and extensive recent running with an upgraded beam and detector is expected to further improve this significantly. This reaction is now becoming interesting from the point of view of constraining SM parameters where the branching ratio is expected to be of order 10^{-10}, and can be written as [3]:

$$\text{B}(K^+ \to \pi^+\nu\overline{\nu}) = \frac{\alpha^2 \text{B}(K^+ \to \pi^o e^+\nu)}{V_{us}^2 2\pi^2 \sin^4\theta_W} \times \sum_{l=e,\mu,\tau} |V_{cs}^* V_{cd} X_{NL}^{\ell} + V_{ts}^* V_{td} X(m_t)|^2 \qquad (1)$$

where $X(m_t)$ is of order 1, and X_{NL}^{ℓ} is several hundred times smaller. This form exhibits the strong dependence of this branching ratio on $|V_{td}|$. It also makes manifest the fact that the *a priori* unknown hadronic matrix element drops out in the comparison to the very well-measured rate of K_{e3} decay. QCD corrections, which are contained in X^{ℓ}_{NL}, are relatively small and now known [21] to $\leq 10\%$. Evaluating the constants in Eq. (1) with $m_t = 175$ GeV, one can cast this result in terms of the CKM parameters A, ρ and η (see our Section on "The Cabibbo-Kobayashi-Maskawa mixing matrix") [21].

$$\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}) \approx 1.2 \times 10^{-10} A^4 [\eta^2 + \frac{2}{3}(\rho^e_o - \rho)^2 + \frac{1}{3}(\rho^\tau_o - \rho)^2] \quad (2)$$

where $\rho^{\ell}_o \equiv 1 + \frac{X^{\ell}_{NL}}{A^2\lambda^4 X(m_t)}$. Thus, $\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu})$ determines a circle in the ρ, η plane with center $(\rho_o, 0)$; $\rho_o \equiv \frac{2}{3}\rho^e_o + \frac{1}{3}\rho^\tau_o \approx 1.4$, and radius $\approx \frac{1}{A^2}\sqrt{\frac{\mathrm{B}(K^+\to\pi^+\nu\overline{\nu})}{1.2\times 10^{-10}}}$.

The decay $K_L \to \mu^+\mu^-$ also has a short distance contribution sensitive to the CKM parameter ρ. For $m_t = 175$ GeV it is given by [21]:

$$\mathrm{B_{SD}}(K_L \to \mu^+\mu^-) \approx 1.9 \times 10^{-9} A^4 (\rho'_o - \rho)^2 \quad (3)$$

where ρ'_o depends on the charm quark mass and is around 1.2. This decay, however, is dominated by a long-distance contribution from a two-photon intermediate state. The absorptive (imaginary) part of the long-distance component is calculated in terms of the measured rate for $K_L \to \gamma\gamma$ to be $\mathrm{B_{abs}}(K_L \to \mu^+\mu^-) = (6.8 \pm 0.3) \times 10^{-9}$; and it almost completely saturates the observed rate $\mathrm{B}(K_L \to \mu^+\mu^-) = (7.2 \pm 0.5) \times 10^{-9}$ listed in the current edition. The difference between the observed rate and the absorptive component can be attributed to the (coherent) sum of the short-distance amplitude and the real part of the long-distance amplitude. In order to use this mode to constrain ρ it is, therefore, necessary to know the real part of the long-distance contribution. Unlike the absorptive part, the real part of the long-distance contribution cannot be derived from the measured rate for $K_L \to \gamma\gamma$. At present, it is not possible to compute this long-distance component reliably and, therefore, it is not possible to constrain ρ from this mode. It is expected that studies of the reactions $K_L \to \ell^+\ell^-\gamma$, and $K_L \to \ell^+\ell^-\ell'^+\ell'^-$ for $\ell, \ell' = e$ or μ will improve our understanding of the long distance effects in $K_L \to \mu^+\mu^-$ (the current data is parameterized in terms of α^*_K, discussed in the Form Factors section of the K^0_L Particle Properties Listings).

D. Searches for CP violation: The mode $K_L \to \pi^0\nu\overline{\nu}$ is dominantly CP-violating and free of hadronic uncertainties [3,22]. The Standard Model predicts a branching ratio of order 10^{-10}; for $m_t = 175$ GeV it is given approximately by [21]:

$$\mathrm{B}(K_L \to \pi^0\nu\overline{\nu}) \approx 5 \times 10^{-10} A^4 \eta^2 \ . \quad (4)$$

The current upper bound is $\mathrm{B}(K_L \to \pi^0\nu\overline{\nu}) \leq 5.8 \times 10^{-5}$ [23] and FNAL799II (KTeV) is expected to place a bound of order 10^{-8} [24].

The decay $K_L \to \pi^0 e^+e^-$ also has sensitivity to the product $A^4\eta^2$. It has a direct CP-violating component that depends on the value of the top-quark mass, and that for $m_t = 175$ GeV is given by [25]:

$$\mathrm{B_{dir}}(K_L \to \pi^0 e^+e^-) \approx 7 \times 10^{-11} A^4 \eta^2 \ . \quad (5)$$

However, like $K_L \to \mu^+\mu^-$ this mode suffers from large theoretical uncertainties due to long distance strong interaction effects. It has an indirect CP-violating component given by:

$$\mathrm{B_{ind}}(K_L \to \pi^0 e^+e^-) = |\epsilon|^2 \frac{\tau_{K_L}}{\tau_{K_S}} \mathrm{B}(K_S \to \pi^0 e^+e^-) \ , \quad (6)$$

that has been estimated to be less than 10^{-12} [26], but that will not be known precisely until a measurement of $K_S \to \pi^0 e^+e^-$ is available [6,27]. There is also a CP-conserving component dominated by a two-photon intermediate state that cannot be computed reliably at present. This component has an absorptive part that can be, in principle, determined from a detailed analysis of $K_L \to \pi^0\gamma\gamma$.

An analysis of $K_L \to \pi^0\gamma\gamma$ within chiral perturbation theory has been carried out in terms of a parameter a_V [28,29] that determines both the rate and the shape of the distribution $d\Gamma/dm_{\gamma\gamma}$. A fit to the distribution has given $-0.32 < a_V < 0.19$ [30]; a value that suggests that the absorptive part of the CP-conserving contribution to $K_L \to \pi^0 e^+e^-$ is significantly smaller than the direct CP-violating component [30]. However, there remains some uncertainty in the interpretation of $K_L \to \pi^0\gamma\gamma$ in terms of a_V. Analyses that go beyond chiral perturbation theory have found larger values of a_V, indicating a sizable CP-conserving component for $K_L \to \pi^0 e^+e^-$. The real part of the CP-conserving contribution to $K_L \to \pi^0 e^+e^-$ is also unknown.

Finally, BNL-845 observed a potential background to $K_L \to \pi^0 e^+e^-$ from the decay $K_L \to \gamma\gamma e^+e^-$ [31]. This was later confirmed with an order of magnitude larger sample by FNAL-799 [32], which measured additional kinematic quantities. It has been estimated that this background will enter at the level of 10^{-11} [33], comparable to the signal level. Because of this, the observation of $K_L \to \pi^0 e^+e^-$ will depend on background subtraction with good statistics.

The current upper bound for the process $K_L \to \pi^0 e^+e^-$ is 4.3×10^{-9} [34]. For the closely related muonic process, the upper bound is $\mathrm{B}(K_L \to \pi^0\mu^+\mu^-) \leq 5.1 \times 10^{-9}$ [35]. FNAL799II expects to reach a sensitivity $\lesssim 10^{-11}$ for both reactions [36].

E. Other long distance dominated modes: The decays $K^+ \to \pi^+\ell^+\ell^-$ ($\ell = e$ or μ) are described by chiral perturbation theory in terms of one parameter, ω^+ [37]. This parameter determines both the rate and distribution $d\Gamma/dm_{\ell\ell}$ for these processes. A careful study of these two reactions can provide a measurement of ω^+ and a test of the chiral perturbation theory description. A simultaneous fit to the rate and spectrum of $K^+ \to \pi^+e^+e^-$ gives: $\omega^+ = 0.89^{+0.24}_{-0.14}$; $\mathrm{B}(K^+ \to \pi^+e^+e^-) = (2.99 \pm 0.22) \times 10^{-7}$ [38]. These two results satisfy the prediction of chiral perturbation theory within two standard deviations [6]. Improved statistics for this mode and a measurement of the mode $K^+ \to \pi^+\mu^+\mu^-$ are thus desired. BNL-787 has observed the process $K^+ \to \pi^+\mu^+\mu^-$ [39] at about the predicted level, but the result is not yet accurate enough to provide additional constraints.

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K^+ DECAY MODES

K^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\mu^+\nu_\mu$		(63.51 ± 0.18) %	S=1.3
Γ_2	$e^+\nu_e$		$(1.55\pm0.07)\times10^{-5}$	
Γ_3	$\pi^+\pi^0$		(21.16 ± 0.14) %	S=1.1
Γ_4	$\pi^+\pi^+\pi^-$		(5.59 ± 0.05) %	S=1.8
Γ_5	$\pi^+\pi^0\pi^0$		(1.73 ± 0.04) %	S=1.2
Γ_6	$\pi^0\mu^+\nu_\mu$ Called $K^+_{\mu3}$.		(3.18 ± 0.08) %	S=1.5
Γ_7	$\pi^0 e^+\nu_e$ Called K^+_{e3}.		(4.82 ± 0.06) %	S=1.3
Γ_8	$\pi^0\pi^0 e^+\nu_e$		$(2.1\pm0.4)\times10^{-5}$	
Γ_9	$\pi^+\pi^- e^+\nu_e$		$(3.91\pm0.17)\times10^{-5}$	
Γ_{10}	$\pi^+\pi^-\mu^+\nu_\mu$		$(1.4\pm0.9)\times10^{-5}$	
Γ_{11}	$\pi^0\pi^0\pi^0 e^+\nu_e$		$< 3.5 \times10^{-6}$	CL=90%
Γ_{12}	$\pi^+\gamma\gamma$	[a]	$< 1 \times10^{-6}$	CL=90%
Γ_{13}	$\pi^+3\gamma$	[a]	$< 1.0 \times10^{-4}$	CL=90%
Γ_{14}	$\mu^+\nu_\mu\nu\overline{\nu}$		$< 6.0 \times10^{-6}$	CL=90%
Γ_{15}	$e^+\nu_e\nu\overline{\nu}$		$< 6 \times10^{-5}$	CL=90%
Γ_{16}	$\mu^+\nu_\mu e^+e^-$		$(1.06\pm0.32)\times10^{-6}$	
Γ_{17}	$e^+\nu_e e^+e^-$		$(2.1\ ^{+2.1}_{-1.1})\times10^{-7}$	
Γ_{18}	$\mu^+\nu_\mu\mu^+\mu^-$		$< 4.1 \times10^{-7}$	CL=90%
Γ_{19}	$\mu^+\nu_\mu\gamma$	[a,b]	$(5.50\pm0.28)\times10^{-3}$	
Γ_{20}	$\pi^+\pi^0\gamma$	[a,b]	$(2.75\pm0.15)\times10^{-4}$	
Γ_{21}	$\pi^+\pi^0\gamma$(DE)	[a,c]	$(1.8\pm0.4)\times10^{-5}$	
Γ_{22}	$\pi^+\pi^+\pi^-\gamma$	[a,b]	$(1.04\pm0.31)\times10^{-4}$	
Γ_{23}	$\pi^+\pi^0\pi^0\gamma$	[a,b]	$(7.5\ ^{+5.5}_{-3.0})\times10^{-6}$	
Γ_{24}	$\pi^0\mu^+\nu_\mu\gamma$	[a,b]	$< 6.1 \times10^{-5}$	CL=90%
Γ_{25}	$\pi^0 e^+\nu_e\gamma$	[a,b]	$(2.62\pm0.20)\times10^{-4}$	
Γ_{26}	$\pi^0 e^+\nu_e\gamma$(SD)	[d]	$< 5.3 \times10^{-5}$	CL=90%
Γ_{27}	$\pi^0\pi^0 e^+\nu_e\gamma$		$< 5 \times10^{-6}$	CL=90%
	Lepton Family number (*LF*), Lepton number (*L*), $\Delta S = \Delta Q$ (*SQ*) violating modes, or $\Delta S = 1$ weak neutral current (*S1*) modes			
Γ_{28}	$\pi^+\pi^+e^-\overline{\nu}_e$	*SQ*	$< 1.2 \times10^{-8}$	CL=90%
Γ_{29}	$\pi^+\pi^+\mu^-\overline{\nu}_\mu$	*SQ*	$< 3.0 \times10^{-6}$	CL=95%
Γ_{30}	$\pi^+e^+e^-$	*S1*	$(2.74\pm0.23)\times10^{-7}$	
Γ_{31}	$\pi^+\mu^+\mu^-$	*S1*	$< 2.3 \times10^{-7}$	CL=90%
Γ_{32}	$\pi^+\nu\overline{\nu}$	*S1*	$< 2.4 \times10^{-9}$	CL=90%
Γ_{33}	$\mu^-\nu e^+e^+$	*LF*	$< 2.0 \times10^{-8}$	CL=90%
Γ_{34}	$\mu^+\nu_e$	*LF* [e]	$< 4 \times10^{-3}$	CL=90%
Γ_{35}	$\pi^+\mu^+e^-$	*LF*	$< 2.1 \times10^{-10}$	CL=90%
Γ_{36}	$\pi^+\mu^-e^+$	*LF*	$< 7 \times10^{-9}$	CL=90%
Γ_{37}	$\pi^-\mu^+e^+$	*L*	$< 7 \times10^{-9}$	CL=90%
Γ_{38}	$\pi^-e^+e^+$	*L*	$< 1.0 \times10^{-8}$	CL=90%
Γ_{39}	$\pi^-\mu^+\mu^+$	*L*	$< 1.5 \times10^{-4}$	CL=90%
Γ_{40}	$\mu^+\overline{\nu}_e$	*L* [e]	$< 3.3 \times10^{-3}$	CL=90%
Γ_{41}	$\pi^0e^+\overline{\nu}_e$	*L* [e]	$< 3 \times10^{-3}$	CL=90%
Γ_{42}	$\pi^+\gamma$			

[a] See the Particle Listings below for the energy limits used in this measurement.
[b] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.
[c] Direct-emission branching fraction.
[d] Structure-dependent part.
[e] Derived from an analysis of neutrino-oscillation experiments.

CONSTRAINED FIT INFORMATION

An overall fit to the mean life, 2 decay rate, and 20 branching ratios uses 60 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 78.1$ for 53 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta p_i \delta p_j\right>/(\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−58						
x_4	−41	−12					
x_5	−27	−4	21				
x_6	−48	−17	14	2			
x_7	−50	−16	34	6	39		
x_8	−3	−1	2	0	2	6	
Γ	7	2	−18	−4	−2	−6	0
	x_1	x_3	x_4	x_5	x_6	x_7	x_8

	Mode	Rate (10^8 s^{-1})	Scale factor
Γ_1	$\mu^+\nu_\mu$	0.5128 ±0.0018	1.5
Γ_3	$\pi^+\pi^0$	0.1708 ±0.0012	1.1
Γ_4	$\pi^+\pi^+\pi^-$	0.0452 ±0.0004	1.8
Γ_5	$\pi^+\pi^0\pi^0$	0.01399±0.00032	1.2
Γ_6	$\pi^0\mu^+\nu_\mu$ Called $K^+_{\mu 3}$.	0.0257 ±0.0006	1.5
Γ_7	$\pi^0 e^+\nu_e$ Called K^+_{e3}.	0.0389 ±0.0005	1.3
Γ_8	$\pi^0\pi^0 e^+\nu_e$	$(1.69\ ^{+0.34}_{-0.29}) \times 10^{-5}$	

$K^{\pm}$ DECAY RATES

$\Gamma(\mu^+\nu_\mu)$ — Γ_1

VALUE (10^6 s^{-1})	DOCUMENT ID		TECN	CHG
51.28±0.18 OUR FIT Error includes scale factor of 1.5.				
51.2 ±0.8	FORD	67	CNTR	±

$\Gamma(\pi^+\pi^+\pi^-)$ — Γ_4

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	CHG
4.52 ±0.04 OUR FIT Error includes scale factor of 1.8.					
4.511±0.024		[6] FORD	70	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.529±0.032	3.2M	[6] FORD	70	ASPK	
4.496±0.030		[6] FORD	67	CNTR	±

[6] First FORD 70 value is second FORD 70 combined with FORD 67.

$(\Gamma(K^+) - \Gamma(K^-))\ /\ \Gamma(K)$

$K^{\pm} \to \mu^{\pm}\nu_\mu$ RATE DIFFERENCE/AVERAGE

Test of *CPT* conservation.

VALUE (%)	DOCUMENT ID		TECN
−0.54±0.41	FORD	67	CNTR

$K^{\pm} \to \pi^{\pm}\pi^+\pi^-$ RATE DIFFERENCE/AVERAGE

Test of *CP* conservation.

VALUE (%)	EVTS	DOCUMENT ID		TECN	CHG
0.07±0.12 OUR AVERAGE					
0.08±0.12		[7] FORD	70	ASPK	
−0.50±0.90		FLETCHER	67	OSPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.02±0.16		[8] SMITH	73	ASPK	±
0.10±0.14	3.2M	[7] FORD	70	ASPK	
−0.04±0.21		[7] FORD	67	CNTR	

[7] First FORD 70 value is second FORD 70 combined with FORD 67.
[8] SMITH 73 value of $K^{\pm} \to \pi^{\pm}\pi^+\pi^-$ rate difference is derived from SMITH 73 value of $K^{\pm} \to \pi^{\pm} 2\pi^0$ rate difference.

$K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ RATE DIFFERENCE/AVERAGE

Test of *CP* conservation.

VALUE (%)	EVTS	DOCUMENT ID		TECN	CHG
0.0 ±0.6 OUR AVERAGE					
0.08±0.58		SMITH	73	ASPK	±
−1.1 ±1.8	1802	HERZO	69	OSPK	

$K^{\pm} \to \pi^{\pm}\pi^0$ RATE DIFFERENCE/AVERAGE

Test of *CPT* conservation.

VALUE (%)	DOCUMENT ID		TECN
0.8±1.2	HERZO	69	OSPK

$K^{\pm} \to \pi^{\pm}\pi^0\gamma$ RATE DIFFERENCE/AVERAGE

Test of *CP* conservation.

VALUE (%)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.9± 3.3 OUR AVERAGE						
0.8± 5.8	2461	SMITH	76	WIRE	±	E_π 55–90 MeV
1.0± 4.0	4000	ABRAMS	73B	ASPK	±	E_π 51–100 MeV
0.0±24.0	24	EDWARDS	72	OSPK		E_π 58–90 MeV

K^+ BRANCHING RATIOS

$\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_1/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
63.51±0.18 OUR FIT Error includes scale factor of 1.3.						
63.24±0.44	62k	CHIANG	72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
56.9 ±2.6		[9] ALEXANDER	57	EMUL	+	
58.5 ±3.0		[9] BIRGE	56	EMUL	+	

[9] Old experiments not included in averaging.

$\Gamma(\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_1/Γ_4

VALUE	EVTS	DOCUMENT ID		TECN	CHG
11.35±0.12 OUR FIT Error includes scale factor of 1.8.					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
10.38±0.82	427	[10] YOUNG	65	EMUL	+

[10] Deleted from overall fit because YOUNG 65 constrains his results to add up to 1. Only YOUNG 65 measured $(\mu\nu)$ directly.

$\Gamma(e^+\nu_e)/\Gamma_{total}$ — Γ_2/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$2.1^{+1.8}_{-1.3}$		4	BOWEN	67B	OSPK	+
<160.0	95		BORREANI	64	HBC	+

$\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ — Γ_2/Γ_1

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG
2.45±0.11 OUR AVERAGE					
2.51±0.15	404	HEINTZE	76	SPEC	+
2.37±0.17	534	HEARD	75B	SPEC	+
2.42±0.42	112	CLARK	72	OSPK	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.8\ ^{+0.8}_{-0.6}$	8	MACEK	69	ASPK	+
$1.9\ ^{+0.7}_{-0.5}$	10	BOTTERILL	67	ASPK	+

$\Gamma(\pi^+\pi^0)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
21.16±0.14 OUR FIT Error includes scale factor of 1.1.						
21.18±0.28	16k	CHIANG	72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
21.0 ±0.6		CALLAHAN	65	HLBC		See $\Gamma(\pi^+\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$
21.6 ±0.6		TRILLING	65B	RVUE		
23.2 ±2.2		[11] ALEXANDER	57	EMUL	+	
27.7 ±2.7		[11] BIRGE	56	EMUL	+	

[11] Earlier experiments not averaged.

$\Gamma(\pi^+\pi^0)/\Gamma(\mu^+\nu_\mu)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.3331±0.0028 OUR FIT Error includes scale factor of 1.1.						
0.3316±0.0032 OUR AVERAGE						
0.3329±0.0047±0.0010	45k	USHER	92	SPEC	+	$p\bar{p}$ at rest
0.3355±0.0057		[12] WEISSENBE...	76	SPEC	+	
0.305 ±0.018	1600	ZELLER	69	ASPK	+	
0.3277±0.0065	4517	[13] AUERBACH	67	OSPK	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.328 ±0.005	25k	[12] WEISSENBE...	74	STRC	+	

[12] WEISSENBERG 76 revises WEISSENBERG 74.
[13] AUERBACH 67 changed from 0.3253 ± 0.0065. See comment with ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$.

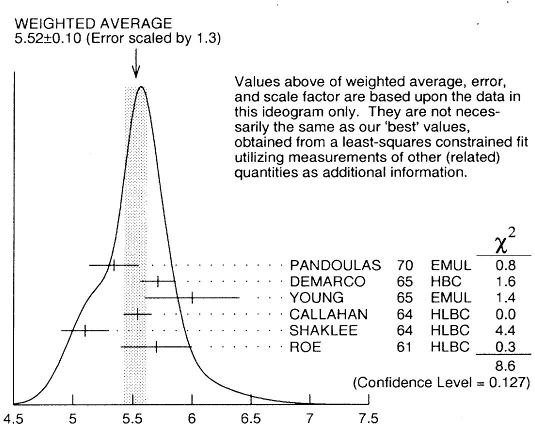
$\Gamma(\pi^+\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_3/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG
3.78±0.04 OUR FIT Error includes scale factor of 1.5.				
3.84±0.27 OUR AVERAGE Error includes scale factor of 1.9.				
3.96±0.15	1045	CALLAHAN 66	FBC	+
3.24±0.34	134	YOUNG 65	EMUL	+

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
5.59±0.05 OUR FIT Error includes scale factor of 1.8.					
5.52±0.10 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
5.34±0.21	693	[14] PANDOULAS 70	EMUL	+	
5.71±0.15		DEMARCO 65	HBC		
6.0 ±0.4	44	YOUNG 65	EMUL	+	
5.54±0.12	2332	CALLAHAN 64	HLBC	+	
5.1 ±0.2	540	SHAKLEE 64	HLBC	+	
5.7 ±0.3		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.56±0.20	2330	[15] CHIANG 72	OSPK	+	1.84 GeV/c K^+
5.2 ±0.3		[16] TAYLOR 59	EMUL	+	
6.8 ±0.4		[16] ALEXANDER 57	EMUL	+	
5.6 ±0.4		[16] BIRGE 56	EMUL	+	

[14] Includes events of TAYLOR 59.
[15] Value is not independent of CHIANG 72 $\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$, $\Gamma(\pi^+\pi^0)/\Gamma_{total}$, $\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{total}$, $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{total}$, and $\Gamma(\pi^0 e^+\nu_e)/\Gamma_{total}$.
[16] Earlier experiments not averaged.

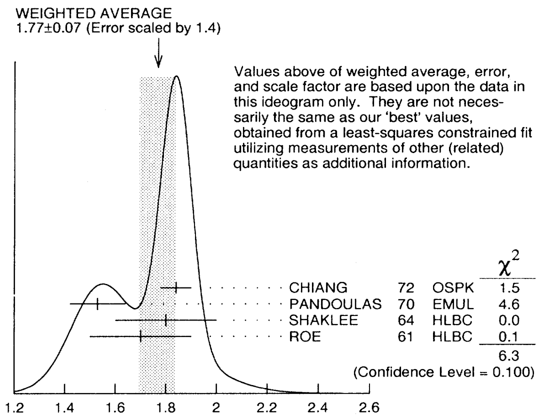


$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{total}$ (units 10^{-2})

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1.73±0.04 OUR FIT Error includes scale factor of 1.2.					
1.77±0.07 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.					
1.84±0.06	1307	CHIANG 72	OSPK	+	1.84 GeV/c K^+
1.53±0.11	198	[17] PANDOULAS 70	EMUL	+	
1.8 ±0.2	108	SHAKLEE 64	HLBC	+	
1.7 ±0.2		ROE 61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.5 ±0.2		[18] TAYLOR 59	EMUL	+	
2.2 ±0.4		[18] ALEXANDER 57	EMUL	+	
2.1 ±0.5		[18] BIRGE 56	EMUL	+	

[17] Includes events of TAYLOR 59.
[18] Earlier experiments not averaged.



$\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{total}$ (units 10^{-2})

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma(\pi^+\pi^0)$ — Γ_5/Γ_3

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.0819±0.0020 OUR FIT Error includes scale factor of 1.2.					
0.081 ±0.005	574	[19] LUCAS 73B	HBC	−	Dalitz pairs only

[19] LUCAS 73B gives $N(\pi 2\pi^0) = 574 \pm 5.9\%$, $N(2\pi) = 3564 \pm 3.1\%$. We quote $0.5N(\pi 2\pi^0)/N(2\pi)$ where 0.5 is because only Dalitz pair π^0's were used.

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_5/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.310±0.007 OUR FIT Error includes scale factor of 1.2.					
0.304±0.009 OUR AVERAGE					
0.303±0.009	2027	BISI 65	BC	+	HBC+HLBC
0.393±0.099	17	YOUNG 65	EMUL	+	

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
3.18±0.08 OUR FIT Error includes scale factor of 1.5.					
3.33±0.16	2345	CHIANG 72	OSPK	+	1.84 GeV/c K^+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.8 ±0.4		[20] TAYLOR 59	EMUL	+	
5.9 ±1.3		[20] ALEXANDER 57	EMUL	+	
2.8 ±1.0		[20] BIRGE 56	EMUL	+	

[20] Earlier experiments not averaged.

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$ — Γ_6/Γ_1

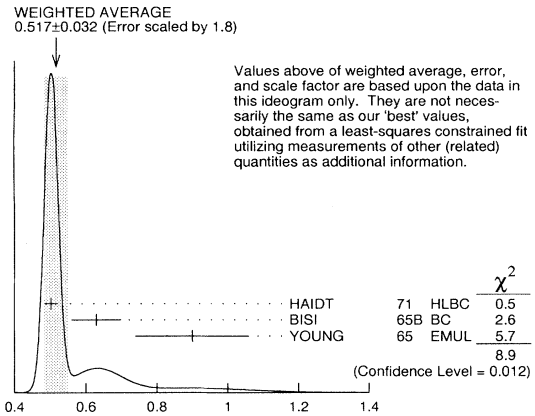
VALUE	EVTS	DOCUMENT ID	TECN	CHG
0.0501±0.0013 OUR FIT Error includes scale factor of 1.5.				
0.0488±0.0026 OUR AVERAGE				
0.054 ±0.009	240	ZELLER 69	ASPK	+
0.0480±0.0037	424	[21] GARLAND 68	OSPK	+
0.0486±0.0040	307	[22] AUERBACH 67	OSPK	+

[21] GARLAND 68 changed from 0.055 ± 0.004 in agreement with μ-spectrum calculation of GAILLARD 70 appendix B. L.G.Pondrom, (private communication 73).
[22] AUERBACH 67 changed from 0.0602 ± 0.0046 by erratum which brings the μ-spectrum calculation into agreement with GAILLARD 70 appendix B.

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_6/Γ_4

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.569±0.014 OUR FIT Error includes scale factor of 1.5.					
0.517±0.032 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.					
0.503±0.019	1505	[23] HAIDT 71	HLBC	+	
0.63 ±0.07	2845	[24] BISI 65B	BC	+	HBC+HLBC
0.90 ±0.16	38	YOUNG 65	EMUL	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.510±0.017	1505	[23] EICHTEN 68	HLBC	+	

[23] HAIDT 71 is a reanalysis of EICHTEN 68.
[24] Error enlarged for background problems. See GAILLARD 70.



$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$

$\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0 e^+\nu_e)$ — Γ_6/Γ_7

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.660±0.015 OUR FIT Error includes scale factor of 1.5.						
0.680±0.013 OUR AVERAGE						
0.705±0.063	554	[25] LUCAS	73B	HBC	−	Dalitz pairs only
0.698±0.025	3480	[26] CHIANG	72	OSPK	+	1.84 GeV/c K^+
0.667±0.017	5601	BOTTERILL	68B	ASPK	+	
0.703±0.056	1509	[27] CALLAHAN	66B	HLBC		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.670±0.014		[28] HEINTZE	77	SPEC	+	
0.67 ±0.12		WEISSENBE...	76	SPEC	+	
0.608±0.014	1585	[29] BRAUN	75	HLBC	+	
0.596±0.025		[30] HAIDT	71	HLBC	+	
0.604±0.022	1398	[30] EICHTEN	68	HLBC		

[25] LUCAS 73B gives $N(K_{\mu3})$ = 554 ± 7.6%, $N(K_{e3})$ = 786 ± 3.1%. We divide.
[26] CHIANG 72 $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0e^+\nu_e)$ is statistically independent of CHIANG 72 $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma_{total}$ and $\Gamma(\pi^0e^+\nu_e)/\Gamma_{total}$.
[27] From CALLAHAN 66B we use only the $K_{\mu3}/K_{e3}$ ratio and do not include in the fit the ratios $K_{\mu3}/(\pi\pi^+\pi^0)$ and $K_{e3}/(\pi\pi^+\pi^0)$, since they show large disagreements with the rest of the data.
[28] HEINTZE 77 value from fit to λ_0. Assumes μ-e universality.
[29] BRAUN 75 value is from form factor fit. Assumes μ-e universality.
[30] HAIDT 71 is a reanalysis of EICHTEN 68. Only individual ratios included in fit (see $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ and $\Gamma(\pi^0e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$).

$[\Gamma(\pi^+\pi^0)+\Gamma(\pi^0\mu^+\nu_\mu)]/\Gamma_{total}$ — $(\Gamma_3+\Gamma_6)/\Gamma$

We combine these two modes for experiments measuring them in xenon bubble chamber because of difficulties of separating them there.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG
24.34±0.15 OUR FIT Error includes scale factor of 1.2.					
24.6 ±1.0 OUR AVERAGE Error includes scale factor of 1.4.					
25.4 ±0.9	886	SHAKLEE	64	HLBC	+
23.4 ±1.1		ROE	61	HLBC	+

$\Gamma(\pi^0 e^+\nu_e)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
4.82±0.06 OUR FIT Error includes scale factor of 1.3.						
4.85±0.09 OUR AVERAGE						
4.86±0.10	3516	CHIANG	72	OSPK	+	1.84 GeV/c K^+
4.7 ±0.3	429	SHAKLEE	64	HLBC	+	
5.0 ±0.5		ROE	61	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
5.1 ±1.3		[31] ALEXANDER	57	EMUL	+	
3.2 ±1.3		[31] BIRGE	56	EMUL	+	

[31] Earlier experiments not averaged.

$\Gamma(\pi^0 e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ — Γ_7/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	CHG
0.0759±0.0011 OUR FIT Error includes scale factor of 1.4.					
0.0752±0.0024 OUR AVERAGE					
0.069 ±0.006	350	ZELLER	69	ASPK	+
0.0775±0.0033	960	BOTTERILL	68C	ASPK	+
0.069 ±0.006	561	GARLAND	68	OSPK	+
0.0791±0.0054	295	[32] AUERBACH	67	OSPK	+

[32] AUERBACH 67 changed from 0.0797 ± 0.0054. See comment with ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\mu^+\nu_\mu)$. The value 0.0785 ± 0.0025 given in AUERBACH 67 is an average of AUERBACH 67 $\Gamma(\pi^0e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ and CESTER 66 $\Gamma(\pi^0e^+\nu_e)/[\Gamma(\mu^+\nu_\mu)+\Gamma(\pi^+\pi^0)]$.

$\Gamma(\pi^0 e^+\nu_e)/\Gamma(\pi^+\pi^0)$ — Γ_7/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.2280±0.0035 OUR FIT Error includes scale factor of 1.3.						
0.221 ±0.012	786	[33] LUCAS	73B	HBC	−	Dalitz pairs only

[33] LUCAS 73B gives $N(K_{e3})$ = 786 ± 3.1%, $N(2\pi)$ = 3564 ± 3.1%. We divide.

$\Gamma(\pi^0 e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_7/Γ_4

VALUE	EVTS	DOCUMENT ID		TECN	CHG
0.862±0.011 OUR FIT Error includes scale factor of 1.3.					
0.860±0.014 OUR AVERAGE					
0.867±0.027	2768	BARMIN	87	XEBC	+
0.856±0.040	2827	BRAUN	75	HLBC	+
0.850±0.019	4385	[34] HAIDT	71	HLBC	+
0.94 ±0.09	854	BELLOTTI	67B	HLBC	
0.90 ±0.06	230	BORREANI	64	HBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.846±0.021	4385	[34] EICHTEN	68	HLBC	+
0.90 ±0.16	37	YOUNG	65	EMUL	+

[34] HAIDT 71 is a reanalysis of EICHTEN 68.

$\Gamma(\pi^0 e^+\nu_e)/[\Gamma(\mu^+\nu_\mu)+\Gamma(\pi^+\pi^0)]$ — $\Gamma_7/(\Gamma_1+\Gamma_3)$

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG
5.70±0.08 OUR FIT Error includes scale factor of 1.4.					
6.01±0.15 OUR AVERAGE					
5.92±0.65		[35] WEISSENBE...	76	SPEC	+
6.16±0.22	5110	ESCHSTRUTH	68	OSPK	+
5.89±0.21	1679	CESTER	66	OSPK	+

[35] Value calculated from WEISSENBERG 76 ($\pi^0 e\nu$), ($\mu\nu$), and ($\pi\pi^0$) values to eliminate dependence on our 1974 ($\pi 2\pi^0$) and ($\pi\pi^+\pi^-$) fractions.

$\Gamma(\pi^0\pi^0 e^+\nu_e)/\Gamma(\pi^0 e^+\nu_e)$ — Γ_8/Γ_7

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG
$4.3^{+0.9}_{-0.7}$ OUR FIT						
$4.1^{+1.0}_{-0.7}$ OUR AVERAGE						
$4.2^{+1.0}_{-0.9}$		25	BOLOTOV	86B	CALO	−
$3.8^{+5.0}_{-1.2}$		2	LJUNG	73	HLBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<37.0	90	0	ROMANO	71	HLBC	+

$\Gamma(\pi^0\pi^0 e^+\nu_e)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG
2.1 ±0.4 OUR FIT					
2.54±0.89	10	BARMIN	88B	HLBC	+

$\Gamma(\pi^+\pi^- e^+\nu_e)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_9/Γ_4

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	CHG
6.99±0.30 OUR AVERAGE Error includes scale factor of 1.2.					
7.21±0.32	30k	ROSSELET	77	SPEC	+
7.36±0.68	500	BOURQUIN	71	ASPK	
7.0 ±0.9	106	SCHWEINB...	71	HLBC	+
5.83±0.63	269	ELY	69	HLBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
6.7 ±1.5	69	BIRGE	65	FBC	+

$\Gamma(\pi^+\pi^-\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.77^{+0.54}_{-0.50}$	1	CLINE	65	FBC	+

$\Gamma(\pi^+\pi^-\mu^+\nu_\mu)/\Gamma(\pi^+\pi^+\pi^-)$ — Γ_{10}/Γ_4

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	CHG
2.57±1.55	7	BISI	67	DBC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 2.5	1	GREINER	64	EMUL	+

$\Gamma(\pi^0\pi^0\pi^0 e^+\nu_e)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<3.5	90	0	BOLOTOV	88	SPEC	−
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<9	90	0	BARMIN	92	XEBC	+

$\Gamma(\pi^+\gamma\gamma)/\Gamma_{total}$ — Γ_{12}/Γ

All values given here assume a phase space pion energy spectrum.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 0.01	90	0	ATIYA	90B	B787		$T\pi$ 117–127 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 0.084	90	0	ASANO	82	CNTR	+	$T\pi$ 117–127 MeV
−0.42 ±0.52		0	ABRAMS	77	SPEC	+	$T\pi$ <92 MeV
< 0.35	90	0	LJUNG	73	HLBC	+	6–102,114–127 MeV
< 0.5	90	0	KLEMS	71	OSPK	+	$T\pi$ <117 MeV
−0.1 ±0.6			CHEN	68	OSPK	+	$T\pi$ 60–90 MeV

$\Gamma(\pi^+ 3\gamma)/\Gamma_{total}$ — Γ_{13}/Γ

Values given here assume a phase space pion energy spectrum.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<1.0	90	ASANO	82	CNTR	+	$T(\pi)$ 117–127 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.0	90	KLEMS	71	OSPK	+	$T(\pi)$ >117 MeV

$\Gamma(\mu^+ \nu_\mu \nu \overline{\nu})/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<6.0	90	0	[36] PANG	73	CNTR	+

[36] PANG 73 assumes μ spectrum from ν-ν interaction of BARDIN 70.

$\Gamma(e^+ \nu_e \nu \overline{\nu})/\Gamma(e^+ \nu_e)$ — Γ_{15}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG
<3.8	90	0	HEINTZE	79	SPEC	+

$\Gamma(\mu^+ \nu_\mu e^+ e^-)/\Gamma(\pi^+ \pi^- e^+ \nu_e)$ — Γ_{16}/Γ_9

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
27. ±8.	14	[37] DIAMANT-...	76	SPEC	+	Extrapolated BR
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3.3 ±0.9	14	[37] DIAMANT-...	76	SPEC	+	m_{ee} >140

[37] DIAMANT-BERGER 76 quotes this result times our 1975 $\pi^+ \pi^- e \nu$ BR ratio. The first DIAMANT-BERGER 76 value is the second value extrapolated to 0 to include low mass e pairs.

$\Gamma(e^+ \nu_e e^+ e^-)/\Gamma(\pi^+ \pi^- e^+ \nu_e)$ — Γ_{17}/Γ_9

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG
$0.54^{+0.54}_{-0.27}$	4	DIAMANT-...	76	SPEC	+

$\Gamma(\mu^+ \nu_\mu \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-7})	CL%	DOCUMENT ID		TECN	CHG
<4.1	90	ATIYA	89	B787	+

$\Gamma(\mu^+ \nu_\mu \gamma)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
5.50±0.28 OUR AVERAGE						
6.6 ±1.5		[38,39] DEMIDOV	90	XEBC		P(μ) < 231.5 MeV/c
6.0 ±0.9		BARMIN	88	HLBC	+	P(μ) < 231.5 MeV/c
5.4 ±0.3		[40] AKIBA	85	SPEC		P(μ) <231.5 MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3.5 ±0.8		[39,41] DEMIDOV	90	XEBC		E(γ) > 20 MeV
3.2 ±0.5	57	[42] BARMIN	88	HLBC	+	$E(\gamma)$ >20 MeV
5.8 ±3.5	12	WEISSENBE...	74	STRC	+	$E(\gamma)$ >9 MeV

[38] P(μ) cut given in DEMIDOV 90 paper, 235.1 MeV/c, is a misprint according to authors (private communication).

[39] DEMIDOV 90 quotes only inner bremsstrahlung (IB) part.

[40] Assumes μ-e universality and uses constraints from $K \rightarrow e \nu \gamma$.

[41] Not independent of above DEMIDOV 90 value. Cuts differ.

[42] Not independent of above BARMIN 88 value. Cuts differ.

$\Gamma(\pi^+ \pi^0 \gamma)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2.75±0.15 OUR AVERAGE							
2.71±0.45		140	BOLOTOV	87	WIRE	−	$T\pi^-$ 55–90 MeV
2.87±0.32		2461	SMITH	76	WIRE	±	$T\pi^\pm$ 55–90 MeV
2.71±0.19		2100	ABRAMS	72	ASPK	±	$T\pi^+$ 55–90 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$1.5\ ^{+1.1}_{-0.6}$			[43] LJUNG	73	HLBC	+	$T\pi^+$ 55–80 MeV
$2.6\ ^{+1.5}_{-1.1}$			[43] LJUNG	73	HLBC	+	$T\pi^+$ 55–90 MeV
$6.8\ ^{+3.7}_{-2.1}$		17	[43] LJUNG	73	HLBC	+	$T\pi^+$ 55–102 MeV
2.4 ±0.8		24	EDWARDS	72	OSPK		$T\pi^+$ 58–90 MeV
<1.0		0	[44] MALTSEV	70	HLBC	+	$T\pi^+$ <55 MeV
<1.9	90	0	EMMERSON	69	OSPK		$T\pi^+$ 55–80 MeV
2.2 ±0.7		18	CLINE	64	FBC	+	$T\pi^+$ 55–80 MeV

[43] The LJUNG 73 values are not independent.

[44] MALTSEV 70 selects low π^+ energy to enhance direct emission contribution.

$\Gamma(\pi^+ \pi^0 \gamma(\text{DE}))/\Gamma_{total}$ — Γ_{21}/Γ

Direct emission part of $\Gamma(\pi^+ \pi^0 \gamma)/\Gamma_{total}$.

VALUE (units 10^{-5})	DOCUMENT ID		TECN	CHG	COMMENT
1.8 ±0.4 OUR AVERAGE					
$2.05\pm0.46^{+0.39}_{-0.23}$	BOLOTOV	87	WIRE	−	$T\pi^-$ 55–90 MeV
2.3 ±3.2	SMITH	76	WIRE	±	$T\pi^\pm$ 55–90 MeV
1.56±0.35±0.5	ABRAMS	72	ASPK	±	$T\pi^\pm$ 55–90 MeV

$\Gamma(\pi^+ \pi^+ \pi^- \gamma)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.04±0.31 OUR AVERAGE						
1.10±0.48	7	BARMIN	89	XEBC		$E(\gamma)$ > 5 MeV
1.0 ±0.4		STAMER	65	EMUL	+	$E(\gamma)$ >11 MeV

$\Gamma(\pi^+ \pi^0 \pi^0 \gamma)/\Gamma(\pi^+ \pi^0 \pi^0)$ — Γ_{23}/Γ_5

VALUE (units 10^{-4})	DOCUMENT ID		TECN	CHG	COMMENT
$4.3^{+3.2}_{-1.7}$	BOLOTOV	85	SPEC	−	$E(\gamma)$ > 10 MeV

$\Gamma(\pi^0 \mu^+ \nu_\mu \gamma)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<6.1	90	0	LJUNG	73	HLBC	+	$E(\gamma)$ >30 MeV

$\Gamma(\pi^0 e^+ \nu_e \gamma)/\Gamma(\pi^0 e^+ \nu_e)$ — Γ_{25}/Γ_7

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.54±0.04 OUR AVERAGE Error includes scale factor of 1.1.						
0.46±0.08	82	[45] BARMIN	91	XEBC		$E(\gamma)$ > 10 MeV, 0.6 < $\cos\theta_{e\ \gamma}$ < 0.9
0.56±0.04	192	[46] BOLOTOV	86B	CALO	−	$E(\gamma)$ >10 MeV
0.76±0.28	13	[47] ROMANO	71	HLBC		$E(\gamma)$ >10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.51±0.25	82	[45] BARMIN	91	XEBC		$E(\gamma)$ > 10 MeV, $\cos\theta_{e\ \gamma}$ < 0.98
0.48±0.20	16	[48] LJUNG	73	HLBC	+	$E(\gamma)$ >30 MeV
$0.22^{+0.15}_{-0.10}$		[48] LJUNG	73	HLBC	+	$E(\gamma)$ >30 MeV
0.53±0.22		[47] ROMANO	71	HLBC	+	$E(\gamma)$ >30 MeV
1.2 ±0.8		BELLOTTI	67	HLBC	+	$E(\gamma)$ >30 MeV

[45] BARMIN 91 quotes branching ratio $\Gamma(K \rightarrow e\pi^0 \nu\gamma)/\Gamma_{all}$. The measured normalization is $[\Gamma(K \rightarrow e\pi^0\nu) + \Gamma(K \rightarrow \pi^+\pi^+\pi^-)]$. For comparison with other experiments we used $\Gamma(K \rightarrow e\pi^0\nu)/\Gamma_{all} = 0.0482$ to calculate the values quoted here.

[46] $\cos\theta(e\gamma)$ between 0.6 and 0.9.

[47] Both ROMANO 71 values are for $\cos\theta(e\gamma)$ between 0.6 and 0.9. Second value is for comparison with second LJUNG 73 value. We use lowest $E(\gamma)$ cut for Summary Table value. See ROMANO 71 for E_γ dependence.

[48] First LJUNG 73 value is for $\cos\theta(e\gamma)$ <0.9, second value is for $\cos\theta(e\gamma)$ between 0.6 and 0.9 for comparison with ROMANO 71.

$\Gamma(\pi^0 e^+ \nu_e \gamma(\text{SD}))/\Gamma_{total}$ — Γ_{26}/Γ

Structure-dependent part.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	CHG
<5.3	90	BOLOTOV	86B	CALO	−

$\Gamma(\pi^0 \pi^0 e^+ \nu_e \gamma)/\Gamma_{total}$ — Γ_{27}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<5	90	0	BARMIN	92	XEBC	+	E_γ > 10 MeV

$\Gamma(\pi^+ \pi^+ e^- \overline{\nu}_e)/\Gamma_{total}$ — Γ_{28}/Γ

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 9.0	95	0	SCHWEINB...	71	HLBC	+
< 6.9	95	0	ELY	69	HLBC	+
<20.	95		BIRGE	65	FBC	+

$\Gamma(\pi^+ \pi^+ e^- \overline{\nu}_e)/\Gamma(\pi^+ \pi^- e^+ \nu_e)$ — Γ_{28}/Γ_9

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN
< 3	90	3	[49] BLOCH	76	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<130.	95	0	BOURQUIN	71	ASPK

[49] BLOCH 76 quotes 3.6×10^{-4} at CL = 95%, we convert.

$\Gamma(\pi^+ \pi^+ \mu^- \overline{\nu}_\mu)/\Gamma_{total}$ — Γ_{29}/Γ

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<3.0	95	0	BIRGE	65	FBC	+

$\Gamma(\pi^+ e^+ e^-)/\Gamma_{total}$ — Γ_{30}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by combined first-order weak and electromagnetic interactions.

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2.74±0.23 OUR AVERAGE							
2.75±0.23±0.13		500	[50] ALLIEGRO	92	SPEC	+	
2.7 ±0.5		41	[51] BLOCH	75	SPEC	+	

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 17	90		CENCE	74	ASPK	+	Three track evts
< 2.7	90		CENCE	74	ASPK	+	Two track events
<320	90		BEIER	72	OSPK	±	
< 44	90		BISI	67	DBC	+	
< 8.8	90		CLINE	67B	FBC	+	
< 24.5	90	1	CAMERINI	64	FBC	+	

[50] ALLIEGRO 92 assumes a vector interaction with a form factor given by $\lambda = 0.105 \pm 0.035 \pm 0.015$ and a correlation coefficient of -0.82.
[51] BLOCH 75 assumes a vector interaction.

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{31}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-7})	CL%	DOCUMENT ID		TECN	CHG
< 2.3	90	ATIYA	89	B787	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<24	90	BISI	67	DBC	+
<30	90	CAMERINI	65	FBC	+

$\Gamma(\pi^+\nu\overline{\nu})/\Gamma_{\text{total}}$ — Γ_{32}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 2.4	90		ADLER	96	B787		
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 7.5	90		ATIYA	93	B787	+	$T(\pi)$ 115–127 MeV
< 5.2	90		[52] ATIYA	93	B787	+	
< 17	90	0	ATIYA	93B	B787	+	$T(\pi)$ 60–100 MeV
< 34	90		ATIYA	90	B787	+	
< 140	90		ASANO	81B	CNTR	+	$T(\pi)$ 116–127 MeV
< 940	90		[53] CABLE	73	CNTR	+	$T(\pi)$ 60–105 MeV
< 560	90		[53] CABLE	73	CNTR	+	$T(\pi)$ 60–127 MeV
<57000	90	0	[54] LJUNG	73	HLBC	+	
< 1400	90		[53] KLEMS	71	OSPK	+	$T(\pi)$ 117–127 MeV

[52] Combining ATIYA 93 and ATIYA 93B results. Superseded by ADLER 96.
[53] KLEMS 71 and CABLE 73 assume π spectrum same as K_{e3} decay. Second CABLE 73 limit combines CABLE 73 and KLEMS 71 data for vector interaction.
[54] LJUNG 73 assumes vector interaction.

$\Gamma(\mu^-\nu e^+e^+)/\Gamma(\pi^+\pi^-e^+\nu_e)$ — Γ_{33}/Γ_9

Test of lepton family number conservation.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<0.5	90	0	[55] DIAMANT-...	76	SPEC	+

[55] DIAMANT-BERGER 76 quotes this result times our 1975 $\pi^+\pi^-e\nu$ BR ratio.

$\Gamma(\mu^+\nu_e)/\Gamma_{\text{total}}$ — Γ_{34}/Γ

Forbidden by lepton family number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<0.004	90	0	LYONS	81	HLBC	0	200 GeV K^+ narrow band ν beam
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<0.012	90		COOPER	82	HLBC		Wideband ν beam

$\Gamma(\pi^+\mu^+e^-)/\Gamma_{\text{total}}$ — Γ_{35}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-10})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 2.1	90	0	LEE	90	SPEC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<11	90	0	CAMPAGNARI	88	SPEC	+	In LEE 90
<48	90	0	DIAMANT-...	76	SPEC	+	

$\Gamma(\pi^+\mu^-e^+)/\Gamma_{\text{total}}$ — Γ_{36}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	CHG
< 7	90	0	[56] DIAMANT-...	76	SPEC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<28	90		[56] BEIER	72	OSPK	±

[56] Measurement actually applies to the sum of the $\pi^+\mu^-e^+$ and $\pi^-\mu^+e^+$ modes.

$\Gamma(\pi^-\mu^+e^+)/\Gamma_{\text{total}}$ — Γ_{37}/Γ

Test of total lepton number conservation.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	CHG
< 7	90	0	[57] DIAMANT-...	76	SPEC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<28	90		[57] BEIER	72	OSPK	±

[57] Measurement actually applies to the sum of the $\pi^+\mu^-e^+$ and $\pi^-\mu^+e^+$ modes.

$\Gamma(\pi^+\mu^-e^+)/\Gamma_{\text{total}}$ — Γ_{36}/Γ

VALUE (units 10^{-8})	CL%	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4	90	BEIER	72	OSPK	±

$\Gamma(\pi^-e^+e^+)/\Gamma_{\text{total}}$ — Γ_{38}/Γ

Test of total lepton number conservation.

VALUE (units 10^{-5})	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.5	CHANG	68	HBC	−

$\Gamma(\pi^-e^+e^+)/\Gamma(\pi^+\pi^-e^+\nu_e)$ — Γ_{38}/Γ_9

Test of total lepton number conservation.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG
<2.5	90	0	[58] DIAMANT-...	76	SPEC	+

[58] DIAMANT-BERGER 76 quotes this result times our 1975 BR ratio.

$\Gamma(\pi^-\mu^+\mu^+)/\Gamma_{\text{total}}$ — Γ_{39}/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN
<1.5	90	[59] LITTENBERG	92	HBC

[59] LITTENBERG 92 is from retroactive data analysis of CHANG 68 bubble chamber data.

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{\text{total}}$ — Γ_{40}/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<3.3	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\pi^0e^+\overline{\nu}_e)/\Gamma_{\text{total}}$ — Γ_{41}/Γ

Forbidden by total lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.003	90	COOPER	82	HLBC	Wideband ν beam

$\Gamma(\pi^+\gamma)/\Gamma_{\text{total}}$ — Γ_{42}/Γ

Violates angular momentum conservation. Not listed in Summary Table.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	CHG
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4	90	ASANO	82	CNTR	+
<4.0	90	[60] KLEMS	71	OSPK	+

[60] Test of model of Selleri, Nuovo Cimento **60A** 291 (1969).

K^+ LONGITUDINAL POLARIZATION OF EMITTED μ^+

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<−0.990	90	[61] AOKI	94	SPEC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<−0.990	90	IMAZATO	92	SPEC	+	Repl. by AOKI 94
−0.970±0.047		[62] YAMANAKA	86	SPEC	+	
−1.0 ±0.1		[62] CUTTS	69	SPRK	+	
−0.96 ±0.12		[62] COOMBES	57	CNTR	+	

[61] AOKI 94 measures $\xi P_\mu = -0.9996 \pm 0.0030 \pm 0.0048$. The above limit is obtained by summing the statistical and systematic errors in quadrature, normalizing to the physically significant region ($|\xi P_\mu| < 1$) and assuming that ξ=1, its maximum value.
[62] Assumes ξ=1.

DALITZ PLOT PARAMETERS FOR $K \to 3\pi$ DECAYS

The Dalitz plot distribution for $K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$, $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$, and $K^0_L \to \pi^+\pi^-\pi^0$ can be parameterized by a series expansion such as that introduced by Weinberg [1]. We use the form

$$\left|M\right|^2 \propto 1 + g\frac{(s_3 - s_0)}{am^2_{\pi^+}} + h\left[\frac{s_3 - s_0}{m^2_{\pi^+}}\right]^2 + j\,\frac{(s_2 - s_1)}{m^2_{\pi^+}} + ak\left[\frac{s_2 - s_1}{m^2_{\pi^+}}\right]^2 + \cdots \ , \tag{1}$$

where $m^2_{\pi^+}$ has been introduced to make the coefficients g, h, j, and k dimensionless, and

$$s_i = (P_K - P_i)^2 = (m_K - m_i)^2 - 2m_K T_i \ , \ i = 1, 2, 3,$$

$$s_0 = \frac{1}{3}\sum_i s_i = \frac{1}{3}(m_K^2 + m_1^2 + m_2^2 + m_3^2)$$

Here the P_i are four-vectors, m_i and T_i are the mass and kinetic energy of the i^{th} pion, and the index 3 is used for the odd pion.

The coefficient g is a measure of the slope in the variable s_3 (or T_3) of the Dalitz plot, while h and k measure the quadratic dependence on s_3 and $(s_2 - s_1)$, respectively. The coefficient j is related to the asymmetry of the plot and must be zero if CP invariance holds. Note also that if CP is good, g, h, and k must be the same for $K^+ \to \pi^+\pi^+\pi^-$ as for $K^- \to \pi^-\pi^-\pi^+$.

Since different experiments use different forms for $\left|M\right|^2$, in order to compare the experiments we have converted to g, h, j, and k whatever coefficients have been measured. Where such conversions have been done, the measured coefficient a_y, a_t, a_u, or a_v is given in the comment at the right. For definitions of these coefficients, details of this conversion, and discussion of the data, see the April 1982 version of this note [2].

References

1. S. Weinberg, Phys. Rev. Lett. **4**, 87 (1960).
2. Particle Data Group, Phys. Lett. **111B**, 69 (1982).

ENERGY DEPENDENCE OF $K^{\pm}$ DALITZ PLOT

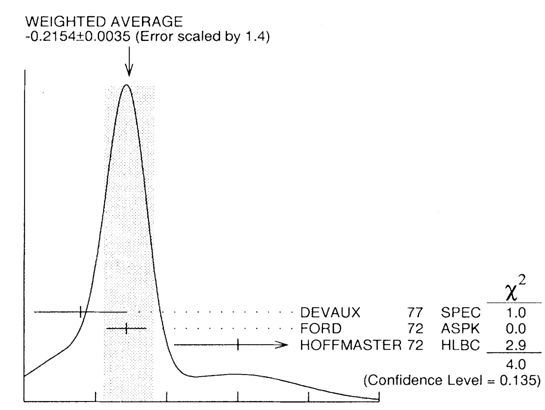
$|\text{matrix element}|^2 = 1 + gu + hu^2 + kv^2$
where $u = (s_3 - s_0) / m_\pi^2$ and $v = (s_1 - s_2) / m_\pi^2$

LINEAR COEFFICIENT $g_{\tau+}$ FOR $K^+ \to \pi^+\pi^+\pi^-$

Some experiments use Dalitz variables x and y. In the comments we give a_y = coefficient of y term. See note above on "Dalitz Plot Parameters for $K \to 3\pi$ Decays." For discussion of the conversion of a_y to g, see the earlier version of the same note in the *Review* published in Physics Letters **111B** 70 (1982).

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.2154±0.0035 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.				
−0.2221±0.0065	225k	DEVAUX	77	SPEC	+	a_y=.2814 ± .0082
−0.2157±0.0028	750k	FORD	72	ASPK	+	a_y=.2734 ± .0035
−0.200 ±0.009	39819	[63] HOFFMASTER	72	HLBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.196 ±0.012	17898	[64] GRAUMAN	70	HLBC	+	a_y=0.228 ± 0.030
−0.218 ±0.016	9994	[65] BUTLER	68	HBC	+	a_y=0.277 ± 0.020
−0.22 ±0.024	5428	[65,66] ZINCHENKO	67	HBC	+	a_y=0.28 ± 0.03

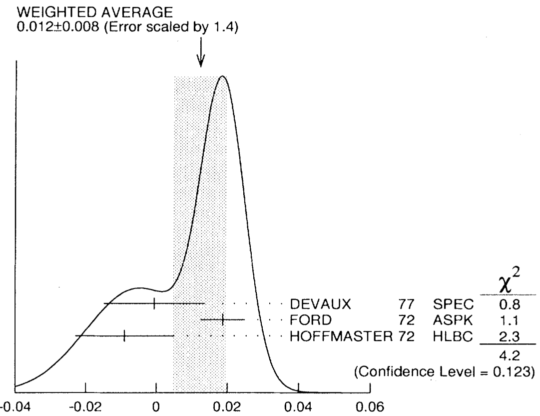
[63] HOFFMASTER 72 includes GRAUMAN 70 data.
[64] Emulsion data added — all events included by HOFFMASTER 72.
[65] Experiments with large errors not included in average.
[66] Also includes DBC events.



Linear energy dependence for $K^+ \to \pi^+\pi^+\pi^-$

QUADRATIC COEFFICIENT h FOR $K^+ \to \pi^+\pi^+\pi^-$

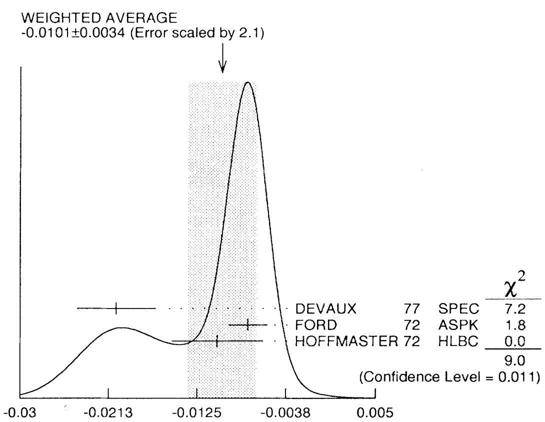
VALUE	EVTS	DOCUMENT ID		TECN	CHG
0.012 ±0.008 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.			
−0.0006±0.0143	225k	DEVAUX	77	SPEC	+
0.0187±0.0062	750k	FORD	72	ASPK	+
−0.009 ±0.014	39819	HOFFMASTER	72	HLBC	+



Quadratic coefficient h for $K^+ \to \pi^+\pi^+\pi^-$

QUADRATIC COEFFICIENT k FOR $K^+ \to \pi^+\pi^+\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	CHG
−0.0101±0.0034 OUR AVERAGE		Error includes scale factor of 2.1. See the ideogram below.			
−0.0205±0.0039	225k	DEVAUX	77	SPEC	+
−0.0075±0.0019	750k	FORD	72	ASPK	+
−0.0105±0.0045	39819	HOFFMASTER	72	HLBC	+



Quadratic coefficient k for $K^+ \to \pi^+\pi^+\pi^-$

LINEAR COEFFICIENT $g_{\tau-}$ FOR $K^- \to \pi^-\pi^-\pi^+$

Some experiments use Dalitz variables x and y. In the comments we give a_y = coefficient of y term. See note above on "Dalitz Plot Parameters for $K \to 3\pi$ Decays." For discussion of the conversion of a_y to g, see the earlier version of the same note in the *Review* published in Physics Letters **111B** 70 (1982).

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.217 ±0.007 OUR AVERAGE		Error includes scale factor of 2.5.				
−0.2186±0.0028	750k	FORD	72	ASPK	−	a_y=.2770 ± .0035
−0.193 ±0.010	50919	MAST	69	HBC	−	a_y=0.244 ± 0.013
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.199 ±0.008	81k	[67] LUCAS	73	HBC	−	a_y=0.252 ± 0.011
−0.190 ±0.023	5778	[68,69] MOSCOSO	68	HBC	−	a_y=0.242 ± 0.029
−0.220 ±0.035	1347	[70] FERRO-LUZZI	61	HBC	−	a_y=0.28 ± 0.045

[67] Quadratic dependence is required by K_L^0 experiments. For comparison we average only those $K^{\pm}$ experiments which quote quadratic fit values.
[68] Experiments with large errors not included in average.
[69] Also includes DBC events.
[70] No radiative corrections included.

QUADRATIC COEFFICIENT h FOR $K^- \to \pi^-\pi^-\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	CHG
0.010 ±0.006 OUR AVERAGE					
0.0125±0.0062	750k	FORD	72	ASPK	−
−0.001 ±0.012	50919	MAST	69	HBC	−

QUADRATIC COEFFICIENT k FOR $K^- \to \pi^-\pi^-\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	CHG
−0.0084±0.0019 OUR AVERAGE					
−0.0083±0.0019	750k	FORD	72	ASPK	−
−0.014 ±0.012	50919	MAST	69	HBC	−

$(g_{\tau^+} - g_{\tau^-}) / (g_{\tau^+} + g_{\tau^-})$ FOR $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$

A nonzero value for this quantity indicates *CP* violation.

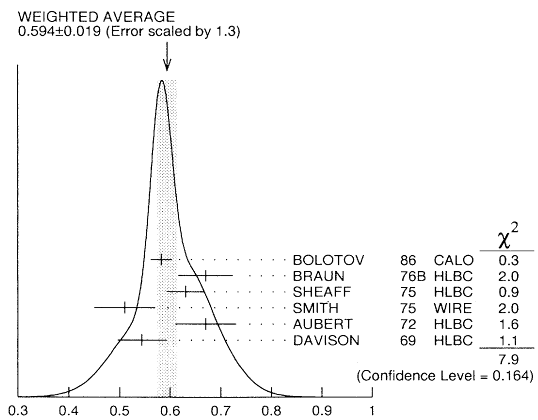
VALUE (%)	EVTS	DOCUMENT ID		TECN
−0.70±0.53	3.2M	FORD	70	ASPK

LINEAR COEFFICIENT g FOR $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$

Unless otherwise stated, all experiments include terms quadratic in $(s_3 - s_0) / m^2_{\pi^+}$. See mini-review above.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.594±0.019 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.					
0.582±0.021	43k	BOLOTOV	86	CALO	−	
0.670±0.054	3263	BRAUN	76B	HLBC	+	
0.630±0.038	5635	SHEAFF	75	HLBC	+	
0.510±0.060	27k	SMITH	75	WIRE	+	
0.67 ±0.06	1365	AUBERT	72	HLBC	+	
0.544±0.048	4048	DAVISON	69	HLBC	+	Also emulsion
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.806±0.220	4639	[71] BERTRAND	76	EMUL	+	
0.484±0.084	574	[72] LUCAS	73B	HBC	−	Dalitz pairs only
0.527±0.102	198	[71] PANDOULAS	70	EMUL	+	
0.586±0.098	1874	[72] BISI	65	HLBC	+	Also HBC
0.48 ±0.04	1792	[72] KALMUS	64	HLBC	+	

[71] Experiments with large errors not included in average.
[72] Authors give linear fit only.



Linear energy dependence for $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$

QUADRATIC COEFFICIENT h FOR $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$

See mini-review above.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.035±0.015 OUR AVERAGE						
0.037±0.024	43k	BOLOTOV	86	CALO	−	
0.152±0.082	3263	BRAUN	76B	HLBC	+	
0.041±0.030	5635	SHEAFF	75	HLBC	+	
0.009±0.040	27k	SMITH	75	WIRE	+	
−0.01 ±0.08	1365	AUBERT	72	HLBC	+	
0.026±0.050	4048	DAVISON	69	HLBC	+	Also emulsion
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.164±0.121	4639	[73] BERTRAND	76	EMUL	+	
0.018±0.124	198	[73] PANDOULAS	70	EMUL	+	

[73] Experiments with large errors not included in average.

$K^{\pm}_{\ell 3}$ AND $K^{0}_{\ell 3}$ FORM FACTORS

Assuming that only the vector current contributes to $K \rightarrow \pi \ell \nu$ decays, we write the matrix element as

$$M \propto f_+(t) \left[(P_K + P_\pi)_\mu \bar{\ell} \gamma_\mu (1 + \gamma_5) \nu \right] + f_-(t) \left[m_\ell \bar{\ell} (1 + \gamma_5) \nu \right] \ , \qquad (1)$$

where P_K and P_π are the four-momenta of the K and π mesons, m_ℓ is the lepton mass, and f_+ and f_- are dimensionless form factors which can depend only on $t = (P_K - P_\pi)^2$, the square of the four-momentum transfer to the leptons. If time-reversal invariance holds, f_+ and f_- are relatively real. $K_{\mu 3}$ experiments measure f_+ and f_-, while K_{e3} experiments are sensitive only to f_+ because the small electron mass makes the f_- term negligible.

(a) $K_{\mu 3}$ *experiments.* Analyses of $K_{\mu 3}$ data frequently assume a linear dependence of f_+ and f_- on t, *i.e.*,

$$f_\pm(t) = f_\pm(0) \left[1 + \lambda_\pm (t/m_\pi^2) \right] \qquad (2)$$

Most $K_{\mu 3}$ data are adequately described by Eq. (2) for f_+ and a constant f_- (*i.e.*, $\lambda_- = 0$). There are two equivalent parametrizations commonly used in these analyses:

(1) $\lambda_+, \xi(0)$ *parametrization.* Analyses of $K_{\mu 3}$ data often introduce the ratio of the two form factors

$$\xi(t) = f_-(t)/f_+(t) \ .$$

The $K_{\mu 3}$ decay distribution is then described by the two parameters λ_+ and $\xi(0)$ (assuming time reversal invariance and $\lambda_- = 0$). These parameters can be determined by three different methods:

Method A. By studying the Dalitz plot or the pion spectrum of $K_{\mu 3}$ decay. The Dalitz plot density is (see, *e.g.*, Chounet *et al.* [1]):

$$\rho(E_\pi, E_\mu) \propto f_+^2(t) \left[A + B\xi(t) + C\xi(t)^2 \right] \ ,$$

where

$$A = m_K \left(2E_\mu E_\nu - m_K E'_\pi \right) + m_\mu^2 \left(\frac{1}{4} E'_\pi - E_\nu \right) \ ,$$

$$B = m_\mu^2 \left(E_\nu - \frac{1}{2} E'_\pi \right) \ ,$$

$$C = \frac{1}{4} m_\mu^2 E'_\pi \ ,$$

$$E'_\pi = E_\pi^{\max} - E_\pi = \left(m_K^2 + m_\pi^2 - m_\mu^2 \right) / 2m_K - E_\pi \ .$$

Here E_π, E_μ, and E_ν are, respectively, the pion, muon, and neutrino energies in the kaon center of mass. The density ρ is fit to the data to determine the values of $\lambda_+, \xi(0)$, and their correlation.

Method B. By measuring the $K_{\mu 3}/K_{e3}$ branching ratio and comparing it with the theoretical ratio (see, *e.g.*, Fearing *et al.* [2]) as given in terms of λ_+ and $\xi(0)$, assuming μ-e universality:

$$\Gamma(K^\pm_{\mu 3})/\Gamma(K^\pm_{e3}) = 0.6457 + 1.4115\lambda_+ + 0.1264\xi(0) + 0.0192\xi(0)^2 + 0.0080\lambda_+\xi(0) \ ,$$

$$\Gamma(K^0_{\mu 3})/\Gamma(K^0_{e3}) = 0.6452 + 1.3162\lambda_+ + 0.1264\xi(0) + 0.0186\xi(0)^2 + 0.0064\lambda_+\xi(0) \ .$$

This cannot determine λ_+ and $\xi(0)$ simultaneously but simply fixes a relationship between them.

Method C. By measuring the muon polarization in $K_{\mu 3}$ decay. In the rest frame of the K, the μ is expected to be polarized in the direction $\mathbf{A}$ with $\mathbf{P} = \mathbf{A}/\left|\mathbf{A}\right|$, where $\mathbf{A}$ is given (Cabibbo and Maksymowicz [3]) by

$$\begin{aligned}\mathbf{A} &= a_1(\xi)\mathbf{p}_\mu \\ &- a_2(\xi)\left[\frac{\mathbf{p}_\mu}{m_\mu}\left(m_K - E_\pi + \frac{\mathbf{p}_\pi \cdot \mathbf{p}_\mu}{\left|\mathbf{p}_\mu\right|^2}(E_\mu - m_\mu)\right) + \mathbf{p}_\pi\right] \\ &+ m_K \mathrm{Im}\xi(t)(\mathbf{p}_\pi \times \mathbf{p}_\mu)\ .\end{aligned}$$

If time-reversal invariance holds, ξ is real, and thus there is no polarization perpendicular to the K-decay plane. Polarization experiments measure the weighted average of $\xi(t)$ over the t range of the experiment, where the weighting accounts for the variation with t of the sensitivity to $\xi(t)$.

(2) λ_+, λ_0 parametrization. Most of the more recent $K_{\mu 3}$ analyses have parameterized in terms of the form factors f_+ and f_0 which are associated with vector and scalar exchange, respectively, to the lepton pair. f_0 is related to f_+ and f_- by

$$f_0(t) = f_+(t) + \left[t/(m_K^2 - m_\pi^2)\right] f_-(t)\ .$$

Here $f_0(0)$ must equal $f_+(0)$ unless $f_-(t)$ diverges at $t = 0$. The earlier assumption that f_+ is linear in t and f_- is constant leads to f_0 linear in t:

$$f_0(t) = f_0(0)\left[1 + \lambda_0(t/m_\pi^2)\right]\ .$$

With the assumption that $f_0(0) = f_+(0)$, the two parametrizations, $(\lambda_+, \xi(0))$ and (λ_+, λ_0) are equivalent as long as correlation information is retained. (λ_+, λ_0) correlations tend to be less strong than $(\lambda_+, \xi(0))$ correlations.

The experimental results for $\xi(0)$ and its correlation with λ_+ are listed in the $K^\pm$ and K_L^0 sections of the Particle Listings in section ξ_A, ξ_B, or ξ_C depending on whether method A, B, or C discussed above was used. The corresponding values of λ_+ are also listed.

Because recent experiments tend to use the (λ_+, λ_0) parametrization, we include a subsection for λ_0 results. Wherever possible we have converted $\xi(0)$ results into λ_0 results and vice versa.

See the 1982 version of this note [4] for additional discussion of the $K_{\mu 3}^0$ parameters, correlations, and conversion between parametrizations, and also for a comparison of the experimental results.

(b) K_{e3} experiments. Analysis of K_{e3} data is simpler than that of $K_{\mu 3}$ because the second term of the matrix element assuming a pure vector current [Eq. (1) above] can be neglected. Here f_+ is usually assumed to be linear in t, and the linear coefficient λ_+ of Eq. (2) is determined.

If we remove the assumption of a pure vector current, then the matrix element for the decay, in addition to the terms in Eq. (2), would contain

$$\begin{aligned}&+2m_K\, f_S\, \bar{\ell}(1+\gamma_5)\nu \\ &+(2f_T/m_K)(P_K)_\lambda(P_\pi)_\mu\, \bar{\ell}\, \sigma_{\lambda\mu}(1+\gamma_5)\nu\ ,\end{aligned}$$

where f_S is the scalar form factor, and f_T is the tensor form factor. In the case of the K_{e3} decays where the f_- term can be neglected, experiments have yielded limits on $|f_S/f_+|$ and $|f_T/f_+|$.

References

1. L.M. Chounet, J.M. Gaillard, and M.K. Gaillard, Phys. Reports **4C**, 199 (1972).
2. H.W. Fearing, E. Fischbach, and J. Smith, Phys. Rev. **D2**, 542 (1970).
3. N. Cabibbo and A. Maksymowicz, Phys. Lett. **9**, 352 (1964).
4. Particle Data Group, Phys. Lett. **111B**, 73 (1982).

$K_{\ell 3}^{\pm}$ FORM FACTORS

In the form factor comments, the following symbols are used.

f_+ and f_- are form factors for the vector matrix element.

f_S and f_T refer to the scalar and tensor term.

$f_0 = f_+ + f_- t/(m_K^2 - m_\pi^2)$.

λ_+, λ_-, and λ_0 are the linear expansion coefficients of f_+, f_-, and f_0.

λ_+ refers to the $K_{\mu 3}^{\pm}$ value except in the $K_{e3}^{\pm}$ sections.

$d\xi(0)/d\lambda_+$ is the correlation between $\xi(0)$ and λ_+ in $K_{\mu 3}^{\pm}$.

$d\lambda_0/d\lambda_+$ is the correlation between λ_0 and λ_+ in $K_{\mu 3}^{\pm}$.

t = momentum transfer to the π in units of m_π^2.

DP = Dalitz plot analysis.

PI = π spectrum analysis.

MU = μ spectrum analysis.

POL= μ polarization analysis.

BR = $K_{\mu 3}^{\pm}/K_{e3}^{\pm}$ branching ratio analysis.

E = positron or electron spectrum analysis.

RC = radiative corrections.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K_{e3}^{\pm}$ DECAY)

For radiative correction of $K_{e3}^{\pm}$ Dalitz plot, see GINSBERG 67 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.0286±0.0022 OUR AVERAGE						
0.0284±0.0027±0.0020	32k	[74] AKIMENKO	91	SPEC		PI, no RC
0.029 ±0.004	62k	[75] BOLOTOV	88	SPEC		PI, no RC
0.027 ±0.008		[76] BRAUN	73B	HLBC	+	DP, no RC
0.029 ±0.011	4017	CHIANG	72	OSPK	+	DP, RC negligible
0.027 ±0.010	2707	STEINER	71	HLBC	+	DP, uses RC
0.045 ±0.015	1458	BOTTERILL	70	OSPK		PI, uses RC
0.08 ±0.04	960	BOTTERILL	68C	ASPK	+	e^+, uses RC
$-0.02\ ^{+0.08}_{-0.12}$	90	EISLER	68	HLBC	+	PI, uses RC
$0.045\ ^{+0.017}_{-0.018}$	854	BELLOTTI	67B	FBC	+	DP, uses RC
+0.016 ±0.016	1393	IMLAY	67	OSPK	+	DP, no RC
$+0.028\ ^{+0.013}_{-0.014}$	515	KALMUS	67	FBC	+	e^+, PI, no RC
−0.04 ±0.05	230	BORREANI	64	HBC	+	e^+, no RC
−0.010 ±0.029	407	JENSEN	64	XEBC	+	PI, no RC
+0.036 ±0.045	217	BROWN	62B	XEBC	+	PI, no RC
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.025 ±0.007		[77] BRAUN	74	HLBC	+	$K_{\mu 3}/K_{e3}$ vs. t

[74] AKIMENKO 91 state that radiative corrections would raise λ_+ by 0.0013.

[75] BOLOTOV 88 state radiative corrections of GINSBERG 67 would raise λ_+ by 0.002.

[76] BRAUN 73B states that radiative corrections of GINSBERG 67 would lower λ_+^e by 0.002 but that radiative corrections of BECHERRAWY 70 disagrees and would raise λ_+^e by 0.005.

[77] BRAUN 74 is a combined $K_{\mu 3}$-K_{e3} result. It is not independent of BRAUN 73C ($K_{\mu 3}$) and BRAUN 73B (K_{e3}) form factor results.

$\xi_A = f_-/f_+$ (determined from $K_{\mu 3}^{\pm}$ spectra)

The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	$d\xi(0)/d\lambda_+$	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.35±0.15 OUR EVALUATION			From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).				
−0.27±0.25	−17	3973	WHITMAN	80	SPEC	+	DP
−0.8 ±0.8	−20	490	[78] ARNOLD	74	HLBC	+	DP
−0.57±0.24	−9	6527	[79] MERLAN	74	ASPK	+	DP
−0.36±0.40	−19	1897	[80] BRAUN	73C	HLBC	+	DP
−0.62±0.28	−12	4025	[81] ANKENBRA...	72	ASPK	+	PI
+0.45±0.28	−15	3480	[82] CHIANG	72	OSPK	+	DP
−1.1 ±0.56	−29	3240	[83] HAIDT	71	HLBC	+	DP
−0.5 ±0.8	−26	2041	[84] KIJEWSKI	69	OSPK	+	PI
+0.72±0.93	−17	444	CALLAHAN	66B	FBC	+	PI

• • • We do not use the following data for averages, fits, limits, etc. • • •

$-0.5\ \pm0.9$	none	78	EISLER	68	HLBC	+	PI, $\lambda_+=0$
$0.0\ ^{+1.1}_{-0.9}$	2648	[85] CALLAHAN		66B	FBC	+	μ, $\lambda_+=0$
$+0.7\ \pm0.5$	87		GIACOMELLI	64	EMUL	+	MU+BR,$\lambda_+=0$
-0.08 ± 0.7		[86] JENSEN		64	XEBC	+	DP+BR
$+1.8\ \pm0.6$	76		BROWN	62B	XEBC	+	DP+BR, $\lambda_+=0$

[78] ARNOLD 74 figure 4 was used to obtain ξ_A and $d\xi(0)/d\lambda_+$.

[79] MERLAN 74 figure 5 was used to obtain $d\xi(0)/d\lambda_+$.

[80] BRAUN 73C gives $\xi(t) = -0.34 \pm 0.20$, $d\xi(t)/d\lambda_+ = -14$ for $\lambda_+ = 0.027$, $t = 6.6$. We calculate above $\xi(0)$ and $d\xi(0)/d\lambda_+$ for their $\lambda_+ = 0.025 \pm 0.017$.

[81] ANKENBRANDT 72 figure 3 was used to obtain $d\xi(0)/d\lambda_+$.

[82] CHIANG 72 figure 10 was used to obtain $d\xi(0)/d\lambda_+$. Fit had $\lambda_- = \lambda_+$ but would not change for $\lambda_- = 0$. L.Pondrom, (private communication 74).

[83] HAIDT 71 table 8 (Dalitz plot analysis) gives $d\xi(0)/d\lambda_+ = (-1.1+0.5)/(0.050-0.029) = -29$, error raised from 0.50 to agree with $d\xi(0) = 0.20$ for fixed λ_+.

[84] KIJEWSKI 69 figure 17 was used to obtain $d\xi(0)/d\lambda_+$ and errors.

[85] CALLAHAN 66 table 1 (π analysis) gives $d\xi(0)/d\lambda_+ = (0.72-0.05)/(0-0.04) = -17$, error raised from 0.80 to agree with $d\xi(0) = 0.37$ for fixed λ_+. t unknown.

[86] JENSEN 64 gives $\lambda_+^{\mu} = \lambda_+^{e} = -0.020 \pm 0.027$. $d\xi(0)/d\lambda_+$ unknown. Includes SHAKLEE 64 $\xi_B(K_{\mu3}/K_{e3})$.

$\xi_B = f_-/f_+$ (determined from $K^{\pm}_{\mu3}/K^{\pm}_{e3}$)

The $K^{\pm}_{\mu3}/K^{\pm}_{e3}$ branching ratio fixes a relationship between $\xi(0)$ and λ_+. We quote the author's $\xi(0)$ and associated λ_+ but do not average because the λ_+ values differ. The fit result and scale factor given below are not obtained from these ξ_B values. Instead they are obtained directly from the fitted $K^{\pm}_{\mu3}/K^{\pm}_{e3}$ ratio $\Gamma(\pi^0\mu^+\nu_\mu)/\Gamma(\pi^0 e^+\nu_e)$, with the exception of HEINTZE 77. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
−0.35±0.15 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
-0.12 ± 0.12	55k	[87] HEINTZE 77	CNTR	+	$\lambda_+=0.029$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.0\ \pm0.15$	5825	CHIANG 72	OSPK	+	$\lambda_+=0.03$, fig.10
-0.81 ± 0.27	1505	[88] HAIDT 71	HLBC	+	$\lambda_+=0.028$, fig.8
-0.35 ± 0.22		[89] BOTTERILL 70	OSPK	+	$\lambda_+=0.045\pm0.015$
$+0.91\pm0.82$		ZELLER 69	ASPK	+	$\lambda_+=0.023$
-0.08 ± 0.15	5601	[89] BOTTERILL 68B	ASPK	+	$\lambda_+=0.023\pm0.008$
-0.60 ± 0.20	1398	[88] EICHTEN 68	HLBC	+	See note
$+1.0\ \pm0.6$	986	GARLAND 68	OSPK	+	$\lambda_+=0$
$+0.75\pm0.50$	306	AUERBACH 67	OSPK	+	$\lambda_+=0$
$+0.4\ \pm0.4$	636	CALLAHAN 66B	FBC	+	$\lambda_+=0$
$+0.6\ \pm0.5$		BISI 65B	HBC	+	$\lambda_+=0$
$+0.8\ \pm0.6$	500	CUTTS 65	OSPK	+	$\lambda_+=0$
$-0.17^{+0.75}_{-0.99}$		SHAKLEE 64	XEBC	+	$\lambda_+=0$

[87] Calculated by us from λ_0 and λ_+ given below.

[88] EICHTEN 68 has $\lambda_+ = 0.023 \pm 0.008$, $t = 4$, independent of λ_-. Replaced by HAIDT 71.

[89] BOTTERILL 70 is re-evaluation of BOTTERILL 68B with different λ_+.

$\xi_C = f_-/f_+$ (determined from μ polarization in $K^{\pm}_{\mu3}$)

The μ polarization is a measure of $\xi(t)$. No assumptions on λ_{+-} necessary, t (weighted by sensitivity to $\xi(t)$) should be specified. In λ_+, $\xi(0)$ parametrization this is $\xi(0)$ for $\lambda_+=0$. $d\xi/d\lambda = \xi t$. For radiative correction to muon polarization in $K^{\pm}_{\mu3}$, see GINSBERG 71. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
−0.35±0.15 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
-0.25 ± 1.20	1585	[90] BRAUN 75	HLBC	+	POL, t=4.2
-0.95 ± 0.3	3133	[91] CUTTS 69	OSPK	+	Total pol. t=4.0
$-1.0\ \pm0.3$	6000	[92] BETTELS 68	HLBC	+	Total pol. t=4.9
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.64 ± 0.27	40k	[93] MERLAN 74	ASPK	+	POL, $d\xi(0)/d\lambda_+ = +1.7$
$-1.4\ \pm1.8$	397	[94] CALLAHAN 66B	FBC	+	Total pol.
$-0.7\ ^{+0.9}_{-3.3}$	2950	[94] CALLAHAN 66B	FBC	+	Long. pol.
$+1.2\ ^{+2.4}_{-1.8}$	2100	[94] BORREANI 65	HLBC	+	Polarization
-4.0 to $+1.7$	500	[94] CUTTS 65	OSPK	+	Long. pol.

[90] BRAUN 75 $d\xi(0)/d\lambda_+ = \xi t = -0.25\times4.2 = -1.0$.

[91] CUTTS 69 $t = 4.0$ was calculated from figure 8. $d\xi(0)/d\lambda_+ = \xi t = -0.95\times4 = -3.8$.

[92] BETTELS 68 $d\xi(0)/d\lambda_+ = \xi t = -1.0\times4.9 = -4.9$.

[93] MERLAN 74 polarization result (figure 5) not possible. See discussion of polarization experiments in note on "$K_{\ell3}$ Form Factors" in the 1982 edition of this *Review* [Physics Letters **111B** (1982)].

[94] t value not given.

Im(ξ) in $K^{\pm}_{\mu3}$ DECAY (from transverse μ pol.)

Test of T reversal invariance.

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
−0.017±0.025 OUR AVERAGE					
-0.016 ± 0.025	20M	CAMPBELL 81	CNTR	+	Pol.
$-0.3\ ^{+0.3}_{-0.4}$	3133	CUTTS 69	OSPK	+	Total pol. fig.7
$-0.1\ \pm0.3$	6000	BETTELS 68	HLBC	+	Total pol.
$0.0\ \pm1.0$	2648	CALLAHAN 66B	FBC	+	MU
$+1.6\ \pm1.3$	397	CALLAHAN 66B	FBC	+	Total pol.
$0.5\ ^{+1.4}_{-0.5}$	2950	CALLAHAN 66B	FBC	+	Long. pol.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.010 ± 0.019	32M	[95] BLATT 83	CNTR		Polarization

[95] Combined result of MORSE 80 ($K^0_{\mu3}$) and CAMPBELL 81 ($K^+_{\mu3}$).

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K^{\pm}_{\mu3}$ DECAY)

See also the corresponding entries and footnotes in sections ξ_A, ξ_C, and λ_0. For radiative correction of $K^{\pm}_{\mu3}$ Dalitz plot, see GINSBERG 70 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.033±0.008 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
$+0.050\pm0.013$	3973	WHITMAN 80	SPEC	+	DP
0.025 ± 0.030	490	ARNOLD 74	HLBC	+	DP
0.027 ± 0.019	6527	MERLAN 74	ASPK	+	DP
0.025 ± 0.017	1897	BRAUN 73C	HLBC	+	DP
0.024 ± 0.019	4025	[96] ANKENBRA... 72	ASPK	+	PI
-0.006 ± 0.015	3480	CHIANG 72	OSPK	+	DP
0.050 ± 0.018	3240	HAIDT 71	HLBC	+	DP
0.009 ± 0.026	2041	KIJEWSKI 69	OSPK	+	PI
$0.0\ \pm0.05$	444	CALLAHAN 66B	FBC	+	PI

[96] ANKENBRANDT 72 λ_+ from figure 3 to match $d\xi(0)/d\lambda_+$. Text gives 0.024 ± 0.022.

λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K^{\pm}_{\mu3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of λ_0 using the associated λ_+^{μ} and $d\xi/d\lambda$.

VALUE	$d\lambda_0/d\lambda_+$	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.004±0.007 OUR EVALUATION			From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
$+0.029\pm0.011$	-0.37	3973	WHITMAN 80	SPEC	+	DP
$+0.019\pm0.010$	$+0.03$	55k	[97] HEINTZE 77	SPEC	+	BR
$+0.008\pm0.097$	$+0.92$	1585	[98] BRAUN 75	HLBC	+	POL
-0.040 ± 0.040	-0.62	490	ARNOLD 74	HLBC	+	DP
-0.019 ± 0.015	$+0.27$	6527	[99] MERLAN 74	ASPK	+	DP
-0.008 ± 0.020	-0.53	1897	[100] BRAUN 73C	HLBC	+	DP
-0.026 ± 0.013	$+0.03$	4025	[101] ANKENBRA... 72	ASPK	+	PI
$+0.030\pm0.014$	-0.21	3480	[101] CHIANG 72	OSPK	+	DP
-0.039 ± 0.029	-1.34	3240	[101] HAIDT 71	HLBC	+	DP
-0.056 ± 0.024	$+0.69$	3133	[98] CUTTS 69	OSPK	+	POL
-0.031 ± 0.045	-1.10	2041	[101] KIJEWSKI 69	OSPK	+	PI
-0.063 ± 0.024	$+0.60$	6000	[98] BETTELS 68	HLBC	+	POL
$+0.058\pm0.036$	-0.37	444	[101] CALLAHAN 66B	FBC	+	PI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
-0.017 ± 0.011			[102] BRAUN 74	HLBC	+	$K_{\mu3}/K_{e3}$ vs. t

[97] HEINTZE 77 uses $\lambda_+ = 0.029 \pm 0.003$. $d\lambda_0/d\lambda_+$ estimated by us.

[98] λ_0 value is for $\lambda_+ = 0.03$ calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[99] MERLAN 74 λ_0 and $d\lambda_0/d\lambda_+$ were calculated by us from ξ_A, λ_+^{μ}, and $d\xi(0)/d\lambda_+$. Their figure 6 gives $\lambda_0 = -0.025 \pm 0.012$ and no $d\lambda_0/d\lambda_+$.

[100] This value and error are taken from BRAUN 75 but correspond to the BRAUN 73C λ_+^{μ} result. $d\lambda_0/d\lambda_+$ is from BRAUN 73C $d\xi(0)/d\lambda_+$ in ξ_A above.

[101] λ_0 calculated by us from $\xi(0)$, λ_+^{μ}, and $d\xi(0)/d\lambda_+$.

[102] BRAUN 74 is a combined $K_{\mu3}$-K_{e3} result. It is not independent of BRAUN 73C ($K_{\mu3}$) and BRAUN 73B (K_{e3}) form factor results.

$|f_S/f_+|$ FOR $K^{\pm}_{e3}$ DECAY

Ratio of scalar to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
0.084±0.023 OUR AVERAGE			Error includes scale factor of 1.2.			
$0.070\pm0.016\pm0.016$		32k	AKIMENKO 91	SPEC		λ_+, f_S, f_T, ϕ fit
$0.00\ \pm0.10$		2827	BRAUN 75	HLBC	+	
$0.14\ ^{+0.03}_{-0.04}$		2707	STEINER 71	HLBC	+	λ_+, f_S, f_T, ϕ fit
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.13	90	4017	CHIANG 72	OSPK	+	
<0.23	90		BOTTERILL 68C	ASPK		
<0.18	90		BELLOTTI 67B	HLBC		
<0.30	95		KALMUS 67	HLBC	+	

$|f_T/f_+|$ FOR $K^\pm_{e3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.38±0.11 OUR AVERAGE			Error includes scale factor of 1.1.				
$0.53^{+0.09}_{-0.10}\pm0.10$		32k	AKIMENKO	91	SPEC		λ_+, f_S, f_T, ϕ fit
0.07 ± 0.37		2827	BRAUN	75	HLBC	+	
$0.24^{+0.16}_{-0.14}$		2707	STEINER	71	HLBC	+	λ_+, f_S, f_T, ϕ fit
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<0.75	90	4017	CHIANG	72	OSPK	+	
<0.58	90		BOTTERILL	68C	ASPK		
<0.58	90		BELLOTTI	67B	HLBC		
<1.1	95		KALMUS	67	HLBC	+	

f_T/f_+ FOR $K^\pm_{\mu3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	EVTS	DOCUMENT ID		TECN
0.02±0.12	1585	BRAUN	75	HLBC

DECAY FORM FACTORS FOR $K^\pm \rightarrow \pi^+\pi^- e^\pm \nu_e$

Given in ROSSELET 77, BEIER 73, and BASILE 71C.

DECAY FORM FACTOR FOR $K^\pm \rightarrow \pi^0\pi^0 e^\pm \nu$

Given in BOLOTOV 86B and BARMIN 88B.

$K^\pm \rightarrow \ell^\pm \nu\gamma$ FORM FACTORS

For definitions of the axial-vector F_A and vector F_V form factor, see the "Note on $\pi^\pm \rightarrow \ell^\pm\nu\gamma$ and $K^\pm \rightarrow \ell^\pm\nu\gamma$ Form Factors" in the $\pi^\pm$ section. In the kaon literature, often different definitions $a_K = F_A/m_K$ and $v_K = F_V/m_K$ are used.

$F_A + F_V$, SUM OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \rightarrow e\nu_e\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.148±0.010 OUR AVERAGE					
0.147 ± 0.011	51	[103] HEINTZE	79	SPEC	$K \rightarrow e\nu\gamma$
$0.150^{+0.018}_{-0.023}$	56	[104] HEARD	75	SPEC	$K \rightarrow e\nu\gamma$

[103] HEINTZE 79 quotes absolute value of $|F_A + F_V|\sin\theta_c$. We use $\sin\theta_c = V_{us} = 0.2205$.

[104] HEARD 75 quotes absolute value of $|F_A + F_V|\sin\theta_c$. We use $\sin\theta_c = V_{us} = 0.2205$.

$F_A + F_V$, SUM OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \rightarrow \mu\nu_\mu\gamma$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 0.23	90	[105] AKIBA	85	SPEC	$K \rightarrow \mu\nu\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−1.2 to 1.1	90	DEMIDOV	90	XEBC	$K \rightarrow \mu\nu\gamma$

[105] AKIBA 85 quotes absolute value.

$F_A - F_V$, DIFFERENCE OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \rightarrow e\nu_e\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
<0.49	90	[106] HEINTZE	79	SPEC	$K \rightarrow e\nu\gamma$

[106] HEINTZE 79 quotes $|F_A - F_V| < \sqrt{11}\,|F_A + F_V|$.

$F_A - F_V$, DIFFERENCE OF AXIAL-VECTOR AND VECTOR FORM FACTOR FOR $K \rightarrow \mu\nu_\mu\gamma$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
−2.2 to 0.3 OUR EVALUATION					
−2.2 to 0.6	90	DEMIDOV	90	XEBC	$K \rightarrow \mu\nu\gamma$
−2.5 to 0.3	90	AKIBA	85	SPEC	$K \rightarrow \mu\nu\gamma$

$K^\pm$ REFERENCES

ADLER 96 PRL 76 1421 +Atiya, Chiang, Frank, Haggerty, Kycia+ (BNL 787 Collab.)
KOPTEV 95 JETPL 61 877 +Mikirtych'yants, Shcherbakov+ (PNPI)
Translated from ZETFP 61 865.
AOKI 94 PR D50 69 +Yamazaki, Imazato, Kawashima+ (INUS, KEK, TOKMS)
ATIYA 93 PRL 70 2521 +Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
Also 93C PRL 71 305 (erratum) Atiya, Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
ATIYA 93B PR D48 R1 +Chiang, Frank, Haggerty, Ito+ (BNL 787 Collab.)
ALLIEGRO 92 PRL 68 278 +Campagnari+ (BNL, FNAL, PSI, WASH, YALE)
BARMIN 92 SJNP 55 547 +Barylov, Chernukha, Davidenko+ (ITEP)
Translated from YAF 55 976.
IMAZATO 92 PRL 69 877 +Kawashima, Tanaka+ (KEK, INUS, TOKY, TOKMS)
IVANOV 92 THESIS (PNPI)
LITTENBERG 92 PRL 68 443 +Shrock (BNL, STON)
USHER 92 PR D45 3961 +Fero, Gee, Graf, Mandelkern, Schultz, Schultz (UCI)
AKIMENKO 91 PL B259 225 +Beloussov+ (SERP, JINR, TBIL, CMNS, SOFU, KOSI)
BARMIN 91 SJNP 53 606 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 53 981.
DENISOV 91 JETPL 54 558 +Zhelamkov, Ivanov, Lapina, Levchenko, Malakhov+ (PNPI)
Translated from ZETFP 54 557.
Also 92 THESIS Ivanov (PNPI)
ATIYA 90 PRL 64 21 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
ATIYA 90B PRL 65 1188 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
DEMIDOV 90 SJNP 52 1006 +Dobrokhotov, Lyublev, Nikitenko+ (ITEP)
Translated from YAF 52 1595.
LEE 90 PRL 64 165 +Alliegro, Campagnari+ (BNL, FNAL, VILL, WASH, YALE)
ATIYA 89 PRL 63 2177 +Chiang, Frank, Haggerty, Ito, Kycia+ (BNL 787 Collab.)
BARMIN 89 SJNP 50 421 +Barylov, Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 50 679.
BARMIN 88 SJNP 47 643 +Barylov, Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 47 1011.
BARMIN 88B SJNP 48 1032 +Barylov, Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 48 1719.
BOLOTOV 88 JETPL 47 7 +Gninenko, Dzhilkibaev, Isakov, Klubakov+ (ASCI)
Translated from ZETFP 47 8.
CAMPAGNARI 88 PRL 61 2062 +Alliegro, Chaloupka+ (BNL, FNAL, PSI, WASH, YALE)
GALL 88 PRL 60 186 +Austin+ (BOST, MIT, WILL, CIT, CMU, WYOM)
BARMIN 87 SJNP 45 62 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 45 97.
BOLOTOV 87 SJNP 45 1023 +Gninenko, Dzhilkibaev, Isakov, Klubakov+ (INRM)
Translated from YAF 45 1652.
BOLOTOV 86 SJNP 44 73 +Gninenko, Dzhilkibaev, Isakov+ (INRM)
Translated from YAF 44 117.
BOLOTOV 86B SJNP 44 68 +Gninenko, Dzhilkibaev, Isakov+ (INRM)
Translated from YAF 44 108.
YAMANAKA 86 PR D34 85 +Hayano, Taniguchi, Ishikawa+ (KEK, TOKY)
Also 84 PRL 52 329 Hayano, Yamanaka, Taniguchi+ (TOKY, KEK)
AKIBA 85 PR D32 2911 +Ishikawa, Iwasaki+ (TOKY, TINT, TSUK, KEK)
BOLOTOV 85 JETPL 42 481 +Gninenko, Dzhilkibaev, Isakov+ (INRM)
Translated from ZETFP 42 390.
BLATT 83 PR D27 1056 +Adair, Black, Campbell+ (YALE, BNL)
ASANO 82 PL 113B 195 +Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
COOPER 82 PL 112B 97 +Guy, Michette, Tyndel, Venus (RL)
PDG 82 PL 111B Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
PDG 82B PL 111B 70 Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
ASANO 81B PL 107B 159 +Kikutani, Kurokawa, Miyachi+(KEK, TOKY, INUS, OSAK)
CAMPBELL 81 PRL 47 1032 +Black, Blatt, Kasha, Schmidt+ (YALE, BNL)
Also 83 PR D27 1056 Blatt, Adair, Black, Campbell+ (YALE, BNL)
LUM 81 PR D23 2522 +Wiegand, Kessler, Deslattes, Seki+ (LBL, NBS+)
LYONS 81 ZPHY C10 215 +Albajar, Myatt (OXF)
MORSE 80 PR D21 1750 +Leipuner, Larsen, Schmidt, Blatt+ (BNL, YALE)
WHITMAN 80 PR D21 652 +Abrams, Carroll, Kycia, Li+ (ILLC, BNL, ILL)
BARKOV 79 NP B148 53 +Vasserman, Zolotorev, Krupin+ (NOVO, KIAE)
HEINTZE 79 NP B149 365 +Heinzelmann, Igo-Kemenes+ (HEIDP, CERN)
ABRAMS 77 PR D15 22 +Carroll, Kycia, Li, Michael, Mockett+ (BNL)
DEVAUX 77 NP B126 11 +Bloch, Diamant-Berger, Maillard+ (SACL, GEVA)
HEINTZE 77 PL 70B 482 +Heinzelmann, Igo-Kemenes+ (HEIDP, CERN)
ROSSELET 77 PR D15 574 +Extermann, Fischer, Guisan+ (GEVA, SACL)
BERTRAND 76 NP B114 387 +Sacton+ (BRUX, KIDR, DUUC, LOUC, WARS)
BLOCH 76 PL 60B 393 +Bunce, Devaux, Diamant-Berger+ (GEVA, SACL)
BRAUN 76B LNC 17 521 +Martyn, Erriquez+ (AACH3, BARI, BELG, CERN)
DIAMANT-... 76 PL 62B 485 Diamant-Berger, Bloch, Devaux+ (SACL, GEVA)
HEINTZE 76 PL 60B 302 +Heinzelmann, Igo-Kemenes, Mundhenke+ (HEIDP)
SMITH 76 NP B109 173 +Booth, Renshall, Jones+ (GLAS, LIVP, OXF, RHEL)
WEISSENBE... 76 NP B115 55 Weissenberg, Egorov, Minervina+ (ITEP, LEBD)
BLOCH 75 PL 56B 201 +Brehin, Bunce, Devaux+ (SACL, GEVA)
BRAUN 75 NP B89 210 +Cornelssen+ (AACH3, BARI, BRUX, CERN)
CHENG 75 NP A254 381 +Asano, Chen, Dugan, Hu, Wu+ (COLU, YALE)
HEARD 75 PL 55B 324 +Heintze, Heinzelmann+ (CERN, HEIDH)
HEARD 75B PL 55B 327 +Heintze, Heinzelmann+ (CERN, HEIDH)
SHEAFF 75 PR D12 2570 (WISC)
SMITH 75 NP B91 45 +Booth, Renshall, Jones+ (GLAS, LIVP, OXF, RHEL)
ARNOLD 74 PR D9 1221 +Roe, Sinclair (MICH)
BRAUN 74 PL 51B 393 +Cornelssen, Martyn+ (AACH3, BARI, BRUX, CERN)
CENCE 74 PR D10 776 +Harris, Jones, Morgado+ (HAWA, LBL, WISC)
Also 73 Thesis unpub. Clarke (WISC)
KUNSELMAN 74 PR C9 2469 (WYOM)
MERLAN 74 PR D9 107 +Kasha, Wanderer, Adair+ (YALE, BNL, LASL)
WEISSENBE... 74 PL 48B 474 Weissenberg, Egorov, Minervina+ (ITEP, LEBD)
ABRAMS 73B PRL 30 500 +Carroll, Kycia, Li, Menes, Michael+ (BNL)
BACKENSTO... 73 PL 43B 431 Backenstoss+ (CERN, KARLK, KARLE, HEID, STOH)
BEIER 73 PRL 30 399 +Buchholz, Mann, Parker, Roberts (PENN)
BRAUN 73B PL 47B 185 +Cornelssen (AACH3, BARI, BRUX, CERN)
Also 75 NP B89 210 Braun, Cornelssen+ (AACH3, BARI, BRUX, CERN)
BRAUN 73C PL 47B 182 +Cornelssen (AACH3, BARI, BRUX, CERN)
Also 75 NP B89 210 Braun, Cornelssen+ (AACH3, BARI, BRUX, CERN)
CABLE 73 PR D8 3807 +Hildebrand, Pang, Stiening (EFI, LBL)
LJUNG 73 PR D8 1307 +Cline (WISC)
Also 72 PRL 28 523 Ljung (WISC)
Also 72 PRL 28 1287 Cline, Ljung (WISC)
Also 69 PRL 23 326 Camerini, Ljung, Sheaff, Cline (WISC)
LUCAS 73 PR D8 719 +Taft, Willis (YALE)
LUCAS 73B PR D8 727 +Taft, Willis (YALE)
PANG 73 PR D8 1989 +Hildebrand, Cable, Stiening (EFI, ARIZ, LBL)
Also 72 PL 40B 699 Cable, Hildebrand, Pang, Stiening (EFI, LBL)
SMITH 73 NP B60 411 +Booth, Renshall, Jones+ (GLAS, LIVP, OXF, RHEL)
ABRAMS 72 PRL 29 1118 +Carroll, Kycia, Li, Menes, Michael+ (BNL)
ANKENBRA... 72 PRL 28 1472 Ankenbrandt, Larsen+ (BNL, LASL, FNAL, YALE)
AUBERT 72 NC 12A 509 +Heusse, Pascaud, Vialle+ (ORSAY, BRUX, EPOL)
BEIER 72 PRL 29 678 +Buchholz, Mann, Parker (PENN)
CHIANG 72 PR D6 1254 +Rosen, Shapiro, Handler, Olsen+ (ROCH, WISC)
CLARK 72 PRL 29 1274 +Cork, Elioff, Kerth, McReynolds, Newton+ (LBL)
EDWARDS 72 PR D5 2720 +Beier, Bertram, Herzo, Koester+ (ILL)
FORD 72 PL 38B 335 +Piroue, Remmel, Smith, Souder (PRIN)
HOFFMASTER 72 NP B36 1 +Koller, Taylor+ (STEV, SETO, LEHI)
BASILE 71C PL 36B 619 +Brehin, Diamant-Berger, Kunz+ (SACL, GEVA)
BOURQUIN 71 PL 36B 615 +Boymond, Extermann, Marasco+ (GEVA, SACL)
GINSBERG 71 PR D4 2893 (MIT)
HAIDT 71 PR D3 10 (AACH, BARI, CERN, EPOL, NIJM+)
Also 69 PL 29B 691 Haidt+ (AACH, BARI, CERN, EPOL, NIJM, ORSAY+)
KLEMS 71 PR D4 66 +Hildebrand, Stiening (CHIC, LRL)
Also 70 PRL 24 1086 Klems, Hildebrand, Stiening (LRL, CHIC)
Also 70B PRL 25 473 Klems, Hildebrand, Stiening (LRL, CHIC)
OTT 71 PR D3 52 +Pritchard (LOQM)
ROMANO 71 PL 36B 525 +Renton, Aubert, Burban-Lutz (BARI, CERN, ORSAY)
SCHWEINB... 71 PL 36B 246 Schweinberger (AACH, BELG, CERN, NIJM+)
STEINER 71 PL 36B 521 (AACH, BARI, CERN, EPOL, ORSAY, NIJM, PADO+)
BARDIN 70 PL 32B 121 +Bilenky, Pontecorvo (JINR)
BECHERRAWY 70 PR D1 1452 (ROCH)
BOTTERILL 70 PL 31B 325 +Brown, Clegg, Corbett, Culligan+ (OXF)
FORD 70 PRL 25 1370 +Piroue, Remmel, Smith, Souder (PRIN)
GAILLARD 70 CERN 70-14 +Chounet (CERN, ORSAY)
GINSBERG 70 PR D1 229 (HAIF)
GRAUMAN 70 PR D1 1277 +Koller, Taylor, Pandoulas+ (STEV, SETO, LEHI)
Also 69 PRL 23 737 Grauman, Koller, Taylor+ (STEV, SETO, LEHI)
MALTSEV 70 SJNP 10 678 +Pestova, Solodovnikova, Fadeev+ (JINR)
Translated from YAF 10 1195.
PANDOULAS 70 PR D2 1205 +Taylor, Koller, Grauman+ (STEV, SETO)
CUTTS 69 PR 184 1380 +Stiening, Wiegand, Deutsch (LRL, MIT)
Also 68 PRL 20 955 Cutts, Stiening, Wiegand, Deutsch (LRL, MIT)
DAVISON 69 PR 180 1333 +Bacastow, Barkas, Evans, Fung, Porter+ (UCR)
ELY 69 PR 180 1319 +Gidal, Hagopian, Kalmus+ (LOUC, WISC, LRL)
EMMERSON 69 PRL 23 393 +Quirk (OXF)
HERZO 69 PR 186 1403 +Banner, Beier, Bertram, Edwards+ (ILL)
KIJEWSKI 69 Thesis UCRL 18433 (LBL)

LOBKOWICZ 69 PR 185 1676 +Melissinos, Nagashima, Tewksbury+ (ROCH, BNL)
Also 66 PRL 17 548 Lobkowicz, Melissinos, Nagashima+ (ROCH, BNL)
MACEK 69 PRL 22 32 +Mann, McFarlane, Roberts+ (PENN, TEMP)
MAST 69 PR 183 1200 +Gershwin, Alston-Garnjost, Bangerter+ (LRL)
SELLERI 69 NC 60A 291
ZELLER 69 PR 182 1420 +Haddock, Helland, Pahl+ (UCLA, LRL)
BETTELS 68 NC 56A 1106 (AACH, BARI, BERG, CERN, EPOL, NIJM, ORSAY+)
Also 71 PR D3 10 Haidt (AACH, BARI, CERN, EPOL, NIJM+)
BOTTERILL 68B PRL 21 766 +Brown, Clegg, Corbett+ (OXF)
BOTTERILL 68C PR 174 1661 +Brown, Clegg, Corbett+ (OXF)
BUTLER 68 UCRL 18420 +Bland, Goldhaber, Goldhaber, Hirata+ (LRL)
CHANG 68 PRL 20 510 +Yodh, Ehrlich, Plano+ (UMD, RUTG)
CHEN 68 PRL 20 73 +Cutts, Kijewski, Stiening+ (LRL, MIT)
EICHTEN 68 PL 27B 586 (AACH, BARI, CERN, EPOL, ORSAY, PADO, VALE)
EISLER 68 PR 169 1090 +Fung, Marateck, Meyer, Plano (RUTG)
ESCHSTRUTH 68 PR 165 1487 +Franklin, Hughes+ (PRIN, PENN)
GARLAND 68 PR 167 1225 +Tsipis, Devons, Rosen+ (COLU, RUTG, WISC)
MOSCOSO 68 Thesis (ORSAY)
AUERBACH 67 PR 155 1505 +Dobbs, Mann+ (PENN, PRIN)
Also 74 PR D9 3216 Auerbach
Erratum.
BELLOTTI 67 Heidelberg Conf. +Pullia (MILA)
BELLOTTI 67B NC 52A 1287 +Fiorini, Pullia (MILA)
Also 66B PL 20 690 Bellotti, Fiorini, Pullia+ (MILA)
BISI 67 PL 25B 572 +Cester, Chiesa, Vigone (TORI)
BOTTERILL 67 PRL 19 982 +Brown, Corbett, Culligan+ (OXF)
Also 68 PR 171 1402 Botterill, Brown, Clegg, Corbett+ (OXF)
BOWEN 67B PR 154 1314 +Mann, McFarlane, Hughes+ (PPA)
CLINE 67B Herceg Novi Tbl. 4
Proc. International School on Elementary Particle Physics.
FLETCHER 67 PRL 19 98 +Beier, Edwards+ (ILL)
FORD 67 PRL 18 1214 +Lemonick, Nauenberg, Piroue (PRIN)
GINSBERG 67 PR 162 1570 (MASB)
IMLAY 67 PR 160 1203 +Eschstruth, Franklin+ (PRIN)
KALMUS 67 PR 159 1187 +Kernan (LRL)
ZINCHENKO 67 Thesis Rutgers (RUTG)
CALLAHAN 66 NC 44A 90 (WISC)
CALLAHAN 66B PR 150 1153 +Camerini+ (WISC, LRL, UCR, BARI)
CESTER 66 PL 21 343 +Eschstruth, Oneill+ (PPA)
See footnote 1 in AUERBACH 67.
Also 67 PR 155 1505 Auerbach, Dobbs, Mann+ (PENN, PRIN)
BIRGE 65 PR 139B 1600 +Ely, Gidal, Camerini, Cline+ (LRL, WISC)
BISI 65 NC 35 768 +Borreani, Cester, Ferraro+ (TORI)
BISI 65B PR 139B 1068 +Borreani, Marzari-Chiesa, Rinaudo+ (TORI)
BORREANI 65 PR 140B 1686 +Gidal, Rinaudo, Caforio+ (BARI, TORI)
CALLAHAN 65 PRL 15 129 +Cline (WISC)
CAMERINI 65 NC 37 1795 +Cline, Gidal, Kalmus, Kernan (WISC, LRL)
CLINE 65 PL 15 293 +Fry (WISC)
CUTTS 65 PR 138B 969 +Elioff, Stiening (LRL)
DEMARCO 65 PR 140B 1430 +Grosso, Rinaudo (TORI, CERN)
FITCH 65B PR 140B 1088 +Quarles, Wilkins (PRIN, MTHO)
GREINER 65 ARNS 15 67 (LRL)
STAMER 65 PR 138B 440 +Huetter, Koller, Taylor, Grauman (STEV)
TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 5.
YOUNG 65 Thesis UCRL 16362 (LRL)
Also 67 PR 156 1464 Young, Osborne, Barkas (LRL)
BORREANI 64 PL 12 123 +Rinaudo, Werbrouck (TORI)
CALLAHAN 64 PR 136B 1463 +March, Stark (WISC)
CAMERINI 64 PRL 13 318 +Cline, Fry, Powell (WISC, LRL)
CLINE 64 PRL 13 101 +Fry (WISC)
GIACOMELLI 64 NC 34 1134 +Monti, Quareni+ (BGNA, MUNI)
GREINER 64 PRL 13 284 +Osborne, Barkas (LRL)
JENSEN 64 PR 136B 1431 +Shaklee, Roe, Sinclair (MICH)
KALMUS 64 PRL 13 99 +Kernan, Pu, Powell, Dowd (LRL, WISC)
SHAKLEE 64 PR 136B 1423 +Jensen, Roe, Sinclair (MICH)
BARKAS 63 PRL 11 26 +Dyer, Heckman (LRL)
BOYARSKI 62 PR 128 2398 +Loh, Niemela, Ritson (MIT)
BROWN 62B PRL 8 450 +Kadyk, Trilling, Roe+ (LRL, MICH)
BARKAS 61 PR 124 1209 +Dyer, Mason, Norris, Nickols, Smit (LRL)
BHOWMIK 61 NC 20 857 +Jain, Mathur (DELH)
FERRO-LUZZI 61 NC 22 1087 +Miller, Murray, Rosenfeld+ (LRL)
NORDIN 61 PR 123 2166 (LRL)
ROE 61 PRL 7 346 +Sinclair, Brown, Glaser+ (MICH, LRL)
FREDEN 60B PR 118 564 +Gilbert, White (LRL)
BURROWES 59 PRL 2 117 +Caldwell, Frisch, Hill+ (MIT)
TAYLOR 59 PR 114 359 +Harris, Orear, Lee, Baumel (COLU)
EISENBERG 58 NC 8 663 +Koch, Lohrmann, Nikolic+ (BERN)
ALEXANDER 57 NC 6 478 +Johnston, Oceallaigh (DUUC)
COHEN 57 Fund. Cons. Phys. +Crowe, Dumond (NAAS, LRL, CIT)
COOMBES 57 PR 108 1348 +Cork, Galbraith, Lambertson, Wenzel (LBL)
BIRGE 56 NC 4 834 +Perkins, Peterson, Stork, Whitehead (LRL)
ILOFF 56 PR 102 927 +Goldhaber, Lannutti, Gilbert+ (LRL)

OTHER RELATED PAPERS

LITTENBERG 93 ARNPS 43 729 +Valencia (BNL, FNAL)
Rare and Radiative Kaon Decays
RITCHIE 93 RMP 65 1149 +Wojcicki
"Rare K Decays"
BATTISTON 92 PRPL 214 293 +Cocolicchio, Fogli, Paver (PGIA, CERN, TRSTT)
Status and Perspectives of K Decay Physics
BRYMAN 89 IJMP A4 79 (TRIU)
"Rare Kaon Decays"
CHOUNET 72 PRPL 4C 199 +Gaillard, Gaillard (ORSAY, CERN)
FEARING 70 PR D2 542 +Fischbach, Smith (STON, BOHR)
HAIDT 69B PL 29B 696 + (AACH, BARI, CERN, EPOL, NIJM, ORSAY+)
CRONIN 68B Vienna Conf. 241 (PRIN)
Rapporteur talk.
WILLIS 67 Heidelberg Conf. 273 (YALE)
Rapporteur talk.
CABIBBO 66 Berkeley Conf. 33 (CERN)
ADAIR 64 PL 12 67 +Leipuner (YALE, BNL)
CABIBBO 64 PL 9 352 +Maksymowicz (CERN)
Also 64B PL 11 360 Cabibbo, Maksymowicz (CERN)
Also 65 PL 14 72 Cabibbo, Maksymowicz (CERN)
BIRGE 63 PRL 11 35 +Ely, Gidal, Camerini+ (LRL, WISC, BARI)
BLOCK 62B CERN Conf. 371 +Lendinara, Monari (NWES, BGNA)
BRENE 61 NP 22 553 +Egardt, Qvist (NORD)

K^0

$I(J^P) = \frac{1}{2}(0^-)$

K^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
497.672±0.031 OUR FIT					
497.672±0.031 OUR AVERAGE					
497.661±0.033	3713	BARKOV	87B	CMD	$e^+e^- \to K^0_L K^0_S$
497.742±0.085	780	BARKOV	85B	CMD	$e^+e^- \to K^0_L K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
497.44 ±0.50		FITCH	67	OSPK	
498.9 ±0.5	4500	BALTAY	66	HBC	K^0 from $\overline{p}p$
497.44 ±0.33	2223	KIM	65B	HBC	K^0 from $\overline{p}p$
498.1 ±0.4		CHRISTENS...	64	OSPK	

$m_{K^0} - m_{K^\pm}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.995±0.034 OUR FIT Error includes scale factor of 1.1.						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3.95 ±0.21	417	HILL	68B	DBC	+	$K^+ d \to K^0 pp$
3.90 ±0.25	9	BURNSTEIN	65	HBC	−	
3.71 ±0.35	7	KIM	65B	HBC	−	$K^- p \to n\overline{K}^0$
5.4 ±1.1		CRAWFORD	59	HBC	+	
3.9 ±0.6		ROSENFELD	59	HBC	−	

$|m_{K^0} - m_{\overline{K}^0}|$ / m_{average}

A test of CPT invariance.

VALUE	DOCUMENT ID
$<9 \times 10^{-19}$ OUR EVALUATION	

K^0 REFERENCES

BARKOV 87B SJNP 46 630 +Vasserman, Vorobev, Ivanov+ (NOVO)
Translated from YAF 46 1088.
BARKOV 85B JETPL 42 138 +Blinov, Vasserman+ (NOVO)
Translated from ZETFP 42 113.
HILL 68B PR 168 1534 +Robinson, Sakitt, Canter (BNL, CMU)
FITCH 67 PR 164 1711 +Roth, Russ, Vernon (PRIN)
BALTAY 66 PR 142 932 +Sandweiss, Stonehill+ (YALE, BNL)
BURNSTEIN 65 PR 138B 895 +Rubin (UMD)
KIM 65B PR 140B 1334 +Kirsch, Miller (COLU)
CHRISTENS... 64 PRL 13 138 Christenson, Cronin, Fitch, Turlay (PRIN)
CRAWFORD 59 PRL 2 112 +Cresti, Good, Stevenson, Ticho (LRL)
ROSENFELD 59 PRL 2 110 +Solmitz, Tripp (LRL)

K^0_S

$I(J^P) = \frac{1}{2}(0^-)$

K^0_S MEAN LIFE

For earlier measurements, beginning with BOLDT 58B, see our our 1986 edition, Physics Letters **170B** 130 (1986).

OUR FIT is described in the note on "CP Violation in K^0_L Decay" in the K^0_L Particle Listings.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.8927±0.0009 OUR FIT					
0.8932±0.0010 OUR AVERAGE					
0.8941±0.0014±0.0009		SCHWINGEN...	95	E773	Δm free, $\phi_{+-}=\phi_{SW}$
0.8929±0.0016		GIBBONS	93	E731	
0.8920±0.0044	214k	GROSSMAN	87	SPEC	
0.881 ±0.009	26k	ARONSON	76	SPEC	
0.8913±0.0032		[1] CARITHERS	75	SPEC	
0.8937±0.0048	6M	GEWENIGER	74B	ASPK	
0.8958±0.0045	50k	[2] SKJEGGEST...	72	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.905 ±0.007		[3] ARONSON	82B	SPEC	
0.867 ±0.024	2173	[4] FACKLER	73	OSPK	
0.856 ±0.008	19994	[5] DONALD	68B	HBC	
0.872 ±0.009	20000	[5,6] HILL	68	DBC	
0.866 ±0.016		[5] ALFF-...	66B	OSPK	
0.843 ±0.013	5000	[5] KIRSCH	66	HBC	

[1] CARITHERS 75 value is for $m_{K^0_L} - m_{K^0_S}$ $\Delta m = 0.5348 \pm 0.0021$. The Δm dependence of the total decay rate (inverse mean life) is $\Gamma(K^0_S) = [(1.122 \pm 0.004) + 0.16(\Delta m - 0.5348)/\Delta m] 10^{10}$/s. Value would not change significantly with our current $\Delta m = 0.5304 \pm 0.0014$.

[2] HILL 68 has been changed by the authors from the published value (0.865 ± 0.009) because of a correction in the shift due to η_{+-}. SKJEGGESTAD 72 and HILL 68 give detailed discussions of systematics encountered in this type of experiment.

[3] ARONSON 82 find that K^0_S mean life may depend on the kaon energy.

[4] FACKLER 73 does not include systematic errors.
[5] Pre-1971 experiments are excluded from the average because of disagreement with later more precise experiments.
[6] HILL 68 has been changed by the authors from the published value (0.865 ± 0.009) because of a correction in the shift due to η_{+-}. SKJEGGESTAD 72 and HILL 68 give detailed discussions of systematics encountered in this type of experiment.

K^0_S DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\pi^+\pi^-$		(68.61 ± 0.28) %	S=1.2
Γ_2	$\pi^0\pi^0$		(31.39 ± 0.28) %	S=1.2
Γ_3	$\pi^+\pi^-\gamma$	[a,b]	$(1.78\pm0.05)\times10^{-3}$	
Γ_4	$\gamma\gamma$		$(2.4\ \pm0.9\ )\times10^{-6}$	
Γ_5	$\pi^+\pi^-\pi^0$		$(3.9\ ^{+5.5}_{-1.9})\times10^{-7}$	
Γ_6	$3\pi^0$		$<3.7\ \times10^{-5}$	CL=90%
Γ_7	$\pi^\pm e^\mp\nu$	[c]	$(6.70\pm0.07)\times10^{-4}$	S=1.3
Γ_8	$\pi^\pm\mu^\mp\nu$	[c]	$(4.69\pm0.06)\times10^{-4}$	S=1.2

$\Delta S = 1$ weak neutral current ($S1$) modes

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_9	$\mu^+\mu^-$	$S1$	$<3.2\ \times10^{-7}$	CL=90%
Γ_{10}	e^+e^-	$S1$	$<2.8\ \times10^{-6}$	CL=90%
Γ_{11}	$\pi^0e^+e^-$	$S1$	$<1.1\ \times10^{-6}$	CL=90%

[a] See the Particle Listings below for the energy limits used in this measurement.

[b] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[c] Calculated from K^0_L semileptonic rates and the K^0_S lifetime assuming $\Delta S = \Delta Q$.

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 17 measurements and one constraint to determine 2 parameters. The overall fit has a $\chi^2 =$ 16.5 for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i\delta x_j\right\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100
	x_1

K^0_S DECAY RATES

$\Gamma(\pi^\pm e^\mp\nu)$ — Γ_7

VALUE (10^6 s^{-1})	*DOCUMENT ID*		*TECN*	*COMMENT*
7.50±0.08 OUR EVALUATION	Error includes scale factor of 1.1. From K^0_L measurements, assuming that $\Delta S = \Delta Q$ in K^0 decay so that $\Gamma(K^0_S \to \pi^\pm e^\mp\nu) = \Gamma(K^0_L \to \pi^\pm e^\mp\nu_e)$.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BURGUN	72	HBC	$K^+p \to K^0p\pi^+$
9.3 ±2.5	AUBERT	65	HLBC	ΔS=ΔQ, CP cons. not assumed

$\Gamma(\pi^\pm\mu^\mp\nu)$ — Γ_8

VALUE (10^6 s^{-1})	*DOCUMENT ID*
5.25±0.07 OUR EVALUATION	Error includes scale factor of 1.1. From K^0_L measurements, assuming that $\Delta S = \Delta Q$ in K^0 decay so that $\Gamma(K^0_S \to \pi^\pm\mu^\mp\nu) = \Gamma(K^0_L \to \pi^\pm\mu^\mp\nu)$.

K^0_S BRANCHING RATIOS

$\Gamma(\pi^+\pi^-)/\Gamma_{\rm total}$ — Γ_1/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.6861±0.0028 OUR FIT Error includes scale factor of 1.2.					
0.671 ±0.010 OUR AVERAGE					
0.670 ±0.010	3447	[7] DOYLE	69	HBC	$\pi^-p \to \Lambda K^0$
0.70 ±0.08		COLUMBIA	60B	HBC	
0.68 ±0.04		CRAWFORD	59B	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.740 ±0.024		[7] ANDERSON	62B	HBC	

[7] Anderson result not published, events added to Doyle sample.

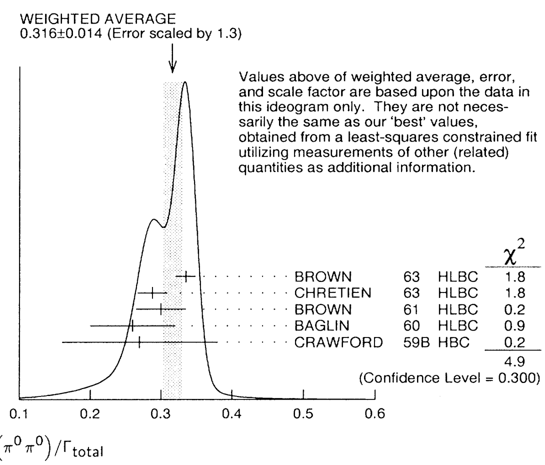
$\Gamma(\pi^+\pi^-)/\Gamma(\pi^0\pi^0)$ — Γ_1/Γ_2

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.186±0.028 OUR FIT Error includes scale factor of 1.2.					
2.197±0.026 OUR AVERAGE					
2.11 ±0.09	1315	EVERHART	76	WIRE	$\pi^-p \to \Lambda K^0$
2.169±0.094	16k	COWELL	74	OSPK	$\pi^-p \to \Lambda K^0$
2.16 ±0.08	4799	HILL	73	DBC	$K^+d \to K^0pp$
2.22 ±0.10	3068	[8] ALITTI	72	HBC	$K^+p \to \pi^+pK^0$
2.22 ±0.08	6380	MORSE	72B	DBC	$K^+n \to K^0p$
2.10 ±0.11	701	[9] NAGY	72	HLBC	$K^+n \to K^0p$
2.22 ±0.095	6150	[10] BALTAY	71	HBC	$Kp \to K^0$ neutrals
2.282±0.043	7944	[11] MOFFETT	70	OSPK	$K^+n \to K^0p$
2.10 ±0.06	3700	MORFIN	69	HLBC	$K^+n \to K^0p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.12 ±0.17	267	[9] BOZOKI	69	HLBC	
2.285±0.055	3016	[11] GOBBI	69	OSPK	$K^+n \to K^0p$

[8] The directly measured quantity is $K^0_S \to \pi^+\pi^-$/all K^0 = 0.345 ± 0.005.
[9] NAGY 72 is a final result which includes BOZOKI 69.
[10] The directly measured quantity is $K^0_S \to \pi^+\pi^-$/all $\overline{K}^0$ = 0.345 ± 0.005.
[11] MOFFETT 70 is a final result which includes GOBBI 69.

$\Gamma(\pi^0\pi^0)/\Gamma_{\rm total}$ — Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*
0.3139±0.0028 OUR FIT Error includes scale factor of 1.2.				
0.316 ±0.014 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.				
0.335 ±0.014	1066	BROWN	63	HLBC
0.288 ±0.021	198	CHRETIEN	63	HLBC
0.30 ±0.035		BROWN	61	HLBC
0.26 ±0.06		BAGLIN	60	HLBC
0.27 ±0.11		CRAWFORD	59B	HBC



$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-)$ — Γ_3/Γ_1

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.60±0.08 OUR AVERAGE					
2.56±0.09	1286	RAMBERG	93	E731	p_γ >50 MeV/c
2.68±0.15		[12] TAUREG	76	SPEC	p_γ >50 MeV/c
2.8 ±0.6		[13] BURGUN	73	HBC	p_γ >50 MeV/c
3.3 ±1.2	10	WEBBER	70	HBC	p_γ >50 MeV/c
no ratio given	27	BELLOTTI	66	HBC	p_γ >50 MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.10±0.22	3723	RAMBERG	93	E731	p_γ >20 MeV/c
3.0 ±0.6	29	[14] BOBISUT	74	HLBC	p_γ >40 MeV/c

[12] TAUREG 76 find direct emission contribution <0.06, CL = 90%.
[13] BURGUN 73 estimates that direct emission contribution is 0.3 ± 0.6.
[14] BOBISUT 74 not included in average because p_γ cut differs. Estimates direct emission contribution to be 0.5 or less, CL = 95%.

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.4±0.9		35	[15] BARR	95B	NA31	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.2±1.1		16	[16] BARR	95B	NA31	
< 13	90		BALATS	89	SPEC	
2.4±1.2		19	BURKHARDT	87	NA31	
< 133	90		BARMIN	86B	XEBC	
< 200	90		VASSERMAN	86	CALO	$\phi \to K^0_S K^0_L$
< 400	90	0	BARMIN	73B	HLBC	
< 710	90	0	[17] BANNER	72B	OSPK	
< 2000	90	0	MORSE	72B	DBC	
< 2200	90	0	[17] REPELLIN	71	OSPK	
<21000	90	0	[17] BANNER	69	OSPK	

[15] BARR 95B quotes this as the combined BARR 95B + BURKHARDT 87 result after rescaling BURKHARDT 87 to use same branching ratios and lifetimes as BARR 95B.
[16] BARR 95B result is calculated using B($K_L \to \gamma\gamma$) = (5.86 ± 0.17) × 10^{-4}.
[17] These limits are for maximum interference in K^0_S-K^0_L to 2γ's.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-7})	CL%	DOCUMENT ID		TECN
$\mathbf{3.9^{+5.4}_{-1.8}{}^{+0.9}_{-0.7}}$		[18] THOMSON	94	E621
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<490	90	[19] BARMIN	85	HLBC
<850	90	METCALF	72	ASPK

[18] THOMSON 94 calculates this branching ratio from their measurements $|\rho_{+-0}|$ = $0.035^{+0.019}_{-0.011}\pm0.004$ and $\phi_\rho = (-59\pm48)^\circ$ where $|\rho_{+-0}|e^{i\phi_\rho}$ = A($K^0_S \to \pi^+\pi^-\pi^0$, $I=2$)/A($K^0_L \to \pi^+\pi^-\pi^0$).
[19] BARMIN 85 assumes that *CP*-allowed and *CP*-violating amplitudes are equally suppressed.

$\Gamma(3\pi^0)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN
<0.37	90	BARMIN	83	HLBC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<4.3	90	BARMIN	73	HLBC

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_9/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN
< 0.032	90	GJESDAL	73	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<14	90	BOHM	69	OSPK
< 0.7	90	HYAMS	69B	OSPK
<22	90	[20] STUTZKE	69	OSPK
< 7	90	BOTT-...	67	OSPK

[20] Value calculated by us, using 2.3 instead of 1 event, 90% CL.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_{10}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.28	90	0	BLICK	94	CNTR	Hyperon facility
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 1.0	90		BARMIN	86	XEBC	
<11	90		BITSADZE	86	CALO	
<34	90		BOHM	69	OSPK	

$\Gamma(\pi^0e^+e^-)/\Gamma_{total}$ — Γ_{11}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN
< 1.1	90	0	BARR	93B	NA31
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<45	90		GIBBONS	88	E731

CP VIOLATION IN $K_S \to 3\pi$

(by T. Nakada, Paul Scherrer Institute and L. Wolfenstein, Carnegie-Mellon University)

The possible final states for the decay $K^0 \to \pi^+\pi^-\pi^0$ have isospin I = 0, 1, 2, and 3. The $I = 0$ and $I = 2$ states have $CP = +1$ and K_S can decay into them without violating CP symmetry, but they are expected to be strongly suppressed by centrifugal barrier effects. The $I = 1$ and $I = 3$ states, which have no centrifugal barrier, have $CP = -1$ so that the K_S decay to these requires CP violation.

In order to see CP violation in $K_S \to \pi^+\pi^-\pi^0$, it is necessary to observe the interference between K_S and K_L decay, which determines the amplitude ratio

$$\eta_{+-0} = \frac{A(K_S \to \pi^+\pi^-\pi^0)}{A(K_L \to \pi^+\pi^-\pi^0)} \ .$$

If η_{+-0} is obtained from an integration over the whole Dalitz plot, there is no contribution from the $I = 0$ and $I = 2$ final states and a nonzero value of η_{+-0} is entirely due to CP violation.

Only $I = 1$ and $I = 3$ states, which are $CP = -1$, are allowed for $K^0 \to \pi^0\pi^0\pi^0$ decays and the decay of K_S into $3\pi^0$ is an unambiguous sign of CP violation. Similarly to η_{+-0}, η_{000} is defined as

$$\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} \ .$$

If one assumes that CPT invariance holds and that there are no transitions to $I = 3$ (or to nonsymmetric $I = 1$ states), it can be shown that

$$\eta_{+-0} = \eta_{000} = \epsilon + i\frac{\text{Im } a_1}{\text{Re } a_1} \ .$$

With the Wu-Yang phase convention, a_1 is the weak decay amplitude for K^0 into $I = 1$ final states; ϵ is determined from CP violation in $K_L \to 2\pi$ decays. The real parts of η_{+-0} and η_{000} are equal to Re(ϵ). Since currently-known upper limits on $|\eta_{+-0}|$ and $|\eta_{000}|$ are much larger than $|\epsilon|$, they can be interpreted as upper limits on Im(η_{+-0}) and Im(η_{000}) and so as limits on the CP-violating phase of the decay amplitude a_1.

CP-VIOLATION PARAMETERS IN K^0_S DECAY

$\text{Im}(\eta_{+-0})^2 = \Gamma(K^0_S \to \pi^+\pi^-\pi^0$, *CP*-violating$)$ / $\Gamma(K^0_L \to \pi^+\pi^-\pi^0)$

CPT assumed valid (i.e. Re(η_{+-0}) ≃ 0).

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.23	90	601	[21] BARMIN	85	HLBC	
<1.2	90	192	BALDO-...	75	HLBC	
<0.71	90	148	MALLARY	73	OSPK	Re(A)=−0.05 ± 0.17
<0.66	90	180	JAMES	72	HBC	
<1.2	90	99	JONES	72	OSPK	
<0.12	90	384	METCALF	72	ASPK	
<1.2	90	99	CHO	71	DBC	
<1.0	90	98	JAMES	71	HBC	Incl. in JAMES 72
<1.2	95	50	[22] MEISNER	71	HBC	CL=90% not avail.
<0.8	90	71	WEBBER	70	HBC	
<0.45	90		BEHR	66	HLBC	
<3.8	90	18	ANDERSON	65	HBC	Incl. in WEBBER 70

[21] BARMIN 85 find Re(η_{+-0}) = (0.05 ± 0.17) and Im(η_{+-0}) = (0.15 ± 0.33). Includes events of BALDO-CEOLIN 75.
[22] These authors find Re(A) = 2.75 ± 0.65, above value at Re(A) = 0.

$\text{Im}(\eta_{+-0}) = \text{Im}(A(K^0_S \to \pi^+\pi^-\pi^0$, *CP*-violating$)$ / $A(K^0_L \to \pi^+\pi^-\pi^0))$

VALUE	EVTS	DOCUMENT ID		TECN
−0.015±0.017±0.025	272k	[23] ZOU	94	SPEC

[23] ZOU 94 use theoretical constraint Re(η_{+-0}) = Re(ϵ) = 0.0016.

$\text{Im}(\eta_{000})^2 = \Gamma(K^0_S \to 3\pi^0) / \Gamma(K^0_L \to 3\pi^0)$

CPT assumed valid (i.e. $\text{Re}(\eta_{000}) \simeq 0$). This limit determines branching ratio $\Gamma(3\pi^0)/\Gamma_{total}$ above.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.1	90	632	[24] BARMIN	83	HLBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.28	90		[25] GJESDAL	74B	SPEC	Indirect meas.
<1.2	90	22	BARMIN	73	HLBC	

[24] BARMIN 83 find $\text{Re}(\eta_{000}) = (-0.08 \pm 0.18)$ and $\text{Im}(\eta_{000}) = (-0.05 \pm 0.27)$. Assuming *CPT* invariance they obtain the limit quoted above.

[25] GJESDAL 74B uses $K2\pi$, $K_{\mu 3}$, and K_{e3} decay results, unitarity, and *CPT*. Calculates $|(\eta_{000})| = 0.26 \pm 0.20$. We convert to upper limit.

K^0_S REFERENCES

BARR 95B PL B351 579 +Buchholz+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
SCHWINGEN... 95 PRL 74 4376 Schwingenheuer+ (EFI, CHIC, ELMT, FNAL, ILL, RUTG)
BLICK 94 PL B334 234 +Kolosov, Kutjin, Shelikov+ (SERP, JINR)
THOMSON 94 PL B337 411 +Zou, Beretvas, Caracappa, Devlin+ (RUTG, MINN, MICH)
ZOU 94 PL B329 519 +Beretvas, Caracappa, Devlin+ (RUTG, MINN, MICH)
BARR 93B PL B304 381 +Buchholz+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
GIBBONS 93 PRL 70 1199 +Barker, Briere, Makoff+ (FNAL E731 Collab.)
RAMBERG 93 PRL 70 2525 +Bock, Coleman, Enagonio, Hsiung+ (FNAL E731 Collab.)
BALATS 89 SJNP 49 828 +Berezin, Bogdanov, Vishnevskii, Vishnyakov+ (ITEP)
Translated from YAF 49 1332.
GIBBONS 88 PRL 61 2661 +Papadimitriou+ (FNAL E731 Collab.)
BURKHARDT 87 PL B199 139 + (CERN, EDIN, MANZ, LALO, PISA, SIEG)
GROSSMAN 87 PRL 59 18 +Heller, James, Shupe+ (MINN, MICH, RUTG)
BARMIN 86 SJNP 44 622 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 44 965.
BARMIN 86B NC 96A 159 +Barylov, Chistyakova, Chuvilo+ (ITEP, PADO)
BITSADZE 86 PL 167B 138 +Budagov (CMNS, SOFI, SERP, TBIL, JINR, BAKU+)
PDG 86B PL 170B 130 Aguilar-Benitez, Porter+ (CERN, CIT+)
VASSERMAN 86 JETPL 43 588 +Golubev, Gluskin, Druzhinin+ (NOVO)
Translated from ZETFP 43 457.
BARMIN 85 NC 85A 67 +Barylov, Chistyakova, Chuvilo+ (ITEP, PADO)
Also 85B SJNP 41 759 Barmin, Barylov, Volkov+ (ITEP)
Translated from YAF 41 1187.
BARMIN 83 PL 128B 129 +Barylov, Chistyakova, Chuvilo+ (ITEP, PADO)
Also 84 SJNP 39 269 Barmin, Barylov, Golubchikov+ (ITEP, PADO)
Translated from YAF 39 428.
ARONSON 82 PRL 48 1078 +Bernstein+ (BNL, CHIC, STAN, WISC)
ARONSON 82B PRL 48 1306 +Bock, Cheng, Fischbach (BNL, CHIC, PURD)
Also 82B PL 116B 73 Fischbach, Cheng+ (PURD, BNL, CHIC)
Also 83 PR D28 476 Aronson, Bock, Cheng+ (BNL, CHIC, PURD)
Also 83B PR D28 495 Aronson, Bock, Cheng+ (BNL, CHIC, PURD)
ARONSON 76 NC 32A 236 +McIntyre, Roehrig+ (WISC, EFI, UCSD, ILLC)
EVERHART 76 PR D14 661 +Kraus, Lande, Long, Lowenstein+ (PENN)
TAUREG 76 PL 65B 92 +Zech, Dydak, Navarria+ (HEIDH, CERN, DORT)
BALDO-... 75 NC 25A 688 Baldo-Ceolin, Bobisut, Calimani+ (PADO, WISC)
CARITHERS 75 PRL 34 1244 +Modis, Nygren, Pun+ (COLU, NYU)
BOBISUT 74 LNC 11 646 +Huzita, Mattioli, Puglierin (PADO)
COWELL 74 PR D10 2083 +Lee-Franzini, Orcutt, Franzini+ (STON, COLU)
GEWENIGER 74B PL 48B 487 +Gjesdal, Presser+ (CERN, HEIDH)
GJESDAL 74B PL 52B 119 +Presser, Steffen+ (CERN, HEIDH)
BARMIN 73 PL 46B 465 +Barylov, Davidenko, Demidov+ (ITEP)
BARMIN 73B PL 47B 463 +Barylov, Davidenko, Demidov+ (ITEP)
BURGUN 73 PL 46B 481 +Bertranet, Lesquoy, Muller, Pauli+ (SACL, CERN)
FACKLER 73 PRL 31 847 +Frisch, Martin, Smoot, Sompayrac (MIT)
GJESDAL 73 PL 44B 217 +Presser, Steffen, Steinberger+ (CERN, HEIDH)
HILL 73 PR D8 1290 +Sakitt, Samios, Burris, Engler+ (BNL, CMU)
MALLARY 73 PR D7 1953 +Binnie, Gallivan, Gomez, Peck, Sciulli+ (CIT)
ALITTI 72 PL 39B 568 +Lesquoy, Muller (SACL)
BANNER 72B PRL 29 237 +Cronin, Hoffman, Knapp, Shochet (PRIN)
BURGUN 72 NP B50 194 +Lesquoy, Muller, Pauli+ (SACL, CERN, OSLO)
JAMES 72 NP B49 1 +Montanet, Paul, Saetre+ (CERN, SACL, OSLO)
JONES 72 NC 9A 151 +Abashian, Graham, Mantsch, Orr, Smith+ (ILL)
METCALF 72 PL 40B 703 +Neuhofer, Niebergall+ (CERN, IPN, WIEN)
MORSE 72B PRL 28 388 +Nauenberg, Bierman, Sager+ (COLO, PRIN, UMD)
NAGY 72 NP B47 94 +Telbisz, Vestergombi (BUDA)
Also 69 PL 30B 498 Bozoki, Fenyves, Gombosi, Nagy+ (BUDA)
SKJEGGEST... 72 NP B48 343 Skjeggestad, James+ (OSLO, CERN, SACL)
BALTAY 71 PRL 27 1678 +Bridgewater, Cooper, Gershwin, Habibi+ (COLU)
Also 71 Thesis Nevis 187 Cooper (COLU)
CHO 71 PR D3 1557 +Dralle, Canter, Engler, Fisk+ (CMU, BNL, CASE)
JAMES 71 PL 35B 265 +Montanet, Paul, Pauli+ (CERN, SACL, OSLO)
MEISNER 71 PR D3 59 +Mann, Hertzbach, Kofler+ (MASA, BNL, YALE)
REPELLIN 71 PL 36B 603 +Wolff, Chollet, Gaillard, Jane+ (ORSAY, CERN)
MOFFETT 70 BAPS 15 512 +Gobbi, Green, Hakel, Rosen (ROCH)
WEBBER 70 PR D1 1967 +Solmitz, Crawford, Alston-Garnjost (LRL)
Also 69 Thesis UCRL 19226 Webber (LRL)
BANNER 69 PR 188 2033 +Cronin, Liu, Pilcher (PRIN)
BOHM 69 Thesis (AACH)
BOZOKI 69 PL 30B 498 +Fenyves, Gombosi, Nagy+ (BUDA)
DOYLE 69 Thesis UCRL 18139 (LRL)
GOBBI 69 PRL 22 682 +Green, Hakel, Moffett, Rosen+ (ROCH)
HYAMS 69B PL 29B 521 +Koch, Potter, VonLindern, Lorenz+ (CERN, MPIM)
MORFIN 69 PRL 23 660 +Sinclair (MICH)
STUTZKE 69 PR 177 2009 +Abashian, Jones, Mantsch, Orr, Smith (ILL)
DONALD 68B PL 27B 58 +Edwards, Nisar+ (LIVP, CERN, IPNP, CDEF)
HILL 68 PR 171 1418 +Robinson, Sakitt+ (BNL, CMU)
BOTT-... 67 PL 24B 194 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
ALFF-... 66B PL 21 595 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
BEHR 66 PL 22 540 +Brisson, Petiau+ (EPOL, MILA, PADO, ORSAY)
BELLOTTI 66 NC 45A 737 +Pullia, Baldo-Ceolin+ (MILA, PADO)
KIRSCH 66 PR 147 939 +Schmidt (COLU)
ANDERSON 65 PRL 14 475 +Crawford, Golden, Stern, Binford+ (LRL, WISC)
AUBERT 65 PL 17 59 +Behr, Canavan, Chounet+ (EPOL, ORSAY)
BROWN 63 PR 130 769 +Kadyk, Trilling, Roe+ (LRL, MICH)
CHRETIEN 63 PR 131 2208 + (BRAN, BROW, HARV, MIT)
ANDERSON 62B CERN Conf. 836 +Crawford+ (LRL)
BROWN 61 NC 19 1155 +Bryant, Burnstein, Glaser, Kadyk+ (MICH)
BAGLIN 60 NC 18 1043 +Bloch, Brisson, Hennessy+ (EPOL)
COLUMBIA 60B Rochester Conf. 727 Schwartz+ (COLU)
CRAWFORD 59B PRL 2 266 +Cresti, Douglass, Good, Ticho+ (LRL)
BOLDT 58B PRL 1 150 +Caldwell, Pal (MIT)

OTHER RELATED PAPERS

LITTENBERG 93 ARNPS 43 729 +Valencia (BNL, FNAL)
Rare and Radiative Kaon Decays
BATTISTON 92 PRPL 214 293 +Cocolicchio, Fogli, Paver (PGIA, CERN, TRSTT)
Status and Perspectives of *K* Decay Physics
TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 115.
CRAWFORD 62 CERN Conf. 827 (LRL)
FITCH 61 NC 22 1160 +Piroue, Perkins (PRIN, LASL)
GOOD 61 PR 124 1223 +Matsen, Muller, Piccioni+ (LRL)
BIRGE 60 Rochester Conf. 601 +Ely+ (LRL, WISC)
MULLER 60 PRL 4 418 +Birge, Fowler, Good, Piccioni+ (LRL, BNL)

K^0_L

$I(J^P) = \frac{1}{2}(0^-)$

$m_{K^0_L} - m_{K^0_S}$

For earlier measurements, beginning with GOOD 61 and FITCH 61, see our our 1986 edition, Physics Letters **170B** 132 (1986).

OUR FIT is described in the note on "*CP* Violation in K^0_L Decay" in the K^0_L Particle Listings.

VALUE ($10^{10}\ \hbar\ s^{-1}$)		DOCUMENT ID		TECN	COMMENT
0.5304±0.0014 OUR FIT					
0.5310±0.0019 OUR AVERAGE Error includes scale factor of 1.2.					
0.5274±0.0029	±0.0005	ADLER	95	CPLR	Charge asymmetry in K^0_{e3}
0.5297±0.0030	±0.0022	[1] SCHWINGEN...	95	E773	20–160 GeV *K* beams
0.5257±0.0049		[1] GIBBONS	93C	E731	20–160 GeV *K* beams
0.5340±0.00255	±0.0015	[2] GEWENIGER	74C	SPEC	Gap method
0.5334±0.0040	±0.0015	[2] GJESDAL	74	SPEC	Charge asymmetry in $K^0_{\ell 3}$
0.542 ±0.006		CULLEN	70	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.5286±0.0028		[3] GIBBONS	93	E731	20–160 GeV *K* beams
0.482 ±0.014		[4] ARONSON	82B	SPEC	*E*=30–110 GeV
0.534 ±0.007		[5] CARNEGIE	71	ASPK	Gap method
0.542 ±0.006		[5] ARONSON	70	ASPK	Gap method

[1] Fits Δm and ϕ_{+-} simultaneously.

[2] These two experiments have a common systematic error due to the uncertainty in the momentum scale, as pointed out in WAHL 89.

[3] GIBBONS 93 value assume $\phi_{+-} = \phi_{00} = \phi_{SW} = (43.7 \pm 0.2)^o$.

[4] ARONSON 82 find that Δm may depend on the kaon energy.

[5] ARONSON 70 and CARNEGIE 71 use K^0_S mean life $= (0.862 \pm 0.006) \times 10^{-10}$ s. We have not attempted to adjust these values for the subsequent change in the K^0_S mean life or in η_{+-}.

K^0_L MEAN LIFE

VALUE (10^{-8} s)	EVTS	DOCUMENT ID		TECN
5.17 ±0.04 OUR FIT Error includes scale factor of 1.1.				
5.15 ±0.04 OUR AVERAGE				
5.154±0.044	0.4M	VOSBURGH	72	CNTR
5.15 ±0.14		DEVLIN	67	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.0 ±0.5		[6] LOWYS	67	HLBC
6.1 $^{+1.5}_{-1.2}$	1700	ASTBURY	65C	CNTR
5.3 ±0.6		FUJII	64	OSPK
5.1 $^{+2.4}_{-1.3}$	15	DARMON	62	FBC
8.1 $^{+3.2}_{-2.4}$	34	BARDON	58	CNTR

[6] Sum of partial decay rates.

K^0_L DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$3\pi^0$		(21.12 ±0.27) %	S=1.1
Γ_2	$\pi^+\pi^-\pi^0$		(12.56 ±0.20) %	S=1.7
Γ_3	$\pi^\pm\mu^\mp\nu$ Called $K^0_{\mu 3}$.	[a]	(27.17 ±0.25) %	S=1.1
Γ_4	$\pi^-\mu^+\nu_\mu$			
Γ_5	$\pi^+\mu^-\overline{\nu}_\mu$			
Γ_6	$\pi^\pm e^\mp\nu_e$ Called K^0_{e3}.	[a]	(38.78 ±0.27) %	S=1.1
Γ_7	$\pi^- e^+\nu_e$			
Γ_8	$\pi^+ e^-\overline{\nu}_e$			

	Mode			Fraction	
Γ_9	2γ			$(5.92 \pm 0.15) \times 10^{-4}$	
Γ_{10}	3γ			$< 2.4 \times 10^{-7}$	CL=90%
Γ_{11}	$\pi^0 2\gamma$		[b]	$(1.70 \pm 0.28) \times 10^{-6}$	
Γ_{12}	$\pi^0 \pi^\pm e^\mp \nu$		[a]	$(5.18 \pm 0.29) \times 10^{-5}$	
Γ_{13}	$(\pi\mu\text{atom})\nu$			$(1.06 \pm 0.11) \times 10^{-7}$	
Γ_{14}	$\pi^\pm e^\mp \nu_e \gamma$		[a,b,c]	(1.3 ± 0.8) %	
Γ_{15}	$\pi^+ \pi^- \gamma$		[b,c]	$(4.61 \pm 0.14) \times 10^{-5}$	
Γ_{16}	$\pi^0 \pi^0 \gamma$			$< 5.6 \times 10^{-6}$	

Charge conjugation × Parity (*CP, CPV*) or Lepton Family number (*LF*) violating modes, or $\Delta S = 1$ weak neutral current (*S1*) modes

	Mode			Fraction	
Γ_{17}	$\pi^+ \pi^-$	*CPV*		$(2.067 \pm 0.035) \times 10^{-3}$	S=1.1
Γ_{18}	$\pi^0 \pi^0$	*CPV*		$(9.36 \pm 0.20) \times 10^{-4}$	
Γ_{19}	$\mu^+ \mu^-$	*S1*		$(7.2 \pm 0.5) \times 10^{-9}$	S=1.4
Γ_{20}	$\mu^+ \mu^- \gamma$	*S1*		$(3.23 \pm 0.30) \times 10^{-7}$	
Γ_{21}	$e^+ e^-$	*S1*		$< 4.1 \times 10^{-11}$	CL=90%
Γ_{22}	$e^+ e^- \gamma$	*S1*		$(9.1 \pm 0.5) \times 10^{-6}$	
Γ_{23}	$e^+ e^- \gamma\gamma$	*S1*	[b]	$(6.5 \pm 1.2) \times 10^{-7}$	
Γ_{24}	$\pi^+ \pi^- e^+ e^-$	*S1*		$< 2.5 \times 10^{-6}$	CL=90%
Γ_{25}	$\mu^+ \mu^- e^+ e^-$	*S1*		$< 4.9 \times 10^{-6}$	CL=90%
Γ_{26}	$e^+ e^- e^+ e^-$	*S1*	[d]	$(4.1 \pm 0.8) \times 10^{-8}$	S=1.2
Γ_{27}	$\pi^0 \mu^+ \mu^-$	*CP,S1*	[e]	$< 5.1 \times 10^{-9}$	CL=90%
Γ_{28}	$\pi^0 e^+ e^-$	*CP,S1*	[e]	$< 4.3 \times 10^{-9}$	CL=90%
Γ_{29}	$\pi^0 \nu \overline{\nu}$	*CP,S1*	[f]	$< 5.8 \times 10^{-5}$	CL=90%
Γ_{30}	$e^\pm \mu^\mp$	*LF*	[a]	$< 3.3 \times 10^{-11}$	CL=90%

[a] The value is for the sum of the charge states of particle/antiparticle states indicated.

[b] See the Particle Listings below for the energy limits used in this measurement.

[c] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[d] $m_{e^+e^-} > 470$ MeV.

[e] Allowed by higher-order electroweak interactions.

[f] Violates *CP* in leading order. Test of direct *CP* violation since the indirect *CP*-violating and *CP*-conserving contributions are expected to be suppressed.

CONSTRAINED FIT INFORMATION

An overall fit to the mean life, 4 decay rate, and 12 branching ratios uses 46 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 41.2$ for 39 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta p_i \delta p_j \rangle / (\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i / \Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_1	x_2	x_3	x_6	x_9	x_{17}	x_{18}
x_2	−19						
x_3	−37	−28					
x_6	−49	−28	−36				
x_9	−8	22	−6	−5			
x_{17}	−12	35	−8	−8	64		
x_{18}	−10	27	−7	−6	84	77	
Γ	0	0	0	0	0	0	0

	Mode		Rate (10^8 s^{-1})	Scale factor
Γ_1	$3\pi^0$		0.0408 ± 0.0006	
Γ_2	$\pi^+ \pi^- \pi^0$		0.0243 ± 0.0004	1.5
Γ_3	$\pi^\pm \mu^\mp \nu$ Called $K^0_{\mu 3}$.	[a]	0.0525 ± 0.0007	1.1
Γ_6	$\pi^\pm e^\mp \nu_e$ Called K^0_{e3}.	[a]	0.0750 ± 0.0008	1.1
Γ_9	2γ		$(1.144 \pm 0.031) \times 10^{-4}$	
Γ_{17}	$\pi^+ \pi^-$		$(4.00 \pm 0.07) \times 10^{-4}$	1.1
Γ_{18}	$\pi^0 \pi^0$		$(1.81 \pm 0.04) \times 10^{-4}$	

K^0_L DECAY RATES

$\Gamma(3\pi^0)$ — Γ_1

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	COMMENT
4.08±0.06 OUR FIT					
$5.22^{+1.03}_{-0.84}$	54	BEHR	66	HLBC	Assumes *CP*

$\Gamma(\pi^+\pi^-\pi^0)$ — Γ_2

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	COMMENT
2.43±0.04 OUR FIT Error includes scale factor of 1.5.					
2.38±0.09 OUR AVERAGE					
$2.32^{+0.13}_{-0.15}$	192	BALDO-...	75	HLBC	Assumes *CP*
2.35±0.20	180	[7] JAMES	72	HBC	Assumes *CP*
2.71±0.28	99	CHO	71	DBC	Assumes *CP*
2.12±0.33	50	MEISNER	71	HBC	Assumes *CP*
2.20±0.35	53	WEBBER	70	HBC	Assumes *CP*
$2.62^{+0.28}_{-0.27}$	136	BEHR	66	HLBC	Assumes *CP*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.5 ±0.3	98	[7] JAMES	71	HBC	Assumes *CP*
3.26±0.77	18	ANDERSON	65	HBC	
1.4 ±0.4	14	FRANZINI	65	HBC	

In the fit this rate is well determined by the mean life and the branching ratio $\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu_e)]$. For this reason the discrepancy between the $\Gamma(\pi^+\pi^-\pi^0)$ measurements does not affect the scale factor of the overall fit.

[7] JAMES 72 is a final measurement and includes JAMES 71.

$\Gamma(\pi^\pm\mu^\mp\nu)$ — Γ_3

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN
5.25±0.07 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$4.54^{+1.24}_{-1.08}$	19	LOWYS	67	HLBC

$\Gamma(\pi^\pm e^\mp\nu_e)$ — Γ_6

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	COMMENT
7.50±0.08 OUR FIT Error includes scale factor of 1.1.					
7.7 ±0.5 OUR AVERAGE					
7.81±0.56	620	CHAN	71	HBC	
$7.52^{+0.85}_{-0.72}$		AUBERT	65	HLBC	$\Delta S = \Delta Q$, *CP* assumed

$\Gamma(\pi^+\pi^-\pi^0) + \Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu_e)$ — $(\Gamma_2+\Gamma_3+\Gamma_6)$

$K^0_L \to$ charged.

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN
15.18±0.14 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
15.1 ±1.9	98	AUERBACH	66B	OSPK

$\Gamma(\pi^\pm\mu^\mp\nu) + \Gamma(\pi^\pm e^\mp\nu_e)$ — $(\Gamma_3+\Gamma_6)$

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	COMMENT
12.75±0.12 OUR FIT Error includes scale factor of 1.1.					
11.9 ±0.6 OUR AVERAGE Error includes scale factor of 1.2.					
12.4 ±0.7	410	[8] BURGUN	72	HBC	$K^+ p \to K^0 p \pi^+$
13.1 ±1.3	252	[8] WEBBER	71	HBC	$K^- p \to n \overline{K}^0$
11.6 ±0.9	393	[8,9] CHO	70	DBC	$K^+ n \to K^0 p$
$9.85^{+1.15}_{-1.05}$	109	[8] FRANZINI	65	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.47±1.69	126	[8] MANN	72	HBC	$K^- p \to n \overline{K}^0$
10.3 ±0.8	335	[9] HILL	67	DBC	$K^+ n \to K^0 p$

[8] Assumes $\Delta S = \Delta Q$ rule.

[9] CHO 70 includes events of HILL 67.

K^0_L BRANCHING RATIOS

$\Gamma(3\pi^0)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN
0.2112±0.0027 OUR FIT Error includes scale factor of 1.1.				
0.2105±0.0028	38k	[10] KREUTZ	95	NA31

[10] KREUTZ 95 measure $3\pi^0$, $\pi^+\pi^-\pi^0$, and $\pi e \nu_e$ modes. They assume PDG 1992 values for $\pi\mu\nu_\mu$, 2π, and 2γ modes.

$\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.68 ±0.04 OUR FIT Error includes scale factor of 1.3.					
1.63 ±0.05 OUR AVERAGE Error includes scale factor of 1.4.					
1.611±0.014±0.034	38k	[11] KREUTZ	95	NA31	
1.80 ±0.13	1010	BUDAGOV	68	HLBC	
2.0 ±0.6	188	ALEKSANYAN	64B	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.65 ±0.07	883	BARMIN	72B	HLBC	Error statistical only

[11] KREUTZ 95 excluded from fit because it is not independent of their $\Gamma(3\pi^0)/\Gamma_{total}$ measurement, which is in the fit.

$\Gamma(3\pi^0)/\Gamma(\pi^\pm e^\mp\nu_e)$ — Γ_1/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN
0.545±0.009 OUR FIT Error includes scale factor of 1.1.				
0.545±0.004±0.009	38k	[12] KREUTZ	95	NA31

[12] KREUTZ 95 measurement excluded from fit because it is not independent of their $\Gamma(3\pi^0)/\Gamma_{total}$ measurement, which is in the fit.

$\Gamma(3\pi^0)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_1/(\Gamma_2+\Gamma_3+\Gamma_6)$

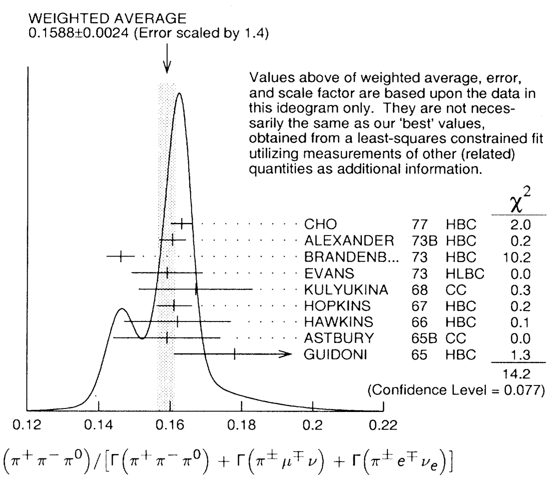
VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.269±0.004 OUR FIT	Error includes scale factor of 1.1.				
0.260±0.011 OUR AVERAGE					
0.251±0.014	549	BUDAGOV	68	HLBC	ORSAY measur.
0.277±0.021	444	BUDAGOV	68	HLBC	Ecole polytec.meas
$0.31\ {}^{+0.07}_{-0.06}$	29	KULYUKINA	68	CC	
0.24 ±0.08	24	ANIKINA	64	CC	

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID
0.1256±0.0020 OUR FIT	Error includes scale factor of 1.7.

$\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_2/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.1600±0.0025 OUR FIT	Error includes scale factor of 1.7.				
0.1588±0.0024 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.				
0.163 ±0.003	6499	CHO	77	HBC	
0.1605±0.0038	1590	ALEXANDER	73B	HBC	
0.146 ±0.004	3200	BRANDENB...	73	HBC	
0.159 ±0.010	558	EVANS	73	HLBC	
0.167 ±0.016	1402	KULYUKINA	68	CC	
0.161 ±0.005		HOPKINS	67	HBC	
0.162 ±0.015	126	HAWKINS	66	HBC	
0.159 ±0.015	326	ASTBURY	65B	CC	
0.178 ±0.017	566	GUIDONI	65	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.15\ {}^{+0.03}_{-0.04}$	66	ASTBURY	65	CC	
0.144 ±0.004	1729	HOPKINS	65	HBC	See HOPKINS 67
0.151 ±0.020	79	ADAIR	64	HBC	
$0.157\ {}^{+0.03}_{-0.04}$	75	LUERS	64	HBC	
0.185 ±0.038	59	ASTIER	61	CC	



$\Gamma(\pi^+\pi^-\pi^0)/\Gamma(\pi^\pm e^\mp\nu_e)$ — Γ_2/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN
0.324±0.006 OUR FIT	Error includes scale factor of 1.6.			
0.336±0.003±0.007	28k	KREUTZ	95	NA31

$\Gamma(\pi^\pm\mu^\mp\nu)/\Gamma(\pi^\pm e^\mp\nu_e)$ — Γ_3/Γ_6

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.701±0.009 OUR FIT					
0.697±0.010 OUR AVERAGE					
0.702±0.011	33k	CHO	80	HBC	
0.662±0.037	10k	WILLIAMS	74	ASPK	
0.741±0.044	6700	BRANDENB...	73	HBC	
0.662±0.030	1309	EVANS	73	HLBC	
0.71 ±0.05	770	BUDAGOV	68	HLBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.68 ±0.08	3548	BASILE	70	OSPK	
0.71 ±0.04	569	[13] BEILLIERE	69	HLBC	
0.648±0.030	1309	EVANS	69	HLBC	Repl. by EVANS 73
0.67 ±0.13		[14] KULYUKINA	68	CC	
0.82 ±0.10		DEBOUARD	67	OSPK	
0.7 ±0.2	273	HAWKINS	67	HBC	
0.81 ±0.08		HOPKINS	67	HBC	
0.81 ±0.19		ADAIR	64	HBC	

[13] BEILLIERE 69 is a scanning experiment using same exposure as BUDAGOV 68.

[14] KULYUKINA 68 $\Gamma(\pi^\pm\mu^\mp\nu)/\Gamma(\pi^\pm e^\mp\nu_e)$ is not measured independently from $\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ and $\Gamma(\pi^\pm e^\mp\nu_e)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$.

$\Gamma(\pi^\pm\mu^\mp\nu)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_3/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN
0.3461±0.0030 OUR FIT	Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.335 ±0.055	330	[15] KULYUKINA	68	CC
$0.39\ {}^{+0.08}_{-0.10}$	172	[15] ASTBURY	65	CC
0.356 ±0.07	251	[15] LUERS	64	HBC

[15] This mode not measured independently from $\Gamma(\pi^+\pi^-\pi^0)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ and $\Gamma(\pi^\pm e^\mp\nu_e)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$.

$\Gamma(\pi^\pm e^\mp\nu_e)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_6/(\Gamma_2+\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN
0.4939±0.0030 OUR FIT	Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.498 ±0.052	500	KULYUKINA	68	CC
$0.46\ {}^{+0.08}_{-0.10}$	202	ASTBURY	65	CC
0.487 ±0.05	153	LUERS	64	HBC
0.46 ±0.11	24	NYAGU	61	CC

$\Gamma(\pi^\pm e^\mp\nu_e)/[\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_6/(\Gamma_3+\Gamma_6)$

VALUE	EVTS	DOCUMENT ID		TECN
0.5880±0.0033 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.415 ±0.120	320	ASTIER	61	CC

$[\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]/\Gamma_{total}$ — $(\Gamma_3+\Gamma_6)/\Gamma$

VALUE	DOCUMENT ID
0.6596±0.0030 OUR FIT	Error includes scale factor of 1.2.

$\Gamma(2\gamma)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
5.92±0.15 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.54±0.84		[16] BANNER	72B	OSPK	
4.5 ±1.0	23	ENSTROM	71	OSPK	K^0_L 1.5–9 GeV/c
5.0 ±1.0		[17] REPELLIN	71	OSPK	
5.5 ±1.1	90	KUNZ	68	OSPK	Norm.to 3 π(C+N)
7.4 ±1.6	33	[18] CRONIN	67	OSPK	
6.7 ±2.2	32	TODOROFF	67	OSPK	Repl. CRIEGEE 66
1.3 ±0.6		[19] CRIEGEE	66	OSPK	

[16] This value uses $(\eta_{00}/\eta_{+-})^2 = 1.05\pm0.14$. In general, $\Gamma(2\gamma)/\Gamma_{total} = [(4.32\pm0.55)\times10^{-4}][(\eta_{00}/\eta_{+-})^2]$.

[17] Assumes regeneration amplitude in copper at 2 GeV is 22 mb. To evaluate for a given regeneration amplitude and error, multiply by (regeneration amplitude/22mb)^2.

[18] CRONIN 67 replaced by KUNZ 68.

[19] CRIEGEE 66 replaced by TODOROFF 67.

$\Gamma(2\gamma)/\Gamma(3\pi^0)$ — Γ_9/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.80±0.08 OUR FIT	Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.13±0.43	28	BARMIN	71	HLBC	
2.24±0.28	115	BANNER	69	OSPK	
2.5 ±0.7	16	ARNOLD	68B	HLBC	Vacuum decay

$\Gamma(2\gamma)/\Gamma(\pi^0\pi^0)$ — Γ_9/Γ_{18}

VALUE	EVTS	DOCUMENT ID		TECN
0.632±0.009 OUR FIT				
0.632±0.004±0.008	110k	BURKHARDT	87	NA31

$\Gamma(3\gamma)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN
<2.4 x 10⁻⁷	90	[20] BARR	95C	NA31

[20] Assumes a phase-space decay distribution.

$\Gamma(\pi^0 2\gamma)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.7 ±0.2 ±0.2		63	[21] BARR	92	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.86±0.60±0.60		60	PAPADIMITR...91		E731	$m_{\gamma\gamma}$ > 280 MeV
< 5.1	90		PAPADIMITR...91		E731	$m_{\gamma\gamma}$ < 264 MeV
2.1 ±0.6		14	[22] BARR	90C	NA31	$m_{\gamma\gamma}$ > 280 MeV
< 2.7	90		PAPADIMITR...89		E731	In PAPADI...91
<230	90	0	BANNER	69	OSPK	

[21] BARR 92 find that $\Gamma(\pi^0 2\gamma,\ m_{\gamma\gamma}$ <240 MeV)/$\Gamma(\pi^0 2\gamma)$< 0.09 (90% CL).

[22] BARR 90C superseded by BARR 92.

$\Gamma(\pi^0\pi^\pm e^\mp\nu)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID	TECN
5.18±0.29 OUR AVERAGE				
5.16±0.20±0.22		729	MAKOFF 93	E731
6.2 ±2.0		16	CARROLL 80C	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<220	90		[23] DONALDSON 74	SPEC

[23] DONALDSON 74 uses $K^0_L \to \pi^+\pi^-\pi^0$/(all K^0_L) decays = 0.126.

$\Gamma((\pi\mu\text{atom})\nu)/\Gamma(\pi^\pm\mu^\mp\nu)$ — Γ_{13}/Γ_3

VALUE (units 10^{-7})	EVTS	DOCUMENT ID	TECN
3.90±0.39	155	[24] ARONSON 86	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	18	COOMBES 76	WIRE

[24] ARONSON 86 quote theoretical value of (4.31 ± 0.08) × 10^{-7}.

$\Gamma(\pi^\pm e^\mp\nu_e\gamma)/\Gamma(\pi^\pm e^\mp\nu_e)$ — Γ_{14}/Γ_6

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
3.3±2.0	10	PEACH 71	HLBC	γ KE >15 MeV

$\Gamma(\pi^+\pi^-\gamma)/\Gamma_{total}$ — Γ_{15}/Γ

For earlier limits see our 1992 edition Physical Review **D45,** 1 June, Part II (1992).

VALUE (units 10^{-5})	EVTS	DOCUMENT ID	TECN	COMMENT
4.61±0.14 OUR AVERAGE				
4.66±0.15	3136	[25] RAMBERG 93	E731	E_γ >20 MeV
4.41±0.32	1062	[26] CARROLL 80B	SPEC	E_γ >20 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.52±0.16	516	[27] CARROLL 80B	SPEC	E_γ >20 MeV
2.89±0.28	546	[28] CARROLL 80B	SPEC	
6.2 ±2.1	24	[29] DONALDSON 74C	SPEC	

[25] RAMBERG 93 finds that fraction of Direct Emission (DE) decays with E_γ >20 MeV is 0.685 ± 0.041.
[26] Both components. Uses $K^0_L \to \pi^+\pi^-\pi^0$/(all K^0_L) decays = 0.1239.
[27] Internal Bremsstrahlung component only.
[28] Direct γ emission component only.
[29] Uses $K^0_L \to \pi^+\pi^-\pi^0$/(all K^0_L) decays = 0.126.

$\Gamma(\pi^0\pi^0\gamma)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN
< 5.6			BARR 94	NA31
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<230	90	0	ROBERTS 94	E799

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{17}/Γ

Violates *CP* conservation.

VALUE (units 10^{-3})	DOCUMENT ID	
2.067±0.035 OUR FIT	Error includes scale factor of 1.1.	
2.107±0.055	[30] ETAFIT 96	

[30] This ETAFIT value is computed from fitted values of $|\eta_{+-}|$, the K^0_L and K^0_S lifetimes, and the $K^0_S \to \pi^+\pi^-$ branching fraction. See the discussion in the "Note on *CP* violation in K^0_L decay."

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ — Γ_{17}/Γ_2

Violates *CP* conservation.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
1.645±0.030 OUR FIT	Error includes scale factor of 1.1.			
1.64 ±0.04	4200	MESSNER 73	ASPK	η_{+-} = 2.23

$\Gamma(\pi^+\pi^-)/[\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_{17}/(\Gamma_3+\Gamma_6)$

Violates *CP* conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
3.13±0.06 OUR FIT	Error includes scale factor of 1.1.			
3.08±0.10 OUR AVERAGE				
3.13±0.14	1687	COUPAL 85	SPEC	η_{+-}=2.28 ± 0.06
3.04±0.14	2703	DEVOE 77	SPEC	η_{+-}=2.25 ± 0.05
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.51±0.23	309	[31] DEBOUARD 67	OSPK	η_{+-}=2.00 ± 0.09
2.35±0.19	525	[31] FITCH 67	OSPK	η_{+-}=1.94 ± 0.08

[31] Old experiments excluded from fit. See subsection on η_{+-} in section on "PARAMETERS FOR $K^0_L \to 2\pi$ DECAY" below for average η_{+-} of these experiments and for note on discrepancy.

$\Gamma(\pi^+\pi^-)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_{17}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Violates *CP* conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.63 ±0.04 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.60 ±0.07	4200	[32] MESSNER 73	ASPK	η_{+-} = 2.23 ± 0.05
1.93 ±0.26		[33] BASILE 66	OSPK	η_{+-} = 1.92 ± 0.13
1.993±0.080		[33] BOTT-... 66	OSPK	η_{+-} = 1.95 ± 0.04
2.08 ±0.35	54	[33] GALBRAITH 65	OSPK	η_{+-} = 1.99 ± 0.16
2.0 ±0.4	45	[33] CHRISTENS... 64	OSPK	η_{+-} = 1.95 ± 0.20

[32] From same data as $\Gamma(\pi^+\pi^-)/\Gamma(\pi^+\pi^-\pi^0)$ MESSNER 73, but with different normalization.
[33] Old experiments excluded from fit. See subsection on η_{+-} in section on "PARAMETERS FOR $K^0_L \to 2\pi$ DECAY" below for average η_{+-}.

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_{18}/Γ

Violates *CP* conservation.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
0.936±0.020 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.5 ±0.8	189	[34] GAILLARD 69	OSPK	η_{00}=3.6 ± 0.6
1.2 $^{+1.5}_{-1.2}$	7	[35] CRIEGEE 66	OSPK	

[34] Latest result of this experiment given by FAISSNER 70 $\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$.
[35] CRIEGEE 66 experiment not designed to measure $2\pi^0$ decay mode.

$\Gamma(\pi^0\pi^0)/\Gamma(3\pi^0)$ — Γ_{18}/Γ_1

Violates *CP* conservation.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT
0.443±0.012 OUR FIT	Error includes scale factor of 1.1.			
0.39 ±0.06 OUR AVERAGE				
0.37 ±0.08	29	BARMIN 70	HLBC	η_{00}=2.02 ± 0.23
0.32 ±0.15	30	BUDAGOV 70	HLBC	η_{00}=1.9 ± 0.5
0.46 ±0.11	57	BANNER 69	OSPK	η_{00}=2.2 ± 0.3
not seen		BARTLETT 68	OSPK	See η_{00} below
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.21 ±0.30	150	[36] REY 76	OSPK	η_{00}=3.8 ± 0.5
0.90 ±0.30	172	[37] FAISSNER 70	OSPK	η_{00}=3.2 ± 0.5
1.31 ±0.31	133	[36] CENCE 69	OSPK	η_{00}=3.7 ± 0.5
1.89 ±0.31	109	[38] CRONIN 67	OSPK	η_{00}=4.9 ± 0.5
1.36 ±0.18		[38] CRONIN 67B	OSPK	η_{00}=3.92 ± 0.3

[36] CENCE 69 events are included in REY 76.
[37] FAISSNER 70 contains same $2\pi^0$ events as GAILLARD 69 $\Gamma(\pi^0\pi^0)/\Gamma_{total}$.
[38] CRONIN 67B is further analysis of CRONIN 67, now both withdrawn.

$\Gamma(\pi^0\pi^0)/\Gamma(\pi^+\pi^-)$ — Γ_{18}/Γ_{17}

Violates *CP* conservation.

VALUE	DOCUMENT ID
0.453 ±0.006 OUR FIT	
0.4535±0.0063	[39] ETAFIT 96

[39] This ETAFIT value is computed from fitted values of $|\eta_{00}\ /\ \eta_{+-}|$ and the $\Gamma(K^0_S \to \pi^+\pi^-)\ /\ \Gamma(K^0_S \to \pi^0\pi^0)$ branching fraction. See the discussion in the "Note on *CP* violation in K^0_L decay."

$\Gamma(\mu^+\mu^-)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_{19}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
< 2.0	90	BOTT-... 67	OSPK
< 35.0	90	FITCH 67	OSPK
<250.0	90	ALFF-... 66B	OSPK
<100.0		ANIKINA 65	CC

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ — Γ_{19}/Γ_{17}

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
3.50±0.21 OUR AVERAGE	Error includes scale factor of 1.4.				
3.87±0.30		179	[40] AKAGI 95	SPEC	
3.38±0.17		707	HEINSON 95	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.9 ±0.3 ±0.1		178	[41] AKAGI 91B	SPEC	In AKAGI 95
3.45±0.18±0.13		368	[42] HEINSON 91	SPEC	In HEINSON 95
4.1 ±0.5		54	INAGAKI 89	SPEC	In AKAGI 91B
2.8 ±0.3 ±0.2		87	MATHIAZHA...89B	SPEC	In HEINSON 91
4.0 $^{+1.4}_{-0.9}$		15	SHOCHET 79	SPEC	
4.2 $^{+5.1}_{-2.6}$		3	[43] FUKUSHIMA 76	SPEC	
5.8 $^{+2.3}_{-1.5}$		9	[44] CARITHERS 73	SPEC	
< 1.53	90	0	[45] CLARK 71	SPEC	
< 18.	90	0	DARRIULAT 70	SPEC	
<140.	90	0	FOETH 69	SPEC	

[40] AKAGI 95 gives this number multiplied by the PDG 1992 average for $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma$(total).

[41] AKAGI 91B give this number multiplied by the 1990 PDG average for $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$.
[42] HEINSON 91 give $\Gamma(K^0_L \to \mu\mu)/\Gamma_{total}$. We divide out the $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma_{total}$ PDG average which they used.
[43] FUKUSHIMA 76 errors are at CL = 90%.
[44] CARITHERS 73 errors are at CL = 68%, W.Carithers, (private communication 79).
[45] CLARK 71 limit raised from 1.2×10^{-6} by FIELD 74 reanalysis. Not in agreement with subsequent experiments. So not averaged.

$\Gamma(\mu^+\mu^-\gamma)/\Gamma_{total}$ — Γ_{20}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN
0.323±0.023±0.019		197	SPENCER	95	E799
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.28 ±0.28		1	[46] CARROLL	80D	SPEC
<7.81	90		[47] DONALDSON	74	SPEC

[46] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.
[47] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_{21}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-10})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.41	90	0	[48] ARISAKA	93B	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 1.6	90	1	AKAGI	95	SPEC	
< 1.6	90	1	AKAGI	91	SPEC	Sup. by AKAGI 95
< 5.6	90		INAGAKI	89	SPEC	In AKAGI 91
< 3.2	90		MATHIAZHA...	89	SPEC	In ARISAKA 93B
< 110	90		COUSINS	88	SPEC	
< 45	90		GREENLEE	88	SPEC	Repl. by JASTRZEMBSKI 88
< 12	90		JASTRZEM...	88	SPEC	
< 15.7	90		[49] CLARK	71	ASPK	
<1500	90	0	FOETH	69	ASPK	

[48] ARISAKA 93B includes all events with <6 MeV radiated energy.
[49] Possible (but unknown) systematic errors. See note on CLARK 71 $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ entry.

$\Gamma(e^+e^-)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_{21}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 23.0	90	BOTT-...	67	OSPK
< 200.0	90	ALFF-...	66B	OSPK
<1000.0		ANIKINA	65	CC

$\Gamma(e^+e^-\gamma)/\Gamma_{total}$ — Γ_{22}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN
9.1±0.5 OUR AVERAGE					
9.2±0.5±0.5		1053	BARR	90B	NA31
$9.1\pm0.4^{+0.6}_{-0.5}$		919	OHL	90B	B845
• • • We do not use the following data for averages, fits, limits, etc. • • •					
17.4±8.7		4	[50] CARROLL	80D	SPEC
<27	90	0	[51] BARMIN	72	HLBC

[50] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.
[51] Uses $K^0_L \to 3\pi^0/\text{total} = 0.214$.

$\Gamma(e^+e^-\gamma\gamma)/\Gamma_{total}$ — Γ_{23}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-7})	EVTS	DOCUMENT ID		TECN	COMMENT
6.5±1.2 OUR AVERAGE					
6.5±1.2±0.6	58	NAKAYA	94	E799	$E_\gamma > 5$ MeV
6.6±3.2		MORSE	92	B845	$E_\gamma > 5$ MeV

$\Gamma(\pi^+\pi^-e^+e^-)/\Gamma_{total}$ — Γ_{24}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN
< 2.5	90	0	BALATS	83	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 8.81	90		[52] DONALDSON	76	SPEC
<30			ANIKINA	73	STRC

[52] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(\mu^+\mu^-e^+e^-)/\Gamma_{total}$ — Γ_{25}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
<4.9	90	BALATS	83	SPEC

$\Gamma(e^+e^-e^+e^-)/\Gamma_{total}$ — Γ_{26}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
4.1 ±0.8 OUR AVERAGE Error includes scale factor of 1.2.						
6 ±2 ±1		18	[53] AKAGI	95	SPEC	m_{ee} >470 MeV
10.4 ±3.7 ±1.1		8	[54] BARR	95	NA31	
3.96±0.78±0.32		27	GU	94	E799	
3.07±1.25±0.26		6	VAGINS	93	B845	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
7 ±3 ±2		6	[53] AKAGI	95	SPEC	m_{ee} >470 MeV
6 ±2 ±1		18	AKAGI	93	CNTR	Sup. by AKAGI 95
4 ±3		2	BARR	91	NA31	Sup. by BARR 95
<260	90		BALATS	83	SPEC	

[53] Values are for the total branching fraction, acceptance-corrected for the m_{ee} cuts shown.
[54] Distribution of angles between two e^+e^- pair planes favors $CP=-1$ for K^0_L.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{total}$ — Γ_{27}/Γ

Violates CP in leading order. Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN
< 5.1	90	0	HARRIS	93	E799
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1200	90	0	[55] CARROLL	80D	SPEC
<56600	90		[56] DONALDSON	74	SPEC

[55] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.
[56] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.126.

$\Gamma(\pi^0e^+e^-)/\Gamma_{total}$ — Γ_{28}/Γ

Violates CP in leading order. Direct and indirect CP-violating contributions are expected to be comparable and to dominate the CP-conserving part. Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN
< 4.3	90	0	HARRIS	93B	E799
< 7.5	90	0	BARKER	90	E731
< 5.5	90	0	OHL	90	B845
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 40	90		BARR	88	NA31
< 320	90		JASTRZEM...	88	SPEC
<2300	90	0	[57] CARROLL	80D	SPEC

[57] Uses $K^0_L \to \pi^+\pi^-\pi^0/(\text{all } K^0_L)$ decays = 0.1239.

$\Gamma(\pi^0\nu\overline{\nu})/\Gamma_{total}$ — Γ_{29}/Γ

Violates CP in leading order. Test of direct CP violation since the indirect CP-violating and CP-conserving contributions are expected to be suppressed. Test of $\Delta S = 1$ weak neutral current.

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN
< 5.8	90	0	WEAVER	94	E799
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 22	90	0	GRAHAM	92	CNTR
<760	90		[58] LITTENBERG	89	RVUE

[58] LITTENBERG 89 is from retroactive data analysis of CRONIN 67.

$\Gamma(e^\pm\mu^\mp)/\Gamma_{total}$ — Γ_{30}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-11})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 3.3	90	0	[59] ARISAKA	93	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 9.4	90	0	AKAGI	95	SPEC	
< 3.9	90	0	ARISAKA	93	B791	
< 9.4	90	0	AKAGI	91	SPEC	Sup. by AKAGI 95
< 43	90		INAGAKI	89	SPEC	In AKAGI 91
< 22	90		MATHIAZHA...	89	SPEC	
< 190	90		SCHAFFNER	89	SPEC	
<1100	90		COUSINS	88	SPEC	
< 670	90		GREENLEE	88	SPEC	Repl. by SCHAFFNER 89
< 157	90		[60] CLARK	71	ASPK	

[59] This is the combined result of ARISAKA 93 and MATHIAZHAGAN 89.
[60] Possible (but unknown) systematic errors. See note on CLARK 71 $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ entry.

$\Gamma(e^\pm\mu^\mp)/[\Gamma(\pi^+\pi^-\pi^0)+\Gamma(\pi^\pm\mu^\mp\nu)+\Gamma(\pi^\pm e^\mp\nu_e)]$ — $\Gamma_{30}/(\Gamma_2+\Gamma_3+\Gamma_6)$

Test of lepton family number conservation.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.1	90	BOTT-...	67	OSPK
< 0.08	90	FITCH	67	OSPK
< 1.0	90	CARPENTER	66	OSPK
<10.0		ANIKINA	65	CC

ENERGY DEPENDENCE OF K^0_L DALITZ PLOT

For discussion, see note on Dalitz plot parameters in the $K^\pm$ section of the Particle Listings above. For definitions of a_v, a_t, a_u, and a_y, see the earlier version of the same note in the 1982 edition of this *Review* published in Physics Letters **111B** 70 (1982).

$|\text{matrix element}|^2 = 1 + gu + hu^2 + jv + kv^2$
where $u = (s_3 - s_0) / m^2_\pi$ and $v = (s_1 - s_2) / m^2_\pi$

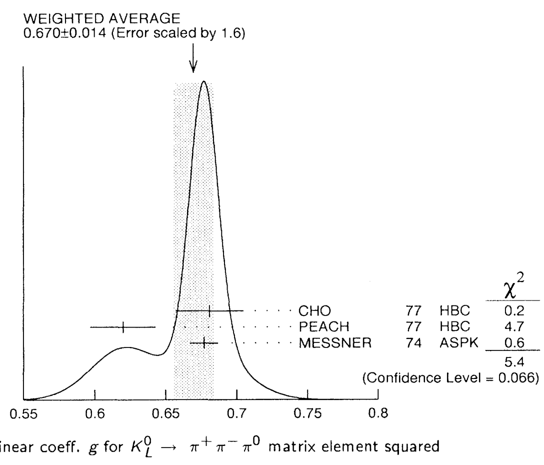
LINEAR COEFFICIENT *g* FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.670±0.014 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
0.681±0.024	6499	CHO	77	HBC	
0.620±0.023	4709	PEACH	77	HBC	
0.677±0.010	509k	MESSNER	74	ASPK	$a_y = -0.917 \pm 0.013$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.69 ±0.07	192	[61] BALDO-...	75	HLBC	
0.590±0.022	56k	[61] BUCHANAN	75	SPEC	$a_u = -0.277 \pm 0.010$
0.619±0.027	20k	[61,62] BISI	74	ASPK	$a_t = -0.282 \pm 0.011$
0.612±0.032		[61] ALEXANDER	73B	HBC	
0.73 ±0.04	3200	[61] BRANDENB...	73	HBC	
0.50 ±0.11	180	[61] JAMES	72	HBC	
0.608±0.043	1486	[61] KRENZ	72	HLBC	$a_t = -0.277 \pm 0.018$
0.688±0.074	384	[61] METCALF	72	ASPK	$a_t = -0.31 \pm 0.03$
0.650±0.012	29k	[61] ALBROW	70	ASPK	$a_y = -0.858 \pm 0.015$
0.593±0.022	36k	[61,63] BUCHANAN	70	SPEC	$a_u = -0.278 \pm 0.010$
0.664±0.056	4400	[61] SMITH	70	OSPK	$a_t = -0.306 \pm 0.024$
0.400±0.045	2446	[61] BASILE	68B	OSPK	$a_t = -0.188 \pm 0.020$
0.649±0.044	1350	[61] HOPKINS	67	HBC	$a_t = -0.294 \pm 0.018$
0.428±0.055	1198	[61] NEFKENS	67	OSPK	$a_u = -0.204 \pm 0.025$
0.64 ±0.17	280	[61] ANIKINA	66	CC	$a_y = -8.2^{+0.9}_{-1.3}$
0.70 ±0.12	126	[61] HAWKINS	66	HBC	$a_y = -8.6 \pm 0.7$
0.32 ±0.13	66	[61] ASTBURY	65	CC	$a_y = -5.5 \pm 1.5$
0.51 ±0.09	310	[61] ASTBURY	65B	CC	$a_y = -7.3^{+0.6}_{-0.8}$
0.55 ±0.23	79	[61] ADAIR	64	HBC	$a_y = -7.6 \pm 1.7$
0.51 ±0.20	77	[61] LUERS	64	HBC	$a_y = -7.3 \pm 1.6$

[61] Quadratic dependence required by some experiments. (See sections on "QUADRATIC COEFFICIENT *h*" and "QUADRATIC COEFFICIENT *k*" below.) Correlations prevent us from averaging results of fits not including *g*, *h*, and *k* terms.

[62] BISI 74 value comes from quadratic fit with quad. term consistent with zero. *g* error is thus larger than if linear fit were used.

[63] BUCHANAN 70 result revised by BUCHANAN 75 to include radiative correlations and to use more reliable K^0_L momentum spectrum of second experiment (had same beam).



Linear coeff. *g* for $K^0_L \rightarrow \pi^+\pi^-\pi^0$ matrix element squared

QUADRATIC COEFFICIENT *h* FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.079±0.007 OUR AVERAGE				
0.095±0.032	6499	CHO	77	HBC
0.048±0.036	4709	PEACH	77	HBC
0.079±0.007	509k	MESSNER	74	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.011±0.018	29k	[64] ALBROW	70	ASPK
0.043±0.052	4400	[64] SMITH	70	OSPK

See notes in section "LINEAR COEFFICIENT *g* FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$ |MATRIX ELEMENT|^2" above.

[64] Quadratic coefficients *h* and *k* required by some experiments. (See section on "QUADRATIC COEFFICIENT *k*" below.) Correlations prevent us from averaging results of fits not including *g*, *h*, and *k* terms.

QUADRATIC COEFFICIENT *k* FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN
0.0098±0.0018 OUR AVERAGE				
0.024 ±0.010	6499	CHO	77	HBC
−0.008 ±0.012	4709	PEACH	77	HBC
0.0097±0.0018	509k	MESSNER	74	ASPK

LINEAR COEFFICIENT *j* FOR $K^0_L \rightarrow \pi^+\pi^-\pi^0$ (*CP*-VIOLATING TERM)

Listed in *CP*-violation section below.

QUADRATIC COEFFICIENT *h* FOR $K^0_L \rightarrow \pi^0\pi^0\pi^0$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN
−3.3±1.1±0.7	5M	[65] SOMALWAR	92	E731

[65] SOMALWAR 92 chose m_{π^+} as normalization to make it compatible with the Particle Data Group $K^0_L \rightarrow \pi^+\pi^-\pi^0$ definitions.

K^0_L FORM FACTORS

For discussion, see note on form factors in the $K^\pm$ section of the Particle Listings above.

In the form factor comments, the following symbols are used.

f_+ and f_- are form factors for the vector matrix element.
f_S and f_T refer to the scalar and tensor term.
$f_0 = f_+ + f_- t/(m^2_K - m^2_\pi)$.
λ_+, λ_-, and λ_0 are the linear expansion coefficients of f_+, f_-, and f_0.
λ_+ refers to the $K^0_{\mu 3}$ value except in the K^0_{e3} sections.
$d\xi(0)/d\lambda_+$ is the correlation between $\xi(0)$ and λ_+ in $K^0_{\mu 3}$.
$d\lambda_0/d\lambda_+$ is the correlation between λ_0 and λ_+ in $K^0_{\mu 3}$.
t = momentum transfer to the π in units of m^2_π.
DP = Dalitz plot analysis.
PI = π spectrum analysis.
MU = μ spectrum analysis.
POL= μ polarization analysis.
BR = $K^0_{\mu 3}/K^0_{e3}$ branching ratio analysis.
E = positron or electron spectrum analysis.
RC = radiative corrections.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN K^0_{e3} DECAY)

For radiative correction of K^0_{e3} DP, see GINSBERG 67 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0300±0.0016 OUR AVERAGE	Error includes scale factor of 1.2.				
0.0306±0.0034	74k	BIRULEV	81	SPEC	DP
0.025 ±0.005	12k	[66] ENGLER	78B	HBC	DP
0.0348±0.0044	18k	HILL	78	STRC	DP
0.0312±0.0025	500k	GJESDAL	76	SPEC	DP
0.0270±0.0028	25k	BLUMENTHAL	75	SPEC	DP
0.044 ±0.006	24k	BUCHANAN	75	SPEC	DP
0.040 ±0.012	2171	WANG	74	OSPK	DP
0.045 ±0.014	5600	ALBROW	73	ASPK	DP
0.019 ±0.013	1871	BRANDENB...	73	HBC	PI transv.
0.022 ±0.014	1910	NEUHOFER	72	ASPK	PI
0.023 ±0.005	42k	BISI	71	ASPK	DP
0.05 ±0.01	16k	CHIEN	71	ASPK	DP, no RC
0.02 ±0.013	1000	ARONSON	68	OSPK	PI
+0.023 ±0.012	4800	BASILE	68	OSPK	DP, no RC
−0.01 ±0.02	762	FIRESTONE	67	HBC	DP, no RC
+0.01 ±0.015	531	KADYK	67	HBC	e,PI, no RC
+0.08 $^{+0.10}_{-0.08}$	240	LOWYS	67	FBC	PI
+0.15 ±0.08	577	FISHER	65	OSPK	DP, no RC
+0.07 ±0.06	153	LUERS	64	HBC	DP, no RC
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.029 ±0.005	19k	[66] CHO	80	HBC	DP
0.0286±0.0049	26k	BIRULEV	79	SPEC	Repl. by BIRULEV 81
0.032 ±0.0042	48k	BIRULEV	76	SPEC	Repl. by BIRULEV 81

[66] ENGLER 78B uses an unique K_{e3} subset of CHO 80 events and is less subject to systematic effects.

$\xi_a = f_-/f_+$ (determined from $K^0_{\mu 3}$ spectra)

The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	$d\xi(0)/d\lambda_+$	EVTS	DOCUMENT ID		TECN	COMMENT
−0.11±0.09 OUR EVALUATION	From a fit discussed in note on $K_{\ell 3}$ form factors in 1982 edition, PL **111B** (April 1982).					
−0.10±0.09	−12	150k	[67] BIRULEV	81	SPEC	DP
+0.26±0.16	−13	14k	[68] CHO	80	HBC	DP
+0.13±0.23	−20	16k	[68] HILL	79	STRC	DP
−0.25±0.22	−5.9	32k	[69] BUCHANAN	75	SPEC	DP
−0.11±0.07	−17	1.6M	[70] DONALDSON	74B	SPEC	DP
−1.00±0.45	−20	1385	[71] PEACH	73	HLBC	DP
−1.5 ±0.7	−28	9086	[72] ALBROW	72	ASPK	DP
+1.2 ±0.8	−18	1341	[73] CARPENTER	66	OSPK	DP

• • • We do not use the following data for averages, fits, limits, etc. • • •

$+0.50\pm0.61$	unknown	16k	[74] DALLY	72	ASPK	DP
$-3.9\ \pm0.4$		3140	[75] BASILE	70	OSPK	DP, indep of λ_+
$-0.68^{+0.12}_{-0.20}$	-26	16k	[74] CHIEN	70	ASPK	DP

[67] BIRULEV 81 error, $d\xi(0)/d\lambda_+$ calculated by us from λ_0, λ_+. $d\lambda_0/d\lambda_+ = 0$ used.

[68] HILL 79 and CHO 80 calculated by us from λ_0, λ_+, and $d\lambda_0/d\lambda_+$.

[69] BUCHANAN 75 is calculated by us from λ_0, λ_+ and $d\lambda_0/d\lambda_+$ because their appendix A value -0.20 ± 22 assumes $\xi(t)$ constant, i.e. $\lambda_- = \lambda_+$.

[70] DONALDSON 74B gives $\xi = -0.11 \pm 0.02$ not including systematics. Above error and $d\xi(0)/d\lambda_+$ were calculated by us from λ_0 and λ_+ errors (which include systematics) and $d\lambda_0/d\lambda_+$.

[71] PEACH 73 gives $\xi(0) = -0.95 \pm 0.45$ for $\lambda_+ = \lambda_- = 0.025$. The above value is for $\lambda_- = 0$. K.Peach, private communication (1974).

[72] ALBROW 72 fit has λ_- free, gets $\lambda_- = -0.030 \pm 0.060$ or $\Lambda = +0.15^{+0.17}_{-0.11}$.

[73] CARPENTER 66 $\xi(0)$ is for $\lambda_+ = 0$. $d\xi(0)/d\lambda_+$ is from figure 9.

[74] CHIEN 70 errors are statistical only. $d\xi(0)/d\lambda_+$ from figure 4. DALLY 72 is a reanalysis of CHIEN 70. The DALLY 72 result is not compatible with assumption $\lambda_- = 0$ so not included in our fit. The nonzero λ_- value and the relatively large λ_+ value found by DALLY 72 come mainly from a single low t bin (figures 1,2). The (f_+,ξ) correlation was ignored. We estimate from figure 2 that fixing $\lambda_- = 0$ would give $\xi(0) = -1.4 \pm 0.3$ and would add 10 to χ^2. $d\xi(0)/d\lambda_+$ is not given.

[75] BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

$\xi_b = f_-/f_+$ (determined from $K^0_{\mu3}/K^0_{e3}$)

The $K^0_{\mu3}/K^0_{e3}$ branching ratio fixes a relationship between $\xi(0)$ and λ_+. We quote the author's $\xi(0)$ and associated λ_+ but do not average because the λ_+ values differ. The fit result and scale factor given below are not obtained from these ξ_b values. Instead they are obtained directly from the authors $K^0_{\mu3}/K^0_{e3}$ branching ratio via the fitted $K^0_{\mu3}/K^0_{e3}$ ratio $(\Gamma(\pi^\pm\mu^\mp\nu)/\Gamma(\pi^\pm e^\mp\nu_e))$. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.11 ± 0.09 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.5\ \pm0.4$	6700	BRANDENB...	73	HBC	BR, λ_+=0.019 ± 0.013
-0.08 ± 0.25	1309	[76] EVANS	73	HLBC	BR, λ_+=0.02
$-0.5\ \pm0.5$	3548	BASILE	70	OSPK	BR, λ_+=0.02
$+0.45\pm0.28$	569	BEILLIERE	69	HLBC	BR, λ_+=0
-0.22 ± 0.30	1309	[76] EVANS	69	HLBC	
$+0.2\ ^{+0.8}_{-1.2}$		KULYUKINA	68	CC	BR, λ_+=0
$+1.1\ \pm1.1$	389	ADAIR	64	HBC	BR, λ_+=0
$+0.66^{+0.9}_{-1.3}$		LUERS	64	HBC	BR, λ_+=0

[76] EVANS 73 replaces EVANS 69.

$\xi_c = f_-/f_+$ (determined from μ polarization in $K^0_{\mu3}$)

The μ polarization is a measure of $\xi(t)$. No assumptions on λ_{+-} necessary, t (weighted by sensitivity to $\xi(t)$) should be specified. In λ_+, $\xi(0)$ parametrization this is $\xi(0)$ for $\lambda_+ = 0$. $d\xi/d\lambda = \xi t$. For radiative correction to μ polarization in $K^0_{\mu3}$, see GINSBERG 73. The parameter ξ is redundant with λ_0 below and is not put into the Meson Summary Table.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$-0.11\ \pm0.09$ OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
$+0.178\pm0.105$	207k	[77] CLARK	77	SPEC	POL, $d\xi(0)/d\lambda_+$=+0.68
-0.385 ± 0.105	2.2M	[78] SANDWEISS	73	CNTR	POL, $d\xi(0)/d\lambda_+$=−6
$-1.81\ ^{+0.50}_{-0.26}$		[79] LONGO	69	CNTR	POL, t=3.3
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$-1.6\ \ \pm0.5$	638	[80] ABRAMS	68B	OSPK	Polarization
$-1.2\ \ \pm0.5$	2608	[80] AUERBACH	66B	OSPK	Polarization

[77] CLARK 77 $t = +3.80$, $d\xi(0)/d\lambda_+ = \xi(t)t = 0.178\times3.80 = +0.68$.

[78] SANDWEISS 73 is for $\lambda_+ = 0$ and $t = 0$.

[79] LONGO 69 $t = 3.3$ calculated from $d\xi(0)/d\lambda_+ = -6.0$ (table 1) divided by $\xi = -1.81$.

[80] t value not given.

Im(ξ) in $K^0_{\mu3}$ DECAY (from transverse μ pol.)

Test of T reversal invariance.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.007 ± 0.026 OUR AVERAGE					
0.009 ± 0.030	12M	MORSE	80	CNTR	Polarization
$0.35\ \pm0.30$	207k	[81] CLARK	77	SPEC	POL, t=0
-0.085 ± 0.064	2.2M	[82] SANDWEISS	73	CNTR	POL, t=0
$-0.02\ \pm0.08$		LONGO	69	CNTR	POL, t=3.3
$-0.2\ \ \pm0.6$		ABRAMS	68B	OSPK	Polarization
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.012 ± 0.026		SCHMIDT	79	CNTR	Repl. by MORSE 80

[81] CLARK 77 value has additional $\xi(0)$ dependence $+0.21\mathrm{Re}[\xi(0)]$.

[82] SANDWEISS 73 value corrected from value quoted in their paper due to new value of Re(ξ). See footnote 4 of SCHMIDT 79.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN $K^0_{\mu3}$ DECAY)

See also the corresponding entries and notes in section "$\xi_A = f_-/f_+$" above and section "λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K^0_{\mu3}$ DECAY)" below. For radiative correction of $K^0_{\mu3}$ Dalitz plot see GINSBERG 70 and BECHERRAWY 70.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.034 ±0.005 OUR EVALUATION		From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
0.0427 ± 0.0044	150k	BIRULEV	81	SPEC	DP
$0.028\ \pm0.010$	14k	CHO	80	HBC	DP
$0.028\ \pm0.011$	16k	HILL	79	STRC	DP
$0.046\ \pm0.030$	32k	BUCHANAN	75	SPEC	DP
$0.030\ \pm0.003$	1.6M	DONALDSON	74B	SPEC	DP
$0.085\ \pm0.015$	9086	ALBROW	72	ASPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0337 ± 0.0033	129k	DZHORD...	77	SPEC	Repl. by BIRULEV 81
$0.046\ \pm0.008$	82k	ALBRECHT	74	WIRE	Repl. by BIRULEV 81
$0.11\ \ \pm0.04$	16k	DALLY	72	ASPK	DP
$0.07\ \ \pm0.02$	16k	CHIEN	70	ASPK	Repl. by DALLY 72

λ_0 (LINEAR ENERGY DEPENDENCE OF f_0 IN $K^0_{\mu3}$ DECAY)

Wherever possible, we have converted the above values of $\xi(0)$ into values of λ_0 using the associated λ^μ_+ and $d\xi(0)/d\lambda_+$.

VALUE	$d\lambda_0/d\lambda_+$	EVTS	DOCUMENT ID		TECN	COMMENT
0.025 ±0.006 OUR EVALUATION			From a fit discussed in note on $K_{\ell3}$ form factors in 1982 edition, PL **111B** (April 1982).			
0.0341 ± 0.0067	unknown	150k	[83] BIRULEV	81	SPEC	DP
$+0.050\ \pm0.008$	-0.11	14k	CHO	80	HBC	DP
$+0.039\ \pm0.010$	-0.67	16k	HILL	79	STRC	DP
$+0.047\ \pm0.009$	1.06	207k	[84] CLARK	77	SPEC	POL
$+0.025\ \pm0.019$	$+0.5$	32k	[85] BUCHANAN	75	SPEC	DP
$+0.019\ \pm0.004$	-0.47	1.6M	[86] DONALDSON	74B	SPEC	DP
$-0.060\ \pm0.038$	-0.71	1385	[87] PEACH	73	HLBC	DP
$-0.018\ \pm0.009$	$+0.49$	2.2M	[84] SANDWEISS	73	CNTR	POL
$-0.043\ \pm0.052$	-1.39	9086	[88] ALBROW	72	ASPK	DP
$-0.140\ ^{+0.043}_{-0.022}$	$+0.49$		[84] LONGO	69	CNTR	POL
$+0.08\ \ \pm0.07$	-0.54	1371	[84] CARPENTER	66	OSPK	DP
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$0.041\ \pm0.008$		14k	[89] CHO	80	HBC	BR, λ_+=0.028
$+0.0485\pm0.0076$		47k	DZHORD...	77	SPEC	In BIRULEV 81
$+0.024\ \pm0.011$		82k	ALBRECHT	74	WIRE	In BIRULEV 81
$+0.06\ \ \pm0.03$		6700	[90] BRANDENB...	73	HBC	BR, λ_+=0.019 ± 0.013
$-0.067\ \pm0.227$	unknown	16k	[91] DALLY	72	ASPK	DP
$-0.333\ \pm0.034$	$+1.$	3140	[92] BASILE	70	OSPK	DP

[83] BIRULEV 81 gives $d\lambda_0/d\lambda_+ = -1.5$, giving an unreasonably narrow error ellipse which dominates all other results. We use $d\lambda_0/d\lambda_+ = 0$.

[84] λ_0 value is for $\lambda_+ = 0.03$ calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[85] BUCHANAN 75 value is from their appendix A and uses only $K_{\mu3}$ data. $d\lambda_0/d\lambda_+$ was obtained by private communication, C.Buchanan, 1976.

[86] DONALDSON 74B $d\lambda_0/d\lambda_+$ obtained from figure 18.

[87] PEACH 73 assumes $\lambda_+ = 0.025$. Calculated by us from $\xi(0)$ and $d\xi(0)/d\lambda_+$.

[88] ALBROW 72 λ_0 is calculated by us from ξ_A, λ_+ and $d\xi(0)/d\lambda_+$. They give $\lambda_0 = -0.043 \pm 0.039$ for $\lambda_- = 0$. We use our larger calculated error.

[89] CHO 80 BR result not independent of their Dalitz plot result.

[90] Fit for λ_0 does not include this value but instead includes the $K_{\mu3}/K_{e3}$ result from this experiment.

[91] DALLY 72 gives $f_0 = 1.20 \pm 0.35$, $\lambda_0 = -0.080 \pm 0.272$, $\lambda_0{}' = -0.006 \pm 0.045$, but with a different definition of λ_0. Our quoted λ_0 is his λ_0/f_0. We cannot calculate true λ_0 error without his (λ_0,f_0) correlations. See also note on DALLY 72 in section ξ_A.

[92] BASILE 70 λ_0 is for $\lambda_+ = 0$. Calculated by us from ξ_A with $d\xi(0)/d\lambda_+ = 0$. BASILE 70 is incompatible with all other results. Authors suggest that efficiency estimates might be responsible.

$|f_S/f_+|$ FOR K^0_{e3} DECAY

Ratio of scalar to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.04	68	25k	BLUMENTHAL	75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.095	95	18k	HILL	78	STRC	
<0.07	68	48k	BIRULEV	76	SPEC	See also BIRULEV 81
<0.19	95	5600	ALBROW	73	ASPK	
<0.15	68		KULYUKINA	67	CC	

$|f_T/f_+|$ FOR K^0_{e3} DECAY

Ratio of tensor to f_+ couplings.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.23	68	25k	BLUMENTHAL	75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.40	95	18k	HILL	78	STRC	
<0.34	68	48k	BIRULEV	76	SPEC	See also BIRULEV 81
<1.0	95	5600	ALBROW	73	ASPK	
<1.0	68		KULYUKINA	67	CC	

$|f_T/f_+|$ FOR $K^0_{\mu 3}$ DECAY

Ratio of tensor to f_+ couplings.

VALUE	DOCUMENT ID		TECN
0.12±0.12	BIRULEV	81	SPEC

α_{K^*} DECAY FORM FACTOR FOR $K_L \to e^+e^-\gamma$

α_{K^*} is the constant in the model of BERGSTROM 83 which measures the relative strength of the vector-vector transition $K_L \to K^*\gamma$ with $K^* \to \rho, \omega, \phi \to \gamma^*$ and the pseudoscalar-pseudoscalar transition $K_L \to \pi, \eta, \eta' \to \gamma\gamma^*$.

VALUE	DOCUMENT ID		TECN
−0.28 ±0.08 OUR AVERAGE			
−0.28 ±0.13	BARR	90B	NA31
$-0.280^{+0.099}_{-0.090}$	OHL	90B	B845

DECAY FORM FACTORS FOR $K^0_L \to \pi^\pm\pi^0 e^\mp \nu_e$

Given in MAKOFF 93.

CP VIOLATION IN K^0_L DECAY

(by L. Wolfenstein, Carnegie-Mellon University and T. Trippe, LBNL)

Experimentally Measured Parameters

CP violation has been observed in the semi-leptonic decays $K^0_L \to \pi^\mp\ell^\pm\nu$ and in the nonleptonic decay $K^0_L \to 2\pi$. The experimental numbers that have been measured are [1]

$$\delta = \frac{\Gamma(K^0_L \to \pi^-\ell^+\nu) - \Gamma(K^0_L \to \pi^+\ell^-\nu)}{\Gamma(K^0_L \to \pi^-\ell^+\nu) + \Gamma(K^0_L \to \pi^+\ell^-\nu)} \tag{1a}$$

$$\begin{aligned}\eta_{+-} &= A(K^0_L \to \pi^+\pi^-)/A(K^0_S \to \pi^+\pi^-) \\ &= |\eta_{+-}|\, e^{i\phi_{+-}} \end{aligned} \tag{1b}$$

$$\begin{aligned}\eta_{00} &= A(K^0_L \to \pi^0\pi^0)/A(K^0_S \to \pi^0\pi^0) \\ &= |\eta_{00}|\, e^{i\phi_{00}} \ . \end{aligned} \tag{1c}$$

Thus there are five real numbers, three magnitudes, and two phases. We list $\delta(\mu)$ for $K^0_L \to \pi\mu\nu$ and $\delta(e)$ for $K^0_L \to \pi e\nu$ separately and a weighted average δ. Experimentally for the $K^0_L \to \pi^0\pi^0$ decay the quantities directly measured (and also of greatest theoretical interest) are $|\eta_{00}/\eta_{+-}|$ and $\phi_{00} - \phi_{+-}$.

Analysis Based on *CPT* Invariance [2]

CP violation can occur either in the K^0–$\overline{K}^0$ mixing or in the decay amplitudes. Assuming *CPT* invariance, the *CP* violation in the mixing is described by a single parameter ϵ:

$$\begin{aligned}|\,K^0_L\rangle &= \Big[(1+\epsilon)\,|\,K^0\,\rangle - (1-\epsilon)\,|\,\overline{K}^0\,\rangle\Big] \\ &\quad /\,\big[2(1+|\,\epsilon\,|^2)\big]^{1/2}\end{aligned} \tag{2a}$$

$$\begin{aligned}|\,K^0_S\rangle &= \Big[(1+\epsilon)\,|\,K^0\,\rangle + (1-\epsilon)\,|\,\overline{K}^0\,\rangle\Big] \\ &\quad /\,\big[2(1+|\,\epsilon\,|^2)\big]^{1/2} \ .\end{aligned} \tag{2b}$$

The decay amplitudes are written

$$\langle\, I=0\,|\,T\,|\,K^0\rangle = e^{i\delta_0}A_0 \tag{3a}$$

$$\langle\, I=2\,|\,T\,|\,K^0\rangle = e^{i\delta_2}A_2 \tag{3b}$$

where δ_I are the $\pi\pi$ scattering phase shifts at the K^0 mass and I is the isospin of the final state. *CP* violation is measured by (Im A_I/Re A_I). One can then write

$$\eta_{+-} = \epsilon + \epsilon' \tag{4a}$$

$$\eta_{00} = \epsilon - 2\epsilon' \tag{4b}$$

where

$$\epsilon' = \frac{i}{\sqrt{2}}\, e^{i(\delta_2-\delta_0)}\, \frac{\text{Re}\,A_2}{\text{Re}\,A_0}\left[\frac{\text{Im}\,A_2}{\text{Re}\,A_2} - \frac{\text{Im}\,A_0}{\text{Re}\,A_0}\right] \tag{5}$$

neglecting small corrections of order ϵ' times Re(A_2/A_0). It is possible by a choice of phase convention to set Im A_0 or Im A_2 or Im$\,\epsilon$ to 0, but none of these is 0 with the usual phase convention in the Standard Model. The choice Im A_0=0 is the Wu-Yang phase convention [3].

By applying *CPT* invariance and unitarity it is possible to relate δ to ϵ and to determine the phases of ϵ and ϵ'. If one assumes the $\Delta S = \Delta Q$ rule (see below note on the "$\Delta S = \Delta Q$ Rule in K^0 Decay") the expression for δ becomes

$$\delta = 2\text{Re}\,\epsilon/(1+\,|\,\epsilon\,|^2) \approx 2\text{Re}\,\epsilon \ . \tag{6}$$

This quantity is independent of phase convention and is seen from Eq. (2) to equal $\langle K^0_L\,|\,K^0_S\rangle$. The phase of ϵ is given by

$$\phi(\epsilon) \approx \tan^{-1}\frac{2(m_{K_L}-m_{K_S})}{\Gamma_{K_S}-\Gamma_{K_L}} = 43.49 \pm 0.08^\circ \tag{7a}$$

while Eq. (5) gives

$$\phi(\epsilon') = \delta_2 - \delta_0 + \frac{\pi}{2} \approx 48 \pm 4^\circ \ . \tag{7b}$$

The approximation in Eq. (7*a*) depends on the assumption that direct *CP* violation is negligible in all K^0 decays and is expected to be good to a few tenths of a degree. Eq. (7*a*) is evaluated using the values of the $K^0_L - K^0_S$ mass difference $\Delta m = (0.5304 \pm 0.0014) \times 10^{10}\hbar\text{s}^{-1}$ and the K^0_S mean life $\tau_s = (0.8927 \pm 0.0009) \times 10^{-10}$s from the current edition. The value of the $\pi\pi$ phase shifts is taken from the fit given by Chell and Olsson [4]. The most important point for the analysis is that $\cos[\phi(\epsilon') - \phi(\epsilon)] \simeq 1$. The consequence of this analysis is that only two real quantities need be measured, the magnitude of ϵ and the value of (ϵ'/ϵ) including its sign. The measured quantity $|\eta_{00}/\eta_{+-}|^2$ which is very close to unity, is given to a good approximation by

$$\begin{aligned}|\eta_{00}/\eta_{+-}|^2 &\approx 1 - 6\text{Re}\,(\epsilon'/\epsilon) \\ &= 1 - 6(\epsilon'/\epsilon)\cos\left[\phi(\epsilon') - \phi(\epsilon)\right] \ .\end{aligned} \tag{8}$$

Since the cos in Eq. (8) is expected theoretically to be very close to unity it is customary to say that $|\eta_{00}/\eta_{+-}|^2$ determines ϵ'/ϵ.

It is possible to use the values of ϕ_{+-} and $\phi_{00} - \phi_{+-}$ to set limits on *CPT* violation. [See Tests of Conservation Laws.]

Models

In the superweak model [5] CP violation is restricted to the mass mixing so that to a high degree of accuracy one expects $\epsilon' = 0$. The phase $\phi(\epsilon)$ is given in this model exactly by Eq. (7a) so that this has sometimes been referred to as the superweak phase; however, as noted above, all CPT-invariant models give Eq. (7a) as a very good approximation. In the Standard Model CP violation is entirely due to the phase in the Cabibbo-Kobayashi-Maskawa mixing matrix [6](q.v.). Since CP violation occurs in first order in decay amplitudes and in second order in mass-matrix mixing, one expects a significant nonzero value of ϵ'. The calculation is uncertain partly because m_t and V_{td} are not well known and primarily because of the difficulty of estimating hadronic matrix elements [7]. The theoretical results for ϵ'/ϵ in the Standard Model are generally in the range from 10^{-4} to 3×10^{-3}.

Fit for ϕ_{+-}, ϕ_{00}, ϕ_{00}–ϕ_{+-}, Δm, and τ_s

The Fermilab E773 experiment has published new results on the CP-violation phases ϕ_{+-} and ϕ_{00}, the $K^0_L - K^0_S$ mass difference Δm, and the K^0_S mean life τ_s (Document ID in our listings: SCHWINGENHEUER 95; reference [8]). The CPLEAR experiment has published new results on ϕ_{+-} (ADLER 95B [9]) and Δm (ADLER 95 [10]).

Fermilab E773 (SCHWINGENHEUER 95 [8]) and E731 (GIBBONS 93 [11]) measure $\phi_{+-} - \phi_f$ and calculate the regeneration phase ϕ_f from the power law momentum dependence of the regeneration amplitude using analyticity and dispersion relations. In the E731 result, a systematic error of ± 0.5 degrees for departures from a pure power-law is included. For the E773 result, they modeled a variety of effects that do distort the amplitude from a pure power law and ascribed a $\pm 0.35°$ systematic error from uncertainties in these effects. Even so, the E731 result remains valid within its quoted errors. KLEINKNECHT 94 [12] and KLEINKNECHT 95 [13] argue that these systematic errors should be around 3°, primarily because of the absence of data on the momentum dependence of the regeneration amplitude above 160 GeV/c. BRIERE 95 [14] and BRIERE 95C [15] reply that the current understanding of regeneration is sufficient to allow a precise and reliable correction for the region above 160 GeV/c. The question is one of judgement about the reliability of the assumptions used. In the absence of any contradictory evidence, we choose to accept the judgement of the E731/E773 experimenters in setting their systematic errors.

In this edition we give a joint fit to the data on ϕ_{+-}, ϕ_{00}, $\phi_{00} - \phi_{+-}$, Δm, and τ_s, including the effects of correlations. Measurements of ϕ_{+-} and ϕ_{00} are highly correlated with Δm and τ_s. The correlations are given in the footnotes of the ϕ_{+-} and ϕ_{00} data listings. In earlier editions of the Review we adjusted the experimental values of ϕ_{+-} and ϕ_{00} to account for correlations with Δm and τ_s but did not include the effects of these correlations when evaluating Δm and τ_s. When a joint fit is done, the ϕ_{+-} measurements and their correlations have a strong influence on the fitted value of Δm. This is because the CERN NA31 vacuum regeneration experiments (CAROSI 90 [16] and GEWENIGER 74B [17]), the Fermilab E773/E731 regenerator experiments (SCHWINGENHEUER 95 [8] and GIBBONS 93 [11]), and the CPLEAR $K^0 - \overline{K}^0$ asymmetry experiment (ADLER 95B [9]) have very different dependences of ϕ_{+-} on Δm, as can be seen in Fig. 1. The correlations move the fitted Δm lower so that the ϕ_{+-} measurements are in good agreement with each other and with ϕ(superweak).

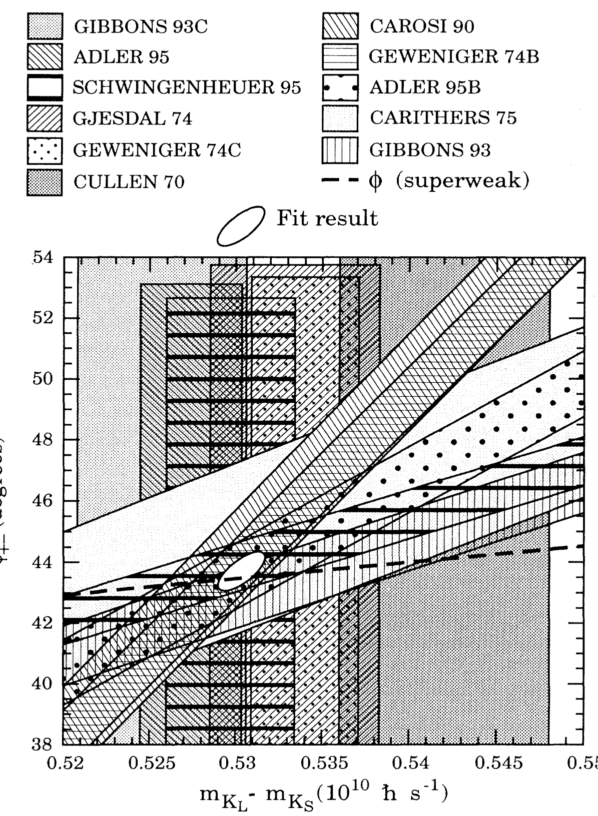


Figure 1: ϕ_{+-} vs Δm. Δm measurements appear as vertical bands spanning $\Delta m \pm 1\sigma$, some of which are cut near the top to aid the eye. The ϕ_{+-} measurements appear as diagonal bands spanning $\phi_{+-} \pm \sigma_\phi$. The dashed line shows ϕ(superweak). The ellipse shows the 1σ contour of the fit result. See Table 1 for data references.

The (ϕ_{+-}, τ_s) correlations influence the τ_s fit result in a similar manner, as can be seen in Fig. 2. The influence of the ϕ_{+-} experiments is not as great on τ_s as it is on Δm because the indirect measurements of τ_s derived from the diagonal crossing bands in Fig. 2 are not as precise as the direct measurements of τ_s from E773/E731 (SCHWINGENHEUER 95 [8] and GIBBONS 93 [11]).

Table 1: References for Fig. 1 and Fig. 2

Meas. / Fig. No.				
ϕ_{+-}	Δm	τ_s	PDG Document ID	Ref.
1,2			CAROSI 90	[16]
1		2	GEWENIGER 74B	[17]
1,2			ADLER 95B	[9]
1		2	CARITHERS 75	[18]
1,2	1	2	SCHWINGENHEUER 95	[8]
1,2		2	GIBBONS 93	[11]
	1		GIBBONS 93C	[19]
	1		ADLER 95	[10]
	1		GJESDAL 74	[20]
	1		GEWENIGER 74C	[21]
	1		CULLEN 70	[22]
		2	ARONSON 76	[23]
		2	GROSSMAN 87	[24]
		2	SKJEGGESTAD 72	[25]

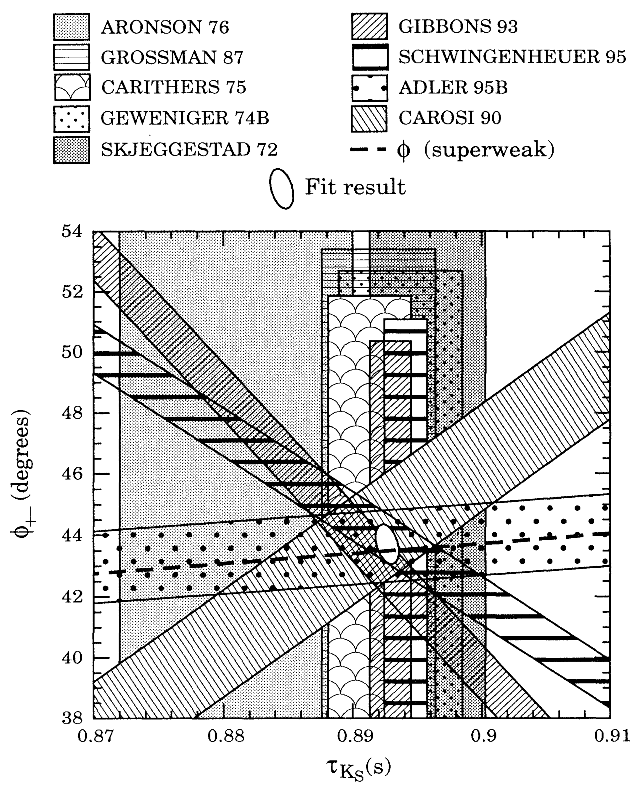


Figure 2: ϕ_{+-} vs τ_s. τ_s measurements appear as vertical bands spanning $\tau_s \pm 1\sigma$, some of which are cut near the top to aid the eye. The ϕ_{+-} measurements appear as diagonal bands spanning $\phi_{+-} \pm \sigma_\phi$. The dashed line shows ϕ(superweak). The ellipse shows the fit result's 1σ contour. See Table 1 for data references.

In Fig. 1 [Fig. 2] the slope of the diagonal ϕ_{+-} bands shows the Δm [τ_s] dependence; the unseen τ_s [Δm] dependent term is evaluated using the fitted τ_s [Δm]. The vertical half-width σ_ϕ of each band is the ϕ_{+-} error for fixed Δm [τ_s] and includes the systematic error due to the error in the fitted τ_s [Δm].

Table 2 gives the resulting fit values for the parameters and Table 3 gives the correlation matrix.

A similar analysis has been done by the CPLEAR Collaboration [26]. The small differences between their results and ours are due primarily to different treatments of τ_s. Their fit constrains τ_s to the PDG 1994 value, while our fit includes the more recent SCHWINGENHEUER 95 [8] τ measurement.

Table 2: Results of the fit for ϕ_{+-}, ϕ_{00}, $\phi_{00} - \phi_{+-}$, Δm, and τ_s. The fit has $\chi^2 = 12.0$ for 18 degrees of freedom (22 measurements -5 parameters $+1$ constraint).

Quantity	Fit Result
ϕ_{+-}	$43.7 \pm 0.6°$
Δm	$(0.5304 \pm 0.0014) \times 10^{10}\hbar\ s^{-1}$
τ_s	$(0.8927 \pm 0.0009) \times 10^{-10}$s
ϕ_{00}	$43.5 \pm 1.0°$
$\Delta\phi$	$-0.2 \pm 0.8°$

Table 3: Correlation matrix for the fitted parameters.

	ϕ_{+-}	Δm	τ_s	ϕ_{00}	$\Delta\phi$
ϕ_{+-}	1.00	0.71	−0.36	0.60	−0.02
Δm	0.71	1.00	−0.21	0.48	0.04
τ_s	−0.36	−0.21	1.00	−0.19	0.04
ϕ_{00}	0.60	0.48	−0.19	1.00	0.79
$\Delta\phi$	−0.02	0.04	0.04	0.79	1.00

Fit for ϵ'/ϵ, $|\eta_{+-}|$, $|\eta_{00}|$, and $B(K_L \to \pi\pi)$

We list measurements of $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$ and ϵ'/ϵ. Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from measurements of the K^0_L and K^0_S lifetimes (τ_s) and branching ratios (B) to $\pi\pi$, using the relations

$$|\eta_{+-}| = \left[\frac{B(K^0_L \to \pi^+\pi^-)}{\tau(K^0_L)} \frac{\tau(K^0_S)}{B(K^0_S \to \pi^+\pi^-)}\right]^{1/2} , \qquad (9a)$$

$$|\eta_{00}| = \left[\frac{B(K^0_L \to \pi^0\pi^0)}{\tau(K^0_L)} \frac{\tau(K^0_S)}{B(K^0_S \to \pi^0\pi^0)}\right]^{1/2} . \qquad (9b)$$

For historical reasons the branching ratio fits and the CP-violation fits are done separately, but we want to include the influence of $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and ϵ'/ϵ measurements on $B(K^0_L \to \pi^+\pi^-)$ and $B(K^0_L \to \pi^0\pi^0)$ and vice versa. We approximate a global fit to all of these measurements by first performing two independent fits: 1) BRFIT, a fit to the K^0_L branching ratios, rates, and mean life, and 2) ETAFIT, a fit to the $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{+-}/\eta_{00}|$, and ϵ'/ϵ measurements. The results from fit 1, along with the K^0_S values from this edition are used to compute values of $|\eta_{+-}|$ and $|\eta_{00}|$ which are included as measurements in the $|\eta_{00}|$ and $|\eta_{+-}|$ sections with a document ID of BRFIT 96. Thus the fit values of $|\eta_{+-}|$ and $|\eta_{00}|$ given in this edition include both the direct measurements and the results from the branching ratio fit.

The process is reversed in order to include the direct $|\eta|$ measurements in the branching ratio fit. The results from fit 2 above (before including BRFIT 96 values) are used along with the K^0_L and K^0_S mean lives and the $K^0_S \to \pi\pi$ branching fractions to compute the K^0_L branching ratios $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$ and $\Gamma(K^0_L \to \pi^0\pi^0)/\Gamma(K^0_L \to \pi^+\pi^-)$. These branching ratio values are included as measurements in the branching ratio section with a document ID of ETAFIT 96. Thus the K^0_L branching ratio fit values in this edition include the results of direct measurements of $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and ϵ'/ϵ. A more detailed discussion of these fits is given in the 1990 edition of this *Review* [27].

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CP-VIOLATION PARAMETERS IN K^0_L DECAYS

CHARGE ASYMMETRY IN $K^0_{\ell 3}$ DECAYS

Such asymmetry violates *CP*. It is related to Re(ϵ).

δ = weighted average of $\delta(\mu)$ and $\delta(e)$

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.327±0.012 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.				
0.333±0.050	33M	WILLIAMS	73	ASPK	$K_{\mu 3} + K_{e3}$

$\delta(\mu) = [\Gamma(\pi^- \mu^+ \nu_\mu) - \Gamma(\pi^+ \mu^- \overline{\nu}_\mu)]$/SUM

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*
The data in this block is included in the average printed for a previous datablock.				
0.304±0.025 OUR AVERAGE				
0.313±0.029	15M	GEWENIGER	74	ASPK
0.278±0.051	7.7M	PICCIONI	72	ASPK
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.60 ±0.14	4.1M	MCCARTHY	73	CNTR
0.57 ±0.17	1M	[93] PACIOTTI	69	OSPK
0.403±0.134	1M	[93] DORFAN	67	OSPK

[93] PACIOTTI 69 is a reanalysis of DORFAN 67 and is corrected for $\mu^+ \mu^-$ range difference in MCCARTHY 72.

$\delta(e) = [\Gamma(\pi^- e^+ \nu_e) - \Gamma(\pi^+ e^- \overline{\nu}_e)]$/SUM

Only the combined value below is put into the Meson Summary Table.

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*
The data in this block is included in the average printed for a previous datablock.				
0.333±0.014 OUR AVERAGE				
0.341±0.018	34M	GEWENIGER	74	ASPK
0.318±0.038	40M	FITCH	73	ASPK
0.346±0.033	10M	MARX	70	CNTR
0.246±0.059	10M	[94] SAAL	69	CNTR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.36 ±0.18	600k	ASHFORD	72	ASPK
0.224±0.036	10M	[94] BENNETT	67	CNTR

[94] SAAL 69 is a reanalysis of BENNETT 67.

PARAMETERS FOR $K^0_L \to 2\pi$ DECAY

$\eta_{+-} = A(K^0_L \to \pi^+\pi^-) \, / \, A(K^0_S \to \pi^+\pi^-)$

$\eta_{00} = A(K^0_L \to \pi^0\pi^0) \, / \, A(K^0_S \to \pi^0\pi^0)$

The fitted values of $|\eta_{+-}|$ and $|\eta_{00}|$ given below are the results of a fit to $|\eta_{+-}|$, $|\eta_{00}|$, $|\eta_{00}/\eta_{+-}|$, and Re(ϵ'/ϵ). Independent information on $|\eta_{+-}|$ and $|\eta_{00}|$ can be obtained from the fitted values of the $K^0_L \to \pi\pi$ and $K^0_S \to \pi\pi$ branching ratios and the K^0_L and K^0_S lifetimes. This information is included as data in the $|\eta_{+-}|$ and $|\eta_{00}|$ sections with a Document ID "BRFIT." See the "Note on *CP* Violation in K^0_L Decay" above for details.

$|\eta_{00}| = |A(K^0_L \to 2\pi^0) \, / \, A(K^0_S \to 2\pi^0)|$

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.275±0.019 OUR FIT	Error includes scale factor of 1.1.				
2.30 ±0.14 OUR AVERAGE					
2.25 ±0.22		[95] BRFIT	96		
2.33 ±0.18		CHRISTENS...	79	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.71 ±0.37	56	[96] WOLFF	71	OSPK	Cu reg., 4γ's
2.95 ±0.63		[96] CHOLLET	70	OSPK	Cu reg., 4γ's

[95] This BRFIT value is computed from fitted values of the K^0_L and K^0_S lifetimes and branching fractions to $\pi\pi$. See the discussion in the "Note on *CP* violation in K^0_L decay."

[96] CHOLLET 70 gives $|\eta_{00}|$ = (1.23 ± 0.24)×(regeneration amplitude, 2 GeV/c Cu)/10000mb. WOLFF 71 gives $|\eta_{00}|$ = (1.13 ± 0.12)×(regeneration amplitude, 2 GeV/c Cu)/10000mb. We compute both $|\eta_{00}|$ values for (regeneration amplitude, 2 GeV/c Cu) = 24 ± 2mb. This regeneration amplitude results from averaging over FAISSNER 69, extrapolated using optical-model calculations of Bohm et al., Physics Letters **27B** 594 (1968) and the data of BALATS 71. (From H. Faissner, private communication).

$|\eta_{+-}| = |A(K^0_L \to \pi^+\pi^-) \, / \, A(K^0_S \to \pi^+\pi^-)|$

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.285±0.019 OUR FIT					
2.284±0.018 OUR AVERAGE					
2.271±0.024		[97] BRFIT	96		
2.310±0.043±0.031		[98] ADLER	95B	CPLR	K^0-$\overline{K}^0$ asymmetry
2.32 ±0.14 ±0.03	10^5	ADLER	92B	SPEC	K^0-$\overline{K}^0$ asymm.
2.27 ±0.12		CHRISTENS...	79B	ASPK	
2.30 ±0.035		GEWENIGER	74B	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.28 ±0.06	1687	[99] COUPAL	85	SPEC	$P(K)$=70 GeV/c
2.09 ±0.02		[100] ARONSON	82B	SPEC	E=30–110 GeV

[97] This BRFIT value is computed from fitted values of the K^0_L and K^0_S lifetimes and branching fractions to $\pi\pi$. See the discussion in the "Note on *CP* violation in K^0_L decay."

[98] ADLER 95B report $(2.312 \pm 0.043 \pm 0.030 - 1[\Delta m - 0.5274] + 9.1[\tau_S - 0.8926]) \times 10^{-3}$. We evaluate for our 1996 best values $\Delta m = (0.5304 \pm 0.0014) \times 10^{-10}\ \hbar s^{-1}$ and $\tau_S = (0.8927 \pm 0.0009) \times 10^{-10}$ s.

[99] COUPAL 85 concludes: no energy dependence of $|\eta_{+-}|$, because their value is consistent with above values which occur at lower energies. Not independent of COUPAL 85 $\Gamma(\pi^+\pi^-)/\Gamma(\pi\ell\nu)$ measurement. Enters $|\eta_{+-}|$ via BRFIT value. In editions prior to 1990, this measurement was erroneously also included in our $|\eta_{+-}|$ average and fit. We thank H. Wahl (WAHL 89) for informing us.

[100] ARONSON 82B find that $|\eta_{+-}|$ may depend on the kaon energy.

$|\eta_{00}/\eta_{+-}|$

VALUE	EVTS	DOCUMENT ID	TECN
0.9956±0.0023 OUR FIT Error includes scale factor of 1.8.			
0.9930±0.0020 OUR AVERAGE			
0.9931±0.0020		[101,102] BARR	93D NA31
0.9904±0.0084±0.0036		[103] WOODS	88 E731
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.9939±0.0013±0.0015	1M	[101] BARR	93D NA31
0.9899±0.0020±0.0025		[101] BURKHARDT	88 NA31
1.014 ±0.016 ±0.007	3152	BERNSTEIN	85B SPEC
0.995 ±0.025	1122	BLACK	85 SPEC
1.00 ±0.09		[104] CHRISTENS...	79 ASPK
1.03 ±0.07	124	BANNER	72 OSPK
1.00 ±0.06	167	HOLDER	72 ASPK

[101] This is the square root of the ratio *R* given by BURKHARDT 88 and BARR 93D.

[102] This is the combined results from BARR 93D and BURKHARDT 88, taking into account a common systematic uncertainty of 0.0014.

[103] We calculate $|\eta_{00}/\eta_{+-}| = 1-3(\epsilon'/\epsilon)$ from WOODS 88 (ϵ'/ϵ) value.

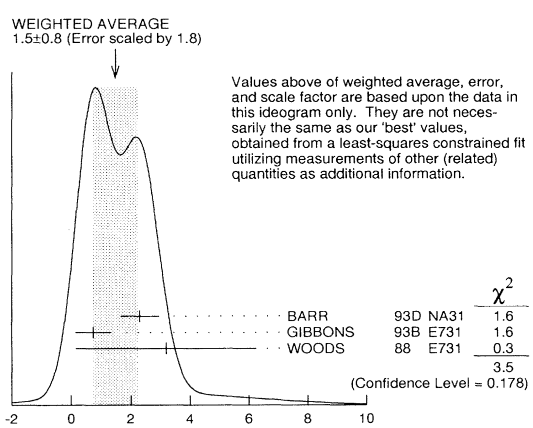
[104] Not independent of $|\eta_{+-}|$ and $|\eta_{00}|$ values which are included in fit.

$\epsilon'/\epsilon \approx \mathrm{Re}(\epsilon'/\epsilon) = (1-|\eta_{00}/\eta_{+-}|)/3$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
1.5 ±0.8 OUR FIT Error includes scale factor of 1.8.				
1.5 ±0.8 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.				
2.3 ±0.65		[105,106] BARR	93D NA31	
0.74±0.52±0.29	>5E5	GIBBONS	93B E731	
3.2 ±2.8 ±1.2		[105] WOODS	88 E731	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.0 ±0.7	1M	[105] BARR	93D NA31	
−0.4 ±1.4 ±0.6		PATTERSON	90 E731	in GIBBONS 93B
3.3 ±1.1		[105] BURKHARDT	88 NA31	

[105] These values are derived from $|\eta_{00}/\eta_{+-}|$ measurements. They enter the average in this section but enter the fit via the $|\eta_{00}/\eta_{+-}|$ section only.

[106] This is the combined results from BARR 93D and BURKHARDT 88, taking into account their common systematic uncertainty.



$\epsilon'/\epsilon \approx \mathrm{Re}(\epsilon'/\epsilon) = (1-|\eta_{00}/\eta_{+-}|)/3$

ϕ_{+-}, PHASE of η_{+-}

The dependence of the phase on Δm and τ_S is given for each experiment in the comments below, where Δm is the K^0_L-K^0_S mass difference in units $10^{10}\ \hbar s^{-1}$ and τ_S is the K_S mean life in units 10^{-10} s. For the "used" data, we have evaluated these mass dependences using our 1996 values, $\Delta m = 0.5304 \pm 0.0014$, $\tau_S = 0.8927 \pm 0.0009$ to obtain the values quoted below. We also give the regeneration phase ϕ_f in the comments below.

OUR FIT is described in the note on "*CP* Violation in K^0_L Decay" in the K^0_L Particle Listings.

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
43.7± 0.6 OUR FIT				
43.6± 1.2		[107] ADLER	95B CPLR	K^0-$\overline{K}^0$ asymmetry
43.9± 0.8		[108,109] SCHWINGEN...95	E773	$CH_{1.1}$ regenerator
42.9± 1.0		[109,110] GIBBONS	93 E731	$CH_{1.1}$ regenerator
44.3± 1.8		[111] CAROSI	90 NA31	Vacuum regen.
44.5± 2.8		[112] CARITHERS	75 SPEC	C regenerator
44.0± 1.3		[113] GEWENIGER	74B ASPK	Vacuum regen.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
42.3± 4.4±1.4	10^5	[114] ADLER	92B SPEC	K^0-$\overline{K}^0$ asymm.
47.7± 2.0±0.9		[109,115] KARLSSON	90 E731	
35.3± 3.9		[116] ARONSON	82B SPEC	
41.7± 3.5		CHRISTENS...	79B ASPK	
36.2± 6.1		[117] CARNEGIE	72 ASPK	Cu regenerator
37 ±12		[118] BALATS	71 OSPK	Cu regenerator
40 ± 4		[119] JENSEN	70 ASPK	Vacuum regen.
34 ±10		[120] BENNETT	69 CNTR	Cu regenerator
44 ±12		[121] BOHM	69B OSPK	Vacuum regen.
45 ± 7		[122] FAISSNER	69 ASPK	Cu regenerator
51 ±11		[123] BENNETT	68B CNTR	Cu reg. uses
70 ±21		[124] BOTT-...	67B OSPK	C regenerator
25 ±35		[124] MISCHKE	67 OSPK	Cu regenerator
30 ±45		[124] FIRESTONE	66 HBC	
45 ±50		[124] FITCH	65 OSPK	Be regenerator

[107] ADLER 95B report $(42.7^\circ \pm 0.9^\circ \pm 0.6^\circ + 316[\Delta m - 0.5274]^\circ + 30[\tau_S - 0.8926]^\circ$.

[108] SCHWINGENHEUER 95 reports $\phi_{+-} = 43.53 \pm 0.76 + 173[\Delta m - 0.5282] - 275[\tau_S - 0.8926]$.

[109] These experiments measure $\phi_{+-}-\phi_f$ and calculate the regeneration phase from the power law momentum dependence of the regeneration amplitude using analyticity and dispersion relations. SCHWINGENHEUER 95 [GIBBONS 93] includes a systematic error of 0.35° [0.5°] for uncertainties in their modeling of the regeneration amplitude. See the discussion of these systematic errors, including criticism that they could be underestimated, in the note on "*C* violation in K^0_L decay."

[110] GIBBONS 93 measures $\phi_{+}-\phi_f$ and calculates the regeneration phase ϕ_f from the power law momentum dependence of the regeneration amplitude using analyticity. An error of 0.6° is included for possible uncertainties in the regeneration phase. They find $\phi_{+-} = 42.21 \pm 0.9 + 189\ [\Delta m - 0.5257] - 460\ [\tau_S - 0.8922]^\circ$, as given in SCHWINGENHEUER 95, footnote 8. GIBBONS 93 reports ϕ_{+-} (42.2 ± 1.4)°

[111] CAROSI 90 $\phi_{+-} = 46.9 \pm 1.4 \pm 0.7 + 579\ [\Delta m - 0.5351] + 303\ [\tau_S - 0.8922]^\circ$.

[112] CARITHERS 75 $\phi_{+-} = (45.5 \pm 2.8) + 224[\Delta m - 0.5348]^\circ$. $\phi_f = -40.9 \pm 2.6^\circ$.

[113] GEWENIGER 74B $\phi_{+-} = (49.4 \pm 1.0) + 565[\Delta m - 0.540]^\circ$.

[114] ADLER 92B quote separately two systematic errors: ±0.4 from their experiment and ±1.0 degrees due to the uncertainty in the value of Δm.

[115] KARLSSON 90 systematic error does not include regeneration phase uncertainty.

[116] ARONSON 82 find that ϕ_{+-} may depend on the kaon energy.

[117] CARNEGIE 72 ϕ_{+-} is insensitive to Δm. $\phi_f = -56.2 \pm 5.2^\circ$.

[118] BALATS 71 $\phi_{+-} = (39.0 \pm 12.0) + 198[\Delta m - 0.544]^\circ$. $\phi_f = -43.0 \pm 4.0^\circ$.

[119] JENSEN 70 $\phi_{+-} = (42.4 \pm 4.0) + 576[\Delta m - 0.538]^\circ$.

[120] BENNETT 69 uses measurement of $(\phi_{+-})-(\phi_f)$ of ALFF-STEINBERGER 66B. BENNETT 69 $\phi_{+-} = (34.9 \pm 10.0) + 69[\Delta m - 0.545]^\circ$. $\phi_f = -49.9 \pm 5.4^\circ$.

[121] BOHM 69B $\phi_{+-} = (41.0 \pm 12.0) + 479(\Delta m - 0.526)^\circ$.

[122] FAISSNER 69 error enlarged to include error in regenerator phase. FAISSNER 69 $\phi_{+-} = (49.3 \pm 7.4) + 205[\Delta m - 0.555]^\circ$. $\phi_f = -42.7 \pm 5.0^\circ$.

[123] BENNETT 69 is a re-evaluation of BENNETT 68B.

[124] Old experiments with large errors not included in average.

ϕ_{00}, PHASE OF η_{00}

See comment in ϕ_{+-} header above for treatment of Δm and τ_S dependence.

OUR FIT is described in the note on "*CP* Violation in K^0_L Decay" in the K^0_L Particle Listings.

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
43.5± 1.0 OUR FIT				
44.5± 2.5		[125] CAROSI	90 NA31	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
47.4± 1.4±0.9		[126] KARLSSON	90 E731	
55.7± 5.8		CHRISTENS...	79 ASPK	
38.0±25.0	56	[127] WOLFF	71 OSPK	Cu reg., 4γ's
51.0±30.0		[128] CHOLLET	70 OSPK	Cu reg., 4γ's
first quadrant preferred		GOBBI	69B OSPK	

[125] CAROSI 90 $\phi_{00} = 47.1 \pm 2.1 \pm 1.0 + 579\ [\Delta m - 0.5351] + 252\ [\tau_S - 0.8922]^\circ$.

[126] KARLSSON 90 systematic error does not include regeneration phase uncertainty.

[127] WOLFF 71 uses regenerator phase $\phi_f = -48.2 \pm 3.5^\circ$.

[128] CHOLLET 70 uses regenerator phase $\phi_f = -46.5 \pm 4.4^\circ$.

PHASE DIFFERENCE $\phi_{00} - \phi_{+-}$

Test of *CPT*.

OUR FIT is described in the note on "*CP* Violation in K^0_L Decay" in the K^0_L Particle Listings.

VALUE (°)	DOCUMENT ID	TECN	COMMENT
− 0.2 ± 0.8 OUR FIT			
− 0.3 ± 0.8 OUR AVERAGE			
− 0.30± 0.88	[129] SCHWINGEN...95		Combined E731, E773
0.2 ± 2.6 ±1.2	[130] CAROSI 90	NA31	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.62± 0.71±0.75	SCHWINGEN...95	E773	
− 1.6 ± 1.2	[131] GIBBONS 93	E731	
− 0.3 ± 2.4 ±1.2	KARLSSON 90	E731	
12.6 ± 6.2	[132] CHRISTENS... 79	ASPK	
7.6 ±18.0	[133] BARBIELLINI 73	ASPK	

[129] This SCHWINGENHEUER 95 values is the combined result of SCHWINGENHEUER 95 and GIBBONS 93, accounting for correlated systematic errors.
[130] CAROSI 90 is excluded from the fit because it is not independent of ϕ_{+-} and ϕ_{00} values.
[131] GIBBONS 93 give detailed dependence of systematic error on lifetime (see the section on the K^0_S mean life) and mass difference (see the section on $m_{K^0_L} - m_{K^0_S}$).
[132] Not independent of ϕ_{+-} and ϕ_{00} values.
[133] Independent of regenerator mechanism, Δm, and lifetimes.

CHARGE ASYMMETRY IN $\pi^+\pi^-\pi^0$ DECAYS

CHARGE ASYMMETRY j FOR $K^0_L \to \pi^+\pi^-\pi^0$

Defined at beginning of section "LINEAR COEFFICIENT g FOR $K^0_L \to \pi^+\pi^-\pi^0$ above. Such asymmetry violates *CP*. See also note on Daltitz plot parameters in $K^\pm$ section and note on *CP* violation in K^0_L decay above.

VALUE	EVTS	DOCUMENT ID	TECN
0.0011±0.0008 OUR AVERAGE			
0.001 ±0.011	6499	CHO 77	
−0.001 ±0.003	4709	PEACH 77	
0.0013±0.0009	3M	SCRIBANO 70	
0.0 ±0.017	4400	SMITH 70	OSPK
0.001 ±0.004	238k	BLANPIED 68	

PARAMETERS for $K^0_L \to \pi^+\pi^-\gamma$ DECAY

$|\eta_{+-\gamma}| = |A(K^0_L \to \pi^+\pi^-\gamma,\ CP \text{ violating})/A(K^0_S \to \pi^+\pi^-\gamma)|$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN
2.35 ±0.07 OUR AVERAGE			
2.359±0.062±0.040	9045	MATTHEWS 95	E773
2.15 ±0.26 ±0.20	3671	RAMBERG 93B	E731

$\phi_{+-\gamma}$ = phase of $\eta_{+-\gamma}$

VALUE (°)	EVTS	DOCUMENT ID	TECN
44 ± 4 OUR AVERAGE			
43.8± 3.5± 1.9	9045	MATTHEWS 95	E773
72 ±23 ±17	3671	RAMBERG 93B	E731

$|\epsilon'_{+-\gamma}|/\epsilon$

VALUE	CL%	EVTS	DOCUMENT ID	TECN
<0.3	90	3671	[134] RAMBERG 93B	E731

[134] RAMBERG 93B limit on $|\epsilon'_{+-\gamma}|/\epsilon$ assumes than any difference between η_{+-} and $\eta_{+-\gamma}$ is due to direct *CP* violation.

$\Delta S = \Delta Q$ IN K^0 DECAYS

The relative amount of $\Delta S \neq \Delta Q$ component present is measured by the parameter x, defined as

$$x = A(\overline{K}^0 \to \pi^-\ell^+\nu)/A(K^0 \to \pi^-\ell^+\nu)\ .$$

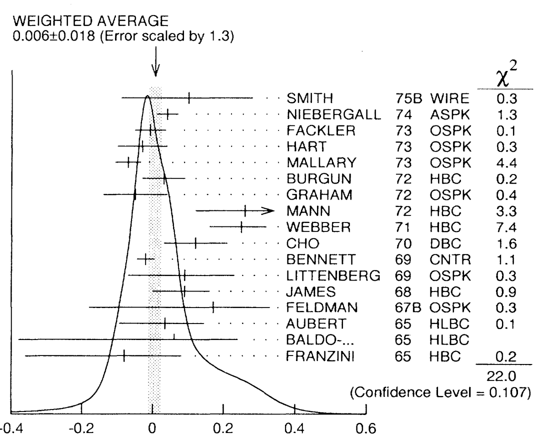
We list Re$\{x\}$ and Im$\{x\}$ for K_{e3} and $K_{\mu 3}$ combined.

$x = A(\overline{K^0} \to \pi^-\ell^+\nu)/A(K^0 \to \pi^-\ell^+\nu) = A(\Delta S{=}-\Delta Q)/A(\Delta S{=}\Delta Q)$

REAL PART OF x

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.006±0.018 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.		
0.10 $^{+0.18}_{-0.19}$	79	SMITH 75B	WIRE	$\pi^- p \to K^0\Lambda$
0.04 ±0.03	4724	NIEBERGALL 74	ASPK	$K^+ p \to K^0 p\pi^+$
−0.008±0.044	1757	FACKLER 73	OSPK	K_{e3} from K^0
−0.03 ±0.07	1367	HART 73	OSPK	K_{e3} from $K^0\Lambda$
−0.070±0.036	1079	MALLARY 73	OSPK	K_{e3} from $K^0\Lambda X$
0.03 ±0.06	410	[135] BURGUN 72	HBC	$K^+ p \to K^0 p\pi^+$
−0.05 ±0.09	442	[136] GRAHAM 72	OSPK	$\pi^- p \to K^0\Lambda$
0.26 $^{+0.10}_{-0.14}$	126	MANN 72	HBC	$K^- p \to n\overline{K}^0$
0.25 $^{+0.07}_{-0.09}$	252	WEBBER 71	HBC	$K^- p \to n\overline{K}^0$
0.12 ±0.09	215	[137] CHO 70	DBC	$K^+ d \to K^0 pp$
−0.020±0.025		[138] BENNETT 69	CNTR	Charge asym+ Cu regen.
0.09 $^{+0.14}_{-0.16}$	686	LITTENBERG 69	OSPK	$K^+ n \to K^0 p$
0.09 $^{+0.07}_{-0.09}$	121	JAMES 68	HBC	$\overline{p}p$
0.17 $^{+0.16}_{-0.35}$	116	FELDMAN 67B	OSPK	$\pi^- p \to K^0\Lambda$
0.035 $^{+0.11}_{-0.13}$	196	AUBERT 65	HLBC	K^+ charge exchange
0.06 $^{+0.18}_{-0.44}$	152	[139] BALDO-... 65	HLBC	K^+ charge exchange
−0.08 $^{+0.16}_{-0.28}$	109	[140] FRANZINI 65	HBC	$\overline{p}p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04 $^{+0.10}_{-0.13}$	100	[136] GRAHAM 72	OSPK	$K_{\mu 3}$ from $K^0\Lambda$
−0.13 ±0.11	342	[136] MANTSCH 72	OSPK	K_{e3} from $K^0\Lambda$
0.04 $^{+0.07}_{-0.08}$	222	[135] BURGUN 71	HBC	$K^+ p \to K^0 p\pi^+$
0.03 ±0.03		[138] BENNETT 68	CNTR	
0.17 ±0.10	335	[137] HILL 67	DBC	$K^+ d \to K^0 pp$

[135] BURGUN 72 is a final result which includes BURGUN 71.
[136] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.
[137] CHO 70 is analysis of unambiguous events in new data and HILL 67.
[138] BENNETT 69 is a reanalysis of BENNETT 68.
[139] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).
[140] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.



Re(x) ($\Delta S = -\Delta Q$ amplitude)

IMAGINARY PART OF x

Assumes $m_{K^0_L} - m_{K^0_S}$ positive. See Listings above.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.003±0.026 OUR AVERAGE		Error includes scale factor of 1.2.		
−0.10 $^{+0.16}_{-0.19}$	79	SMITH 75B	WIRE	$\pi^- p \to K^0\Lambda$
−0.06 ±0.05	4724	NIEBERGALL 74	ASPK	$K^+ p \to K^0 p\pi^+$
−0.017±0.060	1757	FACKLER 73	OSPK	K_{e3} from K^0
0.09 ±0.07	1367	HART 73	OSPK	K_{e3} from $K^0\Lambda$
0.107 $^{+0.092}_{-0.074}$	1079	MALLARY 73	OSPK	K_{e3} from $K^0\Lambda X$
0.07 $^{+0.06}_{-0.07}$	410	[141] BURGUN 72	HBC	$K^+ p \to K^0 p\pi^+$
0.05 ±0.13	442	[142] GRAHAM 72	OSPK	$\pi^- p \to K^0\Lambda$
0.21 $^{+0.15}_{-0.12}$	126	MANN 72	HBC	$K^- p \to n\overline{K}^0$

0.0 ± 0.08	252	WEBBER	71	HBC	$K^- p \rightarrow n \overline{K}^0$
-0.08 ± 0.07	215	[143] CHO	70	DBC	$K^+ d \rightarrow K^0 pp$
$-0.11\ ^{+0.10}_{-0.11}$	686	LITTENBERG	69	OSPK	$K^+ n \rightarrow K^0 p$
$+0.22\ ^{+0.37}_{-0.29}$	121	JAMES	68	HBC	$\overline{p}p$
0.0 ± 0.25	116	FELDMAN	67B	OSPK	$\pi^- p \rightarrow K^0 \Lambda$
$-0.21\ ^{+0.11}_{-0.15}$	196	AUBERT	65	HLBC	K^+ charge exchange
$-0.44\ ^{+0.32}_{-0.19}$	152	[144] BALDO-...	65	HLBC	K^+ charge exchange
$+0.24\ ^{+0.40}_{-0.30}$	109	[145] FRANZINI	65	HBC	$\overline{p}p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.12\ ^{+0.17}_{-0.16}$	100	[142] GRAHAM	72	OSPK	$K_{\mu 3}$ from $K^0 \Lambda$
-0.04 ± 0.16	342	[142] MANTSCH	72	OSPK	K_{e3} from $K^0 \Lambda$
$0.12\ ^{+0.08}_{-0.09}$	222	[141] BURGUN	71	HBC	$K^+ p \rightarrow K^0 p \pi^+$
-0.20 ± 0.10	335	[143] HILL	67	DBC	$K^+ d \rightarrow K^0 pp$

[141] BURGUN 72 is a final result which includes BURGUN 71.
[142] First GRAHAM 72 value is second GRAHAM 72 value combined with MANTSCH 72.
[143] Footnote 10 of HILL 67 should read $+0.58$, not -0.58 (private communication) CHO 70 is analysis of unambiguous events in new data and HILL 67.
[144] BALDO-CEOLIN 65 gives x and θ converted by us to Re(x) and Im(x).
[145] FRANZINI 65 gives x and θ for Re(x) and Im(x). See SCHMIDT 67.

CPT-VIOLATION PARAMETERS IN K^0 DECAY

If *CP*-violating interactions include a *T* conserving part then

$$|K_S\rangle = [|K_1\rangle + (\epsilon + \Delta)|K_2\rangle]/\sqrt{1+|\epsilon+\Delta|^2}$$
$$|K_L\rangle = [|K_2\rangle + (\epsilon - \Delta)|K_1\rangle]/\sqrt{1+|\epsilon-\Delta|^2}$$

where

$$|K_1\rangle = [|K^0\rangle + |\overline{K}^0\rangle]/\sqrt{2}$$
$$|K_2\rangle = [|K^0\rangle - |\overline{K}^0\rangle]/\sqrt{2}$$

and

$$|\overline{K}^0\rangle = CP|K^0\rangle .$$

The parameter Δ specifies the *CPT*-violating part.

Estimates of Δ are given below. See also THOMSON 95 for a test of *CPT*-symmetry conservation in K^0 decays using the Bell-Steinberger relation.

REAL PART OF Δ

A nonzero value violates *CPT* invariance.

VALUE	EVTS	DOCUMENT ID		COMMENT
0.018±0.020	6481	[146] DEMIDOV	95	$K_{\ell 3}$ reanalysis

[146] DEMIDOV 95 reanalyzes data from HART 73 and NIEBERGALL 74.

IMAGINARY PART OF Δ

A nonzero value violates *CPT* invariance.

VALUE	EVTS	DOCUMENT ID		COMMENT
0.021±0.037	6481	[147] DEMIDOV	95	$K_{\ell 3}$ reanalysis

[147] DEMIDOV 95 reanalyzes data from HART 73 and NIEBERGALL 74.

K_L^0 REFERENCES

BRFIT 96 RPP
ETAFIT 96 RPP
ADLER 95 PL B363 237 +Alhalel, Angelopoulos, Apostolakis+ (CPLEAR Collab.)
ADLER 95B PL B363 243 +Alhalel, Angelopoulos, Apostolakis+ (CPLEAR Collab.)
AKAGI 95 PR D51 2061 +Fukuhisa, Hemmi+ (TOHOK, TOKY, KYOT, KEK)
BARR 95 ZPHY C65 361 +Buchholz+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
BARR 95C PL B358 399 +Buchholz+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
DEMIDOV 95 PAN 58 968 +Gusev, Shabalin (ITEP)
From YAF 58 1041.
HEINSON 95 PR D51 985 +Horvath, Knibbe, Mathiazhagan+ (BNL E791 Collab.)
KREUTZ 95 ZPHY C65 67 +Holder, Rost+ (SIEG, EDIN, MANZ, ORSAY, PISAI)
MATTHEWS 95 PRL 75 2803 +Gu, Haas, Hogan+ (RUTG, EFI, ELMT, FNAL, ILL)
SCHWINGEN... 95 PRL 74 4376 Schwingenheuer+ (EFI, CHIC, ELMT, FNAL, ILL, RUTG)
SPENCER 95 PRL 74 3323 + (UCLA, EFI, COLO, ELMT, FNAL, ILL, OSAK, RUTG)
THOMSON 95 PR D51 1412 +Zou (RUTG)
BARR 94 PL B328 528 +Buchholz+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
GU 94 PRL 72 3000 + (RUTG, UCLA, EFI, COLO, ELMT, FNAL, ILL, OSAK)
NAKAYA 94 PRL 73 2169 + (OSAK, UCLA, EFI, COLU, ELMT, FNAL, ILL, RUTG)
ROBERTS 94 PR D50 1874 + (UCLA, EFI, COLU, ELMT, FNAL, ILL, OSAK, RUTG)
WEAVER 94 PRL 72 3758 + (UCLA, EFI, COLU, ELMT, FNAL, ILL, OSAK, RUTG)
AKAGI 93 PR D47 R2644 +Fukuhisa, Hemmi+ (TOHOK, TOKY, KYOT, KEK)
ARISAKA 93 PRL 70 1049 +Auerbach, Axelrod, Belz, Biery+ (BNL E791 Collab.)
ARISAKA 93B PRL 71 3910 +Auerbach, Axelrod, Belz, Biery+ (BNL E791 Collab.)
BARR 93D PL B317 233 +Buchholz+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
GIBBONS 93 PRL 70 1199 +Barker, Briere, Makoff+ (FNAL E731 Collab.)
GIBBONS 93B PRL 70 1203 +Barker, Briere, Makoff+ (FNAL E731 Collab.)
GIBBONS 93C Thesis RX-1487 (CHIC)
HARRIS 93 PRL 71 3914 +Briere, Cheu, Makoff, McFarland+ (FNAL E799 Collab.)
HARRIS 93B PRL 71 3918 +Briere, Cheu, Makoff, McFarlane+ (FNAL E799 Collab.)
MAKOFF 93 PRL 70 1591 +Barker, Briere, Gibbons+ (FNAL E731 Collab.)
Also 95 PRL 75 2069 (erratum)
RAMBERG 93 PRL 70 2525 +Bock, Coleman, Enagonio, Hsiung+ (FNAL E731 Collab.)
RAMBERG 93B PRL 70 2529 +Bock, Coleman, Enagonio, Hsiung+ (FNAL E731 Collab.)
VAGINS 93 PRL 71 35 +Adair, Greenlee, Kasha, Mannelli+ (BNL E845 Collab.)
ADLER 92B PL B286 180 +Alhalel, Angelopoulos, Apostolakis+ (CPLEAR Collab.)
Also 92 SJNP 55 840 Adler, Alhalel, Angelopoulos+ (CPLEAR Collab.)
BARR 92 PL B284 440 +Buchholz+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
GRAHAM 92 PL B295 169 +Barker, Briere, Gibbons, Makoff+ (FNAL E731 Collab.)
MORSE 92 PR D45 36 +Leipuner, Larsen, Jastrzembski+ (BNL, YALE, VASS)
PDG 92 PR D45, 1 June, Part II Hikasa, Barnett, Stone+ (KEK, LBL, BOST+)
SOMALWAR 92 PRL 68 2580 +Barker, Briere, Gibbons+ (FNAL E731 Collab.)
AKAGI 91 PRL 67 2614 +Fukuhisa, Hemmi+ (TOHOK, TOKY, KYOT, KEK)
AKAGI 91B PRL 67 2618 +Fukuhisa, Hemmi+ (TOHOK, TOKY, KYOT, KEK)
BARR 91 PL B259 389 +Carosi+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
HEINSON 91 PR D44 R1 + (UCI, UCLA, LANL, PENN, STAN, TEMP, TEXA+)
PAPADIMITR... 91 PR D44 R573 Papadimitriou, Barker, Briere+ (FNAL E731 Collab.)
BARKER 90 PR D41 3546 +Briere, Gibbons, Makoff+ (FNAL E731 Collab.)
Also 88 PRL 61 2661 Gibbons, Papadimitriou+ (FNAL E731 Collab.)
BARR 90B PL B240 283 +Carosi+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
BARR 90C PL B242 523 +Carosi+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
CAROSI 90 PL B237 303 +Clarke+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
KARLSSON 90 PRL 64 2976 +Gollin, Okamitsu, Tschirhart, Barker+(FNAL E731 Collab.)
OHL 90 PRL 64 2755 +Adair, Greenlee, Kasha, Mannelli+ (BNL E845 Collab.)
OHL 90B PRL 65 1407 +Adair, Greenlee, Kasha, Mannelli+ (BNL E845 Collab.)
PATTERSON 90 PRL 64 1491 +Barker+ (FNAL E731 Collab.)
INAGAKI 89 PR D40 1712 +Kobayashi, Sato, Shinkawa+ (KEK, TOKY, KYOT)
LITTENBERG 89 PR D39 3322 (BNL)
MATHIAZHA... 89 PRL 63 2181 Mathiazhagan+ (UCI, UCLA, LANL, PENN, STAN+)
MATHIAZHA... 89B PRL 63 2185 Mathiazhagan+ (UCI, UCLA, LANL, PENN, STAN+)
PAPADIMITR... 89 PRL 63 28 Papadimitriou, Gibbons, Patterson+ (FNAL E731 Collab.)
SCHAFFNER 89 PR D39 990 +Greenlee, Kasha, Mannelli, Ohl+ (YALE, BNL)
WAHL 89 CERN-EP/89-86, H. Wahl — Rare Decay Symposium, Vancouver (CERN)
BARR 88 PL B214 303 +Clarke+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
BURKHARDT 88 PL B206 169 +Clarke+ (CERN, EDIN, MANZ, LALO, PISA, SIEG)
COUSINS 88 PR D38 2914 +Konigsberg+ (UCLA, LASL, PENN, STAN, TEMP, WILL)
GREENLEE 88 PRL 60 893 +Kasha, Mannelli, Mannelli+ (YALE, BNL)
JASTRZEM... 88 PRL 61 2300 Jastrzembski, Larsen, Leipuner, Morse+ (BNL, YALE)
WOODS 88 PRL 60 1695 +Nishikawa, Patterson, Wah, Winstein+(FNAL E731 Collab.)
BURKHARDT 87 PL B199 139 + (CERN, EDIN, MANZ, LALO, PISA, SIEG)
ARONSON 86 PR D33 3180 +Bernstein, Bock+ (BNL, CHIC, STAN, WISC)
Also 82 PRL 48 1078 Aronson, Bernstein+ (BNL, CHIC, STAN, WISC)
PDG 86C PL 170B 132 Aguilar-Benitez, Porter+ (CERN, CIT+)
BERNSTEIN 85B PRL 54 1631 +Bock, Carlsmith, Coupal+ (CHIC, SACL)
BLACK 85 PRL 54 1628 +Blatt, Campbell, Kasha, Mannelli+ (BNL, YALE)
COUPAL 85 PRL 55 566 +Bernstein, Bock, Carlsmith+ (CHIC, SACL)
BALATS 83 SJNP 38 556 +Berezin, Bogdanov, Vishnevsky+ (ITEP)
Translated from YAF 38 927.
BERGSTROM 83 PL 131B 229 +Masso, Singer (CERN)
ARONSON 82 PRL 48 1078 +Bernstein+ (BNL, CHIC, STAN, WISC)
ARONSON 82B PRL 48 1306 +Bock, Cheng, Fischbach (BNL, CHIC, PURD)
Also 82B PL 116B 73 Fischbach, Cheng+ (PURD, BNL, CHIC)
Also 83 PR D28 476 Aronson, Bock, Cheng+ (BNL, CHIC, PURD)
Also 83B PR D28 495 Aronson, Bock, Cheng+ (BNL, CHIC, PURD)
PDG 82B PL 111B 70 Roos, Porter, Aguilar-Benitez+ (HELS, CIT, CERN)
BIRULEV 81 NP B182 1 +Dzhordzhadze, Genchev, Grigalashvili+ (JINR)
Also 80 SJNP 31 622 Birulev, Vestergombi, Genchev+ (JINR)
Translated from YAF 31 1204.
CARROLL 80B PRL 44 529 +Chiang, Kycia, Li, Littenberg, Marx+ (BNL, ROCH)
CARROLL 80C PL 96B 407 +Chiang, Kycia, Li, Littenberg, Marx+ (BNL, ROCH)
CARROLL 80D PRL 44 525 +Chiang, Kycia, Li, Littenberg, Marx+ (BNL, ROCH)
CHO 80 PR D22 2688 +Derrick, Miller, Schlereth, Engler+ (ANL, CMU)
MORSE 80 PR D21 1750 +Leipuner, Larsen, Schmidt, Blatt+ (BNL, YALE)
BIRULEV 79 SJNP 29 778 +Vestergombi, Gvakhariya, Genchev+ (JINR)
Translated from YAF 29 1516.
CHRISTENS... 79 PRL 43 1209 Christenson, Goldman, Hummel, Roth+ (NYU)
CHRISTENS... 79B PRL 43 1212 Christenson, Goldman, Hummel, Roth+ (NYU)
HILL 79 NP B153 39 +Sakitt, Snape, Stevens+ (BNL, SLAC, SBER)
SCHMIDT 79 PRL 43 556 +Blatt, Campbell, Grannan+ (YALE, BNL)
SHOCHET 79 PR D19 1965 +Linsay, Grosso-Pilcher, Frisch+ (EFI, ANL)
Also 77 PRL 39 59 Shochet, Linsay, Grosso-Pilcher+ (EFI, ANL)
ENGLER 78B PR D18 623 +Keyes, Kraemer, Tanaka, Cho+ (CMU, ANL)
HILL 78 PL 73B 483 +Sakitt, Snape, Stevens+ (BNL, SLAC, SBER)
CHO 77 PR D15 587 +Derrick, Lissauer, Miller, Engler+ (ANL, CMU)
CLARK 77 PR D15 553 +Field, Holley, Johnson, Kerth, Sah, Shen (LBL)
Also 75 Thesis LBL-4275 Shen (LBL)
DEVOE 77 PR D16 565 +Cronin, Frisch, Grosso-Pilcher+ (EFI, ANL)
DZHORD... 77 SJNP 26 478 Dzhordzhadze, Kekelidze, Krivokhizhin+ (JINR)
Translated from YAF 26 910.
PEACH 77 NP B127 399 +Cameron+ (BGNA, EDIN, GLAS, PISA, RHEL)
BIRULEV 76 SJNP 24 178 +Vestergombi, Vovenko, Votruba+ (JINR)
Translated from YAF 24 340.
COOMBES 76 PRL 37 249 +Flexer, Hall, Kennelly, Kirkby+ (STAN, NYU)
DONALDSON 76 PR D14 2839 +Hitlin, Kennelly, Kirkby, Liu+ (SLAC)
Also 74 Thesis SLAC-0184 Donaldson (SLAC)
FUKUSHIMA 76 PRL 36 348 +Jensen, Surko, Thaler+ (PRIN, MASA)
GJESDAL 76 NP B109 118 +Kamae, Presser, Steffen+ (CERN, HEIDH)
REY 76 PR D13 1161 +Cence, Jones, Parker+ (NDAM, HAWA, LBL)
Also 69 PRL 22 1210 Cence, Jones, Peterson, Stenger+ (HAWA, LRL)
BALDO-... 75 NC 25A 688 Baldo-Ceolin, Bobisut, Calimani+ (PADO, WISC)
BLUMENTHAL 75 PRL 34 164 +Frankel, Nagy+ (PENN, CHIC, TEMP)
BUCHANAN 75 PR D11 457 +Drickey, Pepper, Rudnick+ (UCLA, SLAC, JHU)
CARITHERS 75 PRL 34 1244 +Modis, Nygren, Pun+ (COLU, NYU)
SMITH 75B Thesis UCSD unpub. (UCSD)
ALBRECHT 74 PL 48B 393 (JINR, BERL, BUDA. PRAG, SERP, SOFI)
BISI 74 PL 50B 504 +Ferrero (TORI)
DONALDSON 74 Thesis SLAC-0184 (SLAC)
Also 76 PR D14 2839 Donaldson, Hitlin, Kennelly, Kirkby, Liu+ (SLAC)
DONALDSON 74B PR D9 2960 +Fryberger, Hitlin, Liu+ (SLAC, UCSC)
Also 73B PRL 31 337 Donaldson, Fryberger, Hitlin, Liu+ (SLAC, UCSC)
DONALDSON 74C PRL 33 554 +Hitlin, Kennelly, Kirkby+ (SLAC)
Also 74 Thesis SLAC-0184 Donaldson (SLAC)
Also 76 PR D14 2839 Donaldson, Hitlin, Kennelly, Kirkby, Liu+ (SLAC)
FIELD 74 SLAC-PUB-1498 unpub. (SLAC)
GEWENIGER 74 PL 48B 483 +Gjesdal, Kamae, Presser+ (CERN, HEIDH)
Also 74 Thesis CERN Int. 74-4 Luth (CERN)
GEWENIGER 74B PL 48B 487 +Gjesdal, Presser+ (CERN, HEIDH)
Also 74B PL 52B 119 Gjesdal, Presser, Steffen+ (CERN, HEIDH)
GEWENIGER 74C PL 52B 108 +Gjesdal, Presser+ (CERN, HEIDH)
GJESDAL 74 PL 52B 113 +Presser, Kamae, Steffen+ (CERN, HEIDH)
MESSNER 74 PRL 33 1458 +Franklin, Morse+ (COLO, SLAC, UCSC)
NIEBERGALL 74 PL 49B 103 +Regler, Stier+ (CERN, ORSAY, VIEN)
WANG 74 PR D9 540 +Smith, Whatley, Zorn, Hornbostel (UMD, BNL)
WILLIAMS 74 PRL 33 240 +Larsen, Leipuner, Sapp, Sessoms+ (BNL, YALE)
ALBROW 73 NP B58 22 +Aston, Barber, Bird, Ellison+ (MCHS, DARE)
ALEXANDER 73B NP B65 301 +Benary, Borowitz, Lande+ (TELA, HEID)
ANIKINA 73 JINR P1 7539 +Balashov, Bannik+ (JINR)
BARBIELLINI 73 PL 43B 529 +Darriulat, Fainberg+ (CERN)
BRANDENB... 73 PR D8 1978 Brandenburg, Johnson, Leith, Loos+ (SLAC)
CARITHERS 73 PRL 31 1025 +Nygren, Gordon+ (COLU, BNL, CERN)
Also 73B PRL 30 1336 Carithers, Modis, Nygren+ (COLU, CERN, NYU)
EVANS 73 PR D7 36 +Muir, Peach, Budagov+ (EDIN, CERN)
Also 69 PRL 23 427 Evans, Golden, Muir, Peach+ (EDIN, CERN)
FACKLER 73 PRL 31 847 +Frisch, Martin, Smoot, Sompayrac (MIT)
FITCH 73 PRL 31 1524 +Hepp, Jensen, Strovink, Webb (PRIN)
Also 72 Thesis COO-3072-13 Webb (PRIN)
GINSBERG 73 PR D8 3887 +Smith (MIT, STON)
HART 73 NP B66 317 +Hutton, Field, Sharp, Blackmore+ (CAVE, RHEL)
MALLARY 73 PR D7 1953 +Binnie, Gallivan, Gomez, Peck, Sciulli+ (CIT)
Also 70 PRL 25 1214 Sciulli, Gallivan, Binnie, Gomez+ (CIT)
MCCARTHY 73 PR D7 687 +Brewer, Budnitz, Entis, Graven, Miller+ (LBL)
Also 72 PL 42B 291 McCarthy, Brewer, Budnitz, Entis, Graven+ (LBL)
Also 71 Thesis LBL-550 McCarthy (LBL)
MESSNER 73 PRL 30 876 +Morse, Nauenberg, Hitlin+ (COLO, SLAC, UCSC)
PEACH 73 PL 43B 441 +Evans, Muir, Hopkins, Krenz (EDIN, CERN, AACH)
SANDWEISS 73 PRL 30 1002 +Sunderland, Turner, Willis, Keller (YALE, ANL)
WILLIAMS 73 PRL 31 1521 +Larsen, Leipuner, Sapp, Sessoms+ (BNL, YALE)

ALBROW 72 NP B44 1 +Aston, Barber, Bird, Ellison+ (MCHS, DARE)
ASHFORD 72 PL 38B 47 +Brown, Masek, Maung, Miller, Ruderman+ (UCSD)
BANNER 72 PRL 28 1597 +Cronin, Hoffman, Knapp, Shochet (PRIN)
BANNER 72B PRL 29 237 +Cronin, Hoffman, Knapp, Shochet (PRIN)
BARMIN 72 SJNP 15 636 +Davidenko, Demidov, Dolgolenko+ (ITEP)
Translated from YAF 15 1149.
BARMIN 72B SJNP 15 638 +Barylov, Davidenko, Demidov+ (ITEP)
Translated from YAF 15 1152.
BURGUN 72 NP B50 194 +Lesquoy, Muller, Pauli+ (SACL, CERN, OSLO)
CARNEGIE 72 PR D6 2335 +Cester, Fitch, Strovink, Sulak (PRIN)
DALLY 72 PL 41B 647 +Innocenti, Seppi+ (SLAC, JHU, UCLA)
Also 70 PL 33B 627 Chien, Cox, Ettlinger+ (JHU, SLAC, UCLA)
Also 71 PL 35B 261 Chien, Cox, Ettlinger+ (JHU, SLAC, UCLA)
GRAHAM 72 NC 9A 166 +Abashian, Jones, Mantsch, Orr+ (ILL, NEAS)
HOLDER 72 PL 40B 141 +Radermacher, Staude+ (AACH, CERN, TORI)
JAMES 72 NP B49 1 +Montanet, Paul, Saetre+ (CERN, SACL, OSLO)
KRENZ 72 LNC 4 213 +Hopkins, Evans, Muir, Peach (AACH, CERN, EDIN)
MANN 72 PR D6 137 +Kofler, Meisner, Hertzbach+ (MASA, BNL, YALE)
MANTSCH 72 NC 9A 160 +Abashian, Graham, Jones, Orr+ (ILL, NEAS)
MCCARTHY 72 PL 42B 291 +Brewer, Budnitz, Entis, Graven+ (LBL)
METCALF 72 PL 40B 703 +Neuhofer, Niebergall+ (CERN, IPN, WIEN)
NEUHOFER 72 PL 41B 642 +Niebergall, Regler, Stier+ (CERN, ORSAY, VIEN)
PICCIONI 72 PRL 29 1412 +Coombes, Donaldson, Dorfan, Fryberger+ (SLAC)
Also 74 PR D9 2939 Piccioni, Donaldson+ (SLAC, UCSC, COLO)
VOSBURGH 72 PR D6 1834 +Devlin, Esterling, Goz, Bryman+ (RUTG, MASA)
Also 71 PRL 26 866 Vosburgh, Devlin, Esterling, Goz+ (RUTG, MASA)
BALATS 71 SJNP 13 53 +Berezin, Vishnevsky, Galanina+ (ITEP)
Translated from YAF 13 93.
BARMIN 71 PL 35B 604 +Barylov, Veselovsky, Davidenko+ (ITEP)
BISI 71 PL 36B 533 +Darriulat, Ferrero, Rubbia+ (AACH, CERN, TORI)
BURGUN 71 LNC 2 1169 +Lesquoy, Muller, Pauli+ (SACL, CERN, OSLO)
CARNEGIE 71 PR D4 1 +Cester, Fitch, Strovink, Sulak (PRIN)
CHAN 71 Thesis LBL-350 (LBL)
CHIEN 71 PL 35B 261 +Cox, Ettlinger+ (JHU, SLAC, UCLA)
Also 72 PL 41B 647 Dally, Innocenti, Seppi+ (SLAC, JHU, UCLA)
CHO 71 PR D3 1557 +Dralle, Canter, Engler, Fisk+ (CMU, BNL, CASE)
CLARK 71 PRL 26 1667 +Elioff, Field, Frisch, Johnson, Kerth+ (LRL)
Also 70 Thesis UCRL 19709 Johnson (LRL)
Also 71 Thesis UCRL 20264 Frisch (LRL)
Also 74 SLAC-PUB-1498 unpub. Field (SLAC)
ENSTROM 71 PR D4 2629 +Akavia, Coombes, Dorfan+ (SLAC, STAN)
Also 70 Thesis SLAC-0125 Enstrom (STAN)
JAMES 71 PL 35B 265 +Montanet, Paul, Pauli+ (CERN, SACL, OSLO)
MEISNER 71 PR D3 59 +Mann, Hertzbach, Kofler+ (MASA, BNL, YALE)
PEACH 71 PL 35B 351 +Evans, Muir, Budagov, Hopkins+ (EDIN, CERN)
REPELLIN 71 PL 36B 603 +Wolff, Chollet, Gaillard, Jane+ (ORSAY, CERN)
WEBBER 71 PR D3 64 +Solmitz, Crawford, Alston-Garnjost (LRL)
Also 68 PRL 21 498 Webber, Solmitz, Crawford, Alston-Garnjost (LRL)
Also 69 Thesis UCRL 19226 Webber (LRL)
WOLFF 71 PL 36B 517 +Chollet, Repellin, Gaillard+ (ORSAY, CERN)
ALBROW 70 PL 33B 516 +Aston, Barber, Bird, Ellison+ (MCHS, DARE)
ARONSON 70 PRL 25 1057 +Ehrlich, Hofer, Jensen+ (EFI, ILLC, SLAC)
BARMIN 70 PL 33B 377 +Barylov, Borisov, Bysheva+ (ITEP, JINR)
BASILE 70 PR D2 78 +Cronin, Thevent, Turlay, Zylberajch+ (SACL)
BECHERRAWY 70 PR D1 1452 (ROCH)
BUCHANAN 70 PL 33B 623 +Drickey, Rudnick, Shepard+ (SLAC, JHU, UCLA)
Also 71 Private Comm. Cox
BUDAGOV 70 PR D2 815 +Cundy, Myatt, Nezrick+ (CERN, ORSAY, EPOL)
Also 68B PL 28B 215 Budagov, Cundy, Myatt+ (CERN, ORSAY, EPOL)
CHIEN 70 PL 33B 627 +Cox, Ettlinger+ (JHU, SLAC, UCLA)
Also 71 Private Comm. Cox
CHO 70 PR D1 3031 +Dralle, Canter, Engler, Fisk+ (CMU, BNL, CASE)
Also 67 PRL 19 668 Hill, Luers, Robinson, Sakitt+ (BNL, CMU)
CHOLLET 70 PL 31B 658 +Gaillard, Jane, Ratcliffe, Repellin+ (CERN)
CULLEN 70 PL 32B 523 +Darriulat, Deutsch, Foeth+ (AACH, CERN, TORI)
DARRIULAT 70 PL 33B 249 +Ferrero, Grosso, Holder+ (AACH, CERN, TORI)
FAISSNER 70 NC 70A 57 +Reithier, Thome, Gaillard+ (AACH3, CERN, RHEL)
GINSBERG 70 PR D1 229 (HAIF)
JENSEN 70 Thesis (EFI)
Also 69 PRL 23 615 Jensen, Aronson, Ehrlich, Fryberger+ (EFI, ILL)
MARX 70 PL 32B 219 +Nygren, Peoples+ (COLU, HARV, CERN)
Also 70B Thesis Nevis 179 Marx (COLU)
SCRIBANO 70 PL 32B 224 +Mannelli, Pierazzini, Marx+ (PISA, COLU, HARV)
SMITH 70 PL 32B 133 +Wang, Whatley, Zorn, Hornbostel (UMD, BNL)
WEBBER 70 PR D1 1967 +Solmitz, Crawford, Alston-Garnjost (LRL)
Also 69 Thesis UCRL 19226 Webber (LRL)
BANNER 69 PR 188 2033 +Cronin, Liu, Pilcher (PRIN)
Also 68 PRL 21 1103 Banner, Cronin, Liu, Pilcher (PRIN)
Also 68 PRL 21 1107 Cronin, Liu, Pilcher (PRIN)
BEILLIERE 69 PL 30B 202 +Boutang, Limon (EPOL)
BENNETT 69 PL 29B 317 +Nygren, Saal, Steinberger+ (COLU, BNL)
BOHM 69B NP B9 605 +Darriulat, Grosso, Kaftanov+ (CERN)
Also 68 PL 27B 321 Bohm, Darriulat, Grosso, Kaftanov (CERN)
CENCE 69 PRL 22 1210 +Jones, Peterson, Stenger+ (HAWA, LRL)
EVANS 69 PRL 23 427 +Golden, Muir, Peach+ (EDIN, CERN)
FAISSNER 69 PL 30B 204 +Foeth, Staude, Tittel+ (AACH3, CERN, TORI)
FOETH 69 PL 30B 282 +Holder, Radermacher+ (AACH, CERN, TORI)
GAILLARD 69 NC 59A 453 +Galbraith, Hussri, Jane+ (CERN, RHEL, AACH)
Also 67 PRL 18 20 Gaillard, Krienen, Galbraith+ (CERN, RHEL, AACH)
GOBBI 69B PRL 22 685 +Green, Hakel, Moffett, Rosen, Goz+ (ROCH, RUTG)
LITTENBERG 69 PRL 22 654 +Field, Piccioni, Mehlhop+ (UCSD)
LONGO 69 PR 181 1808 +Young, Helland (MICH, UCLA)
PACIOTTI 69 Thesis UCRL 19446 (LRL)
SAAL 69 Thesis (COLU)
ABRAMS 68B PR 176 1603 +Abashian, Mischke, Nefkens, Smith+ (ILL)
ARNOLD 68B PL 28B 56 +Budagov, Cundy, Aubert+ (CERN, ORSAY)
ARONSON 68 PRL 20 287 +Chen (PRIN)
Also 69 PR 175 1708 Aronson, Chen (PRIN)
BARTLETT 68 PRL 21 558 +Carnegie, Fitch+ (PRIN)
BASILE 68 PL 26B 542 +Cronin, Thevenet, Turlay+ (SACL)
BASILE 68B PL 28B 58 +Cronin, Thevenet, Turlay, Zylberajch+ (SACL)
BENNETT 68 PL 27B 244 +Nygren, Steinberger+ (COLU, CERN)
BENNETT 68B PL 27B 248 +Nygren, Steinberger+ (COLU, CERN)
BLANPIED 68 PRL 21 1650 +Levit, Engels+ (CASE, HARV, MCGI)
BOHM 68B PL 27B 594 +
BUDAGOV 68 NC 57A 182 +Burmeister, Cundy+ (CERN, ORSAY, IPNP)
Also 68B PL 28B 215 Budagov, Cundy, Myatt+ (CERN, ORSAY, EPOL)
JAMES 68 NP B8 365 +Briand (IPNP, CERN)
Also 68 PRL 21 257 Helland, Longo, Young (UCLA, MICH)
KULYUKINA 68 JETP 26 20 +Mestvirishvili, Nyagu+ (JINR)
Translated from ZETF 53 29.
KUNZ 68 Thesis PU-68-46 (PRIN)
BENNETT 67 PRL 19 993 +Nygren, Saal, Steinberger+ (COLU)
BOTT-... 67 PL 24B 194 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
BOTT-... 67B PL 24B 438 Bott-Bodenhausen, Debouard, Dekkers+ (CERN)
Also 66B PL 20 212 Bott-Bodenhausen, Debouard, Cassel+ (CERN)
Also 66 PL 23 277 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
CRONIN 67 PRL 18 25 +Kunz, Risk, Wheeler (PRIN)
Also 68 Thesis unpub. Wheeler (PRIN)
CRONIN 67B Princeton 11/67 +Kunz, Risk, Wheeler (PRIN)
DEBOUARD 67 NC 52A 662 +Dekkers, Jordan, Mermod+ (CERN)
Also 65 PL 15 58 DeBouard, Dekkers, Scharff+ (CERN, ORSAY, MPIM)
DEVLIN 67 PRL 18 54 +Solomon, Shepard, Beall+ (PRIN, UMD)
Also 68 PR 169 1045 Sayer, Beall, Devlin, Shephard+ (UMD, PPA, PRIN)
DORFAN 67 PRL 19 987 +Enstrom, Raymond, Schwartz+ (SLAC, LRL)
FELDMAN 67B PR 155 1611 +Frankel, Highland, Sloan (PENN)
FIRESTONE 67 PRL 18 176 +Kim, Lach, Sandweiss+ (YALE, BNL)
FITCH 67 PR 164 1711 +Roth, Russ, Vernon (PRIN)
GINSBERG 67 PR 162 1570 (MASB)
HAWKINS 67 PR 156 1444 (YALE)
HILL 67 PRL 19 668 +Luers, Robinson, Sakitt+ (BNL, CMU)
HOPKINS 67 PRL 19 185 +Bacon, Eisler (BNL)
KADYK 67 PRL 19 597 +Chan, Drijard, Oren, Sheldon (LRL)
KULYUKINA 67 Preprint +Mestvirishvili, Nyagu+ (JINR)
LOWYS 67 PL 24B 75 +Aubert, Chounet, Pascaud+ (EPOL, ORSAY)
MISCHKE 67 PRL 18 138 +Abashian, Abrams+ (ILL)
NEFKENS 67 PR 157 1233 +Abashian, Abrams, Carpenter, Fisher+ (ILL)
SCHMIDT 67 Thesis Nevis 160 (COLU)
TODOROFF 67 Thesis (ILL)
ALFF-... 66B PL 21 595 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
ANIKINA 66 SJNP 2 339 +Vardenga, Zhuravleva+ (JINR)
Translated from YAF 2 471.
AUERBACH 66B PRL 17 980 +Mann, McFarlane, Sciulli (PENN)
BASILE 66 Balaton Conf. +Cronin, Thevenet+ (SACL)
BEHR 66 PL 22 540 +Brisson, Petiau+ (EPOL, MILA, PADO, ORSAY)
BOTT-... 66 PL 23 277 Bott-Bodenhausen, DeBouard, Cassel+ (CERN)
CARPENTER 66 PR 142 871 +Abashian, Abrams, Fisher (ILL)
CRIEGEE 66 PRL 17 150 +Fox, Frauenfelder, Hanson, Moscat+ (ILL)
FIRESTONE 66 PRL 16 556 +Kim, Lach, Sandweiss+ (YALE, BNL)
HAWKINS 66 PL 21 238 (YALE)
Also 67 PR 156 1444 Hawkins (YALE)
ANDERSON 65 PRL 14 475 +Crawford, Golden, Stern, Binford+ (LRL, WISC)
ANIKINA 65 JINR P 2488 +Vardengа, Zhuravleva, Kotlya+ (JINR)
ASTBURY 65 PL 16 80 +Finocchiaro, Beusch+ (CERN, ZURI)
Also 65 HPA 39 523 Pepin
ASTBURY 65B PL 18 175 +Michelini, Beusch+ (CERN, ZURI)
ASTBURY 65C PL 18 178 +Michelini, Beusch+ (CERN, ZURI)
AUBERT 65 PL 17 59 +Behr, Canavan, Chounet+ (EPOL, ORSAY)
Also 67 PL 24B 75 Lowys, Aubert, Chounet, Pascaud+ (EPOL, ORSAY)
BALDO-... 65 NC 38 684 Baldo-Ceolin, Calimani, Ciampolillo+ (PADO)
FISHER 65 ANL 7130 83 +Abashian, Abrams, Carpenter+ (ILL)
FITCH 65 PRL 15 73 +Roth, Russ, Vernon (PRIN)
FRANZINI 65 PR 140B 127 +Kirsch, Plano+ (COLU, RUTG)
GALBRAITH 65 PRL 14 383 +Manning, Jones+ (AERE, BRIS, RHEL)
GUIDONI 65 Argonne Conf. 49 +Barnes, Foelsche, Ferbel, Firestone+ (BNL, YALE)
HOPKINS 65 Argonne Conf. 67 +Bacon, Eisler (VAND, RUTG)
ADAIR 64 PL 12 67 +Leipuner (YALE, BNL)
ALEKSANYAN 64B Dubna Conf. 2 102 +Alikhanyan, Vartazaryan+ (YERE)
Also 64 JETP 19 1019 Aleksanyan+ (LEBD, MPEI, YERE)
Translated from ZETF 46 1504.
ANIKINA 64 JETP 19 42 +Zhuravleva+ (GEOR, JINR)
Translated from ZETF 46 59.
CHRISTENS... 64 PRL 13 138 Christenson, Cronin, Fitch, Turlay (PRIN)
FUJII 64 Dubna Conf. 2 146 +Jovanovich, Turkot+ (BNL, UMD, MIT)
LUERS 64 PR 133B 1276 +Mittra, Willis, Yamamoto (BNL)
DARMON 62 PL 3 57 +Rousset, Six (EPOL)
ASTIER 61 Aix Conf. 1 227 +Blaskovic, Rivet, Siaud+ (EPOL)
FITCH 61 NC 22 1160 +Piroue, Perkins (PRIN, LASL)
GOOD 61 PR 124 1223 +Matsen, Muller, Piccioni+ (LRL)
NYAGU 61 PRL 6 552 +Okonov, Petrov, Rosanova, Rusakov (JINR)
Also 61B JETP 13 1138 Nyagu, Okonov, Petrov, Rozanova+ (JINR)
Translated from ZETF 40 1618.
BARDON 58 ANP 5 156 +Lande, Lederman (COLU, BNL)

OTHER RELATED PAPERS

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PEACH 90 JPG 16 131 (EDIN)
BRYMAN 89 IJMP A4 79 (TRIU)
"Rare Kaon Decays"
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GINSBERG 73 PR D8 3887 +Smith (MIT, STON)
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RUBBIA 67 PL 24B 531 +Steinberger (CERN, COLU)
Also 66C PL 23 167 Rubbia, Steinberger (CERN, COLU)
Also 66C PL 20 207 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
Also 66B PL 21 595 Alff-Steinberger, Heuer, Kleinknecht+ (CERN)
AUERBACH 66 PR 149 1052 +Dobbs, Lande, Mann, Sciulli+ (PENN)
Also 65 PRL 14 192 Auerbach, Lande, Mann, Sciulli, Uto+ (PENN)
FIRESTONE 66B PRL 17 116 +Kim, Lach, Sandweiss+ (YALE, BNL)
BEHR 65 Argonne Conf. 59 +Brisson, Bellotti+ (EPOL, MILA, PADO)
MESTVIRISH... 65 JINR P 2449 Mestvirishvili, Nyagu, Petrov, Rusakov+ (JINR)
TRILLING 65B UCRL 16473 (LRL)
Updated from 1965 Argonne Conference, page 115.
JOVANOV... 63 BNL Conf. 42 Jovanovich, Fischer, Burris+ (BNL, UMD)

$K^*(892)$

$I(J^P) = \frac{1}{2}(1^-)$

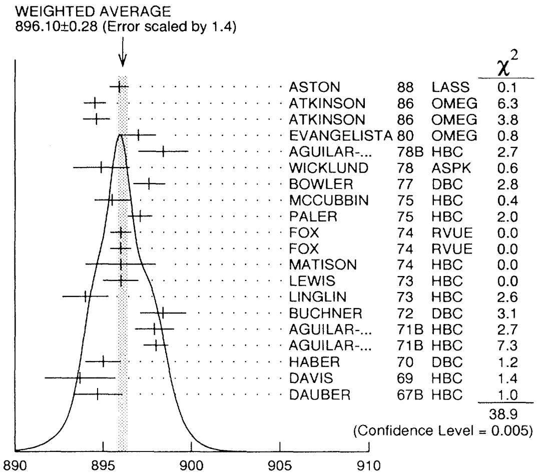
$K^*(892)$ MASS

CHARGED ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
891.59±0.24 OUR AVERAGE		Error includes scale factor of 1.1.			
890.4 ±0.2 ±0.5	79709±801	[1] BIRD	89 LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
892.6 ±0.5	5840	BAUBILLIER	84B HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
888 ±3		NAPIER	84 SPEC	+	200 $\pi^- p \to 2K^0_S X$
891 ±1		NAPIER	84 SPEC	−	200 $\pi^- p \to 2K^0_S X$
891.7 ±2.1	3700	BARTH	83 HBC	+	70 $K^+ p \to K^0 \pi^+ X$
891 ±1	4100	TOAFF	81 HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
892.8 ±1.6		AJINENKO	80 HBC	+	32 $K^+ p \to K^0 \pi^+ X$
890.7 ±0.9	1800	AGUILAR-...	78B HBC	±	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
886.6 ±2.4	1225	BALAND	78 HBC	±	12 $\overline{p} p \to (K\pi)^\pm X$
891.7 ±0.6	6706	COOPER	78 HBC	±	0.76 $\overline{p} p \to (K\pi)^\pm X$
891.9 ±0.7	9000	[2] PALER	75 HBC	−	14.3 $K^- p \to (K\pi)^- X$
892.2 ±1.5	4404	AGUILAR-...	71B HBC	−	3.9,4.6 $K^- p \to (K\pi)^- p$
891 ±2	1000	CRENNELL	69D DBC	−	3.9 $K^- N \to K^0 \pi^- X$
894 ±1.0	2886	[3] FRIEDMAN	69 HBC	−	2.1 $K^- p \to \overline{K}^0 \pi^- p$
892 ±2	728	FRIEDMAN	69 HBC	−	2.45 $K^- p \to \overline{K}^0 \pi^- p$
892 ±1.0	3229	FRIEDMAN	69 HBC	−	2.6 $K^- p \to \overline{K}^0 \pi^- p$
892 ±1.6	1027	FRIEDMAN	69 HBC	−	2.7 $K^- p \to \overline{K}^0 \pi^- p$
890 ±3.0	720	BARLOW	67 HBC	±	1.2 $\overline{p} p \to (K^0 \pi)^\pm K^\mp$
889 ±3.0	600	BARLOW	67 HBC	±	1.2 $\overline{p} p \to (K^0 \pi)^\pm K \pi$
891 ±2.3	620	[3] DEBAERE	67B HBC	+	3.5 $K^+ p \to K^0 \pi^+ p$
891.0 ±1.2	1700	[4] WOJCICKI	64 HBC	−	1.7 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
890.0 ±2.3	800	[3,4] CLELAND	82 SPEC	+	30 $K^+ p \to K^0_S \pi^+ p$
896.0 ±1.1	3200	[3,4] CLELAND	82 SPEC	+	50 $K^+ p \to K^0_S \pi^+ p$
893 ±1	3600	[3,4] CLELAND	82 SPEC	−	50 $K^+ p \to K^0_S \pi^- p$
896.0 ±1.9	380	DELFOSSE	81 SPEC	+	50 $K^\pm p \to K^\pm \pi^0 p$
886.0 ±2.3	187	DELFOSSE	81 SPEC	−	50 $K^\pm p \to K^\pm \pi^0 p$
894.2 ±2.0	765	[3] CLARK	73 HBC	−	3.13 $K^- p \to \overline{K}^0 \pi^- p$
894.3 ±1.5	1150	[3,4] CLARK	73 HBC	−	3.3 $K^- p \to \overline{K}^0 \pi^- p$
888 ±2.5	540	[3] DEWIT	68 HBC	−	3 $K^- n \to \overline{K}^0 \pi^- n$
892.0 ±2.6	341	[3] SCHWEING...	68 HBC	−	5.5 $K^- p \to \overline{K}^0 \pi^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
896.10±0.28 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.			
895.9 ±0.5 ±0.2		ASTON	88 LASS	0	11 $K^- p \to K^- \pi^+ n$
894.52±0.63	25k	[2] ATKINSON	86 OMEG		20–70 γp
894.63±0.76	20k	[2] ATKINSON	86 OMEG		20–70 γp
897 ±1	28k	EVANGELISTA	80 OMEG	0	10 $\pi^- p \to K^+ \pi^- (\Lambda, \Sigma)$
898.4 ±1.4	1180	AGUILAR-...	78B HBC	0	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
894.9 ±1.6		WICKLUND	78 ASPK	0	3,4,6 $K^\pm N \to (K\pi)^0 N$
897.6 ±0.9		BOWLER	77 DBC	0	5.4 $K^+ d \to K^+ \pi^- p p$
895.5 ±1.0	3600	MCCUBBIN	75 HBC	0	3.6 $K^- p \to K^- \pi^+ n$
897.1 ±0.7	22k	[2] PALER	75 HBC	0	14.3 $K^- p \to (K\pi)^0 X$
896.0 ±0.6	10k	FOX	74 RVUE	0	2 $K^- p \to K^- \pi^+ n$
896.0 ±0.6		FOX	74 RVUE	0	2 $K^+ n \to K^+ \pi^- p$
896 ±2		[5] MATISON	74 HBC	0	12 $K^+ p \to K^+ \pi^- \Delta$
896 ±1	3186	LEWIS	73 HBC	0	2.1–2.7 $K^+ p \to K \pi \pi p$
894.0 ±1.3		[5] LINGLIN	73 HBC	0	2–13 $K^+ p \to K^+ \pi^- \pi^+ p$
898.4 ±1.3	1700	[3] BUCHNER	72 DBC	0	4.6 $K^+ n \to K^+ \pi^- p$
897.9 ±1.1	2934	[3] AGUILAR-...	71B HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ n$
898.0 ±0.7	5362	[3] AGUILAR-...	71B HBC	0	3.9,4.6 $K^- p \to K^- \pi^+ \pi^- p$
895 ±1	4300	[4] HABER	70 DBC	0	3 $K^- N \to K^- \pi^+ X$
893.7 ±2.0	10k	DAVIS	69 HBC	0	12 $K^+ p \to K^+ \pi^- \pi^+ p$
894.7 ±1.4	1040	[3] DAUBER	67B HBC	0	2.0 $K^- p \to K^- \pi^+ \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
900.7 ±1.1	5900	BARTH	83 HBC	0	70 $K^+ p \to K^+ \pi^- X$



$K^*(892)^0$ mass (MeV)

[1] From a partial wave amplitude analysis.
[2] Inclusive reaction. Complicated background and phase-space effects.
[3] Mass errors enlarged by us to $\Gamma/\sqrt{N}$. See note.
[4] Number of events in peak reevaluated by us.
[5] From pole extrapolation.

$K^*(892)$ MASSES AND MASS DIFFERENCES

Unrealistically small errors have been reported by some experiments. We use simple "realistic" tests for the minimum errors on the determination of a mass and width from a sample of N events:

$$\delta_{\min}(m) = \frac{\Gamma}{\sqrt{N}}, \quad \delta_{\min}(\Gamma) = 4\frac{\Gamma}{\sqrt{N}} .$$

We consistently increase unrealistic errors before averaging. For a detailed discussion, see the 1971 edition of this Note.

$m_{K^*(892)^0} - m_{K^*(892)^\pm}$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
6.7±1.2 OUR AVERAGE					
7.7±1.7	2980	AGUILAR-...	78B HBC	±0	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
5.7±1.7	7338	AGUILAR-...	71B HBC	−0	3.9,4.6 $K^- p$
6.3±4.1	283	[6] BARASH	67B HBC		0.0 $\overline{p} p$

[6] Number of events in peak reevaluated by us.

$K^*(892)$ RANGE PARAMETER

All from partial wave amplitude analyses.

VALUE (GeV^{-1})	DOCUMENT ID	TECN	CHG	COMMENT
12.1±3.2±3.0	BIRD	89 LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
3.4±0.7	ASTON	88 LASS	0	11 $K^- p \to K^- \pi^+ n$

$K^*(892)$ WIDTH

CHARGED ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
49.8±0.8 OUR FIT					
49.8±0.8 OUR AVERAGE					
45.2±1 ±2	79709±801	[7] BIRD	89 LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
49 ±2	5840	BAUBILLIER	84B HBC	−	8.25 $K^- p \to \overline{K}^0 \pi^- p$
56 ±4		NAPIER	84 SPEC	−	200 $\pi^- p \to 2K^0_S X$
51 ±2	4100	TOAFF	81 HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
50.5±5.6		AJINENKO	80 HBC	+	32 $K^+ p \to K^0 \pi^+ X$
45.8±3.6	1800	AGUILAR-...	78B HBC	±	0.76 $\overline{p} p \to K^\mp K^0_S \pi^\pm$
52.0±2.5	6706	[8] COOPER	78 HBC	±	0.76 $\overline{p} p \to (K\pi)^\pm X$
52.1±2.2	9000	[9] PALER	75 HBC	−	14.3 $K^- p \to (K\pi)^- X$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
46.3 ± 6.7	765	[8] CLARK 73	HBC	$-$	$3.13\ K^-p\to\overline{K}^0\pi^-p$
48.2 ± 5.7	1150	[8,10] CLARK 73	HBC	$-$	$3.3\ K^-p\to\overline{K}^0\pi^-p$
54.3 ± 3.3	4404	[8] AGUILAR-... 71B	HBC	$-$	$3.9,4.6\ K^-p\to(K\pi)^-p$
$53\ \pm4.0$	2886	[8] FRIEDMAN 69	HBC	$-$	$2.1\ K^-p\to\overline{K}^0\pi^-p$
$49\ \pm7.3$	728	[8] FRIEDMAN 69	HBC	$-$	$2.45\ K^-p\to\overline{K}^0\pi^-p$
$46\ \pm3.2$	3229	[8] FRIEDMAN 69	HBC	$-$	$2.6\ K^-p\to\overline{K}^0\pi^-p$
$49\ \pm6.1$	1027	[8] FRIEDMAN 69	HBC	$-$	$2.7\ K^-p\to\overline{K}^0\pi^-p$
$46\ \pm5$	1700	[8,10] WOJCICKI 64	HBC	$-$	$1.7\ K^-p\to\overline{K}^0\pi^-p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
42.8 ± 7.1	3700	BARTH 83	HBC	$+$	$70\ K^+p\to K^0\pi^+X$
64.0 ± 9.2	800	[8,10] CLELAND 82	SPEC	$+$	$30\ K^+p\to K^0_S\pi^+p$
62.0 ± 4.4	3200	[8,10] CLELAND 82	SPEC	$+$	$50\ K^+p\to K^0_S\pi^+p$
$55\ \pm4$	3600	[8,10] CLELAND 82	SPEC	$-$	$50\ K^+p\to K^0_S\pi^-p$
62.6 ± 3.8	380	DELFOSSE 81	SPEC	$+$	$50\ K^\pm p\to K^\pm\pi^0p$
50.5 ± 3.9	187	DELFOSSE 81	SPEC	$-$	$50\ K^\pm p\to K^\pm\pi^0p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
50.5 ± 0.6 OUR FIT Error includes scale factor of 1.1.					
50.5 ± 0.6 OUR AVERAGE Error includes scale factor of 1.1.					
$50.8\pm0.8\pm0.9$		ASTON 88	LASS	0	$11\ K^-p\to K^-\pi^+n$
46.5 ± 4.3	5900	BARTH 83	HBC	0	$70\ K^+p\to K^+\pi^-X$
$54\ \pm2$	28k	EVANGELISTA 80	OMEG	0	$10\ \pi^-p\to K^+\pi^-(\Lambda,\Sigma)$
45.9 ± 4.8	1180	AGUILAR-... 78B	HBC	0	$0.76\ \overline{p}p\to K^\mp K^0_S\pi^\pm$
51.2 ± 1.7		WICKLUND 78	ASPK	0	$3,4,6\ K^\pm N\to(K\pi)^0N$
48.9 ± 2.5		BOWLER 77	DBC	0	$5.4\ K^+d\to K^+\pi^-pp$
$48\ ^{+3}_{-2}$	3600	MCCUBBIN 75	HBC	0	$3.6\ K^-p\to K^-\pi^+n$
50.6 ± 2.5	22k	[9] PALER 75	HBC	0	$14.3\ K^-p\to(K\pi)^0X$
$47\ \pm2$	10k	FOX 74	RVUE	0	$2\ K^-p\to K^-\pi^+n$
$51\ \pm2$		FOX 74	RVUE	0	$2\ K^+n\to K^+\pi^-p$
46.0 ± 3.3	3186	[8] LEWIS 73	HBC	0	$2.1\text{–}2.7\ K^+p\to K\pi\pi p$
51.4 ± 5.0	1700	[8] BUCHNER 72	DBC	0	$4.6\ K^+n\to K^+\pi^-p$
$55.8^{+4.2}_{-3.4}$	2934	[8] AGUILAR-... 71B	HBC	0	$3.9,4.6\ K^-p\to K^-\pi^+n$
48.5 ± 2.7	5362	AGUILAR-... 71B	HBC	0	$3.9,4.6\ K^-p\to K^-\pi^+\pi^-p$
54.0 ± 3.3	4300	[8,10] HABER 70	DBC	0	$3\ K^-N\to K^-\pi^+X$
53.2 ± 2.1	10k	[8] DAVIS 69	HBC	0	$12\ K^+p\to K^+\pi^-\pi^+p$
$44\ \pm5.5$	1040	[8] DAUBER 67B	HBC	0	$2.0\ K^-p\to K^-\pi^+\pi^-p$

[7] From a partial wave amplitude analysis.
[8] Width errors enlarged by us to $4\times\Gamma/\sqrt{N}$; see note.
[9] Inclusive reaction. Complicated background and phase-space effects.
[10] Number of events in peak reevaluated by us.

$K^*(892)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K\pi$	~ 100 %	
Γ_2	$(K\pi)^\pm$	(99.899 ± 0.009) %	
Γ_3	$(K\pi)^0$	(99.770 ± 0.020) %	
Γ_4	$K^0\gamma$	($2.30\ \pm0.20$) $\times10^{-3}$	
Γ_5	$K^\pm\gamma$	($1.01\ \pm0.09$) $\times10^{-3}$	
Γ_6	$K\pi\pi$	$<\ 7$ $\times10^{-4}$	95%

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 18 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2=15.2$ for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i\delta p_j\rangle/(\delta p_i\cdot\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i\equiv\Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_5	-100	
Γ	17	-17
	x_2	x_5

	Mode	Rate (MeV)
Γ_2	$(K\pi)^\pm$	$49.8\ \pm0.8$
Γ_5	$K^\pm\gamma$	0.050 ± 0.005

CONSTRAINED FIT INFORMATION

An overall fit to the total width and a partial width uses 18 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2=18.4$ for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta p_i\delta p_j\rangle/(\delta p_i\cdot\delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i\equiv\Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_4	-100	
Γ	14	-14
	x_3	x_4

	Mode	Rate (MeV)	Scale factor
Γ_3	$(K\pi)^0$	$50.4\ \pm0.6$	1.1
Γ_4	$K^0\gamma$	0.117 ± 0.010	

$K^*(892)$ PARTIAL WIDTHS

$\Gamma(K^0\gamma)$ — Γ_4

VALUE (keV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
$116\ \pm10$ OUR FIT					
$116.5\pm\ 9.9$	584	CARLSMITH 86	SPEC	0	$K^0_LA\to K^0_S\pi^0A$

$\Gamma(K^\pm\gamma)$ — Γ_5

VALUE (keV)	DOCUMENT ID	TECN	CHG	COMMENT
$50\pm\ 5$ OUR FIT				
$50\pm\ 5$ OUR AVERAGE				
48 ± 11	BERG 83	SPEC	$-$	$156\ K^-A\to\overline{K}\pi A$
$51\pm\ 5$	CHANDLEE 83	SPEC	$+$	$200\ K^+A\to K\pi A$

$K^*(892)$ BRANCHING RATIOS

$\Gamma(K^0\gamma)/\Gamma_{\rm total}$ — Γ_4/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	CHG	COMMENT
2.30 ± 0.20 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.5\ \pm0.7$	CARITHERS 75B	CNTR	0	$8\text{–}16\ \overline{K}^0A$

$\Gamma(K^\pm\gamma)/\Gamma_{\rm total}$ — Γ_5/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	CHG	COMMENT
1.01 ± 0.09 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	95	BEMPORAD 73	CNTR	$+$	$10\text{–}16\ K^+A$

$\Gamma(K\pi\pi)/\Gamma((K\pi)^\pm)$ — Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID	TECN	CHG	COMMENT
<0.0007	95	JONGEJANS 78	HBC		$4\ K^-p\to p\overline{K}^0 2\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.002		WOJCICKI 64	HBC	$-$	$1.7\ K^-p\to\overline{K}^0\pi^-p$

$K^*(892)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
ATKINSON	86	ZPHY C30 521	+	(BONN, CERN, GLAS, LANC, MCHS, CURIN+)
CARLSMITH	86	PRL 56 18	+Bernstein, Peyaud, Turlay	(EFI, SACL)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, CURIN)
NAPIER	84	PL 149B 514	+Chen+	(TUFTS, ARIZ, FNAL, FLOR, NDAM+)
BARTH	83	NP B223 296	+Drevermann+	(BRUX, CERN, GENO, MONS+)
BERG	83	Thesis UMI 83-21652		(ROCH)
CHANDLEE	83	PRL 51 168	+Berg, Cihangir, Collick+	(ROCH, FNAL, MINN)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
DELFOSSE	81	NP B183 349	+Guisan, Martin, Muhlemann, Weill+	(GEVA, LAUS)
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
AJINENKO	80	ZPHY C5 177	+Barth, Dujardin+	(SERP, BRUX, MONS, SACL)
EVANGELISTA	80	NP B165 383	+	(BARI, BONN, CERN, DARE, GLAS, LIVP+)
AGUILAR-...	78B	NP B141 101	Aguilar-Benitez+	(MADR, TATA, CERN+)
BALAND	78	NP B140 220	+Grard+	(MONS, BELG, CERN, LOIC, LALO)
COOPER	78	NP B136 365	+Gurtu+	(TATA, CERN, CDEF+)
JONGEJANS	78	NP B139 383	+Cerrada+	(ZEEM, CERN, NIJM, OXF)
WICKLUND	78	PR D17 1197	+Ayres, Diebold, Greene, Kramer, Pawlicki	(ANL)
BOWLER	77	NP B126 31	+Dainton, Drake, Williams	(OXF)
CARITHERS	75B	PRL 35 349	+Muhlemann, Underwood+	(ROCH, MCGI)
MCCUBBIN	75	NP B86 13	+Lyons	(OXF)
PALER	75	NP B96 1	+Tovey, Shah, Spiro+	(RHEL, SACL, EPOL)
FOX	74	NP B80 403	+Griss	(CIT)
MATISON	74	PR D9 1872	+Galtieri, Alston-Garnjost, Flatte, Friedman+	(LBL)
BEMPORAD	73	NP B51 1	+Beusch, Freudenreich+	(CERN, ETH, LOIC)
CLARK	73	NP B54 432	+Lyons, Radojicic	(OXF)
LEWIS	73	NP B60 283	+Allen, Jacobs+	(LOWC, LOIC, CDEF)
LINGLIN	73	NP B55 408		(CERN)
BUCHNER	72	NP B45 333	+Dehm, Charriere, Cornet+	(MPIM, CERN, BRUX)
AGUILAR-...	71B	PR D4 2583	Aguilar-Benitez, Eisner, Kinson	(BNL)
HABER	70	NP B17 289	+Shapira, Alexander+	(REHO, SACL, BGNA, EPOL)
CRENNELL	69D	PRL 22 487	+Karshon, Lai, O'Neall, Scarr	(BNL)
DAVIS	69	PRL 23 1071	+Derenzo, Flatte, Garnjost, Lynch, Solmitz	(LRL)
FRIEDMAN	69	Thesis UCRL 18860		(LRL)
DEWIT	68	Thesis		(ANIK)
SCHWEING...	68	PR 166 1317	Schweingruber, Derrick, Fields+	(ANL, NWES)
BARASH	67B	PR 156 1399	+Kirsch, Miller, Tan	(COLU)
BARLOW	67	NC 50A 701	+Lillestol, Montanet+	(CERN, CDEF, IRAD, LIVP)
DAUBER	67B	PR 153 1403	+Schlein, Slater, Ticho	(UCLA)
DEBAERE	67B	NC 51A 401	+Goldschmidt-Clermont, Henri+	(BRUX, CERN)
WOJCICKI	64	PR 135B 484		(LRL)

OTHER RELATED PAPERS

KAMAL	92	PL B284 421	+Xu	(ALBE)
NAPIER	84	PL 149B 514	+Chen+	(TUFTS, ARIZ, FNAL, FLOR, NDAM+)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
ALEXANDER	62	PRL 8 447	+Kalbfleisch, Miller, Smith	(LRL)
ALSTON	62B	CERN Conf. 291	+Ticho, Wojcicki+	(LRL)
ARMENTEROS	62C	CERN Conf. 295	+Astrer, Montanet+	(CERN, CDEF)
COLLEY	62B	CERN Conf. 315	+Gelfand+	(COLU, RUTG)
ALSTON	61	PRL 6 300	+Alvarez, Eberhard, Good+	(LRL)

$K_1(1270)$

$I(J^P) = \frac{1}{2}(1^+)$

$K_1(1270)$ MASS

VALUE (MeV)	DOCUMENT ID
1273±7 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

PRODUCED BY K^-, BACKWARD SCATTERING, HYPERON EXCHANGE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1275±10	700	GAVILLET	78	HBC	+	$4.2\ K^- p \to \Xi^-(K\pi\pi)^+$

PRODUCED BY K BEAMS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1270±10	DAUM	81C	CNTR	−	$63\ K^- p \to K^- 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1276	[1] TORNQVIST	82B	RVUE		
~ 1300	VERGEEST	79	HBC	−	$4.2\ K^- p \to (\overline{K}\pi\pi)^- p$
1289±25	[2] CARNEGIE	77	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$
~ 1300	BRANDENB...	76	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$
~ 1270	OTTER	76	HBC	−	$10,14,16\ K^- p \to (\overline{K}\pi\pi)^- p$
1260	DAVIS	72	HBC	+	$12\ K^+ p$
1234±12	FIRESTONE	72B	DBC	+	$12\ K^+ d$

[1] From a unitarized quark-model calculation.
[2] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.

PRODUCED BY BEAMS OTHER THAN K MESONS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1294±10	310	RODEBACK	81	HBC		$4\ \pi^- p \to \Lambda K 2\pi$
1300	40	CRENNELL	72	HBC	0	$4.5\ \pi^- p \to \Lambda K 2\pi$
1242^{+9}_{-10}		[3] ASTIER	69	HBC	0	$\overline{p}p$
1300	45	CRENNELL	67	HBC	0	$6\ \pi^- p \to \Lambda K 2\pi$

[3] This was called the C meson.

$K_1(1270)$ WIDTH

VALUE (MeV)	DOCUMENT ID
90±20 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.
87± 7 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

PRODUCED BY K^-, BACKWARD SCATTERING, HYPERON EXCHANGE

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
75±15	700	GAVILLET	78	HBC	+	$4.2\ K^- p \to \Xi^- K\pi\pi$

PRODUCED BY K BEAMS

The data in this block is included in the average printed for a previous datablock.

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
90± 8	DAUM	81C	CNTR	−	$63\ K^- p \to K^- 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 150	VERGEEST	79	HBC	−	$4.2\ K^- p \to (\overline{K}\pi\pi)^- p$
150±71	[4] CARNEGIE	77	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$
~ 200	BRANDENB...	76	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$
120	DAVIS	72	HBC	+	$12\ K^+ p$
188±21	FIRESTONE	72B	DBC	+	$12\ K^+ d$

[4] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.

PRODUCED BY BEAMS OTHER THAN K MESONS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
66±15	310	RODEBACK	81	HBC		$4\ \pi^- p \to \Lambda K 2\pi$
60	40	CRENNELL	72	HBC	0	$4.5\ \pi^- p \to \Lambda K 2\pi$
127^{+7}_{-25}		ASTIER	69	HBC	0	$\overline{p}p$
60	45	CRENNELL	67	HBC	0	$6\ \pi^- p \to \Lambda K 2\pi$

$K_1(1270)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\rho$	(42 ±6) %
Γ_2	$K_0^*(1430)\pi$	(28 ±4) %
Γ_3	$K^*(892)\pi$	(16 ±5) %
Γ_4	$K\omega$	(11.0±2.0) %
Γ_5	$K f_0(1370)$	(3.0±2.0) %

$K_1(1270)$ PARTIAL WIDTHS

$\Gamma(K\rho)$ — Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
57±5	MAZZUCATO	79	HBC	+	$4.2\ K^- p \to \Xi^-(K\pi\pi)^+$
75±6	CARNEGIE	77B	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K_0^*(1430)\pi)$ — Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
26±6	CARNEGIE	77B	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K^*(892)\pi)$ — Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
14±11	MAZZUCATO	79	HBC	+	$4.2\ K^- p \to \Xi^-(K\pi\pi)^+$
2± 2	CARNEGIE	77B	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K\omega)$ — Γ_4

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4±4	MAZZUCATO	79	HBC	+	$4.2\ K^- p \to \Xi^-(K\pi\pi)^+$
24±3	CARNEGIE	77B	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$

$\Gamma(K f_0(1370))$ — Γ_5

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
22±5	CARNEGIE	77B	ASPK	±	$13\ K^\pm p \to (K\pi\pi)^\pm p$

$K_1(1270)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.42±0.06	[5] DAUM	81C	CNTR	$63\ K^- p \to K^- 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
dominant	RODEBACK	81	HBC	$4\ \pi^- p \to \Lambda K 2\pi$

$\Gamma(K_0^*(1430)\pi)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.28±0.04	[5] DAUM	81C	CNTR	$63\ K^- p \to K^- 2\pi p$

$\Gamma(K^*(892)\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.16±0.05	[5] DAUM	81C	CNTR	$63\ K^- p \to K^- 2\pi p$

$\Gamma(K\omega)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.11 ±0.02	[5] DAUM	81C	CNTR	$63\ K^- p \to K^- 2\pi p$

$\Gamma(K\omega)/\Gamma(K\rho)$ — Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	95	RODEBACK	81	HBC	$4\ \pi^- p \to \Lambda K 2\pi$

$\Gamma(K f_0(1370))/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03 ±0.02	[5] DAUM	81C	CNTR	$63\ K^- p \to K^- 2\pi p$

D-wave/S-wave RATIO FOR $K_1(1270) \to K^*(892)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
1.0±0.7	[5] DAUM	81C	CNTR	$63\ K^- p \to K^- 2\pi p$

[5] Average from low and high t data.

$K_1(1270)$ REFERENCES

TORNQVIST 82B NP B203 268 (HELS)
DAUM 81C NP B187 1 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
RODEBACK 81 ZPHY C9 9 +Sjogren+ (CERN, CDEF, MADR, STOH)
MAZZUCATO 79 NP B156 532 +Pennington+ (CERN, ZEEM, NIJM, OXF)
VERGEEST 79 NP B158 265 +Jongejans, Dionisi+ (NIJM, AMST, CERN, OXF)
GAVILLET 78 PL 76B 517 +Diaz, Dionisi+ (AMST, CERN, NIJM, OXF) JP
CARNEGIE 77 NP B127 509 +Cashmore, Davier, Dunwoodie, Lasinski+ (SLAC)
CARNEGIE 77B PL 68B 287 +Cashmore, Dunwoodie, Lasinski+ (SLAC)
BRANDENB... 76 PRL 26 703 Brandenburg, Carnegie, Cashmore+ (SLAC) JP
OTTER 76 NP B106 77 + (AACH3, BERL, CERN, LOIC, VIEN, EPOL+) JP
CRENNELL 72 PR D6 1220 +Gordon, Lai, Scarr (BNL)
DAVIS 72 PR D5 2688 +Alston-Garnjost, Barbaro, Flatte, Friedman, Lynch+ (LBL)
FIRESTONE 72B PR D5 505 +Goldhaber, Lissauer, Trilling (LBL)
ASTIER 69 NP B10 65 +Marechal, Montanet+ (CDEF, CERN, IPNP, LIVP) IJP
CRENNELL 67 PRL 19 44 +Kalbfleisch, Lai, Scarr, Schumann (BNL) I

OTHER RELATED PAPERS

SUZUKI 93 PR D47 1252 (LBL)
BAUBILLIER 82B NP B202 21 + (BIRM, CERN, GLAS, MSU, CURIN)
FERNANDEZ 82 ZPHY C16 95 +Aguilar-Benitez+ (MADR, CERN, CDEF, STOH) JP
GAVILLET 82 ZPHY C16 119 +Armenteros+ (CERN, CDEF, PADO, ROMA)
SHEN 66 PRL 17 726 +Butterworth, Fu, Goldhaber, Trilling (LRL)
Also 66 Private Comm. Goldhaber (LRL)
ALMEIDA 65 PL 16 184 +Atherton, Byer, Dornan, Forson+ (CAVE)
ARMENTEROS 64 PL 9 207 +Edwards, D'Andlau+ (CERN, CDEF)
Also 66 PR 145 1095 Barash, Kirsch, Miller, Tan (COLU)
ARMENTEROS 64B Dubna Conf. 1 577 +Edwards, D'Andlau+ (CERN, CDEF)
Also 64C Dubna Conf. 1 617 Armenteros

$K_1(1400)$

$I(J^P) = \frac{1}{2}(1^+)$

$K_1(1400)$ MASS

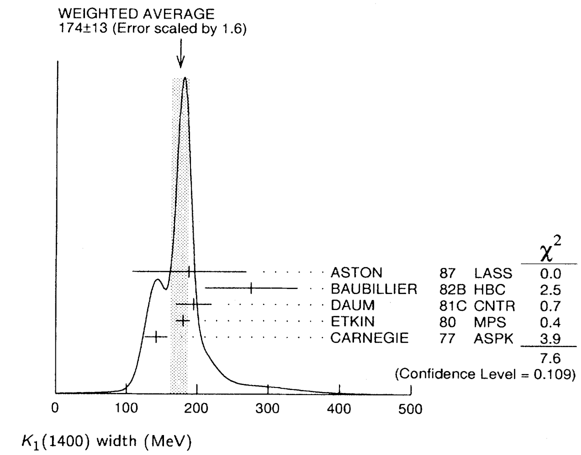
VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1402± 7 OUR AVERAGE					
1373±14±18	[1] ASTON	87	LASS	0	11 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
1392±18	BAUBILLIER	82B	HBC	0	8.25 $K^- p \rightarrow K^0_S \pi^+ \pi^- n$
1410±25	DAUM	81C	CNTR	−	63 $K^- p \rightarrow K^- 2\pi p$
1415±15	ETKIN	80	MPS	0	6 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
1404±10	[2] CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1350	[3] TORNQVIST	82B	RVUE		
~ 1400	VERGEEST	79	HBC	−	4.2 $K^- p \rightarrow (\overline{K}\pi\pi)^- p$
~ 1400	BRANDENB...	76	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$
1420	DAVIS	72	HBC	+	12 $K^+ p$
1368±18	FIRESTONE	72B	DBC	+	12 $K^+ d$

[1] From partial-wave analysis of $K^0 \pi^+ \pi^-$ system.
[2] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.
[3] From a unitarized quark-model calculation.

$K_1(1400)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
174±13 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.					
188±54±60	[4] ASTON	87	LASS	0	11 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
276±65	BAUBILLIER	82B	HBC	0	8.25 $K^- p \rightarrow K^0_S \pi^+ \pi^- n$
195±25	DAUM	81C	CNTR	−	63 $K^- p \rightarrow K^- 2\pi p$
180±10	ETKIN	80	MPS	0	6 $K^- p \rightarrow \overline{K}^0 \pi^+ \pi^- n$
142±16	[5] CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 200	VERGEEST	79	HBC	−	4.2 $K^- p \rightarrow (\overline{K}\pi\pi)^- p$
~ 160	BRANDENB...	76	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$
80	DAVIS	72	HBC	+	12 $K^+ p$
241±30	FIRESTONE	72B	DBC	+	12 $K^+ d$

[4] From partial-wave analysis of $K^0 \pi^+ \pi^-$ system.
[5] From a model-dependent fit with Gaussian background to BRANDENBURG 76 data.



$K_1(1400)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\pi$	(94 ±6) %
Γ_2	$K\rho$	(3.0±3.0) %
Γ_3	$K f_0(1370)$	(2.0±2.0) %
Γ_4	$K\omega$	(1.0±1.0) %
Γ_5	$K^*_0(1430)\pi$	

$K_1(1400)$ PARTIAL WIDTHS

$\Gamma(K^*(892)\pi)$ Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
117±10	CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$\Gamma(K\rho)$ Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2 ±1	CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$\Gamma(K\omega)$ Γ_4

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
23±12	CARNEGIE	77	ASPK	±	13 $K^\pm p \rightarrow (K\pi\pi)^\pm p$

$K_1(1400)$ BRANCHING RATIOS

$\Gamma(K^*(892)\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.94±0.06	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K\rho)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03 ±0.03	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K f_0(1370))/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.02 ±0.02	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K\omega)/\Gamma_{total}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.01 ±0.01	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

$\Gamma(K^*_0(1430)\pi)/\Gamma_{total}$ Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

D-wave/S-wave RATIO FOR $K_1(1400) \rightarrow K^*(892)\pi$

VALUE	DOCUMENT ID		TECN	COMMENT
0.04 ±0.01	[6] DAUM	81C	CNTR	63 $K^- p \rightarrow K^- 2\pi p$

[6] Average from low and high t data.

$K_1(1400)$ REFERENCES

ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, CURIN)
TORNQVIST	82B	NP B203 268		(HELS)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
VERGEEST	79	NP B158 265	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)
CARNEGIE	77	NP B127 509	+Cashmore, Davier, Dunwoodie, Lasinski+	(SLAC)
BRANDENB...	76	PRL 26 703	Brandenburg, Carnegie, Cashmore+	(SLAC) JP
DAVIS	72	PR D5 2688	+Alston-Garnjost, Barbaro, Flatte, Friedman, Lynch+	(LBL)
FIRESTONE	72B	PR D5 505	+Goldhaber, Lissauer, Trilling	(LBL)

OTHER RELATED PAPERS

SUZUKI	93	PR D47 1252		(LBL)
FERNANDEZ	82	ZPHY C16 95	+Aguilar-Benitez+	(MADR, CERN, CDEF, STOH)
SHEN	66	PRL 17 726	+Butterworth, Fu, Goldhaber, Trilling	(LRL)
Also	66	Private Comm.	Goldhaber	(LRL)
ALMEIDA	65	PL 16 184	+Atherton, Byer, Dornan, Forson+	(CAVE)
ARMENTEROS	64	PL 9 207	+Edwards, D'Andlau+	(CERN, CDEF)
Also	66	PR 145 1095	Barash, Kirsch, Miller, Tan	(COLU)
ARMENTEROS	64B	Dubna Conf. 1 577	+Edwards, D'Andlau+	(CERN, CDEF)
Also	64C	Dubna Conf. 1 617	Armenteros	

$K^*(1410)$

$I(J^P) = \frac{1}{2}(1^-)$

$K^*(1410)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1412±12 OUR AVERAGE Error includes scale factor of 1.1.					
1367±54	BIRD	89	LASS	−	$11\ K^-p \to \overline{K}^0\pi^-p$
1380±21±19	ASTON	88	LASS	0	$11\ K^-p \to K^-\pi^+n$
1420± 7±10	ASTON	87	LASS	0	$11\ K^-p \to \overline{K}^0\pi^+\pi^-n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1474±25	BAUBILLIER	82B	HBC	0	$8.25\ K^-p \to \overline{K}^0 2\pi n$
1500±30	ETKIN	80	MPS	0	$6\ K^-p \to \overline{K}^0\pi^+\pi^-n$

$K^*(1410)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
227± 22 OUR AVERAGE Error includes scale factor of 1.1.					
114±101	BIRD	89	LASS	−	$11\ K^-p \to \overline{K}^0\pi^-p$
176± 52±22	ASTON	88	LASS	0	$11\ K^-p \to K^-\pi^+n$
240± 18±12	ASTON	87	LASS	0	$11\ K^-p \to \overline{K}^0\pi^+\pi^-n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
275± 65	BAUBILLIER	82B	HBC	0	$8.25\ K^-p \to \overline{K}^0 2\pi n$
500±100	ETKIN	80	MPS	0	$6\ K^-p \to \overline{K}^0\pi^+\pi^-n$

$K^*(1410)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$K^*(892)\pi$	> 40 %	95%
Γ_2	$K\pi$	(6.6±1.3) %	
Γ_3	$K\rho$	< 7 %	95%

$K^*(1410)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.17	95	ASTON	84	LASS	0	$11\ K^-p \to \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma(K^*(892)\pi)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.16	95	ASTON	84	LASS	0	$11\ K^-p \to \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.066±0.010±0.008	ASTON	88	LASS	0	$11\ K^-p \to K^-\pi^+n$

$K^*(1410)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
ASTON	84	PL 149B 258	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, CURIN)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP

$K_0^*(1430)$

$I(J^P) = \frac{1}{2}(0^+)$

See our minireview in the 1994 edition and in this edition under the $f_0(1370)$.

$K_0^*(1430)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1429 ±4±5	[1] ASTON	88	LASS	0	$11\ K^-p \to K^-\pi^+n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1450	[2] TORNQVIST	96	RVUE		$\pi\pi \to \pi\pi, K\overline{K}, K\pi$
~ 1430	BAUBILLIER	84B	HBC	−	$8.25\ K^-p \to \overline{K}^0\pi^-p$
~ 1425	[3,4] ESTABROOKS	78	ASPK		$13\ K^\pm p \to K^\pm\pi^\pm(n,\Delta)$
~ 1450.0	MARTIN	78	SPEC		$10\ K^\pm p \to K_S^0\pi p$

[1] Uses a model for the background, without this background they get a mass 1340 MeV, where the phase shift passes 90°.
[2] T-matrix pole.
[3] Mass defined by pole position.
[4] From elastic $K\pi$ partial-wave analysis.

$K_0^*(1430)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
287±10±21	ASTON	88	LASS	0	$11\ K^-p \to K^-\pi^+n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 320	[5] TORNQVIST	96	RVUE		$\pi\pi \to \pi\pi, K\overline{K}, K\pi$
~ 200	BAUBILLIER	84B	HBC	−	$8.25\ K^-p \to \overline{K}^0\pi^-p$
200 to 300	[6] ESTABROOKS	78	ASPK		$13\ K^\pm p \to K^\pm\pi^\pm(n,\Delta)$

[5] T-matrix pole.
[6] From elastic $K\pi$ partial-wave analysis.

$K_0^*(1430)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(93±10) %

$K_0^*(1430)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.93±0.04±0.09	ASTON	88	LASS	0	$11\ K^-p \to K^-\pi^+n$

$K_0^*(1430)$ REFERENCES

TORNQVIST	96	PRL 76 1575	+Roos	(HELS)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, CURIN)
ESTABROOKS	78	NP B133 490	+Carnegie+	(MCGI, CARL, DURH, SLAC)
MARTIN	78	NP B134 392	+Shimada, Baldi, Bohringer+	(DURH, GEVA)

OTHER RELATED PAPERS

TORNQVIST	82	PRL 49 624		(HELS)
GOLDBERG	69	PL 30B 434	+Huffer, Laloum+	(SABRE Collab.)
SCHLEIN	69	Argonne Conf. 446		(UCLA)
TRIPPE	68	PL 28B 203	+Chien, Malamud, Mellema, Schlein+	(UCLA)

$K_2^*(1430)$

$I(J^P) = \frac{1}{2}(2^+)$

We consider that phase-shift analyses provide more reliable determinations of the mass and width.

$K_2^*(1430)$ MASS

CHARGED ONLY, WITH FINAL STATE $K\pi$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1425.4± 1.3 OUR AVERAGE Error includes scale factor of 1.1.						
1423.4± 2 ±3	24809± 820	[1] BIRD	89	LASS	−	$11\ K^-p \to \overline{K}^0\pi^-p$
1420 ± 4	1587	BAUBILLIER	84B	HBC	−	$8.25\ K^-p \to \overline{K}^0\pi^-p$
1436 ± 5.5	400	[2,3] CLELAND	82	SPEC	+	$30\ K^+p \to K_S^0\pi^+p$
1430 ± 3.2	1500	[2,3] CLELAND	82	SPEC	+	$50\ K^+p \to K_S^0\pi^+p$
1430 ± 3.2	1200	[2,3] CLELAND	82	SPEC	−	$50\ K^+p \to K_S^0\pi^-p$
1423 ± 5	935	TOAFF	81	HBC	−	$6.5\ K^-p \to \overline{K}^0\pi^-p$
1428.0± 4.6		[4] MARTIN	78	SPEC	+	$10\ K^\pm p \to K_S^0\pi p$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1423.8± 4.6		[4] MARTIN	78 SPEC	−	10 $K^{\pm} p \to K_S^0 \pi p$
1420.0± 3.1	1400	AGUILAR-...	71B HBC	−	3.9,4.6 $K^- p$
1425 ± 8.0	225	[2,3] BARNHAM	71C HBC	+	$K^+ p \to K^0 \pi^+ p$
1416 ±10	220	CRENNELL	69D DBC	−	3.9 $K^- N \to \overline{K}^0 \pi^- N$
1414 ±13.0	60	[2] LIND	69 HBC	+	9 $K^+ p \to K^0 \pi^+ p$
1427 ±12	63	[2] SCHWEING...	68 HBC	−	5.5 $K^- p \to \overline{K} \pi N$
1423 ±11.0	39	[2] BASSANO	67 HBC	−	4.6–5.0 $K^- p \to \overline{K}^0 \pi^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1432.4± 1.3 OUR AVERAGE					
1431.2± 1.8± 0.7		[5] ASTON	88 LASS	0	11 $K^- p \to K^- \pi^+ n$
1434 ± 4 ± 6		[5] ASTON	87 LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1433 ± 6 ±10		[5] ASTON	84B LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
1471 ±12		[5] BAUBILLIER	82B HBC	0	8.25 $K^- p \to N K_S^0 \pi \pi$
1428 ± 3		[5] ASTON	81C LASS	0	11 $K^- p \to K^- \pi^+ n$
1434 ± 2		[5] ESTABROOKS	78 ASPK	0	13 $K^{\pm} p \to p K \pi$
1440 ±10		[5] BOWLER	77 DBC	0	5.5 $K^+ d \to K \pi p p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1420 ± 7	300	HENDRICK	76 DBC		8.25 $K^+ N \to K^+ \pi N$
1421.6± 4.2	800	MCCUBBIN	75 HBC	0	3.6 $K^- p \to K^- \pi^+ n$
1420.1± 4.3		[6] LINGLIN	73 HBC	0	2–13 $K^+ p \to K^+ \pi^- X$
1419.1± 3.7	1800	AGUILAR-...	71B HBC	0	3.9,4.6 $K^- p$
1416 ± 6	600	CORDS	71 DBC	0	9 $K^+ n \to K^+ \pi^- p$
1421.1± 2.6	2200	DAVIS	69 HBC	0	12 $K^+ p \to K^+ \pi^- X$

[1] From a partial wave amplitude analysis.
[2] Errors enlarged by us to $\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[3] Number of events in peak re-evaluated by us.
[4] Systematic error added by us.
[5] From phase shift or partial-wave analysis.
[6] From pole extrapolation, using world $K^+ p$ data summary tape.

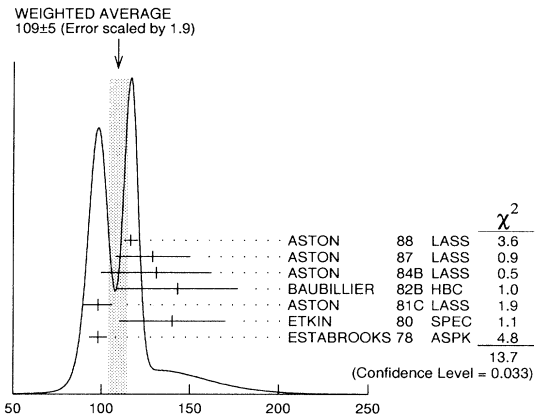
$K_2^*(1430)$ WIDTH

CHARGED ONLY, WITH FINAL STATE $K\pi$

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
98.4± 2.3 OUR FIT					
98.4± 2.4 OUR AVERAGE					
98 ± 4 ±4	24809± 820	[7] BIRD	89 LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
109 ±22	400	[8,9] CLELAND	82 SPEC	+	30 $K^+ p \to K_S^0 \pi^+ p$
124 ±12.8	1500	[8,9] CLELAND	82 SPEC	+	50 $K^+ p \to K_S^0 \pi^+ p$
113 ±12.8	1200	[8,9] CLELAND	82 SPEC	−	50 $K^+ p \to K_S^0 \pi^- p$
85 ±16	935	TOAFF	81 HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
96.5± 3.8		MARTIN	78 SPEC	+	10 $K^{\pm} p \to K_S^0 \pi p$
97.7± 4.0		MARTIN	78 SPEC	−	10 $K^{\pm} p \to K_S^0 \pi p$
$94.7^{+15.1}_{-12.5}$	1400	AGUILAR-...	71B HBC	−	3.9,4.6 $K^- p$

NEUTRAL ONLY

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
109 ± 5 OUR AVERAGE		Error includes scale factor of 1.9. See the ideogram below.			
116.5± 3.6± 1.7		[10] ASTON	88 LASS	0	11 $K^- p \to K^- \pi^+ n$
129 ±15 ±15		[10] ASTON	87 LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
131 ±24 ±20		[10] ASTON	84B LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
143 ±34		[10] BAUBILLIER	82B HBC	0	8.25 $K^- p \to N K_S^0 \pi \pi$
98 ± 8		[10] ASTON	81C LASS	0	11 $K^- p \to K^- \pi^+ n$
140 ±30		[10] ETKIN	80 SPEC	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
98 ± 5		[10] ESTABROOKS	78 ASPK	0	13 $K^{\pm} p \to p K \pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
125 ±29	300	[8] HENDRICK	76 DBC		8.25 $K^+ N \to K^+ \pi N$
116 ±18	800	MCCUBBIN	75 HBC	0	3.6 $K^- p \to K^- \pi^+ n$
61 ±14		[11] LINGLIN	73 HBC	0	2–13 $K^+ p \to K^+ \pi^- X$
$116.6^{+10.3}_{-15.5}$	1800	AGUILAR-...	71B HBC	0	3.9,4.6 $K^- p$
144 ±24.0	600	[8] CORDS	71 DBC	0	9 $K^+ n \to K^+ \pi^- p$
101 ±10	2200	DAVIS	69 HBC	0	12 $K^+ p \to K^+ \pi^- \pi^+ p$



$K_2^*(1430)^0$ width (MeV)

[7] From a partial wave amplitude analysis.
[8] Errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[9] Number of events in peak re-evaluated by us.
[10] From phase shift or partial-wave analysis.
[11] From pole extrapolation, using world $K^+ p$ data summary tape.

$K_2^*(1430)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$K\pi$	(49.7±1.2) %	
Γ_2	$K^*(892)\pi$	(25.2±1.7) %	
Γ_3	$K^*(892)\pi\pi$	(13.0±2.3) %	
Γ_4	$K\rho$	(8.8±0.8) %	S=1.2
Γ_5	$K\omega$	(2.9±0.8) %	
Γ_6	$K^+\gamma$	(2.4±0.5) × 10^{-3}	
Γ_7	$K\eta$	($1.4^{+2.8}_{-0.9}$) × 10^{-3}	S=1.1
Γ_8	$K\omega\pi$	< 7.2 × 10^{-4}	CL=95%
Γ_9	$K^0\gamma$	< 9 × 10^{-4}	CL=90%

CONSTRAINED FIT INFORMATION

An overall fit to the total width, a partial width, and 10 branching ratios uses 28 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 19.5$ for 21 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta p_i \delta p_j \rangle / (\delta p_i \cdot \delta p_j)$, in percent, from the fit to parameters p_i, including the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−16						
x_3	−33	−75					
x_4	−12	39	−54				
x_5	−11	−3	−25	−8			
x_6	−1	−1	−1	−1	0		
x_7	−3	−6	−4	−4	−2	0	
Γ	0	0	0	0	0	−13	0
	x_1	x_2	x_3	x_4	x_5	x_6	x_7

	Mode	Rate (MeV)	Scale factor
Γ_1	$K\pi$	48.9 ±1.7	
Γ_2	$K^*(892)\pi$	24.8 ±1.7	
Γ_3	$K^*(892)\pi\pi$	12.8 ±2.3	
Γ_4	$K\rho$	8.7 ±0.8	1.2
Γ_5	$K\omega$	2.9 ±0.8	
Γ_6	$K^+\gamma$	0.24±0.04	
Γ_7	$K\eta$	$0.14^{+0.28}_{-0.09}$	1.1

$K_2^*(1430)$ PARTIAL WIDTHS

$\Gamma(K^+\gamma)$ — Γ_6

VALUE (keV)	DOCUMENT ID		TECN	CHG	COMMENT
240±40 OUR FIT					
240±45	CIHANGIR	82	SPEC	+	200 $K^+ Z \to Z K^+ \pi^0$, $Z K_S^0 \pi^+$

$\Gamma(K^0\gamma)$ — Γ_9

VALUE (keV)	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<84	90	CARLSMITH	87	SPEC	0	60–200 $K_L^0 A \to K_S^0 \pi^0 A$

$K_2^*(1430)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.497±0.012 OUR FIT					
0.488±0.014 OUR AVERAGE					
0.485±0.006±0.020	[12] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
0.49 ±0.02	[12] ESTABROOKS	78	ASPK	±	13 $K^\pm p \to p K \pi$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ — $\Gamma_2/\Gamma_1 = \Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.47±0.10	BASSANO	67	HBC	−0	4.6,5.0 $K^- p$
0.45±0.13	[13] BADIER	65C	HBC	−	3 $K^- p$

$\Gamma(K\rho)/\Gamma(K\pi)$ — $\Gamma_4/\Gamma_1 = \Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.14±0.10	BASSANO	67	HBC	−0	4.6,5.0 $K^- p$
0.14±0.07	[13] BADIER	65C	HBC	−	3 $K^- p$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.51±0.04 OUR FIT					
0.48±0.05 OUR AVERAGE					
0.44±0.09	ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
0.62±0.19	LAUSCHER	75	HBC	0	10,16 $K^- p \to K^- \pi^+ n$
0.54±0.16	DEHM	74	DBC	0	4.6 $K^+ N$
0.47±0.08	AGUILAR-...	71B	HBC		3.9,4.6 $K^- p$

$\Gamma(K\omega)/\Gamma(K\pi)$ — Γ_5/Γ_1

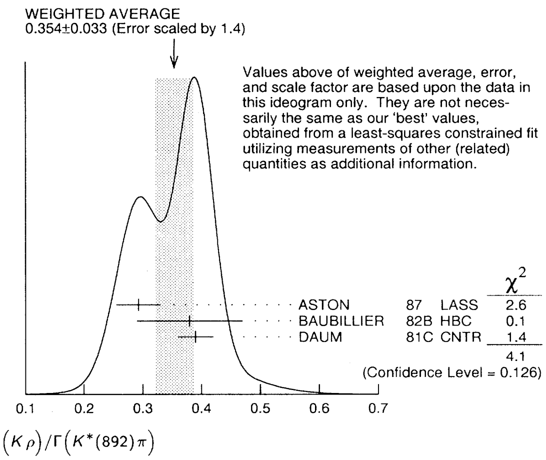
VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.059±0.017 OUR FIT					
0.070±0.035 OUR AVERAGE					
0.05 ±0.04	AGUILAR-...	71B	HBC		3.9,4.6 $K^- p$
0.13 ±0.07	BASSOMPIE...	69	HBC	0	5 $K^+ p$

$\Gamma(K\rho)/\Gamma(K\pi)$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.178±0.018 OUR FIT Error includes scale factor of 1.2.					
$0.153^{+0.034}_{-0.018}$ OUR AVERAGE					
0.18 ±0.05	ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$
$0.02\ ^{+0.10}_{-0.02}$	DEHM	74	DBC	0	4.6 $K^+ N$
0.16 ±0.05	AGUILAR-...	71B	HBC		3.9,4.6 $K^- p$

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ — Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.351±0.032 OUR FIT Error includes scale factor of 1.5.					
0.354±0.033 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.					
0.293±0.032±0.020	ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
0.38 ±0.09	BAUBILLIER	82B	HBC	0	8.25 $K^- p \to N K_S^0 \pi\pi$
0.39 ±0.03	DAUM	81C	CNTR		63 $K^- p \to K^- 2\pi p$



$\Gamma(K\omega)/\Gamma(K^*(892)\pi)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.116±0.034 OUR FIT					
0.10 ±0.04	FIELD	67	HBC	−	3.8 $K^- p$

$\Gamma(K\eta)/\Gamma(K^*(892)\pi)$ — Γ_7/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$0.006^{+0.011}_{-0.004}$ OUR FIT					
0.07 ±0.04	FIELD	67	HBC	−	3.8 $K^- p$

$\Gamma(K\eta)/\Gamma(K\pi)$ — Γ_7/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
$0.0028^{+0.0057}_{-0.0019}$ OUR FIT Error includes scale factor of 1.1.						
0 ±0.0056		[14] ASTON	88B	LASS	−	11 $K^- p \to K^- \eta p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.04	95	AGUILAR-...	71B	HBC		3.9,4.6 $K^- p$
<0.065		[13] BASSOMPIE...	69	HBC		5.0 $K^+ p$
<0.02		BISHOP	69	HBC		3.5 $K^+ p$

$\Gamma(K^*(892)\pi\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.130±0.023 OUR FIT					
0.12 ±0.04	[15] GOLDBERG	76	HBC	−	3 $K^- p \to p \overline{K}^0 \pi\pi\pi$

$\Gamma(K^*(892)\pi\pi)/\Gamma(K\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.26±0.05 OUR FIT					
0.21±0.08	[13,15] JONGEJANS	78	HBC	−	4 $K^- p \to p \overline{K}^0 \pi\pi\pi$

$\Gamma(K\omega\pi)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.72	95	0	JONGEJANS	78	HBC	4 $K^- p \to p \overline{K}^0 4\pi$

[12] From phase shift analysis.

[13] Restated by us.

[14] ASTON 88B quote < 0.0092 at CL=95%. We convert this to a central value and 1 sigma error in order to be abe to use it in our constrained fit.

[15] Assuming $\pi\pi$ system has isospin 1, which is supported by the data.

$K_2^*(1430)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
ASTON	88B	PL B201 169	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
CARLSMITH	87	PR D36 3502	+Bernstein, Bock, Coupal, Peyaud, Turlay+	(EFI, SACL)
ASTON	84B	NP B247 261	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, CURIN)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, CURIN)
CIHANGIR	82	PL 117B 123	+Berg, Biel, Chandlee+	(FNAL, MINN, ROCH)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
ASTON	81C	PL 106B 235	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
ESTABROOKS	78	NP B133 490	+Carnegie+	(MCGI, CARL, DURH, SLAC)
Also	78B	PR D17 658	Estabrooks, Carnegie+	(MCGI, CARL, DURH+)
JONGEJANS	78	NP B139 383	+Cerrada+	(ZEEM, CERN, NIJM, OXF)
MARTIN	78	NP B134 392	+Shimada, Baldi, Bohringer+	(DURH, GEVA)
BOWLER	77	NP B126 31	+Dainton, Drake, Williams	(OXF)

GOLDBERG 76 LNC 17 253 (HAIF)
HENDRICK 76 NP B112 189 +Vignaud, Burlaud+ (MONS, SACL, PARIS, BELG)
LAUSCHER 75 NP B86 189 +Otter, Wieczorek+ (ABCLV Collab.) JP
MCCUBBIN 75 NP B86 13 +Lyons (OXF)
DEHM 74 NP B75 47 +Goebel, Wittek+ (MPIM, BRUX, MONS, CERN)
LINGLIN 73 NP B55 408 (CERN)
AGUILAR-... 71B PR D4 2583 Aguilar-Benitez, Eisner, Kinson (BNL)
BARNHAM 71C NP B28 171 +Colley, Jobes, Griffiths, Hughes+ (BIRM, GLAS)
CORDS 71 PR D4 1974 +Carmony, Erwin, Meiere+ (PURD, UCD, IUPU)
BASSOMPIE... 69 NP B13 189 Bassompierre+ (CERN, BRUX) JP
BISHOP 69 NP B9 403 +Goshaw, Erwin, Walker (WISC)
CRENNELL 69D PRL 22 487 +Karshon, Lai, O'Neall, Scarr (BNL)
DAVIS 69 PRL 23 1071 +Derenzo, Flatte, Garnjost, Lynch, Solmitz (LRL)
LIND 69 NP B14 1 +Alexander, Firestone, Fu, Goldhaber (LRL) JP
SCHWEING... 68 PR 166 1317 Schweingruber, Derrick, Fields+ (ANL, NWES)
Also 67 Thesis Schweingruber (NWES, NWES)
BASSANO 67 PRL 19 968 +Goldberg, Goz, Barnes, Leitner+ (BNL, SYRA)
FIELD 67 PL 24B 638 +Hendricks, Piccioni, Yager (UCSD)
BADIER 65C PL 19 612 +Demoulin, Goldberg+ (EPOL, SACL, AMST)

OTHER RELATED PAPERS

ATKINSON 86 ZPHY C30 521 + (BONN, CERN, GLAS, LANC, MCHS, CURIN+)
BAUBILLIER 82B NP B202 21 + (BIRM, CERN, GLAS, MSU, CURIN)
CHUNG 65 PRL 15 325 +Dahl, Hardy, Hess, Jacobs, Kirz (LRL)
FOCARDI 65 PL 16 351 +Ranzi, Serra+ (BGNA, SACL)
HAQUE 65 PL 14 338 Hague+
HARDY 65 PRL 14 401 +Chung, Dahl, Hess, Kirz, Miller (LRL)

$K(1460)$

$I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE

Observed in $K\pi\pi$ partial-wave analysis. Not seen by VERGEEST 79. Needs confirmation.

$K(1460)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1460	DAUM	81C	CNTR	$-$	63 $K^- p \to K^- 2\pi p$
~ 1400	[1] BRANDENB...	76B	ASPK	$\pm$	13 $K^\pm p \to K\pi\pi N$

[1] Coupled mainly to $K f_0(1370)$. Decay into $K^*(892)\pi$ seen.

$K(1460)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 260	DAUM	81C	CNTR	$-$	63 $K^- p \to K^- 2\pi p$
~ 250	[2] BRANDENB...	76B	ASPK	$\pm$	13 $K^\pm p \to K\pi\pi N$

[2] Coupled mainly to $K f_0(1370)$. Decay into $K^*(892)\pi$ seen.

$K(1460)$ DECAY MODES

	Mode
Γ_1	$K^*(892)\pi$
Γ_2	$K\rho$
Γ_3	$K_0^*(1430)\pi$

$K(1460)$ PARTIAL WIDTHS

$\Gamma(K^*(892)\pi)$ Γ_1

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 109	DAUM	81C	CNTR	63 $K^- p \to K^- 2\pi p$

$\Gamma(K\rho)$ Γ_2

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 34	DAUM	81C	CNTR	63 $K^- p \to K^- 2\pi p$

$\Gamma(K_0^*(1430)\pi)$ Γ_3

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 117	DAUM	81C	CNTR	63 $K^- p \to K^- 2\pi p$

$K(1460)$ REFERENCES

DAUM 81C NP B187 1 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)
VERGEEST 79 NP B158 265 +Jongejans, Dionisi+ (NIJM, AMST, CERN, OXF)
BRANDENB... 76B PRL 36 1239 Brandenburg, Carnegie, Cashmore+ (SLAC) JP

OTHER RELATED PAPERS

BARNES 82 PL B116 365 +Close (RHEL)
TANIMOTO 82 PL 116B 198 (BIEL)
VERGEEST 79 NP B158 265 +Jongejans, Dionisi+ (NIJM, AMST, CERN, OXF)

$K_2(1580)$

$I(J^P) = \frac{1}{2}(2^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K^-\pi^+\pi^-$ system. Needs confirmation.

$K_2(1580)$ MASS

VALUE (MeV)	DOCUMENT ID		CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1580	OTTER	79	$-$	10,14,16 $K^- p$

$K_2(1580)$ WIDTH

VALUE (MeV)	DOCUMENT ID		CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 110	OTTER	79	$-$	10,14,16 $K^- p$

$K_2(1580)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K^*(892)\pi$	seen
Γ_2	$K_2^*(1430)\pi$	possibly seen

$K_2(1580)$ BRANCHING RATIOS

$\Gamma(K^*(892)\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	OTTER	79	HBC	$-$	10,14,16 $K^- p$

$\Gamma(K_2^*(1430)\pi)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
possibly seen	OTTER	79	HBC	$-$	10,14,16 $K^- p$

$K_2(1580)$ REFERENCES

OTTER 79 NP B147 1 +Rudolph+ (AACH3, BERL, CERN, LOIC, WIEN) JP

$K_1(1650)$

$I(J^P) = \frac{1}{2}(1^+)$

OMITTED FROM SUMMARY TABLE

This entry contains various peaks in strange meson systems ($K^+\phi$, $K\pi\pi$) reported in partial-wave analysis in the 1600–1900 mass region.

$K_1(1650)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1650±50	FRAME	86	OMEG	+	13 $K^+ p \to \phi K^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1840	ARMSTRONG	83	OMEG	$-$	18.5 $K^- p \to 3K p$
~ 1800	DAUM	81C	CNTR	$-$	63 $K^- p \to K^- 2\pi p$

$K_1(1650)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
150±50	FRAME	86	OMEG	+	13 $K^+ p \to \phi K^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250	DAUM	81C	CNTR	$-$	63 $K^- p \to K^- 2\pi p$

$K_1(1650)$ DECAY MODES

	Mode
Γ_1	$K\pi\pi$
Γ_2	$K\phi$

$K_1(1650)$ REFERENCES

FRAME 86 NP B276 667 +Hughes, Lynch, Minto, McFadzean+ (GLAS)
ARMSTRONG 83 NP B221 1 + (BARI, BIRM, CERN, MILA, CURIN+)
DAUM 81C NP B187 1 +Hertzberger+ (AMST, CERN, CRAC, MPIM, OXF+)

$K^*(1680)$

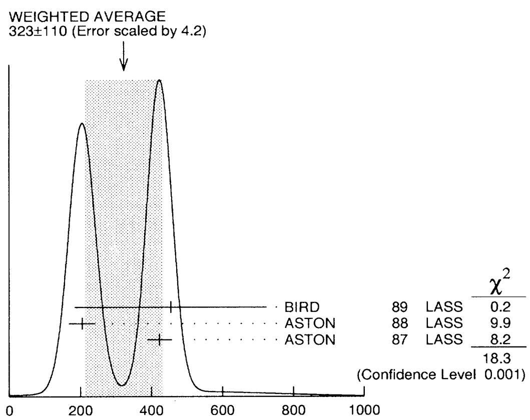
$I(J^P) = \frac{1}{2}(1^-)$

$K^*(1680)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1714±20 OUR AVERAGE Error includes scale factor of 1.1.					
1678±64	BIRD	89	LASS	−	$11\ K^- p \to \overline{K}^0 \pi^- p$
1677±10±32	ASTON	88	LASS	0	$11\ K^- p \to K^- \pi^+ n$
1735±10±20	ASTON	87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1800±70	ETKIN	80	MPS	0	$6\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
~ 1650	ESTABROOKS	78	ASPK	0	$13\ K^\pm p \to K^\pm \pi^\pm n$

$K^*(1680)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
323±110 OUR AVERAGE Error includes scale factor of 4.2. See the ideogram below.					
454±270	BIRD	89	LASS	−	$11\ K^- p \to \overline{K}^0 \pi^- p$
205± 16±34	ASTON	88	LASS	0	$11\ K^- p \to K^- \pi^+ n$
423± 18±30	ASTON	87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
170± 30	ETKIN	80	MPS	0	$6\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$
250 to 300	ESTABROOKS	78	ASPK	0	$13\ K^\pm p \to K^\pm \pi^\pm n$



$K^*(1680)$ width (MeV)

$K^*(1680)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(38.7±2.5) %
Γ_2	$K\rho$	$(31.4^{+4.7}_{-2.1})$ %
Γ_3	$K^*(892)\pi$	$(29.9^{+2.2}_{-4.7})$ %

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 4 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 2.9 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−36	
x_3	−39	−72
	x_1	x_2

$K^*(1680)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.387±0.026 OUR FIT					
0.388±0.014±0.022	ASTON	88	LASS	0	$11\ K^- p \to K^- \pi^+ n$

$\Gamma(K\pi)/\Gamma(K^*(892)\pi)$ — Γ_1/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$1.30^{+0.23}_{-0.14}$ OUR FIT					
2.8 ±1.1	ASTON	84	LASS	0	$11\ K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\rho)/\Gamma(K\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$0.81^{+0.14}_{-0.09}$ OUR FIT					
1.2 ±0.4	ASTON	84	LASS	0	$11\ K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ — Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$1.05^{+0.27}_{-0.11}$ OUR FIT					
$0.97\pm0.09^{+0.30}_{-0.10}$	ASTON	87	LASS	0	$11\ K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K^*(1680)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
ASTON	84	PL 149B 258	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA) JP
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
ESTABROOKS	78	NP B133 490	+Carnegie+	(MCGI, CARL, DURH, SLAC) JP

$K_2(1770)$

$I(J^P) = \frac{1}{2}(2^-)$

THE $K_2(1770)$ AND THE $K_2(1820)$

A partial-wave analysis of the $K^-\omega$ system based on about 100,000 $K^-p \to K^-\omega p$ events (ASTON 93) gives evidence for two $q\bar{q}$ D-wave states near 1.8 GeV. A previous analysis based on about 200,000 diffractively produced $K^-p \to K^-\pi^+\pi^-p$ events (DAUM 81) gave evidence for two $J^P = 2^-$ states in this region, with masses ~ 1780 MeV and ~ 1840 MeV and widths ~ 200 MeV, in good agreement with the results of ASTON 93. In contrast, the masses obtained using a single resonance do not agree well: ASTON 93 obtains 1728 ± 7 MeV, while DAUM 81 estimates ~ 1820 MeV. We conclude that there are indeed two K_2 resonances here.

We list under the $K_2(1770)$ other measurements that do not resolve the two-resonance structure of the enhancement.

$K_2(1770)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1773± 8		[1] ASTON	93	LASS		$11 K^- p \to K^- \omega p$
~ 1780		[2] DAUM	81C	CNTR	−	$63\ K^- p \to K^- 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1810±20		FRAME	86	OMEG	+	$13\ K^+ p \to \phi K^+ p$
~ 1730		ARMSTRONG	83	OMEG	−	$18.5\ K^- p \to 3K p$
1710±15	60	CHUNG	74	HBC	−	$7.3\ K^- p \to K^- \omega p$
1767± 6		BLIEDEN	72	MMS	−	$11–16\ K^- p$
1730±20	306	[3] FIRESTONE	72B	DBC	+	$12\ K^+ d$
1765±40		[4] COLLEY	71	HBC	+	$10\ K^+ p \to K 2\pi N$
1740		DENEGRI	71	DBC	−	$12.6\ K^- d \to \overline{K} 2\pi d$
1745±20		AGUILAR-...	70C	HBC	−	$4.6\ K^- p$
1780±15		BARTSCH	70C	HBC	−	$10.1\ K^- p$
1760±15		LUDLAM	70	HBC	−	$12.6\ K^- p$

[1] From a partial wave analysis of the $K^-\omega$ system.
[2] From a partial wave analysis of the $K^- 2\pi$ system.
[3] Produced in conjunction with excited deuteron.
[4] Systematic errors added correspond to spread of different fits.

$K_2(1770)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
186±14		[5] ASTON	93	LASS		$11 K^- p \to K^- \omega p$
∼ 210		[6] DAUM	81C	CNTR	−	$63 K^- p \to K^- 2\pi p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
140±40		FRAME	86	OMEG	+	$13 K^+ p \to \phi K^+ p$
∼ 220		ARMSTRONG	83	OMEG	−	$18.5 K^- p \to 3K p$
110±50	60	CHUNG	74	HBC	−	$7.3 K^- p \to K^- \omega p$
100±26		BLIEDEN	72	MMS	−	11–16 $K^- p$
210±30	306	[7] FIRESTONE	72B	DBC	+	$12 K^+ d$
90±70		[8] COLLEY	71	HBC	+	$10 K^+ p \to K 2\pi N$
130		DENEGRI	71	DBC	−	$12.6 K^- d \to \overline{K} 2\pi d$
100±50		AGUILAR-...	70C	HBC	−	$4.6 K^- p$
138±40		BARTSCH	70C	HBC	−	$10.1 K^- p$
50^{+40}_{-20}		LUDLAM	70	HBC	−	$12.6 K^- p$

[5] From a partial wave analysis of the $K^- \omega$ system.
[6] From a partial wave analysis of the $K^- 2\pi$ system.
[7] Produced in conjunction with excited deuteron.
[8] Systematic errors added correspond to spread of different fits.

$K_2(1770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi\pi$	
Γ_2	$K_2^*(1430)\pi$	dominant
Γ_3	$K^*(892)\pi$	seen
Γ_4	$K f_2(1270)$	seen
Γ_5	$K\phi$	seen
Γ_6	$K\omega$	seen

$K_2(1770)$ BRANCHING RATIOS

For discussion of the experimental evidence on other decay modes, see HUGHES 71, SLATTERY 71, EISNER 74.

$\Gamma(K_2^*(1430)\pi)/\Gamma(K\pi\pi)$ — Γ_2/Γ_1

$(K_2^*(1430) \to K\pi)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
∼ 0.03	DAUM	81C	CNTR		$63 K^- p \to K^- 2\pi p$
∼ 1.0	[9] FIRESTONE	72B	DBC	+	$12 K^+ d$
<1.0	COLLEY	71	HBC		$10 K^+ p$
0.2 ±0.2	AGUILAR-...	70C	HBC	−	$4.6 K^- p$
<1.0	BARTSCH	70C	HBC	−	$10.1 K^- p$
1.0	BARBARO-...	69	HBC	+	$12.0 K^+ p$

[9] Produced in conjunction with excited deuteron.

$\Gamma(K^*(892)\pi)/\Gamma(K\pi\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
∼ 0.23	DAUM	81C	CNTR	$63 K^- p \to K^- 2\pi p$

$\Gamma(K f_2(1270))/\Gamma(K\pi\pi)$ — Γ_4/Γ_1

$(f_2(1270) \to \pi\pi)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
∼ 0.74	DAUM	81C	CNTR	$63 K^- p \to K^- 2\pi p$

$\Gamma(K\phi)/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	ARMSTRONG	83	OMEG	−	$18.5 K^- p \to K^- \phi N$

$\Gamma(K\omega)/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	OTTER	81	HBC	±	8.25,10,16 $K^\pm p$
seen	CHUNG	74	HBC	−	$7.3 K^- p \to K^- \omega p$

$K_2(1770)$ REFERENCES

ASTON	93	PL B308 186	+Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
FRAME	86	NP B276 667	+Hughes, Lynch, Minto, McFadzean+	(GLAS)
ARMSTRONG	83	NP B221 1	+	(BARI, BIRM, CERN, MILA, CURIN+)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)
OTTER	81	NP B181 1		(AACH3, BERL, LOIC, VIEN, BIRM, BELG, CERN+)
CHUNG	74	PL 51B 413	+Eisner, Protopopescu, Samios, Strand	(BNL)
EISNER	74	Boston Conf. 140		(BNL)
BLIEDEN	72	PL 39B 668	+Finocchiaro, Bowen, Earles+	(STON, NEAS)
FIRESTONE	72B	PR D5 505	+Goldhaber, Lissauer, Trilling	(LBL)
COLLEY	71	NP B26 71	+Jobes, Kenyon, Pathak, Hughes+	(BIRM, GLAS)
DENEGRI	71	NP B28 13	+Antich, Callahan, Carson, Chien, Cox+	(JHU) JP
HUGHES	71	Bologna Conf. 293		(GLAS)
SLATTERY	71	UR-875-332		(ROCH)
AGUILAR-...	70C	PRL 25 54	Aguilar-Benitez, Barnes, Bassano, Chung+	(BNL)
BARTSCH	70C	PL 33B 186	+Deutschmann+	(AACH, BERL, CERN, LOIC, VIEN)
LUDLAM	70	PR D2 1234	+Sandweiss, Slaughter	(YALE)
BARBARO-...	69	PRL 22 1207	Barbaro-Galtieri, Davis, Flatte+	(LRL)

OTHER RELATED PAPERS

BERLINGHIERI	67	PRL 18 1087	+Farber, Ferbel, Forman	(ROCH) I
CARMONY	67	PRL 18 615	+Hendricks, Lander	(UCSD)
JOBES	67	PL 26B 49	+Bassompierre, DeBaere+	(BIRM, CERN, BRUX)
BARTSCH	66	PL 22 357	+Deutschmann+	(AACH, BERL, CERN+)

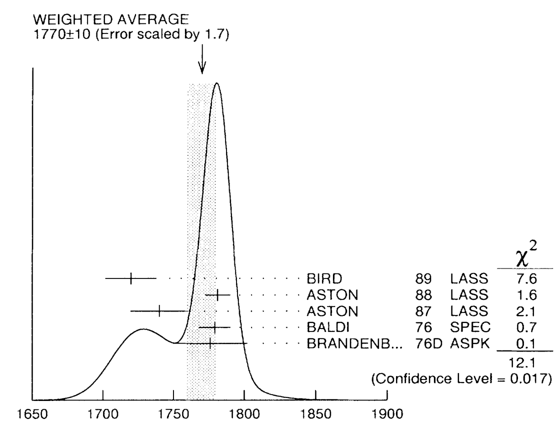
$K_3^*(1780)$

$I(J^P) = \frac{1}{2}(3^-)$

$K_3^*(1780)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1770±10 OUR AVERAGE		Error includes scale factor of 1.7. See the ideogram below.				
1720±10±15	6111	[1] BIRD	89	LASS	−	$11 K^- p \to \overline{K}^0 \pi^- p$
1781± 8± 4		[2] ASTON	88	LASS	0	$11 K^- p \to K^- \pi^+ n$
1740±14±15		[2] ASTON	87	LASS	0	$11 K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1779±11		[3] BALDI	76	SPEC	+	$10 K^+ p \to K^0 \pi^+ p$
1776±26		[4] BRANDENB...	76D	ASPK	0	$13 K^\pm p \to K^\pm \pi^\mp N$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1749±10		ASTON	88B	LASS	−	$11 K^- p \to K^- \eta p$
1780± 9	300	BAUBILLIER	84B	HBC	−	$8.25 K^- p \to \overline{K}^0 \pi^- p$
1790±15		BAUBILLIER	82B	HBC	0	$8.25 K^- p \to K_S^0 2\pi N$
1784± 9	2060	CLELAND	82	SPEC	±	$50 K^+ p \to K_S^0 \pi^\pm p$
1786±15		[5] ASTON	81D	LASS	0	$11 K^- p \to K^- \pi^+ n$
1762± 9	190	TOAFF	81	HBC	−	$6.5 K^- p \to \overline{K}^0 \pi^- p$
1850±50		ETKIN	80	MPS	0	$6 K^- p \to \overline{K}^0 \pi^+ \pi^-$
1812±28		BEUSCH	78	OMEG		$10 K^- p \to \overline{K}^0 \pi^+ \pi^- n$
1786± 8		CHUNG	78	MPS	0	$6 K^- p \to K^- \pi^+ n$

[1] From a partial wave amplitude analysis.
[2] From energy-independent partial-wave analysis.
[3] From a fit to Y_6^2 moment. $J^P = 3^-$ found.
[4] Confirmed by phase shift analysis of ESTABROOKS 78, yields $J^P = 3^-$.
[5] From a fit to the Y_6^0 moment.



$K_3^*(1780)$ mass (MeV)

$K_3^*(1780)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
164±17 OUR AVERAGE		Error includes scale factor of 1.1.				
187±31±20	6111	[6] BIRD	89	LASS	−	$11 K^- p \to \overline{K}^0 \pi^- p$
203±30± 8		[7] ASTON	88	LASS	0	$11 K^- p \to K^- \pi^+ n$
171±42±20		[7] ASTON	87	LASS	0	$11 K^- p \to \overline{K}^0 \pi^+ \pi^- n$
135±22		[8] BALDI	76	SPEC	+	$10 K^+ p \to K^0 \pi^+ p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
193^{+51}_{-37}		ASTON	88B	LASS	−	$11 K^- p \to K^- \eta p$
99±30	300	BAUBILLIER	84B	HBC	−	$8.25 K^- p \to \overline{K}^0 \pi^- p$
∼ 130		BAUBILLIER	82B	HBC	0	$8.25 K^- p \to K_S^0 2\pi N$
191±24	2060	CLELAND	82	SPEC	±	$50 K^+ p \to K_S^0 \pi^\pm p$
225±60		[9] ASTON	81D	LASS	0	$11 K^- p \to K^- \pi^+ n$

~ 80	190	TOAFF	81	HBC	−	6.5 $K^- p \to \overline{K}^0 \pi^- p$
240±50		ETKIN	80	MPS	0	6 $K^- p \to \overline{K}^0 \pi^+ \pi^-$
181±44		[10] BEUSCH	78	OMEG		10 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
96±31		CHUNG	78	MPS	0	6 $K^- p \to K^- \pi^+ n$
270±70		[11] BRANDENB...	76D	ASPK	0	13 $K^\pm p \to K^\pm \pi^\mp N$

[6] From a partial wave amplitude analysis.
[7] From energy-independent partial-wave analysis.
[8] From a fit to Y_6^2 moment. $J^P = 3^-$ found.
[9] From a fit to Y_6^0 moment.
[10] Errors enlarged by us to $4\Gamma/\sqrt{N}$; see the note with the $K^*(892)$ mass.
[11] ESTABROOKS 78 find that BRANDENBURG 76D data are consistent with 175 MeV width. Not averaged.

$K_3^*(1780)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$K\rho$	(45 ±4) %	S=1.4
Γ_2	$K^*(892)\pi$	(27.3±3.2) %	S=1.5
Γ_3	$K\pi$	(19.3±1.0) %	
Γ_4	$K\eta$	(8.0±1.5) %	S=1.4
Γ_5	$K_2^*(1430)\pi$	< 21 %	CL=95%

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 5 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 2.2 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−84		
x_3	−33	−4	
x_4	−35	−14	26
	x_1	x_2	x_3

$K_3^*(1780)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1.66±0.31 OUR FIT	Error includes scale factor of 1.5.				
1.52±0.21±0.10	ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi)$ — Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1.42±0.19 OUR FIT	Error includes scale factor of 1.4.				
1.09±0.26	ASTON	84B	LASS	0	11 $K^- p \to \overline{K}^0 2\pi n$

$\Gamma(K\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.193±0.010 OUR FIT					
0.188±0.010 OUR AVERAGE					
0.187±0.008±0.008	ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$
0.19 ±0.02	ESTABROOKS	78	ASPK	0	13 $K^\pm p \to K\pi N$

$\Gamma(K\eta)/\Gamma(K\pi)$ — Γ_4/Γ_3

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.41±0.07 OUR FIT	Error includes scale factor of 1.5.				
0.41±0.050	[12] BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.50±0.18	ASTON	88B	LASS	−	11 $K^- p \to K^- \eta p$

[12] This result supersedes ASTON 88B.

$\Gamma(K_2^*(1430)\pi)/\Gamma(K^*(892)\pi)$ — Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.78	95	ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K_3^*(1780)$ REFERENCES

BIRD	89	SLAC-332		(SLAC)
ASTON	88	NP B296 493	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
ASTON	88B	PL B201 169	+Awaji, Bienz+	(SLAC, NAGO, CINC, INUS) JP
ASTON	87	NP B292 693	+Awaji, D'Amore+	(SLAC, NAGO, CINC, INUS)
ASTON	84B	NP B247 261	+Carnegie, Dunwoodie+	(SLAC, CARL, OTTA)
BAUBILLIER	84B	ZPHY C26 37	+	(BIRM, CERN, GLAS, MICH, CURIN)
BAUBILLIER	82B	NP B202 21	+	(BIRM, CERN, GLAS, MSU, CURIN)
CLELAND	82	NP B208 189	+Delfosse, Dorsaz, Gloor	(DURH, GEVA, LAUS, PITT)
ASTON	81D	PL 99B 502	+Dunwoodie, Durkin, Fieguth+	(SLAC, CARL, OTTA) JP
TOAFF	81	PR D23 1500	+Musgrave, Ammar, Davis, Ecklund+	(ANL, KANS)
ETKIN	80	PR D22 42	+Foley, Lindenbaum, Kramer+	(BNL, CUNY) JP
BEUSCH	78	PL 74B 282	+Birman, Konigs, Otter+	(CERN, AACH3, ETH) JP
CHUNG	78	PRL 40 355	+Etkin+	(BNL, BRAN, CUNY, MASA, PENN) JP
ESTABROOKS	78	NP B133 490	+Carnegie+	(MCGI, CARL, DURH, SLAC) JP
Also	78B	PR D17 658	Estabrooks, Carnegie+	(MCGI, CARL, DURH+)
BALDI	76	PL 63B 344	+Boehringer, Dorsaz, Hungerbuhler+	(GEVA) JP
BRANDENB...	76D	PL 60B 478	Brandenburg, Carnegie, Cashmore+	(SLAC) JP

OTHER RELATED PAPERS

AGUILAR-...	73	PRL 30 672	Aguilar-Benitez, Chung, Eisner+	(BNL)
WALUCH	73	PR D8 2837	+Flatte, Friedman	(LBL)
CARMONY	71	PRL 27 1160	+Cords, Clopp, Erwin, Meiere+	(PURD, UCD, IUPU)
FIRESTONE	71	PL 36B 513	+Goldhaber, Lissauer, Trilling	(LBL)

$K_2(1820)$

$I(J^P) = \frac{1}{2}(2^-)$

Observed by ASTON 93 from a partial wave analysis of the $K^-\omega$ system. See mini-review under $K_2(1770)$. Needs confirmation.

$K_2(1820)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1816±13	[1] ASTON	93	LASS	11$K^- p \to K^- \omega p$
~ 1840	[2] DAUM	81C	CNTR	63 $K^- p \to K^- 2\pi p$

[1] Fron a partial wave analysis of the $K^-\omega$ system.
[2] From a partial wave analysis of the $K^- 2\pi$ system.

$K_2(1820)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
276±35	[3] ASTON	93	LASS	11$K^- p \to K^- \omega p$
~ 230	[4] DAUM	81C	CNTR	63 $K^- p \to K^- 2\pi p$

[3] Fron a partial wave analysis of the $K^-\omega$ system.
[4] From a partial wave analysis of the $K^- 2\pi$ system.

$K_2(1820)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\phi$	possibly seen
Γ_2	$K\pi\pi$	
Γ_3	$K_2^*(1430)\pi$	seen
Γ_4	$K^*(892)\pi$	seen
Γ_5	$K f_2(1270)$	seen
Γ_6	$K\omega$	seen

$K_2(1820)$ BRANCHING RATIOS

$\Gamma(K_2^*(1430)\pi)/\Gamma(K\pi\pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.77	DAUM	81C	CNTR	63$K^- p \to \overline{K} 2\pi p$

$\Gamma(K^*(892)\pi)/\Gamma(K\pi\pi)$ — Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.05	DAUM	81C	CNTR	63$K^- p \to \overline{K} 2\pi p$

$\Gamma(K f_2(1270))/\Gamma(K\pi\pi)$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 0.18	DAUM	81C	CNTR	63$K^- p \to \overline{K} 2\pi p$

$K_2(1820)$ REFERENCES

ASTON	93	PL B308 186	+Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
DAUM	81C	NP B187 1	+Hertzberger+	(AMST, CERN, CRAC, MPIM, OXF+)

$K(1830)$

$I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of $K^- \phi$ system. Needs confirmation.

$K(1830)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1830	ARMSTRONG	83	OMEG	−	18.5 $K^- p \to 3Kp$

$K(1830)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250	ARMSTRONG	83	OMEG	−	18.5 $K^- p \to 3Kp$

$K(1830)$ DECAY MODES

	Mode
Γ_1	$K\phi$

$K(1830)$ REFERENCES

ARMSTRONG 83 NP B221 1 + (BARI, BIRM, CERN, MILA, CURIN+) JP

$K_0^*(1950)$

$I(J^P) = \frac{1}{2}(0^+)$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K^- \pi^+$ system. Needs confirmation.

$K_0^*(1950)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
1945±10±20	[1] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[1] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
201±34±79	[2] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[2] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(52±14) %

$K_0^*(1950)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.52±0.08±0.12	[3] ASTON	88	LASS	0	11 $K^- p \to K^- \pi^+ n$

[3] We take the central value of the two solutions and the larger error given.

$K_0^*(1950)$ REFERENCES

ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, INUS)

$K_2^*(1980)$

$I(J^P) = \frac{1}{2}(2^+)$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$K_2^*(1980)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1975±22 OUR AVERAGE						
1978±40	241±47	BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$
1973± 8±25		ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K_2^*(1980)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
373±33±60		ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
398±47	241±47	BIRD	89	LASS	−	11 $K^- p \to \overline{K}^0 \pi^- p$

$K_2^*(1980)$ DECAY MODES

	Mode
Γ_1	$K^*(892)\pi$
Γ_2	$K\rho$

$K_2^*(1980)$ BRANCHING RATIOS

$\Gamma(K\rho)/\Gamma(K^*(892)\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
1.49±0.24±0.09	ASTON	87	LASS	0	11 $K^- p \to \overline{K}^0 \pi^+ \pi^- n$

$K_2^*(1980)$ REFERENCES

BIRD 89 SLAC-332 (SLAC)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)

$K_4^*(2045)$

$I(J^P) = \frac{1}{2}(4^+)$

$K_4^*(2045)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2045± 9 OUR AVERAGE Error includes scale factor of 1.1.						
2062± 14±13		[1] ASTON	86	LASS	0	11 $K^- p \to K^- \pi^+ n$
2039± 10	400	[2,3] CLELAND	82	SPEC	±	50 $K^+ p \to K_S^0 \pi^\pm p$
2070^{+100}_{-40}		[4] ASTON	81C	LASS	0	11 $K^- p \to K^- \pi^+ n$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2079± 7	431	TORRES	86	MPSF		400 $pA \to 4KX$
2088± 20	650	BAUBILLIER	82	HBC	−	8.25 $K^- p \to K_S^0 \pi^- p$
2115± 46	488	CARMONY	77	HBC	0	9 $K^+ d \to K^+ \pi$'s X

[1] From a fit to all moments.
[2] From a fit to 8 moments.
[3] Number of events evaluated by us.
[4] From energy-independent partial-wave analysis.

$K_4^*(2045)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
198± 30 OUR AVERAGE						
221± 48±27		[5] ASTON	86	LASS	0	11 $K^- p \to K^- \pi^+ n$
189± 35	400	[6,7] CLELAND	82	SPEC	±	50 $K^+ p \to K_S^0 \pi^\pm p$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
61± 58	431	TORRES	86	MPSF		400 $pA \to 4KX$
170^{+100}_{-50}	650	BAUBILLIER	82	HBC	−	8.25 $K^- p \to K_S^0 \pi^- p$
240^{+500}_{-100}		[8] ASTON	81C	LASS	0	11 $K^- p \to K^- \pi^+ n$
300±200		CARMONY	77	HBC	0	9 $K^+ d \to K^+ \pi$'s X

[5] From a fit to all moments.
[6] From a fit to 8 moments.
[7] Number of events evaluated by us.
[8] From energy-independent partial-wave analysis.

$K_4^*(2045)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(9.9±1.2) %
Γ_2	$K^*(892)\pi\pi$	(9 ±5) %
Γ_3	$K^*(892)\pi\pi\pi$	(7 ±5) %
Γ_4	$\rho K\pi$	(5.7±3.2) %
Γ_5	$\omega K\pi$	(5.0±3.0) %
Γ_6	$\phi K\pi$	(2.8±1.4) %
Γ_7	$\phi K^*(892)$	(1.4±0.7) %

$K_4^*(2045)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.099±0.012	ASTON	88	LASS	0	11 $K^- p \to K^-\pi^+ n$

$\Gamma(K^*(892)\pi\pi)/\Gamma(K\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.89±0.53	BAUBILLIER	82	HBC	−	8.25 $K^- p \to p K^0_S 3\pi$

$\Gamma(K^*(892)\pi\pi\pi)/\Gamma(K\pi)$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.75±0.49	BAUBILLIER	82	HBC	−	8.25 $K^- p \to p K^0_S 3\pi$

$\Gamma(\rho K\pi)/\Gamma(K\pi)$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.58±0.32	BAUBILLIER	82	HBC	−	8.25 $K^- p \to p K^0_S 3\pi$

$\Gamma(\omega K\pi)/\Gamma(K\pi)$ — Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.50±0.30	BAUBILLIER	82	HBC	−	8.25 $K^- p \to p K^0_S 3\pi$

$\Gamma(\phi K\pi)/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.028±0.014	[9] TORRES	86	MPSF	400 $pA \to 4KX$

[9] Error determination is model dependent.

$\Gamma(\phi K^*(892))/\Gamma_{total}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.014±0.007	[10] TORRES	86	MPSF	400 $pA \to 4KX$

[10] Error determination is model dependent.

$K_4^*(2045)$ REFERENCES

ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, INUS)
ASTON 86 PL B180 308 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)
TORRES 86 PR 34 707 +Lai+ (VPI, ARIZ, FNAL, FSU, NDAM, TUFTS+)
BAUBILLIER 82 PL 118B 447 +Burns+ (BIRM, CERN, GLAS, MSU, CURIN)
CLELAND 82 NP B208 189 +Delfosse, Dorsaz, Gloor (DURH, GEVA, LAUS, PITT)
ASTON 81C PL 106B 235 +Carnegie, Dunwoodie+ (SLAC, CARL, OTTA) JP
CARMONY 77 PR D16 1251 +Clopp, Lander, Meiere, Yen+ (PURD, UCD, IUPU)

OTHER RELATED PAPERS

ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)
BROMBERG 80 PR D22 1513 +Haggerty, Abrams, Dzierba (CIT, FNAL, ILLC, IND)
CARMONY 71 PRL 27 1160 +Cords, Clopp, Erwin, Meiere+ (PURD, UCD, IUPU)

$K_2(2250)$

$I(J^P) = \frac{1}{2}(2^-)$

OMITTED FROM SUMMARY TABLE

This entry contains various peaks in strange meson systems reported in the 2150–2260 MeV region, as well as enhancements seen in the antihyperon-nucleon system, either in the mass spectra or in the $J^P = 2^-$ wave.

$K_2(2250)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2247±17 OUR AVERAGE						
2200±40		[1] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda\bar{p}X$
2235±50		[1] BAUBILLIER	81	HBC	−	8 $K^- p \to \Lambda\bar{p}X$
2260±20		[1] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda\bar{p}X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2147± 4	37	CHLIAPNIK...	79	HBC	+	32 $K^+ p \to \bar{\Lambda}pX$
2240±20	20	LISSAUER	70	HBC		9 $K^+ p$

[1] $J^P = 2^-$ from moments analysis.

$K_2(2250)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
180±30 OUR AVERAGE Error includes scale factor of 1.4.						
150±30		[2] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda\bar{p}X$
210±30		[2] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda\bar{p}X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
~ 200		[2] BAUBILLIER	81	HBC	−	8 $K^- p \to \Lambda\bar{p}X$
~ 40	37	CHLIAPNIK...	79	HBC	+	32 $K^+ p \to \bar{\Lambda}pX$
80±20	20	LISSAUER	70	HBC		9 $K^+ p$

[2] $J^P = 2^-$ from moments analysis.

$K_2(2250)$ DECAY MODES

	Mode
Γ_1	$K\pi\pi$
Γ_2	$p\bar{\Lambda}$

$K_2(2250)$ REFERENCES

ARMSTRONG 83C NP B227 365 + (BARI, BIRM, CERN, MILA, CURIN+)
BAUBILLIER 81 NP B183 1 + (BIRM, CERN, GLAS, MSU, CURIN) JP
CLELAND 81 NP B184 1 +Nef, Martin+ (PITT, GEVA, LAUS, DURH) JP
CHLIAPNIK... 79 NP B158 253 Chliapnikov, Gerdyukov+ (CERN, BELG, MONS)
LISSAUER 70 NP B18 491 +Alexander, Firestone, Goldhaber (LBL)

OTHER RELATED PAPERS

ALEXANDER 68B PRL 20 755 +Firestone, Goldhaber, Shen (LRL)

$K_3(2320)$

$I(J^P) = \frac{1}{2}(3^+)$

OMITTED FROM SUMMARY TABLE

Seen in the $J^P = 3^+$ wave of the antihyperon-nucleon system. Needs confirmation.

$K_3(2320)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2324±24 OUR AVERAGE					
2330±40	[1] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda\bar{p}X$
2320±30	[1] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda\bar{p}X$

[1] $J^P = 3^+$ from moments analysis.

$K_3(2320)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
150±30	[2] ARMSTRONG	83C	OMEG	−	18 $K^- p \to \Lambda\bar{p}X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250	[2] CLELAND	81	SPEC	±	50 $K^+ p \to \Lambda\bar{p}X$

[2] $J^P = 3^+$ from moments analysis.

$K_3(2320)$ DECAY MODES

	Mode
Γ_1	$p\bar{\Lambda}$

$K_3(2320)$ REFERENCES

ARMSTRONG 83C NP B227 365 + (BARI, BIRM, CERN, MILA, CURIN+)
CLELAND 81 NP B184 1 +Nef, Martin+ (PITT, GEVA, LAUS, DURH)

$K_5^*(2380)$

$I(J^P) = \frac{1}{2}(5^-)$

OMITTED FROM SUMMARY TABLE

Needs confirmation.

$K_5^*(2380)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2382±14±19	[1] ASTON	86	LASS	0	11 $K^- p \to K^-\pi^+ n$

[1] From a fit to all the moments.

$K_5^*(2380)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
178±37±32	[2] ASTON	86	LASS	0	$11\ K^- p \to K^- \pi^+ n$

[2] From a fit to all the moments.

$K_5^*(2380)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$K\pi$	(6.1±1.2) %

$K_5^*(2380)$ BRANCHING RATIOS

$\Gamma(K\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.061±0.012	ASTON	88	LASS	0	$11\ K^- p \to K^- \pi^+ n$

$K_5^*(2380)$ REFERENCES

ASTON 88 NP B296 493 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, INUS)
ASTON 86 PL B180 308 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)

$K_4(2500)$

$I(J^P) = \frac{1}{2}(4^-)$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$K_4(2500)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
2490±20	[1] CLELAND	81	SPEC	±	$50\ K^+ p \to \Lambda \overline{p}$

[1] $J^P = 4^-$ from moments analysis.

$K_4(2500)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 250	[2] CLELAND	81	SPEC	±	$50\ K^+ p \to \Lambda \overline{p}$

[2] $J^P = 4^-$ from moments analysis.

$K_4(2500)$ DECAY MODES

	Mode
Γ_1	$p\overline{\Lambda}$

$K_4(2500)$ REFERENCES

CLELAND 81 NP B184 1 +Nef, Martin+ (PITT, GEVA, LAUS, DURH)

$K(3100)$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE
Narrow peak observed in several ($\Lambda\overline{p}$ + pions) and ($\overline{\Lambda}p$ + pions) states in Σ^- Be reactions by BOURQUIN 86 and in np and nA reactions by ALEEV 93. Not seen by BOEHNLEIN 91. If due to strong decays, this state has exotic quantum numbers (B=0,Q=+1,S=−1 for $\Lambda\overline{p}\pi^+\pi^+$ and $I \geq 3/2$ for $\Lambda\overline{p}\pi^-$). See also under non-$q\overline{q}$ candidates. Needs confirmation.

$K(3100)$ MASS

VALUE (MeV)	DOCUMENT ID
≈ 3100 OUR ESTIMATE	

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3054±11 OUR AVERAGE				
3060± 7±20	[1] ALEEV	93	BIS2	$K(3100) \to \Lambda\overline{p}\pi^+$
3056± 7±20	[1] ALEEV	93	BIS2	$K(3100) \to \overline{\Lambda}p\pi^-$
3055± 8±20	[1] ALEEV	93	BIS2	$K(3100) \to \Lambda\overline{p}\pi^-$
3045± 8±20	[1] ALEEV	93	BIS2	$K(3100) \to \overline{\Lambda}p\pi^+$

[1] Supersedes ALEEV 90.

4-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3059±11 OUR AVERAGE				
3067± 6±20	[1] ALEEV	93	BIS2	$K(3100) \to \Lambda\overline{p}\pi^+\pi^+$
3060± 8±20	[1] ALEEV	93	BIS2	$K(3100) \to \Lambda\overline{p}\pi^+\pi^-$
3055± 7±20	[1] ALEEV	93	BIS2	$K(3100) \to \overline{\Lambda}p\pi^-\pi^-$
3052± 8±20	[1] ALEEV	93	BIS2	$K(3100) \to \overline{\Lambda}p\pi^-\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3105±30	BOURQUIN	86	SPEC	$K(3100) \to \Lambda\overline{p}\pi^+\pi^+$
3115±30	BOURQUIN	86	SPEC	$K(3100) \to \Lambda\overline{p}\pi^+\pi^-$

5-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3095±30	BOURQUIN	86	SPEC	$K(3100) \to \Lambda\overline{p}\pi^+\pi^+\pi^-$

$K(3100)$ WIDTH

3-BODY DECAYS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
42±16	[2] ALEEV	93	BIS2	$K(3100) \to \Lambda\overline{p}\pi^+$
36±15	[2] ALEEV	93	BIS2	$K(3100) \to \overline{\Lambda}p\pi^-$
50±18	[2] ALEEV	93	BIS2	$K(3100) \to \Lambda\overline{p}\pi^-$
30±15	[2] ALEEV	93	BIS2	$K(3100) \to \overline{\Lambda}p\pi^+$

[2] Supersedes ALEEV 90.

4-BODY DECAYS

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
22± 8		[2] ALEEV	93	BIS2	$K(3100) \to \Lambda\overline{p}\pi^+\pi^+$
28±12		[2] ALEEV	93	BIS2	$K(3100) \to \Lambda\overline{p}\pi^+\pi^-$
32±15		[2] ALEEV	93	BIS2	$K(3100) \to \overline{\Lambda}p\pi^-\pi^-$
30±15		[2] ALEEV	93	BIS2	$K(3100) \to \overline{\Lambda}p\pi^-\pi^+$
<30	90	BOURQUIN	86	SPEC	$K(3100) \to \Lambda\overline{p}\pi^+\pi^+$
<80	90	BOURQUIN	86	SPEC	$K(3100) \to \Lambda\overline{p}\pi^+\pi^-$

5-BODY DECAYS

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<30	90	BOURQUIN	86	SPEC	$K(3100) \to \Lambda\overline{p}\pi^+\pi^+\pi^-$

$K(3100)$ DECAY MODES

	Mode
Γ_1	$K(3100)^0 \to \Lambda\overline{p}\pi^+$
Γ_2	$K(3100)^{--} \to \Lambda\overline{p}\pi^-$
Γ_3	$K(3100)^- \to \Lambda\overline{p}\pi^+\pi^-$
Γ_4	$K(3100)^+ \to \Lambda\overline{p}\pi^+\pi^+$
Γ_5	$K(3100)^0 \to \Lambda\overline{p}\pi^+\pi^+\pi^-$
Γ_6	$K(3100)^0 \to \Sigma(1385)^+\overline{p}$

$\Gamma(\Sigma(1385)^+\overline{p})/\Gamma(\Lambda\overline{p}\pi^+)$ Γ_6/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04	90	ALEEV	93	BIS2	$K(3100)^0 \to \Sigma(1385)^+\overline{p}$

$K(3100)$ REFERENCES

ALEEV 93 PAN 56 1358 +Balandin+ (BIS-2 Collab.)
Translated from YAF 56 100.
BOEHNLEIN 91 NP B21 174 (suppl) +Chung+ (FLOR, BNL, IND, RICE, MASD)
ALEEV 90 ZPHY C47 533 +Arefiev, Balandin+ (BIS-2 Collab.)
BOURQUIN 86 PL B172 113 +Brown+ (GEVA, RAL, HEIDP, LAUS, BRIS, CERN)

CHARMED MESONS
($C = \pm 1$)

$D^+ = c\overline{d}$, $D^0 = c\overline{u}$, $\overline{D}^0 = \overline{c}\,u$, $D^- = \overline{c}\,d$, similarly for D^*'s

NOTE ON D MESONS

(by P.R. Burchat, Stanford University)

The new experimental results on charm meson decays reported in this edition are predominantly from CLEO II at the e^+e^- storage ring CESR and from fixed-target experiments, especially photoproduction experiment E687 at Fermilab. The first results from the BES experiment, operating at an e^+e^- center-of-mass energy of 4.0 GeV, also appear in this edition. BES has measured the branching fractions for the purely leptonic decay $D_s^+ \to \mu^+\nu_\mu$ and for $D_s^+ \to \phi\pi^+$, albeit with large statistical uncertainties.

Semileptonic decays

For a detailed discussion of experimental measurements and theoretical predictions for leptonic and semileptonic decays of both charm and bottom hadrons, see the recent review by J.D. Richman and P.R. Burchat [1]. Also see the "Note on Semileptonic Decays of D and B Mesons, Part I," by R.J. Morrison and J.D. Richman, in our 1994 edition [2].

In this edition, we have added to the Particle Listings the measurements of the form-factor ratios for $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$ and $D_s^+ \to \phi\ell^+\nu_\ell$. The form factors $A_1(q^2)$, $A_2(q^2)$, and $V(q^2)$ are defined in the "Note on Semileptonic Decays of B Mesons" in the B-meson Particle Listings. The ratios $A_2(0)/A_1(0)$ and $V(0)/A_1(0)$ have been measured by Fermilab fixed-target experiments E691, E687, and E653 for the mode $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$, and by E687, E653, and CLEO for the mode $D_s^+ \to \phi\ell^+\nu_\ell$. For each semileptonic mode, the averages of the measured form-factor ratios can be combined with the measured decay rate to extract the values of the form factors themselves [3]. The results are $A_1(0) = 0.55 \pm 0.03$, $A_2(0) = 0.40 \pm 0.08$, and $V(0) = 1.0 \pm 0.2$ for $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$ and $A_1(0) = 0.62 \pm 0.06$, $A_2(0) = 1.0 \pm 0.3$, and $V(0) = 0.9 \pm 0.3$ for $D_s^+ \to \phi\ell^+\nu_\ell$. The measured decay rate for $D \to \overline{K}\ell^+\nu_\ell$ can be used to extract the single vector form factor $f_+(0)$. The result is $f_+(0) = 0.74 \pm 0.03$. Recent quark-model predictions are in good agreement with the D measurements. Lattice gauge calculations are in good agreement with the vector form factors but predict axial form factors that are somewhat higher than the measured values.

Measurements of the ratio $\Gamma(D \to \overline{K}^*\ell^+\nu_\ell)/\Gamma(D \to \overline{K}\ell^+\nu_\ell)$ confirm the initial experimental result that the ratio is only a little over one half, whereas initial theoretical expectations were that it would be about one. By taking into account effects originally ignored, such as relativistic corrections, theorists have managed to accommodate the observed ratio of rates in quark-model calculations. Lattice gauge calculations are also in reasonable agreement with the measured ratio. In contrast to semileptonic B decays, no evidence for higher-mass resonances or nonresonant final states has been observed in semileptonic D decays.

Although the experimental results are statistically limited, the semileptonic decays $D_s^+ \to \phi\ell^+\nu_\ell$ and $D_s^+ \to (\eta \text{ or } \eta')\ell^+\nu_\ell$ appear to follow the pattern of D decays, both in terms of form-factor ratios and of the relative decay rates to vector and pseudoscalar mesons.

Searches for D^0–$\overline{D}^0$ mixing

There have been a number of papers published recently concerning both the sensitivity of $D^0\overline{D}^0$ mixing to new physics and the validity of various assumptions made in existing searches [4]. We have reorganized the mixing limits in the Listings and have added more detailed comments regarding the assumptions made in various searches.

Absolute branching fractions for D_s^+

Two model-independent measurements of the absolute branching fraction for $D_s^+ \to \phi\pi^+$, from BES and CLEO, appear in this edition. All previous measurements depended on theoretical models or on estimates of D_s^+ production cross sections. We no longer use these older results when calculating the average and fit values for $B(D_s^+ \to \phi\pi^+)$. The BES collaboration (BAI 95C) uses $e^+e^- \to D_s^+D_s^-$ events in which one or both of the $D_s^\pm$ decays are reconstructed to obtain a measurement of the $D_s^+ \to \phi\pi^+$ branching fraction without assumptions on the cross section for $D_s^\pm$ production. However, with only two events in which both $D_s^\pm$ decays are reconstructed, the result, $B(D_s^+ \to \phi\pi^+) = (3.9^{+5.1+1.8}_{-1.9-1.1})\%$, has a very large statistical uncertainty. For their new measurement, the CLEO collaboration (ARTUSO 96) measures the branching ratio $B(D_s^+ \to \phi\pi^+)/B(D^0 \to K^-\pi^+) = 0.92 \pm 0.20 \pm 0.11$ by partially reconstructing the decay $\overline{B}^0 \to D^{*+}D_s^{*-}$. They then use their measured value of $B(D^0 \to K^-\pi^+)$ to determine $B(D_s^+ \to \phi\pi^+) = (3.59 \pm 0.77 \pm 0.48)\%$.

In the past, we of necessity relied heavily on estimates of $B(D_s^+ \to \phi\pi^+)$ based on measurements of $\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)/\Gamma(D_s^+ \to \phi\pi^+)$, combined with theoretical predictions for $F = \Gamma(D_s^+ \to \phi\ell^+\nu_\ell)/\Gamma(D^+ \to \overline{K}^{*0}\ell^+\nu_\ell)$ and measurements of $B(D^+ \to \overline{K}^{*0}\ell^+\nu_\ell)$ and the relative D_s^+ and D^+ lifetimes. Although we include the measured values of $\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)/\Gamma(D_s^+ \to \phi\pi^+)$ in the Listings, we no longer use the individual estimates of $B(D_s^+ \to \phi\pi^+)$ since they are each based on different (and sometimes obsolete) estimates of the measured and theoretical correction factors. Here we apply the current best estimates of the correction factors to the current world average, $\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)/\Gamma(D_s^+ \to \phi\pi^+) = 0.54 \pm 0.05$. When we use the world averages $B(D^+ \to \overline{K}^{*0}\ell^+\nu_\ell) = (4.8 \pm 0.4)\%$ and $\tau(D_s^+)/\tau(D^+) = 0.442 \pm 0.017$, we calculate $B(D_s^+ \to \phi\pi^+)$ to be $(3.9 \pm 0.5)\% \cdot F$. Theoretical estimates for F are near 1.0 with a theoretical uncertainty conservatively estimated to be about 25%. Therefore, this estimate for $B(D_s^+ \to \phi\pi^+)$ is in good agreement with the two new model-independent measurements.

D^+ and D_s^+ decay constants

For the leptonic decays $D^+ \to \ell^+\nu_\ell$ and $D_s^+ \to \ell^+\nu_\ell$ only one parameter for each, called the decay constant, is required to describe the nonperturbative physics. (See also the "Note on Pseudoscalar-Meson Decay Constants" in the $\pi^\pm$ Particle Listings.) Decay constants are also used to describe other processes, such as $D^0\overline{D}^0$ and $B^0\overline{B}^0$ mixing, and hence are quite important. Unfortunately, leptonic decays of heavy mesons have small branching fractions and are difficult to reconstruct. However, observations of leptonic D_s^+ decays have now been published by WA75 (AOKI 93), CLEO II (ACOSTA 94), and BES (BAI 95). The systematic and statistical uncertainties on the D_s^+ decay constant are still large. The branching fractions for leptonic B decays are expected to be so small that observation will not be experimentally feasible for some time. Therefore, as the errors on the D_s^+ decay constant decrease with larger data samples, we would benefit from more theoretical work relating the B decay constant to the more easily measured D^+ and D_s^+ decay constants.

References

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$D^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

$D^{\pm}$ MASS

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1869.3± 0.5 OUR FIT	Error includes scale factor of 1.1.				
1869.4± 0.5 OUR AVERAGE					
1870.0± 0.5±1.0	317	BARLAG	90C	ACCM	π^- Cu 230 GeV
1863 ± 4		DERRICK	84	HRS	e^+e^- 29 GeV
1869.4± 0.6		[1] TRILLING	81	RVUE	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1875 ±10	9	ADAMOVICH	87	EMUL	Photoproduction
1860 ±16	6	ADAMOVICH	84	EMUL	Photoproduction
1868.4± 0.5		[1] SCHINDLER	81	MRK2	e^+e^- 3.77 GeV
1874 ± 5		GOLDHABER	77	MRK1	D^0, D^+ recoil spectra
1868.3± 0.9		[1] PERUZZI	77	MRK1	e^+e^- 3.77 GeV
1874 ±11		PICCOLO	77	MRK1	e^+e^- 4.03, 4.41 GeV
1876 ±15	50	PERUZZI	76	MRK1	$K^\mp\pi^\pm\pi^\pm$

[1] PERUZZI 77 and SCHINDLER 81 errors do not include the 0.13% uncertainty in the absolute SPEAR energy calibration. TRILLING 81 uses the high precision $J/\psi(1S)$ and $\psi(2S)$ measurements of ZHOLENTZ 80 to determine this uncertainty and combines the PERUZZI 77 and SCHINDLER 81 results to obtain the value quoted.

$D^{\pm}$ MEAN LIFE

Measurements with an error $> 0.1\times10^{-12}$ s are omitted from the average, and those with an error $> 0.2\times10^{-12}$ s have been omitted from the Listings.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.057±0.015 OUR AVERAGE					
1.048±0.015±0.011	9k	FRABETTI	94D	E687	$D^+ \to K^-\pi^+\pi^+$
1.075±0.040±0.018	2455	FRABETTI	91	E687	γ Be, $D^+ \to K^-\pi^+\pi^+$
1.03 ±0.08 ±0.06	200	ALVAREZ	90	NA14	γ, $D^+ \to K^-\pi^+\pi^+$
$1.05\ ^{+0.077}_{-0.072}$	317	[2] BARLAG	90C	ACCM	π^- Cu 230 GeV
1.05 ±0.08 ±0.07	363	ALBRECHT	88I	ARG	e^+e^- 10 GeV
1.090±0.030±0.025	2992	RAAB	88	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.12\ ^{+0.14}_{-0.11}$	149	AGUILAR-...	87D	HYBR	$\pi^- p$ and pp
$1.09\ ^{+0.19}_{-0.15}$	59	BARLAG	87B	ACCM	K^- and π^- 200 GeV
1.14 ±0.16 ±0.07	247	CSORNA	87	CLEO	e^+e^- 10 GeV
1.09 ±0.14	74	[3] PALKA	87B	SILI	π Be 200 GeV
$0.86 \pm 0.13\ ^{+0.07}_{-0.03}$	48	ABE	86	HYBR	γp 20 GeV

[2] BARLAG 90C estimates the systematic error to be negligible.
[3] PALKA 87B observes this in $D^+ \to \overline{K}^*(892) e\nu$.

D^+ DECAY MODES

D^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes		
Γ_1	e^+ anything	(17.2 ±1.9) %	
Γ_2	K^- anything	(24.2 ±2.8) %	S=1.4
Γ_3	$\overline{K}^0$ anything + K^0 anything	(59 ±7) %	
Γ_4	K^+ anything	(5.8 ±1.4) %	
Γ_5	η anything	[a] < 13 %	CL=90%
Γ_6	μ^+ anything		
Γ_7	$\mu^+\mu^-$ anything		
	Leptonic and semileptonic modes		
Γ_8	$\mu^+\nu_\mu$	< 7.2 $\times 10^{-4}$	CL=90%
Γ_9	$\overline{K}^0\ell^+\nu_\ell$	[b] (6.7 ±0.8) %	
Γ_{10}	$\overline{K}^0 e^+\nu_e$	(6.6 ±0.9) %	
Γ_{11}	$\overline{K}^0\mu^+\nu_\mu$	($7.0\ ^{+3.0}_{-2.0}$) %	
Γ_{12}	$K^-\pi^+e^+\nu_e$	($4.2\ ^{+0.9}_{-0.7}$) %	
Γ_{13}	$\overline{K}^*(892)^0 e^+\nu_e$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(3.2 ±0.33) %	
Γ_{14}	$K^-\pi^+e^+\nu_e$ nonresonant	< 7 $\times 10^{-3}$	CL=90%
Γ_{15}	$K^-\pi^+\mu^+\nu_\mu$	(3.2 ±0.4) %	S=1.1
	In the fit as $\frac{2}{3}\Gamma_{27} + \Gamma_{17}$, where $\frac{2}{3}\Gamma_{27} = \Gamma_{16}$.		
Γ_{16}	$\overline{K}^*(892)^0\mu^+\nu_\mu$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)	(3.0 ±0.4) %	
Γ_{17}	$K^-\pi^+\mu^+\nu_\mu$ nonresonant	(2.7 ±1.1) $\times 10^{-3}$	
Γ_{18}	$\overline{K}^0\pi^+\pi^-e^+\nu_e$		
Γ_{19}	$K^-\pi^+\pi^0e^+\nu_e$		
Γ_{20}	$(\overline{K}^*(892)\pi)^0 e^+\nu_e$	< 1.2 %	CL=90%
Γ_{21}	$(\overline{K}\pi\pi)^0 e^+\nu_e$ non-$\overline{K}^*(892)$	< 9 $\times 10^{-3}$	CL=90%
Γ_{22}	$K^-\pi^+\pi^0\mu^+\nu_\mu$	< 1.4 $\times 10^{-3}$	CL=90%
Γ_{23}	$\pi^0\ell^+\nu_\ell$	[c] (5.7 ±2.2) $\times 10^{-3}$	
Γ_{24}	$\pi^+\pi^-e^+\nu_e$		
	Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.		
Γ_{25}	$\overline{K}^*(892)^0\ell^+\nu_\ell$	[b] (4.8 ±0.4) %	
Γ_{26}	$\overline{K}^*(892)^0 e^+\nu_e$	(4.8 ±0.5) %	
Γ_{27}	$\overline{K}^*(892)^0\mu^+\nu_\mu$	(4.5 ±0.6) %	S=1.1
Γ_{28}	$\rho^0 e^+\nu_e$	< 3.7 $\times 10^{-3}$	CL=90%
Γ_{29}	$\rho^0\mu^+\nu_\mu$	($2.0\ ^{+1.5}_{-1.3}$) $\times 10^{-3}$	
Γ_{30}	$\phi e^+\nu_e$	< 2.09 %	CL=90%
Γ_{31}	$\phi\mu^+\nu_\mu$	< 3.72 %	CL=90%
Γ_{32}	$\eta'(958)\mu^+\nu_\mu$	< 9 $\times 10^{-3}$	CL=90%

Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{33}	$\overline{K}^0\pi^+$		(2.74±0.29) %	
Γ_{34}	$K^-\pi^+\pi^+$	[d]	(9.1 ±0.6) %	
Γ_{35}	$\overline{K}^*(892)^0\pi^+$ $\times$ B$(\overline{K}^{*0}\to K^-\pi^+)$		(1.28±0.13) %	
Γ_{36}	$\overline{K}_0^*(1430)^0\pi^+$ $\times$ B$(\overline{K}_0^*(1430)^0\to K^-\pi^+)$		(2.3 ±0.3) %	
Γ_{37}	$\overline{K}^*(1680)^0\pi^+$ $\times$ B$(\overline{K}^*(1680)^0\to K^-\pi^+)$		(3.7 ±0.8) $\times 10^{-3}$	
Γ_{38}	$K^-\pi^+\pi^+$ nonresonant		(8.6 ±0.9) %	
Γ_{39}	$\overline{K}^0\pi^+\pi^0$	[d]	(9.7 ±3.0) %	S=1.1
Γ_{40}	$\overline{K}^0\rho^+$		(6.6 ±2.5) %	
Γ_{41}	$\overline{K}^*(892)^0\pi^+$ $\times$ B$(\overline{K}^{*0}\to\overline{K}^0\pi^0)$		(6.4 ±0.6) $\times 10^{-3}$	
Γ_{42}	$\overline{K}^0\pi^+\pi^0$ nonresonant		(1.3 ±1.1) %	
Γ_{43}	$K^-\pi^+\pi^+\pi^0$	[d]	(6.4 ±1.1) %	
Γ_{44}	$\overline{K}^*(892)^0\rho^+$ total $\times$ B$(\overline{K}^{*0}\to K^-\pi^+)$		(1.4 ±0.9) %	
Γ_{45}	$\overline{K}_1(1400)^0\pi^+$ $\times$ B$(\overline{K}_1(1400)^0\to K^-\pi^+\pi^0)$		(2.2 ±0.6) %	
Γ_{46}	$K^-\rho^+\pi^+$ total		(3.1 ±1.1) %	
Γ_{47}	$K^-\rho^+\pi^+$ 3-body		(1.1 ±0.4) %	
Γ_{48}	$\overline{K}^*(892)^0\pi^+\pi^0$ total $\times$ B$(\overline{K}^{*0}\to K^-\pi^+)$		(4.5 ±0.9) %	
Γ_{49}	$\overline{K}^*(892)^0\pi^+\pi^0$ 3-body $\times$ B$(\overline{K}^{*0}\to K^-\pi^+)$		(2.8 ±0.9) %	
Γ_{50}	$K^*(892)^-\pi^+\pi^+$ 3-body $\times$ B$(K^{*-}\to K^-\pi^0)$		(7 ±3) $\times 10^{-3}$	
Γ_{51}	$K^-\pi^+\pi^+\pi^0$ nonresonant	[e]	(1.2 ±0.6) %	
Γ_{52}	$\overline{K}^0\pi^+\pi^+\pi^-$	[d]	(7.0 ±1.0) %	
Γ_{53}	$\overline{K}^0 a_1(1260)^+$ $\times$ B$(a_1(1260)^+\to\pi^+\pi^+\pi^-)$		(4.0 ±0.9) %	
Γ_{54}	$\overline{K}_1(1400)^0\pi^+$ $\times$ B$(\overline{K}_1(1400)^0\to\overline{K}^0\pi^+\pi^-)$		(2.2 ±0.6) %	
Γ_{55}	$K^*(892)^-\pi^+\pi^+$ 3-body $\times$ B$(K^{*-}\to\overline{K}^0\pi^-)$		(1.4 ±0.6) %	
Γ_{56}	$\overline{K}^0\rho^0\pi^+$ total		(4.2 ±0.9) %	
Γ_{57}	$\overline{K}^0\rho^0\pi^+$ 3-body		(5 ±5) $\times 10^{-3}$	
Γ_{58}	$\overline{K}^0\pi^+\pi^+\pi^-$ nonresonant		(8 ±4) $\times 10^{-3}$	
Γ_{59}	$K^-\pi^+\pi^+\pi^+\pi^-$		(8.2 ±1.4) $\times 10^{-3}$	
Γ_{60}	$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$ $\times$ B$(\overline{K}^{*0}\to K^-\pi^+)$		(6.8 ±1.8) $\times 10^{-3}$	
Γ_{61}	$\overline{K}^*(892)^0\rho^0\pi^+$ $\times$ B$(\overline{K}^{*0}\to K^-\pi^+)$		(5.1 ±2.2) $\times 10^{-3}$	
Γ_{62}	$K^-\pi^+\pi^+\pi^0\pi^0$		(2.2 $^{+5.0}_{-0.9}$) %	
Γ_{63}	$\overline{K}^0\pi^+\pi^+\pi^-\pi^0$		(5.4 $^{+3.0}_{-1.4}$) %	
Γ_{64}	$\overline{K}^0\pi^+\pi^+\pi^+\pi^-\pi^-$		(8 ±7) $\times 10^{-4}$	
Γ_{65}	$K^-\pi^+\pi^+\pi^+\pi^-\pi^0$		(2.0 ±1.8) $\times 10^{-3}$	
Γ_{66}	$\overline{K}^0\overline{K}^0K^+$		(1.8 ±0.8) %	

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_{67}	$\overline{K}^0\rho^+$		(6.6 ±2.5) %	
Γ_{68}	$\overline{K}^0 a_1(1260)^+$		(8.1 ±1.7) %	
Γ_{69}	$\overline{K}^0 a_2(1320)^+$		< 3 $\times 10^{-3}$	CL=90%
Γ_{70}	$\overline{K}^*(892)^0\pi^+$		(1.92±0.19) %	
Γ_{71}	$\overline{K}^*(892)^0\rho^+$ total		(2.1 ±1.4) %	
Γ_{72}	$\overline{K}^*(892)^0\rho^+$ S-wave	[e]	(1.7 ±1.6) %	
Γ_{73}	$\overline{K}^*(892)^0\rho^+$ P-wave		< 1 $\times 10^{-3}$	CL=90%
Γ_{74}	$\overline{K}^*(892)^0\rho^+$ D-wave		(10 ±7) $\times 10^{-3}$	
Γ_{75}	$\overline{K}^*(892)^0\rho^+$ D-wave longitudinal		< 7 $\times 10^{-3}$	CL=90%
Γ_{76}	$\overline{K}_1(1270)^0\pi^+$		< 7 $\times 10^{-3}$	CL=90%
Γ_{77}	$\overline{K}_1(1400)^0\pi^+$		(5.0 ±1.3) %	
Γ_{78}	$\overline{K}^*(1410)^0\pi^+$		< 7 $\times 10^{-3}$	CL=90%
Γ_{79}	$\overline{K}_0^*(1430)^0\pi^+$		(3.7 ±0.4) %	
Γ_{80}	$\overline{K}^*(1680)^0\pi^+$		(1.45±0.31) %	
Γ_{81}	$\overline{K}^*(892)^0\pi^+\pi^0$ total		(6.7 ±1.4) %	
Γ_{82}	$\overline{K}^*(892)^0\pi^+\pi^0$ 3-body		(4.2 ±1.4) %	
Γ_{83}	$K^*(892)^-\pi^+\pi^+$ total			
Γ_{84}	$K^*(892)^-\pi^+\pi^+$ 3-body		(2.1 ±0.9) %	
Γ_{85}	$K^-\rho^+\pi^+$ total		(3.1 ±1.1) %	
Γ_{86}	$K^-\rho^+\pi^+$ 3-body		(1.1 ±0.4) %	
Γ_{87}	$\overline{K}^0\rho^0\pi^+$ total		(4.2 ±0.9) %	CL=90%
Γ_{88}	$\overline{K}^0\rho^0\pi^+$ 3-body		(5 ±5) $\times 10^{-3}$	
Γ_{89}	$\overline{K}^0 f_0(980)\pi^+$		< 5 $\times 10^{-3}$	CL=90%
Γ_{90}	$\overline{K}^*(892)^0\pi^+\pi^+\pi^-$		(1.02±0.27) %	
Γ_{91}	$\overline{K}^*(892)^0\rho^0\pi^+$		(7.7 ±3.3) $\times 10^{-3}$	

Pionic modes

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_{92}	$\pi^+\pi^0$	(2.5 ±0.7) $\times 10^{-3}$	
Γ_{93}	$\pi^+\pi^+\pi^-$	(3.2 ±0.6) $\times 10^{-3}$	
Γ_{94}	$\rho^0\pi^+$	< 1.4 $\times 10^{-3}$	CL=90%
Γ_{95}	$\pi^+\pi^+\pi^-$ nonresonant	(2.5 ±0.7) $\times 10^{-3}$	
Γ_{96}	$\pi^+\pi^+\pi^-\pi^0$	(1.9 $^{+1.5}_{-1.2}$) %	
Γ_{97}	$\eta\pi^+$ $\times$ B$(\eta\to\pi^+\pi^-\pi^0)$	(1.8 ±0.6) $\times 10^{-3}$	
Γ_{98}	$\omega\pi^+$ $\times$ B$(\omega\to\pi^+\pi^-\pi^0)$	< 6 $\times 10^{-3}$	CL=90%
Γ_{99}	$\pi^+\pi^+\pi^+\pi^-\pi^-$	(1.0 $^{+0.8}_{-0.7}$) $\times 10^{-3}$	
Γ_{100}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$	(2.9 $^{+2.9}_{-2.0}$) $\times 10^{-3}$	

Fractions of some of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_{101}	$\eta\pi^+$	(7.5 ±2.5) $\times 10^{-3}$	
Γ_{102}	$\rho^0\pi^+$	< 1.4 $\times 10^{-3}$	CL=90%
Γ_{103}	$\omega\pi^+$	< 7 $\times 10^{-3}$	CL=90%
Γ_{104}	$\eta\rho^+$	< 1.2 %	CL=90%
Γ_{105}	$\eta'(958)\pi^+$	< 9 $\times 10^{-3}$	CL=90%
Γ_{106}	$\eta'(958)\rho^+$	< 1.5 %	CL=90%

Hadronic modes with a $K\overline{K}$ pair

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_{107}	$K^+\overline{K}^0$		(7.2 ±1.2) $\times 10^{-3}$	
Γ_{108}	$K^+K^-\pi^+$	[d]	(8.9 ±0.8) $\times 10^{-3}$	
Γ_{109}	$\phi\pi^+$ $\times$ B$(\phi\to K^+K^-)$		(3.0 ±0.3) $\times 10^{-3}$	
Γ_{110}	$K^+\overline{K}^*(892)^0$ $\times$ B$(\overline{K}^{*0}\to K^-\pi^+)$		(2.8 ±0.4) $\times 10^{-3}$	
Γ_{111}	$K^+K^-\pi^+$ nonresonant		(4.6 ±0.9) $\times 10^{-3}$	
Γ_{112}	$K^0\overline{K}^0\pi^+$			
Γ_{113}	$K^*(892)^+\overline{K}^0$ $\times$ B$(K^{*+}\to K^0\pi^+)$		(2.0 ±0.9) %	
Γ_{114}	$K^+K^-\pi^+\pi^0$			
Γ_{115}	$\phi\pi^+\pi^0$ $\times$ B$(\phi\to K^+K^-)$		(1.1 ±0.5) %	
Γ_{116}	$\phi\rho^+$ $\times$ B$(\phi\to K^+K^-)$		< 7 $\times 10^{-3}$	CL=90%
Γ_{117}	$K^+K^-\pi^+\pi^0$ non-ϕ		(1.5 $^{+0.7}_{-0.6}$) %	
Γ_{118}	$K^+\overline{K}^0\pi^+\pi^-$		< 2 %	CL=90%
Γ_{119}	$K^0K^-\pi^+\pi^+$		(1.0 ±0.6) %	
Γ_{120}	$K^*(892)^+\overline{K}^*(892)^0$ $\times$ B$^2(K^*\to K\pi^+)$		(1.2 ±0.5) %	
Γ_{121}	$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$		< 7.9 $\times 10^{-3}$	CL=90%
Γ_{122}	$K^+K^-\pi^+\pi^+\pi^-$			
Γ_{123}	$\phi\pi^+\pi^+\pi^-$ $\times$ B$(\phi\to K^+K^-)$		< 1 $\times 10^{-3}$	CL=90%
Γ_{124}	$K^+K^-\pi^+\pi^+\pi^-$ nonresonant		< 3 %	CL=90%

Fractions of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_{125}	$\phi\pi^+$	(6.1 ±0.6) $\times 10^{-3}$	
Γ_{126}	$\phi\pi^+\pi^0$	(2.3 ±1.0) %	
Γ_{127}	$\phi\rho^+$	< 1.5 %	CL=90%
Γ_{128}	$\phi\pi^+\pi^+\pi^-$	< 2 $\times 10^{-3}$	CL=90%
Γ_{129}	$K^+\overline{K}^*(892)^0$	(4.2 ±0.5) $\times 10^{-3}$	
Γ_{130}	$K^*(892)^+\overline{K}^0$	(3.0 ±1.4) %	
Γ_{131}	$K^*(892)^+\overline{K}^*(892)^0$	(2.6 ±1.1) %	

Doubly Cabibbo suppressed (DC) modes, $\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton Family number (LF) or Lepton number (L) violating modes

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_{132}	$K^+\pi^+\pi^-$	DC	(6.5 ±2.6) $\times 10^{-4}$	
Γ_{133}	$K^+\rho^0$	DC	< 6 $\times 10^{-4}$	CL=90%
Γ_{134}	$K^*(892)^0\pi^+$	DC	< 1.9 $\times 10^{-4}$	CL=90%
Γ_{135}	$K^+K^+K^-$	DC	< 1.5 $\times 10^{-4}$	CL=90%

Γ_{136}	ϕK^+	DC	< 1.3	$\times 10^{-4}$	CL=90%
Γ_{137}	$\pi^+ e^+ e^-$	C1	< 6.6	$\times 10^{-5}$	CL=90%
Γ_{138}	$\pi^+ \mu^+ \mu^-$	C1	< 1.8	$\times 10^{-5}$	CL=90%
Γ_{139}	$\rho^+ \mu^+ \mu^-$	C1	< 5.6	$\times 10^{-4}$	CL=90%
Γ_{140}	$K^+ e^+ e^-$		[f] < 4.8	$\times 10^{-3}$	CL=90%
Γ_{141}	$K^+ \mu^+ \mu^-$		[f] < 3.2	$\times 10^{-4}$	CL=90%
Γ_{142}	$\pi^+ e^{\pm} \mu^{\mp}$	LF	[g] < 3.8	$\times 10^{-3}$	CL=90%
Γ_{143}	$\pi^+ e^+ \mu^-$	LF	< 3.3	$\times 10^{-3}$	CL=90%
Γ_{144}	$\pi^+ e^- \mu^+$	LF	< 3.3	$\times 10^{-3}$	CL=90%
Γ_{145}	$K^+ e^+ \mu^-$	LF	< 3.4	$\times 10^{-3}$	CL=90%
Γ_{146}	$K^+ e^- \mu^+$	LF	< 3.4	$\times 10^{-3}$	CL=90%
Γ_{147}	$\pi^- e^+ e^+$	L	< 4.8	$\times 10^{-3}$	CL=90%
Γ_{148}	$\pi^- \mu^+ \mu^+$	L	< 2.2	$\times 10^{-4}$	CL=90%
Γ_{149}	$\pi^- e^+ \mu^+$	L	< 3.7	$\times 10^{-3}$	CL=90%
Γ_{150}	$\rho^- \mu^+ \mu^+$	L	< 5.6	$\times 10^{-4}$	CL=90%
Γ_{151}	$K^- e^+ e^+$	L	< 9.1	$\times 10^{-3}$	CL=90%
Γ_{152}	$K^- \mu^+ \mu^+$	L	< 3.2	$\times 10^{-4}$	CL=90%
Γ_{153}	$K^- e^+ \mu^+$	L	< 4.0	$\times 10^{-3}$	CL=90%
Γ_{154}	$K^*(892)^- \mu^+ \mu^+$	L	< 8.5	$\times 10^{-4}$	CL=90%

Γ_{155} A dummy mode used by the fit. (36 ± 5) %

[a] This is a weighted average of $D^{\pm}$ (44%) and D^0 (56%) branching fractions. See "D^+ and $D^0 \rightarrow$ (ηanything) / (total D^+ and D^0)" under "D^+ Branching Ratios" in these Particle Listings.

[b] This value averages the e^+ and μ^+ branching fractions, after making a small phase-space adjustment to the μ^+ fraction to be able to use it as an e^+ fraction; hence our ℓ^+ is really an e^+.

[c] ℓ indicates e or μ mode, not sum over modes.

[d] The branching fractions for this mode may differ from the sum of the submodes that contribute to it, due to interference effects. See the relevant papers.

[e] The two experiments determining this ratio are in serious disagreement. See the Particle Listings.

[f] This mode is not a useful test for a $\Delta C=1$ weak neutral current because both quarks must change flavor in this decay.

[g] The value is for the sum of the charge states of particle/antiparticle states indicated.

CONSTRAINED FIT INFORMATION

An overall fit to 23 branching ratios uses 37 measurements and one constraint to determine 14 parameters. The overall fit has a $\chi^2 = 13.8$ for 24 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_{10}	x_{12}	x_{17}	x_{26}	x_{27}	x_{33}	x_{34}	x_{39}	x_{43}	x_{52}
x_{12}	4									
x_{17}	4	2								
x_{26}	15	29	8							
x_{27}	12	7	31	26						
x_{33}	41	6	5	20	16					
x_{34}	27	17	14	57	45	35				
x_{39}	0	0	0	0	0	0	0			
x_{43}	6	4	3	13	10	8	23	0		
x_{52}	8	5	4	17	14	10	30	0	18	
x_{70}	18	11	9	37	30	23	65	0	15	20
x_{77}	4	3	2	9	7	5	15	0	31	37
x_{84}	2	1	1	5	4	3	9	0	29	13
x_{155}	−33	−27	−12	−40	−33	−29	−52	−60	−46	−45

	x_{70}	x_{77}	x_{84}
x_{77}	10		
x_{84}	6	12	
x_{155}	−36	−47	−33

D^+ BRANCHING RATIOS

See the "Note on D Mesons" above. Some now-obsolete measurements have been omitted from these Listings.

Inclusive modes

$\Gamma(e^+\text{anything})/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.172±0.019 OUR AVERAGE				
$0.20\ ^{+0.09}_{-0.07}$		AGUILAR-... 87E	HYBR	πp, pp 360, 400 GeV
0.170±0.019±0.007	158	BALTRUSAIT...85B	MRK3	e^+e^- 3.77 GeV
0.168±0.064	23	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.220\ ^{+0.044}_{-0.022}$		BACINO 80	DLCO	e^+e^- 3.77 GeV

D^+ and $D^0 \rightarrow$ (e^+anything) / (total D^+ and D^0)

If measured at the $\psi(3770)$, this quantity is a weighted average of D^+ (44%) and D^0 (56%) branching fractions. Only experiments at E_{cm} = 3.77 GeV are included in the average here.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.110±0.011 OUR AVERAGE	Error includes scale factor of 1.1.			
0.117±0.011	295	BALTRUSAIT...85B	MRK3	e^+e^- 3.77 GeV
0.10 ±0.032		[4] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.072±0.028		FELLER 78	MRK1	e^+e^- 3.772 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.134±0.015±0.010		[5] ABE 93E	VNS	e^+e^- 58 GeV
$0.098\pm0.009\ ^{+0.006}_{-0.005}$	240	[6] ALBRECHT 92F	ARG	$e^+e^- \approx$ 10 GeV
0.096±0.007±0.015		[7] ONG 88	MRK2	e^+e^- 29 GeV
$0.116\ ^{+0.011}_{-0.009}$		[7] PAL 86	DLCO	e^+e^- 29 GeV
0.091±0.009±0.013		[7] AIHARA 85	TPC	e^+e^- 29 GeV
0.092±0.022±0.040		[7] ALTHOFF 84J	TASS	e^+e^- 34.6 GeV
0.091±0.013		[7] KOOP 84	DLCO	See PAL 86
0.08 ±0.015		[8] BACINO 79	DLCO	e^+e^- 3.772 GeV

[4] Isolates D^+ and $D^0 \rightarrow e^+ X$ and weights for relative production (44%–56%).

[5] ABE 93E also measures forward-backward asymmetries and fragmentation functions for c and b quarks.

[6] ALBRECHT 92F uses the excess of right-sign over wrong-sign leptons in a sample of events tagged by fully reconstructed $D^*(2010)^+ \rightarrow D^0\pi^+$ decays.

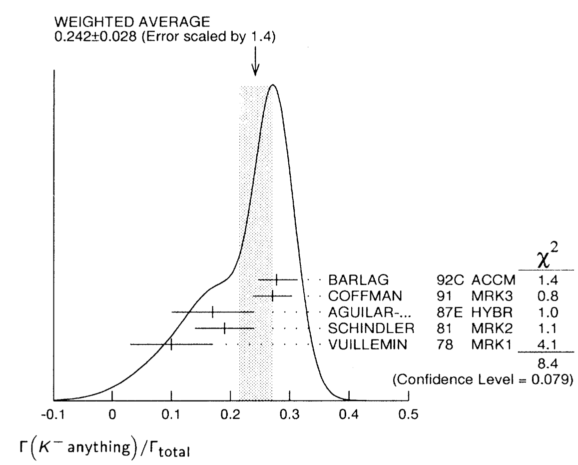
[7] Average BR for charm $\rightarrow e^+ X$. Unlike at E_{cm} = 3.77 GeV, the admixture of charmed mesons is unknown.

[8] Not independent of BACINO 80 measurements of $\Gamma(e^+\text{anything})/\Gamma_{total}$ for the D^+ and D^0 separately.

$\Gamma(K^-\text{anything})/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.242±0.028 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.			
$0.278\ ^{+0.036}_{-0.031}$		[9] BARLAG 92C	ACCM	π^- Cu 230 GeV
0.271±0.023±0.024		COFFMAN 91	MRK3	e^+e^- 3.77 GeV
0.17 ±0.07		AGUILAR-... 87E	HYBR	πp, pp 360, 400 GeV
0.19 ±0.05	26	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.10 ±0.07	3	VUILLEMIN 78	MRK1	e^+e^- 3.772 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.16\ ^{+0.08}_{-0.07}$		AGUILAR-... 86B	HYBR	See AGUILAR-BENITEZ 87E

[9] BARLAG 92C computes the branching fraction using topological normalization.



$[\Gamma(\overline{K}^0 \text{anything}) + \Gamma(K^0 \text{anything})]/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.59 ±0.07 OUR AVERAGE					
0.612±0.065±0.043		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
0.52 ±0.18	15	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.39 ±0.29	3	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

$\Gamma(K^+ \text{anything})/\Gamma_{total}$ — Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.058±0.014 OUR AVERAGE					
0.055±0.013±0.009		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
$0.08\ ^{+0.06}_{-0.05}$		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.06 ±0.04	12	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.06 ±0.06	2	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

D^+ and $D^0 \rightarrow$ (η anything) / (total D^+ and D^0)

If measured at the $\psi(3770)$, this quantity is a weighted average of D^+ (44%) and D^0 (56%) branching fractions. Only the experiment at E_{cm} = 3.77 GeV is used.

VALUE	DOCUMENT ID		TECN	COMMENT
<0.13	PARTRIDGE	81	CBAL	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.02	[10] BRANDELIK	79	DASP	e^+e^- 4.03 GeV

[10] The BRANDELIK 79 result is based on the absence of an η signal at E_{cm} = 4.03 GeV. PARTRIDGE 81 observes a substantially higher η cross section at 4.03 GeV.

$\Gamma(c/\overline{c} \rightarrow \mu^+ \text{anything})/\Gamma(c/\overline{c} \rightarrow \text{anything})$

This is the average branching ratio for charm $\rightarrow$ μ^+X. The mixture of charmed particles is unknown and may actually contain states other than D mesons.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.081^{+0.010}_{-0.009}$ OUR AVERAGE					
$0.086\pm0.017^{+0.008}_{-0.007}$	69	[11] ALBRECHT	92F	ARG	$e^+e^- \approx$ 10 GeV
0.078±0.009±0.012		ONG	88	MRK2	e^+e^- 29 GeV
0.078±0.015±0.02		BARTEL	87	JADE	e^+e^- 34.6 GeV
$0.082\pm0.012^{+0.02}_{-0.01}$		ALTHOFF	84G	TASS	e^+e^- 34.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.089±0.018±0.025		BARTEL	85J	JADE	See BARTEL 87

[11] ALBRECHT 92F uses the excess of right-sign over wrong-sign leptons in a sample of events tagged by fully reconstructed $D^*(2010)^+ \rightarrow D^0\pi^+$ decays.

$\Gamma(c/\overline{c} \rightarrow e^+e^- \text{anything})/\Gamma(c/\overline{c} \rightarrow \text{anything})$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<2.2\times10^{-3}$	90	0.1	[12] HAAS	88	CLEO	e^+e^- 10 GeV

[12] The normalization uses a continuum charm production estimate.

$\Gamma(c/\overline{c} \rightarrow e^+\mu^- \text{anything})/\Gamma(c/\overline{c} \rightarrow \text{anything})$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<3.7\times10^{-3}$	90	0.2	[13] HAAS	88	CLEO	e^+e^- 10 GeV

[13] The normalization uses a continuum charm production estimate.

$\Gamma(c/\overline{c} \rightarrow \mu^+\mu^- \text{anything})/\Gamma(c/\overline{c} \rightarrow \text{anything})$

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.018	90	0.3	[14] HAAS	88	CLEO	e^+e^- 10 GeV
<0.007	95		[15] ALTHOFF	84G	TASS	e^+e^- 34.5 GeV

[14] The normalization uses a continuum charm production estimate.
[15] Average BR for charm $\rightarrow \mu^+\mu^-$X. The mixture of charmed particles is unknown and may actually contain states other than D mesons.

Leptonic and semileptonic modes

$\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_8/Γ

See the "Note on Pseudoscalar-Meson Decay Constants" in the $\pi^\pm$ Listings for the limit inferred on the D^+ decay constant from the limit here on $\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.00072	90		ADLER	88B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.02	90	0	[16] AUBERT	83	SPEC	μ^+ Fe, 250 GeV

[16] AUBERT 83 obtains an upper limit 0.014 assuming the final state contains equal amounts of (D^+,D^-), $(D^+,\overline{D}^0)$, (D^-,D^0), and $(D^0,\overline{D}^0)$. We quote the limit they get under more general assumptions.

$\Gamma(\overline{K}^0\ell^+\nu_\ell)/\Gamma_{total}$ — Γ_9/Γ

We average our $\overline{K}^0e^+\nu_e$ and $\overline{K}^0\mu^+\nu_\mu$ branching fractions, after multiplying the latter by a phase-space factor of 1.03 to be able to use it with the $\overline{K}^0e^+\nu_e$ fraction. Hence our ℓ^+ here is really an e^+.

VALUE	DOCUMENT ID		COMMENT
0.067±0.008 OUR AVERAGE			
0.066±0.009	PDG	96	Our $\Gamma(\overline{K}^0e^+\nu_e)/\Gamma_{total}$
$0.072^{+0.031}_{-0.021}$	PDG	96	1.03 × our $\Gamma(\overline{K}^0\mu^+\nu_\mu)/\Gamma_{total}$

$\Gamma(\overline{K}^0e^+\nu_e)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.066±0.009 OUR FIT					
$0.06\ ^{+0.022}_{-0.013}\pm0.007$	13	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\overline{K}^0e^+\nu_e)/\Gamma(\overline{K}^0\pi^+)$ — Γ_{10}/Γ_{33}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
2.39±0.33 OUR FIT					
2.60±0.35±0.26	186	[17] BEAN	93C	CLEO	$e^+e^- \approx \Upsilon(4S)$

[17] BEAN 93C uses $\overline{K}^0\mu^+\nu_\mu$ as well as $\overline{K}^0e^+\nu_e$ events and makes a small phase-space adjustment to the number of the μ^+ events to use them as e^+ events.

$\Gamma(\overline{K}^0e^+\nu_e)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{10}/Γ_{34}

VALUE	DOCUMENT ID		TECN	COMMENT
0.72±0.10 OUR FIT				
0.66±0.09±0.14	ANJOS	91C	E691	γ Be 80–240 GeV

$\Gamma(\overline{K}^0\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.07\ ^{+0.028}_{-0.016}\pm0.012$	14	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\overline{K}^0\mu^+\nu_\mu)/\Gamma(\mu^+ \text{anything})$ — Γ_{11}/Γ_6

VALUE	EVTS	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.76±0.06	84	[18] AOKI	88	π^- emulsion

[18] From topological branching ratios in emulsion with an identified muon.

$\Gamma(K^-\pi^+e^+\nu_e)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$0.042^{+0.009}_{-0.007}$ OUR FIT						
$0.035^{+0.012}_{-0.007}\pm0.004$		14	[19] BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.057	90		[20] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[19] BAI 91 finds that a fraction $0.79^{+0.15}_{-0.17}{}^{+0.09}_{-0.03}$ of combined D^+ and D^0 decays to $\overline{K}\pi e^+\nu_e$ (24 events) are $\overline{K}^*(892)e^+\nu_e$.
[20] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^*(892)^0\ell^+\nu_\ell)/\Gamma_{total}$ — Γ_{25}/Γ

We average our $\overline{K}^{*0}e^+\nu_e$ and $\overline{K}^{*0}\mu^+\nu_\mu$ branching fractions, after multiplying the latter by a phase-space factor of 1.05 to be able to use it with the $\overline{K}^{*0}e^+\nu_e$ fraction. Hence our ℓ^+ here is really an e^+.

VALUE	DOCUMENT ID		COMMENT
0.048±0.004 OUR AVERAGE			
0.048±0.005	PDG	96	Our $\Gamma(\overline{K}^{*0}e^+\nu_e)/\Gamma_{total}$
0.047±0.006	PDG	96	1.05 × our $\Gamma(\overline{K}^{*0}\mu^+\nu_\mu)/\Gamma_{total}$

$\Gamma(\overline{K}^*(892)^0e^+\nu_e)/\Gamma(K^-\pi^+e^+\nu_e)$ — Γ_{26}/Γ_{12}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$1.16^{+0.21}_{-0.24}$ OUR FIT					
1.0 ±0.3	35	ADAMOVICH	91	OMEG	π^- 340 GeV

$\Gamma(\overline{K}^*(892)^0e^+\nu_e)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{26}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.53±0.05 OUR FIT					
0.54±0.05 OUR AVERAGE					
0.67±0.09±0.07	710	[21] BEAN	93C	CLEO	$e^+e^- \approx \Upsilon(4S)$
0.62±0.15±0.09	35	ADAMOVICH	91	OMEG	π^- 340 GeV
0.55±0.08±0.10	880	ALBRECHT	91	ARG	$e^+e^- \approx$ 10.4 GeV
0.49±0.04±0.05		ANJOS	89B	E691	Photoproduction

[21] BEAN 93C uses $\overline{K}^{*0}\mu^+\nu_\mu$ as well as $\overline{K}^{*0}e^+\nu_e$ events and makes a small phase-space adjustment to the number of the μ^+ events to use them as e^+ events.

$\Gamma(K^-\pi^+e^+\nu_e \text{ nonresonant})/\Gamma_{total}$ — Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.007	90	[22] ANJOS	89B	E691	Photoproduction

[22] ANJOS 89B assumes a $\Gamma(D^+ \rightarrow K^-\pi^+\pi^+)/\Gamma_{total}$ = 9.1 ± 1.3 ± 0.4%.

$\Gamma(K^-\pi^+\mu^+\nu_\mu)/\Gamma_{total}$ — $\Gamma_{15}/\Gamma = (\Gamma_{17}+\frac{2}{3}\Gamma_{27})/\Gamma$

VALUE	DOCUMENT ID
0.032±0.004 OUR FIT	Error includes scale factor of 1.1.

$\Gamma(\overline{K}^*(892)^0\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_{27}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.045 ±0.006 OUR FIT Error includes scale factor of 1.1.					
0.0325±0.0071±0.0075	224	[23] KODAMA	92C	E653	π^- emulsion 600 GeV

[23] KODAMA 92C measures $\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu_\mu)/\Gamma(D^0 \to K^-\mu^+\nu_\mu) = 0.43 \pm 0.09 \pm 0.09$ and then uses $\Gamma(D^0 \to K^-\mu^+\nu_\mu) = (7.0 \pm 0.7) \times 10^{10}\,\mathrm{s}^{-1}$ to get the quoted branching fraction. See also the footnote to KODAMA 92C in the next data block.

$\Gamma(\overline{K}^*(892)^0\mu^+\nu_\mu)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{27}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.49±0.06 OUR FIT Error includes scale factor of 1.1.					
0.53±0.06 OUR AVERAGE					
0.56±0.04±0.06	875	FRABETTI	93E	E687	γ Be $\overline{E}_\gamma \approx$ 200 GeV
0.46±0.07±0.08	224	[24] KODAMA	92C	E653	π^- emulsion 600 GeV

[24] KODAMA 92C uses the same $\overline{K}^{*0}\mu^+\nu_\mu$ events normalizing instead with $D^0 \to K^-\mu^+\nu_\mu$ events, as reported in the preceding data block.

$\Gamma(K^-\pi^+\mu^+\nu_\mu$ nonresonant$)/\Gamma(K^-\pi^+\mu^+\nu_\mu)$ — $\Gamma_{17}/\Gamma_{15} = \Gamma_{17}/(\Gamma_{17}+\frac{2}{3}\Gamma_{27})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.083±0.029 OUR FIT				
0.083±0.029	FRABETTI	93E	E687	< 0.12 (90% CL)

$\Gamma(\overline{K}^0\pi^+\pi^-e^+\nu_e)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.022^{+0.047}_{-0.006}\pm0.004$	1	[25] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[25] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^0e^+\nu_e)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.044^{+0.052}_{-0.013}\pm0.007$	2	[26] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[26] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma((\overline{K}^*(892)\pi)^0e^+\nu_e)/\Gamma_{total}$ — Γ_{20}/Γ

Unseen decay modes of the $\overline{K}^*(892)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.012	90	ANJOS	92	E691	Photoproduction

$\Gamma((\overline{K}\pi\pi)^0e^+\nu_e$ non-$\overline{K}^*(892))/\Gamma_{total}$ — Γ_{21}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.009	90	ANJOS	92	E691	Photoproduction

$\Gamma(K^-\pi^+\pi^0\mu^+\nu_\mu)/\Gamma(K^-\pi^+\mu^+\nu_\mu)$ — $\Gamma_{22}/\Gamma_{15} = \Gamma_{22}/(\Gamma_{17}+\frac{2}{3}\Gamma_{27})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.042	90	FRABETTI	93E	E687	γ Be $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(\pi^0\ell^+\nu_\ell)/\Gamma(\overline{K}^0\ell^+\nu_\ell)$ — Γ_{23}/Γ_9

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.085±0.027±0.014	53	[27] ALAM	93	CLEO	$e^+e^- \approx \Upsilon(4S)$

[27] ALAM 93 thus directly measures the product of ratios squared of CKM matrix elements and form factors at q^2=0: $|V_{cd}/V_{cs}|^2 \cdot |f_+^\pi(0)/f_+^K(0)|^2 = 0.085 \pm 0.027 \pm 0.014$.

$\Gamma(\pi^+\pi^-e^+\nu_e)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.057	90	[28] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[28] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization.

$\Gamma(\rho^0e^+\nu_e)/\Gamma_{total}$ — Γ_{28}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0037	90	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\rho^0\mu^+\nu_\mu)/\Gamma(\overline{K}^*(892)^0\mu^+\nu_\mu)$ — Γ_{29}/Γ_{27}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.044^{+0.031}_{-0.025}\pm0.014}$	4	[29] KODAMA	93C	E653	π^- emulsion 600 GeV

[29] This KODAMA 93C result is based on a final signal of $4.0^{+2.8}_{-2.3}\pm1.3$ events; the estimates of backgrounds that affect this number are somewhat model dependent.

$\Gamma(\phi e^+\nu_e)/\Gamma_{total}$ — Γ_{30}/Γ

Decay modes of the ϕ not included in the search are corrected for.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0209	90	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\phi\mu^+\nu_\mu)/\Gamma_{total}$ — Γ_{31}/Γ

Decay modes of the ϕ not included in the search are corrected for.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0372	90	BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

$\Gamma(\eta'(958)\mu^+\nu_\mu)/\Gamma(\overline{K}^*(892)^0\mu^+\nu_\mu)$ — Γ_{32}/Γ_{27}

Decay modes of the $\eta'(958)$ not included in the search are corrected for.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.20	90	KODAMA	93B	E653	π^- emulsion 600 GeV

Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$

$\Gamma(\overline{K}^0\pi^+)/\Gamma_{total}$ — Γ_{33}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0274±0.0029 OUR FIT					
0.032 ±0.004 OUR AVERAGE					
0.032 ±0.005 ±0.002	161	ADLER	88C	MRK3	e^+e^- 3.77 GeV
0.033 ±0.009	36	[30] SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.033 ±0.013	17	[31] PERUZZI	77	MRK1	e^+e^- 3.77 GeV

[30] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.14 ± 0.03 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

[31] PERUZZI 77 (MARK-1) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.14 ± 0.05 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

$\Gamma(\overline{K}^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{33}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.302±0.031 OUR FIT					
0.274±0.030±0.031	264	ANJOS	90C	E691	Photoproduction

$\Gamma(K^-\pi^+\pi^+)/\Gamma_{total}$ — Γ_{34}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.091±0.006 OUR FIT					
0.091±0.007 OUR AVERAGE					
0.093±0.006±0.008	1502	[32] BALEST	94	CLEO	$e^+e^- \approx \Upsilon(4S)$
0.091±0.013±0.004	1164	ADLER	88C	MRK3	e^+e^- 3.77 GeV
0.091±0.019	239	[33] SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.086±0.020	85	[34] PERUZZI	77	MRK1	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.064^{+0.015}_{-0.014}$		[35] BARLAG	92C	ACCM	π^- Cu 230 GeV
$0.063^{+0.028}_{-0.014}\pm0.011$	8	[35] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[32] BALEST 94 measures the ratio of $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ branching fractions to be 2.35 ± 0.16 ± 0.16 and uses their absolute measurement of the $D^0 \to K^-\pi^+$ fraction (AKERIB 93).

[33] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.38 ± 0.05 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

[34] PERUZZI 77 (MARK-1) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.36 ± 0.06 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

[35] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(\overline{K}^*(892)^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{70}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.212±0.016 OUR FIT					
0.210±0.015 OUR AVERAGE					
0.206±0.009±0.014		FRABETTI	94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
0.255±0.014±0.050		ANJOS	93	E691	γ Be 90–260 GeV
0.21 ±0.06 ±0.06		ALVAREZ	91B	NA14	Photoproduction
0.20 ±0.02 ±0.11		ADLER	87	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.053	90	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\Gamma(\overline{K}_0^*(1430)^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{79}/Γ_{34}

Unseen decay modes of the $\overline{K}_0^*(1430)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.41 ±0.04 OUR AVERAGE				
0.458±0.035±0.094	FRABETTI	94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
0.400±0.031±0.027	ANJOS	93	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^*(1680)^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{80}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(1680)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.160±0.032 OUR AVERAGE Error includes scale factor of 1.1.				
0.182±0.023±0.028	FRABETTI	94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
0.113±0.015±0.050	ANJOS	93	E691	γ Be 90–260 GeV

$\Gamma(K^-\pi^+\pi^+$ nonresonant$)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{38}/Γ_{34}

VALUE	DOCUMENT ID		TECN	COMMENT
0.95 ±0.07 OUR AVERAGE				
0.998±0.037±0.072	FRABETTI	94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
0.838±0.088±0.275	ANJOS	93	E691	γ Be 90–260 GeV
0.79 ±0.07 ±0.15	ADLER	87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^0)/\Gamma_{total}$ — Γ_{39}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.097±0.030 OUR FIT Error includes scale factor of 1.1.				
0.107±0.029 OUR AVERAGE				
0.102±0.025±0.016	159	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.19 ±0.12	10	[36] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

[36] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770))$ × branching fraction to be 0.78 ± 0.48 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.

$\Gamma(\overline{K}^0\rho^+)/\Gamma(\overline{K}^0\pi^+\pi^0)$ — Γ_{40}/Γ_{39}

VALUE	DOCUMENT ID	TECN	COMMENT
0.68±0.08±0.12	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^0)$ — Γ_{70}/Γ_{39}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.20±0.06 OUR FIT			
0.57±0.18±0.18	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^0$ nonresonant$)/\Gamma(\overline{K}^0\pi^+\pi^0)$ — Γ_{42}/Γ_{39}

VALUE	DOCUMENT ID	TECN	COMMENT
0.13±0.07±0.08	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^+\pi^0)/\Gamma_{total}$ — Γ_{43}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.064±0.011 OUR FIT				
0.058±0.012±0.012	142	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.034^{+0.056}_{-0.070}$		[37] BARLAG 92C	ACCM	π^- Cu 230 GeV
$0.022^{+0.047}_{-0.006}\pm0.004$	1	[37] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV
$0.063^{+0.014}_{-0.013}\pm0.012$	175	BALTRUSAIT...86E	MRK3	See COFFMAN 92B

[37] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^0)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{43}/Γ_{34}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.71±0.12 OUR FIT				
0.76±0.11±0.12	91	ANJOS 92C	E691	γ Be 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.69±0.10±0.16		ANJOS 89E	E691	See ANJOS 92C
$0.57^{+0.65}_{-0.17}$	1	AGUILAR-... 83B	HYBR	$\pi^- p$, 360 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+$ total$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{71}/Γ_{43}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.33±0.165±0.12	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+$ S-wave$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{72}/Γ_{43}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included. The two experiments disagree severely here.

VALUE	DOCUMENT ID	TECN	COMMENT
0.26 ±0.25 OUR AVERAGE Error includes scale factor of 3.1.			
0.15 ±0.075±0.045	ANJOS 92C	E691	γ Be 90–260 GeV
0.833±0.116±0.165	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+$ P-wave$)/\Gamma_{total}$ — Γ_{73}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.001	90	ANJOS 92C	E691	γ Be 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.005	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+$ D-wave$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{74}/Γ_{43}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.15±0.09±0.045	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\rho^+$ D-wave longitudinal$)/\Gamma_{total}$ — Γ_{75}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.007	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1400)^0\pi^+)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{77}/Γ_{43}

Unseen decay modes of the $\overline{K}_1(1400)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.77 ±0.20 OUR FIT			
0.907±0.218±0.180	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\rho^+\pi^+$ total$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{85}/Γ_{43}

This includes $\overline{K}^*(892)^0\rho^+$, *etc.* The next entry gives the specifically 3-body fraction.

VALUE	DOCUMENT ID	TECN	COMMENT
0.48±0.13±0.09	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(K^-\rho^+\pi^+$ 3-body$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{86}/Γ_{43}

VALUE	DOCUMENT ID	TECN	COMMENT
0.17 ±0.06 OUR AVERAGE			
0.18 ±0.08 ±0.04	ANJOS 92C	E691	γ Be 90–260 GeV
0.159±0.065±0.060	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^0$ total$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{81}/Γ_{43}

This includes $\overline{K}^*(892)^0\rho^+$, *etc.* The next two entries gives the specifically 3-body fraction. Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
1.05±0.11±0.08	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^0$ 3-body$)/\Gamma_{total}$ — Γ_{82}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.008	90	[38] COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

[38] See, however, the next entry: ANJOS 92C sees a large signal in this channel.

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^0$ 3-body$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{82}/Γ_{43}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.66±0.09±0.17	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(K^*(892)^-\pi^+\pi^+$ 3-body$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{84}/Γ_{43}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.32±0.14 OUR FIT Error includes scale factor of 1.1.			
0.24±0.12±0.09	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(K^-\pi^+\pi^+\pi^0$ nonresonant$)/\Gamma_{total}$ — Γ_{51}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.002	90	[39] ANJOS 92C	E691	γ Be 90–260 GeV

[39] Whereas ANJOS 92C finds no signal here, COFFMAN 92B finds a fairly large one; see the next entry.

$\Gamma(K^-\pi^+\pi^+\pi^0$ nonresonant$)/\Gamma(K^-\pi^+\pi^+\pi^0)$ — Γ_{51}/Γ_{43}

VALUE	DOCUMENT ID	TECN	COMMENT
0.184±0.070±0.050	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{52}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.070±0.010 OUR FIT				
0.071±0.016 OUR AVERAGE				
0.066±0.015±0.005	168	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.12 ±0.05	21	[40] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.042^{+0.019}_{-0.017}$		[41] BARLAG 92C	ACCM	π^- Cu 230 GeV
$0.243^{+0.064}_{-0.041}\pm0.041$	11	[41] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[40] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770))$ × branching fraction to be 0.51 ± 0.08 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 4.2 \pm 0.6 \pm 0.3$ nb.
[41] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{52}/Γ_{34}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.78±0.10 OUR FIT				
0.77±0.07±0.11	229	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^0 a_1(1260)^+)/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ — Γ_{68}/Γ_{52}

Unseen decay modes of the $a_1(1260)^+$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
1.15 ±0.19 OUR AVERAGE Error includes scale factor of 1.1.			
1.66 ±0.28 ±0.40	ANJOS 92C	E691	γ Be 90–260 GeV
1.078±0.114±0.140	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 a_2(1320)^+)/\Gamma_{total}$ — Γ_{69}/Γ

Unseen decay modes of the $a_2(1320)^+$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.003	90	ANJOS 92C	E691	γ Be 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.008	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1270)^0\pi^+)/\Gamma_{total}$ — Γ_{76}/Γ

Unseen decay modes of the $\overline{K}_1(1270)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.007	90	ANJOS 92C	E691	γ Be 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.011	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1400)^0\pi^+)/\Gamma_{total}$ Γ_{77}/Γ

Unseen decay modes of the $\overline{K}_1(1400)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.009	90	[42] ANJOS	92C	E691	γ Be 90–260 GeV

[42] ANJOS 92C sees no evidence for $\overline{K}_1(1400)^0\pi^+$ in either the $\overline{K}^0\pi^+\pi^+\pi^-$ or $K^-\pi^+\pi^+\pi^0$ channels, whereas COFFMAN 92B finds the $\overline{K}_1(1400)^0\pi^+$ branching fraction to be large; see the next entry.

$\Gamma(\overline{K}_1(1400)^0\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{77}/Γ_{52}

Unseen decay modes of the $\overline{K}_1(1400)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.70 ±0.17 OUR FIT				
0.623±0.106±0.180	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(1410)^0\pi^+)/\Gamma_{total}$ Γ_{78}/Γ

Unseen decay modes of the $\overline{K}^*(1410)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.007	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\pi^+\pi^+ \text{total})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{83}/Γ_{52}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.41±0.14	14	ALEEV	94	BIS2	nN 20–70 GeV

$\Gamma(K^*(892)^-\pi^+\pi^+ \text{3-body})/\Gamma_{total}$ Γ_{84}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.021±0.009 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.013	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\pi^+\pi^+ \text{3-body})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{84}/Γ_{52}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.29±0.13 OUR FIT Error includes scale factor of 1.1.				
0.50±0.09±0.21	ANJOS	92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^0\rho^0\pi^+ \text{total})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{87}/Γ_{52}

This includes $\overline{K}^0 a_1(1260)^+$. The next two entries gives the specifically 3-body reaction.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.60±0.10±0.17	90	ANJOS	92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^0\rho^0\pi^+ \text{3-body})/\Gamma_{total}$ Γ_{88}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.004	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\rho^0\pi^+ \text{3-body})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{88}/Γ_{52}

VALUE	DOCUMENT ID		TECN	COMMENT
0.07±0.04±0.06	ANJOS	92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^0 f_0(980)\pi^+)/\Gamma_{total}$ Γ_{89}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.005	90	ANJOS	92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^- \text{ nonresonant})/\Gamma(\overline{K}^0\pi^+\pi^+\pi^-)$ Γ_{58}/Γ_{52}

VALUE	DOCUMENT ID		TECN	COMMENT
0.12±0.06 OUR AVERAGE				
0.10±0.04 ±0.06	ANJOS	92C	E691	γ Be 90–260 GeV
0.17±0.056±0.100	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma_{total}$ Γ_{59}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.0037^{+0.0012}_{-0.0010}$	[43] BARLAG	92C	ACCM	π^- Cu 230 GeV

[43] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ Γ_{59}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.09 ±0.01 ±0.01	113	ANJOS	90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^+\pi^-)$ Γ_{90}/Γ_{59}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
1.25±0.12±0.23	ANJOS	90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\rho^0\pi^+)/\Gamma(\overline{K}^*(892)^0\pi^+\pi^+\pi^-)$ Γ_{91}/Γ_{90}

VALUE	DOCUMENT ID		TECN	COMMENT
0.75±0.17±0.19	ANJOS	90D	E691	Photoproduction

$\Gamma(K^-\pi^+\pi^+\pi^0\pi^0)/\Gamma_{total}$ Γ_{62}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.022^{+0.047}_{-0.008}\pm0.004$	1	[44] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.015		[44] BARLAG	92C	ACCM	π^- Cu 230 GeV

[44] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\pi^0)/\Gamma_{total}$ Γ_{63}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.054^{+0.030}_{-0.014}$ OUR AVERAGE					
$0.099^{+0.036}_{-0.070}$		[45] BARLAG	92C	ACCM	π^- Cu 230 GeV
$0.044^{+0.052}_{-0.013}\pm0.007$	2	[45] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[45] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction by topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ Γ_{64}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0008±0.0007	[46] BARLAG	92C	ACCM	π^- Cu 230 GeV

[46] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^-\pi^+\pi^+\pi^+\pi^-\pi^0)/\Gamma_{total}$ Γ_{65}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0020±0.0018	[47] BARLAG	92C	ACCM	π^- Cu 230 GeV

[47] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^0\overline{K}^0K^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{66}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.20±0.09 OUR AVERAGE Error includes scale factor of 2.4.					
0.14±0.04±0.02	39	ALBRECHT	94I	ARG	$e^+e^- \approx$ 10 GeV
0.34±0.07	70	AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV

Pionic modes

$\Gamma(\pi^+\pi^0)/\Gamma(K^-\pi^+\pi^+)$ Γ_{92}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.028±0.006±0.005	34	SELEN	93	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ Γ_{93}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.035±0.006 OUR AVERAGE					
0.032±0.011±0.003	20	ADAMOVICH	93	WA82	π^- 340 GeV
0.035±0.007±0.003		ANJOS	89	E691	Photoproduction
0.042±0.016±0.010	57	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(\rho^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{94}/Γ_{34}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	90	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^- \text{ nonresonant})/\Gamma(K^-\pi^+\pi^+)$ Γ_{95}/Γ_{34}

VALUE	DOCUMENT ID		TECN	COMMENT
0.027±0.007±0.002	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma_{total}$ Γ_{96}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.019^{+0.015}_{-0.012}$	[48] BARLAG	92C	ACCM	π^- Cu 230 GeV

[48] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+)$ Γ_{96}/Γ_{34}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.4	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\eta\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{101}/Γ_{34}

Unseen decay modes of the η are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.083±0.023±0.014		99	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.12	90		ANJOS	89E	E691	Photoproduction

$\Gamma(\omega\pi^+)/\Gamma(K^-\pi^+\pi^+)$ Γ_{103}/Γ_{34}

Unseen decay modes of the ω are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ Γ_{99}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.0010^{+0.0008}_{-0.0007}$	[49] BARLAG	92C	ACCM	π^- Cu 230 GeV

[49] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{99}/Γ_{34}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.019	90	ANJOS	89	E691	Photoproduction

$\Gamma(\eta\rho^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{104}/Γ_{34}

Unseen decay modes of the η are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.13	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{100}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.0029^{+0.0029}_{-0.0020}$	[50] BARLAG	92C	ACCM	π^- Cu 230 GeV

[50] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\eta'(958)\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{105}/Γ_{34}

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV
<0.1	90	ALVAREZ	91	NA14	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.13	90	ANJOS	91B	E691	γBe, $\overline{E}_\gamma \approx$ 145 GeV

$\Gamma(\eta'(958)\rho^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{106}/Γ_{34}

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.17	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

Hadronic modes with a $K\overline{K}$ pair

$\Gamma(K^+\overline{K}^0)/\Gamma(\overline{K}^0\pi^+)$ — Γ_{107}/Γ_{33}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.263±0.035 OUR AVERAGE					
0.25 ±0.04 ±0.02	129	FRABETTI	95	E687	γBe $\overline{E}_\gamma \approx$ 200 GeV
0.271±0.065±0.039	69	ANJOS	90C	E691	γBe
0.317±0.086±0.048	31	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV
0.25 ±0.15	6	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K^+K^-\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{108}/Γ_{34}

VALUE	DOCUMENT ID		TECN	COMMENT
0.0976±0.0042±0.0046	FRABETTI	95B	E687	Dalitz plot analysis

$\Gamma(\phi\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{125}/Γ_{34}

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.068±0.005 OUR AVERAGE					
0.058±0.006±0.006		FRABETTI	95B	E687	Dalitz plot analysis
0.062±0.017±0.006	19	ADAMOVICH	93	WA82	π^- 340 GeV
0.077±0.011±0.005	128	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV
0.098±0.032±0.014	12	ALVAREZ	90C	NA14	Photoproduction
0.071±0.008±0.007	84	ANJOS	88	E691	Photoproduction
0.084±0.021±0.011	21	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^+\overline{K}^*(892)^0)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{129}/Γ_{34}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.047±0.005 OUR AVERAGE	Error includes scale factor of 1.2.				
0.044±0.003±0.004		[51] FRABETTI	95B	E687	Dalitz plot analysis
0.058±0.009±0.006	73	ANJOS	88	E691	Photoproduction
0.048±0.021±0.011	14	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

[51] See FRABETTI 95B for evidence also of $\overline{K}^*_0(1430)K^+$ in the $D^+ \to K^+K^-\pi^+$ Dalitz plot.

$\Gamma(K^+K^-\pi^+ \text{ nonresonant})/\Gamma(K^-\pi^+\pi^+)$ — Γ_{111}/Γ_{34}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.050±0.009 OUR AVERAGE					
0.049±0.008±0.006	95	ANJOS	88	E691	Photoproduction
0.059±0.026±0.009	37	BALTRUSAIT...	85E	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^+\overline{K}^0)/\Gamma(\overline{K}^0\pi^+)$ — Γ_{130}/Γ_{33}

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.1±0.3±0.4	67	FRABETTI	95	E687	γBe $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(\phi\pi^+\pi^0)/\Gamma_{total}$ — Γ_{126}/Γ

Unseen decay modes of the ϕ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.023±0.010	[52] BARLAG	92C	ACCM	π^- Cu 230 GeV

[52] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\phi\pi^+\pi^0)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{126}/Γ_{34}

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.58	90	ALVAREZ	90C	NA14	Photoproduction
<0.28	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\phi\rho^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{127}/Γ_{34}

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.16	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^+K^-\pi^+\pi^0 \text{ non-}\phi)/\Gamma_{total}$ — Γ_{117}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.015^{+0.007}_{-0.006}$	[53] BARLAG	92C	ACCM	π^- Cu 230 GeV

[53] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^+K^-\pi^+\pi^0 \text{ non-}\phi)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{117}/Γ_{34}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.25	90	ANJOS	89E	E691	Photoproduction

$\Gamma(K^+\overline{K}^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_{118}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^0K^-\pi^+\pi^+)/\Gamma_{total}$ — Γ_{119}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.01 ±0.005±0.003	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.003	[54] BARLAG	92C	ACCM	π^- Cu 230 GeV

[54] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^*(892)^+\overline{K}^*(892)^0)/\Gamma_{total}$ — Γ_{131}/Γ

Unseen decay modes of the $K^*(892)$'s are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.026±0.008±0.007	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^0K^-\pi^+\pi^+ \text{ non-}K^{*+}\overline{K}^{*0})/\Gamma_{total}$ — Γ_{121}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0079	90	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{128}/Γ

Unseen decay modes of the ϕ are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.002	90	0	ANJOS	88	E691	Photoproduction

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{128}/Γ_{34}

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.031	90	ALVAREZ	90C	NA14	Photoproduction

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ — $\Gamma_{128}/\Gamma_{125}$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.6	90	FRABETTI	92	E687	γBe

$\Gamma(K^+K^-\pi^+\pi^+\pi^- \text{ nonresonant})/\Gamma_{total}$ — Γ_{124}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.03	90	12	ANJOS	88	E691	Photoproduction

Rare or forbidden modes

$\Gamma(K^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{132}/Γ_{34}

A doubly Cabibbo-suppressed decay with no simple spectator process possible.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0072±0.0023±0.0017	21	FRABETTI	95E	E687	γBe, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^+\rho^0)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{133}/Γ_{34}

A doubly Cabibbo-suppressed decay with no simple spectator process possible.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0067	90	FRABETTI	95E	E687	γBe, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^*(892)^0\pi^+)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{134}/Γ_{34}

A doubly Cabibbo-suppressed decay with no simple spectator process possible. Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0021	90	FRABETTI	95E	E687	γBe, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^+K^+K^-)/\Gamma(K^-\pi^+\pi^+)$ — Γ_{135}/Γ_{34}

A doubly Cabibbo-suppressed decay with no simple spectator process possible.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0016	90		[55] FRABETTI	95F	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.057 ±0.020±0.007		13	ADAMOVICH	93	WA82	π^- 340 GeV

[55] Using the $\phi\pi^+$ mode to normalize, FRABETTI 95F gets $\Gamma(K^+K^+K^-)/\Gamma(\phi\pi^+)<$ 0.025.

$\Gamma(\phi K^+)/\Gamma(\phi\pi^+)$ — $\Gamma_{136}/\Gamma_{125}$

A doubly Cabibbo-suppressed decay with no simple spectator process possible.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.021	90		FRABETTI	95F	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$0.058^{+0.032}_{-0.026}\pm0.007$		4	[56] ANJOS	92D	E691	γBe, $\overline{E}_\gamma$ = 145 GeV

[56] The evidence of ANJOS 92D is a small excess of events ($4.5^{+2.4}_{-2.0}$).

$\Gamma(\pi^+ e^+ e^-)/\Gamma_{total}$ — Γ_{137}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<6.6 x 10⁻⁵	90		AITALA	96	E791	π^- N 500 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<2.5\times10^{-3}$	90		WEIR	90B	MRK2	e^+e^- 29 GeV
$<2.6\times10^{-3}$	90	39	[57] HAAS	88	CLEO	e^+e^- 10 GeV

[57] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.

$\Gamma(\pi^+ \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{138}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.8\times10^{-5}$	90		AITALA	96	E791	π^- N 500 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<2.2\times10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV
$<5.9\times10^{-3}$	90		WEIR	90B	MRK2	e^+e^- 29 GeV
$<2.9\times10^{-3}$	90	36	[58] HAAS	88	CLEO	e^+e^- 10 GeV

[58] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.

$\Gamma(\rho^+ \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{139}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<5.6\times10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(K^+ e^+ e^-)/\Gamma_{total}$ — Γ_{140}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.8\times10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^+ \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{141}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<3.2\times10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<9.2\times10^{-3}$	90		WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\pi^+ e^\pm \mu^\mp)/\Gamma_{total}$ — Γ_{142}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<3.8\times10^{-3}$	90	58	[59] HAAS	88	CLEO	e^+e^- 10 GeV

[59] The branching ratios are normalized to $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D^{*+} \to D^0\pi^+$ using ADLER 88C.

$\Gamma(\pi^+ e^+ \mu^-)/\Gamma_{total}$ — Γ_{143}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.3\times10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\pi^+ e^- \mu^+)/\Gamma_{total}$ — Γ_{144}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.3\times10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^+ e^+ \mu^-)/\Gamma_{total}$ — Γ_{145}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.4\times10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^+ e^- \mu^+)/\Gamma_{total}$ — Γ_{146}/Γ

A test of lepton-family-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.4\times10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\pi^- e^+ e^+)/\Gamma_{total}$ — Γ_{147}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.8\times10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\pi^- \mu^+ \mu^+)/\Gamma_{total}$ — Γ_{148}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<2.2\times10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<6.8\times10^{-3}$	90		WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\pi^- e^+ \mu^+)/\Gamma_{total}$ — Γ_{149}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.7\times10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(\rho^- \mu^+ \mu^+)/\Gamma_{total}$ — Γ_{150}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<5.6\times10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(K^- e^+ e^+)/\Gamma_{total}$ — Γ_{151}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<9.1\times10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^- \mu^+ \mu^+)/\Gamma_{total}$ — Γ_{152}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<3.2\times10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<4.3\times10^{-3}$	90		WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^- e^+ \mu^+)/\Gamma_{total}$ — Γ_{153}/Γ

A test of lepton-number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.0\times10^{-3}$	90	WEIR	90B	MRK2	e^+e^- 29 GeV

$\Gamma(K^*(892)^- \mu^+ \mu^+)/\Gamma_{total}$ — Γ_{154}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<8.5\times10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$D^\pm$ *CP*-VIOLATING DECAY-RATE ASYMMETRIES

$A_{CP}(K^+K^-\pi^\pm)$ in $D^\pm \to K^+K^-\pi^\pm$

This is the difference between D^+ and D^- partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID		TECN	COMMENT
-0.031 ± 0.068	[60] FRABETTI	94I	E687	$-0.14 < A_{CP} < +0.081$ (90% CL)

[60] FRABETTI 94I measures $N(D^+ \to K^-K^+\pi^+)/N(D^+ \to K^-\pi^+\pi^+)$, the ratio of (efficiency-corrected) numbers of events observed, and similarly for the D^-.

$A_{CP}(K^\pm K^{*0})$ in $D^+ \to K^+\overline{K}^{*0}$ and $D^- \to K^-K^{*0}$

This is the difference between D^+ and D^- partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID		TECN	COMMENT
-0.12 ± 0.13	[61] FRABETTI	94I	E687	$-0.33 < A_{CP} < +0.094$ (90% CL)

[61] FRABETTI 94I measures $N(D^+ \to K^+\overline{K}^*(892)^0)/N(D^+ \to K^-\pi^+\pi^+)$, the ratio of (efficiency-corrected) numbers of events observed, and similarly for the D^-.

$A_{CP}(\phi\pi^\pm)$ in $D^\pm \to \phi\pi^\pm$

This is the difference between D^+ and D^- partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.066\pm0.086$	[62] FRABETTI	94I	E687	$-0.075 < A_{CP} < +0.21$ (90% CL)

[62] FRABETTI 94I measures $N(D^+ \to \phi\pi^+)/N(D^+ \to K^-\pi^+\pi^+)$, the ratio of (efficiency-corrected) numbers of events observed, and similarly for the D^-.

$D^\pm$ PRODUCTION CROSS SECTION AT $\psi(3770)$

A compilation of the cross sections for the direct production of $D^\pm$ mesons at or near the $\psi(3770)$ peak in e^+e^- production.

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$4.2\ \pm0.6\ \pm0.3$	[63] ADLER	88C	MRK3	e^+e^- 3.768 GeV
$5.5\ \pm1.0$	[64] PARTRIDGE	84	CBAL	e^+e^- 3.771 GeV
$6.00\pm0.72\pm1.02$	[65] SCHINDLER	80	MRK2	e^+e^- 3.771 GeV
$9.1\ \pm2.0$	[66] PERUZZI	77	MRK1	e^+e^- 3.774 GeV

[63] This measurement compares events with one detected D to those with two detected D mesons, to determine the the absolute cross section. ADLER 88C measure the ratio of cross sections (neutral to charged) to be $1.36 \pm 0.23 \pm 0.14$. This measurement does not include the decays of the $\psi(3770)$ not associated with charmed particle production.

[64] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. PARTRIDGE 84 measures 6.4 ± 1.15 nb for the cross section. We take the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and we assume that the $\psi(3770)$ is an isosinglet to evaluate the cross sections. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[65] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. SCHINDLER 80 assume the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and that the $\psi(3770)$ is an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[66] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. The phase space division of neutral and charged D mesons in $\psi(3770)$ decay is taken to be 1.33, and $\psi(3770)$ is assumed to be an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction. We exclude this measurement from the average because of uncertainties in the contamination from τ lepton pairs. Also see RAPIDIS 77.

$D^+ \to \overline{K}^*(892)^0 \ell^+ \nu_\ell$ FORM FACTORS

$r_2 \equiv A_2(0)/A_1(0)$ in $D^+ \to \overline{K}^*(892)^0 \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.73±0.15 OUR AVERAGE					
0.78±0.18±0.10	874	[67] FRABETTI	93E	E687	220 GeV γBe
$0.82^{+0.22}_{-0.23}$±0.11	305	[67] KODAMA	92	E653	600 GeV $\pi^- N$
0.0 ±0.5 ±0.2	183	[68] ANJOS	90E	E691	γBe 90–260 GeV

[67] FRABETTI 93E and KODAMA 92 use $D^+ \to \overline{K}^*(892)^0 \mu^+ \nu_\mu$ decays.

[68] ANJOS 90E uses $D^+ \to \overline{K}^*(892)^0 e^+ e_\mu$ decays.

$r_V \equiv V(0)/A_1(0)$ in $D^+ \to \overline{K}^*(892)^0 \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.90±0.25 OUR AVERAGE					
1.74±0.27±0.28	874	[69] FRABETTI	93E	E687	220 GeV γBe
$2.00^{+0.34}_{-0.32}$±0.16	305	[69] KODAMA	92	E653	600 GeV $\pi^- N$
2.0 ±0.6 ±0.3	183	[70] ANJOS	90E	E691	γBe 90–260 GeV

[69] FRABETTI 93E and KODAMA 92 use $D^+ \to \overline{K}^*(892)^0 \mu^+ \nu_\mu$ decays.

[70] ANJOS 90E uses $D^+ \to \overline{K}^*(892)^0 e^+ e_\mu$ decays.

Γ_L/Γ_T in $D^+ \to \overline{K}^*(892)^0 \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.23±0.13 OUR AVERAGE					
1.20±0.13±0.13	874	[71] FRABETTI	93E	E687	220 GeV γBe
1.18±0.18±0.08	305	[71] KODAMA	92	E653	600 GeV $\pi^- N$
1.8 $^{+0.6}_{-0.4}$ ±0.3	183	[72] ANJOS	90E	E691	γBe 90–260 GeV

[71] FRABETTI 93E and KODAMA 92 use $D^+ \to \overline{K}^*(892)^0 \mu^+ \nu_\mu$ decays. Γ_L/Γ_T is evaluated for a lepton mass of zero.

[72] ANJOS 90E uses $D^+ \to \overline{K}^*(892)^0 e^+ e_\mu$ decays.

Γ_+/Γ_- in $D^+ \to \overline{K}^*(892)^0 \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.16±0.04 OUR AVERAGE					
0.16±0.05±0.02	305	[73] KODAMA	92	E653	600 GeV $\pi^- N$
$0.15^{+0.07}_{-0.05}$±0.03	183	[74] ANJOS	90E	E691	γBe 90–260 GeV

[73] KODAMA 92 uses $D^+ \to \overline{K}^*(892)^0 \mu^+ \nu_\mu$ decays. Γ_+/Γ_- is evaluated for a lepton mass of zero.

[74] ANJOS 90E uses $D^+ \to \overline{K}^*(892)^0 e^+ e_\mu$ decays.

$D^{\pm}$ REFERENCES

AITALA 96 PRL 76 364 +Amato, Anjos+ (FNAL E791 Collab.)
PDG 96 PR D54 1
FRABETTI 95 PL B346 199 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 95B PL B351 591 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 95E PL B359 403 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 95F PL B363 259 +Cheung, Cumalat+ (FNAL E687 Collab.)
KODAMA 95 PL B345 85 +Ushida, Mokhtarani+ (FNAL E653 Collab.)
ALBRECHT 94I ZPHY C64 375 +Hamacher, Hofmann+ (ARGUS Collab.)
ALEEV 94 PAN 57 1370 +Balandin+ (Serpukhov BIS-2 Collab.)
Translated from YF 57 1443.
BALEST 94 PRL 72 2328 +Cho, Daoudi, Ford+ (CLEO Collab.)
FRABETTI 94D PL B323 459 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 94G PL B331 217 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 94I PR D50 R2953 +Cheung, Cumalat+ (FNAL E687 Collab.)
ABE 93E PL B313 288 +Amako, Arai, Arima, Asano+ (VENUS Collab.)
ADAMOVICH 93 PL B305 177 +Alexandrov, Antinori+ (CERN WA82 Collab.)
AKERIB 93 PRL 71 3070 +Barish, Chadha, Chan+ (CLEO Collab.)
ALAM 93 PRL 71 1311 +Kim, Nemati, O'Neill+ (CLEO Collab.)
ANJOS 93 PR D48 56 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
BEAN 93C PL B317 647 +Gronberg, Kutschke, Menary+ (CLEO Collab.)
FRABETTI 93E PL B307 262 +Grim, Paolone, Yager+ (FNAL E687 Collab.)
KODAMA 93B PL B313 260 +Ushida, Mokhtarani+ (FNAL E653 Collab.)
KODAMA 93C PL B316 455 +Ushida, Mokhtarani+ (FNAL E653 Collab.)
SELEN 93 PRL 71 1973 +Sadoff, Ammar, Ball+ (CLEO Collab.)
ALBRECHT 92B ZPHY C53 361 +Ehrlichmann, Hamacher, Krueger+ (ARGUS Collab.)
ALBRECHT 92F PL B278 202 +Ehrlichmann, Hamacher+ (ARGUS Collab.)
ANJOS 92 PR D45 R2177 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
ANJOS 92C PR D46 1941 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
ANJOS 92D PRL 69 2892 +Appel, Bean, Bediaga+ (FNAL E691 Collab.)
BARLAG 92C ZPHY C55 383 +Becker, Bozek, Boehringer+ (ACCMOR Collab.)
Also 90D ZPHY C48 29 Barlag, Becker, Boehringer, Bosman+ (ACCMOR Collab.)
COFFMAN 92B PR D45 2196 +DeJongh, Dubois, Eigen+ (Mark III Collab.)
DAOUDI 92 PR D45 3965 +Ford, Johnson, Lingel+ (CLEO Collab.)
FRABETTI 92 PL B281 167 +Bogart, Cheung, Culy+ (FNAL E687 Collab.)
KODAMA 92 PL B274 246 +Ushida, Mokhtarani+ (FNAL E653 Collab.)
KODAMA 92C PL B286 187 +Ushida, Mokhtarani+ (FNAL E653 Collab.)
ADAMOVICH 91 PL B268 142 +Alexandrov, Antinori, Barberis+ (WA82 Collab.)
ALBRECHT 91 PL B255 634 +Ehrlichmann, Hamacher, Krueger+ (ARGUS Collab.)
ALVAREZ 91 PL B255 639 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ALVAREZ 91B ZPHY C50 11 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
AMMAR 91 PR D44 3383 +Baringer, Coppage, Davis+ (CLEO Collab.)
ANJOS 91B PR D43 R2063 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
ANJOS 91C PRL 67 1507 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
BAI 91 PRL 66 1011 +Bolton, Brown, Bunnell+ (Mark III Collab.)
COFFMAN 91 PL B263 135 +DeJongh, Dubois, Eigen, Hitlin+ (Mark III Collab.)
FRABETTI 91 PL B263 584 +Bogart, Cheung, Culy+ (FNAL E687 Collab.)
ALVAREZ 90 ZPHY C47 539 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ALVAREZ 90C PL B246 261 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ANJOS 90C PR D41 2705 +Appel, Bean+ (FNAL E691 Collab.)
ANJOS 90D PR D42 2414 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
ANJOS 90E PRL 65 2630 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
BARLAG 90C ZPHY C46 563 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
WEIR 90B PR D41 1384 +Klein, Abrams, Adolphsen, Akerlof+ (Mark II Collab.)
ANJOS 89 PRL 62 125 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
ANJOS 89B PRL 62 722 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
ANJOS 89E PL B223 267 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
ADLER 88B PRL 60 1375 +Becker, Blaylock+ (Mark III Collab.)
ADLER 88C PRL 60 89 +Becker, Blaylock+ (Mark III Collab.)
ALBRECHT 88I PL B210 267 +Boeckmann, Glaeser+ (ARGUS Collab.)
ANJOS 88 PRL 60 897 +Appel+ (FNAL E691 Collab.)
AOKI 88 PL B209 113 +Arnold, Baroni+ (WA75 Collab.)
HAAS 88 PRL 60 1614 +Hempstead, Jensen+ (CLEO Collab.)
ONG 88 PRL 60 2587 +Weir, Abrams, Amidei+ (Mark II Collab.)
RAAB 88 PR D37 2391 +Anjos, Appel, Bracker+ (FNAL E691 Collab.)
ADAMOVICH 87 EPL 4 887 +Alexandrov, Bolta+ (Photon Emulsion Collab.)
ADLER 87 PL B196 107 +Becker, Blaylock, Bolton+ (Mark III Collab.)
AGUILAR-... 87D PL B193 140 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88B ZPHY C40 321 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
AGUILAR-... 87E ZPHY C36 551 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88B ZPHY C40 321 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
AGUILAR-... 87F ZPHY C36 559 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88 ZPHY C38 520 erratum
BARLAG 87B ZPHY C37 17 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
BARTEL 87 ZPHY C33 339 +Becker, Felst, Haidt+ (JADE Collab.)
CSORNA 87 PL B191 318 +Mestayer, Panvini, Word+ (CLEO Collab.)
PALKA 87B ZPHY C35 151 +Bailey, Becker+ (ACCMOR Collab.)
ABE 86 PR D33 1 + (SLAC Hybrid Facility Photon Collab.)
AGUILAR-... 86B ZPHY C31 491 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
BALTRUSAIT... 86E PRL 56 2140 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
PAL 86 PR D33 2708 +Atwood, Barish, Bonneaud+ (DELCO Collab.)
AIHARA 85 ZPHY C27 39 +Alston-Garnjost, Badtke, Bakken+ (TPC Collab.)
BALTRUSAIT... 85B PRL 54 1976 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BALTRUSAIT... 85E PRL 55 150 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BARTEL 85J PL 163B 277 +Becker, Cords, Felst+ (JADE Collab.)
ADAMOVICH 84 PL 140B 119 +Alexandrov, Bolta, Bravo+ (CERN WA58 Collab.)
ALTHOFF 84G ZPHY C22 219 +Braunschweig, Kirschfink+ (TASSO Collab.)
ALTHOFF 84J PL 146B 443 +Branschweig, Kirschfink+ (TASSO Collab.)
DERRICK 84 PRL 53 1971 +Fernandez, Fries, Hyman+ (HRS Collab.)
KOOP 84 PRL 52 970 +Sakuda, Atwood, Baillon+ (DELCO Collab.)
PARTRIDGE 84 Thesis CALT-68-1150 (Crystal Ball Collab.)
AGUILAR-... 83B PL 123B 98 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
AUBERT 83 NP B213 31 +Bassompierre, Becks, Best+ (EMC Collab.)
PARTRIDGE 81 PRL 47 760 +Peck, Porter, Gu+ (Crystal Ball Collab.)
SCHINDLER 81 PR D24 78 +Alam, Boyarski, Breidenbach+ (Mark II Collab.)
TRILLING 81 PRPL 75 57 (LBL, UCB) J
BACINO 80 PRL 45 329 +Ferguson+ (DELCO Collab.)
SCHINDLER 80 PR D21 2716 +Siegrist, Alam, Boyarski+ (Mark II Collab.)
ZHOLENTZ 80 PL 96B 214 +Kurdadze, Lelchuk, Mishnev+ (NOVO)
Also 81 SJNP 34 814 Zholentz, Kurdadze, Lelchuk+ (NOVO)
Translated from YAF 34 1471.
BACINO 79 PRL 43 1073 +Ferguson, Nodulman+ (DELCO Collab.)
BRANDELIK 79 PL 80B 412 +Braunschweig, Martyn, Sander+ (DASP Collab.)
FELLER 78 PRL 40 274 +Litke, Madaras, Ronan+ (Mark I Collab.)
VUILLEMIN 78 PRL 41 1149 +Feldman, Feller+ (Mark I Collab.)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (Mark I Collab.)
PERUZZI 77 PRL 39 1301 +Piccolo, Feldman+ (Mark I Collab.)
PICCOLO 77 PL 70B 260 +Peruzzi, Luth, Nguyen, Wiss, Abrams+ (Mark I Collab.)
RAPIDIS 77 PRL 39 526 +Gobbi, Luke, Barbaro-Galtieri+ (Mark I Collab.)
PERUZZI 76 PRL 37 569 +Piccolo, Feldman, Nguyen, Wiss+ (Mark I Collab.)

OTHER RELATED PAPERS

RICHMAN 95 RMP 67 893 +Burchat (UCSB, STAN)
ROSNER 95 CNPP 21 369 (CHIC)

D^0

$I(J^P) = \frac{1}{2}(0^-)$

D^0 MASS

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1864.5± 0.5 OUR FIT Error includes scale factor of 1.1.					
1864.1± 1.0 OUR AVERAGE					
1864.6± 0.3±1.0	641	BARLAG	90C	ACCM	π^- Cu 230 GeV
1852 ± 7	16	ADAMOVICH	87	EMUL	Photoproduction
1861 ± 4		DERRICK	84	HRS	e^+e^- 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1856 ±36	22	ADAMOVICH	84B	EMUL	Photoproduction
1847 ± 7	1	FIORINO	81	EMUL	$\gamma N \to \overline{D}^0 +$
1863.8± 0.5		[1] SCHINDLER	81	MRK2	e^+e^- 3.77 GeV
1864.7± 0.6		[1] TRILLING	81	RVUE	e^+e^- 3.77 GeV
1863.0± 2.5	238	ASTON	80E	OMEG	$\gamma p \to \overline{D}^0$
1860 ± 2	143	[2] AVERY	80	SPEC	$\gamma N \to D^{*+}$
1869 ± 4	35	[2] AVERY	80	SPEC	$\gamma N \to D^{*+}$
1854 ± 6	94	[2] ATIYA	79	SPEC	$\gamma N \to D^0 \overline{D}^0$
1850 ±15	64	BALTAY	78C	HBC	$\nu N \to K^0 \pi\pi$
1863 ± 3		GOLDHABER	77	MRK1	D^0, D^+ recoil spectra
1863.3± 0.9		[1] PERUZZI	77	MRK1	e^+e^- 3.77 GeV
1868 ±11		PICCOLO	77	MRK1	e^+e^- 4.03, 4.41 GeV
1865 ±15	234	GOLDHABER	76	MRK1	$K\pi$ and $K3\pi$

[1] PERUZZI 77 and SCHINDLER 81 errors do not include the 0.13% uncertainty in the absolute SPEAR energy calibration. TRILLING 81 uses the high precision $J/\psi(1S)$ and $\psi(2S)$ measurements of ZHOLENTZ 80 to determine this uncertainty and combines the PERUZZI 77 and SCHINDLER 81 results to obtain the value quoted. TRILLING 81 enters the fit in the $D^{\pm}$ mass, and PERUZZI 77 and SCHINDLER 81 enter in the $m_{D^{\pm}} - m_{D^0}$, below.

[2] Error does not include possible systematic mass scale shift, estimated to be less than 5 MeV.

$|m_{D^0_1} - m_{D^0_2}|$

The D^0_1 and D^0_2 are the mass eigenstates of the D^0 meson.

VALUE (10^{10} $\hbar$ s^{-1})	CL%	DOCUMENT ID		TECN	COMMENT
< 21	90	[3,4] ANJOS	88C	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 40	90	[3] ALBRECHT	87K	ARG	e^+e^- 10 GeV
< 24	90	[5] LOUIS	86	SPEC	π^- W 225 GeV
<106	90	[3,6] YAMAMOTO	85	DLCO	e^+e^- 29 GeV
< 99	90	[5] BODEK	82	SPEC	π^-, pFe $\to$ D^0

[3] Limit inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-)$ near the end of the D^0 Listings.

[4] Calculated by us using $\Delta m = (2r/(1-r))^{1/2}\hbar/4.15 \times 10^{-13}$ s, where r is the D^0-$\overline{D}^0$ mixing ratio. See the data on $r \equiv \Gamma(K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-)$ near the end of the D^0 Listings.

[5] Limit inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(\mu^-$ anything (via $\overline{D}^0))/\Gamma(\mu^+$ anything) near the end of the D^0 Listings.

[6] YAMAMOTO 85 gives $\Delta m/\Gamma < 0.44$. We use $\Gamma = \hbar/4.15 \times 10^{-13}$ s.

$m_{D^\pm} - m_{D^0}$

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4.78±0.10 OUR FIT				
4.74±0.28 OUR AVERAGE				
4.7 ±0.3	[7] SCHINDLER	81	MRK2	e^+e^- 3.77 GeV
5.0 ±0.8	[7] PERUZZI	77	MRK1	e^+e^- 3.77 GeV

[7] See the footnote on TRILLING 81 in the D^0 and $D^\pm$ sections on the mass.

D^0 MEAN LIFE

Measurements with an error $> 0.05 \times 10^{-12}$ s are omitted from the average, and those with an error $> 0.1 \times 10^{-12}$ s or that have been superseded by later results have been removed from the Listings.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.415±0.004 OUR AVERAGE					
0.413±0.004±0.003	16k	FRABETTI	94D	E687	$K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$
0.424±0.011±0.007	5118	FRABETTI	91	E687	$K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$
0.417±0.018±0.015	890	ALVAREZ	90	NA14	$K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$
$0.388^{+0.023}_{-0.021}$	641	[8] BARLAG	90C	ACCM	π^- Cu 230 GeV
0.48 ±0.04 ±0.03	776	ALBRECHT	88I	ARG	e^+e^- 10 GeV
0.422±0.008±0.010	4212	RAAB	88	E691	Photoproduction
0.42 ±0.05	90	BARLAG	87B	ACCM	K^- and π^- 200 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.34^{+0.06}_{-0.05}$ ±0.03	58	AMENDOLIA	88	SPEC	Photoproduction
$0.46^{+0.06}_{-0.05}$	145	AGUILAR-...	87D	HYBR	π^-p and pp
0.50 ±0.07 ±0.04	317	CSORNA	87	CLEO	e^+e^- 10 GeV
0.61 ±0.09 ±0.03	50	ABE	86	HYBR	γp 20 GeV
$0.47^{+0.09}_{-0.08}$ ±0.05	74	GLADNEY	86	MRK2	e^+e^- 29 GeV
$0.43^{+0.07}_{-0.05}$ $^{+0.01}_{-0.02}$	58	USHIDA	86B	EMUL	ν wideband
$0.37^{+0.10}_{-0.07}$	26	BAILEY	85	SILI	π^- Be 200 GeV

[8] BARLAG 90C estimate systematic error to be negligible.

$|\Gamma_{D^0_1} - \Gamma_{D^0_2}|/\Gamma_{D^0}$ MEAN LIFE DIFFERENCE/AVERAGE

The D^0_1 and D^0_2 are the mass eigenstates of the D^0 meson.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.17	90	[9,10] ANJOS	88C	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.21	90	[11] LOUIS	86	SPEC	π^- W 225 GeV
<0.8	90	[9] YAMAMOTO	85	DLCO	e^+e^- 29 GeV
<0.55	90	[11] BODEK	82	SPEC	π^-, pFe $\to$ D^0

[9] This limit is inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-)$ near the end of the D^0 Listings.

[10] Calculated by us using $\Delta\Gamma/\Gamma = [8r/(1+r)]^{1/2}$, where r is the D^0-$\overline{D}^0$ mixing ratio. See the data on $r \equiv \Gamma(K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0))/\Gamma(K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-)$ near the end of the D^0 Listings.

[11] Limit inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(\mu^-$ anything (via $\overline{D}^0))/\Gamma(\mu^+$ anything) near the end of the D^0 Listings.

D^0 DECAY MODES

$\overline{D}^0$ modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes			
Γ_1	e^+ anything		(7.7 ±1.2) %	S=1.1
Γ_2	μ^+ anything	[a]	(6.8 ±1.0) %	
Γ_3	K^- anything		(53 ±4) %	S=1.3
Γ_4	$\overline{K}^0$ anything + K^0 anything		(42 ±5) %	
Γ_5	K^+ anything		($3.4^{+0.6}_{-0.4}$) %	
Γ_6	η anything	[b]	< 13 %	CL=90%
	Semileptonic modes			
Γ_7	$K^-\ell^+\nu_\ell$	[c]	(3.48±0.16) %	S=1.1
Γ_8	$K^-e^+\nu_e$		(3.64±0.20) %	S=1.1
Γ_9	$K^-\mu^+\nu_\mu$		(3.23±0.19) %	
Γ_{10}	$K^-\pi^0 e^+\nu_e$		($1.6^{+1.3}_{-0.5}$) %	
Γ_{11}	$\overline{K}^0\pi^- e^+\nu_e$		($2.8^{+1.7}_{-0.9}$) %	
Γ_{12}	$\overline{K}^*(892)^- e^+\nu_e$ $\times$ B($K^{*-} \to \overline{K}^0\pi^-$)		(1.34±0.22) %	
Γ_{13}	$K^*(892)^-\ell^+\nu_\ell$			
Γ_{14}	$K^-\pi^0(\pi^0)e^+\nu_e$			
Γ_{15}	$\overline{K}^0\pi^-(\pi^0)e^+\nu_e$			
Γ_{16}	$\overline{K}^*(892)^0\pi^- e^+\nu_e$			
Γ_{17}	$K^-\pi^+\pi^-\mu^+\nu_\mu$		< 1.2 $\times 10^{-3}$	CL=90%
Γ_{18}	$(\overline{K}^*(892)\pi)^-\mu^+\nu_\mu$		< 1.4 $\times 10^{-3}$	CL=90%
Γ_{19}	$\pi^- e^+\nu_e$		($3.8^{+1.2}_{-1.0}$) $\times 10^{-3}$	

A fraction of the following resonance mode has already appeared above as a submode of a charged-particle mode.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_{20}	$K^*(892)^- e^+\nu_e$		(2.01±0.33) %	
	Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$			
Γ_{21}	$K^-\pi^+$		(3.83±0.12) %	
Γ_{22}	$\overline{K}^0\pi^0$		(2.11±0.21) %	S=1.1
Γ_{23}	$\overline{K}^0\pi^+\pi^-$	[d]	(5.4 ±0.4) %	S=1.2
Γ_{24}	$\overline{K}^0\rho^0$		(1.20±0.17) %	
Γ_{25}	$\overline{K}^0 f_0(980)$ $\times$ B($f_0 \to \pi^+\pi^-$)		(3.0 ±0.8) $\times 10^{-3}$	
Γ_{26}	$\overline{K}^0 f_2(1270)$ $\times$ B($f_2 \to \pi^+\pi^-$)		(2.3 ±0.9) $\times 10^{-3}$	
Γ_{27}	$\overline{K}^0 f_0(1370)$ $\times$ B($f_0 \to \pi^+\pi^-$)		(4.3 ±1.3) $\times 10^{-3}$	
Γ_{28}	$K^*(892)^-\pi^+$ $\times$ B($K^{*-} \to \overline{K}^0\pi^-$)		(3.3 ±0.3) %	
Γ_{29}	$K_0^*(1430)^-\pi^+$ $\times$ B($K_0^*(1430)^- \to \overline{K}^0\pi^-$)		(6.4 ±1.6) $\times 10^{-3}$	
Γ_{30}	$\overline{K}^0\pi^+\pi^-$ nonresonant		(1.46±0.24) %	
Γ_{31}	$K^-\pi^+\pi^0$	[d]	(13.9 ±0.9) %	S=1.3
Γ_{32}	$K^-\rho^+$		(10.8 ±1.0) %	
Γ_{33}	$K^*(892)^-\pi^+$ $\times$ B($K^{*-} \to K^-\pi^0$)		(1.7 ±0.2) %	
Γ_{34}	$\overline{K}^*(892)^0\pi^0$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)		(2.1 ±0.3) %	
Γ_{35}	$K^-\pi^+\pi^0$ nonresonant		(6.9 ±2.5) $\times 10^{-3}$	
Γ_{36}	$\overline{K}^0\pi^0\pi^0$			
Γ_{37}	$\overline{K}^*(892)^0\pi^0$ $\times$ B($\overline{K}^{*0} \to \overline{K}^0\pi^0$)		(1.0 ±0.2) %	
Γ_{38}	$\overline{K}^0\pi^0\pi^0$ nonresonant		(7.8 ±2.0) $\times 10^{-3}$	
Γ_{39}	$K^-\pi^+\pi^+\pi^-$	[d]	(7.5 ±0.4) %	S=1.1
Γ_{40}	$K^-\pi^+\rho^0$ total		(6.3 ±0.4) %	
Γ_{41}	$K^-\pi^+\rho^0$ 3-body		(4.7 ±2.1) $\times 10^{-3}$	
Γ_{42}	$\overline{K}^*(892)^0\rho^0$ $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)		(9.8 ±2.2) $\times 10^{-3}$	
Γ_{43}	$K^- a_1(1260)^+$ $\times$ B($a_1(1260)^+ \to \pi^+\pi^+\pi^-$)		(3.6 ±0.6) %	
Γ_{44}	$\overline{K}^*(892)^0\pi^+\pi^-$ total $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)		(1.5 ±0.4) %	
Γ_{45}	$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body $\times$ B($\overline{K}^{*0} \to K^-\pi^+$)		(9.5 ±2.1) $\times 10^{-3}$	

Γ_{46}	$K_1(1270)^-\pi^+$	[e]	$(3.6 \pm 1.0) \times 10^{-3}$	
	$\times$ B$(K_1(1270)^- \to K^-\pi^+\pi^-)$			
Γ_{47}	$K^-\pi^+\pi^+\pi^-$ nonresonant		(1.75 ± 0.25) %	
Γ_{48}	$\overline{K}^0\pi^+\pi^-\pi^0$	[d]	(10.0 ± 1.2) %	
Γ_{49}	$\overline{K}^0\eta \times$ B$(\eta \to \pi^+\pi^-\pi^0)$		$(1.6 \pm 0.3) \times 10^{-3}$	
Γ_{50}	$\overline{K}^0\omega \times$ B$(\omega \to \pi^+\pi^-\pi^0)$		(1.9 ± 0.4) %	
Γ_{51}	$K^*(892)^-\rho^+$		(4.0 ± 1.6) %	
	$\times$ B$(K^{*-} \to \overline{K}^0\pi^-)$			
Γ_{52}	$\overline{K}^*(892)^0\rho^0$		$(4.9 \pm 1.1) \times 10^{-3}$	
	$\times$ B$(\overline{K}^{*0} \to \overline{K}^0\pi^0)$			
Γ_{53}	$K_1(1270)^-\pi^+$	[e]	$(5.1 \pm 1.4) \times 10^{-3}$	
	$\times$ B$(K_1(1270)^- \to \overline{K}^0\pi^-\pi^0)$			
Γ_{54}	$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body		$(4.7 \pm 1.1) \times 10^{-3}$	
	$\times$ B$(\overline{K}^{*0} \to \overline{K}^0\pi^0)$			
Γ_{55}	$\overline{K}^0\pi^+\pi^-\pi^0$ nonresonant		(2.1 ± 2.1) %	
Γ_{56}	$K^-\pi^+\pi^0\pi^0$		(15 ± 5) %	
Γ_{57}	$K^-\pi^+\pi^+\pi^-\pi^0$		(4.0 ± 0.4) %	
Γ_{58}	$\overline{K}^*(892)^0\pi^+\pi^-\pi^0$		(1.2 ± 0.6) %	
	$\times$ B$(\overline{K}^{*0} \to K^-\pi^+)$			
Γ_{59}	$\overline{K}^*(892)^0\eta$		$(3.0 \pm 0.8) \times 10^{-3}$	
	$\times$ B$(\overline{K}^{*0} \to K^-\pi^+)$			
	$\times$ B$(\eta \to \pi^+\pi^-\pi^0)$			
Γ_{60}	$K^-\pi^+\omega \times$ B$(\omega \to \pi^+\pi^-\pi^0)$		(2.7 ± 0.5) %	
Γ_{61}	$\overline{K}^*(892)^0\omega$		$(7 \pm 3) \times 10^{-3}$	
	$\times$ B$(\overline{K}^{*0} \to K^-\pi^+)$			
	$\times$ B$(\omega \to \pi^+\pi^-\pi^0)$			
Γ_{62}	$\overline{K}^0\pi^+\pi^+\pi^-\pi^-$		$(5.8 \pm 1.6) \times 10^{-3}$	
Γ_{63}	$\overline{K}^0\pi^+\pi^-\pi^0\pi^0(\pi^0)$		$(10.6\ ^{+7.3}_{-3.0})$ %	
Γ_{64}	$\overline{K}^0K^+K^-$		$(9.3 \pm 1.0) \times 10^{-3}$	
	In the fit as $\frac{1}{2}\Gamma_{76} + \Gamma_{66}$, where $\frac{1}{2}\Gamma_{76} = \Gamma_{65}$.			
Γ_{65}	$\overline{K}^0\phi \times$ B$(\phi \to K^+K^-)$		$(4.2 \pm 0.5) \times 10^{-3}$	
Γ_{66}	$\overline{K}^0K^+K^-$ non-ϕ		$(5.0 \pm 0.8) \times 10^{-3}$	
Γ_{67}	$K^0_S K^0_S K^0_S$		$(9.7 \pm 2.3) \times 10^{-4}$	
Γ_{68}	$K^+K^-K^-\pi^+$		$(2.1 \pm 0.5) \times 10^{-4}$	
Γ_{69}	$K^+K^-\overline{K}^0\pi^0$		$(7.2\ ^{+4.8}_{-3.5}) \times 10^{-3}$	

Fractions of many of the following modes with resonances have already appeared above as submodes of particular charged-particle modes. (Modes for which there are only upper limits and $\overline{K}^*(892)\rho$ submodes only appear below.)

Γ_{70}	$\overline{K}^0\eta$		$(7.0 \pm 1.0) \times 10^{-3}$	
Γ_{71}	$\overline{K}^0\rho^0$		(1.20 ± 0.17) %	
Γ_{72}	$K^-\rho^+$		(10.8 ± 1.0) %	S=1.2
Γ_{73}	$\overline{K}^0\omega$		(2.1 ± 0.4) %	
Γ_{74}	$\overline{K}^0\eta'(958)$		(1.70 ± 0.26) %	
Γ_{75}	$\overline{K}^0 f_0(980)$		$(5.7 \pm 1.6) \times 10^{-3}$	
Γ_{76}	$\overline{K}^0\phi$		$(8.5 \pm 1.0) \times 10^{-3}$	
Γ_{77}	$K^- a_1(1260)^+$		(7.3 ± 1.1) %	
Γ_{78}	$\overline{K}^0 a_1(1260)^0$		< 1.9 %	CL=90%
Γ_{79}	$\overline{K}^0 f_2(1270)$		$(4.1 \pm 1.5) \times 10^{-3}$	
Γ_{80}	$\overline{K}^0 f_0(1370)$		$(6.9 \pm 2.1) \times 10^{-3}$	
Γ_{81}	$K^- a_2(1320)^+$		$< 2 \times 10^{-3}$	CL=90%
Γ_{82}	$K^*(892)^-\pi^+$		(5.0 ± 0.4) %	S=1.2
Γ_{83}	$\overline{K}^*(892)^0\pi^0$		(3.1 ± 0.4) %	
Γ_{84}	$\overline{K}^*(892)^0\pi^+\pi^-$ total		(2.3 ± 0.5) %	
Γ_{85}	$\overline{K}^*(892)^0\pi^+\pi^-$ 3-body		(1.42 ± 0.32) %	
Γ_{86}	$K^-\pi^+\rho^0$ total		(6.3 ± 0.4) %	
Γ_{87}	$K^-\pi^+\rho^0$ 3-body		$(4.7 \pm 2.1) \times 10^{-3}$	
Γ_{88}	$\overline{K}^*(892)^0\rho^0$		(1.47 ± 0.33) %	
Γ_{89}	$\overline{K}^*(892)^0\rho^0$ transverse		(1.5 ± 0.5) %	
Γ_{90}	$\overline{K}^*(892)^0\rho^0$ S-wave		(2.8 ± 0.6) %	
Γ_{91}	$\overline{K}^*(892)^0\rho^0$ S-wave long.		$< 3 \times 10^{-3}$	CL=90%
Γ_{92}	$\overline{K}^*(892)^0\rho^0$ P-wave		$< 3 \times 10^{-3}$	CL=90%
Γ_{93}	$\overline{K}^*(892)^0\rho^0$ D-wave		(1.9 ± 0.6) %	
Γ_{94}	$K^*(892)^-\rho^+$		(6.0 ± 2.4) %	
Γ_{95}	$K^*(892)^-\rho^+$ longitudinal		(2.9 ± 1.2) %	
Γ_{96}	$K^*(892)^-\rho^+$ transverse		(3.2 ± 1.8) %	
Γ_{97}	$K^*(892)^-\rho^+$ P-wave		< 1.5 %	CL=90%
Γ_{98}	$K^-\pi^+ f_0(980)$		< 1.1 %	CL=90%
Γ_{99}	$\overline{K}^*(892)^0 f_0(980)$		$< 7 \times 10^{-3}$	CL=90%
Γ_{100}	$K_1(1270)^-\pi^+$	[e]	(1.06 ± 0.29) %	
Γ_{101}	$K_1(1400)^-\pi^+$		< 1.2 %	CL=90%
Γ_{102}	$\overline{K}_1(1400)^0\pi^0$		< 3.7 %	CL=90%
Γ_{103}	$K^*(1410)^-\pi^+$		< 1.2 %	CL=90%
Γ_{104}	$K^*_0(1430)^-\pi^+$		(1.04 ± 0.26) %	
Γ_{105}	$K^*_2(1430)^-\pi^+$		$< 8 \times 10^{-3}$	CL=90%
Γ_{106}	$\overline{K}^*_2(1430)^0\pi^0$		$< 4 \times 10^{-3}$	CL=90%
Γ_{107}	$\overline{K}^*(892)^0\pi^+\pi^-\pi^0$		(1.8 ± 0.9) %	
Γ_{108}	$\overline{K}^*(892)^0\eta$		(1.9 ± 0.5) %	
Γ_{109}	$K^-\pi^+\omega$		(3.0 ± 0.6) %	
Γ_{110}	$\overline{K}^*(892)^0\omega$		(1.1 ± 0.4) %	
Γ_{111}	$K^-\pi^+\eta'(958)$		$(7.0 \pm 1.8) \times 10^{-3}$	
Γ_{112}	$\overline{K}^*(892)^0\eta'(958)$		$< 1.1 \times 10^{-3}$	CL=90%

Pionic modes

Γ_{113}	$\pi^+\pi^-$		$(1.52 \pm 0.11) \times 10^{-3}$	
Γ_{114}	$\pi^0\pi^0$		$(8.4 \pm 2.2) \times 10^{-4}$	
Γ_{115}	$\pi^+\pi^-\pi^0$		(1.6 ± 1.1) %	S=2.7
Γ_{116}	$\pi^+\pi^+\pi^-\pi^-$		$(7.4 \pm 0.6) \times 10^{-3}$	
Γ_{117}	$\pi^+\pi^+\pi^-\pi^-\pi^0$		(1.9 ± 0.4) %	
Γ_{118}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$		$(4.0 \pm 3.0) \times 10^{-4}$	

Hadronic modes with a $K\overline{K}$ pair

Γ_{119}	K^+K^-		$(4.33 \pm 0.27) \times 10^{-3}$	
Γ_{120}	$K^0\overline{K}^0$		$(1.3 \pm 0.4) \times 10^{-3}$	
Γ_{121}	$K^0K^-\pi^+$		$(6.4 \pm 1.0) \times 10^{-3}$	S=1.1
Γ_{122}	$\overline{K}^*(892)^0K^0$		$< 1.1 \times 10^{-3}$	CL=90%
	$\times$ B$(\overline{K}^{*0} \to K^-\pi^+)$			
Γ_{123}	$K^*(892)^+K^-$		$(2.3 \pm 0.5) \times 10^{-3}$	
	$\times$ B$(K^{*+} \to K^0\pi^+)$			
Γ_{124}	$K^0K^-\pi^+$ nonresonant		$(2.3 \pm 2.3) \times 10^{-3}$	
Γ_{125}	$\overline{K}^0K^+\pi^-$		$(4.9 \pm 1.0) \times 10^{-3}$	
Γ_{126}	$K^*(892)^0\overline{K}^0$		$< 5 \times 10^{-4}$	CL=90%
	$\times$ B$(K^{*0} \to K^+\pi^-)$			
Γ_{127}	$K^*(892)^-K^+$		$(1.2 \pm 0.7) \times 10^{-3}$	
	$\times$ B$(K^{*-} \to \overline{K}^0\pi^-)$			
Γ_{128}	$\overline{K}^0K^+\pi^-$ nonresonant		$(3.8\ ^{+2.3}_{-1.9}) \times 10^{-3}$	
Γ_{129}	$K^+K^-\pi^+\pi^-$	[f]	$(2.58 \pm 0.28) \times 10^{-3}$	
Γ_{130}	$\phi\pi^+\pi^- \times$ B$(\phi \to K^+K^-)$		$(5.3 \pm 1.4) \times 10^{-4}$	
Γ_{131}	$\phi\rho^0 \times$ B$(\phi \to K^+K^-)$		$(5.3 \pm 1.4) \times 10^{-4}$	
Γ_{132}	$K^+K^-\rho^0$ 3-body		$(9.0 \pm 2.3) \times 10^{-4}$	
Γ_{133}	$K^*(892)^0K^-\pi^+$		$(2.1 \pm 0.9) \times 10^{-3}$	
	$\times$ B$(K^{*0} \to K^+\pi^-)$			
Γ_{134}	$\overline{K}^*(892)^0K^+\pi^-$		$(1.1 \pm 0.8) \times 10^{-3}$	
	$\times$ B$(\overline{K}^{*0} \to K^-\pi^+)$			
Γ_{135}	$K^*(892)^0\overline{K}^*(892)^0$		$(6 \pm 2) \times 10^{-4}$	
	$\times$ B$^2(K^{*0} \to K^+\pi^-)$			
Γ_{136}	$K^+K^-\pi^+\pi^-$ non-ϕ		$(1.7 \pm 0.5) \times 10^{-3}$	
Γ_{137}	$K^+K^-\pi^+\pi^-$ nonresonant		$< 8 \times 10^{-4}$	CL=90%
Γ_{138}	$K^0\overline{K}^0\pi^+\pi^-$		$(6.8 \pm 2.7) \times 10^{-3}$	
Γ_{139}	$K^+K^-\pi^+\pi^-\pi^0$		$(3.1 \pm 2.0) \times 10^{-3}$	

Fractions of most of the following modes with resonances have already appeared above as submodes of particular charged-particle modes.

Γ_{140}	$\overline{K}^*(892)^0K^0$		$< 1.6 \times 10^{-3}$	CL=90%
Γ_{141}	$K^*(892)^+K^-$		$(3.5 \pm 0.8) \times 10^{-3}$	
Γ_{142}	$K^*(892)^0\overline{K}^0$		$< 8 \times 10^{-4}$	CL=90%
Γ_{143}	$K^*(892)^-K^+$		$(1.8 \pm 1.0) \times 10^{-3}$	
Γ_{144}	$\phi\pi^0$		$< 1.4 \times 10^{-3}$	CL=90%
Γ_{145}	$\phi\eta$		$< 2.8 \times 10^{-3}$	CL=90%
Γ_{146}	$\phi\omega$		$< 2.1 \times 10^{-3}$	CL=90%
Γ_{147}	$\phi\pi^+\pi^-$		$(1.07 \pm 0.29) \times 10^{-3}$	
Γ_{148}	$\phi\rho^0$		$(1.07 \pm 0.29) \times 10^{-3}$	
Γ_{149}	$\phi\pi^+\pi^-$ 3-body		$< 5 \times 10^{-4}$	CL=90%
Γ_{150}	$K^*(892)^0K^-\pi^+$ + c.c.			
Γ_{151}	$K^*(892)^0K^-\pi^+$		$(3.2 \pm 1.3) \times 10^{-3}$	
Γ_{152}	$\overline{K}^*(892)^0K^+\pi^-$		$(1.7 \pm 1.2) \times 10^{-3}$	
Γ_{153}	$K^*(892)^0\overline{K}^*(892)^0$		$(1.4 \pm 0.5) \times 10^{-3}$	

Doubly Cabibbo suppressed (*DC*) modes, $\Delta C = 2$ forbidden via mixing (*C2M*) modes, $\Delta C = 1$ weak neutral current (*C1*) modes, or Lepton Family number (*LF*) violating modes

Γ_{154}	$K^+\pi^-$	DC		$(2.9 \pm 1.4) \times 10^{-4}$	
Γ_{155}	$K^+\pi^-$ (via $\overline{D}^0$)	C2M		$< 1.9 \times 10^{-4}$	CL=90%
Γ_{156}	$K^+\pi^-\pi^+\pi^-$	DC		$< 1.4 \times 10^{-3}$	CL=90%
Γ_{157}	$K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0$)	C2M		$< 4 \times 10^{-4}$	CL=90%
Γ_{158}	μ^- anything (via $\overline{D}^0$)	C2M		$< 4 \times 10^{-4}$	CL=90%
Γ_{159}	e^+e^-	C1		$< 1.3 \times 10^{-5}$	CL=90%
Γ_{160}	$\mu^+\mu^-$	C1		$< 7.6 \times 10^{-6}$	CL=90%
Γ_{161}	$\pi^0 e^+e^-$	C1		$< 4.5 \times 10^{-5}$	CL=90%
Γ_{162}	$\pi^0\mu^+\mu^-$	C1		$< 1.8 \times 10^{-4}$	CL=90%
Γ_{163}	ηe^+e^-	C1		$< 1.1 \times 10^{-4}$	CL=90%
Γ_{164}	$\eta\mu^+\mu^-$	C1		$< 5.3 \times 10^{-4}$	CL=90%
Γ_{165}	$\rho^0 e^+e^-$	C1		$< 1.0 \times 10^{-4}$	CL=90%
Γ_{166}	$\rho^0\mu^+\mu^-$	C1		$< 2.3 \times 10^{-4}$	CL=90%
Γ_{167}	ωe^+e^-	C1		$< 1.8 \times 10^{-4}$	CL=90%
Γ_{168}	$\omega\mu^+\mu^-$	C1		$< 8.3 \times 10^{-4}$	CL=90%
Γ_{169}	ϕe^+e^-	C1		$< 5.2 \times 10^{-5}$	CL=90%
Γ_{170}	$\phi\mu^+\mu^-$	C1		$< 4.1 \times 10^{-4}$	CL=90%
Γ_{171}	$\overline{K}^0 e^+e^-$		[g]	$< 1.1 \times 10^{-4}$	CL=90%
Γ_{172}	$\overline{K}^0\mu^+\mu^-$		[g]	$< 2.6 \times 10^{-4}$	CL=90%
Γ_{173}	$\overline{K}^*(892)^0 e^+e^-$		[g]	$< 1.4 \times 10^{-4}$	CL=90%
Γ_{174}	$\overline{K}^*(892)^0\mu^+\mu^-$		[g]	$< 1.18 \times 10^{-3}$	CL=90%
Γ_{175}	$\pi^+\pi^-\pi^0\mu^+\mu^-$	C1		$< 8.1 \times 10^{-4}$	CL=90%
Γ_{176}	$\mu^\pm e^\mp$	LF	[h]	$< 1.9 \times 10^{-5}$	CL=90%
Γ_{177}	$\pi^0 e^\pm\mu^\mp$	LF	[h]	$< 8.6 \times 10^{-5}$	CL=90%
Γ_{178}	$\eta e^\pm\mu^\mp$	LF	[h]	$< 1.0 \times 10^{-4}$	CL=90%
Γ_{179}	$\rho^0 e^\pm\mu^\mp$	LF	[h]	$< 4.9 \times 10^{-5}$	CL=90%
Γ_{180}	$\omega e^\pm\mu^\mp$	LF	[h]	$< 1.2 \times 10^{-4}$	CL=90%
Γ_{181}	$\phi e^\pm\mu^\mp$	LF	[h]	$< 3.4 \times 10^{-5}$	CL=90%
Γ_{182}	$\overline{K}^0 e^\pm\mu^\mp$	LF	[h]	$< 1.0 \times 10^{-4}$	CL=90%
Γ_{183}	$\overline{K}^*(892)^0 e^\pm\mu^\mp$	LF	[h]	$< 1.0 \times 10^{-4}$	CL=90%
Γ_{184}	A dummy mode used by the fit.			(23.8 ± 3.5) %	S=1.1

[a] This value is calculated from the ratio $\Gamma(K^-\mu^+\nu_\mu)/\Gamma(\mu^+\text{anything})$ in these Particle Listings.

[b] This is a weighted average of $D^\pm$ (44%) and D^0 (56%) branching fractions. See "D^+ and $D^0 \to$ (ηanything) / (total D^+ and D^0)" under "D^+ Branching Ratios" in these Particle Listings.

[c] This value averages the e^+ and μ^+ branching fractions, after making a small phase-space adjustment to the μ^+ fraction to be able to use it as an e^+ fraction; hence our ℓ^+ is really an e^+.

[d] The branching fractions for this mode may differ from the sum of the submodes that contribute to it, due to interference effects. See the relevant papers.

[e] The two experiments determining this ratio are in serious disagreement. See the Particle Listings.

[f] The experiments on the division of this charge mode amongst its submodes disagree, and the submode branching fractions here add up to considerably more than the charged-mode fraction.

[g] This mode is not a useful test for a ΔC=1 weak neutral current because both quarks must change flavor in this decay.

[h] The value is for the sum of the charge states of particle/antiparticle states indicated.

CONSTRAINED FIT INFORMATION

An overall fit to 49 branching ratios uses 114 measurements and one constraint to determine 27 parameters. The overall fit has a $\chi^2 = 60.3$ for 88 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_8	x_9	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{31}	x_{39}	x_{48}
x_9	33									
x_{19}	10	3								
x_{20}	10	5	1							
x_{21}	59	56	6	9						
x_{22}	8	6	1	24	11					
x_{23}	10	8	1	36	14	66				
x_{31}	19	17	2	8	31	18	19			
x_{39}	21	20	2	3	36	4	6	11		
x_{48}	5	4	1	18	8	34	51	10	4	
x_{57}	14	13	1	2	23	3	4	7	34	2
x_{66}	5	4	0	16	7	30	46	9	3	23
x_{70}	5	4	1	17	7	58	47	11	3	24
x_{73}	4	3	0	13	5	24	37	7	3	43
x_{76}	6	5	1	22	9	40	60	12	4	30
x_{82}	9	7	1	31	13	56	84	20	5	43
x_{83}	9	8	1	7	15	25	19	44	5	10
x_{85}	5	4	0	1	8	1	1	2	22	1
x_{89}	3	3	0	2	5	3	5	2	12	9
x_{100}	3	2	0	7	4	13	20	4	4	40
x_{108}	5	5	1	2	9	4	5	24	3	2
x_{119}	31	29	3	5	52	6	8	16	19	4
x_{120}	3	3	0	6	5	12	17	4	2	9
x_{121}	6	5	1	14	9	26	39	9	3	20
x_{125}	5	4	0	11	8	20	30	7	3	15
x_{141}	3	2	0	11	4	20	30	6	2	15
x_{184}	−29	−26	−6	−36	−40	−55	−72	−54	−31	−69

	x_{57}	x_{66}	x_{70}	x_{73}	x_{76}	x_{82}	x_{83}	x_{85}	x_{89}	x_{100}
x_{66}	2									
x_{70}	2	22								
x_{73}	1	17	17							
x_{76}	2	7	28	22						
x_{82}	3	39	40	31	50					
x_{83}	3	9	15	7	12	18				
x_{85}	7	1	1	1	1	1	1			
x_{89}	4	2	2	4	3	4	1	3		
x_{100}	2	9	10	17	12	17	4	1	4	
x_{108}	2	2	3	2	3	5	10	1	1	1
x_{119}	12	4	4	3	5	7	8	4	2	2
x_{120}	1	8	8	6	10	15	4	0	1	4
x_{121}	2	18	19	15	24	33	8	1	2	8
x_{125}	2	14	14	11	18	25	6	1	2	6
x_{141}	1	14	14	11	18	26	6	0	2	6
x_{184}	−25	−34	−39	−45	−44	−66	−41	−16	−24	−35

	x_{108}	x_{119}	x_{120}	x_{121}	x_{125}	x_{141}
x_{119}	5					
x_{120}	1	7				
x_{121}	2	5	7			
x_{125}	2	4	5	12		
x_{141}	1	2	5	12	9	
x_{184}	−26	−22	−15	−32	−25	−24

D^0 BRANCHING RATIOS

See the "Note on D Mesons" in the $D^{\pm}$ Listings.

Some older now obsolete results have been omitted from these Listings.

Inclusive modes

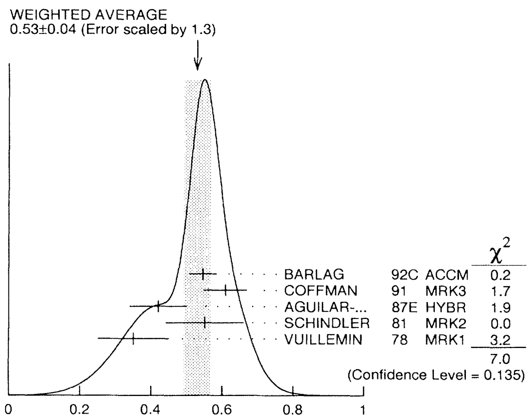
$\Gamma(e^+\text{anything})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.077±0.012 OUR AVERAGE		Error includes scale factor of 1.1.			
0.15 ±0.05		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.075±0.011±0.004	137	BALTRUSAIT...	85B	MRK3	e^+e^- 3.77 GeV
0.055±0.037	12	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K^-\text{anything})/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.53 ±0.04 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
$0.546^{+0.039}_{-0.038}$		[12] BARLAG	92C	ACCM	π^- Cu 230 GeV
0.609±0.032±0.052		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
0.42 ±0.08		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.55 ±0.11	121	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.35 ±0.10	19	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

[12] BARLAG 92C computes the branching fraction using topological normalization.



$\Gamma(K^-\text{anything})/\Gamma_{\text{total}}$

$[\Gamma(\overline{K}^0\text{anything}) + \Gamma(K^0\text{anything})]/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.42 ±0.05 OUR AVERAGE					
0.455±0.050±0.032		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
0.29 ±0.11	13	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV
0.57 ±0.26	6	VUILLEMIN	78	MRK1	e^+e^- 3.772 GeV

$\Gamma(K^+\text{anything})/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.034^{+0.006}_{-0.004}$ OUR AVERAGE					
$0.034^{+0.007}_{-0.005}$		[13] BARLAG	92C	ACCM	π^- Cu 230 GeV
0.028±0.009±0.004		COFFMAN	91	MRK3	e^+e^- 3.77 GeV
$0.03\ ^{+0.05}_{-0.02}$		AGUILAR-...	87E	HYBR	πp, pp 360, 400 GeV
0.08 ±0.03	25	SCHINDLER	81	MRK2	e^+e^- 3.771 GeV

[13] BARLAG 92C computes the branching fraction using topological normalization.

Semileptonic modes

$\Gamma(K^-\ell^+\nu_\ell)/\Gamma_{\text{total}}$ — Γ_7/Γ

We average our $K^-e^+\nu_e$ and $K^-\mu^+\nu_\mu$ branching fractions, after multiplying the latter by a phase-space factor of 1.03 to be able to use it with the $K^-e^+\nu_e$ fraction. Hence our ℓ^+ here is really an e^+.

VALUE	DOCUMENT ID		COMMENT
0.0349±0.0016 OUR AVERAGE	Error includes scale factor of 1.1.		
0.0364±0.0020	PDG	96	Our $\Gamma(K^-e^+\nu_e)/\Gamma_{\text{total}}$
0.0333±0.0020	PDG	96	1.03 × our $\Gamma(K^-\mu^+\nu_\mu)/\Gamma_{\text{total}}$

$\Gamma(K^-e^+\nu_e)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0364±0.0020 OUR FIT		Error includes scale factor of 1.1.			
0.034 ±0.005 ±0.004	55	ADLER	89	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-e^+\nu_e)/\Gamma(K^-\pi^+)$ — Γ_8/Γ_{21}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.95 ±0.04 OUR FIT					
0.95 ±0.04 OUR AVERAGE					
0.978±0.027±0.044	2510	[14] BEAN	93C	CLEO	$e^+e^- \approx \Upsilon(4S)$
0.90 ±0.06 ±0.06	584	[15] CRAWFORD	91B	CLEO	$e^+e^- \approx$ 10.5 GeV
0.91 ±0.07 ±0.11	250	[16] ANJOS	89F	E691	Photoproduction

[14] BEAN 93C uses $K^-\mu^+\nu_\mu$ as well as $K^-e^+\nu_e$ events and makes a small phase-space adjustment to the number of the μ^+ events to use them as e^+ events. A pole mass of 2.00 ± 0.12 ± 0.18 GeV/c^2 is obtained from the q^2 dependence of the decay rate.

[15] CRAWFORD 91B uses $K^-e^+\nu_e$ and $K^-\mu^+\nu_\mu$ candidates to measure a pole mass of $2.1^{+0.4}_{-0.2}{}^{+0.3}_{-0.2}$ GeV/c^2 from the q^2 dependence of the decay rate.

[16] ANJOS 89F measures a pole mass of $2.1^{+0.4}_{-0.2}$ ± 0.2 GeV/c^2 from the q^2 dependence of the decay rate.

$\Gamma(K^-\mu^+\nu_\mu)/\Gamma(K^-\pi^+)$ — Γ_9/Γ_{21}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.84 ±0.04 OUR FIT					
0.84 ±0.04 OUR AVERAGE					
0.852±0.034±0.028	1897	[17] FRABETTI	95G	E687	γ Be $\overline{E}_\gamma$ = 220 GeV
0.82 ±0.13 ±0.13	338	[18] FRABETTI	93I	E687	γ Be $\overline{E}_\gamma$ = 221 GeV
0.79 ±0.08 ±0.09	231	[19] CRAWFORD	91B	CLEO	$e^+e^- \approx$ 10.5 GeV

[17] FRABETTI 95G extracts the ratio of form factors $f_-(0)/f_+(0) = -1.3^{+3.6}_{-3.4} \pm 0.6$, and measures a pole mass of $1.87^{+0.11}_{-0.08}{}^{+0.07}_{-0.06}$ GeV/c^2 from the q^2 dependence of the decay rate.

[18] FRABETTI 93I measures a pole mass of $2.1^{+0.7}_{-0.3}{}^{+0.7}_{-0.3}$ GeV/c^2 from the q^2 dependence of the decay rate.

[19] CRAWFORD 91B measures a pole mass of 2.00 ± 0.12 ± 0.18 GeV/c^2 from the q^2 dependence of the decay rate.

$\Gamma(K^-\mu^+\nu_\mu)/\Gamma(\mu^+\text{anything})$ — Γ_9/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.472±0.051±0.040	232	KODAMA	94	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.32 ±0.05 ±0.05	124	KODAMA	91	EMUL	pA 800 GeV

$\Gamma(K^-\pi^0e^+\nu_e)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.016^{+0.013}_{-0.005}$±0.002	4	[20] BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

[20] BAI 91 finds that a fraction $0.79^{+0.15}_{-0.17}{}^{+0.09}_{-0.03}$ of combined D^+ and D^0 decays to $\overline{K}\pi e^+\nu_e$ (24 events) are $\overline{K}^*(892)e^+\nu_e$. BAI 91 uses 56 $K^-e^+\nu_e$ events to measure a pole mass of 1.8 ± 0.3 ± 0.2 GeV/c^2 from the q^2 dependence of the decay rate.

$\Gamma(\overline{K}^0\pi^-e^+\nu_e)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.028^{+0.017}_{-0.008}$±0.003	6	[21] BAI	91	MRK3	$e^+e^- \approx$ 3.77 GeV

[21] BAI 91 finds that a fraction $0.79^{+0.15}_{-0.17}{}^{+0.09}_{-0.03}$ of combined D^+ and D^0 decays to $\overline{K}\pi e^+\nu_e$ (24 events) are $\overline{K}^*(892)e^+\nu_e$.

$\Gamma(K^*(892)^-e^+\nu_e)/\Gamma(K^-e^+\nu_e)$ — Γ_{20}/Γ_8

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.55±0.09 OUR FIT				
0.51±0.18±0.06	CRAWFORD	91B	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^*(892)^-e^+\nu_e)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{20}/Γ_{23}

Unseen decay modes of the $\overline{K}^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.37±0.06 OUR FIT					
0.38±0.06±0.03	152	[22] BEAN	93C	CLEO	$e^+e^- \approx \Upsilon(4S)$

[22] BEAN 93C uses $K^{*-}\mu^+\nu_\mu$ as well as $K^{*-}e^+\nu_e$ events and makes a small phase-space adjustment to the number of the μ^+ events to use them as e^+ events.

$\Gamma(K^*(892)^-\ell^+\nu_\ell)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{13}/Γ_{23}

This an average of the $K^*(892)^-e^+\nu_e$ and $K^*(892)^-\mu^+\nu_\mu$ ratios. Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.24±0.07±0.06	137	[23] ALEXANDER	90B	CLEO	e^+e^- 10.5–11 GeV

[23] ALEXANDER 90B cannot exclude extra π^0's in the final state. See nearby data blocks for more detailed results.

$\Gamma(K^-\pi^0(\pi^0)e^+\nu_e)/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.023^{+0.050}_{-0.006}$±0.001	1	[24] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[24] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization. Does not distinguish presence of a second π^0.

$\Gamma(\overline{K}^0 \pi^- (\pi^0) e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{15}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.079^{+0.069}_{-0.023}\pm0.005$	3	[25] AGUILAR-... 87F	HYBR	πp, pp 360, 400 GeV

[25] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization. Does not distinguish presence of a second π^0.

$\Gamma(\overline{K}^*(892)^0 \pi^- e^+ \nu_e)/\Gamma(K^*(892)^- e^+ \nu_e)$ Γ_{16}/Γ_{20}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.64	90	[26] CRAWFORD 91B	CLEO	$e^+e^- \approx$ 10.5 GeV

[26] The limit on $(\overline{K}^*(892)\pi)^- \mu^+ \nu_\mu$ below is much stronger.

$\Gamma(K^- \pi^+ \pi^- \mu^+ \nu_\mu)/\Gamma(K^- \mu^+ \nu_\mu)$ Γ_{17}/Γ_9

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.037	90	KODAMA 93B	E653	π^- emulsion 600 GeV

$\Gamma((\overline{K}^*(892)\pi)^- \mu^+ \nu_\mu)/\Gamma(K^- \mu^+ \nu_\mu)$ Γ_{18}/Γ_9

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.043	90	[27] KODAMA 93B	E653	π^- emulsion 600 GeV

[27] KODAMA 93B searched in $K^- \pi^+ \pi^- \mu^+ \nu_\mu$, but the limit includes other $(\overline{K}^*(892)\pi)^-$ charge states.

$\Gamma(\pi^- e^+ \nu_e)/\Gamma_{\text{total}}$ Γ_{19}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.0038^{+0.0012}_{-0.0010}}$ **OUR FIT**				
$\mathbf{0.0039^{+0.0023}_{-0.0011}\pm0.0004}$	7	[28] ADLER 89	MRK3	e^+e^- 3.77 GeV

[28] This result of ADLER 89 gives $\left|\frac{V_{cd}}{V_{cs}} \cdot \frac{f_+^\pi(0)}{f_+^K(0)}\right|^2 = 0.057^{+0.038}_{-0.015} \pm 0.005$.

$\Gamma(\pi^- e^+ \nu_e)/\Gamma(K^- e^+ \nu_e)$ Γ_{19}/Γ_8

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.105^{+0.033}_{-0.028}}$ **OUR FIT**				
0.103±0.039±0.013	87	[29] BUTLER 95	CLEO	< 0.156 (90% CL)

[29] BUTLER 95 has 87 ± 33 $\pi^- e^+ \nu_e$ events. The result gives $\left|\frac{V_{cd}}{V_{cs}} \cdot \frac{f_+^\pi(0)}{f_+^K(0)}\right|^2 = 0.052 \pm 0.020 \pm 0.007$.

Hadronic modes with a $\overline{K}$ or $\overline{K}K\overline{K}$

$\Gamma(K^- \pi^+)/\Gamma_{\text{total}}$ Γ_{21}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0383±0.0012 OUR FIT				
0.0386±0.0014 OUR AVERAGE				
0.045 ±0.006 ±0.004		[30] ALBRECHT 94	ARG	$e^+e^- \approx \Upsilon(4S)$
0.0341±0.0012±0.0028	1173	[31] ALBRECHT 94F	ARG	$e^+e^- \approx \Upsilon(4S)$
0.0391±0.0008±0.0017	4208	[31,32] AKERIB 93	CLEO	$e^+e^- \approx \Upsilon(4S)$
0.0362±0.0034±0.0044		[31] DECAMP 91J	ALEP	From Z decays
0.045 ±0.008 ±0.005	56	[31] ABACHI 88	HRS	e^+e^- 29 GeV
0.042 ±0.004 ±0.004	930	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.041 ±0.006	263	[33] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.043 ±0.010	130	[34] PERUZZI 77	MRK1	e^+e^- 3.77 GeV

[30] ALBRECHT 94 uses D^0 mesons from $\overline{B}^0 \to D^{*+} \ell^- \overline{\nu}_\ell$ decays. This is a different set of events than used by ALBRECHT 94F.

[31] ABACHI 88, DECAMP 91J, AKERIB 93, and ALBRECHT 94F use $D^*(2010)^+ \to D^0\pi^+$ decays. The π^+ is both slow and of low p_T with respect to the event thrust axis ($\approx D^{*+}$ direction). The excess number of such π^+'s over background gives the number of $D^*(2010)^+ \to D^0\pi^+$ events, and the fraction with $D^0 \to K^-\pi^+$ gives the $D^0 \to K^-\pi^+$ branching fraction.

[32] Radiative corrections increase this AKERIB 93 value to $0.0395 \pm 0.0008 \pm 0.0017$.

[33] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.24 ± 0.02 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

[34] PERUZZI 77 (MARK-1) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.25 ± 0.05 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

$\Gamma(\overline{K}^0 \pi^0)/\Gamma(K^- \pi^+)$ Γ_{22}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.55±0.06 OUR FIT Error includes scale factor of 1.1.				
1.36±0.23±0.22	119	ANJOS 92B	E691	γ Be 80–240 GeV

$\Gamma(\overline{K}^0 \pi^0)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{22}/Γ_{23}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.390±0.031 OUR FIT				
0.378±0.033 OUR AVERAGE				
0.44 ±0.02 ±0.05	1942	PROCARIO 93B	CLEO	e^+e^- 10.36–10.7 GeV
0.34 ±0.04 ±0.02	92	[35] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV
0.36 ±0.04 ±0.08	104	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV

[35] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^0 \pi^+ \pi^-)/\Gamma_{\text{total}}$ Γ_{23}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.054 ±0.004 OUR FIT Error includes scale factor of 1.2.				
0.055 ±0.005 OUR AVERAGE				
0.0503±0.0039±0.0049	284	[36] ALBRECHT 94F	ARG	$e^+e^- \approx \Upsilon(4S)$
0.064 ±0.005 ±0.010		ADLER 87	MRK3	e^+e^- 3.77 GeV
0.052 ±0.016	32	[37] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.079 ±0.023	28	[38] PERUZZI 77	MRK1	e^+e^- 3.77 GeV

[36] See the footnote on the ALBRECHT 94F measurement of $\Gamma(K^-\pi^+)/\Gamma_{\text{total}}$ for the method used.

[37] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.30 ± 0.08 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

[38] PERUZZI 77 (MARK-1) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.46 ± 0.12 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

$\Gamma(\overline{K}^0 \pi^+ \pi^-)/\Gamma(K^- \pi^+)$ Γ_{23}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.41±0.11 OUR FIT Error includes scale factor of 1.2.				
1.65±0.17 OUR AVERAGE				
1.61±0.10±0.15	856	FRABETTI 94J	E687	γ Be $\overline{E}_\gamma$=220 GeV
1.7 ±0.8	35	AVERY 80	SPEC	$\gamma N \to D^{*+}$
2.8 ±1.0	116	PICCOLO 77	MRK1	e^+e^- 4.03, 4.41 GeV

$\Gamma(\overline{K}^0 \rho^0)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{24}/Γ_{23}

VALUE	DOCUMENT ID	TECN	COMMENT
0.223±0.027 OUR AVERAGE Error includes scale factor of 1.2.			
0.350±0.028±0.067	FRABETTI 94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
0.227±0.032±0.009	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV
0.215±0.051±0.037	ANJOS 93	E691	γ Be 90–260 GeV
0.20 ±0.06 ±0.03	FRABETTI 92B	E687	γ Be $\overline{E}_\gamma$= 221 GeV
0.12 ±0.01 ±0.07	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 f_0(980))/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{75}/Γ_{23}

Unseen decay modes of the $f_0(980)$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.105±0.029 OUR AVERAGE			
0.131±0.031±0.034	FRABETTI 94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
0.088±0.035±0.012	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^0 f_2(1270))/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{79}/Γ_{23}

Unseen decay modes of the $f_2(1270)$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.076±0.028 OUR AVERAGE			
0.065±0.025±0.030	FRABETTI 94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
0.088±0.037±0.014	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^0 f_0(1370))/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{80}/Γ_{23}

Unseen decay modes of the $f_0(1370)$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.13 ±0.04 OUR AVERAGE			
0.123±0.035±0.049	FRABETTI 94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
0.131±0.045±0.021	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^*(892)^- \pi^+)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{82}/Γ_{23}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.93 ±0.04 OUR FIT Error includes scale factor of 1.1.				
0.96 ±0.04 OUR AVERAGE				
0.938±0.054±0.038		FRABETTI 94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
1.08 ±0.063±0.045		ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV
0.720±0.145±0.185		ANJOS 93	E691	γ Be 90–260 GeV
0.96 ±0.12 ±0.075		FRABETTI 92B	E687	γ Be $\overline{E}_\gamma$= 221 GeV
0.84 ±0.06 ±0.08		ADLER 87	MRK3	e^+e^- 3.77 GeV
$1.05\ {}^{+0.23}_{-0.26}\ {}^{+0.07}_{-0.09}$	25	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K_0^*(1430)^- \pi^+)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{104}/Γ_{23}

Unseen decay modes of the $\overline{K}_0^*(1430)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.19 ±0.05 OUR AVERAGE			
0.176±0.044±0.047	FRABETTI 94G	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
0.208±0.055±0.034	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K_2^*(1430)^- \pi^+)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{105}/Γ_{23}

Unseen decay modes of the $\overline{K}_2^*(1430)^-$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.15	90	ALBRECHT 93D	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^0 \pi^+ \pi^- \text{ nonresonant})/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ Γ_{30}/Γ_{23}

VALUE	DOCUMENT ID	TECN	COMMENT
0.27 ±0.04 OUR AVERAGE			
0.263±0.024±0.041	ANJOS 93	E691	γ Be 90–260 GeV
0.26 ±0.08 ±0.05	FRABETTI 92B	E687	γ Be $\overline{E}_\gamma$= 221 GeV
0.33 ±0.05 ±0.10	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^0)/\Gamma_{total}$ — Γ_{31}/Γ

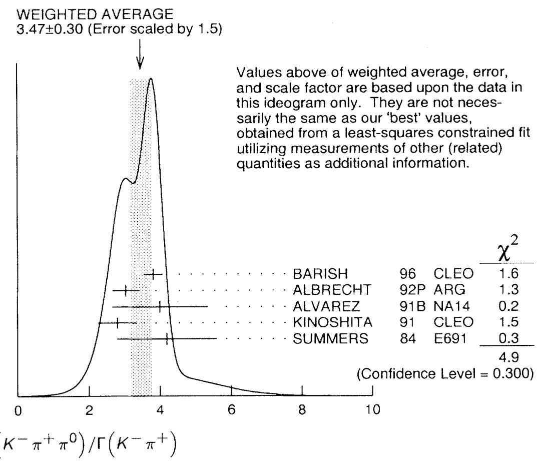
VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.139±0.009 OUR FIT Error includes scale factor of 1.3.				
0.131±0.016 OUR AVERAGE				
0.133±0.012±0.013	931	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.117±0.043	37	[39] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

[39] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.68 ± 0.23 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

$\Gamma(K^-\pi^+\pi^0)/\Gamma(K^-\pi^+)$ — Γ_{31}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
3.62±0.24 OUR FIT Error includes scale factor of 1.4.				
3.47±0.30 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.				
3.81±0.07±0.26	10k	BARISH 96	CLEO	$e^+e^- \approx \Upsilon(4S)$
3.04±0.16±0.34	931	[40] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV
4.0 ±0.9 ±1.0	69	ALVAREZ 91B	NA14	Photoproduction
2.8 ±0.14±0.52	1050	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV
4.2 ±1.4	41	SUMMERS 84	E691	Photoproduction

[40] This value is calculated from numbers in Table 1 of ALBRECHT 92P.



$\Gamma(K^-\rho^+)/\Gamma(K^-\pi^+\pi^0)$ — Γ_{32}/Γ_{31}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.78 ±0.05 OUR AVERAGE				
0.765±0.041±0.054		FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.647±0.039±0.150		ANJOS 93	E691	γBe 90–260 GeV
0.81 ±0.03 ±0.06		ADLER 87	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.31 $^{+0.20}_{-0.14}$	13	SUMMERS 84	E691	Photoproduction
0.85 $^{+0.11}_{-0.15}$ $^{+0.09}_{-0.10}$	31	SCHINDLER 81	MRK2	e^+e^- 3.771 GeV

$\Gamma(K^*(892)^-\pi^+)/\Gamma(K^-\pi^+\pi^0)$ — Γ_{82}/Γ_{31}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.362±0.035 OUR FIT Error includes scale factor of 1.3.			
0.28 ±0.04 OUR AVERAGE			
0.444±0.084±0.147	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.252±0.033±0.035	ANJOS 93	E691	γBe 90–260 GeV
0.36 ±0.06 ±0.09	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^0)/\Gamma(K^-\pi^+\pi^0)$ — Γ_{83}/Γ_{31}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.227±0.027 OUR FIT			
0.221±0.029 OUR AVERAGE			
0.248±0.047±0.023	FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.213±0.027±0.035	ANJOS 93	E691	γBe 90–260 GeV
0.20 ±0.03 ±0.05	ADLER 87	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^0$ nonresonant$)/\Gamma(K^-\pi^+\pi^0)$ — Γ_{35}/Γ_{31}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.049±0.018 OUR AVERAGE Error includes scale factor of 1.1.				
0.101±0.033±0.040		FRABETTI 94G	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
0.036±0.004±0.018		ANJOS 93	E691	γBe 90–260 GeV
0.09 ±0.02 ±0.04		ADLER 87	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.51 ±0.22	21	SUMMERS 84	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\pi^0)/\Gamma(\overline{K}^0\pi^0)$ — Γ_{83}/Γ_{22}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.49±0.23 OUR FIT Error includes scale factor of 1.1.				
1.65$^{+0.39}_{-0.31}$±0.20	122	PROCARIO 93B	CLEO	$\overline{K}^0\pi^0\pi^0$ Dalitz plot

$\Gamma(\overline{K}^*_2(1430)^0\pi^0)/\Gamma(\overline{K}^*(892)^0\pi^0)$ — Γ_{106}/Γ_{83}

Unseen decay modes of the $\overline{K}^*_2(1430)^0$ and $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.12	90	PROCARIO 93B	CLEO	$\overline{K}^0\pi^0\pi^0$ Dalitz plot

$\Gamma(\overline{K}^0\pi^0\pi^0$ nonresonant$)/\Gamma(\overline{K}^0\pi^0)$ — Γ_{38}/Γ_{22}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.37±0.08±0.04	76	PROCARIO 93B	CLEO	$\overline{K}^0\pi^0\pi^0$ Dalitz plot

$\Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{39}/Γ

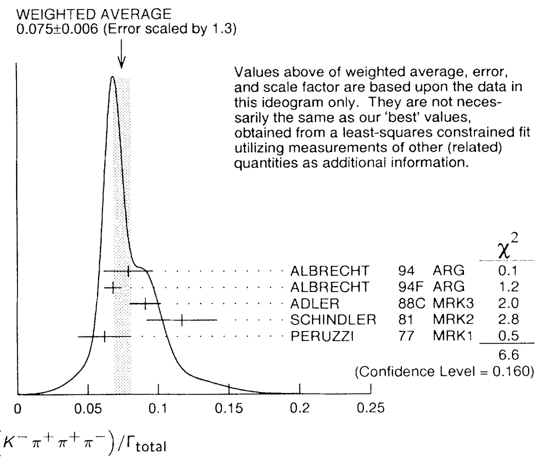
VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.075 ±0.004 OUR FIT Error includes scale factor of 1.1.				
0.075 ±0.006 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.				
0.079 ±0.015 ±0.009		[41] ALBRECHT 94	ARG	$e^+e^- \approx \Upsilon(4S)$
0.0680±0.0027±0.0057	1430	[42] ALBRECHT 94F	ARG	$e^+e^- \approx \Upsilon(4S)$
0.091 ±0.008 ±0.008	992	ADLER 88C	MRK3	e^+e^- 3.77 GeV
0.117 ±0.025	185	[43] SCHINDLER 81	MRK2	e^+e^- 3.771 GeV
0.062 ±0.019	44	[44] PERUZZI 77	MRK1	e^+e^- 3.77 GeV

[41] ALBRECHT 94 uses D^0 mesons from $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ decays. This is a different set of events than used by ALBRECHT 94F.

[42] See the footnote on the ALBRECHT 94F measurement of $\Gamma(K^-\pi^+)/\Gamma_{total}$ for the method used.

[43] SCHINDLER 81 (MARK-2) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.68 ± 0.11 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.

[44] PERUZZI 77 (MARK-1) measures $\sigma(e^+e^- \to \psi(3770)) \times$ branching fraction to be 0.36 ± 0.10 nb. We use the MARK-3 (ADLER 88C) value of $\sigma = 5.8 \pm 0.5 \pm 0.6$ nb.



$\Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{39}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.97±0.10 OUR FIT				
2.01±0.13 OUR AVERAGE				
1.7 ±0.2 ±0.2	1745	ANJOS 92C	E691	γBe 90–260 GeV
1.90±0.25±0.20	337	ALVAREZ 91B	NA14	Photoproduction
2.12±0.16±0.09		BORTOLETTO 88	CLEO	e^+e^- 10.55 GeV
2.0 ±0.9	48	BAILEY 86	ACCM	π^- Be fixed target
2.17±0.28±0.23		ALBRECHT 85F	ARG	e^+e^- 10 GeV
2.0 ±1.0	10	BAILEY 83B	SPEC	π^- Be $\to D^0$
2.2 ±0.8	214	PICCOLO 77	MRK1	e^+e^- 4.03, 4.41 GeV

$\Gamma(K^-\pi^+\rho^0$ total$)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{40}/Γ_{39}

This includes $K^- a_1(1260)^+$, $\overline{K}^*(892)^0\rho^0$, etc. The next entry gives the specifically 3-body fraction. We rely on the MARK III and E691 full amplitude analyses of the $K^-\pi^+\pi^+\pi^-$ channel for values of the resonant substructure.

VALUE	DOCUMENT ID	TECN	COMMENT
0.835±0.035 OUR AVERAGE			
0.80 ±0.03 ±0.05	ANJOS 92C	E691	γBe 90–260 GeV
0.855±0.032±0.030	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.98 ±0.12 ±0.10	ALVAREZ 91B	NA14	Photoproduction

$\Gamma(K^-\pi^+\rho^0\ \text{3-body})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{41}/Γ_{39}

We rely on the MARK III and E691 full amplitude analyses of the $K^-\pi^+\pi^+\pi^-$ channel for values of the resonant substructure.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.063±0.028 OUR AVERAGE				
0.05 ±0.03 ±0.02		ANJOS 92C	E691	γ Be 90–260 GeV
0.084±0.022±0.04		COFFMAN 92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.77 ±0.06 ±0.06		[45] ALVAREZ 91B	NA14	Photoproduction
$0.85\ ^{+0.11}_{-0.22}$	180	PICCOLO 77	MRK1	e^+e^- 4.03, 4.41 GeV

[45] This value is for ρ^0 $(K^-\pi^+)$-nonresonant. ALVAREZ 91B cannot determine what fraction of this is $K^-a_1(1260)^+$.

$\Gamma(\overline{K}^*(892)^0\rho^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{88}/Γ_{39}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included. We rely on the MARK III and E691 full amplitude analyses of the $K^-\pi^+\pi^+\pi^-$ channel for values of the resonant substructure.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.195±0.03±0.03		ANJOS 92C	E691	γ Be 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.34 ±0.09±0.09		ALVAREZ 91B	NA14	Photoproduction
0.75 ±0.3	5	BAILEY 83B	SPEC	πBe $\rightarrow D^0$
$0.15\ ^{+0.16}_{-0.15}$	20	PICCOLO 77	MRK1	e^+e^- 4.03, 4.41 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0\ \text{transverse})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{89}/Γ_{39}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.20 ±0.07 OUR FIT			
0.213±0.024±0.075	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0\ S\text{-wave})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{90}/Γ_{39}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.375±0.045±0.06	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0\ S\text{-wave long.})/\Gamma_{\text{total}}$ Γ_{91}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.003	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0\ P\text{-wave})/\Gamma_{\text{total}}$ Γ_{92}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.003	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.009	90	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\rho^0\ D\text{-wave})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{93}/Γ_{39}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.255±0.045±0.06	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^*(892)^0 f_0(980))/\Gamma_{\text{total}}$ Γ_{99}/Γ

Unseen decay modes of the $\overline{K}^*(892)^0$ and $f_0(980)$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.007	90	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(K^-a_1(1260)^+)/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{77}/Γ_{39}

Unseen decay modes of the $a_1(1260)^+$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.97 ±0.14 OUR AVERAGE			
0.94 ±0.13 ±0.20	ANJOS 92C	E691	γ Be 90–260 GeV
0.984±0.048±0.16	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-a_2(1320)^+)/\Gamma_{\text{total}}$ Γ_{81}/Γ

Unseen decay modes of the $a_2(1320)^+$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.002	90	ANJOS 92C	E691	γ Be 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.006	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K_1(1270)^-\pi^+)/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{100}/Γ_{39}

Unseen decay modes of the $K_1(1270)^-$ are included. The two experiments disagree considerably here.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.14 ±0.04 OUR FIT				
0.194±0.056±0.088		COFFMAN 92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.013	90	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(K_1(1400)^-\pi^+)/\Gamma_{\text{total}}$ Γ_{101}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.012	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(1410)^-\pi^+)/\Gamma_{\text{total}}$ Γ_{103}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.012	90	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-\ \text{total})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{84}/Γ_{39}

This includes $\overline{K}^*(892)^0\rho^0$, *etc.* The next entry gives the specifically 3-body fraction. Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.30±0.06±0.03	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-\ \text{3-body})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{85}/Γ_{39}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.19 ±0.04 OUR FIT			
0.18 ±0.04 OUR AVERAGE			
0.165±0.03 ±0.045	ANJOS 92C	E691	γ Be 90–260 GeV
0.210±0.027±0.06	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+f_0(980))/\Gamma_{\text{total}}$ Γ_{98}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.011	90	ANJOS 92C	E691	γ Be 90–260 GeV

$\Gamma(K^-\pi^+\pi^+\pi^-\ \text{nonresonant})/\Gamma(K^-\pi^+\pi^+\pi^-)$ Γ_{47}/Γ_{39}

VALUE	DOCUMENT ID	TECN	COMMENT
0.233±0.032 OUR AVERAGE			
0.23 ±0.02 ±0.03	ANJOS 92C	E691	γ Be 90–260 GeV
0.242±0.025±0.06	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ Γ_{48}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.100±0.012 OUR FIT				
0.103±0.022±0.025	140	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.134\ ^{+0.032}_{-0.033}$		[46] BARLAG 92C	ACCM	π^- Cu 230 GeV

[46] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{48}/Γ_{23}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
1.85±0.20 OUR FIT				
1.86±0.23 OUR AVERAGE				
1.80±0.20±0.21	190	[47] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV
2.8 ±0.8 ±0.8	46	ANJOS 92C	E691	γ Be 90–260 GeV
1.85±0.26±0.30	158	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV

[47] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^0\eta)/\Gamma(K^-\pi^+)$ Γ_{70}/Γ_{21}

Unseen decay modes of the η are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.64	90	ALBRECHT 89D	ARG	e^+e^- 10 GeV

$\Gamma(\overline{K}^0\eta)/\Gamma(\overline{K}^0\pi^0)$ Γ_{70}/Γ_{22}

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.33±0.04 OUR FIT				
0.32±0.04±0.03	225	PROCARIO 93B	CLEO	$\eta\rightarrow\gamma\gamma$

$\Gamma(\overline{K}^0\eta)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{70}/Γ_{23}

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.130±0.017 OUR FIT				
0.14 ±0.02 ±0.02	80	PROCARIO 93B	CLEO	$\eta\rightarrow\pi^+\pi^-\pi^0$

$\Gamma(\overline{K}^0\omega)/\Gamma(K^-\pi^+)$ Γ_{73}/Γ_{21}

Unseen decay modes of the ω are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.54±0.10 OUR FIT			
1.00±0.36±0.20	ALBRECHT 89D	ARG	e^+e^- 10 GeV

$\Gamma(\overline{K}^0\omega)/\Gamma(\overline{K}^0\pi^+\pi^-)$ Γ_{73}/Γ_{23}

Unseen decay modes of the ω are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.38±0.07 OUR FIT				
0.33±0.09 OUR AVERAGE Error includes scale factor of 1.1.				
0.29±0.08±0.05	16	[48] ALBRECHT 92P	ARG	$e^+e^- \approx$ 10 GeV
0.54±0.14±0.16	40	KINOSHITA 91	CLEO	$e^+e^- \sim$ 10.7 GeV

[48] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^0\omega)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ Γ_{73}/Γ_{48}

Unseen decay modes of the ω are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.21 ±0.04 OUR FIT			
0.220±0.048±0.0116	COFFMAN 92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\eta'(958))/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{74}/Γ_{23}

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.32±0.04 OUR AVERAGE					
0.31±0.02±0.04	594	PROCARIO	93B	CLEO	$\eta' \to \eta\pi^+\pi^-$, $\rho^0\gamma$
0.37±0.13±0.06	18	[49] ALBRECHT	92P	ARG	$e^+e^- \approx$ 10 GeV

[49] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(K^*(892)^-\rho^+)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{94}/Γ_{48}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.606±0.188±0.126	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\rho^+ \text{ longitudinal})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{95}/Γ_{48}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.290±0.111	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\rho^+ \text{ transverse})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{96}/Γ_{48}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.317±0.180	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^*(892)^-\rho^+ \text{ P-wave})/\Gamma_{total}$ — Γ_{97}/Γ

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	90	[50] COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

[50] Obtained using other $\overline{K}^*(892)\rho$ P-wave limits and isospin relations.

$\Gamma(\overline{K}^*(892)^0\rho^0 \text{ transverse})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{89}/Γ_{48}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 ±0.06 OUR FIT				
0.126±0.111	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 a_1(1260)^0)/\Gamma_{total}$ — Γ_{78}/Γ

Unseen decay modes of the $a_1(1260)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.019	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K_1(1270)^-\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{100}/Γ_{48}

Unseen decay modes of the $K_1(1270)^-$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.106±0.028 OUR FIT				
0.10 ±0.03	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}_1(1400)^0\pi^0)/\Gamma_{total}$ — Γ_{102}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.037	90	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^- \text{ 3-body})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{85}/Γ_{48}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.14 ±0.04 OUR FIT Error includes scale factor of 1.1.				
0.191±0.105	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0 \text{ nonresonant})/\Gamma(\overline{K}^0\pi^+\pi^-\pi^0)$ — Γ_{55}/Γ_{48}

VALUE	DOCUMENT ID		TECN	COMMENT
0.210±0.147±0.150	COFFMAN	92B	MRK3	e^+e^- 3.77 GeV

$\Gamma(K^-\pi^+\pi^0\pi^0)/\Gamma_{total}$ — Γ_{56}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.149±0.037±0.030	24	[51] ADLER	88C	MRK3	e^+e^- 3.77 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.177±0.029		[52] BARLAG	92C	ACCM	π^- Cu 230 GeV
$0.209^{+0.074}_{-0.043}\pm0.012$	9	[52] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[51] ADLER 88C uses an absolute normalization method finding this decay channel opposite a detected $\overline{D}^0 \to K^+\pi^-$ in pure $D\overline{D}$ events.

[52] AGUILAR-BENITEZ 87F and BARLAG 92C compute the branching fraction using topological normalization. They do not distinguish the presence of a third π^0, and thus are not included in the average.

$\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+)$ — Γ_{57}/Γ_{21}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.06±0.10 OUR FIT					
0.98±0.11±0.11	225	[53] ALBRECHT	92P	ARG	$e^+e^- \approx$ 10 GeV

[53] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{57}/Γ_{39}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.54±0.05 OUR FIT					
0.56±0.07 OUR AVERAGE					
$0.55\pm0.07^{+0.12}_{-0.09}$	167	KINOSHITA	91	CLEO	$e^+e^- \sim$ 10.7 GeV
0.57±0.06±0.05	180	ANJOS	90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\pi^+\pi^-\pi^0)/\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)$ — Γ_{107}/Γ_{57}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.45±0.15±0.15	ANJOS	90D	E691	Photoproduction

$\Gamma(\overline{K}^*(892)^0\eta)/\Gamma(K^-\pi^+)$ — Γ_{108}/Γ_{21}

Unseen decay modes of the $\overline{K}^*(892)^0$ and η are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.49±0.12 OUR FIT					
$\mathbf{0.58\pm0.19^{+0.24}_{-0.28}}$	46	KINOSHITA	91	CLEO	$e^+e^- \sim$ 10.7 GeV

$\Gamma(\overline{K}^*(892)^0\eta)/\Gamma(K^-\pi^+\pi^0)$ — Γ_{108}/Γ_{31}

Unseen decay modes of the $\overline{K}^*(892)^0$ and η are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.134±0.034 OUR FIT					
0.13 ±0.02 ±0.03	214	PROCARIO	93B	CLEO	$\overline{K}^{*0}\eta \to K^-\pi^+/\gamma\gamma$

$\Gamma(K^-\pi^+\omega)/\Gamma(K^-\pi^+)$ — Γ_{109}/Γ_{21}

Unseen decay modes of the ω are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.78±0.12±0.10	99	[54] ALBRECHT	92P	ARG	$e^+e^- \approx$ 10 GeV

[54] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^*(892)^0\omega)/\Gamma(K^-\pi^+)$ — Γ_{110}/Γ_{21}

Unseen decay modes of the $\overline{K}^*(892)^0$ and ω are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.28±0.11±0.04	17	[55] ALBRECHT	92P	ARG	$e^+e^- \approx$ 10 GeV

[55] This value is calculated from numbers in Table 1 of ALBRECHT 92P.

$\Gamma(\overline{K}^*(892)^0\omega)/\Gamma(K^-\pi^+\pi^+\pi^-\pi^0)$ — Γ_{110}/Γ_{57}

Unseen decay modes of the $\overline{K}^*(892)^0$ and ω are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.44	90	[56] ANJOS	90D	E691	Photoproduction

[56] Recovered from the published limit, $\Gamma(\overline{K}^*(892)^0\omega)/\Gamma_{total}$, in order to make our normalization consistent.

$\Gamma(K^-\pi^+\eta'(958))/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{111}/Γ_{39}

Unseen decay modes of the $\eta'(958)$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.093±0.014±0.019	286	PROCARIO	93B	CLEO	$\eta' \to \eta\pi^+\pi^-$, $\rho^0\gamma$

$\Gamma(\overline{K}^*(892)^0\eta'(958))/\Gamma(K^-\pi^+\eta'(958))$ — $\Gamma_{112}/\Gamma_{111}$

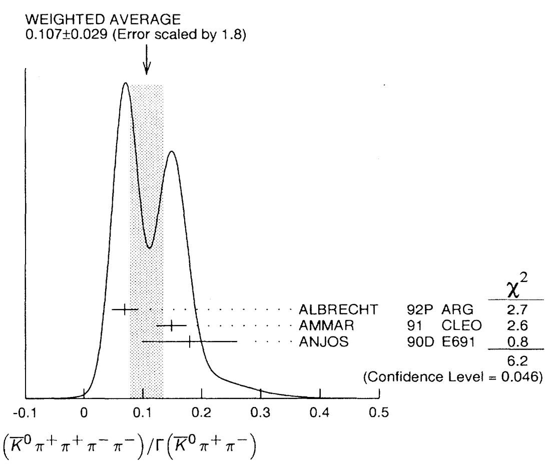
Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN
<0.15	90	PROCARIO	93B	CLEO

$\Gamma(\overline{K}^0\pi^+\pi^+\pi^-\pi^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{62}/Γ_{23}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.107±0.029 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.					
0.07 ±0.02 ±0.01	11	[57] ALBRECHT	92P	ARG	$e^+e^- \approx$ 10 GeV
0.149±0.026	56	AMMAR	91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.18 ±0.07 ±0.04	6	ANJOS	90D	E691	Photoproduction

[57] This value is calculated from numbers in Table 1 of ALBRECHT 92P.



$\Gamma(\overline{K}^0\pi^+\pi^-\pi^0\pi^0(\pi^0))/\Gamma_{total}$ — Γ_{63}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.106^{+0.073}_{-0.029}\pm0.006}$	4	[58] AGUILAR-...	87F	HYBR	πp, pp 360, 400 GeV

[58] AGUILAR-BENITEZ 87F computes the branching fraction using topological normalization, and does not distinguish the presence of a third π^0.

$\Gamma(\overline{K}^0 K^+ K^-)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ — $\Gamma_{64}/\Gamma_{23} = (\Gamma_{66}+\frac{1}{2}\Gamma_{76})/\Gamma_{23}$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.172±0.014 OUR FIT				
0.178±0.019 OUR AVERAGE				
0.20 ±0.05 ±0.04	47	FRABETTI 92B	E687	γ Be $\overline{E}_\gamma$ = 221 GeV
0.170±0.022	136	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.24 ±0.08		BEBEK 86	CLEO	e^+e^- near $\Upsilon(4S)$
0.185±0.055	52	ALBRECHT 85B	ARG	e^+e^- 10 GeV

$\Gamma(\overline{K}^0 \phi)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ — Γ_{76}/Γ_{23}

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.158±0.016 OUR FIT				
0.156±0.017 OUR AVERAGE				
0.13 ±0.06 ±0.02	13	FRABETTI 92B	E687	γ Be $\overline{E}_\gamma$ = 221 GeV
0.163±0.023	63	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.155±0.033	56	ALBRECHT 87E	ARG	e^+e^- 10 GeV
0.14 ±0.05	29	BEBEK 86	CLEO	e^+e^- near $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.186±0.052	26	ALBRECHT 85B	ARG	See ALBRECHT 87E

$\Gamma(\overline{K}^0 K^+ K^- \text{ non-}\phi)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ — Γ_{66}/Γ_{23}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.093±0.014 OUR FIT				
0.088±0.019 OUR AVERAGE				
0.11 ±0.04 ±0.03	20	FRABETTI 92B	E687	γ Be $\overline{E}_\gamma$ = 221 GeV
0.084±0.020		ALBRECHT 87E	ARG	e^+e^- 10 GeV

$\Gamma(K^0_S K^0_S K^0_S)/\Gamma(\overline{K}^0 \pi^+ \pi^-)$ — Γ_{67}/Γ_{23}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.018±0.004 OUR AVERAGE				
0.035±0.012±0.006	10	FRABETTI 94J	E687	γ Be $\overline{E}_\gamma$=220 GeV
0.016±0.005	22	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.017±0.007±0.005	5	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^+ K^- K^- \pi^+)/\Gamma(K^- \pi^+ \pi^+ \pi^-)$ — Γ_{68}/Γ_{39}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0028±0.0007±0.0001	20	FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(K^+ K^- \overline{K}^0 \pi^0)/\Gamma_{total}$ — Γ_{69}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.0072^{+0.0048}_{-0.0035}$	[59] BARLAG 92C	ACCM	π^- Cu 230 GeV

[59] BARLAG 92C computes the branching fraction using topological normalization.

Pionic modes

$\Gamma(\pi^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{113}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0396±0.0027 OUR AVERAGE				
0.043 ±0.007 ±0.003	177	FRABETTI 94C	E687	γ Be $\overline{E}_\gamma$ = 220 GeV
0.0348±0.0030±0.0023	227	SELEN 93	CLEO	$e^+e^- \approx \Upsilon(4S)$
0.048 ±0.013 ±0.008	51	ADAMOVICH 92	OMEG	π^- 340 GeV
0.055 ±0.008 ±0.005	120	ANJOS 91D	E691	Photoproduction
0.040 ±0.007 ±0.006	57	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV
0.050 ±0.007 ±0.005	110	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV
0.033 ±0.010 ±0.006	39	BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV
0.033 ±0.015		ABRAMS 79D	MRK2	e^+e^- 3.77 GeV

$\Gamma(\pi^0\pi^0)/\Gamma(K^-\pi^+)$ — Γ_{114}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.022±0.004±0.004	40	SELEN 93	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{115}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.016 ±0.011 OUR AVERAGE Error includes scale factor of 2.7.				
$0.0390^{+0.0100}_{-0.0095}$		[60] BARLAG 92C	ACCM	π^- Cu 230 GeV
0.011 ±0.004 ±0.002	10	[61] BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV

[60] BARLAG 92C computes the branching fraction using topological normalization. Possible contamination by extra π^0's may partly explain the unexpectedly large value.
[61] All the BALTRUSAITIS 85E events are consistent with $\rho^0\pi^0$.

$\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{116}/Γ_{39}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.098±0.006 OUR AVERAGE				
0.095±0.007±0.002	814	FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
0.115±0.023±0.016	64	ADAMOVICH 92	OMEG	π^- 340 GeV
0.108±0.024±0.008	79	FRABETTI 92	E687	γ Be
0.102±0.013	345	[62] AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.096±0.018±0.007	66	ANJOS 91	E691	γ Be 80–240 GeV

[62] AMMAR 91 finds 1.25 ± 0.25 ± 0.25 ρ^0's per $\pi^+\pi^+\pi^-\pi^-$ decay, but can't untangle the resonant substructure ($\rho^0\rho^0$, $a_1^\pm\pi^\mp$, $\rho^0\pi^+\pi^-$).

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{117}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$0.0192^{+0.0041}_{-0.0038}$	[63] BARLAG 92C	ACCM	π^- Cu 230 GeV

[63] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma_{total}$ — Γ_{118}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0004±0.0003	[64] BARLAG 92C	ACCM	π^- Cu 230 GeV

[64] BARLAG 92C computes the branching fraction using topological normalization.

Hadronic modes with a $K\overline{K}$ pair

$\Gamma(K^+K^-)/\Gamma(K^-\pi^+)$ — Γ_{119}/Γ_{21}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.113±0.006 OUR FIT				
0.113±0.006 OUR AVERAGE				
0.109±0.007±0.009	581	FRABETTI 94C	E687	γ Be $\overline{E}_\gamma$ = 220 GeV
0.107±0.029±0.015	103	ADAMOVICH 92	OMEG	π^- 340 GeV
0.138±0.027±0.010	155	FRABETTI 92	E687	γ Be
0.16 ±0.05	34	ALVAREZ 91B	NA14	Photoproduction
0.107±0.010±0.009	193	ANJOS 91D	E691	Photoproduction
0.10 ±0.02 ±0.01	131	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV
0.117±0.010±0.007	249	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV
0.122±0.018±0.012	118	BALTRUSAIT...85E	MRK3	e^+e^- 3.77 GeV
0.113±0.030		ABRAMS 79D	MRK2	e^+e^- 3.77 GeV

$\Gamma(K^+K^-)/\Gamma(\pi^+\pi^-)$ — $\Gamma_{119}/\Gamma_{113}$

The unused results here are redundant with $\Gamma(K^+K^-)/\Gamma(K^-\pi^+)$ and $\Gamma(\pi^+\pi^-)/\Gamma(K^-\pi^+)$ measurements by the same experiments.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.53±0.46±0.19		FRABETTI 94C	E687	γ Be $\overline{E}_\gamma$ = 220 GeV
2.23±0.81±0.46		ADAMOVICH 92	OMEG	π^- 340 GeV
1.95±0.34±0.22		ANJOS 91D	E691	Photoproduction
2.5 ±0.7		ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV
2.35±0.37±0.28	110	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV

$\Gamma(K^0\overline{K}^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{120}/Γ_{23}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.023^{+0.008}_{-0.007}$ OUR FIT				
$0.025^{+0.010}_{-0.008}$ OUR AVERAGE				
0.039±0.013±0.013	20	FRABETTI 94J	E687	γ Be $\overline{E}_\gamma$=220 GeV
$0.021^{+0.011}_{-0.008}$±0.002	5	ALEXANDER 90	CLEO	e^+e^- 10.5–11 GeV

$\Gamma(K^0\overline{K}^0)/\Gamma(K^+K^-)$ — $\Gamma_{120}/\Gamma_{119}$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$0.29^{+0.09}_{-0.08}$ OUR FIT				
0.24±0.16	4	[65] CUMALAT 88	SPEC	nN 0–800 GeV

[65] Includes a correction communicated to us by the authors of CUMALAT 88.

$\Gamma(K^0K^-\pi^+)/\Gamma(K^-\pi^+)$ — Γ_{121}/Γ_{21}

VALUE	DOCUMENT ID	TECN	COMMENT
0.167±0.026 OUR FIT Error includes scale factor of 1.1.			
0.16 ±0.06	[66] ANJOS 91	E691	γ Be 80–240 GeV

[66] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^0K^-\pi^+)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{121}/Γ_{23}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.119±0.018 OUR FIT Error includes scale factor of 1.1.				
0.119±0.021 OUR AVERAGE Error includes scale factor of 1.3.				
0.108±0.019	61	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.16 ±0.03 ±0.02	39	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^*(892)^0 K^0)/\Gamma(K^-\pi^+)$ — Γ_{140}/Γ_{21}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.00^{+0.03}_{-0.00}$	[67] ANJOS 91	E691	γ Be 80–240 GeV

[67] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\overline{K}^*(892)^0 K^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{140}/Γ_{23}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.029	90	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.03	90	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^*(892)^+ K^-)/\Gamma(K^-\pi^+)$ — Γ_{141}/Γ_{21}

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
0.090±0.020 OUR FIT			
0.16 $^{+0.08}_{-0.06}$	[68] ANJOS 91	E691	γ Be 80–240 GeV

[68] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^*(892)^+ K^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{141}/Γ_{23}

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.064±0.014 OUR FIT Error includes scale factor of 1.1.				
0.058±0.014 OUR AVERAGE				
0.064±0.018	23	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.05 ±0.02 ±0.01	15	ALBRECHT 90C	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^0 K^-\pi^+ \text{ nonresonant})/\Gamma(K^-\pi^+)$ — Γ_{124}/Γ_{21}

VALUE	DOCUMENT ID	TECN	COMMENT
0.06±0.06	[69] ANJOS 91	E691	γ Be 80–240 GeV

[69] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\overline{K}^0 K^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{125}/Γ_{21}

VALUE	DOCUMENT ID	TECN	COMMENT
0.129±0.025 OUR FIT			
0.10 ±0.05	[70] ANJOS 91	E691	γ Be 80–240 GeV

[70] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\overline{K}^0 K^+\pi^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{125}/Γ_{23}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.091±0.018 OUR FIT				
0.098±0.020	55	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^*(892)^0\overline{K}^0)/\Gamma(K^-\pi^+)$ — Γ_{142}/Γ_{21}

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.00^{+0.04}_{-0.00}$	[71] ANJOS 91	E691	γ Be 80–240 GeV

[71] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^*(892)^0\overline{K}^0)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{142}/Γ_{23}

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.015	90	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^*(892)^- K^+)/\Gamma(K^-\pi^+)$ — Γ_{143}/Γ_{21}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.00^{+0.03}_{-0.00}$	[72] ANJOS 91	E691	γ Be 80–240 GeV

[72] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(K^*(892)^- K^+)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{143}/Γ_{23}

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.034±0.019	12	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(\overline{K}^0 K^+\pi^- \text{ nonresonant})/\Gamma(K^-\pi^+)$ — Γ_{128}/Γ_{21}

VALUE	DOCUMENT ID	TECN	COMMENT
$0.10^{+0.06}_{-0.05}$	[73] ANJOS 91	E691	γ Be 80–240 GeV

[73] The factor 100 at the top of column 2 of Table I of ANJOS 91 should be omitted.

$\Gamma(\phi\pi^0)/\Gamma_{total}$ — Γ_{144}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0014	90	ALBRECHT 94I	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\phi\eta)/\Gamma_{total}$ — Γ_{145}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0028	90	ALBRECHT 94I	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\phi\omega)/\Gamma_{total}$ — Γ_{146}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0021	90	ALBRECHT 94I	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^+K^-\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{129}/Γ_{39}

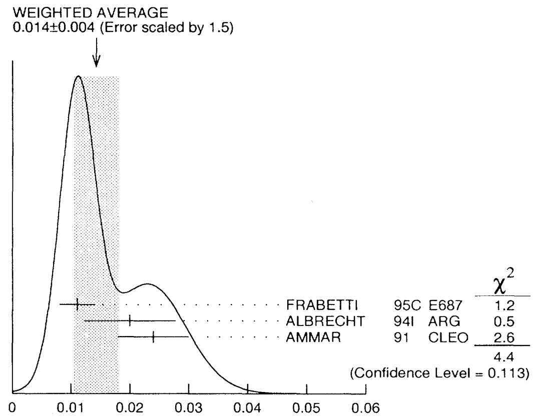
VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0342±0.0033 OUR AVERAGE				
0.035 ±0.004 ±0.002	244	FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
0.041 ±0.007 ±0.005	114	ALBRECHT 94I	ARG	$e^+e^- \approx$ 10 GeV
0.0314±0.010	89	AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
0.028 $^{+0.008}_{-0.007}$		ANJOS 91	E691	γ Be 80–240 GeV

$\Gamma(\phi\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{147}/Γ_{39}

Unseen decay modes of the ϕ are included. Everyone (through 1995) agrees that this mode is dominated by $\phi\rho^0$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.014 ±0.004 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.				
0.011 ±0.003		FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
0.020 ±0.006 ±0.005	28	ALBRECHT 94I	ARG	$e^+e^- \approx$ 10 GeV
0.024 ±0.006	34	[74] AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.0076^{+0.0066}_{-0.0049}$	3	ANJOS 91	E691	γ Be 80–240 GeV

[74] AMMAR 91 measures $\phi\rho^0$, but notes that $\phi\rho^0$ dominates $\phi\pi^+\pi^-$. We put the measurement here to keep from having more $\phi\rho^0$ than $\phi\pi^+\pi^-$.



$\Gamma(\phi\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$

$\Gamma(\phi\rho^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{148}/Γ_{39}

Unseen decay modes of the ϕ are included. Everyone (through 1995) agrees that $\phi\rho^0$ dominates $\phi\pi^+\pi^-$, so for now we equate the two branching fractions.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.005±0.003		FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
0.020±0.006±0.005	28	ALBRECHT 94I	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\phi\pi^+\pi^- \text{ 3-body})/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{149}/Γ_{39}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.006	90	FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(K^+K^-\rho^0 \text{ 3-body})/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{132}/Γ_{39}

VALUE	DOCUMENT ID	TECN	COMMENT
0.012 ±0.003	FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(K^*(892)^0 K^-\pi^+ + \text{c.c.})/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{150}/Γ_{39}

Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.017	90	[75] FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
$0.010^{+0.016}_{-0.010}$		ANJOS 91	E691	γ Be 80–240 GeV

[75] This FRABETTI 95C upper limit is in conflict with values in the next two data blocks.

$\Gamma(K^*(892)^0 K^-\pi^+)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{151}/Γ_{39}

The $K^{*0}K^-\pi^+$ and $\overline{K}^{*0}K^+\pi^-$ modes are distinguished by the charge of the pion in $D^*(2010)^\pm \to D^0\pi^\pm$ decays. Unseen decay modes of the $K^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.043±0.014±0.009	55	ALBRECHT 94I	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(\overline{K}^*(892)^0 K^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{152}/Γ_{39}

The $K^{*0}K^-\pi^+$ and $\overline{K}^{*0}K^+\pi^-$ modes are distinguished by the charge of the pion in $D^*(2010)^\pm \to D^0\pi^\pm$ decays. Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.023±0.013±0.009	30	ALBRECHT 94I	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^*(892)^0\overline{K}^*(892)^0)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{153}/Γ_{39}

Unseen decay modes of the $K^*(892)^0$ and $\overline{K}^*(892)^0$ are included.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.018±0.007 OUR AVERAGE Error includes scale factor of 1.2.					
0.016±0.006			FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
$0.036^{+0.020}_{-0.016}$		11	ANJOS 91	E691	γ Be 80–240 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.033	90		[76] AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV

[76] A corrected value (G. Moneti, private communication).

$\Gamma(K^+K^-\pi^+\pi^- \text{ non-}\phi)/\Gamma_{\text{total}}$ — Γ_{136}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0017±0.0005	[77] BARLAG 92C	ACCM	π^- Cu 230 GeV

[77] BARLAG 92C computes the branching fraction using topological normalization.

$\Gamma(K^+K^-\pi^+\pi^- \text{ nonresonant})/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{137}/Γ_{39}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.011	90	FRABETTI 95C	E687	γ Be, $\overline{E}_\gamma \approx$ 200 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.001^{+0.011}_{-0.001}$		ANJOS 91	E691	γ Be 80–240 GeV

$\Gamma(K^0\overline{K}^0\pi^+\pi^-)/\Gamma(\overline{K}^0\pi^+\pi^-)$ — Γ_{138}/Γ_{23}

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.126±0.038±0.030	25	ALBRECHT 94I	ARG	$e^+e^- \approx$ 10 GeV

$\Gamma(K^+K^-\pi^+\pi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_{139}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0031±0.0020	[78] BARLAG 92C	ACCM	π^- Cu 230 GeV

[78] BARLAG 92C computes the branching fraction using topological normalization.

Rare or forbidden modes

$\Gamma(K^+\pi^-)/\Gamma(K^-\pi^+)$ — Γ_{154}/Γ_{21}

The $D^0 \to K^+\pi^-$ mode is doubly Cabibbo suppressed.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0077±0.0025±0.0025		19	[79] CINABRO 94	CLEO	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.011	90		[79] AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
<0.015	90	1 ± 6	[80] ANJOS 88C	E691	Photoproduction
<0.014	90		[81] ALBRECHT 87K	ARG	e^+e^- 10 GeV
<0.04	90		[81] ABACHI 86D	HRS	e^+e^- 29 GeV
<0.07	90	0	[82] BAILEY 86	ACCM	π^- Be fixed target
<0.11	90	2	[81] ALBRECHT 85F	ARG	e^+e^- 10 GeV
<0.081	90		[81,83] YAMAMOTO 85	DLCO	e^+e^- 29 GeV
<0.23	90		[81,83] ALTHOFF 84B	TASS	e^+e^- 34.4 GeV
<0.11	90		[81,83] AVERY 80	SPEC	$\gamma N \to D^{*+}$
<0.16	90		[81,83] FELDMAN 77B	MRK1	e^+e^- 4 GeV
<0.18	90		[81,83] GOLDHABER 77	MRK1	e^+e^- 4 GeV

[79] These experiments cannot distinguish between doubly Cabibbo-suppressed decay and D^0-$\overline{D}^0$ mixing.

[80] ANJOS 88C uses decay-time information to distinguish doubly Cabibbo-suppressed (DCS) decays from D^0-$\overline{D}^0$ mixing. However, the result assumes no interference between the DCS and mixing amplitudes. When interference is allowed, the limit degrades to 0.049.

[81] In these measurements, the charge of the pion in $D^{*\pm} \to (D^0 \text{ or } \overline{D}^0)\pi^\pm$ is used to tell whether a D^0 or a $\overline{D}^0$ was born. None of the measurements can distinguish between double Cabibbo suppression and mixing for the decay.

[82] BAILEY 86 searches for events with an oppositely charged eK pair. The limit is actually for $\Gamma(D^0 \to K^+\pi^- \text{ or } K^+\pi^-\pi^+\pi^-)/\Gamma(D^0 \to K^-\pi^+ \text{ or } K^-\pi^+\pi^+\pi^-)$.

[83] The results are given as $\Gamma(K^+\pi^-)/[\Gamma(K^-\pi^+)+\Gamma(K^+\pi^-)]$ but do not change significantly for our denominator.

$\Gamma(K^+\pi^- (\text{via } \overline{D}^0))/\Gamma(K^-\pi^+)$ — Γ_{155}/Γ_{21}

This is a D^0-$\overline{D}^0$ mixing limit.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.005	90	1 ± 4	[84] ANJOS 88C	E691	Photoproduction

[84] ANJOS 88C uses decay-time information to distinguish doubly Cabibbo-suppressed (DCS) decays from D^0-$\overline{D}^0$ mixing. However, the result assumes no interference between the DCS and mixing amplitudes. When interference is allowed, the limit degrades to 0.019. Combined with results on $K^\pm\pi^\mp\pi^+\pi^-$, the limit is, assuming no interference, 0.0037. See also the data on $|m_{D^0_1} - m_{D^0_2}|$ and on $|\Gamma_{D^0_1} - \Gamma_{D^0_2}|/\Gamma$ near the beginning of the D^0 Listings.

$\Gamma(K^+\pi^-\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{156}/Γ_{39}

Doubly Cabibbo suppressed.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.018	90		[85] AMMAR 91	CLEO	$e^+e^- \approx$ 10.5 GeV
<0.018	90	5 ± 12	[86] ANJOS 88C	E691	Photoproduction

[85] AMMAR 91 cannot distinguish between doubly Cabibbo-suppressed decay and D^0-$\overline{D}^0$ mixing.

[86] ANJOS 88C uses decay-time information to distinguish doubly Cabibbo-suppressed (DCS) decays from D^0-$\overline{D}^0$ mixing. However, the result assumes no interference between the DCS and mixing amplitudes. When interference is allowed, the limit degrades to 0.033.

$\Gamma(K^+\pi^-\pi^+\pi^- (\text{via } \overline{D}^0))/\Gamma(K^-\pi^+\pi^+\pi^-)$ — Γ_{157}/Γ_{39}

This is a D^0-$\overline{D}^0$ mixing limit.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.005	90	0 ± 4	[87] ANJOS 88C	E691	Photoproduction

[87] ANJOS 88C uses decay-time information to distinguish doubly Cabibbo-suppressed (DCS) decays from D^0-$\overline{D}^0$ mixing. However, the result assumes no interference between the DCS and mixing amplitudes. When interference is allowed, the limit degrades to 0.007. Combined with results on $K^\pm\pi^\mp$, the limit is, assuming no interference, 0.0037. See also the data on $|m_{D^0_1} - m_{D^0_2}|$ and on $|\Gamma_{D^0_1} - \Gamma_{D^0_2}|/\Gamma$ near the beginning of the D^0 Listings.

$\Gamma(\mu^- \text{ anything } (\text{via } \overline{D}^0))/\Gamma(\mu^+ \text{ anything})$ — Γ_{158}/Γ_2

This is a D^0-$\overline{D}^0$ mixing limit. See the somewhat better limits above from $D^0 \to K^+\pi^-$ and $D^0 \to K^+\pi^-\pi^+\pi^-$ (via $\overline{D}^0$).

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0056	90	LOUIS 86	SPEC	π^- W 225 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.012	90	BENVENUTI 85	CNTR	μC, 200 GeV
<0.044	90	BODEK 82	SPEC	π^-, pFe $\to D^0$

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ — Γ_{159}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<1.3 x 10⁻⁵	90	0	FREYBERGER 96	CLEO	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.3 \times 10^{-4}$	90		ADLER 88	MRK3	e^+e^- 3.77 GeV
$<1.7 \times 10^{-4}$	90	7	ALBRECHT 88G	ARG	e^+e^- 10 GeV
$<2.2 \times 10^{-4}$	90	8	HAAS 88	CLEO	e^+e^- 10 GeV

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{160}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<7.6 \times 10^{-6}$	90	0	ADAMOVICH 95	BEAT	π^- Cu, W 350 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.4 \times 10^{-5}$	90	1	FREYBERGER 96	CLEO	$e^+e^- \approx \Upsilon(4S)$
$<4.4 \times 10^{-5}$	90	0	KODAMA 95	E653	π^- emulsion 600 GeV
$<3.1 \times 10^{-5}$	90		[88] MISHRA 94	E789	−4.1 ± 4.8 events
$<7.0 \times 10^{-5}$	90	3	ALBRECHT 88G	ARG	e^+e^- 10 GeV
$<1.1 \times 10^{-5}$	90		LOUIS 86	SPEC	π^- W 225 GeV
$<3.4 \times 10^{-4}$	90		AUBERT 85	EMC	Deep inelast. $\mu^- N$

[88] Here MISHRA 94 uses "the statistical approach advocated by the PDG." For an alternate approach, giving a limit of 9×10^{-6} at 90% confidence level, see the paper.

$\Gamma(\pi^0 e^+e^-)/\Gamma_{\text{total}}$ — Γ_{161}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<4.5 \times 10^{-5}$	90	0	FREYBERGER 96	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{162}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.8 \times 10^{-4}$	90	2	KODAMA 95	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.4 \times 10^{-4}$	90	3	FREYBERGER 96	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\eta e^+e^-)/\Gamma_{\text{total}}$ — Γ_{163}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.1 \times 10^{-4}$	90	0	FREYBERGER 96	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\eta\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{164}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<5.3 \times 10^{-4}$	90	0	FREYBERGER 96	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\rho^0 e^+e^-)/\Gamma_{\text{total}}$ — Γ_{165}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$<1.0 \times 10^{-4}$	90	2	[89] FREYBERGER 96	CLEO	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.5 \times 10^{-4}$	90	2	HAAS 88	CLEO	e^+e^- 10 GeV

[89] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 1.8 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\rho^0 \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{166}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<2.3 \times 10^{-4}$	90	0	KODAMA	95	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<4.9 \times 10^{-4}$	90	1	[90] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$
$<8.1 \times 10^{-4}$	90	5	HAAS	88	CLEO	e^+e^- 10 GeV

[90] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 4.5 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\omega e^+ e^-)/\Gamma_{total}$ — Γ_{167}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.8 \times 10^{-4}$	90	1	[91] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[91] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 2.7 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\omega \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{168}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<8.3 \times 10^{-4}$	90	0	[92] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[92] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 6.5 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\phi e^+ e^-)/\Gamma_{total}$ — Γ_{169}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<5.2 \times 10^{-5}$	90	2	[93] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[93] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 7.6 \times 10^{-5}$ using a photon pole amplitude model.

$\Gamma(\phi \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{170}/Γ

A test for the $\Delta C = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<4.1 \times 10^{-4}$	90	0	[94] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[94] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 2.4 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\overline{K}^0 e^+ e^-)/\Gamma_{total}$ — Γ_{171}/Γ

Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.1 \times 10^{-4}$	90	0	FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.7 \times 10^{-3}$	90		ADLER	89C	MRK3	e^+e^- 3.77 GeV

$\Gamma(\overline{K}^0 \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{172}/Γ

Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<2.6 \times 10^{-4}$	90	2	KODAMA	95	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<6.7 \times 10^{-4}$	90	1	FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\overline{K}^*(892)^0 e^+ e^-)/\Gamma_{total}$ — Γ_{173}/Γ

Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.4 \times 10^{-4}$	90	1	[95] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[95] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 2.0 \times 10^{-4}$ using a photon pole amplitude model.

$\Gamma(\overline{K}^*(892)^0 \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{174}/Γ

Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.18 \times 10^{-3}$	90	1	[96] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[96] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 1.0 \times 10^{-3}$ using a photon pole amplitude model.

$\Gamma(\pi^+ \pi^- \pi^0 \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{175}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<8.1 \times 10^{-4}$	90	1	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(\mu^\pm e^\mp)/\Gamma_{total}$ — Γ_{176}/Γ

A test of lepton family number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$< 1.9 \times 10^{-5}$	90	2	FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 1.0 \times 10^{-4}$	90	4	ALBRECHT	88G	ARG	e^+e^- 10 GeV
$< 2.7 \times 10^{-4}$	90	9	HAAS	88	CLEO	e^+e^- 10 GeV
$< 1.2 \times 10^{-4}$	90		BECKER	87C	MRK3	e^+e^- 3.77 GeV
$< 9 \times 10^{-4}$	90		PALKA	87	SILI	200 GeV πp
$<21 \times 10^{-4}$	90	0	[97] RILES	87	MRK2	e^+e^- 29 GeV

[97] RILES 87 assumes $B(D \to K\pi) = 3.0\%$ and has production model dependency.

$\Gamma(\pi^0 e^\pm \mu^\mp)/\Gamma_{total}$ — Γ_{177}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<8.6 \times 10^{-5}$	90	2	FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\eta e^\pm \mu^\mp)/\Gamma_{total}$ — Γ_{178}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.0 \times 10^{-4}$	90	0	FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\rho^0 e^\pm \mu^\mp)/\Gamma_{total}$ — Γ_{179}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<4.9 \times 10^{-5}$	90	0	[98] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[98] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 5.0 \times 10^{-5}$ using a photon pole amplitude model.

$\Gamma(\omega e^\pm \mu^\mp)/\Gamma_{total}$ — Γ_{180}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.2 \times 10^{-4}$	90	0	[99] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[99] This FREYBERGER 96 limit is obtained using a phase-space model. The same limit is obtained using a photon pole amplitude model.

$\Gamma(\phi e^\pm \mu^\mp)/\Gamma_{total}$ — Γ_{181}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<3.4 \times 10^{-5}$	90	0	[100] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[100] This FREYBERGER 96 limit is obtained using a phase-space model. The limit changes to $< 3.3 \times 10^{-5}$ using a photon pole amplitude model.

$\Gamma(\overline{K}^0 e^\pm \mu^\mp)/\Gamma_{total}$ — Γ_{182}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.0 \times 10^{-4}$	90	0	FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\overline{K}^*(892)^0 e^\pm \mu^\mp)/\Gamma_{total}$ — Γ_{183}/Γ

A test of lepton family number conservation. The value is for the sum of the two charge states.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$<1.0 \times 10^{-4}$	90	0	[101] FREYBERGER	96	CLEO	$e^+e^- \approx \Upsilon(4S)$

[101] This FREYBERGER 96 limit is obtained using a phase-space model. The same limit is obtained using a photon pole amplitude model.

D^0 *CP*-VIOLATING DECAY-RATE ASYMMETRIES

$A_{CP}(K^+K^-)$ in $D^0, \overline{D}^0 \to K^+K^-$

This is the difference between D^0 and $\overline{D}^0$ partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID		TECN	COMMENT
0.06 ±0.05 OUR AVERAGE				
$+0.080\pm0.061$	BARTELT	95	CLEO	$-0.022 < A_{CP} < +0.18$ (90%CL)
$+0.024\pm0.084$	[102] FRABETTI	94I	E687	$-0.11 < A_{CP} < +0.16$ (90% CL)

[102] FRABETTI 94I measures $N(D^0 \to K^+K^-)/N(D^0 \to K^-\pi^+)$, the ratio of (efficiency-corrected) numbers of events observed, and similarly for the $\overline{D}^0$.

$A_{CP}(K^0_S \phi)$ in $D^0, \overline{D}^0 \to K^0_S \phi$

This is the difference between D^0 and $\overline{D}^0$ partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID		TECN	COMMENT
-0.028 ± 0.094	BARTELT	95	CLEO	$-0.182 < A_{CP} < +0.126$ (90%CL)

$A_{CP}(K^0_S \pi^0)$ in $D^0, \overline{D}^0 \to K^0_S \pi^0$

This is the difference between D^0 and $\overline{D}^0$ partial widths for these modes divided by the sum of the widths.

VALUE	DOCUMENT ID		TECN	COMMENT
-0.018 ± 0.030	BARTELT	95	CLEO	$-0.067 < A_{CP} < +0.031$ (90%CL)

D^0 PRODUCTION CROSS SECTION AT $\psi(3770)$

A compilation of the cross sections for the direct production of D^0 mesons at or near the $\psi(3770)$ peak in e^+e^- production.

VALUE (nanobarns)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$5.8 \pm0.5 \pm0.6$	[103] ADLER	88C	MRK3	e^+e^- 3.768 GeV
7.3 ± 1.3	[104] PARTRIDGE	84	CBAL	e^+e^- 3.771 GeV
$8.00\pm0.95\pm1.21$	[105] SCHINDLER	80	MRK2	e^+e^- 3.771 GeV
11.5 ± 2.5	[106] PERUZZI	77	MRK1	e^+e^- 3.774 GeV

[103] This measurement compares events with one detected D to those with two detected D mesons, to determine the the absolute cross section. ADLER 88C find the ratio of cross sections (neutral to charged) to be $1.36 \pm 0.23 \pm 0.14$.

[104] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. PARTRIDGE 84 measures 6.4 ± 1.15 nb for the cross section. We take the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and we assume that the $\psi(3770)$ is an isosinglet to evaluate the cross sections. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[105] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. SCHINDLER 80 assume the phase space division of neutral and charged D mesons in $\psi(3770)$ decay to be 1.33, and that the $\psi(3770)$ is an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction.

[106] This measurement comes from a scan of the $\psi(3770)$ resonance and a fit to the cross section. The phase space division of neutral and charged D mesons in $\psi(3770)$ decay is taken to be 1.33, and $\psi(3770)$ is assumed to be an isosinglet. The noncharm decays (e.g. radiative) of the $\psi(3770)$ are included in this measurement and may amount to a few percent correction. We exclude this measurement from the average because of uncertainties in the contamination from τ lepton pairs. Also see RAPIDIS 77.

D^0 REFERENCES

BARISH 96 PL B373 334 +Chadha, Chan, Eigen+ (CLEO Collab.)
FREYBERGER 96 PRL 76 3065 +Gibaut, Kinoshita+ (CLEO Collab.)
PDG 96 PR D54 1
ADAMOVICH 95 PL B353 563 +Adinolfi, Alexandrov+ (CERN BEATRICE Collab.)
BARTELT 95 PR D52 4860 +Csorna, Egyed, Jain+ (CLEO Collab.)
BUTLER 95 PR D52 2656 +Fu, Nemati, Ross, Skubic+ (CLEO Collab.)
FRABETTI 95C PL B354 486 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 95G PL B364 127 +Cheung, Cumalat+ (FNAL E687 Collab.)
KODAMA 95 PL B345 85 +Ushida, Mokhtarani+ (FNAL E653 Collab.)
ALBRECHT 94 PL B324 249 +Ehrlichmann, Hamacher+ (ARGUS Collab.)
ALBRECHT 94F PL B340 125 +Hamacher, Hofmann+ (ARGUS Collab.)
ALBRECHT 94I ZPHY C64 375 +Hamacher, Hofmann+ (ARGUS Collab.)
CINABRO 94 PRL 72 1406 +Henderson, Liu, Saulnier+ (CLEO Collab.)
FRABETTI 94C PL B321 295 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 94D PL B323 459 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 94G PL B331 217 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 94I PR D50 R2953 +Cheung, Cumalat+ (FNAL E687 Collab.)
FRABETTI 94J PL B340 254 +Cheung, Cumalat+ (FNAL E687 Collab.)
KODAMA 94 PL B336 605 +Ushida, Mokhtarani+ (FNAL E653 Collab.)
MISHRA 94 PR D50 R9 +Brown, Cooper+ (FNAL E789 Collab.)
AKERIB 93 PRL 71 3070 +Barish, Chadha, Chan+ (CLEO Collab.)
ALBRECHT 93D PL B308 435 +Ehrlichmann, Hamacher+ (ARGUS Collab.)
ANJOS 93 PR D48 56 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
BEAN 93C PL B317 647 +Gronberg, Kutschke, Menary+ (CLEO Collab.)
FRABETTI 93I PL B315 203 +Bogart, Cheung, Culy+ (FNAL E687 Collab.)
KODAMA 93B PL B313 260 +Ushida, Mokhtarani+ (FNAL E653 Collab.)
PROCARIO 93B PR D48 4007 +Yang, Akerib, Barish+ (CLEO Collab.)
SELEN 93 PRL 71 1973 +Sadoff, Ammar, Ball+ (CLEO Collab.)
ADAMOVICH 92 PL B280 163 +Alexandrov, Antinori+ (CERN WA82 Collab.)
ALBRECHT 92P ZPHY C56 7 +Cronstroem, Ehrlichmann+ (ARGUS Collab.)
ANJOS 92B PR D46 R1 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
ANJOS 92C PR D46 1941 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
BARLAG 92C ZPHY C55 383 +Becker, Bozek, Boehringer+ (ACCMOR Collab.)
Also 90D ZPHY C48 29 Barlag, Becker, Boehringer, Bosman+ (ACCMOR Collab.)
COFFMAN 92B PR D45 2196 +DeJongh, Dubois, Eigen+ (Mark III Collab.)
Also 90 PRL 64 2615 Adler, Blaylock, Bolton+ (Mark III Collab.)
FRABETTI 92 PL B281 167 +Bogart, Cheung, Culy+ (FNAL E687 Collab.)
FRABETTI 92B PL B286 195 +Bogart, Cheung, Culy+ (FNAL E687 Collab.)
ALVAREZ 91B ZPHY C50 11 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
AMMAR 91 PR D44 3383 +Baringer, Coppage, Davis+ (CLEO Collab.)
ANJOS 91 PR D43 R635 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
ANJOS 91D PR D44 R3371 +Appel, Bean, Bracker+ (FNAL-TPS Collab.)
BAI 91 PRL 66 1011 +Bolton, Brown, Bunnell+ (Mark III Collab.)
COFFMAN 91 PL B263 135 +DeJongh, Dubois, Eigen, Hitlin+ (Mark III Collab.)
CRAWFORD 91B PR D44 3394 +Fulton, Gan, Jensen+ (CLEO Collab.)
DECAMP 91J PL B266 218 +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
FRABETTI 91 PL B263 584 +Bogart, Cheung, Culy+ (FNAL E687 Collab.)
KINOSHITA 91 PR D43 2836 +Pipkin, Procario, Wilson+ (CLEO Collab.)
KODAMA 91 PRL 66 1819 +Ushida, Mokhtarani, Paolone+ (FNAL E653 Collab.)
ALBRECHT 90C ZPHY C46 9 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALEXANDER 90 PRL 65 1184 +Artuso, Bebek, Berkelman+ (CLEO Collab.)
ALEXANDER 90B PRL 65 1531 +Artuso, Bebek, Berkelman+ (CLEO Collab.)
ALVAREZ 90 ZPHY C47 539 +Barate, Bloch, Bonamy+ (CERN NA14/2 Collab.)
ANJOS 90D PR D42 2414 +Appel, Bean, Bracker+ (FNAL E691 Collab.)
BARLAG 90C ZPHY C46 563 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
ADLER 89 PRL 62 1821 +Becker, Blaylock, Bolton+ (Mark III Collab.)
ADLER 89C PR D40 906 +Bai, Becker, Blaylock, Bolton+ (Mark III Collab.)
ALBRECHT 89D ZPHY C43 181 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
ANJOS 89F PRL 62 1587 +Appel, Bean, Bracker, Browder+ (FNAL E691 Collab.)
ABACHI 88 PL B205 411 +Akerlof, Baringer+ (HRS Collab.)
ADLER 88 PR D37 2023 +Becker, Blaylock+ (Mark III Collab.)
ADLER 88C PRL 60 89 +Becker, Blaylock+ (Mark III Collab.)
ALBRECHT 88G PL B209 380 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88I PL B210 267 +Boeckmann, Glaeser+ (ARGUS Collab.)
AMENDOLIA 88 EPL 5 407 +Bagliesi, Batignani+ (NA1 Collab.)
ANJOS 88C PRL 60 1239 +Appel+ (FNAL E691 Collab.)
BORTOLETTO 88 PR D37 1719 +Goldberg, Horwitz, Mestayer, Moneti+ (CLEO Collab.)
Also 89D PR D39 1471 erratum
CUMALAT 88 PL B210 253 +Shipbaugh, Binkley+ (E-400 Collab.)
HAAS 88 PRL 60 1614 +Hempstead, Jensen+ (CLEO Collab.)
RAAB 88 PR D37 2391 +Anjos, Appel, Bracker+ (FNAL E691 Collab.)
ADAMOVICH 87 EPL 4 887 +Alexandrov, Bolta+ (Photon Emulsion Collab.)
ADLER 87 PL B196 107 +Becker, Blaylock, Bolton+ (Mark III Collab.)
AGUILAR-... 87D PL B193 140 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88B ZPHY C40 321 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
AGUILAR-... 87E ZPHY C36 551 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88B ZPHY C40 321 Aguilar-Benitez, Allison, Bailly+ (LEBC-EHS Collab.)
AGUILAR-... 87F ZPHY C36 559 Aguilar-Benitez, Allison+ (LEBC-EHS Collab.)
Also 88 ZPHY C38 520 erratum
ALBRECHT 87E ZPHY C33 359 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87K PL B199 447 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
BARLAG 87B ZPHY C37 17 +Becker, Boehringer, Bosman+ (ACCMOR Collab.)
BECKER 87C PL B193 147 +Blaylock, Bolton, Brown+ (Mark III Collab.)
Also 87D PL B198 590 erratum Becker, Blaylock, Bolton+ (Mark III Collab.)
CSORNA 87 PL B191 318 +Mestayer, Panvini, Word+ (CLEO Collab.)
PALKA 87 PL B189 238 +Bailey, Becker, Belau+ (ACCMOR Collab.)
RILES 87 PR D35 2914 +Dorfan, Abrams, Amidei+ (Mark II Collab.)
ABACHI 86D PL B182 101 +Akerlof, Baringer, Ballam+ (HRS Collab.)
ABE 86 PR D33 1 + (SLAC Hybrid Facility Photon Collab.)
BAILEY 86 ZPHY C30 51 +Belau, Boehringer, Bosman+ (ACCMOR Collab.)
BEBEK 86 PRL 56 1893 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
GLADNEY 86 PR D34 2601 +Jaros, Ong, Barklow+ (Mark II Collab.)
LOUIS 86 PRL 56 1027 +Adolphsen, Alexander+ (PRIN, CHIC, ISU)
USHIDA 86B PRL 56 1771 +Kondo+ (AICH, FNAL, KOBE, SEOU, MCGI+)
ALBRECHT 85B PL 158B 525 +Binder, Harder, Philipp+ (ARGUS Collab.)
ALBRECHT 85F PL 150B 235 +Binder, Harder, Philipp+ (ARGUS Collab.)
AUBERT 85 PL 155B 461 +Bassompierre, Becks, Benchouk+ (EMC Collab.)
BAILEY 85 ZPHY C28 357 +Belau, Boehringer, Bosman+ (ABCCMR Collab.)
BALTRUSAIT... 85B PRL 54 1976 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BALTRUSAIT... 85E PRL 55 150 Baltrusaitis, Becker, Blaylock, Brown+ (Mark III Collab.)
BENVENUTI 85 PL 158B 531 +Bollini, Bruni, Camporesi+ (BCDMS Collab.)
YAMAMOTO 85 PRL 54 522 +Yamamoto, Atwood, Baillon+ (DELCO Collab.)
ADAMOVICH 84B PL 140B 123 +Alexandrov, Bravo+ (CERN WA58 Collab.)
ALTHOFF 84B PL 138B 317 +Braunschweig, Kirschfink+ (TASSO Collab.)
DERRICK 84 PRL 53 1971 +Fernandez, Fries, Hyman+ (HRS Collab.)
PARTRIDGE 84 Thesis CALT-68-1150 (Crystal Ball Collab.)
SUMMERS 84 PRL 52 410 + (UCSB, CARL, COLO, FNAL, TNTO, OKLA, CNRC)
BAILEY 83B PL 132B 237 +Bardsley, Becker, Blanar+ (ACCMOR Collab.)
BODEK 82 PL 113B 82 +Breedon+ (ROCH, CIT, CHIC, FNAL, STAN)
FIORINO 81 LNC 30 166 + (Photon-Emulsion and Omega-Photon Collab.)
SCHINDLER 81 PR D24 78 +Alam, Boyarski, Breidenbach+ (Mark II Collab.)
TRILLING 81 PRPL 75 57 (LBL, UCB) J
ASTON 80E PL 94B 113 + (BONN, CERN, EPOL, GLAS, LANC, MCHS+)
AVERY 80 PRL 44 1309 +Wiss, Butler, Gladding+ (ILL, FNAL, COLU)
SCHINDLER 80 PR D21 2716 +Siegrist, Alam, Boyarski+ (Mark II Collab.)
ZHOLENTZ 80 PL 96B 214 +Kurdadze, Lelchuk, Mishnev+ (NOVO)
Also 81 SJNP 34 814 Zholentz, Kurdadze, Lelchuk+ (NOVO)
Translated from YAF 34 1471.
ABRAMS 79D PRL 43 481 +Alam, Blocker, Boyarski+ (Mark II Collab.)
ATIYA 79 PRL 43 414 +Holmes, Knapp, Lee+ (COLU, ILL, FNAL)
BALTAY 78C PRL 41 73 +Caroumbalis, French, Hibbs, Hylton+ (COLU, BNL)
VUILLEMIN 78 PRL 41 1149 +Feldman, Feller+ (Mark I Collab.)
FELDMAN 77B PRL 38 1313 +Peruzzi, Piccolo, Abrams, Alam+ (Mark I Collab.)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (Mark I Collab.)
PERUZZI 77 PRL 39 1301 +Piccolo, Feldman+ (Mark I Collab.)
PICCOLO 77 PL 70B 260 +Peruzzi, Luth, Nguyen, Wiss, Abrams+ (Mark I Collab.)
RAPIDIS 77 PRL 39 526 +Gobbi, Luke, Barbaro-Galtieri+ (Mark I Collab.)
GOLDHABER 76 PRL 37 255 +Pierre, Abrams, Alam+ (Mark I Collab.)

OTHER RELATED PAPERS

RICHMAN 95 RMP 67 893 +Burchat (UCSB, STAN)
ROSNER 95 CNPP 21 369 (CHIC)

$D^*(2007)^0$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

J consistent with 1, value 0 ruled out (NGUYEN 77).

$D^*(2007)^0$ MASS

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
2006.7±0.5 OUR FIT Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2006 ±1.5	[1] GOLDHABER 77	MRK1	e^+e^-

[1] From simultaneous fit to $D^*(2010)^+$, $D^*(2007)^0$, D^+, and D^0.

$m_{D^*(2007)^0} - m_{D^0}$

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
142.12±0.07 OUR FIT				
142.12±0.07 OUR AVERAGE				
142.2 ±0.3 ±0.2	145	ALBRECHT 95F	ARG	$e^+e^- \to$ hadrons
142.12±0.05±0.05	1176	BORTOLETTO 92B	CLE2	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
142.2 ±2.0		SADROZINSKI 80	CBAL	$D^{*0} \to D^0\pi^0$
142.7 ±1.7		[2] GOLDHABER 77	MRK1	e^+e^-

[2] From simultaneous fit to $D^*(2010)^+$, $D^*(2007)^0$, D^+, and D^0.

$D^*(2007)^0$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
<2.1	90	[3] ABACHI 88B	HRS	$D^{*0} \to D^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5		GOLDHABER 76B	MRK1	$e^+e^- \to D^*D^*$

[3] Assuming $m_{D^{*0}} = 2007.2 \pm 2.1$ MeV/c^2.

$D^*(2007)^0$ DECAY MODES

$\overline{D}^*(2007)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^0$	(61.9±2.9) %
Γ_2	$D^0\gamma$	(38.1±2.9) %

CONSTRAINED FIT INFORMATION

An overall fit to a branching ratio uses 3 measurements and one constraint to determine 2 parameters. The overall fit has a $\chi^2 = 0.5$ for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_1
x_2	−100

$D^*(2007)^0$ BRANCHING RATIOS

$\Gamma(D^0\pi^0)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.619±0.029 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.596±0.035±0.028	858	ALBRECHT	95F ARG	$e^+e^- \to$ hadrons
0.636±0.023±0.033	1097	[4] BUTLER	92 CLE2	$e^+e^- \to$ hadrons

$\Gamma(D^0\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.381±0.029 OUR FIT				
0.381±0.029 OUR AVERAGE				
0.404±0.035±0.028	456	ALBRECHT	95F ARG	$e^+e^- \to$ hadrons
0.364±0.023±0.033	621	[4] BUTLER	92 CLE2	$e^+e^- \to$ hadrons
0.37 ±0.08 ±0.08		ADLER	88D MRK3	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.47 ±0.23		LOW	87 HRS	29 GeV e^+e^-
0.53 ±0.13		BARTEL	85G JADE	e^+e^-, hadrons
0.47 ±0.12		COLES	82 MRK2	e^+e^-
0.45 ±0.15		GOLDHABER	77 MRK1	e^+e^-

[4] The BUTLER 92 branching ratios are not independent, they have been constrained by the authors to sum to 100%.

$D^*(2007)^0$ REFERENCES

ALBRECHT	95F	ZPHY C66 63	+Ehrlichmann+	(ARGUS Collab.)
BORTOLETTO	92B	PRL 69 2046	+Brown, Dominick+	(CLEO Collab.)
BUTLER	92	PRL 69 2041	+Fu, Kalbfleish+	(CLEO Collab.)
ABACHI	88B	PL B212 533	+Akerlof+	(ANL, IND, MICH, PURD, LBL)
ADLER	88D	PL B208 152	+Becker+	(Mark III Collab.)
LOW	87	PL B183 232	+Abachi, Akerlof, Baringer+	(HRS Collab.)
BARTEL	85G	PL 161B 197	+Dietrich, Ambrus+	(JADE Collab.)
COLES	82	PR D26 2190	+Abrams, Blocker, Blondel+	(LBL, SLAC)
SADROZINSKI	80	Madison Conf. 681	+	(PRIN, CIT, HARV, SLAC, STAN)
GOLDHABER	77	PL 69B 503	+Wiss, Abrams, Alam+	(Mark I Collab.)
NGUYEN	77	PRL 39 262	+Wiss, Abrams, Alam, Boyarski+	(LBL, SLAC) J
GOLDHABER	76B	SLAC Conf. 379		(LBL, SLAC)

Available as LBL-5534.

OTHER RELATED PAPERS

KAMAL	92	PL B284 421	+Xu	(ALBE)
TRILLING	81	PRPL 75 57		(LBL, UCB)
FELDMAN	77C	Banff Sum. Inst. 75		(SLAC)
GOLDHABER	76	PRL 37 255	+Pierre, Abrams, Alam+	(Mark I Collab.)

$D^*(2010)^\pm$

$I(J^P) = \frac{1}{2}(1^-)$
I, J, P need confirmation.

$D^*(2010)^\pm$ MASS

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
2010.0±0.5 OUR FIT Error includes scale factor of 1.1.				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2008 ±3	[1] GOLDHABER	77 MRK1	±	e^+e^-
2008.6±1.0	[2] PERUZZI	77 MRK1	±	e^+e^-

[1] From simultaneous fit to $D^*(2010)^+$, $D^*(2007)^0$, D^+, and D^0; not independent of FELDMAN 77B mass difference below.
[2] PERUZZI 77 mass not independent of FELDMAN 77B mass difference below and PERUZZI 77 D^0 mass value.

$m_{D^*(2010)^+} - m_{D^+}$

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
140.64±0.09 OUR FIT				
140.64±0.08±0.06	620	BORTOLETTO	92B CLE2	$e^+e^- \to$ hadrons

$m_{D^*(2010)^+} - m_{D^0}$

The fit includes $D^\pm$, D^0, $D_s^\pm$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
145.42±0.05 OUR FIT				
145.42±0.04 OUR AVERAGE				
145.39±0.06±0.03		BARLAG	92B ACCM	π^- 230 GeV
145.40±0.05±0.10		ABACHI	88B HRS	$D^{*\pm} \to D^0\pi^\pm$
145.46±0.07±0.03		ALBRECHT	85F ARG	$D^{*\pm} \to D^0\pi^+$
145.8 ±1.5	16	AHLEN	83 HRS	$D^{*+} \to D^0\pi^+$
145.1 ±1.8	12	BAILEY	83 SPEC	$D^{*\pm} \to D^0\pi^\pm$
145.5 ±0.3	28	BAILEY	83 SPEC	$D^{*\pm} \to D^0\pi^\pm$
145.1 ±0.5	14	BAILEY	83 SPEC	$D^{*\pm} \to D^0\pi^\pm$
145.5 ±0.5	14	YELTON	82 MRK2	29 $e^+e^- \to K^-\pi^+$
145.5 ±0.3	60	FITCH	81 SPEC	π^- A
145.2 ±0.6	2	BLIETSCHAU	79 BEBC	νp
145.3 ±0.5	30	FELDMAN	77B MRK1	$D^{*+} \to D^0\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
145.4 ±0.2	48	[3] DERRICK	95 ZEUS	$D^{*\pm} \to D^0\pi^\pm$
145.5 ±0.2	115	[3] ALEXANDER	91B OPAL	$D^{*\pm} \to D^0\pi^\pm$
145.30±0.06		[3] DECAMP	91J ALEP	$D^{*\pm} \to D^0\pi^\pm$
~ 145.5		AVERY	80 SPEC	γA

[3] Systematic error not evaluated.

$m_{D^*(2010)^+} - m_{D^*(2007)^0}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.6±1.8	[4] PERUZZI	77 MRK1	e^+e^-

[4] Not independent of FELDMAN 77B mass difference above, PERUZZI 77 D^0 mass, and GOLDHABER 77 $D^*(2007)^0$ mass.

$D^*(2010)^\pm$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.131	90	110	BARLAG	92B ACCM	π^- 230 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.1	90		ABACHI	88B HRS	$D^{*\pm} \to D^0\pi^\pm$
<2.2			YELTON	82 MRK2	$e^+e^- \to K^-\pi^+\pi^-$
<2.0	90	30	FELDMAN	77B MRK1	$D^{*+} \to D^0\pi^+$

$D^*(2010)^\pm$ DECAY MODES

$D^*(2010)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^+$	(68.3±1.4) %
Γ_2	$D^+\pi^0$	(30.6±2.5) %
Γ_3	$D^+\gamma$	$(1.1^{+2.1}_{-0.7})$ %

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 3 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 = 0.0$ for 1 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_1	x_2
x_2	−55	
x_3	0	−83

$D^*(2010)^+$ BRANCHING RATIOS

$\Gamma(D^0\pi^+)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.683±0.014 OUR FIT			
0.683±0.014 OUR AVERAGE			
0.688±0.024±0.013	ALBRECHT	95F ARG	$e^+e^- \to$ hadrons
0.681±0.010±0.013	[7] BUTLER	92 CLE2	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.57 ±0.04 ±0.04	ADLER	88D MRK3	e^+e^-
0.44 ±0.10	COLES	82 MRK2	e^+e^-
0.6 ±0.15	[5] GOLDHABER	77 MRK1	e^+e^-

[5] Assuming that isospin is conserved in the decay.

$\Gamma(D^+\pi^0)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.306±0.025 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.312±0.011±0.008	1404	ALBRECHT	95F	ARG	$e^+e^- \to$ hadrons
0.308±0.004±0.008	410	[7] BUTLER	92	CLE2	$e^+e^- \to$ hadrons
0.26 ±0.02 ±0.02		ADLER	88D	MRK3	e^+e^-
0.34 ±0.07		COLES	82	MRK2	e^+e^-

$\Gamma(D^+\gamma)/\Gamma_{total}$ — Γ_3/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$0.011^{+0.021}_{-0.007}$ OUR FIT						
0.011±0.014±0.016		12	[7] BUTLER	92	CLE2	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.052	90		ALBRECHT	95F	ARG	$e^+e^- \to$ hadrons
0.17 ±0.05 ±0.05			ADLER	88D	MRK3	e^+e^-
0.22 ±0.12			[6] COLES	82	MRK2	e^+e^-

[6] Not independent of $\Gamma(D^0\pi^+)/\Gamma_{total}$ and $\Gamma(D^+\pi^0)/\Gamma_{total}$ measurement.

[7] The BUTLER 92 branching ratios are not independent, they have been constrained by the authors to sum to 100%.

$D^*(2010)^\pm$ REFERENCES

ALBRECHT	95F	ZPHY C66 63	+Ehrlichmann+	(ARGUS Collab.)
DERRICK	95	PL B349 225	+Krakauer, et al	(ZEUS Collab.)
BARLAG	92B	PL B278 480	+Becker, Bozek+	(ACCMOR Collab.)
BORTOLETTO	92B	PRL 69 2046	+Brown, Dominick+	(CLEO Collab.)
BUTLER	92	PRL 69 2041	+Fu, Kalbfleish+	(CLEO Collab.)
ALEXANDER	91B	PL B262 341	+Allison, Allport, Anderson, Arcelli+	(OPAL Collab.)
DECAMP	91J	PL B266 218	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
ABACHI	88B	PL B212 533	+Akerlof+	(ANL, IND, MICH, PURD, LBL)
ADLER	88D	PL B208 152	+Becker+	(Mark III Collab.)
ALBRECHT	85F	PL 150B 235	+Binder, Harder, Philipp+	(ARGUS Collab.)
AHLEN	83	PRL 51 1147	+Akerlof+	(ANL, IND, LBL, MICH, PURD, SLAC)
BAILEY	83	PL 132B 230	+Bardsley+	(AMST, BRIS, CERN, CRAC, MPIM+)
COLES	82	PR D26 2190	+Abrams, Blocker, Blondel+	(LBL, SLAC)
YELTON	82	PRL 49 430	+Feldman, Goldhaber+	(SLAC, LBL, UCB, HARV)
FITCH	81	PRL 46 761	+Devaux, Cavaglia, May+	(PRIN, SACL, TORI, BNL)
AVERY	80	PRL 44 1309	+Wiss, Butler, Gladding+	(ILL, FNAL, COLU)
BLIETSCHAU	79	PL 86B 108	+	(AACH3, BONN, CERN, MPIM, OXF)
FELDMAN	77B	PRL 38 1313	+Peruzzi, Piccolo, Abrams, Alam+	(Mark I Collab.)
GOLDHABER	77	PL 69B 503	+Wiss, Abrams, Alam+	(Mark I Collab.)
PERUZZI	77	PRL 39 1301	+Piccolo, Feldman+	(Mark I Collab.)

OTHER RELATED PAPERS

KAMAL	92	PL B284 421	+Xu	(ALBE)
ALTHOFF	83C	PL 126B 493	+Fischer, Burkhardt+	(TASSO Collab.)
BEBEK	82	PRL 49 610	+	(HARV, OSU, ROCH, RUTG, SYRA, VAND+)
TRILLING	81	PRPL 75 57		(LBL, UCB)
PERUZZI	76	PRL 37 569	+Piccolo, Feldman, Nguyen, Wiss+	(Mark I Collab.)

$D_1(2420)^0$

$I(J^P) = \frac{1}{2}(1^+)$
I, J, P need confirmation.

Seen in $D^*(2010)^+\pi^-$. $J^P = 1^+$ according to ALBRECHT 89H.

$D_1(2420)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2422.2±1.8 OUR AVERAGE Error includes scale factor of 1.2.					
$2421\ ^{+1}_{-2}\ \pm2$	286	AVERY	94C	CLE2	$e^+e^- \to D^{*+}\pi^-X$
2422 ±2 ±2	51	FRABETTI	94B	E687	$\gamma\,\mathrm{Be} \to D^{*+}\pi^-X$
2428 ±3 ±2	279	AVERY	90	CLEO	$e^+e^- \to D^{*+}\pi^-X$
2414 ±2 ±5	171	ALBRECHT	89H	ARG	$e^+e^- \to D^{*+}\pi^-X$
2428 ±8 ±5	171	ANJOS	89C	TPS	$\gamma N \to D^{*+}\pi^-X$

$D_1(2420)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$18.9^{+\ 4.6}_{-\ 3.5}$ OUR AVERAGE					
$20\ ^{+\ 6}_{-\ 5}\ \pm\ 3$	286	AVERY	94C	CLE2	$e^+e^- \to D^{*+}\pi^-X$
15 ± 8 ± 4	51	FRABETTI	94B	E687	$\gamma\,\mathrm{Be} \to D^{*+}\pi^-X$
$23\ ^{+\ 8}_{-\ 6}\ ^{+10}_{-\ 3}$	279	AVERY	90	CLEO	$e^+e^- \to D^{*+}\pi^-X$
$13\ \pm\ 6\ ^{+10}_{-\ 5}$	171	ALBRECHT	89H	ARG	$e^+e^- \to D^{*+}\pi^-X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
58 ±14 ±10	171	ANJOS	89C	TPS	$\gamma N \to D^{*+}\pi^-X$

$D_1(2420)^0$ DECAY MODES

$\overline{D}_1(2420)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^+\pi^-$	seen
Γ_2	$D^+\pi^-$	not seen

$D_1(2420)^0$ BRANCHING RATIOS

$\Gamma(D^*(2010)^+\pi^-)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AVERY	90	CLEO	$e^+e^- \to D^{*+}\pi^-X$
seen	ALBRECHT	89H	ARG	$e^+e^- \to D^*\pi^-X$
seen	ANJOS	89C	TPS	$\gamma N \to D^{*+}\pi^-X$

$\Gamma(D^+\pi^-)/\Gamma(D^*(2010)^+\pi^-)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.24	90	AVERY	90	CLEO	$e^+e^- \to D^+\pi^-X$

$D_1(2420)^0$ REFERENCES

AVERY	94C	PL B331 236	+Freyberger, Rodriguez+	(CLEO Collab.)
FRABETTI	94B	PRL 72 324	+Cheung, Cumalat+	(FNAL E687 Collab.)
AVERY	90	PR D41 774	+Besson	(CLEO Collab.)
ALBRECHT	89H	PL B232 398	+Glaser, Harder+	(ARGUS Collab.) JP
ANJOS	89C	PRL 62 1717	+Appel+	(FNAL E691 Collab.)

$D_1(2420)^\pm$

$I(J^P) = \frac{1}{2}(?^?)$
I needs confirmation.

OMITTED FROM SUMMARY TABLE

Seen in $D^*(2007)^0\pi^+$. $J^P = 0^+$ ruled out.

$D_1(2420)^\pm$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2427±5 OUR AVERAGE Error includes scale factor of 2.0.					
2425±2±2	146	BERGFELD	94B	CLE2	$e^+e^- \to D^{*0}\pi^+X$
2443±7±5	190	ANJOS	89C	TPS	$\gamma N \to D^0\pi^+X^0$

$m_{D_1^*(2420)^\pm} - m_{D_1^*(2420)^0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$4^{+2}_{-3}\pm3$	BERGFELD	94B	CLE2	$e^+e^- \to$ hadrons

$D_1(2420)^\pm$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
28± 8 OUR AVERAGE					
$26\ ^{+\ 8}_{-\ 7}\pm4$	146	BERGFELD	94B	CLE2	$e^+e^- \to D^{*0}\pi^+X$
41±19±8	190	ANJOS	89C	TPS	$\gamma N \to D^0\pi^+X^0$

$D_1(2420)^\pm$ DECAY MODES

$D_1^*(2420)^-$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2007)^0\pi^+$	seen
Γ_2	$D^0\pi^+$	not seen

$D_1(2420)^\pm$ BRANCHING RATIOS

$\Gamma(D^*(2007)^0\pi^+)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ANJOS	89C	TPS	$\gamma N \to D^0\pi^+X^0$

$\Gamma(D^0\pi^+)/\Gamma(D^*(2007)^0\pi^+)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.18	90	BERGFELD	94B	CLE2	$e^+e^- \to$ hadrons

$D_1(2420)^\pm$ REFERENCES

BERGFELD	94B	PL B340 194	+Eisenstein, Gollin+	(CLEO Collab.)
ANJOS	89C	PRL 62 1717	+Appel+	(FNAL E691 Collab.)

$D_2^*(2460)^0$

$I(J^P) = \frac{1}{2}(2^+)$

$J^P = 2^+$ assignment strongly favored (ALBRECHT 89B).

$D_2^*(2460)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2458.9±2.0 OUR AVERAGE		Error includes scale factor of 1.2.			
2465 ±3 ±3	486	AVERY	94C	CLE2	$e^+e^- \rightarrow D^+\pi^- X$
2453 ±3 ±2	128	FRABETTI	94B	E687	γ Be $\rightarrow D^+\pi^- X$
2461 ±3 ±1	440	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
2455 ±3 ±5	337	ALBRECHT	89B	ARG	$e^+e^- \rightarrow D^+\pi^- X$
2459 ±3 ±2	153	ANJOS	89C	TPS	$\gamma N \rightarrow D^+\pi^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2466 ±7	1	ASRATYAN	95	BEBC	53,40 $\nu(\overline{\nu}) \rightarrow p + X, d + X$

$D_2^*(2460)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
23± 5 OUR AVERAGE					
$28^{+8}_{-7} \pm 6$	486	AVERY	94C	CLE2	$e^+e^- \rightarrow D^+\pi^- X$
25±10± 5	128	FRABETTI	94B	E687	γ Be $\rightarrow D^+\pi^- X$
$20^{+9}_{-12}{}^{+9}_{-10}$	440	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
$15^{+13}_{-10}{}^{+5}_{-10}$	337	ALBRECHT	89B	ARG	$e^+e^- \rightarrow D^+\pi^- X$
20±10± 5	153	ANJOS	89C	TPS	$\gamma N \rightarrow D^+\pi^- X$

$D_2^*(2460)^0$ DECAY MODES

$\overline{D}_2^*(2460)^0$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^+\pi^-$	seen
Γ_2	$D^*(2010)^+\pi^-$	seen

$D_2^*(2460)^0$ BRANCHING RATIOS

$\Gamma(D^+\pi^-)/\Gamma_{total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	337	ALBRECHT	89B	ARG	$e^+e^- \rightarrow D^+\pi^- X$
seen		ANJOS	89C	TPS	$\gamma N \rightarrow D^+\pi^- X$

$\Gamma(D^*(2010)^+\pi^-)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AVERY	90	CLEO	$e^+e^- \rightarrow D^{*+}\pi^- X$
seen	ALBRECHT	89H	ARG	$e^+e^- \rightarrow D^*\pi^- X$

$\Gamma(D^+\pi^-)/\Gamma(D^*(2010)^+\pi^-)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
2.3±0.6 OUR AVERAGE				
2.2±0.7±0.6	AVERY	94C	CLE2	$e^+e^- \rightarrow D^{*+}\pi^- X$
2.3±0.8	AVERY	90	CLEO	e^+e^-
3.0±1.1±1.5	ALBRECHT	89H	ARG	$e^+e^- \rightarrow D^*\pi^- X$

$D_2^*(2460)^0$ REFERENCES

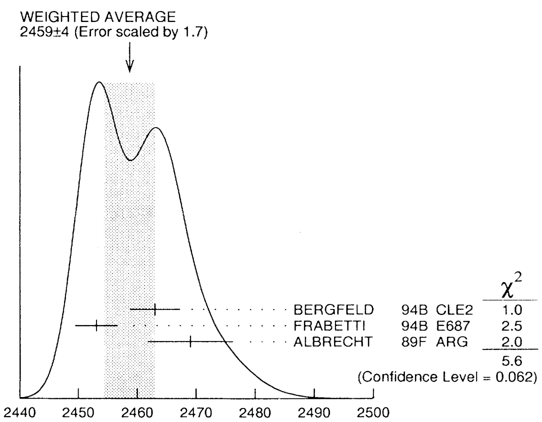
ASRATYAN 95 ZPHY C68 43 + (BIRM, BELG, CERN, SERP, ITEP, MPIM, RAL)
AVERY 94C PL B331 236 +Freyberger, Rodriguez+ (CLEO Collab.)
FRABETTI 94B PRL 72 324 +Cheung, Cumalat+ (FNAL E687 Collab.)
AVERY 90 PR D41 774 +Besson (CLEO Collab.)
ALBRECHT 89B PL B221 422 +Boeckmann+ (ARGUS Collab.) JP
ALBRECHT 89H PL B232 398 +Glaser, Harder+ (ARGUS Collab.) JP
ANJOS 89C PRL 62 1717 +Appel+ (FNAL E691 Collab.)

$D_2^*(2460)^\pm$

$I(J^P) = \frac{1}{2}(2^+)$

$D_2^*(2460)^\pm$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2459±4 OUR AVERAGE		Error includes scale factor of 1.7. See the ideogram below.			
2463±3±3	310	BERGFELD	94B	CLE2	$e^+e^- \rightarrow D^0\pi^+ X$
2453±3±2	185	FRABETTI	94B	E687	γ Be $\rightarrow D^0\pi^+ X$
2469±4±6		ALBRECHT	89F	ARG	$e^+e^- \rightarrow D^0\pi^+ X$



$D_2^*(2460)^\pm$ mass (MeV)

$m_{D_2^*(2460)^\pm} - m_{D_2^*(2460)^0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.9±3.3 OUR AVERAGE	Error includes scale factor of 1.1.			
− 2 ±4 ±4	BERGFELD	94B	CLE2	$e^+e^- \rightarrow$ hadrons
0 ±4	FRABETTI	94B	E687	γ Be $\rightarrow D\pi X$
14 ±5 ±8	ALBRECHT	89F	ARG	$e^+e^- \rightarrow D^0\pi^+ X$

$D_2^*(2460)^\pm$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
25^{+8}_{-7} OUR AVERAGE					
$27^{+11}_{-8} \pm 5$	310	BERGFELD	94B	CLE2	$e^+e^- \rightarrow D^0\pi^+ X$
23± 9±5	185	FRABETTI	94B	E687	γ Be $\rightarrow D^0\pi^+ X$

$D_2^*(2460)^\pm$ DECAY MODES

$D_2^*(2460)^-$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^0\pi^+$	seen
Γ_2	$D^{*0}\pi^+$	seen

$D_2^*(2460)^\pm$ BRANCHING RATIOS

$\Gamma(D^0\pi^+)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ALBRECHT	89F	ARG	$e^+e^- \rightarrow D^0\pi^+ X$

$\Gamma(D^0\pi^+)/\Gamma(D^{*0}\pi^+)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
1.9±1.1±0.3	BERGFELD	94B	CLE2	$e^+e^- \rightarrow$ hadrons

$D_2^*(2460)^\pm$ REFERENCES

BERGFELD 94B PL B340 194 +Eisenstein, Gollin+ (CLEO Collab.)
FRABETTI 94B PRL 72 324 +Cheung, Cumalat+ (FNAL E687 Collab.)
ALBRECHT 89F PL B231 208 +Glaeser+ (ARGUS Collab.)

CHARMED, STRANGE MESONS
($C = S = \pm1$)

$D_s^+ = c\overline{s}$, $D_s^- = \overline{c}s$, similarly for D_s^*'s

$D_s^{\pm}$
was $F^{\pm}$

$I(J^P) = 0(0^-)$

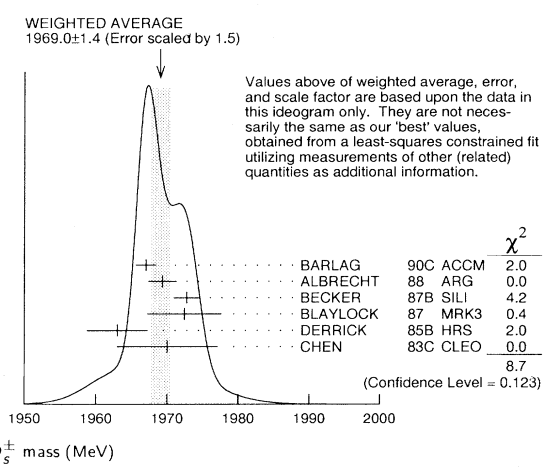
The angular distributions of the decays of the ϕ and $\overline{K}^*(892)^0$ in the $\phi\pi^+$ and $K^+\overline{K}^*(892)^0$ modes strongly indicate that the spin is zero. The parity given is that expected of a $c\overline{s}$ ground state.

$D_s^{\pm}$ MASS

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements. Measurements of the $D_s^{\pm}$ mass with an error greater than 10 MeV are omitted from the fit and average. A number of early measurements have been omitted altogether.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1968.5± 0.6 OUR FIT Error includes scale factor of 1.1.					
1969.0± 1.4 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.					
1967.0± 1.0± 1.0	54	BARLAG	90C	ACCM	π^- Cu 230 GeV
1969.3± 1.4± 1.4		ALBRECHT	88	ARG	e^+e^- 9.4–10.6 GeV
1972.7± 1.5± 1.0	21	BECKER	87B	SILI	200 GeV π,K,p
1972.4± 3.7± 3.7	27	BLAYLOCK	87	MRK3	e^+e^- 4.14 GeV
1963 ± 3 ± 3	30	DERRICK	85B	HRS	e^+e^- 29 GeV
1970 ± 5 ± 5	104	CHEN	83C	CLEO	e^+e^- 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1968.3± 0.7± 0.7	290	[1] ANJOS	88	E691	Photoproduction
1980 ±15	6	USHIDA	86	EMUL	ν wideband
1973.6± 2.6± 3.0	163	ALBRECHT	85D	ARG	e^+e^- 10 GeV
1948 ±28 ±10	65	AIHARA	84D	TPC	e^+e^- 29 GeV
1975 ± 9 ±10	49	ALTHOFF	84	TASS	e^+e^- 14–25 GeV
1975 ± 4	3	BAILEY	84	ACCM	hadron$^+$ Be $\rightarrow \phi\pi^+X$

[1] ANJOS 88 enters the fit via $m_{D_s^{\pm}} - m_{D^{\pm}}$ (see below).



$m_{D_s^{\pm}} - m_{D^{\pm}}$

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
99.2±0.5 OUR FIT Error includes scale factor of 1.1.					
99.2±0.5 OUR AVERAGE					
99.5±0.6±0.3		BROWN	94	CLEO	$e^+e^- \approx \Upsilon(4S)$
98.5±1.5	555	CHEN	89	CLEO	e^+e^- 10.5 GeV
99.0±0.8	290	ANJOS	88	E691	Photoproduction

$D_s^{\pm}$ MEAN LIFE

Measurements with an error greater than 0.2×10^{-12} s are omitted from the average.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.467±0.017 OUR AVERAGE					
0.475±0.020±0.007	900	FRABETTI	93F	E687	γBe, $D_s^+ \rightarrow \phi\pi^+$
$0.33\ ^{+0.12}_{-0.08}$ ±0.03	15	ALVAREZ	90	NA14	γ, $D_s^+ \rightarrow \phi\pi^+$
$0.469^{+0.102}_{-0.086}$	54	[2] BARLAG	90C	ACCM	π^- Cu 230 GeV
0.50 ±0.06 ±0.03	104	FRABETTI	90	E687	γBe, $\phi\pi^+$
$0.56\ ^{+0.13}_{-0.12}$ ±0.08	144	ALBRECHT	88I	ARG	e^+e^- 10 GeV
0.47 ±0.04 ±0.02	228	RAAB	88	E691	Photoproduction
$0.33\ ^{+0.10}_{-0.06}$	21	[3] BECKER	87B	SILI	200 GeV π,K,p
$0.26\ ^{+0.16}_{-0.09}$	6	USHIDA	86	EMUL	ν wideband
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.31\ ^{+0.24}_{-0.20}$ ±0.05	18	AVERILL	89	HRS	e^+e^- 29 GeV
$0.48\ ^{+0.06}_{-0.05}$ ±0.02	99	ANJOS	87B	E691	See RAAB 88
$0.57\ ^{+0.36}_{-0.26}$ ±0.09	9	BRAUNSCH...	87	TASS	e^+e^- 35–44 GeV
0.47 ±0.22 ±0.05	141	CSORNA	87	CLEO	e^+e^- 10 GeV
$0.35\ ^{+0.24}_{-0.18}$ ±0.09	17	JUNG	86	HRS	See AVERILL 89
$0.32\ ^{+0.30}_{-0.13}$	3	BAILEY	84	ACCM	hadron$^+$ Be $\rightarrow \phi\pi^+X$
$0.19\ ^{+0.13}_{-0.07}$	4	USHIDA	83	EMUL	See USHIDA 86

[2] BARLAG 90C estimates the systematic error to be negligible.
[3] BECKER 87B estimates the systematic error to be negligible.

D_s^+ DECAY MODES

Branching fractions for modes with a resonance in the final state include all the decay modes of the resonance. D_s^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
	Inclusive modes			
Γ_1	K^- anything		$(13\ ^{+14}_{-12})$ %	
Γ_2	$\overline{K}^0$ anything + K^0 anything		(39 ±28) %	
Γ_3	K^+ anything		$(20\ ^{+18}_{-14})$ %	
Γ_4	non-$K\overline{K}$ anything		(64 ±17) %	
Γ_5	e^+ anything		< 20 %	90%
	Leptonic and semileptonic modes			
Γ_6	$\mu^+\nu_\mu$		(9 ± 4) $\times 10^{-3}$	
Γ_7	$\phi\ell^+\nu_\ell$	[a]	(1.9± 0.5) %	
Γ_8	$\eta\ell^+\nu_\ell$ + $\eta'(958)\ell^+\nu_\ell$		(3.3± 1.0) %	
Γ_9	$\eta\ell^+\nu_\ell$		(2.5± 0.7) %	
Γ_{10}	$\eta'(958)\ell^+\nu_\ell$		(8.7± 3.4) $\times 10^{-3}$	
	Hadronic modes with a $K\overline{K}$ pair (including from a ϕ)			
Γ_{11}	$K^+\overline{K}^0$		(3.6± 1.1) %	
Γ_{12}	$K^+K^-\pi^+$	[b]	(4.6± 1.2) %	
Γ_{13}	$\phi\pi^+$		(3.6± 0.9) %	
Γ_{14}	$K^+\overline{K}^*(892)^0$		(3.4± 0.9) %	
Γ_{15}	$f_0(980)\pi^+$		(1.1± 0.4) %	
Γ_{16}	$K^+\overline{K}_0^*(1430)^0$		(7 ± 4) $\times 10^{-3}$	
Γ_{17}	$f_J(1710)\pi^+ \rightarrow K^+K^-\pi^+$	[c]	(1.5± 2.0) $\times 10^{-3}$	
Γ_{18}	$K^+K^-\pi^+$ nonresonant		(9 ± 4) $\times 10^{-3}$	
Γ_{19}	$K^0\overline{K}^0\pi^+$			
Γ_{20}	$K^*(892)^+\overline{K}^0$		(4.3± 1.4) %	
Γ_{21}	$K^+K^-\pi^+\pi^0$			
Γ_{22}	$\phi\pi^+\pi^0$		(9 ± 5) %	
Γ_{23}	$\phi\rho^+$		(6.7± 2.3) %	
Γ_{24}	$\phi\pi^+\pi^0$ 3-body		< 2.6 %	90%
Γ_{25}	$K^+K^-\pi^+\pi^0$ non-ϕ		< 9 %	90%
Γ_{26}	$K^+\overline{K}^0\pi^+\pi^-$		< 2.8 %	90%
Γ_{27}	$K^0K^-\pi^+\pi^+$		(4.3± 1.5) %	
Γ_{28}	$K^*(892)^+\overline{K}^*(892)^0$		(5.8± 2.5) %	
Γ_{29}	$K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0}$		< 2.9 %	90%
Γ_{30}	$K^+K^-\pi^+\pi^+\pi^-$			
Γ_{31}	$\phi\pi^+\pi^+\pi^-$		(1.8± 0.6) %	
Γ_{32}	$K^+K^-\pi^+\pi^+\pi^-$ non-ϕ		$(3.0\ ^{+3.0}_{-2.0}) \times 10^{-3}$	

Other hadronic modes (0, 1, or 3 K's)

Γ_{33}	$\pi^+\pi^+\pi^-$	(1.4 ± 0.4) %	
Γ_{34}	$\rho^0\pi^+$	$< 2.9 \times 10^{-3}$	90%
Γ_{35}	$f_0(980)\pi^+$	(1.2 ± 0.5) %	
Γ_{36}	$\pi^+\pi^+\pi^-$ nonresonant	(1.0 ± 0.4) %	
Γ_{37}	$\pi^+\pi^+\pi^-\pi^0$	< 12 %	90%
Γ_{38}	$\eta\pi^+$	(2.0 ± 0.6) %	
Γ_{39}	$\omega\pi^+$	< 1.8 %	90%
Γ_{40}	$\pi^+\pi^+\pi^+\pi^-\pi^-$	$(3.0^{+4.0}_{-3.0}) \times 10^{-3}$	
Γ_{41}	$\pi^+\pi^+\pi^-\pi^0\pi^0$		
Γ_{42}	$\eta\rho^+$	(10.3 ± 3.2) %	
Γ_{43}	$\eta\pi^+\pi^0$ 3-body	< 3.0 %	90%
Γ_{44}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$	(4.9 ± 3.2) %	
Γ_{45}	$\eta'(958)\pi^+$	(4.9 ± 1.8) %	
Γ_{46}	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$		
Γ_{47}	$\eta'(958)\rho^+$	(12 ± 4) %	
Γ_{48}	$\eta'(958)\pi^+\pi^0$ 3-body	< 3.1 %	90%
Γ_{49}	$K^0\pi^+$	$< 8 \times 10^{-3}$	90%
Γ_{50}	$K^+\pi^+\pi^-$	(1.0 ± 0.4) %	
Γ_{51}	$K^+\rho^0$	$< 2.9 \times 10^{-3}$	90%
Γ_{52}	$K^*(892)^0\pi^+$	$(6.5\pm 2.8) \times 10^{-3}$	
Γ_{53}	$K^+K^+K^-$	$< 6 \times 10^{-4}$	90%
Γ_{54}	ϕK^+	$< 5 \times 10^{-4}$	90%

$\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton number (L) violating modes

Γ_{55}	$\pi^+\mu^+\mu^-$		[d] $< 4.3 \times 10^{-4}$	90%
Γ_{56}	$K^+\mu^+\mu^-$	$C1$	$< 5.9 \times 10^{-4}$	90%
Γ_{57}	$K^*(892)^+\mu^+\mu^-$	$C1$	$< 1.4 \times 10^{-3}$	90%
Γ_{58}	$\pi^-\mu^+\mu^+$	L	$< 4.3 \times 10^{-4}$	90%
Γ_{59}	$K^-\mu^+\mu^+$	L	$< 5.9 \times 10^{-4}$	90%
Γ_{60}	$K^*(892)^-\mu^+\mu^+$	L	$< 1.4 \times 10^{-3}$	90%
Γ_{61}	A dummy mode used by the fit.		(82 ± 4) %	

[a] For now, we average together measurements of the $\phi e^+\nu_e$ and $\phi\mu^+\nu_\mu$ branching fractions. This is the *average*, not the *sum*.

[b] The branching fractions for this mode may differ from the sum of the submodes that contribute to it, due to interference effects. See the relevant papers.

[c] This value includes only K^+K^- decays of the $f_J(1710)$, because branching fractions of this resonance are not known.

[d] This mode is not a useful test for a ΔC=1 weak neutral current because both quarks must change flavor in this decay.

CONSTRAINED FIT INFORMATION

An overall fit to 10 branching ratios uses 18 measurements and one constraint to determine 8 parameters. The overall fit has a $\chi^2 = 8.3$ for 11 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i\delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_9	87						
x_{10}	67	57					
x_{12}	84	73	56				
x_{13}	92	80	61	91			
x_{14}	86	74	57	92	93		
x_{35}	55	48	37	55	60	56	
x_{61}	−94	−86	−67	−95	−97	−95	−65
	x_7	x_9	x_{10}	x_{12}	x_{13}	x_{14}	x_{35}

D_s^+ BRANCHING RATIOS

A few older, now obsolete results have been omitted. They may be found in earlier editions.

Inclusive modes

$\Gamma(K^-\text{anything})/\Gamma_{\rm total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.13^{+0.14}_{-0.12}\pm 0.02$	COFFMAN	91	MRK3	e^+e^- 4.14 GeV

$[\Gamma(\overline{K}^0\text{anything}) + \Gamma(K^0\text{anything})]/\Gamma_{\rm total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.39^{+0.28}_{-0.27}\pm 0.04$	COFFMAN	91	MRK3	e^+e^- 4.14 GeV

$\Gamma(K^+\text{anything})/\Gamma_{\rm total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.20^{+0.18}_{-0.13}\pm 0.04$	COFFMAN	91	MRK3	e^+e^- 4.14 GeV

$\Gamma(\text{non-}K\overline{K}\text{anything})/\Gamma_{\rm total}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.64\pm 0.17\pm 0.03$	[4] COFFMAN	91	MRK3	e^+e^- 4.14 GeV

[4] COFFMAN 91 uses the direct measurements of the kaon content to determine this non-$K\overline{K}$ fraction. This number implies that a large fraction of D_s^+ decays involve η, η', and/or non-spectator decays.

$\Gamma(e^+\text{anything})/\Gamma_{\rm total}$ Γ_5/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.20	90	[5] BAI	90	MRK3	e^+e^- 4.14 GeV

[5] Expressed as a value, the BAI 90 result is $\Gamma(e^+\text{anything})/\Gamma_{\rm total} = 0.05 \pm 0.05 \pm 0.02$.

Leptonic and semileptonic modes

$\Gamma(\mu^+\nu_\mu)/\Gamma_{\rm total}$ Γ_6/Γ

See the "Note on Pseudoscalar-Meson Decay Constants" in the Listings for the $\pi^\pm$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.015^{+0.013}_{-0.006}{}^{+0.003}_{-0.002}$	3	[6] BAI	95	BES	$e^+e^- \to D_s^+D_s^-$
$0.004^{+0.0018}_{-0.0014}{}^{+0.0020}_{-0.0019}$	8	[7] AOKI	93	WA75	π^- emulsion 350 GeV
<0.03	0	[8] AUBERT	83	SPEC	μ^+ Fe, 250 GeV

[6] BAI 95 uses one actual $D_s^+ \to \mu^+\nu_\mu$ event together with two $D_s^+ \to \tau^+\nu_\tau$ events and assumes μ-τ universality. This value of $\Gamma(\mu^+\nu_\mu)/\Gamma_{\rm total}$ gives a pseudoscalar decay constant of $(430^{+150}_{-130} \pm 40)$ MeV.

[7] AOKI 93 assumes the ratio of production cross sections of the D_s^+ and D^0 is 0.27. The value of $\Gamma(\mu^+\nu_\mu)/\Gamma_{\rm total}$ gives a pseudoscalar decay constant $f_{D_s} = (232 \pm 45 \pm 52)$ MeV.

[8] AUBERT 83 assume that the $D_s^\pm$ production rate is 20% of total charm production rate.

$\Gamma(\mu^+\nu_\mu)/\Gamma(\phi\pi^+)$ Γ_6/Γ_{13}

See the "Note on Pseudoscalar-Meson Decay Constants" in the Listings for the $\pi^\pm$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.245\pm 0.052\pm 0.074$	39	[9] ACOSTA	94	CLEO	$e^+e^- \approx \Upsilon(4S)$

[9] ACOSTA 94 obtains $f_{D_s} = (344 \pm 37 \pm 52 \pm 42)$ MeV from this measurement, using $\Gamma(D_s^+ \to \phi\pi^+)/\Gamma(\text{total}) = 0.037 \pm 0.009$.

$\Gamma(\phi\ell^+\nu_\ell)/\Gamma(\phi\pi^+)$ Γ_7/Γ_{13}

For now, we average together measurements of the $\Gamma(\phi e^+\nu_e)/\Gamma(\phi\pi^+)$ and $\Gamma(\phi\mu^+\nu_\mu)/\Gamma(\phi\pi^+)$ ratios. See the end of the D_s^+ Listings for measurements of $D_s^+ \to \phi\ell^+\nu_\ell$ form-factor ratios.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.54±0.05 OUR FIT					
0.54±0.05 OUR AVERAGE					
0.54±0.05±0.04	367	[10] BUTLER	94	CLEO	$e^+e^- \approx \Upsilon(4S)$
0.58±0.17±0.07	97	[11] FRABETTI	93G	E687	γ Be $\overline{E}_\gamma$= 220 GeV
0.57±0.15±0.15	104	[12] ALBRECHT	91	ARG	$e^+e^- \approx$ 10.4 GeV
$0.49\pm 0.10^{+0.10}_{-0.14}$	54	[13] ALEXANDER	90B	CLEO	e^+e^- 10.5–11 GeV

[10] BUTLER 94 uses both $\phi e^+\nu_e$ and $\phi\mu^+\nu_\mu$ events, and makes a phase-space adjustment to the latter to use them as $\phi e^+\nu_e$ events.

[11] FRABETTI 93G measures the $\Gamma(\phi\mu^+\nu_\mu)/\Gamma(\phi\pi^+)$ ratio.

[12] ALBRECHT 91 measures the $\Gamma(\phi e^+\nu_e)/\Gamma(\phi\pi^+)$ ratio.

[13] ALEXAN-DER 90B measures an average of the $\Gamma(\phi e^+\nu_e)/\Gamma(\phi\pi^+)$ and $\Gamma(\phi\mu^+\nu_\mu)/\Gamma(\phi\pi^+)$ ratios.

$\Gamma(\eta\ell^+\nu_\ell)/\Gamma(\phi\ell^+\nu_\ell)$ Γ_9/Γ_7

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.27±0.19 OUR FIT					
1.24±0.12±0.15	440	[14] BRANDENB...	95	CLEO	$e^+e^- \approx \Upsilon(4S)$

[14] BRANDENBURG 95 uses both e^+ and μ^+ events and makes a phase-space adjustment to use the μ^+ events as e^+ events.

$\Gamma(\eta'(958)\ell^+\nu_\ell)/\Gamma(\phi\ell^+\nu_\ell)$ Γ_{10}/Γ_7

Unseen decay modes of the resonances are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.44±0.13 OUR FIT						
0.43±0.11±0.07		29	[15] BRANDENB...	95	CLEO	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.6	90		[16] KODAMA	93B	E653	π^- emulsion 600 GeV

[15] BRANDENBURG 95 uses both e^+ and μ^+ events and makes a phase-space adjustment to use the μ^+ events as e^+ events.
[16] KODAMA 93B uses μ^+ events.

$[\Gamma(\eta\ell^+\nu_\ell)+\Gamma(\eta'(958)\ell^+\nu_\ell)]/\Gamma(\phi\ell^+\nu_\ell)$ $\Gamma_8/\Gamma_7 = (\Gamma_9+\Gamma_{10})/\Gamma_7$

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.72±0.23 OUR FIT					
3.9 ±1.6	13	[17] KODAMA	93	E653	π^- emulsion 600 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.67±0.17±0.17		[18] BRANDENB...	95	CLEO	$e^+e^- \approx \Upsilon(4S)$

[17] KODAMA 93 uses μ^+ events.
[18] This BRANDENBURG 95 data is redundant with data in previous blocks.

Hadronic modes with a $K\overline{K}$ pair.

$\Gamma(K^+\overline{K}^0)/\Gamma(\phi\pi^+)$ Γ_{11}/Γ_{13}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.01±0.16 OUR AVERAGE					
1.15±0.31±0.19	68	ANJOS	90C	E691	γ Be
0.92±0.32±0.20		ADLER	89B	MRK3	e^+e^- 4.14 GeV
0.99±0.17±0.10		CHEN	89	CLEO	e^+e^- 10 GeV

$\Gamma(\phi\pi^+)/\Gamma_{total}$ Γ_{13}/Γ

For the first time, we have model-independent measurements of this branching fraction, and so we no longer use the earlier, model-dependent results. See the "Note on D Mesons" in the D^+ Listings for a discussion.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.036 ±0.009 OUR FIT						
0.036 ±0.009 OUR AVERAGE						
0.0359±0.0077±0.0048			[19] ARTUSO	96	CLEO	e^+e^- at $\Upsilon(4S)$
$0.039\ ^{+0.051}_{-0.019}\ ^{+0.018}_{-0.011}$			[20] BAI	95C	BES	e^+e^- 4.03 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.051 ±0.004 ±0.008			[21] BUTLER	94	CLEO	$e^+e^- \approx \Upsilon(4S)$
<0.048	90		MUHEIM	94		
0.046 ±0.015			[22] MUHEIM	94		
0.031 ±0.009			[22] MUHEIM	94		
0.031 ±0.009 ±0.006			[21] FRABETTI	93G	E687	γBe $\overline{E}_\gamma$= 220 GeV
0.024 ±0.010			[21] ALBRECHT	91	ARG	$e^+e^- \approx$ 10.4 GeV
<0.041	90	0	[20] ADLER	90B	MRK3	e^+e^- 4.14 GeV
$0.031 \pm0.006\ ^{+0.011}_{-0.009}$			[21] ALEXANDER	90B	CLEO	e^+e^- 10.5–11 GeV
0.048 ±0.017 ±0.019			[23] ALVAREZ	90C	NA14	Photoproduction
>0.034	90		[21] ANJOS	90B	E691	γBe, $\overline{E}_\gamma \approx$ 145 GeV
0.02 ±0.01		405	[24] CHEN	89	CLEO	e^+e^- 10 GeV
0.033 ±0.016 ±0.010		9	[24] BRAUNSCH...	87	TASS	e^+e^- 35–44 GeV
0.033 ±0.011		30	[24] DERRICK	85B	HRS	e^+e^- 29 GeV

[19] ARTUSO 96 uses partially reconstructed $\overline{B}^0 \to D^{*+}D_s^{*-}$ decays to get a model-independent value for $\Gamma(D_s^- \to \phi\pi^-)/\Gamma(D^0 \to K^-\pi^+)$ of 0.92 ± 0.20 ± 0.11.
[20] BAI 95C uses $e^+e^- \to D_s^+D_s^-$ events in which one or both of the $D_s^{\pm}$ are observed to obtain the first model-independent measurement of the $D_s^+ \to \phi\pi^+$ branching fraction, without assumptions about $\sigma(D_s^{\pm})$. However, with only two "doubly-tagged" events, the statistical error is too large for the result to be competitive with indirect measurements. ADLER 90B used the same method to set a limit.
[21] BUTLER 94, FRABETTI 93G, ALBRECHT 91, ALEXANDER 90B, and ANJOS 90B measure the ratio $\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)/\Gamma(D_s^+ \to \phi\pi^+)$, where $\ell = e$ and/or μ, and then use a theoretical calculation of the ratio of widths $\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)/\Gamma(D^+ \to \overline{K}^{*0}\ell^+\nu)$. Not everyone uses the same value for this ratio.
[22] The two MUHEIM 94 values here are model-dependent calculations based on distinct data sets. The first uses measurements of the $D_2^*(2460)^0$ and $D_{s1}(2536)^+$, the second uses B-decay factorization and $\Gamma(D_s^+ \to \mu^+\nu_\mu)/\Gamma(D_s^+ \to \phi\ell^+\nu_\ell)$. A third calculation using the semileptonic width of $D_s^+ \to \phi\ell^+\nu_\ell$ is not independent of other results listed here. Note also the upper limit, based on the sum of established D_s^+ branching ratios.
[23] ALVAREZ 90C relies on the Lund model to estimate the ratio of D_s^+ to D^+ cross sections.
[24] Values based on crude estimates of the $D_s^{\pm}$ production level. DERRICK 85B errors are statistical only.

$\Gamma(\phi\pi^+)/\Gamma(K^+K^-\pi^+)$ Γ_{13}/Γ_{12}

Unseen decay modes of the ϕ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.79 ±0.09 OUR FIT				
0.807±0.067±0.096	FRABETTI	95B	E687	Dalitz plot analysis

$\Gamma(K^+\overline{K}^*(892)^0)/\Gamma(K^+K^-\pi^+)$ Γ_{14}/Γ_{12}

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.74 ±0.08 OUR FIT				
0.717±0.069±0.060	FRABETTI	95B	E687	Dalitz plot analysis

$\Gamma(K^+\overline{K}^*(892)^0)/\Gamma(\phi\pi^+)$ Γ_{14}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.93±0.09 OUR FIT					
0.95±0.10 OUR AVERAGE					
0.85±0.34±0.20	9	ALVAREZ	90C	NA14	Photoproduction
0.84±0.30±0.22		ADLER	89B	MRK3	e^+e^- 4.14 GeV
1.05±0.17±0.12		CHEN	89	CLEO	e^+e^- 10 GeV
0.87±0.13±0.05	117	ANJOS	88	E691	Photoproduction
1.44±0.37	87	ALBRECHT	87F	ARG	e^+e^- 10 GeV

$\Gamma(f_0(980)\pi^+)/\Gamma(K^+K^-\pi^+)$ Γ_{35}/Γ_{12}

Unseen decay modes of the $f_0(980)$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.25±0.09 OUR FIT				
1.00±0.32±0.24	FRABETTI	95B	E687	Dalitz plot analysis

$\Gamma(f_J(1710)\pi^+ \to K^+K^-\pi^+)/\Gamma(K^+K^-\pi^+)$ Γ_{17}/Γ_{12}

This includes *only* K^+K^- decays of the $f_J(1710)$, because branching ratios of this resonance are not known.

VALUE	DOCUMENT ID		TECN	COMMENT
0.034±0.023±0.035	FRABETTI	95B	E687	Dalitz plot analysis

$\Gamma(K^+\overline{K}_0^*(1430)^0)/\Gamma(K^+K^-\pi^+)$ Γ_{16}/Γ_{12}

Unseen decay modes of the $\overline{K}_0^*(1430)^0$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.150±0.052±0.052	FRABETTI	95B	E687	Dalitz plot analysis

$\Gamma(K^+K^-\pi^+$ nonresonant$)/\Gamma(\phi\pi^+)$ Γ_{18}/Γ_{13}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.07±0.05	48	ANJOS	88	E691	Photoproduction

$\Gamma(K^*(892)^+\overline{K}^0)/\Gamma(\phi\pi^+)$ Γ_{20}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	DOCUMENT ID		TECN	COMMENT
1.20±0.21±0.13	CHEN	89	CLEO	e^+e^- 10 GeV

$\Gamma(K^*(892)^+\overline{K}^0)/\Gamma(K^+\overline{K}^0)$ Γ_{20}/Γ_{11}

Unseen decay modes of the $K^*(892)^+$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.9	90	FRABETTI	95	E687	γBe $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(\phi\pi^+\pi^0)/\Gamma(\phi\pi^+)$ Γ_{22}/Γ_{13}

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.4±1.0±0.5		11	ANJOS	89E	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.6	90		ALVAREZ	90C	NA14	Photoproduction

$\Gamma(\phi\rho^+)/\Gamma(\phi\pi^+)$ Γ_{23}/Γ_{13}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{1.86\pm0.26^{+0.29}_{-0.40}}$	253	AVERY	92	CLEO	$e^+e^- \simeq$ 10.5 GeV

$\Gamma(\phi\pi^+\pi^0$ 3-body$)/\Gamma(\phi\pi^+)$ Γ_{24}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.71	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^+K^-\pi^+\pi^0$ non-$\phi)/\Gamma(\phi\pi^+)$ Γ_{25}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.4	90	[25] ANJOS	89E	E691	Photoproduction

[25] Total minus ϕ component.

$\Gamma(K^+\overline{K}^0\pi^+\pi^-)/\Gamma(\phi\pi^+)$ Γ_{26}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.77	90	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^0K^-\pi^+\pi^+)/\Gamma(\phi\pi^+)$ Γ_{27}/Γ_{13}

VALUE	DOCUMENT ID		TECN	COMMENT
1.2 ±0.2 ±0.2	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^*(892)^+\overline{K}^*(892)^0)/\Gamma(\phi\pi^+)$ Γ_{28}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	DOCUMENT ID		TECN	COMMENT
1.6±0.4±0.4	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(K^0K^-\pi^+\pi^+$ non-$K^{*+}\overline{K}^{*0})/\Gamma(\phi\pi^+)$ Γ_{29}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.80	90	ALBRECHT	92B	ARG	$e^+e^- \simeq$ 10.4 GeV

$\Gamma(\phi\pi^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ — Γ_{31}/Γ_{13}

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.51±0.12 OUR AVERAGE						
0.58±0.21±0.10		21	FRABETTI	92	E687	γ Be
0.42±0.13±0.07		19	ANJOS	88	E691	Photoproduction
1.11±0.37±0.28		62	ALBRECHT	85D	ARG	e^+e^- 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.24	90		ALVAREZ	90C	NA14	Photoproduction

$\Gamma(K^+K^-\pi^+\pi^+\pi^-\text{ non-}\phi)/\Gamma_{total}$ — Γ_{32}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.003\ ^{+0.003}_{-0.002}$	BARLAG	92C	ACCM	π^- 230 GeV

$\Gamma(K^+K^-\pi^+\pi^+\pi^-\text{ non-}\phi)/\Gamma(\phi\pi^+)$ — Γ_{32}/Γ_{13}

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.32	90	10	ANJOS	88	E691	Photoproduction

Other hadronic modes (0, 1, or 3 K's)

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ — Γ_{33}/Γ_{13}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.39±0.08 OUR AVERAGE					
0.33±0.10±0.04	29	ADAMOVICH	93	WA82	π^- 340 GeV
0.44±0.10±0.04		ANJOS	89	E691	Photoproduction

$\Gamma(\rho^0\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{34}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	90	ANJOS	89	E691	Photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.22	90	ALBRECHT	87G	ARG	e^+e^- 10 GeV

$\Gamma(f_0(980)\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{35}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.32±0.10 OUR FIT				
0.28±0.10±0.03	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\text{ nonresonant})/\Gamma(\phi\pi^+)$ — Γ_{36}/Γ_{13}

VALUE	DOCUMENT ID		TECN	COMMENT
0.29±0.09±0.03	ANJOS	89	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^-\pi^0)/\Gamma(\phi\pi^+)$ — Γ_{37}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.3	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\eta\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{38}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.54±0.09±0.06		165	ALEXANDER	92	CLEO	$\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5	90		ANJOS	89E	E691	Photoproduction

$\Gamma(\omega\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{39}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.5	90	ANJOS	89E	E691	Photoproduction

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{40}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.003\ ^{+0.004}_{-0.003}$	BARLAG	92C	ACCM	π^- 230 GeV

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(\phi\pi^+)$ — Γ_{40}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.29	90	ANJOS	89	E691	Photoproduction

$\Gamma(\eta\rho^+)/\Gamma(\phi\pi^+)$ — Γ_{42}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$2.86\pm0.38^{+0.36}_{-0.38}$	217	AVERY	92	CLEO	$\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$

$\Gamma(\eta\pi^+\pi^0\text{ 3-body})/\Gamma(\phi\pi^+)$ — Γ_{43}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.82	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

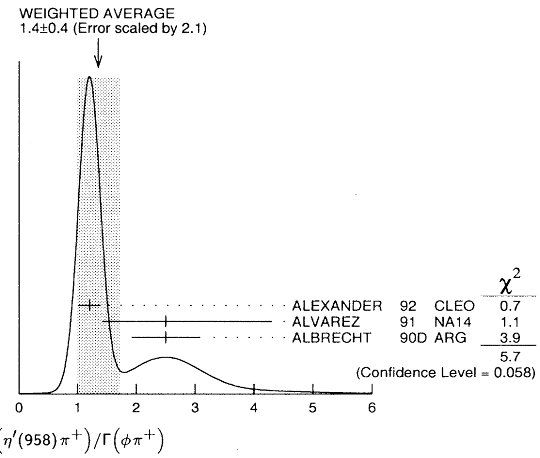
$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.049^{+0.033}_{-0.030}$	BARLAG	92C	ACCM	π^- 230 GeV

$\Gamma(\eta'(958)\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{45}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.4 ±0.4 OUR AVERAGE Error includes scale factor of 2.1. See the ideogram below.						
1.20±0.15±0.11		281	ALEXANDER	92	CLEO	$\eta' \to \eta\pi^+\pi^-$, $\rho^0\gamma$
$2.5\ \pm1.0\ ^{+1.5}_{-0.4}$		22	ALVAREZ	91	NA14	Photoproduction
2.5 ±0.5 ±0.3		215	ALBRECHT	90D	ARG	$e^+e^- \approx$ 10.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	90		ANJOS	91B	E691	γ Be, $\overline{E}_\gamma \approx$ 145 GeV



$\Gamma(\eta'(958)\rho^+)/\Gamma(\phi\pi^+)$ — Γ_{47}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$3.44\pm0.62^{+0.44}_{-0.46}$	68	AVERY	92	CLEO	$\eta' \to \eta\pi^+\pi^-$

$\Gamma(\eta'(958)\pi^+\pi^0\text{ 3-body})/\Gamma(\phi\pi^+)$ — Γ_{48}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.85	90	DAOUDI	92	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Gamma(K^0\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{49}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.21	90	ADLER	89B	MRK3	e^+e^- 4.14 GeV

$\Gamma(K^0\pi^+)/\Gamma(K^+\overline{K}^0)$ — Γ_{49}/Γ_{11}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.53	90	FRABETTI	95	E687	γ Be $\overline{E}_\gamma \approx$ 200 GeV

$\Gamma(K^+\pi^+\pi^-)/\Gamma(\phi\pi^+)$ — Γ_{50}/Γ_{13}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.28±0.06±0.05	85	FRABETTI	95E	E687	γ Be, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^+\rho^0)/\Gamma(\phi\pi^+)$ — Γ_{51}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	90	FRABETTI	95E	E687	γ Be, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^*(892)^0\pi^+)/\Gamma(\phi\pi^+)$ — Γ_{52}/Γ_{13}

Unseen decay modes of the resonances are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.18±0.05±0.04	25	FRABETTI	95E	E687	γ Be, $\overline{E}_\gamma$= 220 GeV

$\Gamma(K^+K^+K^-)/\Gamma(\phi\pi^+)$ — Γ_{53}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.016	90	FRABETTI	95F	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV

$\Gamma(\phi K^+)/\Gamma(\phi\pi^+)$ — Γ_{54}/Γ_{13}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.013	90	FRABETTI	95F	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.071	90	ANJOS	92D	E691	γ Be, $\overline{E}_\gamma$ = 145 GeV

Rare or forbidden modes

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{total}$ — Γ_{55}/Γ

This mode is not a useful test for a ΔC=1 weak neutral current because both quarks must change flavor in this decay.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<4.3 × 10⁻⁴	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(K^+\mu^+\mu^-)/\Gamma_{total}$ — Γ_{56}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<5.9 × 10^−4	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(K^*(892)^+\mu^+\mu^-)/\Gamma_{total}$ — Γ_{57}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.4 × 10^−3	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(\pi^-\mu^+\mu^+)/\Gamma_{total}$ — Γ_{58}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<4.3 × 10^−4	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(K^-\mu^+\mu^+)/\Gamma_{total}$ — Γ_{59}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<5.9 × 10^−4	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(K^*(892)^-\mu^+\mu^+)/\Gamma_{total}$ — Γ_{60}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.4 × 10^−3	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$D_s^+ \to \phi \ell^+ \nu_\ell$ FORM FACTORS

$r_2 \equiv A_2(0)/A_1(0)$ in $D_s^+ \to \phi \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.6±0.4 OUR AVERAGE					
1.4±0.5±0.3	308	[26] AVERY	94B	CLEO	e^+e^- 10 GeV
1.1±0.8±0.1	90	[27] FRABETTI	94F	E687	γBe, $\overline{E}_\gamma$= 220 GeV
$2.1^{+0.6}_{-0.5}\pm0.2$	19	[27] KODAMA	93	E653	600 GeV $\pi^- N$

[26] AVERY 94B uses $D_s^+ \to \phi e^+ \nu_e$ decays.

[27] FRABETTI 94F and KODAMA 93 use $D_s^+ \to \phi \mu^+ \nu_\mu$ decays.

$r_V \equiv V(0)/A_1(0)$ in $D_s^+ \to \phi \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.5±0.5 OUR AVERAGE					
0.9±0.6±0.3	308	[28] AVERY	94B	CLEO	e^+e^- 10 GeV
1.8±0.9±0.2	90	[29] FRABETTI	94F	E687	γBe, $\overline{E}_\gamma$= 220 GeV
$2.3^{+1.1}_{-0.9}\pm0.4$	19	[29] KODAMA	93	E653	600 GeV $\pi^- N$

[28] AVERY 94B uses $D_s^+ \to \phi e^+ \nu_e$ decays.

[29] FRABETTI 94F and KODAMA 93 use $D_s^+ \to \phi \mu^+ \nu_\mu$ decays.

Γ_L/Γ_T in $D_s^+ \to \phi \ell^+ \nu_\ell$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.72±0.18 OUR AVERAGE					
1.0 ±0.3 ±0.2	308	[30] AVERY	94B	CLEO	e^+e^- 10 GeV
1.0 ±0.5 ±0.1	90	[31] FRABETTI	94F	E687	γBe, $\overline{E}_\gamma$= 220 GeV
0.54±0.21±0.10	19	[31] KODAMA	93	E653	600 GeV $\pi^- N$

[30] AVERY 94B uses $D_s^+ \to \phi e^+ \nu_e$ decays.

[31] FRABETTI 94F and KODAMA 93 use $D_s^+ \to \phi \mu^+ \nu_\mu$ decays. Γ_L/Γ_T is evaluated for a lepton mass of zero.

$D_s^{\pm}$ REFERENCES

ARTUSO	96	PL B378 364	+Efimov, Gao, Goldberg+	(CLEO Collab.)
BAI	95	PRL 74 4599	+Bardon, Blum, Breakstone+	(BES Collab.)
BAI	95C	PR D52 3781	+Bardon, Blum, Breakstone+	(BES Collab.)
BRANDENB...	95	PRL 75 3804	Brandenburg, Cinabro, Liu+	(CLEO Collab.)
FRABETTI	95	PL B346 199	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95B	PL B351 591	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95E	PL B359 403	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	95F	PL B363 259	+Cheung, Cumalat+	(FNAL E687 Collab.)
KODAMA	95	PL B345 85	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
ACOSTA	94	PR D49 5690	+Athanas, Masek, Paar+	(CLEO Collab.)
AVERY	94B	PL B337 405	+Freyberger, Rodriguez+	(CLEO Collab.)
BROWN	94	PR D50 1884	+Fast, McIlwain, Miao+	(CLEO Collab.)
BUTLER	94	PL B324 255	+Fu, Kalbfleisch, Ross+	(CLEO Collab.)
FRABETTI	94F	PL B328 187	+Cheung, Cumalat+	(FNAL E687 Collab.)
MUHEIM	94	PR D49 3767	+Stone	(SYRA)
ADAMOVICH	93	PL B305 177	+Alexandrov, Antinori+	(CERN WA82 Collab.)
AOKI	93	PTP 89 131	+Baroni, Bisi, Breslin+	(CERN WA75 Collab.)
FRABETTI	93F	PRL 71 827	+Cheung, Cumalat, Dallapiccola+	(FNAL E687 Collab.)
FRABETTI	93G	PL B313 253	+Cheung, Cumalat+	(FNAL E687 Collab.)
KODAMA	93	PL B309 483	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
KODAMA	93B	PL B313 260	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
ALBRECHT	92B	ZPHY C53 361	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALEXANDER	92	PRL 68 1275	+Bebek, Berkelman, Besson+	(CLEO Collab.)
ANJOS	92D	PRL 69 2892	+Appel, Bean, Bediaga+	(FNAL E691 Collab.)
AVERY	92	PRL 68 1279	+Freyberger, Rodriguez, Yelton+	(CLEO Collab.)
BARLAG	92C	ZPHY C55 383	+Becker, Bozek, Boehringer+	(ACCMOR Collab.)
Also	90D	ZPHY C48 29	Barlag, Becker, Boehringer, Bosman+	(ACCMOR Collab.)
DAOUDI	92	PR D45 3965	+Ford, Johnson, Lingel+	(CLEO Collab.)
FRABETTI	92	PL B281 167	+Bogart, Cheung, Culy+	(FNAL E687 Collab.)
ALBRECHT	91	PL B255 634	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALVAREZ	91	PL B255 639	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ANJOS	91B	PR D43 R2063	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
COFFMAN	91	PL B263 135	+DeJongh, Dubois, Eigen, Hitlin+	(Mark III Collab.)
ADLER	90B	PRL 64 169	+Bai, Blaylock, Bolton+	(Mark III Collab.)
ALBRECHT	90D	PL B245 315	+Ehrlichmann, Glaeser, Harder+	(ARGUS Collab.)
ALEXANDER	90B	PRL 65 1531	+Artuso, Bebek, Berkelman+	(CLEO Collab.)
ALVAREZ	90	ZPHY C47 539	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ALVAREZ	90C	PL B246 261	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ANJOS	90B	PRL 64 2885	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	90C	PR D41 2705	+Appel, Bean+	(FNAL E691 Collab.)
BAI	90	PRL 65 686	+Blaylock, Bolton, Brient+	(Mark III Collab.)
BARLAG	90C	ZPHY C46 563	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
FRABETTI	90	PL B251 639	+Bogart, Cheung, Coteus+	(FNAL E687 Collab.)
ADLER	89B	PRL 63 1211	+Bai, Becker, Blaylock, Bolton+	(Mark III Collab.)
Also	89D	PRL 63 2858 erratum		
ANJOS	89	PRL 62 125	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
ANJOS	89E	PL B223 267	+Appel, Bean, Bracker+	(FNAL E691 Collab.)
AVERILL	89	PR D39 123	+Blockus, Brabson+	(HRS Collab.)
CHEN	89	PL B226 192	+McIlwain, Miller, Ng, Shibata+	(CLEO Collab.)
ALBRECHT	88	PL B207 349	+Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	88I	PL B210 267	+Boeckmann, Glaeser+	(ARGUS Collab.)
ANJOS	88	PRL 60 897	+Appel+	(FNAL E691 Collab.)
RAAB	88	PR D37 2391	+Anjos, Appel, Bracker+	(FNAL E691 Collab.)
ALBRECHT	87F	PL B179 398	+Binder, Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	87G	PL B195 102	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
ANJOS	87B	PRL 58 1818	+Appel, Bracker, Browder+	(FNAL E691 Collab.)
BECKER	87B	PL B184 277	+Boehringer, Bosman+	(NA11 and NA32 Collab.)
BLAYLOCK	87	PRL 58 2171	+Bolton, Brown, Bunnell+	(Mark III Collab.)
BRAUNSCH...	87	ZPHY C35 317	Braunschweig, Gerhards+	(TASSO Collab.)
CSORNA	87	PL B191 318	+Mestayer, Panvini, Word+	(CLEO Collab.)
JUNG	86	PRL 56 1775	+Abachi+	(HRS Collab.)
USHIDA	86	PRL 56 1767	+Kondo, Tasaka, Park+	(FNAL E531 Collab.)
ALBRECHT	85D	PL 153B 343	+Drescher, Binder, Drews+	(ARGUS Collab.)
DERRICK	85B	PRL 54 2568	+Fernandez, Fries, Hyman+	(HRS Collab.)
AIHARA	84D	PRL 53 2465	+Alston-Garnjost, Badtke, Bakken+	(TPC Collab.)
ALTHOFF	84	PL 136B 130	+Braunschweig, Kirschfink+	(TASSO Collab.)
BAILEY	84	PL 139B 320	+Belau, Bohringer, Bosman+	(ACCMOR Collab.)
AUBERT	83	NP B213 31	+Bassompierre, Becks, Best+	(EMC Collab.)
CHEN	83C	PRL 51 634	+Alam, Giles, Kagan+	(CLEO Collab.)
USHIDA	83	PRL 51 2362	+Kondo, Fujioka, Fukushima+	(FNAL E653 Collab.)

OTHER RELATED PAPERS

RICHMAN	95	RMP 67 893	+Burchat	(UCSB, STAN)

$D_s^{*\pm}$

$I(J^P) = ?(?^?)$

$D_s^{*\pm}$ MASS

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2112.4±0.7 OUR FIT Error includes scale factor of 1.1.				
2106.6±2.1±2.7	[1] BLAYLOCK	87	MRK3	$e^+e^- \to D_s^+ \gamma X$

[1] Assuming D_s^+ mass = 1968.7 ± 0.9 MeV.

$m_{D_s^{*\pm}} - m_{D_s^{\pm}}$

The fit includes $D^{\pm}$, D^0, $D_s^{\pm}$, $D^{*\pm}$, D^{*0}, and $D_s^{*\pm}$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
143.8 ± 0.4 OUR FIT					
143.9 ± 0.4 OUR AVERAGE					
143.76± 0.39±0.40		GRONBERG	95	CLE2	e^+e^-
144.22± 0.47±0.37		BROWN	94	CLE2	e^+e^-
142.5 ± 0.8 ±1.5		[2] ALBRECHT	88	ARG	$e^+e^- \to D_s^+ \gamma X$
139.5 ± 8.3 ±9.7	60	AIHARA	84D	TPC	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
143.0 ±18.0	8	ASRATYAN	85	HLBC	FNAL 15-ft, ν-^{2}H
110 ±46		BRANDELIK	79	DASP	$e^+e^- \to D_s^+ \gamma X$

[2] Result includes data of ALBRECHT 84B.

$D_s^{*\pm}$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
< 1.9	90	GRONBERG	95	CLE2	e^+e^-
< 4.5	90	ALBRECHT	88	ARG	E_{cm}^{ee} = 10.2 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.9	90	BROWN	94	CLE2	e^+e^-
<22	90	BLAYLOCK	87	MRK3	$e^+e^- \to D_s^+ \gamma X$

D_s^{*+} DECAY MODES

D_s^{*-} modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D_s^+ \gamma$	seen
Γ_2	$D_s^+ \pi^0$	seen

D_s^{*+} BRANCHING RATIOS

$\Gamma(D_s^+\gamma)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
dominant OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	ASRATYAN	91	HLBC	$\overline{\nu}_\mu$ Ne
seen	ALBRECHT	88	ARG	$e^+e^- \to D_s^\pm\gamma X$
seen	AIHARA	84D		
seen	ALBRECHT	84B		
seen	BRANDELIK	79		

$\Gamma(D_s^+\pi^0)/\Gamma(D_s^+\gamma)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
$0.062^{+0.020}_{-0.018}\pm0.022$	GRONBERG	95	CLE2	e^+e^-

$D_s^{*\pm}$ REFERENCES

GRONBERG 95 PRL 75 3232 +Korte, Kutschke+ (CLEO Collab.)
BROWN 94 PR D50 1884 +Fast, McIlwain, Miao+ (CLEO Collab.)
ASRATYAN 91 PL B257 525 +Marage+(ITEP, BELG, SACL, SERP, CRAC, BARI, CERN)
ALBRECHT 88 PL B207 349 +Binder, Boeckmann+ (ARGUS Collab.)
BLAYLOCK 87 PRL 58 2171 +Bolton, Brown, Bunnell+ (Mark III Collab.)
ASRATYAN 85 PL 156B 441 +Fedotov, Ammosov, Burtovoy+ (ITEP, SERP)
AIHARA 84D PRL 53 2465 +Alston-Garnjost, Badtke, Bakken+ (TPC Collab.)
ALBRECHT 84B PL 146B 111 +Drescher, Heller+ (ARGUS Collab.)
BRANDELIK 79 PL 80B 412 +Braunschweig, Martyn, Sander+ (DASP Collab.)

OTHER RELATED PAPERS

KAMAL 92 PL B284 421 +Xu (ALBE)
BRANDELIK 78C PL 76B 361 +Cords+ (DASP Collab.)
BRANDELIK 77B PL 70B 132 +Braunschweig, Martyn, Sander+ (DASP Collab.)

$D_{s1}(2536)^\pm$

$I(J^P) = 0(1^+)$
I, J, P need confirmation.

Seen in $D^*(2010)^+K^0$. Not seen in D^+K^0 or D^0K^+. $J^P = 1^+$ assignment strongly favored.

$D_{s1}(2536)^\pm$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2535.35± 0.34 OUR AVERAGE					
2534.2 ± 1.2	9	ASRATYAN	94	BEBC	$\nu N \to D^*K^0X, D^{*0}K^\pm X$
2535 ± 0.6 ±1	75	FRABETTI	94B	E687	γBe $\to D^{*+}K^0X, D^{*0}K^+X$
2535.3 ± 0.2 ±0.5	134	ALEXANDER	93	CLE2	$e^+e^- \to D^{*0}K^+X$
2534.8 ± 0.6 ±0.6	44	ALEXANDER	93	CLE2	$e^+e^- \to D^{*+}K^0X$
2535.2 ± 0.5 ±1.5	28	ALBRECHT	92R	ARG	$10.4\ e^+e^- \to D^{*0}K^+X$
2536.6 ± 0.7 ±0.4		AVERY	90	CLEO	$e^+e^- \to D^{*+}K^0X$
2535.9 ± 0.6 ±2.0		ALBRECHT	89E	ARG	$D_{s1}^* \to D^*(2010)K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2535 ±28		[1] ASRATYAN	88	HLBC	$\nu N \to D_s\gamma\gamma X$

[1] Not seen in D^*K.

$m_{D_{s1}(2536)^\pm} - m_{D_s^*(2111)}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
424±28	ASRATYAN	88	HLBC	$D_s^{*\pm}\gamma$

$D_{s1}(2536)^\pm$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.3	90		ALEXANDER	93	CLEO	$e^+e^- \to D^{*0}K^+X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.2	90	75	FRABETTI	94B	E687	γBe $\to D^{*+}K^0X, D^{*0}K^+X$
<3.9	90		ALBRECHT	92R	ARG	$10.4\ e^+e^- \to D^{*0}K^+X$
<5.44	90		AVERY	90	CLEO	$e^+e^- \to D^{*+}K^0X$
<4.6	90		ALBRECHT	89E	ARG	$D_{s1}^* \to D^*(2010)K^0$

$D_{s1}(2536)^+$ DECAY MODES

$D_{s1}(2536)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$D^*(2010)^+K^0$	seen
Γ_2	$D^*(2007)^0K^+$	seen
Γ_3	D^+K^0	not seen
Γ_4	D^0K^+	not seen
Γ_5	$D_s^{*+}\gamma$	possibly seen

$D_{s1}(2536)^+$ BRANCHING RATIOS

$\Gamma(D^+K^0)/\Gamma(D^*(2010)^+K^0)$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.40	90	ALEXANDER	93	CLEO	$e^+e^- \to D^{*+}K^0X$
<0.43	90	ALBRECHT	89E	ARG	$D_{s1}^* \to D^*(2010)K^0$

$\Gamma(D_s^{*+}\gamma)/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
possibly seen	ASRATYAN	88	HLBC	$\nu N \to D_s\gamma\gamma X$

$\Gamma(D^0K^+)/\Gamma(D^*(2007)^0K^+)$ — Γ_4/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.12	90	ALEXANDER	93	CLEO	$e^+e^- \to D^{*0}K^+X$

$\Gamma(D_s^{*+}\gamma)/\Gamma(D^*(2007)^0K^+)$ — Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.42	90	ALEXANDER	93	CLEO	$e^+e^- \to D^{*0}K^+X$

$D_{s1}(2536)^\pm$ REFERENCES

ASRATYAN 94 ZPHY C 61 563 +Aderholz+ (BIRM, BELG, CERN, SERP, ITEP, RAL)
FRABETTI 94B PRL 72 324 +Cheung, Cumalat+ (FNAL E687 Collab.)
ALEXANDER 93 PL B303 377 +Bebek+ (CLEO Collab.)
ALBRECHT 92R PL B297 425 +Ehrlichmann+ (ARGUS Collab.)
AVERY 90 PR D41 774 +Besson (CLEO Collab.)
ALBRECHT 89E PL B230 162 +Glaser, Harder+ (ARGUS Collab.)
ASRATYAN 88 ZPHY C40 483 +Fedotov+ (ITEP, SERP)

$D_{sJ}(2573)^\pm$

$I(J^P) = ?(?^?)$

J^P is natural, width and decay modes consistent with 2^+.

$D_{sJ}(2573)^\pm$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2573.5±1.7 OUR AVERAGE						
2574.5±3.3±1.6		ALBRECHT	96	ARG		$e^+e^- \to D^0K^+X$
$2573.2^{+1.7}_{-1.6}\pm0.9$	217	KUBOTA	94	CLE2	+	$e^+e^-\sim$ 10.5 GeV

$D_{sJ}(2573)^\pm$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$15\ ^{+5}_{-4}$ OUR AVERAGE						
10.4±8.3±3.0		ALBRECHT	96	ARG		$e^+e^- \to D^0K^+X$
$16\ ^{+5}_{-4}\ \pm3$	217	KUBOTA	94	CLE2	+	$e^+e^-\sim$ 10.5 GeV

$D_{sJ}(2573)^+$ DECAY MODES

$D_{sJ}(2573)^-$ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)
Γ_1	D^0K^+	seen
Γ_2	$D^*(2007)^0K^+$	seen

$D_{sJ}(2573)^+$ BRANCHING RATIOS

$\Gamma(D^0K^+)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
seen	217	KUBOTA	94	CLE2	±	$e^+e^-\sim$ 10.5 GeV

$\Gamma(D^*(2007)^0K^+)/\Gamma(D^0K^+)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.33	90	KUBOTA	94	CLE2	+	$e^+e^-\sim$ 10.5 GeV

$D_{sJ}(2573)^\pm$ REFERENCES

ALBRECHT 96 ZPHY C69 405 +Hamacher, Hofmann+ (ARGUS Collab.)
KUBOTA 94 PRL 72 1972 +Lattery, Nelson, Patton+ (CLEO Collab.)

BOTTOM MESONS
$(B = \pm 1)$

$B^+ = u\overline{b}$, $B^0 = d\overline{b}$, $\overline{B}^0 = \overline{d}\,b$, $B^- = \overline{u}\,b$, similarly for B^*'s

B-particle organization

Many measurements of B decays involve admixtures of B hadrons. Previously we arbitrarily included such admixtures in the $B^\pm$ section, but because of their importance we have created two new sections: "$B^\pm/B^0$ Admixture" for $\Upsilon(4S)$ results and "$B^\pm/B^0/B^0_s/b$-baryon Admixture" for results at higher energies. Most inclusive decay branching fractions are found in the Admixture sections. B^0-$\overline{B}^0$ mixing data are found in the B^0 section, while B^0_s-$\overline{B}^0_s$ mixing data and B-$\overline{B}$ mixing data for a B^0/B^0_s admixture are found in the B^0_s section. CP-violation data are found in the B^0 section. b-baryons are found near the end of the Baryon section.

The organization of the B sections is now as follows, where bullets indicate particle sections and brackets indicate reviews.

- [Production and Decay of b-flavored Hadrons]
- [Semileptonic Decays of B Mesons]
- • $B^\pm$
  - mass
  - mean life
  - branching fractions
- • B^0
  - mass
  - mean life
  - branching fractions
  - polarization in B^0 decay
  - B^0-$\overline{B}^0$ mixing
  - [B^0-$\overline{B}^0$ Mixing and CP Violation in B Decay]
  - CP violation
- • $B^\pm$ B^0 Admixture
  - branching fractions
- • $B^\pm/B^0/B^0_s/b$-baryon Admixture
  - mean life
  - production fractions
  - branching fractions
- • B^*
  - mass
- • $B^*_J(5732)$
  - mass
  - width
- • B^0_s
  - mass
  - mean life
  - branching fractions
  - polarizaton in B^0_s decay
  - B^0_s-$\overline{B}^0_s$ mixing
  - B-$\overline{B}$ mixing (admixture of B^0, B^0_s)
- • B^*_s
  - mass
- • $B^*_{sJ}(5850)$
  - mass
  - width

At end of Baryon Listings:

- • Λ_b
  - mass
  - mean life
  - branching fractions
- • Ξ^0_b, Ξ^-_b
  - mean life

PRODUCTION AND DECAY OF b-FLAVORED HADRONS

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In the two years since the last edition of this review our understanding of the physics of B mesons and b-flavored baryons has significantly improved. 1995 was another record setting year for the CLEO experiment as well as the Cornell e^+e^- storage ring (CESR) which reached an instantaneous luminosity of 3.3×10^{32} cm^{-2}s^{-1}. More than 4 fb^{-1} have been logged by the CLEO Collaboration. At CERN, the Z program has been completed and each of the four LEP experiments has recorded data samples containing about 3 million Z decays, corresponding to approximately 0.7×10^6 produced $b\overline{b}$ quark pairs. The FNAL $p\overline{p}$ collider run continued throughout most of 1995 and the CDF and DØ experiments have collected close to 100 pb^{-1} of new data. SLD has begun to contribute to B physics. Using the excellent resolution of their vertex detector they have obtained precise measurements of B-meson lifetimes. New results in this edition include:

- The first observation of exclusive semileptonic $b \to u$ transitions.
- The determination of the decay rate for inclusive $b \to s\gamma$ transitions.
- Updated lifetimes and masses for b-flavored hadrons.
- Improved measurements of B^0–$\overline{B}^0$ and B^0_s–$\overline{B}^0_s$ oscillations.
- A new set of inclusive branching ratios for B mesons.
- Updated limits on rare B decays including new results on $b \to s$ gluon.

Weak decays of heavy quarks test the Standard Model and can be used to determine its parameters, in particular the weak-mixing angles of the Cabibbo-Kobayashi-Maskawa matrix. Experiments with B mesons may lead to the first precise determination of the fourth CKM parameter, the complex phase. While the underlying decay of the heavy quark is governed by the weak interaction, it is the strong force that is responsible for the formation of the hadrons that are observed by experimenters. Hence, in order to extract the Standard Model parameters from the experimental data, an understanding of the interplay of the weak and strong interaction is needed.

Production and spectroscopy

Elementary particles are characterized by their masses, lifetimes, and internal quantum numbers. The bound states with a b quark and a $\overline{u}$ or $\overline{d}$ antiquark are referred to as the B_d ($\overline{B^0}$) and the B_u (B^-) mesons, respectively. The first radial excitation is called the B^* meson. B^{**} is the generic name for the four orbitally excited ($L = 1$) B meson states that correspond to the P-wave mesons in the charm system, D^{**}.

Experimental studies of b decay are performed at the $\Upsilon(4S)$ resonance near the production threshold as well as at higher energies in proton-antiproton collisions and Z decays. For quantitative analyses of B decays the initial composition of the data sample must be known. At the threshold experiments this is determined by the ratio of charged to neutral decays of the $\Upsilon(4S)$. This ratio is denoted

$$\frac{f_+}{f_0} = \frac{\Upsilon(4S) \to B^+B^-}{\Upsilon(4S) \to B^0\overline{B}^0} \tag{1}$$

The $\Upsilon(4S)$ resonance decays only to $B^0\overline{B}^0$ and B^+B^- pairs, while heavier states such as B_s or B_c are not accessible. The current experimental limit for non-$B\overline{B}$ decays of the $\Upsilon(4S)$ is less than 4% at the 95% confidence level [1]. CLEO has measured the production ratio using semileptonic B decays and found [2]

$$\frac{f_+}{f_0} = 1.13 \pm 0.14 \pm 0.13 \pm 0.06 \tag{2}$$

where the last error is due to the uncertainties in the ratio of B^0 and B^+ lifetimes. This is consistent with equal production of B^+B^- and $B^0\overline{B}^0$ pairs and unless explicitly stated otherwise we will assume $f_+/f_0 = 1$. This assumption is further supported by the near equality of the B^+ and B^0 masses.

At high energy collider experiments the b quarks hadronize as B_d, B_u, B_s, and B_c mesons or as baryons containing b quarks. The composition of the initial sample is not very precisely known although over the last year significant improvements have been achieved. Several methods have been developed to determine f_{B_s} and f_{Λ_b}, the fractions of B_s mesons, and b-flavored baryons produced in $Z \to b\overline{b}$ decays. ALEPH use their measurement of the product branching fraction, $f_{B_s} \times \mathrm{B}(\overline{B}^0_s \to D_s^+\ell^-\overline{\nu}_\ell \text{ anything}) = 0.82 \pm 0.09^{+0.13}_{-0.14}\%$ [3]. Under the assumption of equal semileptonic partial widths for b-flavored hadrons results from the $\Upsilon(4S)$ experiments can be used to obtain an estimate for $\mathrm{B}(\overline{B}^0_s \to D_s^+\ell^-\overline{\nu}_\ell)$. Using these results ALEPH [4] extract the fraction of b quarks that hadronize to B_s mesons to†

$$f_{B_s} = 11.1^{+2.5}_{-2.6}\% \tag{3}$$

A similar procedure is followed to obtain an estimate for the fraction of b baryons [5]:

$$f_{\Lambda_b} = 13.2 \pm 2.4 \pm 3.3\% \tag{4}$$

An alternative methods to determine f_{B_s} starts with the time integrated mixing parameter

$$\overline{\chi} = f_{B_s}\chi_s + f_{B^0}\chi_d \tag{5}$$

Assuming $\chi_s = 0.5$ and using the measured value for χ_d the fraction of B_s mesons can be extracted [6]

$$f_{B_s} = 11.3^{+2.5}_{-2.6}\% \tag{6}$$

Averaging the two measurements of f_{B_s} with correlated systematics taken into account yields

$$< f_{B_s} >= 11.2^{+1.8}_{-1.9}\% \tag{7}$$

Assuming that $f_{B^0} = f_{B^+}$ and $f_{B^0} + f_{B^+} + f_{B_s} + f_{\Lambda_b} = 1$ we obtain the results listed in Table 1.

Table 1: Fractions of weakly decaying b-hadron species in $Z \to b\overline{b}$ decay.

b-hadron	Fraction [%]
B^+	37.8 ± 2.2
B^0	37.8 ± 2.2
B_s	$11.2^{+1.8}_{-1.9}$
Λ_b	13.2 ± 4.1

To date, the existence of four b-flavored mesons (B^-, $\overline{B}^0$, B^*, B_s) has been established. The LEP experiments have provided evidence for excited B^{**} and B_s^{**} states. The B_c is still not observed. The Λ_b baryon has been exclusively reconstructed by CDF and the LEP experiments. First indications of Σ_b and Ξ_b production have been presented by the LEP collaborations [7]. DELPHI has measured the Σ_b^*–Σ_b hyperfine splitting to 56 ± 16 MeV [8].

Lifetimes

The lifetime of a b-flavored hadron is given by its hadronic and semileptonic decay rates

$$\frac{1}{\tau_B} = \Gamma_{\rm tot} = \Gamma_{\rm hadronic} + \Gamma_{\rm semileptonic} \tag{8}$$

In the naive spectator model the heavy quark can decay only via the external spectator mechanism and thus the lifetimes of all mesons and baryons containing b quarks would be equal. Nonspectator effects such as the interference between contributing amplitudes modify this simple picture and give rise to a lifetimes hierarchy for b-flavored hadrons similar to the charm sector. However, since the lifetime differences are expected to scale as $1/m_Q^2$, where m_Q is the mass of the heavy quark, the variation in the b system should be significantly smaller, of order 10% or less [9]. For the b system we expect

$$\tau(B^-) \geq \tau(\overline{B}^0) \approx \tau(B_s) > \tau(\Lambda_b^0) \tag{9}$$

Measurements of lifetimes for the various b-flavored hadrons thus provide a means to determine the importance of nonspectator mechanisms in the b sector.

The experimental errors on individual B-lifetime measurements are approaching the 5–10% level. However, in order to reach the precision necessary to test theoretical predictions, the results from different experiments need to be averaged. Using the conventional approach of weighting the measurements according to their error does not take into account the underlying exponential lifetime distribution. If a measurement fluctuates low then its weight in the average will increase, leading to a bias towards low values. Combining lifetime measurements correctly is a difficult task that requires detailed knowledge of common systematic uncertainties and correlations between the results from different experiments. The average lifetimes for b-flavored hadrons given in this edition have been determined by L. Di Ciaccio (DELPHI) and the LEP B Lifetimes Working Group. Among other things, they considered uncertainties in the composition of the b sample and background, correlation

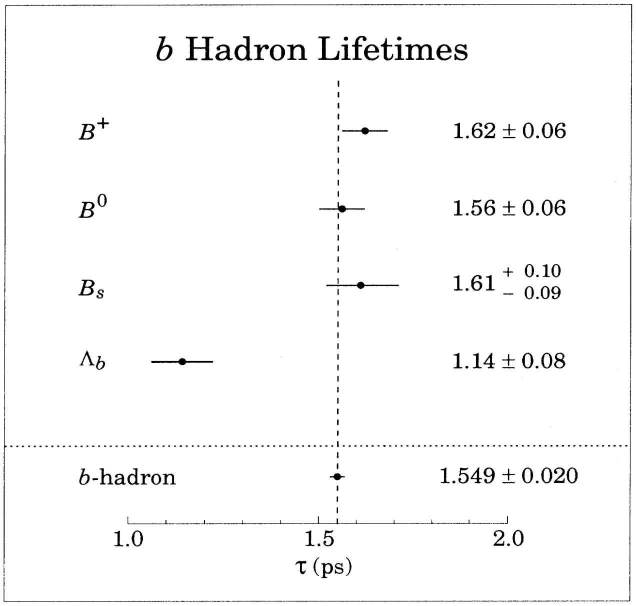

Figure 1: Summary of lifetime measurements for individual b hadrons and for the b-hadron admixture at high energy (LEP and CDF).

in the b momentum estimation and common errors in b and c branching fractions. A detailed description of their procedures and the treatment of correlated and uncorrelated errors can be found in [10]. The experimental papers used in this calculation are given in the Particle Listing sections on b-flavored mesons and baryons. A summary of the average b-hadron lifetimes is shown in Fig. 1. The pattern of measured lifetimes follows the theoretical expectations outlined above and nonspectator effects are observed to be small. However, the Λ_b baryon lifetime is unexpectedly short. As has been noted by several authors, the observed value of the Λ_b lifetime is quite difficult to accommodate theoretically [11,12].

Semileptonic decays and mixing

Measurements of semileptonic B decays are important for the determination of the weak couplings $|V_{cb}|$ and $|V_{ub}|$ and test our understanding of the dynamics of heavy quark decay. A measurement technique using events with two leptons was introduced by the ARGUS experiment [13] which significantly reduces the model dependence associated with the subtraction of the $b \to c \to \ell$ cascade component. A high momentum lepton is selected ($p_\ell > 1.4$ GeV) which tags a $b\overline{b}$ event. This primary lepton is then combined with an additional lepton candidate which has a momentum above 0.5 GeV. In the absence of mixing, if the second lepton has a charge opposite to the tagging lepton it is a primary lepton from the b decay, while if the second lepton has the same sign as the tag it is a cascade lepton. Models of semileptonic B decay are only needed for the small extrapolation to zero lepton momentum. Using this method, CLEO II finds

$$B_{\rm sl} = (10.49 \pm 0.17 \pm 0.43)\,\% \qquad (10)$$

consistent with the conventional single lepton analysis.

Assuming the semileptonic decay width is the same for all b-flavored hadrons, the semileptonic branching ratio should be slightly different at LEP since other b particles are produced:

$$B_{\rm sl}(\Upsilon(4S)) = \frac{\Gamma_{\rm sl}}{\Gamma_{\rm tot}} = \Gamma_{\rm sl} \times \frac{(\tau_{B^+} + \tau_{B^0})}{2} \qquad (11)$$

while

$$B_{\rm sl}(Z) = \Gamma_{\rm sl} \times \tau_b \qquad (12)$$

Using the world averages for the B lifetimes and the CLEO semileptonic branching fraction this gives

$$B_{\rm sl}(Z) = \frac{2\tau_b}{(\tau_{B^+} + \tau_{B^0})} \times B_{\rm sl}(\Upsilon(4S)) = 10.2 \pm 0.4\% \qquad (13)$$

Note that the contribution of other hadrons *reduces* the expected average semileptonic branching fraction at the Z. This is below the experimental average from LEP, $B_{\rm sl}(Z) = 10.9 \pm 0.1 \pm 0.3$, but the errors are still too large to draw any conclusions.

It is interesting to compare the inclusive semileptonic branching fraction to the sum of branching fractions for exclusive modes. CLEO and the LEP collaborations have updated their measurements of $B(B \to D\ell\nu_\ell)$ and $B(B \to D^*\ell\nu_\ell)$. Including the recent observations of $B \to D^{**}(2420)\ell\nu_\ell$ and $B \to D^{**}(2460)$ by OPAL and ALEPH the sum of exclusive semileptonic branching fractions amounts to $8.81 \pm 0.1\%$. The remaining decays may correspond to $B \to D^{**}\ell\nu_\ell$ where D^{**} denotes a p-wave charmed meson with a large width (*e.g.* the very broad but as of now unobserved $1^3P_1(2490)$ and $1^3P_0(2440)$ states). It is also possible that the other missing decays are $B \to D\pi\ell^-\nu_\ell$ where the $D\pi$ system is nonresonant or originates from the decay of a broad excited charm meson. These possibilities are difficult to check experimentally. It is also conceivable that the difference between the sum of the exclusive modes and the inclusive semileptonic rate is due to a systematic error in the D meson absolute branching fraction scale.

The ALEPH, DELPHI, OPAL, and CDF experiments have performed explicit measurements of Prob$(B^0 \to \overline{B^0})$ as a function of time to obtain the parameter $x_d = \Delta m_d/\Gamma$ [6]. The initial state b quark flavor is tagged either using leptons or jet charge, while the flavor of the final state b quark is tagged using either $\overline{B}_d \to D^{*+}\ell^- X$, $\overline{B}_d \to D^{*+}X$, or $\overline{B}_d \to \ell^- X$. If the final state is not fully reconstructed, as is the case for the analyses using dileptons, then the decay time must be determined using a topological vertexing technique where the lepton from the B decay and the other tracks in the same jet hemisphere are combined. The boost is determined using the observed energy, missing momentum and a correction factor determined from a Monte Carlo simulation. Averaging these results gives $\Delta m_d = 0.458 \pm 0.020$ ps^{-1} which is statistically superior to the results obtained from time integrated measurements by experiments at the $\Upsilon(4S)$.

The measurement of the mixing parameter $x_s = \Delta m_s/\Gamma$ for the B_s meson combined with the results on B^0–$\overline{B}^0$ oscillations allows the determination of the ratio of the CKM matrix elements $|V_{td}|^2/|V_{ts}|^2$ with significantly reduced theoretical uncertainties. Experimentally the measurement of x_s is a challenge. For large values, as expected for the B_s meson, time integrated measurements of B_s mixing become insensitive to x_s and one must make time dependent measurements in order to extract this parameter. These are very difficult because of the rapid oscillation rate of the B_s meson. Using an event sample with a lepton and a tag based on a jet charge technique where each track is weighted by its rapidity, ALEPH has searched for a high frequency component in their fit to the proper time distribution. They find $\Delta m_s > 6$ ps^{-1} or $x_s > 8.8$ at the 95% confidence level [6].

Hadronic decays

CLEO has presented a set of new measurements of inclusive B-meson decay rates that can be used to test the parton level expectation that most B decays proceed via a $b \to c$ transition. If we neglect the small contributions from $b \to u$ and penguin transitions, we expect about 1.15 charm quarks to be produced per B decay. The additional 15% is due to the fact that the virtual W forms a $s\overline{c}$ quark pair with a probability of approximately 0.15. This expectation can be verified experimentally by adding all inclusive $b \to c$ branching fractions. Using the world averages for the $b \to c$ branching fractions we find [14]:

$$\begin{aligned}\text{Charm yield} &= \mathrm{B}(B \to D^0X) + \mathrm{B}(B \to D^+X) + \mathrm{B}(B \to D_sX) \\ &+ \mathrm{B}(B \to \Lambda_cX) + \mathrm{B}(B \to \Xi_c^+X) + \mathrm{B}(B \to \Xi_c^0X) \\ &+ 2 \times \mathrm{B}(B \to \psi X) + 2 \times \mathrm{B}(B \to \psi' X) \\ &+ 2 \times \mathrm{B}(B \to \chi_{c1}X) + 2 \times \mathrm{B}(B \to \chi_{c2}X) \\ &+ 2 \times \mathrm{B}(B \to \eta_cX \text{ (incl. other } c\overline{c})) \\ &= 1.15 \pm 0.05 \qquad (14)\end{aligned}$$

The factor of 2 which multiplies $\mathrm{B}(B \to c\overline{c}X)$ accounts for the two charm quarks produced in $b \to c\overline{c}s$ transitions. Wherever possible the branching fractions for direct production are used. The contribution of $B \to \eta_cX$ and other charmonia is generously taken to be at the CLEO 90% confidence level upper limit $\mathrm{B}(B \to \eta_cX) < 0.90\%$.

Another interesting quantity is the fraction of B decays in which two charm quarks are produced. In a parton level calculation, Palmer and Stech [15] find that $\mathrm{B}(B \to X_{c\overline{c}}) = 19 \pm 1\%$ where the theoretical error is the uncertainty due to the choice of quark masses. This can be compared to the sum of the experimental measurements [14]

$$\begin{aligned}\mathrm{B}(B \to X_{c\overline{c}}) &= \mathrm{B}(B \to D_sX) + \mathrm{B}(B \to \psi X) + \mathrm{B}(B \to \psi' X) \\ &+ \mathrm{B}(B \to \chi_{c1}X) + \mathrm{B}(B \to \chi_{c2}X) + \mathrm{B}(B \to \Xi_cX) \\ &+ \mathrm{B}(B \to \eta_cX \text{ (incl. other } \overline{c})) \\ &= (15.8 \pm 2.8)\% \qquad (15)\end{aligned}$$

where the direct $B \to \psi$ and $B \to \chi_{c1}$ branching fraction have been used. The contribution from $B \to \Xi_c^0X$ is reduced by 1/3 to take into account the fraction that is not produced by the $b \to c\overline{c}s$ subprocess but by $b \to c\overline{u}d + s\overline{s}$ quark popping.

A possible contribution of $B \to D\overline{D}KX$ decays, which corresponds to the quark level process $b \to c\overline{c}s$ with popping of a light quark pair, is not included in the sum calculated above. Buchalla, Dunietz, and Yamamoto have recently suggested that the latter mechanism may be significant [16]. This possibility leads to wrong sign D–ℓ correlations and is currently under investigation at CLEO. Preliminary results [17] indicate a significant branching fraction on the order of 10% for $B \to \overline{D}_{\text{upper vertex}}X$.

The charm yield per B-meson decay is related to an intriguing puzzle in B physics: the experimental value for the semileptonic branching ratio of B mesons is significantly below the theoretical lower bound $\mathrm{B} > 12.5\%$ from QCD calculations within the parton model [18]. An enhanced hadronic decay rate would resolve this discrepancy and several explanations have been proposed. The theoretically preferred solution calls for an enhancement of the $b \to c\overline{c}s$ channel [19]. Increasing the $b \to c\overline{c}s$ component, however, would increase the average number of c quarks produced per b-quark decay and lead to another interesting problem: the predicted number of charm quarks per b decay would rise to 1.3 while the current experimental value for this number is 1.15 ± 0.05. Moreover, as noted above, $\mathrm{B}(B \to X_{c\overline{c}}) = 15.8 \pm 2.8$ is far below the required 30%. A systematic study of inclusive hadronic B decays to mesons and baryons and more precise measurements of charm meson branching fractions will be required to resolve this problem.

Measurements of exclusive hadronic B decays have reached sufficient precision to challenge our understanding of the dynamics of these decays. The factorization hypothesis has been experimentally confirmed for decays with large energy release. By comparing hadronic B^- and $\overline{B}^0$ decays, the relative contributions from external and internal spectator decays have been disentangled. For all decay modes studied the B^- branching ratio was found to be larger than the corresponding $\overline{B}^0$ branching ratio indicating constructive interference between the external and internal spectator amplitudes. This came as a surprise since destructive interference was observed in hadronic charm decay. However, the B^- modes analyzed so far comprise only a small fraction of the total hadronic rate. Further experimental study is required to determine at what level constructive interference is present in the remainder of hadronic B^- decays.

Rare decays

All B meson decays that do not occur through the usual $b \rightarrow c$ transition are known as rare B decays. The simplest diagram for a rare B decay is obtained by replacing the $b \rightarrow c$ transition by a CKM suppressed $b \rightarrow u$ transition. These decays probe the small CKM matrix element V_{ub}, the magnitude of which sets bounds on the combination $\rho^2 + \eta^2$ in the Wolfenstein parameterization of the CKM matrix. So far the only measurement of the magnitude of V_{ub} has been obtained from measurements of inclusive semileptonic B decays [20]. Last year CLEO reported the observation of exclusive semileptonic transitions. Using their large data sample and employing the excellent hermiticity of the CLEO II detector they were able to measure (using the BSW model) $\mathrm{B}(B^0 \rightarrow \pi^- \ell^+ \nu_\ell) = (1.63 \pm 0.46 \pm 0.34) \times 10^{-4}$ and $\mathrm{B}(B^0 \rightarrow \rho^- \ell^+ \nu_\ell) = (3.88 \pm 0.54 \pm 0.34) \times 10^{-4}$ [21].

While the errors are still large these results are an important step towards establishing a reliable value of $|V_{ub}|$.

Exclusive hadronic $b \rightarrow u$ transitions still await experimental discovery. CLEO sees a significant signal in the combined $B^0 \rightarrow \pi^+\pi^-$, $K^+\pi^-$ channels but detector resolution and statistics are not sufficient to separate the two modes.

The observation of the decay $B \rightarrow K^*(892)\gamma$, reported in 1993 by the CLEO II experiment, provided first evidence for the 1-loop penguin diagram [22]. The observed branching fractions were used to constrain a large class of Standard Model extensions [23]. However, due to the uncertainties in the hadronization, only the inclusive $b \rightarrow s\gamma$ rate can be reliably compared with theoretical calculations. This rate can be measured from the endpoint of the inclusive photon spectrum in B decay. CLEO found $\mathrm{B}(b \rightarrow s\gamma) = (2.32 \pm 0.54 \pm 0.35) \times 10^{-4}$.

A larger total rate is expected for gluonic penguins, the counterpart of $b \rightarrow s\gamma$ with the photon replaced by a gluon. However, it is a major experimental challenge to measure the inclusive $b \rightarrow sg$ rate, where the virtual gluon hadronizes as a $q\overline{q}$ pair. Since the coupling of gluons to quark-antiquark pairs is flavor independent, it is expected that except for modifications due to phase space $b \rightarrow s\overline{s}s$ will be comparable to $b \rightarrow s\overline{u}u$, $b \rightarrow s\overline{d}d$. A recent CLEO search revealed no signal for exclusive $b \rightarrow s\overline{s}s$ decays such as $\overline{B} \rightarrow \phi K^{(*)}$ nor did they find an excess in the endpoint of the ϕ momentum spectrum for inclusive $B \rightarrow \phi$ transitions.

Outlook

With the end of the Fermilab collider run and the change of the LEP beam energies CLEO and SLD will be the only collider experiments in the next few years to collect data. While this might slow down the current rate of rapid progress in our understanding of heavy flavor physics there are still many answers hidden in the large data samples collected by CDF and the LEP collaborations. This combined with the ever-growing CLEO data sample will provide many new insights into all aspects of B physics.

The one exception is a measurement of the complex phase in CKM matrix. Data samples at least one order of magnitude larger than those available at present are needed to observe CP asymmetries in the B-meson system and to perform one of the most fundamental consistency check of the Standard Model. This is the justification for the construction of high luminosity e^+e^- storage rings (PEP II/BaBar, CESR III/CLEO III, TRISTAN II/BELLE) as well as a dedicated fixed target experiment at the HERA ring at DESY. Hadron collider experiments dedicated to the study of CP violation have also been proposed at Fermilab and at CERN.

Notes and References

† The results given in this section have been obtained by O. Hayes (ALEPH) and M. Jimack (OPAL). Their analysis is based on the average branching ratio, mixing parameters, and lifetimes listed in this compilation.

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SEMILEPTONIC DECAYS OF B MESONS

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In this section, we discuss some of the key questions related to semileptonic decays of B mesons: the inclusive semileptonic branching fraction, the determination of $|V_{cb}|$ and $|V_{ub}|$ from inclusive and exclusive measurements, recent progress in exclusive semileptonic decays, and form factor measurements and tests of heavy-quark effective theory. We emphasize the uncertainties that arise in extracting $|V_{cb}|$ and $|V_{ub}|$ from data. Further discussions of these and related issues are given in the references [1,2,3]. Before addressing the experimental progress, we review the formalism of form factors for both D and B exclusive semileptonic decays. Measurements of form factors in semileptonic D decays are included in the D meson Particle Listings.

Form-factor formalism for exclusive semileptonic decays

The amplitude for an exclusive semileptonic process can be constructed from the available four-vectors in the decay and from form factors, which are Lorentz invariant functions of q^2, the square of the mass of the virtual W. Because these functions describe the effect of strong interactions, nonperturbative techniques such as lattice QCD are needed to calculate them. Form factors are generally largest at the maximum value of q^2, where the daughter meson has the smallest recoil velocity and the overlap between the parent- and daughter-meson wave functions is largest. Studies of form factors in D semileptonic decays have focused on the modes $D \to \overline{K}\ell^+\nu_\ell$ and $D \to \overline{K}^*\ell^+\nu_\ell$, which dominate the inclusive semileptonic rate. In B decays, the analogous modes, $B \to \overline{D}\ell^+\nu_\ell$ and $B \to \overline{D}^*\ell^+\nu_\ell$, account for about two-thirds of the inclusive semileptonic rate. The decay $B \to \overline{D}\ell^+\nu_\ell$ has a large background from $B \to \overline{D}^*\ell^+\nu_\ell$, so in B decays, form factor measurements have focused mainly on $B \to \overline{D}^*\ell^+\nu_\ell$. In this section, we discuss the formalism used in form-factor measurements for the decays $P \to P'\ell\nu_\ell$, where P and P' are pseudoscalar mesons, and $P \to V\ell\nu_\ell$, where V is a vector meson.

The differential decay rate for $P(Q\overline{q}) \to P'(q'\overline{q})\,\ell\nu_\ell$ is

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{q'Q}|^2 k_{P'}^3 |f_+(q^2)|^2}{24\pi^3} \,. \tag{1}$$

Here G_F is the Fermi decay constant, $V_{q'Q}$ is the relevant CKM matrix element, $k_{P'}$ is the momentum of P' in the rest frame of the parent meson, and $f_+(q^2)$ is a vector form factor. (Eq. (1) assumes massless charged leptons, which is almost exact for electrons and a very good approximation for muons, but it is not correct for τ's.) The dominant q^2 dependence comes from the p-wave factor $k_{P'}^3$, which can be written in terms of q^2 and the particle masses. This factor increases the rate at low q^2, which is opposite to the q^2 dependence of the form factor f_+.

The exclusive decay rate for $P \to V\ell\nu_\ell$ can be expressed in terms of three q^2-dependent helicity amplitudes, $H_\pm(q^2)$ and $H_0(q^2)$, where the subscripts indicate the helicity of either the virtual W or the vector meson. The rate is given by

$$\frac{d\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos_V\, d\chi} = \frac{3G_F^2|V_{q'Q}|^2\, k_V\, q^2}{8(4\pi)^4 M^2}$$

$$\Big\{[(1+\eta\cos\theta_\ell)^2|H_+(q^2)|^2 + (1-\eta\cos\theta_\ell)^2|H_-(q^2)|^2]\sin^2\theta_V$$
$$+4\sin^2\theta_\ell\cos^2\theta_V|H_0(q^2)|^2$$
$$-2\sin^2\theta_\ell\sin^2\theta_V\cos(2\chi)H_+(q^2)H_-(q^2)$$
$$-4\eta\sin\theta_\ell(1+\eta\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi\, H_+(q^2)H_0(q^2)$$
$$+4\eta\sin\theta_\ell(1-\eta\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi\, H_-(q^2)H_0(q^2)\Big\} \,. \tag{2}$$

Here M is the mass of the parent meson, k_V is the momentum of the vector meson and is a function of q^2, and the factor η=+1 ($\eta = -1$) applies to B (D) decays. The angles θ_ℓ, θ_V, and χ are defined in Fig. 1. The helicity amplitudes $H_\pm$ and H_0 can be expressed in terms of two axial-vector form factors, $A_1(q^2)$ and $A_2(q^2)$, and a vector form factor $V(q^2)$:

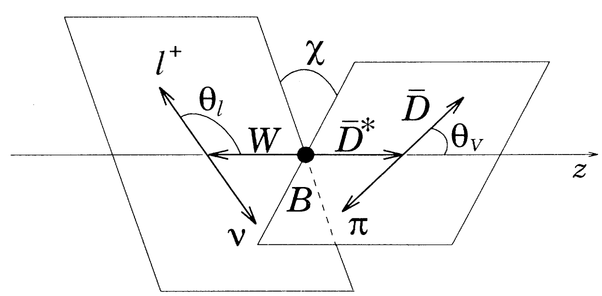

Figure 1: Definition of the angles θ_ℓ, θ_V, and χ. The decay $B \to \overline{D}^*\ell^+\nu_\ell$ is used as an example. The polar angles θ_ℓ and θ_V are defined in the rest frames of the virtual W and the $\overline{D}^*$, respectively, and χ is the azimuthal angle between the projections of the lepton and the $\overline{D}$ momentum vectors in the plane perpendicular to z.

$$H_\pm(q^2) = (M+m)A_1(q^2) \mp \frac{2M\,k_V}{(M+m)}V(q^2)$$

$$H_0(q^2) = \frac{1}{2m\sqrt{q^2}}\Big[(M^2-m^2-q^2)(M+m)A_1(q^2) - \frac{4M^2\,k_V^2}{(M+m)}A_2(q^2)\Big] \,, \tag{3}$$

where m is the mass of the daughter meson. The form factors f_+, A_1, A_2, and V are dimensionless.

The $V-A$ coupling results in a larger amplitude to produce a negative-helicity vector meson in $c\overline{q}$ or $b\overline{q}$ decay than one of positive helicity: $|H_-| > |H_+|$. This difference produces a forward-backward asymmetry for the charged lepton in the virtual-W rest frame, since the net angular momentum along the decay axis of the initial heavy meson must be zero. For $D(c\overline{q})$ decays, a positively charged (right-handed) lepton is produced in association with a left-handed daughter s or d quark, resulting in a softer energy spectrum for the charged lepton than for the neutrino after boosting the lepton energy into the D rest frame. (A similar argument shows that the shape of the spectrum is the same for a $\overline{D}$ decay.) For $\overline{B}(b\overline{q})$ decays, a negatively charged (left-handed) lepton is produced in association with a left-handed daughter quark, giving a harder energy spectrum for the charged lepton than for the neutrino in the B rest frame. In $P \to P'\ell\nu_\ell$ decays, there is no asymmetry, since the P' meson can only have helicity zero. Thus, the effect of $V-A$ is to soften the inclusive lepton spectrum in D decays and to harden it in B decays. It is useful to define rates for decays into specific helicity states:

$$\Gamma_i = \frac{G_F^2 |V_{q'Q}|^2}{96\pi^3} \int dq^2\, k_V \frac{q^2}{M^2} |H_i(q^2)|^2 \,. \qquad (4)$$

Experiments extract various ratios of these rates, including Γ_+/Γ_-, $\Gamma_L/\Gamma_T = \Gamma_0/(\Gamma_- + \Gamma_+)$, the lepton forward-backward asymmetry $A_{FB} = (3\eta/4)(\Gamma_- - \Gamma_+)/\Gamma$, and the polarization parameter $\alpha = 2\Gamma_0/(\Gamma_+ + \Gamma_-) - 1$. Because the form factor A_1 appears in all three helicity amplitudes, the ratios of form factors V/A_1 and A_2/A_1, can be obtained by fitting the measured shape of the distribution of variables q^2, θ_ℓ, θ_V, and χ. The actual values of the form factors can be extracted from these form-factor ratios and the measured total decay rate.

The inclusive semileptonic branching fraction

The b-hadron inclusive semileptonic branching fraction, $\mathcal{B}_{SL}$, has been measured both at the $\Upsilon(4S)$, where the b hadrons are a mixture of B^+ and B^0 mesons, and at the Z, where B_s mesons and b baryons are produced as well. Here $\mathcal{B}_{SL}$ is the branching fraction to either electrons or muons, not their sum. Semileptonic decays to τ leptons are suppressed by phase space and have been observed, within large errors, at the expected level [4,5]. Measurements of $\mathcal{B}_{SL}$ are given in Table 1 for single-lepton measurements at the $\Upsilon(4S)$, in Table 2 for the LEP experiments, and in Table 3 for dilepton measurements at the $\Upsilon(4S)$.

Table 2: Measurements from LEP experiments of the inclusive b-hadron semileptonic branching fraction, $\mathrm{B}(X_{\overline{b}} \to X\ell^+\nu_\ell)$, where X_b is a hadron containing a b-quark. At the Z, the population of b hadrons includes not only B^0 and B^+ mesons, but also a small fraction of B_s mesons and b baryons. The three errors are statistical, systematic, and the uncertainty due to model dependence.

Expt.	Ref.	$\mathrm{B}(X_{\overline{b}} \to X\ell^+\nu_\ell)\%$
ALEPH	[11]	$11.39 \pm 0.33 \pm 0.33 \pm 0.26$
DELPHI	[12]	$11.06 \pm 0.39 \pm 0.12 \pm 0.19$
L3 (prelim.)	[13]	$11.73 \pm 0.48 \pm 0.28 \pm 0.31$
OPAL	[14]	$10.5 \pm 0.6 \pm 0.4 \pm 0.3$
LEP Avg.		11.2 ± 0.4

Table 3: Measurements from CLEO and ARGUS experiments of the inclusive B-meson semileptonic branching fraction, using the dilepton method, which reduces the model dependence of the result.

Expt.	Ref.	$\mathcal{B}(B \to X\ell^+\nu_\ell)\%$
ARGUS	[15]	$9.6 \pm 0.5 \pm 0.4$
CLEO II	[16]	$10.49 \pm 0.17 \pm 0.43$
Average		10.19 ± 0.37

Table 1: Measurements of the inclusive semileptonic branching fraction (%), $\mathcal{B}_{SL} = \mathrm{B}(B \to X\ell^+\nu_\ell)$, averaged over the B mesons produced at the $\Upsilon(4S)$ (B^+ and B^0). These results are based on analyses of the inclusive single-lepton spectrum. Results are given separately for each of the models used to extract $\mathcal{B}_{SL}$. In the ARGUS measurement, the first error combines both statistical and systematic uncertainties; the second error in the ARGUS ACCMM value is due to the extra free parameters present in this model. The fit of the CLEO data using the unmodified ISGW model is poor, so the results from that fit are less reliable. The table also gives the CLEO inclusive branching fraction to charm final states ($X_{\overline{c}}$) only, which is extracted from the same fit. (Sources of error in these measurements are discussed in the text.)

Expt. (1ℓ method)	ACCMM	ISGW	ISGW**
ARGUS [6]	$10.2 \pm 0.5 \pm 0.2$	9.8 ± 0.5	
CRYSTAL BALL [7]	$12.0 \pm 0.5 \pm 0.7$	$11.9 \pm 0.4 \pm 0.7$	
CUSB-II [8]	$10.0 \pm 0.4 \pm 0.3$	$10.0 \pm 0.4 \pm 0.3$	
CLEO-I [9]	$10.5 \pm 0.2 \pm 0.4$	$9.9 \pm 0.1 \pm 0.4$	$11.2 \pm 0.3 \pm 0.4$
CLEO-II (prelim.) [10]	$10.65 \pm 0.05 \pm 0.33$	$10.42 \pm 0.05 \pm 0.33$	$10.98 \pm 0.10 \pm 0.33$
Average	10.51 ± 0.21	10.22 ± 0.20	11.05 ± 0.28
CLEO-II (prelim.) [10] $B \to X_{\overline{c}}\ell^+\nu_\ell$	$10.48 \pm 0.07 \pm 0.33$	$10.41 \pm 0.07 \pm 0.33$	$10.87 \pm 0.10 \pm 0.33$

The challenge for inclusive measurements is to determine what part of the observed lepton momentum spectrum is due to leptons from b-hadron decay (primary leptons) and what part is due to leptons from charm decay (secondary leptons) or to other sources (misidentified hadrons, photon conversions, $J/\psi(1S)$ decays, *etc.*). The standard technique is to fit the observed lepton momentum spectrum to a sum of the shapes expected for primary and secondary decays, after subtracting out backgrounds from other sources. Thus, a large part of the effort (and uncertainty) in the analysis is in the determination of these shapes.

Experiments at the $\Upsilon(4S)$ (ARGUS and CLEO) use theoretical models to describe the primary lepton spectrum. Some of these models have free parameters that are determined from the fit. The ACCMM model [17], for example, is based on an inclusive calculation of b-quark decay, and it has parameters corresponding to the c-quark mass and the Fermi momentum of the spectator quark, among others. A commonly used exclusive model is ISGW [18], in which the dominant contributions to the primary spectrum are from $B \to \overline{D}\ell^+\nu_\ell$ and $B \to \overline{D}^*\ell^+\nu_\ell$, with some $B \to \overline{D}^{**}\ell^+\nu_\ell$. Here, D^{**} refers to a mixture of p-wave and radially excited charm mesons. CLEO finds [9,10] that the amount of $B \to \overline{D}^{**}\ell^+\nu_\ell$ in this model is too low to adequately describe the lepton momentum spectrum, so a modified version of the ISGW model, ISGW**, has been created. In ISGW**, the D^{**} fraction is allowed to vary, but the D^*-to-D ratio is fixed at the value (2.3) predicted by ISGW. The fit to the CLEO data using ISGW** is significantly better than that using ISGW.

The shape used to describe the secondary lepton spectrum in these fits, although somewhat more complicated to obtain, is based on data. The DELCO charm-decay lepton spectrum [19] is fit to a theoretical model (ACCMM) and then boosted according to the inclusive D-meson momentum spectrum measured at the $\Upsilon(4S)$. Future measurements should be able to use a charm lepton spectrum obtained by summing the spectra for the known exclusive charm semileptonic modes, which account for most of the inclusive rate.

LEP experiments (ALEPH, DELPHI, L3, and OPAL) measure $\mathcal{B}_{SL}$ by fitting the spectra of p and p_T (the momentum transverse to the jet axis) in single lepton and dilepton events. The shape of the primary spectrum is taken from CLEO or ARGUS, so that model-related uncertainties in these experiments are propagated into the LEP results.

The extraction of the B semileptonic branching fraction from the momentum spectrum of single leptons, therefore, relies on models. In CLEO, which currently has the largest data sample, the spread of values obtained using different models is comparable to the experimental errors. The dominant experimental errors are due to tracking and lepton identification uncertainties.

The ARGUS collaboration [15] has introduced a second method, using dilepton events, that substantially reduces the need for models. One lepton (the "tagging lepton") is required to have high momentum and is thus nearly always primary. The analysis then examines the momentum spectrum of the second lepton in the event. By requiring that both leptons be in the same hemisphere, events in which the two leptons come from the decay chain of a single B meson (produced nearly at rest at the $\Upsilon(4S)$) are effectively removed. Thus, (1) the tagging lepton is primary, and (2) the leptons are from different B mesons. Then, unless mixing occurs, a lepton whose charge is opposite to that of the tagging lepton must be primary, while one with the same charge as the tagging lepton must be secondary. One corrects for mixing by using the known mixing probability. The relative charges of the two leptons, therefore, can be used to separate the primary and secondary spectra of the second lepton. There is a lower momentum cutoff due to experimental acceptance, however, and a small extrapolation, based on models, is required to obtain the total semileptonic rate. The ARGUS and CLEO measurements based on this technique are listed in Table 3. This method also very much reduces the sensitivity to any possible non-$B\overline{B}$ decays of the $\Upsilon(4S)$, which are assumed to be negligible in the single-lepton method.

The values of $\mathcal{B}_{SL}$ given in Table 1, Table 2, Table 3 are lower than most of the theoretical predictions, which give [20] $\mathcal{B}_{SL} \geq 12.5\%$. Such calculations, however, are difficult partly because they must determine the total hadronic rate, which has uncertainties associated with both perturbative and non-perturbative QCD effects. In particular, enhancements to the $b \to c\bar{c}s$ rate have been discussed as a possible explanation for the low value of $\mathcal{B}_{SL}$. For example, a recent analysis by Bagan, *et al.* [21] predicts values of $\mathcal{B}_{SL}$ in the range 11% to 12% (with large uncertainties), as well as a somewhat larger average number, n_c, of charm quarks per decay than is found by experiment [1]. The problem of $\mathcal{B}_{SL}$ is perhaps best rephrased as the joint problem of understanding $\mathcal{B}_{SL}$ and n_c.

The semileptonic branching fraction can be used to calculate $|V_{cb}|$ using $\mathcal{B}_{SL} = \gamma_{\rm thy}|V_{cb}|^2\tau_B$, where $\gamma_{\rm thy}$ is a constant predicted by theory and τ_B is the appropriate B-hadron lifetime. Whereas the model dependence in the determination of $\mathcal{B}_{SL}$ is associated with the predicted shapes of momentum spectra, the extraction of $|V_{cb}|$ is also sensitive to the uncertainty in $\gamma_{\rm thy}$. It is difficult to assign errors to rate predictions based on quark-model calculations. Quite often, a nominal theoretical error of 20% in the rate is assumed, leading to a 10% theoretical error on $|V_{cb}|$. For example, the value of $|V_{cb}|$ using the ACCMM model and the average of all experiments performing a single-lepton analysis at the $\Upsilon(4S)$ is $|V_{cb}| = 0.041 \pm 0.001$ (expt) ± 0.004 (thy) (assuming the value $\tau_B = 1.55 \pm 0.06$ ps used in Sec. 11, "The Cabibbo-Kobayashi-Maskawa Mixing Matrix"). However, some of the calculations based on heavy-quark expansions suggest that this theoretical uncertainty may be overestimated by a factor of two. HQET-based calculations have been presented by Shifman *et al.* [22], Luke and Savage [23], and Ball *et al.* [24]; this subject is controversial and is reviewed by Richman and Burchat [1], who assign a theoretical uncertainty of ± 0.003.

The lepton endpoint region and determination of $|V_{ub}|$

The determination of $|V_{ub}|$ is one of the most important and challenging measurements in B physics. For $|V_{ub}/V_{cb}| \approx 0.1$, the rate for $B \to X_{\overline{u}}\ell^+\nu_\ell$, where $X_{\overline{u}}$ is a charmless hadronic system, is expected to be only about 1% of the inclusive semileptonic rate. By working in the region at and beyond the lepton-momentum-spectrum endpoint for $B \to X_{\overline{c}}\ell^+\nu_\ell$ processes, however, one gains enormously in sensitivity to $B \to X_{\overline{u}}\ell^+\nu_\ell$ decays.

Although the advantages of working in this endpoint region ($2.3 < p_\ell < 2.6$ GeV/c) are decisive, there are also disadvantages. A major difficulty is the need to convert the measured rate for this tiny portion of phase space into a value of $|V_{ub}|$. This calculation can be performed using either inclusive or exclusive models, but both have substantial uncertainties in predicting the rate in the endpoint region. Inclusive models are expected to be fairly reliable, if one considers a large enough part of phase space, but they may not be reliable in the endpoint region, which some theorists argue [18] is dominated by a small set of exclusive channels ($B \to \rho\ell^+\nu_\ell$, $B^+ \to \omega\ell^+\nu_\ell$, and $B \to \pi\ell^+\nu_\ell$). Alternatively, exclusive models can be used to predict the sum of contributions of individual modes in this region. However, large uncertainties exist in the calculations of the rates for exclusive modes, and some of the observed rate may be due to nonresonant final states [25]. The exclusive calculations here are more difficult than those for $B \to X_{\overline{c}}\ell^+\nu_\ell$: because the u-quark mass is small, the kinematic configuration in which the final-state hadron has zero recoil velocity does not provide a reliable place to normalize the form factors, as it does in $b \to c$ decays. Furthermore, the range of recoil velocities available to the light final-state mesons in a $B \to X_{\overline{u}}\ell^+\nu_\ell$ transition is much larger than for the charm mesons in a $B \to X_{\overline{c}}\ell^+\nu_\ell$ decay. One therefore expects a much larger variation in the form factors. As a result, measurements of $|V_{ub}|$ are currently quite model dependent, and there is substantial variation among values obtained using different models.

The analysis of the endpoint region, although an "inclusive" measurement, is quite different from the measurement of $\mathcal{B}_{SL}$ described in the previous section: at the $\Upsilon(4S)$, nonresonant (continuum) processes produce high-momentum leptons that constitute an enormous background (relative to a $B \to X_{\overline{u}}\ell^+\nu_\ell$ signal) unless suppressed by kinematic cuts. The signal efficiency of these cuts is model dependent, unlike the very loose cuts used in the analysis of the inclusive lepton spectrum. In particular, the efficiency depends on the q^2 distribution of the signal events, so the value obtained for the rate in the endpoint region depends on the shape assumed for this distribution. The most important sensitivity to models, however, arises when one converts the rate to $|V_{ub}|$.

Table 4 lists the measurements of $|V_{ub}/V_{cb}|$ from CLEO and ARGUS. The CLEO-II studies, which are based on about five times as much data as either the original ARGUS or the CLEO-I analyses, yield values of $|V_{ub}/V_{cb}|$ significantly lower than the earlier measurements.

Table 4: Measurements of $|V_{ub}/V_{cb}|$ using the inclusive rate in the endpoint region. The ARGUS and CLEO-I results are each based on about $200,000$ $b\overline{b}$ events, and the CLEO-II results are based on about $955,000$ $b\overline{b}$ events.

Model	ARGUS [26]	CLEO-I [27]	CLEO-II [28]
ACCMM	0.11 ± 0.012	0.09 ± 0.01	0.076 ± 0.008
ISGW	0.20 ± 0.023	0.15 ± 0.02	0.101 ± 0.010

Progress on exclusive semileptonic decays

In the past year, substantial progress has been made in understanding the exclusive semileptonic decays of B mesons. In particular, the observation of $B \to \pi\ell^+\nu_\ell$ and $B \to \rho\ell^+\nu_\ell$ by CLEO represents a milestone for these studies. In this section, we give an overview of the exclusive modes, focusing primarily on recent progress.

Measurements of exclusive semileptonic decays of B mesons are less precise and less complete than those for D mesons. Unlike D decays, where $D \to K\ell^+\nu_\ell$ and $D \to K^*\ell^+\nu_\ell$ come close to saturating the Cabibbo-favored rate, the analogous modes $B \to \overline{D}\ell^+\nu_\ell$ and $B \to \overline{D}^*\ell^+\nu_\ell$ account for only 60% to 70% of the rate for $b \to c\ell\nu_\ell$. The only well-measured semileptonic decay is $B \to \overline{D}^*\ell^+\nu_\ell$, which has the largest branching fraction of all B decays, accounting for about 45% of the semileptonic rate. Recently, there has been some progress in improving the measurement for $B \to \overline{D}\ell^+\nu_\ell$ [29], which has a large background due to feed down from $B \to \overline{D}^*\ell^+\nu_\ell$. Another contrast with D semileptonic decays is that the ratio of $B \to \overline{D}^*\ell^+\nu_\ell$ to $B \to \overline{D}\ell^+\nu_\ell$ is about 2.3, whereas in D decays the analogous vector-to-pseudoscalar ratio is about 0.6. LEP experiments [30,31] have made significant progress in observing the decays $B \to \overline{D}_1\ell^+\nu_\ell$ and $B \to \overline{D}_2^*\ell^+\nu_\ell$, where the use of high-precision vertex detectors has proved to be a powerful technique for reducing combinatorial background.

The most significant recent development has been the observation [32] of exclusive charmless semileptonic decays, which should eventually lead to better determinations of $|V_{ub}|$. For these decays, unlike $B \to X_{\overline{c}}\ell^+\nu_\ell$, model predictions [18] indicate that the rate should be distributed over many exclusive channels, with no dominant modes. The decays with the largest expected branching fractions are $B^0 \to \rho^-\ell^+\nu_\ell$, $B^+ \to \rho^0\ell^+\nu_\ell$, and $B^+ \to \omega\ell^+\nu_\ell$, which in the quark model are predicted to occur in the ratio 2:1:1. The branching fractions for $B^0 \to \pi^-\ell^+\nu_\ell$ and $B^+ \to \pi^0\ell^+\nu_\ell$ are expected to be roughly one-third to one-half of those for the corresponding decays to ρ mesons. For reasons that are largely independent of models, the lepton spectra for the decays to vector mesons are expected to be harder than those for the decays to pseudoscalars. CLEO has now obtained preliminary branching fractions for $B \to \pi\ell^+\nu_\ell$ and $B \to \rho\ell^+\nu_\ell$, which are listed in Table 5. These branching fractions are consistent with predictions based on models, assuming the value of $|V_{ub}|$ obtained from the analysis of the lepton spectrum endpoint.

Table 5: Preliminary CLEO II branching fractions for exclusive B semileptonic decays to final states without charm. These results assume efficiencies obtained from the ISGW model [18]; if the WSB model [33] is used, the branching fractions are somewhat higher. The first error is statistical and the second systematic. The third error on the $B^0 \to \rho^- \ell^+ \nu_\ell$ branching fraction is due to a possible non-resonant $\pi\pi$ contribution.

Mode	Ref.	Branching fraction
$B^0 \to \rho^- \ell^+ \nu_\ell$	[32]	$(2.28 \pm 0.36 \pm 0.59^{+0.00}_{-0.46}) \times 10^{-4}$
$B^0 \to \pi^- \ell^+ \nu_\ell$	[32]	$(1.34 \pm 0.35 \pm 0.28) \times 10^{-4}$

Measurement of $|V_{cb}|$ from $B \to \overline{D}^* \ell^+ \nu_\ell$

Three types of measurements can be used to determine $|V_{cb}|$: (1) the inclusive semileptonic rate (discussed above), (2) the rates for $B \to \overline{D} \ell^+ \nu_\ell$ or $B \to \overline{D}^* \ell^+ \nu_\ell$, and (3) the partial rate for $B \to \overline{D}^* \ell^+ \nu_\ell$ for the region of phase space in which the D^* recoils slowly. The $B \to \overline{D}^* \ell^+ \nu_\ell$ mode is especially well suited to measuring $|V_{cb}|$. With HQET, the rate for this process can be accurately predicted (as a function of $|V_{cb}|^2$) for the kinematic configuration in which the D^* is produced at rest (with the lepton and neutrino back to back in the B rest frame). This configuration occurs when $q^2 = q^2_{\rm max} = (m_B - m_{D^*})^2$. The light constituents of the initial B meson are then essentially undisturbed by the $B \to X_{\overline{c}} \ell^+ \nu_\ell$ transition, at least in the limit where the b and c quark masses are taken to be very large compared with $\Lambda_{\rm QCD}$.

In this heavy-quark symmetry (HQS) limit, all of the $B \to \overline{D}^* \ell^+ \nu_\ell$ form factors are related to a single form factor, the Isgur-Wise function, which depends only on the relative four-velocities of the initial and final hadrons: $\xi = \xi(v_B \cdot v_{D^*})$. Note that $v_B \cdot v_{D^*} = \gamma_{D^*}$, where the relativistic factor γ_{D^*} is measured in the B-meson rest frame. The quantity $v \cdot v'$, where v is the initial and v' is the final meson four-velocity, is often called w or y in the literature. It is linearly related to q^2 by

$$w = v \cdot v' = \frac{M^2 + m^2 - q^2}{2Mm} \ , \tag{5}$$

where M and m are the masses of the parent and daughter mesons.

At zero recoil ($w = 1$ or $q^2 = q^2_{\rm max}$), the normalization of ξ is known in the HQS limit, $\xi(1) = 1$, which means that the decay rate in this configuration can be accurately predicted as a function of $|V_{cb}|^2$. Corrections to this picture arise from hard-gluon corrections and because the masses of the b and c quarks are not truly infinite. However, the HQS-limit prediction for $B \to \overline{D}^* \ell^+ \nu_\ell$ is partly protected by Luke's theorem [34], which states that at zero recoil there are no leading order $(1/m_Q)$ nonperturbative corrections at $w = 1$, where m_Q is the mass of a heavy quark (c or b). As a consequence, the leading nonperturbative corrections to the zero-recoil decay-rate prediction arise at order $1/m_Q^2$. The calculation of these corrections, which introduces some model dependence, has been the subject of many investigations. The results are generally expressed in terms of a function $\mathcal{F}(w)$ that can be derived from the form factors and which determines the differential rate through [35]

$$\frac{1}{\tau_B} \cdot \frac{d\mathrm{B}(B^0 \to D^{*-} \ell^+ \nu_\ell)}{dw} = \frac{G_F^2}{48\pi^3} m^3_{D^*} (m_B - m_{D^*})^2$$
$$\times \sqrt{w^2 - 1}(w+1)^2 \Big[1 + \frac{4w}{w+1} \frac{1 - 2wr + r^2}{(1-r)^2}\Big]$$
$$\times |V_{cb}|^2 \mathcal{F}(w)^2, \tag{6}$$

where $r = m_{D^*}/m_B$. The rate at zero recoil is determined by $\mathcal{F}(1)$, which is predicted to be in the range 0.89 to 0.96 [36,37,22]. These predictions can be used to determine $|V_{cb}|$ from the measured rate at zero recoil. Strictly speaking, there is no phase space for this configuration, so in practice one has to measure the rate in a small region near $w = 1$.

Current experiments have difficulty in measuring the rate in this region due to limited statistics. The rate at zero recoil is therefore obtained by measuring the rate as a function of w and then extrapolating to $w = 1$. This procedure introduces some model dependence because HQET does not predict the w dependence of the form factors, which involves nonperturbative QCD physics. (Several groups are using lattice QCD and QCD sum rules to predict the w dependence and are beginning to obtain interesting results [38,3].) Because the w range is small, however, the form factors are expected to have only modest variation, which is approximately linear. CLEO, ARGUS, ALEPH, and DELPHI use a variety of functional forms to parametrize the w dependence. The different extrapolations to $w = 1$ lead to a range of values for $|V_{cb}|$. This method leads to $|V_{cb}| = 0.041 \pm 0.003 \pm 0.002$, as discussed in Sec. 11, "The Cabibbo-Kobayashi-Maskawi Mixing Matrix." Thus, the inclusive and zero-recoil methods agree well. It should be noted that $|V_{cb}|$ can also be obtained from the total rates for $B \to \overline{D} \ell^+ \nu_\ell$ and $B \to \overline{D}^* \ell^+ \nu_\ell$. These values tend to be somewhat lower [1]. However, the theoretical predictions for the full decay rate are expected to be less reliable than those for the zero-recoil configuration of $B \to \overline{D}^* \ell^+ \nu_\ell$, since the form factors must be known over the full q^2 range.

Form factor measurements

Both CLEO and ARGUS have used measurements of kinematic distributions to obtain information on the form factors for $B \to \overline{D}^* \ell^+ \nu_\ell$. In contrast to D-meson semileptonic decays, however, one expects the predictions of heavy quark effective theory to be applicable to $B \to X_{\overline{c}} \ell^+ \nu_\ell$. Here, both the initial- and final-state quarks are heavy compared with the typical hadronic scale set by $\Lambda_{\rm QCD}$.

The differential decay rate for $\overline{B}^0 \to D^{*+} \ell^+ \nu_\ell$, $D^{*+} \to D^0 \pi^+$ can be expressed in terms of three form factors $A_1(q^2)$, $A_2(q^2)$, and $V(q^2)$, as discussed at the beginning of this article.

In the heavy-quark symmetry limit, the form factors are related to the Isgur-Wise function ξ:

$$V(q^2) = A_2(q^2) = \frac{A_1(q^2)}{\left[1 - \frac{q^2}{(m_B+m_{D^*})^2}\right]} = \frac{(m_B + m_{D^*})}{2\sqrt{m_B m_{D^*}}}\, \xi(w) \ . \qquad (7)$$

This limit motivates the choice of form factor ratios [3]

$$R_1 \equiv \left[1 - \frac{q^2}{(m_B + m_{D^*})^2}\right] \frac{V(q^2)}{A_1(q^2)}$$

$$R_2 \equiv \left[1 - \frac{q^2}{(m_B + m_{D^*})^2}\right] \frac{A_2(q^2)}{A_1(q^2)} \ , \qquad (8)$$

which are predicted to be unity, independent of w, in the heavy-quark symmetry limit. For finite heavy-quark masses, R_1 and R_2 are expected to have a mild dependence on w. Note that these quantities differ from the traditional form-factor ratios (A_2/A_1 and V/A_1) used to describe charm semileptonic decays, where heavy-quark symmetry is not expected to be a good approximation. To consider departures from the heavy-quark symmetry limit but still express the form factors in a manner that makes this limit transparent, one can use

$$A_1(q^2) = \frac{m_B + m_{D^*}}{2\sqrt{m_B m_{D^*}}} \left[1 - \frac{q^2}{(m_B + m_{D^*})^2}\right] h_{A_1}(w) \ ,$$

$$A_2(q^2) = \frac{m_B + m_{D^*}}{2\sqrt{m_B m_{D^*}}} R_2(w)\, h_{A_1}(w) \ ,$$

$$V(q^2) = \frac{m_B + m_{D^*}}{2\sqrt{m_B m_{D^*}}} R_1(w)\, h_{A_1}(w) \ , \qquad (9)$$

where $h_{A_1}(w) \to \xi(w)$ in the heavy-quark symmetry limit. Departures from this limit produce two effects: deviations of $R_1(1)$ and $R_2(1)$ from unity and a slight variation of R_1 and R_2 with w.

To measure the form factors, CLEO has performed [39] a four-dimensional fit, including correlations, to the kinematic variables q^2, $\cos\theta_\ell$, $\cos\theta_V$, and χ. (The angles are defined at the beginning of this article.) In this fit, R_1 and R_2 were assumed to be constant, while h_{A_1} was assumed to have a linear dependence on w, with slope $\rho^2_{A_1}$: $h_{A_1}(w) = h_{A_1}(1)(1 - \rho^2_{A_1}(w-1))$. The preliminary fit results are

$$R_1 = 1.18 \pm 0.30 \pm 0.12 \ ,$$

$$R_2 = 0.71 \pm 0.22 \pm 0.07 \ ,$$

$$\rho^2_{A_1} = 0.91 \pm 0.15 \pm 0.06 \ . \qquad (10)$$

The values of R_1 and R_2 are in good agreement with predictions based on HQET with corrections [3,40]. The results for R_1 and R_2 are rather insensitive both to the form assumed for $h_{A_1}(w)$ and to the mild w dependence of R_1 and R_2 suggested by these theoretical calculations. However, the value of $\rho^2_{A_1}$ is sensitive to the form of h_{A_1}. Functions with curvature, such as exponentials or pole forms, give somewhat larger values of $\rho^2_{A_1}$.

Earlier results obtained by CLEO [41,42] and ARGUS [43] obtained A_{FB}, the lepton forward-backward asymmetry, and A_{pol}, the D^* polarization, each integrated over phase space. These results are consistent with the new result discussed above [1] but have lower precision.

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$B^{\pm}$

$I(J^P) = \frac{1}{2}(0^-)$

Quantum numbers not measured. Values shown are quark-model predictions.

See also the $B^{\pm}/B^0$ ADMIXTURE and $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE sections.

$B^{\pm}$ MASS

The fit uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B^0_s}$, and $(m_{B^0_s} - (m_{B^+} + m_{B^0})/2)$ to determine m_{B^+}, m_{B^0}, $m_{B^0_s}$, and the mass differences.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5278.9±1.8 OUR FIT					
5278.9±1.5 OUR AVERAGE					
5279.1±1.7 ±1.4	147	[1] ABE	96B	CDF	$p\bar{p}$ at 1.8 TeV
5278.8±0.54±2.0	362	[2] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
5278.3±0.4 ±2.0		[2] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
5280.5±1.0 ±2.0		[2,3] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
5278.6±0.8 ±2.0		[2] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5275.8±1.3 ±3.0	32	ALBRECHT	87C	ARG	$e^+e^- \to \Upsilon(4S)$
5278.2±1.8 ±3.0	12	[4] ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$

[1] Excluded from fit because it is not independent of ABE 96B B^0_s mass and B^0_s-B mass difference.
[2] These experiments all report a common systematic error 2.0 MeV. We have artificially increased the systematic error to allow the experiments to be treated as independent measurements in our average. See "Treatment of Errors" section of the Introductory Text. These experiments actually measure the difference between half of E_{cm} and the B mass.
[3] ALBRECHT 90J assumes 10580 for $\Upsilon(4S)$ mass. Supersedes ALBRECHT 87C and ALBRECHT 87D.
[4] Found using fully reconstructed decays with $J/\psi(1S)$. ALBRECHT 87D assume $m_{\Upsilon(4S)}$ = 10577 MeV.

$B^{\pm}$ MEAN LIFE

See $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE section for data on B-hadron mean life averaged over species of bottom particles.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^{\pm}$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.62±0.06 OUR EVALUATION					
1.56±0.13±0.06		[5] ABE	96C	CDF	$p\bar{p}$ at 1.8 TeV
1.58±0.09±0.04		[5] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
$1.58^{+0.21}_{-0.18}{}^{+0.04}_{-0.03}$	94	[6] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
1.61±0.16±0.12		[5,7] ABREU	95Q	DLPH	$e^+e^- \to Z$
1.72±0.08±0.06		[8] ADAM	95	DLPH	$e^+e^- \to Z$
1.52±0.14±0.09		[5] AKERS	95T	OPAL	$e^+e^- \to Z$
1.61±0.16±0.05	148	[6] ABE	94D	CDF	$p\bar{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.58±0.09±0.03		[9] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
1.70±0.09		[10] ADAM	95	DLPH	$e^+e^- \to Z$
$1.30^{+0.33}_{-0.29}\pm0.16$	92	[5] ABREU	93D	DLPH	Sup. by ABREU 95Q
1.56±0.19±0.13	134	[8] ABREU	93G	DLPH	Sup. by ADAM 95
$1.51^{+0.30}_{-0.28}{}^{+0.12}_{-0.14}$	59	[5] ACTON	93C	OPAL	Sup. by AKERS 95T
$1.47^{+0.22}_{-0.19}{}^{+0.15}_{-0.14}$	77	[5] BUSKULIC	93D	ALEP	Sup. by BUSKULIC 96G

[5] Data analyzed using $D/D^*\ell X$ event vertices.
[6] Measured mean life using fully reconstructed decays.
[7] ABREU 95Q assumes B($B^0 \to D^{**-}\ell^+\nu_\ell$) = 3.2 ± 1.7%.
[8] Data analyzed using vertex-charge technique to tag B charge.
[9] Combined result of $D/D^*\ell X$ analysis and fully reconstructed B analysis.
[10] Combined ABREU 95Q and ADAM 95 result.

B^+ DECAY MODES

B^- modes are charge conjugates of the modes below. Modes which do not identify the charge state of the B are listed in the $B^{\pm}/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\bar{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed D, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_1	$\ell^+\nu_\ell$ anything	[a]	(10.1 ±2.3) %	
Γ_2	$\bar{D}^0\ell^+\nu_\ell$	[a]	(1.6 ±0.7) %	
Γ_3	$\bar{D}^*(2007)^0\ell^+\nu_\ell$	[a]	(5.3 ±0.8) %	
Γ_4	$\pi^0 e^+\nu_e$		< 2.2 × 10^{-3}	CL=90%
Γ_5	$\omega\ell^+\nu_\ell$	[a]	< 2.1 × 10^{-4}	CL=90%
Γ_6	$\omega\mu^+\nu_\mu$			
Γ_7	$\rho^0\ell^+\nu_\ell$	[a]	< 2.1 × 10^{-4}	CL=90%
Γ_8	$e^+\nu_e$		< 1.5 × 10^{-5}	CL=90%
Γ_9	$\mu^+\nu_\mu$		< 2.1 × 10^{-5}	CL=90%
Γ_{10}	$\tau^+\nu_\tau$		< 1.8 × 10^{-3}	CL=90%
	D, D^*, or D_s modes			
Γ_{11}	$\bar{D}^0\pi^+$		(5.3 ±0.5) × 10^{-3}	
Γ_{12}	$\bar{D}^0\rho^+$		(1.34±0.18) %	
Γ_{13}	$\bar{D}^0\pi^+\pi^+\pi^-$		(1.1 ±0.4) %	
Γ_{14}	$\bar{D}^0\pi^+\pi^+\pi^-$ nonresonant		(5 ±4) × 10^{-3}	
Γ_{15}	$\bar{D}^0\pi^+\rho^0$		(4.2 ±3.0) × 10^{-3}	
Γ_{16}	$\bar{D}^0 a_1(1260)^+$		(5 ±4) × 10^{-3}	
Γ_{17}	$D^*(2010)^-\pi^+\pi^+$		(2.1 ±0.6) × 10^{-3}	
Γ_{18}	$D^-\pi^+\pi^+$		< 1.4 × 10^{-3}	CL=90%
Γ_{19}	$\bar{D}^*(2007)^0\pi^+$		(5.2 ±0.8) × 10^{-3}	
Γ_{20}	$\bar{D}^*(2007)^0\rho^+$		(1.55±0.31) %	
Γ_{21}	$\bar{D}^*(2007)^0\pi^+\pi^+\pi^-$		(9.4 ±2.6) × 10^{-3}	
Γ_{22}	$\bar{D}^*(2007)^0 a_1(1260)^+$		(1.9 ±0.5) %	
Γ_{23}	$D^*(2010)^-\pi^+\pi^+\pi^0$		(1.5 ±0.7) %	
Γ_{24}	$D^*(2010)^-\pi^+\pi^+\pi^+\pi^-$		< 1 %	CL=90%
Γ_{25}	$\bar{D}^*_1(2420)^0\pi^+$		(1.5 ±0.6) × 10^{-3}	S=1.3
Γ_{26}	$\bar{D}^*_1(2420)^0\rho^+$		< 1.4 × 10^{-3}	CL=90%
Γ_{27}	$\bar{D}^*_2(2460)^0\pi^+$		< 1.3 × 10^{-3}	CL=90%

Γ_{28}	$\overline{D}_2^*(2460)^0 \rho^+$	< 4.7	$\times 10^{-3}$	CL=90%
Γ_{29}	$\overline{D}^0 D_s^+$	(1.7 ±0.6) %		
Γ_{30}	$\overline{D}^0 D_s^{*+}$	(1.2 ±1.0) %		
Γ_{31}	$\overline{D}^*(2007)^0 D_s^+$	(10 ±7) $\times 10^{-3}$		
Γ_{32}	$\overline{D}^*(2007)^0 D_s^{*+}$	(2.3 ±1.4) %		
Γ_{33}	$D_s^+ \pi^0$	< 2.0	$\times 10^{-4}$	CL=90%
Γ_{34}	$D_s^{*+} \pi^0$	< 3.3	$\times 10^{-4}$	CL=90%
Γ_{35}	$D_s^+ \eta$	< 5	$\times 10^{-4}$	CL=90%
Γ_{36}	$D_s^{*+} \eta$	< 8	$\times 10^{-4}$	CL=90%
Γ_{37}	$D_s^+ \rho^0$	< 4	$\times 10^{-4}$	CL=90%
Γ_{38}	$D_s^{*+} \rho^0$	< 5	$\times 10^{-4}$	CL=90%
Γ_{39}	$D_s^+ \omega$	< 5	$\times 10^{-4}$	CL=90%
Γ_{40}	$D_s^{*+} \omega$	< 7	$\times 10^{-4}$	CL=90%
Γ_{41}	$D_s^+ a_1(1260)^0$	< 2.2	$\times 10^{-3}$	CL=90%
Γ_{42}	$D_s^{*+} a_1(1260)^0$	< 1.6	$\times 10^{-3}$	CL=90%
Γ_{43}	$D_s^+ \phi$	< 3.2	$\times 10^{-4}$	CL=90%
Γ_{44}	$D_s^{*+} \phi$	< 4	$\times 10^{-4}$	CL=90%
Γ_{45}	$D_s^+ \overline{K}^0$	< 1.1	$\times 10^{-3}$	CL=90%
Γ_{46}	$D_s^{*+} \overline{K}^0$	< 1.1	$\times 10^{-3}$	CL=90%
Γ_{47}	$D_s^+ \overline{K}^*(892)^0$	< 5	$\times 10^{-4}$	CL=90%
Γ_{48}	$D_s^{*+} \overline{K}^*(892)^0$	< 4	$\times 10^{-4}$	CL=90%
Γ_{49}	$D_s^- \pi^+ K^+$	< 8	$\times 10^{-4}$	CL=90%
Γ_{50}	$D_s^{*-} \pi^+ K^+$	< 1.2	$\times 10^{-3}$	CL=90%
Γ_{51}	$D_s^- \pi^+ K^*(892)^+$	< 6	$\times 10^{-3}$	CL=90%
Γ_{52}	$D_s^{*-} \pi^+ K^*(892)^+$	< 8	$\times 10^{-3}$	CL=90%
	Charmonium modes			
Γ_{53}	$J/\psi(1S) K^+$	(1.01±0.14) $\times 10^{-3}$		
Γ_{54}	$J/\psi(1S) K^+ \pi^+ \pi^-$	(1.4 ±0.6) $\times 10^{-3}$		
Γ_{55}	$J/\psi(1S) K^*(892)^+$	(1.7 ±0.5) $\times 10^{-3}$		
Γ_{56}	$J/\psi(1S) \pi^-$	(4.4 ±2.4) $\times 10^{-5}$		
Γ_{57}	$\psi(2S) K^+$	(6.9 ±3.1) $\times 10^{-4}$		S=1.3
Γ_{58}	$\psi(2S) K^*(892)^+$	< 3.0	$\times 10^{-3}$	CL=90%
Γ_{59}	$\psi(2S) K^*(892)^+ \pi^+ \pi^-$	(1.9 ±1.2) $\times 10^{-3}$		
Γ_{60}	$\chi_{c1}(1P) K^+$	(1.0 ±0.4) $\times 10^{-3}$		
Γ_{61}	$\chi_{c1}(1P) K^*(892)^+$	< 2.1	$\times 10^{-3}$	CL=90%
	***K* or *K** modes**			
Γ_{62}	$K^0 \pi^+$	< 4.8	$\times 10^{-5}$	CL=90%
Γ_{63}	$K^+ \pi^0$	< 1.4	$\times 10^{-5}$	CL=90%
Γ_{64}	$K^*(892)^0 \pi^+$	< 4.1	$\times 10^{-5}$	CL=90%
Γ_{65}	$K^*(892)^+ \pi^0$	< 9.9	$\times 10^{-5}$	CL=90%
Γ_{66}	$K^+ \pi^- \pi^+$ (no charm)	< 1.9	$\times 10^{-4}$	CL=90%
Γ_{67}	$K_1(1400)^0 \pi^+$	< 2.6	$\times 10^{-3}$	CL=90%
Γ_{68}	$K_2^*(1430)^0 \pi^+$	< 6.8	$\times 10^{-4}$	CL=90%
Γ_{69}	$K^+ \rho^0$	< 1.9	$\times 10^{-5}$	CL=90%
Γ_{70}	$K^0 \rho^+$	< 4.8	$\times 10^{-5}$	CL=90%
Γ_{71}	$K^*(892)^+ \pi^+ \pi^-$	< 1.1	$\times 10^{-3}$	CL=90%
Γ_{72}	$K^*(892)^+ \rho^0$	< 9.0	$\times 10^{-4}$	CL=90%
Γ_{73}	$K_1(1400)^+ \rho^0$	< 7.8	$\times 10^{-4}$	CL=90%
Γ_{74}	$K_2^*(1430)^+ \rho^0$	< 1.5	$\times 10^{-3}$	CL=90%
Γ_{75}	$K^+ K^- K^+$	< 3.1	$\times 10^{-4}$	CL=90%
Γ_{76}	$K^+ \phi$	< 1.2	$\times 10^{-5}$	CL=90%
Γ_{77}	$K^*(892)^+ K^+ K^-$	< 1.6	$\times 10^{-3}$	CL=90%
Γ_{78}	$K^*(892)^+ \phi$	< 7.0	$\times 10^{-5}$	CL=90%
Γ_{79}	$K_1(1400)^+ \phi$	< 1.1	$\times 10^{-3}$	CL=90%
Γ_{80}	$K_2^*(1430)^+ \phi$	< 3.4	$\times 10^{-3}$	CL=90%
Γ_{81}	$K^+ f_0(980)$	< 8	$\times 10^{-5}$	CL=90%
Γ_{82}	$K^*(892)^+ \gamma$	(5.7 ±3.3) $\times 10^{-5}$		
Γ_{83}	$K_1(1270)^+ \gamma$	< 7.3	$\times 10^{-3}$	CL=90%
Γ_{84}	$K_1(1400)^+ \gamma$	< 2.2	$\times 10^{-3}$	CL=90%
Γ_{85}	$K_2^*(1430)^+ \gamma$	< 1.4	$\times 10^{-3}$	CL=90%
Γ_{86}	$K^*(1680)^+ \gamma$	< 1.9	$\times 10^{-3}$	CL=90%
Γ_{87}	$K_3^*(1780)^+ \gamma$	< 5.5	$\times 10^{-3}$	CL=90%
Γ_{88}	$K_4^*(2045)^+ \gamma$	< 9.9	$\times 10^{-3}$	CL=90%
	Light unflavored meson modes			
Γ_{89}	$\pi^+ \pi^0$	< 1.7	$\times 10^{-5}$	CL=90%
Γ_{90}	$\pi^+ \pi^+ \pi^-$	< 1.9	$\times 10^{-4}$	CL=90%
Γ_{91}	$\rho^0 \pi^+$	< 4.3	$\times 10^{-5}$	CL=90%
Γ_{92}	$\pi^+ f_0(980)$	< 1.4	$\times 10^{-4}$	CL=90%
Γ_{93}	$\pi^+ f_2(1270)$	< 2.4	$\times 10^{-4}$	CL=90%
Γ_{94}	$\pi^+ \pi^0 \pi^0$	< 8.9	$\times 10^{-4}$	CL=90%
Γ_{95}	$\rho^+ \pi^0$	< 7.7	$\times 10^{-5}$	CL=90%
Γ_{96}	$\pi^+ \pi^- \pi^+ \pi^0$	< 4.0	$\times 10^{-3}$	CL=90%
Γ_{97}	$\rho^+ \rho^0$	< 1.0	$\times 10^{-3}$	CL=90%
Γ_{98}	$a_1(1260)^+ \pi^0$	< 1.7	$\times 10^{-3}$	CL=90%
Γ_{99}	$a_1(1260)^0 \pi^+$	< 9.0	$\times 10^{-4}$	CL=90%
Γ_{100}	$\omega \pi^+$	< 4.0	$\times 10^{-4}$	CL=90%
Γ_{101}	$\eta \pi^+$	< 7.0	$\times 10^{-4}$	CL=90%
Γ_{102}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^-$	< 8.6	$\times 10^{-4}$	CL=90%
Γ_{103}	$\rho^0 a_1(1260)^+$	< 6.2	$\times 10^{-4}$	CL=90%
Γ_{104}	$\rho^0 a_2(1320)^+$	< 7.2	$\times 10^{-4}$	CL=90%
Γ_{105}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0$	< 6.3	$\times 10^{-3}$	CL=90%
Γ_{106}	$a_1(1260)^+ a_1(1260)^0$	< 1.3	%	CL=90%
	Baryon modes			
Γ_{107}	$p \overline{p} \pi^+$	< 1.6	$\times 10^{-4}$	CL=90%
Γ_{108}	$p \overline{p} \pi^+ \pi^+ \pi^-$	< 5.2	$\times 10^{-4}$	CL=90%
Γ_{109}	$p \overline{\Lambda}$	< 6	$\times 10^{-5}$	CL=90%
Γ_{110}	$p \overline{\Lambda} \pi^+ \pi^-$	< 2.0	$\times 10^{-4}$	CL=90%
Γ_{111}	$\overline{\Delta}^0 p$	< 3.8	$\times 10^{-4}$	CL=90%
Γ_{112}	$\Delta^{++} \overline{p}$	< 1.5	$\times 10^{-4}$	CL=90%

Lepton Family number (*LF*) or Lepton number (*L*) violating modes, or $\Delta B = 1$ weak neutral current (*B1*) modes

Γ_{113}	$\pi^+ e^+ e^-$	*B1*	< 3.9	$\times 10^{-3}$	CL=90%
Γ_{114}	$\pi^+ \mu^+ \mu^-$	*B1*	< 9.1	$\times 10^{-3}$	CL=90%
Γ_{115}	$K^+ e^+ e^-$	*B1*			
Γ_{116}	$K^+ \mu^+ \mu^-$	*B1*	< 1.7	$\times 10^{-4}$	CL=90%
Γ_{117}	$K^*(892)^+ e^+ e^-$	*B1*	< 6.9	$\times 10^{-4}$	CL=90%
Γ_{118}	$K^*(892)^+ \mu^+ \mu^-$	*B1*	< 1.2	$\times 10^{-3}$	CL=90%
Γ_{119}	$\pi^+ e^+ \mu^-$	*LF*	< 6.4	$\times 10^{-3}$	CL=90%
Γ_{120}	$\pi^+ e^- \mu^+$	*LF*	< 6.4	$\times 10^{-3}$	CL=90%
Γ_{121}	$K^+ e^+ \mu^-$	*LF*	< 6.4	$\times 10^{-3}$	CL=90%
Γ_{122}	$K^+ e^- \mu^+$	*LF*	< 6.4	$\times 10^{-3}$	CL=90%
Γ_{123}	$\pi^- e^+ e^+$	*L*	< 3.9	$\times 10^{-3}$	CL=90%
Γ_{124}	$\pi^- \mu^+ \mu^+$	*L*	< 9.1	$\times 10^{-3}$	CL=90%
Γ_{125}	$\pi^- e^+ \mu^+$	*L*	< 6.4	$\times 10^{-3}$	CL=90%
Γ_{126}	$K^- e^+ e^+$	*L*	< 3.9	$\times 10^{-3}$	CL=90%
Γ_{127}	$K^- \mu^+ \mu^+$	*L*	< 9.1	$\times 10^{-3}$	CL=90%
Γ_{128}	$K^- e^+ \mu^+$	*L*	< 6.4	$\times 10^{-3}$	CL=90%

[*a*] ℓ indicates e or μ mode, not sum over modes.

B^+ BRANCHING RATIOS

$\Gamma(\ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.101±0.018±0.015	ATHANAS	94	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\overline{D}^0 \ell^+ \nu_\ell)/\Gamma_{\text{total}}$ — Γ_2/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	DOCUMENT ID		TECN	COMMENT
0.016±0.006±0.003	[11] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$

[11] FULTON 91 assumes equal production of $B^0 \overline{B}^0$ and $B^+ B^-$ at the $\Upsilon(4S)$.

$\Gamma(\overline{D}^*(2007)^0 \ell^+ \nu_\ell)/\Gamma_{\text{total}}$ — Γ_3/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.053 ±0.008 OUR AVERAGE					
0.0513±0.0054±0.0064	302	[12] BARISH	95	CLE2	$e^+e^- \to \Upsilon(4S)$
0.066 ±0.016 ±0.015		[13] ALBRECHT	92C	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	398	[14] SANGHERA	93	CLE2	$e^+e^- \to \Upsilon(4S)$
0.041 ±0.008 $^{+0.008}_{-0.009}$		[15] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$
0.070 ±0.018 ±0.014		[16] ANTREASYAN	90B	CBAL	$e^+e^- \to \Upsilon(4S)$

[12] BARISH 95 use B($D^0 \to K^- \pi^+$) = (3.91 ± 0.08 ± 0.17)% and B($D^{*0} \to D^0 \pi^0$) = (63.6 ± 2.3 ± 3.3)%.

[13] ALBRECHT 92C reports 0.058±0.014±0.013. We rescale using the method described in STONE 94 but with the updated PDG 94 B($D^0 \to K^- \pi^+$). Assumes equal production of $B^0 \overline{B}^0$ and $B^+ B^-$ at the $\Upsilon(4S)$.

[14] Combining $\overline{D}^{*0} \ell^+ \nu_\ell$ and $\overline{D}^{*-} \ell^+ \nu_\ell$ SANGHERA 93 test $V-A$ structure and fit the decay angular distributions to obtain $A_{FB} = 3/4*(\Gamma^- - \Gamma^+)/\Gamma = 0.14 \pm 0.06 \pm 0.03$. Assuming a value of V_{cb}, they measure V, A_1, and A_2, the three form factors for the $D^* \ell \nu_\ell$ decay, where results are slightly dependent on model assumptions.

[15] Assumes equal production of $B^0 \overline{B}^0$ and $B^+ B^-$ at the $\Upsilon(4S)$. Uncorrected for D and D^* branching ratio assumptions.

[16] ANTREASYAN 90B is average over B and $\overline{D}^*(2010)$ charge states.

$\Gamma(\pi^0 e^+ \nu_e)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0022	90	ANTREASYAN	90B	CBAL	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\omega \ell^+ \nu_\ell)/\Gamma_{total}$ — Γ_5/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.1 × 10⁻⁴	90	[17] BEAN	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[17] BEAN 93B limit set using ISGW Model. Using isospin and the quark model to combine $\Gamma(\rho^0 \ell^+ \nu_\ell)$ and $\Gamma(\rho^- \ell^+ \nu_\ell)$ with this result, they obtain a limit $<(1.6\text{–}2.7) \times 10^{-4}$ at 90% CL for $B^+ \rightarrow \omega \ell^+ \nu_\ell$. The range corresponds to the ISGW, WSB, and KS models. An upper limit on $|V_{ub}/V_{cb}| < 0.8$–0.13 at 90% CL is derived as well.

$\Gamma(\omega \mu^+ \nu_\mu)/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	[18] ALBRECHT	91C	ARG

[18] In ALBRECHT 91C, one event is fully reconstructed providing evidence for the $b \rightarrow u$ transition.

$\Gamma(\rho^0 \ell^+ \nu_\ell)/\Gamma_{total}$ — Γ_7/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.1 × 10⁻⁴	90	[19] BEAN	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[19] BEAN 93B limit set using ISGW Model. Using isospin and the quark model to combine $\Gamma(\omega^0 \ell^+ \nu_\ell)$ and $\Gamma(\rho^- \ell^+ \nu_\ell)$ with this result, they obtain a limit $<(1.6\text{–}2.7) \times 10^{-4}$ at 90% CL for $B^+ \rightarrow \rho^0 \ell^+ \nu_\ell$. The range corresponds to the ISGW, WSB, and KS models. An upper limit on $|V_{ub}/V_{cb}| < 0.8$–0.13 at 90% CL is derived as well.

$\Gamma(e^+ \nu_e)/\Gamma_{total}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.5 × 10⁻⁵	90	ARTUSO	95	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(\mu^+ \nu_\mu)/\Gamma_{total}$ — Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.1 × 10⁻⁵	90	ARTUSO	95	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(\tau^+ \nu_\tau)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.8 × 10⁻³	90	[20] BUSKULIC	95	ALEP	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.04 × 10⁻²	90	[21] ALBRECHT	95D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
<2.2 × 10⁻³	90	ARTUSO	95	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[20] BUSKULIC 95 uses same missing-energy technique as in $\overline{b} \rightarrow \tau^+ \nu_\tau X$, but analysis is restricted to endpoint region of missing-energy distribution.
[21] ALBRECHT 95D use full reconstruction of one B decay as tag.

$\Gamma(\overline{D}^0 \pi^+)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0053±0.0005 OUR AVERAGE					
0.0055±0.0004±0.0005	304	[22] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.0050±0.0007±0.0006	54	[23] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
$0.0054^{+0.0018+0.0012}_{-0.0015-0.0009}$	14	[24] BEBEK	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0020±0.0008±0.0006	12	[23] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.0019±0.0010±0.0006	7	[25] ALBRECHT	88K	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[22] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \rightarrow K^- \pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^- \pi^+ \pi^0)/B(D^0 \rightarrow K^- \pi^+)$ and $B(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/B(D^0 \rightarrow K^- \pi^+)$.
[23] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses the Mark III branching fractions for the D.
[24] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.
[25] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- ratio is 45:55. Superseded by ALBRECHT 90J.

$\Gamma(\overline{D}^0 \rho^+)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0134±0.0018 OUR AVERAGE					
0.0135±0.0012±0.0015	212	[26] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.013 ±0.004 ±0.004	19	[27] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.021 ±0.008 ±0.009	10	[28] ALBRECHT	88K	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[26] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \rightarrow K^- \pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^- \pi^+ \pi^0)/B(D^0 \rightarrow K^- \pi^+)$ and $B(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/B(D^0 \rightarrow K^- \pi^+)$.
[27] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses the Mark III branching fractions for the D.
[28] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- ratio is 45:55.

$\Gamma(\overline{D}^0 \pi^+ \pi^+ \pi^-)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0115±0.0029±0.0021	[29] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[29] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}^0 \pi^+ \pi^+ \pi^-$ nonresonant$)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0051±0.0034±0.0023	[30] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[30] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}^0 \pi^+ \rho^0)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0042±0.0023±0.0020	[31] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[31] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}^0 a_1(1260)^+)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0045±0.0019±0.0031	[32] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[32] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^- \pi^+ \pi^+)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.0021±0.0006 OUR AVERAGE						
0.0019±0.0007±0.0003		14	[33] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.0026±0.0014±0.0007		11	[34] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$0.0024^{+0.0017+0.0010}_{-0.0016-0.0006}$		3	[35] BEBEK	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.004	90		[36] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
0.005 ±0.002 ±0.003		7	[37] ALBRECHT	87C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[33] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2010)^+ \rightarrow D^0 \pi^+)$ and absolute $B(D^0 \rightarrow K^- \pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^- \pi^+ \pi^0)/B(D^0 \rightarrow K^- \pi^+)$ and $B(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/B(D^0 \rightarrow K^- \pi^+)$.
[34] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses the Mark III branching fractions for the D.
[35] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.
[36] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$. The authors also find the product branching fraction into $D^{**}\pi$ followed by $D^{**} \rightarrow D^*(2010)\pi$ to be $0.0014^{+0.0008}_{-0.0006} \pm 0.0003$ where D^{**} represents all orbitally excited D mesons.
[37] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \rightarrow B^+B^-) = 55\%$ and $B(\Upsilon(4S) \rightarrow B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.

$\Gamma(D^- \pi^+ \pi^+)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0014	90		[38] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.007	90		[39] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
$0.0025^{+0.0041+0.0024}_{-0.0023-0.0008}$		1	[40] BEBEK	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[38] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III $B(D^+ \rightarrow K^- \pi^+ \pi^+)$.
[39] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D. The product branching fraction into $D_0^*(2340)\pi$ followed by $D_0^*(2340) \rightarrow D\pi$ is < 0.005 at 90%CL and into $D_2^*(2460)$ followed by $D_2^*(2460) \rightarrow D\pi$ is < 0.004 at 90%CL.
[40] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. $B(D^- \rightarrow K^+ \pi^- \pi^-) = (9.1 \pm 1.3 \pm 0.4)\%$ is assumed.

$\Gamma(\overline{D}^*(2007)^0 \pi^+)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0052±0.0008 OUR AVERAGE					
0.0052±0.0007±0.0007	71	[41] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.0072±0.0018±0.0016		[42] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
0.0040±0.0014±0.0012	9	[42] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0027±0.0044		[43] BEBEK	87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[41] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \rightarrow D^0 \pi^0)$ and absolute $B(D^0 \rightarrow K^- \pi^+)$ and the PDG 1992 $B(D^0 \rightarrow K^- \pi^+ \pi^0)/B(D^0 \rightarrow K^- \pi^+)$ and $B(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/B(D^0 \rightarrow K^- \pi^+)$.
[42] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.
[43] This is a derived branching ratio, using the inclusive pion spectrum and other two-body B decays. BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\overline{D}^*(2007)^0 \rho^+)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0155±0.0031 OUR AVERAGE					
0.0168±0.0021±0.0028	86	[44] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.010 ±0.006 ±0.004	7	[45] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[44] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2007)^0 \rightarrow D^0\pi^0$) and absolute B($D^0 \rightarrow K^-\pi^+$) and the PDG 1992 B($D^0 \rightarrow K^-\pi^+\pi^0$)/B($D^0 \rightarrow K^-\pi^+$) and B($D^0 \rightarrow K^-\pi^+\pi^+\pi^-$)/B($D^0 \rightarrow K^-\pi^+$). The nonresonant $\pi^+\pi^0$ contribution under the ρ^+ is negligible.

[45] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

$\Gamma(\overline{D}^*(2007)^0 \pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0094±0.0020±0.0017	48	[46,47] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[46] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2007)^0 \rightarrow D^0\pi^0$) and absolute B($D^0 \rightarrow K^-\pi^+$) and the PDG 1992 B($D^0 \rightarrow K^-\pi^+\pi^0$)/B($D^0 \rightarrow K^-\pi^+$) and B($D^0 \rightarrow K^-\pi^+\pi^+\pi^-$)/B($D^0 \rightarrow K^-\pi^+$).

[47] The three pion mass is required to be between 1.0 and 1.6 GeV consistent with an a_1 meson. (If this channel is dominated by a_1^+, the branching ratio for $\overline{D}^{*0} a_1^+$ is twice that for $\overline{D}^{*0}\pi^+\pi^+\pi^-$.)

$\Gamma(\overline{D}^*(2007)^0 a_1(1260)^+)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0188±0.0040±0.0034	[48,49] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[48] ALAM 94 value is twice their $\Gamma(\overline{D}^*(2007)^0\pi^+\pi^+\pi^-)/\Gamma_{total}$ value based on their observation that the three pions are dominantly in the $a_1(1260)$ mass range 1.0 to 1.6 GeV.

[49] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2007)^0 \rightarrow D^0\pi^0$) and absolute B($D^0 \rightarrow K^-\pi^+$) and the PDG 1992 B($D^0 \rightarrow K^-\pi^+\pi^0$)/B($D^0 \rightarrow K^-\pi^+$) and B($D^0 \rightarrow K^-\pi^+\pi^+\pi^-$)/B($D^0 \rightarrow K^-\pi^+$).

$\Gamma(D^*(2010)^- \pi^+\pi^+\pi^0)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0150±0.0070±0.0003	26	[50] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.043 ±0.013 ±0.026	24	[51] ALBRECHT	87C	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[50] ALBRECHT 90J reports $0.018 \pm 0.007 \pm 0.005$ for B($D^*(2010)^+ \rightarrow D^0\pi^+$) = 0.57 ± 0.06. We rescale to our best value B($D^*(2010)^+ \rightarrow D^0\pi^+$) = $(68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[51] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume B($\Upsilon(4S) \rightarrow B^+B^-$) = 55% and B($\Upsilon(4S) \rightarrow B^0\overline{B}^0$) = 45%. Superseded by ALBRECHT 90J.

$\Gamma(D^*(2010)^- \pi^+\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	[52] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[52] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

$\Gamma(\overline{D}_1^*(2420)^0 \pi^+)/\Gamma_{total}$ — Γ_{25}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0015±0.0006 OUR AVERAGE		Error includes scale factor of 1.3.			
0.0011±0.0005±0.0002	8	[53] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.0025±0.0007±0.0006		[54] ALBRECHT	94D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[53] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \rightarrow D^0\pi^+$) and absolute B($D^0 \rightarrow K^-\pi^+$) and the PDG 1992 B($D^0 \rightarrow K^-\pi^+\pi^0$)/B($D^0 \rightarrow K^-\pi^+$) and assuming B($D_1(2420)^0 \rightarrow D^*(2010)^+\pi^-$) = 67%.

[54] ALBRECHT 94D assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \rightarrow D^0\pi^+$) assuming B($D_1(2420)^0 \rightarrow D^*(2010)^+\pi^-$) = 67%.

$\Gamma(\overline{D}_1^*(2420)^0 \rho^+)/\Gamma_{total}$ — Γ_{26}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0014	90	[55] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[55] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \rightarrow D^0\pi^+$) assuming B($D_1(2420)^0 \rightarrow D^*(2010)^+\pi^-$) = 67%.

$\Gamma(\overline{D}_2^*(2460)^0 \pi^+)/\Gamma_{total}$ — Γ_{27}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0013	90	[56] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0028	90	[57] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
<0.0023	90	[58] ALBRECHT	94D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[56] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III B($D^+ \rightarrow K^-\pi^+\pi^+$) and B($D_2^*(2460)^0 \rightarrow D^+\pi^-$) = 30%.

[57] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III B($D^+ \rightarrow K^-\pi^+\pi^+$), the CLEO II B($D^*(2010)^+ \rightarrow D^0\pi^+$) and B($D_2^*(2460)^0 \rightarrow D^*(2010)^+\pi^-$) = 20%.

[58] ALBRECHT 94D assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \rightarrow D^0\pi^+$) and B($D_2^*(2460)^0 \rightarrow D^*(2010)^+\pi^-$) = 30%.

$\Gamma(\overline{D}_2^*(2460)^0 \rho^+)/\Gamma_{total}$ — Γ_{28}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0047	90	[59] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
<0.005	90	[60] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[59] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III B($D^+ \rightarrow K^-\pi^+\pi^+$) and B($D_2^*(2460)^0 \rightarrow D^+\pi^-$) = 30%.

[60] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the Mark III B($D^+ \rightarrow K^-\pi^+\pi^+$), the CLEO II B($D^*(2010)^+ \rightarrow D^0\pi^+$) and B($D_2^*(2460)^0 \rightarrow D^*(2010)^+\pi^-$) = 20%.

$\Gamma(\overline{D}^0 D_s^+)/\Gamma_{total}$ — Γ_{29}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.017±0.006 OUR AVERAGE					
0.018±0.009±0.004		[61] ALBRECHT	92G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.016±0.007±0.004	5	[62] BORTOLETTO	90	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[61] ALBRECHT 92G reports $0.024 \pm 0.012 \pm 0.004$ for B($D_s^+ \rightarrow \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \rightarrow \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^0 branching ratios, e.g., B($D^0 \rightarrow K^-\pi^+$) = 3.71 ± 0.25%.

[62] BORTOLETTO 90 reports 0.029 ± 0.013 for B($D_s^+ \rightarrow \phi\pi^+$) = 0.02. We rescale to our best value B($D_s^+ \rightarrow \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{D}^0 D_s^{*+})/\Gamma_{total}$ — Γ_{30}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.012±0.009±0.003	[63] ALBRECHT	92G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[63] ALBRECHT 92G reports $0.016 \pm 0.012 \pm 0.003$ for B($D_s^+ \rightarrow \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \rightarrow \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^0 branching ratios, e.g., B($D^0 \rightarrow K^-\pi^+$) = 3.71 ± 0.25%.

$\Gamma(\overline{D}^*(2007)^0 D_s^+)/\Gamma_{total}$ — Γ_{31}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.010±0.007±0.002	[64] ALBRECHT	92G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[64] ALBRECHT 92G reports $0.013 \pm 0.009 \pm 0.002$ for B($D_s^+ \rightarrow \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \rightarrow \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^0 and $D^*(2007)^0$ branching ratios, e.g., B($D^0 \rightarrow K^-\pi^+$) = 3.71 ± 0.25% and B($D^*(2007)^0 \rightarrow D^0\pi^0$) = 55 ± 6%.

$\Gamma(\overline{D}^*(2007)^0 D_s^{*+})/\Gamma_{total}$ — Γ_{32}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.023±0.013±0.006	[65] ALBRECHT	92G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[65] ALBRECHT 92G reports $0.031 \pm 0.016 \pm 0.005$ for B($D_s^+ \rightarrow \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \rightarrow \phi\pi^+$) = $(3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^0 and $D^*(2007)^0$ branching ratios, e.g., B($D^0 \rightarrow K^-\pi^+$) = 3.71 ± 0.25% and B($D^*(2007)^0 \rightarrow D^0\pi^0$) = 55 ± 6%.

$\Gamma(D_s^+ \pi^0)/\Gamma_{total}$ — Γ_{33}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.00020	90	[66] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[66] ALEXANDER 93B reports $< 2.0 \times 10^{-4}$ for B($D_s^+ \rightarrow \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \rightarrow \phi\pi^+$) = 0.036.

$[\Gamma(D_s^+ \pi^0) + \Gamma(D_s^{*+} \pi^0)]/\Gamma_{total}$ — $(\Gamma_{33}+\Gamma_{34})/\Gamma$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0007	90	[67] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[67] ALBRECHT 93E reports $< 0.9 \times 10^{-3}$ for B($D_s^+ \rightarrow \phi\pi^+$) = 0.027. We rescale to our best value B($D_s^+ \rightarrow \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+} \pi^0)/\Gamma_{total}$ — Γ_{34}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.00033	90	[68] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[68] ALEXANDER 93B reports $< 3.2 \times 10^{-4}$ for B($D_s^+ \rightarrow \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \rightarrow \phi\pi^+$) = 0.036.

$\Gamma(D_s^+ \eta)/\Gamma_{total}$ — Γ_{35}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0005	90	[69] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[69] ALEXANDER 93B reports $< 4.6 \times 10^{-4}$ for B($D_s^+ \rightarrow \phi\pi^+$) = 0.037. We rescale to our best value B($D_s^+ \rightarrow \phi\pi^+$) = 0.036.

$\Gamma(D_s^{*+}\eta)/\Gamma_{total}$ — Γ_{36}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0008	90	[70] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[70] ALEXANDER 93B reports $< 7.5 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^+\rho^0)/\Gamma_{total}$ — Γ_{37}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0004	90	[71] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[71] ALEXANDER 93B reports $< 3.7 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$[\Gamma(D_s^+\rho^0) + \Gamma(D_s^+\overline{K}^*(892)^0)]/\Gamma_{total}$ — $(\Gamma_{37}+\Gamma_{47})/\Gamma$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0025	90	[72] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[72] ALBRECHT 93E reports $< 3.4 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+}\rho^0)/\Gamma_{total}$ — Γ_{38}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0005	90	[73] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[73] ALEXANDER 93B reports $< 4.8 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$[\Gamma(D_s^{*+}\rho^0) + \Gamma(D_s^{*+}\overline{K}^*(892)^0)]/\Gamma_{total}$ — $(\Gamma_{38}+\Gamma_{48})/\Gamma$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0015	90	[74] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[74] ALBRECHT 93E reports $< 2.0 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^+\omega)/\Gamma_{total}$ — Γ_{39}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0005	90	[75] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0025	90	[76] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[75] ALEXANDER 93B reports $< 4.8 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[76] ALBRECHT 93E reports $< 3.4 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+}\omega)/\Gamma_{total}$ — Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0007	90	[77] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0014	90	[78] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[77] ALEXANDER 93B reports $< 6.8 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[78] ALBRECHT 93E reports $< 1.9 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^+ a_1(1260)^0)/\Gamma_{total}$ — Γ_{41}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0022	90	[79] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[79] ALBRECHT 93E reports $< 3.0 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+} a_1(1260)^0)/\Gamma_{total}$ — Γ_{42}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0016	90	[80] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[80] ALBRECHT 93E reports $< 2.2 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^+\phi)/\Gamma_{total}$ — Γ_{43}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.00032	90	[81] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0013	90	[82] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[81] ALEXANDER 93B reports $< 3.1 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[82] ALBRECHT 93E reports $< 1.7 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+}\phi)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0004	90	[83] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0016	90	[84] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[83] ALEXANDER 93B reports $< 4.2 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[84] ALBRECHT 93E reports $< 2.1 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^+\overline{K}^0)/\Gamma_{total}$ — Γ_{45}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0011	90	[85] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0019	90	[86] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[85] ALEXANDER 93B reports $< 10.3 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[86] ALBRECHT 93E reports $< 2.5 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+}\overline{K}^0)/\Gamma_{total}$ — Γ_{46}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0011	90	[87] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0023	90	[88] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[87] ALEXANDER 93B reports $< 10.9 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

[88] ALBRECHT 93E reports $< 3.1 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^+\overline{K}^*(892)^0)/\Gamma_{total}$ — Γ_{47}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0005	90	[89] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[89] ALEXANDER 93B reports $< 4.4 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+}\overline{K}^*(892)^0)/\Gamma_{total}$ — Γ_{48}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0004	90	[90] ALEXANDER	93B	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[90] ALEXANDER 93B reports $< 4.3 \times 10^{-4}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^-\pi^+K^+)/\Gamma_{total}$ — Γ_{49}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0008	90	[91] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[91] ALBRECHT 93E reports $< 1.1 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*-}\pi^+K^+)/\Gamma_{total}$ — Γ_{50}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0012	90	[92] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[92] ALBRECHT 93E reports $< 1.6 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^-\pi^+K^*(892)^+)/\Gamma_{total}$ — Γ_{51}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.006	90	[93] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[93] ALBRECHT 93E reports $< 8.6 \times 10^{-3}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*-}\pi^+K^*(892)^+)/\Gamma_{total}$ — Γ_{52}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.008	90	[94] ALBRECHT	93E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[94] ALBRECHT 93E reports $< 1.1 \times 10^{-2}$ for $B(D_s^+ \rightarrow \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \rightarrow \phi\pi^+) = 0.036$.

$\Gamma(J/\psi(1S)K^+)/\Gamma_{total}$ — Γ_{53}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
10.1 ± 1.4 OUR AVERAGE					
11.0 ± 1.5 ±0.9	59	[95] ALAM	94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
9.16± 3.01±0.30		[96] BORTOLETTO	92	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
8.0 ± 3.5 ±0.3	6	[97] ALBRECHT	90J	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

22 ±10 ±2			BUSKULIC	92G	ALEP	$e^+e^- \to Z$
7 ± 4		3	[98] ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$
10 ± 7 ±2		3	[99] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
9 ± 5		3	[100] ALAM	86	CLEO	$e^+e^- \to \Upsilon(4S)$

[95] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[96] BORTOLETTO 92 reports $8 \pm 2 \pm 2$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[97] ALBRECHT 90J reports $7 \pm 3 \pm 1$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[98] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Superseded by ALBRECHT 90J.

[99] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.

[100] ALAM 86 assumes $B^{\pm}/B^0$ ratio is 60/40.

$\Gamma(J/\psi(1S)K^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{54}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.0014 ±0.0006 OUR AVERAGE						
0.00137±0.00081±0.00004			[101] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.00137±0.00090±0.00004		6	[102] ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.0018	90		[103] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[101] BORTOLETTO 92 reports $0.0012 \pm 0.0006 \pm 0.0004$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[102] ALBRECHT 87D reports 0.0012 ± 0.0008 for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. They actually report 0.0011 ± 0.0007 assuming $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. We rescale to 50/50. Analysis explicitly removes $B^+ \to \psi(2S)K^+$.

[103] ALBRECHT 90J reports < 0.0016 for $B(J/\psi(1S) \to e^+e^-) = 0.069$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = 0.0602$. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(J/\psi(1S)K^*(892)^+)/\Gamma_{total}$ — Γ_{55}/Γ

For polarization information see the Listings at the end of the "B^0 Branching Ratios" section.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0017 ±0.0005 OUR AVERAGE					
0.00178±0.00051±0.00023	13	[104] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.00149±0.00107±0.00005		[105] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0018 ±0.0013 ±0.0001	2	[106] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[104] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[105] BORTOLETTO 92 reports $0.0013 \pm 0.0009 \pm 0.0003$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[106] ALBRECHT 90J reports $0.0016 \pm 0.0011 \pm 0.0003$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(J/\psi(1S)\pi^-)/\Gamma(J/\psi(1S)K^+)$ — Γ_{56}/Γ_{53}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.043±0.023	5	[107] ALEXANDER	95	CLE2	$e^+e^- \to \Upsilon(4S)$

[107] Assumes equal production of B^+B^- and $B^0\overline{B}^0$ on $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^+)/\Gamma_{total}$ — Γ_{57}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
6.9± 3.1 OUR AVERAGE	Error includes scale factor of 1.3.					
6.1± 2.3±0.9		7	[108] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
18 ± 8 ±4		5	[108] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 5	90		[108] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
22 ±17		3	[109] ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$

[108] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[109] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Superseded by ALBRECHT 90J.

$\Gamma(\psi(2S)K^*(892)^+)/\Gamma_{total}$ — Γ_{58}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0030	90	[110] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0035	90	[110] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.0049	90	[110] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[110] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^*(892)^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{59}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0019±0.0011±0.0004	3	[111] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[111] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\chi_{c1}(1P)K^+)/\Gamma_{total}$ — Γ_{60}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0010 ±0.0004 OUR AVERAGE					
0.00097±0.00040±0.00009	6	[112] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0019 ±0.0013 ±0.0006		[113] ALBRECHT	92E	ARG	$e^+e^- \to \Upsilon(4S)$

[112] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[113] ALBRECHT 92E assumes no $\chi_{c2}(1P)$ production and $B(\Upsilon(4S) \to B^+B^-) = 50\%$.

$\Gamma(\chi_{c1}(1P)K^*(892)^+)/\Gamma_{total}$ — Γ_{61}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0021	90	[114] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$

[114] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(K^0\pi^+)/\Gamma_{total}$ — Γ_{62}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.8 × 10^{-5}	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.9 × 10^{-4}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
<1.0 × 10^{-4}	90	[115] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<6.8 × 10^{-4}	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[115] AVERY 89B reports $< 9 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^+\pi^0)/\Gamma_{total}$ — Γ_{63}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.4 × 10^{-5}	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0\pi^+)/\Gamma_{total}$ — Γ_{64}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.1 × 10^{-5}	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.8 × 10^{-4}	90	[116] ABREU	95N	DLPH	$e^+e^- \to Z$
<1.7 × 10^{-4}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
<1.5 × 10^{-4}	90	[117] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<2.6 × 10^{-4}	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[116] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[117] AVERY 89B reports $< 1.3 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+\pi^0)/\Gamma_{total}$ — Γ_{65}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9.9 × 10^{-5}	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+\pi^-\pi^+(\text{no charm}))/\Gamma_{total}$ — Γ_{66}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.9 × 10^{-4}	90	[118] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.0 × 10^{-4}	90	[119] ABREU	95N	DLPH	$e^+e^- \to Z$
<3.3 × 10^{-4}	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

[118] AVERY 89B reports $< 1.7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[119] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

$\Gamma(K_1(1400)^0\pi^+)/\Gamma_{total}$ — Γ_{67}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.6 × 10^{-3}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^0\pi^+)/\Gamma_{total}$ — Γ_{68}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<6.8 × 10^{-4}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+\rho^0)/\Gamma_{total}$ — Γ_{69}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.9 × 10^{-5}	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.9 × 10^{-4}	90	[120] ABREU	95N	DLPH	$e^+e^- \to Z$
<1.8 × 10^{-4}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
<8 × 10^{-5}	90	[121] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<2.6 × 10^{-4}	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[120] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

[121] AVERY 89B reports $< 7 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^0\rho^+)/\Gamma_{total}$ — Γ_{70}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.8 × 10^{-5}	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^+\pi^+\pi^-)/\Gamma_{total}$ Γ_{71}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10^{-3}	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^+\rho^0)/\Gamma_{total}$ Γ_{72}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9.0 × 10^{-4}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)^+\rho^0)/\Gamma_{total}$ Γ_{73}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7.8 × 10^{-4}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^+\rho^0)/\Gamma_{total}$ Γ_{74}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.5 × 10^{-3}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+K^-K^+)/\Gamma_{total}$ Γ_{75}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.1 × 10^{-4}	90	[122] ABREU	95N	DLPH	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.5 × 10^{-4}	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

[122] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.

$\Gamma(K^+\phi)/\Gamma_{total}$ Γ_{76}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.2 × 10^{-5}	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.4 × 10^{-4}	90	[123] ABREU	95N	DLPH	$e^+e^- \to Z$
<1.8 × 10^{-4}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
<9 × 10^{-5}	90	[124] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<2.1 × 10^{-4}	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[123] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.
[124] AVERY 89B reports $< 8 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+K^+K^-)/\Gamma_{total}$ Γ_{77}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.6 × 10^{-3}	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^+\phi)/\Gamma_{total}$ Γ_{78}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7.0 × 10^{-5}	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.3 × 10^{-3}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)^+\phi)/\Gamma_{total}$ Γ_{79}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10^{-3}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^+\phi)/\Gamma_{total}$ Γ_{80}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.4 × 10^{-3}	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^+f_0(980))/\Gamma_{total}$ Γ_{81}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8 × 10^{-5}	90	[125] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$

[125] AVERY 89B reports $< 7 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+\gamma)/\Gamma_{total}$ Γ_{82}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
(5.7±3.1±1.1) × 10^{-5}		5	[126] AMMAR	93	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 5.5 × 10^{-4}	90		[127] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$
< 5.5 × 10^{-4}	90		[128] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
< 1.8 × 10^{-3}	90		AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[126] AMMAR 93 observed 4.1 ± 2.3 events above background.
[127] Assumes the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$.
[128] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K_1(1270)^+\gamma)/\Gamma_{total}$ Γ_{83}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0073	90	[129] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[129] ALBRECHT 89G reports < 0.0066 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1400)^+\gamma)/\Gamma_{total}$ Γ_{84}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0022	90	[130] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[130] ALBRECHT 89G reports < 0.0020 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_2^*(1430)^+\gamma)/\Gamma_{total}$ Γ_{85}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0014	90	[131] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[131] ALBRECHT 89G reports < 0.0013 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(1680)^+\gamma)/\Gamma_{total}$ Γ_{86}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0019	90	[132] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[132] ALBRECHT 89G reports < 0.0017 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_3^*(1780)^+\gamma)/\Gamma_{total}$ Γ_{87}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0055	90	[133] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[133] ALBRECHT 89G reports < 0.005 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_4^*(2045)^+\gamma)/\Gamma_{total}$ Γ_{88}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0099	90	[134] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[134] ALBRECHT 89G reports < 0.0090 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^0)/\Gamma_{total}$ Γ_{89}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.7 × 10^{-5}	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.4 × 10^{-4}	90	[135] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$
<2.3 × 10^{-3}	90	[136] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[135] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.
[136] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(\pi^+\pi^+\pi^-)/\Gamma_{total}$ Γ_{90}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.9 × 10^{-4}	90	[137] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.2 × 10^{-4}	90	[138] ABREU	95N	DLPH	$e^+e^- \to Z$
<4.5 × 10^{-4}	90	[139] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[137] BORTOLETTO 89 reports $< 1.7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[138] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.
[139] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0\pi^+)/\Gamma_{total}$ Γ_{91}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<4.3 × 10^{-5}	90		ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.6 × 10^{-4}	90		[140] ABREU	95N	DLPH	$e^+e^- \to Z$
<1.5 × 10^{-4}	90		[141] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$
<1.7 × 10^{-4}	90		[142] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
<2.3 × 10^{-4}	90		[142] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
<6 × 10^{-4}	90	0	GILES	84	CLEO	Repl. by BEBEK 87

[140] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.
[141] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.
[142] Papers assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+f_0(980))/\Gamma_{total}$ Γ_{92}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.4 × 10^{-4}	90	[143] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$

[143] BORTOLETTO 89 reports $< 1.2 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+f_2(1270))/\Gamma_{total}$ Γ_{93}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.4 × 10^{-4}	90	[144] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$

[144] BORTOLETTO 89 reports $< 2.1 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^0\pi^0)/\Gamma_{total}$ Γ_{94}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8.9 × 10^{-4}	90	[145] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[145] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^+\pi^0)/\Gamma_{total}$ — Γ_{95}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<7.7 × 10⁻⁵	90	ASNER 96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5.5 × 10⁻⁴	90	[146] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[146] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^-\pi^+\pi^0)/\Gamma_{total}$ — Γ_{96}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.0 × 10⁻³	90	[147] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[147] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^+\rho^0)/\Gamma_{total}$ — Γ_{97}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.0 × 10⁻³	90	[148] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[148] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+\pi^0)/\Gamma_{total}$ — Γ_{98}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.7 × 10⁻³	90	[149] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[149] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^0\pi^+)/\Gamma_{total}$ — Γ_{99}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<9.0 × 10⁻⁴	90	[150] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[150] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\omega\pi^+)/\Gamma_{total}$ — Γ_{100}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<4.0 × 10⁻⁴	90	[151] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[151] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\eta\pi^+)/\Gamma_{total}$ — Γ_{101}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<7.0 × 10⁻⁴	90	[152] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[152] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_{102}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<8.6 × 10⁻⁴	90	[153] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[153] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0 a_1(1260)^+)/\Gamma_{total}$ — Γ_{103}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6.2 × 10⁻⁴	90	[154] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.0 × 10⁻⁴	90	[155] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$
<3.2 × 10⁻³	90	[154] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[154] BORTOLETTO 89 reports $< 5.4 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[155] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0 a_2(1320)^+)/\Gamma_{total}$ — Γ_{104}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<7.2 × 10⁻⁴	90	[156] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.6 × 10⁻³	90	[157] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[156] BORTOLETTO 89 reports $< 6.3 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[157] BEBEK 87reports $< 2.3 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{105}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6.3 × 10⁻³	90	[158] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[158] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+ a_1(1260)^0)/\Gamma_{total}$ — Γ_{106}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.3 × 10⁻²	90	[159] ALBRECHT 90B	ARG	$e^+e^- \to \Upsilon(4S)$

[159] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(p\overline{p}\pi^+)/\Gamma_{total}$ — Γ_{107}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 1.6 × 10⁻⁴	90	[160] BEBEK 89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 5.0 × 10⁻⁴	90	[161] ABREU 95N	DLPH	$e^+e^- \to Z$
(5.7±1.5±2.1) × 10⁻⁴		[162] ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

[160] BEBEK 89 reports $< 1.4 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[161] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.
[162] ALBRECHT 88F reports $(5.2 \pm 1.4 \pm 1.9) \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{p}\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{108}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5.2 × 10⁻⁴	90	[163] ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

[163] ALBRECHT 88F reports $< 4.7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{\Lambda})/\Gamma_{total}$ — Γ_{109}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6 × 10⁻⁵	90	[164] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<9.3 × 10⁻⁵	90	[165] ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

[164] AVERY 89B reports $< 5 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[165] ALBRECHT 88F reports $< 8.5 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{\Lambda}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{110}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.0 × 10⁻⁴	90	[166] ALBRECHT 88F	ARG	$e^+e^- \to \Upsilon(4S)$

[166] ALBRECHT 88F reports $< 1.8 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\overline{\Delta}^0 p)/\Gamma_{total}$ — Γ_{111}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.8 × 10⁻⁴	90	[167] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$

[167] BORTOLETTO 89 reports $< 3.3 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\Delta^{++}\overline{p})/\Gamma_{total}$ — Γ_{112}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.5 × 10⁻⁴	90	[168] BORTOLETTO 89	CLEO	$e^+e^- \to \Upsilon(4S)$

[168] BORTOLETTO 89 reports $< 1.3 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+e^+e^-)/\Gamma_{total}$ — Γ_{113}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0039	90	[169] WEIR 90B	MRK2	e^+e^- 29 GeV

[169] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^+\mu^+\mu^-)/\Gamma_{total}$ — Γ_{114}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0091	90	[170] WEIR 90B	MRK2	e^+e^- 29 GeV

[170] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+e^+e^-)/\Gamma_{total}$ — Γ_{115}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<9.9 × 10⁻⁵	90	[171] ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$
<6.8 × 10⁻³	90	[172] WEIR 90B	MRK2	e^+e^- 29 GeV
<6 × 10⁻⁵	90	[173] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<2.5 × 10⁻⁴	90	[174] AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[171] ALBRECHT 91E reports $< 9.0 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.
[172] WEIR 90B assumes B^+ production cross section from LUND.
[173] AVERY 89B reports $< 5 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[174] AVERY 87 reports $< 2.1 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^+\mu^+\mu^-)/\Gamma_{total}$ — Γ_{116}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.7 × 10⁻⁴	90	[175] AVERY 89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.4 × 10⁻⁴	90	[176] ALBRECHT 91E	ARG	$e^+e^- \to \Upsilon(4S)$
<6.4 × 10⁻³	90	[177] WEIR 90B	MRK2	e^+e^- 29 GeV
<3.8 × 10⁻⁴	90	[178] AVERY 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[175] AVERY 89B reports $< 1.5 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[176] ALBRECHT 91E reports $< 2.2 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.
[177] WEIR 90B assumes B^+ production cross section from LUND.
[178] AVERY 87 reports $< 3.2 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+ e^+ e^-)/\Gamma_{total}$ — Γ_{117}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<6.9 × 10⁻⁴	90	[179] ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

[179] ALBRECHT 91E reports $< 6.3 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+ \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{118}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.2 × 10⁻³	90	[180] ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

[180] ALBRECHT 91E reports $< 1.1 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+ e^+ \mu^-)/\Gamma_{total}$ — Γ_{119}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0064	90	[181] WEIR	90B	MRK2	e^+e^- 29 GeV

[181] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^+ e^- \mu^+)/\Gamma_{total}$ — Γ_{120}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0064	90	[182] WEIR	90B	MRK2	e^+e^- 29 GeV

[182] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+ e^+ \mu^-)/\Gamma_{total}$ — Γ_{121}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0064	90	[183] WEIR	90B	MRK2	e^+e^- 29 GeV

[183] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^+ e^- \mu^+)/\Gamma_{total}$ — Γ_{122}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0064	90	[184] WEIR	90B	MRK2	e^+e^- 29 GeV

[184] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^- e^+ e^+)/\Gamma_{total}$ — Γ_{123}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0039	90	[185] WEIR	90B	MRK2	e^+e^- 29 GeV

[185] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^- \mu^+ \mu^+)/\Gamma_{total}$ — Γ_{124}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0091	90	[186] WEIR	90B	MRK2	e^+e^- 29 GeV

[186] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(\pi^- e^+ \mu^+)/\Gamma_{total}$ — Γ_{125}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0064	90	[187] WEIR	90B	MRK2	e^+e^- 29 GeV

[187] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^- e^+ e^+)/\Gamma_{total}$ — Γ_{126}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0039	90	[188] WEIR	90B	MRK2	e^+e^- 29 GeV

[188] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^- \mu^+ \mu^+)/\Gamma_{total}$ — Γ_{127}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0091	90	[189] WEIR	90B	MRK2	e^+e^- 29 GeV

[189] WEIR 90B assumes B^+ production cross section from LUND.

$\Gamma(K^- e^+ \mu^+)/\Gamma_{total}$ — Γ_{128}/Γ

Test of total lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0064	90	[190] WEIR	90B	MRK2	e^+e^- 29 GeV

[190] WEIR 90B assumes B^+ production cross section from LUND.

$B^{\pm}$ REFERENCES

ABE 96B PR D53 3496 +Albrow, Amendolia, Amidei+ (CDF Collab.)
ABE 96C PRL (to be publ.) +Akimoto, Akopian, Albrow+ (CDF Collab.)
CDF/PUB/BOTTOM/PUB/3492
ASNER 96 PR D53 1039 +Athanas, Bliss, Brower+ (CLEO Collab.)
BUSKULIC 96G ZPHY C (submitted) +De Bonis, Decamp, Ghez+ (ALEPH Collab.)
CERN-PPE/96-14
ABREU 95N PL B357 255 +Adam, Adye, Agasi+ (DELPHI Collab.)
ABREU 95Q ZPHY C68 13 +Adam, Adye, Agasi+ (DELPHI Collab.)
ADAM 95 ZPHY C68 363 +Adye, Agasi, Ajinenko+ (DELPHI Collab.)
AKERS 95T ZPHY C67 379 +Alexander, Allison, Ametewee+ (OPAL Collab.)
ALBRECHT 95D PL B353 554 +Hamacher, Hofmann, Kirchoff+ (ARGUS Collab.)
ALEXANDER 95 PL B341 435 +Bebek, Berkelman, Bloom+ (CLEO Collab.)
Also 95C PL B347 469 (erratum) Alexander, Bebek, Berkelman, Bloom+ (CLEO Collab.)
ARTUSO 95 PRL 75 785 +Gao, Goldberg, He+ (CLEO Collab.)
BARISH 95 PR D51 1014 +Chadha, Chan, Cowen+ (CLEO Collab.)
BUSKULIC 95 PL B343 444 +Casper, De Bonis, Decamp, Ghez, Goy+ (ALEPH Collab.)
ABE 94D PRL 72 3456 +Albrow, Amidei, Anway-Wiese, Apollinari (CDF Collab.)
ALAM 94 PR D50 43 +Kim, Nemati, O'Neill, Severini+ (CLEO Collab.)
ALBRECHT 94D PL B335 526 +Hamacher, Hofmann, Kirchhoff, Mankel+ (ARGUS Collab.)
ATHANAS 94 PRL 73 3503 +Brower, Masek, Paar, Gronberg+ (CLEO Collab.)
Also 95 PRL 74 3090 (erratum) Athanas, Brower, Masek, Paar+ (CLEO Collab.)
PDG 94 PR D50 1173 Montanet+ (CERN, LBL, BOST, IFIC+)
STONE 94 HEPSY 93-11
ABREU 93D ZPHY C57 181 +Adam, Adye, Agasi, Alekseev+ (DELPHI Collab.)
ABREU 93G PL B312 253 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
ACTON 93C PL B307 247 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALBRECHT 93E ZPHY C60 11 +Ehrlichmann, Hamacher, Hofmann+ (ARGUS Collab.)
ALEXANDER 93B PL B319 365 +Bebek, Berkelman, Bloom, Browder+ (CLEO Collab.)
AMMAR 93 PRL 71 674 +Ball, Baringer, Coppage, Copty+ (CLEO Collab.)
BEAN 93B PRL 70 2681 +Gronberg, Kutschke, Menary, Morrison+ (CLEO Collab.)
BUSKULIC 93D PL B307 194 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
Also 94H PL B325 537 (errata)
SANGHERA 93 PR D47 791 +Skwarnicki, Stroynowski, Artuso, Goldberg+(CLEO Collab.)
ALBRECHT 92C PL B275 195 +Ehrlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
ALBRECHT 92E PL B277 209 +Ehrlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
ALBRECHT 92G ZPHY C54 1 +Ehrlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
BORTOLETTO 92 PR D45 21 +Brown, Dominick, McIlwain+ (CLEO Collab.)
BUSKULIC 92G PL B295 396 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
ALBRECHT 91B PL B254 288 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
ALBRECHT 91C PL B255 297 +Ehrlichmann, Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 91E PL B262 148 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
BERKELMAN 91 ARNPS 41 1 +Stone (CORN, SYRA)
"Decays of *B* Mesons"
FULTON 91 PR D43 651 +Jensen, Johnson, Kagan, Kass+ (CLEO Collab.)
ALBRECHT 90B PL B241 278 +Glaeser, Harder, Krueger, Nilsson+ (ARGUS Collab.)
ALBRECHT 90J ZPHY C48 543 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
ANTREASYAN 90B ZPHY C48 553 +Bartels, Bieler, Bienlein, Bizzeti+ (Crystal Ball Collab.)
BORTOLETTO 90 PRL 64 2117 +Goldberg, Horwitz, Jain, Mestayer+ (CLEO Collab.)
Also 92 PR D45 21 Bortoletto, Brown, Dominick, McIlwain+ (CLEO Collab.)
WEIR 90B PR D41 1384 +Klein, Abrams, Adolphsen, Akerlof+ (Mark II Collab.)
ALBRECHT 89G PL B229 304 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
AVERY 89B PL B223 470 +Besson, Garren, Yelton+ (CLEO Collab.)
BEBEK 89 PRL 62 8 +Berkelman, Blucher+ (CLEO Collab.)
BORTOLETTO 89 PRL 62 2436 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
ALBRECHT 88F PL B209 119 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 88K PL B215 424 +Boeckmann, Glaeser+ (ARGUS Collab.)
ALBRECHT 87C PL B185 218 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87D PL B199 451 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
AVERY 87 PL B183 429 +Besson, Bowcock, Giles+ (CLEO Collab.)
BEBEK 87 PR D36 1289 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
ALAM 86 PR D34 3279 +Katayama, Kim, Sun+ (CLEO Collab.)
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
GILES 84 PR D30 2279 +Hassard, Hempstead, Kinoshita+ (CLEO Collab.)

OTHER RELATED PAPERS

BERKELMAN 91 ARNPS 41 1 +Stone (CORN, SYRA)
"Decays of *B* Mesons"
MILLER 90 MPL A5 2683
"Recent Results in *B* Physics"
SCHINDLER 88 High Energy Electron-Positron Physics 234 (SLAC)
Editors: A. Ali and P. Soeding, World Scientific, Singapore
SCHUBERT 87 IHEP-HD/87-7 (HEIDH)
EPS Conference – Uppsala, Proc., Vol. 2, p. 791

B^0

$I(J^P) = \frac{1}{2}(0^-)$

Quantum numbers not measured. Values shown are quark-model predictions.

See also the $B^{\pm}/B^0$ ADMIXTURE and $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE sections.

See the Notes "Experimental Highlights of *B* Meson Production and Decay" and "Semileptonic Decays of *B* Mesons" at the beginning of the $B^{\pm}$ Particle Listings and the Note on "B^0-$\overline{B}^0$ Mixing and *CP* Violation in *B* Decay" near the end of the B^0 Particle Listings.

B^0 MASS

The fit uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B^0_s}$, and $(m_{B^0_s} - (m_{B^+} + m_{B^0})/2)$ to determine m_{B^+}, m_{B^0}, $m_{B^0_s}$, and the mass differences. m_{B^0} data are excluded from the fit because they are not independent.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5279.2±1.8 OUR FIT					
5279.8±1.6 OUR AVERAGE					
5281.3±2.2 ±1.4	51	[1] ABE	96B	CDF	$p\overline{p}$ at 1.8 TeV
5279.2±0.54±2.0	340	[2] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
5278.0±0.4 ±2.0		[2] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
5279.6±0.7 ±2.0	40	[2,3] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
5280.6±0.8 ±2.0		[2] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

5278.2±1.0 ±3.0	40	ALBRECHT	87C	ARG	$e^+e^- \to \Upsilon(4S)$
5279.5±1.6 ±3.0	7	[4] ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$

[1] Excluded from fit because it is not independent of ABE 96B B_s^0 mass and B_s^0-B mass difference.

[2] These experiments all report a common systematic error 2.0 MeV. We have artificially increased the systematic error to allow the experiments to be treated as independent measurements in our average. See "Treatment of Errors" section of the Introductory Text. These experiments actually measure the difference between half of E_{cm} and the B mass.

[3] ALBRECHT 90J assumes 10580 for $\Upsilon(4S)$ mass. Supersedes ALBRECHT 87C and ALBRECHT 87D.

[4] Found using fully reconstructed decays with J/ψ. ALBRECHT 87D assume $m_{\Upsilon(4S)}$ = 10577 MeV.

$m_{B^0} - m_{B^+}$

The mass difference measurements are not independent of the $B^\pm$ and B^0 mass measurement by the same experimenters. The fit uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B_s^0}$, and $(m_{B_s^0} - (m_{B^+} + m_{B^0})/2)$ to determine m_{B^+}, m_{B^0}, $m_{B_s^0}$, and the mass differences.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.35±0.29 OUR FIT	Error includes scale factor of 1.1.			
0.34±0.32 OUR AVERAGE	Error includes scale factor of 1.2.			
0.41±0.25±0.19	ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
−0.4 ±0.6 ±0.5	BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
−0.9 ±1.2 ±0.5	ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
2.0 ±1.1 ±0.3	[5] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[5] BEBEK 87 actually measure the difference between half of E_{cm} and the $B^\pm$ or B^0 mass, so the $m_{B^0} - m_{B^\pm}$ is more accurate. Assume $m_{\Upsilon(4S)}$ = 10580 MeV.

$m_{B_H^0} - m_{B_L^0}$

See the B^0-$\overline{B}^0$ MIXING section near the end of these B^0 Listings.

B^0 MEAN LIFE

See $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE section for data on B-hadron mean life averaged over species of bottom particles.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^\pm$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.56±0.06 OUR EVALUATION					
1.54±0.08±0.06		[6] ABE	96C	CDF	$p\overline{p}$ at 1.8 TeV
1.61±0.07±0.04		[6] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
$1.25^{+0.15}_{-0.13}\pm0.05$	121	[7] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
$1.49^{+0.17+0.08}_{-0.15-0.06}$		[8] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
$1.61^{+0.14}_{-0.13}\pm0.08$		[6,9] ABREU	95Q	DLPH	$e^+e^- \to Z$
1.63±0.14±0.13		[10] ADAM	95	DLPH	$e^+e^- \to Z$
1.53±0.12±0.08		[6,11] AKERS	95T	OPAL	$e^+e^- \to Z$
1.57±0.18±0.08	121	[7] ABE	94D	CDF	$p\overline{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.55±0.06±0.03		[12] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
1.62±0.12		[13] ADAM	95	DLPH	$e^+e^- \to Z$
$1.17^{+0.29}_{-0.23}\pm0.16$	96	[6] ABREU	93D	DLPH	Sup. by ABREU 95Q
1.55±0.25±0.18	76	[10] ABREU	93G	DLPH	Sup. by ADAM 95
$1.51^{+0.24+0.12}_{-0.23-0.14}$	78	[6] ACTON	93C	OPAL	Sup. by AKERS 95T
$1.52^{+0.20+0.07}_{-0.18-0.13}$	77	[6] BUSKULIC	93D	ALEP	Sup. by BUSKULIC 96G
$1.20^{+0.52+0.16}_{-0.36-0.14}$	15	[14] WAGNER	90	MRK2	E^{ee}_{cm}= 29 GeV
$0.82^{+0.57}_{-0.37}\pm0.27$		[15] AVERILL	89	HRS	E^{ee}_{cm}= 29 GeV

[6] Data analyzed using $D/D^*\ell X$ event vertices.

[7] Measured mean life using fully reconstructed decays.

[8] Measured mean life using partially reconstructed $D^{*-}\pi^+X$ vertices.

[9] ABREU 95Q assumes B($B^0 \to D^{**-}\ell^+\nu_\ell$) = 3.2 ± 1.7%.

[10] Data analyzed using vertex-charge technique to tag B charge.

[11] AKERS 95T assumes B($B^0 \to D_s^{(*)}D^{0(*)}$) = 5.0 ± 0.9% to find B^+/B^0 yield.

[12] Combined result of $D/D^*\ell x$ analysis, fully reconstructed B analysis, and partially reconstructed $D^{*-}\pi^+X$ analysis.

[13] Combined ABREU 95Q and ADAM 95 result.

[14] WAGNER 90 tagged B^0 mesons by their decays into $D^{*-}e^+\nu$ and $D^{*-}\mu^+\nu$ where the D^{*-} is tagged by its decay into $\pi^-\overline{D}^0$.

[15] AVERILL 89 is an estimate of the B^0 mean lifetime assuming that $B^0 \to D^{*+} + X$ always.

MEAN LIFE RATIO τ_{B^+}/τ_{B^0}

τ_{B^+}/τ_{B^0} (average of direct and inferred)

VALUE	DOCUMENT ID
1.02±0.05 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.

τ_{B^+}/τ_{B^0} (direct measurements)

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^\pm$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.					
1.03±0.06 OUR EVALUATION					
1.01±0.11±0.02		[16] ABE	96C	CDF	$p\overline{p}$ at 1.8 TeV
0.98±0.08±0.03		[16] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
$1.27^{+0.23+0.03}_{-0.19-0.02}$		[17] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
$1.00^{+0.17}_{-0.15}\pm0.10$		[16,18] ABREU	95Q	DLPH	$e^+e^- \to Z$
$1.06^{+0.13}_{-0.10}\pm0.10$		[19] ADAM	95	DLPH	$e^+e^- \to Z$
$0.99\pm0.14^{+0.05}_{-0.04}$		[16,20] AKERS	95T	OPAL	$e^+e^- \to Z$
1.02±0.16±0.05	269	[17] ABE	94D	CDF	$p\overline{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.03±0.08±0.02		[21] BUSKULIC	96G	ALEP	$e^+e^- \to Z$
$1.11^{+0.51}_{-0.39}\pm0.11$	188	[16] ABREU	93D	DLPH	Sup. by ABREU 95Q
$1.01^{+0.29}_{-0.22}\pm0.12$	253	[19] ABREU	93G	DLPH	Sup. by ADAM 95
$1.0\ ^{+0.33}_{-0.25}\pm0.08$	130	ACTON	93C	OPAL	Sup. by AKERS 95T
$0.96^{+0.19+0.18}_{-0.15-0.12}$	154	[16] BUSKULIC	93D	ALEP	Sup. by BUSKULIC 96G

[16] Data analyzed using $D/D^*\ell X$ vertices.

[17] Measurement using fully reconstructed decays.

[18] ABREU 95Q assumes B($B^0 \to D^{**-}\ell^+\nu_\ell$) = 3.2 ± 1.7%.

[19] Data analyzed using vertex-charge technique to tag B charge.

[20] AKERS 95T assumes B($B^0 \to D_s^{(*)}D^{0(*)}$) = 5.0 ± 0.9% to find B^+/B^0 yield.

[21] Combined result of $D/D^*\ell X$ analysis and fully reconstructed B analysis.

τ_{B^+}/τ_{B^0} (inferred from branching fractions)

These measurements are inferred from the branching fractions for semileptonic decay or other spectator-dominated decays by assuming that the rates for such decays are equal for B^0 and B^+. We do not use measurements which assume equal production of B^0 and B^+ because of the large uncertainty in the production ratio.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.						
0.93±0.18±0.12			[22] ATHANAS	94	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.91±0.27±0.21			[23] ALBRECHT	92C	ARG	$e^+e^- \to \Upsilon(4S)$
1.0 ±0.4		29	[23,24] ALBRECHT	92G	ARG	$e^+e^- \to \Upsilon(4S)$
0.89±0.19±0.13			[23] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$
1.00±0.23±0.14			[23] ALBRECHT	89L	ARG	$e^+e^- \to \Upsilon(4S)$
0.49 to 2.3	90		[25] BEAN	87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[22] ATHANAS 94 uses events tagged by fully reconstructed B^- decays and partially or fully reconstructed B^0 decays.

[23] Assumes equal production of B^0 and B^+.

[24] ALBRECHT 92G data analyzed using $B \to D_s\overline{D}$, $D_s\overline{D}^*$, $D_s^*\overline{D}$, $D_s^*\overline{D}^*$ events.

[25] BEAN 87B assume the fraction of $B^0\overline{B}^0$ events at the $\Upsilon(4S)$ is 0.41.

B^0 DECAY MODES

$\overline{B}^0$ modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing. Modes which do not identify the charge state of the B are listed in the $B^\pm/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed D, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_1	$\ell^+\nu_\ell$ anything	[a]	(10.3 ±1.0) %	
Γ_2	$D^-\ell^+\nu_\ell$	[a]	(1.9 ±0.5) %	
Γ_3	$D^*(2010)^-\ell^+\nu_\ell$	[a]	(4.56±0.27) %	
Γ_4	$\rho^-\ell^+\nu_\ell$	[a]	< 4.1 × 10^{-4}	CL=90%
Γ_5	$\pi^-\mu^+\nu_\mu$			

D, D^*, or D_s modes

	Mode	Fraction	Confidence level
Γ_{6}	$D^- \pi^+$	$(3.0 \pm 0.4) \times 10^{-3}$	
Γ_{7}	$D^- \rho^+$	$(7.8 \pm 1.4) \times 10^{-3}$	
Γ_{8}	$\overline{D}^0 \pi^+ \pi^-$	$< 1.6 \times 10^{-3}$	CL=90%
Γ_{9}	$D^*(2010)^- \pi^+$	$(2.6 \pm 0.4) \times 10^{-3}$	
Γ_{10}	$D^- \pi^+ \pi^+ \pi^-$	$(8.0 \pm 2.5) \times 10^{-3}$	
Γ_{11}	$(D^- \pi^+ \pi^+ \pi^-)$ nonresonant	$(3.9 \pm 1.9) \times 10^{-3}$	
Γ_{12}	$D^- \pi^+ \rho^0$	$(1.1 \pm 1.0) \times 10^{-3}$	
Γ_{13}	$D^- a_1(1260)^+$	$(6.0 \pm 3.3) \times 10^{-3}$	
Γ_{14}	$D^*(2010)^- \pi^+ \pi^0$	(1.5 ± 0.5) %	
Γ_{15}	$D^*(2010)^- \rho^+$	$(7.3 \pm 1.5) \times 10^{-3}$	
Γ_{16}	$D^*(2010)^- \pi^+ \pi^+ \pi^-$	$(7.6 \pm 1.7) \times 10^{-3}$	S=1.3
Γ_{17}	$(D^*(2010)^- \pi^+ \pi^+ \pi^-)$ non-resonant	$(0.0 \pm 2.5) \times 10^{-3}$	
Γ_{18}	$D^*(2010)^- \pi^+ \rho^0$	$(5.7 \pm 3.1) \times 10^{-3}$	
Γ_{19}	$D^*(2010)^- a_1(1260)^+$	(1.30 ± 0.27) %	
Γ_{20}	$D^*(2010)^- \pi^+ \pi^+ \pi^- \pi^0$	(3.4 ± 1.8) %	
Γ_{21}	$\overline{D}{}_2^*(2460)^- \pi^+$	$< 2.2 \times 10^{-3}$	CL=90%
Γ_{22}	$\overline{D}{}_2^*(2460)^- \rho^+$	$< 4.9 \times 10^{-3}$	CL=90%
Γ_{23}	$D^- D_s^+$	$(7 \pm 4) \times 10^{-3}$	
Γ_{24}	$D^*(2010)^- D_s^+$	(1.2 ± 0.6) %	
Γ_{25}	$D^- D_s^{*+}$	(2.0 ± 1.5) %	
Γ_{26}	$D^*(2010)^- D_s^{*+}$	(1.9 ± 1.2) %	
Γ_{27}	$D_s^+ \pi^-$	$< 2.8 \times 10^{-4}$	CL=90%
Γ_{28}	$D_s^{*+} \pi^-$	$< 5 \times 10^{-4}$	CL=90%
Γ_{29}	$D_s^+ \rho^-$	$< 7 \times 10^{-4}$	CL=90%
Γ_{30}	$D_s^{*+} \rho^-$	$< 8 \times 10^{-4}$	CL=90%
Γ_{31}	$D_s^+ a_1(1260)^-$	$< 2.6 \times 10^{-3}$	CL=90%
Γ_{32}	$D_s^{*+} a_1(1260)^-$	$< 2.2 \times 10^{-3}$	CL=90%
Γ_{33}	$D_s^- K^+$	$< 2.4 \times 10^{-4}$	CL=90%
Γ_{34}	$D_s^{*-} K^+$	$< 1.7 \times 10^{-4}$	CL=90%
Γ_{35}	$D_s^- K^*(892)^+$	$< 9.9 \times 10^{-4}$	CL=90%
Γ_{36}	$D_s^{*-} K^*(892)^+$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{37}	$D_s^- \pi^+ K^0$	$< 5 \times 10^{-3}$	CL=90%
Γ_{38}	$D_s^{*-} \pi^+ K^0$	$< 3.1 \times 10^{-3}$	CL=90%
Γ_{39}	$D_s^- \pi^+ K^*(892)^0$	$< 4 \times 10^{-3}$	CL=90%
Γ_{40}	$D_s^{*-} \pi^+ K^*(892)^0$	$< 2.0 \times 10^{-3}$	CL=90%
Γ_{41}	$\overline{D}^0 \pi^0$	$< 4.8 \times 10^{-4}$	CL=90%
Γ_{42}	$\overline{D}^0 \rho^0$	$< 5.5 \times 10^{-4}$	CL=90%
Γ_{43}	$\overline{D}^0 \eta$	$< 6.8 \times 10^{-4}$	CL=90%
Γ_{44}	$\overline{D}^0 \eta'$	$< 8.6 \times 10^{-4}$	CL=90%
Γ_{45}	$\overline{D}^0 \omega$	$< 6.3 \times 10^{-4}$	CL=90%
Γ_{46}	$\overline{D}^*(2007)^0 \pi^0$	$< 9.7 \times 10^{-4}$	CL=90%
Γ_{47}	$\overline{D}^*(2007)^0 \rho^0$	$< 1.17 \times 10^{-3}$	CL=90%
Γ_{48}	$\overline{D}^*(2007)^0 \eta$	$< 6.9 \times 10^{-4}$	CL=90%
Γ_{49}	$\overline{D}^*(2007)^0 \eta'$	$< 2.7 \times 10^{-3}$	CL=90%
Γ_{50}	$\overline{D}^*(2007)^0 \omega$	$< 2.1 \times 10^{-3}$	CL=90%

Charmonium modes

	Mode	Fraction	Confidence level
Γ_{51}	$J/\psi(1S) K^0$	$(7.5 \pm 2.1) \times 10^{-4}$	
Γ_{52}	$J/\psi(1S) K^+ \pi^-$	$(1.1 \pm 0.6) \times 10^{-3}$	
Γ_{53}	$J/\psi(1S) K^*(892)^0$	$(1.58 \pm 0.27) \times 10^{-3}$	
Γ_{54}	$J/\psi(1S) \pi^0$	$< 6.9 \times 10^{-3}$	CL=90%
Γ_{55}	$\psi(2S) K^0$	$< 8 \times 10^{-4}$	CL=90%
Γ_{56}	$\psi(2S) K^+ \pi^-$	$< 1 \times 10^{-3}$	CL=90%
Γ_{57}	$\psi(2S) K^*(892)^0$	$(1.4 \pm 0.9) \times 10^{-3}$	
Γ_{58}	$\chi_{c1}(1P) K^0$	$< 2.7 \times 10^{-3}$	CL=90%
Γ_{59}	$\chi_{c1}(1P) K^*(892)^0$	$< 2.1 \times 10^{-3}$	CL=90%

K or K^* modes

	Mode	Fraction	Confidence level
Γ_{60}	$K^+ \pi^-$	$< 1.7 \times 10^{-5}$	CL=90%
Γ_{61}	$K^0 \pi^0$	$< 4.0 \times 10^{-5}$	CL=90%
Γ_{62}	$K^+ K^-$	$< 4 \times 10^{-6}$	CL=90%
Γ_{63}	$K^+ \rho^-$	$< 3.5 \times 10^{-5}$	CL=90%
Γ_{64}	$K^0 \pi^+ \pi^-$		
Γ_{65}	$K^0 \rho^0$	$< 3.9 \times 10^{-5}$	CL=90%
Γ_{66}	$K^0 f_0(980)$	$< 3.6 \times 10^{-4}$	CL=90%
Γ_{67}	$K^*(892)^+ \pi^-$	$< 7.2 \times 10^{-5}$	CL=90%
Γ_{68}	$K^*(892)^0 \pi^0$	$< 2.8 \times 10^{-5}$	CL=90%
Γ_{69}	$K_2^*(1430)^+ \pi^-$	$< 2.6 \times 10^{-3}$	CL=90%
Γ_{70}	$K^0 K^+ K^-$	$< 1.3 \times 10^{-3}$	CL=90%
Γ_{71}	$K^0 \phi$	$< 8.8 \times 10^{-5}$	CL=90%
Γ_{72}	$K^- \pi^+ \pi^+ \pi^-$	[b] $< 2.1 \times 10^{-4}$	CL=90%
Γ_{73}	$K^*(892)^0 \pi^+ \pi^-$	$< 1.4 \times 10^{-3}$	CL=90%
Γ_{74}	$K^*(892)^0 \rho^0$	$< 4.6 \times 10^{-4}$	CL=90%
Γ_{75}	$K^*(892)^0 f_0(980)$	$< 1.7 \times 10^{-4}$	CL=90%
Γ_{76}	$K_1(1400)^+ \pi^-$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{77}	$K^- a_1(1260)^+$	[b] $< 3.9 \times 10^{-4}$	CL=90%
Γ_{78}	$K^*(892)^0 K^+ K^-$	$< 6.1 \times 10^{-4}$	CL=90%
Γ_{79}	$K^*(892)^0 \phi$	$< 4.3 \times 10^{-5}$	CL=90%
Γ_{80}	$K_1(1400)^0 \rho^0$	$< 3.0 \times 10^{-3}$	CL=90%
Γ_{81}	$K_1(1400)^0 \phi$	$< 5.0 \times 10^{-3}$	CL=90%
Γ_{82}	$K_2^*(1430)^0 \rho^0$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{83}	$K_2^*(1430)^0 \phi$	$< 1.4 \times 10^{-3}$	CL=90%
Γ_{84}	$K^*(892)^0 \gamma$	$(4.0 \pm 1.9) \times 10^{-5}$	
Γ_{85}	$K_1(1270)^0 \gamma$	$< 7.0 \times 10^{-3}$	CL=90%
Γ_{86}	$K_1(1400)^0 \gamma$	$< 4.3 \times 10^{-3}$	CL=90%
Γ_{87}	$K_2^*(1430)^0 \gamma$	$< 4.0 \times 10^{-4}$	CL=90%
Γ_{88}	$K^*(1680)^0 \gamma$	$< 2.0 \times 10^{-3}$	CL=90%
Γ_{89}	$K_3^*(1780)^0 \gamma$	< 1.0 %	CL=90%
Γ_{90}	$K_4^*(2045)^0 \gamma$	$< 4.3 \times 10^{-3}$	CL=90%
Γ_{91}	$\phi \phi$	$< 3.9 \times 10^{-5}$	CL=90%

Light unflavored meson modes

	Mode	Fraction	Confidence level
Γ_{92}	$\pi^+ \pi^-$	$< 2.0 \times 10^{-5}$	CL=90%
Γ_{93}	$\pi^0 \pi^0$	$< 9.1 \times 10^{-6}$	CL=90%
Γ_{94}	$\eta \pi^0$	$< 2.5 \times 10^{-4}$	CL=90%
Γ_{95}	$\eta \eta$	$< 4.1 \times 10^{-4}$	CL=90%
Γ_{96}	$\pi^+ \pi^- \pi^0$	$< 7.2 \times 10^{-4}$	CL=90%
Γ_{97}	$\rho^0 \pi^0$	$< 2.4 \times 10^{-5}$	CL=90%
Γ_{98}	$\rho^\mp \pi^\pm$	[c] $< 8.8 \times 10^{-5}$	CL=90%
Γ_{99}	$\pi^+ \pi^- \pi^+ \pi^-$	$< 2.8 \times 10^{-4}$	CL=90%
Γ_{100}	$\rho^0 \rho^0$	$< 2.8 \times 10^{-4}$	CL=90%
Γ_{101}	$a_1(1260)^\mp \pi^\pm$	[c] $< 4.9 \times 10^{-4}$	CL=90%
Γ_{102}	$a_2(1320)^\mp \pi^\pm$	[c] $< 3.0 \times 10^{-4}$	CL=90%
Γ_{103}	$\pi^+ \pi^- \pi^0 \pi^0$	$< 3.1 \times 10^{-3}$	CL=90%
Γ_{104}	$\rho^+ \rho^-$	$< 2.2 \times 10^{-3}$	CL=90%
Γ_{105}	$a_1(1260)^0 \pi^0$	$< 1.1 \times 10^{-3}$	CL=90%
Γ_{106}	$\omega \pi^0$	$< 4.6 \times 10^{-4}$	CL=90%
Γ_{107}	$\pi^+ \pi^+ \pi^- \pi^- \pi^0$	$< 9.0 \times 10^{-3}$	CL=90%
Γ_{108}	$a_1(1260)^+ \rho^-$	$< 3.4 \times 10^{-3}$	CL=90%
Γ_{109}	$a_1(1260)^0 \rho^0$	$< 2.4 \times 10^{-3}$	CL=90%
Γ_{110}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^-$	$< 3.0 \times 10^{-3}$	CL=90%
Γ_{111}	$a_1(1260)^+ a_1(1260)^-$	$< 2.8 \times 10^{-3}$	CL=90%
Γ_{112}	$\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0$	< 1.1 %	CL=90%

Baryon modes

	Mode	Fraction	Confidence level
Γ_{113}	$p \overline{p}$	$< 3.4 \times 10^{-5}$	CL=90%
Γ_{114}	$p \overline{p} \pi^+ \pi^-$	$< 2.5 \times 10^{-4}$	CL=90%
Γ_{115}	$p \overline{\Lambda} \pi^-$	$< 1.8 \times 10^{-4}$	CL=90%
Γ_{116}	$\Delta^0 \overline{\Delta}^0$	$< 1.5 \times 10^{-3}$	CL=90%
Γ_{117}	$\Delta^{++} \Delta^{--}$	$< 1.1 \times 10^{-4}$	CL=90%
Γ_{118}	$\overline{\Sigma}{}_c^{--} \Delta^{++}$	$< 1.2 \times 10^{-3}$	CL=90%

Lepton Family number (LF) violating modes, or $\Delta B = 1$ weak neutral current ($B1$) modes

	Mode		Fraction	Confidence level
Γ_{119}	$\gamma \gamma$	$B1$	$< 3.9 \times 10^{-5}$	CL=90%
Γ_{120}	$e^+ e^-$	$B1$	$< 5.9 \times 10^{-6}$	CL=90%
Γ_{121}	$\mu^+ \mu^-$	$B1$	$< 5.9 \times 10^{-6}$	CL=90%
Γ_{122}	$K^0 e^+ e^-$	$B1$	$< 3.0 \times 10^{-4}$	CL=90%
Γ_{123}	$K^0 \mu^+ \mu^-$	$B1$	$< 3.6 \times 10^{-4}$	CL=90%
Γ_{124}	$K^*(892)^0 e^+ e^-$	$B1$	$< 2.9 \times 10^{-4}$	CL=90%
Γ_{125}	$K^*(892)^0 \mu^+ \mu^-$	$B1$	$< 2.3 \times 10^{-5}$	CL=90%
Γ_{126}	$e^\pm \mu^\mp$	LF	[c] $< 5.9 \times 10^{-6}$	CL=90%
Γ_{127}	$e^\pm \tau^\mp$	LF	[c] $< 5.3 \times 10^{-4}$	CL=90%
Γ_{128}	$\mu^\pm \tau^\mp$	LF	[c] $< 8.3 \times 10^{-4}$	CL=90%

[a] ℓ indicates e or μ mode, not sum over modes.

[b] B^0 and B_s^0 contributions not separated. Limit is on weighted average of the two decay rates.

[c] The value is for the sum of the charge states of particle/antiparticle states indicated.

B^0 BRANCHING RATIOS

For branching ratios in which the charge of the decaying B is not determined, see the $B^\pm$ section.

$\Gamma(\ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.103±0.010 OUR AVERAGE				
$0.093 \pm 0.011 \pm 0.015$	ALBRECHT	94	ARG	$e^+ e^- \to \Upsilon(4S)$
$0.109 \pm 0.007 \pm 0.011$	ATHANAS	94	CLE2	$e^+ e^- \to \Upsilon(4S)$
$0.099 \pm 0.030 \pm 0.009$	HENDERSON	92	CLEO	$e^+ e^- \to \Upsilon(4S)$

$\Gamma(D^- \ell^+ \nu_\ell)/\Gamma_{total}$ Γ_2/Γ

ℓ denotes e or μ, not the sum.

VALUE	DOCUMENT ID		TECN	COMMENT
0.019±0.005 OUR AVERAGE				
0.018±0.006±0.003	[26] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$
0.020±0.007±0.006	[27] ALBRECHT	89J	ARG	$e^+e^- \to \Upsilon(4S)$

[26] FULTON 91 assumes assuming equal production of B^0 and B^+ at the $\Upsilon(4S)$ and uses Mark III D and D^* branching ratios.

[27] ALBRECHT 89J reports $0.018 \pm 0.006 \pm 0.005$. We rescale using the method described in STONE 94 but with the updated PDG 94 B($D^0 \to K^-\pi^+$).

$\Gamma(D^*(2010)^- \ell^+ \nu_\ell)/\Gamma_{total}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0456±0.0027 OUR AVERAGE					
0.0449±0.0032±0.0039	376	[28] BARISH	95	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0518±0.0030±0.0062	410	[29] BUSKULIC	95N	ALEP	$e^+e^- \to Z$
0.045 ±0.003 ±0.004		[30] ALBRECHT	94	ARG	$e^+e^- \to \Upsilon(4S)$
0.047 ±0.005 ±0.005	235	[31] ALBRECHT	93	ARG	$e^+e^- \to \Upsilon(4S)$
0.040 ±0.004 ±0.006		[32] BORTOLETTO	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	398	[33] SANGHERA	93	CLE2	$e^+e^- \to \Upsilon(4S)$
0.070 ±0.018 ±0.014		[34] ANTREASYAN	90B	CBAL	$e^+e^- \to \Upsilon(4S)$
		[35] ALBRECHT	89C	ARG	$e^+e^- \to \Upsilon(4S)$
0.060 ±0.010 ±0.014		[36] ALBRECHT	89J	ARG	$e^+e^- \to \Upsilon(4S)$
0.070 ±0.012 ±0.019	47	[37] ALBRECHT	87J	ARG	$e^+e^- \to \Upsilon(4S)$

[28] BARISH 95 use B($D^0 \to K^-\pi^+$) = $(3.91 \pm 0.08 \pm 0.17)$% and B($D^{*+} \to D^0\pi^+$) = $(68.1 \pm 1.0 \pm 1.3)$%.

[29] BUSKULIC 95N assumes fraction (B^+) = fraction (B^0) = $38.2 \pm 1.3 \pm 2.2$% and $\tau_{B^0} = 1.58 \pm 0.06$ ps. $\Gamma(D^{*-}\ell^+\nu_\ell)$/total = [5.18 − 0.13(fraction(B^0)−38.2)−1.5(τ_{B^0} − 1.58)]%.

[30] ALBRECHT 94 assumes B($D^{*+} \to D^0\pi^+$) = $68.1 \pm 1.0 \pm 1.3$%. Uses partial reconstruction of D^{*+} and is independent of D^0 branching ratios.

[31] ALBRECHT 93 reports $0.052 \pm 0.005 \pm 0.006$. We rescale using the method described in STONE 94 but with the updated PDG 94 B($D^0 \to K^-\pi^+$). We have taken their average e and μ value. They also obtain $\alpha = 2*\Gamma^0/(\Gamma^- + \Gamma^+) - 1 = 1.1 \pm 0.4 \pm 0.2$, $A_{AF} = 3/4*(\Gamma^- - \Gamma^+)/\Gamma = 0.2 \pm 0.08 \pm 0.06$ and a value of $|V_{cb}|$ = 0.036–0.045 depending on model assumptions.

[32] We have taken average of the the BORTOLETTO 89B values for electrons and muons, $0.046 \pm 0.005 \pm 0.007$. We rescale using the method described in STONE 94 but with the updated PDG 94 B($D^0 \to K^-\pi^+$). The measurement suggests a D^* polarization parameter value $\alpha = 0.65 \pm 0.66 \pm 0.25$.

[33] Combining $\overline{D}^{*0}\ell^+\nu_\ell$ and $\overline{D}^{*-}\ell^+\nu_\ell$ SANGHERA 93 test $V-A$ structure and fit the decay angular distributions to obtain $A_{FB} = 3/4*(\Gamma^- - \Gamma^+)/\Gamma = 0.14 \pm 0.06 \pm 0.03$. Assuming a value of V_{cb}, they measure V, A_1, and A_2, the three form factors for the $D^*\ell\nu_\ell$ decay, where results are slightly dependent on model assumptions.

[34] ANTREASYAN 90B is average over B and $\overline{D}^*(2010)$ charge states.

[35] The measurement of ALBRECHT 89C suggests a D^* polarization γ_L/γ_T of 0.85 ± 0.45. or $\alpha = 0.7 \pm 0.9$.

[36] ALBRECHT 89J is ALBRECHT 87J value rescaled using B($D^*(2010)^- \to D^0\pi^-$) = $0.57 \pm 0.04 \pm 0.04$. Superseded by ALBRECHT 93.

[37] ALBRECHT 87J assume μ-e universality, the B($\Upsilon(4S) \to B^0\overline{B}^0$) = 0.45, the B($D^0 \to K^-\pi^+$) = $(0.042 \pm 0.004 \pm 0.004)$, and the B($D^*(2010)^- \to D^0\pi^-$) = 0.49 ± 0.08. Superseded by ALBRECHT 89J.

$\Gamma(\rho^- \ell^+ \nu_\ell)/\Gamma_{total}$ Γ_4/Γ

$\ell = e$ or μ, not sum over e and μ modes.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.1 × 10⁻⁴	90	[38] BEAN	93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[38] BEAN 93B limit set using ISGW Model. Using isospin and the quark model to combine $\Gamma(\rho^0\ell^+\nu_\ell)$ and $\Gamma(\omega\ell^+\nu_\ell)$ with this result, they obtain a limit $<(1.6\text{–}2.7) \times 10^{-4}$ at 90% CL for $B^+ \to (\omega \text{ or } \rho^0)\ell^+\nu_\ell$. The range corresponds to the ISGW, WSB, and KS models. An upper limit on $|V_{ub}/V_{cb}| <$ 0.8–0.13 at 90% CL is derived as well.

$\Gamma(\pi^- \mu^+ \nu_\mu)/\Gamma_{total}$ Γ_5/Γ

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
seen	[39] ALBRECHT	91C	ARG

[39] In ALBRECHT 91C, one event is fully reconstructed providing evidence for the $b \to u$ transition.

$\Gamma(D^- \pi^+)/\Gamma_{total}$ Γ_6/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0030±0.0004 OUR AVERAGE					
0.0029±0.0004±0.0002	81	[40] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0027±0.0006±0.0005		[41] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0048±0.0011±0.0011	22	[42] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
$0.0051^{+0.0028}_{-0.0025}{}^{+0.0013}_{-0.0012}$	4	[43] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0031±0.0013±0.0010	7	[42] ALBRECHT	88K	ARG	$e^+e^- \to \Upsilon(4S)$

[40] ALAM 94 reports [B($B^0 \to D^-\pi^+$) × B($D^+ \to K^-\pi^+\pi^+$)] = $0.000265 \pm 0.000032 \pm 0.000023$. We divide by our best value B($D^+ \to K^-\pi^+\pi^+$) = $(9.1 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[41] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[42] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55. Superseded by ALBRECHT 90J which assumes 50:50.

[43] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.

$\Gamma(D^- \rho^+)/\Gamma_{total}$ Γ_7/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0078±0.0014 OUR AVERAGE					
0.0078±0.0013±0.0005	79	[44] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.009 ±0.005 ±0.003	9	[45] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.022 ±0.012 ±0.009	6	[45] ALBRECHT	88K	ARG	$e^+e^- \to \Upsilon(4S)$

[44] ALAM 94 reports [B($B^0 \to D^-\rho^+$) × B($D^+ \to K^-\pi^+\pi^+$)] = $0.000704 \pm 0.000096 \pm 0.000070$. We divide by our best value B($D^+ \to K^-\pi^+\pi^+$) = $(9.1 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[45] ALBRECHT 88K assumes $B^0\overline{B}^0$:B^+B^- production ratio is 45:55. Superseded by ALBRECHT 90J which assumes 50:50.

$\Gamma(\overline{D}^0 \pi^+ \pi^-)/\Gamma_{total}$ Γ_8/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0016	90		[46] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.007	90		[47] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.034	90		[48] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
0.07 ±0.05		5	[49] BEHRENDS	83	CLEO	$e^+e^- \to \Upsilon(4S)$

[46] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[47] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D. The product branching fraction into $D_0^*(2340)\pi$ followed by $D_0^*(2340) \to D^0\pi$ is < 0.0001 at 90% CL and into $D_2^*(2460)$ followed by $D_2^*(2460) \to D^0\pi$ is < 0.0004 at 90% CL.

[48] BEBEK 87 assume the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%. B($D^0 \to K^-\pi^+$) = $(4.2 \pm 0.4 \pm 0.4)$% and B($D^0 \to K^-\pi^+\pi^+\pi^-$) = $(9.1 \pm 0.8 \pm 0.8)$% were used.

[49] Corrected by us using assumptions: B($D^0 \to K^-\pi^+$) = (0.042 ± 0.006) and B($\Upsilon(4S) \to B^0\overline{B}^0$) = 50%. The product branching ratio is B($B^0 \to \overline{D}^0\pi^+\pi^-$)B($\overline{D}^0 \to K^+\pi^-$) = $(0.39 \pm 0.26) \times 10^{-2}$.

$\Gamma(D^*(2010)^- \pi^+)/\Gamma_{total}$ Γ_9/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0026 ±0.0004 OUR AVERAGE					
0.0026 ±0.0003 ±0.0004	82	[50] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0033 ±0.0010 ±0.0001		[51] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.00234±0.00087±0.00005	12	[52] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$
$0.00234^{+0.00148}_{-0.00109}\pm0.00005$	5	[53] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.010 ±0.004 ±0.001	8	[54] AKERS	94J	OPAL	$e^+e^- \to Z$
0.0027 ±0.0014 ±0.0010	5	[55] ALBRECHT	87C	ARG	$e^+e^- \to \Upsilon(4S)$
0.0035 ±0.002 ±0.002		[56] ALBRECHT	86F	ARG	$e^+e^- \to \Upsilon(4S)$
0.017 ±0.005 ±0.005	41	[57] GILES	84	CLEO	$e^+e^- \to \Upsilon(4S)$

[50] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II B($D^*(2010)^+ \to D^0\pi^+$) and absolute B($D^0 \to K^-\pi^+$) and the PDG 1992 B($D^0 \to K^-\pi^+\pi^0$)/B($D^0 \to K^-\pi^+$) and B($D^0 \to K^-\pi^+\pi^+\pi^-$)/B($D^0 \to K^-\pi^+$).

[51] BORTOLETTO 92 reports $0.0040 \pm 0.0010 \pm 0.0007$ for B($D^*(2010)^+ \to D^0\pi^+$) = 0.57 ± 0.06. We rescale to our best value B($D^*(2010)^+ \to D^0\pi^+$) = $(68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[52] ALBRECHT 90J reports $0.0028 \pm 0.0009 \pm 0.0006$ for B($D^*(2010)^+ \to D^0\pi^+$) = 0.57 ± 0.06. We rescale to our best value B($D^*(2010)^+ \to D^0\pi^+$) = $(68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[53] BEBEK 87 reports $0.0028^{+0.0015}_{-0.0012}{}^{+0.0010}_{-0.0006}$ for B($D^*(2010)^+ \to D^0\pi^+$) = 0.57 ± 0.06. We rescale to our best value B($D^*(2010)^+ \to D^0\pi^+$) = $(68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92 and ALBRECHT 90J.

[54] Assumes B($Z \to b\overline{b}$) = 0.217 and 38% B_d production fraction.

[55] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume B($\Upsilon(4S) \to B^+B^-$) = 55% and B($\Upsilon(4S) \to B^0\overline{B}^0$) = 45%. Superseded by ALBRECHT 90J.

[56] ALBRECHT 86F uses pseudomass that is independent of D^0 and D^+ branching ratios.

[57] Assumes B($D^*(2010)^+ \to D^0\pi^+$) = $0.60^{+0.08}_{-0.15}$. Assumes B($\Upsilon(4S) \to B^0\overline{B}^0$) = 0.40 ± 0.02 Does not depend on D branching ratios.

$\Gamma(D^- \pi^+ \pi^+ \pi^-)/\Gamma_{total}$ Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0080±0.0021±0.0014	[58] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$

[58] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma((D^- \pi^+ \pi^+ \pi^-)$ nonresonant$)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0039±0.0014±0.0013	[59] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[59] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^- \pi^+ \rho^0)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0011±0.0009±0.0004	[60] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[60] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^- a_1(1260)^+)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0060±0.0022±0.0024	[61] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[61] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^- \pi^+ \pi^0)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0150±0.0051±0.0003	51	[62] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.015 ±0.008 ±0.008	8	[63] ALBRECHT 87C	ARG	$e^+e^- \to \Upsilon(4S)$

[62] ALBRECHT 90J reports $0.018 \pm 0.004 \pm 0.005$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[63] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.

$\Gamma(D^*(2010)^- \rho^+)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0073±0.0015 OUR AVERAGE				
0.0074±0.0010±0.0014	76	[64,65] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0159±0.0112±0.0003		[66] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0058±0.0035±0.0001	19	[67] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.081 ±0.029 $^{+0.059}_{-0.024}$	19	[68] CHEN 85	CLEO	$e^+e^- \to \Upsilon(4S)$

[64] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2010)^+ \to D^0\pi^+)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

[65] This decay is nearly completely longitudinally polarized, $\Gamma_L/\Gamma = (93 \pm 5 \pm 5)\%$, as expected from the factorization hypothesis (ROSNER 90). The nonresonant $\pi^+\pi^0$ contribution under the ρ^+ is less than 9% at 90% CL.

[66] BORTOLETTO 92 reports $0.019 \pm 0.008 \pm 0.011$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[67] ALBRECHT 90J reports $0.007 \pm 0.003 \pm 0.003$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[68] Uses $B(D^* \to D^0\pi^+) = 0.6 \pm 0.15$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 0.4$. Does not depend on D branching ratios.

$\Gamma(D^*(2010)^- \pi^+ \pi^+ \pi^-)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.0076±0.0017 OUR AVERAGE			Error includes scale factor of 1.3. See the ideogram below.		
0.0063±0.0010±0.0011		49	[69,70] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0133±0.0036±0.0003			[71] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0100±0.0040±0.0002		26	[72] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.033 ±0.009 ±0.016		27	[73] ALBRECHT 87C	ARG	$e^+e^- \to \Upsilon(4S)$
<0.042	90		[74] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[69] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2010)^+ \to D^0\pi^+)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

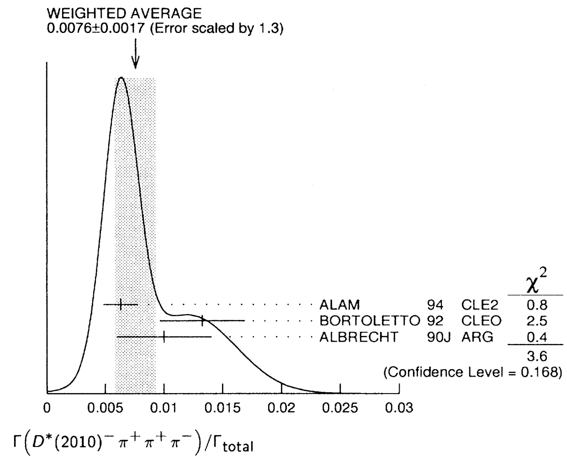
[70] The three pion mass is required to be between 1.0 and 1.6 GeV consistent with an a_1 meson. (If this channel is dominated by a_1^+, the branching ratio for $\overline{D}^{*-} a_1^+$ is twice that for $\overline{D}^{*-}\pi^+\pi^+\pi^-$.)

[71] BORTOLETTO 92 reports $0.0159 \pm 0.0028 \pm 0.0037$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[72] ALBRECHT 90J reports $0.012 \pm 0.003 \pm 0.004$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[73] ALBRECHT 87C use PDG 86 branching ratios for D and $D^*(2010)$ and assume $B(\Upsilon(4S) \to B^+B^-) = 55\%$ and $B(\Upsilon(4S) \to B^0\overline{B}^0) = 45\%$. Superseded by ALBRECHT 90J.

[74] BEBEK 87 value has been updated in BERKELMAN 91 to use same assumptions as noted for BORTOLETTO 92.



$\Gamma((D^*(2010)^- \pi^+ \pi^+ \pi^-)$ nonresonant$)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0000±0.0019±0.0016	[75] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[75] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

$\Gamma(D^*(2010)^- \pi^+ \rho^0)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0057±0.0031±0.0001	[76] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[76] BORTOLETTO 92 reports $0.0068 \pm 0.0032 \pm 0.0021$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^- a_1(1260)^+)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.0130±0.0027 OUR AVERAGE			
0.0126±0.0020±0.0022	[77,78] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0150±0.0069±0.0003	[79] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$

[77] ALAM 94 value is twice their $\Gamma(D^*(2010)^-\pi^+\pi^+\pi^-)/\Gamma_{total}$ value based on their observation that the three pions are dominantly in the $a_1(1260)$ mass range 1.0 to 1.6 GeV.

[78] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2010)^+ \to D^0\pi^+)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

[79] BORTOLETTO 92 reports $0.018 \pm 0.006 \pm 0.006$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(D^*(2010)^- \pi^+ \pi^+ \pi^- \pi^0)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.034±0.018±0.001	28	[80] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$

[80] ALBRECHT 90J reports $0.041 \pm 0.015 \pm 0.016$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

$\Gamma(\overline{D}_2^*(2460)^- \pi^+)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0022	90	[81] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[81] ALAM 94 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \to K^-\pi^+)$ and $B(D_2^*(2460)^+ \to D^0\pi^+) = 30\%$.

$\Gamma(\overline{D}{}_2^*(2460)^- \rho^+)/\Gamma_{\rm total}$ — Γ_{22}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0049	90	[82] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$

[82] ALAM 94 assumesequal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \to K^-\pi^+)$ and $B(D_2^*(2460)^+ \to D^0\pi^+) = 30\%$.

$\Gamma(D^- D_s^+)/\Gamma_{\rm total}$ — Γ_{23}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.007±0.004 OUR AVERAGE					
0.013±0.011±0.003		[83] ALBRECHT	92G	ARG	$e^+e^- \to \Upsilon(4S)$
0.007±0.004±0.002		[84] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.012±0.007	3	[85] BORTOLETTO	90	CLEO	$e^+e^- \to \Upsilon(4S)$

[83] ALBRECHT 92G reports $0.017 \pm 0.013 \pm 0.006$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^+ branching ratios, e.g., $B(D^+ \to K^-\pi^+\pi^+) = 7.7 \pm 1.0\%$.

[84] BORTOLETTO 92 reports $0.0080 \pm 0.0045 \pm 0.0030$ for $B(D_s^+ \to \phi\pi^+) = 0.030 \pm 0.011$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[85] BORTOLETTO 90 assume $B(D_s \to \phi\pi^+) = 2\%$. Superseded by BORTOLETTO 92.

$\Gamma(D^*(2010)^- D_s^+)/\Gamma_{\rm total}$ — Γ_{24}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.012±0.006 OUR AVERAGE					
0.010±0.008±0.003		[86] ALBRECHT	92G	ARG	$e^+e^- \to \Upsilon(4S)$
0.013±0.008±0.003		[87] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.024±0.014	3	[88] BORTOLETTO	90	CLEO	$e^+e^- \to \Upsilon(4S)$

[86] ALBRECHT 92G reports $0.014 \pm 0.010 \pm 0.003$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^+ and $D^*(2010)^+$ branching ratios, e.g., $B(D^0 \to K^-\pi^+) = 3.71 \pm 0.25\%$, $B(D^+ \to K^-\pi^+\pi^+) = 7.1 \pm 1.0\%$, and $B(D^*(2010)^+ \to D^0\pi^+) = 55 \pm 4\%$.

[87] BORTOLETTO 92 reports $0.016 \pm 0.009 \pm 0.006$ for $B(D_s^+ \to \phi\pi^+) = 0.030 \pm 0.011$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D and $D^*(2010)$.

[88] BORTOLETTO 90 assume $B(D_s \to \phi\pi^+) = 2\%$. Superseded by BORTOLETTO 92.

$\Gamma(D^- D_s^{*+})/\Gamma_{\rm total}$ — Γ_{25}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.020±0.014±0.005	[89] ALBRECHT	92G	ARG	$e^+e^- \to \Upsilon(4S)$

[89] ALBRECHT 92G reports $0.027 \pm 0.017 \pm 0.009$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^+ branching ratios, e.g., $B(D^+ \to K^-\pi^+\pi^+) = 7.7 \pm 1.0\%$.

$[\Gamma(D^*(2010)^- D_s^+) + \Gamma(D^*(2010)^- D_s^{*+})]/\Gamma_{\rm total}$ — $(\Gamma_{24}+\Gamma_{26})/\Gamma$

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
$4.15 \pm 1.11^{+0.99}_{-1.02}$	22	[90] BORTOLETTO	90	CLEO	$e^+e^- \to \Upsilon(4S)$

[90] BORTOLETTO 90 reports 7.5 ± 2.0 for $B(D_s^+ \to \phi\pi^+) = 0.02$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D^*(2010)^- D_s^{*+})/\Gamma_{\rm total}$ — Γ_{26}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.019±0.011±0.005	[91] ALBRECHT	92G	ARG	$e^+e^- \to \Upsilon(4S)$

[91] ALBRECHT 92G reports $0.026 \pm 0.014 \pm 0.006$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes PDG 1990 D^+ and $D^*(2010)^+$ branching ratios, e.g., $B(D^0 \to K^-\pi^+) = 3.71 \pm 0.25\%$, $B(D^+ \to K^-\pi^+\pi^+) = 7.1 \pm 1.0\%$, and $B(D^*(2010)^+ \to D^0\pi^+) = 55 \pm 4\%$.

$\Gamma(D_s^+ \pi^-)/\Gamma_{\rm total}$ — Γ_{27}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.00028	90	[92] ALEXANDER	93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0013	90	[93] BORTOLETTO	90	CLEO	$e^+e^- \to \Upsilon(4S)$

[92] ALEXANDER 93B reports $< 2.7 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

[93] BORTOLETTO 90 assume $B(D_s \to \phi\pi^+) = 2\%$.

$\Gamma(D_s^{*+} \pi^-)/\Gamma_{\rm total}$ — Γ_{28}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0005	90	[94] ALEXANDER	93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[94] ALEXANDER 93B reports $< 4.4 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$[\Gamma(D_s^+ \pi^-) + \Gamma(D_s^- K^+)]/\Gamma_{\rm total}$ — $(\Gamma_{27}+\Gamma_{33})/\Gamma$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0013	90	[95] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[95] ALBRECHT 93E reports $< 1.7 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$[\Gamma(D_s^{*+} \pi^-) + \Gamma(D_s^{*-} K^+)]/\Gamma_{\rm total}$ — $(\Gamma_{28}+\Gamma_{34})/\Gamma$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0009	90	[96] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[96] ALBRECHT 93E reports $< 1.2 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^+ \rho^-)/\Gamma_{\rm total}$ — Γ_{29}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0007	90	[97] ALEXANDER	93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0016	90	[98] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[97] ALEXANDER 93B reports $< 6.6 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

[98] ALBRECHT 93E reports $< 2.2 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+} \rho^-)/\Gamma_{\rm total}$ — Γ_{30}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0008	90	[99] ALEXANDER	93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0019	90	[100] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[99] ALEXANDER 93B reports $< 7.4 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

[100] ALBRECHT 93E reports $< 2.5 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^+ a_1(1260)^-)/\Gamma_{\rm total}$ — Γ_{31}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0026	90	[101] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[101] ALBRECHT 93E reports $< 3.5 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*+} a_1(1260)^-)/\Gamma_{\rm total}$ — Γ_{32}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0022	90	[102] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[102] ALBRECHT 93E reports $< 2.9 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^- K^+)/\Gamma_{\rm total}$ — Γ_{33}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.00024	90	[103] ALEXANDER	93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0013	90	[104] BORTOLETTO	90	CLEO	$e^+e^- \to \Upsilon(4S)$

[103] ALEXANDER 93B reports $< 2.3 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

[104] BORTOLETTO 90 assume $B(D_s \to \phi\pi^+) = 2\%$.

$\Gamma(D_s^{*-} K^+)/\Gamma_{\rm total}$ — Γ_{34}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.00017	90	[105] ALEXANDER	93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[105] ALEXANDER 93B reports $< 1.7 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^- K^*(892)^+)/\Gamma_{\rm total}$ — Γ_{35}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0010	90	[106] ALEXANDER	93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0034	90	[107] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[106] ALEXANDER 93B reports $< 9.7 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

[107] ALBRECHT 93E reports $< 4.6 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*-} K^*(892)^+)/\Gamma_{total}$ — Γ_{36}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0011	90	[108] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.004	90	[109] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[108] ALEXANDER 93B reports $< 11.0 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

[109] ALBRECHT 93E reports $< 5.8 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^- \pi^+ K^0)/\Gamma_{total}$ — Γ_{37}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.005	90	[110] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[110] ALBRECHT 93E reports $< 7.3 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*-} \pi^+ K^0)/\Gamma_{total}$ — Γ_{38}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0031	90	[111] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[111] ALBRECHT 93E reports $< 4.2 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^- \pi^+ K^*(892)^0)/\Gamma_{total}$ — Γ_{39}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.004	90	[112] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[112] ALBRECHT 93E reports $< 5.0 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^{*-} \pi^+ K^*(892)^0)/\Gamma_{total}$ — Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0020	90	[113] ALBRECHT 93E	ARG	$e^+e^- \to \Upsilon(4S)$

[113] ALBRECHT 93E reports $< 2.7 \times 10^{-3}$ for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(\overline{D}^0 \pi^0)/\Gamma_{total}$ — Γ_{41}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00048	90	[114] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[114] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^0 \rho^0)/\Gamma_{total}$ — Γ_{42}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.00055	90		[115] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0006	90		[116] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.0027	90	4	[117] ALBRECHT 88K	ARG	$e^+e^- \to \Upsilon(4S)$

[115] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

[116] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$ and uses Mark III branching fractions for the D.

[117] ALBRECHT 88K reports < 0.003 assuming $B^0\overline{B}^0$:B^+B^- production ratio is 45:55. We rescale to 50%.

$\Gamma(\overline{D}^0 \eta)/\Gamma_{total}$ — Γ_{43}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00068	90	[118] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[118] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^0 \eta')/\Gamma_{total}$ — Γ_{44}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00086	90	[119] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[119] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^0 \omega)/\Gamma_{total}$ — Γ_{45}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00063	90	[120] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[120] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0 \pi^0)/\Gamma_{total}$ — Γ_{46}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00097	90	[121] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[121] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0 \rho^0)/\Gamma_{total}$ — Γ_{47}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00117	90	[122] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[122] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0 \eta)/\Gamma_{total}$ — Γ_{48}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.00069	90	[123] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[123] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0 \eta')/\Gamma_{total}$ — Γ_{49}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0027	90	[124] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[124] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(\overline{D}^*(2007)^0 \omega)/\Gamma_{total}$ — Γ_{50}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0021	90	[125] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[125] ALAM 94 assume equal production of B^+ and B^0 at the $\Upsilon(4S)$ and use the CLEO II $B(D^*(2007)^0 \to D^0\pi^0)$ and absolute $B(D^0 \to K^-\pi^+)$ and the PDG 1992 $B(D^0 \to K^-\pi^+\pi^0)/B(D^0 \to K^-\pi^+)$ and $B(D^0 \to K^-\pi^+\pi^+\pi^-)/B(D^0 \to K^-\pi^+)$.

$\Gamma(J/\psi(1S) K^0)/\Gamma_{total}$ — Γ_{51}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
7.5 ±2.1 OUR AVERAGE					
7.5 ±2.4 ±0.8		10	[126] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
6.87±4.03±0.22			[126] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
9.2 ±7.1 ±0.3		2	[127] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<50	90		ALAM 86	CLEO	$e^+e^- \to \Upsilon(4S)$

[126] BORTOLETTO 92 reports $6 \pm 3 \pm 2$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[127] ALBRECHT 90J reports $8 \pm 6 \pm 2$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(J/\psi(1S) K^+\pi^-)/\Gamma_{total}$ — Γ_{52}/Γ

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.00115±0.00055±0.00004			[128] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0013	90		[129] ALBRECHT 87D	ARG	$e^+e^- \to \Upsilon(4S)$
<0.0063	90	2	GILES 84	CLEO	$e^+e^- \to \Upsilon(4S)$

[128] BORTOLETTO 92 reports $0.0010 \pm 0.0004 \pm 0.0003$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[129] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. $K\pi$ system is specifically selected as nonresonant.

$\Gamma(J/\psi(1S) K^*(892)^0)/\Gamma_{total}$ — Γ_{53}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.00158±0.00027 OUR AVERAGE				
0.00169±0.00031±0.00018	29	[130] ALAM 94	CLE2	$e^+e^- \to \Upsilon(4S)$
0.00126±0.00065±0.00004		[131] BORTOLETTO92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.00126±0.00059±0.00004	6	[132] ALBRECHT 90J	ARG	$e^+e^- \to \Upsilon(4S)$
0.0040 ±0.0018 ±0.0001	5	[133] BEBEK 87	CLEO	$e^+e^- \to \Upsilon(4S)$

• • • We do not use the following data for averages, fits, limits, etc. • • •

		[134] ALBRECHT	94G	ARG	$e^+e^- \to \Upsilon(4S)$
0.0040 ±0.0030		[135] ALBAJAR	91E	UA1	$E_{\rm cm}^{p\overline{p}} = 630$ GeV
0.0033 ±0.0018	5	[136] ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$
0.0041 ±0.0018	5	[137] ALAM	86	CLEO	Repl. by BEBEK 87

[130] The neutral and charged B events together are predominantly longitudinally polarized, $\Gamma_L/\Gamma = 0.080 \pm 0.08 \pm 0.05$. This can be compared with a prediction using HQET, 0.73 (KRAMER 92). This polarization indicates that the $B \to \psi K^*$ decay is dominated by the $CP = -1$ CP eigenstate. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[131] BORTOLETTO 92 reports $0.0011 \pm 0.0005 \pm 0.0003$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[132] ALBRECHT 90J reports $0.0011 \pm 0.0005 \pm 0.0002$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

[133] BEBEK 87 reports $0.0035 \pm 0.0016 \pm 0.0003$ for $B(J/\psi(1S) \to e^+e^-) = 0.069 \pm 0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Updated in BORTOLETTO 92 to use the same assumptions.

[134] ALBRECHT 94G measures the polarization in the vector-vector decay to be predominantly longitudinal, $\Gamma_T/\Gamma = 0.03 \pm 0.16 \pm 0.15$ making the neutral decay a CP eigenstate when the K^{*0} decays through $K_S^0\pi^0$.

[135] ALBAJAR 91E assumes B_d^0 production fraction of 36%.

[136] ALBRECHT 87D assume $B^+B^-/B^0\overline{B}^0$ ratio is 55/45. Superseded by ALBRECHT 90J.

[137] ALAM 86 assumes $B^\pm/B^0$ ratio is 60/40. The observation of the decay $B^+ \to J/\psi K^*(892)^+$ (HAAS 85) has been retracted in this paper.

$\Gamma(J/\psi(1S)\pi^0)/\Gamma_{\rm total}$ — Γ_{54}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<6.9 × 10⁻³	90	1	[138] ALEXANDER	95	CLE2	$e^+e^- \to \Upsilon(4S)$

[138] Assumes equal production of B^+B^- and $B^0\overline{B}^0$ on $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^0)/\Gamma_{\rm total}$ — Γ_{55}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0008	90	[139] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0015	90	[139] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.0028	90	[139] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[139] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^+\pi^-)/\Gamma_{\rm total}$ — Γ_{56}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.001	90	[140] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[140] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\psi(2S)K^*(892)^0)/\Gamma_{\rm total}$ — Γ_{57}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.0014±0.0008±0.0004		[141] BORTOLETTO	92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0019	90	[141] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$
<0.0023	90	[141] ALBRECHT	90J	ARG	$e^+e^- \to \Upsilon(4S)$

[141] Assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\chi_{c1}(1P)K^0)/\Gamma_{\rm total}$ — Γ_{58}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0027	90	[142] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$

[142] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(\chi_{c1}(1P)K^*(892)^0)/\Gamma_{\rm total}$ — Γ_{59}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0021	90	[143] ALAM	94	CLE2	$e^+e^- \to \Upsilon(4S)$

[143] BORTOLETTO 92 assumes equal production of B^+ and B^0 at the $\Upsilon(4S)$.

$\Gamma(K^+\pi^-)/\Gamma_{\rm total}$ — Γ_{60}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.7 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<9 \times 10^{-5}$	90	[144] ABREU	95N	DLPH	$e^+e^- \to Z$
$<8.1 \times 10^{-5}$	90	[145] AKERS	94L	OPAL	$e^+e^- \to Z$
$<2.6 \times 10^{-5}$	90	[146] BATTLE	93	CLE2	$e^+e^- \to \Upsilon(4S)$
$<1.8 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<9 \times 10^{-5}$	90	[147] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<3.2 \times 10^{-4}$	90	AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[144] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12. Contributions from B^0 and B_s^0 decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

[145] Assumes $B(Z \to b\overline{b}) = 0.217$ and B_d^0 (B_s^0) fraction 39.5% (12%).

[146] BATTLE 93 assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

[147] Assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$.

$\Gamma(K^0\pi^0)/\Gamma_{\rm total}$ — Γ_{61}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.0 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$[\Gamma(K^+\pi^-) + \Gamma(\pi^+\pi^-)]/\Gamma_{\rm total}$ — $(\Gamma_{60}+\Gamma_{92})/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{(1.8^{+0.6}_{-0.5}{}^{+0.3}_{-0.4}) \times 10^{-5}}$	17.2	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$(2.4^{+0.8}_{-0.7} \pm 0.2) \times 10^{-5}$		[148] BATTLE	93	CLE2	$e^+e^- \to \Upsilon(4S)$

[148] BATTLE 93 assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(K^+K^-)/\Gamma_{\rm total}$ — Γ_{62}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.4 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.2 \times 10^{-4}$	90	[149] ABREU	95N	DLPH	$e^+e^- \to Z$
$<0.7 \times 10^{-5}$	90	[150] BATTLE	93	CLE2	$e^+e^- \to \Upsilon(4S)$

[149] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12. Contributions from B^0 and B_s^0 decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

[150] BATTLE 93 assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(K^+\rho^-)/\Gamma_{\rm total}$ — Γ_{63}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.5 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0\pi^+\pi^-)/\Gamma_{\rm total}$ — Γ_{64}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.4 \times 10^{-4}$	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0\rho^0)/\Gamma_{\rm total}$ — Γ_{65}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.9 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3.2 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<5.0 \times 10^{-4}$	90	[151] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.064	90	[152] AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[151] AVERY 89B reports $< 5.8 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[152] AVERY 87 reports < 0.08 assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^0 f_0(980))/\Gamma_{\rm total}$ — Γ_{66}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.6 × 10⁻⁴	90	[153] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$

[153] AVERY 89B reports $< 4.2 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^+\pi^-)/\Gamma_{\rm total}$ — Γ_{67}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7.2 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6.2 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<3.8 \times 10^{-4}$	90	[154] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<5.6 \times 10^{-4}$	90	[155] AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[154] AVERY 89B reports $< 4.4 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[155] AVERY 87 reports $< 7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^0\pi^0)/\Gamma_{\rm total}$ — Γ_{68}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.8 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^+\pi^-)/\Gamma_{\rm total}$ — Γ_{69}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.6 × 10⁻³	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0K^+K^-)/\Gamma_{\rm total}$ — Γ_{70}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.3 × 10⁻³	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^0\phi)/\Gamma_{\rm total}$ — Γ_{71}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8.8 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<7.2 \times 10^{-4}$	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
$<4.2 \times 10^{-4}$	90	[156] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
$<1.0 \times 10^{-3}$	90	[157] AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[156] AVERY 89B reports $< 4.9 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

[157] AVERY 87 reports $< 1.3 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^-\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{72}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.1 × 10⁻⁴	90	[158] ABREU	95N	DLPH	$e^+e^- \to Z$

[158] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12. Contributions from B^0 and B^0_s decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

$\Gamma(K^*(892)^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_{73}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.4 × 10⁻³	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0\rho^0)/\Gamma_{total}$ — Γ_{74}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.6 × 10⁻⁴	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5.8 × 10⁻⁴	90	[159] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<9.6 × 10⁻⁴	90	[160] AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[159] AVERY 89B reports $< 6.7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[160] AVERY 87 reports $< 1.2 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^0 f_0(980))/\Gamma_{total}$ — Γ_{75}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.7 × 10⁻⁴	90	[161] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$

[161] AVERY 89B reports $< 2.0 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1400)^+\pi^-)/\Gamma_{total}$ — Γ_{76}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10⁻³	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^- a_1(1260)^+)/\Gamma_{total}$ — Γ_{77}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.9 × 10⁻⁴	90	[162] ABREU	95N	DLPH	$e^+e^- \to Z$

[162] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12. Contributions from B^0 and B^0_s decays cannot be separated. Limits are given for the weighted average of the decay rates for the two neutral B mesons.

$\Gamma(K^*(892)^0 K^+K^-)/\Gamma_{total}$ — Γ_{78}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<6.1 × 10⁻⁴	90	ALBRECHT	91E	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0\phi)/\Gamma_{total}$ — Γ_{79}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.3 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.2 × 10⁻⁴	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$
<3.8 × 10⁻⁴	90	[163] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<3.8 × 10⁻⁴	90	[164] AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[163] AVERY 89B reports $< 4.4 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[164] AVERY 87 reports $< 4.7 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1400)^0\rho^0)/\Gamma_{total}$ — Γ_{80}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.0 × 10⁻³	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_1(1400)^0\phi)/\Gamma_{total}$ — Γ_{81}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.0 × 10⁻³	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^0\rho^0)/\Gamma_{total}$ — Γ_{82}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10⁻³	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2^*(1430)^0\phi)/\Gamma_{total}$ — Γ_{83}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.4 × 10⁻³	90	ALBRECHT	91B	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0\gamma)/\Gamma_{total}$ — Γ_{84}/Γ

VALUE (units 10⁻⁵)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
4.0±1.7±0.8		8	[165] AMMAR	93	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 42	90		ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$
< 24	90		[166] AVERY	89B	CLEO	$e^+e^- \to \Upsilon(4S)$
<210	90		AVERY	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[165] AMMAR 93 observed 6.6 ± 2.8 events above background.
[166] AVERY 89B reports $< 2.8 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1270)^0\gamma)/\Gamma_{total}$ — Γ_{85}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0070	90	[167] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[167] ALBRECHT 89G reports < 0.0078 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_1(1400)^0\gamma)/\Gamma_{total}$ — Γ_{86}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0043	90	[168] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[168] ALBRECHT 89G reports < 0.0048 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_2^*(1430)^0\gamma)/\Gamma_{total}$ — Γ_{87}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.0 × 10⁻⁴	90	[169] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[169] ALBRECHT 89G reports $< 4.4 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(1680)^0\gamma)/\Gamma_{total}$ — Γ_{88}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0020	90	[170] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[170] ALBRECHT 89G reports < 0.0022 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_3^*(1780)^0\gamma)/\Gamma_{total}$ — Γ_{89}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.010	90	[171] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[171] ALBRECHT 89G reports < 0.011 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K_4^*(2045)^0\gamma)/\Gamma_{total}$ — Γ_{90}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0043	90	[172] ALBRECHT	89G	ARG	$e^+e^- \to \Upsilon(4S)$

[172] ALBRECHT 89G reports < 0.0048 assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\phi\phi)/\Gamma_{total}$ — Γ_{91}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.9 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{92}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.0 × 10⁻⁵	90		ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<5.5 × 10⁻⁵	90		[173] ABREU	95N	DLPH	$e^+e^- \to Z$
<4.7 × 10⁻⁵	90		[174] AKERS	94L	OPAL	$e^+e^- \to Z$
<2.9 × 10⁻⁵	90		[175] BATTLE	93	CLE2	$e^+e^- \to \Upsilon(4S)$
<1.3 × 10⁻⁴	90		[175] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$
<7.7 × 10⁻⁵	90		[176] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
<2.6 × 10⁻⁴	90		[176] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$
<5 × 10⁻⁴	90	4	GILES	84	CLEO	$e^+e^- \to \Upsilon(4S)$

[173] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.
[174] Assumes B($Z \to b\overline{b}$) = 0.217 and B^0_d (B^0_s) fraction 39.5% (12%).
[175] Assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.
[176] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_{93}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.91 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.0 × 10⁻⁵	90	[177] ACCIARRI	95H	L3	$e^+e^- \to Z$

[177] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\eta\pi^0)/\Gamma_{total}$ — Γ_{94}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.5 × 10⁻⁴	90	[178] ACCIARRI	95H	L3	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.8 × 10⁻³	90	[179] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[178] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.
[179] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_{95}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.1 × 10⁻⁴	90	[180] ACCIARRI	95H	L3	$e^+e^- \to Z$

[180] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{96}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7.2 × 10⁻⁴	90	[181] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[181] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0\pi^0)/\Gamma_{total}$ — Γ_{97}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.4 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.0 × 10⁻⁴	90	[182] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[182] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^\mp\pi^\pm)/\Gamma_{total}$ — Γ_{98}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8.8 × 10⁻⁵	90	ASNER	96	CLE2	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5.2 × 10⁻⁴	90	[183] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$
<5.2 × 10⁻³	90	[184] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[183] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.
[184] BEBEK 87 reports $< 6.1 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^-\pi^+\pi^-)/\Gamma_{total}$ — Γ_{99}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.8 × 10⁻⁴	90	[185] ABREU	95N	DLPH	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.7 × 10⁻⁴	90	[186] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[185] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.
[186] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^0\rho^0)/\Gamma_{total}$ — Γ_{100}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.8 × 10⁻⁴	90	[187] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.9 × 10⁻⁴	90	[188] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
<4.3 × 10⁻⁴	90	[188] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[187] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.
[188] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(a_1(1260)^\mp\pi^\pm)/\Gamma_{total}$ — Γ_{101}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.9 × 10⁻⁴	90	[189] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.3 × 10⁻⁴	90	[190] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$
<1.0 × 10⁻³	90	[189] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[189] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[190] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_2(1320)^\mp\pi^\pm)/\Gamma_{total}$ — Γ_{102}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.0 × 10⁻⁴	90	[191] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4 × 10⁻³	90	[191] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[191] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\pi^+\pi^-\pi^0\pi^0)/\Gamma_{total}$ — Γ_{103}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.1 × 10⁻³	90	[192] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[192] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\rho^+\rho^-)/\Gamma_{total}$ — Γ_{104}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.2 × 10⁻³	90	[193] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[193] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^0\pi^0)/\Gamma_{total}$ — Γ_{105}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10⁻³	90	[194] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[194] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\omega\pi^0)/\Gamma_{total}$ — Γ_{106}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.6 × 10⁻⁴	90	[195] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[195] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^+\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{107}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9.0 × 10⁻³	90	[196] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[196] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+\rho^-)/\Gamma_{total}$ — Γ_{108}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.4 × 10⁻³	90	[197] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[197] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^0\rho^0)/\Gamma_{total}$ — Γ_{109}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.4 × 10⁻³	90	[198] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[198] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-)/\Gamma_{total}$ — Γ_{110}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.0 × 10⁻³	90	[199] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[199] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(a_1(1260)^+a_1(1260)^-)/\Gamma_{total}$ — Γ_{111}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.8 × 10⁻³	90	[200] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.0 × 10⁻³	90	[201] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[200] BORTOLETTO 89 reports $< 3.2 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[201] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0)/\Gamma_{total}$ — Γ_{112}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10⁻²	90	[202] ALBRECHT	90B	ARG	$e^+e^- \to \Upsilon(4S)$

[202] ALBRECHT 90B limit assumes equal production of $B^0\overline{B}^0$ and B^+B^- at $\Upsilon(4S)$.

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_{113}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.4 × 10⁻⁵	90	[203] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.5 × 10⁻⁴	90	[204] ABREU	95N	DLPH	$e^+e^- \to Z$
<1.2 × 10⁻⁴	90	[205] ALBRECHT	88F	ARG	$e^+e^- \to \Upsilon(4S)$
<1.7 × 10⁻⁴	90	[203] BEBEK	87	CLEO	$e^+e^- \to \Upsilon(4S)$

[203] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[204] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.
[205] ALBRECHT 88F reports $< 1.3 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{p}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{114}/Γ

VALUE (units 10⁻⁴)	CL%	DOCUMENT ID		TECN	COMMENT
<2.5	90	[206] BEBEK	89	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<9.5	90	[207] ABREU	95N	DLPH	$e^+e^- \to Z$
5.4±1.8±2.0		[208] ALBRECHT	88F	ARG	$e^+e^- \to \Upsilon(4S)$

[206] BEBEK 89 reports $< 2.9 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[207] Assumes a B^0, B^- production fraction of 0.39 and a B_s production fraction of 0.12.
[208] ALBRECHT 88F reports $6.0 \pm 2.0 \pm 2.2$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(p\overline{\Lambda}\pi^-)/\Gamma_{total}$ — Γ_{115}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.8 × 10⁻⁴	90	[209] ALBRECHT	88F	ARG	$e^+e^- \to \Upsilon(4S)$

[209] ALBRECHT 88F reports $< 2.0 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\Delta^0\overline{\Delta}^0)/\Gamma_{total}$ — Γ_{116}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0015	90	[210] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$

[210] BORTOLETTO 89 reports < 0.0018 assuming $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\Delta^{++}\Delta^{--})/\Gamma_{total}$ — Γ_{117}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10⁻⁴	90	[211] BORTOLETTO	89	CLEO	$e^+e^- \to \Upsilon(4S)$

[211] BORTOLETTO 89 reports $< 1.3 \times 10^{-4}$ assuming $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\overline{\Sigma}_c^{--}\Delta^{++})/\Gamma_{total}$ — Γ_{118}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0012	90	[212] PROCARIO	94	CLE2	$e^+e^- \to \Upsilon(4S)$

[212] PROCARIO 94 reports < 0.0012 for $B(\Lambda_c^+ \to pK^-\pi^+) = 0.043$. We rescale to our best value $B(\Lambda_c^+ \to pK^-\pi^+) = 0.044$.

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{119}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.9 × 10⁻⁵	90	[213] ACCIARRI	95I	L3	$e^+e^- \to Z$

[213] ACCIARRI 95I assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_{120}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5.9 × 10^{-6}	90	AMMAR 94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.6 × 10^{-5}	90	[214] AVERY 89B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
<7.6 × 10^{-5}	90	[215] ALBRECHT 87D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
<6.4 × 10^{-5}	90	[216] AVERY 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
<3 × 10^{-4}	90	GILES 84	CLEO	Repl. by AVERY 87

[214] AVERY 89B reports $< 3 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[215] ALBRECHT 87D reports $< 8.5 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.
[216] AVERY 87 reports $< 8 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_{121}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5.9 × 10^{-6}	90	AMMAR 94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<8.3 × 10^{-6}	90	[217] ALBAJAR 91C	UA1	$E_{cm}^{p\overline{p}}$= 630 GeV
<1.2 × 10^{-5}	90	[218] ALBAJAR 91C	UA1	$E_{cm}^{p\overline{p}}$= 630 GeV
<4.3 × 10^{-5}	90	[219] AVERY 89B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
<4.5 × 10^{-5}	90	[220] ALBRECHT 87D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
<7.7 × 10^{-5}	90	[221] AVERY 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
<2 × 10^{-4}	90	GILES 84	CLEO	Repl. by AVERY 87

[217] B^0 and B_s^0 are not separated.
[218] Obtained from unseparated B^0 and B_s^0 measurement by assuming a B^0:B_s^0 ratio 2:1.
[219] AVERY 89B reports $< 5 \times 10^{-3}$ assuming the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[220] ALBRECHT 87D reports $< 5 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.
[221] AVERY 87 reports $< 9 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^0 e^+e^-)/\Gamma_{total}$ — Γ_{122}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.0 × 10^{-4}	90	ALBRECHT 91E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5.2 × 10^{-4}	90	[222] AVERY 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[222] AVERY 87 reports $< 6.5 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^0\mu^+\mu^-)/\Gamma_{total}$ — Γ_{123}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.6 × 10^{-4}	90	[223] AVERY 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5.2 × 10^{-4}	90	ALBRECHT 91E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[223] AVERY 87 reports $< 4.5 \times 10^{-4}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(K^*(892)^0 e^+e^-)/\Gamma_{total}$ — Γ_{124}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.9 × 10^{-4}	90	ALBRECHT 91E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(K^*(892)^0\mu^+\mu^-)/\Gamma_{total}$ — Γ_{125}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.3 × 10^{-5}	90	[224] ALBAJAR 91C	UA1	$E_{cm}^{p\overline{p}}$= 630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.4 × 10^{-4}	90	ALBRECHT 91E	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[224] ALBAJAR 91C assumes 36% of $\overline{b}$ quarks give B^0 mesons.

$\Gamma(e^\pm\mu^\mp)/\Gamma_{total}$ — Γ_{126}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5.9 × 10^{-6}	90	AMMAR 94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<3.4 × 10^{-5}	90	[225] AVERY 89B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
<4.5 × 10^{-5}	90	[226] ALBRECHT 87D	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
<7.7 × 10^{-5}	90	[227] AVERY 87	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
<3 × 10^{-4}	90	GILES 84	CLEO	Repl. by AVERY 87

[225] Paper assumes the $\Upsilon(4S)$ decays 43% to $B^0\overline{B}^0$. We rescale to 50%.
[226] ALBRECHT 87D reports $< 5 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 45% to $B^0\overline{B}^0$. We rescale to 50%.
[227] AVERY 87 reports $< 9 \times 10^{-5}$ assuming the $\Upsilon(4S)$ decays 40% to $B^0\overline{B}^0$. We rescale to 50%.

$\Gamma(e^\pm\tau^\mp)/\Gamma_{total}$ — Γ_{127}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<5.3 × 10^{-4}	90	AMMAR 94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

$\Gamma(\mu^\pm\tau^\mp)/\Gamma_{total}$ — Γ_{128}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<8.3 × 10^{-4}	90	AMMAR 94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

POLARIZATION IN B^0 DECAY

Γ_L/Γ in $B^0 \rightarrow J/\psi(1S)K^*(892)^0$

$\Gamma_L/\Gamma = 1[0]$ would indicate that $B^0 \rightarrow J/\psi(1S)K^*(892)^0$ followed by $K^*(892)^0 \rightarrow K_S^0\pi^0$ is a pure CP eigenstate with $CP = -1[+1]$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.76±0.07 OUR AVERAGE				
0.65±0.10±0.04	65	ABE 95Z	CDF	$p\overline{p}$ at 1.8 TeV
0.80±0.08±0.05	42	[228] ALAM 94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.97±0.16±0.15	13	[228] ALBRECHT 94G	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

[228] Averaged over an admixture of B^0 and B^+ decays.

Γ_L/Γ in $B^0 \rightarrow D^{*-}\rho^+$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.93±0.05±0.05	76	ALAM 94	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

B^0-$\overline{B}^0$ MIXING

For a discussion of B^0-$\overline{B}^0$ mixing see the note on "B^0-$\overline{B}^0$ Mixing and CP Violation in B Decay" below.

χ_d

This B^0-$\overline{B}^0$ mixing parameter is the the probability (integrated over time) that a produced B^0 (or $\overline{B}^0$) decays as a $\overline{B}^0$ (or B^0), e.g. for inclusive lepton decays

$$\chi_d = \Gamma(B^0 \rightarrow \ell^- X \text{ (via } \overline{B}^0))/\Gamma(B^0 \rightarrow \ell^\pm X)$$
$$= \Gamma(\overline{B}^0 \rightarrow \ell^+ X \text{ (via } B^0))/\Gamma(\overline{B}^0 \rightarrow \ell^\pm X)$$

Where experiments have measured the parameter $r = \chi/(1-\chi)$, we have converted to χ. Mixing violates the $\Delta B \neq 2$ rule.

Note that the measurement of χ at energies higher than the $\Upsilon(4S)$ have not separated χ_d from χ_s where the subscripts indicate $B^0(\overline{b}d)$ or $B_s^0(\overline{b}s)$. They are listed in the B_s^0-$\overline{B}_s^0$ MIXING section.

The experiments at $\Upsilon(4S)$ make an assumption about the $B^0\overline{B}^0$ fraction and about the ratio of the $B^\pm$ and B^0 semileptonic branching ratios (usually that it equals one).

OUR EVALUATION includes χ_d calculated from Δm_{B^0} and τ_{B^0}.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.175±0.016 OUR EVALUATION				
0.156±0.024 OUR AVERAGE				
0.16 ±0.04 ±0.04		[229] ALBRECHT 94	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
0.149±0.023±0.022		[230] BARTELT 93	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
0.171±0.048		[231] ALBRECHT 92L	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24 ±0.12		[232] ELSEN 90	JADE	e^+e^- 35–44 GeV
$0.158^{+0.052}_{-0.059}$		ARTUSO 89	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
0.17 ±0.05		[233] ALBRECHT 87I	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
<0.19	90	[234] BEAN 87B	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$
<0.27	90	[235] AVERY 84	CLEO	$e^+e^- \rightarrow \Upsilon(4S)$

[229] ALBRECHT 94 reports r=0.194 ± 0.062 ± 0.054. We convert to χ for comparison. Uses tagged events (lepton + pion from D^*).
[230] BARTELT 93 analysis performed using tagged events (lepton+pion from D^*). Using dilepton events they obtain $0.157 \pm 0.016^{+0.033}_{-0.028}$.
[231] ALBRECHT 92L is a combined measurement employing several lepton-based techniques. It uses all previous ARGUS data in addition to new data and therefore supersedes ALBRECHT 87I. A value of $r = 20.6 \pm 7.0$% is directly measured. The value can be used to measure $x = \Delta M/\Gamma = 0.72 \pm 0.15$ for the B_d meson. Assumes $f_{+-}/f_0 = 1.0 \pm 0.05$ and uses $\tau_{B^\pm}/\tau_{B^0} = (0.95 \pm 0.14)\ (f_{+-}/f_0)$.
[232] These experiments see a combination of B_s and B_d mesons.
[233] ALBRECHT 87I is inclusive measurement with like-sign dileptons, with tagged B decays plus leptons, and one fully reconstructed event. Measures r=0.21 ± 0.08. We convert to χ for comparison. Superseded by ALBRECHT 92L.
[234] BEAN 87B measured $r <$ 0.24; we converted to χ.
[235] Same-sign dilepton events. Limit assumes semileptonic BR for B^+ and B^0 equal. If $B^0/B^\pm$ ratio <0.58, no limit exists. The limit was corrected in BEAN 87B from $r < 0.30$ to $r < 0.37$. We converted this limit to χ.

$\Delta m_{B^0} = m_{B^0_H} - m_{B^0_L}$

Δm_{B^0} is the B^0-$\overline{B}^0$ oscillation frequency in time-dependent mixing experiments.

OUR EVALUATION includes Δm_{B^0} calculated from χ_d and τ_{B^0}.

VALUE (10^{12} $\hbar$ s^{-1})	EVTS	DOCUMENT ID		TECN	COMMENT
0.474±0.031 OUR EVALUATION					
0.50 ±0.04 OUR AVERAGE					
0.496±0.046		236 AKERS	95J	OPAL	$e^+e^- \rightarrow Z$
0.50 ±0.12 ±0.06		237 ABREU	94M	DLPH	$e^+e^- \rightarrow Z$
$0.50\ ^{+0.07}_{-0.06}\ ^{+0.11}_{-0.10}$		238 BUSKULIC	94B	ALEP	$e^+e^- \rightarrow Z$
$0.52\ ^{+0.10}_{-0.11}\ ^{+0.04}_{-0.03}$		239 BUSKULIC	93K	ALEP	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.462^{+0.040}_{-0.053}{}^{+0.052}_{-0.035}$		238 AKERS	95J	OPAL	$e^+e^- \rightarrow Z$
0.508±0.075±0.025		240 AKERS	94C	OPAL	$e^+e^- \rightarrow Z$
0.57 ±0.11 ±0.02	153	239 AKERS	94H	OPAL	$e^+e^- \rightarrow Z$

236 This AKERS 95J value combines the jet charge measurement, $D^{*\pm}$ lepton correlation measurement, and dilepton measurement from OPAL taking into account common systematic errors.
237 ABREU 94M uses $D^{*\pm}$ and hemisphere charges.
238 Uses dileptons.
239 Uses $D^{*\pm}$ lepton correlations.
240 AKERS 94C uses $D^{*\pm}\ell^{\mp}$ events and jet charge.

$x_d = \Delta m_{B^0}/\Gamma_{B^0}$

This section combines results from the previous two sections.

Time integrated mixing measurements of χ determine this quantity directly via

$$\frac{\Delta m_{B^0}}{\Gamma_{B^0}} = \left(\frac{\chi}{0.5-\chi}\right)^{1/2}$$

while time-dependent mixing measurements determine $\Delta m_{B^0} = m_{B^0_H} - m_{B^0_L}$ which are combined with τ_{B^0} to give

$$\frac{\Delta m_{B^0}}{\Gamma_{B^0}} = \frac{(m_{B^0_H} - m_{B^0_L})\ \tau_{B^0}}{\hbar} .$$

The averaging takes into account the common systematic errors on the LEP experiments due to τ_{B^0}.

VALUE	DOCUMENT ID		TECN	COMMENT
0.73±0.05 OUR AVERAGE				
0.77±0.07±0.03	241 AKERS	95J	OPAL	$e^+e^- \rightarrow Z$
0.78±0.21±0.03	241 ABREU	94M	DLPH	$e^+e^- \rightarrow Z$
0.69±0.18	242 ALBRECHT	94	ARG	$e^+e^- \rightarrow \Upsilon(4S)$
$0.78^{+0.20}_{-0.18}\pm0.03$	241 BUSKULIC	94B	ALEP	$e^+e^- \rightarrow Z$
0.65±0.10	242 BARTELT	93	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$
$0.81^{+0.17}_{-0.18}\pm0.03$	241 BUSKULIC	93K	ALEP	$e^+e^- \rightarrow Z$
0.72±0.15	242 ALBRECHT	92L	ARG	$e^+e^- \rightarrow \Upsilon(4S)$

241 Value is their Δm_{B^0} measurement combined with τ_{B^0} = (1.56 ± 0.06) ps, the average from this edition. The systematic error on τ_B and is common to experiments bearing this footnote. The averaging takes this into account.
242 Derived from time-integrated mixing parameter χ.

B^0–$\overline{B}^0$ MIXING AND CP VIOLATION IN B DECAY

(by H. Quinn, SLAC)

The neutral B meson system is like the neutral kaon system, in that two CP-conjugate states exist. For early work on CP violation in the B system see Ref. 1. The mass eigenstates are not CP eigenstates, but are mixtures of the two CP-conjugate quark states, the mixing being due to box diagrams, shown in Figure 1. The two mass eigenstates can be written

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle \ ,$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle \ . \qquad (1)$$

Here H and L stand for Heavy and Light, respectively.

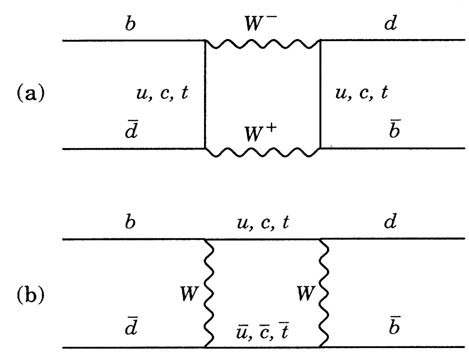


Figure 1: Mixing Diagrams.

Whereas in the kaon case the lifetimes of the two eigenstates are significantly different and the difference in masses between them is small, in the B system it is the mass differences that dominate the physics, and the two states have nearly equal predicted widths (and thus lifetimes).

$$\Gamma = (\Gamma_H + \Gamma_L)/2 \ , \ \Delta\Gamma = \Gamma_H - \Gamma_L \ . \qquad (2)$$

The difference between the widths of the two eigenstates is produced by the contributions from channels to which both B^0 and $\overline{B}^0$ can decay. These have branching ratios of $\mathcal{O}(10^{-3})$ [2]. Furthermore there are contributions of both signs to the difference, so there is no reason that the net effect should be much larger than the individual terms. Conservatively, one expects $\Delta\Gamma/\Gamma \leq 10^{-2}$. Experimentally no effect of a difference in lifetimes has been observed. In what follows, we neglect any effects from $\Delta\Gamma$, except where explicitly stated. We define also

$$M \equiv (M_H + M_L)/2 \ , \quad \Delta M \equiv M_H - M_L \ . \qquad (3)$$

The proper time evolution of an initially ($t = 0$) pure B^0 or $\overline{B}^0$ is given by

$$|B^0_{\rm phys}(t)\rangle = \exp(-\Gamma t/2)\exp(-iMt) \times \{\cos(\Delta M t/2)|B^0\rangle + i(q/p)\sin(\Delta M t/2)|\overline{B}^0\rangle\} \ ,$$

$$|\overline{B}^0_{\rm phys}(t)\rangle = \exp(-\Gamma t/2)\exp(-iMt) \times \{i(p/q)\sin(\Delta M t/2)|B^0\rangle + \cos(\Delta M t/2)|\overline{B}^0\rangle\} \ . \quad (4)$$

The probability that an initial B^0 ($\overline{B}^0$) decays as a $\overline{B}^0$ (B^0) is thus

$$P(t) = \tfrac{1}{2}e^{-\Gamma t}(1 - \cos(\Delta M t)) \quad (5)$$

where we have used $|p/q| = 1$ which is true when we neglect the effects of $\Delta\Gamma$. Time-dependent mixing measurements are now being done; earlier experiments measured only the time-integrated mixing, which is parameterized by a parameter χ_d for B_d (*i.e.*, B^0) and χ_s for B_s (*i.e.*, B^0_s). The quantity χ measures the total probability that a created B^0 decays as a $\overline{B}^0$; it is given by

$$\chi_q = \int_0^\infty P_q(t)dt = \frac{x_q^2}{2(1+x_q^2)} \ , \quad (6)$$

where $q = d, s$ and $x_q = \frac{\Delta M_q}{\Gamma_q}$, the ratio of the $B^0_q - \overline{B}^0_q$ oscillation frequency to the decay rate. The value of x_d is about 0.7, not very different from the similar quantity for the K^0 which is 0.48. The value of x_s is expected to be much larger, so that the quantity χ_s will be close to its upper limit of 0.5. This means that one cannot determine x_s accurately by measuring χ_s. It will require excellent time resolution to resolve the time-dependent mixing of the B^0_s system, and thereby determine $\Delta M_{B^0_s}$ [3].

In the B^0–$\overline{B}^0$ mixing section of the B^0 Particle Listings, we list the χ_d measurements, most of which come from $\Upsilon(4S)$ data, and the Δm_{B^0} measurements, which come from Z data. We average these sections separately, but then include the results from both sections in "OUR EVALUATION" of χ_s and $\Delta M_{B^0_s}$. We convert both of these sets of measurements and list them in the x_d section. The x_d values obtained from Δm_{B^0} measurements have a common systematic error due to the error on τ_{B^0}. The averaging takes this common systematic error into account.

In the B^0_s–$\overline{B}^0_s$ mixing section of the B^0_s Particle Listings, we give measurements of χ_B, the mixing parameter for a high-energy admixture of b-hadrons

$$\chi_B = f_d \frac{\mathcal{B}_d}{\langle\mathcal{B}\rangle}\chi_d + f_s \frac{\mathcal{B}_s}{\langle\mathcal{B}\rangle}\chi_s \ . \quad (7)$$

Here f_d and f_s are the fractions of b hadrons that are produced as B^0 and B^0_s mesons respectively, and $\mathcal{B}_d$, $\mathcal{B}_s$, and $\langle\mathcal{B}\rangle$ are branching fractions for B_d, B_s, and the b-hadron admixture respectively decaying to the observed mode. If we assume that $\chi_s = 0.5$ and $\mathcal{B}_d/\langle\mathcal{B}\rangle = \mathcal{B}_s/\langle\mathcal{B}\rangle = 1$, Eq. (7) can be used to determine f_s as discussed in the note on "Production and Decay of b-Flavored Hadrons."

CP violation in B decays—Standard Model predictions: There are three symmetries of the strong interactions that are not conserved in weak processes. These are the symmetries C, charge conjugation, which relates particle to antiparticle, P, parity, which relates a left-handed particle to a similar right-handed one, and T, time-reversal invariance, which relates a process or state to the time-reversed process or state. In all field theories the product of these three operations, CPT, is an exact symmetry of the equations of motion. All weak decays violate P and C, and a very small part of the weak decays also violate the product CP (and thus T). In the Standard Model this CP violation occurs because there is a single phase that remains in the Cabibbo-Kobayashi-Maskawa (CKM) matrix after all possible field redefinitions that can remove such phases have been made. In a minimal two-generation Standard Model no such phase occurs. The presence of CP-violating effects in K decays was interpreted by Kobayashi and Maskawa in 1973 to suggest a third quark generation. Other extensions beyond the minimal Standard Model, such as theories with additional Higgs multiplets, give further ways to introduce CP violation into the theory. Hence it is of great interest to study whether the pattern of CP-violating effects that can be observed in B decays follows the predictions of the minimal Standard Model, or instead requires the introduction of beyond Standard Model effects. In what follows we first discuss the predictions of the minimal Standard Model. Cosmologists attempting to understand the process by which the matter-antimatter asymmetry of the universe arose suggest that additional sources of CP violation may be needed to give the observed baryon to photon ratio of the universe [4]. Many models which go beyond the Standard Model indeed introduce such possibilities; a few of these are discussed in the final section of this review.

The CKM matrix is the matrix of weak couplings in the three generation Standard Model, expressed in the basis of quark mass eigenstates. This matrix, which must be unitary if the three generations are the complete theory, is discussed in some detail in a separate article in this *Review*. Here we need only remind ourselves of some notation that is commonly used in this context. The matrix can be written

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (8)$$

$$\simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \ .$$

The second expression here is a parameterization due to Wolfenstein [5] with $\lambda = \sin(\theta_{\rm Cabibbo})$, which is frequently used in discussing CP-violating effects. It is given here up to terms of order λ^3, since higher order terms in λ are negligible in most situations. For a way to include higher order terms see Ref. 6. The unitarity triangle is a simple geometrical representation of a relationship which results from the unitarity of the three-generation CKM matrix V:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \ , \tag{9}$$

(In fact there are nine such relationships given by the unitarity of the CKM matrix, but only three are independent conditions and of those the other two will be more difficult to test because they have one term that is of order λ^2 relative to the others.) The three complex quantities $V_{id}V_{ib}^*$ form a triangle in the complex plane. The three angles of this triangle are labeled

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \ , \quad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \ ,$$
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \ . \tag{10}$$

In terms of the Wolfenstein parameters we can also write

$$\tan(\alpha) = \frac{\eta}{(\eta^2 - \rho(1-\rho))} \ , \quad \tan(\beta) = \frac{\eta}{(1-\rho)} \ ,$$
$$\tan(\gamma) = \frac{\eta}{\rho} \ . \tag{11}$$

Notice that the sign as well the magnitude of these angles is meaningful and can be measured.

Figure 2 shows the unitarity triangle, as it is usually drawn, rescaled by $V_{cd}V_{cb}^*$. This makes the base of the triangle real and of unit length and the apex of the triangle is then the point(ρ, η) in the complex plane. A major aim of CP-violation studies of B decays is to make enough independent measurements of the sides and angles that this triangle is overdetermined and thus to check the validity of the Standard Model. Already a number of constraints can be made on the basis of present data on x_d, V_{ub}/V_{cb}, and ϵ in K decays. These constraints have been discussed in many places in the literature; for a recent summary see Ref. 7. Their exact form depends on the mass of the top quark and on the range of values allowed for the B_K parameter in K decays and the parameter combination $B_B f_B^2$ in B decays.

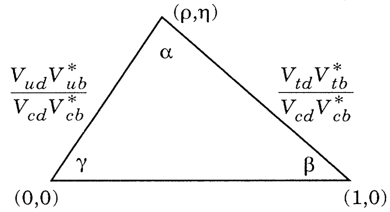


Figure 2: The (rescaled) Unitarity Triangle.

The CKM phases, that is the phases in decay amplitudes which arise because of the phase in the CKM matrix, are often called weak phases, in contrast to the phases which arise from final state rescattering effects, which are referred to as strong phases. When one compares the amplitude for decay to a CP eigenstate to that for the related CP conjugate process, the weak phase ϕ_i of each contribution changes sign, while the strong phase δ_i is unchanged:

$$\mathcal{A} = \Sigma_i \mathcal{A}_i e^{i(\delta_i + \phi_i)} \ , \ \overline{\mathcal{A}} = \Sigma_i \mathcal{A}_i e^{i(\delta_i - \phi_i)} \ . \tag{12}$$

Direct CP violation is a difference in the direct decay rate between $B \to f$ and $\overline{B} \to \overline{f}$ without any contribution from mixing effects. This requires $|\mathcal{A}| \neq |\overline{\mathcal{A}}|$, which occurs only if there is more than one term in the sum Eq. (12), and only if the two terms have both different weak phases and different strong phases. A nonzero result for Re ϵ' in K decay is a direct CP-violation effect. Direct CP violation can occur both in charged channels and in neutral channels.

In the Standard Model direct CP violation occurs when there are two sets of diagrams with different weak phases that contribute to the same decay. There are two major classes of diagrams that contribute to weak decays, tree diagrams and penguin diagrams, examples of which are shown in Figure 3. Tree diagrams are those in which the W does not reconnect to the quark line from which it was emitted. Penguin diagrams are loop diagrams in which the W is reabsorbed on the same quark line, producing a net change of flavor, and a gluon, photon or Z is emitted from the loop. There may be several different tree diagrams for a given process, namely emission from the heavy quark line accompanied by W decay, W exchange between the initial valence quarks, and/or valence quark-antiquark annihilation to produce the W. However all such contributions which enter a given transition do so with the same CKM (weak) phase. Thus, in the Standard Model, direct CP violation occurs because of interference between tree diagrams and penguin diagrams when these have different weak phases, or, in channels where there are no tree contributions, it can also arise because of different weak phases of different penguin contributions. This latter can be a significant effect for $b \to s\bar{s}d$ decays, as is discussed below.

To calculate the size of expected CP-violation effects one begins from the relevant quark decay diagrams. In general weak-decay amplitudes for b quarks can be divided into two factors: a CKM factor given by the CKM-matrix elements that enter at each W vertex, and a Feynman amplitude from evaluating the diagram. In addition to the suppression from being loop diagrams, penguin diagrams for B decay require the emission of a hard gluon (or photon) from the loop to account for the mass difference between the b quark and the s or d quark produced when the W is reabsorbed. The Feynman amplitude of the penguin diagram is thus suppressed relative to tree diagrams by a factor of order $\alpha_s(m_b)/4\pi$. It is difficult to make firm predictions based on this argument for the strength of the CP-violating effects in exclusive charged B-decay channels

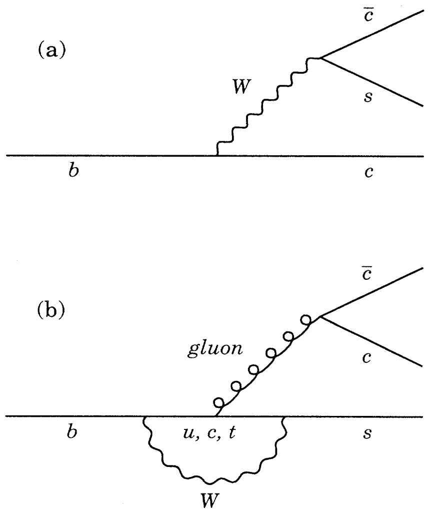


Figure 3: Quark level processes for $b \to c\overline{c}s$: (a) Tree diagram; (b) Penguin diagram. In the case of elelectroweak penguin contributions, the *gluon* is replaced by a Z or a γ.

because the relationship between the free-quark decay diagrams and the exclusive meson-decay amplitudes is model dependent. Furthermore one cannot reliably predict the strong phases that contribute to the asymmetry.

There are additional CP-violating effects in neutral B decays which arise from interference between the two paths to a given final state f

$$B \to f \text{ or } B \to \overline{B} \to f$$

This CP violation in the interference between the mixed and unmixed decay paths is sometimes called CP violation due to interference between mixing and decay. It is similar to the effect measured by the parameter Im ϵ in K decay. The interference between the two contributions can produce rate differences between the decay and its CP conjugate. These effects are of particular interest because they do not depend upon strong phases and hence the measured asymmetries can be directly related to the CKM phases. In some channels there can be direct CP violation in addition to this effect. In such channels the relationship between the measured asymmetry and the CKM parameters is more complicated. We will briefly discuss techniques to separate such contributions later in this review.

A third type of CP violation, referred to as indirect CP violation, or CP violation in the mixing, would arise from any difference in the widths $\Delta\Gamma$ of the two mass eigenstates, or more precisely from complex mixing effects that would also give a nonvanishing lifetime difference for the two B mass eigenstates. Such effects are expected to be tiny in the B_d system. For B_s a small difference in the widths is possible, due to the fact that a number of the simplest two-body channels contribute only to a single CP. The difference in widths could be as much as 20% of the total width in the B_s system [8]. In the particular case of semileptonic decays there are no penguin diagram contributions, and hence, in the approximations used throughout the discussion above, the CP-conjugate decay rates are equal. An indirect CP-violating asymmetry would be seen as an charge asymmetry in the same-sign dilepton events produced via mixing from an incoherent state that initially contains a $B^0\overline{B}^0$ pair. This asymmetry vanishes with $\Delta\Gamma$; it is expected to be no larger than 1% in B_d decays. [9].

A simple way to distinguish the three types of CP violation is to note that direct CP violation occurs when $|\overline{\mathcal{A}}/\mathcal{A}| \neq 1$, indirect CP violation requires $|q/p| \neq 1$, but CP violation due the interference between direct decay and decay after mixing can occur when both quantities have unit absolute value; it requires only that their product have a nonzero weak phase [10].

Neutral B decays to CP eigenstates: The decays of neutral B's into CP eigenstates is of particular interest because many of these decays allow clean theoretical interpretation in terms of the parameters of the Standard Model [11]. We denote such a state by f_{CP}, for example $f_{CP} = J/\psi(1S)K_S$ or $f_{CP} = \pi\pi$, and define the amplitudes

$$\mathcal{A}_{f_{CP}} \equiv \langle f_{CP}|B^0\rangle\,, \quad \overline{\mathcal{A}}_{f_{CP}} \equiv \langle f_{CP}|\overline{B}^0\rangle \ . \tag{13}$$

For convenience let us introduce the quantity $r_{f_{CP}}$

$$r_{f_{CP}} \equiv \frac{q}{p}\frac{\overline{\mathcal{A}_{f_{CP}}}}{\mathcal{A}_{f_{CP}}} \ . \tag{14}$$

In the limit of no CP violation, $r_{f_{CP}} = \pm 1$, where the sign is given by the CP eigenvalue of the particular state f_{CP}. (Note that in the literature the quantity $r_{f_{CP}}$ is frequently denoted by λ, but we have chosen to avoid this notation as it introduces a confusion with the $\lambda = \sin(\theta_{\text{Cabibbo}})$ in the Wolfenstein parameterization of the CKM matrix.)

The time-dependent rates for initially pure B^0 or $\overline{B}^0$ states to decay into a final state f_{CP} at time t is then given by:

$$\begin{aligned}
&\langle f_{CP}|B^0_{\text{phys}}(t)\rangle = \\
&\quad \mathcal{A}_{f_{CP}} \exp(-\Gamma t/2)\exp(-iMt) \\
&\qquad \times [\cos(\Delta Mt/2) + i r_{f_{CP}} \sin(\Delta Mt/2)] \ , \\
&\langle f_{CP}|\overline{B}^0_{\text{phys}}(t)\rangle = \\
&\quad \mathcal{A}_{f_{CP}} \exp(-\Gamma t/2)\exp(-iMt)(p/q) \\
&\qquad \times [i \sin(\Delta Mt/2) + r_{f_{CP}} \cos(\Delta Mt/2)] \ .
\end{aligned} \tag{15}$$

Thus

$$\begin{aligned}
&\Gamma(B^0_{\text{phys}}(t) \to f_{CP}) = \\
&\quad |\mathcal{A}_{f_{CP}}|^2 e^{-\Gamma t}\Big[\frac{1+|r_{f_{CP}}|^2}{2} + \frac{1-|r_{f_{CP}}|^2}{2} \\
&\qquad \times \cos(\Delta Mt) - \text{Im}\ r_{f_{CP}} \sin(\Delta Mt)\Big],
\end{aligned}$$

$$\Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP}) =$$
$$|\mathcal{A}_{f_{CP}}|^2 e^{-\Gamma t}\Big[\frac{1+|r_{f_{CP}}|^2}{2} - \frac{1-|r_{f_{CP}}|^2}{2} \times \cos(\Delta M t) + {\rm Im}\, r_{f_{CP}} \sin(\Delta M t)\Big] \ . \qquad (16)$$

The time-dependent CP asymmetry is

$$a_{f_{CP}}(t) \equiv \frac{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) - \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})}{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) + \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})} \qquad (17)$$

and thus

$$a_{f_{CP}}(t) = \frac{(1-|r_{f_{CP}}|^2)\cos(\Delta M t) - 2{\rm Im}\,(r_{f_{CP}})\sin(\Delta M t)}{1+|r_{f_{CP}}|^2} \ . \qquad (18)$$

When the small difference in width of the two B_d states is ignored we can write

$$(q/p)_{B_d} = \frac{(V^*_{tb}V_{td})}{(V_{tb}V^*_{td})} \ , \qquad (19)$$

and thus

$$q/p = e^{-2i\phi_M} \ , \qquad (20)$$

where $2\phi_M$ denotes the CKM phase of the B–$\overline{B}$ mixing diagram. Further, when there is no direct CP violation in a channel, that is when all amplitudes that contribute have the same CKM decay-phase, ϕ_D, then $|\mathcal{A}_{f_{CP}}/\overline{\mathcal{A}_{f_{CP}}}| = 1$. In that case $r_{f_{CP}}$ depends on CKM-matrix parameters only, without hadronic uncertainties, and can be written $r_{f_{CP}} = \pm e^{-2i(\phi_D+\phi_M)}$. Then Eq. (18) simplifies to

$$a_{f_{CP}}(t) = \mp{\rm Im}\,(r_{f_{CP}})\sin(\Delta M t) = \pm\sin(2(\phi_M+\phi_D))\sin(\Delta M t) \ . \qquad (21)$$

where the overall sign is given by the CP eigenvalue, ± 1, of the final state f_{CP}. The mixing phase ϕ_M and the decay phase ϕ_D are each convention dependent, that is their value can be changed by redefining the phases of some of the quark fields. However Im $r_{f_{CP}}$ depends on convention-independent combinations of CKM parameters only, and thus from Eq. (21) one can directly relate the measured CP-violating asymmetry to the phase of particular combination of CKM-matrix elements in the Standard Model.

In an e^+e^- B collider running at the $\Upsilon(4S)$ resonance, the initial B system is produced in a definite CP-eigenstate state which evolves coherently and thus remains $B^0\overline{B}^0$ until such time as one of the particles decays. The time evolution of the second particle to decay thus begins at the time of the first decay. Events where one B decays to a flavor-tagging mode while the other decays to a CP-study mode can be used to reconstruct the dependence of the asymmetry on the time between the tagging decay and the CP-study mode decay. The tagging decay may be later, in which case the event is assigned a negative time. Note that the measurement of time dependence is essential at such a machine since, in the interesting cases where Eq. (21) applies, the time-integrated CP asymmetry vanishes.

Hadron machines on the other hand produce uncorrelated B and $\overline{B}$ mesons. In that case the time in the above equations is the time between production and decay, which is always positive, so time-integrated asymmetries do not vanish. Both the tagging particle and the particle decaying to the CP-study mode evolve through mixing, beginning from the time of production. Such machines produce many more B's than will an e^+e^- B factory but the necessity of triggering selections to isolate B events reduces the effective signal somewhat. In addition there are significant backgrounds to contend with in purely hadronic channels, so those channels with leptonic signatures are more readily studied in this environment. The results from the two types of machines will have many complementary features.

Extracting CKM parameters from measured asymmetries: In order to relate the measured asymmetries to the CKM-matrix parameters one looks at the CKM elements that appear in the relevant decay amplitudes and in the mixing diagrams. If the final state of the decay includes a K_S, an additional contribution from the K-mixing phase must be included in relating the measured asymmetry to the CKM parameters.

Table 1 gives the CKM factors for the various b-quark decay channels. For penguin diagrams the table gives the CKM factor of the dominant contributions. Unitarity of the CKM matrix is used to re-express the three different up-type quark loop contributions as a sum of two terms, one of which dominates the contribution. In the case of $b \to d$ processes the subdominant term is suppressed by a term which vanishes with the difference between charm and up quark masses. In the case of $b \to s$ decays the subdominant penguin amplitudes are suppressed by two powers of λ relative to the dominant term given here.

The columns labeled "Sample B_d Modes" and "Sample B_s Modes" list some of the simplest CP-study modes for each case. (These are either CP eigenstates, or modes from which CP-eigenstate contributions can be isolated, for example by angular analysis.) The columns labeled "Angle" show the particular combination of CKM phases $\phi_M + \phi_D$ that is measured by the CP-violating asymmetry in these decays, given as an angle of the unitarity triangle. For most channels the measured asymmetry in a time-dependent measurement is $\pm\sin(2(\phi_M+\phi_D))\sin(\Delta M t)$. For a time-integrated measurement (uncorrelated production) the asymmetry is $\pm(x_q/(1+x_q^2))\sin(2(\phi_M+\phi_D))$. The sign is given by the CP eigenvalue of the particular final state studied. (The exception to these statements is the channel DK discussed below.)

In obtaining the results given in the table several simplifying approximations have been used. Terms of higher order in $\lambda = \sin(\theta_{\rm Cabibbo})$ have been dropped. Penguin diagrams that occur at the same order of λ as the corresponding tree diagrams are neglected in stating the relationship of the asymmetry to angles in the unitarity triangle. The comments below the table state where these assumptions are used. Even with these assumptions there are cases where the tree and penguin diagrams are expected to give comparable contributions with different CKM phases. For these decays, as with other direct CP-violating processes, there is no simple relationship between the measured asymmetry and a CKM phase, and thus no entry in the "Angle" columns in Table 1.

The mode $D^0K^*(892)$ is listed even though it is not a CP eigenstate because it has been shown that an analysis of this mode can be used to extract the angle γ [12]. The same type of analysis can also be applied to charged B decays [13]. However the relationship between the decay asymmetry and the angle is not as simple as Eq. (21) in this case. The result will require accurate measurements of a number of branching ratios.

In the case of the $b \rightarrow u\overline{u}d + d\overline{d}d$, the penguin contributions occur at the same order in λ as the tree diagrams and are thus are expected to be small compared to them because of the $\alpha(m_b)/\pi$ suppression factor. The result given in Table 1 makes this approximation. If however this expectation proves false, so that the contributions are comparable, one still may be able to extract a measurement of $\sin(2\alpha)$ from the $\pi^+\pi^-$ asymmetry. This is achieved by measuring the rates in several isospin-related channels and using a multiparameter fit to separate tree and penguin contributions to the amplitudes [14]. The impact of electroweak penguins, which will not be removed by this analysis [15] is quite small in this channel. [16] The isospin analysis will require measuring the decay rate for channel $\pi^0\pi^0$, which will be a challenge. For the $\rho\pi$ decays, if penguins are not negligible, the restrictions due to isospin can again be used to make a multiparameter fit to the ρ-regions of the Dalitz plot for $\pi^+\pi^-\pi^0$ distribution [17]. The interference between different ρ-charge channels is significant and may provide sufficient information to allow the separation of tree and penguin effects and thus extraction of the parameter α. Such analyses at the very least can be used to test whether the penguin contributions are indeed small enough to be neglected in the determination of α.

In the case $b \rightarrow s\overline{s}d$ there are no tree graph contributions. The phase of the dominant penguin contribution is such that, combined with mixing effects, it gives a zero asymmetry for

Table 1: B decay modes for CP studies.

Quark Process	Tree CKM	Leading Penguin CKM	Sample B_d Modes	B_d Angle	Sample B_s Modes	B_s Angle	Comments
$b \rightarrow c\overline{c}s$	$V_{cb}V^*_{cs} = A\lambda^2$	$V_{cb}V^*_{cs} = A\lambda^2$	$J/\psi(1S)K_S$	β	$J/\psi(1S)\eta', D_s\overline{D}_s$	0	(a)
$b \rightarrow s\overline{s}s$	0	$V_{cb}V^*_{cs} = A\lambda^2$	ϕK_S	β	$\phi\eta'$	0	(b)
$b \rightarrow u\overline{u}s$	$V_{ub}V^*_{us} = A\lambda^4(\rho - i\eta)$	$V_{cb}V^*_{cs} = A\lambda^2$	$K_S\pi^0, K_S\rho^0$	–	$\phi\pi^0, K^+K^-$	–	(c)
$b \rightarrow d\overline{d}s$	0	$V_{cb}V^*_{cs} = A\lambda^2$	$K_S\pi^0, K_S\rho^0$	–	$\phi\pi^0, K_S\overline{K}_S$	–	(c)
$b \rightarrow c\overline{c}d$	$V_{cb}V^*_{cd} = -A\lambda^3$	$V_{tb}V^*_{td} = A\lambda^3(1 - \rho + i\eta)$	$D^+D^-, J/\psi(1S)\pi^0, D^0\overline{D}^0(\dagger)$	β	$J/\psi(1S)K_S$	0	(d)
$b \rightarrow s\overline{s}d$	0	$V_{tb}V^*_{td} = A\lambda^3(1 - \rho + i\eta)$	$\phi\pi^0, K_S\overline{K}_S$	–	ϕK_S	β	(c)
$b \rightarrow u\overline{u}d$ $b \rightarrow d\overline{d}d$	$V_{ub}V^*_{ud} = A\lambda^3(\rho - i\eta)$ 0	$V_{tb}V^*_{td} = A\lambda^3(1 - \rho + i\eta)$	$\pi\pi, \pi\rho, \pi a_1$	α	π^0K_S, ρ^0K_S	γ	(e)
$b \rightarrow c\overline{u}s$ $b \rightarrow u\overline{c}s$	$V_{cb}V^*_{us} = A\lambda^3$ $V_{ub}V^*_{cs} = A\lambda^3(\rho - i\eta)$	0	$D^0_{CP}K^*(892)$	γ	$D^0_{CP}\phi$	–	$(f), (g)$
$b \rightarrow c\overline{u}d$ $b \rightarrow u\overline{c}d$	$V_{cb}V^*_{ud} = A\lambda^2$ $V_{ub}V^*_{cd} = A\lambda^4(\rho - i\eta)$	0	$D^0_{CP}\pi^0, D^0_{CP}\rho^0$	–	$D^0_{CP}K_S$	–	(g)

(a) Tree and penguin contribute with same weak phase.
(b) Penguin only, rare decays.
(c) Tree and penguin compete. Isospin analysis may allow extraction of α, β, for B_d channels, γ, 0 for B_s, where these angles come from tree and penguin contributions respectively. $K_S\overline{K}_S$ penguin only, except 0 asymmetry.
(d) Ignoring penguin relative to tree.
(e) Ignoring penguin relative to tree, or using isospin analysis.
(f) Self-tagging $K^*(892)$ decay modes can give γ when data from $B_d \rightarrow D^0_{CP}$, *i.e.* decays to CP eigenstates, and D^0- or $\overline{D}^0$-identified modes are combined. Similar results for charged $B \rightarrow DK$.
(g) Asymmetry in $D^0_{CP}\pi$, $D^0_{CP}K_S$, *etc.* modes is difficult to relate to CKM angles.
$(\dagger)$ $D^0\overline{D}^0$ from rescattering only, rate expected to be small.

B_d decays and an asymmetry proportional to β for B_s decays. However, Gérard and Hou [18] have pointed out that the sub-dominant penguin terms, proportional to $V_{ub}V^*_{ud}$ can give significant direct CP-violation asymmetries for such channels. Fleischer [19] has estimated that this asymmetry is possibly as large as 50%. While the sub-dominant term in this case would vanish if the masses of the up quark and the charm quark were equal, these estimates, based on the actual quark mass values and operator matrix elements estimated using models, cannot be excluded. Thus, contrary to some comments in the literature, observation of CP-violating asymmetries in channels such as $B_d \rightarrow \phi\pi^0$ or $K^0\overline{K}^0$ would not necessarily require beyond-Standard-Model effects to explain them. The B_s decays $b \rightarrow c\overline{c}s$ and $b \rightarrow s\overline{s}s$ are not affected by this argument. In the first of these the tree terms dominate and the dominant penguin contributions have the same weak phase as those, so the doubly Cabibbo-suppressed sub-dominant penguin contributions are truly negligible. Even in the second case, where there are no tree contributions, the sub-dominant penguin terms are again doubly Cabibbo-suppressed ($V_{ub}V^*_{us}$ compared to $V_{cb}V^*_{cs}$) and thus the possible Standard Model asymmetry is less than a few percent.

There are some common decay channels of the B^0 and $\overline{B}^0$ which are not CP eigenstates. For example the channel $J/\psi(1S)K^*(892)$ where the $K^*(892) \rightarrow K_S\pi^0$, the final state is not a CP eigenstate because both even and odd relative angular momenta between the $J/\psi(1S)$ and the $K^*(892)$ are allowed. If there is sufficient data one can use angular analysis to separate the different CP final states and measure the asymmetry in each [21]. The same applies in many quasi-two-body decays, such as other vector-vector channels, or those with higher-spin particles in final states. The branching ratio to these channels can be significantly larger than the CP-eigenstate (vector-scalar or scalar-scalar) channels with the same quark content. Such angular analyses may therefore be important in achieving accurate values for the parameters α and β.

Additional ways to extract CKM parameters by relationships between rates for channels such as $\pi\pi$, πK that can be extracted using SU(3) invariance have received considerable recent attention in the literature. [20] While these relationships will be interesting to investigate, the uncertainties introduced by SU(3) corrections may be significant. The review by Buras cited above gives a good summary of these ideas.

Beyond-Standard-Model effects: The predictions given above are all for the Standard Model. Models beyond the Standard Model may introduce additional contributions to the mixing amplitudes and thereby destroy the relationships given here; in addition they may introduce further direct CP violation.

One model often used as a "straw man" in evaluating the potential of experimental tests of Standard Model predictions is the superweak model, which was one of the earliest proposals for the mechanism of CP violation; in fact it predates the Standard Model [22]. In the modernized version of this model it is assumed that the CKM matrix is real and that all CP-violating effects arise from a contribution to the mixing that comes from beyond the Standard Model. In this case *all* the CP-eigenstate channels for B decay would have the same CP-violating asymmetry (up to a sign which differs for CP-odd and CP-even channels) [23]. This applies even to those channels predicted to have zero asymmetry in the Standard Model, as well as those for which the Standard Model prediction is complicated by the competition between tree and penguin contributions. Observation of significantly different asymmetries in any two neutral B decay CP-eigenstate channels would rule out such a model. In addition the observation of any asymmetry in a charged B decay or in a neutral B decay to a flavor-tagging final state would be evidence for direct CP violation [24] and would exclude the superweak model.

Many other models for the physics beyond the Standard Model have been discussed in the literature [25]. The most common additional CP-violating effect is a new contribution to the mixing process, due for example to charged Higgs contributions. The appearance of such contributions in K mixing is already severely restricted by the neutral-K mass difference. However this does not rule out additional contributions to B mixing that would destroy the relationship between the mixing phase ϕ_M and the CKM-matrix elements. This in turn would lead to violations of the predictions given in Table 1 which are based on this relationship. Models with additional (exotic or fourth generation) quarks would remove the constraints of the three-generation mixing matrix and hence lead to the failure of Eq. (9) and would allow new contributions to $B^0 - \overline{B}^0$ mixing and hence lead to the failure of Eq. (19) [26]. *Any* observed deviations from the relationships predicted by the Standard Model will provide a window on the nature of physics beyond the Standard Model.

While the discussion above stresses those channels in which there is a simple relationship between an observed asymmetry and the parameters of the CKM matrix in the Standard Model, this does not mean that other channels are entirely without interest. To date CP violation has only been observed in the neutral K system. Any observation of CP violation in B decays would be exciting. The Standard Model prediction is that direct CP-violating asymmetries are likely to be at most a few percent, so large effects in these channels would suggest beyond Standard Model effects. On the other hand, even within the Standard Model the asymmetries due to the interference between decays with and without mixing in the neutral B system can be quite large; current constraints do not rule out cases where Im $(r_{f_{CP}})$ is 1. It is likely that study of the many common decay channels of the B^0 and the $\overline{B}^0$ will greatly expand our understanding of the sources of CP violation.

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CP VIOLATION PARAMETERS

$|\mathrm{Re}(\epsilon_{B^0})|$

CP Impurity in B^0_d system. It is obtained from $a_{\ell\ell}$, the charge asymmetry in like-sign dilepton events at the $\Upsilon(4S)$.

$$\mathrm{Re}(\epsilon_{B^0}) \simeq \tfrac{1}{4} a_{\ell\ell} = \tfrac{1}{4}\ \frac{N(\ell^+\ell^+)-N(\ell^-\ell^-)}{N(\ell^+\ell^+)+N(\ell^-\ell^-)} .$$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.045	[243] BARTELT	93	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[243] BARTELT 93 finds $a_{\ell\ell} = 0.031 \pm 0.096 \pm 0.032$ which corresponds to $|a_{\ell\ell}| < 0.18$, which yields the above $\mathrm{Re}(\epsilon_{B^0})$.

B^0 REFERENCES

ABE 96B PR D53 3496 +Albrow, Amendolia, Amidei+ (CDF Collab.)
ABE 96C PRL (to be publ.) +Akimoto, Akopian, Albrow+ (CDF Collab.)
CDF/PUB/BOTTOM/PUB/3492
ASNER 96 PR D53 1039 +Athanas, Bliss, Brower+ (CLEO Collab.)
BUSKULIC 96G ZPHY C (submitted) +De Bonis, Decamp, Ghez+ (ALEPH Collab.)
CERN-PPE/96-14
ABE 95Z PRL 75 3068 +Albrow, Amendolia, Amidei+ (CDF Collab.)
ABREU 95N PL B357 255 +Adam, Adye, Agasi+ (DELPHI Collab.)
ABREU 95Q ZPHY C68 13 +Adam, Adye, Agasi+ (DELPHI Collab.)
ACCIARRI 95H PL B363 127 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
ACCIARRI 95I PL B363 137 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
ADAM 95 ZPHY C68 363 +Adye, Agasi, Ajinenko+ (DELPHI Collab.)
AKERS 95J ZPHY C66 555 +Alexander, Allison, Ametewee+ (OPAL Collab.)
AKERS 95T ZPHY C67 379 +Alexander, Allison, Ametewee+ (OPAL Collab.)
ALEXANDER 95 PL B341 435 +Bebek, Berkelman, Bloom+ (CLEO Collab.)
Also 95C PL B347 469 (erratum) Alexander, Bebek, Berkelman, Bloom+ (CLEO Collab.)
BARISH 95 PR D51 1014 +Chadha, Chan, Cowen+ (CLEO Collab.)
BUSKULIC 95N PL B359 236 +Casper, De Bonis, Decamp+ (ALEPH Collab.)
ABE 94D PRL 72 3456 +Albrow, Amidei, Anway-Wiese, Apollinari (CDF Collab.)
ABREU 94M PL B338 409 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
AKERS 94C PL B327 411 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
AKERS 94H PL B336 585 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
AKERS 94J PL B337 196 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
AKERS 94L PL B337 393 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
ALAM 94 PR D50 43 +Kim, Nemati, O'Neill, Severini+ (CLEO Collab.)
ALBRECHT 94 PL B324 249 +Ehrlichmann, Hamacher+ (ARGUS Collab.)
ALBRECHT 94G PL B340 217 +Hamacher, Hofmann, Kirchhoff, Mankel+ (ARGUS Collab.)
AMMAR 94 PR D49 5701 +Ball, Baringer, Bean, Besson, Coppage+ (CLEO Collab.)
ATHANAS 94 PRL 73 3503 +Brower, Masek, Paar, Gronberg+ (CLEO Collab.)
Also 95 PRL 74 3090 (erratum) Athanas, Brower, Masek, Paar+ (CLEO Collab.)
BUSKULIC 94B PL B322 441 +De Bonis, Decamp, Ghez, Goy, Lees+ (ALEPH Collab.)
PDG 94 PR D50 1173 Montanet+ (CERN, LBL, BOST, IFIC+)
PROCARIO 94 PRL 73 1306 +Balest, Cho, Daoudi, Ford+ (CLEO Collab.)
STONE 94 HEPSY 93-11
ABREU 93D ZPHY C57 181 +Adam, Adye, Agasi, Alekseev+ (DELPHI Collab.)
ABREU 93G PL B312 253 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
ACTON 93C PL B307 247 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALBRECHT 93 ZPHY C57 533 +Ehrlichmann, Hamacher, Hofmann+ (ARGUS Collab.)
ALBRECHT 93E ZPHY C60 11 +Ehrlichmann, Hamacher, Hofmann+ (ARGUS Collab.)
ALEXANDER 93B PL B319 365 +Bebek, Berkelman, Bloom, Browder+ (CLEO Collab.)
AMMAR 93 PRL 71 674 +Ball, Baringer, Coppage, Copty+ (CLEO Collab.)
BARTELT 93 PRL 71 1680 +Csorna, Egyed, Jain, Sheldon+ (CLEO Collab.)
BATTLE 93 PRL 71 3922 +Ernst, Kroha, Kwon, Roberts+ (CLEO Collab.)
BEAN 93B PRL 70 2681 +Gronberg, Kutschke, Menary, Morrison+ (CLEO Collab.)
BUSKULIC 93D PL B307 194 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
Also 94H PL B325 537 (errata)
BUSKULIC 93K PL B313 498 +De Bonis, Decamp, Ghez, Goy+ (ALEPH Collab.)
SANGHERA 93 PR D47 791 +Skwarnicki, Stroynowski, Artuso, Goldberg+(CLEO Collab.)
ALBRECHT 92C PL B275 195 +Ehrlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
ALBRECHT 92G ZPHY C54 1 +Ehrlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
ALBRECHT 92L ZPHY C55 357 +Ehrlichmann, Hamacher, Krueger, Nau+ (ARGUS Collab.)
BORTOLETTO 92 PR D45 21 +Brown, Dominick, McIlwain+ (CLEO Collab.)
HENDERSON 92 PR D45 2212 +Kinoshita, Pipkin, Procario+ (CLEO Collab.)
KRAMER 92 PL B279 181 +Palmer (HAMB, OSU)
ALBAJAR 91C PL B262 163 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
ALBAJAR 91E PL B273 540 +Albrow, Allkofer, Ankoviak+ (UA1 Collab.)
ALBRECHT 91B PL B254 288 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
ALBRECHT 91C PL B255 297 +Ehrlichmann, Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 91E PL B262 148 +Glaeser, Harder, Krueger, Nippe+ (ARGUS Collab.)
BERKELMAN 91 ARNPS 41 1 +Stone (CORN, SYRA)
"Decays of *B* Mesons"
FULTON 91 PR D43 651 +Jensen, Johnson, Kagan, Kass+ (CLEO Collab.)
ALBRECHT 90B PL B241 278 +Glaeser, Harder, Krueger, Nilsson+ (ARGUS Collab.)
ALBRECHT 90J ZPHY C48 543 +Ehrlichmann, Harder, Krueger+ (ARGUS Collab.)
ANTREASYAN 90B ZPHY C48 553 +Bartels, Bieler, Bienlein, Bizzeti+ (Crystal Ball Collab.)
BORTOLETTO 90 PRL 64 2117 +Goldberg, Horwitz, Jain, Mestayer+ (CLEO Collab.)
ELSEN 90 ZPHY C46 349 +Allison, Ambrus, Barlow, Bartel+ (JADE Collab.)
ROSNER 90 PR D42 3732
WAGNER 90 PRL 64 1095 +Hinshaw, Ong, Snyder+ (Mark II Collab.)
ALBRECHT 89C PL B219 121 +Boeckmannn, Glaeser, Harder+ (ARGUS Collab.)
ALBRECHT 89G PL B229 304 +Glaeser, Harder, Krueger+ (ARGUS Collab.)
ALBRECHT 89J PL B229 175 +Glaser, Harder+ (ARGUS Collab.)
ALBRECHT 89L PL B232 554 +Glaeser, Harder, Krueger, Nippe, Oest+ (ARGUS Collab.)
ARTUSO 89 PRL 62 2233 +Bebek, Berkelman, Blucher+ (CLEO Collab.)
AVERILL 89 PR D39 123 +Blockus, Brabson+ (HRS Collab.)
AVERY 89B PL B223 470 +Besson, Garren, Yelton+ (CLEO Collab.)
BEBEK 89 PRL 62 8 +Berkelman, Blucher+ (CLEO Collab.)
BORTOLETTO 89 PRL 62 2436 +Goldberg, Horwitz, Mestayer+ (CLEO Collab.)
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ALBRECHT 88F PL B209 119 +Boeckmann, Glaeser+ (ARGUS Collab.)
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ALBRECHT 87C PL B185 218 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
ALBRECHT 87D PL B199 451 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
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ALBRECHT 87J PL B197 452 +Andam, Binder, Boeckmann+ (ARGUS Collab.)
AVERY 87 PL B183 429 +Besson, Bowcock, Giles+ (CLEO Collab.)
BEAN 87B PRL 58 183 +Bobbink, Brock, Engler+ (CLEO Collab.)
BEBEK 87 PR D36 1289 +Berkelman, Blucher, Cassel+ (CLEO Collab.)
ALAM 86 PR D34 3279 +Katayama, Kim, Sun+ (CLEO Collab.)
ALBRECHT 86F PL B182 95 +Binder, Boeckmann, Glaser+ (ARGUS Collab.)
PDG 86 PL 170B Aguilar-Benitez, Porter+ (CERN, CIT+)
CHEN 85 PR D31 2386 +Goldberg, Horwitz, Jawahery+ (CLEO Collab.)
HAAS 85 PRL 55 1248 +Hempstead, Jensen, Kagan+ (CLEO Collab.)
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$B^{\pm}/B^0$ ADMIXTURE

B DECAY MODES

The branching fraction measurements are for an admixture of B mesons at the $\Upsilon(4S)$. The values quoted assume that $B(\Upsilon(4S) \to B\overline{B}) = 100\%$.

For inclusive branching fractions, *e.g.*, $B \to D^{\pm}$ anything, the treatment of multiple D's in the final state must be defined. One possibility would be to count the number of events with one-or-more D's and divide by the total number of B's. Another possibility would be to count the total number of D's and divide by the total number of B's, which is the definition of average multiplicity. The two definitions are identical when only one of the specified particles is allowed in the final state. Even though the "one-or-more" definition seems sensible, for practical reasons inclusive branching fractions are almost always measured using the multiplicity definition. For heavy final state particles, authors call their results inclusive branching fractions while for light particles some authors call their results multiplicities. In the B sections, we list all results as inclusive branching fractions, adopting a multiplicity definition. This means that inclusive branching fractions can exceed 100% and that inclusive partial widths can exceed total widths, just as inclusive cross sections can exceed total cross sections.

$\overline{B}$ modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_1	$e^+ \nu_e$ anything	[a]	(10.4 ±0.4) %	S=1.3
Γ_2	$\overline{p} e^+ \nu_e$ anything		< 1.6 × 10^{-3}	CL=90%
Γ_3	$\mu^+ \nu_\mu$ anything	[a]	(10.3 ±0.5) %	
Γ_4	$\ell^+ \nu_\ell$ anything	[a,b]	(10.43±0.24) %	
Γ_5	$D^- \ell^+ \nu_\ell$ anything	[b]	(2.7 ±0.8) %	
Γ_6	$\overline{D}^0 \ell^+ \nu_\ell$ anything	[b]	(7.0 ±1.4) %	
Γ_7	$D^{*-} \ell^+ \nu_\ell$ anything			
Γ_8	$D^{*0} \ell^+ \nu_\ell$ anything			
Γ_9	$\overline{D}^{**} \ell^+ \nu_\ell$	[b,c]	(2.7 ±0.7) %	
Γ_{10}	$\overline{D}(1)(2420)^0 \ell^+ \nu_\ell$ anything		seen	
Γ_{11}	$\overline{D}(2)^*(2460)^0 \ell^+ \nu_\ell$ anything		not seen	
Γ_{12}	$D^{*-} \pi^+ \ell^+ \nu_\ell$ anything		(1.00±0.34) %	
Γ_{13}	$D_s^- \ell^+ \nu_\ell$ anything	[b]	< 9 × 10^{-3}	CL=90%
Γ_{14}	$D_s^- \ell^+ \nu_\ell K^+$ anything	[b]	< 6 × 10^{-3}	CL=90%
Γ_{15}	$D_s^- \ell^+ \nu_\ell K^0$ anything	[b]	< 9 × 10^{-3}	CL=90%
Γ_{16}	$\ell^+ \nu_\ell$ noncharmed	[b]		
Γ_{17}	$K^+ \ell^+ \nu_\ell$ anything	[b]	(6.0 ±0.5) %	
Γ_{18}	$K^- \ell^+ \nu_\ell$ anything	[b]	(10 ±4) × 10^{-3}	
Γ_{19}	$K^0 / \overline{K}^0 \ell^+ \nu_\ell$ anything	[b]	(4.4 ±0.5) %	
	***D*, *D**, or *D$_s$* modes**			
Γ_{20}	$D^{\pm}$ anything		(24.2 ±3.3) %	
Γ_{21}	$D^0 / \overline{D}^0$ anything		(58 ±5) %	S=1.1
Γ_{22}	$D^*(2010)^{\pm}$ anything		(23.1 ±3.3) %	S=1.1
Γ_{23}	$D_s^{\pm}$ anything	[d]	(8.6 ±1.6) %	
Γ_{24}	$D_s D$, $D_s^* D$, $D_s D^*$, or $D_s^* D^*$	[d]	(4.9 ±1.1) %	
Γ_{25}	$D^*(2010)\gamma$		< 1.1 × 10^{-3}	CL=90%
Γ_{26}	$D_s^+ \pi^-$, $D_s^{*+} \pi^-$, $D_s^+ \rho^-$, $D_s^{*+} \rho^-$, $D_s^+ \pi^0$, $D_s^{*+} \pi^0$, $D_s^+ \eta$, $D_s^{*+} \eta$, $D_s^+ \rho^0$, $D_s^{*+} \rho^0$, $D_s^+ \omega$, $D_s^{*+} \omega$	[d]	< 5 × 10^{-4}	CL=90%
	Charmonium modes			
Γ_{27}	$J/\psi(1S)$ anything		(1.14±0.06) %	
Γ_{28}	$J/\psi(1S)$ (direct) anything		(8.0 ±0.8) × 10^{-3}	
Γ_{29}	$\psi(2S)$ anything		(3.5 ±0.5) × 10^{-3}	
Γ_{30}	$\chi_{c1}(1P)$ anything		(4.2 ±0.7) × 10^{-3}	
Γ_{31}	$\chi_{c1}(1P)$ (direct) anything		(3.7 ±0.7) × 10^{-3}	
Γ_{32}	$\chi_{c2}(1P)$ anything		< 3.8 × 10^{-3}	CL=90%
Γ_{33}	$\eta_c(1S)$ anything		< 9 × 10^{-3}	CL=90%
	***K* or *K** modes**			
Γ_{34}	$K^{\pm}$ anything	[d]	(78.9 ±2.5) %	
Γ_{35}	K^+ anything		(66 ±5) %	
Γ_{36}	K^- anything		(13 ±4) %	
Γ_{37}	$K^0 / \overline{K}^0$ anything	[d]	(64 ±4) %	
Γ_{38}	$K^*(892)^{\pm}$ anything		(18 ±6) %	
Γ_{39}	$K^*(892)^0 / \overline{K}^*(892)^0$ anything	[d]	(14.6 ±2.6) %	
Γ_{40}	$K^*(892)\gamma$			
Γ_{41}	$K_1(1400)\gamma$		< 4.1 × 10^{-4}	CL=90%
Γ_{42}	$K_2^*(1430)\gamma$		< 8.3 × 10^{-4}	CL=90%
Γ_{43}	$K_2(1770)\gamma$		< 1.2 × 10^{-3}	CL=90%
Γ_{44}	$K_3^*(1780)\gamma$		< 3.0 × 10^{-3}	CL=90%
Γ_{45}	$K_4^*(2045)\gamma$		< 1.0 × 10^{-3}	CL=90%
Γ_{46}	$\overline{b} \to \overline{s}\gamma$		(2.3 ±0.7) × 10^{-4}	
Γ_{47}	$\overline{b} \to \overline{s}$gluon			
	Light unflavored meson modes			
Γ_{48}	$\pi^{\pm}$ anything	[d,e]	(359 ±7) %	
Γ_{49}	ρ^0 anything		(21 ±5) %	
Γ_{50}	ω anything		< 81 %	CL=90%
Γ_{51}	ϕ anything		(3.5 ±0.7) %	S=1.8
	Baryon modes			
Γ_{52}	charmed-baryon anything		(6.4 ±1.1) %	
Γ_{53}	$\overline{\Sigma}_c^{--}$ anything		(4.8 ±2.5) × 10^{-3}	
Γ_{54}	$\overline{\Sigma}_c^{-}$ anything		< 1.1 %	CL=90%
Γ_{55}	$\overline{\Sigma}_c^{0}$ anything		(5.2 ±2.5) × 10^{-3}	
Γ_{56}	$\overline{\Sigma}_c^{0} N (N = p$ or $n)$		< 1.7 × 10^{-3}	CL=90%
Γ_{57}	$p / \overline{p}$ anything	[d]	(8.0 ±0.4) %	
Γ_{58}	$p / \overline{p}$(direct) anything	[d]	(5.5 ±0.5) %	
Γ_{59}	$\Lambda / \overline{\Lambda}$ anything	[d]	(4.0 ±0.5) %	
Γ_{60}	$\Xi^- / \overline{\Xi}^+$ anything	[d]	(2.7 ±0.6) × 10^{-3}	
Γ_{61}	baryons anything		(6.8 ±0.6) %	
Γ_{62}	$p\overline{p}$ anything		(2.47±0.23) %	
Γ_{63}	$\Lambda\overline{p} / \overline{\Lambda} p$ anything	[d]	(2.5 ±0.4) %	
Γ_{64}	$\Lambda\overline{\Lambda}$ anything		< 5 × 10^{-3}	CL=90%
	$\Delta B = 1$ weak neutral current (*B1*) modes			
Γ_{65}	$e^+ e^-$ anything	B1	< 2.4 × 10^{-3}	CL=90%
Γ_{66}	$\mu^+ \mu^-$ anything	B1	< 2.4 × 10^{-3}	CL=90%

[a] These values are model dependent. See 'Note on Semileptonic Decays' in the B^+ Particle Listings.

[b] ℓ indicates e or μ mode, not sum over modes.

[c] D^{**} stands for the sum of the $D(1\,^1P_1)$, $D(1\,^3P_0)$, $D(1\,^3P_1)$, $D(1\,^3P_2)$, $D(2\,^1S_0)$, and $D(2\,^1S_1)$ resonances.

[d] The value is for the sum of the charge states of particle/antiparticle states indicated.

[e] Inclusive branching fractions have a multiplicity definition and can be greater than 100%.

$B^{\pm}/B^0$ ADMIXTURE BRANCHING RATIOS

$\Gamma(\ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_4/Γ

These branching fraction values are model dependent. See the note on "Semileptonic Decays of B Mesons at the beginning of the B^+ Particle Listings.

VALUE	DOCUMENT ID	TECN	COMMENT
0.1043±0.0024 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.		
0.108 ±0.002 ±0.0056	[1] HENDERSON 92	CLEO	$e^+e^- \to \Upsilon(4S)$

[1] HENDERSON 92 measurement employs e and μ. The systematic error contains 0.004 in quadrature from model dependence. The authors average a variation of the Isgur, Scora, Grinstein, and Wise model with that of the Altarelli-Cabibbo-Corbò-Maiani-Martinelli model for semileptonic decays to correct the acceptance.

$\Gamma(e^+ \nu_e \text{anything})/\Gamma_{\text{total}}$ — Γ_1/Γ

These branching fraction values are model dependent. See the note on "Semileptonic Decays of B Mesons at the beginning of the B^+ Particle Listings.

VALUE	DOCUMENT ID	TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.			
0.104±0.004 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.		
0.097±0.005±0.004	[2] ALBRECHT 93H	ARG	$e^+e^- \to \Upsilon(4S)$
0.100±0.004±0.003	[3] YANAGISAWA 91	CSB2	$e^+e^- \to \Upsilon(4S)$
0.103±0.006±0.002	[4] ALBRECHT 90H	ARG	$e^+e^- \to \Upsilon(4S)$
0.117±0.004±0.010	[5] WACHS 89	CBAL	Direct e at $\Upsilon(4S)$
0.120±0.007±0.005	CHEN 84	CLEO	Direct e at $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.132±0.008±0.014	[6] KLOPFEN... 83B	CUSB	Direct e at $\Upsilon(4S)$

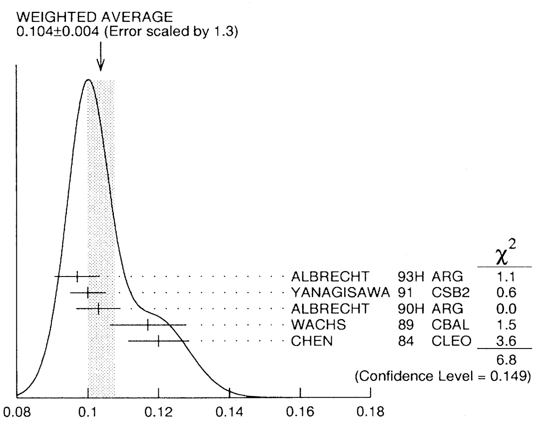
[2] ALBRECHT 93H analysis performed using tagged semileptonic decays of the B. This technique is almost model independent for the lepton branching ratio.

[3] YANAGISAWA 91 also measures an average semileptonic branching ratio at the $\Upsilon(5S)$ of 9.6–10.5% depending on assumptions about the relative production of different B meson species.

[4] ALBRECHT 90H uses the model of ALTARELLI 82 to correct over all lepton momenta. 0.099 ± 0.006 is obtained using ISGUR 89B.

[5] Using data above $p(e)$ = 2.4 GeV, WACHS 89 determine $\sigma(B \to e\nu \text{up})/\sigma(B \to e\nu \text{charm}) < 0.065$ at 90% CL.

[6] Ratio $\sigma(b \to e\nu \text{up})/\sigma(b \to e\nu \text{charm}) < 0.055$ at CL = 90%.



$\Gamma(e^+ \nu_e \text{anything})/\Gamma_{\text{total}}$

$\Gamma(\mu^+ \nu_\mu \text{anything})/\Gamma_{\text{total}}$ — Γ_3/Γ

These branching fraction values are model dependent. See the note on "Semileptonic Decays of B Mesons at the beginning of the B^+ Particle Listings.

VALUE	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.				
0.103±0.005 OUR AVERAGE				
0.100±0.006±0.002	[7] ALBRECHT	90H	ARG	$e^+e^- \to \Upsilon(4S)$
0.108±0.006±0.01	CHEN	84	CLEO	Direct μ at $\Upsilon(4S)$
0.112±0.009±0.01	LEVMAN	84	CUSB	Direct μ at $\Upsilon(4S)$

[7] ALBRECHT 90H uses the model of ALTARELLI 82 to correct over all lepton momenta. 0.097 ± 0.006 is obtained using ISGUR 89B.

$\Gamma(\overline{p} e^+ \nu_e \text{anything})/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0016	90	ALBRECHT	90H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(D^- \ell^+ \nu_\ell \text{anything})/\Gamma(\ell^+ \nu_\ell \text{anything})$ — Γ_5/Γ_4

$\ell = e$ or μ.

VALUE	DOCUMENT ID		TECN	COMMENT
0.26±0.07±0.04	[8] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$

[8] FULTON 91 uses $B(D^+ \to K^-\pi^+\pi^+) = (9.1 \pm 1.3 \pm 0.4)\%$ as measured by MARK III.

$\Gamma(\overline{D}^0 \ell^+ \nu_\ell \text{anything})/\Gamma(\ell^+ \nu_\ell \text{anything})$ — Γ_6/Γ_4

$\ell = e$ or μ.

VALUE	DOCUMENT ID		TECN	COMMENT
0.67±0.09±0.10	[9] FULTON	91	CLEO	$e^+e^- \to \Upsilon(4S)$

[9] FULTON 91 uses $B(D^0 \to K^-\pi^+) = (4.2 \pm 0.4 \pm 0.4)\%$ as measured by MARK III.

$\Gamma(D^{*-} \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.6±0.3±0.1	[10] BARISH	95	CLE2	$e^+e^- \to \Upsilon(4S)$

[10] BARISH 95 use $B(D^0 \to K^-\pi^+) = (3.91 \pm 0.08 \pm 0.17)\%$ and $B(D^{*+} \to D^0\pi^+) = (68.1 \pm 1.0 \pm 1.3)\%$.

$\Gamma(D^{*0} \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.6±0.6±0.1	[11] BARISH	95	CLE2	$e^+e^- \to \Upsilon(4S)$

[11] BARISH 95 use $B(D^0 \to K^-\pi^+) = (3.91 \pm 0.08 \pm 0.17)\%$, $B(D^{*+} \to D^0\pi^+) = (68.1 \pm 1.0 \pm 1.3)\%$, $B(D^{*0} \to D^0\pi^0) = (63.6 \pm 2.3 \pm 3.3)\%$.

$\Gamma(\overline{D}^{**} \ell^+ \nu_\ell)/\Gamma_{\text{total}}$ — Γ_9/Γ

D^{**} stands for the sum of the $D(1\,^1P_1)$, $D(1\,^3P_0)$, $D(1\,^3P_1)$, $D(1\,^3P_2)$, $D(2\,^1S_0)$, and $D(2\,^1S_1)$ resonances. $\ell = e$ or μ, not sum over e and μ modes.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.027±0.005±0.005		63	[12] ALBRECHT	93	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.028	95		[13] BARISH	95	CLE2	$e^+e^- \to \Upsilon(4S)$

[12] ALBRECHT 93 assumes the GISW model to correct for unseen modes. Using the BHKT model, the result becomes 0.023 ± 0.006 ± 0.004. Assumes $B(D^{*+} \to D^0\pi^+) = 68.1\%$, $B(D^0 \to K^-\pi^+) = 3.65\%$, $B(D^0 \to K^-\pi^+\pi^-\pi^+) = 7.5\%$. We have taken their average e and μ value.

[13] BARISH 95 use $B(D^0 \to K^-\pi^+) = (3.91 \pm 0.08 \pm 0.17)\%$, assume all nonresonant channels are zero, and use GISW model for relative abundances of D^{**} states.

$\Gamma(\overline{D}(1)(2420)^0 \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[14] BUSKULIC	95B	ALEP	$e^+e^- \to Z$

[14] BUSKULIC 95B reports $f_B \times B(B \to \overline{D}_1(2420)^0 \ell^+ \nu_\ell \text{anything}) \times B(\overline{D}_1(2420)^0 \to \overline{D}^*(2010)^- \pi^+) = (2.04 \pm 0.58 \pm 0.34)10^{-3}$, where f_B is the production fraction for a single B charge state.

$\Gamma(\overline{D}(2)^*(2460)^0 \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	[15] BUSKULIC	95B	ALEP	$e^+e^- \to Z$

[15] BUSKULIC 95B reports $f_B \times B(B \to \overline{D}_2^*(2460)^0 \ell^+ \nu_\ell \text{anything}) \times B(\overline{D}_2^*(2460)^0 \to \overline{D}^*(2010)^- \pi^+) \le 0.81 \times 10^{-3}$ at CL=95%, where f_B is the production fraction for a single B charge state.

$\Gamma(D^{*-} \pi^+ \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_{12}/Γ

Includes resonant and nonresonant contributions.

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
10.0±2.7±2.1	[16] BUSKULIC	95B	ALEP	$e^+e^- \to Z$

[16] BUSKULIC 95B reports $f_B \times B(B \to \overline{D}^*(2010)^- \pi^+ \ell^+ \nu_\ell \text{anything}) = (3.7 \pm 1.0 \pm 0.7)10^{-3}$. Above value assumes $f_B = 0.37 \pm 0.03$.

$\Gamma(D_s^- \ell^+ \nu_\ell \text{anything})/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.009	90	[17] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[17] ALBRECHT 93E reports < 0.012 for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^- \ell^+ \nu_\ell K^+ \text{anything})/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.006	90	[18] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[18] ALBRECHT 93E reports < 0.008 for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(D_s^- \ell^+ \nu_\ell K^0 \text{anything})/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.009	90	[19] ALBRECHT	93E	ARG	$e^+e^- \to \Upsilon(4S)$

[19] ALBRECHT 93E reports < 0.012 for $B(D_s^+ \to \phi\pi^+) = 0.027$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$.

$\Gamma(\ell^+ \nu_\ell \text{noncharmed})/\Gamma(\ell^+ \nu_\ell \text{anything})$ — Γ_{16}/Γ_4

ℓ denotes e or μ, not the sum. These experiments measure this ratio in very limited momentum intervals.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
			[20] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
		107	[21] BARTELT	93B	CLE2	$e^+e^- \to \Upsilon(4S)$
		77	[22] ALBRECHT	91C	ARG	$e^+e^- \to \Upsilon(4S)$
		76	[23] FULTON	90	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		41	[24] ALBRECHT	90	ARG	$e^+e^- \to \Upsilon(4S)$
<0.04	90		[25] BEHRENDS	87	CLEO	$e^+e^- \to \Upsilon(4S)$
<0.04	90		CHEN	84	CLEO	Direct e at $\Upsilon(4S)$
<0.055	90		KLOPFEN...	83B	CUSB	Direct e at $\Upsilon(4S)$

[20] ALBRECHT 94C find $\Gamma(b \to c)/\Gamma(b \to \text{all}) = 0.99 \pm 0.02 \pm 0.04$.

[21] BARTELT 93B (CLEO II) measures an excess of 107 ± 15 ± 11 leptons in the lepton momentum interval 2.3–2.6 GeV/c which is attributed to $b \to u \ell \nu_\ell$. This corresponds to a model-dependent partial branching ratio ΔB_{ub} between $(1.15 \pm 0.16 \pm 0.15) \times 10^{-4}$, as evaluated using the KS model (KOERNER 88), and $(1.54 \pm 0.22 \pm 0.20) \times 10^{-4}$ using the ACCMM model (ARTUSO 93). The corresponding values of $|V_{ub}|/|V_{cb}|$ are 0.056 ± 0.006 and 0.076 ± 0.008, respectively.

[22] ALBRECHT 91C result supersedes ALBRECHT 90. Two events are fully reconstructed providing evidence for the $b \to u$ transition. Using the model of ALTARELLI 82, they obtain $|V_{ub}/V_{cb}| = 0.11 \pm 0.012$ from 77 leptons in the 2.3–2.6 GeV momentum range.

[23] FULTON 90 observe 76 ± 20 excess e and μ (lepton) events in the momentum interval p = 2.4–2.6 GeV signaling the presence of the $b \to u$ transition. The average branching ratio, $(1.8 \pm 0.4 \pm 0.3) \times 10^{-4}$, corresponds to a model-dependent measurement of approximately $|V_{ub}/V_{cb}| = 0.1$ using $B(b \to c\ell\nu) = 10.2 \pm 0.2 \pm 0.7\%$.

[24] ALBRECHT 90 observes 41 ± 10 excess e and μ (lepton) events in the momentum interval p = 2.3–2.6 GeV signaling the presence of the $b \to u$ transition. The events correspond to a model-dependent measurement of $|V_{ub}/V_{cb}| = 0.10 \pm 0.01$.

[25] The quoted possible limits range from 0.018 to 0.04 for the ratio, depending on which model or momentum range is chosen. We select the most conservative limit they have calculated. This corresponds to a limit on $|V_{ub}|/|V_{cb}| < 0.20$. While the endpoint technique employed is more robust than their previous results in CHEN 84, these results do not provide a numerical improvement in the limit.

$\Gamma(K^+ \ell^+ \nu_\ell \text{anything})/\Gamma(\ell^+ \nu_\ell \text{anything})$ — Γ_{17}/Γ_4

ℓ denotes e or μ, not the sum.

VALUE	DOCUMENT ID	TECN	COMMENT
0.58 ±0.05 OUR AVERAGE			
0.594±0.021±0.056	ALBRECHT 94C	ARG	$e^+e^- \to \Upsilon(4S)$
0.54 ±0.07 ±0.06	[26] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[26] ALAM 87B measurement relies on lepton-kaon correlations.

$\Gamma(K^- \ell^+ \nu_\ell \text{anything})/\Gamma(\ell^+ \nu_\ell \text{anything})$ — Γ_{18}/Γ_4

ℓ denotes e or μ, not the sum.

VALUE	DOCUMENT ID	TECN	COMMENT
0.092±0.035 OUR AVERAGE			
0.086±0.011±0.044	ALBRECHT 94C	ARG	$e^+e^- \to \Upsilon(4S)$
0.10 ±0.05 ±0.02	[27] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[27] ALAM 87B measurement relies on lepton-kaon correlations.

$\Gamma(K^0/\overline{K}^0 \ell^+ \nu_\ell \text{anything})/\Gamma(\ell^+ \nu_\ell \text{anything})$ — Γ_{19}/Γ_4

ℓ denotes e or μ, not the sum. Sum over K^0 and $\overline{K}^0$ states.

VALUE	DOCUMENT ID	TECN	COMMENT
0.42 ±0.05 OUR AVERAGE			
0.452±0.038±0.056	[28] ALBRECHT 94C	ARG	$e^+e^- \to \Upsilon(4S)$
0.39 ±0.06 ±0.04	[29] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[28] ALBRECHT 94C assume a $K^0/\overline{K}^0$ multiplicity twice that of K^0_S.

[29] ALAM 87B measurement relies on lepton-kaon correlations.

$\Gamma(c/\overline{c})/\Gamma_{total}$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.98±0.16±0.12	[30] ALAM 87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[30] From the difference between K^- and K^+ widths. ALAM 87B measurement relies on lepton-kaon correlations. It does not consider the possibility of $B\overline{B}$ mixing. We have thus removed it from the average.

$\Gamma(D^{\pm} \text{anything})/\Gamma_{total}$ — Γ_{20}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.242±0.033 OUR AVERAGE				
0.25 ±0.04 ±0.02		[31] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.23 ±0.05 $^{+0.01}_{-0.02}$		[32] ALBRECHT 91H	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.21 ±0.05 ±0.01	20k	[33] BORTOLETTO 87	CLEO	Sup. by BORTOLETTO 92

[31] BORTOLETTO 92 reports $[B(B \to D^{\pm}\text{anything}) \times B(D^+ \to K^-\pi^+\pi^+)] = 0.0226 \pm 0.0030 \pm 0.0018$. We divide by our best value $B(D^+ \to K^-\pi^+\pi^+) = (9.1 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[32] ALBRECHT 91H reports $[B(B \to D^{\pm}\text{anything}) \times B(D^+ \to K^-\pi^+\pi^+)] = 0.0209 \pm 0.0027 \pm 0.0040$. We divide by our best value $B(D^+ \to K^-\pi^+\pi^+) = (9.1 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[33] BORTOLETTO 87 reports $[B(B \to D^{\pm}\text{anything}) \times B(D^+ \to K^-\pi^+\pi^+)] = 0.019 \pm 0.004 \pm 0.002$. We divide by our best value $B(D^+ \to K^-\pi^+\pi^+) = (9.1 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D^0/\overline{D}^0 \text{anything})/\Gamma_{total}$ — Γ_{21}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.58±0.05 OUR AVERAGE Error includes scale factor of 1.1.				
0.61±0.05±0.02		[34] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.51±0.08±0.02		[35] ALBRECHT 91H	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.55±0.07±0.02	21k	[36] BORTOLETTO 87	CLEO	$e^+e^- \to \Upsilon(4S)$
0.63±0.19±0.02		[37] GREEN 83	CLEO	Repl. by BORTOLETTO 87

[34] BORTOLETTO 92 reports $[B(B \to D^0/\overline{D}^0\text{anything}) \times B(D^0 \to K^-\pi^+)] = 0.0233 \pm 0.0012 \pm 0.0014$. We divide by our best value $B(D^0 \to K^-\pi^+) = (3.83 \pm 0.12) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[35] ALBRECHT 91H reports $[B(B \to D^0/\overline{D}^0\text{anything}) \times B(D^0 \to K^-\pi^+)] = 0.0194 \pm 0.0015 \pm 0.0025$. We divide by our best value $B(D^0 \to K^-\pi^+) = (3.83 \pm 0.12) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[36] BORTOLETTO 87 reports $[B(B \to D^0/\overline{D}^0\text{anything}) \times B(D^0 \to K^-\pi^+)] = 0.0210 \pm 0.0015 \pm 0.0021$. We divide by our best value $B(D^0 \to K^-\pi^+) = (3.83 \pm 0.12) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[37] GREEN 83 reports $[B(B \to D^0/\overline{D}^0\text{anything}) \times B(D^0 \to K^-\pi^+)] = 0.024 \pm 0.006 \pm 0.004$. We divide by our best value $B(D^0 \to K^-\pi^+) = (3.83 \pm 0.12) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D^*(2010)^{\pm} \text{anything})/\Gamma_{total}$ — Γ_{22}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.231±0.033 OUR AVERAGE Error includes scale factor of 1.1.				
0.209±0.035±0.004		[38] BORTOLETTO 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.28 ±0.05 ±0.01		[39] ALBRECHT 91H	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22 ±0.04 $^{+0.07}_{-0.04}$	5200	[40] BORTOLETTO 87	CLEO	$e^+e^- \to \Upsilon(4S)$
0.27 ±0.06 $^{+0.08}_{-0.06}$	510	[41] CSORNA 85	CLEO	Repl. by BORTOLETTO 87

[38] BORTOLETTO 92 reports $0.25 \pm 0.03 \pm 0.04$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.57 \pm 0.06$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. They also use the Mark III $B(D^0 \to K^-\pi^+)$ branching fraction.

[39] ALBRECHT 91H reports $0.348 \pm 0.060 \pm 0.035$ for $B(D^*(2010)^+ \to D^0\pi^+) = 0.55 \pm 0.04$. We rescale to our best value $B(D^*(2010)^+ \to D^0\pi^+) = (68.3 \pm 1.4) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Uses the PDG 90 $B(D^0 \to K^-\pi^+) = 0.0371 \pm 0.0025$.

[40] BORTOLETTO 87 uses old MARK III (BALTRUSAITIS 86E) branching ratios $B(D^0 \to K^-\pi^+) = 0.056 \pm 0.004 \pm 0.003$ and also assumes $B(D^*(2010)^+ \to D^0\pi^+) = 0.60^{+0.08}_{-0.15}$. The product branching ratio for $B(B \to D^*(2010)^+)\, B(D^*(2010)^+ \to D^0\pi^+)$ is $0.13 \pm 0.02 \pm 0.012$. Superseded by BORTOLETTO 92.

[41] $V-A$ momentum spectrum used to extrapolate below p = 1 GeV. We correct the value assuming $B(D^0 \to K^-\pi^+) = 0.042 \pm 0.006$ and $B(D^{*+} \to D^0\pi^+) = 0.6^{+0.08}_{-0.15}$. The product branching fraction is $B(B \to D^{*+}X) \cdot B(D^{*+} \to \pi^+ D^0) \cdot B(D^0 \to K^-\pi^+) = (68 \pm 15 \pm 9) \times 10^{-4}$.

$\Gamma(D_s^{\pm} \text{anything})/\Gamma_{total}$ — Γ_{23}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.086±0.016 OUR AVERAGE				
0.081±0.014$^{+0.019}_{-0.020}$		[42] ALBRECHT 92G	ARG	$e^+e^- \to \Upsilon(4S)$
0.085±0.013$^{+0.020}_{-0.021}$	257	[43] BORTOLETTO 90	CLEO	$e^+e^- \to \Upsilon(4S)$
0.105±0.028$^{+0.025}_{-0.026}$		[44] HAAS 86	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.116±0.030±0.028		[45] ALBRECHT 87H	ARG	$e^+e^- \to \Upsilon(4S)$

[42] ALBRECHT 92G reports $[B(B \to D_s^{\pm}\text{anything}) \times B(D_s^+ \to \phi\pi^+)] = 0.00292 \pm 0.00039 \pm 0.00031$. We divide by our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[43] BORTOLETTO 90 reports $[B(B \to D_s^{\pm}\text{anything}) \times B(D_s^+ \to \phi\pi^+)] = 0.00306 \pm 0.00047$. We divide by our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[44] HAAS 86 reports $[B(B \to D_s^{\pm}\text{anything}) \times B(D_s^+ \to \phi\pi^+)] = 0.0038 \pm 0.0010$. We divide by our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. 64 ± 22% decays are 2-body.

[45] ALBRECHT 87H reports $[B(B \to D_s^{\pm}\text{anything}) \times B(D_s^+ \to \phi\pi^+)] = 0.0042 \pm 0.0009 \pm 0.0006$. We divide by our best value $B(D_s^+ \to \phi\pi^+) = (3.6 \pm 0.9) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. 46 ± 16% of $B \to D_s X$ decays are 2-body. Superseded by ALBRECHT 92G.

$\Gamma(D_s D,\ D_s^* D,\ D_s D^*, \text{or } D_s^* D^*)/\Gamma(D_s^{\pm} \text{anything})$ — Γ_{24}/Γ_{23}

Sum over modes.

VALUE	DOCUMENT ID	TECN	COMMENT
0.57±0.08 OUR AVERAGE			
0.58±0.07±0.09	ALBRECHT 92G	ARG	$e^+e^- \to \Upsilon(4S)$
0.56±0.10	BORTOLETTO 90	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(D^*(2010)\gamma)/\Gamma_{total}$ — Γ_{25}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<1.1 × 10⁻³	90	[46] LESIAK 92	CBAL	$e^+e^- \to \Upsilon(4S)$

[46] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

$\Gamma(D_s^+\pi^-,\ D_s^{*+}\pi^-,\ D_s^+\rho^-,\ D_s^{*+}\rho^-,\ D_s^+\pi^0,\ D_s^{*+}\pi^0,\ D_s^+\eta,\ D_s^{*+}\eta,\ D_s^+\rho^0,\ D_s^{*+}\rho^0,\ D_s^+\omega,\ D_s^{*+}\omega)/\Gamma_{total}$ — Γ_{26}/Γ

Sum over modes.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0005	90	[47] ALEXANDER 93B	CLE2	$e^+e^- \to \Upsilon(4S)$

[47] ALEXANDER 93B reports $< 4.8 \times 10^{-4}$ for $B(D_s^+ \to \phi\pi^+) = 0.037$. We rescale to our best value $B(D_s^+ \to \phi\pi^+) = 0.036$. This branching ratio limit provides a model-dependent upper limit $|V_{ub}|/|V_{cb}| < 0.16$ at CL=90%.

$\Gamma(J/\psi(1S)\text{anything})/\Gamma_{total}$ — Γ_{27}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
1.14±0.06 OUR AVERAGE					
1.11±0.05±0.04	1489	[48] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$
1.28±0.44±0.04	27	[49] MASCHMANN	90	CBAL	$e^+e^- \to \Upsilon(4S)$
1.23±0.27±0.04	120	[50] ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$
1.34±0.24±0.04	52	[51] ALAM	86	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.4\ ^{+0.6}_{-0.5}$	7	[52] ALBRECHT	85H	ARG	$e^+e^- \to \Upsilon(4S)$
1.1 ±0.21±0.23	46	[53] HAAS	85	CLEO	Repl. by ALAM 86

[48] BALEST 95B reports $1.12 \pm 0.04 \pm 0.06$ for $B(J/\psi(1S) \to e^+e^-) = 0.0599 \pm 0.0025$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.. They measure $J/\psi(1S) \to e^+e^-$ and $\mu^+\mu^-$ and use PDG 1994 values for the branching fractions. The rescaling is the same for either mode so we use e^+e^-.

[49] MASCHMANN 90 reports $1.12\pm0.33\pm0.25$ for $B(J/\psi(1S) \to e^+e^-) = 0.069\pm0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[50] ALBRECHT 87D reports $1.07 \pm 0.16 \pm 0.22$ for $B(J/\psi(1S) \to e^+e^-) = 0.069\pm0.009$. We rescale to our best value $B(J/\psi(1S) \to e^+e^-) = (6.02 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. ALBRECHT 87D find the branching ratio for J/ψ not from $\psi(2S)$ to be 0.0081 ± 0.0023.

[51] ALAM 86 reports $1.09 \pm 0.16 \pm 0.21$ for $B(J/\psi(1S) \to \mu^+\mu^-) = 0.074 \pm 0.012$. We rescale to our best value $B(J/\psi(1S) \to \mu^+\mu^-) = (6.01 \pm 0.19) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[52] Statistical and systematic errors were added in quadrature. ALBRECHT 85H also report a CL = 90% limit of 0.007 for $B \to J/\psi(1S)+$ X where m_X <1 GeV.

[53] Dimuon and dielectron events used.

$\Gamma(J/\psi(1S)(\text{direct})\text{anything})/\Gamma_{total}$ — Γ_{28}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0080±0.0008	[54] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$

[54] BALEST 95B assume PDG 1994 values for sub mode branching ratios. $J/\psi(1S)$ mesons are reconstructed in $J/\psi(1S) \to e^+e^-$ and $J/\psi(1S) \to \mu^+\mu^-$. The $B \to J/\psi(1S)$X branching ratio contains $J/\psi(1S)$ mesons directly from B decays and also from feeddown through $\psi(2S) \to J/\psi(1S)$, $\chi_{c1}(1P) \to J/\psi(1S)$, or $\chi_{c2}(1P) \to J/\psi(1S)$. Using the measured inclusive rates, BALEST 95B corrects for the feeddown and finds the $B \to J/\psi(1S)$(direct) X branching ratio.

$\Gamma(\psi(2S)\text{anything})/\Gamma_{total}$ — Γ_{29}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0035±0.0005 OUR AVERAGE					
0.0034±0.0004±0.0003	240	[55] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0046±0.0017±0.0011	8	ALBRECHT	87D	ARG	$e^+e^- \to \Upsilon(4S)$

[55] BALEST 95B assume PDG 1994 values for sub mode branching ratios. They find $B(B \to \psi(2S)X,\ \psi(2S) \to \ell^+\ell^-) = 0.30 \pm 0.05 \pm 0.04$ and $B(B \to \psi(2S)X,\ \psi(2S) \to J/\psi(1S)\pi^+\pi^-) = 0.37\pm0.05\pm0.05$. Weighted average is quoted for $B(B \to \psi(2S)X)$.

$\Gamma(\chi_{c1}(1P)\text{anything})/\Gamma_{total}$ — Γ_{30}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0042±0.0007 OUR AVERAGE					
0.0040±0.0006±0.0004	112	[56] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$
0.0105±0.0035±0.0025		[57] ALBRECHT	92E	ARG	$e^+e^- \to \Upsilon(4S)$

[56] BALEST 95B assume $B(\chi_{c1}(1P) \to J/\psi(1S)\gamma) = (27.3 \pm 1.6) \times 10^{-2}$, the PDG 1994 value. Fit to ψ-photon invariant mass distribution allows for a $\chi_{c1}(1P)$ and a $\chi_{c2}(1P)$ component.

[57] ALBRECHT 92E assumes no $\chi_{c2}(1P)$ production.

$\Gamma(\chi_{c1}(1P)(\text{direct})\text{anything})/\Gamma_{total}$ — Γ_{31}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0037±0.0007	[58] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$

[58] BALEST 95B assume PDG 1994 values. $J/\psi(1S)$ mesons are reconstructed in the e^+e^- and $\mu^+\mu^-$ modes. The $B \to \chi_{c1}(1P)$X branching ratio contains $\chi_{c1}(1P)$ mesons directly from B decays and also from feeddown through $\psi(2S) \to \chi_{c1}(1P)\gamma$. Using the measured inclusive rates, BALEST 95B corrects for the feeddown and finds the $B \to \chi_{c1}(1P)$(direct) X branching ratio.

$\Gamma(\chi_{c2}(1P)\text{anything})/\Gamma_{total}$ — Γ_{32}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.0038	90	35	[59] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$

[59] BALEST 95B assume $B(\chi_{c2}(1P) \to J/\psi(1S)\gamma) = (13.5 \pm 1.1) \times 10^{-2}$, the PDG 1994 value. $J/\psi(1S)$ mesons are reconstructed in the e^+e^- and $\mu^+\mu^-$ modes, and PDG 1994 branching fractions are used. If interpreted as signal, the 35 ± 13 events correspond to $B(B \to \chi_{c2}(1P)X) = (0.25 \pm 0.10 \pm 0.03) \times 10^{-2}$.

$\Gamma(\eta_c(1S)\text{anything})/\Gamma_{total}$ — Γ_{33}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.009	90	[60] BALEST	95B	CLE2	$e^+e^- \to \Upsilon(4S)$

[60] BALEST 95B assume PDG 1994 values for sub mode branching ratios. $J/\psi(1S)$ mesons are reconstructed in $J/\psi(1S) \to e^+e^-$ and $J/\psi(1S) \to \mu^+\mu^-$. Search region 2960 $< m_{\eta_c(1S)} <$3010 MeV/c^2.

$\Gamma(K^{\pm}\text{anything})/\Gamma_{total}$ — Γ_{34}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.789±0.025 OUR AVERAGE				
0.82 ±0.01 ±0.05	ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
0.775±0.015±0.025	[61] ALBRECHT	93I	ARG	$e^+e^- \to \Upsilon(4S)$
0.85 ±0.07 ±0.09	ALAM	87B	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	[62] BRODY	82	CLEO	$e^+e^- \to \Upsilon(4S)$
seen	[63] GIANNINI	82	CUSB	$e^+e^- \to \Upsilon(4S)$

[61] ALBRECHT 93I value is not independent of the sum of $B \to K^+$anything and $B \to K^-$anything ALBRECHT 94C values.

[62] Assuming $\Upsilon(4S) \to B\overline{B}$, a total of $3.38 \pm 0.34 \pm 0.68$ kaons per $\Upsilon(4S)$ decay is found (the second error is systematic). In the context of the standard B-decay model, this leads to a value for (b-quark $\to$ c-quark)/(b-quark $\to$ all) of $1.09 \pm 0.33 \pm 0.13$.

[63] GIANNINI 82 at CESR-CUSB observed 1.58 ± 0.35 K^0 per hadronic event much higher than 0.82 ± 0.10 below threshold. Consistent with predominant $b \to cX$ decay.

$\Gamma(K^+\text{anything})/\Gamma_{total}$ — Γ_{35}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.66 ±0.05	[64] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.620±0.013±0.038	[65] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
0.66 ±0.05 ±0.07	[65] ALAM	87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[64] Measurement relies on lepton-kaon correlations. It is for the weak decay vertex and does not include mixing of the neutral B meson. Mixing effects were corrected for by assuming a mixing parameter r of (18.1 ± 4.3)%.

[65] Measurement relies on lepton-kaon correlations. It includes production through mixing of the neutral B meson.

$\Gamma(K^-\text{anything})/\Gamma_{total}$ — Γ_{36}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.13 ±0.04	[66] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.165±0.011±0.036	[67] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
0.19 ±0.05 ±0.02	[67] ALAM	87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[66] Measurement relies on lepton-kaon correlations. It is for the weak decay vertex and does not include mixing of the neutral B meson. Mixing effects were corrected for by assuming a mixing parameter r of (18.1 ± 4.3)%.

[67] Measurement relies on lepton-kaon correlations. It includes production through mixing of the neutral B meson.

$\Gamma(K^0/\overline{K}^0\text{anything})/\Gamma_{total}$ — Γ_{37}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.64 ±0.04 OUR AVERAGE				
0.642±0.010±0.042	[68] ALBRECHT	94C	ARG	$e^+e^- \to \Upsilon(4S)$
0.63 ±0.06 ±0.06	ALAM	87B	CLEO	$e^+e^- \to \Upsilon(4S)$

[68] ALBRECHT 94C assume a $K^0/\overline{K}^0$ multiplicity twice that of K^0_S.

$\Gamma(K^*(892)^{\pm}\text{anything})/\Gamma_{total}$ — Γ_{38}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.182±0.054±0.024	ALBRECHT	94J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)^0/\overline{K}^*(892)^0\text{anything})/\Gamma_{total}$ — Γ_{39}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.146±0.016±0.020	ALBRECHT	94J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K^*(892)\gamma)/\Gamma_{total}$ — Γ_{40}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.5 \times 10^{-3}$	90	[69] LESIAK	92	CBAL	$e^+e^- \to \Upsilon(4S)$
$<2.4 \times 10^{-4}$	90	ALBRECHT	88H	ARG	$e^+e^- \to \Upsilon(4S)$

[69] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

$\Gamma(K_1(1400)\gamma)/\Gamma_{total}$ — Γ_{41}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.1 \times 10^{-4}$	90	ALBRECHT	88H	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.6 \times 10^{-3}$	90	[70] LESIAK	92	CBAL	$e^+e^- \to \Upsilon(4S)$

[70] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

$\Gamma(K_2^*(1430)\gamma)/\Gamma_{total}$ — Γ_{42}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<8.3 \times 10^{-4}$	90	ALBRECHT	88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_2(1770)\gamma)/\Gamma_{total}$ — Γ_{43}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.2 \times 10^{-3}$	90	[71] LESIAK	92	CBAL	$e^+e^- \to \Upsilon(4S)$

[71] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

See key on page 199

$\Gamma(K_3^*(1780)\gamma)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<3.0 \times 10^{-3}$	90	ALBRECHT 88H	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(K_4^*(2045)\gamma)/\Gamma_{total}$ — Γ_{45}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<1.0 \times 10^{-3}$	90	[72] LESIAK 92	CBAL	$e^+e^- \to \Upsilon(4S)$

[72] LESIAK 92 set a limit on the inclusive process $B(b \to s\gamma) < 2.8 \times 10^{-3}$ at 90% CL for the range of masses of 892–2045 MeV, independent of assumptions about s-quark hadronization.

$\Gamma(\overline{b} \to \overline{s}\gamma)/\Gamma_{total}$ — Γ_{46}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$(2.32\pm0.57\pm0.35) \times 10^{-4}$	ALAM 95	CLE2	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\overline{b} \to \overline{s}\,\text{gluon})/\Gamma_{total}$ — Γ_{47}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.08	2	[73] ALBRECHT 95D	ARG	$e^+e^- \to \Upsilon(4S)$

[73] ALBRECHT 95D use full reconstruction of one B decay as tag. Two candidate events for charmless B decay can be interpreted as either $b \to s$gluon or $b \to u$ transition. If interpreted as $b \to s$gluon they find a branching ratio of ~ 0.026 or the upper limit quoted above. Result is highly model dependent.

$\Gamma(\pi^{\pm}\,\text{anything})/\Gamma_{total}$ — Γ_{48}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
3.585±0.025±0.070	[74] ALBRECHT 93I	ARG	$e^+e^- \to \Upsilon(4S)$

[74] ALBRECHT 93 excludes $\pi^{\pm}$ from K_S^0 and Λ decays. If included, they find $4.105 \pm 0.025 \pm 0.080$.

$\Gamma(\rho^0\,\text{anything})/\Gamma_{total}$ — Γ_{49}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.208±0.042±0.032	ALBRECHT 94J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\omega\,\text{anything})/\Gamma_{total}$ — Γ_{50}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.81	90	ALBRECHT 94J	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\phi\,\text{anything})/\Gamma_{total}$ — Γ_{51}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.035 ±0.007 OUR AVERAGE	Error includes scale factor of 1.8.		
0.0390±0.0030±0.0035	ALBRECHT 94J	ARG	$e^+e^- \to \Upsilon(4S)$
0.023 ±0.006 ±0.005	BORTOLETTO 86	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\text{charmed-baryon anything})/\Gamma_{total}$ — Γ_{52}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
0.064±0.008±0.008		[75] CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.14 ±0.09		[76] ALBRECHT 88E	ARG	$e^+e^- \to \Upsilon(4S)$
<0.112	90	[77] ALAM 87	CLEO	$e^+e^- \to \Upsilon(4S)$

[75] CRAWFORD 92 result derived from lepton baryon correlations. Assumes all charmed baryons in B^0 and $B^{\pm}$ decay are Λ_c.

[76] ALBRECHT 88E measured $B(B \to \Lambda_c^+ X)\cdot B(\Lambda_c^+ \to pK^-\pi^+) = (0.30\pm0.12\pm0.06)\%$ and used $B(\Lambda_c^+ \to pK^-\pi^+) = (2.2\pm1.0)\%$ from ABRAMS 80 to obtain above number.

[77] Assuming all baryons result from charmed baryons, ALAM 86 conclude the branching fraction is $7.4 \pm 2.9\%$. The limit given above is model independent.

$\Gamma(\overline{\Sigma}_c^{--}\,\text{anything})/\Gamma_{total}$ — Γ_{53}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0048±0.0024±0.0006	77	[78] PROCARIO 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[78] PROCARIO 94 reports $[B(B \to \overline{\Sigma}_c^{--}\text{anything}) \times B(\Lambda_c^+ \to pK^-\pi^+)] = 0.00021 \pm 0.00008 \pm 0.00007$. We divide by our best value $B(\Lambda_c^+ \to pK^-\pi^+) = (4.4 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{\Sigma}_c^{-}\,\text{anything})/\Gamma_{total}$ — Γ_{54}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.011	90	[79] PROCARIO 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[79] PROCARIO 94 reports $[B(B \to \overline{\Sigma}_c^{-}\,\text{anything}) \times B(\Lambda_c^+ \to pK^-\pi^+)] = < 0.00048$. We divide by our best value $B(\Lambda_c^+ \to pK^-\pi^+) = 0.044$.

$\Gamma(\overline{\Sigma}_c^{0}\,\text{anything})/\Gamma_{total}$ — Γ_{55}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0052±0.0024±0.0007	76	[80] PROCARIO 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[80] PROCARIO 94 reports $[B(B \to \overline{\Sigma}_c^{0}\,\text{anything}) \times B(\Lambda_c^+ \to pK^-\pi^+)] = 0.00023 \pm 0.00008 \pm 0.00007$. We divide by our best value $B(\Lambda_c^+ \to pK^-\pi^+) = (4.4 \pm 0.6) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{\Sigma}_c^{0} N(N = p \text{ or } n))/\Gamma_{total}$ — Γ_{56}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0017	90	[81] PROCARIO 94	CLE2	$e^+e^- \to \Upsilon(4S)$

[81] PROCARIO 94 reports < 0.0017 for $B(\Lambda_c^+ \to pK^-\pi^+) = 0.043$. We rescale to our best value $B(\Lambda_c^+ \to pK^-\pi^+) = 0.044$.

$\Gamma(p/\overline{p}\,\text{anything})/\Gamma_{total}$ — Γ_{57}/Γ

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.080±0.004 OUR AVERAGE				
0.080±0.005±0.005		ALBRECHT 93I	ARG	$e^+e^- \to \Upsilon(4S)$
0.080±0.005±0.003		CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
$0.082\pm0.005^{+0.013}_{-0.010}$	2163	[82] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.021		[83] ALAM 83B	CLEO	$e^+e^- \to \Upsilon(4S)$

[82] ALBRECHT 89K include direct and nondirect protons.

[83] ALAM 83B reported their result as $> 0.036 \pm 0.006 \pm 0.009$. Data are consistent with equal yields of p and $\overline{p}$. Using assumed yields below cut, $B(B \to p + X) = 0.03$ not including protons from Λ decays.

$\Gamma(p/\overline{p}(\text{direct})\,\text{anything})/\Gamma_{total}$ — Γ_{58}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.055±0.005 OUR AVERAGE				
0.055±0.005±0.0035		ALBRECHT 93I	ARG	$e^+e^- \to \Upsilon(4S)$
0.056±0.006±0.005		CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.055±0.016	1220	[84] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

[84] ALBRECHT 89K subtract contribution of Λ decay from the inclusive proton yield.

$\Gamma(\Lambda/\overline{\Lambda}\,\text{anything})/\Gamma_{total}$ — Γ_{59}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.040±0.005 OUR AVERAGE				
0.038±0.004±0.006	2998	CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.042±0.005±0.006	943	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.011		[85] ALAM 83B	CLEO	$e^+e^- \to \Upsilon(4S)$

[85] ALAM 83B reported their result as $> 0.022 \pm 0.007 \pm 0.004$. Values are for $(B(\Lambda X)+B(\overline{\Lambda}X))/2$. Data are consistent with equal yields of p and $\overline{p}$. Using assumed yields below cut, $B(B \to \Lambda X) = 0.03$.

$\Gamma(\Xi^-/\Xi^+\,\text{anything})/\Gamma_{total}$ — Γ_{60}/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0027±0.0006 OUR AVERAGE				
0.0027±0.0005±0.0004	147	CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.0028±0.0014	54	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\text{baryons anything})/\Gamma_{total}$ — Γ_{61}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.068±0.005±0.003	[86] ALBRECHT 92O	ARG	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.076±0.014	[87] ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

[86] ALBRECHT 92O result is from simultaneous analysis of p and Λ yields, $p\overline{p}$ and $\Lambda\overline{p}$ correlations, and various lepton-baryon and lepton-baryon-antibaryon correlations. Supersedes ALBRECHT 89K.

[87] ALBRECHT 89K obtain this result by adding their their measurements $(5.5 \pm 1.6)\%$ for direct protons and $(4.2 \pm 0.5 \pm 0.6)\%$ for inclusive Λ production. They then assume $(5.5 \pm 1.6)\%$ for neutron production and add it in also. Since each B decay has two baryons, they divide by 2 to obtain $(7.6 \pm 1.4)\%$.

$\Gamma(p\overline{p}\,\text{anything})/\Gamma_{total}$ — Γ_{62}/Γ

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0247±0.0023 OUR AVERAGE				
0.024 ±0.001 ±0.004		CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.025 ±0.002 ±0.002	918	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(p\overline{p}\,\text{anything})/\Gamma(p/\overline{p}\,\text{anything})$ — Γ_{62}/Γ_{57}

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.30±0.02±0.05	[88] CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$

[88] CRAWFORD 92 value is not independent of their $\Gamma(p\overline{p}\text{anything})/\Gamma_{total}$ value.

$\Gamma(\Lambda\overline{p}/\overline{\Lambda}p\,\text{anything})/\Gamma_{total}$ — Γ_{63}/Γ

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.025±0.004 OUR AVERAGE				
0.029±0.005±0.005		CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$
0.023±0.004±0.003	165	ALBRECHT 89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Lambda\overline{p}/\overline{\Lambda}p\,\text{anything})/\Gamma(\Lambda/\overline{\Lambda}\,\text{anything})$ — Γ_{63}/Γ_{59}

Includes p and $\overline{p}$ from Λ and $\overline{\Lambda}$ decay.

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.76±0.11±0.08	[89] CRAWFORD 92	CLEO	$e^+e^- \to \Upsilon(4S)$

[89] CRAWFORD 92 value is not independent of their $[\Gamma(\Lambda\overline{p}\text{anything})+\Gamma(\overline{\Lambda}p\text{anything})]/\Gamma_{total}$ value.

$\Gamma(\Lambda\overline{\Lambda}\text{anything})/\Gamma_{\text{total}}$ — Γ_{64}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.005	90		CRAWFORD	92	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.0088	90	12	ALBRECHT	89K	ARG	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\Lambda\overline{\Lambda}\text{anything})/\Gamma(\Lambda/\overline{\Lambda}\text{anything})$ — Γ_{64}/Γ_{59}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.13	90	[90] CRAWFORD	92	CLEO	$e^+e^- \to \Upsilon(4S)$

[90] CRAWFORD 92 value is not independent of their $\Gamma(\Lambda\overline{\Lambda}\text{anything})/\Gamma_{\text{total}}$ value.

$\Gamma(e^+e^-\text{anything})/\Gamma_{\text{total}}$ — Γ_{65}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	BEBEK	81	CLEO	$e^+e^- \to \Upsilon(4S)$

$\Gamma(\mu^+\mu^-\text{anything})/\Gamma_{\text{total}}$ — Γ_{66}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.017	90	CHADWICK	81	CLEO	$e^+e^- \to \Upsilon(4S)$

$[\Gamma(e^+e^-\text{anything}) + \Gamma(\mu^+\mu^-\text{anything})]/\Gamma_{\text{total}}$ — $(\Gamma_{65}+\Gamma_{66})/\Gamma$

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0024	90	[91] BEAN	87	CLEO	$e^+e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0062	90	[92] AVERY	84	CLEO	Repl. by BEAN 87

[91] BEAN 87 reports $[(\mu^+\mu^-)+(e^+e^-)]/2$ and we converted it.

[92] Determine ratio of B^+ to B^0 semileptonic decays to be in the range 0.25–2.9.

$B^{\pm}/B^0$ ADMIXTURE REFERENCES

ALAM	95	PRL 74 2885	+Kim, Ling, Mahmood+	(CLEO Collab.)
ALBRECHT	95D	PL B353 554	+Hamacher, Hofmann, Kirchoff+	(ARGUS Collab.)
BALEST	95B	PR D52 2661	+Cho, Ford, Johnson+	(CLEO Collab.)
BARISH	95	PR D51 1014	+Chadha, Chan, Cowen+	(CLEO Collab.)
BUSKULIC	95B	PL B345 103	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ALBRECHT	94C	ZPHY C62 371	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	94J	ZPHY C61 1	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
PROCARIO	94	PRL 73 1306	+Balest, Cho, Daoudi, Ford+	(CLEO Collab.)
ALBRECHT	93	ZPHY C57 533	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	93E	ZPHY C60 11	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	93H	PL B318 397	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	93I	ZPHY C58 191	+Cronstroem, Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALEXANDER	93B	PL B319 365	+Bebek, Berkelman, Bloom, Browder+	(CLEO Collab.)
ARTUSO	93	PL B311 307		(SYRA)
BARTELT	93B	PRL 71 4111	+Csorna, Egyed, Jain, Akerib+	(CLEO Collab.)
ALBRECHT	92E	PL B277 209	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
ALBRECHT	92G	ZPHY C54 1	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
ALBRECHT	92O	ZPHY C56 1	+Cronstroem, Ehrlichmann+	(ARGUS Collab.)
BORTOLETTO	92	PR D45 21	+Brown, Dominick, McIlwain+	(CLEO Collab.)
CRAWFORD	92	PR D45 752	+Fulton, Jensen, Johnson+	(CLEO Collab.)
HENDERSON	92	PR D45 2212	+Kinoshita, Pipkin, Procario+	(CLEO Collab.)
LESIAK	92	ZPHY C55 33	+Antreasyan, Bartels, Besset, Bieler+	(Crystal Ball Collab.)
ALBRECHT	91C	PL B255 297	+Ehrlichmann, Glaeser, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	91H	ZPHY C52 353	+Ehrlichmann, Hamacher, Harder+	(ARGUS Collab.)
FULTON	91	PR D43 651	+Jensen, Johnson, Kagan, Kass+	(CLEO Collab.)
YANAGISAWA	91	PRL 66 2436	+Heintz, Lee-Franzini, Lovelock, Narain+	(CUSB II Collab.)
ALBRECHT	90	PL B234 409	+Glaeser, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	90H	PL B249 359	+Ehrlichmann, Glaeser, Harder, Krueger+	(Argus Collab.)
BORTOLETTO	90	PRL 64 2117	+Goldberg, Horwitz, Jain, Mestayer+	(CLEO Collab.)
Also	92	PR D45 21	Bortoletto, Brown, Dominick, McIlwain+	(CLEO Collab.)
FULTON	90	PRL 64 16	+Hempstead, Jensen, Johnson+	(CLEO Collab.)
MASCHMANN	90	ZPHY C46 555	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
PDG	90	PL B239	Hernandez, Stone, Porter+	(IFIC, BOST, CIT+)
ALBRECHT	89K	ZPHY C42 519	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ISGUR	89B	PR D39 799	+Scora, Grinstein, Wise	(TNTO, CIT)
WACHS	89	ZPHY C42 33	+Antreasyan, Bartels, Bieler+	(Crystal Ball Collab.)
ALBRECHT	88E	PL B210 263	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	88H	PL B210 258	+Boeckmann, Glaeser+	(ARGUS Collab.)
KOERNER	88	ZPHY C38 511	+Schuler	(MANZ, DESY)
ALAM	87	PRL 59 22	+Kitukama, Kim, Li+	(CLEO Collab.)
ALAM	87B	PRL 58 1814	+Katayama, Kim, Sun+	(CLEO Collab.)
ALBRECHT	87D	PL B199 451	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	87H	PL B187 425	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
BEAN	87	PR D35 3533	+Bobbink, Brock, Engler+	(CLEO Collab.)
BEHRENDS	87	PRL 59 407	+Morrow, Guida, Guida+	(CLEO Collab.)
BORTOLETTO	87	PR D35 19	+Chen, Garren, Goldberg+	(CLEO Collab.)
ALAM	86	PR D34 3279	+Katayama, Kim, Sun+	(CLEO Collab.)
BALTRUSAIT...	86E	PRL 56 2140	Baltrusaitis, Becker, Blaylock, Brown+	(Mark III Collab.)
BORTOLETTO	86	PRL 56 800	+Chen, Garren, Goldberg+	(CLEO Collab.)
HAAS	86	PRL 56 2781	+Hempstead, Jensen, Kagan+	(CLEO Collab.)
ALBRECHT	85H	PL 162B 395	+Binder, Harder+	(ARGUS Collab.)
CSORNA	85	PRL 54 1894	+Garren, Mestayer, Panvini+	(CLEO Collab.)
HAAS	85	PRL 55 1248	+Hempstead, Jensen, Kagan+	(CLEO Collab.)
AVERY	84	PRL 53 1309	+Bebek, Berkelman, Cassel+	(CLEO Collab.)
CHEN	84	PRL 52 1084	+Goldberg, Horwitz, Jawahery+	(CLEO Collab.)
LEVMAN	84	PL 141B 271	+Sreedhar, Han, Imlay+	(CUSB Collab.)
ALAM	83B	PRL 51 1143	+Csorna, Garren, Mestayer+	(CLEO Collab.)
GREEN	83	PRL 51 347	+Hicks, Sannes, Skubic+	(CLEO Collab.)
KLOPFEN...	83B	PL 130B 444	Klopfenstein, Horstkotte+	(CUSB Collab.)
ALTARELLI	82	NP B208 365	+Cabibbo, Corbo, Maini, Martinelli	(ROMA, INFN, FRAS)
BRODY	82	PRL 48 1070	+Chen, Goldberg, Horwitz+	(CLEO Collab.)
GIANNINI	82	NP B206 1	+Finocchiaro, Franzini+	(CUSB Collab.)
BEBEK	81	PRL 46 84	+Haggerty, izen, Longuemare+	(CLEO Collab.)
CHADWICK	81	PRL 46 88	+Ganci, Kagar, Kass+	(CLEO Collab.)
ABRAMS	80	PRL 44 10	+Alam, Blocker, Boyarski+	(SLAC, LBL)

$B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE

$B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE MEAN LIFE

These measurements of the B mean life are averages over bottom particles produced, weighted by their semileptonic branching ratios, unless otherwise stated. Only the measurements at high energy are averaged since it is expected that the admixtures of b hadrons from Z decay and 1.8 TeV $p\overline{p}$ collisions should should not differ significantly.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^{\pm}$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.549±0.020 OUR EVALUATION					
1.582±0.011±0.027		[1] ABREU	96E	DLPH	$e^+e^- \to Z$
1.533±0.013±0.022	19.8k	[2] BUSKULIC	96F	ALEP	$e^+e^- \to Z$
1.564±0.030±0.036		[3] ABE,K	95B	SLD	$e^+e^- \to Z$
1.542±0.021±0.045		[4] ABREU	94L	DLPH	$e^+e^- \to Z$
1.46 ±0.06 ±0.06	5344	[5] ABE	93J	CDF	$p\overline{p}$ at 1.8 TeV
1.523±0.034±0.038	5372	[6] ACTON	93L	OPAL	$e^+e^- \to Z$
1.535±0.035±0.028	7357	[6] ADRIANI	93K	L3	$e^+e^- \to Z$
1.511±0.022±0.078		[7] BUSKULIC	93O	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.575±0.010±0.026		[8] ABREU	96E	DLPH	$e^+e^- \to Z$
$1.50\ ^{+0.24}_{-0.21}\ \pm0.03$		[9] ABREU	94P	DLPH	$e^+e^- \to Z$
$1.23\ ^{+0.14}_{-0.13}\ \pm0.15$	188	[10] ABREU	93D	DLPH	Sup. by ABREU 94L
1.49 ±0.11 ±0.12	253	[11] ABREU	93G	DLPH	Sup. by ABREU 94L
$1.51\ ^{+0.16}_{-0.14}\ \pm0.11$	130	[12] ACTON	93C	OPAL	$e^+e^- \to Z$
1.28 ±0.10		[13] ABREU	92	DLPH	Sup. by ABREU 94L
1.37 ±0.07 ±0.06	1354	[14] ACTON	92	OPAL	Sup. by ACTON 93L
1.49 ±0.03 ±0.06		[15] BUSKULIC	92F	ALEP	Sup. by BUSKULIC 96F
$1.35\ ^{+0.19}_{-0.17}\ \pm0.05$		[16] BUSKULIC	92G	ALEP	$e^+e^- \to Z$
1.32 ±0.08 ±0.09	1386	[17] ADEVA	91H	L3	Sup. by ADRIANI 93K
$1.32\ ^{+0.31}_{-0.25}\ \pm0.15$	37	[18] ALEXANDER	91G	OPAL	$e^+e^- \to Z$
1.29 ±0.06 ±0.10	2973	[19] DECAMP	91C	ALEP	Sup. by BUSKULIC 92F
$1.36\ ^{+0.25}_{-0.23}$		[20] HAGEMANN	90	JADE	E^{ee}_{cm}= 35 GeV
1.13 ±0.15		[21] LYONS	90	RVUE	
1.35 ±0.10 ±0.24		BRAUNSCH...	89B	TASS	E^{ee}_{cm}= 35 GeV
0.98 ±0.12 ±0.13		ONG	89	MRK2	E^{ee}_{cm}= 29 GeV
$1.17\ ^{+0.27}_{-0.22}\ ^{+0.17}_{-0.16}$		KLEM	88	DLCO	E^{ee}_{cm}= 29 GeV
1.29 ±0.20 ±0.21		[22] ASH	87	MAC	E^{ee}_{cm}= 29 GeV
$1.02\ ^{+0.42}_{-0.39}$	301	[23] BROM	87	HRS	E^{ee}_{cm}= 29 GeV

[1] Uses inclusively reconstructed secondary vertices.
[2] BUSKULIC 96F analyzed using 3D impact parameter.
[3] ABE,K 95B uses an inclusive topological technique.
[4] ABREU 94L uses charged particle impact parameters. Their result from inclusively reconstructed secondary vertices is superseded by ABREU 96E.
[5] ABE 93J analyzed using $J/\psi(1S) \to \mu\mu$ vertices.
[6] ACTON 93L and ADRIANI 93K analyzed using lepton (e and μ) impact parameter at Z.
[7] BUSKULIC 93O analyzed using dipole method.
[8] Combines ABREU 96E secondary vertex result with ABREU 94L impact parameter result.
[9] From proper time distribution of $b \to J/\psi(1S)$anything.
[10] ABREU 93D data analyzed using $D/D^*\ell$anything event vertices.
[11] ABREU 93G data analyzed using charged and neutral vertices.
[12] ACTON 93C analysed using $D/D^*\ell$anything event vertices.
[13] ABREU 92 is combined result of muon and hadron impact parameter analyses. Hadron tracks gave $(12.7 \pm 0.4 \pm 1.2) \times 10^{-13}$ s for an admixture of B species weighted by production fraction and mean charge multiplicity, while muon tracks gave $(13.0 \pm 1.0 \pm 0.8) \times 10^{-13}$ s for an admixture weighted by production fraction and semileptonic branching fraction.
[14] ACTON 92 is combined result of muon and electron impact parameter analyses.
[15] BUSKULIC 92F uses the lepton impact parameter distribution for data from the 1991 run.
[16] BUSKULIC 92G use $J/\psi(1S)$ tags to measure the average b lifetime. This is comparable to other methods only if the $J/\psi(1S)$ branching fractions of the different b-flavored hadrons are in the same ratio.
[17] Using $Z \to e^+$X or μ^+X, ADEVA 91H determined the average lifetime for an admixture of B hadrons from the impact parameter distribution of the lepton.
[18] Using $Z \to J/\psi(1S)$X, $J/\psi(1S) \to \ell^+\ell^-$, ALEXANDER 91G determined the average lifetime for an admixture of B hadrons from the decay point of the $J/\psi(1S)$.
[19] Using $Z \to e$X or μX, DECAMP 91C determines the average lifetime for an admixture of B hadrons from the signed impact parameter distribution of the lepton.
[20] HAGEMANN 90 uses electrons and muons in an impact parameter analysis.
[21] LYONS 90 combine the results of the B lifetime measuresments of ONG 89, BRAUNSCHWEIG 89B, KLEM 88, and ASH 87, and JADE data by private communication. They use statistical techniques which include variation of the error with the mean life, and possible correlations between the systematic errors. This result is not independent of the measured results used in our average.
[22] We have combined an overall scale error of 15% in quadrature with the systematic error of ±0.7 to obtain ±2.1 systematic error.
[23] Statistical and systematic errors were combined by BROM 87.

CHARGED b-HADRON ADMIXTURE MEAN LIFE

VALUE (10^{-12} s)	DOCUMENT ID		TECN	COMMENT
1.72±0.08±0.06	[24] ADAM	95	DLPH	$e^+e^- \to Z$

[24] ADAM 95 data analyzed using vertex-charge technique to tag b-hadron charge.

NEUTRAL b-HADRON ADMIXTURE MEAN LIFE

VALUE (10^{-12} s)	DOCUMENT ID		TECN	COMMENT
1.58±0.11±0.09	[25] ADAM	95	DLPH	$e^+e^- \to Z$

[25] ADAM 95 data analyzed using vertex-charge technique to tag b-hadron charge.

MEAN LIFE RATIO $\tau_{\text{charged } b\text{-hadron}}/\tau_{\text{neutral } b\text{-hadron}}$

VALUE	DOCUMENT ID		TECN	COMMENT
$1.09^{+0.11}_{-0.10}\pm0.08$	[26] ADAM	95	DLPH	$e^+e^- \to Z$

[26] ADAM 95 data analyzed using vertex-charge technique to tag b-hadron charge.

$\overline{b}$ PRODUCTION FRACTIONS AND DECAY MODES

The branching fraction measurements are for an admixture of B mesons and baryons at energies above the $\Upsilon(4S)$. Only the highest energy results (LEP, Tevatron, $Sp\overline{p}S$) are used in the branching fraction averages. The production fractions give our best current estimate of the admixture at LEP.

For inclusive branching fractions, *e.g.*, $B \to D^{\pm}$ anything, the treatment of multiple D's in the final state must be defined. One possibility would be to count the number of events with one-or-more D's and divide by the total number of B's. Another possibility would be to count the total number of D's and divide by the total number of B's, which is the definition of average multiplicity. The two definitions are identical when only one of the specified particles is allowed in the final state. Even though the "one-or-more" definition seems sensible, for practical reasons inclusive branching fractions are almost always measured using the multiplicity definition. For heavy final state particles, authors call their results inclusive branching fractions while for light particles some authors call their results multiplicities. In the B sections, we list all results as inclusive branching fractions, adopting a multiplicity definition. This means that inclusive branching fractions can exceed 100% and that inclusive partial widths can exceed total widths, just as inclusive cross sections can exceed total cross sections.

The modes below are listed for a $\overline{b}$ initial state. b modes are their charge conjugates. Reactions indicate the weak decay vertex and do not include mixing.

	Mode		Fraction (Γ_i/Γ)	Confidence level
	PRODUCTION FRACTIONS			

The production fractions for weakly decaying b-hadrons at the Z have been calculated from the best values of mean lives, mixing parameters, and branching fractions in this edition by O. Hayes (CERN) and M. Jimack (U. Birmingham) as described in the note "Production and Decay of b-Flavored Hadrons" in the $B^{\pm}$ Particle Listings. Values assume

$$B(\overline{b} \to B^+) = B(\overline{b} \to B^0)$$
$$B(\overline{b} \to B^+) + B(\overline{b} \to B^0) + B(\overline{b} \to B^0_s) + B(b \to \Lambda_b) = 100\ \%.$$

The notation for production fractions varies in the literature (f_{B^0}, $f(b \to \overline{B}^0)$, $\text{Br}(b \to \overline{B}^0)$). We use our own branching fraction notation here, $B(\overline{b} \to B^0)$.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\overline{b} \to B^+$		(37.8 ± 2.2) %	
Γ_2	$\overline{b} \to B^0$		(37.8 ± 2.2) %	
Γ_3	$\overline{b} \to B^0_s$		$(\ 11.2\ ^{+\ 1.8}_{-\ 1.9}\ )$ %	
Γ_4	$b \to \Lambda_b$		(13.2 ± 4.1) %	
	DECAY MODES			
	Semileptonic and leptonic modes			
Γ_5	$\overline{b} \to e^+\nu_e$ anything	[a]	(11.1 ± 1.0) %	
Γ_6	$\overline{b} \to \mu^+\nu_\mu$ anything	[a]	(10.7 ± 0.7) %	
Γ_7	$\overline{b} \to \ell^+\nu_\ell$ anything	[a,b]	(11.13± 0.29) %	
Γ_8	$\overline{b} \to D^-\ell^+\nu_\ell$ anything	[b]	(2.01± 0.29) %	
Γ_9	$\overline{b} \to \overline{D}^0\ell^+\nu_\ell$ anything	[b]	(6.6 ± 0.6) %	
Γ_{10}	$\overline{b} \to D^{*-}\ell^+\nu_\ell$ anything	[b]	(2.76± 0.29) %	
Γ_{11}	$\overline{b} \to \overline{D}^0_j\ell^+\nu_\ell$ anything	[b,c]	seen	
Γ_{12}	$\overline{b} \to D^-_j\ell^+\nu_\ell$ anything	[b,c]	seen	
Γ_{13}	$\overline{b} \to \overline{D}^*_2(2460)^0\ell^+\nu_\ell$ anything		seen	
Γ_{14}	$\overline{b} \to D^*_2(2460)^-\ell^+\nu_\ell$ anything		seen	
Γ_{15}	$\overline{b} \to \tau^+\nu_\tau$ anything		(2.7 ± 0.4) %	
Γ_{16}	$\overline{b} \to \overline{b} \to \overline{c} \to \ell^-\overline{\nu}_\ell$ anything	[b]	(7.9 ± 0.8) %	
	Charmonium modes			
Γ_{17}	$\overline{b} \to J/\psi(1S)$ anything		(1.16± 0.10) %	
Γ_{18}	$\overline{b} \to \psi(2S)$ anything		(4.8 ± 2.4) $\times 10^{-3}$	
Γ_{19}	$\overline{b} \to \chi_{c1}(1P)$ anything		(1.8 ± 0.5) %	
	K or K* modes			
Γ_{20}	$\overline{b} \to \overline{s}\gamma$		< 1.2 $\times 10^{-3}$	90%
Γ_{21}	$\overline{b} \to K^{\pm}$ anything		(88 ±19) %	
Γ_{22}	$\overline{b} \to K^0_S$ anything		(29.0 ± 2.9) %	
	Baryon modes			
Γ_{23}	$\overline{b} \to p/\overline{p}$ anything		(14 ± 6) %	
Γ_{24}	$\overline{b} \to \Lambda/\overline{\Lambda}$ anything		(5.9 ± 1.1) %	
	Other modes			
Γ_{25}	$\overline{b} \to$ charged anything	[d]	(584 ±40) %	
	$\Delta B = 1$ weak neutral current ($B1$) modes			
Γ_{26}	$\overline{b} \to e^+e^-$ anything	$B1$		
Γ_{27}	$\overline{b} \to \mu^+\mu^-$ anything	$B1$	< 5.0 $\times 10^{-5}$	90%
Γ_{28}	$\overline{b} \to \nu\overline{\nu}$ anything	$B1$	< 3.9 $\times 10^{-4}$	

[a] These values are model dependent. See 'Note on Semileptonic Decays' in the B^+ Particle Listings.

[b] ℓ indicates e or μ mode, not sum over modes.

[c] D_j represents an unresolved mixture of pseudoscalar and tensor D^{**} (P-wave) states.

[d] Inclusive branching fractions have a multiplicity definition and can be greater than 100%.

$B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE BRANCHING RATIOS

$\Gamma(\ell^+\nu_\ell\,\text{anything})/\Gamma_{\text{total}}$ — Γ_7/Γ

These branching fraction values are model dependent. See the note on "Semileptonic Decays of D and B Mesons, Part II" at the beginning of the B^+ Particle Listings.

VALUE	DOCUMENT ID		TECN	COMMENT
0.1113±0.0029 OUR AVERAGE	Includes data from the 2 datablocks that follow this one.			
0.1106±0.0039±0.0022	[27] ABREU	95D	DLPH	$e^+e^- \to Z$
0.114 ±0.003 ±0.004	[28] BUSKULIC	94G	ALEP	$e^+e^- \to Z$

[27] ABREU 95D give systematic errors ±0.0019 (model) and 0.0012 (R_c). We combine these in quadrature.

[28] BUSKULIC 94G uses e and μ events. This value is from a global fit to the lepton p and p_T (relative to jet) spectra which also determines the b and c production fractions, the fragmentation functions, and the forward-backward asymmetries. This branching ratio depends primarily on the ratio of dileptons to single leptons at high p_T, but the lower p_T portion of the lepton spectrum is included in the global fit to reduce the model dependence. The model dependence is ±0.0026 and is included in the systematic error.

$\Gamma(e^+\nu_e\,\text{anything})/\Gamma_{\text{total}}$ — Γ_5/Γ

These branching fraction values are model dependent. See the note on "Semileptonic Decays of D and B Mesons, Part II" at the beginning of the B^+ Particle Listings.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
The data in this block is included in the average printed for a previous datablock.					
0.111±0.010 OUR AVERAGE					
0.107±0.015±0.007	260	[29] ABREU	93C	DLPH	$e^+e^- \to Z$
$0.109^{+0.014}_{-0.013}\pm0.0055$	2719	[30] AKERS	93B	OPAL	$e^+e^- \to Z$
0.138±0.032±0.008		[31] ADEVA	91C	L3	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.086±0.027±0.008		[32] ABE	93E	VNS	E^{ee}_{cm}= 58 GeV
0.111±0.028±0.026		BEHREND	90D	CELL	E^{ee}_{cm}= 43 GeV
0.150±0.011±0.022		BEHREND	90D	CELL	E^{ee}_{cm}= 35 GeV
0.112±0.009±0.011		ONG	88	MRK2	E^{ee}_{cm}= 29 GeV
$0.149^{+0.022}_{-0.019}$		PAL	86	DLCO	E^{ee}_{cm}= 29 GeV
0.110±0.018±0.010		AIHARA	85	TPC	E^{ee}_{cm}= 29 GeV
0.111±0.034±0.040		ALTHOFF	84J	TASS	E^{ee}_{cm}= 34.6 GeV
0.146±0.028		KOOP	84	DLCO	Repl. by PAL 86
0.116±0.021±0.017		NELSON	83	MRK2	E^{ee}_{cm}= 29 GeV

[29] ABREU 93C event count includes ee events. Combining ee, $\mu\mu$, and $e\mu$ events, they obtain 0.100 ± 0.007 ± 0.007.

[30] AKERS 93B analysis performed using single and dilepton events.

[31] ADEVA 91C measure the average $B(b \to eX)$ branching ratio using single and double tagged b enhanced Z events. Combining e and μ results, they obtain 0.113 ± 0.010 ± 0.006. Constraining the initial number of b quarks by the Standard Model prediction (378 ± 3 MeV) for the decay of the Z into $b\overline{b}$, the electron result gives 0.112 ± 0.004 ± 0.008. They obtain 0.119 ± 0.003 ± 0.006 when e and μ results are combined. Used to measure the $b\overline{b}$ width itself, this electron result gives 370 ± 12 ± 24 MeV and combined with the muon result gives 385 ± 7 ± 22 MeV.

[32] ABE 93E experiment also measures forward-backward asymmetries and fragmentation functions for b and c.

$\Gamma(\mu^+\nu_\mu \text{anything})/\Gamma_{total}$ — Γ_6/Γ

These branching fraction values are model dependent. See the note on "Semileptonic Decays of D and B Mesons, Part II" at the beginning of the B^+ Particle Listings.

The data in this block is included in the average printed for a previous datablock.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.107±0.007 OUR AVERAGE					
0.110±0.012±0.007	656	[33] ABREU	93C	DLPH	$e^+e^- \to Z$
$0.101^{+0.010}_{-0.009}$±0.0055	4248	[34] AKERS	93B	OPAL	$e^+e^- \to Z$
0.113±0.012±0.006		[35] ADEVA	91C	L3	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.104±0.023±0.016		BEHREND	90D	CELL	E^{ee}_{cm}= 43 GeV
0.148±0.010±0.016		BEHREND	90D	CELL	E^{ee}_{cm}= 35 GeV
0.118±0.012±0.010		ONG	88	MRK2	E^{ee}_{cm}= 29 GeV
0.117±0.016±0.015		BARTEL	87	JADE	E^{ee}_{cm}= 34.6 GeV
0.114±0.018±0.025		BARTEL	85J	JADE	Repl. by BARTEL 87
0.117±0.028±0.010		ALTHOFF	84G	TASS	E^{ee}_{cm}= 34.5 GeV
0.105±0.015±0.013		ADEVA	83B	MRKJ	E^{ee}_{cm}= 33–38.5 GeV
$0.155^{+0.054}_{-0.029}$		FERNANDEZ	83D	MAC	E^{ee}_{cm}= 29 GeV

[33] ABREU 93C event count includes $\mu\mu$ events. Combining ee, $\mu\mu$, and $e\mu$ events, they obtain 0.100 ± 0.007 ± 0.007.
[34] AKERS 93B analysis performed using single and dilepton events.
[35] ADEVA 91C measure the average B($b \to eX$) branching ratio using single and double tagged b enhanced Z events. Combining e and μ results, they obtain 0.113 ± 0.010 ± 0.006. Constraining the initial number of b quarks by the Standard Model prediction (378±3 MeV) for the decay of the Z into $b\overline{b}$, the muon result gives 0.123±0.003±0.006. They obtain 0.119 ± 0.003 ± 0.006 when e and μ results are combined. Used to measure the $b\overline{b}$ width itself, this muon result gives 394 ± 9 ± 22 MeV and combined with the electron result gives 385 ± 7 ± 22 MeV.

$\Gamma(D^-\ell^+\nu_\ell \text{anything})/\Gamma_{total}$ — Γ_8/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0201±0.0026±0.0013	[36] AKERS	95Q	OPAL	$e^+e^- \to Z$

[36] AKERS 95Q reports [B($\overline{b} \to D^-\ell^+\nu_\ell$anything) × B($D^+ \to K^-\pi^+\pi^+$)] = (1.82 ± 0.20 ± 0.12) × 10^{-3}. We divide by our best value B($D^+ \to K^-\pi^+\pi^+$) = (9.1 ± 0.6) × 10^{-2}. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\overline{D}^0\ell^+\nu_\ell \text{anything})/\Gamma_{total}$ — Γ_9/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.066±0.006±0.002	[37] AKERS	95Q	OPAL	$e^+e^- \to Z$

[37] AKERS 95Q reports [B($\overline{b} \to \overline{D}^0\ell^+\nu_\ell$anything) × B($D^0 \to K^-\pi^+$)] = (2.52 ± 0.14 ± 0.17) × 10^{-3}. We divide by our best value B($D^0 \to K^-\pi^+$) = (3.83 ± 0.12) × 10^{-2}. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(D^{*-}\ell^+\nu_\ell \text{anything})/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0276±0.0027±0.0011	[38] AKERS	95Q	OPAL	$e^+e^- \to Z$

[38] AKERS 95Q reports [B($\overline{b} \to D^*\ell^+\nu_\ell X$) × B($D^{*+} \to D^0\pi^+$) × B($D^0 \to K^-\pi^+$)] = ((7.53 ± 0.47 ± 0.56) × 10^{-4}) and uses B($D^{*+} \to D^0\pi^+$) = 0.681 ± 0.013 and B($D^0 \to K^-\pi^+$) = 0.0401 ± 0.0014 to obtain the above result. The first error is the experiments error and the second error is the systematic error from the D^{*+} and D^0 branching ratios.

$\Gamma(\overline{D}_j\ell^+\nu_\ell \text{anything})/\Gamma_{total}$ — Γ_{11}/Γ

D_j represents an unresolved mixture of pseudoscalar and tensor D^{**} (P-wave) states.

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[39] AKERS	95Q	OPAL	$e^+e^- \to Z$

[39] AKERS 95Q quotes the product branching ratio B($\overline{b} \to \overline{D}^0_j\ell^+\nu_\ell X$) B($\overline{D}^0_j \to D^{*+}\pi^-$) = ((6.1 ± 1.3 ± 1.3) × 10^{-3}).

$\Gamma(D^-_j\ell^+\nu_\ell \text{anything})/\Gamma_{total}$ — Γ_{12}/Γ

D_j represents an unresolved mixture of pseudoscalar and tensor D^{**} (P-wave) states.

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[40] AKERS	95Q	OPAL	$e^+e^- \to Z$

[40] AKERS 95Q quotes the product branching ratio B($\overline{b} \to D^-_j\ell^+\nu_\ell$anything) B($D^-_j \to D^0\pi^-$) = ((7.0 ± $1.9^{+1.2}_{-1.3}$) × 10^{-3}).

$\Gamma(\overline{D}^*_2(2460)^0\ell^+\nu_\ell \text{anything})/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[41] AKERS	95Q	OPAL	$e^+e^- \to Z$

[41] AKERS 95Q quotes the product branching ratio B($\overline{b} \to \overline{D}^*_2(2460)^0\ell^+\nu_\ell$anything) B($D^*_2(2460)^0 \to D^+\pi^-$) = (1.6 ± 0.7 ± 0.3) × 10^{-3}.

$\Gamma(D^*_2(2460)^-\ell^+\nu_\ell \text{anything})/\Gamma_{total}$ — Γ_{14}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[42] AKERS	95Q	OPAL	$e^+e^- \to Z$

[42] AKERS 95Q quotes the product branching ratio B($\overline{b} \to D^*_2(2460)\ell^+\nu_\ell$anything) B($D^*_2(2460)^+ \to D^0\pi^-$) = 4.2 ± $1.3^{+0.7}_{-1.2}$.

$\Gamma(\tau^+\nu_\tau \text{anything})/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
2.7 ±0.4 OUR AVERAGE					
2.75±0.30±0.37	405	[43] BUSKULIC	95	ALEP	$e^+e^- \to Z$
2.4 ±0.7 ±0.8	1032	[44] ACCIARRI	94C	L3	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.08±0.76±0.62		BUSKULIC	93B	ALEP	Repl. by BUSKULIC 95

[43] BUSKULIC 95 uses missing-energy technique.
[44] This is a direct result using tagged $b\overline{b}$ events at the Z, but species are not separated.

$\Gamma(\overline{b} \to \overline{c} \to \ell^-\overline{\nu}_\ell \text{anything})/\Gamma_{total}$ — Γ_{16}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.079 ±0.008 OUR AVERAGE				
0.0770±0.0097±0.0046	[45] ABREU	95D	DLPH	$e^+e^- \to Z$
0.082 ±0.003 ±0.012	[46] BUSKULIC	94G	ALEP	$e^+e^- \to Z$

[45] ABREU 95D give systematic errors ±0.0033 (model) and 0.0032 (R_c). We combine these in quadrature. This result is from the same global fit as their $\Gamma(\overline{b} \to \ell^+\nu_\ell X)$ data.
[46] BUSKULIC 94G uses e and μ events. This value is from the same global fit as their $\Gamma(\overline{b} \to \ell^+\nu_\ell \text{anything})/\Gamma_{total}$ data.

$\Gamma(J/\psi(1S) \text{anything})/\Gamma_{total}$ — Γ_{17}/Γ

VALUE (units 10^{-2})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.16±0.10 OUR AVERAGE						
1.12±0.12±0.10			[47] ABREU	94P	DLPH	$e^+e^- \to Z$
1.16±0.16±0.14		121	[48] ADRIANI	93J	L3	$e^+e^- \to Z$
1.21±0.13±0.08			BUSKULIC	92G	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.3 ±0.2 ±0.2			[49] ADRIANI	92	L3	$e^+e^- \to Z$
<4.9	90		MATTEUZZI	83	MRK2	E^{ee}_{cm}= 29 GeV

[47] ABREU 94P is an inclusive measurement from b decays at the Z. Uses $J/\psi(1S) \to e^+e^-$ and $\mu^+\mu^-$ channels. Assumes $\Gamma(Z \to b\overline{b})/\Gamma_{hadron}$=0.22.
[48] ADRIANI 93J is an inclusive measurement from b decays at the Z. Uses $J/\psi(1S) \to \mu^+\mu^-$ and $J/\psi(1S) \to e^+e^-$ channels.
[49] ADRIANI 92 measurement is an inclusive result for B($Z \to J/\psi(1S)X$) = (4.1 ± 0.7 ± 0.3) × 10^{-3} which is used to extract the b-hadron contribution to $J/\psi(1S)$ production.

$\Gamma(\psi(2S) \text{anything})/\Gamma_{total}$ — Γ_{18}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0048±0.0022±0.0010	[50] ABREU	94P	DLPH	$e^+e^- \to Z$

[50] ABREU 94P is an inclusive measurement from b decays at the Z. Uses $\psi(2S) \to J/\psi(1S)\pi^+\pi^-$, $J/\psi(1S) \to \mu^+\mu^-$ channels. Assumes $\Gamma(Z \to b\overline{b})/\Gamma_{hadron}$=0.22.

$\Gamma(\chi_{c1}(1P) \text{anything})/\Gamma_{total}$ — Γ_{19}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.018±0.005 OUR AVERAGE					
0.014±0.006$^{+0.004}_{-0.002}$		[51] ABREU	94P	DLPH	$e^+e^- \to Z$
0.024±0.009±0.002	19	[52] ADRIANI	93J	L3	$e^+e^- \to Z$

[51] ABREU 94P is an inclusive measurement from b decays at the Z. Uses $\chi_{c1}(1P) \to J/\psi(1S)\gamma$, $J/\psi(1S) \to \mu^+\mu^-$ channels. Assumes no $\chi_{c2}(1P)$ and $\Gamma(Z \to b\overline{b})/\Gamma_{hadron}$=0.22.
[52] ADRIANI 93J is an inclusive measurement and assumes χ_{c1} come from b decays at Z. Uses $J/\psi(1S) \to \mu^+\mu^-$ channel.

$\Gamma(\chi_{c1}(1P) \text{anything})/\Gamma(J/\psi(1S) \text{anything})$ — Γ_{19}/Γ_{17}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.92±0.82	121	[53] ADRIANI	93J	L3	$e^+e^- \to Z$

[53] ADRIANI 93J is a ratio of inclusive measurements from b decays at the Z using only the $J/\psi(1S) \to \mu^+\mu^-$ channel since some systematics cancel.

$\Gamma(\overline{s}\gamma)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0012	90	[54] ADRIANI	93L	L3	$e^+e^- \to Z$

[54] ADRIANI 93L result is for $\overline{b} \to \overline{s}\gamma$ is performed inclusively.

$\Gamma(K^{\pm} \text{anything})/\Gamma_{total}$ — Γ_{21}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.88±0.05±0.18	ABREU	95C	DLPH	$e^+e^- \to Z$

$\Gamma(K^0_S \text{anything})/\Gamma_{total}$ — Γ_{22}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.290±0.011±0.027	ABREU	95C	DLPH	$e^+e^- \to Z$

$\Gamma(p/\overline{p} \text{anything})/\Gamma_{total}$ — Γ_{23}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.141±0.018±0.056	ABREU	95C	DLPH	$e^+e^- \to Z$

$\Gamma(\Lambda/\overline{\Lambda} \text{anything})/\Gamma_{total}$ — Γ_{24}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.059±0.007±0.009	ABREU	95C	DLPH	$e^+e^- \to Z$

Γ(charged anything)/Γ_{total} — Γ_{25}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
5.84±0.04±0.38	ABREU	95C	DLPH	$e^+e^- \to Z$

$\Gamma(\mu^+\mu^-$ anything)/Γ_{total} — Γ_{27}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.0 × 10^{-5}	90	ALBAJAR	91C	UA1	$E_{cm}^{p\overline{p}}$= 630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	95	ALTHOFF	84G	TASS	E_{cm}^{ee}= 34.5 GeV
<0.007	95	ADEVA	83	MRKJ	E_{cm}^{ee}= 30–38 GeV
<0.007	95	BARTEL	83B	JADE	E_{cm}^{ee}= 33–37 GeV

$[\Gamma(e^+e^-$ anything) + $\Gamma(\mu^+\mu^-$ anything)]/Γ_{total} — $(\Gamma_{26}+\Gamma_{27})/\Gamma$

Test for $\Delta B = 1$ weak neutral current.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.008	90	MATTEUZZI	83	MRK2	E_{cm}^{ee}= 29 GeV

$\Gamma(\nu\overline{\nu}$anything)/Γ_{total} — Γ_{28}/Γ

Test for $\Delta B = 1$ weak neutral current.

VALUE	DOCUMENT ID		TECN	COMMENT
<3.9 × 10^{-4}	[55] GROSSMAN	96	RVUE	$e^+e^- \to Z$

[55] GROSSMAN 96 limit is derived from the ALEPH BUSKULIC 95 limit B($B^+ \to \tau^+\nu_\tau$) < 1.8 × 10^{-3} at CL=90% using conservative simplifying assumptions.

$B^{\pm}/B^0/B_s^0/b$-baryon ADMIXTURE REFERENCES

ABREU 96E PL B377 195 +Adam, Adye, Agasi+ (DELPHI Collab.)
BUSKULIC 96F PL B369 151 +Casper, De Bonis, Decamp+ (ALEPH Collab.)
GROSSMAN 96 NP B465 369 +Ligeti, Nardi (REHO, CIT)
ABE,K 95B PRL 75 3624 Abe, Abt, Ahn, Akagi+ (SLD Collab.)
ABREU 95C PL B347 447 +Adam, Adye, Agasi+ (DELPHI Collab.)
ABREU 95D ZPHY C66 323 +Adam, Adye, Agasi+ (DELPHI Collab.)
ADAM 95 ZPHY C68 363 +Adye, Agasi, Ajinenko+ (DELPHI Collab.)
AKERS 95Q ZPHY C67 57 +Alexander, Allison, Ametewee+ (OPAL Collab.)
BUSKULIC 95 PL B343 444 +Casper, De Bonis, Decamp, Ghez, Goy+ (ALEPH Collab.)
ABREU 94L ZPHY C63 3 +Adam, Adye, Agasi, Aleksan+ (DELPHI Collab.)
ABREU 94P PL B341 109 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
ACCIARRI 94C PL B332 201 +Adam, Adriani, Aguilar-Benitez, Ahlen+ (L3 Collab.)
BUSKULIC 94G ZPHY C62 179 +Casper, De Bonis, Decamp, Ghez+ (ALEPH Collab.)
ABE 93E PL B313 288 +Amako, Arai, Arima, Asano+ (VENUS Collab.)
ABE 93J PRL 71 3421 +Albrow, Amidei, Anway-Wiese+ (CDF Collab.)
ABREU 93C PL B301 145 +Adam, Adye, Agasi, Aleksan+ (DELPHI Collab.)
ABREU 93D ZPHY C57 181 +Adam, Adye, Agasi, Alekseev+ (DELPHI Collab.)
ABREU 93G PL B312 253 +Adam, Adye, Agasi, Ajinenko+ (DELPHI Collab.)
ACTON 93C PL B307 247 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ACTON 93L ZPHY C60 217 +Akers, Alexander, Allison, Anderson+ (OPAL Collab.)
ADRIANI 93J PL B317 467 +Aguilar-Benitez, Ahlen, Alcaraz+ (L3 Collab.)
ADRIANI 93K PL B317 474 +Aguilar-Benitez, Ahlen, Alcarez+ (L3 Collab.)
ADRIANI 93L PL B317 637 +Aguilar-Benitez, Ahlen, Alcaraz+ (L3 Collab.)
AKERS 93B ZPHY C60 199 +Alexander, Allison, Anderson, Arcelli+ (OPAL Collab.)
BUSKULIC 93B PL B298 479 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
BUSKULIC 93O PL B314 459 +De Bonis, Decamp, Ghez, Goy+ (ALEPH Collab.)
ABREU 92 ZPHY C53 567 +Adam, Adami, Adye+ (DELPHI Collab.)
ACTON 92 PL B274 513 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ADRIANI 92 PL B288 412 +Aguilar-Benitez, Ahlen, Akbari+ (L3 Collab.)
BUSKULIC 92F PL B295 174 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
BUSKULIC 92G PL B295 396 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
ADEVA 91C PL B261 177 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ADEVA 91H PL B270 111 +Adrani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ALBAJAR 91C PL B262 163 +Albrow, Allkofer, Ankoviak, Apsimon+ (UA1 Collab.)
ALEXANDER 91G PL B266 485 +Allison, Allport+ (OPAL Collab.)
DECAMP 91C PL B257 492 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
BEHREND 90D ZPHY C47 333 +Criegee, Field, Franke, Jung+ (CELLO Collab.)
HAGEMANN 90 ZPHY C48 401 +Ramcke, Allison, Ambrus, Barlow+ (JADE Collab.)
LYONS 90 PR D41 982 +Martin, Saxon (OXF, BRIS, RAL)
BRAUNSCH... 89B ZPHY C44 1 Braunschweig, Gerhards, Kirschfink+ (TASSO Collab.)
ONG 89 PRL 62 1236 +Jaros, Abrams, Amidei, Baden+ (Mark II Collab.)
KLEM 88 PR D37 41 +Atwood, Barish+ (DELCO Collab.)
ONG 88 PRL 60 2587 +Weir, Abrams, Amidei+ (Mark II Collab.)
ASH 87 PRL 58 640 +Band, Bloom, Bosman+ (MAC Collab.)
BARTEL 87 ZPHY C33 339 +Becker, Felst, Haidt+ (JADE Collab.)
BROM 87 PL B195 301 +Abachi, Akerlof, Baringer+ (HRS Collab.)
PAL 86 PR D33 2708 +Atwood, Barish, Bonneaud+ (DELCO Collab.)
AIHARA 85 ZPHY C27 39 +Alston-Garnjost, Badtke, Bakken+ (TPC Collab.)
BARTEL 85J PL 163B 277 +Becker, Cords, Felst+ (JADE Collab.)
ALTHOFF 84G ZPHY C22 219 +Braunschweig, Kirschfink+ (TASSO Collab.)
ALTHOFF 84J PL 146B 443 +Branschweig, Kirschfink+ (TASSO Collab.)
KOOP 84 PRL 52 970 +Sakuda, Atwood, Baillon+ (DELCO Collab.)
ADEVA 83 PRL 50 799 +Barber, Becker, Berdugo+ (Mark-J Collab.)
ADEVA 83B PRL 51 443 +Barber, Becker, Berdugo+ (Mark-J Collab.)
BARTEL 83B PL 132B 241 +Becker, Bowdery, Cords+ (JADE Collab.)
FERNANDEZ 83D PRL 50 2054 +Ford, Read, Smith+ (MAC Collab.)
MATTEUZZI 83 PL 129B 141 +Abrams, Amidei, Blocker+ (Mark II Collab.)
NELSON 83 PRL 50 1542 +Blondel, Trilling, Abrams+ (Mark II Collab.)

B^*

$I(J^P) = \frac{1}{2}(1^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

B^* MASS

From mass difference below and the average of our B masses $(m_{B^\pm}+m_{B^0})/2$.

VALUE (MeV)	DOCUMENT ID
5324.8±1.8 OUR FIT	

$m_{B^*} - m_B$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
45.7±0.4 OUR FIT					
45.7±0.4 OUR AVERAGE					
45.3±0.35±0.87	4227	[1] BUSKULIC	96D	ALEP	E_{cm}^{ee}= 88–94 GeV
45.5±0.3 ±0.8		[1] ABREU	95R	DLPH	E_{cm}^{ee}= 88–94 GeV
46.3±1.9	1378	[1] ACCIARRI	95B	L3	E_{cm}^{ee}= 88–94 GeV
46.4±0.3 ±0.8		[2] AKERIB	91	CLE2	$e^+e^- \to \gamma X$
45.6±0.8		[2] WU	91	CSB2	$e^+e^- \to \gamma X$, $\gamma \ell X$
45.4±1.0		[3] LEE-FRANZINI	90	CSB2	$e^+e^- \to \Upsilon(5S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
52 ±2 ±4	1400	[4] HAN	85	CUSB	$e^+e^- \to \gamma e X$

[1] u, d, s flavor averaged.

[2] These papers report E_γ in the B^* center of mass. The $m_{B^*} - m_B$ is 0.2 MeV higher. E_{cm} = 10.61–10.7 GeV. Admixture of B^0 and B^+ mesons, but not B_s.

[3] LEE-FRANZINI 90 value is for an admixture of B^0 and B^+. They measure 46.7 ± 0.4 ± 0.2 MeV for an admixture of B^0, B^+, and B_s, and use the shape of the photon line to separate the above value.

[4] HAN 85 is for E_{cm} = 10.6–11.2 GeV, giving an admixture of B^0, B^+, and B_s.

$|(m_{B^{*+}} - m_{B^+}) - (m_{B^{*0}} - m_{B^0})|$

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<6	95	ABREU	95R	DLPH	E_{cm}^{ee}= 88–94 GeV

B^* DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$B\gamma$	dominant

B^* REFERENCES

BUSKULIC 96D ZPHY C69 393 +Casper, De Bonis, Decamp+ (ALEPH Collab.)
ABREU 95R ZPHY C68 353 +Adam, Adye, Agasi+ (DELPHI Collab.)
ACCIARRI 95B PL B345 589 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
AKERIB 91 PRL 67 1692 +Barish, Cown, Eigen, Stroynowski+ (CLEO Collab.)
WU 91 PL B273 177 +Franzini, Kanekal, Tuts+ (CUSB II Collab.)
LEE-FRANZINI 90 PRL 65 2947 +Heintz, Lovelock, Narain, Schamberger+ (CUSB II Collab.)
HAN 85 PRL 55 36 +Klopfenstein, Mageras+ (COLU, LSU, MPIM, STON)

$B_J^*(5732)$

$I(J^P) = ?(?^?)$
I, J, P need confirmation.

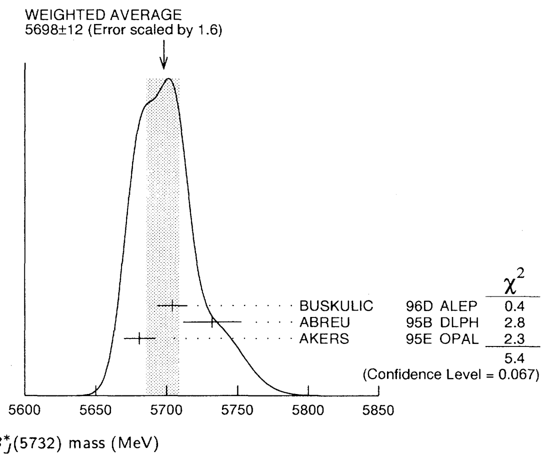
OMITTED FROM SUMMARY TABLE

Signal can be interpreted as stemming from several narrow and broad resonances. Needs confirmation.

$B_J^*(5732)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5698±12 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.					
5704± 4±10	1944	[1] BUSKULIC	96D	ALEP	$E_{\rm cm}^{ee}$= 88–94 GeV
5732± 5±20	2157	ABREU	95B	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
5681±11	1738	AKERS	95E	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV

[1] Using $m_{B\pi} - m_B$ = 424 ± 4 ± 10 MeV.



$B_J^*(5732)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
128±18 OUR AVERAGE					
145±28	2157	ABREU	95B	DLPH	$E_{\rm cm}^{ee}$= 88–94 GeV
116±24	1738	AKERS	95E	OPAL	$E_{\rm cm}^{ee}$= 88–94 GeV

$B_J^*(5732)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$B^*\pi + B\pi$	dominant

$B_J^*(5732)$ REFERENCES

BUSKULIC	96D	ZPHY C69 393	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ABREU	95B	PL B345 598	+	(DELPHI Collab.)
AKERS	95E	ZPHY C66 19	+Alexander, Allison+	(OPAL Collab.)

BOTTOM, STRANGE MESONS
($B = \pm1$, $S = \mp1$)

$B^0_s = s\overline{b}$, $\overline{B}^0_s = \overline{s}b$, similarly for B^*_s's

B^0_s

$I(J^P) = 0(0^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

B^0_s MASS

The fit uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B^0_s}$, and $(m_{B^0_s} - (m_{B^+} + m_{B^0})/2)$ to determine m_{B^+}, m_{B^0}, $m_{B^0_s}$, and the mass differences.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
5369.3± 2.0 OUR FIT				
5369.6± 2.4 OUR AVERAGE				
5369.9± 2.3±1.3	32	[1] ABE 96B	CDF	$p\overline{p}$ at 1.8 TeV
5374 ±16 ±2	3	ABREU 94D	DLPH	$e^+e^- \to Z$
5359 ±19 ±7	1	[1] AKERS 94J	OPAL	$e^+e^- \to Z$
5368.6± 5.6±1.5	2	BUSKULIC 93G	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5370 ±40	6	[2] AKERS 94J	OPAL	$e^+e^- \to Z$
5383.3± 4.5±5.0	14	ABE 93F	CDF	Repl by ABE 96B

[1] From the decay $B_s \to J/\psi(1S)\phi$.
[2] From the decay $B_s \to D^-_s\pi^+$.

$m_{B^0_s} - m_B$

m_B is the average of our B masses $(m_{B^\pm}+m_{B^0})/2$. The fits uses m_{B^+}, $(m_{B^0} - m_{B^+})$, $m_{B^0_s}$, and $m_{B^0_s} - m_B$ to determine m_{B^+}, m_{B^0}, $m_{B^0_s}$, and the mass differences.

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
90.2±2.2 OUR FIT				
89.7±2.7±1.2		ABE 96B	CDF	$p\overline{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
80 to 130	68	LEE-FRANZINI 90	CSB2	$e^+e^- \to \Upsilon(5S)$

$m_{B^0_{sH}} - m_{B^0_{sL}}$

See the B^0_s-$\overline{B}^0_s$ MIXING section near the end of these B^0_s Listings.

B^0_s MEAN LIFE

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^\pm$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID	TECN	COMMENT
$1.61^{+0.10}_{-0.09}$ OUR EVALUATION				
$1.56^{+0.29}_{-0.26}{}^{+0.08}_{-0.07}$		[3] ABREU 96F	DLPH	$e^+e^- \to Z$
$1.65^{+0.34}_{-0.31}\pm0.12$		[4] ABREU 96F	DLPH	$e^+e^- \to Z$
$1.76\pm0.20^{+0.15}_{-0.10}$		[5] ABREU 96F	DLPH	$e^+e^- \to Z$
$1.60\pm0.26^{+0.13}_{-0.15}$		[6] ABREU 96F	DLPH	$e^+e^- \to Z$
$1.61^{+0.30}_{-0.29}{}^{+0.18}_{-0.16}$	90	[4] BUSKULIC 96E	ALEP	$e^+e^- \to Z$
$1.42^{+0.27}_{-0.23}\pm0.11$	76	[3] ABE 95R	CDF	$p\overline{p}$ at 1.8 TeV
$1.74^{+1.08}_{-0.69}\pm0.07$	8	[7] ABE 95R	CDF	$p\overline{p}$ at 1.8 TeV
$1.54^{+0.25}_{-0.21}\pm0.06$	79	[3] AKERS 95G	OPAL	$e^+e^- \to Z$
$1.59^{+0.17}_{-0.15}\pm0.03$	134	[3] BUSKULIC 95O	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.67±0.14		[8] ABREU 96F	DLPH	$e^+e^- \to Z$
0.96±0.37	41	[9] ABREU 94E	DLPH	Sup. by ABREU 96F
$1.92^{+0.45}_{-0.35}\pm0.04$	31	[3] BUSKULIC 94C	ALEP	Sup. by BUSKULIC 95O
$1.13^{+0.35}_{-0.26}\pm0.09$	22	[3] ACTON 93H	OPAL	Sup. by AKERS 95G

[3] Measured using $D^-_s\ell^+$ vertices.
[4] Measured using D_s hadron vertices.
[5] Measured using $\phi\ell$ vertices.
[6] Measured using inclusive D_s vertices.
[7] Exclusive reconstruction of $B_s \to \psi\phi$.
[8] Combined result for the four ABREU 96F methods.
[9] ABREU 94E uses the flight-distance distribution of D_s vertices, ϕ-lepton vertices, and $D_s\mu$ vertices.

B^0_s DECAY MODES

These branching fractions all scale with $B(\overline{b} \to B^0_s)$, the LEP B^0_s production fraction. The first four were evaluated using $B(\overline{b} \to B^0_s) = (11.2^{+1.8}_{-1.9})\%$ and the rest assume $B(\overline{b} \to B^0_s) = 12\%$.

The branching fraction $B(B^0_s \to D^-_s\ell^+\nu_\ell \text{anything})$ is not a pure measurement since the measured product branching fraction $B(\overline{b} \to B^0_s) \times B(B^0_s \to D^-_s\ell^+\nu_\ell\text{anything})$ was used to determine $B(\overline{b} \to B^0_s)$, as described in the note on "Production and Decay of b-Flavored Hadrons."

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	D^-_s anything		(87 ±31) %	
Γ_2	$D^-_s\ell^+\nu_\ell$ anything	[a]	(7.6 ± 2.4) %	
Γ_3	$D^-_s\pi^+$		< 12 %	
Γ_4	$J/\psi(1S)\phi$		< 6 $\times 10^{-3}$	
Γ_5	$\psi(2S)\phi$		seen	
Γ_6	$\pi^0\pi^0$		< 2.1 $\times 10^{-4}$	90%
Γ_7	$\eta\pi^0$		< 1.0 $\times 10^{-3}$	90%
Γ_8	$\eta\eta$		< 1.5 $\times 10^{-3}$	90%
Γ_9	π^+K^-		< 2.6 $\times 10^{-4}$	90%
Γ_{10}	K^+K^-		< 1.4 $\times 10^{-4}$	90%
	$\Delta B = 1$ weak neutral current (B1) modes			
Γ_{11}	$\gamma\gamma$	B1	< 1.48 $\times 10^{-4}$	90%

[a] Not a pure measurement. See note at head of B^0_s Decay Modes.

B^0_s BRANCHING RATIOS

$\Gamma(D^-_s\text{ anything})/\Gamma_{total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.87±0.31 OUR AVERAGE				
0.76±0.23±0.23	90	[10] BUSKULIC 96E	ALEP	$e^+e^- \to Z$
1.46±0.54±0.44	147	[11] ACTON 92N	OPAL	$e^+e^- \to Z$

[10] BUSKULIC 96E separate $c\overline{c}$ and $b\overline{b}$ sources of D^+_s mesons using a lifetime tag, subtract generic $\overline{b} \to W^+ \to D^+_s$ events, and obtain $B(\overline{b} \to B^0_s) \times B(B^0_s \to D^-_s \text{anything}) = 0.088 \pm 0.020 \pm 0.020$ assuming $B(D_s \to \phi\pi) = (3.5 \pm 0.4) \times 10^{-2}$ and PDG 1994 values for the relative partial widths to other D_s channels. We evaluate using our current values $B(\overline{b} \to B^0_s) = 0.112^{+0.018}_{-0.019}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B^0_s)$ and $B(D_s \to \phi\pi)$.
[11] ACTON 92N assume that excess of 147 ± 48 D^0_s events over that expected from B^0, B^+, and $c\overline{c}$ is all from B^0_s decay. The product branching fraction is measured to be $B(\overline{b} \to B^0_s)B(B^0_s \to D^-_s\text{anything}) \times B(D^-_s \to \phi\pi^-) = (5.9 \pm 1.9 \pm 1.1) \times 10^{-3}$. We evaluate using our current values $B(\overline{b} \to B^0_s) = 0.112^{+0.018}_{-0.019}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B^0_s)$ and $B(D_s \to \phi\pi)$.

$\Gamma(D^-_s\ell^+\nu_\ell\text{anything})/\Gamma_{total}$ Γ_2/Γ

The values and averages in this section serve only to show what values result if one assumes our $B(\overline{b} \to B^0_s)$. They cannot be thought of as measurements since the underlying product branching fractions were also used to determinine $B(\overline{b} \to B^0_s)$ as described in the note on "Production and Decay of b-Flavored Hadrons."

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.076±0.024 OUR AVERAGE				
$0.071^{+0.011}_{-0.012}\pm0.021$	134	[12] BUSKULIC 95O	ALEP	$e^+e^- \to Z$
0.14 ±0.06 ±0.04	7	[13] ABREU 92M	DLPH	$e^+e^- \to Z$
0.097±0.034±0.029	18	[14] ACTON 92N	OPAL	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.13 ±0.04 ±0.04	27	[15] BUSKULIC 92E	ALEP	$e^+e^- \to Z$

[12] BUSKULIC 95O use $D_s\ell$ correlations. The measured product branching ratio is $B(\overline{b} \to B_s) \times B(B_s \to D^-_s\ell^+\nu_\ell\text{anything}) = (0.82 \pm 0.09^{+0.13}_{-0.14})\%$ assuming $B(D_s \to \phi\pi) = (3.5 \pm 0.4) \times 10^{-2}$ and PDG 1994 values for the relative partial widths to the six other D_s channels used in this analysis. Combined with results from $\Upsilon(4S)$ experiments this can be used to extract $B(\overline{b} \to B_s) = (11.0 \pm 1.2^{+2.5}_{-2.6})\%$. We evaluate using our current values $B(\overline{b} \to B^0_s) = 0.112^{+0.018}_{-0.019}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B^0_s)$ and $B(D_s \to \phi\pi)$.
[13] ABREU 92M measured muons only and obtained product branching ratio $B(Z \to b \text{ or } \overline{b}) \times B(\overline{b} \to B_s) \times B(B_s \to D_s\mu^+\nu_\mu\text{anything}) \times B(D_s \to \phi\pi) = (18 \pm 8) \times 10^{-5}$. We evaluate using our current values $B(\overline{b} \to B^0_s) = 0.112^{+0.018}_{-0.019}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B^0_s)$ and $B(D_s \to \phi\pi)$. We use $B(Z \to b \text{ or } \overline{b}) = 2B(Z \to b\overline{b}) = 2\times(0.1546 \pm 0.0014)$.

[14] ACTON 92N is measured using $D_s \to \phi\pi^+$ and $K^*(892)^0 K^+$ events. The product branching fraction measured is measured to be $B(\overline{b} \to B^0_s)B(B^0_s \to D^-_s \ell^+ \nu_\ell \text{anything}) \times B(D^-_s \to \phi\pi^-) = (3.9 \pm 1.1 \pm 0.8) \times 10^{-4}$. We evaluate using our current values $B(\overline{b} \to B^0_s) = 0.112^{+0.018}_{-0.019}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B^0_s)$ and $B(D_s \to \phi\pi)$.

[15] BUSKULIC 92E is measured using $D_s \to \phi\pi^+$ and $K^*(892)^0 K^+$ events. They use $2.7 \pm 0.7\%$ for the $\phi\pi^+$ branching fraction. The average product branching fraction is measured to be $B(\overline{b} \to B^0_s)B(B^0_s \to D^-_s \ell^+ \nu_\ell \text{anything}) = 0.020 \pm 0.0055^{+0.005}_{-0.006}$. We evaluate using our current values $B(\overline{b} \to B^0_s) = 0.112^{+0.018}_{-0.019}$ and $B(D_s \to \phi\pi) = 0.036 \pm 0.009$. Our first error is their experiment's and our second error is that due to $B(\overline{b} \to B^0_s)$ and $B(D_s \to \phi\pi)$. Superseded by BUSKULIC 95O.

$\Gamma(D^-_s \pi^+)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
<0.12	6	[16] AKERS	94J	OPAL	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	1	BUSKULIC	93G	ALEP	$e^+e^- \to Z$

[16] AKERS 94J sees ≤ 6 events and measures the limit on the product branching fraction $f(\overline{b} \to B^0_s) \cdot B(B^0_s \to D^-_s \pi^+) < 1.3\%$ at CL = 90%. We divide by our current value $B(\overline{b} \to B^0_s) = 0.112$.

$\Gamma(J/\psi(1S)\phi)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
<0.006	1	[17] AKERS	94J	OPAL	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	14	[18] ABE	93F	CDF	$p\overline{p}$ at 1.8 TeV
seen	1	[19] ACTON	92N	OPAL	Sup. by AKERS 94J

[17] AKERS 94J sees one event and measures the limit on the product branching fraction $f(\overline{b} \to B^0_s) \cdot B(B^0_s \to J/\psi(1S)\phi) < 7 \times 10^{-4}$ at CL = 90%. We divide by our current value $B(\overline{b} \to B^0_s) = 0.112$.

[18] ABE 93F measured using $J/\psi(1S) \to \mu^+\mu^-$ and $\phi \to K^+K^-$.

[19] In ACTON 92N a limit on the product branching fraction is measured to be $f(\overline{b} \to B^0_s) \cdot B(B^0_s \to J/\psi(1S)\phi) \leq 0.22 \times 10^{-2}$.

$\Gamma(\psi(2S)\phi)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	1	BUSKULIC	93G	ALEP	$e^+e^- \to Z$

$\Gamma(\pi^0\pi^0)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.1 x 10⁻⁴	90	[20] ACCIARRI	95H	L3	$e^+e^- \to Z$

[20] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\eta\pi^0)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.0 \times 10^{-3}$	90	[21] ACCIARRI	95H	L3	$e^+e^- \to Z$

[21] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\eta\eta)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.5 \times 10^{-3}$	90	[22] ACCIARRI	95H	L3	$e^+e^- \to Z$

[22] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

$\Gamma(\pi^+K^-)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.6 \times 10^{-4}$	90	[23] AKERS	94L	OPAL	$e^+e^- \to Z$

[23] Assumes $B(Z \to b\overline{b}) = 0.217$ and B^0_d (B^0_s) fraction 39.5% (12%).

$\Gamma(K^+K^-)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.4 \times 10^{-4}$	90	[24] AKERS	94L	OPAL	$e^+e^- \to Z$

[24] Assumes $B(Z \to b\overline{b}) = 0.217$ and B^0_d (B^0_s) fraction 39.5% (12%).

$\Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

Test for $\Delta B = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<14.8 \times 10^{-5}$	90	[25] ACCIARRI	95I	L3	$e^+e^- \to Z$

[25] ACCIARRI 95I assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

POLARIZATION IN B^0_s DECAY

Γ_L/Γ in $B^0_s \to J/\psi(1S)\phi$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.56 \pm 0.21^{+0.02}_{-0.04}$	19	ABE	95Z	CDF	$p\overline{p}$ at 1.8 TeV

B^0_s-$\overline{B}^0_s$ MIXING

For a discussion of B^0_s-$\overline{B}^0_s$ mixing see the note on "B^0-$\overline{B}^0$ Mixing and *CP* Violation in *B* Decay" in the B^0 Particle Listings above.

χ_s

This B^0_s-$\overline{B}^0_s$ mixing parameter measures the probability (integrated over time) that a produced B^0_s ($\overline{B}^0_s$) decays as a $\overline{B}^0_s$ (B^0_s). It cannot exceed 0.50. Mixing violates $\Delta B \neq 2$ rule.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
>0.49	95	[26] BUSKULIC	95J	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.74 ± 0.27	95	[27] ABREU	94F	RVUE	$e^+e^- \to Z$
$0.43^{+0.26}_{-0.17}$		[28] ACCIARRI	94D	RVUE	
0.46 ± 0.21		[29] ADEVA	92C	RVUE	Sup. by ACCIARRI 94D
0.53 ± 0.15		[30] ALBAJAR	91D	RVUE	

[26] BUSKULIC 95J is their $\Delta m_{B^0_s}$ measurement combined with $\tau_{B^0_s} = 1.61$ ps, our central value. Assumes $f_s = 11.2\%$.

[27] From a combination of DELPHI (ABREU 94F), CLEO (ARTUSO 89), and ARGUS (ALBRECHT 92L). Estimated from ABREU 94F figure 7.

[28] Uses BARTELT 93 to remove B_d mixing contribution and assuming $f_d = 0.375 \pm 0.05$ and $f_s = 0.15 \pm 0.05$.

[29] From combination of L3 (ADEVA 92C), CLEO (ARTUSO 89), and ARGUS (ALBRECHT 92L). Corresponding limit is > 0.16 at 90%CL.

[30] From combination of UA1 (ALBAJAR 91D), CLEO (BEAN 87B), ARGUS (ALBRECHT 87I), ALEPH (DECAMP 91), and L3 (ADEVA 90P). Corresponding limits are > 0.23 at 95% CL and > 0.27 at 90% CL.

χ_B at high energy

This is a B-$\overline{B}$ mixing measurement for an admixture of B^0 and B^0_s at high energy.

$$\chi_B = f_d \chi_d + f_s \chi_s$$

where f_d and f_s are the production fractions of B^0_d and B^0_s mesons relative to all *b*-flavored hadrons. Only the measurements at the *Z* and higher energy $p\overline{p}$ are averaged.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.126±0.008 OUR AVERAGE						
$0.121 \pm 0.016 \pm 0.006$			[31] ABREU	94J	DLPH	$e^+e^- \to Z$
$0.123 \pm 0.012 \pm 0.008$			ACCIARRI	94D	L3	$e^+e^- \to Z$
$0.114 \pm 0.014 \pm 0.008$			[32] BUSKULIC	94G	ALEP	$e^+e^- \to Z$
$0.143^{+0.022}_{-0.021} \pm 0.007$			[33] AKERS	93B	OPAL	$e^+e^- \to Z$
0.129 ± 0.022			[34] BUSKULIC	92B	ALEP	$e^+e^- \to Z$
$0.176 \pm 0.031 \pm 0.032$		1112	[35] ABE	91G	CDF	$p\overline{p}$ 1.8 TeV
$0.148 \pm 0.029 \pm 0.017$			[36] ALBAJAR	91D	UA1	$p\overline{p}$ 630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$0.144 \pm 0.014^{+0.017}_{-0.011}$			[37] ABREU	94F	DLPH	Sup. by ABREU 94J
0.131 ± 0.014			[38] ABREU	94J	DLPH	$e^+e^- \to Z$
$0.157 \pm 0.020 \pm 0.032$			[39] ALBAJAR	94	UA1	$\sqrt{s} = 630$ GeV
$0.121^{+0.044}_{-0.040} \pm 0.017$		1665	[40] ABREU	93C	DLPH	Sup. by ABREU 94J
$0.145^{+0.041}_{-0.035} \pm 0.018$			[41] ACTON	92C	OPAL	$e^+e^- \to Z$
$0.121 \pm 0.017 \pm 0.006$			[42] ADEVA	92C	L3	Sup. by ACCIARRI 94D
$0.132 \pm 0.22\ ^{+0.015}_{-0.012}$		823	[43] DECAMP	91	ALEP	$e^+e^- \to Z$
$0.178^{+0.049}_{-0.040} \pm 0.020$			[44] ADEVA	90P	L3	$e^+e^- \to Z$
$0.17\ ^{+0.15}_{-0.08}$			[45,46] WEIR	90	MRK2	e^+e^- 29 GeV
$0.21\ ^{+0.29}_{-0.15}$			[45] BAND	88	MAC	$E^{ee}_{cm} = 29$ GeV
>0.02	90		[45] BAND	88	MAC	$E^{ee}_{cm} = 29$ GeV
0.121 ± 0.047			[45,47] ALBAJAR	87C	UA1	Repl. by ALBAJAR 91D
<0.12	90		[45,48] SCHAAD	85	MRK2	$E^{ee}_{cm} = 29$ GeV

[31] This ABREU 94J result is from 5182 $\ell\ell$ and 279 $\Lambda\ell$ events. The systematic error includes 0.004 for model dependence.

[32] BUSKULIC 94G data analyzed using ee, $e\mu$, and $\mu\mu$ events.

[33] AKERS 93B analysis performed using dilepton events.

[34] BUSKULIC 92B uses a jet charge technique combined with electrons and muons.

[35] ABE 91G measurement of χ is done with $e\mu$ and ee events.

[36] ALBAJAR 91D measurement of χ is done with dimuons.

[37] ABREU 94F uses the average electric charge sum of the jets recoiling against a *b*-quark jet tagged by a high p_T muon. The result is for $\overline{\chi} = f_d \chi_d + 0.9 f_s \chi_s$.

[38] This ABREU 94J result combines $\ell\ell$, $\Lambda\ell$, and jet-charge ℓ (ABREU 94F) analyses. It is for $\overline{\chi} = f_d \chi_d + 0.96 f_s \chi_s$.

[39] ALBAJAR 94 uses dimuon events. Not independent of ALBAJAR 91D.

[40] ABREU 93C data analyzed using ee, $e\mu$, and $\mu\mu$ events.

[41] ACTON 92C uses electrons and muons. Superseded by AKERS 93B.

[42] ADEVA 92C uses electrons and muons.

[43] DECAMP 91 done with opposite and like-sign dileptons. Superseded by BUSKULIC 92B.

[44] ADEVA 90P measurement uses ee, $\mu\mu$, and $e\mu$ events from 118k events at the *Z*. Superseded by ADEVA 92C.

[45] These experiments are not in the average because the combination of B_s and B_d mesons which they see could differ from those at higher energy.

[46] The WEIR 90 measurement supersedes the limit obtained in SCHAAD 85. The 90% CL are 0.06 and 0.38.

[47] ALBAJAR 87C measured $\chi = (\overline{B}^0 \to B^0 \to \mu^+ X)$ divided by the average production weighted semileptonic branching fraction for *B* hadrons at 546 and 630 GeV.

[48] Limit is average probability for hadron containing *B* quark to produce a positive lepton.

$\Delta m_{B_s^0} = m_{B_{sH}^0} - m_{B_{sL}^0}$

$\Delta m_{B_s^0}$ is a measure of the B_s^0-$\overline{B}_s^0$ oscillation frequency in time-dependent mixing experiments.

VALUE (10^{12} $\hbar$ s^{-1})	CL%	DOCUMENT ID		TECN	COMMENT
>5.9	95	[49] BUSKULIC	95J	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>2.2	95	[50] AKERS	95J	OPAL	$e^+e^- \to Z$
>1.8	95	[50] BUSKULIC	94B	ALEP	$e^+e^- \to Z$

[49] BUSKULIC 95J determine $\Delta m_{B_s^0}$ from time dependence of B mixing using a jet charge technique to tag initial quark state and a lepton tag to determine flavor of the decaying b quark. They find $\Delta m_s > 5.6$ [> 6.1] $\hbar$ ps^{-1} when $f_s = 10\%$ [12%]. We interpolate to our central value $f_s = 11.2\%$.

[50] Uses dileptons.

$x_s = \Delta m_{B_s^0}/\Gamma_{B_s^0}$

This section combines the results from the previous two sections.

Time integrated mixing measurement of χ determine this quantity directly via

$$\frac{\Delta m_{B_s^0}}{\Gamma_{B_s^0}} = \left(\frac{\chi}{0.5-\chi}\right)^{1/2}$$

while time-dependent mixing measurements determine $\Delta m_{B_s^0} = m_{B_{sH}^0} - m_{B_{sL}^0}$ which are combined with $\tau_{B_s^0}$ to give

$$\frac{\Delta m_{B_s^0}}{\Gamma_{B_s^0}} = \frac{(m_{B_{sH}^0} - m_{B_{sL}^0})\,\tau_{B_s^0}}{\hbar}.$$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
>9.5	95	[51] BUSKULIC	95J	ALEP	$e^+e^- \to Z$

[51] BUSKULIC 95J is their $\Delta m_{B_s^0}$ measurement combined with $\tau_{B_s^0} = 1.61$ ps, our central value. Assumes $f_s = 11.2\%$.

B_s^0 REFERENCES

ABE	96B	PR D53 3496	+Albrow, Amendolia, Amidei+	(CDF Collab.)
ABREU	96F	ZPHY C (submitted)	+Adam, Adye, Agasi+	(DELPHI Collab.)
CERN-PPE/96-32				
BUSKULIC	96E	ZPHY C69 585	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ABE	95R	PRL 74 4988	+Albrow, Amendolia, Amidei+	(CDF Collab.)
ABE	95Z	PRL 75 3068	+Albrow, Amendolia, Amidei+	(CDF Collab.)
ACCIARRI	95H	PL B363 127	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	95I	PL B363 137	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
AKERS	95G	PL B350 273	+Alexander, Allison, Ametewee+	(OPAL Collab.)
AKERS	95J	ZPHY C66 555	+Alexander, Allison, Ametewee+	(OPAL Collab.)
BUSKULIC	95J	PL B356 409	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
BUSKULIC	95O	PL B361 221	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ABREU	94D	PL B324 500	+Adam, Adye, Agasi, Aleksan+	(DELPHI Collab.)
ABREU	94E	ZPHY C61 407	+Adam, Adye, Agasi, Aleksan+	(DELPHI Collab.)
Also	92M	PL B289 199	Abreu, Adam, Adye, Agasi, Alekseev+	(DELPHI Collab.)
ABREU	94F	PL B322 459	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ABREU	94J	PL B332 488	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACCIARRI	94D	PL B335 542	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
AKERS	94J	PL B337 196	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
AKERS	94L	PL B337 393	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
ALBAJAR	94	ZPHY C61 41	+Ankoviak, Bartha, Bezaguet, Boehrer+	(UA1 Collab.)
BUSKULIC	94B	PL B322 441	+De Bonis, Decamp, Ghez, Goy, Lees+	(ALEPH Collab.)
BUSKULIC	94C	PL B322 275	+De Bonis, Decamp, Ghez, Goy, Lees+	(ALEPH Collab.)
BUSKULIC	94G	ZPHY C62 179	+Casper, De Bonis, Decamp, Ghez+	(ALEPH Collab.)
ABE	93F	PRL 71 1685	+Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ABREU	93C	PL B301 145	+Adam, Adye, Agasi, Aleksan+	(DELPHI Collab.)
ACTON	93H	PL B312 501	+Akers, Alexander, Allison, Anderson+	(OPAL Collab.)
AKERS	93B	ZPHY C60 199	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
BARTELT	93	PRL 71 1680	+Csorna, Egyed, Jain, Sheldon+	(CLEO Collab.)
BUSKULIC	93G	PL B311 425	+De Bonis, Decamp, Ghez, Goy, Lees+	(ALEPH Collab.)
ABREU	92M	PL B289 199	+Adam, Adye, Agasi, Alekseev+	(DELPHI Collab.)
ACTON	92C	PL B276 379	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ACTON	92N	PL B295 357	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ADEVA	92C	PL B288 395	+Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ALBRECHT	92L	ZPHY C55 357	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
BUSKULIC	92B	PL B284 177	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
BUSKULIC	92E	PL B294 145	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
ABE	91G	PRL 67 3351	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALBAJAR	91D	PL B262 171	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
DECAMP	91	PL B258 236	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
ADEVA	90P	PL B252 703	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
LEE-FRANZINI	90	PRL 65 2947	+Heintz, Lovelock, Narain, Schamberger+	(CUSB II Collab.)
WEIR	90	PL B240 289	+Abrams, Adolphsen, Alexander, Alvarez+	(Mark II Collab.)
ARTUSO	89	PRL 62 2233	+Bebek, Berkelman, Blucher+	(CLEO Collab.)
BAND	88	PL B200 221	+Camporesi, Chadwick+	(MAC Collab.)
ALBAJAR	87C	PL B186 247	+Albrow, Allkofer, Arnison+	(UA1 Collab.)
ALBRECHT	87I	PL B192 245	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
BEAN	87B	PRL 58 183	+Bobbink, Brock, Engler+	(CLEO Collab.)
SCHAAD	85	PL 160B 188	+Nelson, Abrams, Amidei+	(Mark II Collab.)

OTHER RELATED PAPERS

ALI	93	JPG 19 1069	+London	(DESY, MONT)

"Prospects for measuring the B_s^0-$\overline{B}_s^0$ mixing ratio x_s"

B_s^*

$I(J^P) = ?(?^?)$
I, J, P need confirmation.

OMITTED FROM SUMMARY TABLE
Needs confirmation.

B_s^* MASS

From mass difference below and the B_s^0 mass.

VALUE (MeV)	DOCUMENT ID
5416.3±3.3 OUR FIT	

$m_{B_s^*} - m_{B_s}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
47.0±2.6 OUR FIT				
47.0±2.6	[1] LEE-FRANZINI	90	CSB2	$e^+e^- \to \Upsilon(5S)$

[1] LEE-FRANZINI 90 measure 46.7 ± 0.4 ± 0.2 MeV for an admixture of B^0, B^+, and B_s. They use the shape of the photon line to separate the above value for B_s.

$|(m_{B_s^*} - m_{B_s}) - (m_{B^*} - m_B)|$

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<6	95	ABREU	95R	DLPH	E_{cm}^{ee} = 88–94 GeV

B_s^* DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$B_s\gamma$	dominant

B_s^* REFERENCES

ABREU	95R	ZPHY C68 353	+Adam, Adye, Agasi+	(DELPHI Collab.)
LEE-FRANZINI	90	PRL 65 2947	+Heintz, Lovelock, Narain, Schamberger+	(CUSB II Collab.)

$B_{sJ}^*(5850)$

$I(J^P) = ?(?^?)$
I, J, P need confirmation.

OMITTED FROM SUMMARY TABLE
Signal can be interpreted as coming from $\overline{b}s$ states. Needs confirmation.

$B_{sJ}^*(5850)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5853±15	141	AKERS	95E	OPAL	E_{cm}^{ee} = 88–94 GeV

$B_{sJ}^*(5850)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
47±22	141	AKERS	95E	OPAL	E_{cm}^{ee} = 88–94 GeV

$B_{sJ}^*(5850)$ REFERENCES

AKERS	95E	ZPHY C66 19	+Alexander, Allison+	(OPAL Collab.)

$c\bar{c}$ MESONS

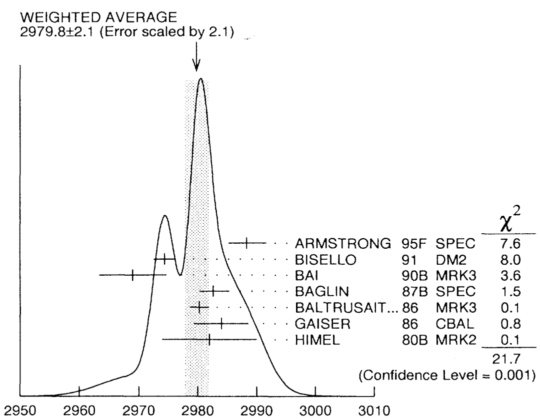
$\eta_c(1S)$

$I^G(J^{PC}) = 0^+(0^{-+})$

$\eta_c(1S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
2979.8± 2.1 OUR AVERAGE		Error includes scale factor of 2.1. See the ideogram below.		
$2988.3^{+3.3}_{-3.1}$		ARMSTRONG 95F	SPEC	$\bar{p}p \to \gamma\gamma$
2974.4± 1.9		[1] BISELLO 91	DM2	$J/\psi \to \eta_c\gamma$
2969 ± 4 ± 4	80	BAI 90B	MRK3	$J/\psi \to \gamma K^+K^-K^+K^-$
$2982.6^{+2.7}_{-2.3}$	12	BAGLIN 87B	SPEC	$\bar{p}p \to \gamma\gamma$
2980.2± 1.6		[1] BALTRUSAIT..86	MRK3	$J/\psi \to \eta_c\gamma$
2984 ± 2.3± 4.0		GAISER 86	CBAL	$J/\psi \to \gamma X$, $\psi(2S) \to \gamma X$
2982 ± 8	18	[2] HIMEL 80B	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2956 ±12 ±12		BAI 90B	MRK3	$J/\psi \to \gamma K^+K^-K^0_S K^0_L$
2976 ± 8		[3] BALTRUSAIT..84	MRK3	$J/\psi \to 2\phi\gamma$
2980 ± 9		[2] PARTRIDGE 80B	CBAL	e^+e^-

[1] Average of several decay modes.
[2] Mass adjusted by us to correspond to $J/\psi(1S)$ mass = 3097 MeV.
[3] $\eta_c \to \phi\phi$.



$\eta_c(1S)$ mass (MeV)

$\eta_c(1S)$ WIDTH

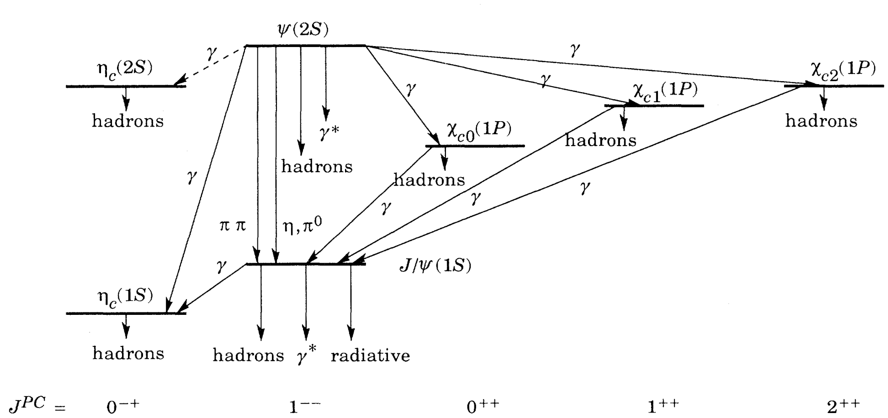
VALUE (MeV)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{13.2^{+3.8}_{-3.2}}$ **OUR AVERAGE**					
$23.9^{+12.6}_{-7.1}$			ARMSTRONG 95F	SPEC	$\bar{p}p \to \gamma\gamma$
$7.0^{+7.5}_{-7.0}$		12	BAGLIN 87B	SPEC	$\bar{p}p \to \gamma\gamma$
$10.1^{+33.0}_{-8.2}$		23	[4] BALTRUSAIT..86	MRK3	$J/\psi \to \gamma p\bar{p}$
11.5± 4.5			GAISER 86	CBAL	$J/\psi \to \gamma X$, $\psi(2S) \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<40	90	18	HIMEL 80B	MRK2	e^+e^-
<20	90		PARTRIDGE 80B	CBAL	e^+e^-

[4] Positive and negative errors correspond to 90% confidence level.

$\eta_c(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Decays involving hadronic resonances		
Γ_1	$\eta'(958)\pi\pi$	(4.1 ±1.7) %	
Γ_2	$\rho\rho$	(2.6 ±0.9) %	
Γ_3	$K^*(892)^0K^-\pi^+$ + c.c.	(2.0 ±0.7) %	
Γ_4	$K^*(892)\overline{K}^*(892)$	(8.5 ±3.1) × 10^{-3}	
Γ_5	$\phi\phi$	(7.1 ±2.8) × 10^{-3}	
Γ_6	$a_0(980)\pi$	< 2 %	90%
Γ_7	$a_2(1320)\pi$	< 2 %	90%
Γ_8	$K^*(892)\overline{K}$ + c.c.	< 1.28 %	90%
Γ_9	$f_2(1270)\eta$	< 1.1 %	90%
Γ_{10}	$\omega\omega$	< 3.1 × 10^{-3}	90%
	Decays into stable hadrons		
Γ_{11}	$K\overline{K}\pi$	(5.5 ±1.7) %	
Γ_{12}	$\eta\pi\pi$	(4.9 ±1.8) %	
Γ_{13}	$\pi^+\pi^-K^+K^-$	$(2.0^{+0.7}_{-0.6})$ %	
Γ_{14}	$2(K^+K^-)$	(2.1 ±1.2) %	
Γ_{15}	$2(\pi^+\pi^-)$	(1.2 ±0.4) %	
Γ_{16}	$p\bar{p}$	(1.2 ±0.4) × 10^{-3}	
Γ_{17}	$K\overline{K}\eta$	< 3.1 %	90%
Γ_{18}	$\pi^+\pi^-p\bar{p}$	< 1.2 %	90%
Γ_{19}	$\Lambda\bar{\Lambda}$	< 2 × 10^{-3}	90%
	Radiative decays		
Γ_{20}	$\gamma\gamma$	(3.0 ±1.2) × 10^{-4}	

THE CHARMONIUM SYSTEM



The current state of knowledge of the charmonium system and transitions, as interpreted by the charmonium model. Uncertain states and transitions are indicated by dashed lines. The notation γ^* refers to decay processes involving intermediate virtual photons, including decays to e^+e^- and $\mu^+\mu^-$.

$\eta_c(1S)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_{20}

VALUE (keV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$7.5^{+1.6}_{-1.4}$ OUR AVERAGE						
$6.7^{+2.4}_{-1.7}\pm2.3$			ARMSTRONG	95F	SPEC	$\overline{p}p \to \gamma\gamma$
11.3 ± 4.2			ALBRECHT	94H	ARG	$\gamma\gamma$
$8.0\pm2.3\pm2.4$		17	ADRIANI	93N	L3	$e^+e^- \to e^+e^-\eta_c$
$5.9^{+2.1}_{-1.8}\pm1.9$			CHEN	90B	CLEO	$e^+e^- \to e^+e^-\eta_c$
$6.4^{+5.0}_{-3.4}$			AIHARA	88D	TPC	$e^+e^- \to e^+e^-X$
28 ± 15			[5] BERGER	86	PLUT	$\gamma\gamma \to K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<11	90		BLINOV	86	MD1	$e^+e^- \to e^+e^-X$

[5] Re-evaluated by AIHARA 88D.

$\eta_c(1S)$ $\Gamma(i)\Gamma(\gamma\gamma)/\Gamma(\text{total})$

$\Gamma(K\overline{K}\pi) \times \Gamma(\gamma\gamma)/\Gamma_{\text{total}}$ — $\Gamma_{11}\Gamma_{20}/\Gamma$

VALUE (keV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.94 ± 0.18 OUR AVERAGE						
0.84 ± 0.21			[6] ALBRECHT	94H	ARG	$\gamma\gamma \to K^\pm K^0_S\pi^\mp$
$1.06\pm0.41\pm0.27$		11	BRAUNSCH...	89	TASS	$\gamma\gamma \to K\overline{K}\pi$
$1.5\ ^{+0.60}_{-0.45}\pm0.3$		7	[6] BERGER	86	PLUT	$\gamma\gamma \to K\overline{K}\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.63	95		[6] BEHREND	89	CELL	$\gamma\gamma \to K^0_S K^\pm\pi^\mp$
<4.4	95		ALTHOFF	85B	TASS	$\gamma\gamma \to K\overline{K}\pi$

[6] $K^\pm K^0_S\pi^\mp$ corrected to $K\overline{K}\pi$ by factor 3.

$\eta_c(1S)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(\eta'(958)\pi\pi)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.041 ± 0.017	14	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\rho\rho)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
26 ± 9 OUR EVALUATION (Treating systematicerrors as correlated.)						
25 ± 8 OUR AVERAGE						
$26.0\pm2.4\pm8.8$		113	[7] BISELLO	91	DM2	$J/\psi \to \gamma\rho^0\rho^0$
$23.6\pm10.6\pm8.2$		32	[7] BISELLO	91	DM2	$J/\psi \to \gamma\rho^+\rho^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<140	90		[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(K^*(892)^0K^-\pi^+ + \text{c.c.})/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.02 ± 0.007	63	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(K^*(892)\overline{K}^*(892))/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
85 ± 31 OUR AVERAGE					
$82\pm28\pm27$	14	[7] BISELLO	91	DM2	$e^+e^- \to \gamma K^+K^-\pi^+\pi^-$
90 ± 50	9	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(K^*(892)\overline{K} + \text{c.c.})/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0128	90	BISELLO	91	DM2	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
<0.0132	90	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^+K^-\pi^0$

$\Gamma(\phi\phi)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
71 ± 28 OUR EVALUATION (Treating systematic errors as correlated.)					
71 ± 22 OUR AVERAGE					
$74\pm18\pm24$	80	[7] BAI	90B	MRK3	$J/\psi \to \gamma K^+K^-K^+K^-$
$67\pm21\pm24$		[7] BAI	90B	MRK3	$J/\psi \to \gamma K^+K^-K^0_S K^0_L$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$31\pm7\pm10$	19	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^+K^-K^+K^-$
$30^{+18}_{-12}\pm10$	5	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^+K^-K^0_S K^0_L$

$\Gamma(a_0(980)\pi)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[7,8] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(a_2(1320)\pi)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(f_2(1270)\eta)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\omega\omega)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0031	90	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0063		[7] BISELLO	91	DM2	$J/\psi \to \gamma\omega\omega$

$\Gamma(K\overline{K}\pi)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.055 ± 0.017 OUR EVALUATION (Treating systematic errors as correlated.)						
0.055 ± 0.008 OUR AVERAGE						
$0.0690\pm0.0142\pm0.0132$		33	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^+K^-\pi^0$
$0.0543\pm0.0094\pm0.0094$		68	[7] BISELLO	91	DM2	$J/\psi \to \gamma K^\pm\pi^\mp K^0_S$
0.048 ± 0.011		95	[7,9] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$
$0.161\ ^{+0.092}_{-0.073}$			[10] HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.107	90		[7] PARTRIDGE	80B	CBAL	$J/\psi \to \eta_c\gamma$

$\Gamma(\eta\pi\pi)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.049 ± 0.018 OUR EVALUATION					
0.047 ± 0.015 OUR AVERAGE					
0.054 ± 0.020	75	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$
$0.037\pm0.013\pm0.020$	18	[7] PARTRIDGE	80B	CBAL	$J/\psi \to \eta\pi^+\pi^-\gamma$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.020^{+0.007}_{-0.006}$ OUR AVERAGE					
0.021 ± 0.007	110	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$
$0.014^{+0.022}_{-0.009}$		[10] HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(2(\pi^+\pi^-))/\Gamma_{\text{total}}$ — Γ_{15}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.012 ± 0.004 OUR EVALUATION					
0.0120 ± 0.0031 OUR AVERAGE					
$0.0105\pm0.0017\pm0.0034$	137	[7] BISELLO	91	DM2	$J/\psi \to \gamma 2\pi^+2\pi^-$
0.013 ± 0.006	25	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$
$0.020\ ^{+0.015}_{-0.010}$		[10] HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(2(K^+K^-))/\Gamma_{\text{total}}$ — Γ_{14}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$0.021\pm0.010\pm0.006$	ALBRECHT	94H	ARG	$\gamma\gamma \to K^+K^-K^+K^-$

$\Gamma(p\overline{p})/\Gamma_{\text{total}}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
12 ± 4 OUR AVERAGE					
$10\pm3\pm4$	18	[7] BISELLO	91	DM2	$J/\psi \to \gamma p\overline{p}$
11 ± 6	23	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$
29^{+29}_{-15}		[10] HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(K\overline{K}\eta)/\Gamma_{\text{total}}$ — Γ_{17}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.031	90	[7] BALTRUSAIT..86		MRK3	$J/\psi \to \eta_c\gamma$

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{\text{total}}$ — Γ_{18}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.012	90	HIMEL	80B	MRK2	$\psi(2S) \to \eta_c\gamma$

$\Gamma(\Lambda\overline{\Lambda})/\Gamma_{\text{total}}$ — Γ_{19}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.002	90	[7] BISELLO	91	DM2	$e^+e^- \to \gamma\Lambda\overline{\Lambda}$

$\Gamma_i\Gamma_f/\Gamma^2_{\text{total}}$ in $p\overline{p} \to \eta_c(1S) \to \phi\phi$ — $\Gamma_{16}\Gamma_5/\Gamma^2$

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
$4.0^{+3.5}_{-3.2}$	BAGLIN	89	SPEC	$\overline{p}p \to K^+K^-K^+K^-$

[7] The quoted branching ratios use $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.0127 \pm 0.0036$. Where relevant, the error in this branching ratio is treated as a common systematic in computing averages.

[8] We are assuming $B(a_0(980) \to \eta\pi) > 0.5$.

[9] Average from $K^+K^-\pi^0$ and $K^\pm K^0{}'s\pi^\mp$ decay channels.

[10] Estimated using $B(\psi(2S) \to \gamma\eta_c(1S)) = 0.0028 \pm 0.0006$.

RADIATIVE DECAYS

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
3.0 ±1.2 OUR AVERAGE					
$2.80^{+0.67}_{-0.58}\pm1.0$		ARMSTRONG	95F	SPEC	$\overline{p}p \to \gamma\gamma$
$6\ ^{+4}_{-3}\ \pm4$		BAGLIN	87B	SPEC	$\overline{p}p \to \gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<9	90	[7] BISELLO	91	DM2	$J/\psi \to \gamma\gamma\gamma$
<18	90	[11] BLOOM	83	CBAL	$J/\psi \to \eta_c\gamma$

[11] Using $B(J/\psi(1S) \to \gamma\eta_c(1S)) = 0.0127 \pm 0.0036$.

$\Gamma_i\Gamma_f/\Gamma^2_{total}$ in $p\overline{p} \to \eta_c(1S) \to \gamma\gamma$ — $\Gamma_{16}\Gamma_{20}/\Gamma^2$

VALUE (units 10^{-6})	EVTS	DOCUMENT ID		TECN	COMMENT
$0.36\ ^{+0.08}_{-0.07}$ OUR AVERAGE Error includes scale factor of 1.1.					
$0.336^{+0.080}_{-0.070}$		ARMSTRONG	95F	SPEC	$\overline{p}p \to \gamma\gamma$
$0.68\ ^{+0.42}_{-0.31}$	12	BAGLIN	87B	SPEC	$\overline{p}p \to \gamma\gamma$

$\eta_c(1S)$ REFERENCES

ARMSTRONG 95F PR D52 4839 +Bettoni+ (FNAL, FERR, GENO, UCI, NWES+)
ALBRECHT 94H PL B338 390 +Hamacher, Hofmann+ (ARGUS Collab.)
ADRIANI 93N PL B318 575 +Aguilar-Benitez, Ahlen+ (L3 Collab.)
BISELLO 91 NP B350 1 +Busetto+ (DM2 Collab.)
BAI 90B PRL 65 1309 +Blaylock+ (Mark III Collab.)
CHEN 90B PL B243 169 +McIlwain+ (CLEO Collab.)
BAGLIN 89 PL B231 557 +Baird, Bassompierre (R704 Collab.)
BEHREND 89 ZPHY C42 367 +Criegee+ (CELLO Collab.)
BRAUNSCH... 89 ZPHY C41 533 Braunschweig, Bock+ (TASSO Collab.)
AIHARA 88D PRL 60 2355 +Alston-Garnjost+ (TPC Collab.)
BAGLIN 87B PL B187 191 +Baird, Bassompierre, Borreani+ (R704 Collab.)
BALTRUSAIT... 86 PR D33 629 Baltrusaitis, Coffman, Hauser+ (Mark III Collab.)
BERGER 86 PL 167B 120 +Genzel, Lackas, Pielorz+ (PLUTO Collab.)
BLINOV 86 +Blinov, Bondar, Bukin+ (NOVO)
Proc. XXIII Int. HEP Conf., Berkeley, CA (1986); World Scientific, Singapore, 1987, ed. S.C. Loken
GAISER 86 PR D34 711 +Bloom, Bulos, Godfrey+ (Crystal Ball Collab.)
ALTHOFF 85B ZPHY C29 189 +Braunschweig, Kirschfink+ (TASSO Collab.)
BALTRUSAIT... 84 PRL 52 2126 Baltrusaitis+ (CIT, UCSC, ILL, SLAC, WASH) JP
BLOOM 83 ARNS 33 143 +Peck (SLAC, CIT)
HIMEL 80B PRL 45 1146 +Trilling, Abrams, Alam+ (SLAC, LBL, UCB)
PARTRIDGE 80B PRL 45 1150 +Peck+ (CIT, HARV, PRIN, STAN, SLAC)

OTHER RELATED PAPERS

ARMSTRONG 89 PL B221 216 +Benayoun+(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
BLOOM 79 Fermilab Symp. 92 (CIT, HARV, PRIN, SLAC, STAN)

$J/\psi(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$J/\psi(1S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3096.88±0.04 OUR AVERAGE					
3096.87±0.03±0.03		ARMSTRONG	93B	SPEC	$\overline{p}p \to e^+e^-$
3096.95±0.1 ±0.3	193	BAGLIN	87	SPEC	$\overline{p}p \to e^+e^-X$
3098.4 ±2.0	38k	LEMOIGNE	82	GOLI	190 GeV π^- Be $\to 2\mu$
3096.93±0.09	502	ZHOLENTZ	80	REDE	e^+e^-
3097.0 ±1		[1] BRANDELIK	79C	DASP	e^+e^-

[1] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$ and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.

$J/\psi(1S)$ WIDTH

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
87 ± 5 OUR AVERAGE				
84.4± 8.9	BAI	95B	BES	e^+e^-
99 ±12 ±6	ARMSTRONG	93B	SPEC	$\overline{p}p \to e^+e^-$
$85.5^{+\ 6.1}_{-\ 5.8}$	[2] HSUEH	92	RVUE	See Υ mini-review

[2] Using data from COFFMAN 92, BALDINI-CELIO 75, BOYARSKI 75, ESPOSITO 75B, BRANDELIK 79C.

$J/\psi(1S)$ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons		(87.7 ±0.5) %	
Γ_2	virtual$\gamma \to$ hadrons		(17.0 ±2.0) %	
Γ_3	e^+e^-		(6.02±0.19) %	
Γ_4	$\mu^+\mu^-$		(6.01±0.19) %	
	Decays involving hadronic resonances			
Γ_5	$\rho\pi$		(1.28±0.10) %	
Γ_6	$\rho^0\pi^0$		(4.2 ±0.5) $\times 10^{-3}$	
Γ_7	$a_2(1320)\rho$		(1.09±0.22) %	
Γ_8	$\omega\pi^+\pi^+\pi^-\pi^-$		(8.5 ±3.4) $\times 10^{-3}$	
Γ_9	$\omega\pi^+\pi^-$		(7.2 ±1.0) $\times 10^{-3}$	
Γ_{10}	$K^*(892)^0\overline{K}^*_2(1430)^0$ + c.c.		(6.7 ±2.6) $\times 10^{-3}$	
Γ_{11}	$\omega K^*(892)\overline{K}$ + c.c.		(5.3 ±2.0) $\times 10^{-3}$	
Γ_{12}	$\omega f_2(1270)$		(4.3 ±0.6) $\times 10^{-3}$	
Γ_{13}	$K^+\overline{K}^*(892)^-$ + c.c.		(5.0 ±0.4) $\times 10^{-3}$	
Γ_{14}	$K^0\overline{K}^*(892)^0$ + c.c.		(4.2 ±0.4) $\times 10^{-3}$	
Γ_{15}	$\omega\pi^0\pi^0$		(3.4 ±0.8) $\times 10^{-3}$	
Γ_{16}	$b_1(1235)^\pm\pi^\mp$	[a]	(3.0 ±0.5) $\times 10^{-3}$	
Γ_{17}	$\omega K^\pm K^0_S\pi^\mp$	[a]	(3.0 ±0.7) $\times 10^{-3}$	
Γ_{18}	$b_1(1235)^0\pi^0$		(2.3 ±0.6) $\times 10^{-3}$	
Γ_{19}	$\phi K^*(892)\overline{K}$ + c.c.		(2.04±0.28) $\times 10^{-3}$	
Γ_{20}	$\omega K\overline{K}$		(1.9 ±0.4) $\times 10^{-3}$	
Γ_{21}	$\omega f_J(1710) \to \omega K\overline{K}$		(4.8 ±1.1) $\times 10^{-4}$	
Γ_{22}	$\phi 2(\pi^+\pi^-)$		(1.60±0.32) $\times 10^{-3}$	
Γ_{23}	$\Delta(1232)^{++}\overline{p}\pi^-$		(1.6 ±0.5) $\times 10^{-3}$	
Γ_{24}	$\omega\eta$		(1.58±0.16) $\times 10^{-3}$	
Γ_{25}	$\phi K\overline{K}$		(1.48±0.22) $\times 10^{-3}$	
Γ_{26}	$\phi f_J(1710) \to \phi K\overline{K}$		(3.6 ±0.6) $\times 10^{-4}$	
Γ_{27}	$p\overline{p}\omega$		(1.30±0.25) $\times 10^{-3}$	S=1.3
Γ_{28}	$\Delta(1232)^{++}\overline{\Delta}(1232)^{--}$		(1.10±0.29) $\times 10^{-3}$	
Γ_{29}	$\Sigma(1385)^-\overline{\Sigma}(1385)^+$ (or c.c.)	[a]	(1.03±0.13) $\times 10^{-3}$	
Γ_{30}	$p\overline{p}\eta'(958)$		(9 ±4) $\times 10^{-4}$	S=1.7
Γ_{31}	$\phi f'_2(1525)$		(8 ±4) $\times 10^{-4}$	S=2.7
Γ_{32}	$\phi\pi^+\pi^-$		(8.0 ±1.2) $\times 10^{-4}$	
Γ_{33}	$\phi K^\pm K^0_S\pi^\mp$	[a]	(7.2 ±0.9) $\times 10^{-4}$	
Γ_{34}	$\omega f_1(1420)$		(6.8 ±2.4) $\times 10^{-4}$	
Γ_{35}	$\phi\eta$		(6.5 ±0.7) $\times 10^{-4}$	
Γ_{36}	$\Xi(1530)^-\overline{\Xi}^+$		(5.9 ±1.5) $\times 10^{-4}$	
Γ_{37}	$pK^-\overline{\Sigma}(1385)^0$		(5.1 ±3.2) $\times 10^{-4}$	
Γ_{38}	$\omega\pi^0$		(4.2 ±0.6) $\times 10^{-4}$	S=1.4
Γ_{39}	$\phi\eta'(958)$		(3.3 ±0.4) $\times 10^{-4}$	
Γ_{40}	$\phi f_0(980)$		(3.2 ±0.9) $\times 10^{-4}$	S=1.9
Γ_{41}	$\Xi(1530)^0\overline{\Xi}^0$		(3.2 ±1.4) $\times 10^{-4}$	
Γ_{42}	$\Sigma(1385)^-\overline{\Sigma}^+$ (or c.c.)	[a]	(3.1 ±0.5) $\times 10^{-4}$	
Γ_{43}	$\phi f_1(1285)$		(2.6 ±0.5) $\times 10^{-4}$	S=1.1
Γ_{44}	$\rho\eta$		(1.93±0.23) $\times 10^{-4}$	
Γ_{45}	$\omega\eta'(958)$		(1.67±0.25) $\times 10^{-4}$	
Γ_{46}	$\omega f_0(980)$		(1.4 ±0.5) $\times 10^{-4}$	
Γ_{47}	$\rho\eta'(958)$		(1.05±0.18) $\times 10^{-4}$	
Γ_{48}	$p\overline{p}\phi$		(4.5 ±1.5) $\times 10^{-5}$	
Γ_{49}	$a_2(1320)^\pm\pi^\mp$	[a]	< 4.3 $\times 10^{-3}$	CL=90%
Γ_{50}	$K\overline{K}^*_2(1430)$ + c.c.		< 4.0 $\times 10^{-3}$	CL=90%
Γ_{51}	$K^*_2(1430)^0\overline{K}^*_2(1430)^0$		< 2.9 $\times 10^{-3}$	CL=90%
Γ_{52}	$K^*(892)^0\overline{K}^*(892)^0$		< 5 $\times 10^{-4}$	CL=90%
Γ_{53}	$\phi f_2(1270)$		< 3.7 $\times 10^{-4}$	CL=90%
Γ_{54}	$p\overline{p}\rho$		< 3.1 $\times 10^{-4}$	CL=90%
Γ_{55}	$\phi\eta(1440) \to \phi\eta\pi\pi$		< 2.5 $\times 10^{-4}$	CL=90%
Γ_{56}	$\omega f'_2(1525)$		< 2.2 $\times 10^{-4}$	CL=90%
Γ_{57}	$\Sigma(1385)^0\overline{\Lambda}$		< 2 $\times 10^{-4}$	CL=90%
Γ_{58}	$\Delta(1232)^+\overline{p}$		< 1 $\times 10^{-4}$	CL=90%
Γ_{59}	$\Sigma^0\overline{\Lambda}$		< 9 $\times 10^{-5}$	CL=90%
Γ_{60}	$\phi\pi^0$		< 6.8 $\times 10^{-6}$	CL=90%
	Decays into stable hadrons			
Γ_{61}	$2(\pi^+\pi^-)\pi^0$		(3.37±0.26) %	
Γ_{62}	$3(\pi^+\pi^-)\pi^0$		(2.9 ±0.6) %	
Γ_{63}	$\pi^+\pi^-\pi^0$		(1.50±0.20) %	
Γ_{64}	$\pi^+\pi^-\pi^0K^+K^-$		(1.20±0.30) %	
Γ_{65}	$4(\pi^+\pi^-)\pi^0$		(9.0 ±3.0) $\times 10^{-3}$	
Γ_{66}	$\pi^+\pi^-K^+K^-$		(7.2 ±2.3) $\times 10^{-3}$	
Γ_{67}	$K\overline{K}\pi$		(6.1 ±1.0) $\times 10^{-3}$	
Γ_{68}	$p\overline{p}\pi^+\pi^-$		(6.0 ±0.5) $\times 10^{-3}$	S=1.3
Γ_{69}	$2(\pi^+\pi^-)$		(4.0 ±1.0) $\times 10^{-3}$	
Γ_{70}	$3(\pi^+\pi^-)$		(4.0 ±2.0) $\times 10^{-3}$	
Γ_{71}	$n\overline{n}\pi^+\pi^-$		(4 ±4) $\times 10^{-3}$	
Γ_{72}	$\Sigma\overline{\Sigma}$		(3.8 ±0.5) $\times 10^{-3}$	
Γ_{73}	$2(\pi^+\pi^-)K^+K^-$		(3.1 ±1.3) $\times 10^{-3}$	
Γ_{74}	$p\overline{p}\pi^+\pi^-\pi^0$	[b]	(2.3 ±0.9) $\times 10^{-3}$	S=1.9
Γ_{75}	$p\overline{p}$		(2.14±0.10) $\times 10^{-3}$	

Γ_{76}	$p\overline{p}\eta$		$(2.09\pm0.18)\times10^{-3}$	
Γ_{77}	$p\overline{n}\pi^-$		$(2.00\pm0.10)\times10^{-3}$	
Γ_{78}	$n\overline{n}$		$(1.9\pm0.5)\times10^{-3}$	
Γ_{79}	$\Xi\overline{\Xi}$		$(1.8\pm0.4)\times10^{-3}$	S=1.8
Γ_{80}	$\Lambda\overline{\Lambda}$		$(1.35\pm0.14)\times10^{-3}$	S=1.2
Γ_{81}	$p\overline{p}\pi^0$		$(1.09\pm0.09)\times10^{-3}$	
Γ_{82}	$\Lambda\overline{\Sigma}^-\pi^+$ (or c.c.)	[a]	$(1.06\pm0.12)\times10^{-3}$	
Γ_{83}	$pK^-\overline{\Lambda}$		$(8.9\pm1.6)\times10^{-4}$	
Γ_{84}	$2(K^+K^-)$		$(7.0\pm3.0)\times10^{-4}$	
Γ_{85}	$pK^-\overline{\Sigma}^0$		$(2.9\pm0.8)\times10^{-4}$	
Γ_{86}	K^+K^-		$(2.37\pm0.31)\times10^{-4}$	
Γ_{87}	$\Lambda\overline{\Lambda}\pi^0$		$(2.2\pm0.7)\times10^{-4}$	
Γ_{88}	$\pi^+\pi^-$		$(1.47\pm0.23)\times10^{-4}$	
Γ_{89}	$K^0_S K^0_L$		$(1.08\pm0.14)\times10^{-4}$	
Γ_{90}	$\Lambda\overline{\Sigma}$+ c.c.		$<1.5\times10^{-4}$	CL=90%
Γ_{91}	$K^0_S K^0_S$		$<5.2\times10^{-6}$	CL=90%

Radiative decays

Γ_{92}	$\gamma\eta_c(1S)$		(1.3 ± 0.4) %	
Γ_{93}	$\gamma\pi^+\pi^-2\pi^0$		$(8.3\pm3.1)\times10^{-3}$	
Γ_{94}	$\gamma\eta\pi\pi$		$(6.1\pm1.0)\times10^{-3}$	
Γ_{95}	$\gamma\eta(1440)\rightarrow\gamma K\overline{K}\pi$	[c]	$(9.1\pm1.8)\times10^{-4}$	
Γ_{96}	$\gamma\eta(1440)\rightarrow\gamma\gamma\rho^0$		$(6.4\pm1.4)\times10^{-5}$	
Γ_{97}	$\gamma\rho\rho$		$(4.5\pm0.8)\times10^{-3}$	
Γ_{98}	$\gamma\eta'(958)$		$(4.31\pm0.30)\times10^{-3}$	
Γ_{99}	$\gamma 2\pi^+2\pi^-$		$(2.8\pm0.5)\times10^{-3}$	S=1.9
Γ_{100}	$\gamma f_4(2050)$		$(2.7\pm0.7)\times10^{-3}$	
Γ_{101}	$\gamma\omega\omega$		$(1.59\pm0.33)\times10^{-3}$	
Γ_{102}	$\gamma\eta(1440)\rightarrow\gamma\rho^0\rho^0$		$(1.7\pm0.4)\times10^{-3}$	S=1.3
Γ_{103}	$\gamma f_2(1270)$		$(1.38\pm0.14)\times10^{-3}$	
Γ_{104}	$\gamma f_J(1710)\rightarrow\gamma K\overline{K}$		$(9.7\pm1.2)\times10^{-4}$	
Γ_{105}	$\gamma\eta$		$(8.6\pm0.8)\times10^{-4}$	
Γ_{106}	$\gamma f_1(1420)\rightarrow\gamma K\overline{K}\pi$		$(8.3\pm1.5)\times10^{-4}$	
Γ_{107}	$\gamma f_1(1285)$		$(6.5\pm1.0)\times10^{-4}$	
Γ_{108}	$\gamma f'_2(1525)$		$(6.3\pm1.0)\times10^{-4}$	
Γ_{109}	$\gamma\phi\phi$		$(4.0\pm1.2)\times10^{-4}$	S=2.1
Γ_{110}	$\gamma p\overline{p}$		$(3.8\pm1.0)\times10^{-4}$	
Γ_{111}	$\gamma\eta(2225)$		$(2.9\pm0.6)\times10^{-4}$	
Γ_{112}	$\gamma\eta(1760)\rightarrow\gamma\rho^0\rho^0$		$(1.3\pm0.9)\times10^{-4}$	
Γ_{113}	$\gamma\pi^0$		$(3.9\pm1.3)\times10^{-5}$	
Γ_{114}	$\gamma p\overline{p}\pi^+\pi^-$		$<7.9\times10^{-4}$	CL=90%
Γ_{115}	$\gamma\gamma$		$<5\times10^{-4}$	CL=90%
Γ_{116}	$\gamma\Lambda\overline{\Lambda}$		$<1.3\times10^{-4}$	CL=90%
Γ_{117}	3γ		$<5.5\times10^{-5}$	CL=90%
Γ_{118}	$\gamma f_0(2200)$			
Γ_{119}	$\gamma f_J(2220)$			
Γ_{120}	$\gamma f_0(1370)$		$(3.4\pm0.7)\times10^{-4}$	
Γ_{121}	$\gamma f_0(1500)$		$(8.2\pm1.5)\times10^{-4}$	

[a] The value is for the sum of the charge states of particle/antiparticle states indicated.

[b] Includes $p\overline{p}\pi^+\pi^-\gamma$ and excludes $p\overline{p}\eta$, $p\overline{p}\omega$, $p\overline{p}\eta'$.

[c] See the "Note on the $\eta(1440)$" in the $\eta(1440)$ Particle Listings.

$J/\psi(1S)$ PARTIAL WIDTHS

Γ(hadrons) — Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
74.1 ± 8.1	BAI	95B	BES	e^+e^-
59 ± 24	BALDINI-...	75	FRAG	e^+e^-
59 ± 14	BOYARSKI	75	MRK1	e^+e^-
50 ± 25	ESPOSITO	75B	FRAM	e^+e^-

Γ(virtual $\gamma\rightarrow$ hadrons) — Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
12 ±2	[3] BOYARSKI	75	MRK1	e^+e^-

[3] Included in Γ(hadrons).

$\Gamma(e^+e^-)$ — Γ_3

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
5.26±0.37 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.14 ± 0.39	BAI	95B	BES	e^+e^-
$5.36^{+0.29}_{-0.28}$	[4] HSUEH	92	RVUE	See Υ mini-review
4.72 ± 0.35	ALEXANDER	89	RVUE	See Υ mini-review
4.4 ± 0.6	[4] BRANDELIK	79C	DASP	e^+e^-
4.6 ± 0.8	[5] BALDINI-...	75	FRAG	e^+e^-
4.8 ± 0.6	BOYARSKI	75	MRK1	e^+e^-
4.6 ± 1.0	ESPOSITO	75B	FRAM	e^+e^-

[4] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$, and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.

[5] Assuming equal partial widths for e^+e^- and $\mu^+\mu^-$.

$\Gamma(\mu^+\mu^-)$ — Γ_4

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.13 ± 0.52	BAI	95B	BES	e^+e^-
4.8 ± 0.6	BOYARSKI	75	MRK1	e^+e^-
5 ± 1	ESPOSITO	75B	FRAM	e^+e^-

$\Gamma(\gamma\gamma)$ — Γ_{115}

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<5.4	90	BRANDELIK	79C	DASP	e^+e^-

$J/\psi(1S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma$(total)

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel$_i$ in the e^+e^- annihilation.

Γ(hadrons) × $\Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4 ± 0.8	[7] BALDINI-...	75	FRAG	e^+e^-
3.9 ± 0.8	[7] ESPOSITO	75B	FRAM	e^+e^-

$\Gamma(e^+e^-)$ × $\Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_3\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.35 ± 0.02	BRANDELIK	79C	DASP	e^+e^-
0.32 ± 0.07	[7] BALDINI-...	75	FRAG	e^+e^-
0.34 ± 0.14	BEMPORAD	75	FRAB	e^+e^-
0.34 ± 0.09	[7] ESPOSITO	75B	FRAM	e^+e^-
0.36 ± 0.10	[7] FORD	75	SPEC	e^+e^-

$\Gamma(\mu^+\mu^-)$ × $\Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_4\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.31 ± 0.09	BEMPORAD	75	FRAB	e^+e^-
0.51 ± 0.09	DASP	75	DASP	e^+e^-
0.38 ± 0.05	[7] ESPOSITO	75B	FRAM	e^+e^-
0.46 ± 0.10	[7] LIBERMAN	75	SPEC	e^+e^-

$\Gamma(p\overline{p})$ × $\Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_{75}\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
9.7±1.7	[6] ARMSTRONG	93B	SPEC	$\overline{p}p\rightarrow e^+e^-$

[6] Using $\Gamma_{total} = 85.5^{+6.1}_{-5.8}$ MeV.

[7] Data redundant with branching ratios or partial widths above.

$J/\psi(1S)$ BRANCHING RATIOS

For the first four branching ratios, see also the partial widths, and (partial widths) × $\Gamma(e^+e^-)/\Gamma_{total}$ above.

Γ(hadrons)/Γ_{total} — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.877±0.005 OUR AVERAGE				
0.878 ± 0.005	BAI	95B	BES	e^+e^-
0.86 ± 0.02	BOYARSKI	75	MRK1	e^+e^-

Γ(virtual $\gamma\rightarrow$ hadrons)/Γ_{total} — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.17 ±0.02	[8] BOYARSKI	75	MRK1	e^+e^-

[8] Included in Γ(hadrons)/Γ_{total}.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0602±0.0019 OUR AVERAGE				
0.0609±0.0033	BAI	95B	BES	e^+e^-
0.0592±0.0015±0.0020	COFFMAN	92	MRK3	$\psi(2S) \to J/\psi\pi^+\pi^-$
0.069 ±0.009	BOYARSKI	75	MRK1	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0601±0.0019 OUR AVERAGE				
0.0608±0.0033	BAI	95B	BES	e^+e^-
0.0590±0.0015±0.0019	COFFMAN	92	MRK3	$\psi(2S) \to J/\psi\pi^+\pi^-$
0.069 ±0.009	BOYARSKI	75	MRK1	e^+e^-

$\Gamma(e^+e^-)/\Gamma(\mu^+\mu^-)$ — Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.00±0.07	BAI	95B	BES	e^+e^-
1.00±0.05	BOYARSKI	75	MRK1	e^+e^-
0.91±0.15	ESPOSITO	75B	FRAM	e^+e^-
0.93±0.10	FORD	75	SPEC	e^+e^-

HADRONIC DECAYS

$\Gamma(\rho\pi)/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0128±0.0010 OUR AVERAGE					
0.0142±0.0001±0.0019		COFFMAN	88	MRK3	e^+e^-
0.013 ±0.003	150	FRANKLIN	83	MRK2	e^+e^-
0.016 ±0.004	183	ALEXANDER	78	PLUT	e^+e^-
0.0133±0.0021		BRANDELIK	78B	DASP	e^+e^-
0.010 ±0.002	543	BARTEL	76	CNTR	e^+e^-
0.013 ±0.003	153	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\rho^0\pi^0)/\Gamma(\rho\pi)$ — Γ_6/Γ_5

VALUE	DOCUMENT ID		TECN	COMMENT
0.328±0.005±0.027	COFFMAN	88	MRK3	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.36 ±0.03	SCHARRE	79B	MRK1	e^+e^-
0.35 ±0.08	ALEXANDER	78	PLUT	e^+e^-
0.32 ±0.08	BRANDELIK	78B	DASP	e^+e^-
0.39 ±0.11	BARTEL	76	CNTR	e^+e^-
0.37 ±0.09	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(a_2(1320)\rho)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
10.9±2.2 OUR AVERAGE					
11.7±0.7±2.5	7584	AUGUSTIN	89	DM2	$J/\psi \to \rho^0\rho^\pm\pi^\mp$
8.4±4.5	36	VANNUCCI	77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
85±34	140	VANNUCCI	77	MRK1	$e^+e^- \to 3(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^-)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
7.2±1.0 OUR AVERAGE					
7.0±1.6	18058	AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$
7.8±1.6	215	BURMESTER	77D	PLUT	e^+e^-
6.8±1.9	348	VANNUCCI	77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma(\omega\pi^+\pi^-)/\Gamma(2(\pi^+\pi^-)\pi^0)$ — Γ_9/Γ_{61}

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.3	[9] JEAN-MARIE	76	MRK1	e^+e^-

[9] Final state $(\pi^+\pi^-)\pi^0$ under the assumption that $\pi\pi$ is isospin 0.

$\Gamma(K^*(892)^0\overline{K}{}^*_2(1430)^0 + c.c.)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
67±26	40	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-K^+K^-$

$\Gamma(\omega K^*(892)\overline{K} + c.c.)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
53±14±14	530±140	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\omega f_2(1270))/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.3±0.6 OUR AVERAGE					
4.3±0.2±0.6	5860	AUGUSTIN	89	DM2	e^+e^-
4.0±1.6	70	BURMESTER	77D	PLUT	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.9±0.8	81	VANNUCCI	77	MRK1	$e^+e^- \to 2(\pi^+\pi^-)\pi^0$

$\Gamma(K^+\overline{K}{}^*(892)^- + c.c.)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
5.0 ±0.4 OUR AVERAGE					
4.57±0.17±0.70	2285	JOUSSET	90	DM2	$J/\psi \to$ hadrons
5.26±0.13±0.53		COFFMAN	88	MRK3	$J/\psi \to K^\pm K^0_S\pi^\mp$, $K^+K^-\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.6 ±0.6	24	FRANKLIN	83	MRK2	$J/\psi \to K^+K^-\pi^0$
3.2 ±0.6	48	VANNUCCI	77	MRK1	$J/\psi \to K^\pm K^0_S\pi^\mp$
4.1 ±1.2	39	BRAUNSCH...	76	DASP	$J/\psi \to K^\pm X$

$\Gamma(K^0\overline{K}{}^*(892)^0 + c.c.)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.2 ±0.4 OUR AVERAGE					
3.96±0.15±0.60	1192	JOUSSET	90	DM2	$J/\psi \to$ hadrons
4.33±0.12±0.45		COFFMAN	88	MRK3	$J/\psi \to K^\pm K^0_S\pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.7 ±0.6	45	VANNUCCI	77	MRK1	$J/\psi \to K^\pm K^0_S\pi^\mp$

$\Gamma(K^0\overline{K}{}^*(892)^0 + c.c.)/\Gamma(K^+\overline{K}{}^*(892)^- + c.c.)$ — Γ_{14}/Γ_{13}

VALUE	DOCUMENT ID		TECN	COMMENT
0.82±0.05±0.09	COFFMAN	88	MRK3	$J/\psi \to K\overline{K}{}^*(892)$+c.c.

$\Gamma(\omega\pi^0\pi^0)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.4±0.3±0.7	509	AUGUSTIN	89	DM2	$J/\psi \to \pi^+\pi^-3\pi^0$

$\Gamma(b_1(1235)^\pm\pi^\mp)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
30±5 OUR AVERAGE					
31±6	4600	AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$
29±7	87	BURMESTER	77D	PLUT	e^+e^-

$\Gamma(\omega K^\pm K^0_S\pi^\mp)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
29.5±1.4±7.0	879±41	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(b_1(1235)^0\pi^0)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
23±3±5	229	AUGUSTIN	89	DM2	e^+e^-

$\Gamma(\phi K^*(892)\overline{K} + c.c.)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
20.4±2.8 OUR AVERAGE					
20.7±2.4±3.0		FALVARD	88	DM2	$J/\psi \to$ hadrons
20 ±3 ±3	155±20	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\omega K\overline{K})/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
19 ± 4 OUR AVERAGE					
19.8± 2.1±3.9		[10] FALVARD	88	DM2	$J/\psi \to$ hadrons
16 ±10	22	FELDMAN	77	MRK1	e^+e^-

[10] Addition of ωK^+K^- and $\omega K^0\overline{K}{}^0$ branching ratios.

$\Gamma(\omega f_J(1710) \to \omega K\overline{K})/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
4.8±1.1±0.3	[11,12] FALVARD	88	DM2	$J/\psi \to$ hadrons

[11] Includes unknown branching fraction $f_J(1710) \to K\overline{K}$.
[12] Addition of $f_J(1710) \to K^+K^-$ and $f_J(1710) \to K^0\overline{K}{}^0$ branching ratios.

$\Gamma(\phi 2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
16.0±1.0±3.0	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(\Delta(1232)^{++}\overline{p}\pi^-)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.58±0.23±0.40	332	EATON	84	MRK2	e^+e^-

$\Gamma(\omega\eta)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.58±0.16 OUR AVERAGE					
1.43±0.10±0.21	378	JOUSSET	90	DM2	$J/\psi \to$ hadrons
1.71±0.08±0.20		COFFMAN	88	MRK3	$e^+e^- \to 3\pi\eta$

$\Gamma(\phi K\overline{K})/\Gamma_{total}$ — Γ_{25}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
14.8±2.2 OUR AVERAGE					
14.6±0.8±2.1		[13] FALVARD	88	DM2	$J/\psi \to$ hadrons
18 ±8	14	FELDMAN	77	MRK1	e^+e^-

[13] Addition of ϕK^+K^- and $\phi K^0\overline{K}{}^0$ branching ratios.

$\Gamma(\phi f_J(1710) \to \phi K\overline{K})/\Gamma_{total}$ — Γ_{26}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
3.6± .2±0.6	[14,15] FALVARD	88	DM2	$J/\psi \to$ hadrons

[14] Including interference with $f'_2(1525)$.
[15] Includes unknown branching fraction $f_J(1710) \to K\overline{K}$.

$\Gamma(p\overline{p}\omega)/\Gamma_{total}$ — Γ_{27}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.30±0.25 OUR AVERAGE Error includes scale factor of 1.3.					
1.10±0.17±0.18	486	EATON	84	MRK2	e^+e^-
1.6 ±0.3	77	PERUZZI	78	MRK1	e^+e^-

$\Gamma(\Delta(1232)^{++}\overline{\Delta}(1232)^{--})/\Gamma_{total}$ — Γ_{28}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.10±0.09±0.28	233	EATON	84	MRK2	e^+e^-

$\Gamma(\Sigma(1385)^-\overline{\Sigma}(1385)^+$ (or c.c.)$)/\Gamma_{total}$ — Γ_{29}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.03±0.13 OUR AVERAGE					
1.00±0.04±0.21	631±25	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*-}$
1.19±0.04±0.25	754±27	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*+}$
0.86±0.18±0.22	56	EATON	84	MRK2	$e^+e^- \to \Sigma^{*-}$
1.03±0.24±0.25	68	EATON	84	MRK2	$e^+e^- \to \Sigma^{*+}$

$\Gamma(p\overline{p}\eta'(958))/\Gamma_{total}$ — Γ_{30}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.9 ±0.4 OUR AVERAGE Error includes scale factor of 1.7.					
0.68±0.23±0.17	19	EATON	84	MRK2	e^+e^-
1.8 ±0.6	19	PERUZZI	78	MRK1	e^+e^-

$\Gamma(\phi f'_2(1525))/\Gamma_{total}$ — Γ_{31}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
8 ±4 OUR AVERAGE Error includes scale factor of 2.7.					
12.3±0.6±2.0		[16,17] FALVARD	88	DM2	$J/\psi \to$ hadrons
4.8±1.8	46	[16] GIDAL	81	MRK2	$J/\psi \to K^+K^-K^+K^-$

[16] Re-evaluated using $B(f'_2(1525) \to K\overline{K}) = 0.713$.
[17] Including interference with $f_J(1710)$.

$\Gamma(\phi\pi^+\pi^-)/\Gamma_{total}$ — Γ_{32}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.80±0.12 OUR AVERAGE					
0.78±0.03±0.12		FALVARD	88	DM2	$J/\psi \to$ hadrons
2.1 ±0.9	23	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\phi K^{\pm} K^0_S \pi^{\mp})/\Gamma_{total}$ — Γ_{33}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
7.2±0.9 OUR AVERAGE					
7.4±0.9±1.1		FALVARD	88	DM2	$J/\psi \to$ hadrons
7 ±0.6±1.0	163±15	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\omega f_1(1420))/\Gamma_{total}$ — Γ_{34}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$6.8^{+1.9}_{-1.6}$±1.7	111^{+31}_{-26}	BECKER	87	MRK3	$e^+e^- \to$ hadrons

$\Gamma(\phi\eta)/\Gamma_{total}$ — Γ_{35}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.65 ±0.07 OUR AVERAGE					
0.64 ±0.04 ±0.11	346	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.661±0.045±0.078		COFFMAN	88	MRK3	$e^+e^- \to K^+K^-\eta$

$\Gamma(\Xi(1530)^-\overline{\Xi}^+)/\Gamma_{total}$ — Γ_{36}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.59±0.09±0.12	75±11	HENRARD	87	DM2	e^+e^-

$\Gamma(pK^-\overline{\Sigma}(1385)^0)/\Gamma_{total}$ — Γ_{37}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.51±0.26±0.18	89	EATON	84	MRK2	e^+e^-

$\Gamma(\omega\pi^0)/\Gamma_{total}$ — Γ_{38}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.42 ±0.06 OUR AVERAGE Error includes scale factor of 1.4.					
0.360±0.028±0.054	222	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.482±0.019±0.064		COFFMAN	88	MRK3	$e^+e^- \to \pi^0\pi^+\pi^-\pi^0$

$\Gamma(\phi\eta'(958))/\Gamma_{total}$ — Γ_{39}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.33 ±0.04 OUR AVERAGE						
0.41 ±0.03 ±0.08		167	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.308±0.034±0.036			COFFMAN	88	MRK3	$e^+e^- \to K^+K^-\eta'$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	90		VANNUCCI	77	MRK1	e^+e^-

$\Gamma(\phi f_0(980))/\Gamma_{total}$ — Γ_{40}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
3.2±0.9 OUR AVERAGE Error includes scale factor of 1.9.					
4.6±0.4±0.8		[18] FALVARD	88	DM2	$J/\psi \to$ hadrons
2.6±0.6	50	[18] GIDAL	81	MRK2	$J/\psi \to K^+K^-K^+K^-$

[18] Assuming $B(f_0(980) \to \pi\pi) = 0.78$.

$\Gamma(\Xi(1530)^0\overline{\Xi}^0)/\Gamma_{total}$ — Γ_{41}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.32±0.12±0.07	24±9	HENRARD	87	DM2	e^+e^-

$\Gamma(\Sigma(1385)^-\overline{\Sigma}^+$ (or c.c.)$)/\Gamma_{total}$ — Γ_{42}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.31±0.05 OUR AVERAGE					
0.30±0.03±0.07	74±8	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*-}$
0.34±0.04±0.07	77±9	HENRARD	87	DM2	$e^+e^- \to \Sigma^{*+}$
0.29±0.11±0.10	26	EATON	84	MRK2	$e^+e^- \to \Sigma^{*-}$
0.31±0.11±0.11	28	EATON	84	MRK2	$e^+e^- \to \Sigma^{*+}$

$\Gamma(\phi f_1(1285))/\Gamma_{total}$ — Γ_{43}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.6±0.5 OUR AVERAGE Error includes scale factor of 1.1.					
3.2±0.6±0.4		JOUSSET	90	DM2	$J/\psi \to \phi 2(\pi^+\pi^-)$
2.1±0.5±0.4	25	[19] JOUSSET	90	DM2	$J/\psi \to \phi\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.6±0.2±0.1	16±6	BECKER	87	MRK3	$J/\psi \to \phi K\overline{K}\pi$

[19] We attrribute to the $f_1(1285)$ the signal observed in the $\pi^+\pi^-\eta$ invariant mass distribution at 1297 Mev.

$\Gamma(\rho\eta)/\Gamma_{total}$ — Γ_{44}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.193±0.023 OUR AVERAGE					
0.194±0.017±0.029	299	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.193±0.013±0.029		COFFMAN	88	MRK3	$e^+e^- \to \pi^+\pi^-\eta$

$\Gamma(\omega\eta'(958))/\Gamma_{total}$ — Γ_{45}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.167±0.025 OUR AVERAGE					
$0.18\ ^{+0.10}_{-0.08}$ ±0.03	6	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.166±0.017±0.019		COFFMAN	88	MRK3	$e^+e^- \to 3\pi\eta'$

$\Gamma(\omega f_0(980))/\Gamma_{total}$ — Γ_{46}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
1.41±0.27±0.47	[20] AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$

[20] Assuming $B(f_0(980) \to \pi\pi) = 0.78$.

$\Gamma(\rho\eta'(958))/\Gamma_{total}$ — Γ_{47}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.105±0.018 OUR AVERAGE					
0.083±0.030±0.012	19	JOUSSET	90	DM2	$J/\psi \to$ hadrons
0.114±0.014±0.016		COFFMAN	88	MRK3	$J/\psi \to \pi^+\pi^-\eta'$

$\Gamma(p\overline{p}\phi)/\Gamma_{total}$ — Γ_{48}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
0.45±0.13±0.07	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(a_2(1320)^{\pm}\pi^{\mp})/\Gamma_{total}$ — Γ_{49}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<43	90	BRAUNSCH...	76	DASP	e^+e^-

$\Gamma(K\overline{K}^*_2(1430)+\text{c.c.})/\Gamma_{total}$ — Γ_{50}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<40	90	VANNUCCI	77	MRK1	$e^+e^- \to K^0\overline{K}^{*0}_2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<66	90	BRAUNSCH...	76	DASP	$e^+e^- \to K^{\pm}\overline{K}^{*\mp}_2$

$\Gamma(K_2^*(1430)^0 \overline{K}_2^*(1430)^0)/\Gamma_{total}$ — Γ_{51}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<29	90	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^- K^+K^-$

$\Gamma(K^*(892)^0 \overline{K}^*(892)^0)/\Gamma_{total}$ — Γ_{52}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^- K^+K^-$

$\Gamma(\phi f_2(1270))/\Gamma_{total}$ — Γ_{53}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<3.7	90	VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^- K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.5	90	FALVARD	88	DM2	$J/\psi \to$ hadrons

$\Gamma(p\overline{p}\rho)/\Gamma_{total}$ — Γ_{54}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.31	90	EATON	84	MRK2	$e^+e^- \to$ hadronsγ

$\Gamma(\phi\eta(1440) \to \phi\eta\pi\pi)/\Gamma_{total}$ — Γ_{55}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2.5	90	[21] FALVARD	88	DM2	$J/\psi \to$ hadrons

[21] Includes unknown branching fraction $\eta(1440) \to \eta\pi\pi$.

$\Gamma(\omega f_2'(1525))/\Gamma_{total}$ — Γ_{56}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2.2	90	[22] VANNUCCI	77	MRK1	$e^+e^- \to \pi^+\pi^-\pi^0 K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.8	90	[22] FALVARD	88	DM2	$J/\psi \to$ hadrons

[22] Re-evaluated assuming $B(f_2'(1525) \to K\overline{K}) = 0.713$.

$\Gamma(\Sigma(1385)^0\overline{\Lambda})/\Gamma_{total}$ — Γ_{57}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.2	90	HENRARD	87	DM2	e^+e^-

$\Gamma(\Delta(1232)^+\overline{p})/\Gamma_{total}$ — Γ_{58}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.1	90	HENRARD	87	DM2	e^+e^-

$\Gamma(\Sigma^0\overline{\Lambda})/\Gamma_{total}$ — Γ_{59}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.9	90	HENRARD	87	DM2	e^+e^-

$\Gamma(\phi\pi^0)/\Gamma_{total}$ — Γ_{60}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.068	90	COFFMAN	88	MRK3	$e^+e^- \to K^+K^-\pi^0$

$\Gamma(2(\pi^+\pi^-)\pi^0)/\Gamma_{total}$ — Γ_{61}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0337±0.0026 OUR AVERAGE					
0.0325±0.0049	46055	AUGUSTIN	89	DM2	$J/\psi \to 2(\pi^+\pi^-)\pi^0$
0.0317±0.0042	147	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons
0.0364±0.0052	1500	BURMESTER	77D	PLUT	e^+e^-
0.04 ±0.01	675	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-)\pi^0)/\Gamma_{total}$ — Γ_{62}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.029±0.006 OUR AVERAGE					
0.028±0.009	11	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons
0.029±0.007	181	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{63}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.015 ±0.002	168	FRANKLIN	83	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0149±0.0022		EINSWEILER	83	MRK3	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0 K^+K^-)/\Gamma_{total}$ — Γ_{64}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.012 ±0.003	309	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(4(\pi^+\pi^-)\pi^0)/\Gamma_{total}$ — Γ_{65}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
90±30	13	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(\pi^+\pi^- K^+K^-)/\Gamma_{total}$ — Γ_{66}/Γ

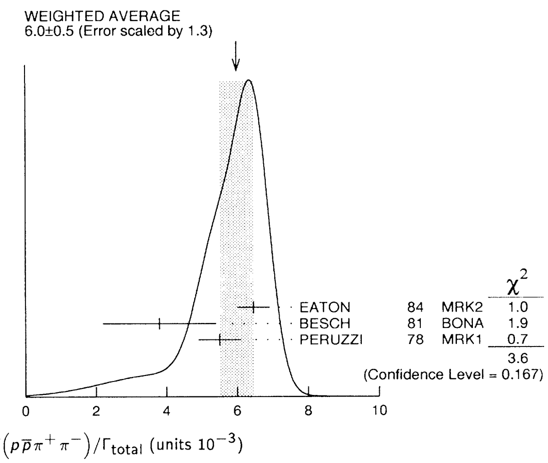
VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
72±23	205	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(K\overline{K}\pi)/\Gamma_{total}$ — Γ_{67}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
61 ±10 OUR AVERAGE					
55.2±12.0	25	FRANKLIN	83	MRK2	$e^+e^- \to K^+K^-\pi^0$
78.0±21.0	126	VANNUCCI	77	MRK1	$e^+e^- \to K_S^0 K^\pm\pi^\mp$

$\Gamma(p\overline{p}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{68}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
6.0 ±0.5 OUR AVERAGE Error includes scale factor of 1.3. See the ideogram below.					
6.46±0.17±0.43	1435	EATON	84	MRK2	e^+e^-
3.8 ±1.6	48	BESCH	81	BONA	e^+e^-
5.5 ±0.6	533	PERUZZI	78	MRK1	e^+e^-



$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_{69}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.004 ±0.001	76	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_{70}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
40±20	32	JEAN-MARIE	76	MRK1	e^+e^-

$\Gamma(n\overline{n}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{71}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.8±3.6	5	BESCH	81	BONA	e^+e^-

$\Gamma(\Sigma\overline{\Sigma})/\Gamma_{total}$ — Γ_{72}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
3.8 ±0.5 OUR AVERAGE					
3.18±0.12±0.69	884±30	PALLIN	87	DM2	e^+e^-
4.74±0.48±0.75	90	EATON	84	MRK2	$e^+e^- \to \Sigma^0\overline{\Sigma}^0$
7.2 ±7.8	3	BESCH	81	BONA	$e^+e^- \to \Sigma^+\overline{\Sigma}^-$
3.9 ±1.2	52	PERUZZI	78	MRK1	$e^+e^- \to \Sigma^0\overline{\Sigma}^0$

$\Gamma(2(\pi^+\pi^-)K^+K^-)/\Gamma_{total}$ — Γ_{73}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
31±13	30	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(p\overline{p}\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{74}/Γ

Including $p\overline{p}\pi^+\pi^-\gamma$ and excluding ω, η, η'

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.3 ±0.9 OUR AVERAGE Error includes scale factor of 1.9.					
3.36±0.65±0.28	364	EATON	84	MRK2	e^+e^-
1.6 ±0.6	39	PERUZZI	78	MRK1	e^+e^-

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_{75}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.14±0.10 OUR AVERAGE					
2.0 ±0.3	48	ANTONELLI	93	SPEC	e^+e^-
1.91±0.04±0.30		PALLIN	87	DM2	e^+e^-
2.16±0.07±0.15	1420	EATON	84	MRK2	e^+e^-
2.5 ±0.4	133	BRANDELIK	79C	DASP	e^+e^-
2.0 ±0.5		BESCH	78	BONA	e^+e^-
2.2 ±0.2	331	[23] PERUZZI	78	MRK1	e^+e^-

[23] Assuming angular distribution $(1+\cos^2\theta)$.

$\Gamma(p\overline{p})/\Gamma(\mu^+\mu^-)$ — Γ_{75}/Γ_4

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.051±0.02	20	[24] WIIK	75	PLUT	e^+e^-

[24] Assuming angular distribution $(1+\cos^2\theta)$.

$\Gamma(p\overline{p}\eta)/\Gamma_{total}$ — Γ_{76}/Γ

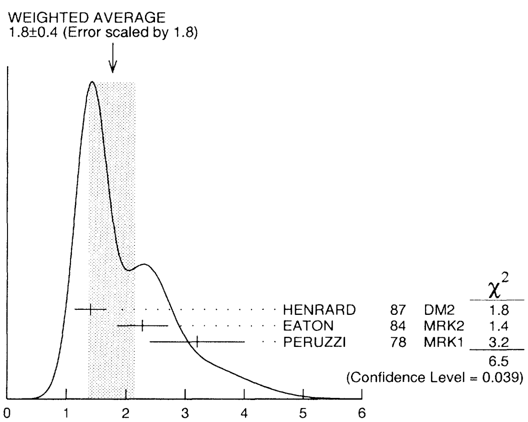
VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.09±0.18 OUR AVERAGE					
2.03±0.13±0.15	826	EATON	84	MRK2	e^+e^-
2.5 ±1.2		BRANDELIK	79C	DASP	e^+e^-
2.3 ±0.4	197	PERUZZI	78	MRK1	e^+e^-

$\Gamma(p\overline{n}\pi^-)/\Gamma_{total}$ — Γ_{77}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.00±0.10 OUR AVERAGE					
2.02±0.07±0.16	1288	EATON	84	MRK2	$e^+e^- \to p\pi^-$
1.93±0.07±0.16	1191	EATON	84	MRK2	$e^+e^- \to \overline{p}\pi^+$
1.7 ±0.7	32	BESCH	81	BONA	$e^+e^- \to p\pi^-$
1.6 ±1.2	5	BESCH	81	BONA	$e^+e^- \to \overline{p}\pi^+$
2.16±0.29	194	PERUZZI	78	MRK1	$e^+e^- \to p\pi^-$
2.04±0.27	204	PERUZZI	78	MRK1	$e^+e^- \to \overline{p}\pi^+$

$\Gamma(\Xi\overline{\Xi})/\Gamma_{total}$ — Γ_{79}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.8 ±0.4 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.					
1.40±0.12±0.24	132±11	HENRARD	87	DM2	$e^+e^- \to \Xi^-\overline{\Xi}^+$
2.28±0.16±0.40	194	EATON	84	MRK2	$e^+e^- \to \Xi^-\overline{\Xi}^+$
3.2 ±0.8	71	PERUZZI	78	MRK1	e^+e^-



$\Gamma(\Xi\overline{\Xi})/\Gamma_{total}$ (units 10^{-3})

$\Gamma(n\overline{n})/\Gamma_{total}$ — Γ_{78}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
0.19 ±0.05 OUR AVERAGE					
0.190±0.055	40	ANTONELLI	93	SPEC	e^+e^-
0.18 ±0.09		BESCH	78	BONA	e^+e^-

$\Gamma(\Lambda\overline{\Lambda})/\Gamma_{total}$ — Γ_{80}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.35±0.14 OUR AVERAGE Error includes scale factor of 1.2.					
1.38±0.05±0.20	1847	PALLIN	87	DM2	e^+e^-
1.58±0.08±0.19	365	EATON	84	MRK2	e^+e^-
2.6 ±1.6	5	BESCH	81	BONA	e^+e^-
1.1 ±0.2	196	PERUZZI	78	MRK1	e^+e^-

$\Gamma(p\overline{p}\pi^0)/\Gamma_{total}$ — Γ_{81}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.09±0.09 OUR AVERAGE					
1.13±0.09±0.09	685	EATON	84	MRK2	e^+e^-
1.4 ±0.4		BRANDELIK	79C	DASP	e^+e^-
1.00±0.15	109	PERUZZI	78	MRK1	e^+e^-

$\Gamma(\Lambda\overline{\Sigma}^-\pi^+ \text{(or c.c.)})/\Gamma_{total}$ — Γ_{82}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.06±0.12 OUR AVERAGE					
0.90±0.06±0.16	225±15	HENRARD	87	DM2	$e^+e^- \to \Lambda\overline{\Sigma}^+\pi^-$
1.11±0.06±0.20	342±18	HENRARD	87	DM2	$e^+e^- \to \Lambda\overline{\Sigma}^-\pi^+$
1.53±0.17±0.38	135	EATON	84	MRK2	$e^+e^- \to \Lambda\overline{\Sigma}^+\pi^-$
1.38±0.21±0.35	118	EATON	84	MRK2	$e^+e^- \to \Lambda\overline{\Sigma}^-\pi^+$

$\Gamma(pK^-\overline{\Lambda})/\Gamma_{total}$ — Γ_{83}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.89±0.07±0.14	307	EATON	84	MRK2	e^+e^-

$\Gamma(2(K^+K^-))/\Gamma_{total}$ — Γ_{84}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
7 ±3	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(pK^-\overline{\Sigma}^0)/\Gamma_{total}$ — Γ_{85}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.29±0.06±0.05	90	EATON	84	MRK2	e^+e^-

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_{86}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.37±0.31 OUR AVERAGE					
2.39±0.24±0.22	107	BALTRUSAIT...	85D	MRK3	e^+e^-
2.2 ±0.9	6	BRANDELIK	79C	DASP	e^+e^-

$\Gamma(\Lambda\overline{\Lambda}\pi^0)/\Gamma_{total}$ — Γ_{87}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.22±0.05±0.05	19±4	HENRARD	87	DM2	e^+e^-

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{88}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.47±0.23 OUR AVERAGE					
1.58±0.20±0.15	84	BALTRUSAIT...	85D	MRK3	e^+e^-
1.0 ±0.5	5	BRANDELIK	78B	DASP	e^+e^-
1.6 ±1.6	1	VANNUCCI	77	MRK1	e^+e^-

$\Gamma(K^0_S K^0_L)/\Gamma_{total}$ — Γ_{89}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.08±0.14 OUR AVERAGE					
1.18±0.12±0.18		JOUSSET	90	DM2	$J/\psi \to$ hadrons
1.01±0.16±0.09	74	BALTRUSAIT...	85D	MRK3	e^+e^-

$\Gamma(\Lambda\overline{\Sigma} + \text{c.c.})/\Gamma_{total}$ — Γ_{90}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.15	90	PERUZZI	78	MRK1	$e^+e^- \to \Lambda X$

$\Gamma(K^0_S K^0_S)/\Gamma_{total}$ — Γ_{91}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<0.052	90	[25] BALTRUSAIT...	85C	MRK3	e^+e^-

[25] Forbidden by *CP*.

RADIATIVE DECAYS

$\Gamma(\gamma\eta_c(1S))/\Gamma_{total}$ — Γ_{92}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0127±0.0036		GAISER	86	CBAL	$J/\psi \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	16	BALTRUSAIT...	84	MRK3	$J/\psi \to 2\phi\gamma$

$\Gamma(\gamma\pi^+\pi^-2\pi^0)/\Gamma_{total}$ — Γ_{93}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
8.3±0.2±3.1	[26] BALTRUSAIT...	86B	MRK3	$J/\psi \to 4\pi\gamma$

[26] 4π mass less than 2.0 GeV.

$\Gamma(\gamma\eta\pi\pi)/\Gamma_{total}$ — Γ_{94}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
6.1 ±1.0 OUR AVERAGE				
5.85±0.3±1.05	[27] EDWARDS	83B	CBAL	$J/\psi \to \eta\pi^+\pi^-$
7.8 ±1.2±2.4	[27] EDWARDS	83B	CBAL	$J/\psi \to \eta 2\pi^0$

[27] Broad enhancement at 1700 MeV.

$\Gamma(\gamma\eta(1440) \to \gamma K\overline{K}\pi)/\Gamma_{total}$ — Γ_{95}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.91±0.18 OUR AVERAGE				
0.83±0.13±0.18	[28,29] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\overline{K}\pi$
$1.03^{+0.21}_{-0.18}{}^{+0.26}_{-0.19}$	[28,30] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.78±0.21±0.33	[28,31] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\overline{K}\pi$
3.8 ±0.3 ±0.6	[28] AUGUSTIN	90	DM2	$J/\psi \to \gamma K\overline{K}\pi$
$0.66^{+0.17}_{-0.16}{}^{+0.24}_{-0.15}$	[28,32] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$
6.3 ±1.4	[28] WISNIEWSKI	87	MRK3	$J/\psi \to K\overline{K}\pi\gamma$
4.0 ±0.7 ±1.0	[28] EDWARDS	82E	CBAL	$J/\psi \to K^+K^-\pi^0\gamma$
4.3 ±1.7	[28,33] SCHARRE	80	MRK2	e^+e^-

[28] Includes unknown branching fraction $\eta(1440) \to K\overline{K}\pi$.
[29] From fit to the $K^*(892)K$ 0^{-+} partial wave.
[30] From $K^*(890)K$ final state.
[31] From fit to the $a_0(980)\pi$ 0^{-+} partial wave.
[32] From $a_0(980)\pi$ final state.
[33] Corrected for spin-zero hypothesis for $\eta(1440)$.

$\Gamma(\gamma\eta(1440) \to \gamma\gamma\rho^0)/\Gamma_{total}$ — Γ_{96}/Γ

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
6.4±1.2±0.7	[34] COFFMAN	90	MRK3	$J/\psi \to \gamma\gamma\pi^+\pi^-$

[34] Includes unknown branching fraction $\eta(1440) \to \gamma\rho^0$.

$\Gamma(\gamma\rho\rho)/\Gamma_{total}$ — Γ_{97}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
4.5 ±0.8 OUR AVERAGE					
4.7 ±0.3 ±0.9		[35] BALTRUSAIT..86B		MRK3	$J/\psi \to 4\pi\gamma$
3.75±1.05±1.20		[36] BURKE	82	MRK2	$J/\psi \to 4\pi\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.09	90	[37] BISELLO	89B		$J/\psi \to 4\pi\gamma$

[35] 4π mass less than 2.0 GeV.
[36] 4π mass less than 2.0 GeV, $2\rho^0$ corrected to 2ρ by factor of 3.
[37] 4π mass in the range 2.0–25 GeV.

$\Gamma(\gamma\eta'(958))/\Gamma_{total}$ — Γ_{98}/Γ

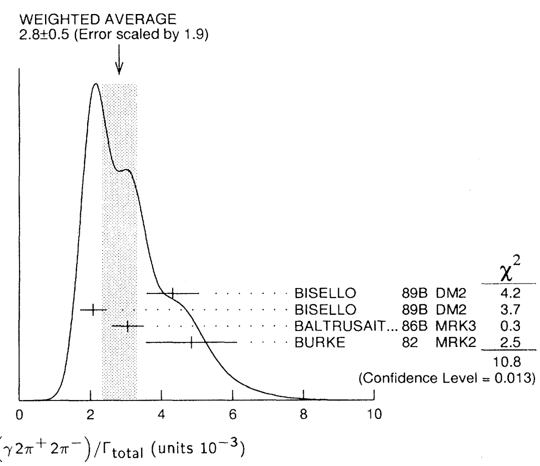
VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
4.31±0.30 OUR AVERAGE					
4.50±0.14±0.53		BOLTON	92B	MRK3	$J/\psi \to \gamma\pi^+\pi^-\eta$, $\eta \to \gamma\gamma$
4.30±0.31±0.71		BOLTON	92B	MRK3	$J/\psi \to \gamma\pi^+\pi^-\eta$, $\eta \to \pi^+\pi^-\pi^0$
4.04±0.16±0.85	622	AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$
4.39±0.09±0.66	2420	AUGUSTIN	90	DM2	$J/\psi \to \gamma\gamma\pi^+\pi^-$
4.1 ±0.3 ±0.6		BLOOM	83	CBAL	$e^+e^- \to 3\gamma$ + hadronsγ
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.9 ±1.1	6	BRANDELIK	79C	DASP	$e^+e^- \to 3\gamma$
3.8 ±1.3		[38] SCHARRE	79B	MRK1	$e^+e^- \to \gamma X$
3.4 ±0.7		SCHARRE	79B	MRK1	$e^+e^- \to 2\pi 2\gamma$
2.4 ±0.7	57	BARTEL	76	CNTR	$e^+e^- \to 2\gamma\rho$

[38] From the inclusive γ decay spectrum.

$\Gamma(\gamma 2\pi^+2\pi^-)/\Gamma_{total}$ — Γ_{99}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.8 ±0.5 OUR AVERAGE	Error includes scale factor of 1.9. See the ideogram below.			
4.32±0.14±0.73	[39] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$
2.08±0.13±0.35	[40] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$
3.05±0.08±0.45	[40] BALTRUSAIT..86B		MRK3	$J/\psi \to 4\pi\gamma$
4.85±0.45±1.20	[41] BURKE	82	MRK2	e^+e^-

[39] 4π mass less than 3.0 GeV.
[40] 4π mass less than 2.0 GeV.
[41] 4π mass less than 2.5 GeV.



$\Gamma(\gamma f_4(2050))/\Gamma_{total}$ — Γ_{100}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.7±0.5±0.5	[42] BALTRUSAIT..87		MRK3	$J/\psi \to \gamma\pi^+\pi^-$

[42] Assuming branching fraction $f_4(2050) \to \pi\pi$/ total = 0.167.

$\Gamma(\gamma\omega\omega)/\Gamma_{total}$ — Γ_{101}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.59±0.33 OUR AVERAGE					
1.41±0.2 ±0.42	120±17	BISELLO	87	SPEC	e^+e^-, hadronsγ
1.76±0.09±0.45		BALTRUSAIT..85C		MRK3	$e^+e^- \to$ hadronsγ

$\Gamma(\gamma\eta(1440) \to \gamma\rho^0\rho^0)/\Gamma_{total}$ — Γ_{102}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
1.7 ±0.4 OUR AVERAGE	Error includes scale factor of 1.3.			
2.1 ±0.4	BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$
1.36±0.38	[43,44] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[43] Estimated by us from various fits.
[44] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma f_2(1270))/\Gamma_{total}$ — Γ_{103}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.38±0.14 OUR AVERAGE						
1.33±0.05±0.20		[45] AUGUSTIN	87	DM2		$J/\psi \to \gamma\pi^+\pi^-$
1.36±0.09±0.23		[45] BALTRUSAIT..87		MRK3		$J/\psi \to \gamma\pi^+\pi^-$
1.48±0.25±0.30	178	EDWARDS	82B	CBAL		$e^+e^- \to 2\pi^0\gamma$
2.0 ±0.7	35	ALEXANDER	78	PLUT	0	e^+e^-
1.2 ±0.6	30	[46] BRANDELIK	78B	DASP		$e^+e^- \to \pi^+\pi^-\gamma$

[45] Estimated using B($f_2(1270) \to \pi\pi$)=0.843 ± 0.012. The errors do not contain the uncertainty in the $f_2(1270)$ decay.
[46] Restated by us to take account of spread of E1, M2, E3 transitions.

$\Gamma(\gamma f_J(1710) \to \gamma K\overline{K})/\Gamma_{total}$ — Γ_{104}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
9.7±1.2 OUR AVERAGE					
9.2±1.4±1.4		[47] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
10.4±1.2±1.6		[47] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
9.6±1.2±1.8		[47] BALTRUSAIT..87		MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.8	90	[48] BISELLO	89B		$J/\psi \to 4\pi\gamma$
1.6±0.4±0.3		[49] BALTRUSAIT..87		MRK3	$J/\psi \to \gamma\pi^+\pi^-$
3.8±1.6		[50] EDWARDS	82D	CBAL	$e^+e^- \to \eta\eta\gamma$

[47] Includes unknown branching fraction to K^+K^- or $K^0_S K^0_S$. We have multiplied K^+K^- measurement by 2, and $K^0_S K^0_S$ by 4 to obtain $K\overline{K}$ result.
[48] Includes unknown branching fraction to $\rho^0\rho^0$.
[49] Includes unknown branching fraction to $\pi^+\pi^-$.
[50] Includes unknown branching fraction to $\eta\eta$.

$\Gamma(\gamma\eta)/\Gamma_{total}$ — Γ_{105}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.86±0.08 OUR AVERAGE					
0.88±0.08±0.11		BLOOM	83	CBAL	e^+e^-
0.82±0.10		BRANDELIK	79C	DASP	e^+e^-
1.3 ±0.4	21	BARTEL	77	CNTR	e^+e^-

$\Gamma(\gamma f_1(1420) \to \gamma K\overline{K}\pi)/\Gamma_{total}$ — Γ_{106}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.83±0.15 OUR AVERAGE				
0.76±0.15±0.21	[51,52] AUGUSTIN	92	DM2	$J/\psi \to \gamma K\overline{K}\pi$
$0.87\pm0.14^{+0.14}_{-0.11}$	[51] BAI	90C	MRK3	$J/\psi \to \gamma K^0_S K^\pm\pi^\mp$

[51] Included unknown branching fraction $f_1(1420) \to K\overline{K}\pi$.
[52] From fit to the $K^*(892)K$ 1^{++} partial wave.

$\Gamma(\gamma f_1(1285))/\Gamma_{total}$ — Γ_{107}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.65 ±0.10 OUR AVERAGE				
0.625±0.063±0.103	[53] BOLTON	92	MRK3	$J/\psi \to \gamma f_1(1285)$
0.70 ±0.08 ±0.16	[54] BOLTON	92B	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$

[53] Obtained summing the sequential decay channels
$B(J/\psi \to \gamma f_1(1285), f_1(1285) \to \pi\pi\pi\pi) = (1.44 \pm 0.39 \pm 0.27) \times 10^{-4}$;
$B(J/\psi \to \gamma f_1(1285), f_1(1285) \to \delta\pi, \delta \to \eta\pi) = (3.90 \pm 0.42 \pm 0.87) \times 10^{-4}$;
$B(J/\psi \to \gamma f_1(1285), f_1(1285) \to \delta\pi, \delta \to K\overline{K}) = (0.66 \pm 0.26 \pm 0.29) \times 10^{-4}$;
$B(J/\psi \to \gamma f_1(1285), f_1(1285) \to \gamma\rho^0) = (0.25 \pm 0.07 \pm 0.03) \times 10^{-4}$.
[54] Using B($f_1(1285) \to a_0(980)\pi$) = 0.37, and including unknown branching ratio for $a_0(980) \to \eta\pi$.

$\Gamma(\gamma f'_2(1525))/\Gamma_{total}$ — Γ_{108}/Γ

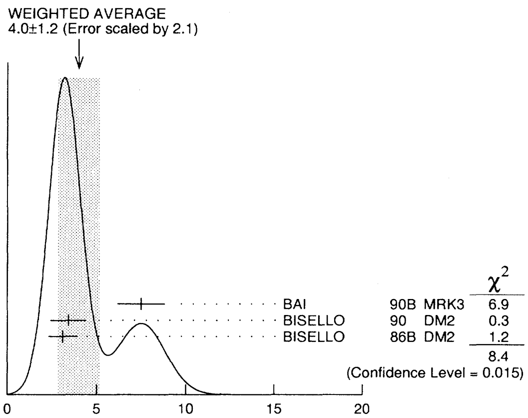
VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.63±0.10 OUR AVERAGE						
0.70±0.17±0.11			[55] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+K^-$
0.56±0.06±0.11			[55] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
0.84±0.20±0.17			[55] BALTRUSAIT..87		MRK3	$J/\psi \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.25±0.14			[55] FRANKLIN	83B	MRK2	$J/\psi \to \gamma K\overline{K}$
<0.34	90	4	[56] BRANDELIK	79C	DASP	$e^+e^- \to \pi^+\pi^-\gamma$
<0.23	90	3	ALEXANDER	78	PLUT	$e^+e^- \to K^+K^-\gamma$

[55] Using B($f'_2(1525) \to K\overline{K}$) = 0.713.
[56] Assuming isotropic production and decay of the $f'_2(1525)$ and isospin.

$\Gamma(\gamma\phi\phi)/\Gamma_{total}$ — Γ_{109}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
4.0±1.2 OUR AVERAGE Error includes scale factor of 2.1. See the ideogram below.					
7.5±0.6±1.2	168	BAI	90B	MRK3	$J/\psi \to \gamma 4K$
3.4±0.8±0.6	33 ± 7	[57] BISELLO	90	DM2	$J/\psi \to \gamma K^+ K^- K^0_S K^0_L$
3.1±0.7±0.4		[57] BISELLO	86B	DM2	$J/\psi \to \gamma K^+ K^- K^+ K^-$

[57] $\phi\phi$ mass less than 2.9 GeV, η_c excluded.



$\Gamma(\gamma\phi\phi)/\Gamma_{total}$ (units 10^{-4})

$\Gamma(\gamma p\bar{p})/\Gamma_{total}$ — Γ_{110}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.38±0.07±0.07		49	EATON	84	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.11	90		PERUZZI	78	MRK1	e^+e^-

$\Gamma(\gamma\eta(2225))/\Gamma_{total}$ — Γ_{111}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.29±0.06 OUR AVERAGE				
0.33±0.08±0.05	[58] BAI	90B	MRK3	$J/\psi \to \gamma K^+ K^- K^+ K^-$
0.27±0.06±0.06	[58] BAI	90B	MRK3	$J/\psi \to \gamma K^+ K^- K^0_S K^0_L$
$0.24^{+0.15}_{-0.10}$	[59,60] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[58] Includes unknown branching fraction to $\phi\phi$.
[59] Estimated by us from various fits.
[60] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma\eta(1760) \to \gamma\rho^0\rho^0)/\Gamma_{total}$ — Γ_{112}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
0.13±0.09	[61,62] BISELLO	89B	DM2	$J/\psi \to 4\pi\gamma$

[61] Estimated by us from various fits.
[62] Includes unknown branching fraction to $\rho^0\rho^0$.

$\Gamma(\gamma\pi^0)/\Gamma_{total}$ — Γ_{113}/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.039±0.013 OUR AVERAGE					
0.036±0.011±0.007		BLOOM	83	CBAL	e^+e^-
0.073±0.047	10	BRANDELIK	79C	DASP	e^+e^-

$\Gamma(\gamma p\bar{p}\pi^+\pi^-)/\Gamma_{total}$ — Γ_{114}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.79	90	EATON	84	MRK2	e^+e^-

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{115}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.5	90	BARTEL	77	CNTR	e^+e^-

$\Gamma(\gamma\Lambda\bar{\Lambda})/\Gamma_{total}$ — Γ_{116}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.13	90	HENRARD	87	DM2	e^+e^-

$\Gamma(3\gamma)/\Gamma_{total}$ — Γ_{117}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.055	90	PARTRIDGE	80	CBAL	e^+e^-

$\Gamma(\gamma f_0(2200))/\Gamma_{total}$ — Γ_{118}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.5	[63] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$

[63] Includes unknown branching fraction to $K^0_S K^0_S$.

$\Gamma(\gamma f_J(2220))/\Gamma_{total}$ — Γ_{119}/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 2.3	95	[64] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^+ K^-$
< 1.6	95	[64] AUGUSTIN	88	DM2	$J/\psi \to \gamma K^0_S K^0_S$
$12.4^{+6.4}_{-5.2}\pm2.8$	23	[64] BALTRUSAIT...86D		MRK3	$J/\psi \to \gamma K^0_S K^0_S$
$8.4^{+3.4}_{-2.8}\pm1.6$	93	[64] BALTRUSAIT...86D		MRK3	$J/\psi \to \gamma K^+ K^-$

[64] Includes unknown branching fraction to K^+K^- or $K^0_S K^0_S$.

$\Gamma(\gamma f_0(1370))/\Gamma_{total}$ — Γ_{120}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
3.38±0.33±0.64		[65] BOLTON	92B	MRK3	$J/\psi \to \gamma\eta\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.0 ±0.6 ±1.1	261	[65] AUGUSTIN	90	DM2	$J/\psi \to \gamma\eta\pi^+\pi^-$

[65] Includes unknown branching fraction to $\eta\pi^+\pi^-$.

$\Gamma(\gamma f_0(1500))/\Gamma_{total}$ — Γ_{121}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
8.2±1.5	[66] BUGG	95	MRK3	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$

[66] Including unknown branching ratio for $f0(1525) \to \pi^+\pi^-\pi^+\pi^-$.

$J/\psi(1S)$ REFERENCES

BAI	95B	PL B355 374	+Chen, Chen+	(BES Collab.)
BUGG	95	PL B353 378	+Scott, Zoli+	(LOQM, PNPI, WASH)
ANTONELLI	93	PL B301 317	+Baldini+	(FENICE Collab.)
ARMSTRONG	93B	PR D47 772	+Bettoni, Bharadwaj+	(FNAL E760 Collab.)
AUGUSTIN	92	PR D46 1951	+Cosme	(DM2 Collab.)
BOLTON	92	PL B278 495	+Brown, Bunnell+	(Mark III Collab.)
BOLTON	92B	PRL 69 1328	+Brown, Bunnell+	(Mark III Collab.)
COFFMAN	92	PRL 68 282	+DeJongh, Dubois, Hitlin+	(Mark III Collab.)
HSUEH	92	PR D45 R2181	+Palestini	(FNAL, TORI)
AUGUSTIN	90	PR D42 10	+Cosme+	(DM2 Collab.)
BAI	90B	PRL 65 1309	+Blaylock+	(Mark III Collab.)
BAI	90C	PRL 65 2507	+Blaylock+	(Mark III Collab.)
BISELLO	90	PL B241 617	+Busetto+	(DM2 Collab.)
COFFMAN	90	PR D41 1410	+De Jongh+	(Mark III Collab.)
JOUSSET	90	PR D41 1389	+Ajaltouni+	(DM2 Collab.)
ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
AUGUSTIN	89	NP B320 1	+Cosme	(DM2 Collab.)
BISELLO	89B	PR D39 701	Busetto+	(DM2 Collab.)
AUGUSTIN	88	PRL 60 2238	+Calcaterra+	(DM2 Collab.)
COFFMAN	88	PR D38 2695	+Dubois, Eigen, Hauser+	(Mark III Collab.)
FALVARD	88	PR D38 2706	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
AUGUSTIN	87	ZPHY C36 369	+Cosme+	(LALO, CLER, FRAS, PADO)
BAGLIN	87	NP B286 592	+	(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
BALTRUSAIT...	87	PR D35 2077	Baltrusaitis, Coffman, Dubois+	(Mark III Collab.)
BECKER	87	PRL 59 186	+Blaylock, Bolton, Brown+	(Mark III Collab.)
BISELLO	87	PL B192 239	+Ajaltouni, Baldini+	(PADO, CLER, FRAS, LALO)
HENRARD	87	NP B292 670	+Ajaltouni, et al	(CLER, FRAS, LALO, PADO)
PALLIN	87	NP B292 653	+Ajaltouni+	(CLER, FRAS, LALO, PADO)
WISNIEWSKI	87	Hadron 87 Conf.		(Mark III Collab.)
BALTRUSAIT...	86B	PR D33 1222	Baltrusaitis, Coffman, Hauser+	(Mark III Collab.)
BALTRUSAIT...	86D	PRL 56 107	Baltrusaitis	(CIT, UCSC, ILL, SLAC, WASH)
BISELLO	86B	PL B179 294	+Busetto, Castro, Limentani+	(DM2 Collab.)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
BALTRUSAIT...	85C	PRL 55 1723	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH)
BALTRUSAIT...	85D	PR D32 566	Baltrusaitis, Coffman+	(CIT, UCSC, ILL, SLAC, WASH)
BALTRUSAIT...	84	PRL 52 2126	Baltrusaitis+	(CIT, UCSC, ILL, SLAC, WASH)
EATON	84	PR D29 804	+Goldhaber, Abrams, Alam, Boyarski+	(LBL, SLAC)
BLOOM	83	ARNS 33 143	+Peck	(SLAC, CIT)
EDWARDS	83B	PRL 51 859	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
EINSWEILER	83	Brighton Conf. 348		(Mark III Collab.)
FRANKLIN	83	PRL 51 963	+Franklin, Feldman, Abrams, Alam+	(LBL, SLAC)
FRANKLIN	83B	Thesis SLAC-0254		(STAN)
BURKE	82	PRL 49 632	+Trilling, Abrams, Alam, Blocker+	(LBL, SLAC)
EDWARDS	82B	PR D25 3065	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
EDWARDS	82D	PRL 48 458	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
Also	83	ARNS 33 143	Bloom, Peck	(SLAC, CIT)
EDWARDS	82E	PRL 49 259	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
BESCH	81	ZPHY C8 1	+Eisermann, Lohr, Kowalski+	(BONN, DESY, MANZ)
GIDAL	81	PL 107B 153	+Goldhaber, Guy, Millikan, Abrams+	(SLAC, LBL)
PARTRIDGE	80	PRL 44 712	+Peck+	(CIT, HARV, PRIN, SLAC, STAN)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814	Zholentz, Kurdadze, Lelchuk+	(NOVO)
		Translated from YAF 34 1471.		
BRANDELIK	79C	ZPHY C1 233	+Cords+	(DASP Collab.)
SCHARRE	79B	SLAC-PUB-2321		(SLAC, LBL)
Also	79	LBL-9502	Abrams, Alam, Blocker, Boyarski+	(SLAC, LBL)
ALEXANDER	78	PL 72B 493	+Criegee+	(DESY, HAMB, SIEG, WUPP)
BESCH	78	PL 78B 347	+Eisermann, Kowalski, Eyss+	(BONN, DESY, MANZ)
BRANDELIK	78B	PL 74B 292	+Cords+	(DASP Collab.)
PERUZZI	78	PR D17 2901	+Piccolo, Alam, Boyarski, Goldhaber+	(SLAC, LBL)
BARTEL	77	PL 66B 489	+Duinker, Olsson, Heintze+	(DESY, HEIDP)
BURMESTER	77D	PL 72B 135	+Criegee+	(DESY, HAMB, SIEG, WUPP)
FELDMAN	77	PRPL 33C 285	+Perl	(LBL, SLAC)
VANNUCCI	77	PR D15 1814	+Abrams, Alam, Boyarski+	(SLAC, LBL)
BARTEL	76	PL 64B 483	+Duinker, Olsson, Steffen, Heintze+	(DESY, HEIDP)
BRAUNSCH...	76	PL 63B 487	Braunschweig+	(DASP Collab.)
JEAN-MARIE	76	PRL 36 291	+Abrams, Boyarski, Breidenbach+	(SLAC, LBL) IG
BALDINI-...	75	PL 58B 471	Baldini-Celio, Bozzo, Capon+	(FRAS, ROMA)
BEMPORAD	75	Stanford Symp. 113		(PISA, FRAS)
BOYARSKI	75	PRL 34 1357	+Breidenbach, Bulos, Feldman+	(SLAC, LBL) JPC

DASP	75	PL 56B 491	Braunschweig, Konigs+	(DASP Collab.)
ESPOSITO	75B	LNC 14 73	+Bartoli, Bisello+	(FRAS, NAPL, PADO, ROMA)
FORD	75	PRL 34 604	+Beron, Hilger, Hofstadter+	(SLAC, PENN)
LIBERMAN	75	Stanford Symp. 55		(STAN)
WIIK	75	Stanford Symp. 69		(DESY)

OTHER RELATED PAPERS

BAGLIN	85	SLAC Summer Inst. 609		(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
LEE	85	SLAC 282		(SLAC)
BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
ABRAMS	74	PRL 33 1453	+Briggs, Augustin, Boyarski+	(LBL, SLAC)
ASH	74	LNC 11 705	+Zorn, Bartoli+	(FRAS, UMD, NAPL, PADO, ROMA)
AUBERT	74	PRL 33 1404	+Becker, Biggs, Burger, Chen, Everhart	(MIT, BNL)
AUGUSTIN	74	PRL 33 1406	+Boyarski, Abrams, Briggs+	(SLAC, LBL)
BACCI	74	PRL 33 1408	+Bartoli, Barbarino, Barbiellini+	(FRAS)
Also	74B	PRL 33 1649	Bacci	
BALDINI-...	74	LNC 11 711	Baldini-Celio, Bacci+	(FRAS, ROMA)
BARBIELLINI	74	LNC 11 718	+Bemporad+	(FRAS, NAPL, PISA, ROMA)
BRAUNSCH...	74	PL 53B 393	Braunschweig+	(DASP Collab.)
CHRISTENS...	70	PRL 25 1523	Christenson, Hicks, Lederman+	(COLU, BNL, CERN)

$\chi_{c0}(1P)$

$I^G(J^{PC}) = 0^+(0^{++})$

$\chi_{c0}(1P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3415.1± 1.0 OUR AVERAGE					
3417.8± 0.4±4		[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$
3414.8± 1.1		[2,3] HIMEL	79	MRK2	$e^+e^- \to$ hadrons
3422 ±10		[2] BARTEL	78B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3416 ± 3 ±4		[2] TANENBAUM	78	MRK1	e^+e^-
3415 ± 9		[2] BIDDICK	77	CNTR	$e^+e^- \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3407 ± 8	2	[4] WIIK	75	DASP	$e^+e^- \to J/\psi 2\gamma$

[1] Using mass of $\psi(2S)$ = 3686.0 MeV.
[2] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.
[3] Systematic error added linearly by us.
[4] Only two events; this mass apparently never published.

$\chi_{c0}(1P)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
13.5±3.3±4.2	GAISER	86	CBAL	$\psi(2S) \to \gamma X$, $\gamma\pi^0\pi^0$

$\chi_{c0}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$2(\pi^+\pi^-)$	(3.7 ± 0.7) %	
Γ_2	$\pi^+\pi^-K^+K^-$	(3.0 ± 0.7) %	
Γ_3	$\rho^0\pi^+\pi^-$	(1.6 ± 0.5) %	
Γ_4	$3(\pi^+\pi^-)$	(1.5 ± 0.5) %	
Γ_5	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(1.2 ± 0.4) %	
Γ_6	$\pi^+\pi^-$	$(7.5\pm2.1)\times10^{-3}$	
Γ_7	K^+K^-	$(7.1\pm2.4)\times10^{-3}$	
Γ_8	$\pi^+\pi^-p\overline{p}$	$(5.0\pm2.0)\times10^{-3}$	
Γ_9	$\pi^0\pi^0$	$(3.1\pm0.6)\times10^{-3}$	
Γ_{10}	$\eta\eta$	$(2.5\pm1.1)\times10^{-3}$	
Γ_{11}	$p\overline{p}$	$< 9.0 \times10^{-4}$	90%
	Radiative decays		
Γ_{12}	$\gamma J/\psi(1S)$	$(6.6\pm1.8)\times10^{-3}$	
Γ_{13}	$\gamma\gamma$	$(4.0\pm2.3)\times10^{-4}$	

$\chi_{c0}(1P)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$ — Γ_{13}

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
< 6.2	95	CHEN	90B	CLEO	$e^+e^- \to e^+e^-\chi_{c0}$
4.0±2.8		LEE	85	CBAL	$\psi' \to$ photons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<17	95	AIHARA	88D	TPC	$e^+e^- \to e^+e^-X$

$\chi_{c0}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.037±0.007	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.030±0.007	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.016±0.005	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.015±0.005	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + c.c.)/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.012±0.004	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
75±21 OUR AVERAGE				
70±30	[5] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$
80±30	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
71±24 OUR AVERAGE				
60±30	[5] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$
90±40	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{total}$ — Γ_8/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.005 ±0.002	[5] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
3.1±0.4±0.5	[6] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
2.5±0.8±0.8	[6] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<9.0	90	[5] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$

[5] Calculated using $B(\psi(2S) \to \gamma\chi_{c0}(1P)) = 0.094$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.
[6] Calculated using $B(\psi(2S) \to \gamma\chi_{c0}(1P)) = 0.093 \pm 0.008$.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
66± 18 OUR AVERAGE				
60± 18	GAISER	86	CBAL	$\psi(2S) \to \gamma\chi_{c0}$
320±210	[7] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c0}$
150±100	[7] BARTEL	78B	CNTR	$\psi(2S) \to \gamma\chi_{c0}$
210±210	[7] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c0}$

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
4.0±2.0±1.1		[6] LEE	85	CBAL	$\psi' \to$ photons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<15	90	[7] YAMADA	77	DASP	$e^+e^- \to 3\gamma$

[7] Calculated using $B(\psi(2S) \to \gamma\chi_{c0}(1P)) = 0.094$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\chi_{c0}(1P)$ REFERENCES

CHEN	90B	PL B243 169	+McIlwain+	(CLEO Collab.)
AIHARA	88D	PRL 60 2355	+Alston-Garnjost+	(TPC Collab.)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
LEE	85	SLAC 282		(SLAC)
BRANDELIK	79B	NP B160 426	+Cords+	(DASP Collab.)
HIMEL	79	Thesis SLAC-0223		(SLAC)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEIDP)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
YAMADA	77	Hamburg Conf. 69		(DASP Collab.)
WIIK	75	Stanford Symp. 69		(DESY)

OTHER RELATED PAPERS

OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
FELDMAN	75B	PRL 35 821	+Jean-Marie, Sadoulet, Vannucci+	(LBL, SLAC)
Also	75C	PRL 35 1189	Feldman	
Erratum.				
TANENBAUM	75	PRL 35 1323	+Whitaker, Abrams+	(LBL, SLAC)

$\chi_{c1}(1P)$

$I^G(J^{PC}) = 0^+(1^{++})$

$\chi_{c1}(1P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
3510.53± 0.12 OUR AVERAGE				
3510.53± 0.04±0.12	513	ARMSTRONG 92	SPEC	$\overline{p}p \rightarrow e^+e^-\gamma$
3511.3 ± 0.4 ±0.4	30	BAGLIN 86B	SPEC	$\overline{p}p \rightarrow e^+e^-X$
3512.3 ± 0.3 ±4.0		[1] GAISER 86	CBAL	$\psi(2S) \rightarrow \gamma X$
3507.4 ± 1.7	91	[2] LEMOIGNE 82	GOLI	190 GeV π^- Be $\rightarrow \gamma 2\mu$
3510.4 ± 0.6		OREGLIA 82	CBAL	$e^+e^- \rightarrow J/\psi 2\gamma$
3510.1 ± 1.1	254	[3] HIMEL 80	MRK2	$e^+e^- \rightarrow J/\psi 2\gamma$
3509 ±11	21	BRANDELIK 79B	DASP	$e^+e^- \rightarrow J/\psi 2\gamma$
3507 ± 3		[3] BARTEL 78B	CNTR	$e^+e^- \rightarrow J/\psi 2\gamma$
3505.0 ± 4 ±4		[3,4] TANENBAUM 78	MRK1	e^+e^-
3513 ± 7	367	[3] BIDDICK 77	CNTR	$\psi(2S) \rightarrow \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3510 ±20		BARTEL 76B	CNTR	$e^+e^- \rightarrow J/\psi 2\gamma$
3500 ±10	40	TANENBAUM 75	MRK1	Hadrons γ
3507 ± 7	7	WIIK 75	DASP	$e^+e^- \rightarrow J/\psi 2\gamma$

[1] Using mass of $\psi(2S)$ = 3686.0 MeV.
[2] $J/\psi(1S)$ mass constrained to 3097 MeV.
[3] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.
[4] From a simultaneous fit to radiative and hadronic decay channels.

$\chi_{c1}(1P)$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.88±0.11±0.08		513	ARMSTRONG 92	SPEC	$\overline{p}p \rightarrow e^+e^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.3	95		BAGLIN 86B	SPEC	$\overline{p}p \rightarrow e^+e^-X$
<3.8	90		GAISER 86	CBAL	$\psi(2S) \rightarrow \gamma X$

$\chi_{c1}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
	Hadronic decays	
Γ_1	$3(\pi^+\pi^-)$	(2.2±0.8) %
Γ_2	$2(\pi^+\pi^-)$	(1.6±0.5) %
Γ_3	$\pi^+\pi^-K^+K^-$	(9 ±4) × 10^{-3}
Γ_4	$\rho^0\pi^+\pi^-$	(3.9±3.5) × 10^{-3}
Γ_5	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(3.2±2.1) × 10^{-3}
Γ_6	$\pi^+\pi^-p\overline{p}$	(1.4±0.9) × 10^{-3}
Γ_7	$p\overline{p}$	(8.6±1.2) × 10^{-5}
Γ_8	$\pi^+\pi^-$ + K^+K^-	< 2.1 × 10^{-3}
	Radiative decays	
Γ_9	$\gamma J/\psi(1S)$	(27.3±1.6) %
Γ_{10}	$\gamma\gamma$	

$\chi_{c1}(1P)$ PARTIAL WIDTHS

$\Gamma(p\overline{p})$ — Γ_7

VALUE (eV)	EVTS	DOCUMENT ID	TECN	COMMENT
74± 9 OUR AVERAGE				
76±10±5	513	[5] ARMSTRONG 92	SPEC	$\overline{p}p \rightarrow e^+e^-\gamma$
69^{+16}_{-13}±4		[5] BAGLIN 86B	SPEC	$\overline{p}p \rightarrow e^+e^-X$

[5] Restated by us using $B(\chi_{c1}(1P) \rightarrow J/\psi(1S)\gamma)B(J/\psi(1S) \rightarrow e^+e^-) = 0.0171 \pm 0.0011$.

$\chi_{c1}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.022±0.008	[7] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.016±0.005	[7] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
90±40	[7] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
39±35	[7] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + c.c.)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
32±21	[7] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$

$\Gamma(\pi^+\pi^-p\overline{p})/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID	TECN	COMMENT
14±9	[7] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.86±0.12		513	[6] ARMSTRONG 92	SPEC	$\overline{p}p \rightarrow e^+e^-\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 0.54	95		BAGLIN 86B	SPEC	$\overline{p}p \rightarrow e^+e^-X$
<12.0	90		[7] BRANDELIK 79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c1}$

[6] Restated by us using $B(\chi_{c1}(1P) \rightarrow J/\psi(1S)\gamma)B(J/\psi(1S) \rightarrow e^+e^-) = 0.0171 \pm 0.0011$.

$[\Gamma(\pi^+\pi^-) + \Gamma(K^+K^-)]/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID	TECN	COMMENT
<21		[7] FELDMAN 77	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<38	90	[7] BRANDELIK 79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c1}$

[7] Estimated using $B(\psi(2S) \rightarrow \gamma\chi_{c1}(1P)) = 0.087$. The errors do not contain the uncertainty in the $\psi(2S)$ decay.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{total}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.273±0.016 OUR AVERAGE				
0.284±0.021		GAISER 86	CBAL	$\psi(2S) \rightarrow \gamma X$
0.274±0.046	943	[8] OREGLIA 82	CBAL	$\psi(2S) \rightarrow \gamma\chi_{c1}$
0.28 ±0.07		[8] HIMEL 80	MRK2	$\psi(2S) \rightarrow \gamma\chi_{c1}$
0.19 ±0.05		[8] BRANDELIK 79B	DASP	$\psi(2S) \rightarrow \gamma\chi_{c1}$
0.29 ±0.05		[8] BARTEL 78B	CNTR	$\psi(2S) \rightarrow \gamma\chi_{c1}$
0.28 ±0.09		[8] TANENBAUM 78	MRK1	$\psi(2S) \rightarrow \gamma\chi_{c1}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.57 ±0.17		[8] BIDDICK 77	CNTR	$\psi(2S) \rightarrow \gamma X$

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.0015	90	[8] YAMADA 77	DASP	$e^+e^- \rightarrow 3\gamma$

[8] Estimated using $B(\psi(2S) \rightarrow \gamma\chi_{c1}(1P)) = 0.087$. The errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\chi_{c1}(1P)$ REFERENCES

ARMSTRONG	92	NP B373 35	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
Also	92B	PRL 68 1468	Armstrong, Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
BAGLIN	86B	PL B172 455		(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
Also	82B	Private Comm.	Oreglia	(EFI)
HIMEL	80	PRL 44 920	+Abrams, Alam, Blocker+	(LBL, SLAC)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BRANDELIK	79B	NP B160 426	+Cords+	(DASP Collab.)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEIDP)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
FELDMAN	77	PRPL 33C 285	+Perl	(LBL, SLAC)
YAMADA	77	Hamburg Conf. 69		(DASP Collab.)
BARTEL	76B	Tbilisi Conf. N75	+Duinker, Olsson, Heintze+	(DESY, HEIDP)
TANENBAUM	75	PRL 35 1323	+Whitaker, Abrams+	(LBL, SLAC)
WIIK	75	Stanford Symp. 69		(DESY)

OTHER RELATED PAPERS

BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
BRAUNSCH...	75B	PL 57B 407	Braunschweig, Konigs+	(DASP Collab.)
FELDMAN	75	Stanford Symp. 39		(SLAC)
HEINTZE	75	Stanford Symp. 97		(HEIDP)
SIMPSON	75	PRL 35 699	+Beron, Ford, Hilger, Hofstadter+	(STAN, PENN)

$h_c(1P)$

$I^G(J^{PC}) = ?^?(?^{??})$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$h_c(1P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3526.14±0.24 OUR AVERAGE					
3526.20±0.15±0.20	59	ARMSTRONG	92D	SPEC	$\bar{p}p \to J/\psi\pi^0$
3525.4 ±0.8 ±0.4	5	BAGLIN	86	SPEC	$\bar{p}p \to J/\psi X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3527 ±8	42	ANTONIAZZI	94	E705	300 $\pi^{\pm}$, pLi $\to J/\psi\pi^0 X$

$h_c(1P)$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.1	90	59	ARMSTRONG	92D	SPEC	$\bar{p}p \to J/\psi\pi^0$

$h_c(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$J/\psi(1S)\pi^0$	seen
Γ_2	$J/\psi(1S)\pi\pi$	not seen
Γ_3	$p\bar{p}$	

$\Gamma(J/\psi(1S)\pi\pi)/\Gamma(J/\psi(1S)\pi^0)$ — Γ_2/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.18	90	ARMSTRONG	92D	SPEC	$\bar{p}p \to J/\psi\pi^0$

$h_c(1P)$ REFERENCES

ANTONIAZZI 94 PR D50 4258 +Arenton+ (E705 Collab.)
ARMSTRONG 92D PRL 69 2337 +Bettoni+ (FNAL, FERR, GENO, UCI, PENN, TORI)
BAGLIN 86 PL B171 135 +Baird+ (LAPP, CERN, TORI, STRB, OSLO, ROMA+)

$\chi_{c2}(1P)$

$I^G(J^{PC}) = 0^+(2^{++})$

$\chi_{c2}(1P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3556.17± 0.13 OUR AVERAGE					
3556.15± 0.07±0.12	585	ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^-\gamma$
3556.9 ± 0.4 ±0.5	50	BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$
3557.8 ± 0.2 ±4		[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$
3553.4 ± 2.2	66	[2] LEMOIGNE	82	GOLI	190 GeV π^- Be $\to \gamma 2\mu$
3555.9 ± 0.7		[3] OREGLIA	82	CBAL	$e^+e^- \to J/\psi 2\gamma$
3557 ± 1.5	69	[4] HIMEL	80	MRK2	$e^+e^- \to J/\psi 2\gamma$
3551 ±11	15	BRANDELIK	79B	DASP	$e^+e^- \to J/\psi 2\gamma$
3553 ± 4		[4] BARTEL	78B	CNTR	$e^+e^- \to J/\psi 2\gamma$
3553 ± 4 ±4		[4,5] TANENBAUM	78	MRK1	e^+e^-
3563 ± 7	360	[4] BIDDICK	77	CNTR	$e^+e^- \to \gamma X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3550 ±10		TRILLING	76	MRK1	$e^+e^- \to$ hadronsγ
3543 ±10	4	WHITAKER	76	MRK1	$e^+e^- \to J/\psi 2\gamma$

[1] Using mass of $\psi(2S)$ = 3686.0 MeV.
[2] $J/\psi(1S)$ mass constrained to 3097 MeV.
[3] Assuming $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.
[4] Mass value shifted by us by amount appropriate for $\psi(2S)$ mass = 3686 MeV and $J/\psi(1S)$ mass = 3097 MeV.
[5] From a simultaneous fit to radiative and hadronic decay channels.

$\chi_{c2}(1P)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2.00±0.18 OUR AVERAGE					
1.98±0.17±0.07	585	ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^-\gamma$
$2.6\ ^{+1.4}_{-1.0}$	50	BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$
$2.8\ ^{+2.1}_{-2.0}$		[6] GAISER	86	CBAL	$\psi(2S) \to \gamma X$

[6] Errors correspond to 90% confidence level; authors give only width range.

$\chi_{c2}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
	Hadronic decays		
Γ_1	$2(\pi^+\pi^-)$	(2.2 ±0.5) %	
Γ_2	$\pi^+\pi^-K^+K^-$	(1.9 ±0.5) %	
Γ_3	$3(\pi^+\pi^-)$	(1.2 ±0.8) %	
Γ_4	$\rho^0\pi^+\pi^-$	(7 ±4) $\times 10^{-3}$	
Γ_5	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(4.8 ±2.8) $\times 10^{-3}$	
Γ_6	$\pi^+\pi^-p\bar{p}$	(3.3 ±1.3) $\times 10^{-3}$	
Γ_7	$\pi^+\pi^-$	(1.9 ±1.0) $\times 10^{-3}$	
Γ_8	K^+K^-	(1.5 ±1.1) $\times 10^{-3}$	
Γ_9	$p\bar{p}$	(10.0 ±1.0) $\times 10^{-5}$	
Γ_{10}	$\pi^0\pi^0$	(1.10±0.28) $\times 10^{-3}$	
Γ_{11}	$\eta\eta$	(8 ±5) $\times 10^{-4}$	
Γ_{12}	$J/\psi(1S)\pi^+\pi^-\pi^0$	< 1.5 %	90%
	Radiative decays		
Γ_{13}	$\gamma J/\psi(1S)$	(13.5 ±1.1) %	
Γ_{14}	$\gamma\gamma$	(1.6 ±0.5) $\times 10^{-4}$	

$\chi_{c2}(1P)$ PARTIAL WIDTHS

$\Gamma(p\bar{p})$ — Γ_9

VALUE (eV)	EVTS	DOCUMENT ID		TECN	COMMENT
206±22 OUR AVERAGE					
197±18±16	585	[7] ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^-\gamma$
$252^{+55}_{-48}\pm21$		[7] BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$

[7] Restated by us using $B(\chi_{c2}(1P) \to J/\psi(1S)\gamma)B(J/\psi(1S) \to e^+e^-) = 0.0085 \pm 0.0007$.

$\Gamma(\gamma\gamma)$ — Γ_{14}

VALUE (keV)	CL%	DOCUMENT ID		TECN	COMMENT
0.37 ±0.17 OUR AVERAGE		Error includes scale factor of 1.9.			
1.08 ±0.30 ±0.26		DOMINICK	94	CLE2	$e^+e^- \to e^+e^-\chi_{c2}$
0.321±0.078±0.054		[8] ARMSTRONG	93	SPEC	$\bar{p}p \to \gamma\gamma$
3.4 ±1.7 ±0.9		BAUER	93	TPC	$e^+e^- \to e^+e^-\chi_{c2}$
$2.9\ ^{+1.3}_{-1.0}\ \pm1.7$		BAGLIN	87B	SPEC	$\bar{p}p \to \gamma\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.2	95	UEHARA	91	VNS	$e^+e^- \to e^+e^-\chi_{c2}$
<1.0	95	CHEN	90B	CLEO	$e^+e^- \to e^+e^-\chi_{c2}$
<4.2	95	AIHARA	88D	TPC	$e^+e^- \to e^+e^- X$
<1.6	90	YAMADA	77	DASP	$e^+e^- \to 3\gamma$

[8] Using $B(\chi_{c2}(1P) \to p\bar{p}) = (1.00 \pm 0.23) \times 10^{-4}$ and $\Gamma_{total} = 2.00 \pm 0.18$ MeV.

$\chi_{c2}(1P)$ BRANCHING RATIOS

HADRONIC DECAYS

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.022±0.005	[10] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-K^+K^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.019±0.005	[10] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.012±0.008	[10] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
68±40	[10] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
48±28	[10] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^- p\bar{p})/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
33±13	[10] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.9±1.0	4	[10] BRANDELIK	79C	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$[\Gamma(\pi^+\pi^-) + \Gamma(K^+K^-)]/\Gamma_{total}$ — $(\Gamma_7+\Gamma_8)/\Gamma$

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
24±10	[10] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.5±1.1	2	[10] BRANDELIK	79C	DASP	$\psi(2S) \to \gamma\chi_{c2}$

$\Gamma(p\bar{p})/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.00±0.10 OUR AVERAGE						
1.00±0.11		585	[9] ARMSTRONG	92	SPEC	$\bar{p}p \to e^+e^-\gamma$
$0.97^{+0.44}_{-0.28}\pm0.08$			BAGLIN	86B	SPEC	$\bar{p}p \to e^+e^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<9.5	90		[10] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c2}$

[9] Restated by us using $B(\chi_{c2}(1P) \to J/\psi(1S)\gamma)B(J/\psi(1S) \to e^+e^-) = 0.0085 \pm 0.0007$.

$\Gamma_i\Gamma_f/\Gamma^2_{total}$ in $p\bar{p} \to \chi_{c2}(1P) \to \gamma\gamma$ — $\Gamma_9\Gamma_{14}/\Gamma^2$

VALUE (units 10^{-7})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.160±0.039±0.016		ARMSTRONG	93	SPEC	$\bar{p}p \to \gamma\gamma$
$0.99^{+0.46}_{-0.35}$	6	[11] BAGLIN	87B	SPEC	$\bar{p}p \to \gamma\gamma$

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-3})	DOCUMENT ID		TECN	COMMENT
1.1 ±0.2 ±0.2	[12] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(\eta\eta)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
7.9±4.1±2.4	[12] LEE	85	CBAL	$\psi' \to$ photons

$\Gamma(J/\psi(1S)\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	90	BARATE	81	SPEC	190 GeV π^- Be $\to 2\pi 2\mu$

[10] Estimated using $B(\psi(2S) \to \gamma\chi_{c2}(1P)) = 0.078$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.
[11] Assuming isotropic $\chi_{c2}(1P) \to \gamma\gamma$ distribution.
[12] LEE 85 result is calculated using $B(\psi(2S) \to \gamma\chi_{c2}(1P)) = 0.078 \pm 0.008$.

RADIATIVE DECAYS

$\Gamma(\gamma J/\psi(1S))/\Gamma_{total}$ — Γ_{13}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.135±0.011 OUR AVERAGE					
0.124±0.015		GAISER	86	CBAL	$\psi(2S) \to \gamma X$
0.162±0.028	479	[13] OREGLIA	82	CBAL	$\psi(2S) \to \gamma\chi_{c2}$
0.14 ±0.04		[13] HIMEL	80	MRK2	$\psi(2S) \to \gamma\chi_{c2}$
0.18 ±0.05		[13] BRANDELIK	79B	DASP	$\psi(2S) \to \gamma\chi_{c2}$
0.13 ±0.03		[13] BARTEL	78B	CNTR	$\psi(2S) \to \gamma\chi_{c2}$
$0.11\ ^{+0.13}_{-0.07}$		[13] SPITZER	78	PLUT	$\psi(2S) \to \gamma\chi_{c2}$
0.13 ±0.08		[13] TANENBAUM	78	MRK1	$\psi(2S) \to \gamma\chi_{c2}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.28 ±0.13		[13] BIDDICK	77	CNTR	$\psi(2S) \to \gamma X$

[13] Estimated using $B(\psi(2S) \to \gamma\chi_{c2}(1P)) = 0.078$; the errors do not contain the uncertainty in the $\psi(2S)$ decay.

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
1.60±0.39±0.23	[14] ARMSTRONG	93	SPEC	$\bar{p}p \to \gamma\gamma$

[14] Using $B(\chi_{c2}(1P) \to p\bar{p}) = (1.00 \pm 0.23) \times 10^{-4}$.

$\chi_{c2}(1P)$ REFERENCES

DOMINICK	94	PR D50 4265	+Sanghera+	(CLEO Collab.)
ARMSTRONG	93	PRL 70 2988	+Bettoni, Bharadwaj+	(FNAL E760 Collab.)
BAUER	93	PL B302 345	+Belcinski+	(TPC Collab.)
ARMSTRONG	92	NP B373 35	+Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
Also	92B	PRL 68 1468	Armstrong, Bettoni+	(FNAL, FERR, GENO, UCI, NWES+)
UEHARA	91	PL B266 188	+Abe+	(VENUS Collab.)
CHEN	90B	PL B243 169	+McIlwain+	(CLEO Collab.)
AIHARA	88D	PRL 60 2355	+Alston-Garnjost+	(TPC Collab.)
BAGLIN	87B	PL B187 191	+Baird, Bassompierre, Borreani+	(R704 Collab.)
BAGLIN	86B	PL B172 455		(LAPP, CERN, GENO, LYON, OSLO, ROMA+)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
LEE	85	SLAC 282		(SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
Also	82B	Private Comm.	Oreglia	(EFI)
BARATE	81	PR D24 2994	+Astbury+	(SACL, LOIC, SHMP, CERN, IND)
HIMEL	80	PRL 44 920	+Abrams, Alam, Blocker+	(LBL, SLAC)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BRANDELIK	79B	NP B160 426	+Cords+	(DASP Collab.)
BRANDELIK	79C	ZPHY C1 233	+Cords+	(DASP Collab.)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEIDP)
SPITZER	78	Kyoto Sum. Inst. 47		(HAMB)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
Also	82	Private Comm.	Trilling	(LBL, UCB)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
YAMADA	77	Hamburg Conf. 69		(DASP Collab.)
TRILLING	76	Stanford Symp. 437		(LBL)
WHITAKER	76	PRL 37 1596	+Tanenbaum, Abrams, Alam+	(SLAC, LBL)

OTHER RELATED PAPERS

BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
FELDMAN	75B	PRL 35 821	+Jean-Marie, Sadoulet, Vannucci+	(LBL, SLAC)
Also	75C	PRL 35 1189	Feldman	
Erratum.				
TANENBAUM	75	PRL 35 1323	+Whitaker, Abrams+	(LBL, SLAC)

$\eta_c(2S)$

$I^G(J^{PC}) = ?^?(?^{?+})$

OMITTED FROM SUMMARY TABLE
Needs confirmation.

$\eta_c(2S)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3594±5	[1] EDWARDS	82C	CBAL	$e^+e^- \to \gamma X$

[1] Assuming mass of $\psi(2S) = 3686$ MeV.

$\eta_c(2S)$ WIDTH

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<8.0	95	EDWARDS	82C	CBAL	$e^+e^- \to \gamma X$

$\eta_c(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	seen
Γ_2	$\gamma\gamma$	

$\eta_c(2S)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	EDWARDS	82C	CBAL	$e^+e^- \to \gamma X$

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.01	90	LEE	85	CBAL	$\psi' \to$ photons

$\eta_c(2S)$ REFERENCES

LEE	85	SLAC 282		(SLAC)
EDWARDS	82C	PRL 48 70	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)

OTHER RELATED PAPERS

OREGLIA	82	PR D25 2259	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
PORTER	81	SLAC Summer Inst. 355	+Edwards+	(CIT, HARV, PRIN, STAN, SLAC)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEIDP)

$\psi(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\psi(2S)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3686.00±0.09 OUR AVERAGE					
3686.02±0.09±0.27		ARMSTRONG	93B	SPEC	$\bar{p}p \to e^+e^-$
3686.00±0.10	413	ZHOLENTZ	80	OLYA	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3683 ±5	77	ANTONIAZZI	94	E705	300 $\pi^\pm$, pLi $\to J/\psi\pi^+\pi^-X$

$m_{\psi(2S)} - m_{J/\psi(1S)}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
589.07±0.13 OUR AVERAGE				
589.7 ±1.2	LEMOIGNE	82	GOLI	190 GeV π^- Be $\to 2\mu$
589.07±0.13	[1] ZHOLENTZ	80	OLYA	e^+e^-
588.7 ±0.8	LUTH	75	MRK1	

[1] Redundant with data in mass above.

$\psi(2S)$ WIDTH

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
277±31 OUR AVERAGE Error includes scale factor of 1.1.				
306±36±16	ARMSTRONG	93B	SPEC	$\bar{p}p \to e^+e^-$
243±43	[2] PDG	92	RVUE	

[2] Uses $\Gamma(ee)$ from ALEXANDER 89 and $B(ee) = (88 \pm 13) \times 10^{-4}$ from FELDMAN 77.

$\psi(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons	(98.10±0.30) %	
Γ_2	virtual$\gamma \to$ hadrons	(2.9 ±0.4) %	
Γ_3	e^+e^-	(8.8 ±1.3) × 10^{-3}	
Γ_4	$\mu^+\mu^-$	(7.7 ±1.7) × 10^{-3}	
	Decays into $J/\psi(1S)$ and anything		
Γ_5	$J/\psi(1S)$anything	(57 ±4) %	
Γ_6	$J/\psi(1S)$neutrals	(23.2 ±2.6) %	
Γ_7	$J/\psi(1S)\pi^+\pi^-$	(32.4 ±2.6) %	
Γ_8	$J/\psi(1S)\pi^0\pi^0$	(18.4 ±2.7) %	
Γ_9	$J/\psi(1S)\eta$	(2.7 ±0.4) %	S=1.7
Γ_{10}	$J/\psi(1S)\pi^0$	(9.7 ±2.1) × 10^{-4}	
	Hadronic decays		
Γ_{11}	$3(\pi^+\pi^-)\pi^0$	(3.5 ±1.6) × 10^{-3}	
Γ_{12}	$2(\pi^+\pi^-)\pi^0$	(3.1 ±0.7) × 10^{-3}	
Γ_{13}	$\pi^+\pi^-K^+K^-$	(1.6 ±0.4) × 10^{-3}	
Γ_{14}	$\pi^+\pi^-p\bar{p}$	(8.0 ±2.0) × 10^{-4}	
Γ_{15}	$K^+\overline{K}^*(892)^0\pi^-$ + c.c.	(6.7 ±2.5) × 10^{-4}	
Γ_{16}	$2(\pi^+\pi^-)$	(4.5 ±1.0) × 10^{-4}	
Γ_{17}	$\rho^0\pi^+\pi^-$	(4.2 ±1.5) × 10^{-4}	
Γ_{18}	$\bar{p}p$	(1.9 ±0.5) × 10^{-4}	
Γ_{19}	$3(\pi^+\pi^-)$	(1.5 ±1.0) × 10^{-4}	
Γ_{20}	$\bar{p}p\pi^0$	(1.4 ±0.5) × 10^{-4}	
Γ_{21}	K^+K^-	(1.0 ±0.7) × 10^{-4}	
Γ_{22}	$\pi^+\pi^-\pi^0$	(9 ±5) × 10^{-5}	
Γ_{23}	$\pi^+\pi^-$	(8 ±5) × 10^{-5}	
Γ_{24}	$\Lambda\bar{\Lambda}$	< 4 × 10^{-4}	CL=90%
Γ_{25}	$\Xi^-\overline{\Xi}^+$	< 2 × 10^{-4}	CL=90%
Γ_{26}	$\rho\pi$	< 8.3 × 10^{-5}	CL=90%
Γ_{27}	$K^+K^-\pi^0$	< 2.96 × 10^{-5}	CL=90%
Γ_{28}	$K^+\overline{K}^*(892)^-$ + c.c.	< 5.4 × 10^{-5}	CL=90%
	Radiative decays		
Γ_{29}	$\gamma\chi_{c0}(1P)$	(9.3 ±0.8) %	
Γ_{30}	$\gamma\chi_{c1}(1P)$	(8.7 ±0.8) %	
Γ_{31}	$\gamma\chi_{c2}(1P)$	(7.8 ±0.8) %	
Γ_{32}	$\gamma\eta_c(1S)$	(2.8 ±0.6) × 10^{-3}	
Γ_{33}	$\gamma\eta_c(2S)$		
Γ_{34}	$\gamma\pi^0$	< 5.4 × 10^{-3}	CL=95%
Γ_{35}	$\gamma\eta'(958)$	< 1.1 × 10^{-3}	CL=90%
Γ_{36}	$\gamma\eta$		
Γ_{37}	$\gamma\gamma$	< 1.6 × 10^{-4}	CL=90%
Γ_{38}	$\gamma\eta(1440) \to \gamma K\overline{K}\pi$	< 1.2 × 10^{-4}	CL=90%
	Mode needed for fitting purposes		
Γ_{39}	1. − other fit modes	(30 ±4) %	

CONSTRAINED FIT INFORMATION

An overall fit to 7 branching ratios uses 13 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 =$ 6.9 for 8 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i\delta x_j\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_8	35				
x_9	0	−11			
x_{30}	1	−7	0		
x_{31}	0	−3	0	0	
x_{39}	−80	−78	−4	−14	−16
	x_7	x_8	x_9	x_{30}	x_{31}

$\psi(2S)$ PARTIAL WIDTHS

Γ(hadrons) — Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
224±56	LUTH	75	MRK1	e^+e^-

$\Gamma(e^+e^-)$ — Γ_3

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
2.14±0.21	ALEXANDER	89	RVUE	See Υ mini-review
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.0 ±0.3	BRANDELIK	79C	DASP	e^+e^-
2.1 ±0.3	[3] LUTH	75	MRK1	e^+e^-

[3] From a simultaneous fit to e^+e^-, $\mu^+\mu^-$, and hadronic channels assuming $\Gamma(e^+e^-) = \Gamma(\mu^+\mu^-)$.

$\Gamma(\gamma\gamma)$ — Γ_{37}

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
<43	90	BRANDELIK	79C	DASP	e^+e^-

$\psi(2S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(total)$

This combination of a partial width with the partial width into e^+e^- and with the total width is obtained from the integrated cross section into channel$_i$ in the e^+e^- annihilation. We list only data that have not been used to determine the partial width $\Gamma(i)$ or the branching ratio $\Gamma(i)$/total.

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_1\Gamma_3/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.2±0.4	ABRAMS	75	MRK1	e^+e^-

$\psi(2S)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.981 ±0.003	[4] LUTH	75	MRK1	e^+e^-

$\Gamma(\text{virtual}\gamma \to \text{hadrons})/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.029±0.004	[5] LUTH	75	MRK1	e^+e^-

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
88±13	[6] FELDMAN	77	RVUE	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
77±17	[7] HILGER	75	SPEC	e^+e^-

$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ — Γ_4/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.89±0.16	BOYARSKI	75C	MRK1	e^+e^-

[4] Includes cascade decay into $J/\psi(1S)$.
[5] Included in $\Gamma(\text{hadrons})/\Gamma_{total}$.
[6] From an overall fit assuming equal partial widths for e^+e^- and $\mu^+\mu^-$. For a measurement of the ratio see the entry $\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-)$ below. Includes LUTH 75, HILGER 75, BURMESTER 77.
[7] Restated by us using $B(\psi(2S) \to J/\psi(1S)\text{anything}) = 0.55$.

DECAYS INTO $J/\psi(1S)$ AND ANYTHING

$\Gamma(J/\psi(1S)\,\text{anything})/\Gamma_{total}$ — $\Gamma_5/\Gamma = (\Gamma_7+\Gamma_8+\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.57±0.04 OUR FIT				
0.55±0.07 OUR AVERAGE				
0.51±0.12	BRANDELIK	79C	DASP	$e^+e^- \to \mu^+\mu^- X$
0.57±0.08	ABRAMS	75B	MRK1	$e^+e^- \to \mu^+\mu^- X$

$\Gamma(J/\psi(1S)\,\text{neutrals})/\Gamma_{total}$ — $\Gamma_6/\Gamma = (0.9761\Gamma_8+0.708\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})/\Gamma$

VALUE	DOCUMENT ID
0.232±0.026 OUR FIT	

$\Gamma(J/\psi(1S)\,\text{neutrals})/\Gamma(J/\psi(1S)\,\text{anything})$ — $\Gamma_6/\Gamma_5 = (0.9761\Gamma_8+0.708\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})/(\Gamma_7+\Gamma_8+\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.409±0.026 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44 ±0.03	[8] ABRAMS	75B	MRK1	$e^+e^- \to J/\psi X$

$\Gamma(J/\psi(1S)\,\text{neutrals})/\Gamma(J/\psi(1S)\pi^+\pi^-)$ — $\Gamma_6/\Gamma_7 = (0.9761\Gamma_8+0.708\Gamma_9+0.273\Gamma_{30}+0.135\Gamma_{31})/\Gamma_7$

VALUE	DOCUMENT ID		TECN	COMMENT
0.72±0.08 OUR FIT				
0.73±0.09	[8] TANENBAUM	76	MRK1	e^+e^-

$\Gamma(J/\psi(1S)\pi^+\pi^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.324±0.026 OUR FIT				
0.332±0.033 OUR AVERAGE				
0.32 ±0.04	ABRAMS	75B	MRK1	$e^+e^- \to J/\psi\pi^+\pi^-$
0.36 ±0.06	WIIK	75	DASP	$e^+e^- \to J/\psi\pi^+\pi^-$

$\Gamma(J/\psi(1S)\pi^0\pi^0)/\Gamma_{total}$ — Γ_8/Γ

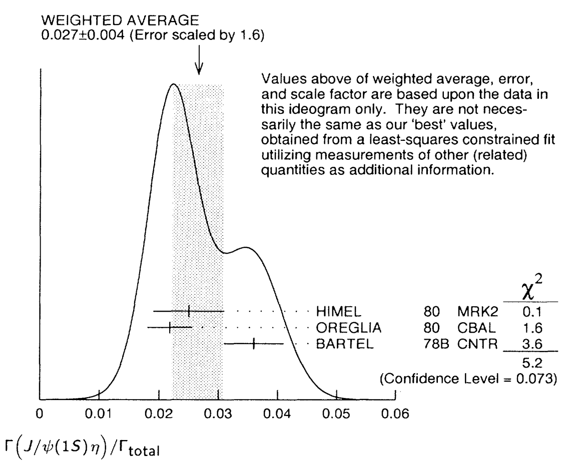
VALUE	DOCUMENT ID		TECN	COMMENT
0.184±0.027 OUR FIT				
0.18 ±0.06	WIIK	75	DASP	$e^+e^- \to J/\psi 2\pi^0$

$\Gamma(J/\psi(1S)\pi^0\pi^0)/\Gamma(J/\psi(1S)\pi^+\pi^-)$ — Γ_8/Γ_7

VALUE	DOCUMENT ID		TECN	COMMENT
0.57±0.08 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.53±0.06	[9] TANENBAUM	76	MRK1	e^+e^-
0.64±0.15	[10] HILGER	75	SPEC	e^+e^-

$\Gamma(J/\psi(1S)\eta)/\Gamma_{total}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.027 ±0.004 OUR FIT Error includes scale factor of 1.7.					
0.027 ±0.004 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.					
0.025 ±0.006	166	HIMEL	80	MRK2	e^+e^-
0.0218±0.0014±0.0035	386	OREGLIA	80	CBAL	$e^+e^- \to J/\psi 2\gamma$
0.036 ±0.005	164	BARTEL	78B	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.035 ±0.009	17	[11] BRANDELIK	79B	DASP	$e^+e^- \to J/\psi 2\gamma$
0.043 ±0.008	44	[11] TANENBAUM	76	MRK1	e^+e^-



$\Gamma(J/\psi(1S)\eta)/\Gamma_{total}$

$\Gamma(J/\psi(1S)\pi^0)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
9.7±2.1 OUR AVERAGE					
15 ±6	7	HIMEL	80	MRK2	e^+e^-
9 ±2 ±1	23	OREGLIA	80	CBAL	$\psi(2S) \to J/\psi 2\gamma$

[8] The ABRAMS 75B measurement of Γ_6/Γ_5 and the TANENBAUM 76 result for Γ_6/Γ_7 are not independent. The TANENBAUM 76 result is used in the fit because it includes more accurate corrections for angular distributions.

[9] Not independent of the TANENBAUM 76 result for Γ_6/Γ_7.

[10] Ignoring the $J/\psi(1S)\eta$ and $J/\psi(1S)\gamma\gamma$ decays.

[11] Low statistics data removed from average.

HADRONIC DECAYS

$\Gamma(3(\pi^+\pi^-)\pi^0)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
35±16	6	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons

$\Gamma(2(\pi^+\pi^-)\pi^0)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
31± 7 OUR AVERAGE					
30± 8	42	FRANKLIN	83	MRK2	e^+e^-
35±15		ABRAMS	75	MRK1	e^+e^-

$\Gamma(\pi^+\pi^- K^+K^-)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
16±4	[12] TANENBAUM	78	MRK1	e^+e^-

$\Gamma(\pi^+\pi^- p\bar{p})/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
8 ±2	[12] TANENBAUM	78	MRK1	e^+e^-

$\Gamma(K^+\overline{K}^*(892)^0\pi^- + \text{c.c.})/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
6.7±2.5	TANENBAUM	78	MRK1	e^+e^-

$\Gamma(2(\pi^+\pi^-))/\Gamma_{total}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
4.5±1.0	TANENBAUM	78	MRK1	e^+e^-

$\Gamma(\rho^0\pi^+\pi^-)/\Gamma_{total}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
4.2±1.5	TANENBAUM	78	MRK1	e^+e^-

$\Gamma(\bar{p}p)/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.9±0.5 OUR AVERAGE					
1.4±0.8	4	BRANDELIK	79C	DASP	e^+e^-
2.3±0.7		FELDMAN	77	MRK1	e^+e^-

$\Gamma(3(\pi^+\pi^-))/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
1.5±1.0	[12] TANENBAUM	78	MRK1	e^+e^-

$\Gamma(\bar{p}p\pi^0)/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.4±0.5	9	FRANKLIN	83	MRK2	e^+e^-

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
1.0±0.7		BRANDELIK	79C	DASP	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.5	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
0.8±0.5		BRANDELIK	79C	DASP	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.5	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.85±0.46	4	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons

$\Gamma(\Lambda\overline{\Lambda})/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<4	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\Xi^-\overline{\Xi}^+)/\Gamma_{total}$ — Γ_{25}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2	90	FELDMAN	77	MRK1	e^+e^-

$\Gamma(\rho\pi)/\Gamma_{total}$ — Γ_{26}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.83	90	1	FRANKLIN	83	MRK2	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<10	90		BARTEL	76	CNTR	e^+e^-
<10	90		[13] ABRAMS	75	MRK1	e^+e^-

$\Gamma(K^+K^-\pi^0)/\Gamma_{total}$ — Γ_{27}/Γ

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.96	90	1	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons

$\Gamma(K^+\overline{K}^*(892)^- + c.c.)/\Gamma_{total}$ — Γ_{28}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<5.4	90	FRANKLIN	83	MRK2	$e^+e^- \to$ hadrons

[12] Assuming entirely strong decay.
[13] Final state $\rho^0\pi^0$.

RADIATIVE DECAYS

$\Gamma(\gamma\chi_{c0}(1P))/\Gamma_{total}$ — Γ_{29}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
9.3±0.8 OUR AVERAGE				
9.9±0.5±0.8	[14] GAISER	86	CBAL	$e^+e^- \to \gamma X$
7.2±2.3	[14] BIDDICK	77	CNTR	$e^+e^- \to \gamma X$
7.5±2.6	[14] WHITAKER	76	MRK1	e^+e^-

$\Gamma(\gamma\chi_{c1}(1P))/\Gamma_{total}$ — Γ_{30}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
8.7±0.8 OUR FIT				
8.7±0.8 OUR AVERAGE				
9.0±0.5±0.7	[15] GAISER	86	CBAL	$e^+e^- \to \gamma X$
7.1±1.9	[16] BIDDICK	77	CNTR	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{c2}(1P))/\Gamma_{total}$ — Γ_{31}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
7.8±0.8 OUR FIT				
7.8±0.8 OUR AVERAGE				
8.0±0.5±0.7	[17] GAISER	86	CBAL	$e^+e^- \to \gamma X$
7.0±2.0	[16] BIDDICK	77	CNTR	$e^+e^- \to \gamma X$

$\Gamma(\gamma\eta_c(1S))/\Gamma_{total}$ — Γ_{32}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
0.28±0.06	GAISER	86	CBAL	$e^+e^- \to \gamma X$

$\Gamma(\gamma\eta_c(2S))/\Gamma_{total}$ — Γ_{33}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.2 to 1.3	95	EDWARDS	82C	CBAL	$e^+e^- \to \gamma X$

$\Gamma(\gamma\pi^0)/\Gamma_{total}$ — Γ_{34}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 54	95	[18] LIBERMAN	75	SPEC	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<100	90	WIIK	75	DASP	e^+e^-

$\Gamma(\gamma\eta'(958))/\Gamma_{total}$ — Γ_{35}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
<0.11	90	[19] BARTEL	76	CNTR	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.6	90	[20] BRAUNSCH...	77	DASP	e^+e^-

$\Gamma(\gamma\eta)/\Gamma_{total}$ — Γ_{36}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	90	YAMADA	77	DASP	$e^+e^- \to 3\gamma$

$\Gamma(\gamma\eta(1440) \to \gamma K\overline{K}\pi)/\Gamma_{total}$ — Γ_{38}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<0.12	90	[21] SCHARRE	80	MRK1	e^+e^-

[14] Angular distribution $(1+\cos^2\theta)$ assumed.
[15] Angular distribution $(1-0.189\cos^2\theta)$ assumed.
[16] Valid for isotropic distribution of the photon.
[17] Angular distribution $(1-0.052\cos^2\theta)$ assumed.
[18] Restated by us using $B(\psi(2S) \to \mu^+\mu^-) = 0.0077$.
[19] The value is normalized to the branching ratio for $\Gamma(J/\psi(1S)\eta)/\Gamma_{total}$.
[20] Restated by us using total decay width 228 keV.
[21] Includes unknown branching fraction $\eta(1440) \to K\overline{K}\pi$.

$\psi(2S)$ REFERENCES

ANTONIAZZI	94	PR D50 4258	+Arenton+	(E705 Collab.)
ARMSTRONG	93B	PR D47 772	+Bettoni, Bharadwaj+	(FNAL E760 Collab.)
PDG	92	PR D45, 1 June, Part II	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
GAISER	86	PR D34 711	+Bloom, Bulos, Godfrey+	(Crystal Ball Collab.)
FRANKLIN	83	PRL 51 963	+Franklin, Feldman, Abrams, Alam+	(LBL, SLAC)
EDWARDS	82C	PRL 48 70	+Partridge, Peck+	(CIT, HARV, PRIN, STAN, SLAC)
LEMOIGNE	82	PL 113B 509	+Barate, Astbury+	(SACL, LOIC, SHMP, IND)
HIMEL	80	PRL 44 920	+Abrams, Alam, Blocker+	(LBL, SLAC)
OREGLIA	80	PRL 45 959	+Partridge+	(SLAC, CIT, HARV, PRIN, STAN)
SCHARRE	80	PL 97B 329	+Trilling, Abrams, Alam, Blocker+	(SLAC, LBL)
ZHOLENTZ	80	PL 96B 214	+Kurdadze, Lelchuk, Mishnev+	(NOVO)
Also	81	SJNP 34 814	Zholentz, Kurdadze, Lelchuk+	(NOVO)
		Translated from YAF 34 1471.		
BRANDELIK	79B	NP B160 426	+Cords+	(DASP Collab.)
BRANDELIK	79C	ZPHY C1 233	+Cords+	(DASP Collab.)
BARTEL	78B	PL 79B 492	+Dittmann, Duinker, Olsson, O'Neill+	(DESY, HEIDP)
TANENBAUM	78	PR D17 1731	+Alam, Boyarski+	(SLAC, LBL)
BIDDICK	77	PRL 38 1324	+Burnett+	(UCSD, UMD, PAVI, PRIN, SLAC, STAN)
BRAUNSCH...	77	PL 67B 249	Braunschweig+	(DASP Collab.)
BURMESTER	77	PL 66B 395	+Criegee+	(DESY, HAMB, SIEG, WUPP)
FELDMAN	77	PRPL 33C 285	+Perl	(LBL, SLAC)
YAMADA	77	Hamburg Conf. 69		(DASP Collab.)
BARTEL	76	PL 64B 483	+Duinker, Olsson, Steffen, Heintze+	(DESY, HEIDP)
TANENBAUM	76	PRL 36 402	+Abrams, Boyarski, Bulos+	(SLAC, LBL) IG
WHITAKER	76	PRL 37 1596	+Tanenbaum, Abrams, Alam+	(SLAC, LBL)
ABRAMS	75	Stanford Symp. 25		(LBL)
ABRAMS	75B	PRL 34 1181	+Briggs, Chinowsky, Friedberg+	(LBL, SLAC)
BOYARSKI	75C	Palermo Conf. 54	+Breidenbach, Bulos, Abrams, Briggs+	(SLAC, LBL)
HILGER	75	PRL 35 625	+Beron, Ford, Hofstadter, Howell+	(STAN, PENN)
LIBERMAN	75	Stanford Symp. 55		(STAN)
LUTH	75	PRL 35 1124	+Boyarski, Lynch, Breidenbach+	(SLAC, LBL) JPC
WIIK	75	Stanford Symp. 69		(DESY)

OTHER RELATED PAPERS

LEE	85	SLAC 282		(SLAC)
BARATE	83	PL 121B 449	+Bareyre, Bonamy+	(SACL, LOIC, SHMP, IND)
FRANKLIN	83B	Thesis SLAC-0254		(STAN)
AUBERT	75B	PRL 33 1624	+Becker, Biggs, Burger, Glenn+	(MIT, BNL)
BRAUNSCH...	75B	PL 57B 407	Braunschweig, Konigs+	(DASP Collab.)
CAMERINI	75	PRL 35 483	+Learned, Prepost, Ash, Anderson+	(WISC, SLAC)
FELDMAN	75B	PRL 35 821	+Jean-Marie, Sadoulet, Vannucci+	(LBL, SLAC)
GRECO	75	PL 56B 367	+Pancheri-Srivastava, Srivastava	(FRAS)
JACKSON	75	NIM 128 13	+Scharre	(LBL)
SIMPSON	75	PRL 35 699	+Beron, Ford, Hilger, Hofstadter+	(STAN, PENN)
ABRAMS	74	PRL 33 1453	+Briggs, Augustin, Boyarski+	(LBL, SLAC)

$\psi(3770)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\psi(3770)$ MASS

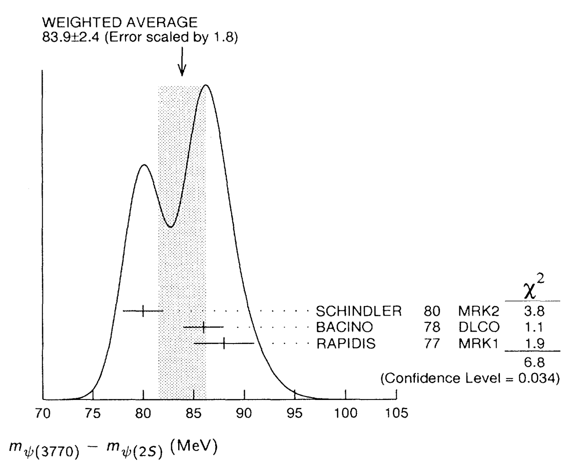
VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3769.9±2.5 OUR EVALUATION	Error includes scale factor of 1.8. From $m_{\psi(3685)}$ and mass difference below.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3764 ±5	[1] SCHINDLER	80	MRK2	e^+e^-
3770 ±6	[1] BACINO	78	DLCO	e^+e^-
3772 ±6	[1] RAPIDIS	77	MRK1	e^+e^-

[1] Errors include systematic common to all experiments.

$m_{\psi(3770)} - m_{\psi(2S)}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
83.9±2.4 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.			
80 ±2	SCHINDLER	80	MRK2	e^+e^-
86 ±2	[2] BACINO	78	DLCO	e^+e^-
88 ±3	RAPIDIS	77	MRK1	e^+e^-

[2] SPEAR $\psi(2S)$ mass subtracted (see SCHINDLER 80).



$\psi(3770)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
23.6±2.7 OUR FIT Error includes scale factor of 1.1.				
25.3±2.9 OUR AVERAGE				
24 ±5	SCHINDLER	80	MRK2	e^+e^-
24 ±5	BACINO	78	DLCO	e^+e^-
28 ±5	RAPIDIS	77	MRK1	e^+e^-

$\psi(3770)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	$D\overline{D}$	dominant	
Γ_2	e^+e^-	$(1.12\pm0.17)\times10^{-5}$	1.2

$\psi(3770)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.26 ±0.04 OUR FIT Error includes scale factor of 1.2.				
0.24 ±0.05 OUR AVERAGE Error includes scale factor of 1.2.				
0.276±0.050	SCHINDLER	80	MRK2	e^+e^-
0.18 ±0.06	BACINO	78	DLCO	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.37 ±0.09	[3] RAPIDIS	77	MRK1	e^+e^-

[3] See also $\Gamma(e^+e^-)/\Gamma_{total}$ below.

$\psi(3770)$ BRANCHING RATIOS

$\Gamma(D\overline{D})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
dominant	PERUZZI	77	MRK1	$e^+e^-\to D\overline{D}$

$\Gamma(e^+e^-)/\Gamma_{total}$ Γ_2/Γ

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
1.12±0.17 OUR FIT Error includes scale factor of 1.2.				
1.3 ±0.2	RAPIDIS	77	MRK1	e^+e^-

$\psi(3770)$ REFERENCES

SCHINDLER 80 PR D21 2716 +Siegrist, Alam, Boyarski+ (Mark II Collab.)
BACINO 78 PRL 40 671 +Baumgarten, Birkwood+ (SLAC, UCLA, UCI)
PERUZZI 77 PRL 39 1301 +Piccolo, Feldman+ (Mark I Collab.)
RAPIDIS 77 PRL 39 526 +Gobbi, Luke, Barbaro-Galtieri+ (Mark I Collab.)

$\psi(4040)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\psi(4040)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4040±10	BRANDELIK	78C	DASP	e^+e^-

$\psi(4040)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
52±10	BRANDELIK	78C	DASP	e^+e^-

$\psi(4040)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(1.4\pm0.4)\times10^{-5}$
Γ_2	$D^0\overline{D}^0$	seen
Γ_3	$D^*(2007)^0\overline{D}^0$ + c.c.	seen
Γ_4	$D^*(2007)^0\overline{D}^*(2007)^0$	seen
Γ_5	$J/\psi(1S)$ hadrons	
Γ_6	$\mu^+\mu^-$	

$\psi(4040)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.75±0.15	BRANDELIK	78C	DASP	e^+e^-

$\psi(4040)$ BRANCHING RATIOS

$\Gamma(e^+e^-)/\Gamma_{total}$ Γ_1/Γ

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
~ 1.0	FELDMAN	77	MRK1	e^+e^-

$\Gamma(D^0\overline{D}^0)/\Gamma(D^*(2007)^0\overline{D}^0$ + c.c.) Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 ±0.03	[1] GOLDHABER	77	MRK1	e^+e^-

[1] Phase-space factor (p^3) explicitly removed.

$\Gamma(D^*(2007)^0\overline{D}^*(2007)^0)/\Gamma(D^*(2007)^0\overline{D}^0$ + c.c.) Γ_4/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
32.0±12.0	[2] GOLDHABER	77	MRK1	e^+e^-

[2] Phase-space factor (p^3) explicitly removed.

$\psi(4040)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (DASP Collab.)
Also 79C ZPHY C1 233 Brandelik, Cords+ (DASP Collab.)
FELDMAN 77 PRPL 33C 285 +Perl (LBL, SLAC)
GOLDHABER 77 PL 69B 503 +Wiss, Abrams, Alam+ (Mark I Collab.)

OTHER RELATED PAPERS

HEIKKILA 84 PR D29 110 +Tornqvist, Ono (HELS, AACHT)
ONO 84 ZPHY C26 307 (ORSAY)
SIEGRIST 82 PR D26 969 +Schwitters, Alam, Chinowsky+ (SLAC, LBL)
AUGUSTIN 75 PRL 34 764 +Boyarski, Abrams, Briggs+ (SLAC, LBL)
BACCI 75 PL 58B 481 +Bidoli, Penso, Stella+ (ROMA, FRAS)
BOYARSKI 75B PRL 34 762 +Breidenbach, Abrams, Briggs+ (SLAC, LBL)
ESPOSITO 75 PL 58B 478 +Felicetti, Peruzzi+ (FRAS, NAPL, PADO, ROMA)

$\psi(4160)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\psi(4160)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4159±20	BRANDELIK	78C	DASP	e^+e^-

$\psi(4160)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
78±20	BRANDELIK	78C	DASP	e^+e^-

$\psi(4160)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(10\pm4)\times10^{-6}$

$\psi(4160)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.77±0.23	BRANDELIK	78C	DASP	e^+e^-

$\psi(4160)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (DASP Collab.)

OTHER RELATED PAPERS

ONO 84 ZPHY C26 307 (ORSAY)
KIRKBY 79B Fermilab Symp. 107 (SLAC)
BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)

$\psi(4415)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\psi(4415)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
4415± 6 OUR AVERAGE			
4417±10	BRANDELIK 78C	DASP	e^+e^-
4414± 7	SIEGRIST 76	MRK1	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •			
~ 4400	KNIES 77	PLUT	$e^+e^- \to \mu^+\mu^-$

$\psi(4415)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
43±15 OUR AVERAGE Error includes scale factor of 1.8.			
66±15	BRANDELIK 78C	DASP	e^+e^-
33±10	SIEGRIST 76	MRK1	e^+e^-

$\psi(4415)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	dominant
Γ_2	e^+e^-	$(1.1\pm0.4)\times10^{-5}$

$\psi(4415)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_2

VALUE (keV)	DOCUMENT ID	TECN	COMMENT
0.47±0.10 OUR AVERAGE			
0.49±0.13	BRANDELIK 78C	DASP	e^+e^-
0.44±0.14	SIEGRIST 76	MRK1	e^+e^-

$\psi(4415)$ BRANCHING RATIOS

$\Gamma(\text{hadrons})/\Gamma_{\text{total}}$ Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
dominant	SIEGRIST 76	MRK1	e^+e^-

$\psi(4415)$ REFERENCES

BRANDELIK 78C PL 76B 361 +Cords+ (DASP Collab.)
KNIES 77 Hamburg Symp. 93 (PLUTO Collab.)
SIEGRIST 76 PRL 36 700 +Abrams, Boyarski, Breidenbach+ (LBL, SLAC)

OTHER RELATED PAPERS

BURMESTER 77 PL 66B 395 +Criegee+ (DESY, HAMB, SIEG, WUPP)
LUTH 77 PL 70B 120 +Pierre, Abrams, Alam, Boyarski+ (LBL, SLAC)

$b\bar{b}$ MESONS

WIDTH DETERMINATIONS OF THE Υ STATES

As is the case for the $J/\psi(1S)$ and $\psi(2S)$, the full widths of the $b\bar{b}$ states $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ are not directly measurable, since they are much narrower than the energy resolution of the e^+e^- storage rings where these states are produced. The common indirect method to determine Γ starts from

$$\Gamma = \Gamma_{\ell\ell}/B_{\ell\ell} \ , \qquad (1)$$

where $\Gamma_{\ell\ell}$ is one leptonic partial width and $B_{\ell\ell}$ is the corresponding branching fraction ($\ell = e$, μ, or τ). One then assumes e-μ-τ universality and uses

$$\Gamma_{\ell\ell} = \Gamma_{ee}$$

$$B_{\ell\ell} = \text{average of } B_{ee},\ B_{\mu\mu}, \text{ and } B_{\tau\tau} \ . \qquad (2)$$

The electronic partial width Γ_{ee} is also not directly measurable at e^+e^- storage rings, only in the combination $\Gamma_{ee}\Gamma_{\text{had}}/\Gamma$, where Γ_{had} is the hadronic partial width and

$$\Gamma_{\text{had}} + 3\Gamma_{ee} = \Gamma \ . \qquad (3)$$

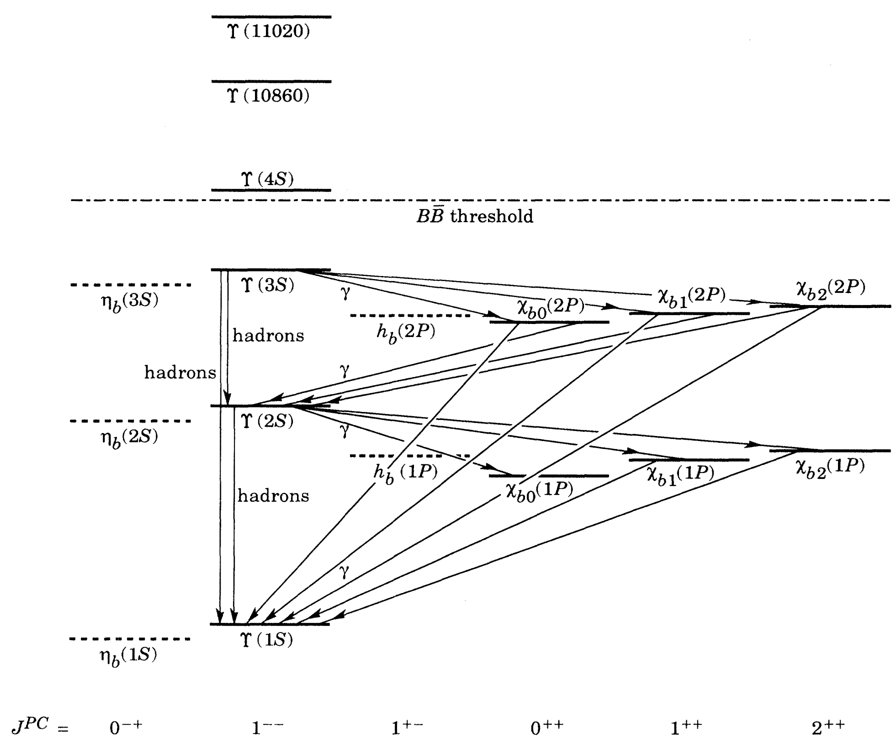
This combination is obtained experimentally from the energy-integrated hadronic cross section

$$\int_{\text{resonance}} \sigma(e^+e^- \to \Upsilon \to \text{hadrons})dE$$

$$= \frac{6\pi^2}{M^2}\frac{\Gamma_{ee}\Gamma_{\text{had}}}{\Gamma}C_r = \frac{6\pi^2}{M^2}\frac{\Gamma_{ee}^{(0)}\Gamma_{\text{had}}}{\Gamma}C_r^{(0)} \ , \qquad (4)$$

where M is the Υ mass, and C_r and $C_r^{(0)}$ are radiative correction factors. C_r is used for obtaining Γ_{ee} as defined in Eq. (1), and contains corrections from all orders of QED for describing $(b\bar{b}) \to e^+e^-$. The lowest order QED value $\Gamma_{ee}^{(0)}$, relevant for comparison with potential-model calculations, is defined by the lowest order QED graph (Born term) alone, and is about 7% lower than Γ_{ee}.

THE BOTTOMONIUM SYSTEM



The level scheme of the $b\bar{b}$ states showing experimentally established states with solid lines. Singlet states are called η_b and h_b, triplet states Υ and χ_{bJ}. In parentheses it is sufficient to give the radial quantum number and the orbital angular momentum to specify the states with all their quantum numbers. *E.g.*, $h_b(2P)$ means 2^1P_1 with $n = 2$, $L = 1$, $S = 0$, $J = 1$, $PC = +-$. If found, D-wave states would be called $\eta_b(nD)$ and $\Upsilon_J(nD)$, with $J = 1,2,3$ and $n = 1,2,3,4,\cdots$. For the χ_b states, the spins of only the $\chi_{b2}(1P)$ and $\chi_{b1}(1P)$ have been experimentally established. The spins of the other χ_b are given as the preferred values, based on the quarkonium models. The figure also shows the observed hadronic and radiative transitions.

The Listings give experimental results on B_{ee}, $B_{\mu\mu}$, $B_{\tau\tau}$, and $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$. The entries of the last quantity have been re-evaluated consistently using the correction procedure of KURAEV 85.The partial width Γ_{ee} is obtained from the average values for $\Gamma_{ee}\Gamma_{\rm had}/\Gamma$ and $B_{\ell\ell}$ using

$$\Gamma_{ee} = \frac{\Gamma_{ee}\Gamma_{\rm had}}{\Gamma(1-3B_{\ell\ell})} \,. \qquad (5)$$

The total width Γ is then obtained from Eq. (1). We do not list Γ_{ee} and Γ values of individual experiments. The Γ_{ee} values in the Meson Summary Table are also those defined in Eq. (1).

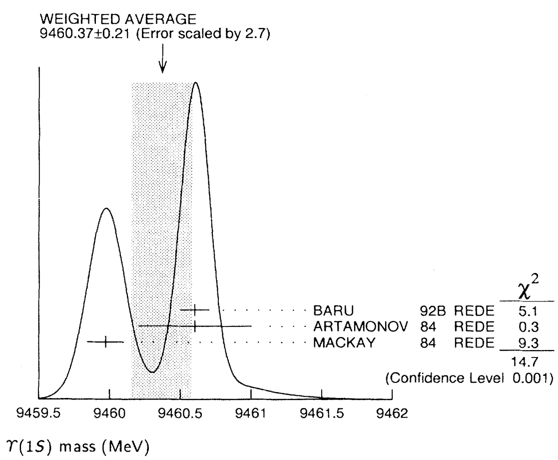
$\Upsilon(1S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(1S)$ MASS

VALUE (MeV)		DOCUMENT ID		TECN	COMMENT
9460.37±0.21 OUR AVERAGE	Error includes scale factor of 2.7. See the ideogram below.				
9460.60±0.09±0.05		[1] BARU	92B	REDE	$e^+e^- \to$ hadrons
9460.6 ±0.4		[2] ARTAMONOV	84	REDE	$e^+e^- \to$ hadrons
9459.97±0.11±0.07		MACKAY	84	REDE	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
9460.59±0.12		BARU	86	REDE	$e^+e^- \to$ hadrons

[1] Superseding BARU 86.
[2] Value includes data of ARTAMONOV 82.



$\Upsilon(1S)$ WIDTH

VALUE (keV)	DOCUMENT ID
52.5±1.8 OUR EVALUATION	See Υ mini-review.

$\Upsilon(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\tau^+\tau^-$	$(2.67^{+0.14}_{-0.16})$ %	
Γ_2	e^+e^-	(2.52 ± 0.17) %	
Γ_3	$\mu^+\mu^-$	(2.48 ± 0.07) %	S=1.1
	Hadronic decays		
Γ_4	$J/\psi(1S)$anything	$(1.1 \pm0.4) \times 10^{-3}$	
Γ_5	$\rho\pi$	$< 2 \times 10^{-4}$	CL=90%
Γ_6	$\pi^+\pi^-$	$< 5 \times 10^{-4}$	CL=90%
Γ_7	K^+K^-	$< 5 \times 10^{-4}$	CL=90%
Γ_8	$p\overline{p}$	$< 5 \times 10^{-4}$	CL=90%
Γ_9	$D^*(2010)^\pm$anything		
	Radiative decays		
Γ_{10}	$\gamma 2h^+2h^-$	$(7.0 \pm1.5) \times 10^{-4}$	
Γ_{11}	$\gamma 3h^+3h^-$	$(5.4 \pm2.0) \times 10^{-4}$	
Γ_{12}	$\gamma 4h^+4h^-$	$(7.4 \pm3.5) \times 10^{-4}$	
Γ_{13}	$\gamma\pi^+\pi^-K^+K^-$	$(2.9 \pm0.9) \times 10^{-4}$	
Γ_{14}	$\gamma 2\pi^+2\pi^-$	$(2.5 \pm0.9) \times 10^{-4}$	
Γ_{15}	$\gamma 3\pi^+3\pi^-$	$(2.5 \pm1.2) \times 10^{-4}$	
Γ_{16}	$\gamma 2\pi^+2\pi^-K^+K^-$	$(2.4 \pm1.2) \times 10^{-4}$	
Γ_{17}	$\gamma\pi^+\pi^-p\overline{p}$	$(1.5 \pm0.6) \times 10^{-4}$	
Γ_{18}	$\gamma 2\pi^+2\pi^-p\overline{p}$	$(4 \pm6) \times 10^{-5}$	
Γ_{19}	$\gamma 2K^+2K^-$	$(2.0 \pm2.0) \times 10^{-5}$	
Γ_{20}	$\gamma\eta'(958)$	$< 1.3 \times 10^{-3}$	CL=90%
Γ_{21}	$\gamma\eta$	$< 3.5 \times 10^{-4}$	CL=90%
Γ_{22}	$\gamma f'_2(1525)$	$< 1.4 \times 10^{-4}$	CL=90%
Γ_{23}	$\gamma f_2(1270)$	$< 1.3 \times 10^{-4}$	CL=90%
Γ_{24}	$\gamma\eta(1440)$	$< 8.2 \times 10^{-5}$	CL=90%
Γ_{25}	$\gamma f_J(1710) \to \gamma K\overline{K}$	$< 2.6 \times 10^{-4}$	CL=90%
Γ_{26}	$\gamma f_0(2200) \to \gamma K^+K^-$	$< 2 \times 10^{-4}$	CL=90%
Γ_{27}	$\gamma f_J(2220) \to \gamma K^+K^-$	$< 1.5 \times 10^{-5}$	CL=90%
Γ_{28}	$\gamma\eta(2225) \to \gamma\phi\phi$	$< 3 \times 10^{-3}$	CL=90%
Γ_{29}	γX X = pseudoscalar with $m<$ 7.2 GeV)	$< 3 \times 10^{-5}$	CL=90%
Γ_{30}	$\gamma X\overline{X}$ $X\overline{X}$ = vectors with $m<$ 3.1 GeV)	$< 1 \times 10^{-3}$	CL=90%

$\Upsilon(1S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(e^+e^-) \times \Gamma(\mu^+\mu^-)/\Gamma_{\rm total}$ — $\Gamma_2\Gamma_3/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
31.2±1.6±1.7	KOBEL	92	CBAL	$e^+e^- \to \mu^+\mu^-$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{\rm total}$ — $\Gamma_0\Gamma_2/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
1.216±0.027 OUR AVERAGE				
1.187±0.023±0.031	[3] BARU	92B	MD1	$e^+e^- \to$ hadrons
1.23 ±0.02 ±0.05	[3] JAKUBOWSKI	88	CBAL	$e^+e^- \to$ hadrons
1.37 ±0.06 ±0.09	[4] GILES	84B	CLEO	$e^+e^- \to$ hadrons
1.23 ±0.08 ±0.04	[4] ALBRECHT	82	DASP	$e^+e^- \to$ hadrons
1.13 ±0.07 ±0.11	[4] NICZYPORUK	82	LENA	$e^+e^- \to$ hadrons
1.09 ±0.25	[4] BOCK	80	CNTR	$e^+e^- \to$ hadrons
1.35 ±0.14	[5] BERGER	79	PLUT	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.17 ±0.06 ±0.10	[4] TUTS	83	CUSB	$e^+e^- \to$ hadrons

[3] Radiative corrections evaluated following KURAEV 85.
[4] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.
[5] Radiative corrections reevaluated by ALEXANDER 89 using B($\mu\mu$) = 0.026.

$\Upsilon(1S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
1.32±0.04±0.03	[6] ALBRECHT	95E	ARG	$e^+e^- \to$ hadrons

[6] Applying the formula of Kuraev and Fadin.

$\Upsilon(1S)$ BRANCHING RATIOS

$\Gamma(\tau^+\tau^-)/\Gamma_{\rm total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.0267^{+0.0014}_{-0.0016}$ OUR AVERAGE					
$0.0261\pm0.0012^{+0.0009}_{-0.0013}$	25k	CINABRO	94B	CLE2	$e^+e^- \to \tau^+\tau^-$
0.027 ±0.004 ±0.002		[7] ALBRECHT	85C	ARG	$\Upsilon(2S) \to \pi^+\pi^-\tau^+\tau^-$
0.034 ±0.004 ±0.004		GILES	83	CLEO	$e^+e^- \to \tau^+\tau^-$

[7] Using B($\Upsilon(1S) \to ee$) = B($\Upsilon(1S) \to \mu\mu$) = 0.0256; not used for width evaluations.

$\Gamma(\mu^+\mu^-)/\Gamma_{\rm total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0248±0.0007 OUR AVERAGE	Error includes scale factor of 1.1.				
0.0212±0.0020±0.0010		[8] BARU	92	MD1	$e^+e^- \to \mu^+\mu^-$
0.0231±0.0012±0.0010		[8] KOBEL	92	CBAL	$e^+e^- \to \mu^+\mu^-$
0.0252±0.0007±0.0007		CHEN	89B	CLEO	$e^+e^- \to \mu^+\mu^-$
0.0261±0.0009±0.0011		KAARSBERG	89	CSB2	$e^+e^- \to \mu^+\mu^-$
0.0230±0.0025±0.0013	86	ALBRECHT	87	ARG	$\Upsilon(2S) \to \pi^+\pi^-\mu^+\mu^-$
0.029 ±0.003 ±0.002	864	BESSON	84	CLEO	$\Upsilon(2S) \to \pi^+\pi^-\mu^+\mu^-$

0.027 ±0.003 ±0.003		ANDREWS	83	CLEO	$e^+e^- \to \mu^+\mu^-$
0.032 ±0.013 ±0.003		ALBRECHT	82	DASP	$e^+e^- \to \mu^+\mu^-$
0.038 ±0.015 ±0.002		NICZYPORUK	82	LENA	$e^+e^- \to \mu^+\mu^-$
$0.014 \ {}^{+0.034}_{-0.014}$		BOCK	80	CNTR	$e^+e^- \to \mu^+\mu^-$
0.022 ±0.020		BERGER	79	PLUT	$e^+e^- \to \mu^+\mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.027 ±0.003 ±0.003		TUTS	83	CUSB	$e^+e^- \to \mu^+\mu^-$

[8] Taking into account interference between the resonance and continuum.

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0252±0.0017 OUR AVERAGE					
0.0242±0.0014±0.0014	307	ALBRECHT	87	ARG	$\Upsilon(2S) \to \pi^+\pi^- e^+e^-$
0.028 ±0.003 ±0.002	826	BESSON	84	CLEO	$\Upsilon(2S) \to \pi^+\pi^- e^+e^-$
0.051 ±0.030		BERGER	80C	PLUT	$e^+e^- \to e^+e^-$

$\Gamma(J/\psi(1S)\,\text{anything})/\Gamma_{total}$ — Γ_4/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
< 0.68	90	ALBRECHT	92J	ARG	$e^+e^- \to e^+e^- X$, $e^+e^- \to \mu^+\mu^- X$
1.1 ±0.4±0.2		[9] FULTON	89	CLEO	$e^+e^- \to \mu^+\mu^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.7	90	MASCHMANN	90	CBAL	$e^+e^- \to$ hadrons
<20	90	NICZYPORUK	83	LENA	

[9] Using $B((J/\psi) \to \mu^+\mu^-) = (6.9 \pm 0.9)\%$.

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	BARU	92	MD1	$\Upsilon(1S) \to \pi^+\pi^-$

$\Gamma(K^+K^-)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	BARU	92	MD1	$\Upsilon(1S) \to K^+K^-$

$\Gamma(p\overline{p})/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<5	90	[10] BARU	96	MD1	$\Upsilon(1S) \to p\overline{p}$

[10] Supersedes BARU 92 in this node.

$\Gamma(\gamma X)/\Gamma_{total}$ — Γ_{29}/Γ

(X = pseudoscalar with $m <$ 7.2 GeV)

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<3	90	[11] BALEST	95	CLEO	$e^+e^- \to \gamma + X$

[11] For a noninteracting pseudoscalar X with mass < 7.2 GeV.

$\Gamma(\gamma X\overline{X})/\Gamma_{total}$ — Γ_{30}/Γ

($X\overline{X}$ = vectors with $m <$ 3.1 GeV)

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1	90	[12] BALEST	95	CLEO	$e^+e^- \to \gamma + X\overline{X}$

[12] For a noninteracting vector X with mass < 3.1 GeV.

$\Gamma(\gamma 2\pi^+ 2\pi^-)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.5±0.7±0.5	26 ± 7	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma\pi^+\pi^- K^+K^-)/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.9±0.7±0.6	29 ± 8	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma\pi^+\pi^- p\overline{p})/\Gamma_{total}$ — Γ_{17}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.5±0.5±0.3	22 ± 6	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2K^+ 2K^-)/\Gamma_{total}$ — Γ_{19}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.2 ±0.2	2 ± 2	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 3\pi^+ 3\pi^-)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.5±0.9±0.8	17 ± 5	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2\pi^+ 2\pi^- K^+K^-)/\Gamma_{total}$ — Γ_{16}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.4±0.9±0.8	18 ± 7	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2\pi^+ 2\pi^- p\overline{p})/\Gamma_{total}$ — Γ_{18}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.4±0.4±0.4	7 ± 6	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 2h^+ 2h^-)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
7.0±1.1±1.0	80 ± 12	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 3h^+ 3h^-)/\Gamma_{total}$ — Γ_{11}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
5.4±1.5±1.3	39 ± 11	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\gamma 4h^+ 4h^-)/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
7.4±2.5±2.5	36 ± 12	FULTON	90B	CLEO	$e^+e^- \to$ hadrons

$\Gamma(\rho\pi)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 2	90	FULTON	90B		$\Upsilon(1S) \to \rho^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<10	90	BLINOV	90	MD1	$\Upsilon(1S) \to \rho^0\pi^0$
<21	90	NICZYPORUK	83	LENA	$\Upsilon(1S) \to \rho^0\pi^0$

$\Gamma(D^*(2010)^\pm\,\text{anything})/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<19	90	[13] ALBRECHT	92J	ARG	$e^+e^- \to D^0\pi^\pm X$

[13] For $x_p > 0.2$.

$\Gamma(\gamma\eta(1440))/\Gamma_{total}$ — Γ_{24}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<8.2	90	[14] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^+\pi^\mp K^0_S$

[14] Includes unknown branching ratio of $\eta(1440) \to K^\pm\pi^\mp K^0_S$.

$\Gamma(\gamma\eta'(958))/\Gamma_{total}$ — Γ_{20}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.3	90	SCHMITT	88	CBAL	$\Upsilon(1S) \to \gamma X$

$\Gamma(\gamma\eta)/\Gamma_{total}$ — Γ_{21}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<3.5	90	SCHMITT	88	CBAL	$\Upsilon(1S) \to \gamma X$

$\Gamma(\gamma f'_2(1525))/\Gamma_{total}$ — Γ_{22}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<14	90	[15] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<19.4	90	[15] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$

[15] Assuming $B(f'_2(1525) \to K\overline{K}) = 0.71$.

$\Gamma(\gamma f_J(1710) \to \gamma K\overline{K})/\Gamma_{total}$ — Γ_{25}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 2.6	90	[16] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 6.3	90	[16] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^+K^-$
<19	90	[16] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^0_S K^0_S$
< 8	90	[17] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
<24	90	[18] SCHMITT	88	CBAL	$\Upsilon(1S) \to \gamma X$

[16] Assuming $B(f_J(1710) \to K\overline{K}) = 0.38$.
[17] Assuming $B(f_J(1710) \to \pi\pi) = 0.04$.
[18] Assuming $B(f_J(1710) \to \eta\eta) = 0.18$.

$\Gamma(\gamma f_2(1270))/\Gamma_{total}$ — Γ_{23}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<13	90	[19] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<21	90	[19] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma\pi^+\pi^-$
<81	90	SCHMITT	88	CBAL	$\Upsilon(1S) \to \gamma X$

[19] Using $B(f_2(1270) \to \pi\pi) = 0.84$.

$\Gamma(\gamma f_J(2220) \to \gamma K^+ K^-)/\Gamma_{total}$ — Γ_{27}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
< 1.5	90	[20] FULTON	90B	CLEO	$\Upsilon(1S) \to \gamma K^+ K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 2.9	90	[20] ALBRECHT	89	ARG	$\Upsilon(1S) \to \gamma K^+ K^-$
<20	90	[20] BARU	89	MD1	$\Upsilon(1S) \to \gamma K^+ K^-$

[20] Including unknown branching ratio of $f_J(2220) \to K^+ K^-$.

$\Gamma(\gamma\eta(2225) \to \gamma\phi\phi)/\Gamma_{total}$ — Γ_{28}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.003	90	[21] BARU	89	MD1	$\Upsilon(1S) \to \gamma K^+ K^- K^+ K^-$

[21] Assuming that the $\eta(2225)$ decays only into $\phi\phi$.

$\Gamma(\gamma f_0(2200) \to \gamma K^+ K^-)/\Gamma_{total}$ — Γ_{26}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0002	90	[22] BARU	89	MD1	$\Upsilon(1S) \to \gamma K^+ K^-$

[22] Assuming that the $f_0(2200)$ decays only into $K^+ K^-$.

$\Upsilon(1S)$ REFERENCES

BARU	96	PRPL 267 71	+Blinov, Blinov, Bondar+	(NOVO)
ALBRECHT	95E	ZPHY C65 619	+Hamacher+	(ARGUS Collab.)
BALEST	95	PR D51 2053	+Cho, Ford, Johnson+	(CLEO Collab.)
CINABRO	94B	PL B340 129	+Liu, Saulnier, Wilson+	(CLEO Collab.)
ALBRECHT	92J	ZPHY C55 25	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
BARU	92	ZPHY C54 229	+Beilin, Blinov+	(NOVO)
BARU	92B	ZPHY C56 547	+Blinov, Blinov, Bondar+	(NOVO)
KOBEL	92	ZPHY C53 193	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
BLINOV	90	PL B245 311	+Bondar+	(NOVO)
FULTON	90B	PR D41 1401	+Hempstead+	(CLEO Collab.)
MASCHMANN	90	ZPHY C46 555	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
ALBRECHT	89	ZPHY C42 349	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
BARU	89	ZPHY C42 505	+Beilin, Blinov, Blinov+	(NOVO)
CHEN	89B	PR D39 3528	+McIlwain, Miller+	(CLEO Collab.)
FULTON	89	PL B224 445	+Haas, Hempstead+	(CLEO Collab.)
KAARSBERG	89	PRL 62 2077	+Heintz+	(CUSB Collab.)
BUCHMUEL...	88	HE $e^+ e^-$ Physics 412	Buchmueller, Cooper	(HANN, DESY, MIT)
		Editors: A. Ali and P. Soeding, World Scientific, Singapore		
JAKUBOWSKI	88	ZPHY C40 49	+Antreasyan, Bartels+	(Crystal Ball Collab.) IGJPC
SCHMITT	88	ZPHY C40 199	+Antreasyan+	(Crystal Ball Collab.)
ALBRECHT	87	ZPHY C35 283	+Binder, Boeckmann, Glaeser+	(ARGUS Collab.)
BARU	86	ZPHY C30 551	+Blinov, Bondar, Bukin+	(NOVO)
ALBRECHT	85C	PL 154B 452	+Drescher, Heller+	(ARGUS Collab.)
KURAEV	85	SJNP 41 466	+Fadin	(NOVO)
		Translated from YAF 41 733.		
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
BESSON	84	PR D30 1433	+Green, Hicks, Namjoshi, Sannes+	(CLEO Collab.)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
MACKAY	84	PR D29 2483	+Hasard, Giles, Hempstead+	(CUSB Collab.)
ANDREWS	83	PRL 50 807	+Avery, Berkelman, Cassel+	(CLEO Collab.)
GILES	83	PRL 50 877	+	(HARV, OSU, ROCH, RUTG, SYRA, VAND+)
NICZYPORUK	83	ZPHY C17 197	+Jakubowski, Zeludziewicz+	(LENA Collab.)
TUTS	83	Cornell Conf. 284		(CUSB Collab.)
ALBRECHT	82	PL 116B 383	+Hofmann+	(DESY, DORT, HEIDH, LUND, ITEP)
ARTAMONOV	82	PL 118B 225	+Baru, Blinov, Bondar, Bukin, Groshev+	(NOVO)
NICZYPORUK	82	ZPHY C15 299	+Folger, Bienlein+	(LENA Collab.)
BERGER	80C	PL 93B 497	+Lackas, Raupach+	(PLUTO Collab.)
BOCK	80	ZPHY C6 125	+Blanar, Blum+	(HEIDP, MPIM, DESY, HAMB)
BERGER	79	ZPHY C1 343	+Alexander+	(PLUTO Collab.)

OTHER RELATED PAPERS

COOPER	86	Berkeley Conf. 67		(MIT)
KOENIGS...	86	DESY 86/136	Koenigsmann	(DESY)
ALBRECHT	84	PL 134B 137	+Drescher, Heller+	(ARGUS Collab.)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
ARTAMONOV	82	PL 118B 225	+Baru, Blinov, Bondar, Bukin, Groshev+	(NOVO)
BERGER	78	PL 76B 243	+Alexander, Daum+	(PLUTO Collab.)
BIENLEIN	78	PL 78B 360	+Glawe, Bock, Blanar+	(DESY, HAMB, HEIDP, MPIM)
DARDEN	78	PL 76B 246	+Hofmann, Schubert+	(DESY, DORT, HEIDH, LUND)
GARELICK	78	PR D18 945	+Gauthier, Hicks, Oliver+	(NEAS, WASH, TUFTS)
KAPLAN	78	PRL 40 435	+Appel, Herb, Hom+	(STON, FNAL, COLU)
YOH	78	PRL 41 684	+Herb, Hom, Lederman+	(COLU, FNAL, STON)
COBB	77	PL 72B 273	+Iwata, Fabjan+	(BNL, CERN, SYRA, YALE)
HERB	77	PRL 39 252	+Hom, Lederman, Appel, Ito+	(COLU, FNAL, STON)
INNES	77	PRL 39 1240	+Appel, Brown, Herb, Hom+	(COLU, FNAL, STON)

$\chi_{b0}(1P)$

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b0}(1P)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9859.8±1.3 OUR AVERAGE				
9860.0±0.5±1.4	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
9858.3±1.6±2.7	[1] NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
9864.1±7 ±1	[1] HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
• • • We do not use the following data for averages, fits, limits, etc. • • •				
9872.8±0.7±5.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
162.3±1.3 OUR AVERAGE				
162.1±0.5±1.4	ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
163.8±1.6±2.7	NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
158.0±7 ±1	HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
• • • We do not use the following data for averages, fits, limits, etc. • • •				
149.4±0.7±5.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$

$\chi_{b0}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\gamma\Upsilon(1S)$	<6 %	90%

$\chi_{b0}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\Upsilon(1S))/\Gamma_{total}$ — Γ_1/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.06	90	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.11	90	PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b0}(1P)$ REFERENCES

WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
PAUSS	83	PL 130B 439	+Dietl, Eigen+	(MPIM, COLU, CORN, LSU, STON)

$\chi_{b1}(1P)$

$I^G(J^{PC}) = 0^+(1^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$. $J = 1$ from SKWARNICKI 87.

$\chi_{b1}(1P)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9891.9±0.7 OUR AVERAGE				
9890.8±0.9±1.3	[1] WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
9890.8±0.3±1.1	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
9892.0±0.8±2.4	[1] NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
9893.6±0.8±1.0	[1] HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
9894.4±0.4±3.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$
9892 ±3	[1] PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
130.6±0.7 OUR AVERAGE				
131.7±0.9±1.3	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
131.7±0.3±1.1	ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
130.6±0.8±2.4	NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
129 ±0.8±1	HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
128.1±0.4±3.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$
130.6±3.0	PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

See key on page 199

$\chi_{b1}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\,\Upsilon(1S)$	(35±8) %

$\chi_{b1}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\,\Upsilon(1S))/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.35±0.08 OUR AVERAGE				
0.32±0.06±0.07	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
0.47±0.18	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b1}(1P)$ REFERENCES

SKWARNICKI	87	PRL 58 972	+Antreasyan, Besset+	(Crystal Ball Collab.) J
WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
PAUSS	83	PL 130B 439	+Dietl, Eigen+	(MPIM, COLU, CORN, LSU, STON)

$\chi_{b2}(1P)$

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$. $J = 2$ from SKWARNICKI 87.

$\chi_{b2}(1P)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9913.2±0.6 OUR AVERAGE				
9915.8±1.1±1.3	[1] WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
9912.2±0.3±0.9	[1] ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
9912.4±0.8±2.2	[1] NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
9913.3±0.7±1.0	[1] HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
9914.6±0.3±2.0	[1] KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$
9914 ±4	[1] PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

[1] From γ energy below, assuming $\Upsilon(2S)$ mass = 10023.4 MeV.

γ ENERGY IN $\Upsilon(2S)$ DECAY

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
109.6±0.6 OUR AVERAGE				
107.0±1.1±1.3	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
110.6±0.3±0.9	ALBRECHT	85E	ARG	$\Upsilon(2S) \to$ conv.γX
110.4±0.8±2.2	NERNST	85	CBAL	$\Upsilon(2S) \to \gamma X$
109.5±0.7±1.0	HAAS	84	CLEO	$\Upsilon(2S) \to$ conv.γX
108.2±0.3±2.0	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma X$
108.8±4.0	PAUSS	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b2}(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\,\Upsilon(1S)$	(22±4) %

$\chi_{b2}(1P)$ BRANCHING RATIOS

$\Gamma(\gamma\,\Upsilon(1S))/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.22±0.04 OUR AVERAGE				
0.27±0.06±0.06	WALK	86	CBAL	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$
0.20±0.05	KLOPFEN...	83	CUSB	$\Upsilon(2S) \to \gamma\gamma\ell^+\ell^-$

$\chi_{b2}(1P)$ REFERENCES

SKWARNICKI	87	PRL 58 972	+Antreasyan, Besset+	(Crystal Ball Collab.) J
WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
PAUSS	83	PL 130B 439	+Dietl, Eigen+	(MPIM, COLU, CORN, LSU, STON)

$\Upsilon(2S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(2S)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.02330±0.00031 OUR AVERAGE				
10.0236 ±0.0005	[1] BARU	86B	REDE	$e^+e^- \to$ hadrons
10.0231 ±0.0004	BARBER	84	REDE	$e^+e^- \to$ hadrons

[1] Reanalysis of ARTAMONOV 84.

$\Upsilon(2S)$ WIDTH

VALUE (keV)	DOCUMENT ID
44±7 OUR EVALUATION	See Υ mini-review.

$\Upsilon(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Upsilon(1S)\pi^+\pi^-$	(18.5 ±0.8) %	
Γ_2	$\Upsilon(1S)\pi^0\pi^0$	(8.8 ±1.1) %	
Γ_3	$\tau^+\tau^-$	(1.7 ±1.6) %	
Γ_4	$\mu^+\mu^-$	(1.31±0.21) %	
Γ_5	e^+e^-	seen	
Γ_6	$\Upsilon(1S)\pi^0$	$< 8 \times 10^{-3}$	90%
Γ_7	$\Upsilon(1S)\eta$	$< 2 \times 10^{-3}$	90%
Γ_8	$J/\psi(1S)$ anything	$< 6 \times 10^{-3}$	90%
	Radiative decays		
Γ_9	$\gamma\chi_{b1}(1P)$	(6.7 ±0.9) %	
Γ_{10}	$\gamma\chi_{b2}(1P)$	(6.6 ±0.9) %	
Γ_{11}	$\gamma\chi_{b0}(1P)$	(4.3 ±1.0) %	
Γ_{12}	$\gamma f_J(1710)$	$< 5.9 \times 10^{-4}$	90%
Γ_{13}	$\gamma f_2'(1525)$	$< 5.3 \times 10^{-4}$	90%
Γ_{14}	$\gamma f_2(1270)$	$< 2.41 \times 10^{-4}$	90%
Γ_{15}	$\gamma f_J(2220)$		

$\Upsilon(2S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(e^+e^-) \times \Gamma(\mu^+\mu^-)/\Gamma_{total}$ $\Gamma_5\Gamma_4/\Gamma$

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
6.5±1.5±1.0	KOBEL	92	CBAL	$e^+e^- \to \mu^+\mu^-$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{total}$ $\Gamma_0\Gamma_5/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.553±0.023 OUR AVERAGE				
0.552±0.031±0.017	[2] BARU	96	MD1	$e^+e^- \to$ hadrons
0.54 ±0.04 ±0.02	[2] JAKUBOWSKI	88	CBAL	$e^+e^- \to$ hadrons
0.58 ±0.03 ±0.04	[3] GILES	84B	CLEO	$e^+e^- \to$ hadrons
0.60 ±0.12 ±0.07	[3] ALBRECHT	82	DASP	$e^+e^- \to$ hadrons
0.54 ±0.07 $^{+0.09}_{-0.05}$	[3] NICZYPORUK	81C	LENA	$e^+e^- \to$ hadrons
0.41 ±0.18	[3] BOCK	80	CNTR	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.59 ±0.03 ±0.05	[3] TUTS	83	CUSB	$e^+e^- \to$ hadrons

[2] Radiative corrections evaluated following KURAEV 85.
[3] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.

$\Upsilon(2S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ Γ_5

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.52 ±0.03 OUR ESTIMATE				
0.52 ±0.03 ±0.01	[4] ALBRECHT	95E	ARG	$e^+e^- \to$ hadrons

[4] Applying the formula of Kuraev and Fadin.

$\Upsilon(2S)$ BRANCHING RATIOS

$\Gamma(J/\psi(1S)\text{anything})/\Gamma_{total}$ Γ_8/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.006	90	MASCHMANN	90	CBAL	$e^+e^- \to$ hadrons

$\Gamma(\Upsilon(1S)\pi^+\pi^-)/\Gamma_{total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.185±0.008 OUR AVERAGE					
0.181±0.005±0.010	11.6k	ALBRECHT	87	ARG	$e^+e^- \to \pi^+\pi^-$ MM
0.169±0.040		GELPHMAN	85	CBAL	$e^+e^- \to e^+e^-\pi^+\pi^-$
0.191±0.012±0.006		BESSON	84	CLEO	$\pi^+\pi^-$ MM
0.189±0.026		FONSECA	84	CUSB	$e^+e^- \to \ell^+\ell^-\pi^+\pi^-$
0.21 ±0.07	7	NICZYPORUK	81B	LENA	$e^+e^- \to \ell^+\ell^-\pi^+\pi^-$

$\Gamma(\Upsilon(1S)\pi^0\pi^0)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.088±0.011 OUR AVERAGE					
0.095±0.019±0.019	25	ALBRECHT	87	ARG	$e^+e^- \to \pi^0\pi^0\ell^+\ell^-$
0.080±0.015		GELPHMAN	85	CBAL	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$
0.103±0.023		FONSECA	84	CUSB	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\tau^+\tau^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.017±0.015±0.006	HAAS	84B	CLEO	$e^+e^- \to \tau^+\tau^-$

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_4/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.0131±0.0021 OUR AVERAGE					
0.0122±0.0028±0.0019		[5] KOBEL	92	CBAL	$e^+e^- \to \mu^+\mu^-$
0.0138±0.0025±0.0015		KAARSBERG	89	CSB2	$e^+e^- \to \mu^+\mu^-$
0.009 ±0.006 ±0.006		[6] ALBRECHT	85	ARG	$e^+e^- \to \mu^+\mu^-$
0.018 ±0.008 ±0.005		HAAS	84B	CLEO	$e^+e^- \to \mu^+\mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.038	90	NICZYPORUK	81C	LENA	$e^+e^- \to \mu^+\mu^-$

[5] Taking into account interference between the resonance and continuum.

[6] Re-evaluated using $B(\Upsilon(1S) \to \mu^+\mu^-) = 0.026$.

$\Gamma(\Upsilon(1S)\pi^0)/\Gamma_{total}$ — Γ_6/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.008	90	LURZ	87	CBAL	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

$\Gamma(\Upsilon(1S)\eta)/\Gamma_{total}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.002	90	FONSECA	84	CUSB	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.005	90	ALBRECHT	87	ARG	$e^+e^- \to \pi^+\pi^-\ell^+\ell^-$ MM
<0.007	90	LURZ	87	CBAL	$e^+e^- \to \ell^+\ell^-(\gamma\gamma, 3\pi^0)$
<0.010	90	BESSON	84	CLEO	

$\Gamma(\gamma\chi_{b1}(1P))/\Gamma_{total}$ — Γ_9/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.067±0.009 OUR AVERAGE				
0.091±0.018±0.022	ALBRECHT	85E	ARG	$e^+e^- \to \gamma$conv. X
0.065±0.007±0.012	NERNST	85	CBAL	$e^+e^- \to \gamma X$
0.080±0.017±0.016	HAAS	84	CLEO	$e^+e^- \to \gamma$conv. X
0.059±0.014	KLOPFEN...	83	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b2}(1P))/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.066±0.009 OUR AVERAGE				
0.098±0.021±0.024	ALBRECHT	85E	ARG	$e^+e^- \to \gamma$conv. X
0.058±0.007±0.010	NERNST	85	CBAL	$e^+e^- \to \gamma X$
0.102±0.018±0.021	HAAS	84	CLEO	$e^+e^- \to \gamma$conv. X
0.061±0.014	KLOPFEN...	83	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma\chi_{b0}(1P))/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.043±0.010 OUR AVERAGE				
0.064±0.014±0.016	ALBRECHT	85E	ARG	$e^+e^- \to \gamma$conv. X
0.036±0.008±0.009	NERNST	85	CBAL	$e^+e^- \to \gamma X$
0.044±0.023±0.009	HAAS	84	CLEO	$e^+e^- \to \gamma$conv. X
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.035±0.014	KLOPFEN...	83	CUSB	$e^+e^- \to \gamma X$

$\Gamma(\gamma f_J(1710))/\Gamma_{total}$ — Γ_{12}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<59	90	[7] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma K^+K^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 5.9	90	[8] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma\pi^+\pi^-$

[7] Re-evaluated assuming $B(f_J(1710) \to K^+K^-) = 0.19$.

[8] Includes unknown branching ratio of $f_J(1710) \to \pi^+\pi^-$.

$\Gamma(\gamma f_2'(1525))/\Gamma_{total}$ — Γ_{13}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<53	90	[9] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma K^+K^-$

[9] Re-evaluated assuming $B(f_2'(1525) \to K\overline{K}) = 0.71$.

$\Gamma(\gamma f_2(1270))/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<24.1	90	[10] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma\pi^+\pi^-$

[10] Using $B(f_2(1270) \to \pi\pi) = 0.84$.

$\Gamma(\gamma f_J(2220))/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<6.8	90	[11] ALBRECHT	89	ARG	$\Upsilon(2S) \to \gamma K^+K^-$

[11] Includes unknown branching ratio of $f_J(2220) \to K^+K^-$.

$\Upsilon(2S)$ REFERENCES

BARU	96	PRPL 267 71	+Blinov, Blinov, Bondar+	(NOVO)
ALBRECHT	95E	ZPHY C65 619	+Hamacher+	(ARGUS Collab.)
KOBEL	92	ZPHY C53 193	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
MASCHMANN	90	ZPHY C46 555	+Antreasyan, Bartels, Besset+	(Crystal Ball Collab.)
ALBRECHT	89	ZPHY C42 349	+Boeckmann, Glaeser, Harder+	(ARGUS Collab.)
KAARSBERG	89	PRL 62 2077	+Heintz+	(CUSB Collab.)
BUCHMUEL...	88	HE e^+e^- Physics 412	Buchmueller, Cooper	(HANN, DESY, MIT)
		Editors: A. Ali and P. Soeding, World Scientific, Singapore		
JAKUBOWSKI	88	ZPHY C40 49	+Antreasyan, Bartels+	(Crystal Ball Collab.) IGJPC
ALBRECHT	87	ZPHY C35 283	+Binder, Boeckmann, Glaeser+	(ARGUS Collab.)
LURZ	87	ZPHY C36 383	+Antreasyan, Besset+	(Crystal Ball Collab.)
BARU	86B	ZPHY C32 622	+Blinov, Bondar, Bukin+	(NOVO)
ALBRECHT	85	ZPHY C28 45	+Dreschell, Heller+	(ARGUS Collab.)
ALBRECHT	85E	PL 160B 331	+Drescher, Heller+	(ARGUS Collab.)
GELPHMAN	85	PR D11 2893	+Lurz, Antreasyan+	(Crystal Ball Collab.)
KURAEV	85	SJNP 41 466	+Fadin	(NOVO)
		Translated from YAF 41 733.		
NERNST	85	PRL 54 2195	+Antreasyan, Aschman+	(Crystal Ball Collab.)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
BARBER	84	PL 135B 498	+	(DESY, ARGUS Collab., Crystal Ball Collab.)
BESSON	84	PR D30 1433	+Green, Hicks, Namjoshi, Sannes+	(CLEO Collab.)
FONSECA	84	NP B242 31	+Mageras, Son, Dietl, Eigen+	(CUSB Collab.)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
HAAS	84	PRL 52 799	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
HAAS	84B	PR D30 1996	+Jensen, Kagan, Kass, Behrends+	(CLEO Collab.)
KLOPFEN...	83	PRL 51 160	Klopfenstein, Horstkotte+	(CUSB Collab.)
TUTS	83	Cornell Conf. 284		(CUSB Collab.)
ALBRECHT	82	PL 116B 383	+Hofmann+	(DESY, DORT, HEIDH, LUND, ITEP)
NICZYPORUK	81B	PL 100B 95	+Chen, Folger, Lurz+	(LENA Collab.)
NICZYPORUK	81C	PL 99B 169	+Chen, Vogel, Wegener+	(LENA Collab.)
BOCK	80	ZPHY C6 125	+Blanar, Blum+	(HEIDP, MPIM, DESY, HAMB)

OTHER RELATED PAPERS

ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
COOPER	86	Berkeley Conf. 67		(MIT)
WALK	86	PR D34 2611	+Zschorsch+	(Crystal Ball Collab.)
ALBRECHT	84	PL 134B 137	+Drescher, Heller+	(ARGUS Collab.)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
ANDREWS	83	PRL 50 807	+Avery, Berkelman, Cassel+	(CLEO Collab.)
GREEN	82	PRL 49 617	+Sannes, Skubic, Snyder+	(CLEO Collab.)
BIENLEIN	78	PL 78B 360	+Glawe, Bock, Blanar+	(DESY, HAMB, HEIDP, MPIM)
DARDEN	78	PL 76B 246	+Hofmann, Schubert+	(DESY, DORT, HEIDH, LUND)
KAPLAN	78	PRL 40 435	+Appel, Herb, Hom+	(STON, FNAL, COLU)
YOH	78	PRL 41 684	+Herb, Hom, Lederman+	(COLU, FNAL, STON)
COBB	77	PL 72B 273	+Iwata, Fabjan+	(BNL, CERN, SYRA, YALE)
HERB	77	PRL 39 252	+Hom, Lederman, Appel, Ito+	(COLU, FNAL, STON)
INNES	77	PRL 39 1240	+Appel, Brown, Herb, Hom+	(COLU, FNAL, STON)

$\chi_{b0}(2P)$

$I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b0}(2P)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.2321±0.0006 OUR AVERAGE				
10.2312±0.0008±0.0012	[1] HEINTZ	92	CSB2	$e^+e^- \to \gamma X, \ell^+\ell^-\gamma\gamma$
10.2323±0.0007	[2] MORRISON	91	CLE2	$e^+e^- \to \gamma X$

[1] From the average photon energy for inclusive and exclusive events and assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. Supersedes HEINTZ 91 and NARAIN 91.

[2] From γ energy below assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. The error on the $\Upsilon(3S)$ mass is not included in the individual measurements. It is included in the final average.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
122.8±0.5 OUR AVERAGE Error includes scale factor of 1.1.					
123.0±0.8	4959	[3] HEINTZ	92	CSB2	$e^+e^- \to \gamma X$
124.6±1.4	17	[4] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
122.3±0.3±0.6	9903	MORRISON	91	CLE2	$e^+e^- \to \gamma X$

[3] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes NARAIN 91.

[4] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes HEINTZ 91.

$\chi_{b0}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\Upsilon(2S)$	(4.6±2.1) %
Γ_2	$\gamma\Upsilon(1S)$	(9 ±6) × 10^{-3}

$\chi_{b0}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\, \Upsilon(2S))/\Gamma_{total}$ — Γ_1/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.089	90	[5] CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
0.046±0.020±0.007		[6] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[5] Using $B(\Upsilon(2S) \to \mu^+\mu^-) = (1.37 \pm 0.26)\%$, $B(\Upsilon(3S) \to \gamma\gamma\,\Upsilon(2S))\times 2\,B(\Upsilon(2S) \to \mu^+\mu^-) < 1.19 \times 10^{-4}$, and $B(\Upsilon(3S) \to \chi_{b0}(2P)\gamma) = 0.049$.

[6] Using $B(\Upsilon(2S) \to \mu^+\mu^-) = (1.44 \pm 0.10)\%$, $B(\Upsilon(3S) \to \gamma\chi_{b0}(2P)) = (6.0 \pm 0.4 \pm 0.6)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\Gamma(\gamma\, \Upsilon(1S))/\Gamma_{total}$ — Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.025	90	[7] CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
0.009±0.006±0.001		[8] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[7] Using $B(\Upsilon(1S) \to \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \to \gamma\gamma\,\Upsilon(1S))\times 2\,B(\Upsilon(1S) \to \mu^+\mu^-) < 0.63 \times 10^{-4}$, and $B(\Upsilon(3S) \to \chi_{b0}(2P)\gamma) = 0.049$.

[8] Using $B(\Upsilon(1S) \to \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \to \gamma\chi_{b0}(2P)) = (6.0 \pm 0.4 \pm 0.6)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\chi_{b0}(2P)$ REFERENCES

CRAWFORD	92B	PL B294 139	+Fulton	(CLEO Collab.)
HEINTZ	92	PR D46 1928	+Lee, Franzini+	(CUSB II Collab.)
HEINTZ	91	PRL 66 1563	+Kaarsberg+	(CUSB Collab.)
MORRISON	91	PRL 67 1696	+Schmidt+	(CLEO Collab.)
NARAIN	91	PRL 66 3113	+Lovelock+	(CUSB Collab.)

OTHER RELATED PAPERS

TUTS	83	Cornell Conf. 284		(CUSB Collab.)
EIGEN	82	PRL 49 1616	+Bohringer, Herb+	(CUSB Collab.)
HAN	82	PRL 49 1612	+Horstkotte, Imlay+	(CUSB Collab.)

$\chi_{b1}(2P)$

$I^G(J^{PC}) = 0^+(1^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b1}(2P)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.2552±0.0005 OUR AVERAGE				
10.2547±0.0004±0.0010	[1] HEINTZ	92	CSB2	$e^+e^- \to \gamma X, \ell^+\ell^-\gamma\gamma$
10.2553±0.0005	[2] MORRISON	91	CLE2	$e^+e^- \to \gamma X$

[1] From the average photon energy for inclusive and exclusive events and assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. Supersedes HEINTZ 91 and NARAIN 91.

[2] From γ energy below assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. The error on the $\Upsilon(3S)$ mass is not included in the individual measurements. It is included in the final evaluation.

$m_{\chi_{b1}(2P)} - m_{\chi_{b0}(2P)}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
23.5±0.7±0.7	[3] HEINTZ	92	CSB2	$e^+e^- \to \gamma X, \ell^+\ell^-\gamma\gamma$

[3] From the average photon energy for inclusive and exclusive events. Supersedes NARAIN 91.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
99.90±0.26 OUR AVERAGE					
99 ±1	169	CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
100.1 ±0.4	11147	[4] HEINTZ	92	CSB2	$e^+e^- \to \gamma X$
100.2 ±0.5	223	[5] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
99.5 ±0.1 ±0.5	25759	MORRISON	91	CLE2	$e^+e^- \to \gamma X$

[4] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes NARAIN 91.

[5] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes HEINTZ 91.

$\chi_{b1}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	$\gamma\,\Upsilon(2S)$	(21 ±4) %	1.5
Γ_2	$\gamma\,\Upsilon(1S)$	(8.5±1.3) %	1.3

$\chi_{b1}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\, \Upsilon(2S))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.21 ±0.04 OUR AVERAGE	Error includes scale factor of 1.5.			
0.356±0.042±0.092	[6] CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
0.199±0.020±0.022	[7] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[6] Using $B(\Upsilon(2S) \to \mu^+\mu^-) = (1.37 \pm 0.26)\%$, $B(\Upsilon(3S) \to \gamma\gamma\,\Upsilon(2S))\times 2\,B(\Upsilon(2S) \to \mu^+\mu^-) = (10.23 \pm 1.20 \pm 1.26)\times 10^{-4}$, and $B(\Upsilon(3S) \to \gamma\chi_{b1}(2P)) = 0.105^{+0.003}_{-0.002} \pm 0.013$.

[7] Using $B(\Upsilon(2S) \to \mu^+\mu^-) = (1.44 \pm 0.10)\%$, $B(\Upsilon(3S) \to \gamma\chi_{b1}(2P)) = (11.5 \pm 0.5 \pm 0.5)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\Gamma(\gamma\, \Upsilon(1S))/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.085±0.013 OUR AVERAGE	Error includes scale factor of 1.3.			
0.120±0.021±0.021	[8] CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
0.080±0.009±0.007	[9] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[8] Using $B(\Upsilon(1S) \to \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \to \gamma\gamma\,\Upsilon(1S))\times 2\,B(\Upsilon(1S) \to \mu^+\mu^-) = (6.47 \pm 1.12 \pm 0.82)\times 10^{-4}$ and $B(\Upsilon(3S) \to \gamma\chi_{b1}(2P)) = 0.105^{+0.003}_{-0.002} \pm 0.013$.

[9] Using $B(\Upsilon(1S) \to \mu^+\mu^-) = (2.57 \pm 0.07)\%$, $B(\Upsilon(3S) \to \gamma\chi_{b1}(2P)) = (11.5 \pm 0.5 \pm 0.5)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\chi_{b1}(2P)$ REFERENCES

CRAWFORD	92B	PL B294 139	+Fulton	(CLEO Collab.)
HEINTZ	92	PR D46 1928	+Lee, Franzini+	(CUSB II Collab.)
HEINTZ	91	PRL 66 1563	+Kaarsberg+	(CUSB Collab.)
MORRISON	91	PRL 67 1696	+Schmidt+	(CLEO Collab.)
NARAIN	91	PRL 66 3113	+Lovelock+	(CUSB Collab.)

OTHER RELATED PAPERS

TUTS	83	Cornell Conf. 284		(CUSB Collab.)
EIGEN	82	PRL 49 1616	+Bohringer, Herb+	(CUSB Collab.)
HAN	82	PRL 49 1612	+Horstkotte, Imlay+	(CUSB Collab.)

$\chi_{b2}(2P)$

$I^G(J^{PC}) = 0^+(2^{++})$
J needs confirmation.

Observed in radiative decay of the $\Upsilon(3S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

$\chi_{b2}(2P)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.2685±0.0004 OUR AVERAGE				
10.2681±0.0004±0.0010	[1] HEINTZ	92	CSB2	$e^+e^- \to \gamma X, \ell^+\ell^-\gamma\gamma$
10.2685±0.0004	[2] MORRISON	91	CLE2	$e^+e^- \to \gamma X$

[1] From the average photon energy for inclusive and exclusive events and assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. Supersedes HEINTZ 91 and NARAIN 91.

[2] From γ energy below, assuming $\Upsilon(3S)$ mass = 10355.3 ± 0.5 MeV. The error on the $\Upsilon(3S)$ mass is not included in the individual measurements. It is included in the final average.

$m_{\chi_{b2}(2P)} - m_{\chi_{b1}(2P)}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
13.5±0.4±0.5	[3] HEINTZ	92	CSB2	$e^+e^- \to \gamma X, \ell^+\ell^-\gamma\gamma$

[3] From the average photon energy for inclusive and exclusive events. Supersedes NARAIN 91.

γ ENERGY IN $\Upsilon(3S)$ DECAY

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
86.64±0.23 OUR AVERAGE					
86 ±1	101	CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
86.7 ±0.4	10319	[4] HEINTZ	92	CSB2	$e^+e^- \to \gamma X$
86.9 ±0.4	157	[5] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
86.4 ±0.1 ±0.4	30741	MORRISON	91	CLE2	$e^+e^- \to \gamma X$

[4] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes NARAIN 91.

[5] A systematic uncertainty on the energy scale of 0.9% not included. Supersedes HEINTZ 91.

$\chi_{b2}(2P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\,\Upsilon(2S)$	(16.2±2.4) %
Γ_2	$\gamma\,\Upsilon(1S)$	(7.1±1.0) %

$\chi_{b2}(2P)$ BRANCHING RATIOS

$\Gamma(\gamma\,\Upsilon(2S))/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.162±0.024 OUR AVERAGE				
0.135±0.025±0.035	[6] CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
0.173±0.021±0.019	[7] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[6] Using B($\Upsilon(2S) \to \mu^+\mu^-$) = (1.37 ± 0.26)%, B($\Upsilon(3S) \to \gamma\gamma\,\Upsilon(2S)$)×2 B($\Upsilon(2S) \to \mu^+\mu^-$) = (4.98 ± 0.94 ± 0.62)×10^{-4}, and B($\Upsilon(3S) \to \gamma\chi_{b2}(2P)$) = 0.135 ± 0.003 ± 0.017.

[7] Using B($\Upsilon(2S) \to \mu^+\mu^-$) = (1.44 ± 0.10)%, B($\Upsilon(3S) \to \gamma\chi_{b2}(2P)$) = (11.1 ± 0.5 ± 0.4)% and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\Gamma(\gamma\,\Upsilon(1S))/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.071±0.010 OUR AVERAGE				
0.072±0.014±0.013	[8] CRAWFORD	92B	CLE2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$
0.070±0.010±0.006	[9] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\gamma\gamma$

[8] Using B($\Upsilon(1S) \to \mu^+\mu^-$) = (2.57 ± 0.07)%, B($\Upsilon(3S) \to \gamma\gamma\,\Upsilon(2S)$)×2 B($\Upsilon(1S) \to \mu^+\mu^-$) = (5.03 ± 0.94 ± 0.63)×10^{-4}, and B($\Upsilon(3S) \to \gamma\chi_{b2}(2P)$) = 0.135 ± 0.003 ± 0.017.

[9] Using B($\Upsilon(1S) \to \mu^+\mu^-$) = (2.57 ± 0.07)%, B($\Upsilon(3S) \to \gamma\chi_{b2}(2P)$) = (11.1 ± 0.5 ± 0.4)% and assuming $e\mu$ universality. Supersedes HEINTZ 91.

$\chi_{b2}(2P)$ REFERENCES

CRAWFORD	92B	PL B294 139	+Fulton	(CLEO Collab.)
HEINTZ	92	PR D46 1928	+Lee, Franzini+	(CUSB II Collab.)
HEINTZ	91	PRL 66 1563	+Kaarsberg+	(CUSB Collab.)
MORRISON	91	PRL 67 1696	+Schmidt+	(CLEO Collab.)
NARAIN	91	PRL 66 3113	+Lovelock+	(CUSB Collab.)

OTHER RELATED PAPERS

TUTS	83	Cornell Conf. 284		(CUSB Collab.)
EIGEN	82	PRL 49 1616	+Bohringer, Herb+	(CUSB Collab.)
HAN	82	PRL 49 1612	+Horstkotte, Imlay+	(CUSB Collab.)

$\Upsilon(3S)$

$I^G(J^{PC}) = 0^-(1^{--})$

$\Upsilon(3S)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.3553±0.0005	[1] BARU	86B	REDE	$e^+e^- \to$ hadrons

[1] Reanalysis of ARTAMONOV 84.

$\Upsilon(3S)$ WIDTH

VALUE (keV)	DOCUMENT ID
26.3±3.5 OUR EVALUATION	See Υ mini-review.

$\Upsilon(3S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor
Γ_1	$\Upsilon(2S)$anything	(10.6 ±0.8) %	
Γ_2	$\Upsilon(2S)\pi^+\pi^-$	(2.8 ±0.6) %	2.2
Γ_3	$\Upsilon(2S)\pi^0\pi^0$	(2.00±0.32) %	
Γ_4	$\Upsilon(2S)\gamma\gamma$	(5.0 ±0.7) %	
Γ_5	$\Upsilon(1S)\pi^+\pi^-$	(4.48±0.21) %	
Γ_6	$\Upsilon(1S)\pi^0\pi^0$	(2.06±0.28) %	
Γ_7	$\Upsilon(1S)\eta$		
Γ_8	$\mu^+\mu^-$	(1.81±0.17) %	
Γ_9	e^+e^-	seen	
	Radiative decays		
Γ_{10}	$\gamma\chi_{b2}(2P)$	(11.4 ±0.8) %	1.3
Γ_{11}	$\gamma\chi_{b1}(2P)$	(11.3 ±0.6) %	
Γ_{12}	$\gamma\chi_{b0}(2P)$	(5.4 ±0.6) %	1.1

$\Upsilon(3S)$ $\Gamma(i)\Gamma(e^+e^-)/\Gamma(\text{total})$

$\Gamma(\text{hadrons}) \times \Gamma(e^+e^-)/\Gamma_{total}$ — $\Gamma_0\Gamma_9/\Gamma$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.45±0.03±0.03	[2] GILES	84B	CLEO	$e^+e^- \to$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.39±0.02±0.03	[2] TUTS	83	CUSB	$e^+e^- \to$ hadrons

[2] Radiative corrections reevaluated by BUCHMUELLER 88 following KURAEV 85.

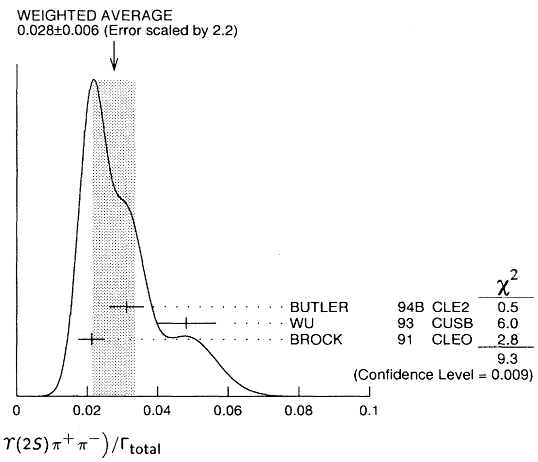
$\Upsilon(3S)$ BRANCHING RATIOS

$\Gamma(\Upsilon(2S)\text{anything})/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.106 ±0.008 OUR AVERAGE					
0.1023±0.0105	4625	[3,4,5] BUTLER	94B	CLE2	$e^+e^- \to \ell^+\ell^- X$
0.111 ±0.012	4891	[4,5,6] BROCK	91	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$

$\Gamma(\Upsilon(2S)\pi^+\pi^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.028 ±0.006 OUR AVERAGE Error includes scale factor of 2.2. See the ideogram below.					
0.0312±0.0049	980	[3,7] BUTLER	94B	CLE2	$e^+e^- \to \pi^+\pi^-\ell^+\ell^-$
0.0482±0.0065±0.0053	138	[6] WU	93	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
0.0213±0.0038	974	[6] BROCK	91	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.031 ±0.020	5	MAGERAS	82	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$



$\Gamma(\Upsilon(2S)\pi^0\pi^0)/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0200±0.0032 OUR AVERAGE					
0.0216±0.0039		[7,8] BUTLER	94B	CLE2	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$
0.017 ±0.005 ±0.002	10	[9] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\Upsilon(2S)\gamma\gamma)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0502±0.0069	[7] BUTLER	94B	CLE2	$e^+e^- \to \ell^+\ell^- 2\gamma$

$\Gamma(\Upsilon(1S)\pi^+\pi^-)/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0448±0.0021 OUR AVERAGE					
0.0452±0.0035	11830	[4] BUTLER	94B	CLE2	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
0.0446±0.0034±0.0050	451	[4] WU	93	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
0.0446±0.0030	11221	[4] BROCK	91	CLEO	$e^+e^- \to \pi^+\pi^- X$, $\pi^+\pi^-\ell^+\ell^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.049 ±0.010	22	GREEN	82	CLEO	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$
0.039 ±0.013	26	MAGERAS	82	CUSB	$\Upsilon(3S) \to \pi^+\pi^-\ell^+\ell^-$

$\Gamma(\Upsilon(1S)\pi^0\pi^0)/\Gamma_{total}$ — Γ_6/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0206±0.0028 OUR AVERAGE					
0.0199±0.0034	56	[4] BUTLER	94B	CLE2	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$
0.022 ±0.004 ±0.003	33	[10] HEINTZ	92	CSB2	$e^+e^- \to \ell^+\ell^-\pi^0\pi^0$

$\Gamma(\Upsilon(1S)\eta)/\Gamma_{total}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0022	90	BROCK	91	CLEO	$e^+e^- \to \pi^+\pi^-\pi^0\ell^+\ell^-$

$\Gamma(\mu^+\mu^-)/\Gamma_{total}$ — Γ_8/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0181±0.0017 OUR AVERAGE					
0.0202±0.0019±0.0033		CHEN	89B	CLEO	$e^+e^- \rightarrow \mu^+\mu^-$
0.0173±0.0015±0.0011		KAARSBERG	89	CSB2	$e^+e^- \rightarrow \mu^+\mu^-$
0.033 ±0.013 ±0.007	1096	ANDREWS	83	CLEO	$e^+e^- \rightarrow \mu^+\mu^-$

$\Gamma(\gamma\chi_{b2}(2P))/\Gamma_{total}$ — Γ_{10}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.114±0.008 OUR AVERAGE	Error includes scale factor of 1.3.				
0.111±0.005±0.004	10319	[11] HEINTZ	92	CSB2	$e^+e^- \rightarrow \gamma$
0.135±0.003±0.017	30741	MORRISON	91	CLE2	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\chi_{b1}(2P))/\Gamma_{total}$ — Γ_{11}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.113±0.006 OUR AVERAGE					
0.115±0.005±0.005	11147	[11] HEINTZ	92	CSB2	$e^+e^- \rightarrow \gamma$
$0.105^{+0.003}_{-0.002}\pm0.013$	25759	MORRISON	91	CLE2	$e^+e^- \rightarrow \gamma X$

$\Gamma(\gamma\chi_{b0}(2P))/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.054±0.006 OUR AVERAGE	Error includes scale factor of 1.1.				
0.060±0.004±0.006	4959	[11] HEINTZ	92	CSB2	$e^+e^- \rightarrow \gamma$
$0.049^{+0.003}_{-0.004}\pm0.006$	9903	MORRISON	91	CLE2	$e^+e^- \rightarrow \gamma X$

[3] Using $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\gamma\gamma) = (0.038 \pm 0.007)\%$, and $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^0\pi^0) = (1/2)B(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-)$.
[4] Using $B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (2.48 \pm 0.06)\%$. With the assumption of $e\mu$ universality.
[5] Using $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-) = (18.5 \pm 0.8)\%$.
[6] Using $B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (1.31 \pm 0.21)\%$, $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\gamma\gamma)\times 2B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (0.188 \pm 0.035)\%$, and $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^0\pi^0)\times 2B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (0.436 \pm 0.056)\%$. With the assumption of $e\mu$ universality.
[7] From the exclusive mode.
[8] $B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (1.31 \pm 0.21)\%$ and assuming $e\mu$ universality.
[9] $B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (1.44 \pm 0.10)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.
[10] Using $B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = (2.57 \pm 0.07)\%$ and assuming $e\mu$ universality. Supersedes HEINTZ 91.
[11] Supersedes NARAIN 91.

$\Upsilon(3S)$ REFERENCES

BUTLER	94B	PR D49 40	+Fu, Kalbfleisch, Lambrecht+	(CLEO Collab.)
WU	93	PL B301 307	+Franzini, Kanekal+	(CUSB Collab.)
HEINTZ	92	PR D46 1928	+Lee, Franzini+	(CUSB II Collab.)
BROCK	91	PR D43 1448	+Ferguson+	(CLEO Collab.)
HEINTZ	91	PRL 66 1563	+Kaarsberg+	(CUSB Collab.)
MORRISON	91	PRL 67 1696	+Schmidt+	(CLEO Collab.)
NARAIN	91	PRL 66 3113	+Lovelock+	(CUSB Collab.)
CHEN	89B	PR D39 3528	+McIlwain, Miller+	(CLEO Collab.)
KAARSBERG	89	PRL 62 2077	+Heintz+	(CUSB Collab.)
BUCHMUEL...	88	HE e^+e^- Physics 412	Buchmueller, Cooper	(HANN, DESY, MIT)
		Editors: A. Ali and P. Soeding, World Scientific, Singapore		
BARU	86B	ZPHY C32 622	+Blinov, Bondar, Bukin+	(NOVO)
KURAEV	85	SJNP 41 466	+Fadin	(NOVO)
		Translated from YAF 41 733.		
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
ANDREWS	83	PRL 50 807	+Avery, Berkelman, Cassel+	(CLEO Collab.)
TUTS	83	Cornell Conf. 284		(CUSB Collab.)
GREEN	82	PRL 49 617	+Sannes, Skubic, Snyder+	(CLEO Collab.)
MAGERAS	82	PL 118B 453	+Herb, Imlay+	(COLU, CORN, LSU, MPIM, STON)

OTHER RELATED PAPERS

ALEXANDER	89	NP B320 45	+Bonvicini, Drell, Frey, Luth	(LBL, MICH, SLAC)
ARTAMONOV	84	PL 137B 272	+Baru, Blinov, Bondar+	(NOVO)
GILES	84B	PR D29 1285	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
HAN	82	PRL 49 1612	+Horstkotte, Imlay+	(CUSB Collab.)
PETERSON	82	PL 114B 277	+Giannini, Lee-Franzini+	(CUSB Collab.)
KAPLAN	78	PRL 40 435	+Appel, Herb, Hom+	(STON, FNAL, COLU)
YOH	78	PRL 41 684	+Herb, Hom, Lederman+	(COLU, FNAL, STON)
COBB	77	PL 72B 273	+Iwata, Fabjan+	(BNL, CERN, SYRA, YALE)
HERB	77	PRL 39 252	+Hom, Lederman, Appel, Ito+	(COLU, FNAL, STON)
INNES	77	PRL 39 1240	+Appel, Brown, Herb, Hom+	(COLU, FNAL, STON)

$\Upsilon(4S)$ or $\Upsilon(10580)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(4S)$ MASS

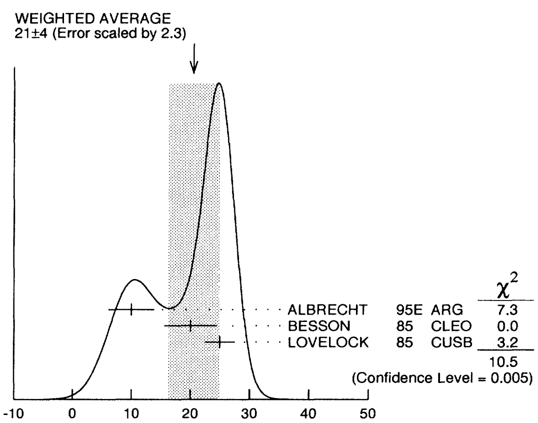
VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.5800±0.0035	[1] BEBEK	87	CLEO	$e^+e^- \rightarrow$ hadrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
10.5774±0.0010	[2] LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

[1] Reanalysis of BESSON 85.
[2] No systematic error given.

$\Upsilon(4S)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
21 ±4 OUR AVERAGE	Error includes scale factor of 2.3. See the ideogram below.			
10.0±2.8±2.7	[3] ALBRECHT	95E	ARG	$e^+e^- \rightarrow$ hadrons
20 ±2 ±4	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
25 ±2.5	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

[3] Using LEYAOUANC 77 parametrization of $\Gamma(s)$.



$\Upsilon(4S)$ width (MeV)

$\Upsilon(4S)$ DECAY MODES

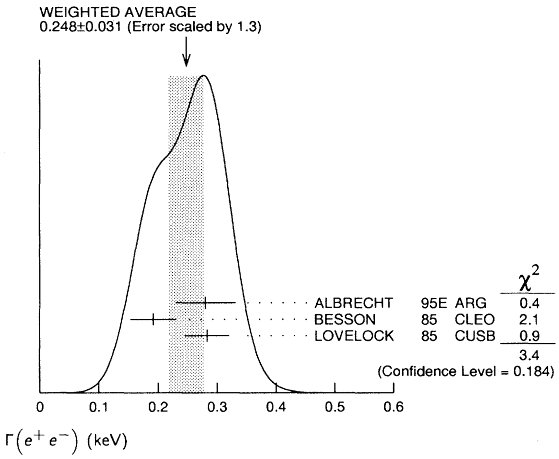
	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$B\overline{B}$	dominant	
Γ_2	e^+e^-	$(2.8\pm0.7)\times10^{-5}$	
Γ_3	$J/\psi(3097)$ anything	$(2.2\pm0.7)\times10^{-3}$	
Γ_4	D^{*+} anything + c.c.	< 7.4 %	90%
Γ_5	ϕ anything	$< 2.3 \times10^{-3}$	90%
Γ_6	$\Upsilon(1S)$ anything	$< 4 \times10^{-3}$	90%
Γ_7	non-$B\overline{B}$	< 4 %	95%

$\Upsilon(4S)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_2

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.248±0.031 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.			
0.28 ±0.05 ±0.01	[4] ALBRECHT	95E	ARG	$e^+e^- \rightarrow$ hadrons
0.192±0.007±0.038	BESSON	85	CLEO	$e^+e^- \rightarrow$ hadrons
0.283±0.037	LOVELOCK	85	CUSB	$e^+e^- \rightarrow$ hadrons

[4] Using LEYAOUANC 77 parametrization of $\Gamma(s)$.



$\Upsilon(4S)$ BRANCHING RATIOS

$\Gamma(e^+e^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
2.77±0.50±0.49	[5] ALBRECHT	95E	ARG	$e^+e^- \to$ hadrons

[5] Using LEYAOUANC 77 parametrization of $\Gamma(s)$.

$\Gamma(J/\psi(3097)\,\text{anything})/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0022±0.0006±0.0004	ALEXANDER	90C	CLEO	e^+e^-

$[\Gamma(D^{*+}\,\text{anything}) + \Gamma(\text{c.c.})]/\Gamma_{total}$ — Γ_4/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.074	90	[6] ALEXANDER	90C	CLEO	e^+e^-

[6] For $x > 0.473$.

$\Gamma(\phi\,\text{anything})/\Gamma_{total}$ — Γ_5/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0023	90	[7] ALEXANDER	90C	CLEO	e^+e^-

[7] For $x > 0.52$.

$\Gamma(\Upsilon(1S)\,\text{anything})/\Gamma_{total}$ — Γ_6/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.004	90	ALEXANDER	90C	CLEO	e^+e^-

$\Gamma(\text{non-}B\overline{B})/\Gamma_{total}$ — Γ_7/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04	95	BARISH	96B	CLEO	e^+e^-

$\Upsilon(4S)$ REFERENCES

BARISH	96B	PRL 76 1570	+Chadha, Chan, et al	(CLEO Collab.)
ALBRECHT	95E	ZPHY C65 619	+Hamacher+	(ARGUS Collab.)
ALEXANDER	90C	PRL 64 2226	+Artuso+	(CLEO Collab.)
BEBEK	87	PR D36 1289	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
BESSON	85	PRL 54 381	+Green, Namjoshi, Sannes+	(CLEO Collab.)
LOVELOCK	85	PRL 54 377	+Horstkotte, Klopfenstein+	(CUSB Collab.)
LEYAOUANC	77	PL B71 397	+Oliver, Pene, Raynal	(ORSAY)

OTHER RELATED PAPERS

HENDERSON	92	PR D45 2212	+Kinoshita, Pipkin, Procario+	(CLEO Collab.)
ANDREWS	80B	PRL 45 219	+Berkelman, Cabenda, Cassel+	(CLEO Collab.)
FINOCCHI...	80	PRL 45 222	Finocchiaro, Giannini, Lee-Franzini+	(CUSB Collab.)

$\Upsilon(10860)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(10860)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
10.865±0.008 OUR AVERAGE	Error includes scale factor of 1.1.			
10.868±0.006±0.005	BESSON	85	CLEO	$e^+e^- \to$ hadrons
10.845±0.020	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(10860)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110±13 OUR AVERAGE				
112±17±23	BESSON	85	CLEO	$e^+e^- \to$ hadrons
110±15	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(10860)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(2.8\pm0.7)\times10^{-6}$

$\Upsilon(10860)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.31 ±0.07 OUR AVERAGE	Error includes scale factor of 1.3.			
0.22 ±0.05 ±0.07	BESSON	85	CLEO	$e^+e^- \to$ hadrons
0.365±0.070	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(10860)$ REFERENCES

BESSON	85	PRL 54 381	+Green, Namjoshi, Sannes+	(CLEO Collab.)
LOVELOCK	85	PRL 54 377	+Horstkotte, Klopfenstein+	(CUSB Collab.)

$\Upsilon(11020)$

$I^G(J^{PC}) = ?^?(1^{--})$

$\Upsilon(11020)$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
11.019±0.008 OUR AVERAGE				
11.019±0.005±0.007	BESSON	85	CLEO	$e^+e^- \to$ hadrons
11.020±0.030	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(11020)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
79±16 OUR AVERAGE				
61±13±22	BESSON	85	CLEO	$e^+e^- \to$ hadrons
90±20	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(11020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$(1.6\pm0.5)\times10^{-6}$

$\Upsilon(11020)$ PARTIAL WIDTHS

$\Gamma(e^+e^-)$ — Γ_1

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
0.130±0.030 OUR AVERAGE				
0.095±0.03 ±0.035	BESSON	85	CLEO	$e^+e^- \to$ hadrons
0.156±0.040	LOVELOCK	85	CUSB	$e^+e^- \to$ hadrons

$\Upsilon(11020)$ REFERENCES

BESSON	85	PRL 54 381	+Green, Namjoshi, Sannes+	(CLEO Collab.)
LOVELOCK	85	PRL 54 377	+Horstkotte, Klopfenstein+	(CUSB Collab.)

NON-$q\overline{q}$ CANDIDATES

We include here mini-reviews and reference lists on gluonium and other non-$q\overline{q}$ candidates. See also $N\overline{N}$(1100–3600) for possible bound states.

NON-$q\overline{q}$ MESONS

The existence of gluon self coupling in QCD suggests that gluonia (or glueballs) and hybrids ($q\overline{q}g$) might exist. Another possible kind of non-$q\overline{q}$ mesons is multiquark states. For detailed reviews, see HEUSCH 86, CLOSE 87, TOKI 88, and BURNETT 90. Among the signatures naively expected for glueballs are (i) no place in $q\overline{q}$ nonets, (ii) flavor-singlet couplings, (iii) enhanced production in gluon-rich channels such as $J/\psi(1S)$ decay, and (iv) reduced $\gamma\gamma$ coupling. However, mixing effects with $q\overline{q}$ states, and other dynamical effects such as form factors, may obscure these simple signatures. If mixing is large, only the finding of more states than are predicted by the $q\overline{q}$ quark model remains as a clear signal for non-exotic non-$q\overline{q}$ states.

Lattice gauge theory calculations in the quenched approximation (without quark loops) predict the lightest glueball to be a scalar with a mass of typically 1550±95 MeV (BALI 93). The same calculations find a tensor glueball mass of 2270±100 MeV, and glueballs with other spin-parities are predicted to be still heavier. A more recent lattice calculation (SEXTON 95) predicts a slightly higher mass, 1740 ± 71 MeV. Including dynamical quarks will, however, change the predicted masses.

Hybrid mesons are $q\overline{q}$ states combined with a gluonic excitation (BARNES 82, CHANOWITZ 83, ISGUR 85, CLOSE 95). Hybrids span flavor nonets, may have exotic (non-$q\overline{q}$) quantum numbers (a $J^{PC} = 1^{-+}$ state is expected in all models), and are predicted to have characteristic decay modes (LEYAOUANC 85, CLOSE 95). The masses of the lightest hybrids are typically predicted to be in the range 1500 to 2000 MeV. Charm hybrids ($c\overline{c}g$) are attractive experimentally since they may appear as supernumerary states in the predictable charmonium spectrum. The $\psi(4040)$ and $\psi(4160)$ are possibly mixtures of $c\overline{c}$ and $c\overline{c}g$ states (CLOSE 96).

The third class of non-$q\overline{q}$ states, the multiquark states, can be either baglike or clusters of mesons (VOLOSHIN 76, JAFFE 77, GUTBROD 79). A subclass of the latter are the deuteronlike meson-meson bound states, or deusons, where the long-range pion exchange is the major source of binding (TORNQVIST 91 and 94, ERICSON 93, MANOHAR 93). Many of the best non-$q\overline{q}$ candidates discussed below lie close to important thresholds, which suggests that they might be bound states of a meson pair. Examples include the $f_0(980)$ and $a_0(980)$ (close to the $K\overline{K}$ threshold), the $f_1(1420)$ (above the $K\overline{K}^*$ threshold, thus not a bound state but perhaps a threshold enhancement), the $f_0(1500)$ and $f_2(1520)$ ($\omega\omega$ and $\rho\rho$), the $f_J(1710)$ ($K^*\overline{K}^*$), and the $\psi(4040)$ ($D^*\overline{D}^*$). Many suggestions for such mesonium candidates, involving both light and heavy quarks and binding mechanisms, have appeared (WEINSTEIN 90, DOVER 91, BARNES 92, DOOLEY 92).

The candidates we discuss below are chosen because they are difficult to interpret as conventional $q\overline{q}$ states. We do not see it as our task to discuss theoretical interpretations of the candidates, but merely to catalogue the observations of possible relevance.

Scalar mesons: There are four known isoscalars with $J^{PC} = 0^{++}$: the $f_0(400\text{–}1200)$, a very broad structure around 800 MeV, the $f_0(980)$, the $f_0(1370)$, and the $f_0(1500)$; the spin of another established isoscalar, the $f_J(1710)$, may be 0 or 2. In the quark model, one expects two 1^3P_0 states and one 2^3P_0 ($u\overline{u} + d\overline{d}$)-like state below 1.8 GeV. Thus, there are too many scalars to find a place in the quark model.

However, for scalar resonances, naive quark model expectations, in particular ideal mixing, could be strongly broken by the opening of inelastic thresholds. Thus, the physical scalar $q\overline{q}$ spectrum may be very much distorted from naive expectations. For a detailed discussion of this sector, see our Note under the $f_0(1370)$.

In this edition, we have merged the $f_0(1590)$ observed in $\pi^- p$ interactions at high energies with the $f_0(1525)$ observed in $\overline{p}p$ annihilations, under the new name $f_0(1500)$. The $\pi\pi$ and $\eta\eta$ S-waves have a T-matrix pole at $m - i\Gamma/2 \sim 1500 - i60$ MeV, which corresponds to the physical mass and width (AMSLER 95B, AMSLER 95C), while a simple Breit-Wigner description gives a slightly higher mass and width (AMSLER 92, ALDE 88). For consistency, we average the mass and width determined by the T-matrix poles. A coupled-channel analysis taking unitarity constraints into account has been performed in $\overline{p}p$ (AMSLER 95D) but not in $\pi^- p$. Thus, we do not view the apparent discrepancies in the decay branching ratios to $\pi^0\pi^0$, $\eta\eta$, and $\eta\eta'$ between the $\overline{p}p$ and $\pi^- p$ experiments to be serious.

In the model of AMSLER 95E and AMSLER 96, the (nearly ideally mixed) ground state scalar $q\overline{q}$ nonet consists of the $a_0(1450)$, the $K_0^*(1430)$, the $f_0(1370)$, and the still missing isoscalar $s\overline{s}$ state, which cannot be the $f_0(1500)$ due to its comparatively narrow width and low $K\overline{K}$ decay branching ratio. The $f_0(1500)$ is interpreted as a scalar glueball mixed with the two nearby $q\overline{q}$ isoscalars.

The $f_J(1710)$ (whose spin is uncertain) has been seen mainly in the gluon-rich $J/\psi(1S)$ radiative decay, where it is copiously produced. Before 1991, the spin of the $f_J(1710)$ was believed to be 2, and the subsequent spin-0 determination in $J/\psi(1S)$ radiative decay (CHEN 91) has not been confirmed. In central production, the WA76 experiment (ARMSTRONG 89D) on 300 GeV/c pp interactions sees a structure at the same mass, but favors spin 2. The $f_J(1710)$ has not been seen in hadronic production ($K^- p \to K\overline{K}\Lambda$) (ASTON 88D), nor in $\gamma\gamma$ fusion. The ratio of the branching fractions in $J/\psi(1S) \to \omega f_J$ and $J/\psi(1S) \to \phi f_J$ suggests that nonstrange and strange components are both important in this state. Its mass and width are consistent with the prediction for the ground-state glueball, according to the most recent lattice gauge calculations (SEXTON 95), if one assumes that the spin is indeed zero.

Pseudoscalar mesons: The established isoscalars with $J^{PC} = 0^{-+}$ are the η, the $\eta'(958)$, the $\eta(1295)$, and the $\eta(1440)$ [which may be two pseudoscalar resonances, an $\eta(1410)$ and an $\eta(1490)$; see the Note under the $\eta(1440)$]. In the $q\overline{q}$ model, one expects two 1^1S_0 and two 2^1S_0 pseudoscalars between 500 and 1800 MeV.

Identifying the $\eta(1280)$ with the 2^1S_0 $(u\overline{u}+d\overline{d})$ state is natural, but it is more problematic to identify one of the two peaks in the $\eta(1440)$ region with the 2^1S_0 $s\overline{s}$ state. The $\eta(1440)$ is observed in $s\overline{s}$-depleted reactions like $\pi^-p \to \eta\pi\pi n$ (ANDO 86), $p\overline{p}$ annihilation (BAILLON 67, AMSLER 95F, BERTIN 95), and $\pi^-p \to a_0(980)\pi p$ (CHUNG 85, BIRMAN 88), and is not seen in the $s\overline{s}$-enriched channels like $K^-p \to K^*(892)\overline{K}\Lambda$ (ASTON 87). The fact that ANDO 86 sees the $\eta(1440)$ and $\eta(1280)$ with similar intensities argues that these states are of a similar nature, *e.g.*, radial excitations of the η and $\eta'(958)$. However, as there are suggestions that the $\eta(1440)$ is in fact two η's, the situation remains confused.

The $\pi(1770)$ (BERDNIKOV 94, AMELIN 95B) has a surprisingly narrow width (if interpreted as the second radial excitation of the π), a large coupling to $K\overline{K}$, and decays to a pair of mesons, one with $\ell(q\overline{q}) = 0$, the other with $\ell(q\overline{q}) = 1$. This is the signature expected for a hybrid meson (CLOSE 95).

Axial-vector mesons: The $q\overline{q}$ model predicts a nonet that includes two isoscalar 1^3P_1 states with masses below about 1.6 GeV. Three such 1^{++} states are known, the $f_1(1285)$, the $f_1(1420)$, and the $f_1(1530)$, which suggests that one of these is a non-$q\overline{q}$ meson. The $f_1(1420)$ is the most likely candidate: see CALDWELL 90 and the Note under the $f_1(1420)$. The proximity of the $K\overline{K}^*$ threshold suggests this may be a dominantly $K\overline{K}^*$ mesonium resonance or a threshold enhancement (LONGACRE 90, TORNQVIST 91).

Tensor mesons: The two 1^3P_2 $q\overline{q}$ states are very likely the well-known $f_2(1270)$ and $f_2'(1525)$. There are several other states, which have been suggested as $J^{PC} = 2^{++}$ non-$q\overline{q}$ candidates: the $f_2(1430)$, $f_2(1520)$, $f_J(1710)$, $f_2(1810)$, $f_2(2010)$, $f_2(2150)$, $f_2(2300)$, and $f_2(2340)$.

The $f_2(1520)$ is observed by the ASTERIX Collaboration (MAY 89) in $p\overline{p}$ P-wave annihilation in the $\pi^+\pi^-\pi^0$ channel and by the Crystal Barrel Collaboration (ANISOVICH 94, AMSLER 95B) in $3\pi^0$, close to the $\rho\rho$ and $\omega\omega$ thresholds. It has no place in a $q\overline{q}$ scheme, since all nearby $q\overline{q}$ states are already accounted for. Similarly, the $f_J(1710)$ could be composed of $K^*\overline{K}^*$ and $\omega\phi$ (DOOLEY 92), since it lies close to these thresholds.

Of the heavier states, the $f_2(1810)$ is likely to be the 2^3P_2, and among those above 2 GeV one expects the 2^3P_2 $s\overline{s}$, 1^3F_2 $s\overline{s}$, and 3^2P_2 $s\overline{s}$, but a gluonium interpretation of one of the four states is not excluded. These three f_2 resonances have been observed in the OZI-rule forbidden process $\pi p \to \phi\phi n$ (ETKIN 88), which has been claimed as favoring the gluonium interpretation.

A similar $\phi\phi$ mass spectrum is seen by ARMSTRONG 89B in the Ω spectrometer. The DM2 and MARK-III collaborations see threshold $\phi\phi$ production, but favor $J^P = 0^-$, not 2^+.

In $\gamma\gamma \to 4\pi$ near the $\rho\rho$ threshold, TASSO (BRANDELIK 80B, ALTHOFF 82), MARK2 (BURKE 81), CELLO (BEHREND 84E), PLUTO (BERGER 88B), SLAC TPC (AIHARA 88), and ARGUS (ALBRECHT 91F) observe a resonance-like structure. This is dominated by $\rho^0\rho^0$, and the cross section peaks a little above the $f_2(1520)$. This process has not been explained by models in which only conventional resonances dominate. The fact that the $\gamma\gamma \to \rho^+\rho^-$ is small (ALBRECHT 91F quotes 1/4 for the $\rho^+\rho^-/\rho^0\rho^0$ ratio) requires both isospin 0 and 2 for the $\rho\rho$ system. A resonance interpretation in terms of $q^2\overline{q}^2$ states thus requires the presence of a flavor exotic $I = 2$ resonance (ACHASOV 82, 87, 90). The 2^{++} partial wave is found to dominate the $\rho\rho$ structure (BERGER 88B, ALBRECHT 91F), with some 0^{++} at the low-energy end, while $J^P = 0^-$ and 2^- contribute very little.

In $\gamma\gamma \to \omega\rho$ and $\phi\rho$, there are also broad enhancements that peak near 1.7 GeV. The dominant partial wave is 2^{++} in $\omega\rho$, while 2^{-+} is favored in $\phi\rho$ (ALBRECHT 94Z).

Other exotic or non-$q\overline{q}$ candidates: An isovector $\phi\pi^0$ resonance at 1480 MeV has been reported by BITYUKOV 87 in $\pi^-p \to \phi\pi^0 n$ (listed under the $\rho(1450)$). Preliminary indications favor the nonexotic $J^{PC} = 1^{--}$, but the large OZI-rule violating branching ratio $\phi\pi$:$\omega\pi$ seems peculiar for a $(u\overline{u}$-$d\overline{d})$ $I = 1$ $q\overline{q}$ object. However, ACHASOV 88 shows that the threshold effect from the two-step process $\rho(1600) \to K\overline{K}^* \to \pi\phi$ can violate the rule, especially near threshold. No sign of this candidate is seen in $\pi\omega$ (FUKUI 91). In addition, the small coupling to the photon makes an identification with the $\rho(1450)$ difficult (CLEGG 88). More recently DONNACHIE 93, analyzing e^+e^--annihilation and diffractive-photoproduction data, suggests there may be 4-quark states near 1100 and 1300 MeV.

Another exotic candidate is the $\hat{\rho}(1405)$ (ALDE 88B, IDDIR 88), seen in the GAMS experiment under the $a_2(1320)$ in $\pi^-p \to \eta\pi^0 n$ with the exotic quantum numbers $J^{PC} = 1^{-+}$. The analysis of ALDE 88B has, however, been questioned by PROKOSHKIN 95B, 95C. Although the forward-backward asymmetry demands an $\eta\pi$ P-wave, it may be due to a nonresonant amplitude. The Crystal Barrel Collaboration has reported results on the corresponding P-wave in $\eta\pi$ seen in $p\overline{p} \to \eta\pi\pi$; they see a much broader effect, which can be explained as non-resonant or as a resonance with $\Gamma \approx 600$ MeV (AMSLER 94D). AOYAGI 93 also notes the $\eta\pi$ P-wave, but its interpretation is unclear.

Another possible 1^{-+} candidate is the isosinglet $X(1910)$ (ALDE 89), which seems to decay to $\eta\eta'$ but not to $\pi^0\pi^0$ or $\eta\eta$ (ALDE 89). An enhancement with quantum numbers 1^{-+}, decaying to $f_1(1285)$, has also been reported around 1900 MeV (LEE 94).

A narrow resonance, listed under the $K_J(3100)$, has been reported at about 3100 MeV (BOURQUIN 86, ALEEV 93) in several $\Lambda\overline{p}+$pions and $\overline{\Lambda}p+$pions states. The observation of the doubly-charged states $\Lambda\overline{p}\pi^-$ and $\overline{\Lambda}p\pi^+$ implies, assuming the decay is strong, $I = 3/2$, clearly not a $q\overline{q}$ state. In addition, a narrow peak is observed at about 3250 MeV, listed under the $X(3250)$, in the hidden strangeness combinations containing a baryon-antibaryon pair (ALEEV 93). However, all these observations need confirmation.

Non-$q\overline{q}$ Candidates

OMITTED FROM SUMMARY TABLE

NON-$q\overline{q}$ CANDIDATES REFERENCES

AMSLER 96 PR D53 295 +Close (ZURI, RAL)
CLOSE 96 PL B366 323 +Page (RAL)
AMELIN 95B PL B356 595 +Berdnikov, Bityukov+ (SERP, TBIL)
AMSLER 95B PL B342 433 +Armstrong, Brose+ (Crystal Barrel Collab.)
AMSLER 95C PL B353 571 +Armstrong, Hackman+ (Crystal Barrel Collab.)
AMSLER 95D PL B355 425 +Armstrong, Spanier+ (Crystal Barrel Collab.)
AMSLER 95E PL B353 385 +Close (ZURI, RAL)
AMSLER 95F PL B358 389 +Armstrong, Urner+ (Crystal Barrel Collab.)
BERTIN 95 PL B361 187 +Bruschi+ (OBELIX Collab.)
CLOSE 95 NP B443 233 +Page (RAL)
PROKOSHKIN 95B PAN 58 606 +Sadovski (SERP)
Translated from YAF 58 662.
PROKOSHKIN 95C PAN 58 853 +Sadovski (SERP)
Translated from YAF 58 921.
SEXTON 95 PRL 75 4563 +Vaccarino, Weingarten+ (IBM)
ALBRECHT 94Z PL B332 451 +Ehrlichmann+ (ARGUS Collab.)
AMSLER 94D PL B333 277 +Anisovich, Spanier+ (Crystal Barrel Collab.)
ANISOVICH 94 PL B323 233 +Armstrong+ (Crystal Barrel Collab.)
BERDNIKOV 94 PL B337 219 +Bityukov+ (SERP, TBIL)
LEE 94 PL B323 227 +Chung, Kirk+ (BNL, IND, KYUN, MASD, RICE)
TORNQVIST 94 ZPHY C61 525 Tornquist (HELS)
ALEEV 93 PAN 56 1358 +Balandin+ (BIS-2 Collab.)
Translated from YAF 56 100.
AOYAGI 93 PL B314 246 +Fukui, Hasegawa+ (BKEI Collab.)
BALI 93 PL B309 378 +Schilling, Hulsebo, Irving, Michael+ (LIVP)
DONNACHIE 93 ZP C60 187 +Kalashnikova, Clegg (BNL)
ERICSON 93 PL B309 426 +Karl (CERN)
MANOHAR 93 NP B399 17 +Wise (MIT)
AMSLER 92 PL B291 347 +Augustin, Baker+ (Crystal Barrel Collab.)
BARNES 92 PR D46 131 +Swanson (ORNL)
DOOLEY 92 PL B275 478 +Swanson, Barnes (ORNL)
ALBRECHT 91F ZPHY C50 1 +Appuan, Paulini, Funk+ (ARGUS Collab.)
CHEN 91 Hadron 91 Conf. (Mark III Collab.)
SLAC-PUB-5669
DOVER 91 PR C43 379 +Gutsche, Faessler (BNL)
FUKUI 91 PL B257 241 +Horikawa+ (SUGI, NAGO, KEK, KYOT, MIYA)
TORNQVIST 91 PRL 67 556 (HELS)
ACHASOV 90 TF 20 (178) +Shestakov (NOVM)
BREAKSTONE 90 ZPHY C48 569 + (ISU, BGNA, CERN, DORT, HEIDH, WARS)
BURNETT 90 ARNPS 46 332 +Sharpe (RAL)
CALDWELL 90 Hadron 89 Conf. p 127 (UCSB)
LONGACRE 90 PR D42 874 (BNL)
WEINSTEIN 90 PR D41 2236 +Isgur (TNTO)
ALDE 89 PL B216 447 +Binon, Bricman, Donskov+ (SERP, BELG, LANL, LAPP)
ARMSTRONG 89B PL B221 221 +Benayoun+(CERN, CDEF, BIRM, BARI, ATHU, CURIN+)
ARMSTRONG 89D PL B227 186 +Benayoun (ATHU, BARI, BIRM, CERN, CDEF)
MAY 89 PL B225 450 +Duch, Heel+ (ASTERIX Collab.)
ACHASOV 88 PL B207 199 +Kozhevnikov (NOVM)
AIHARA 88 PR D37 28 +Alston, Avery, Barbaro-Galtieri+ (TPC-2γ Collab.)
ALDE 88 PL B201 160 +Bellazzini, Binon+ (SERP, BELG, LANL, LAPP, PISA)
ALDE 88B PL B205 397 +Binon, Boutemeur+ (SERP, BELG, LANL, LAPP)
ASTON 88D NP B301 525 +Awaji, Bienz+ (SLAC, NAGO, CINC, INUS)
BERGER 88B ZPHY C38 521 +Klovning, Burger+ (PLUTO Collab.)
BIRMAN 88 PRL 61 1557 +Chung, Peaslee+ (BNL, FSU, IND, MASD)
CLEGG 88 ZPHY C40 313 +Donnachie (MCHS, LANC)
ETKIN 88 PL B201 568 +Foley, Lindenbaum+ (BNL, CUNY)
IDDIR 88 PL B205 564 +Le Yaouanc, Ono+ (ORSAY, TOKY)
TOKI 88 AIP Conf. (SLAC)
ACHASOV 87 ZPHY C36 161 +Karnakov, Shestakov (NOVM)
ASTON 87 NP B292 693 +Awaji, D'Amore+ (SLAC, NAGO, CINC, INUS)
BITYUKOV 87 PL B188 383 +Dzhelyadin, Dorofeev, Golovkin+ (SERP)
CLOSE 87 RPP 51 833 (RHEL)
ANDO 86 PRL 57 1296 +Imai+ (KEK, KYOT, NIRS, SAGA, INUS, TSUK+)
BOURQUIN 86 PL B172 113 +Brown+ (GEVA, RAL, HEIDP, LAUS, BRIS, CERN)
HEUSCH 86 Seewinkel Symposium on Multiparticle Dynamics (SLAC)
CHUNG 85 PRL 55 779 +Fernow, Boehnlein+ (BNL, FLOR, IND, MASD)
ISGUR 85 PRL 54 869 +Kokorski, Patou (TNTO)
LEYAOUANC 85 ZPHY C28 309 +Olivek, Pene, Raynal, Ono (ORSAY)
BEHREND 84E ZPHY C21 205 +Achenberg, Deboer+ (CELLO Collab.)
BINON 83 NC 78A 313 +Donskov, Duteil+ (BELG, LAPP, SERP, CERN)
WEINSTEIN 83B PR D27 588 +Isgur (TNTO)
AIHARA 82 PR D37 28 +Alston, Avery, Barbaro-Galtieri+ (TPC Collab.)
ALTHOFF 82 ZPHY C16 13 +Boerner, Burkhardt+ (TASSO Collab.)
BARNES 82 PL B116 365 +Close (RHEL)
BURKE 81 PL B103 153 +Abrams, Alam, BLocher+ (Mark II Collab.)
BRANDELIK 80B PL B97 448 +Boerner, Burkhard+ (TASSO Collab.)
GUTBROD 79 ZP C1 391 +Kramer, Rumpf (DESY)
JAFFE 77 PR D15 267,281 (MIT)
VOLOSHIN 76 JETPL 23 333 +Okun (ITEP)
Translated from ZETFP 23 369.
BAILLON 67 NC 50A 393 +Edwards, D'Andlau, Astier+ (CERN, CDEF, IRAD)

ACHASOV 82 PL B108 134 +Devyanin, Shestakov (NOVM)

Notes in the Baryon Listings

N BARYONS
($S = 0$, $I = 1/2$)

p, $N^+ = uud$; n, $N^0 = udd$

p

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

p MASS

The mass is known much more precisely in u (atomic mass units) than in MeV; see the footnote. The conversion from u to MeV, 1 u = 931.49432±0.00028 MeV, involves the relatively poorly known electronic charge.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
938.27231±0.00028	[1] COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
938.2796 ±0.0027	COHEN	73	RVUE	1973 CODATA value

[1] The mass is known much more precisely in u: $m = 1.007276470 \pm 0.000000012$ u.

$\overline{p}$ MASS

See, however, the next entry in the Listings, which establishes the $\overline{p}$ mass much more precisely.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
938.30 ±0.13	ROBERTS	78	CNTR	
938.229±0.049	ROBERSON	77	CNTR	
938.179±0.058	HU	75	CNTR	Exotic atoms
938.3 ±0.5	BAMBERGER	70	CNTR	

$\overline{p}/p$ CHARGE-TO-MASS RATIO, $|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p})$

A test of *CPT* invariance. Listed here are measurements involving the *inertial* masses. For a discussion of what may be inferred about the ratio of $\overline{p}$ and p *gravitational* masses, see ERICSON 90; they obtain an upper bound of 10^{-6}–10^{-7} for violation of the equivalence principle for $\overline{p}$'s.

VALUE	DOCUMENT ID		TECN	COMMENT
1.0000000015±0.0000000011	[2] GABRIELSE	95	TRAP	Penning trap
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.000000023 ±0.000000042	[3] GABRIELSE	90	TRAP	Penning trap

[2] Equation (2) of GABRIELSE 95 should read $M(\overline{p})/M(p) = 0.999\,999\,9985(11)$ (G. Gabrielse, private communication).

[3] GABRIELSE 90 also measures $m_{\overline{p}}/m_{e^-} = 1836.152660 \pm 0.000083$ and $m_p/m_{e^-} = 1836.152680 \pm 0.000088$. Both are completely consistent with the 1986 CODATA (COHEN 87) value for m_p/m_{e^-} of 1836.152701 ± 0.000037. We use the CODATA values of the masses (they come from an overall fit to a variety of data on the fundamental constants) and don't try to take into account more recent measurements involving the masses.

$(|\frac{q_{\overline{p}}}{m_{\overline{p}}}| - \frac{q_p}{m_p})/|\frac{q}{m}|_{\text{average}}$

A test of *CPT* invariance. Taken from the $\overline{p}/p$ charge-to-mass ratio, above.

VALUE	DOCUMENT ID
(1.5±1.1) × 10^{-9} OUR EVALUATION	

$|q_p + q_{\overline{p}}|/e$

A test of *CPT* invariance. Note that the $\overline{p}/p$ charge-to-mass ratio, given above, is much better determined. See also a similar test involving the electron.

VALUE	DOCUMENT ID		TECN
<2 × 10^{-5}	[4] HUGHES	92	RVUE

[4] HUGHES 92 uses recent measurements of Rydberg-energy and cyclotron-frequency ratios.

$|q_p + q_e|/e$

See DYLLA 73 for a summary of experiments on the neutrality of matter. See also "n CHARGE" in the neutron Listings.

VALUE	DOCUMENT ID		COMMENT
<1.0 × 10^{-21}	[5] DYLLA	73	Neutrality of SF_6
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.8 × 10^{-21}	MARINELLI	84	Magnetic levitation

[5] Assumes that $q_n = q_p + q_e$.

p MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
2.792847386±0.000000063	COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.7928456 ±0.0000011	COHEN	73	RVUE	1973 CODATA value

$\overline{p}$ MAGNETIC MOMENT

A few early results have been omitted.

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
−2.800 ±0.008 OUR AVERAGE				
−2.8005±0.0090	KREISSL	88	CNTR	$\overline{p}$ ^{208}Pb 11→ 10 X-ray
−2.817 ±0.048	ROBERTS	78	CNTR	
−2.791 ±0.021	HU	75	CNTR	Exotic atoms

$(\mu_p - |\mu_{\overline{p}}|)$ / $|\mu_{\text{average}}|$

A test of *CPT* invariance. Calculated from the p and $\overline{p}$ magnetic moments, above.

VALUE	DOCUMENT ID
(−2.6±2.9) × 10^{-3} OUR EVALUATION	

p ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both T invariance and P invariance.

VALUE (10^{-23} ecm)	EVTS	DOCUMENT ID		TECN	COMMENT
− 3.7± 6.3		CHO	89	NMR	Tl F molecules
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 400		DZUBA	85	THEO	Uses ^{129}Xe moment
130 ± 200		[6] WILKENING	84		
900 ±1400		[7] WILKENING	84		
700 ± 900	1G	HARRISON	69	MBR	Molecular beam

[6] This WILKENING 84 value includes a finite-size effect and a magnetic effect.

[7] This WILKENING 84 value is more cautious than the other and excludes the finite-size effect, which relies on uncertain nuclear integrals.

p ELECTRIC POLARIZABILITY $\overline{\alpha}_p$

VALUE (10^{-4} fm^3)	DOCUMENT ID		TECN	COMMENT
12.1 ±0.8 ±0.5	[8] MACGIBBON	95	RVUE	global average
• • • We do not use the following data for averages, fits, limits, etc. • • •				
12.5 ±0.6 ±0.9	MACGIBBON	95	CNTR	γp Compton scattering
9.8 ±0.4 ±1.1	HALLIN	93	CNTR	γp Compton scattering
$10.62^{+1.25}_{-1.19}{}^{+1.07}_{-1.03}$	ZIEGER	92	CNTR	γp Compton scattering
10.9 ±2.2 ±1.3	[9] FEDERSPIEL	91	CNTR	γp Compton scattering

[8] MACGIBBON 95 combine the results of ZIEGER 92, FEDERSPIEL 91, and their own experiment to get a "global average" in which model errors and systematic errors are treated in a consistent way. See MACGIBBON 95 for a discussion.

[9] FEDERSPIEL 91 obtains for the (static) electric polarizablity α_p, defined in terms of the induced electric dipole moment by $\mathbf{D} = 4\pi\epsilon_0\alpha_p\mathbf{E}$, the value $(7.0 \pm 2.2 \pm 1.3) \times 10^{-4}$ fm^3.

p MAGNETIC POLARIZABILITY $\overline{\beta}_p$

The electric and magnetic polarizabilities are subject to a dispersion sum-rule constraint $\overline{\alpha} + \overline{\beta} = (14.2 \pm 0.5) \times 10^{-4}$ fm^3. Errors here are anticorrelated with those on $\overline{\alpha}_p$ due to this constraint.

VALUE (10^{-4} fm^3)	DOCUMENT ID		TECN	COMMENT
2.1 ±0.8 ±0.5	[10] MACGIBBON	95	RVUE	global average
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.7 ±0.6 ±0.9	MACGIBBON	95	CNTR	γp Compton scattering
4.4 ±0.4 ±1.1	HALLIN	93	CNTR	γp Compton scattering
$3.58^{+1.19}_{-1.25}{}^{+1.03}_{-1.07}$	ZIEGER	92	CNTR	γp Compton scattering
3.3 ±2.2 ±1.3	FEDERSPIEL	91	CNTR	γp Compton scattering

[10] MACGIBBON 95 combine the results of ZIEGER 92, FEDERSPIEL 91, and their own experiment to get a "global average" in which model errors and systematic errors are treated in a consistent way. See MACGIBBON 95 for a discussion.

p MEAN LIFE

A test of baryon conservation. See the "p Partial Mean Lives" section below for limits that depend on decay modes. p = proton, n = bound neutron.

LIMIT (years)	PARTICLE	DOCUMENT ID	TECN
>1.6 × 10^25	**p, n**	[11,12] EVANS 77	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
>3 × 10^23	p	[12] DIX 70	CNTR
>3 × 10^23	p, n	[12,13] FLEROV 58	

[11] Mean lifetime of nucleons in ^{130}Te nuclei.
[12] Converted to mean life by dividing half-life by ln(2) = 0.693.
[13] Mean lifetime of nucleons in ^{232}Th nuclei.

$\overline{p}$ MEAN LIFE

The best limit by far, that of GOLDEN 79, relies, however, on a number of astrophysical assumptions. The other limits come from direct observations of stored antiprotons. See also "$\overline{p}$ Partial Mean Lives" after "p Partial Mean Lives," below.

LIMIT (years)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.28			GABRIELSE 90	TRAP	Penning trap
>0.08	90	1	BELL 79	CNTR	Storage ring
>1 × 10^7			GOLDEN 79	SPEC	$\overline{p}/p$, cosmic rays
>3.7 × 10^−3			BREGMAN 78	CNTR	Storage ring

p DECAY MODES

Below, for N decays, p and n distinguish proton and neutron partial lifetimes. See also the "Note on Nucleon Decay" in our 1994 edition (Phys. Rev. **D50**, 1673) for a short review.

The "partial mean life" limits tabulated here are the limits on τ/B_i, where τ is the total mean life and B_i is the branching fraction for the mode in question.

	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	> 130 (n), > 550 (p)	90%
τ_2	$N \to \mu^+\pi$	> 100 (n), > 270 (p)	90%
τ_3	$N \to \nu\pi$	> 100 (n), > 25 (p)	90%
τ_4	$p \to e^+\eta$	> 140	90%
τ_5	$p \to \mu^+\eta$	> 69	90%
τ_6	$n \to \nu\eta$	> 54	90%
τ_7	$N \to e^+\rho$	> 58 (n), > 75 (p)	90%
τ_8	$N \to \mu^+\rho$	> 23 (n), > 110 (p)	90%
τ_9	$N \to \nu\rho$	> 19 (n), > 27 (p)	90%
τ_{10}	$p \to e^+\omega$	> 45	90%
τ_{11}	$p \to \mu^+\omega$	> 57	90%
τ_{12}	$n \to \nu\omega$	> 43	90%
τ_{13}	$N \to e^+K$	> 1.3 (n), > 150 (p)	90%
τ_{14}	$p \to e^+K^0_S$	> 76	90%
τ_{15}	$p \to e^+K^0_L$	> 44	90%
τ_{16}	$N \to \mu^+K$	> 1.1 (n), > 120 (p)	90%
τ_{17}	$p \to \mu^+K^0_S$	> 64	90%
τ_{18}	$p \to \mu^+K^0_L$	> 44	90%
τ_{19}	$N \to \nu K$	> 86 (n), > 100 (p)	90%
τ_{20}	$p \to e^+K^*(892)^0$	> 52	90%
τ_{21}	$N \to \nu K^*(892)$	> 22 (n), > 20 (p)	90%
	Antilepton + mesons		
τ_{22}	$p \to e^+\pi^+\pi^-$	> 21	90%
τ_{23}	$p \to e^+\pi^0\pi^0$	> 38	90%
τ_{24}	$n \to e^+\pi^-\pi^0$	> 32	90%
τ_{25}	$p \to \mu^+\pi^+\pi^-$	> 17	90%
τ_{26}	$p \to \mu^+\pi^0\pi^0$	> 33	90%
τ_{27}	$n \to \mu^+\pi^-\pi^0$	> 33	90%
τ_{28}	$n \to e^+K^0\pi^-$	> 18	90%
	Lepton + meson		
τ_{29}	$n \to e^-\pi^+$	> 65	90%
τ_{30}	$n \to \mu^-\pi^+$	> 49	90%
τ_{31}	$n \to e^-\rho^+$	> 62	90%
τ_{32}	$n \to \mu^-\rho^+$	> 7	90%
τ_{33}	$n \to e^-K^+$	> 32	90%
τ_{34}	$n \to \mu^-K^+$	> 57	90%
	Lepton + mesons		
τ_{35}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{36}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{37}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{38}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
τ_{39}	$p \to e^-\pi^+K^+$	> 20	90%
τ_{40}	$p \to \mu^-\pi^+K^+$	> 5	90%
	Antilepton + photon(s)		
τ_{41}	$p \to e^+\gamma$	> 460	90%
τ_{42}	$p \to \mu^+\gamma$	> 380	90%
τ_{43}	$n \to \nu\gamma$	> 24	90%
τ_{44}	$p \to e^+\gamma\gamma$	> 100	90%
	Three leptons		
τ_{45}	$p \to e^+e^+e^-$	> 510	90%
τ_{46}	$p \to e^+\mu^+\mu^-$	> 81	90%
τ_{47}	$p \to e^+\nu\nu$	> 11	90%
τ_{48}	$n \to e^+e^-\nu$	> 74	90%
τ_{49}	$n \to \mu^+e^-\nu$	> 47	90%
τ_{50}	$n \to \mu^+\mu^-\nu$	> 42	90%
τ_{51}	$p \to \mu^+e^+e^-$	> 91	90%
τ_{52}	$p \to \mu^+\mu^+\mu^-$	> 190	90%
τ_{53}	$p \to \mu^+\nu\nu$	> 21	90%
τ_{54}	$p \to e^-\mu^+\mu^+$	> 6	90%
τ_{55}	$n \to 3\nu$	> 0.0005	90%
	Inclusive modes		
τ_{56}	$N \to e^+$ anything	> 0.6 (n, p)	90%
τ_{57}	$N \to \mu^+$ anything	> 12 (n, p)	90%
τ_{58}	$N \to \nu$ anything		
τ_{59}	$N \to e^+\pi^0$ anything	> 0.6 (n, p)	90%
τ_{60}	$N \to$ 2 bodies, ν-free		
	$\Delta B = 2$ dinucleon modes		
	The following are lifetime limits per iron nucleus.		
τ_{61}	$pp \to \pi^+\pi^+$	> 0.7	90%
τ_{62}	$pn \to \pi^+\pi^0$	> 2	90%
τ_{63}	$nn \to \pi^+\pi^-$	> 0.7	90%
τ_{64}	$nn \to \pi^0\pi^0$	> 3.4	90%
τ_{65}	$pp \to e^+e^+$	> 5.8	90%
τ_{66}	$pp \to e^+\mu^+$	> 3.6	90%
τ_{67}	$pp \to \mu^+\mu^+$	> 1.7	90%
τ_{68}	$pn \to e^+\overline{\nu}$	> 2.8	90%
τ_{69}	$pn \to \mu^+\overline{\nu}$	> 1.6	90%
τ_{70}	$nn \to \nu_e\overline{\nu}_e$	> 0.000012	90%
τ_{71}	$nn \to \nu_\mu\overline{\nu}_\mu$	> 0.000006	90%

$\overline{p}$ DECAY MODES

	Mode	Partial mean life (years)	Confidence level
τ_{72}	$\overline{p} \to e^-\gamma$	> 1848	95%
τ_{73}	$\overline{p} \to e^-\pi^0$	> 554	95%
τ_{74}	$\overline{p} \to e^-\eta$	> 171	95%
τ_{75}	$\overline{p} \to e^-K^0_S$	> 29	95%
τ_{76}	$\overline{p} \to e^-K^0_L$	> 9	95%

p PARTIAL MEAN LIVES

The "partial mean life" limits tabulated here are the limits on τ/B_i, where τ is the total mean life for the proton and B_i is the branching fraction for the mode in question.

Decaying particle: p = proton, n = bound neutron. The same event may appear under more than one partial decay mode. Background estimates may be accurate to a factor of two.

$\tau(N \to e^+\pi)$ — τ_1

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>550	**p**	**90**	**0**	**0.7**	[14] BECKER-SZ... 90	IMB3
>130	**n**	**90**	**0**	**<0.2**	HIRATA 89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 70	p	90	0	0.5	BERGER	91	FREJ
> 70	n	90	0	≤ 0.1	BERGER	91	FREJ
>260	p	90	0	<0.04	HIRATA	89C	KAMI
>310	p	90	0	0.6	SEIDEL	88	IMB
>100	n	90	0	1.6	SEIDEL	88	IMB
> 1.3	n	90	0		BARTELT	87	SOUD
> 1.3	p	90	0		BARTELT	87	SOUD
>250	p	90	0	0.3	HAINES	86	IMB
> 31	n	90	8	9	HAINES	86	IMB
> 64	p	90	0	<0.4	ARISAKA	85	KAMI
> 26	n	90	0	<0.7	ARISAKA	85	KAMI
> 82	p (free)	90	0	0.2	BLEWITT	85	IMB
>250	p	90	0	0.2	BLEWITT	85	IMB
> 25	n	90	4	4	PARK	85	IMB
> 15	p, n	90	0		BATTISTONI	84	NUSX
> 0.5	p	90	1	0.3	[15] BARTELT	83	SOUD
> 0.5	n	90	1	0.3	[15] BARTELT	83	SOUD
> 5.8	p	90	2		[16] KRISHNA...	82	KOLR
> 5.8	n	90	2		[16] KRISHNA...	82	KOLR
> 0.1	n	90			[17] GURR	67	CNTR

[14] This BECKER-SZENDY 90 result includes data from SEIDEL 88.
[15] Limit based on zero events.
[16] We have calculated 90% CL limit from 1 confined event.
[17] We have converted half-life to 90% CL mean life.

$\tau(N \rightarrow \mu^+ \pi)$ τ_2

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>100	**n**	**90**	**0**	**<0.2**	HIRATA	89C	KAMI
>270	**p**	**90**	**0**	**0.5**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 81	p	90	0	0.2	BERGER	91	FREJ
> 35	n	90	1	1.0	BERGER	91	FREJ
>230	p	90	0	<0.07	HIRATA	89C	KAMI
> 63	n	90	0	0.5	SEIDEL	88	IMB
> 76	p	90	2	1	HAINES	86	IMB
> 23	n	90	8	7	HAINES	86	IMB
> 46	p	90	0	<0.7	ARISAKA	85	KAMI
> 20	n	90	0	<0.4	ARISAKA	85	KAMI
> 59	p (free)	90	0	0.2	BLEWITT	85	IMB
>100	p	90	1	0.4	BLEWITT	85	IMB
> 38	n	90	1	4	PARK	85	IMB
> 10	p, n	90	0		BATTISTONI	84	NUSX
> 1.3	p, n	90	0		ALEKSEEV	81	BAKS

$\tau(N \rightarrow \nu \pi)$ τ_3

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
> 25	**p**	**90**	**32**	**32.8**	HIRATA	89C	KAMI
>100	**n**	**90**	**1**	**3**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 13	n	90	1	1.2	BERGER	89	FREJ
> 10	p	90	11	14	BERGER	89	FREJ
> 6	n	90	73	60	HAINES	86	IMB
> 2	p	90	16	13	KAJITA	86	KAMI
> 40	n	90	0	1	KAJITA	86	KAMI
> 7	n	90	28	19	PARK	85	IMB
> 7	n	90	0		BATTISTONI	84	NUSX
> 2	p	90	≤ 3		BATTISTONI	84	NUSX
> 5.8	p	90	1		[18] KRISHNA...	82	KOLR
> 0.3	p	90	2		[19] CHERRY	81	HOME
> 0.1	p	90			[20] GURR	67	CNTR

[18] We have calculated 90% CL limit from 1 confined event.
[19] We have converted 2 possible events to 90% CL limit.
[20] We have converted half-life to 90% CL mean life.

$\tau(p \rightarrow e^+ \eta)$ τ_4

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>140	**p**	**90**	**0**	**<0.04**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 44	p	90	0	0.1	BERGER	91	FREJ
>100	p	90	0	0.6	SEIDEL	88	IMB
>200	p	90	5	3.3	HAINES	86	IMB
> 64	p	90	0	<0.8	ARISAKA	85	KAMI
> 64	p (free)	90	5	6.5	BLEWITT	85	IMB
>200	p	90	5	4.7	BLEWITT	85	IMB
> 1.2	p	90	2		[21] CHERRY	81	HOME

[21] We have converted 2 possible events to 90% CL limit.

$\tau(p \rightarrow \mu^+ \eta)$ τ_5

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>69	**p**	**90**	**1**	**<0.08**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

>26	p	90	1	0.8	BERGER	91	FREJ
> 1.3	p	90	0	0.7	PHILLIPS	89	HPW
>34	p	90	1	1.5	SEIDEL	88	IMB
>46	p	90	7	6	HAINES	86	IMB
>26	p	90	1	<0.8	ARISAKA	85	KAMI
>17	p (free)	90	6	6	BLEWITT	85	IMB
>46	p	90	7	8	BLEWITT	85	IMB

$\tau(n \rightarrow \nu \eta)$ τ_6

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>54	**n**	**90**	**2**	**0.9**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

>29	n	90	0	0.9	BERGER	89	FREJ
>16	n	90	3	2.1	SEIDEL	88	IMB
>25	n	90	7	6	HAINES	86	IMB
>30	n	90	0	0.4	KAJITA	86	KAMI
>18	n	90	4	3	PARK	85	IMB
> 0.6	n	90	2		[22] CHERRY	81	HOME

[22] We have converted 2 possible events to 90% CL limit.

$\tau(N \rightarrow e^+ \rho)$ τ_7

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>75	**p**	**90**	**2**	**2.7**	HIRATA	89C	KAMI
>58	**n**	**90**	**0**	**1.9**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

>29	p	90	0	2.2	BERGER	91	FREJ
>41	n	90	0	1.4	BERGER	91	FREJ
>38	n	90	2	4.1	SEIDEL	88	IMB
> 1.2	p	90	0		BARTELT	87	SOUD
> 1.5	n	90	0		BARTELT	87	SOUD
>17	p	90	7	7	HAINES	86	IMB
>14	n	90	9	4	HAINES	86	IMB
>12	p	90	0	<1.2	ARISAKA	85	KAMI
> 6	n	90	2	<1	ARISAKA	85	KAMI
> 6.7	p (free)	90	6	6	BLEWITT	85	IMB
>17	p	90	7	7	BLEWITT	85	IMB
>12	n	90	4	2	PARK	85	IMB
> 0.6	n	90	1	0.3	[23] BARTELT	83	SOUD
> 0.5	p	90	1	0.3	[23] BARTELT	83	SOUD
> 9.8	p	90	1		[24] KRISHNA...	82	KOLR
> 0.8	p	90	2		[25] CHERRY	81	HOME

[23] Limit based on zero events.
[24] We have calculated 90% CL limit from 0 confined events.
[25] We have converted 2 possible events to 90% CL limit.

$\tau(N \rightarrow \mu^+ \rho)$ τ_8

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>110	**p**	**90**	**0**	**1.7**	HIRATA	89C	KAMI
> 23	**n**	**90**	**1**	**1.8**	HIRATA	89C	KAMI

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 12	p	90	0	0.5	BERGER	91	FREJ
> 22	n	90	0	1.1	BERGER	91	FREJ
> 4.3	p	90	0	0.7	PHILLIPS	89	HPW
> 30	p	90	0	0.5	SEIDEL	88	IMB
> 11	n	90	1	1.1	SEIDEL	88	IMB
> 16	p	90	4	4.5	HAINES	86	IMB
> 7	n	90	6	5	HAINES	86	IMB
> 12	p	90	0	<0.7	ARISAKA	85	KAMI
> 5	n	90	1	<1.2	ARISAKA	85	KAMI
> 5.5	p (free)	90	4	5	BLEWITT	85	IMB
> 16	p	90	4	5	BLEWITT	85	IMB
> 9	n	90	1	2	PARK	85	IMB

$\tau(N \rightarrow \nu \rho)$ τ_9

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>27	**p**	**90**	**5**	**1.5**	HIRATA	89C	KAMI
>19	**n**	**90**	**0**	**0.5**	SEIDEL	88	IMB

• • • We do not use the following data for averages, fits, limits, etc. • • •

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>9	*n*	90	4	2.4	BERGER	89	FREJ
>24	*p*	90	0	0.9	BERGER	89	FREJ
>13	*n*	90	4	3.6	HIRATA	89C	KAMI
>13	*p*	90	1	1.1	SEIDEL	88	IMB
>8	*p*	90	6	5	HAINES	86	IMB
>2	*n*	90	15	10	HAINES	86	IMB
>11	*p*	90	2	1	KAJITA	86	KAMI
>4	*n*	90	2	2	KAJITA	86	KAMI
>4.1	*p* (free)	90	6	7	BLEWITT	85	IMB
>8.4	*p*	90	6	5	BLEWITT	85	IMB
>2	*n*	90	7	3	PARK	85	IMB
>0.9	*p*	90	2		[26] CHERRY	81	HOME
>0.6	*n*	90	2		[26] CHERRY	81	HOME

[26] We have converted 2 possible events to 90% CL limit.

$\tau(p \to e^+ \omega)$ — τ_{10}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>45	***p***	**90**	**2**	**1.45**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>17	*p*	90	0	1.1	BERGER	91	FREJ
>26	*p*	90	1	1.0	SEIDEL	88	IMB
>1.5	*p*	90	0		BARTELT	87	SOUD
>37	*p*	90	6	5.3	HAINES	86	IMB
>25	*p*	90	1	<1.4	ARISAKA	85	KAMI
>12	*p* (free)	90	6	7.5	BLEWITT	85	IMB
>37	*p*	90	6	5.7	BLEWITT	85	IMB
>0.6	*p*	90	1	0.3	[27] BARTELT	83	SOUD
>9.8	*p*	90	1		[28] KRISHNA...	82	KOLR
>2.8	*p*	90	2		[29] CHERRY	81	HOME

[27] Limit based on zero events.
[28] We have calculated 90% CL limit from 0 confined events.
[29] We have converted 2 possible events to 90% CL limit.

$\tau(p \to \mu^+ \omega)$ — τ_{11}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>57	***p***	**90**	**2**	**1.9**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>11	*p*	90	0	1.0	BERGER	91	FREJ
>4.4	*p*	90	0	0.7	PHILLIPS	89	HPW
>10	*p*	90	2	1.3	SEIDEL	88	IMB
>23	*p*	90	2	1	HAINES	86	IMB
>6.5	*p* (free)	90	9	8.7	BLEWITT	85	IMB
>23	*p*	90	8	7	BLEWITT	85	IMB

$\tau(n \to \nu \omega)$ — τ_{12}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>43	***n***	**90**	**3**	**2.7**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>17	*n*	90	1	0.7	BERGER	89	FREJ
>6	*n*	90	2	1.3	SEIDEL	88	IMB
>12	*n*	90	6	6	HAINES	86	IMB
>18	*n*	90	2	2	KAJITA	86	KAMI
>16	*n*	90	1	2	PARK	85	IMB
>2.0	*n*	90	2		[30] CHERRY	81	HOME

[30] We have converted 2 possible events to 90% CL limit.

$\tau(N \to e^+ K)$ — τ_{13}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>150	***p***	**90**	**0**	**<0.27**	HIRATA	89C	KAMI
>1.3	***n***	**90**	**0**		ALEKSEEV	81	BAKS
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>60	*p*	90	0		BERGER	91	FREJ
>70	*p*	90	0	1.8	SEIDEL	88	IMB
>77	*p*	90	5	4.5	HAINES	86	IMB
>38	*p*	90	0	<0.8	ARISAKA	85	KAMI
>24	*p* (free)	90	7	8.5	BLEWITT	85	IMB
>77	*p*	90	5	4	BLEWITT	85	IMB
>1.3	*p*	90	0		ALEKSEEV	81	BAKS

$\tau(p \to e^+ K^0_S)$ — τ_{14}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>76	***p***	**90**	**0**	**0.5**	BERGER	91	FREJ

$\tau(p \to e^+ K^0_L)$ — τ_{15}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>44	***p***	**90**	**0**	**≤0.1**	BERGER	91	FREJ

$\tau(N \to \mu^+ K)$ — τ_{16}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>120	***p***	**90**	**1**	**0.4**	HIRATA	89C	KAMI
>1.1	***n***	**90**	**0**		BARTELT	87	SOUD
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>54	*p*	90	0		BERGER	91	FREJ
>3.0	*p*	90	0	0.7	PHILLIPS	89	HPW
>19	*p*	90	3	2.5	SEIDEL	88	IMB
>1.5	*p*	90	0		[31] BARTELT	87	SOUD
>40	*p*	90	7	6	HAINES	86	IMB
>19	*p*	90	1	<1.1	ARISAKA	85	KAMI
>6.7	*p* (free)	90	11	13	BLEWITT	85	IMB
>40	*p*	90	7	8	BLEWITT	85	IMB
>6	*p*	90	1		BATTISTONI	84	NUSX
>0.6	*p*	90	0		[32] BARTELT	83	SOUD
>0.4	*n*	90	0		[32] BARTELT	83	SOUD
>5.8	*p*	90	2		[33] KRISHNA...	82	KOLR
>2.0	*p*	90	0		CHERRY	81	HOME
>0.2	*n*	90			[34] GURR	67	CNTR

[31] BARTELT 87 limit applies to $p \to \mu^+ K^0_S$.
[32] Limit based on zero events.
[33] We have calculated 90% CL limit from 1 confined event.
[34] We have converted half-life to 90% CL mean life.

$\tau(p \to \mu^+ K^0_S)$ — τ_{17}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>64	***p***	**90**	**0**	**1.2**	BERGER	91	FREJ

$\tau(p \to \mu^+ K^0_L)$ — τ_{18}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>44	***p***	**90**	**0**	**≤0.1**	BERGER	91	FREJ

$\tau(N \to \nu K)$ — τ_{19}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>100	***p***	**90**	**9**	**7.3**	HIRATA	89C	KAMI
>86	***n***	**90**	**0**	**2.4**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>15	*n*	90	1	1.8	BERGER	89	FREJ
>15	*p*	90	1	1.8	BERGER	89	FREJ
>0.28	*p*	90	0	0.7	PHILLIPS	89	HPW
>0.3	*p*	90	0		BARTELT	87	SOUD
>0.75	*n*	90	0		[35] BARTELT	87	SOUD
>10	*p*	90	6	5	HAINES	86	IMB
>15	*n*	90	3	5	HAINES	86	IMB
>28	*p*	90	3	3	KAJITA	86	KAMI
>32	*n*	90	0	1.4	KAJITA	86	KAMI
>1.8	*p* (free)	90	6	11	BLEWITT	85	IMB
>9.6	*p*	90	6	5	BLEWITT	85	IMB
>10	*n*	90	2	2	PARK	85	IMB
>5	*n*	90	0		BATTISTONI	84	NUSX
>2	*p*	90	0		BATTISTONI	84	NUSX
>0.3	*n*	90	0		[36] BARTELT	83	SOUD
>0.1	*p*	90	0		[36] BARTELT	83	SOUD
>5.8	*p*	90	1		[37] KRISHNA...	82	KOLR
>0.3	*n*	90	2		[38] CHERRY	81	HOME

[35] BARTELT 87 limit applies to $n \to \nu K^0_S$.
[36] Limit based on zero events.
[37] We have calculated 90% CL limit from 1 confined event.
[38] We have converted 2 possible events to 90% CL limit.

$\tau(p \to e^+ K^*(892)^0)$ — τ_{20}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>52	***p***	**90**	**2**	**1.55**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>10	*p*	90	0	0.8	BERGER	91	FREJ
>10	*p*	90	1	<1	ARISAKA	85	KAMI

$\tau(N \to \nu K^*(892))$ — τ_{21}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>22	***n***	**90**	**0**	**2.1**	BERGER	89	FREJ
>20	***p***	**90**	**5**	**2.1**	HIRATA	89C	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>17	*p*	90	0	2.4	BERGER	89	FREJ
>21	*n*	90	4	2.4	HIRATA	89C	KAMI
>10	*p*	90	7	6	HAINES	86	IMB
>5	*n*	90	8	7	HAINES	86	IMB
>8	*p*	90	3	2	KAJITA	86	KAMI
>6	*n*	90	2	1.6	KAJITA	86	KAMI
>5.8	*p* (free)	90	10	16	BLEWITT	85	IMB
>9.6	*p*	90	7	6	BLEWITT	85	IMB
>7	*n*	90	1	4	PARK	85	IMB
>2.1	*p*	90	1		[39] BATTISTONI	82	NUSX

[39] We have converted 1 possible event to 90% CL limit.

$\tau(p \to e^+ \pi^+ \pi^-)$ — τ_{22}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>21	**p**	**90**	**0**	**2.2**	BERGER	91	FREJ

$\tau(p \to e^+ \pi^0 \pi^0)$ — τ_{23}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>38	**p**	**90**	**1**	**0.5**	BERGER	91	FREJ

$\tau(n \to e^+ \pi^- \pi^0)$ — τ_{24}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>32	**n**	**90**	**1**	**0.8**	BERGER	91	FREJ

$\tau(p \to \mu^+ \pi^+ \pi^-)$ — τ_{25}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>17	**p**	**90**	**1**	**2.6**	BERGER	91	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 3.3	p	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to \mu^+ \pi^0 \pi^0)$ — τ_{26}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>33	**p**	**90**	**1**	**0.9**	BERGER	91	FREJ

$\tau(n \to \mu^+ \pi^- \pi^0)$ — τ_{27}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>33	**n**	**90**	**0**	**1.1**	BERGER	91	FREJ

$\tau(n \to e^+ K^0 \pi^-)$ — τ_{28}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>18	**n**	**90**	**1**	**0.2**	BERGER	91	FREJ

$\tau(n \to e^- \pi^+)$ — τ_{29}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>65	**n**	**90**	**0**	**1.6**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>55	n	90	0	1.09	BERGER	91B	FREJ
>16	n	90	9	7	HAINES	86	IMB
>25	n	90	2	4	PARK	85	IMB

$\tau(n \to \mu^- \pi^+)$ — τ_{30}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>49	**n**	**90**	**0**	**0.5**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>33	n	90	0	1.40	BERGER	91B	FREJ
> 2.7	n	90	0	0.7	PHILLIPS	89	HPW
>25	n	90	7	6	HAINES	86	IMB
>27	n	90	2	3	PARK	85	IMB

$\tau(n \to e^- \rho^+)$ — τ_{31}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>62	**n**	**90**	**2**	**4.1**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>12	n	90	13	6	HAINES	86	IMB
>12	n	90	5	3	PARK	85	IMB

$\tau(n \to \mu^- \rho^+)$ — τ_{32}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>7	**n**	**90**	**1**	**1.1**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>2.6	n	90	0	0.7	PHILLIPS	89	HPW
>9	n	90	7	5	HAINES	86	IMB
>9	n	90	2	2	PARK	85	IMB

$\tau(n \to e^- K^+)$ — τ_{33}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>32	**n**	**90**	**3**	**2.96**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 0.23	n	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to \mu^- K^+)$ — τ_{34}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>57	**n**	**90**	**0**	**2.18**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 4.7	n	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to e^- \pi^+ \pi^+)$ — τ_{35}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>30	**p**	**90**	**1**	**2.50**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 2.0	p	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to e^- \pi^+ \pi^0)$ — τ_{36}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>29	**n**	**90**	**1**	**0.78**	BERGER	91B	FREJ

$\tau(p \to \mu^- \pi^+ \pi^+)$ — τ_{37}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>17	**p**	**90**	**1**	**1.72**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 7.8	p	90	0	0.7	PHILLIPS	89	HPW

$\tau(n \to \mu^- \pi^+ \pi^0)$ — τ_{38}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>34	**n**	**90**	**0**	**0.78**	BERGER	91B	FREJ

$\tau(p \to e^- \pi^+ K^+)$ — τ_{39}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>20	**p**	**90**	**3**	**2.50**	BERGER	91B	FREJ

$\tau(p \to \mu^- \pi^+ K^+)$ — τ_{40}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>5	**p**	**90**	**2**	**0.78**	BERGER	91B	FREJ

$\tau(p \to e^+ \gamma)$ — τ_{41}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>460	**p**	**90**	**0**	**0.6**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>133	p	90	0	0.3	BERGER	91	FREJ
>360	p	90	0	0.3	HAINES	86	IMB
> 87	p (free)	90	0	0.2	BLEWITT	85	IMB
>360	p	90	0	0.2	BLEWITT	85	IMB
> 0.1	p	90			[40] GURR	67	CNTR

[40] We have converted half-life to 90% CL mean life.

$\tau(p \to \mu^+ \gamma)$ — τ_{42}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>380	**p**	**90**	**0**	**0.5**	SEIDEL	88	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>155	p	90	0	0.1	BERGER	91	FREJ
> 97	p	90	3	2	HAINES	86	IMB
> 61	p (free)	90	0	0.2	BLEWITT	85	IMB
>280	p	90	0	0.6	BLEWITT	85	IMB
> 0.3	p	90			[41] GURR	67	CNTR

[41] We have converted half-life to 90% CL mean life.

$\tau(n \to \nu \gamma)$ — τ_{43}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>24	**n**	**90**	**10**	**6.86**	BERGER	91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 9	n	90	73	60	HAINES	86	IMB
>11	n	90	28	19	PARK	85	IMB

$\tau(p \to e^+ \gamma \gamma)$ — τ_{44}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>100	**p**	**90**	**1**	**0.8**	BERGER	91	FREJ

$\tau(p \to e^+ e^+ e^-)$ — τ_{45}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>510	**p**	**90**	**0**	**0.3**	HAINES	86	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>147	p	90	0	0.1	BERGER	91	FREJ
> 89	p (free)	90	0	0.5	BLEWITT	85	IMB
>510	p	90	0	0.7	BLEWITT	85	IMB

$\tau(p \to e^+ \mu^+ \mu^-)$ — τ_{46}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>81	**p**	**90**	**0**	**0.16**	BERGER	91	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 5.0	p	90	0	0.7	PHILLIPS	89	HPW

$\tau(p \to e^+ \nu\nu)$ — τ_{47}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>11	**p**	**90**	**11**	**6.08**	BERGER 91B	FREJ

$\tau(n \to e^+ e^- \nu)$ — τ_{48}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>74	**n**	**90**	**0**	**< 0.1**	BERGER 91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>45	n	90	5	5	HAINES 86	IMB
>26	n	90	4	3	PARK 85	IMB

$\tau(n \to \mu^+ e^- \nu)$ — τ_{49}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>47	**n**	**90**	**0**	**< 0.1**	BERGER 91B	FREJ

$\tau(n \to \mu^+ \mu^- \nu)$ — τ_{50}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>42	**n**	**90**	**0**	**1.4**	BERGER 91B	FREJ
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 5.1	n	90	0	0.7	PHILLIPS 89	HPW
>16	n	90	14	7	HAINES 86	IMB
>19	n	90	4	7	PARK 85	IMB

$\tau(p \to \mu^+ e^+ e^-)$ — τ_{51}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>91	**p**	**90**	**0**	**≤ 0.1**	BERGER 91	FREJ

$\tau(p \to \mu^+ \mu^+ \mu^-)$ — τ_{52}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>190	**p**	**90**	**1**	**0.1**	HAINES 86	IMB
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>119	p	90	0	0.2	BERGER 91	FREJ
> 10.5	p	90	0	0.7	PHILLIPS 89	HPW
> 44	p (free)	90	1	0.7	BLEWITT 85	IMB
>190	p	90	1	0.9	BLEWITT 85	IMB
> 2.1	p	90	1		[42] BATTISTONI 82	NUSX

[42] We have converted 1 possible event to 90% CL limit.

$\tau(p \to \mu^+ \nu\nu)$ — τ_{53}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>21	**p**	**90**	**7**	**11.23**	BERGER 91B	FREJ

$\tau(p \to e^- \mu^+ \mu^+)$ — τ_{54}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>6.0	**p**	**90**	**0**	**0.7**	PHILLIPS 89	HPW

$\tau(n \to 3\nu)$ — τ_{55}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>0.00049	**n**	**90**	**2**	**2**	[43] SUZUKI 93B	KAMI
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.00003	n	90	11	6.1	[44] BERGER 91B	FREJ
>0.00012	n	90	7	11.2	[44] BERGER 91B	FREJ
>0.0005	n	90	0		LEARNED 79	RVUE

[43] The SUZUKI 93B limit applies to any of $\nu_e \nu_e \overline{\nu}_e$, $\nu_\mu \nu_\mu \overline{\nu}_\mu$, or $\nu_\tau \nu_\tau \overline{\nu}_\tau$.
[44] The first BERGER 91B limit is for $n \to \nu_e \nu_e \overline{\nu}_e$, the second is for $n \to \nu_\mu \nu_\mu \overline{\nu}_\mu$.

$\tau(N \to e^+$ anything) — τ_{56}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>0.6	**p, n**	**90**			[45] LEARNED 79	RVUE

[45] The electron may be primary or secondary.

$\tau(N \to \mu^+$ anything) — τ_{57}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>12	**p, n**	**90**	**2**		[46,47] CHERRY 81	HOME
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 1.8	p, n	90			[47] COWSIK 80	CNTR
> 6	p, n	90			[47] LEARNED 79	RVUE

[46] We have converted 2 possible events to 90% CL limit.
[47] The muon may be primary or secondary.

$\tau(N \to \nu$ anything) — τ_{58}

Anything = π, ρ, K, etc.

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.0002	p, n	90	0		LEARNED 79	RVUE

$\tau(N \to e^+ \pi^0$ anything) — τ_{59}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>0.6	**p, n**	**90**	**0**		LEARNED 79	RVUE

$\tau(N \to 2$ bodies, ν-free) — τ_{60}

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>1.3	p, n	90	0		ALEKSEEV 81	BAKS

$\tau(pp \to \pi^+ \pi^+)$ — τ_{61}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>0.7	**90**	**4**	**2.34**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pn \to \pi^+ \pi^0)$ — τ_{62}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>2.0	**90**	**0**	**0.31**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(nn \to \pi^+ \pi^-)$ — τ_{63}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>0.7	**90**	**4**	**2.18**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(nn \to \pi^0 \pi^0)$ — τ_{64}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>3.4	**90**	**0**	**0.78**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pp \to e^+ e^+)$ — τ_{65}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>5.8	**90**	**0**	**<0.1**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pp \to e^+ \mu^+)$ — τ_{66}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>3.6	**90**	**0**	**<0.1**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pp \to \mu^+ \mu^+)$ — τ_{67}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>1.7	**90**	**0**	**0.62**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pn \to e^+ \overline{\nu})$ — τ_{68}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>2.8	**90**	**5**	**9.67**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(pn \to \mu^+ \overline{\nu})$ — τ_{69}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>1.6	**90**	**4**	**4.37**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(nn \to \nu_e \overline{\nu}_e)$ — τ_{70}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>0.000012	**90**	**5**	**9.7**	BERGER 91B	FREJ	τ per iron nucleus

$\tau(nn \to \nu_\mu \overline{\nu}_\mu)$ — τ_{71}

LIMIT (10^{30} years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	COMMENT
>0.000006	**90**	**4**	**4.4**	BERGER 91B	FREJ	τ per iron nucleus

$\overline{p}$ PARTIAL MEAN LIVES

The "partial mean life" limits tabulated here are the limits on $\overline{\tau}/B_j$, where $\overline{\tau}$ is the total mean life for the antiproton and B_j is the branching fraction for the mode in question.

$\tau(\overline{p} \to e^- \gamma)$ — τ_{72}

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
>1848	95	GEER 94	CALO	8.9 GeV/c $\overline{p}$ beam

$\tau(\overline{p} \to e^- \pi^0)$ — τ_{73}

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
>554	95	GEER 94	CALO	8.9 GeV/c $\overline{p}$ beam

$\tau(\overline{p} \to e^- \eta)$ — τ_{74}

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
>171	95	GEER 94	CALO	8.9 GeV/c $\overline{p}$ beam

$\tau(\overline{p} \to e^- K^0_S)$ — τ_{75}

VALUE (years)	CL%	DOCUMENT ID	TECN	COMMENT
>29	95	GEER 94	CALO	8.9 GeV/c $\overline{p}$ beam

$\tau(\overline{p} \to e^- K^0_L)$ — τ76

VALUE (years)	CL%	DOCUMENT ID		TECN	COMMENT
>9	95	GEER	94	CALO	8.9 GeV/c $\overline{p}$ beam

p REFERENCES

GABRIELSE	95	PRL 74 3544	+Phillips, Quint+	(HARV, MANZ, SEOUL)
MACGIBBON	95	PR C52 2097	+Garino, Lucas, Nathan+	(ILL, SASK, INRM)
GEER	94	PRL 72 1596	+Marriner, Ray+	(FNAL, UCLA, PSU)
HALLIN	93	PR C48 1497	+Amendt, Bergstrom+	(SASK, BOST, ILL)
SUZUKI	93B	PL B311 357	+Fukuda, Hirata, Inoue+	(KAMIOKANDE Collab.)
HUGHES	92	PRL 69 578	+Deutch	(LANL, AARH)
ZIEGER	92	PL B278 34	+Van de Vyver, Christmann, DeGraeve+	(MPCM)
Also	92B	PL B281 417 (erratum)	Zieger, ..., Van den Abeele, Ziegler	(MPCM)
BERGER	91	ZPHY C50 385	+Froehlich, Moench, Nisius+	(FREJUS Collab.)
BERGER	91B	PL B269 227	+Froehlich, Moench, Nisius+	(FREJUS Collab.)
FEDERSPIEL	91	PRL 67 1511	+Eisenstein, Lucas, MacGibbon+	(ILL)
BECKER-SZ...	90	PR D42 2974	Becker-Szendy, Bratton, Cady, Casper+	(IMB-3 Collab.)
ERICSON	90	EPL 11 295	+Richter	(CERN, DARM)
GABRIELSE	90	PRL 65 1317	+Fei, Orozco, Tjoelker+	(HARV, MANZ, WASH, IBS)
BERGER	89	NP B313 509	+Froehlich, Moench+	(FREJUS Collab.)
CHO	89	PRL 63 2559	+Sangster, Hinds	(YALE)
HIRATA	89C	PL B220 308	+Kajita, Kifune, Kihara+	(Kamiokande Collab.)
PHILLIPS	89	PL B224 348	+Matthews, Aprile, Cline+	(HPW Collab.)
KREISSL	88	ZPHY C37 557	+Hancock, Koch, Koehler, Poth+	(CERN PS176 Collab.)
SEIDEL	88	PRL 61 2522	+Bionta, Blewitt, Bratton+	(IMB Collab.)
BARTELT	87	PR D36 1990	+Courant, Heller+	(Soudan Collab.)
Also	89	PR D40 1701 erratum	Bartelt, Courant, Heller+	(Soudan Collab.)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
HAINES	86	PRL 57 1986	+Bionta, Blewitt, Bratton, Casper+	(IMB Collab.)
KAJITA	86	JPSJ 55 711	+Arisaka, Koshiba, Nakahata+	(Kamiokande Collab.)
ARISAKA	85	JPSJ 54 3213	+Kajita, Koshiba, Nakahata+	(Kamiokande Collab.)
BLEWITT	85	PRL 55 2114	+LoSecco, Bionta, Bratton+	(IMB Collab.)
DZUBA	85	PL 154B 93	+Flambaum, Silvestrov	(NOVO)
PARK	85	PRL 54 22	+Blewitt, Cortez, Foster+	(IMB Collab.)
BATTISTONI	84	PL 133B 454	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
MARINELLI	84	PL 137B 439	+Morpurgo	(GENO)
WILKENING	84	PR A29 425	+Ramsey, Larson	(HARV, VIRG)
BARTELT	83	PRL 50 651	+Courant, Heller, Joyce, Marshak+	(MINN, ANL)
BATTISTONI	82	PL 118B 461	+Bellotti, Bologna, Campana+	(NUSEX Collab.)
KRISHNA...	82	PL 115B 349	Krishnaswamy, Menon+	(TATA, OSKC, INUS)
ALEKSEEV	81	JETPL 33 651	+Bakatanov, Butkevich, Voevodskii+	(PNPI)
		Translated from ZETFP 33 664.		
CHERRY	81	PRL 47 1507	+Deakyne, Lande, Lee, Steinberg+	(PENN, BNL)
COWSIK	80	PR D22 2204	+Narasimhan	(TATA)
BELL	79	PL 86B 215	+Calvetti, Carron, Chaney, Cittolin+	(CERN)
GOLDEN	79	PRL 43 1196	+Horan, Mauger, Badhwar, Lacy+	(NASA, PSLL)
LEARNED	79	PRL 43 907	+Reines, Soni	(UCI)
BREGMAN	78	PL 78B 174	+Calvetti, Carron, Cittolin, Hauer, Herr+	(CERN)
ROBERTS	78	PR D17 358		(WILL, RHEL)
EVANS	77	Science 197 989	+Steinberg	(BNL, PENN)
ROBERSON	77	PR C16 1945	+King, Kunselman+	(WYOM, CIT, CMU, VPI, WILL)
HU	75	NP A254 403	+Asano, Chen, Cheng, Dugan+	(COLU, YALE)
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
DYLLA	73	PR A7 1224	+King	(MIT)
BAMBERGER	70	PL 33B 233	+Lynen, Piekarz+	(MPIH, CERN, KARL)
DIX	70	Thesis Case		(CASE)
HARRISON	69	PRL 22 1263	+Sandars, Wright	(OXF)
GURR	67	PR 158 1321	+Kropp, Reines, Meyer	(CASE, WITW)
FLEROV	58	DOKL 3 79	+Klochkov, Skobkin, Terentev	(ASCI)

n

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. See our earlier editions.

n MASS

The mass is known much more precisely in u (atomic mass units) than in MeV; see the footnotes. The conversion from u to MeV, 1 u = 931.49432±0.00028 MeV, involves the relatively poorly known electronic charge. The DIFILIPPO 94 value, in u, is by far the best, but when converted to MeV differs only negligibly from the 1986 CODATA value, which, for consistency, we stick with.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
939.56563±0.00028	[1] COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
939.56565±0.00028	[2] DIFILIPPO	94		Penning trap
939.56564±0.00028	[3,4] GREENE	86	SPEC	$np \to d\gamma$
939.5731 ±0.0027	[4] COHEN	73	RVUE	1973 CODATA value

[1] The mass is known much more precisely in u: $m = 1.008664904 \pm 0.000000014$ u.

[2] The mass is known much more precisely in u: $m = 1.0086649235 \pm 0.0000000023$ u. We use the conversion factor given above to get the mass in MeV.

[3] The mass is known much more precisely in u: $m = 1.008664919 \pm 0.000000014$ u.

[4] These determinations are not independent of the $m_n - m_p$ measurements below.

$\overline{n}$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
939.485±0.051	59	[5] CRESTI	86	HBC	$\overline{p}p \to \overline{n}n$

[5] This is a corrected result (see the erratum). The error is statistical. The maximum systematic error is 0.029 MeV.

$(m_n - m_{\overline{n}}) \,/\, m_{\text{average}}$

A test of CPT invariance. Calculated from the n and $\overline{n}$ masses, above.

VALUE	DOCUMENT ID
(9±5) x 10^{-5} OUR EVALUATION	

$m_n - m_p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1.293318 ±0.000009	[6] COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.2933328±0.0000072	GREENE	86	SPEC	$np \to d\gamma$
1.293429 ±0.000036	COHEN	73	RVUE	1973 CODATA value

[6] Calculated by us from the COHEN 87 ratio $m_n/m_p = 1.001378404 \pm 0.000000009$. In u, $m_n - m_p = 0.001388434 \pm 0.000000009$ u.

n MEAN LIFE

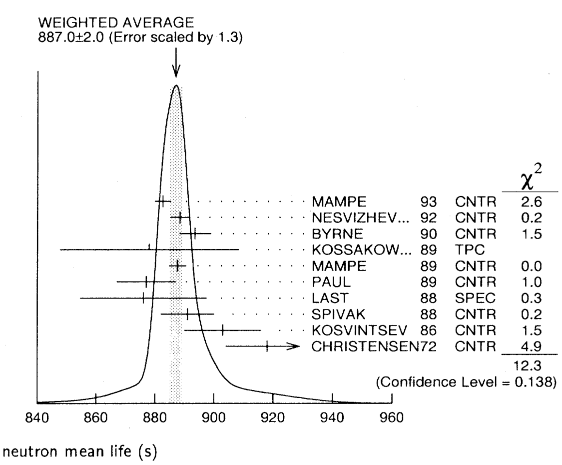
We now compile only direct measurements of the lifetime, not those inferred from decay correlation measurements. (Limits on lifetimes for *bound* neutrons are given in the section "p PARTIAL MEAN LIVES.")

For a review, see EROZOLIMSKII 89 and papers that follow it in an issue of NIM devoted to the "Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons" (Grenoble 1989). For later reviews and/or commentary, see FREEDMAN 90, SCHRECKENBACH 92, and PENDLEBURY 93.

VALUE (s)	DOCUMENT ID		TECN	COMMENT
887.0± 2.0 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.			
882.6± 2.7	[7] MAMPE	93	CNTR	Gravitational trap
888.4± 3.1± 1.1	NESVIZHEV...	92	CNTR	Gravitational trap
893.6± 3.8± 3.7	BYRNE	90	CNTR	Penning trap
878 ±27 ±14	KOSSAKOW...	89	TPC	Pulsed beam
887.6± 3.0	MAMPE	89	CNTR	Gravitational trap
877 ±10	PAUL	89	CNTR	Storage ring
876 ±10 ±19	LAST	88	SPEC	Pulsed beam
891 ± 9	SPIVAK	88	CNTR	Beam
903 ±13	KOSVINTSEV	86	CNTR	Gravitational trap
918 ±14	CHRISTENSEN	72	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
888.4± 2.9	ALFIMENKOV	90	CNTR	See NESVIZHEVSKII 92
937 ±18	[8] BYRNE	80	CNTR	
875 ±95	KOSVINTSEV	80	CNTR	
881 ± 8	BONDAREN...	78	CNTR	See SPIVAK 88

[7] IGNATOVICH 95 calls into question some of the corrections and averaging procedures used by MAMPE 93. If MAMPE 93 is removed from the data averaged here, our new average is 889.2 ± 2.2 s, with a scale factor of 1.1.

[8] This measurement has been withdrawn (J. Byrne, private communication, 1990).



n MAGNETIC MOMENT

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
−1.91304275±0.00000045	COHEN	87	RVUE	1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−1.91304277±0.00000048	[9] GREENE	82	MRS	

[9] GREENE 82 measures the moment to be $(1.04187564 \pm 0.00000026) \times 10^{-3}$ Bohr magnetons. The value above is obtained by multiplying this by $m_p/m_e = 1836.152701 \pm 0.000037$ (the 1986 CODATA value from COHEN 87).

n ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance. A number of early results have been omitted. See RAMSEY 90 and GOLUB 94 for reviews.

VALUE (10^{-25} ecm)	CL%	DOCUMENT ID		TECN	COMMENT
< 1.1	95	ALTAREV	92	MRS	$(+0.26\pm0.42\pm0.16)\times10^{-25}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.2	95	SMITH	90	MRS	$d=(-0.3\pm0.5)\times10^{-25}$
< 2.6	95	ALTAREV	86	MRS	$d=(-1.4\pm0.6)\times10^{-25}$
0.3±4.8		PENDLEBURY	84	MRS	Ultracold neutrons
< 6	90	ALTAREV	81	MRS	$d=(2.1\pm2.4)\times10^{-25}$
<16	90	ALTAREV	79	MRS	$d=(4.0\pm7.5)\times10^{-25}$

n ELECTRIC POLARIZABILITY α_n

Following is the electric polarizability α_n defined in terms of the induced electric dipole moment by $\mathbf{D}=4\pi\epsilon_0\alpha_n\mathbf{E}$. For a review, see SCHMIEDMAYER 89.

VALUE (10^{-3} fm^3)	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.98^{+0.19}_{-0.23}}$ **OUR AVERAGE**	Error includes scale factor of 1.1.			
0.0 ±0.5	[10] KOESTER	95	CNTR	*n* Pb, *n* Bi transmission
1.20±0.15±0.20	SCHMIEDM...	91	CNTR	*n* Pb transmission
$1.07^{+0.33}_{-1.07}$	ROSE	90B	CNTR	$\gamma d\to\gamma np$
0.8 ±1.0	KOESTER	88	CNTR	*n* Pb, *n* Bi transmission
1.2 ±1.0	SCHMIEDM...	88	CNTR	*n* Pb, *n* C transmission
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.17^{+0.43}_{-1.17}$	ROSE	90	CNTR	See ROSE 90B

[10] KOESTER 95 uses natural Pb and the isotopes 208, 207, and 206. See this paper for a discussion of methods used by various groups to extract α_n from data.

n CHARGE

See also "$|q_p+q_e|/e$" in the proton Listings.

VALUE (10^{-21} e)	DOCUMENT ID		TECN	COMMENT
− 0.4± 1.1	[11] BAUMANN	88		Cold *n* deflection
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−15 ±22	[12] GAEHLER	82	CNTR	Reactor neutrons

[11] The BAUMANN 88 error ±1.1 gives the 68% CL limits about the the value −0.4.
[12] The GAEHLER 82 error ±22 gives the 90% CL limits about the the value −15.

LIMIT ON $n\overline{n}$ OSCILLATIONS

Mean Time for $n\overline{n}$ Transition in Vacuum

A test of ΔB=2 baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\overline{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, and ALBERICO 91 for discussions. Direct searches for $n\to\overline{n}$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table.

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{>1.2\times10^8}$	90	BERGER	90	FREJ	*n* bound in iron
$\mathbf{>1.2\times10^8}$	90	TAKITA	86	CNTR	Kamiokande
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>8.6\times10^7$	90	BALDO-...	94	CNTR	Reactor neutrons
$>1\ \times10^7$	90	BALDO-...	90	CNTR	See BALDO-CEOLIN 94
$>4.9\times10^5$	90	BRESSI	90	CNTR	Reactor neutrons
$>4.7\times10^5$	90	BRESSI	89	CNTR	See BRESSI 90
$>1\ \times10^6$	90	FIDECARO	85	CNTR	Reactor neutrons
$>8.8\times10^7$	90	PARK	85B	CNTR	
$>3\ \times10^7$		BATTISTONI	84	NUSX	
$>2.7\times10^7$–1.1×10^8		JONES	84	CNTR	
$>2\ \times10^7$		CHERRY	83	CNTR	

n DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$pe^-\overline{\nu}_e$	100 %	
Γ_2	hydrogen-atom $\overline{\nu}_e$		
	Charge conservation (*Q*) violating mode		
Γ_3	$p\nu_e\overline{\nu}_e$	*Q* $<\ 9\times10^{-24}$	90%

n BRANCHING RATIOS

Γ(hydrogen-atom $\overline{\nu}_e$)/Γ_{total} Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN
$<3\times10^{-2}$	95	[13] GREEN	90	RVUE

[13] GREEN 90 infers that τ(hydrogen-atom $\overline{\nu}_e$) > 3×10^4 s by comparing neutron lifetime measurements made in storage experiments with those made in β-decay experiments. However, the result depends sensitively on the lifetime measurements, and does not of course take into account more recent measurements of same.

$\Gamma(p\nu_e\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_3/Γ

Forbidden by charge conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{<9\ \times10^{-24}}$	90	BARABANOV	80	CNTR	^{71}Ga → ^{71}GeX
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<9.7\times10^{-18}$	90	ROY	83	CNTR	^{113}Cd → ^{113m}In neut.
$<7.9\times10^{-21}$		VAIDYA	83	CNTR	^{87}Rb → ^{87m}Sr neut.
$<3\ \times10^{-19}$		NORMAN	79	CNTR	^{87}Rb → ^{87m}Sr neut.

NOTE ON BARYON DECAY PARAMETERS

(by E.D. Commins, University of California, Berkeley)

Baryon semileptonic decays

The typical spin-1/2 baryon semileptonic decay is described by a matrix element, the hadronic part of which may be written as:

$$\overline{B}_f\left[f_1(q^2)\gamma_\lambda+i\ f_2(q^2)\sigma_{\lambda\mu}q^\mu+g_1(q^2)\gamma_\lambda\gamma_5+g_3(q^2)\gamma_5q_\lambda\right]B_i\ .$$

Here B_i and $\overline{B}_f$ are spinors describing the initial and final baryons, and $q=p_i-p_f$, while the terms in f_1, f_2, g_1, and g_3 account for vector, induced tensor ("weak magnetism"), axial vector, and induced pseudoscalar contributions [1]. Second-class current contributions are ignored here. In the limit of zero momentum transfer, f_1 reduces to the vector coupling constant g_V, and g_1 reduces to the axial-vector coupling constant g_A. The latter coefficients are related by Cabibbo's theory [2], generalized to six quarks (and three mixing angles) by Kobayashi and Maskawa [3]. The g_3 term is negligible for transitions in which an $e^\pm$ is emitted, and gives a very small correction, which can be estimated by PCAC [4], for $\mu^\pm$ modes. Recoil effects include weak magnetism, and are taken into account adequately by considering terms of first order in

$$\delta=\frac{m_i-m_f}{m_i+m_f}\ ,$$

where m_i and m_f are the masses of the initial and final baryons.

The experimental quantities of interest are the total decay rate, the lepton-neutrino angular correlation, the asymmetry coefficients in the decay of a polarized initial baryon, and the polarization of the decay baryon in its own rest frame for an unpolarized initial baryon. Formulae for these quantities are derived by standard means [5] and are analogous to formulae for nuclear beta decay [6]. We use the notation of Ref. 6 in the Listings for neutron beta decay. For comparison with experiments at higher q^2, it is necessary to modify the form factors at $q^2=0$ by a "dipole" q^2 dependence, and for high-precision comparisons to apply appropriate radiative corrections [7].

The ratio g_A/g_V may be written as

$$g_A/g_V=|\,g_A/g_V\,|\,e^{i\phi_{AV}}\ .$$

The presence of a "triple correlation" term in the transition probability, proportional to $\mathrm{Im}(g_A/g_V)$ and of the form

$$\boldsymbol{\sigma}_i\cdot(\mathbf{p}_\ell \times \mathbf{p}_\nu)$$

for initial baryon polarization or

$$\boldsymbol{\sigma}_f\cdot(\mathbf{p}_\ell \times \mathbf{p}_\nu)$$

for final baryon polarization, would indicate failure of time-reversal invariance. The phase angle ϕ has been measured precisely only in neutron decay (and in ^{19}Ne nuclear beta decay), and the results are consistent with T invariance.

Hyperon nonleptonic decays

The amplitude for a spin-1/2 hyperon decaying into a spin-1/2 baryon and a spin-0 meson may be written in the form

$$M = G_F\, m_\pi^2 \cdot \overline{B}_f\,(A - B\gamma_5)\, B_i \ ,$$

where A and B are constants [1]. The transition rate is proportional to

$$R = 1 + \gamma\,\widehat{\boldsymbol{\omega}}_f \cdot \widehat{\boldsymbol{\omega}}_i + (1-\gamma)(\widehat{\boldsymbol{\omega}}_f \cdot \widehat{\mathbf{n}})(\widehat{\boldsymbol{\omega}}_i \cdot \widehat{\mathbf{n}})$$
$$+\ \alpha(\widehat{\boldsymbol{\omega}}_f \cdot \widehat{\mathbf{n}} + \widehat{\boldsymbol{\omega}}_i \cdot \widehat{\mathbf{n}}) + \beta\widehat{\mathbf{n}} \cdot (\widehat{\boldsymbol{\omega}}_f \times \widehat{\boldsymbol{\omega}}_i) \ ,$$

where $\widehat{\mathbf{n}}$ is a unit vector in the direction of the final baryon momentum, and $\widehat{\boldsymbol{\omega}}_i$ and $\widehat{\boldsymbol{\omega}}_f$ are unit vectors in the directions of the initial and final baryon spins. (The sign of the last term in the above equation was incorrect in our 1988 and 1990 editions.) The parameters α, β, and γ are defined as

$$\alpha = 2\,\mathrm{Re}(s^*p)/(\,|\,s\,|^2 + \,|\,p\,|^2) \ ,$$
$$\beta = 2\,\mathrm{Im}(s^*p)/(\,|\,s\,|^2 + \,|\,p\,|^2) \ ,$$
$$\gamma = (\,|\,s\,|^2 - \,|\,p\,|^2)/(\,|\,s\,|^2 + \,|\,p\,|^2) \ ,$$

where $s = A$ and $p = \,|\,\mathbf{p}_f\,|\,B/(E_f + m_f)$; here E_f and $\mathbf{p}_f$ are the energy and momentum of the final baryon. The parameters α, β, and γ satisfy

$$\alpha^2 + \beta^2 + \gamma^2 = 1 \ .$$

If the hyperon polarization is $\mathbf{P}_Y$, the polarization $\mathbf{P}_B$ of the decay baryons is

$$\mathbf{P}_B = \frac{(\alpha + \mathbf{P}_Y \cdot \widehat{\mathbf{n}})\widehat{\mathbf{n}} + \beta(\mathbf{P}_Y \times \widehat{\mathbf{n}}) + \gamma\widehat{\mathbf{n}} \times (\mathbf{P}_Y \times \widehat{\mathbf{n}})}{1 + \alpha\mathbf{P}_Y \cdot \widehat{\mathbf{n}}} \ .$$

Here $\mathbf{P}_B$ is defined in the rest system of the baryon, obtained by a Lorentz transformation along $\widehat{\mathbf{n}}$ from the hyperon rest frame, in which $\widehat{\mathbf{n}}$ and $\mathbf{P}_Y$ are defined.

An additional useful parameter ϕ is defined by

$$\beta = (1 - \alpha^2)^{1/2}\,\sin\!\phi \ .$$

In the Listings, we compile α and ϕ for each decay, since these quantities are most closely related to experiment and are essentially uncorrelated. When necessary, we have changed the signs of reported values to agree with our sign conventions. In the Baryon Summary Table, we give α, ϕ, and Δ (defined below) with errors, and also give the value of γ without error.

Time-reversal invariance requires, in the absence of final-state interactions, that s and p be relatively real, and therefore that $\beta = 0$. However, for the decays discussed here, the final-state interaction is strong. Thus

$$s = \,|\,s\,|\,e^{i\delta_s} \text{ and } p = \,|\,p\,|\,e^{i\delta_p} \ ,$$

where δ_s and δ_p are the pion-baryon s- and p-wave strong interaction phase shifts. We then have

$$\beta = \frac{-2\,|\,s\,|\,\,|\,p\,|}{|\,s\,|^2 + \,|\,p\,|^2}\,\sin(\delta_s - \delta_p) \ .$$

One also defines $\Delta = -\tan^{-1}(\beta/\alpha)$. If T invariance holds, $\Delta = \delta_s - \delta_p$. For $\Lambda \to p\pi^-$ decay, the value of Δ may be compared with the s- and p-wave phase shifts in low-energy $\pi^- p$ scattering, and the results are consistent with T invariance.

Radiative hyperon decays

For the radiative decay of a polarized spin-1/2 hyperon, $B_i \to B_f\gamma$, the angular distribution of the direction $\widehat{p}$ of the final spin-1/2 baryon in the hyperon rest frame is

$$\frac{d\Gamma_\gamma}{d\Omega} = \frac{\Gamma_\gamma}{4\pi}\,(1 + \alpha_\gamma \widehat{p} \cdot \mathbf{P}_i) \ ,$$

where $\mathbf{P}_i$ is the hyperon polarization and the asymmetry parameter α_γ is

$$\alpha_\gamma = \frac{2\mathrm{Re}\left[g_1'(0) f_M^*(0)\right]}{|g_1'(0)|^2 + |f_M(0)|^2} \ .$$

Here $f_M = \dfrac{(m_i - m_f)}{(m_i + m_f)}\left[(m_i + m_f) f_2' - f_1'\right]$, where $f_1'(q^2)$, $f_2'(q^2)$, and $g_1'(q^2)$ are the $\Delta Q = 0$ analogs of the $|\Delta Q| = 1$ form factors defined above.

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$n \to pe^- \bar{\nu}$ DECAY PARAMETERS

See the above "Note on Baryon Decay Parameters." For discussions of recent results, see the references cited at the beginning of the section on the neutron mean life. For discussions of the values of the weak coupling constants g_A and g_V obtained using the neutron and asymmetry parameter *A*, comparisons with other methods of obtaining these constants, and implications for particle physics and for astrophysics, see DUBBERS 91 and WOOLCOCK 91. For tests of the $V-A$ theory of neutron decay, see EROZOLIMSKII 91B.

g_A / g_V

VALUE	DOCUMENT ID		TECN	COMMENT
−1.2601±0.0025 OUR AVERAGE	Error includes scale factor of 1.1.			
−1.266 ±0.004	SCHRECK...	95	TPC	*e* mom-*n* spin corr.
−1.2544±0.0036	EROZOLIM...	91	CNTR	*e* mom-*n* spin corr.
−1.262 ±0.005	BOPP	86	SPEC	*e* mom-*n* spin corr.
−1.261 ±0.012	[14] EROZOLIM...	79	CNTR	*e* mom-*n* spin corr.
−1.259 ±0.017	[14] STRATOWA	78	CNTR	proton recoil spectrum
−1.258 ±0.015	[15] KROHN	75	CNTR	*e* mom-*n* spin corr.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−1.226 ±0.042	MOSTOVOY	83	RVUE	
−1.263 ±0.015	EROZOLIM...	77	CNTR	See EROZOLIMSKII 79
−1.250 ±0.036	[14] DOBROZE...	75	CNTR	See STRATOWA 78
−1.263 ±0.016	[16] KROPF	74	RVUE	*n* decay alone
−1.250 ±0.009	[16] KROPF	74	RVUE	*n* decay + nuclear ft

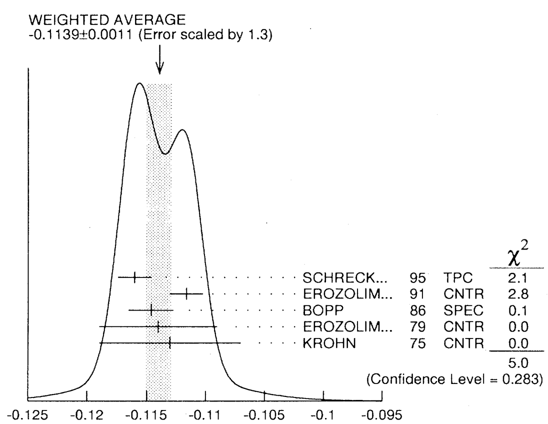
[14] These experiments measure the absolute value of g_A/g_V only.
[15] KROHN 75 includes events of CHRISTENSEN 70.
[16] KROPF 74 reviews all data through 1972.

β ASYMMETRY PARAMETER *A*

This is the neutron-spin electron-momentum correlation coefficient. Unless otherwise noted, the values are corrected for radiative effects and weak magnetism.

VALUE	DOCUMENT ID		TECN	COMMENT
−0.1139±0.0011 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.			
−0.1160±0.0009±0.0011	SCHRECK...	95	TPC	*e* mom-*n* spin corr.
−0.1116±0.0014	EROZOLIM...	91	CNTR	
−0.1146±0.0019	BOPP	86	SPEC	
−0.114 ±0.005	[17] EROZOLIM...	79	CNTR	
−0.113 ±0.006	[17] KROHN	75	CNTR	

[17] These results are not corrected for radiative effects and weak magnetism, but the corrections are small compared to the errors.



β ASYMMETRY PARAMETER *A*

$\bar{\nu}$ ASYMMETRY PARAMETER *B*

This is the neutron-spin antineutrino-momentum correlation coefficient.

VALUE	DOCUMENT ID		TECN	COMMENT
0.990 ±0.008 OUR AVERAGE				
0.9894±0.0083	KUZNETSOV	95	CNTR	Cold polarized neutrons
0.995 ±0.034	CHRISTENSEN	70	CNTR	
1.00 ±0.05	EROZOLIM...	70C	CNTR	

e-$\bar{\nu}$ ANGULAR CORRELATION COEFFICIENT *a*

VALUE	DOCUMENT ID		TECN	COMMENT
−0.102 ±0.005 OUR AVERAGE				
−0.1017±0.0051	STRATOWA	78	CNTR	Proton recoil spectrum
−0.091 ±0.039	GRIGOREV	68	SPEC	Proton recoil spectrum

ϕ_{AV}, PHASE OF g_A RELATIVE TO g_V

Time reversal invariance requires this to be 0 or 180°.

VALUE (°)	DOCUMENT ID		TECN	COMMENT
180.07±0.18 OUR EVALUATION	Using the average value for quantity *D* given in the next data block and $\lambda \equiv g_A/g_V$ in $\sin\phi_{AV} = D(1+3\lambda^2)/2\lambda$.			
180.09±0.18 OUR AVERAGE				
179.71±0.39	EROZOLIM...	78	CNTR	Polarized neutrons
180.35±0.43	EROZOLIM...	74	CNTR	Polarized neutrons
180.14±0.22	STEINBERG	74	CNTR	Polarized neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •				
181.1 ±1.3	[18] KROPF	74	RVUE	*n* decay

[18] KROPF 74 reviews all data through 1972.

TRIPLE CORRELATION COEFFICIENT *D*

These are measurements of the component of *n* spin perpendicular to the decay plane in β decay. Should be zero if *T* invariance is not violated.

VALUE	DOCUMENT ID		TECN	COMMENT
(−0.5 ±1.4) × 10⁻³ OUR AVERAGE				
+ 0.0022±0.0030	EROZOLIM...	78	CNTR	Polarized neutrons
− 0.0027±0.0050	[19] EROZOLIM...	74	CNTR	Polarized neutrons
− 0.0011±0.0017	STEINBERG	74	CNTR	Polarized neutrons

[19] EROZOLIMSKII 78 says asymmetric proton losses and nonuniform beam polarization may give a systematic error up to 0.003, thus increasing the EROZOLIMSKII 74 error to 0.005. STEINBERG 74 and STEINBERG 76 estimate these systematic errors to be insignificant in their experiment.

n REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

IGNATOVICH 95 JETPL 62 1 (JINR)
Translated from ZETFP 62 3.
KOESTER 95 PR C51 3363 +Waschkowski, Mitsyna+ (MUNT, JINR, LATV)
KUZNETSOV 95 PRL 75 794 +Serebrov, Stepanenko+ (PNPI, KIAE, HARV, NIST)
SCHRECK... 95 PL B349 427 Schreckenbach, Liaud+ (MUNT, ILLG, LAPP)
BALDO-... 94 ZPHY C63 409 Baldo-Ceolin, Benetti+ (HEID, ILLG, PADO, PAVI)
DIFILIPPO 94 PRL 73 1481 +Natarajan, Boyce, Pritchard (MIT)
Also 93 PRL 71 1998 Natarajan, Boyce, DiFilippo, Pritchard (MIT)
GOLUB 94 PRPL 237C 1 +Lamoreaux (HAHN, WASH)
MAMPE 93 JETPL 57 82 +Bondarenko, Morozov+ (KIAE)
Translated from ZETFP 57 77.
PENDLEBURY 93 ARNPS 43 687 (ILLG)
ALTAREV 92 PL B276 242 +Borisov, Borovikova, Ivanov+ (PNPI)
NESVIZHEV... 92 JETP 75 405 Nesvizhevskii, Serebrov, Tal'daev+ (PNPI, JINR)
Translated from ZETF 102 740.
SCHRECK... 92 JPG 18 1 Schreckenbach, Mampe (ILLG)
ALBERICO 91 NP A523 488 +de Pace, Pignone (TORI)
DUBBERS 91 NP A527 239c (ILLG)
Also 90 EPL 11 195 Dubbers, Mampe, Doehner (ILLG, HEID)
EROZOLIM... 91 PL B263 33 Erozolimskii, Kuznetsov, Stepanenko, Kuida+ (PNPI, KIAE)
Also 90 SJNP 52 999 Erozolimskii, Kuznetsov, Stepanenko, Kuida+ (PNPI, KIAE)
Translated from YAF 52 1583.
EROZOLIM... 91B SJNP 53 260 Erozolimskii, Mostovoi (KIAE)
Translated from YAF 53 418.
SCHMIEDM... 91 PRL 66 1015 Schmiedmayer, Riehs, Harvey, Hill (TUW, ORNL)
WOOLCOCK 91 MPL A6 2579 (CANB)
ALFIMENKOV 90 JETPL 52 373 +Varlamov, Vasil'ev, Gudkov+ (PNPI, JINR)
Translated from ZETFP 52 984.
BALDO-... 90 PL B236 95 Baldo-Ceolin, Benetti, Bitter+ (PADO, PAVI, HEIDP, ILLG)
BERGER 90 PL B240 237 +Froehlich, Moench, Nisius+ (FREJUS Collab.)
BRESSI 90 NC 103A 731 +Calligarich, Cambiaghi+ (PAVI, ROMA, MILA)
BYRNE 90 PRL 65 289 +Dawber, Spain, Williams+ (SUSS, NBS, SCOT, CBNM)
FREEDMAN 90 CNPP 19 209 (ANL)
GREEN 90 JPG 16 L75 +Thompson (RAL)
RAMSEY 90 ARNPS 40 1 (HARV)
ROSE 90 PL B234 460 +Zurmuehl, Rullhusen, Ludwig+ (GOET, MPCM, MANZ)
ROSE 90B NP A514 621 +Zurmuehl, Rullhusen, Ludwig+ (GOET, MPCM)
SMITH 90 PL B234 191 +Crampin+ (SUSS, RAL, HARV, WASH, ILLG, MUNT)
BRESSI 89 ZPHY C43 175 +Calligarich, Cambiaghi+ (INFN, MILA, PAVI, ROMA)
DOVER 89 NIM A284 13 +Gal, Richard (BNL, HEBR, ISNG)
EROZOLIM... 89 NIM A284 89 Erozolimskii (PNPI)
KOSSAKOW... 89 NP A503 473 Kossakowski, Grivot+ (LAPP, SAVO, ISNG, ILLG)
MAMPE 89 PRL 63 593 +Ageron, Bates, Pendlebury, Steyerl (ILLG, RISL, SUSS, URI)
MOHAPATRA 89 NIM A284 1 (UMD)
PAUL 89 ZPHY C45 25 +Anton, Paul, Paul, Mampe (BONN, WUPP, MPIH, ILLG)
SCHMIEDM... 89 NIM A284 137 Schmiedmayer, Rauch, Riehs (WIEN)
BAUMANN 88 PR D37 3107 +Gaehler, Kalus, Mampe (BAYR, MUNI, ILLG)
KOESTER 88 ZPHY A329 229 +Waschkowski, Meier (MUNI, MUNT)
LAST 88 PRL 60 995 +Arnold, Doehner, Dubbers+ (HEIDP, ILLG, ANL)
SCHMIEDM... 88 PRL 61 1065 Schmiedmayer, Rauch, Riehs (TUW)
Also 88B PRL 61 2509 erratum Schmiedmayer, Rauch, Riehs (TUW)
SPIVAK 88 JETP 67 1735 (KIAE)
Translated from ZETF 94 1.
COHEN 87 RMP 59 1121 +Taylor (RISC, NBS)
ALTAREV 86 JETPL 44 460 +Borisov, Borovikova, Brandin, Egorov+ (PNPI)
Translated from ZETFP 44 360.
BOPP 86 PRL 56 919 +Dubbers, Hornig, Klemt, Last+ (HEIDP, ANL, ILLG)
Also 88 ZPHY C37 179 Klemt, Bopp, Hornig, Last+ (HEIDP, ANL, ILLG)
CRESTI 86 PL B177 206 +Pasquali, Peruzzo, Pinori, Sartori (PADO)
Also 88 PL B200 587 erratum Cresti, Pasquali, Peruzzo, Pinori, Sartori (PADO)
GREENE 86 PRL 56 819 +Kessler, Deslattes, Boerner (NBS, ILLG)
KOSVINTSEV 86 JETPL 44 571 +Morozov, Terekhov (KIAE)
Translated from ZETFP 44 444.
TAKITA 86 PR D34 902 +Arisaka, Kajita, Kifune+ (KEK, TOKY+)
DOVER 85 PR C31 1423 +Gal, Richard (BNL)
FIDECARO 85 PL 156B 122 +Lanceri+ (CERN, ILLG, PADO, RAL, SUSS)
PARK 85B NP B252 261 +Blewitt, Cortez, Foster+ (IMB Collab.)
BATTISTONI 84 PL 133B 454 +Bellotti, Bologna, Campana+ (NUSEX Collab.)
JONES 84 PRL 52 720 +Bionta, Blewitt, Bratton+ (IMB Collab.)
PENDLEBURY 84 PL 136B 327 +Smith, Golub, Byrne+ (SUSS, HARV, RAL, ILLG)
CHERRY 83 PRL 50 1354 +Lande, Lee, Steinberg, Cleveland (PENN, BNL)
DOVER 83 PR D27 1090 +Gal, Richards (BNL)
KABIR 83 PRL 51 231 (HARV)
MOSTOVOY 83 JETPL 37 196 (KIAE)
Translated from ZETFP 37 162.

ROY 83 PR D28 1770 +Vaidya, Ephraim, Datar, Bhatki+ (TATA)
VAIDYA 83 PR D27 486 +Roy, Ephraim, Datar, Bhattacherjee (TATA)
GAEHLER 82 PR D25 2887 +Kalus, Mampe (BAYR, ILLG)
GREENE 82 Metrologia 18 93 + (YALE, HARV, ILLG, SUSS, ORNL, CENG)
ALTAREV 81 PL 102B 13 +Borisov, Borovikova, Brandin, Egorov+ (PNPI)
BARABANOV 80 JETPL 32 359 +Veretenkin, Gavrin+ (PNPI)
Translated from ZETFP 32 384.
BYRNE 80 PL 92B 274 +Morse, Smith, Shaikh, Green, Greene (SUSS, RL)
KOSVINTSEV 80 JETPL 31 236 +Kushnir, Morozov, Terekhov (JINR)
Translated from ZETFP 31 257.
MOHAPATRA 80 PRL 44 1316 +Marshak (CUNY, VPI)
ALTAREV 79 JETPL 29 730 +Borisov, Brandin, Egorov, Ezhov, Ivanov+ (PNPI)
Translated from ZETFP 29 794.
EROZOLIM... 79 SJNP 30 356 Erozolimskii, Frank, Mostovoy+ (KIAE)
Translated from YAF 30 692.
NORMAN 79 PRL 43 1226 +Seamster (WASH)
BONDAREN... 78 JETPL 28 303 Bondarenko, Kurguzov, Prokofev+ (KIAE)
Translated from ZETFP 28 328.
Also 82 Smolenice Conf. Bondarenko (KIAE)
EROZOLIM... 78 SJNP 28 48 Erozolimskii, Mostovoy, Fedunin, Frank+ (KIAE)
Translated from YAF 28 98.
STRATOWA 78 PR D18 3970 +Dobrozemsky, Weinzierl (SEIB)
EROZOLIM... 77 JETPL 23 663 Erozolimskii, Frank, Mostovoy+ (KIAE)
Translated from ZETFP 23 720.
STEINBERG 76 PR D13 2469 +Liaud, Vignon, Hughes (YALE, ISNG)
DOBROZE... 75 PR D11 510 Dobrozemsky, Kerschbaum, Moraw, Paul+ (SEIB)
KROHN 75 PL 55B 175 +Ringo (ANL)
EROZOLIM... 74 JETPL 20 345 Erozolimskii, Mostovoy, Fedunin, Frank+
Translated from ZETFP 20 745.
KROPF 74 ZPHY 267 129 +Paul (LINZ)
Also 70 NP A154 160 Paul (VIEN)
STEINBERG 74 PRL 33 41 +Liaud, Vignon, Hughes (YALE, ISNG)
COHEN 73 JPCRD 2 663 +Taylor (RISC, NBS)
CHRISTENSEN 72 PR D5 1628 +Nielson, Bahnsen, Brown+ (RISO)
CHRISTENSEN 70 PR C1 1693 +Krohn, Ringo (ANL)
EROZOLIM... 70C PL 33B 351 Erozolimskii, Bondarenko, Mostovoy, Obinyakov+ (KIAE)
GRIGOREV 68 SJNP 6 239 Grigor'ev, Grishin, Vladimirsky, Nikolaevskii+ (ITEP)
Translated from YAF 6 329.

NOTE ON N AND Δ RESONANCES

I. Introduction

The excited states of the nucleon have been studied in a large number of formation and production experiments. The masses, widths, and elasticities of the N and Δ resonances in the Baryon Summary Table come almost entirely from partial-wave analyses of πN total, elastic, and charge-exchange scattering data (Sec. II). Partial-wave analyses have also been performed on much smaller data sets to get $N\eta$, ΛK, and ΣK branching fractions. Other branching fractions come from isobar-model analyses of $\pi N \to N\pi\pi$ data (Sec. III). Finally, many $N\gamma$ branching fractions have been determined from photoproduction experiments (Sec. IV).

Table 1 lists all the N and Δ entries in the Baryon Listings and gives our evaluation of the status of each, both overall and channel by channel. Only the "established" resonances (overall status 3 or 4 stars) appear in the Baryon Summary Table. We consider a resonance to be established only if it has been seen in at least two independent analyses of elastic scattering and if the relevant partial-wave amplitudes do not behave erratically or have large uncertainties.

The Baryon Particle Listings give, in addition to the usual Breit-Wigner parameters, the positions and residues of the nearest poles of the resonant partial waves on the second sheet of the complex energy plane. These come from $\pi N \to \pi N$ partial-wave analyses and from a $\pi N \to N\pi\pi$ isobar-model analysis (Sec. III).

The interested reader will find further discussions in two extensive (but now somewhat dated) reviews [1,2] and in the *Proceedings of the 6th International Symposium on Meson-Nucleon Physics and the Structure of the Nucleon* [3].

(References for this Section are at the end of Sec. II.)

Table 1. The status of the N and Δ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

			Status as seen in —						
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*	*					
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	***	***	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	e		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r				**	
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*	d					
$\Delta(2390)$	F_{37}	*	*	e					
$\Delta(2400)$	G_{39}	**	**	n					
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

II. Elastic partial-wave analyses and resonance parameters

(by R.L. Workman, Virginia Polytechnic Institute and State University)

A general discussion was given in previous editions [4]. In the following, we only consider new results.

New data: Experimental activity over the past two years has mainly concentrated on the region below 600 MeV [5]. Some of these data remain in preliminary form. The new pionic atom measurement [6] from PSI is particularly interesting as it has updated the πN scattering lengths used in dispersion relations. An experiment at the ITEP accelerator has measured spin-rotation parameters for $\pi^+ p$ elastic scattering at 1.43 GeV/c [7]. The results are surprising, as they strongly contradict predictions from the CMU-Berkeley (CMB) [8] and Karlsruhe-Helsinki (KH) [9] analyses. More spin-rotation measurements are planned for this energy region.

New Partial-Wave Analyses: The VPI group has updated its resonance parameters [10]. The new determinations are based upon a partial-wave analysis with fixed-t dispersion relation constraints. A search was made for 'small' structures, and two new resonance candidates were found. Discrepancies between this analysis and the CMB [8] and KH [9] analyses still exist.

Batinić *et al.* [11] have used a coupled-channel model to describe the elastic πN amplitudes together with data for $\pi N \to \eta N$. One variant of this model contains two additional (S_{11} and P_{11}) resonances with masses near 1750 MeV. The extra S_{11} resonance is similar to one of the small structures found in the VPI analysis. While there is other circumstantial evidence [12] for this state, further verification is needed.

The Petersburg analysis [13] is now published. The associated preprint was described in the 1992 review. While the published version does not report some of the higher partial waves, the partial-wave solutions are identical.

Resonance Parameters: Höhler has generated pole parameters for the KH solution using the speed-plot method. This study is continuing [14]. Manley [15] has related and compared the pole and Breit-Wigner parameters from the KSU [16], CMB [8], KH [9], and VPI [10] analyses. Good agreement was found for the $\Delta(1232)\,P_{33}$, $N(1520)\,D_{13}$, $N(1650)\,S_{11}$, $N(1675)\,D_{15}$, $N(1680)\,F_{15}$, and $\Delta(1950)\,F_{37}$ pole parameters. The most recent VPI analysis has added a small structure to the high-energy shoulder of the $N(1650)\,S_{11}$. As a result, the associated parameters have changed significantly.

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III. Inelastic two-body and quasi-two-body reactions

(by D.M. Manley, Kent State University)

Since the last edition, no new data nor partial-wave analyses have been published for the inelastic two-body reactions $\pi N \to \Lambda K$ and $\pi N \to \Sigma K$. However, new data *have* been measured and a new analysis published for the $\pi N \to N\eta$ reaction. In particular, an experiment [1] that measured the cross section for $\pi^- p \to n\eta$ from threshold to $p_\pi = 750$ MeV/c ($\sqrt{s} = 1527$ MeV) was recently completed using the AGS at Brookhaven National Laboratory. In addition, the same collaboration also measured the cross section for $K^- p \to \Lambda\eta$. The data from these measurements are currently being analyzed.

A new energy-dependent partial-wave analysis of the reaction $\pi N \to N\eta$ has also been published [2]. The analysis used a coupled three-channel model to describe reactions involving the $N\pi$ and $N\eta$ channels simultaneously. (The third channel was an effective nonphysical two-body $N\pi\pi$ channel.) The eight lowest $I = \frac{1}{2}$ $\pi N \to N\eta$ partial waves were fitted up to a c.m. energy of 2.5 GeV using the πN elastic amplitudes from the Karlsruhe-Helsinki partial-wave analysis [3] as part of the input data base.

Essentially all information on quasi-two-body reactions such as $\pi N \to \Delta\pi$ and $\pi N \to N\rho$ comes from isobar-model analyses of $\pi N \to N\pi\pi$ reactions. Since the last edition, no new analysis of these reactions has been published. A brief review of $\pi N \to N\pi\pi$ analyses can be found in our 1992 edition; for a more recent and extensive review, the interested reader should see [4].

Since the last edition, two new narrow resonance candidates were observed in experiments investigating the diffractive production of hadrons by 70-GeV protons at the SPHINX facility of the IHEP accelerator [5]. In the reaction on carbon nuclei, $p + C \to [\Sigma(1385)^0 K^+] + C$, evidence was found for an $N(2050)$ with mass $M = (2052 \pm 6)$ MeV and width $\Gamma = 35^{+22}_{-35}$ MeV. In the reaction, $p + C \to [\Sigma^0 K^+] + C$, evidence was found for an $N(2000)$ with $M = 1999 \pm 6$ MeV and $\Gamma = 91 \pm 17$ MeV.

The small decay widths and large branching ratios for decays involving hyperons make these states candidates for exotic $qqqs\bar{s}$ baryons. Further evidence suggesting the possible existence of narrow exotic baryons was found by a recent analysis of photographic data obtained during irradiation of the 2-meter hydrogen bubble chamber at CERN by a 16-GeV/c π^- beam [6]. A narrow peak that may be due to the production of a neutral baryon with $M = 3521 \pm 3$ MeV and $\Gamma = 6^{+21}_{-6}$ MeV was observed in the invariant mass spectrum of the $K^0_s K^+ p \pi^- \pi^-$ system.

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IV. Electromagnetic interactions

(by R.L. Crawford, University of Glasgow)

Nearly all the entries in the Listings relating to electromagnetic properties of the N and Δ resonances are $N\gamma$ couplings. These couplings, the helicity amplitudes $A_{1/2}$ and $A_{3/2}$, have been obtained in a large number of partial-wave analyses of single-pion photoproduction, $\gamma N \to \pi N$, on protons and neutrons. The large amount of data has permitted an accurate evaluation of the couplings for many of the resonances with masses below 2 GeV, and has given at least qualitative information about most of the others. Most photoproduction analyses take as input the existence, masses, and widths of the resonances derived from the $\pi N \to \pi N$ analyses, and only determine the $N\gamma$ couplings. In addition to the pion photoproduction analyses, a few couplings have been extracted from η photoproduction and from Compton scattering. A brief description of the various methods of analysis of photoproduction data may be found in our 1992 edition [1].

Our Listings omit a number of analyses that are now obsolete. Most of the older results may be found in our 1982 edition [2]. The errors quoted for the couplings in the Listings are calculated in different ways in different analyses and therefore should be used with care. In general, the systematic differences between the analyses caused by using different parametrization schemes are probably more indicative of the true uncertainties than are the quoted errors.

Probably the most reliable analyses are ARAI 80, CRAWFORD 80, AWAJI 81, FUJII 81, CRAWFORD 83, and ARNDT 96. The Listings include our estimates of the couplings, using the results of these analyses. The errors we give are a combination of the stated statistical errors on the analyses and the systematic differences between them. The analyses are given equal weight, except ARNDT 96 is weighted, rather arbitrarily, by a factor of two because its data set is at least 50% larger than those of the other analyses and contains many new high-quality measurements.

The Baryon Summary Table gives $N\gamma$ branching fractions for those resonances whose couplings are considered to be reasonably well established. The $N\gamma$ partial width Γ_γ is given in terms of the helicity amplitudes $A_{1/2}$ and $A_{3/2}$ by

$$\Gamma_\gamma = \frac{k^2}{\pi} \frac{2M_N}{(2J+1)M_R} \left[|A_{1/2}|^2 + |A_{3/2}|^2 \right] .$$

Here M_N and M_R are the nucleon and resonance masses, J is the resonance spin, and k is the photon c.m. decay momentum.

The Listings include results of several new analyses of the $N(1535) \to N\gamma$ couplings obtained using recent accurate measurements of the reaction $\gamma N \to N\eta$ near threshold.

Burkert and Elouadrhiri [4] report the result of an analysis of π^0 electroproduction on protons at a virtual photon mass of $Q^2 = -3.2$ (GeV/c)^2 using data from DESY. They evaluated the ratio of electric quadrupole and scalar quadrupole to magnetic dipole amplitudes for the $\Delta(1232)$. Their values,

$$E_{1+}/M_{1+} = 0.06 \pm 0.02 \pm 0.03$$

and

$$S_{1+}/M_{1+} = 0.07 \pm 0.02 \pm 0.03 ,$$

agree with typical quark model predictions and are qualitatively similar to those obtained from previous analyses for smaller values of $|Q^2|$. They disagree with the predictions from perturbative QCD that $E_{1+}/M_{1+} \to 1$ and $S_{1+}/M_{1+} \to 0$ at large $|Q^2|$.

Mart, Bennhold, and Hyde-Wright [5] apply isobar models developed for $\gamma p \to K^+ \Sigma^0$ and $\gamma p \to K^+ \Lambda$ to $\gamma p \to K^0 \Sigma^+$ and $\gamma n \to K^- \Sigma^+$ and find that they can drastically overpredict the measurements. Including the data for charged Σ production results in drastically reduced values for the Born-term couplings, $g_{K\Sigma N}$ and $g_{K\Lambda N}$, to values well below the SU(3) predictions and values obtained from hadronic processes. The resulting description of the process is resonance dominated. They point out the importance for future analyses of including data for all channels. Their results are not included in the Listings because of the scatter of the values obtained.

Additional information about recent results for the electromagnetic interactions may be found in our 1992 and 1994 editions [1,3]. These include Compton scattering, $K\Lambda$ photoproduction, pion electroproduction, the E2/M1 ratio, and the magnetic moment of the $\Delta(1232)$.

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V. Outlook

(by D.M. Manley, Kent State University)

Much new data related to the study of nucleon resonances will soon come from experiments with electromagnetic probes at CEBAF, which can provide beams of electrons to three experimental halls (A, B, and C) with energies up to 4 GeV. Experiments are now being carried out in Hall C and the commissioning experiments for Hall A are expected to run in mid 1996. The majority of experiments to study nucleon resonances will be carried out in Hall B, which is expected to be completed in late 1996. A very short summary of the experimental program in Hall B can be found in our last edition.

New experiments to study nucleon resonances at European laboratories are already producing interesting results. For example, measurements of total cross sections for the reaction $\gamma p \to p\eta$ at eight c.m. energies between 1487 and 1493 MeV were performed at the ELSA electron facility at Bonn [1] by solely detecting the recoil proton. In addition, very precise measurements of total and differential cross sections for $\gamma p \to p\eta$ from threshold to 1537 MeV (c.m. energy) were performed using the MAMI accelerator in Mainz [2] with the neutral meson spectrometer TAPS. Other facilities are or will be involved in such programs using hadronic beams. For example, two experiments were approved in 1995 to study baryon spectroscopy at the AGS of Brookhaven National Laboratory. The processes, $\pi^- p \to n\eta$, $K^- p \to \Lambda\eta$, and $K^- p \to \Sigma^0\eta$, among others, will be studied by using the Crystal Ball detector (formerly located at SLAC) to identify multiphoton final states [3,4]. As by-products of these investigations, new and improved data also will be obtained for $\pi^- p \to n\pi^0$, and for the inverse photoproduction reactions, $K^- p \to \Lambda\gamma$ and $K^- p \to \Sigma^0\gamma$.

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VI. Non-qqq baryon candidates

The standard quark-model assignments for baryons are outlined in Sec. 12.3 "Baryons: qqq states". As in the meson spectrum (see the "Note on Non-$q\bar{q}$ mesons"), there have been suggestions that some states fall outside this assignment scheme. These include hybrid ($qqqg$) baryons and unstable meson-nucleon bound states [1] (see the "Note on the $\Lambda(1405)$").

If non-qqq states exist, they will be more difficult to verify than hybrid mesons. Hybrid baryons would not have the clean signature of exotic quantum numbers. They should also mix with ordinary qqq states. The identification of such states will be based upon (a) characteristics of their formation and decay, and (b) an over-population of expected qqq states.

Most investigations have focused on the properties of the lightest predicted hybrids. If the first hybrid state lies below 2 GeV, as is suggested by bag-model calculations [2,3,4], it may already exist in the Baryon Particle Listings. (Note, however, that some estimates [5] put the lightest state significantly above 2 GeV.) At present, there are actually not enough known resonances to fill the known multiplets. This is the 'missing resonance' problem. If an existing resonance is identified as a hybrid, we must also account for the expected qqq state.

The Roper resonance, $N(1440)\,P_{11}$, has been considered as a hybrid candidate based upon its quantum numbers [2] and difficulties with its mass and electromagnetic couplings. If so, this would alter our interpretation of the low-lying P_{11}, P_{13}, P_{31}, and P_{33} resonances [2,6]. In Ref. 6, both the $N(1440)\,P_{11}$ and $\Delta(1600)\,P_{33}$ are hybrid candidates, and the $N(1540)\,P_{13}$ and $\Delta(1550)\,P_{31}$ states are predicted. The P_{13} and P_{31} (1-star) states were listed in the 1990 RPP [7] but were removed from the listings in 1992 [8].

Both photoproduction [6,9,10] and electroproduction [10,11] have been considered in the search for a unique hybrid signature. In Ref. 12, QCD counting rules were used to reveal a characteristic of hybrid electroproduction at high Q^2. If the Roper is a hybrid, its transverse form factor is expected to fall asymptotically $O(1/Q^2)$ faster than a pure qqq state. However, mixing between qqq and $qqqg$ states will make this identification more difficult.

A number of recent experiments have searched for pentaquark ($qqqq\bar{q}$) resonances and H-dibaryon (six-quark $uuddss$ states). Narrow structures found in proton-nucleus scattering [13] have been attributed to $qqqs\bar{s}$ states (see Sec. III), but these require confirmation. The H-dibaryon experiments, while finding possible candidates, have generally quoted upper limits [14] for exotic resonance production. Searches for narrow dibaryons in the nucleon-nucleon interaction are also continuing [15].

For an extensive review of exotic hadrons, see Landsberg [16].

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$N(1440)\ P_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(1440) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1430 to 1470 (≈ 1440) OUR ESTIMATE				
1462±10	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1440±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1410±12	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1463± 7	ARNDT	96	IPWA	$\gamma N \to \pi N$
1467	ARNDT	95	DPWA	$\pi N \to N\pi$
1421±18	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
1465	LI	93	IPWA	$\gamma N \to \pi N$
1471	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
1411	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1472	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
1417	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1460	BERENDS	77	IPWA	$\gamma N \to \pi N$
1380	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1390	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1440) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
250 to 450 (≈ 350) OUR ESTIMATE				
391± 34	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
545±170	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
340± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
135± 10	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
360± 20	ARNDT	96	IPWA	$\gamma N \to \pi N$
440	ARNDT	95	DPWA	$\pi N \to N\pi$
250± 63	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$
315	LI	93	IPWA	$\gamma N \to \pi N$
334	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
113	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
331	BARBOUR	78	DPWA	$\gamma N \to \pi N$
279	BERENDS	77	IPWA	$\gamma N \to \pi N$
200	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
200	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1440) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1346	[4] ARNDT	95	DPWA	$\pi N \to N\pi$
1385	[5] HOEHLER	93	SPED	$\pi N \to \pi N$
1370	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
1375±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1360	[6] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1381 or 1379	[7] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1360 or 1333	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
176	[4] ARNDT	95	DPWA	$\pi N \to N\pi$
164	[5] HOEHLER	93	SPED	$\pi N \to \pi N$
228	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
180±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
252	[6] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
209 or 210	[7] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
167 or 234	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1440) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
42	[4] ARNDT	95	DPWA	$\pi N \to N\pi$
40	HOEHLER	93	SPED	$\pi N \to \pi N$
74	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
52±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
109	[6] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−101	[4] ARNDT	95	DPWA	$\pi N \to N\pi$
− 84	CUTKOSKY	90	IPWA	$\pi N \to \pi N$
−100±35	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
− 93	[6] ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1440) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	60–70 %
Γ_2	$N\eta$	
Γ_3	$N\pi\pi$	30–40 %
Γ_4	$\Delta\pi$	20–30 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$N\rho$	<8 %
Γ_7	$N\rho$, S=1/2, P-wave	
Γ_8	$N\rho$, S=3/2, P-wave	
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–10 %
Γ_{10}	$p\gamma$	0.035–0.048 %
Γ_{11}	$p\gamma$, helicity=1/2	0.035–0.048 %
Γ_{12}	$n\gamma$	0.009–0.032 %
Γ_{13}	$n\gamma$, helicity=1/2	0.009–0.032 %

N(1440) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.6 to 0.7 OUR ESTIMATE				
0.69±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.68±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.51±0.05	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.68	ARNDT	95	DPWA	$\pi N \to N\pi$
0.56±0.08	BATINIC	95	DPWA	$\pi N \to N\pi, N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	[1] BAKER	79	DPWA	$\pi^- p \to n\eta$
+0.328	[8] FELTESSE	75	DPWA	1488–1745 MeV

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to \Delta(1232)\pi$, *P*-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.37 to +0.41 OUR ESTIMATE				
+0.39±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.41	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.37	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to N\rho$, S=1/2, *P*-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.07 to ±0.25 OUR ESTIMATE				
−0.11	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.23	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to N\rho$, S=3/2, *P*-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.18	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1440) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.17 to ±0.25 OUR ESTIMATE				
+0.24±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.18	[2,9] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.23	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1440)$ PHOTON DECAY AMPLITUDES

$N(1440) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.065 ±0.004 OUR ESTIMATE				
−0.063 ±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.069 ±0.018	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.063 ±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.069 ±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.066 ±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.079 ±0.009	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
−0.068 ±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.0584±0.0148	ISHII	80	DPWA	Compton scattering
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.085 ±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.129	[10] WADA	84	DPWA	Compton scattering
−0.075 ±0.015	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.125	[11] NOELLE	78		$\gamma N \to \pi N$
−0.076	BERENDS	77	IPWA	$\gamma N \to \pi N$
−0.087 ±0.006	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1440) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.040±0.010 OUR ESTIMATE				
0.045±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.037±0.010	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.030±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
0.023±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.019±0.012	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.056±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.029±0.035	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.085±0.006	LI	93	IPWA	$\gamma N \to \pi N$
+0.059±0.016	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.062	[11] NOELLE	78		$\gamma N \to \pi N$

$N(1440)$ FOOTNOTES

[1] BAKER 79 finds a coupling of the $N(1440)$ to the $N\eta$ channel near (but slightly below) threshold.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] ARNDT 95 also finds a second-sheet pole with real part = 1383 MeV, −2×imaginary part = 210 MeV, and residue with modulus 92 MeV and phase = −54°.

[5] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[6] ARNDT 91 (Soln SM90) also finds a second-sheet pole with real part = 1413 MeV, −2 × imaginary part = 256 MeV, and residue = (78−153*i*) MeV.

[7] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[8] An alternative which cannot be distinguished from this is to have a P_{13} resonance with M = 1530 MeV, Γ = 79 MeV, and elasticity = +0.271.

[9] LONGACRE 77 considers this coupling to be well determined.

[10] WADA 84 is inconsistent with other analyses; see the Note on N and Δ Resonances.

[11] Converted to our conventions using M = 1486 MeV, Γ = 613 MeV from NOELLE 78.

$N(1440)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CUTKOSKY	90	PR D42 235	+Wang	(CMU)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KFTI)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, INUS)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1520)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1520)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1515 to 1530 (≈ 1520) OUR ESTIMATE				
1524± 4	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1525±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1519± 4	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1516±10	ARNDT	96	IPWA	$\gamma N \to \pi N$
1515	ARNDT	95	DPWA	$\pi N \to N\pi$
1526±18	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1510	LI	93	IPWA	$\gamma N \to \pi N$
1504	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1503	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1510	BERENDS	77	IPWA	$\gamma N \to \pi N$
1510	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1520	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1520)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110 to 135 (≈ 120) OUR ESTIMATE				
124± 8	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
120±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
114± 7	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
106± 4	ARNDT	96	IPWA	$\gamma N \to \pi N$
106	ARNDT	95	DPWA	$\pi N \to N\pi$
143±32	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
120	LI	93	IPWA	$\gamma N \to \pi N$
124	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
183	BAKER	79	DPWA	$\pi^- p \to n\eta$
135	BARBOUR	78	DPWA	$\gamma N \to \pi N$
105	BERENDS	77	IPWA	$\gamma N \to \pi N$
110	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
150	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1520) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1515	ARNDT	95	DPWA	$\pi N \to N\pi$
1510	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
1510±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1511	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1514 or 1511	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1508 or 1505	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
110	ARNDT	95	DPWA	$\pi N \to N\pi$
120	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
114±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
108	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
146 or 137	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
109 or 107	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1520) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
34	ARNDT	95	DPWA	$\pi N \to N\pi$
32	HOEHLER	93	ARGD	$\pi N \to \pi N$
35±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
33	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
7	ARNDT	95	DPWA	$\pi N \to N\pi$
− 8	HOEHLER	93	ARGD	$\pi N \to \pi N$
−12±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−10	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1520) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	50–60 %
Γ_2	$N\eta$	
Γ_3	$N\pi\pi$	40–50 %
Γ_4	$\Delta\pi$	15–25 %
Γ_5	$\Delta(1232)\pi$, S-wave	5–12 %
Γ_6	$\Delta(1232)\pi$, D-wave	10–14 %
Γ_7	$N\rho$	15–25 %
Γ_8	$N\rho$, S=1/2, D-wave	
Γ_9	$N\rho$, S=3/2, S-wave	
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<8 %
Γ_{12}	$p\gamma$	0.46–0.56 %
Γ_{13}	$p\gamma$, helicity=1/2	0.001–0.034 %
Γ_{14}	$p\gamma$, helicity=3/2	0.44–0.53 %
Γ_{15}	$n\gamma$	0.30–0.53 %
Γ_{16}	$n\gamma$, helicity=1/2	0.04–0.10 %
Γ_{17}	$n\gamma$, helicity=3/2	0.25–0.45 %

N(1520) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.5 to 0.6 OUR ESTIMATE				
0.59±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.58±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.54±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.61	ARNDT	95	DPWA	$\pi N \to N\pi$
0.46±0.06	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.001±0.002	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1520) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.02	BAKER	79	DPWA	$\pi^- p \to n\eta$
+0.011	FELTESSE	75	DPWA	Soln A; see BAKER 79

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1520) \to \Delta(1232)\pi$, S-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.26 to −0.20 OUR ESTIMATE				
−0.18±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.26	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.24	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1520) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.28 to −0.24 OUR ESTIMATE				
−0.29±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.21	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1520) \to N\rho$, S=3/2, S-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.35 to −0.31 OUR ESTIMATE				
−0.35±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.35	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.24	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1520) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.22 to −0.06 OUR ESTIMATE				
−0.13	[1,5] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.17	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1520) PHOTON DECAY AMPLITUDES

N(1520) → $p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.024 ±0.009 OUR ESTIMATE				
−0.020 ±0.007	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.028 ±0.014	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.007 ±0.004	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.032 ±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.032 ±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.031 ±0.009	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
−0.019 ±0.007	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.0430±0.0063	ISHII	80	DPWA	Compton scattering
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.020 ±0.002	LI	93	IPWA	$\gamma N \to \pi N$
−0.012	WADA	84	DPWA	Compton scattering
−0.016 ±0.008	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.008	[6] NOELLE	78		$\gamma N \to \pi N$
−0.021	BERENDS	77	IPWA	$\gamma N \to \pi N$
−0.005 ±0.005	FELLER	76	DPWA	$\gamma N \to \pi N$

N(1520) → $p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.166 ±0.005 OUR ESTIMATE				
0.167 ±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.156 ±0.022	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.168 ±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.178 ±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.162 ±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.166 ±0.005	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
0.167 ±0.010	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.1695±0.0014	ISHII	80	DPWA	Compton scattering
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.167 ±0.002	LI	93	IPWA	$\gamma N \to \pi N$
0.168	WADA	84	DPWA	Compton scattering
+0.157 ±0.007	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.206	[6] NOELLE	78		$\gamma N \to \pi N$
+0.075	BERENDS	77	IPWA	$\gamma N \to \pi N$
+0.164 ±0.008	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1520) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.059±0.009 OUR ESTIMATE				
−0.048±0.008	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.066±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.067±0.004	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.076±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.071±0.011	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.056±0.011	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.050±0.014	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.058±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.055±0.014	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.060	[6] NOELLE	78		$\gamma N \to \pi N$

$N(1520) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.139±0.011 OUR ESTIMATE				
−0.140±0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.124±0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.158±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.147±0.008	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.148±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.144±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.118±0.011	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.131±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.141±0.015	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.127	[6] NOELLE	78		$\gamma N \to \pi N$

$N(1520)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] LONGACRE 77 considers this coupling to be well determined.

[6] Converted to our conventions using $M = 1528$ MeV, $\Gamma = 187$ MeV from NOELLE 78.

$N(1520)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982). For very early references, see Reviews of Modern Physics **37** 633 (1965).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KFTI)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, INUS)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1535)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1535)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1520 to 1555 (≈ 1535) OUR ESTIMATE				
1534± 7	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1550±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1526± 7	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1549± 2	ABAEV	96	DPWA	$\pi^- p \to \eta n$
1525±10	ARNDT	96	IPWA	$\gamma N \to \pi N$
1535	ARNDT	95	DPWA	$\pi N \to N\pi$
1542± 6	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1537	BATINIC	95B	DPWA	$\pi N \to N\pi$, $N\eta$
1544±13	KRUSCHE	95	DPWA	$\gamma p \to p\eta$
1518	LI	93	IPWA	$\gamma N \to \pi N$
1513	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1511	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1500	BERENDS	77	IPWA	$\gamma N \to \pi N$
1547± 6	BHANDARI	77	DPWA	Uses $N\eta$ cusp
1520	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1510	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1535)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 250 (≈ 150) OUR ESTIMATE				
151±27	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
240±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
169±12	ABAEV	96	DPWA	$\pi^- p \to \eta n$
103± 5	ARNDT	96	IPWA	$\gamma N \to \pi N$
66	ARNDT	95	DPWA	$\pi N \to N\pi$
150±15	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
145	BATINIC	95B	DPWA	$\pi N \to N\pi$, $N\eta$
200±40	KRUSCHE	95	DPWA	$\gamma p \to p\eta$
84	LI	93	IPWA	$\gamma N \to \pi N$
136	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
180	BAKER	79	DPWA	$\pi^- p \to n\eta$
132	BARBOUR	78	DPWA	$\gamma N \to \pi N$
57	BERENDS	77	IPWA	$\gamma N \to \pi N$
139±33	BHANDARI	77	DPWA	Uses $N\eta$ cusp
135	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
100	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1535)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1501	ARNDT	95	DPWA	$\pi N \to N\pi$
1487	[3] HOEHLER	93	SPED	$\pi N \to \pi N$
1510±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1499	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1496 or 1499	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1519± 4	BHANDARI	77	DPWA	Uses $N\eta$ cusp
1525 or 1527	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
124	ARNDT	95	DPWA	$\pi N \to N\pi$
260±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
110	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
103 or 105	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
140±32	BHANDARI	77	DPWA	Uses $N\eta$ cusp
135 or 123	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1535)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
31	ARNDT	95	DPWA	$\pi N \to N\pi$
120±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
23	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−12	ARNDT	95	DPWA	$\pi N \to N\pi$
+15±45	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−13	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(1535)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–55 %
Γ_2	$N\eta$	30–55 %
Γ_3	$N\pi\pi$	1–10 %
Γ_4	$\Delta\pi$	<1 %
Γ_5	$\Delta(1232)\pi$, D-wave	
Γ_6	$N\rho$	<4 %
Γ_7	$N\rho$, S=1/2, S-wave	
Γ_8	$N\rho$, S=3/2, D-wave	
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<3 %
Γ_{10}	$N(1440)\pi$	<7 %
Γ_{11}	$p\gamma$	0.08–0.27 %
Γ_{12}	$p\gamma$, helicity=1/2	0.08–0.27 %
Γ_{13}	$n\gamma$	0.004–0.29 %
Γ_{14}	$n\gamma$, helicity=1/2	0.004–0.29 %

$N(1535)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.35 to 0.55 OUR ESTIMATE				
0.51 ±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.50 ±0.10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.38 ±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.31	ARNDT	95	DPWA	$\pi N \to N\pi$
0.34 ±0.09	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
0.297±0.026	BHANDARI	77	DPWA	Uses $N\eta$ cusp

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.59±0.02	ABAEV	96	DPWA	$\pi^- p \to \eta n$
0.63±0.07	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1535) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.44 to +0.50 OUR ESTIMATE				
+0.47±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.33	BAKER	79	DPWA	$\pi^- p \to n\eta$
+0.48	FELTESSE	75	DPWA	1488–1745 MeV

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1535) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.04 to +0.06 OUR ESTIMATE				
+0.00±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.00	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.06	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1535) \to N\rho$, S=1/2, S-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.14 to −0.06 OUR ESTIMATE				
−0.10±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.10	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.09	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1535) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03 to +0.13 OUR ESTIMATE				
+0.07±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.08	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.09	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1535) \to N(1440)\pi$ — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.10±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$N(1535)$ PHOTON DECAY AMPLITUDES

$N(1535) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.070 ±0.012 OUR ESTIMATE				
0.060 ±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.097 ±0.006	BENMERROU...	95	DPWA	$\gamma N \to N\eta$
0.095 ±0.011	[5] BENMERROU...	91		$\gamma p \to p\eta$
0.053 ±0.015	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.077 ±0.021	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.083 ±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.080 ±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.029 ±0.007	BRATASHEV...	80	DPWA	$\gamma N \to \pi N$
0.065 ±0.016	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.0704±0.0091	ISHII	80	DPWA	Compton scattering
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.110 to 0.140	KRUSCHE	95	DPWA	$\gamma p \to p\eta$
0.125 ±0.025	KRUSCHE	95C	IPWA	$\gamma d \to \eta N(N)$
0.061 ±0.003	LI	93	IPWA	$\gamma N \to \pi N$
0.055	WADA	84	DPWA	Compton scattering
+0.082 ±0.019	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.046	[6] NOELLE	78		$\gamma N \to \pi N$
+0.034	BERENDS	77	IPWA	$\gamma N \to \pi N$
+0.070 ±0.004	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1535) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.046±0.027 OUR ESTIMATE				
−0.020±0.035	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.035±0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.062±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.075±0.019	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.075±0.018	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.098±0.026	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.011±0.017	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.100±0.030	KRUSCHE	95C	IPWA	$\gamma d \to \eta N(N)$
−0.046±0.005	LI	93	IPWA	$\gamma N \to \pi N$
−0.112±0.034	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.048	[6] NOELLE	78		$\gamma N \to \pi N$

$N(1535) \to N\gamma$, ratio $A^n_{1/2}/A^p_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.84±0.15	MUKHOPAD...	95B	IPWA

$N(1535)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] BENMERROUCHE 91 uses an effective Lagrangian approach to analyze η photoproduction data.

[6] Converted to our conventions using M = 1548 MeV, Γ = 73 MeV from NOELLE 78.

$N(1535)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ABAEV	96	PR C53 385	+Nefkens	(UCLA)
ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
BATINIC	95B	PR C52 2188	+Slaus, Svarc	(BOSK)
BENMERROU...	95	PR D51 3237	Benmerrouche, Mukhopadhyay, Zhang	(RPI, SASK)
KRUSCHE	95	PRL 74 3736	+Ahrens, Anton+	(GIES, MANZ, GLAS, BONN, DARM)
KRUSCHE	95C	PL B358 40	+Ahrens+	(GIES, MANZ, GLAS, BONN, DARM)
MUKHOPAD...	95B	PL B364 1	Mukhopadhyay, Zhang, Benmerrouche	(RPI, SASK)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BENMERROU...	91	PRL 67 1070	Benmerrouche, Mukhopadhyay	(RPI)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)

FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
BRATASHEV...	80	NP B166 525	Bratashevskij, Gorbenko, Derebchinskij+	(KFTI)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
ISHII	80	NP B165 189	+Egawa, Kato, Miyachi+	(KYOT, INUS)
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOELLE	78	PTP 60 778		(NAGO)
BERENDS	77	NP B136 317	+Donnachie	(LEID, MCHS) IJP
BHANDARI	77	PR D15 192	+Chao	(CMU) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1650)\ S_{11}$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(1650) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1640 to 1680 (≈ 1650) OUR ESTIMATE				
1659± 9	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1650±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1670± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1677± 8	ARNDT	96	IPWA	$\gamma N \to \pi N$
1667	ARNDT	95	DPWA	$\pi N \to N\pi$
1712	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
1669±17	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1713±27	[2] BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1674	LI	93	IPWA	$\gamma N \to \pi N$
1688	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1672	MUSETTE	80	IPWA	$\pi^- p \to \Lambda K^0$
1680	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1680	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1694	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1700± 5	[3] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1680	[3] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1700	[4] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1675	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1660	[5] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1650) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
145 to 190 (≈ 150) OUR ESTIMATE				
173±12	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
150±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
180±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
160±12	ARNDT	96	IPWA	$\gamma N \to \pi N$
90	ARNDT	95	DPWA	$\pi N \to N\pi$
184	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
215±32	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
279±54	[2] BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
225	LI	93	IPWA	$\gamma N \to \pi N$
183	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
179	MUSETTE	80	IPWA	$\pi^- p \to \Lambda K^0$
120	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
90	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
193	BARBOUR	78	DPWA	$\gamma N \to \pi N$
130±10	[3] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
90	[3] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
170	[4] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
170	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
130	[5] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1650) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1673	ARNDT	95	DPWA	$\pi N \to N\pi$
1689	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
1670	[6] HOEHLER	93	ARGD	$\pi N \to \pi N$
1640±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1657	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1648 or 1651	[7] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1699 or 1698	[4] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
82	ARNDT	95	DPWA	$\pi N \to N\pi$
192	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
163	[6] HOEHLER	93	ARGD	$\pi N \to \pi N$
150±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
160	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
117 or 119	[7] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
174 or 173	[4] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1650) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
22	ARNDT	95	DPWA	$\pi N \to N\pi$
72	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
39	HOEHLER	93	ARGD	$\pi N \to \pi N$
60±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
54	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
29	ARNDT	95	DPWA	$\pi N \to N\pi$
−85	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
−37	HOEHLER	93	ARGD	$\pi N \to \pi N$
−75±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−38	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1650) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	55–90 %
Γ_2	$N\eta$	3–10 %
Γ_3	ΛK	3–11 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	10–20 %
Γ_6	$\Delta\pi$	1–7 %
Γ_7	$\Delta(1232)\pi$, D-wave	
Γ_8	$N\rho$	4–12 %
Γ_9	$N\rho$, S=1/2, S-wave	
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	<4 %
Γ_{12}	$N(1440)\pi$	<5 %
Γ_{13}	$p\gamma$	0.04–0.18 %
Γ_{14}	$p\gamma$, helicity=1/2	0.04–0.18 %
Γ_{15}	$n\gamma$	0.003–0.17 %
Γ_{16}	$n\gamma$, helicity=1/2	0.003–0.17 %

N(1650) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.65 to 0.90 OUR ESTIMATE				
0.89±0.07	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.65±0.10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.61±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.99	ARNDT	95	DPWA	$\pi N \to N\pi$
0.27	[1] ARNDT	95	DPWA	$\pi N \to N\pi$
0.94±0.07	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
0.49±0.21	[2] BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.06±0.05	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
0.02±0.03	[2] BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.09	[8] BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.27 to −0.17 OUR ESTIMATE			
−0.22	BELL 83	DPWA	$\pi^- p \to \Lambda K^0$
−0.22	SAXON 80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.25	[9] BAKER 78	DPWA	See SAXON 80
−0.23±0.01	[3] BAKER 77	IPWA	$\pi^- p \to \Lambda K^0$
−0.25	[3] BAKER 77	DPWA	$\pi^- p \to \Lambda K^0$
0.12	KNASEL 75	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.254	LIVANOS 80	DPWA	$\pi p \to \Sigma K$
0.066 to 0.137	[10] DEANS 75	DPWA	$\pi N \to \Sigma K$
0.20	KNASEL 75	DPWA	

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to \Delta(1232)\pi$, *D*-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.15 to 0.23 OUR ESTIMATE			
+0.12±0.04	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.29	[4,11] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.15	[5] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N\rho$, S=1/2, *S*-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
±0.03 to ±0.19 OUR ESTIMATE			
−0.01±0.09	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.17	[4,11] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
−0.16	[5] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N\rho$, S=3/2, *D*-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.17 to +0.29 OUR ESTIMATE			
+0.16±0.06	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.29	[4,11] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.04 to +0.18 OUR ESTIMATE			
+0.12±0.08	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.00	[4,11] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$
+0.25	[5] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1650) \to N(1440)\pi$ $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.11±0.06	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$N(1650)$ PHOTON DECAY AMPLITUDES

$N(1650) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
+0.053±0.016 OUR ESTIMATE			
0.069±0.005	ARNDT 96	IPWA	$\gamma N \to \pi N$
0.033±0.015	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.050±0.010	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.065±0.005	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.061±0.005	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.031±0.017	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.068±0.003	LI 93	IPWA	$\gamma N \to \pi N$
0.091	WADA 84	DPWA	Compton scattering
+0.048±0.017	BARBOUR 78	DPWA	$\gamma N \to \pi N$
+0.068±0.009	FELLER 76	DPWA	$\gamma N \to \pi N$

$N(1650) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.015±0.021 OUR ESTIMATE			
−0.015±0.005	ARNDT 96	IPWA	$\gamma N \to \pi N$
−0.008±0.004	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.004±0.004	FUJII 81	DPWA	$\gamma N \to \pi N$
0.010±0.020	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.008±0.019	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.068±0.040	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
−0.011±0.011	TAKEDA 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.002±0.002	LI 93	IPWA	$\gamma N \to \pi N$
−0.045±0.024	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$N(1650)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1650) \to \Lambda K^+$ (E_{0+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID	TECN
7.8 ±0.3	WORKMAN 90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •		
8.13	TANABE 89	DPWA

$p\gamma \to N(1650) \to \Lambda K^+$ phase angle θ (E_{0+} amplitude)

VALUE (degrees)	DOCUMENT ID	TECN
−107 ±3	WORKMAN 90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •		
−107.8	TANABE 89	DPWA

$N(1650)$ FOOTNOTES

[1] ARNDT 95 finds two distinct states.
[2] BATINIC 95 finds two distinct states. This second resonance was associated with the $N(2090)$ S_{11}.
[3] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.
[4] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[5] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[6] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.
[7] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[8] BAKER 79 fixed this coupling during fitting, but the negative sign relative to the $N(1535)$ is well determined.
[9] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions. Superseded by SAXON 80.
[10] The range given for DEANS 75 is from the four best solutions.
[11] LONGACRE 77 considers this coupling to be well determined.

$N(1650)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WORKMAN	90	PR C42 781		(VPI)
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
MUSETTE	80	NC 57A 37		(BRUX) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAVE) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1675)$ D_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1675)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1670 to 1685 (≈ 1675) OUR ESTIMATE				
1676± 2	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1675±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1679± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1673± 5	ARNDT	96	IPWA	$\gamma N \to \pi N$
1673	ARNDT	95	DPWA	$\pi N \to N\pi$
1683±19	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1666	LI	93	IPWA	$\gamma N \to \pi N$
1685	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1670	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1680	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1650	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1660	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1675)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
140 to 180 (≈ 150) OUR ESTIMATE				
159± 7	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
160±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
120±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
154± 7	ARNDT	96	IPWA	$\gamma N \to \pi N$
154	ARNDT	95	DPWA	$\pi N \to N\pi$
142±23	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
136	LI	93	IPWA	$\gamma N \to \pi N$
191	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
40	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
88	BAKER	79	DPWA	$\pi^- p \to n\eta$
192	BARBOUR	78	DPWA	$\gamma N \to \pi N$
130	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
150	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1675)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1663	ARNDT	95	DPWA	$\pi N \to N\pi$
1656	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
1660±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1655	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1663 or 1668	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1649 or 1650	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
152	ARNDT	95	DPWA	$\pi N \to N\pi$
126	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
140±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
124	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
146 or 171	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
127 or 127	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1675)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
29	ARNDT	95	DPWA	$\pi N \to N\pi$
23	HOEHLER	93	ARGD	$\pi N \to \pi N$
31±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
28	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
− 6	ARNDT	95	DPWA	$\pi N \to N\pi$
−22	HOEHLER	93	ARGD	$\pi N \to \pi N$
−30±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−17	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(1675)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	40–50 %
Γ_2	$N\eta$	
Γ_3	ΛK	<1 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	50–60 %
Γ_6	$\Delta\pi$	50–60 %
Γ_7	$\Delta(1232)\pi$, D-wave	
Γ_8	$\Delta(1232)\pi$, G-wave	
Γ_9	$N\rho$	< 1–3 %
Γ_{10}	$N\rho$, S=1/2, D-wave	
Γ_{11}	$N\rho$, S=3/2, D-wave	
Γ_{12}	$N\rho$, S=3/2, G-wave	
Γ_{13}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	
Γ_{14}	$p\gamma$	0.004–0.023 %
Γ_{15}	$p\gamma$, helicity=1/2	0.0–0.015 %
Γ_{16}	$p\gamma$, helicity=3/2	0.0–0.011 %
Γ_{17}	$n\gamma$	0.02–0.12 %
Γ_{18}	$n\gamma$, helicity=1/2	0.006–0.046 %
Γ_{19}	$n\gamma$, helicity=3/2	0.01–0.08 %

$N(1675)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.4 to 0.5 OUR ESTIMATE				
0.47±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.38±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.38±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.38	ARNDT	95	DPWA	$\pi N \to N\pi$
0.31±0.06	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.001±0.001	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to N(1675) \to N\eta$ — $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.07	BAKER	79	DPWA	$\pi^- p \to n\eta$
+0.009	FELTESSE	75	DPWA	Soln A; see BAKER 79

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to N(1675) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.04 to ±0.08 OUR ESTIMATE				
−0.01	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.036	[5] SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.034±0.006	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to N(1675) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.003	[6] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to N(1675) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_7)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.46 to +0.50 OUR ESTIMATE				
+0.496±0.003	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.46	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.50	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.5	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to N(1675) \to N\rho$, S=1/2, D-wave — $(\Gamma_1\Gamma_{10})^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.04±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1675) \rightarrow N\rho$, S=3/2, D-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.12 to −0.06 OUR ESTIMATE				
−0.03±0.02	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
−0.15	[1,7] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow N(1675) \rightarrow N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03	[1,7] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1675)$ PHOTON DECAY AMPLITUDES

$N(1675) \rightarrow p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.019±0.008 OUR ESTIMATE				
0.015±0.010	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
0.021±0.011	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.034±0.005	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.006±0.005	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.006±0.004	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.023±0.015	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.012±0.002	LI	93	IPWA	$\gamma N \rightarrow \pi N$
+0.022±0.010	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.034±0.004	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$N(1675) \rightarrow p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.015±0.009 OUR ESTIMATE				
0.010±0.007	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
0.015±0.009	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.024±0.008	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
0.030±0.004	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
0.029±0.004	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
0.003±0.012	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.021±0.002	LI	93	IPWA	$\gamma N \rightarrow \pi N$
+0.015±0.006	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
+0.019±0.009	FELLER	76	DPWA	$\gamma N \rightarrow \pi N$

$N(1675) \rightarrow n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.043±0.012 OUR ESTIMATE				
−0.049±0.010	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
−0.057±0.024	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.033±0.004	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
−0.039±0.017	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.025±0.027	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.059±0.015	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
−0.021±0.011	TAKEDA	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.060±0.003	LI	93	IPWA	$\gamma N \rightarrow \pi N$
−0.066±0.020	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(1675) \rightarrow n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.058±0.013 OUR ESTIMATE				
−0.051±0.010	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
−0.077±0.018	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
−0.069±0.004	FUJII	81	DPWA	$\gamma N \rightarrow \pi N$
−0.066±0.026	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 1)
−0.071±0.022	ARAI	80	DPWA	$\gamma N \rightarrow \pi N$ (fit 2)
−0.059±0.020	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
−0.030±0.012	TAKEDA	80	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.074±0.003	LI	93	IPWA	$\gamma N \rightarrow \pi N$
−0.073±0.014	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$

$N(1675)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] SAXON 80 finds the coupling phase is near 90°.

[6] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \rightarrow \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[7] LONGACRE 77 considers this coupling to be well determined.

[8] A Breit-Wigner fit to the HERNDON 75 IPWA.

$N(1675)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)

$N(1680)$ F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(1680)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1675 to 1690 (≈ 1680) OUR ESTIMATE				
1684± 4	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
1680±10	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1684± 3	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1679± 5	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
1678	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1674±12	BATINIC	95	DPWA	$\pi N \rightarrow N\pi$, $N\eta$
1682	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1680	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1660	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
1685	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1670	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1680)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
120 to 140 (≈ 130) OUR ESTIMATE				
139± 8	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
120±10	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
128± 8	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
124± 4	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
126	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
126±20	BATINIC	95	DPWA	$\pi N \rightarrow N\pi$, $N\eta$
121	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
119	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
150	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
155	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
130	[2] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1680)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1670	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1673	[3] HOEHLER	93	ARGD	$\pi N \rightarrow \pi N$
1667±5	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1670	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
1668 or 1674	[4] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1656 or 1653	[1] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
120	ARNDT	95	DPWA	$\pi N \to N\pi$
135	[3] HOEHLER	93	ARGD	$\pi N \to \pi N$
110±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
116	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
132 or 137	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
145 or 143	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1680) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40	ARNDT	95	DPWA	$\pi N \to N\pi$
44	HOEHLER	93	ARGD	$\pi N \to \pi N$
34±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
37	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
+ 1	ARNDT	95	DPWA	$\pi N \to N\pi$
−17	HOEHLER	93	ARGD	$\pi N \to \pi N$
−25±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−14	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1680) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	60–70 %
Γ_2	$N\eta$	
Γ_3	ΛK	
Γ_4	ΣK	
Γ_5	$N\pi\pi$	30–40 %
Γ_6	$\Delta\pi$	5–15 %
Γ_7	$\Delta(1232)\pi$, P-wave	6–14 %
Γ_8	$\Delta(1232)\pi$, F-wave	<2 %
Γ_9	$N\rho$	3–15 %
Γ_{10}	$N\rho$, S=1/2, F-wave	
Γ_{11}	$N\rho$, S=3/2, P-wave	<12 %
Γ_{12}	$N\rho$, S=3/2, F-wave	1–5 %
Γ_{13}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–20 %
Γ_{14}	$p\gamma$	0.21–0.32 %
Γ_{15}	$p\gamma$, helicity=1/2	0.001–0.011 %
Γ_{16}	$p\gamma$, helicity=3/2	0.20–0.32 %
Γ_{17}	$n\gamma$	0.021–0.046 %
Γ_{18}	$n\gamma$, helicity=1/2	0.004–0.029 %
Γ_{19}	$n\gamma$, helicity=3/2	0.01–0.024 %

N(1680) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.6 to 0.7 OUR ESTIMATE				
0.70±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.62±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.65±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.68	ARNDT	95	DPWA	$\pi N \to N\pi$
0.69±0.04	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	BAKER	79	DPWA	$\pi^- p \to n\eta$

$\Gamma(N\eta)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.01 ±0.004	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
0.0005 or 0.001	[5] CARRERAS	70	MPWA	t pole + resonance
0.0004	[5] BOTKE	69	MPWA	t pole + resonance
0.003 ±0.002	[5] DEANS	69	MPWA	t pole + resonance

$\Gamma(N\eta)/\Gamma(N\pi)$ Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.027	HEUSCH	66	RVUE	π^0, η photoproduction

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

Coupling to ΛK not required in the analyses of BAKER 77, SAXON 80, or BELL 83.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.01	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
−0.009±0.009	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.001	[6] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.31 to −0.21 OUR ESTIMATE				
−0.26±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.27	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.25	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.38	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to \Delta(1232)\pi$, F-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03 to +0.11 OUR ESTIMATE				
+0.07±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.07	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.08	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.05	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.30 to −0.10 OUR ESTIMATE				
−0.20±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.23	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.34	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to N\rho$, S=3/2, F-wave $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.18 to −0.10 OUR ESTIMATE				
−0.13±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.15	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1680) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.25 to +0.35 OUR ESTIMATE				
+0.29±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.31	[1,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.42	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

N(1680) PHOTON DECAY AMPLITUDES

$N(1680) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.015±0.006 OUR ESTIMATE				
−0.010±0.004	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.017±0.018	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.009±0.006	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.028±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.026±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.018±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.006±0.002	LI	93	IPWA	$\gamma N \to \pi N$
−0.005±0.015	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.009±0.002	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1680) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.133±0.012 OUR ESTIMATE				
0.145±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.132±0.010	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.115±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.115±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.122±0.003	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.141±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.154±0.002	LI	93	IPWA	$\gamma N \to \pi N$
+0.138±0.021	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.121±0.010	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1680) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.029±0.010 OUR ESTIMATE				
0.030±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.017±0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.032±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
0.026±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.028±0.014	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.044±0.012	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.025±0.010	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.022±0.002	LI	93	IPWA	$\gamma N \to \pi N$
+0.037±0.010	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1680) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.033±0.009 OUR ESTIMATE				
−0.040±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.033±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.023±0.005	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.024±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.029±0.017	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.033±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.035±0.012	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.048±0.002	LI	93	IPWA	$\gamma N \to \pi N$
−0.038±0.018	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1680)$ FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The parametrization used may be double counting.

[6] The range given is from 3 of 4 best solutions; not present in solution 1. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[7] LONGACRE 77 considers this coupling to be well determined.

[8] A Breit-Wigner fit to the HERNDON 75 IPWA.

$N(1680)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982). For very early references, see Reviews of Modern Physics **37** 633 (1965).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
CARRERAS	70	NP B16 35	+Donnachie	(DARE, MCHS)
BOTKE	69	PR 180 1417		(UCSB)
DEANS	69	PR 185 1797	+Wooten	(SFLA)
HEUSCH	66	PRL 17 1019	+Prescott, Dashen	(CIT)

$N(1700)\ D_{13}$

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various partial-wave analyses do not agree very well.

$N(1700)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1650 to 1750 (≈ 1700) OUR ESTIMATE				
1737±44	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1675±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1731±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1791±46	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1709	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1650	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1690 to 1710	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1719	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1670±10	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1690	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1660	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1710	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 150 (≈ 100) OUR ESTIMATE				
250±220	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
90± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
110± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
215± 60	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
166	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
70	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
70 to 100	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
126	BARBOUR	78	DPWA	$\gamma N \to \pi N$
90± 25	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
100	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
600	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
300	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1700	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
1660±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1710 or 1678	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1616 or 1613	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
120	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
90±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
607 or 567	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
577 or 575	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
5	HOEHLER	93	SPED	$\pi N \to \pi N$
6±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
0±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(1700)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	$N\eta$	
Γ_3	ΛK	<3 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	85–95 %
Γ_6	$\Delta\pi$	
Γ_7	$\Delta(1232)\pi$, S-wave	
Γ_8	$\Delta(1232)\pi$, D-wave	
Γ_9	$N\rho$	<35 %
Γ_{10}	$N\rho$, S=1/2, D-wave	
Γ_{11}	$N\rho$, S=3/2, S-wave	
Γ_{12}	$N\rho$, S=3/2, D-wave	
Γ_{13}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	
Γ_{14}	$p\gamma$	0.01–0.05 %
Γ_{15}	$p\gamma$, helicity=1/2	0.0–0.024 %
Γ_{16}	$p\gamma$, helicity=3/2	0.002–0.026 %
Γ_{17}	$n\gamma$	0.01–0.13 %
Γ_{18}	$n\gamma$, helicity=1/2	0.0–0.09 %
Γ_{19}	$n\gamma$, helicity=3/2	0.01–0.05 %

$N(1700)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.01±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.11±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.08±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04±0.05	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10±0.06	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.06 to +0.04 OUR ESTIMATE				
−0.012	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.012	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.04	[6] BAKER	78	DPWA	See SAXON 80
−0.03 ±0.004	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
−0.03	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
+0.026±0.019	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
<0.017	[7] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Delta(1232)\pi$, S-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.00 to ±0.08 OUR ESTIMATE				
+0.02±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.00	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.16	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.04 to ±0.20 OUR ESTIMATE				
+0.10±0.09	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.12	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.14	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to N\rho$, S=3/2, S-wave — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.01 to ±0.13 OUR ESTIMATE				
−0.04±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.07	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.07	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1700) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{13})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.02 to ±0.28 OUR ESTIMATE				
+0.02±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.00	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.2	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1700)$ PHOTON DECAY AMPLITUDES

$N(1700) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.018±0.013 OUR ESTIMATE				
−0.016±0.014	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.002±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.028±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.029±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.024±0.019	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.033±0.021	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.014±0.025	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1700) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.002±0.024 OUR ESTIMATE				
−0.009±0.012	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.029±0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.002±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.014±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.017±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.014±0.025	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.0 ±0.014	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1700) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.000±0.050 OUR ESTIMATE				
0.006±0.024	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.002±0.013	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.052±0.030	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.055±0.030	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.052±0.035	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.050±0.042	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1700) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.003±0.044 OUR ESTIMATE				
−0.033±0.017	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.018±0.018	FUJII	81	DPWA	$\gamma N \to \pi N$
−0.037±0.036	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.035±0.024	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.041±0.030	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.035±0.030	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1700)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1700) \to \Lambda K^+$ — (E_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.09	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1700) \to \Lambda K^+$ — (M_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−7.09	TANABE	89	DPWA

$p\gamma \rightarrow N(1700) \rightarrow \Lambda K^+$ phase angle θ (E_{2-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−35.9	TANABE	89	DPWA

$N(1700)$ FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.
[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[4] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.
[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[6] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions.
[7] The range given is from the four best solutions.

$N(1700)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAVE) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)

$N(1710)$ P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various partial-wave analyses do not agree very well.

$N(1710)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1680 to 1740 (≈ 1710) OUR ESTIMATE				
1717±28	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
1700±50	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1723± 9	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1720±10	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
1766±34	[1] BATINIC	95	DPWA	$\pi N \rightarrow N\pi$, $N\eta$
1706	CUTKOSKY	90	IPWA	$\pi N \rightarrow \pi N$
1692	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1730	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1690	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$
1650 to 1680	BAKER	78	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1721	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1625±10	[2] BAKER	77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
1650	[2] BAKER	77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1720	[3] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
1670	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
1710	[4] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1710)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 250 (≈ 100) OUR ESTIMATE				
480±230	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
93± 30	CUTKOSKY	90	IPWA	$\pi N \rightarrow \pi N$
90± 30	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
120± 15	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
105± 10	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
185± 61	BATINIC	95	DPWA	$\pi N \rightarrow N\pi$, $N\eta$
540	BELL	83	DPWA	$\pi^- p \rightarrow \Lambda K^0$
200	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
550	SAXON	80	DPWA	$\pi^- p \rightarrow \Lambda K^0$
97	BAKER	79	DPWA	$\pi^- p \rightarrow n\eta$
90 to 150	BAKER	78	DPWA	$\pi^- p \rightarrow \Lambda K^0$
167	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
160± 6	[2] BAKER	77	IPWA	$\pi^- p \rightarrow \Lambda K^0$
95	[2] BAKER	77	DPWA	$\pi^- p \rightarrow \Lambda K^0$
120	[3] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$
174	KNASEL	75	DPWA	$\pi^- p \rightarrow \Lambda K^0$
75	[4] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1710)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1770	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1690	[5] HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
1698	CUTKOSKY	90	IPWA	$\pi N \rightarrow \pi N$
1690±20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1636	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
1708 or 1712	[6] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
1720 or 1711	[3] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
378	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
200	[5] HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
88	CUTKOSKY	90	IPWA	$\pi N \rightarrow \pi N$
80±20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
544	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
17 or 22	[6] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$
123 or 115	[3] LONGACRE	77	IPWA	$\pi N \rightarrow N\pi\pi$

$N(1710)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
37	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
15	HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
9	CUTKOSKY	90	IPWA	$\pi N \rightarrow \pi N$
8±2	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
149	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−167	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
−167	CUTKOSKY	90	IPWA	$\pi N \rightarrow \pi N$
175±35	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
149	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

$N(1710)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	
Γ_3	ΛK	5–25 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	40–90 %
Γ_6	$\Delta\pi$	15–40 %
Γ_7	$\Delta(1232)\pi$, P-wave	

Γ_8	$N\rho$	5–25 %
Γ_9	$N\rho$, S=1/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, P-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	10–40 %
Γ_{12}	$p\gamma$	0.002–0.05%
Γ_{13}	$p\gamma$, helicity=1/2	0.002–0.05%
Γ_{14}	$n\gamma$	0.0–0.02%
Γ_{15}	$n\gamma$, helicity=1/2	0.0–0.02%

$N(1710)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE				
0.09±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.20±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.12±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.08±0.14	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.16±0.10	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22	BAKER	79	DPWA	$\pi^- p \to n\eta$
+0.383	FELTESSE	75	DPWA	Soln A; see BAKER 79

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.12 to +0.18 OUR ESTIMATE				
+0.16	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.14	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.12	[7] BAKER	78	DPWA	See SAXON 80
−0.05±0.03	[2] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
−0.10	[2] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
0.10	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.034	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.075 to 0.203	[8] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.16 to ±0.22 OUR ESTIMATE				
−0.21±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.17	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.20	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to N\rho$, S=1/2, P-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.09 to ±0.19 OUR ESTIMATE				
+0.05±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.19	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.20	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.31	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1710) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.14 to ±0.22 OUR ESTIMATE				
+0.04±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.26	[3] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.28	[4] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$N(1710)$ PHOTON DECAY AMPLITUDES

$N(1710) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.009±0.022 OUR ESTIMATE				
0.007±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.006±0.018	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.028±0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.009±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.012±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.015±0.025	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.037±0.002	LI	93	IPWA	$\gamma N \to \pi N$
+0.001±0.039	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.053±0.019	FELLER	76	DPWA	$\gamma N \to \pi N$

$N(1710) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.002±0.014 OUR ESTIMATE				
−0.002±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.000±0.018	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.001±0.003	FUJII	81	DPWA	$\gamma N \to \pi N$
0.005±0.013	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.011±0.021	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.017±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.052±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.028±0.045	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1710)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1710) \to \Lambda K^+$ — (M_{1-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
−10.6 ±0.4	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
− 7.21	TANABE	89	DPWA

$p\gamma \to N(1710) \to \Lambda K^+$ phase angle θ — (M_{1-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
215 ±3	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
176.3	TANABE	89	DPWA

$N(1710)$ FOOTNOTES

[1] BATINIC 95 finds a second state with a 6 MeV mass difference.
[2] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.
[3] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[4] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[5] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.
[6] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[7] The overall phase of BAKER 78 couplings has been changed to agree with previous conventions.
[8] The range given for DEANS 75 is from the four best solutions.

$N(1710)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CUTKOSKY	90	PR D42 235	+Wang	(CMU)
WORKMAN	90	PR C42 781		(VPI)
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
FUJII	81	NP B187 53	+Hayashii, Iwata, Kajikawa+	(NAGO, OSAK)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)

CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAVE) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
FELTESSE	75	NP B93 242	+Ayed, Bareyre, Borgeaud, David+	(SACL) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1720)$ P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(1720) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1650 to 1750 (≈ 1720) OUR ESTIMATE				
1717±31	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1700±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1710±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1713±10	ARNDT	96	IPWA	$\gamma N \to \pi N$
1820	ARNDT	95	DPWA	$\pi N \to N\pi$
1711±26	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1720	LI	93	IPWA	$\gamma N \to \pi N$
1785	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1690	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
1710 to 1790	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
1809	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1640±10	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
1710	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
1750	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1850	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
1720	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1720) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 200 (≈ 150) OUR ESTIMATE				
380±180	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
125± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
190± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
153± 15	ARNDT	96	IPWA	$\gamma N \to \pi N$
354	ARNDT	95	DPWA	$\pi N \to N\pi$
235± 51	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
200	LI	93	IPWA	$\gamma N \to \pi N$
308	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
120	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
447	BAKER	79	DPWA	$\pi^- p \to n\eta$
300 to 400	BAKER	78	DPWA	$\pi^- p \to \Lambda K^0$
285	BARBOUR	78	DPWA	$\gamma N \to \pi N$
200± 50	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
500	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$
130	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
327	KNASEL	75	DPWA	$\pi^- p \to \Lambda K^0$
150	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1720) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1717	ARNDT	95	DPWA	$\pi N \to N\pi$
1686	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
1680±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1675	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1716 or 1716	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1745 or 1748	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
388	ARNDT	95	DPWA	$\pi N \to N\pi$
187	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
120±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
114	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
124 or 126	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
135 or 123	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1720) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
39	ARNDT	95	DPWA	$\pi N \to N\pi$
15	HOEHLER	93	SPED	$\pi N \to \pi N$
8±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
11	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
− 70	ARNDT	95	DPWA	$\pi N \to N\pi$
−160±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−130	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1720) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	
Γ_3	ΛK	1–15 %
Γ_4	ΣK	
Γ_5	$N\pi\pi$	>70 %
Γ_6	$\Delta\pi$	
Γ_7	$\Delta(1232)\pi$, P-wave	
Γ_8	$N\rho$	70–85 %
Γ_9	$N\rho$, S=1/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, P-wave	
Γ_{11}	$N(\pi\pi)^{I=0}_{S\text{-wave}}$	
Γ_{12}	$p\gamma$	0.003–0.10 %
Γ_{13}	$p\gamma$, helicity=1/2	0.003–0.08 %
Γ_{14}	$p\gamma$, helicity=3/2	0.001–0.03 %
Γ_{15}	$n\gamma$	0.002–0.39 %
Γ_{16}	$n\gamma$, helicity=1/2	0.0–0.002 %
Γ_{17}	$n\gamma$, helicity=3/2	0.001–0.39 %

N(1720) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE				
0.13±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.10±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.16	ARNDT	95	DPWA	$\pi N \to N\pi$
0.18±0.04	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.002±0.01	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.08	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.14 to −0.06 OUR ESTIMATE				
−0.09	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.11	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.09	[6] BAKER	78	DPWA	See SAXON 80
−0.06±0.02	[1] BAKER	77	IPWA	$\pi^- p \to \Lambda K^0$
−0.09	[1] BAKER	77	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.051 to 0.087	[7] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to \Delta(1232)\pi$, *P*-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.27 to ±0.37 OUR ESTIMATE				
−0.17	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N\rho$, S=1/2, *P*-wave $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.34±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.26	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.40	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N\rho$, S=3/2, *P*-wave $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.15	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1720) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.19	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

N(1720) PHOTON DECAY AMPLITUDES

$N(1720) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.018±0.030 OUR ESTIMATE				
−0.015±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.044±0.066	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.004±0.007	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.051±0.009	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.071±0.010	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.038±0.050	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.012±0.003	LI	93	IPWA	$\gamma N \to \pi N$
+0.111±0.047	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1720) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.019±0.020 OUR ESTIMATE				
0.007±0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.024±0.006	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.040±0.016	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.058±0.010	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.011±0.011	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.014±0.040	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.022±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.063±0.032	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1720) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.001±0.015 OUR ESTIMATE				
0.007±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.002±0.005	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.019±0.033	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.001±0.038	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.003±0.034	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.050±0.004	LI	93	IPWA	$\gamma N \to \pi N$
+0.007±0.020	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1720) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.029±0.061 OUR ESTIMATE				
−0.005±0.025	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.015±0.019	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.139±0.039	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.134±0.044	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.018±0.028	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.017±0.004	LI	93	IPWA	$\gamma N \to \pi N$
+0.051±0.051	BARBOUR	78	DPWA	$\gamma N \to \pi N$

N(1720) $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1720) \to \Lambda K^+$ (E_{1+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
10.2 ±0.2	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
9.52	TANABE	89	DPWA

$p\gamma \to N(1720) \to \Lambda K^+$ phase angle θ (E_{1+} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
−124 ±2	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−103.4	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(1720) \to \Lambda K^+$ (M_{1+} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
−4.5 ±0.2	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.18	TANABE	89	DPWA

N(1720) FOOTNOTES

[1] The two BAKER 77 entries are from an IPWA using the Barrelet-zero method and from a conventional energy-dependent analysis.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] The overall phase of BAKER 78 copulings has been changed to agree with previous conventions.

[7] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

N(1720) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WORKMAN	90	PR C42 781		(VPI)
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BAKER	78	NP B141 29	+Blissett, Bloodworth, Broome+	(RL, CAVE) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
BAKER	77	NP B126 365	+Blissett, Bloodworth, Broome, Hart+	(RHEL) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
KNASEL	75	PR D11 1	+Lindquist, Nelson+	(CHIC, WUSL, OSU, ANL) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$N(1900)$ P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

N(1900) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1900 OUR ESTIMATE				
1879±17	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

N(1900) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
498±78	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

N(1900) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$N\rho$, $S=1/2$, P-wave

N(1900) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.26±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1900) \to N\rho$, $S=1/2$, P-wave $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.34±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

N(1900) REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT)
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)

$N(1990)$ F_{17}

$I(J^P) = \frac{1}{2}(\frac{7}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various analyses do not agree very well with one another.

N(1990) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1990 OUR ESTIMATE				
2086± 28	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2018	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1970± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2005±150	HOEHLER	79	IPWA	$\pi N \to \pi N$
1999	BARBOUR	78	DPWA	$\gamma N \to \pi N$

N(1990) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
535±120	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
295	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
350±120	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
350±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
216	BARBOUR	78	DPWA	$\gamma N \to \pi N$

N(1990) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(1990) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
9±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−60±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

N(1990) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$p\gamma$, helicity=1/2
Γ_7	$p\gamma$, helicity=3/2
Γ_8	$n\gamma$, helicity=1/2
Γ_9	$n\gamma$, helicity=3/2

N(1990) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.06±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1990) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.043	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1990) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.01	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
−0.021±0.033	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1990) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.010 to 0.023	[1] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.06	LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 1)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(1990) \to N\pi\pi$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

N(1990) PHOTON DECAY AMPLITUDES

$N(1990) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.030±0.029	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.001±0.040	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.040	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.086±0.060	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.004±0.025	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.004	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.001	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.078±0.030	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.069	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.178	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.116±0.045	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.072	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(1990)$ FOOTNOTES

[1] The range given for DEANS 75 is from the four best solutions.

$N(1990)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP

$N(2000)$ F_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Older results have been retained simply because there is little information at all about this possible state.

$N(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2000 OUR ESTIMATE				
1903±87	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1882±10	HOEHLER	79	IPWA	$\pi N \to \pi N$
2025	AYED	76	IPWA	$\pi N \to \pi N$
1970	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)
2175	ALMEHED	72	IPWA	$\pi N \to \pi N$
1930	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1814	ARNDT	95	DPWA	$\pi N \to N\pi$

$N(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
490±310	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
95± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
157	AYED	76	IPWA	$\pi N \to \pi N$
170	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)
150	ALMEHED	72	IPWA	$\pi N \to \pi N$
112	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
176	ARNDT	95	DPWA	$\pi N \to N\pi$

$N(2000)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$\Delta(1232)\pi$, P-wave
Γ_7	$N\rho$, S=3/2, P-wave
Γ_8	$N\rho$, S=3/2, F-wave
Γ_9	$p\gamma$

$N(2000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.05	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08	AYED	76	IPWA	$\pi N \to \pi N$
0.25	ALMEHED	72	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10	ARNDT	95	DPWA	$\pi N \to N\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to \Sigma K$ $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.022	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$
0.05	[1] LANGBEIN	73	IPWA	$\pi N \to \Sigma K$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.10±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.22±0.08	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2000) \to N\rho$, S=3/2, F-wave $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.11±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(2000) \to \Lambda K$ $(\Gamma_9\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0022	DEANS	72	MPWA	$\gamma p \to \Lambda K$ (sol. D)

$N(2000)$ FOOTNOTES

[1] Not seen in solution 1 of LANGBEIN 73.
[2] Value given is from solution 1 of DEANS 75; not present in solutions 2, 3, or 4.

$N(2000)$ REFERENCES

ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
AYED	76	Thesis CEA-N-1921		(SACL) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP
ALMEHED	72	NP B40 157	+Lovelace	(LUND, RUTG) IJP
DEANS	72	PR D6 1906	+Jacobs, Lyons, Montgomery	(SFLA) IJP

$N(2080)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

There is some evidence for two resonances in this wave between 1800 and 2200 MeV (see CUTKOSKY 80). However, the solution of HOEHLER 79 is quite different.

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$N(2080)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2080 OUR ESTIMATE				
1804± 55	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1920	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
1880±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2060± 80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1900	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2081± 20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1986± 75	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
1880	BAKER	79	DPWA	$\pi^- p \to n\eta$

$N(2080)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
450±185	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
320	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
180± 60	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
300±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)
240	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
265± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1050±225	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
87	BAKER	79	DPWA	$\pi^- p \to n\eta$

N(2080) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1880±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
2050± 70	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
160±80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
200±80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(2080) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
10± 5	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
30±20	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
100± 80	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
0±100	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)

N(2080) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK
Γ_4	ΣK
Γ_5	$N\pi\pi$
Γ_6	$\Delta(1232)\pi$, S-wave
Γ_7	$\Delta(1232)\pi$, D-wave
Γ_8	$N\rho$, S=3/2, S-wave
Γ_9	$N(\pi\pi)^{I=0}_{S\text{-wave}}$
Γ_{10}	$p\gamma$, helicity=1/2
Γ_{11}	$p\gamma$, helicity=3/2
Γ_{12}	$n\gamma$, helicity=1/2
Γ_{13}	$n\gamma$, helicity=3/2
Γ_{14}	$p\gamma$

N(2080) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.23±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.10±0.04	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (lower m)
0.14±0.07	[1] CUTKOSKY	80	IPWA	$\pi N \to \pi N$ (higher m)
0.06±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.09±0.02	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.07±0.04	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.065	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.04	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
+0.03	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.014 to 0.037	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to \Delta(1232)\pi$, S-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09±0.09	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.22±0.07	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to N\rho$, S=3/2, S-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.24±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2080) \to N(\pi\pi)^{I=0}_{S\text{-wave}}$ — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.25±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(2080) \to N\eta$ — $(\Gamma_{14}\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.0037	HICKS	73	MPWA	$\gamma p \to p\eta$

N(2080) PHOTON DECAY AMPLITUDES

N(2080) → $p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.020±0.008	AWAJI	81	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.026±0.052	DEVENISH	74	DPWA	$\gamma N \to \pi N$

N(2080) → $p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.017±0.011	AWAJI	81	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.128±0.057	DEVENISH	74	DPWA	$\gamma N \to \pi N$

N(2080) → $n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
0.007±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.053±0.083	DEVENISH	74	DPWA	$\gamma N \to \pi N$

N(2080) → $n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.053±0.034	AWAJI	81	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.100±0.141	DEVENISH	74	DPWA	$\gamma N \to \pi N$

N(2080) $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(2080) \to \Lambda K^+$ — (E_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
5.5 ±0.3	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.09	TANABE	89	DPWA

$p\gamma \to N(2080) \to \Lambda K^+$ phase angle θ — (E_{2-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
−48 ±5	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−35.9	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(2080) \to \Lambda K^+$ — (M_{2-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
−6.7 ±0.2	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−4.09	TANABE	89	DPWA

N(2080) FOOTNOTES

[1] CUTKOSKY 80 finds a lower mass D_{13} resonance, as well as one in this region. Both are listed here.

[2] The range given for DEANS 75 is from the four best solutions. Disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(2080)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WORKMAN	90	PR C42 781		(VPI)
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
DEVENISH	74	PL 52B 227	+Lyth, Rankin	(DESY, LANC, BONN) IJP
HICKS	73	PR D7 2614	+Deans, Jacobs, Lyons+	(CMU, ORNL, SFLA) IJP

$N(2090)$ S_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

Any structure in the S_{11} wave above 1800 MeV is listed here. A few early results that are now obsolete have been omitted.

$N(2090)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2090 OUR ESTIMATE				
1928±59	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2180±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1880±20	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2090)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
414±157	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
95± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$

$N(2090)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2150±70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1937 or 1949	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
139 or 131	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$N(2090)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
0±90	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2090)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΛK
Γ_3	$N\pi\pi$

$N(2090)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10±0.10	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.18±0.08	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.09±0.05	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2090) \to \Lambda K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2090)$ FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

$N(2090)$ REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)

$N(2100)$ P_{11}

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

$N(2100)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2100 OUR ESTIMATE				
1885±30	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2125±75	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2050±20	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2203±70	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$N(2100)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
113± 44	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
260±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
200± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
418±171	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$N(2100)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2120±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
240±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$N(2100)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
14±7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
35±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2100)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	$N\pi\pi$
Γ_4	$\Delta(1232)\pi$, P-wave

$N(2100)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.12±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.10±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11±0.07	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.86 ± 0.07	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2100) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.19 ± 0.08	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

N(2100) REFERENCES

BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP

$N(2190)$ G_{17}

$I(J^P) = \frac{1}{2}(\frac{7}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(2190) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100 to 2200 (≈ 2190) OUR ESTIMATE				
2127 ± 9	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2200 ± 70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2140 ± 12	HOEHLER	79	IPWA	$\pi N \to \pi N$
2140 ± 40	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2131	ARNDT	95	DPWA	$\pi N \to N\pi$
2198 ± 68	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
2098	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
2180	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2140	BAKER	79	DPWA	$\pi^- p \to n\eta$
2117	BARBOUR	78	DPWA	$\gamma N \to \pi N$

N(2190) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350 to 550 (≈ 450) OUR ESTIMATE				
550 ± 50	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
500 ± 150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
390 ± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
270 ± 50	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
476	ARNDT	95	DPWA	$\pi N \to N\pi$
805 ± 140	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$
238	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
80	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
319	BAKER	79	DPWA	$\pi^- p \to n\eta$
220	BARBOUR	78	DPWA	$\gamma N \to \pi N$

N(2190) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2030	ARNDT	95	DPWA	$\pi N \to N\pi$
2042	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
2100 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2060	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
460	ARNDT	95	DPWA	$\pi N \to N\pi$
482	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
400 ± 160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
464	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(2190) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
46	ARNDT	95	DPWA	$\pi N \to N\pi$
45	HOEHLER	93	SPED	$\pi N \to \pi N$
25 ± 10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
54	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−23	ARNDT	95	DPWA	$\pi N \to N\pi$
-30 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−44	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(2190) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	
Γ_3	ΛK	
Γ_4	ΣK	
Γ_5	$N\pi\pi$	
Γ_6	$N\rho$	
Γ_7	$N\rho$, S=3/2, D-wave	
Γ_8	$p\gamma$, helicity=1/2	
Γ_9	$p\gamma$, helicity=3/2	
Γ_{10}	$n\gamma$, helicity=1/2	
Γ_{11}	$n\gamma$, helicity=3/2	

N(2190) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.2 OUR ESTIMATE				
0.22 ± 0.01	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.12 ± 0.06	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14 ± 0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.16 ± 0.04	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.23	ARNDT	95	DPWA	$\pi N \to N\pi$
0.19 ± 0.05	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.001 ± 0.003	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2190) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.052	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2190) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.02	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.02	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2190) \to \Sigma K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.014 to 0.019	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2190) \to N\rho$, S=3/2, D-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.25 ± 0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

N(2190) PHOTON DECAY AMPLITUDES

$N(2190) \to p\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.055	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.030	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190) \to p\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.081	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.180	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190) \to n\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.042	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
−0.085	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190) \to n\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.126	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
+0.007	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$N(2190)$ $\gamma p \to \Lambda K^+$ AMPLITUDES

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(2190) \to \Lambda K^+$ (E_{4-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
2.5 ±1.0	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.04	TANABE	89	DPWA

$p\gamma \to N(2190) \to \Lambda K^+$ phase angle θ (E_{4-} amplitude)

VALUE (degrees)	DOCUMENT ID		TECN
− 4 ±9	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−27.5	TANABE	89	DPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $p\gamma \to N(2190) \to \Lambda K^+$ (M_{4-} amplitude)

VALUE (units 10^{-3})	DOCUMENT ID		TECN
−7.0 ±0.7	WORKMAN	90	DPWA
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−5.78	TANABE	89	DPWA

$N(2190)$ FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[2] The range given for DEANS 75 is from the four best solutions. Disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

$N(2190)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
HOEHLER	93	πN Newsletter 9 1		(KARL)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WORKMAN	90	PR C42 781		(VPI)
TANABE	89	PR C39 741	+Kohno, Bennhold	(MANZ)
Also	89	NC 102A 193	Kohno, Tanabe, Bennhold	(MANZ)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP

$N(2200)$ D_{15}

$I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

The mass is not well determined. A few early results have been omitted.

$N(2200)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2200 OUR ESTIMATE				
1900	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
2180±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1920	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
2228±30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2240±65	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$N(2200)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
130	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
400±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
220	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$
310± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
761±139	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$N(2200)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
360±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2200)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
20±10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−90±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$N(2200)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\eta$
Γ_3	ΛK

$N(2200)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.07±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.08±0.04	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$\Gamma(N\eta)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.001±0.01	BATINIC	95	DPWA	$\pi N \to N\pi$, $N\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2200) \to N\eta$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.066	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2200) \to \Lambda K$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.03	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
−0.05	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

$N(2200)$ REFERENCES

BATINIC	95	PR C51 2310	+Slaus, Svarc, Nefkens	(BOSK, UCLA)
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP

$N(2220)$ H_{19}

$I(J^P) = \frac{1}{2}(\frac{9}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

N(2220) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2180 to 2310 (≈ 2220) OUR ESTIMATE				
2230± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2205± 10	HOEHLER	79	IPWA	$\pi N \to \pi N$
2300±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2258	ARNDT	95	DPWA	$\pi N \to N\pi$
2050	BAKER	79	DPWA	$\pi^- p \to n\eta$

N(2220) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
320 to 550 (≈ 400) OUR ESTIMATE				
500±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
365± 30	HOEHLER	79	IPWA	$\pi N \to \pi N$
450±150	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
334	ARNDT	95	DPWA	$\pi N \to N\pi$

N(2220) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2203	ARNDT	95	DPWA	$\pi N \to N\pi$
2135	[1] HOEHLER	93	ARGD	$\pi N \to \pi N$
2160±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2253	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
536	ARNDT	95	DPWA	$\pi N \to N\pi$
400	[1] HOEHLER	93	ARGD	$\pi N \to \pi N$
480±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
640	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(2220) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
68	ARNDT	95	DPWA	$\pi N \to N\pi$
40	HOEHLER	93	ARGD	$\pi N \to \pi N$
45±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
85	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−43	ARNDT	95	DPWA	$\pi N \to N\pi$
−50	HOEHLER	93	ARGD	$\pi N \to \pi N$
−45±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−62	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(2220) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	$N\eta$	
Γ_3	ΛK	

N(2220) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.2 OUR ESTIMATE				
0.15±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.18±0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.12±0.04	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.26	ARNDT	95	DPWA	$\pi N \to N\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2220) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.034	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2220) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not required	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

N(2220) FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

N(2220) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(2250)$ G_{19}

$I(J^P) = \frac{1}{2}(\frac{9}{2}^-)$ Status: ∗∗∗∗

N(2250) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2170 to 2310 (≈ 2250) OUR ESTIMATE				
2250± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2268± 15	HOEHLER	79	IPWA	$\pi N \to \pi N$
2200±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2291	ARNDT	95	DPWA	$\pi N \to N\pi$

N(2250) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
290 to 470 (≈ 400) OUR ESTIMATE				
480±120	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$
350±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
772	ARNDT	95	DPWA	$\pi N \to N\pi$

N(2250) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2087	ARNDT	95	DPWA	$\pi N \to N\pi$
2187	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
2150±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2243	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
680	ARNDT	95	DPWA	$\pi N \to N\pi$
388	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
360±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
650	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(2250) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
24	ARNDT	95	DPWA	$\pi N \to N\pi$
21	HOEHLER	93	SPED	$\pi N \to \pi N$
20±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
47	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−44	ARNDT	95	DPWA	$\pi N \to N\pi$
−50±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−37	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

N(2250) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	$N\eta$	
Γ_3	ΛK	

N(2250) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.10±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.10±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.09±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10	ARNDT	95	DPWA	$\pi N \to N\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2250) \to N\eta$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.043	BAKER	79	DPWA	$\pi^- p \to n\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to N(2250) \to \Lambda K$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.02	BELL	83	DPWA	$\pi^- p \to \Lambda K^0$
not seen	SAXON	80	DPWA	$\pi^- p \to \Lambda K^0$

N(2250) FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

N(2250) REFERENCES

ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BELL	83	NP B222 389	+Blissett, Broome, Daley, Hart, Lintern+	(RL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
SAXON	80	NP B162 522	+Baker, Bell, Blissett, Bloodworth+	(RHEL, BRIS) IJP
BAKER	79	NP B156 93	+Brown, Clark, Davies, Depagter, Evans+	(RHEL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

N(2600) $I_{1,11}$

$I(J^P) = \frac{1}{2}(\frac{11}{2}^-)$ Status: ∗∗∗

N(2600) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2550 to 2750 (≈ 2600) OUR ESTIMATE				
2577± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
2700±100	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2600) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
500 to 800 (≈ 650) OUR ESTIMATE				
400±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
900±100	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2600) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–10 %

N(2600) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.1 OUR ESTIMATE				
0.05±0.01	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2600) REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

N(2700) $K_{1,13}$

$I(J^P) = \frac{1}{2}(\frac{13}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

N(2700) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2700 OUR ESTIMATE				
2612± 45	HOEHLER	79	IPWA	$\pi N \to \pi N$
3000±100	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2700) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
900±150	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2700) DECAY MODES

	Mode
Γ_1	$N\pi$

N(2700) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.04±0.01	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.07±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

N(2700) REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$N(\sim 3000$ Region) Partial-Wave Analyses

OMITTED FROM SUMMARY TABLE

We list here miscellaneous high-mass candidates for isospin-1/2 resonances found in partial-wave analyses.

Our 1982 edition had an $N(3245)$, an $N(3690)$, and an $N(3755)$, each a narrow peak seen in a production experiment. Since nothing has been heard from them since the 1960's, we declare them to be dead. There was also an $N(3030)$, deduced from total cross-section and 180° elastic cross-section measurements; it is the KOCH 80 $L_{1,15}$ state below.

$N(\sim 3000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 3000 OUR ESTIMATE				
2600	KOCH	80	IPWA	$\pi N \rightarrow \pi N\ D_{13}$
3100	KOCH	80	IPWA	$\pi N \rightarrow \pi N\ L_{1,15}$ wave
3500	KOCH	80	IPWA	$\pi N \rightarrow \pi N\ M_{1,17}$ wave
3500 to 4000	KOCH	80	IPWA	$\pi N \rightarrow \pi N\ N_{1,19}$ wave
3500±200	HENDRY	78	MPWA	$\pi N \rightarrow \pi N\ L_{1,15}$ wave
3800±200	HENDRY	78	MPWA	$\pi N \rightarrow \pi N\ M_{1,17}$ wave
4100±200	HENDRY	78	MPWA	$\pi N \rightarrow \pi N\ N_{1,19}$ wave

$N(\sim 3000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1300±200	HENDRY	78	MPWA	$\pi N \rightarrow \pi N\ L_{1,15}$ wave
1600±200	HENDRY	78	MPWA	$\pi N \rightarrow \pi N\ M_{1,17}$ wave
1900±300	HENDRY	78	MPWA	$\pi N \rightarrow \pi N\ N_{1,19}$ wave

$N(\sim 3000)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$N(\sim 3000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.055±0.02	HENDRY	78	MPWA	$\pi N \rightarrow \pi N\ L_{1,15}$ wave
0.040±0.015	HENDRY	78	MPWA	$\pi N \rightarrow \pi N\ M_{1,17}$ wave
0.030±0.015	HENDRY	78	MPWA	$\pi N \rightarrow \pi N\ N_{1,19}$ wave

$N(\sim 3000)$ REFERENCES

KOCH	80	Toronto Conf. 3		(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND) IJP

Δ BARYONS
(S = 0, I = 3/2)

$\Delta^{++} = uuu$, $\Delta^{+} = uud$, $\Delta^{0} = udd$, $\Delta^{-} = ddd$

Δ(1232) P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1977 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

Δ(1232) MASSES

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1230 to 1234 (≈ 1232) OUR ESTIMATE				
1231±1	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1232±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1233±2	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1233	ARNDT	95	DPWA	$\pi N \to N\pi$

Δ(1232)$^{++}$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1230.9±0.3	KOCH	80B	IPWA	$\pi N \to \pi N$
1231.1±0.2	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

Δ(1232)$^{+}$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1234.9±1.4	MIROSHNIC...	79		Fit photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1231.6	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1231.2	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1231.8	BERENDS	75	IPWA	$\gamma p \to \pi N$

Δ(1232)^{0} MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1233.6±0.5	KOCH	80B	IPWA	$\pi N \to \pi N$
1233.8±0.2	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

$m_{\Delta^0} - m_{\Delta^{++}}$

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2.7±0.3	[1] PEDRONI	78	See the masses

Δ(1232) WIDTHS

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
115 to 125 (≈ 120) OUR ESTIMATE				
118±4	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
120±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
116±5	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
114	ARNDT	95	DPWA	$\pi N \to N\pi$

Δ(1232)$^{++}$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
111.0±1.0	KOCH	80B	IPWA	$\pi N \to \pi N$
111.3±0.5	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

Δ(1232)$^{+}$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
131.1±2.4	MIROSHNIC...	79		Fit photoproduction
• • • We do not use the following data for averages, fits, limits, etc. • • •				
111.2	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
111.0	BARBOUR	78	DPWA	$\gamma N \to \pi N$

Δ(1232)^{0} WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
113.0±1.5	KOCH	80B	IPWA	$\pi N \to \pi N$
117.9±0.9	PEDRONI	78		$\pi N \to \pi N$ 70–370 MeV

Δ^{0}-Δ^{++} WIDTH DIFFERENCE

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
6.6±1.0	PEDRONI	78	See the widths

Δ(1232) POLE POSITIONS

REAL PART, MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1211	ARNDT	95	DPWA	$\pi N \to N\pi$
1209	[2] HOEHLER	93	ARGD	$\pi N \to \pi N$
1210±1	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1210	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−IMAGINARY PART, MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50	ARNDT	95	DPWA	$\pi N \to N\pi$
50	[2] HOEHLER	93	ARGD	$\pi N \to \pi N$
50±1	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
50	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

REAL PART, Δ(1232)$^{++}$

VALUE (MeV)	DOCUMENT ID		COMMENT
1209.6±0.5	[3] VASAN	76B	Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1210.5 to 1210.8	[4] VASAN	76B	Fit to CARTER 73

−IMAGINARY PART, Δ(1232)$^{++}$

VALUE (MeV)	DOCUMENT ID		COMMENT
50.4±0.5	[3] VASAN	76B	Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •			
49.9 to 50.0	[4] VASAN	76B	Fit to CARTER 73

REAL PART, Δ(1232)$^{+}$

VALUE (MeV)	DOCUMENT ID		COMMENT
1206.9±0.9 to 1210.5 ± 1.8	MIROSHNIC...	79	Fit photoproduction
1208.0±2.0	CAMPBELL	76	Fit photoproduction

−IMAGINARY PART, Δ(1232)$^{+}$

VALUE (MeV)	DOCUMENT ID		COMMENT
55.6±1.0 to 58.3 ± 1.1	MIROSHNIC...	79	Fit photoproduction
53.0±2.0	CAMPBELL	76	Fit photoproduction

REAL PART, Δ(1232)^{0}

VALUE (MeV)	DOCUMENT ID		COMMENT
1210.75±0.6	[3] VASAN	76B	Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1210.2	[4] VASAN	76B	Fit to CARTER 73

−IMAGINARY PART, Δ(1232)^{0}

VALUE (MeV)	DOCUMENT ID		COMMENT
52.8±0.6	[3] VASAN	76B	Fit to CARTER 73
• • • We do not use the following data for averages, fits, limits, etc. • • •			
52.9 to 53.1	[4] VASAN	76B	Fit to CARTER 73

Δ(1232) ELASTIC POLE RESIDUES

ABSOLUTE VALUE, MIXED CHARGES

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
38	ARNDT	95	DPWA	$\pi N \to N\pi$
50	HOEHLER	93	ARGD	$\pi N \to \pi N$
53±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
52	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE, MIXED CHARGES

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−22	ARNDT	95	DPWA	$\pi N \to N\pi$
−48	HOEHLER	93	ARGD	$\pi N \to \pi N$
−47±1	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−31	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

ABSOLUTE VALUE, Δ(1232)$^{++}$

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
52.4 to 53.2	[3] VASAN	76B	Fit to CARTER 73
52.1 to 52.4	[4] VASAN	76B	Fit to CARTER 73

PHASE, $\Delta(1232)^{++}$

VALUE (rad)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.822 to −0.833	[3] VASAN	76B	Fit to CARTER 73
−0.823 to −0.830	[4] VASAN	76B	Fit to CARTER 73

ABSOLUTE VALUE, $\Delta(1232)^0$

VALUE (MeV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
54.8 to 55.0	[3] VASAN	76B	Fit to CARTER 73
55.2 to 55.3	[4] VASAN	76B	Fit to CARTER 73

PHASE, $\Delta(1232)^0$

VALUE (rad)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.840 to −0.847	[3] VASAN	76B	Fit to CARTER 73
−0.848 to −0.856	[4] VASAN	76B	Fit to CARTER 73

$\Delta(1232)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	>99 %
Γ_2	$N\gamma$	0.54–0.61 %
Γ_3	$N\gamma$, helicity=1/2	0.12–0.14 %
Γ_4	$N\gamma$, helicity=3/2	0.41–0.47 %

$\Delta(1232)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.993 to 0.995 OUR ESTIMATE				
1.0	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1.0	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1.0	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0	ARNDT	95	DPWA	$\pi N \to N\pi$

$\Delta(1232)$ PHOTON DECAY AMPLITUDES

$\Delta(1232) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.140±0.005 OUR ESTIMATE				
−0.141±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.135±0.016	DAVIDSON	91B	FIT	$\gamma N \to \pi N$
−0.145±0.015	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.138±0.004	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.147±0.001	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.145±0.001	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.136±0.006	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.143±0.004	LI	93	IPWA	$\gamma N \to \pi N$
−0.140±0.007	DAVIDSON	90	FIT	See DAVIDSON 91B
−0.142±0.007	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.140	[5] NOELLE	78		$\gamma N \to \pi N$
−0.141±0.004	FELLER	76	DPWA	$\gamma N \to \pi N$

$\Delta(1232) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.258±0.006 OUR ESTIMATE				
−0.261±0.005	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.251±0.033	DAVIDSON	91B	FIT	$\gamma N \to \pi N$
−0.263±0.026	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.259±0.006	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.264±0.002	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.261±0.002	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.247±0.010	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.262±0.004	LI	93	IPWA	$\gamma N \to \pi N$
−0.254±0.011	DAVIDSON	90	FIT	See DAVIDSON 91B
−0.271±0.010	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.247	[5] NOELLE	78		$\gamma N \to \pi N$
−0.256±0.003	FELLER	76	DPWA	$\gamma N \to \pi N$

$\Delta(1232) \to N\gamma$, E_2/M_1 ratio

VALUE	DOCUMENT ID		TECN	COMMENT
−0.015 ±0.004 OUR AVERAGE				
−0.015 ±0.005	WORKMAN	92	IPWA	$\gamma N \to \pi N$
−0.0157±0.0072	DAVIDSON	91B	FIT	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.0107±0.0037	DAVIDSON	90	FIT	$\gamma N \to \pi N$
−0.015 ±0.002	DAVIDSON	86	FIT	$\gamma N \to \pi N$
+0.037 ±0.004	TANABE	85	FIT	$\gamma N \to \pi N$

$\Delta(1232)$ PHASE OF M1+(3/2) PHOTOPRODUCTION MULTIPOLE AMPLITUDE POLE RESIDUE

Information on the phase (and magnitude) of the M1+(3/2) multipole amplitude pole residue is contained implicitly in the paper of MIROSHNICHENKO 79. They find that the phase is consistent with being equal to that of the elastic pole residue.

$\Delta(1232)^{++}$ MAGNETIC MOMENT

The values are extracted from UCLA and SIN data on $\pi^+ p$ bremsstrahlung using a variety of different theoretical approximations and methods. Our estimate is *only* a rough guess of the range we expect the moment to lie within.

VALUE (μ_N)	DOCUMENT ID		COMMENT
3.7 to 7.5 OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
4.52±0.50±0.45	BOSSHARD	91	$\pi^+ p \to \pi^+ p\gamma$ (SIN data)
3.7 to 4.2	LIN	91B	$\pi^+ p \to \pi^+ p\gamma$ (from UCLA data)
4.6 to 4.9	LIN	91B	$\pi^+ p \to \pi^+ p\gamma$ (from SIN data)
5.6 to 7.5	WITTMAN	88	$\pi^+ p \to \pi^+ p\gamma$ (from UCLA data)
6.9 to 9.8	HELLER	87	$\pi^+ p \to \pi^+ p\gamma$ (from UCLA data)
4.7 to 6.7	NEFKENS	78	$\pi^+ p \to \pi^+ p\gamma$ (UCLA data)

$\Delta(1232)$ FOOTNOTES

[1] Using $\pi^{\pm} d$ as well, PEDRONI 78 determine $(M^- - M^{++}) + (M^0 - M^+)/3 = 4.6 \pm 0.2$ MeV.

[2] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[3] This VASAN 76B value is from fits to the coulomb-barrier-corrected CARTER 73 phase shift.

[4] This VASAN 76B value is from fits to the CARTER 73 nuclear phase shift without coulomb barrier corrections.

[5] Converted to our conventions using $M = 1232$ MeV, $\Gamma = 110$ MeV from NOELLE 78.

$\Delta(1232)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
WORKMAN	92	PR C46 1546	+Arndt, Li	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
BOSSHARD	91	PR D44 1962	+Amsler+	(ZURI, LBL, VILL, LAUS, UCLA, CATH)
Also	90	PRL 64 2619	Bosshard+	(CATH, LAUS, LBL, VILL, UCLA, ZURI)
DAVIDSON	91B	PR D43 71	+Mukhopadhyay, Wittman	(RPI)
LIN	91B	PR C44 1819	+Liou, Ding	(CUNY, CSOK)
Also	91	PR C43 R930	Lin, Liou	(CUNY)
DAVIDSON	90	PR D42 20	+Mukhopadhyay	(RPI)
WITTMAN	88	PR C37 2075		(TRIU)
HELLER	87	PR C35 718	+Kumano, Martinez, Moniz	(LANL, MIT, ILL)
DAVIDSON	86	PRL 56 804	+Mukhopadhyay, Wittman	(RPI)
TANABE	85	PR C31 1876	+Ohta	(KOMAB)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
KOCH	80B	NP A336 331	+Pietarinen	(KARLT) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
MIROSHNIC...	79	SJNP 29 94	Miroshnichenko, Nikiforov, Sanin+	(KFTI) IJP
		Translated from YAF 29 188.		
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
NEFKENS	78	PR D18 3911	+Arman, Ballagh, Glodis, Haddock+	(UCLA, CATH) IJP
NOELLE	78	PTP 60 778		(NAGO)
PEDRONI	78	NP A300 321	+Gabathuler, Domingo, Hirt+	(SIN, ISNG, KARLE+) IJP
CAMPBELL	76	PR D14 2431	+Shaw, Ball	(BOIS, UCI, UTAH) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
VASAN	76B	NP B106 535		(CMU) IJP
Also	76	NP B106 526	Vasan	(CMU) IJP
BERENDS	75	NP B84 342	+Donnachie	(LEID, MCHS)
CARTER	73	NP B58 378	+Bugg, Carter	(CAVE, LOQM) IJP

Δ(1600) P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various analyses are not in good agreement.

Δ(1600) MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1550 to 1700 (≈ 1600) OUR ESTIMATE				
1706±10	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1600±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1522±13	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1672±15	ARNDT	96	IPWA	$\gamma N \to \pi N$
1706	LI	93	IPWA	$\gamma N \to \pi N$
1690	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
1560	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1640	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1600) WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
250 to 450 (≈ 350) OUR ESTIMATE				
430± 73	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
220± 40	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
315± 20	ARNDT	96	IPWA	$\gamma N \to \pi N$
215	LI	93	IPWA	$\gamma N \to \pi N$
250	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
180	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
300	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1600) POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1675	ARNDT	95	DPWA	$\pi N \to N\pi$
1550	[3] HOEHLER	93	SPED	$\pi N \to \pi N$
1550±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1612	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1609 or 1610	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1541 or 1542	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
386	ARNDT	95	DPWA	$\pi N \to N\pi$
200±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
230	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
323 or 325	[4] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
178 or 178	[1] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

Δ(1600) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
52	ARNDT	95	DPWA	$\pi N \to N\pi$
17±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
16	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
+ 14	ARNDT	95	DPWA	$\pi N \to N\pi$
−150±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
− 73	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

Δ(1600) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–25 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	75–90 %
Γ_4	$\Delta\pi$	40–70 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$\Delta(1232)\pi$, F-wave	
Γ_7	$N\rho$	<25 %
Γ_8	$N\rho$, S=1/2, P-wave	
Γ_9	$N\rho$, S=3/2, P-wave	
Γ_{10}	$N\rho$, S=3/2, F-wave	
Γ_{11}	$N(1440)\pi$	10–35 %
Γ_{12}	$N(1440)\pi$, P-wave	
Γ_{13}	$N\gamma$	0.001–0.02 %
Γ_{14}	$N\gamma$, helicity=1/2	0.0–0.02 %
Γ_{15}	$N\gamma$, helicity=3/2	0.001–0.005 %

Δ(1600) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ $\quad \Gamma_1/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.10 to 0.25 OUR ESTIMATE				
0.12±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.18±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.21±0.06	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to \Sigma K$ $\quad (\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.36 to −0.28 OUR ESTIMATE				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.006 to 0.042	[5] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to \Delta(1232)\pi$, P-wave $\quad (\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.27 to +0.33 OUR ESTIMATE				
+0.29±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.24±0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
+0.34	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.30	[2] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to \Delta(1232)\pi$, F-wave $\quad (\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.15 to −0.03 OUR ESTIMATE				
−0.07	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to N\rho$, S=1/2, P-wave $\quad (\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.10	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to N\rho$, S=3/2, P-wave $\quad (\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.10	[1,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1600) \to N(1440)\pi$, P-wave $\quad (\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.15 to +0.23 OUR ESTIMATE				
+0.16±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.23±0.04	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$

Δ(1600) PHOTON DECAY AMPLITUDES

$\Delta(1600) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.023±0.020 OUR ESTIMATE				
−0.018±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.039±0.030	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
−0.046±0.013	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.005±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.026±0.002	LI	93	IPWA	$\gamma N \to \pi N$
−0.200	[7] WADA	84	DPWA	Compton scattering
0.000±0.030	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.0 ±0.020	FELLER	76	DPWA	$\gamma N \to \pi N$

Δ(1600) → $N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.009±0.021 OUR ESTIMATE				
−0.025±0.015	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.013±0.014	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.025±0.031	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.009±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.016±0.002	LI	93	IPWA	$\gamma N \to \pi N$
0.023	WADA	84	DPWA	Compton scattering
0.000±0.045	BARBOUR	78	DPWA	$\gamma N \to \pi N$
0.0 ±0.015	FELLER	76	DPWA	$\gamma N \to \pi N$

Δ(1600) FOOTNOTES

[1] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[2] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[5] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[6] LONGACRE 77 considers this coupling to be well determined.

[7] WADA 84 is inconsistent with other analyses — see the Note on N and Δ Resonances.

Δ(1600) REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

Δ(1620) S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

Δ(1620) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1615 to 1675 (≈ 1620) OUR ESTIMATE				
1672 ± 7	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1620 ±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1610 ± 7	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1672 ± 5	ARNDT	96	IPWA	$\gamma N \to \pi N$
1617	ARNDT	95	DPWA	$\pi N \to N\pi$
1669	LI	93	IPWA	$\gamma N \to \pi N$
1620	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
1712.8± 6.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1786.7± 2.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1657	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1662	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1580	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1600	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1620) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
120 to 180 (≈ 150) OUR ESTIMATE				
154 ±37	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
140 ±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
139 ±18	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
147 ± 8	ARNDT	96	IPWA	$\gamma N \to \pi N$
108	ARNDT	95	DPWA	$\pi N \to N\pi$
184	LI	93	IPWA	$\gamma N \to \pi N$
120	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
228.3±18.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (lower mass)
30.0± 6.4	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (higher mass)
161	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
180	BARBOUR	78	DPWA	$\gamma N \to \pi N$
120	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
150	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

Δ(1620) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1585	ARNDT	95	DPWA	$\pi N \to N\pi$
1608	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
1600±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1587	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1583 or 1583	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1575 or 1572	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
104	ARNDT	95	DPWA	$\pi N \to N\pi$
116	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
120±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
120	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
143 or 149	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
119 or 128	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

Δ(1620) ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
14	ARNDT	95	DPWA	$\pi N \to N\pi$
19	HOEHLER	93	SPED	$\pi N \to \pi N$
15±2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
15	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−121	ARNDT	95	DPWA	$\pi N \to N\pi$
− 95	HOEHLER	93	SPED	$\pi N \to \pi N$
−110±20	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−125	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

Δ(1620) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	20–30 %
Γ_2	$N\pi\pi$	70–80 %
Γ_3	$\Delta\pi$	30–60 %
Γ_4	$\Delta(1232)\pi$, D-wave	
Γ_5	$N\rho$	7–25 %
Γ_6	$N\rho$, S=1/2, S-wave	
Γ_7	$N\rho$, S=3/2, D-wave	
Γ_8	$N(1440)\pi$	
Γ_9	$N\gamma$	0.004–0.044 %
Γ_{10}	$N\gamma$, helicity=1/2	0.004–0.044 %

$\Delta(1620)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.2 to 0.3 OUR ESTIMATE				
0.09±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.25±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.35±0.06	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29	ARNDT	95	DPWA	$\pi N \to N\pi$
0.60	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (lower mass)
0.36	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$ (higher mass)

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1620) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.36 to −0.28 OUR ESTIMATE				
−0.24±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.33±0.06	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
−0.39	[2,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.40	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1620) \to N\rho$, S=1/2, S-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.12 to +0.22 OUR ESTIMATE				
+0.15±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.40±0.10	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
+0.08	[2,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.28	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1620) \to N\rho$, S=3/2, D-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.15 to −0.03 OUR ESTIMATE				
−0.06±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
−0.13	[2,6] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1620) \to N(1440)\pi$ — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.11±0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$

$\Delta(1620)$ PHOTON DECAY AMPLITUDES

$\Delta(1620) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.027±0.011 OUR ESTIMATE				
0.035±0.020	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.035±0.010	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.010±0.015	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.022±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.026±0.008	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.021±0.020	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
0.126±0.021	TAKEDA	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.042±0.003	LI	93	IPWA	$\gamma N \to \pi N$
0.066	WADA	84	DPWA	Compton scattering
+0.034±0.028	BARBOUR	78	DPWA	$\gamma N \to \pi N$
−0.005±0.016	FELLER	76	DPWA	$\gamma N \to \pi N$

$\Delta(1620)$ FOOTNOTES

[1] CHEW 80 reports two S_{31} resonances at somewhat higher masses than other analyses. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] LONGACRE 77 considers this coupling to be well determined.

$\Delta(1620)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
WADA	84	NP B247 313	+Egawa, Imanishi, Ishii, Kato, Ukai+	(INUS)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
TAKEDA	80	NP B168 17	+Arai, Fujii, Ikeda, Iwasaki+	(TOKY, INUS)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1700)$ D_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1700)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1670 to 1770 (≈ 1700) OUR ESTIMATE				
1762 ±44	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1710 ±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1680 ±70	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1690 ±15	ARNDT	96	IPWA	$\gamma N \to \pi N$
1680	ARNDT	95	DPWA	$\pi N \to N\pi$
1655	LI	93	IPWA	$\gamma N \to \pi N$
1650	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
$1718.4^{+13.1}_{-13.0}$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1622	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1629	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1600	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
1680	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1700)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 to 400 (≈ 300) OUR ESTIMATE				
600 ±250	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
280 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
230 ± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
285 ± 20	ARNDT	96	IPWA	$\gamma N \to \pi N$
272	ARNDT	95	DPWA	$\pi N \to N\pi$
348	LI	93	IPWA	$\gamma N \to \pi N$
160	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
193.3± 26.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
209	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
216	BARBOUR	78	DPWA	$\gamma N \to \pi N$
200	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
240	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1700)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1655	ARNDT	95	DPWA	$\pi N \to N\pi$
1651	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
1675±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1646	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1681 or 1672	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
1600 or 1594	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
242	ARNDT	95	DPWA	$\pi N \to N\pi$
159	[4] HOEHLER	93	SPED	$\pi N \to \pi N$
220±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
208	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
245 or 241	[5] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$
208 or 201	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1700)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
16	ARNDT	95	DPWA	$\pi N \to N\pi$
10	HOEHLER	93	SPED	$\pi N \to \pi N$
13±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
13	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−12	ARNDT	95	DPWA	$\pi N \to N\pi$
−20±25	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−22	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1700)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	80–90 %
Γ_4	$\Delta\pi$	30–60 %
Γ_5	$\Delta(1232)\pi$, S-wave	25–50 %
Γ_6	$\Delta(1232)\pi$, D-wave	1–7 %
Γ_7	$N\rho$	30–55 %
Γ_8	$N\rho$, S=1/2, D-wave	
Γ_9	$N\rho$, S=3/2, S-wave	5–20 %
Γ_{10}	$N\rho$, S=3/2, D-wave	
Γ_{11}	$N\gamma$	0.12–0.26 %
Γ_{12}	$N\gamma$, helicity=1/2	0.08–0.16 %
Γ_{13}	$N\gamma$, helicity=3/2	0.025–0.12 %

$\Delta(1700)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 to 0.20 OUR ESTIMATE				
0.14±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.12±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.20±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.16	ARNDT	95	DPWA	$\pi N \to N\pi$
0.16	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1700) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.002	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.001 to 0.011	[6] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1700) \to \Delta(1232)\pi$, S-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.21 to +0.29 OUR ESTIMATE				
+0.32±0.06	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.18±0.04	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
+0.30	[2,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.24	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1700) \to \Delta(1232)\pi$, D-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.05 to +0.11 OUR ESTIMATE				
+0.08±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.14±0.04	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$
+0.05	[2,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
+0.10	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1700) \to N\rho$, S=1/2, D-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.17±0.05	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1700) \to N\rho$, S=3/2, S-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
±0.11 to ±0.19 OUR ESTIMATE				
+0.10±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.04	[2,7] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
−0.30	[3] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1700) \to N\rho$, S=3/2, D-wave — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.07	BARNHAM	80	IPWA	$\pi N \to N\pi\pi$

$\Delta(1700)$ PHOTON DECAY AMPLITUDES

$\Delta(1700) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.104±0.015 OUR ESTIMATE				
0.090±0.025	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.111±0.017	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.089±0.033	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.112±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.130±0.006	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.123±0.022	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.121±0.004	LI	93	IPWA	$\gamma N \to \pi N$
+0.130±0.037	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.072±0.033	FELLER	76	DPWA	$\gamma N \to \pi N$

$\Delta(1700) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.085±0.022 OUR ESTIMATE				
0.097±0.020	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.107±0.015	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.060±0.015	AWAJI	81	DPWA	$\gamma N \to \pi N$
0.047±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.050±0.007	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.102±0.015	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.115±0.004	LI	93	IPWA	$\gamma N \to \pi N$
+0.098±0.036	BARBOUR	78	DPWA	$\gamma N \to \pi N$
+0.087±0.023	FELLER	76	DPWA	$\gamma N \to \pi N$

$\Delta(1700)$ FOOTNOTES

[1] Problems with CHEW 80 are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[4] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[5] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[6] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.

[7] LONGACRE 77 considers this coupling to be well determined.

$\Delta(1700)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
BARNHAM	80	NP B168 243	+Glickman, Mier-Jedrzejowicz+	(LOIC)

CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
FELLER	76	NP B104 219	+Fukushima, Horikawa, Kajikawa+	(NAGO, OSAK) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1750)$ P_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(1750)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1750 OUR ESTIMATE				
1744 ±36	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1715.2±21.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1778.4± 9.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$\Delta(1750)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300 ±120	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
93.3± 55.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
23.0± 29.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$\Delta(1750)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$N(1440)\pi$

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.18	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.20	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1700) \to N(1440)\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.15±0.03	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$\Delta(1750)$ FOOTNOTES

[1] CHEW 80 reports four resonances in the P_{31} wave — see also the $\Delta(1910)$. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

$\Delta(1750)$ REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT)
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
CHEW	80	Toronto Conf. 123		(LBL)

$\Delta(1900)$ S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: ***

$\Delta(1900)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1850 to 1950 (≈ 1900) OUR ESTIMATE				
1920 ±24	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1890 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1908 ±30	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1918.5±23.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1803	CRAWFORD	80	DPWA	$\gamma N \to \pi N$

$\Delta(1900)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
140 to 240 (≈ 200) OUR ESTIMATE				
263 ±39	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
170 ±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
140 ±40	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
93.5±54.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
137	CRAWFORD	80	DPWA	$\gamma N \to \pi N$

$\Delta(1900)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1780	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
1870±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
2029 or 2025	[2] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$-2\times$IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
180±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
164 or 163	[2] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1900)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
10±3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
+20±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1900)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–30 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$\Delta\pi$	
Γ_5	$\Delta(1232)\pi$, D-wave	
Γ_6	$N\rho$	
Γ_7	$N\rho$, S=1/2, S-wave	
Γ_8	$N\rho$, S=3/2, D-wave	
Γ_9	$N(1440)\pi$, S-wave	
Γ_{10}	$N\gamma$, helicity=1/2	

$\Delta(1900)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.3 OUR ESTIMATE				
0.41±0.04	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.10±0.03	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.08±0.04	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.28	CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1900) \rightarrow \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.03	CANDLIN	84	DPWA	$\pi^+ p \rightarrow \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.076	[3] DEANS	75	DPWA	$\pi N \rightarrow \Sigma K$
0.11	LANGBEIN	73	IPWA	$\pi N \rightarrow \Sigma K$ (sol. 1)
0.12	LANGBEIN	73	IPWA	$\pi N \rightarrow \Sigma K$ (sol. 2)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1900) \rightarrow \Delta(1232)\pi$, *D*-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.25±0.07	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1900) \rightarrow N\rho$, S=1/2, *S*-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.14±0.11	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1900) \rightarrow N\rho$, S=3/2, *D*-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.37±0.07	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \rightarrow \Delta(1900) \rightarrow N(1440)\pi$, *S*-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.16±0.11	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$

$\Delta(1900)$ PHOTON DECAY AMPLITUDES

$\Delta(1900) \rightarrow N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.004±0.016	CRAWFORD	83	IPWA	$\gamma N \rightarrow \pi N$
0.029±0.008	AWAJI	81	DPWA	$\gamma N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.006 to −0.025	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$

$\Delta(1900)$ FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[2] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \rightarrow N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

[3] The value given is from solution 1; the resonance is not present in solutions 2, 3, or 4.

$\Delta(1900)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

HOEHLER	93	πN Newsletter 9 1		(KARL)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LANGBEIN	73	NP B53 251	+Wagner	(MUNI) IJP

$\Delta(1905)$ F_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1905)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1870 to 1920 (≈ 1905) OUR ESTIMATE				
1881 ±18	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
1910 ±30	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
1905 ±20	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1895 ± 8	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
1850	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1960 ±40	CANDLIN	84	DPWA	$\pi^+ p \rightarrow \Sigma^+ K^+$
$1787.0^{+6.0}_{-5.7}$	CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
1880	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
1892	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
1830	[1] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$\Delta(1905)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
280 to 440 (≈ 350) OUR ESTIMATE				
327 ± 51	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
400 ±100	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
260 ± 20	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
354 ± 10	ARNDT	96	IPWA	$\gamma N \rightarrow \pi N$
294	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
270 ± 40	CANDLIN	84	DPWA	$\pi^+ p \rightarrow \Sigma^+ K^+$
$66.0^{+24.0}_{-16.0}$	CHEW	80	BPWA	$\pi^+ p \rightarrow \pi^+ p$
193	CRAWFORD	80	DPWA	$\gamma N \rightarrow \pi N$
159	BARBOUR	78	DPWA	$\gamma N \rightarrow \pi N$
220	[1] LONGACRE	75	IPWA	$\pi N \rightarrow N\pi\pi$

$\Delta(1905)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1832	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
1829	[2] HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
1830±40	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1794	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
1813 or 1808	[3] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
254	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
303	[2] HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
280±60	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
230	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90
193 or 187	[3] LONGACRE	78	IPWA	$\pi N \rightarrow N\pi\pi$

$\Delta(1905)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
12	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
25	HOEHLER	93	SPED	$\pi N \rightarrow \pi N$
25±8	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
14	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
− 4	ARNDT	95	DPWA	$\pi N \rightarrow N\pi$
−50±20	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−40	ARNDT	91	DPWA	$\pi N \rightarrow \pi N$ Soln SM90

$\Delta(1905)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	85–95 %
Γ_4	$\Delta\pi$	<25 %
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$\Delta(1232)\pi$, F-wave	
Γ_7	$N\rho$	>60 %
Γ_8	$N\rho$, S=3/2, P-wave	
Γ_9	$N\rho$, S=3/2, F-wave	
Γ_{10}	$N\rho$, S=1/2, F-wave	
Γ_{11}	$N\gamma$	0.01–0.03 %
Γ_{12}	$N\gamma$, helicity=1/2	0.0–0.1 %
Γ_{13}	$N\gamma$, helicity=3/2	0.004–0.03 %

$\Delta(1905)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE			
0.12±0.03	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.08±0.03	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
0.15±0.02	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.12	ARNDT 95	DPWA	$\pi N \to N\pi$
0.11	CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1905) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.015±0.003	CANDLIN 84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
−0.013	LIVANOS 80	DPWA	$\pi p \to \Sigma K$
0.021 to 0.054	[4] DEANS 75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1905) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
−0.04±0.05	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1905) \to \Delta(1232)\pi$, F-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.02±0.03	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.20	[1] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.17	[5] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$
+0.06	[6] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1905) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID	TECN	COMMENT
+0.030 to +0.36 OUR ESTIMATE			
+0.33 ±0.03	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.33	[1] LONGACRE 75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
+0.26	[5] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$
+0.11 to +0.33	[7] NOVOSELLER 78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1905)$ PHOTON DECAY AMPLITUDES

$\Delta(1905) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
+0.026±0.011 OUR ESTIMATE			
0.022±0.005	ARNDT 96	IPWA	$\gamma N \to \pi N$
0.021±0.010	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
0.043±0.020	AWAJI 81	DPWA	$\gamma N \to \pi N$
0.022±0.010	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
0.031±0.009	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
0.024±0.014	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.055±0.004	LI 93	IPWA	$\gamma N \to \pi N$
+0.033±0.018	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$\Delta(1905) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID	TECN	COMMENT
−0.045±0.020 OUR ESTIMATE			
−0.045±0.005	ARNDT 96	IPWA	$\gamma N \to \pi N$
−0.056±0.028	CRAWFORD 83	IPWA	$\gamma N \to \pi N$
−0.025±0.023	AWAJI 81	DPWA	$\gamma N \to \pi N$
−0.029±0.007	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.045±0.006	ARAI 80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.072±0.035	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.002±0.003	LI 93	IPWA	$\gamma N \to \pi N$
−0.055±0.019	BARBOUR 78	DPWA	$\gamma N \to \pi N$

$\Delta(1905)$ FOOTNOTES

[1] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[2] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.
[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[4] The range given for DEANS 75 is from the four best solutions.
[5] A Breit-Wigner fit to the HERNDON 75 IPWA.
[6] A Breit-Wigner fit to the NOVOSELLER 78B IPWA.
[7] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near 90°.

$\Delta(1905)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
NOVOSELLER	78B	NP B137 445		(CIT) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1910)$ P_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1910)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1870 to 1920 (≈ 1910) OUR ESTIMATE			
1882 ±10	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1910 ±40	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
1888 ±20	HOEHLER 79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
2152	ARNDT 95	DPWA	$\pi N \to N\pi$
1960.1±21.0	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
$2121.4^{+13.0}_{-14.3}$	[1] CHEW 80	BPWA	$\pi^+ p \to \pi^+ p$
1921	CRAWFORD 80	DPWA	$\gamma N \to \pi N$
1899	BARBOUR 78	DPWA	$\gamma N \to \pi N$
1790	[2] LONGACRE 77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1910)$ WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
190 to 270 (≈ 250) OUR ESTIMATE			
239 ±25	MANLEY 92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
225 ±50	CUTKOSKY 80	IPWA	$\pi N \to \pi N$
280 ±50	HOEHLER 79	IPWA	$\pi N \to \pi N$

• • • We do not use the following data for averages, fits, limits, etc. • • •

760	ARNDT	95	DPWA	$\pi N \to N\pi$
152.9±60.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
172.2±37.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
351	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
230	BARBOUR	78	DPWA	$\gamma N \to \pi N$
170	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1910)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1810	ARNDT	95	DPWA	$\pi N \to N\pi$
1874	[3] HOEHLER	93	SPED	$\pi N \to \pi N$
1880±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1950	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1792 or 1801	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
494	ARNDT	95	DPWA	$\pi N \to N\pi$
283	[3] HOEHLER	93	SPED	$\pi N \to \pi N$
200±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
398	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
172 or 165	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$\Delta(1910)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
53	ARNDT	95	DPWA	$\pi N \to N\pi$
38	HOEHLER	93	SPED	$\pi N \to \pi N$
20±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
37	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−176	ARNDT	95	DPWA	$\pi N \to N\pi$
− 90±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
− 91	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1910)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	15–30 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$\Delta\pi$	
Γ_5	$\Delta(1232)\pi$, P-wave	
Γ_6	$N\rho$	
Γ_7	$N\rho$, S=3/2, P-wave	
Γ_8	$N(1440)\pi$	
Γ_9	$N(1440)\pi$, P-wave	
Γ_{10}	$N\gamma$	0.0–0.2 %
Γ_{11}	$N\gamma$, helicity=1/2	0.0–0.2 %

$\Delta(1910)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 to 0.3 OUR ESTIMATE				
0.23±0.08	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.19±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.24±0.06	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.26	ARNDT	95	DPWA	$\pi N \to N\pi$
0.17	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.40	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1910) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.03	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.019	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.082 to 0.184	[4] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1910) \to \Delta(1232)\pi$, P-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.06	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1910) \to N\rho$, S=3/2, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.29	[2] LONGACRE	77	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.17	[5] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1910) \to N(1440)\pi$, P-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.39±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$\Delta(1910)$ PHOTON DECAY AMPLITUDES

$\Delta(1910) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
+0.003±0.014 OUR ESTIMATE				
−0.002±0.008	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.014±0.030	CRAWFORD	83	IPWA	$\gamma N \to \pi N$
0.025±0.011	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.012±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.031±0.004	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.005±0.030	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.032±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.035±0.021	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1910)$ FOOTNOTES

[1] CHEW 80 reports four resonances in the P_{31} wave — see also the $\Delta(1750)$. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] LONGACRE 77 pole positions are from a search for poles in the unitarized T-matrix; the first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis. The other LONGACRE 77 values are from eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.

[3] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[4] The range given for DEANS 75 is from the four best solutions.

[5] Evidence for this coupling is weak; see NOVOSELLER 78. This coupling assumes the mass is near 1820 MeV.

$\Delta(1910)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CRAWFORD	83	NP B211 1	+Morton	(GLAS)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
NOVOSELLER	78	NP B137 509		(CIT) IJP
Also	78B	NP B137 445	Novoseller	(CIT) IJP
LONGACRE	77	NP B122 493	+Dolbeau	(SACL) IJP
Also	76	NP B108 365	Dolbeau, Triantis, Neveu, Cadiet	(SACL) IJP
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP

$\Delta(1920)$ P_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1920)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1900 to 1970 (≈ 1920) OUR ESTIMATE				
2014 ±16	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1920 ±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1868 ±10	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1840 ±40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
1955.0±13.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
$2065.0^{+13.6}_{-12.9}$	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$\Delta(1920)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
150 to 300 (≈ 200) OUR ESTIMATE				
152 ± 55	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
300 ±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
220 ± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
200 ± 40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
88.3± 35.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
62.0± 44.0	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$\Delta(1920)$ POLE POSITION

REAL PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1900	[2] HOEHLER	93	SPED	$\pi N \to \pi N$
1900±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1920)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
24±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	*DOCUMENT ID*		*TECN*	*COMMENT*
−150±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1920)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–20 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$\Delta(1232)\pi$, P-wave	
Γ_5	$N(1440)\pi$, P-wave	
Γ_6	$N\gamma$, helicity=1/2	
Γ_7	$N\gamma$, helicity=3/2	

$\Delta(1920)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.05 to 0.2 OUR ESTIMATE				
0.02±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.20±0.05	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.14±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.18	[1] CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to \Delta(1920) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.052±0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.049	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.048 to 0.120	[3] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to \Delta(1920) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_4)^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.13±0.04	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.3	[4] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
0.27	[5] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\pi \to \Delta(1920) \to N(1440)\pi$, P-wave $(\Gamma_1\Gamma_5)^{½}/\Gamma$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
+0.06±0.07	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$\Delta(1920)$ PHOTON DECAY AMPLITUDES

$\Delta(1920) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.040±0.014	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1920) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.023±0.017	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1920)$ FOOTNOTES

[1] CHEW 80 reports two P_{33} resonances in this mass region. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

[2] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[3] The range given for DEANS 75 is from the four best solutions.

[4] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near −90°.

[5] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near −90°.

$\Delta(1920)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

HOEHLER	93	πN Newsletter 9 1		(KARL)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
NOVOSELLER	78	NP B137 509		(CIT)
NOVOSELLER	78B	NP B137 445		(CIT)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)

$\Delta(1930)$ D_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ Status: ∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

The various analyses are not in good agreement.

$\Delta(1930)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1920 to 1970 (≈ 1930) OUR ESTIMATE				
1956 ±22	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1940 ±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1901 ±15	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1955 ±15	ARNDT	96	IPWA	$\gamma N \to \pi N$
2056	ARNDT	95	DPWA	$\pi N \to N\pi$
1963	LI	93	IPWA	$\gamma N \to \pi N$
$1910.0^{+15.0}_{-17.2}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
2000	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
2024	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
250 to 450 (≈ 350) OUR ESTIMATE				
530 ±140	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
320 ± 60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
195 ± 60	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
350 ± 20	ARNDT	96	IPWA	$\gamma N \to \pi N$
590	ARNDT	95	DPWA	$\pi N \to N\pi$
260	LI	93	IPWA	$\gamma N \to \pi N$
$74.8^{+17.0}_{-16.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
442	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
462	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1913	ARNDT	95	DPWA	$\pi N \to N\pi$
1850	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
1890±50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2018	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
246	ARNDT	95	DPWA	$\pi N \to N\pi$
180	[1] HOEHLER	93	SPED	$\pi N \to \pi N$
260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
398	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1930)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8	ARNDT	95	DPWA	$\pi N \to N\pi$
20	HOEHLER	93	SPED	$\pi N \to \pi N$
18±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
15	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−47	ARNDT	95	DPWA	$\pi N \to N\pi$
−20±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−24	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1930)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	10–20 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$N\gamma$	0.0–0.02 %
Γ_5	$N\gamma$, helicity=1/2	0.0–0.01 %
Γ_6	$N\gamma$, helicity=3/2	0.0–0.01 %

$\Delta(1930)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.2 OUR ESTIMATE				
0.18±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.14±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.11	ARNDT	95	DPWA	$\pi N \to N\pi$
0.11	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1930) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.031	LIVANOS	80	DPWA	$\pi p \to \Sigma K$
0.018 to 0.035	[2] DEANS	75	DPWA	$\pi N \to \Sigma K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1930) \to N\pi\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1930)$ PHOTON DECAY AMPLITUDES

$\Delta(1930) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.009±0.028 OUR ESTIMATE				
−0.007±0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
0.009±0.009	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.030±0.047	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.019±0.001	LI	93	IPWA	$\gamma N \to \pi N$
−0.062±0.064	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.018±0.028 OUR ESTIMATE				
0.005±0.010	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.025±0.011	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.033±0.060	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.009±0.001	LI	93	IPWA	$\gamma N \to \pi N$
+0.019±0.054	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1930)$ FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

[2] The range given for DEANS 75 is from the four best solutions.

$\Delta(1930)$ REFERENCES

For early references, see Physics Letters **111B** 70 (1982).

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
LIVANOS	80	Toronto Conf. 35	+Baton, Coutures, Kochowski, Neveu	(SACL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(1940)$ D_{33}

$I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(1940)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1940 OUR ESTIMATE				
2057 ±110	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2058.1± 34.5	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1940 ±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1940)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
460 ±320	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
198.4± 45.5	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
200 ±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1940)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1915 or 1926	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
190 or 186	[1] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1940)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8 ± 3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
135 ± 45	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(1940)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK
Γ_3	$N\pi\pi$
Γ_4	$\Delta(1232)\pi$, S-wave
Γ_5	$\Delta(1232)\pi$, D-wave
Γ_6	$N\rho$, S=3/2, S-wave
Γ_7	$N\gamma$, helicity=1/2
Γ_8	$N\gamma$, helicity=3/2

$\Delta(1940)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ $\quad\Gamma_1/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.18 ± 0.12	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.18	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.05 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1940) \to \Sigma K$ $\quad(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1940) \to \Delta(1232)\pi$, S-wave $\quad(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.11\pm0.10$	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1940) \to \Delta(1232)\pi$, D-wave $\quad(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.27\pm0.16$	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1940) \to N\rho$, S=3/2, S-wave $\quad(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.25\pm0.10$	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$\Delta(1940)$ PHOTON DECAY AMPLITUDES

$\Delta(1940) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.036 ± 0.058	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1940) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE ($GeV^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
-0.031 ± 0.012	AWAJI	81	DPWA	$\gamma N \to \pi N$

$\Delta(1940)$ FOOTNOTES

[1] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.

$\Delta(1940)$ REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)

$\Delta(1950)$ F_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

$\Delta(1950)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1940 to 1960 (≈ 1950) OUR ESTIMATE				
1945 ± 2	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
1950 ± 15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1913 ± 8	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1947 ± 9	ARNDT	96	IPWA	$\gamma N \to \pi N$
1921	ARNDT	95	DPWA	$\pi N \to N\pi$
1940	LI	93	IPWA	$\gamma N \to \pi N$
1925 ± 20	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$1855.0^{+11.0}_{-10.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
1902	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
1912	BARBOUR	78	DPWA	$\gamma N \to \pi N$
1925	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
290 to 350 (≈ 300) OUR ESTIMATE				
300 ± 7	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
340 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
224 ± 10	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
302 ± 9	ARNDT	96	IPWA	$\gamma N \to \pi N$
232	ARNDT	95	DPWA	$\pi N \to N\pi$
306	LI	93	IPWA	$\gamma N \to \pi N$
330 ± 40	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
$157.2^{+22.0}_{-19.0}$	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
225	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
198	BARBOUR	78	DPWA	$\gamma N \to \pi N$
240	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1880	ARNDT	95	DPWA	$\pi N \to N\pi$
1878	[2] HOEHLER	93	ARGD	$\pi N \to \pi N$
1890 ± 15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1884	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
1924 or 1924	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$-2\times$IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
236	ARNDT	95	DPWA	$\pi N \to N\pi$
230	[2] HOEHLER	93	ARGD	$\pi N \to \pi N$
260 ± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
238	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90
258 or 258	[3] LONGACRE	78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
54	ARNDT	95	DPWA	$\pi N \to N\pi$
47	HOEHLER	93	ARGD	$\pi N \to \pi N$
50 ± 7	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
61	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
-17	ARNDT	95	DPWA	$\pi N \to N\pi$
-32	HOEHLER	93	ARGD	$\pi N \to \pi N$
-33 ± 8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-23	ARNDT	91	DPWA	$\pi N \to \pi N$ Soln SM90

$\Delta(1950)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	35–40 %
Γ_2	ΣK	
Γ_3	$N\pi\pi$	
Γ_4	$\Delta\pi$	20–30 %
Γ_5	$\Delta(1232)\pi$, *F*-wave	
Γ_6	$\Delta(1232)\pi$, *H*-wave	
Γ_7	$N\rho$	<10 %
Γ_8	$N\rho$, S=1/2, *F*-wave	
Γ_9	$N\rho$, S=3/2, *F*-wave	
Γ_{10}	$N\gamma$	0.08–0.13 %
Γ_{11}	$N\gamma$, helicity=1/2	0.03–0.055 %
Γ_{12}	$N\gamma$, helicity=3/2	0.05–0.075 %

$\Delta(1950)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.35 to 0.4 OUR ESTIMATE				
0.38±0.01	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.39±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.38±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.49	ARNDT	95	DPWA	$\pi N \to N\pi$
0.44	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1950) \to \Sigma K$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.053±0.005	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.022 to 0.040	[4] DEANS	75	DPWA	$\pi N \to \Sigma K$

Note: Signs of couplings from $\pi N \to N\pi\pi$ analyses were changed in the 1986 edition to agree with the baryon-first convention; the overall phase ambiguity is resolved by choosing a negative sign for the $\Delta(1620)$ S_{31} coupling to $\Delta(1232)\pi$.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1950) \to \Delta(1232)\pi$, *F*-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.28 to +0.32 OUR ESTIMATE				
+0.27±0.02	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
+0.32	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.21	[5] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
0.38	[6] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(1950) \to N\rho$, S=3/2, *F*-wave — $(\Gamma_1\Gamma_9)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.24	[1] LONGACRE	75	IPWA	$\pi N \to N\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24	[7] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$
0.43	[8] NOVOSELLER	78	IPWA	$\pi N \to N\pi\pi$

$\Delta(1950)$ PHOTON DECAY AMPLITUDES

$\Delta(1950) \to N\gamma$, helicity-1/2 amplitude $A_{1/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.076±0.012 OUR ESTIMATE				
−0.079±0.006	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.068±0.007	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.091±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.083±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.067±0.014	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.102±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.058±0.013	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1950) \to N\gamma$, helicity-3/2 amplitude $A_{3/2}$

VALUE (GeV$^{-1/2}$)	DOCUMENT ID		TECN	COMMENT
−0.097±0.010 OUR ESTIMATE				
−0.103±0.006	ARNDT	96	IPWA	$\gamma N \to \pi N$
−0.094±0.016	AWAJI	81	DPWA	$\gamma N \to \pi N$
−0.101±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 1)
−0.100±0.005	ARAI	80	DPWA	$\gamma N \to \pi N$ (fit 2)
−0.082±0.017	CRAWFORD	80	DPWA	$\gamma N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.115±0.003	LI	93	IPWA	$\gamma N \to \pi N$
−0.075±0.020	BARBOUR	78	DPWA	$\gamma N \to \pi N$

$\Delta(1950)$ FOOTNOTES

[1] From method II of LONGACRE 75: eyeball fits with Breit-Wigner circles to the T-matrix amplitudes.
[2] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.
[3] LONGACRE 78 values are from a search for poles in the unitarized T-matrix. The first (second) value uses, in addition to $\pi N \to N\pi\pi$ data, elastic amplitudes from a Saclay (CERN) partial-wave analysis.
[4] The range given is from the four best solutions. DEANS 75 disagrees with $\pi^+ p \to \Sigma^+ K^+$ data of WINNIK 77 around 1920 MeV.
[5] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near −60°.
[6] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near −60°.
[7] A Breit-Wigner fit to the HERNDON 75 IPWA; the phase is near 120°.
[8] A Breit-Wigner fit to the NOVOSELLER 78B IPWA; the phase is near 120°.

$\Delta(1950)$ REFERENCES

ARNDT	96	PR C53 430	+Strakovsky, Workman	(VPI)
ARNDT	95	PR C52 2120	+Strakovsky, Workman, Pavan	(VPI, BRCO)
HOEHLER	93	πN Newsletter 9 1		(KARL)
LI	93	PR C47 2759	+Arndt, Roper, Workman	(VPI)
MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
ARNDT	91	PR D43 2131	+Li, Roper, Workman, Ford	(VPI, TELE) IJP
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
AWAJI	81	Bonn Conf. 352	+Kajikawa	(NAGO)
Also	82	NP B197 365	Fujii, Hayashii, Iwata, Kajikawa+	(NAGO)
ARAI	80	Toronto Conf. 93		(INUS)
Also	82	NP B194 251	Arai, Fujii	(INUS)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CRAWFORD	80	Toronto Conf. 107		(GLAS)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
BARBOUR	78	NP B141 253	+Crawford, Parsons	(GLAS)
LONGACRE	78	PR D17 1795	+Lasinski, Rosenfeld, Smadja+	(LBL, SLAC)
NOVOSELLER	78	NP B137 509		(CIT) IJP
NOVOSELLER	78B	NP B137 445		(CIT) IJP
WINNIK	77	NP B128 66	+Toaff, Revel, Goldberg, Berny	(HAIF) I
DEANS	75	NP B96 90	+Mitchell, Montgomery+	(SFLA, ALAH) IJP
HERNDON	75	PR D11 3183	+Longacre, Miller, Rosenfeld+	(LBL, SLAC)
LONGACRE	75	PL 55B 415	+Rosenfeld, Lasinski, Smadja+	(LBL, SLAC) IJP

$\Delta(2000)$ F_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

$\Delta(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2000 OUR ESTIMATE				
1752± 32	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2200±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
251± 93	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
400±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2000)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2150±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2000)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
16±5	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
150±90	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2000)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	$N\pi\pi$
Γ_3	$\Delta(1232)\pi$, *P*-wave
Γ_4	$\Delta(1232)\pi$, *F*-wave
Γ_5	$N\rho$, S=3/2, *P*-wave

$\Delta(2000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.02 ± 0.01	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.07 ± 0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2000) \to \Delta(1232)\pi$, P-wave $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.07\pm0.03$	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2000) \to \Delta(1232)\pi$, F-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.09\pm0.04$	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2000) \to N\rho$, S=3/2, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.06 ± 0.01	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$

$\Delta(2000)$ REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL)
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)

$\Delta(2150)$ S_{31}

$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(2150)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2150 OUR ESTIMATE				
$2047.4\pm\ 27.0$	[1] CHEW	80	BPWA	$\pi^+p \to \pi^+p$
$2203.2\pm\ \ 8.4$	[1] CHEW	80	BPWA	$\pi^+p \to \pi^+p$
$2150\ \ \pm100$	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$121.6\pm\ 62.0$	[1] CHEW	80	BPWA	$\pi^+p \to \pi^+p$
$120.5\pm\ 45.0$	[1] CHEW	80	BPWA	$\pi^+p \to \pi^+p$
$200\ \ \pm100$	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2140 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
7 ± 2	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
-60 ± 90	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2150)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2150)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.41	[1] CHEW	80	BPWA	$\pi^+p \to \pi^+p$
0.37	[1] CHEW	80	BPWA	$\pi^+p \to \pi^+p$
0.08 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2150) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.03	CANDLIN	84	DPWA	$\pi^+p \to \Sigma^+K^+$

$\Delta(2150)$ FOOTNOTES

[1] CHEW 80 reports two S_{31} resonances in this mass region. Problems with this analysis are discussed in section 2.1.11 of HOEHLER 83.

$\Delta(2150)$ REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
HOEHLER	83	Landolt-Boernstein 1/9B2		(KARLT)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)

$\Delta(2200)$ G_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^-)$ Status: *

OMITTED FROM SUMMARY TABLE

The various analyses are not in good agreement.

$\Delta(2200)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2200 OUR ESTIMATE				
2200 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2215 ± 60	HOEHLER	79	IPWA	$\pi N \to \pi N$
2280 ± 80	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2280 ± 40	CANDLIN	84	DPWA	$\pi^+p \to \Sigma^+K^+$

$\Delta(2200)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
450 ± 100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
400 ± 100	HOEHLER	79	IPWA	$\pi N \to \pi N$
400 ± 150	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$400\pm\ 50$	CANDLIN	84	DPWA	$\pi^+p \to \Sigma^+K^+$

$\Delta(2200)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2100 ± 50	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
340 ± 80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2200)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8 ± 3	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
-70 ± 40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2200)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2200)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06 ± 0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.05 ± 0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.09 ± 0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2200) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.014 ± 0.005	CANDLIN	84	DPWA	$\pi^+p \to \Sigma^+K^+$

$\Delta(2200)$ REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL) IJP
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2300) H_{39}

$I(J^P) = \frac{3}{2}(\frac{9}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2300) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2300 OUR ESTIMATE				
2204.5± 3.4	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
2400 ±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2217 ± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
2450 ±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2300) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
32.3± 1.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
425 ±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300 ±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
500 ±200	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
200	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2300) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2370±80	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
420±160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2300) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
10±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−20±30	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2300) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2300) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$
0.06±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.03±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.08±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2300) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.017	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2300) REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2350) D_{35}

$I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Δ(2350) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2350 OUR ESTIMATE				
2171± 18	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
2400±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2305± 26	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(2350) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
264± 51	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
400±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300± 70	HOEHLER	79	IPWA	$\pi N \to \pi N$

Δ(2350) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2400±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
400±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2350) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
15±8	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−70±70	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2350) DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

Δ(2350) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.020±0.003	MANLEY	92	IPWA	$\pi N \to \pi N$ & $N\pi\pi$
0.20 ±0.10	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.04 ±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2350) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2350) REFERENCES

MANLEY	92	PR D45 4002	+Saleski	(KENT) IJP
Also	84	PR D30 904	Manley, Arndt, Goradia, Teplitz	(VPI)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP

$\Delta(2390)$ F_{37}

$I(J^P) = \frac{3}{2}(\frac{7}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

$\Delta(2390)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2390 OUR ESTIMATE				
2350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2425± 60	HOEHLER	79	IPWA	$\pi N \to \pi N$

$\Delta(2390)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
300± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$

$\Delta(2390)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2350±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
260±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2390)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
12±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−90±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2390)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2390)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.04	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.07±0.04	HOEHLER	79	IPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2390) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2390)$ REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP

$\Delta(2400)$ G_{39}

$I(J^P) = \frac{3}{2}(\frac{9}{2}^-)$ Status: **

OMITTED FROM SUMMARY TABLE

$\Delta(2400)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2400 OUR ESTIMATE				
2300±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2468± 50	HOEHLER	79	IPWA	$\pi N \to \pi N$
2200±100	HENDRY	78	MPWA	$\pi N \to \pi N$

$\Delta(2400)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
330±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
480±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
450±200	HENDRY	78	MPWA	$\pi N \to \pi N$

$\Delta(2400)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2260±60	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
320±160	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2400)$ ELASTIC POLE RESIDUE

MODULUS $|r|$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
8±4	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−25±15	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

$\Delta(2400)$ DECAY MODES

	Mode
Γ_1	$N\pi$
Γ_2	ΣK

$\Delta(2400)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05±0.02	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.06±0.03	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.10±0.03	HENDRY	78	MPWA	$\pi N \to \pi N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2400) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.015	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

$\Delta(2400)$ REFERENCES

CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2420) $H_{3,11}$

$I(J^P) = \frac{3}{2}(\frac{11}{2}^+)$ Status: ∗∗∗∗

Most of the results published before 1975 are now obsolete and have been omitted. They may be found in our 1982 edition, Physics Letters **111B** (1982).

Δ(2420) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2300 to 2500 (≈ 2420) OUR ESTIMATE				
2400 ±125	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
2416 ± 17	HOEHLER	79	IPWA	$\pi N \to \pi N$
2400 ± 60	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
2358.0± 9.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(2420) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300 to 500 (≈ 400) OUR ESTIMATE				
450 ±150	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
340 ± 28	HOEHLER	79	IPWA	$\pi N \to \pi N$
460 ±100	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
400	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$
202.2± 45.0	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

Δ(2420) POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2300	[1] HOEHLER	93	ARGD	$\pi N \to \pi N$
2360±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
620	[1] HOEHLER	93	ARGD	$\pi N \to \pi N$
420±100	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2420) ELASTIC POLE RESIDUE

MODULUS |r|

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
39	HOEHLER	93	ARGD	$\pi N \to \pi N$
18±6	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

PHASE θ

VALUE (°)	DOCUMENT ID		TECN	COMMENT
−60	HOEHLER	93	ARGD	$\pi N \to \pi N$
−30±40	CUTKOSKY	80	IPWA	$\pi N \to \pi N$

Δ(2420) DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	5–15 %
Γ_2	ΣK	

Δ(2420) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.08±0.03	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
0.08±0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.11±0.02	HENDRY	78	MPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.22	CHEW	80	BPWA	$\pi^+ p \to \pi^+ p$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\pi \to \Delta(2420) \to \Sigma K$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.016	CANDLIN	84	DPWA	$\pi^+ p \to \Sigma^+ K^+$

Δ(2420) FOOTNOTES

[1] See HOEHLER 93 for a detailed discussion of the evidence for and the pole parameters of N and Δ resonances as determined from Argand diagrams of πN elastic partial-wave amplitudes and from plots of the speeds with which the amplitudes traverse the diagrams.

Δ(2420) REFERENCES

HOEHLER	93	πN Newsletter 9 1		(KARL)
CANDLIN	84	NP B238 477	+Lowe, Peach, Scotland+	(EDIN, RAL, LOWC)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
CHEW	80	Toronto Conf. 123		(LBL) IJP
CUTKOSKY	80	Toronto Conf. 19	+Forsyth, Babcock, Kelly, Hendrick	(CMU, LBL) IJP
Also	79	PR D20 2839	Cutkosky, Forsyth, Hendrick, Kelly	(CMU, LBL)
HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2750) $I_{3,13}$

$I(J^P) = \frac{3}{2}(\frac{13}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2750) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2750 OUR ESTIMATE				
2794± 80	HOEHLER	79	IPWA	$\pi N \to \pi N$
2650±100	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2750) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
350±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
500±100	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2750) DECAY MODES

	Mode
Γ_1	$N\pi$

Δ(2750) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.04±0.015	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.05±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2750) REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Δ(2950) $K_{3,15}$

$I(J^P) = \frac{3}{2}(\frac{15}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Δ(2950) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2950 OUR ESTIMATE				
2990±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
2850±100	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2950) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
330±100	HOEHLER	79	IPWA	$\pi N \to \pi N$
700±200	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2950) DECAY MODES

	Mode
Γ_1	$N\pi$

Δ(2950) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.04±0.02	HOEHLER	79	IPWA	$\pi N \to \pi N$
0.03±0.01	HENDRY	78	MPWA	$\pi N \to \pi N$

Δ(2950) REFERENCES

HOEHLER	79	PDAT 12-1	+Kaiser, Koch, Pietarinen	(KARLT) IJP
Also	80	Toronto Conf. 3	Koch	(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

$\Delta(\sim 3000$ Region) Partial-Wave Analyses

OMITTED FROM SUMMARY TABLE

We list here miscellaneous high-mass candidates for isospin-3/2 resonances found in partial-wave analyses.

Our 1982 edition also had a $\Delta(2850)$ and a $\Delta(3230)$. The evidence for them was deduced from total cross-section and 180° elastic cross-section measurements. The $\Delta(2850)$ has been resolved into the $\Delta(2750)$ $I_{3,13}$ and $\Delta(2950)$ $K_{3,15}$. The $\Delta(3230)$ is perhaps related to the $K_{3,13}$ of HENDRY 78 and to the $L_{3,17}$ of KOCH 80.

$\Delta(\sim 3000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 3000 OUR ESTIMATE				
3300	[1] KOCH	80	IPWA	$\pi N \rightarrow \pi N$ $L_{3,17}$ wave
3500	[1] KOCH	80	IPWA	$\pi N \rightarrow \pi N$ $M_{3,19}$ wave
2850±150	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $I_{3,11}$ wave
3200±200	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $K_{3,13}$ wave
3300±200	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $L_{3,17}$ wave
3700±200	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $M_{3,19}$ wave
4100±300	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $N_{3,21}$ wave

$\Delta(\sim 3000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
700±200	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $I_{3,11}$ wave
1000±300	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $K_{3,13}$ wave
1100±300	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $L_{3,17}$ wave
1300±400	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $M_{3,19}$ wave
1600±500	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $N_{3,21}$ wave

$\Delta(\sim 3000)$ DECAY MODES

	Mode
Γ_1	$N\pi$

$\Delta(\sim 3000)$ BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06 ±0.02	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $I_{3,11}$ wave
0.045±0.02	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $K_{3,13}$ wave
0.03 ±0.01	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $L_{3,17}$ wave
0.025±0.01	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $M_{3,19}$ wave
0.018±0.01	HENDRY	78	MPWA	$\pi N \rightarrow \pi N$ $N_{3,21}$ wave

$\Delta(\sim 3000)$ FOOTNOTES

[1] In addition, KOCH 80 reports some evidence for an S_{31} $\Delta(2700)$ and a P_{33} $\Delta(2800)$.

$\Delta(\sim 3000)$ REFERENCES

KOCH	80	Toronto Conf. 3		(KARLT) IJP
HENDRY	78	PRL 41 222		(IND, LBL) IJP
Also	81	ANP 136 1	Hendry	(IND)

Λ BARYONS
$(S = -1, I = 0)$

$\Lambda^0 = uds$

Λ

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Λ MASS

The fit uses Λ, Σ^+, Σ^0, Σ^- mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1115.684±0.006 OUR FIT					
1115.683±0.006 OUR AVERAGE					
1115.678±0.006±0.006	20k	HARTOUNI	94	SPEC	pp 27.5 GeV/c
1115.690±0.008±0.006	18k	[1] HARTOUNI	94	SPEC	pp 27.5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1115.59 ±0.08	935	HYMAN	72	HEBC	
1115.39 ±0.12	195	MAYEUR	67	EMUL	
1115.6 ±0.4		LONDON	66	HBC	
1115.65 ±0.07	488	[2] SCHMIDT	65	HBC	
1115.44 ±0.12		[3] BHOWMIK	63	RVUE	

[1] We assume CPT invariance: this is the $\overline{\Lambda}$ mass as measured by HARTOUNI 94. See below for the fractional mass difference, testing CPT.

[2] The SCHMIDT 65 masses have been reevaluated using our April 1973 proton and $K^\pm$ and $\pi^\pm$ masses. P. Schmidt, private communication (1974).

[3] The mass has been raised 35 keV to take into account a 46 keV increase in the proton mass and an 11 keV decrease in the $\pi^\pm$ mass (note added Reviews of Modern Physics **39** 1 (1967)).

$(m_\Lambda - m_{\overline{\Lambda}}) / m_\Lambda$

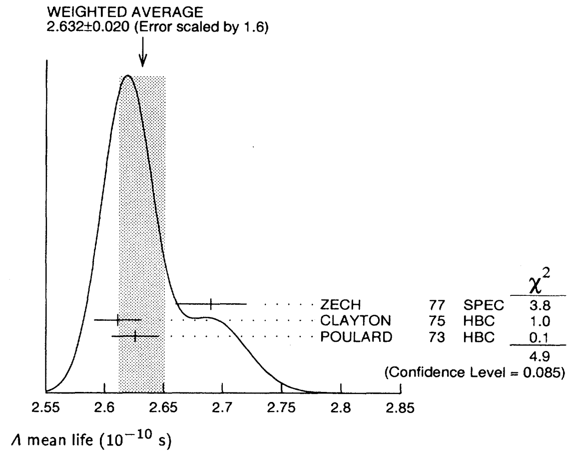
A test of CPT invariance.

VALUE (units 10^{-5})	DOCUMENT ID		TECN	COMMENT
− 1.0 ± 0.9 OUR AVERAGE				
− 1.08± 0.90	HARTOUNI	94	SPEC	pp 27.5 GeV/c
−26 ±13	BADIER	67	HBC	2.4 GeV/c $\overline{p}p$
4.5 ± 5.4	CHIEN	66	HBC	6.9 GeV/c $\overline{p}p$

Λ MEAN LIFE

Measurements with an error $\geq$ 0.1 × 10^{-10} s have been omitted altogether, and only the latest high-statistics measurements are used for the average.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
2.632±0.020 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
2.69 ±0.03	53k	ZECH	77	SPEC	Neutral hyperon beam
2.611±0.020	34k	CLAYTON	75	HBC	0.96–1.4 GeV/c $K^- p$
2.626±0.020	36k	POULARD	73	HBC	0.4–2.3 GeV/c $K^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.69 ±0.05	6582	ALTHOFF	73B	OSPK	$\pi^+ n \to \Lambda K^+$
2.54 ±0.04	4572	BALTAY	71B	HBC	$K^- p$ at rest
2.535±0.035	8342	GRIMM	68	HBC	
2.47 ±0.08	2600	HEPP	68	HBC	
2.35 ±0.09	916	BURAN	66	HLBC	
$2.452^{+0.056}_{-0.054}$	2213	ENGELMANN	66	HBC	
2.59 ±0.09	794	HUBBARD	64	HBC	
2.59 ±0.07	1378	SCHWARTZ	64	HBC	
2.36 ±0.06	2239	BLOCK	63	HEBC	



$(\tau_\Lambda - \tau_{\overline{\Lambda}}) / \tau_{\text{average}}$

A test of CPT invariance.

VALUE	DOCUMENT ID		TECN	COMMENT
0.044±0.085	BADIER	67	HBC	2.4 GeV/c $\overline{p}p$

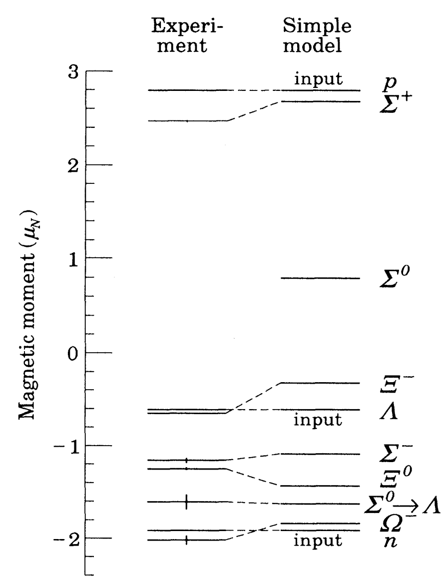
BARYON MAGNETIC MOMENTS

The figure shows the measured magnetic moments of the stable baryons. It also shows the predictions of the simplest quark model, using the measured p, n, and Λ moments as input. In this model, the moments are [1]

$$\mu_p = (4\mu_u - \mu_d)/3 \qquad \mu_n = (4\mu_d - \mu_u)/3$$
$$\mu_{\Sigma^+} = (4\mu_u - \mu_s)/3 \qquad \mu_{\Sigma^-} = (4\mu_d - \mu_s)/3$$
$$\mu_{\Xi^0} = (4\mu_s - \mu_u)/3 \qquad \mu_{\Xi^-} = (4\mu_s - \mu_d)/3$$
$$\mu_\Lambda = \mu_s \qquad \mu_{\Sigma^0} = (2\mu_u + 2\mu_d - \mu_s)/3$$
$$\mu_{\Omega^-} = 3\mu_s$$

and the $\Sigma^0 \to \Lambda$ transition moment is

$$\mu_{\Sigma^0\Lambda} = (\mu_d - \mu_u)/\sqrt{3}\ .$$



The quark moments that result from this model are $\mu_u = +1.852\,\mu_N$, $\mu_d = -0.972\,\mu_N$, and $\mu_s = -0.613\,\mu_N$. The corresponding effective quark masses, taking the quarks to be Dirac point particles, where $\mu = q\hbar/2m$, are 338, 322, and 510 MeV. As the figure shows, the model gives a good first approximation to the experimental moments. For efforts to make a better model, we refer to the literature [2].

References

1. See, for example, D.H. Perkins, *Introduction to High Energy Physics* (Addison-Wesley, Reading, MA, 1987), or D. Griffiths, *Introduction to Elementary Particles* (Harper & Row, New York, 1987).
2. See, for example, J. Franklin, Phys. Rev. **D29**, 2648 (1984); H.J. Lipkin, Nucl. Phys. **B241**, 477 (1984); K. Suzuki, H. Kumagai, and Y. Tanaka, Europhys. Lett. **2**, 109 (1986); S.K. Gupta and S.B. Khadkikar, Phys. Rev. **D36**, 307 (1987); M.I. Krivoruchenko, Sov. J. Nucl. Phys. **45**, 109 (1987); L. Brekke and J.L. Rosner, Comm. Nucl. Part. Phys. **18**, 83 (1988); K.-T. Chao, Phys. Rev. **D41**, 920 (1990) and references cited therein Also, see references cited in discussions of results in the experimental papers..

Λ MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" above. Measurements with an error $\geq 0.15\ \mu_N$ have been omitted.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
−0.613 ±0.004 OUR AVERAGE					
−0.606 ±0.015	200k	COX	81	SPEC	
−0.6138±0.0047	3M	SCHACHIN...	78	SPEC	
−0.59 ±0.07	350k	HELLER	77	SPEC	
−0.57 ±0.05	1.2M	BUNCE	76	SPEC	
−0.66 ±0.07	1300	DAHL-JENSEN	71	EMUL	200 kG field

Λ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-16} ecm)	CL%	DOCUMENT ID		TECN
< 1.5	95	[4] PONDROM	81	SPEC
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<100	95	[5] BARONI	71	EMUL
<500	95	GIBSON	66	EMUL

[4] PONDROM 81 measures $(-3.0 \pm 7.4) \times 10^{-17}$ e-cm.
[5] BARONI 71 measures $(-5.9 \pm 2.9) \times 10^{-15}$ e-cm.

Λ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$p\pi^-$	(63.9 ±0.5) %
Γ_2	$n\pi^0$	(35.8 ±0.5) %
Γ_3	$n\gamma$	(1.75±0.15) × 10^{-3}
Γ_4	$p\pi^-\gamma$	[a] (8.4 ±1.4) × 10^{-4}
Γ_5	$pe^-\overline{\nu}_e$	(8.32±0.14) × 10^{-4}
Γ_6	$p\mu^-\overline{\nu}_\mu$	(1.57±0.35) × 10^{-4}

[a] See the Particle Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 5 branching ratios uses 20 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 =$ 10.5 for 16 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100			
x_3	−2	−1		
x_5	46	−46	−1	
x_6	0	0	0	0
	x_1	x_2	x_3	x_5

Λ BRANCHING RATIOS

$\Gamma(p\pi^-)/\Gamma(N\pi)$ — $\Gamma_1/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.641±0.005 OUR FIT					
0.640±0.005 OUR AVERAGE					
0.646±0.008	4572	BALTAY	71B	HBC	K^-p at rest
0.635±0.007	6736	DOYLE	69	HBC	$\pi^-p \to \Lambda K^0$
0.643±0.016	903	HUMPHREY	62	HBC	
0.624±0.030		CRAWFORD	59B	HBC	$\pi^-p \to \Lambda K^0$

$\Gamma(n\pi^0)/\Gamma(N\pi)$ — $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID		TECN
0.359±0.005 OUR FIT				
0.310±0.028 OUR AVERAGE				
0.35 ±0.05		BROWN	63	HLBC
0.291±0.034	75	CHRETIEN	63	HLBC

$\Gamma(n\gamma)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.75±0.15 OUR FIT					
1.75±0.15	1816	LARSON	93	SPEC	K^-p at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.78\pm0.24^{+0.14}_{-0.16}$	287	NOBLE	92	SPEC	See LARSON 93

$\Gamma(n\gamma)/\Gamma(n\pi^0)$ — Γ_3/Γ_2

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.86±0.74±0.57	24	BIAGI	86	SPEC	SPS hyperon beam

$\Gamma(p\pi^-\gamma)/\Gamma(p\pi^-)$ — Γ_4/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.32±0.22	72	BAGGETT	72C	HBC	π^- < 95 MeV/c

$\Gamma(pe^-\overline{\nu}_e)/\Gamma(p\pi^-)$ — Γ_5/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.301±0.019 OUR FIT					
1.301±0.019 OUR AVERAGE					
1.335±0.056	7111	BOURQUIN	83	SPEC	SPS hyperon beam
1.313±0.024	10k	WISE	80	SPEC	
1.23 ±0.11	544	LINDQUIST	77	SPEC	$\pi^-p \to K^0\Lambda$
1.27 ±0.07	1089	KATZ	73	HBC	
1.31 ±0.06	1078	ALTHOFF	71	OSPK	
1.17 ±0.13	86	[6] CANTER	71	HBC	K^-p at rest
1.20 ±0.12	143	[7] MALONEY	69	HBC	
1.17 ±0.18	120	[7] BAGLIN	64	FBC	K^- freon 1.45 GeV/c
1.23 ±0.20	150	[7] ELY	63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.32 ±0.15	218	[6] LINDQUIST	71	OSPK	See LINDQUIST 77

[6] Changed by us from $\Gamma(pe^-\overline{\nu}_e)/\Gamma(N\pi)$ assuming the authors used $\Gamma(p\pi^-)/\Gamma_{total}$ = 2/3.
[7] Changed by us from $\Gamma(pe^-\overline{\nu}_e)/\Gamma(N\pi)$ because $\Gamma(pe^-\nu)/\Gamma(p\pi^-)$ is the directly measured quantity.

$\Gamma(p\mu^-\overline{\nu}_\mu)/\Gamma(N\pi)$ — $\Gamma_6/(\Gamma_1+\Gamma_2)$

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.57±0.35 OUR FIT					
1.57±0.35 OUR AVERAGE					
1.4 ±0.5	14	BAGGETT	72B	HBC	K^-p at rest
2.4 ±0.8	9	CANTER	71B	HBC	K^-p at rest
1.3 ±0.7	3	LIND	64	RVUE	
1.5 ±1.2	2	RONNE	64	FBC	

Λ DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings. Some early results have been omitted.

α_- FOR $\Lambda \to p\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.642±0.013 OUR AVERAGE					
0.584±0.046	8500	ASTBURY	75	SPEC	
0.649±0.023	10325	CLELAND	72	OSPK	
0.67 ±0.06	3520	DAUBER	69	HBC	From Ξ decay
0.645±0.017	10130	OVERSETH	67	OSPK	Λ from $\pi^- p$
0.62 ±0.07	1156	CRONIN	63	CNTR	Λ from $\pi^- p$

ϕ ANGLE FOR $\Lambda \to p\pi^-$ ($\tan\phi = \beta / \gamma$)

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
− 6.5± 3.5 OUR AVERAGE					
− 7.0± 4.5	10325	CLELAND	72	OSPK	Λ from $\pi^- p$
− 8.0± 6.0	10130	OVERSETH	67	OSPK	Λ from $\pi^- p$
13.0±17.0	1156	CRONIN	63	OSPK	Λ from $\pi^- p$

$\alpha_0 / \alpha_- = \alpha(\Lambda \to n\pi^0) / \alpha(\Lambda \to p\pi^-)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.01 ±0.07 OUR AVERAGE					
1.000±0.068	4760	[8] OLSEN	70	OSPK	$\pi^+ n \to \Lambda K^+$
1.10 ±0.27		CORK	60	CNTR	

[8] OLSEN 70 compares proton and neutron distributions from Λ decay.

$[\alpha_-(\Lambda) + \alpha_+(\overline{\Lambda})] / [\alpha_-(\Lambda) - \alpha_+(\overline{\Lambda})]$

Zero if *CP* is conserved.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.03±0.06 OUR AVERAGE					
+0.01±0.10	770	TIXIER	88	DM2	$J/\psi \to \Lambda\overline{\Lambda}$
−0.07±0.09	4063	BARNES	87	CNTR	$\overline{p}p \to \overline{\Lambda}\Lambda$ LEAR
−0.02±0.14	10k	[9] CHAUVAT	85	CNTR	pp, $\overline{p}p$ ISR

[9] CHAUVAT 85 actually gives $\alpha_+(\overline{\Lambda})/\alpha_-(\Lambda) = -1.04 \pm 0.29$. Assumes polarization is same in $\overline{p}p \to \overline{\Lambda}X$ and $pp \to \Lambda X$. Tests of this assumption, based on *C*-invariance and fragmentation, are satisfied by the data.

g_A / g_V FOR $\Lambda \to pe^-\overline{\nu}_e$

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with our conventions, which are given in the "Note on Baryon Decay Parameters" in the neutron Listings. The measurements all assume that the form factor $g_2 = 0$. See also the footnote on DWORKIN 90.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.718±0.015 OUR AVERAGE					
−0.719±0.016±0.012	37k	[10] DWORKIN	90	SPEC	$e\nu$ angular corr.
−0.70 ±0.03	7111	BOURQUIN	83	SPEC	$\Xi \to \Lambda\pi^-$
−0.734±0.031	10k	[11] WISE	81	SPEC	$e\nu$ angular correl.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.63 ±0.06	817	ALTHOFF	73	OSPK	Polarized Λ

[10] The tabulated result assumes the weak-magnetism coupling $w \equiv g_W(0)/g_V(0)$ to be 0.97, as given by the CVC hypothesis and as assumed by the other listed measurements. However, DWORKIN 90 *measures* w to be 0.15 ± 0.30, and then $g_A/g_V = -0.731 \pm 0.016$.

[11] This experiment measures only the absolute value of g_A/g_V.

Λ REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

HARTOUNI	94	PRL 72 1322	+Jensen, Kreisler+	(BNL E766 Collab.)
Also	94B	PRL 72 2821 (erratum)	Hartouni, Jensen+	(BNL E766 Collab.)
LARSON	93	PR D47 799	+Noble, Bassalleck+	(BNL-811 Collab.)
NOBLE	92	PRL 69 414	+	(BIRM, BOST, BRCO, BNL, CASE, BUDA, LANL+)
DWORKIN	90	PR D41 780	+Cox, Dukes, Overseth+	(MICH, WISC, RUTG, MINN)
TIXIER	88	PL B212 523	+Ajaltouni, Falvard, Jousset+	(DM2 Collab.)
BARNES	87	PL B199 147	+	(CMU, SACL, LANL, VIEN, FREIB, ILL, UPPS+)
BIAGI	86	ZPHY C30 201	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
CHAUVAT	85	PL 163B 273	+Erhan, Hayes+	(CERN, CLER, UCLA, SACL)
BOURQUIN	83	ZPHY C21 1	+Brown+	(BRIS, GEVA, HEIDP, LALO, RL, STRB)
COX	81	PRL 46 877	+Dworkin+	(MICH, WISC, RUTG, MINN, BNL)
PONDROM	81	PR D23 814	+Handler, Sheaff, Cox+	(WISC, MICH, RUTG, MINN)
WISE	81	PL 98B 123	+Jensen, Kreisler, Lomanno, Poster+	(MASA, BNL)
WISE	80	PL 91B 165	+Jensen, Kreisler, Lomanno, Poster+	(MASA, BNL)
SCHACHIN...	78	PRL 41 1348	Schachinger, Bunce, Cox+	(MICH, RUTG, WISC)
HELLER	77	PL 68B 480	+Overseth, Bunce, Dydak+	(MICH, WISC, HEIDH)
LINDQUIST	77	PR D16 2104	+Swallow, Sumner+	(EFI, OSU, ANL)
Also	76	JPG 2 L211	Lindquist, Swallow+	(EFI, WUSL, OSU, ANL)
ZECH	77	NP B124 413	+Dydak, Navarria+	(SIEG, CERN, DORT, HEIDH)
BUNCE	76	PRL 36 1113	+Handler, March, Martin+	(WISC, MICH, RUTG)
ASTBURY	75	NP B99 30	+Gallivan, Jafar+	(LOIC, CERN, ETH, SACL)
CLAYTON	75	NP B95 130	+Bacon, Butterworth, Waters+	(LOIC, RHEL)
ALTHOFF	73	PL 43B 237	+Brown, Freytag, Heard, Heintze+	(CERN, HEID)
ALTHOFF	73B	NP B66 29	+Brown, Freytag, Heard, Heintze+	(CERN, HEID)
KATZ	73	Thesis MDDP-TR-74-044		(UMD)
POULARD	73	PL 46B 135	+Givernaud, Borg	(SACL)
BAGGETT	72B	ZPHY 252 362	+Baggett, Eisele, Filthuth, Frehse+	(HEID)
BAGGETT	72C	PL 42B 379	+Baggett, Eisele, Filthuth, Frehse, Hepp+	(HEID)
CLELAND	72	NP B40 221	+Conforto, Eaton, Gerber+	(CERN, GEVA, LUND)
HYMAN	72	PR D5 1063	+Bunnell, Derrick, Fields, Katz+	(ANL, CMU)
ALTHOFF	71	PL 37B 531	+Brown, Freytag, Heard, Heintze+	(CERN, HEID)
BALTAY	71B	PR D4 670	+Bridgewater, Cooper, Habibi+	(COLU, BING)
BARONI	71	LNC 2 1256	+Petrera, Romano	(ROMA)
CANTER	71	PRL 26 868	+Cole, Lee-Franzini, Loveless+	(STON, COLU)
CANTER	71B	PRL 27 59	+Cole, Lee-Franzini, Loveless+	(STON, COLU)
DAHL-JENSEN	71	NC 3A 1	+	(CERN, ANKA, LAUS, MPIM, ROMA)
LINDQUIST	71	PRL 27 612	+Sumner+	(EFI, WUSL, OSU, ANL)
OLSEN	70	PRL 24 843	+Pondrom, Handler, Limon, Smith+	(WISC, MICH)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)
DOYLE	69	Thesis UCRL 18139		(LRL)
MALONEY	69	PRL 23 425	+Sechi-Zorn	(UMD)
GRIMM	68	NC 54A 187		(HEID)
HEPP	68	ZPHY 214 71	+Schleich	(HEID)
BADIER	67	PL 25B 152	+Bonnet, Briandet, Sadoulet	(EPOL)
MAYEUR	67	U.Libr.Brux.Bul. 32	+Tompa, Wickens	(BELG, LOUC)
OVERSETH	67	PRL 19 391	+Roth	(MICH, PRIN)
PDG	67	RMP 39 1	Rosenfeld, Barbaro-Galtieri, Podolsky+	(LRL, CERN, YALE)
BURAN	66	PL 20 318	+Eivindson, Skjeggestad, Tofte+	(OSLO)
CHIEN	66	PR 152 1171	+Lach, Sandweiss, Taft, Yeh, Oren+	(YALE, BNL)
ENGELMANN	66	NC 45A 1038	+Filthuth, Alexander+	(HEID, REHO)
GIBSON	66	NC 45A 882	+Green	(BRIS)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
SCHMIDT	65	PR 140B 1328		(COLU)
BAGLIN	64	NC 35 977	+Bingham+	(EPOL, CERN, LOUC, RHEL, BERG)
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
LIND	64	PR 135B 1483	+Binford, Good, Stern	(WISC)
RONNE	64	PL 11 357	+	(CERN, EPOL, LOUC, BERG+)
SCHWARTZ	64	Thesis UCRL 11360		(LRL)
BHOWMIK	63	NC 28 1494	+Goyal	(DELH)
BLOCK	63	PR 130 766	+Gessaroli, Ratti+	(NWES, BGNA, SYRA, ORNL)
BROWN	63	PR 130 769	+Kadyk, Trilling, Roe+	(LRL, MICH)
CHRETIEN	63	PR 131 2208	+	(BRAN, BROW, HARV, MIT)
CRONIN	63	PR 129 1795	+Overseth	(PRIN)
ELY	63	PR 131 868	+Gidal, Kalmus, Oswald, Powell+	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)
CORK	60	PR 120 1000	+Kerth, Wenzel, Cronin+	(LRL, PRIN, BNL)
CRAWFORD	59B	PRL 2 266	+Cresti, Douglass, Good, Ticho+	(LRL)

Λ AND Σ RESONANCES

Introduction: There are no new results at all on Λ and Σ resonances. The field remains at a standstill and will only be revived if a kaon factory is built. What follows is a much abbreviated version of the note on Λ and Σ Resonances from our 1990 edition. In particular, see that edition for some representative Argand plots from partial-wave analyses.

Table 1 is an attempt to evaluate the status, both overall and channel by channel, of each Λ and Σ resonance in the Particle Listings. The evaluations are of course partly subjective. A blank indicates there is no evidence at all: either the relevant couplings are small or the resonance does not really exist. The main Baryon Summary Table includes only the established resonances (overall status 3 or 4 stars). A number of the 1- and 2-star entries may eventually disappear, but there are certainly many resonances yet to be discovered underlying the established ones.

Sign conventions for resonance couplings: In terms of the isospin-0 and -1 elastic scattering amplitudes A_0 and A_1, the amplitude for $K^- p \to \overline{K}^0 n$ scattering is $\pm(A_1 - A_0)/2$, where the sign depends on conventions used in conjunction with the Clebsch-Gordan coefficients (such as, is the baryon or the meson the "first" particle). If this reaction is partial-wave analyzed and if the overall phase is chosen so that, say, the $\Sigma(1775)D_{15}$ amplitude at resonance points along the positive imaginary axis (points "up"), then any Σ at resonance will point "up" and any Λ at resonance will point "down" (along the negative imaginary axis). Thus the phase at resonance determines the isospin. The above ignores background amplitudes in the resonating partial waves.

That is the basic idea. In a similar but somewhat more complicated way, the phases of the $\overline{K}N \to \Lambda\pi$ and $\overline{K}N \to \Sigma\pi$ amplitudes for a resonating wave help determine the SU(3) multiplet to which the resonance belongs. Again, a convention has to be adopted for some overall arbitrary phases: which way is "up"? Our convention is that of Levi-Setti [1] and is shown in Fig. 1, which also compares experimental results with theoretical predictions for the signs of several resonances. In the Listings, a + or − sign in front of a measurement of an inelastic resonance coupling indicates the sign (the *absence* of a sign means that the sign is not determined, *not* that it is positive). For more details, see Appendix II of our 1982 edition [2].

Errors on masses and widths: The errors quoted on resonance parameters from partial-wave analyses are often only statistical, and the parameters can change by more than these errors when a different parametrization of the waves is used.

Table 1. The status of the Λ and Σ resonances. Only those with an overall status of *** or **** are included in the main Baryon Summary Table.

Particle	$L_{I\cdot 2J}$	Overall status	Status as seen in — $N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	P_{01}	****		F		$N\pi$(weakly)
$\Lambda(1405)$	S_{01}	****	****	o	****	
$\Lambda(1520)$	D_{03}	****	****	r	****	$\Lambda\pi\pi, \Lambda\gamma$
$\Lambda(1600)$	P_{01}	***	***	b	**	
$\Lambda(1670)$	S_{01}	****	****	i	****	$\Lambda\eta$
$\Lambda(1690)$	D_{03}	****	****	d	****	$\Lambda\pi\pi, \Sigma\pi\pi$
$\Lambda(1800)$	S_{01}	***	***	d	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(1810)$	P_{01}	***	***	e	**	$N\overline{K}^*$
$\Lambda(1820)$	F_{05}	****	****	n	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	D_{05}	****	***	F	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	P_{03}	****	****	o	**	$N\overline{K}^*, \Sigma(1385)\pi$
$\Lambda(2000)$		*		r	*	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2020)$	F_{07}	*	*	b	*	
$\Lambda(2100)$	G_{07}	****	****	i	***	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2110)$	F_{05}	***	**	d	*	$\Lambda\omega, N\overline{K}^*$
$\Lambda(2325)$	D_{03}	*	*	d		$\Lambda\omega$
$\Lambda(2350)$		***	***	e	*	
$\Lambda(2585)$		**	**	n		
$\Sigma(1193)$	P_{11}	****				$N\pi$(weakly)
$\Sigma(1385)$	P_{13}	****		****	****	
$\Sigma(1480)$		*	*	*	*	
$\Sigma(1560)$		**		**	**	
$\Sigma(1580)$	D_{13}	**	*	*		
$\Sigma(1620)$	S_{11}	**	**	*	*	
$\Sigma(1660)$	P_{11}	***	***	*	**	
$\Sigma(1670)$	D_{13}	****	****	****	****	several others
$\Sigma(1690)$		**	*	**	*	$\Lambda\pi\pi$
$\Sigma(1750)$	S_{11}	***	***	**	*	$\Sigma\eta$
$\Sigma(1770)$	P_{11}	*				
$\Sigma(1775)$	D_{15}	****	****	****	***	several others
$\Sigma(1840)$	P_{13}	*	*	**	*	
$\Sigma(1880)$	P_{11}	**	**	**		$N\overline{K}^*$
$\Sigma(1915)$	F_{15}	****	***	****	***	$\Sigma(1385)\pi$
$\Sigma(1940)$	D_{13}	***	*	***	**	quasi-2-body
$\Sigma(2000)$	S_{11}	*		*		$N\overline{K}^*, \Lambda(1520)\pi$
$\Sigma(2030)$	F_{17}	****	****	****	**	several others
$\Sigma(2070)$	F_{15}	*	*		*	
$\Sigma(2080)$	P_{13}	**		**		
$\Sigma(2100)$	G_{17}	*		*	*	
$\Sigma(2250)$		***	***	*	*	
$\Sigma(2455)$		**	*			
$\Sigma(2620)$		**	*			
$\Sigma(3000)$		*	*	*		
$\Sigma(3170)$		*				multi-body

**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

Furthermore, the different analyses use more or less the same data, so it is not really appropriate to treat the different determinations of the resonance parameters as independent or to average them together. In any case, the spread of the masses, widths, and branching fractions from the different analyses is certainly a better indication of the uncertainties than are the quoted errors. In the Baryon Summary Table, we usually give a range reflecting the spread of the values rather than a particular value with error.

For three states, the $\Lambda(1520)$, the $\Lambda(1820)$, and the $\Sigma(1775)$, there is enough information to make an overall fit to the various branching fractions. It is then necessary to use the quoted errors, but the errors obtained from the fit should not be taken seriously.

Production experiments: Partial-wave analyses of course separate partial waves, whereas a peak in a cross section or an invariant mass distribution usually cannot be disentangled from background and analyzed for its quantum numbers; and more than one resonance may be contributing to the peak. Results from partial-wave analyses and from production experiments are generally kept separate in the Listings, and in the Baryon Summary Table results from production experiments are used only for the low-mass states. The $\Sigma(1385)$ and $\Lambda(1405)$ of course lie below the $\overline{K}N$ threshold and nearly everything about them is learned from production experiments; and production and formation experiments agree quite well in the case of $\Lambda(1520)$ and results have been combined. There is some disagreement between production and formation experiments in the 1600–1700 MeV region: see the note on the $\Sigma(1670)$.

References

1. R. Levi-Setti, in *Proceedings of the Lund International Conference on Elementary Particles* (Lund, 1969), p. 339.
2. Particle Data Group, Phys. Lett. **111B** (1982).

$\Lambda(1405)$ S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

THE $\Lambda(1405)$

(by R.H. Dalitz, Oxford University)

It is generally accepted that the $\Lambda(1405)$ is a well-established $J^P = 1/2^-$ resonance. It is assigned to the lowest $L = 1$ supermultiplet of the 3-quark system and paired with the $J^P = 3/2^-$ $\Lambda(1520)$. Lying about 30 MeV below the $N\overline{K}$ threshold, the $\Lambda(1405)$ can be observed directly only as a resonance bump in the $(\Sigma\pi)^0$ subsystem in final states of production experiments. It was first reported by ALSTON 61B in the reaction $K^-p \to \Sigma\pi\pi\pi$ at 1.15 GeV/c and has since been seen in at least eight other experiments. However, only two of them had enough events for a detailed analysis: THOMAS 73, with about 400 $\Sigma^\pm\pi^\mp$ events from $\pi^-p \to K^0(\Sigma\pi)^0$ at 1.69 GeV/c; and HEMINGWAY 85, with 766 $\Sigma^+\pi^-$ and 1106 $\Sigma^-\pi^+$ events from $K^-p \to (\Sigma\pi\pi)^+\pi^-$ at 4.2 GeV/c, after the selections $1600 \leq M(\Sigma\pi\pi)^+ \leq 1720$ MeV and momentum transfer ≤ 1.0 (GeV/c)^2 to purify the $\Lambda(1405) \to (\Sigma\pi)^0$ sample. These experiments agree on a mass of about 1395–1400 MeV and a width of about 60 MeV. (Hemingway's mass of 1391 ± 1 MeV is from his best, but unacceptably poor, Breit-Wigner fit.)

The Byers-Fenster tests on these data allow any spin and either parity: neither J nor P has yet been determined *directly*. The early indications for $J^P = 1/2^-$ came from finding Re $A_{I=0}$ to be large and negative in a constant-scattering-length analysis of low-energy $N\overline{K}$ reaction data (see KIM 65, SAKITT 65, and earlier references cited therein). The first multichannel energy-dependent K-matrix analysis (KIM 67) strengthened the case for a resonance around 1400–1420 MeV strongly coupled to the $I = 0$ S-wave $N\overline{K}$ system.

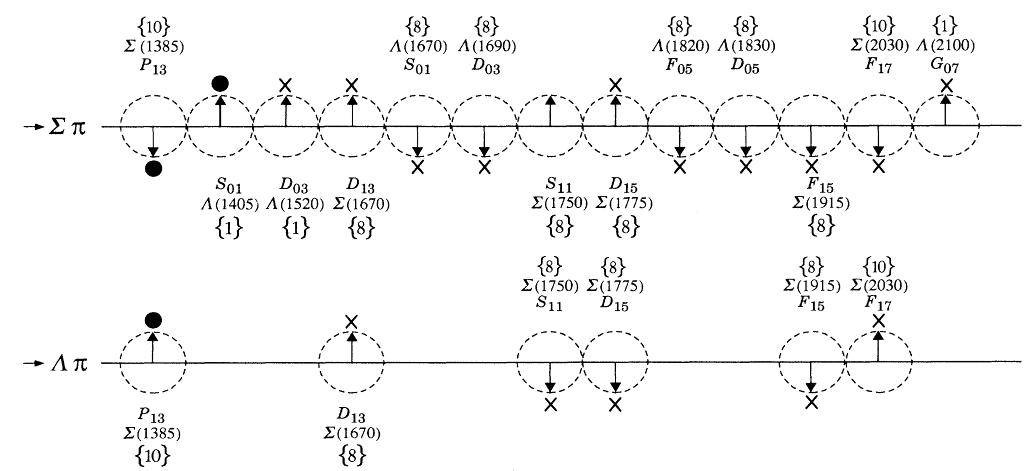


Figure 1. The signs of the imaginary parts of resonating amplitudes in the $\overline{K}N \to \Lambda\pi$ and $\Sigma\pi$ channels. The signs of the $\Sigma(1385)$ and $\Lambda(1405)$, marked with a •, are set by convention, and then the others are determined relative to them. The signs required by the SU(3) assignments of the resonances are shown with an arrow, and the experimentally determined signs are shown with an ×.

THOMAS 73 and HEMINGWAY 85 both found the $\Lambda(1405)$ bump to be asymmetric and not well fitted by a Breit-Wigner resonance function with constant parameters. The asymmetry involves a rapid fall in intensity as the $N\overline{K}$ threshold energy is approached from below. This is readily understood as due to a strong coupling of the $\Lambda(1405)$ to the S-wave $N\overline{K}$ channel (see DALITZ 81). This striking S-shaped cusp behavior at a new threshold is characteristic of S-wave coupling; the other below-threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its $N\overline{K}$ coupling is P-wave. For the $\Lambda(1405)$, this asymmetry is the *sole direct evidence* that $J^P = 1/2^-$.

Following the early work cited above, a considerable literature has developed on proper procedures for phenomenological extrapolation below the $N\overline{K}$ threshold, partly in order to strengthen the evidence for the spin-parity of the $\Lambda(1405)$, and partly to provide an estimate for the amplitude $f(N\overline{K})$ in the unphysical domain below the $N\overline{K}$ threshold; the latter is needed for the evaluation of the dispersion relation for $N\overline{K}$ and NK forward scattering amplitudes. For recent reviews, see MILLER 84 and BARRETT 89. In most recent work, the $(\Sigma\pi)^0$ production spectrum is included in the data fitted (see, *e.g.*, CHAO 73, MARTIN 81).

It is now accepted that the data can be fitted only with an S-wave pole in the reaction amplitudes below $N\overline{K}$ threshold (see, however, FINK 90), but there is still controversy about the physical origin of this pole (for a review, see DALITZ 81 and DALITZ 82). Two extreme possibilities are: (a) an $L = 1$ SU(3)-singlet *uds* state coupled with the S-wave meson-baryon systems; or (b) an unstable $N\overline{K}$ bound state, analogous to the (stable) deuteron in the NN system. The problem with (a) is that the $\Lambda(1405)$ mass is so much lower than that of its partner, the $\Lambda(1520)$. This requires, in the QCD-inspired quark model, rather large spin-orbit couplings, whether or not one uses relativistic kinetic energies. ISGUR 80, CAPSTICK 86, and CAPSTICK 89 conclude that a proper QCD calculation leads only to small energy splittings, whereas LEINWEBER 90, using QCD sum rules, obtains a good fit to this splitting.

On the other hand, the problem with (b) is that then another $J^P = 1/2^- \Lambda$ is needed to replace the $\Lambda(1405)$ in the $L = 1$ supermultiplet, and it would have to lie close to the $\Lambda(1520)$, a region already well explored by $N\overline{K}$ experiments without result. Intermediate structures are possible; for example, the cloudy bag model allows the configurations (a) and (b) to mix and finds the intensity of (a) in the $\Lambda(1405)$ to be only 14% (VEIT 84, VEIT 85, JENNINGS 86). Such models naturally predict a second $1/2^-$ Λ close to the $\Lambda(1520)$.

The determination of the mass and width of the resonance from $(\Sigma\pi)^0$ data is usually based on the "Watson approximation," which states that the production rate $R(\Sigma\pi)$ of the $(\Sigma\pi)^0$ state has a mass dependence proportional to $(\sin^2\delta_{\Sigma\pi})/q$, q being the $\Sigma\pi$ c.m. momentum, in a $\Sigma\pi$ mass range where $\delta_{\Sigma\pi}$ is not far from $\pi/2$ and only the $\Sigma\pi$ channel is open, *i.e.*, between the $\Sigma\pi$ and the $N\overline{K}$ thresholds. Then $q\,R(\Sigma\pi)$ is proportional to $\sin^2\delta_{\Sigma\pi}$, and the mass M may be defined as the energy at which $\sin^2\delta_{\Sigma\pi} = 1$. The width Γ may be determined from the rate at which $\delta_{\Sigma\pi}$ goes through $\pi/2$, or from the FWHM; this is a matter of convention.

This determination of M and Γ from the data suffers from the following defects:

(i) The determination of $\sin^2\delta_{\Sigma\pi}$ requires that $R(\Sigma\pi)$ be scaled to give $\sin^2\delta_{\Sigma\pi} = 1$ at the peak for the best fit to the data; *i.e.*, the bump must be *assumed* to arise from a resonance. However, this assumption is supported by the analysis of the low-energy $N\overline{K}$ data and its extrapolation below threshold.

(ii) Owing to the nearby $N\overline{K}$ threshold, the shape of the best fit to the $M(\Sigma\pi)$ bump is uncertain. For energies below this threshold at $E_{N\overline{K}}$, the general form for $\delta_{\Sigma\pi}$ is

$$q\cot\delta_{\Sigma\pi} = \frac{1+\kappa\alpha}{\gamma+\kappa(\alpha\gamma-\beta^2)} \;.$$

Here α, β, and γ are the (generally energy-dependent) NN, $N\Sigma$, and $\Sigma\Sigma$ elements of the $I = 0$ S-wave K-matrix for the $(\Sigma\pi, N\overline{K})$ system, and κ is the magnitude of the (imaginary) c.m. momentum k_K for the $N\overline{K}$ system below threshold. The elements α, β, γ are real functions of E; they have no branch cuts at the $\Sigma\pi$ and $N\overline{K}$ thresholds, but they are permitted to have poles in E along the real E axis. The resonance asymmetry arises from the effect of κ on $\delta_{\Sigma\pi}$. We note that $\delta_{\Sigma\pi} = \pi/2$ when $\kappa = -1/\alpha$.

Accepting this close connection of $\delta_{\Sigma\pi}$ with the low-energy $N\overline{K}$ data, it is natural to analyze the two sets of data together (*e.g.*, MARTIN 81), and there is now a large body of accurate $N\overline{K}$ data for laboratory momenta between 100 and 300 MeV/c (see MILLER 84). The two sets of data span c.m. energies from 1370 MeV to 1490 MeV, and the K-matrix elements will not be energy independent over such a broad range. For the $I = 0$ channels, a linear energy dependence for K^{-1} has been adopted routinely ever since the work of KIM 67, and it is essential when fitting the $q\,R(\Sigma\pi)$ and $N\overline{K}$ data together. However, $q\,R(\Sigma\pi)$ is not always well fitted in this procedure; the value obtained for the $\Lambda(1405)$ mass M varies a good deal with the type of fit, not a surprising result when the $\Sigma\pi$ mass spectrum contributes only nine data points in a total of about 200. The value of M obtained from an overall fit is not necessarily much better than from one using only the $q\,R(\Sigma\pi)$ data; and M may be a function of the representation—K-matrix, K^{-1}-matrix, relativistic-separable or nonseparable potentials, *etc.*— used in fitting over the full energy range. DALITZ 90 fitted the $qR(\Sigma^+\pi^-)$ Hemingway data with each of the first three representations just mentioned, constrained to the $I = 0$ $N\overline{K}$ threshold scattering length from low-energy $N\overline{K}$ data. The (nonseparable) meson-exchange potentials of MÜLLER-GROELING 90, fitted to the low-energy $N\overline{K}$ (and NK) data, predicted an unstable $N\overline{K}$ bound state with mass and width compatible with the $\Lambda(1405)$.

The present status of the $\Lambda(1405)$ thus depends heavily on theoretical arguments, a somewhat unsatisfactory basis for a four-star rating. Nevertheless, there is no known reason to doubt its existence or quantum numbers. A measurement of the energy-level shifts and widths for the atomic levels of kaonic hydrogen (and deuterium) would give a valuable check on analyses of the $(\Sigma\pi, N\overline{K})$ amplitudes, since the energy of the K^-p atom lies roughly midway between those for the two sets of data. The three measurements of $(\Delta E - i\Gamma/2)$ for kaonic hydrogen are inconsistent with one another and require that the sign of $\mathrm{Re}(A_{I=0} + A_{I=1})$ be opposite that deduced from $N\overline{K}$ reaction data (see BATTY 89). Accurate measurements of $(\Delta E - i\Gamma/2)$ values for kaonic hydrogen are badly needed, but may not be possible until the KAON factory becomes operational.

To definitively settle the nature of the $\Lambda(1405)$ will require much further work, both experimental and theoretical. Higher-statistics experiments on the production and decay of the $\Lambda(1405)$ are needed, but suitable K^- beams will not be available until KAON. The low-energy reaction cross sections, especially for the $\overline{K}^0p$ interactions, last studied 25 years ago, need to be better determined.

$\Lambda(1405)$ MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1406.5± 4.0		[1] DALITZ	91		M-matrix fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1391 ± 1	700	[1] HEMINGWAY	85	HBC	K^-p 4.2 GeV/c
~ 1405	400	[2] THOMAS	73	HBC	π^-p 1.69 GeV/c
1405	120	BARBARO-...	68B	DBC	K^-d 2.1–2.7 GeV/c
1400 ± 5	67	BIRMINGHAM	66	HBC	K^-p 3.5 GeV/c
1382 ± 8		ENGLER	65	HDBC	π^-p, π^+d 1.68 GeV/c
1400 ±24		MUSGRAVE	65	HBC	$\overline{p}p$ 3–4 GeV/c
1410		ALEXANDER	62	HBC	π^-p 2.1 GeV/c
1405		ALSTON	62	HBC	K^-p 1.2–0.5 GeV/c
1405		ALSTON	61B	HBC	K^-p 1.15 GeV/c

EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1411	[3] MARTIN	81		K-matrix fit
1406	[4] CHAO	73	DPWA	0-range fit (sol. B)
1421	MARTIN	70	RVUE	Constant K-matrix
1416 ±4	MARTIN	69	HBC	Constant K-matrix
1403 ±3	KIM	67	HBC	K-matrix fit
1407.5±1.2	[5] KITTEL	66	HBC	0-effective-range fit
1410.7±1.0	KIM	65	HBC	0-effective-range fit
1409.6±1.7	[5] SAKITT	65	HBC	0-effective-range fit

$\Lambda(1405)$ WIDTH

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
50 ± 2		[1] DALITZ	91		M-matrix fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
32 ± 1	700	[1] HEMINGWAY	85	HBC	K^-p 4.2 GeV/c
45 to 55	400	[2] THOMAS	73	HBC	π^-p 1.69 GeV/c
35	120	BARBARO-...	68B	DBC	K^-d 2.1–2.7 GeV/c
50 ±10	67	BIRMINGHAM	66	HBC	K^-p 3.5 GeV/c
89 ±20		ENGLER	65	HDBC	
60 ±20		MUSGRAVE	65	HBC	
35 ± 5		ALEXANDER	62	HBC	
50		ALSTON	62	HBC	
20		ALSTON	61B	HBC	

EXTRAPOLATIONS BELOW $N\overline{K}$ THRESHOLD

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
30	[3] MARTIN	81		K-matrix fit
55	[4,6] CHAO	73	DPWA	0-range fit (sol. B)
20	MARTIN	70	RVUE	Constant K-matrix
29 ±6	MARTIN	69	HBC	Constant K-matrix
50 ±5	KIM	67	HBC	K-matrix fit
34.1±4.1	[5] KITTEL	66	HBC	
37.0±3.2	KIM	65	HBC	
28.2±4.1	[5] SAKITT	65	HBC	

$\Lambda(1405)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Sigma\pi$	100 %
Γ_2	$\Lambda\gamma$	
Γ_3	$\Sigma^0\gamma$	
Γ_4	$N\overline{K}$	

$\Lambda(1405)$ PARTIAL WIDTHS

$\Gamma(\Lambda\gamma)$ Γ_2

VALUE (keV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
27±8	BURKHARDT	91	Isobar model fit

$\Gamma(\Sigma^0\gamma)$ Γ_3

VALUE (keV)	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
10 ± 4 or 23 ± 7	BURKHARDT	91	Isobar model fit

$\Lambda(1405)$ BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3	95	HEMINGWAY	85	HBC	K^-p 4.2 GeV/c

$\Lambda(1405)$ FOOTNOTES

[1] DALITZ 91 fits the HEMINGWAY 85 data.
[2] THOMAS 73 data is fit by CHAO 73 (see next section).
[3] The MARTIN 81 fit includes the $K^{\pm}p$ forward scattering amplitudes and the dispersion relations they must satisfy.
[4] See also the accompanying paper of THOMAS 73.
[5] Data of SAKITT 65 are used in the fit by KITTEL 66.
[6] An asymmetric shape, with $\Gamma/2$ = 41 MeV below resonance, 14 MeV above.

$\Lambda(1405)$ REFERENCES

BURKHARDT 91 PR C44 607 +Lowe (NOTT, UNM, BIRM)
DALITZ 91 JPG 17 289 +Deloff (OXFTP, WINR)
HEMINGWAY 85 NP B253 742 (CERN) J
MARTIN 81 NP B179 33 (DURH)
CHAO 73 NP B56 46 +Kraemer, Thomas, Martin (RHEL, CMU, LOUC)
THOMAS 73 NP B56 15 +Engler, Fisk, Kraemer (CMU) J
MARTIN 70 NP B16 479 +Ross (DURH)
MARTIN 69 PR 183 1352 +Sakitt (LOUC, BNL)
Also 69B PR 183 1345 Martin, Sakitt (LOUC, BNL)
BARBARO-... 68B PRL 21 573 Barbaro-Galtieri, Chadwick+ (LRL, SLAC)
KIM 67 PRL 19 1074 (YALE)
BIRMINGHAM 66 PR 152 1148 (BIRM, GLAS, LOIC, OXF, RHEL)
KITTEL 66 PL 21 349 +Otter, Wacek (VIEN)
ENGLER 65 PRL 15 224 +Fisk, Kraemer, Meltzer, Westgard+ (CMU, BNL) IJ
KIM 65 PRL 14 29 (COLU)
MUSGRAVE 65 NC 35 735 +Petmezas+ (BIRM, CERN, EPOL, LOIC, SACL)
SAKITT 65 PR 139B 719 +Day, Glasser, Seeman, Friedman+ (UMD, LRL)
ALEXANDER 62 PRL 8 447 +Kalbfleisch, Miller, Smith (LRL) I
ALSTON 62 CERN Conf. 311 +Alvarez, Ferro-Luzzi+ (LRL) I
ALSTON 61B PRL 6 698 +Alvarez, Eberhard, Good+ (LRL) I

OTHER RELATED PAPERS

FINK 90 PR C41 2720 +He, Landau, Schnick (IBMY, ORST, ANSM)
LEINWEBER 90 ANP 198 203 (MCMS)
MUELLER-GR... 90 NP A513 557 Mueller-Groeling, Holinde, Speth (JULI)
BARRETT 89 NC 102A 179 (SURR)
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CAPSTICK 89 Excited Baryons '88, p. 32 (GUEL)
LOWE 89 NC 102A 167 (BIRM)
WHITEHOUSE 89 PRL 63 1352 + (BIRM, BOST, BRCO, BNL, CASE, BUDA, TRIU)
SIEGEL 88 PR C38 2221 +Weise (REGE)
WORKMAN 88 PR D37 3117 +Fearing (TRIU)
SCHNICK 87 PRL 58 1719 +Landau (ORST)
CAPSTICK 86 PR D34 2809 +Isgur (TNTO)
JENNINGS 86 PL B176 229 (TRIU)
MALTMAN 86 PR D34 1372 +Isgur (LANL, TNTO)
ZHONG 86 PL B171 471 +Thomas, Jennings, Barrett (ADLD, TRIU, SURR)
BURKHARDT 85 NP A440 653 +Lowe, Rosenthal (NOTT, BIRM, WMIU)
DAREWYCH 85 PR D32 1765 +Koniuk, Isgur (YORKC, TNTO)
VEIT 85 PR D31 1033 +Jennings, Thomas, Barrett (TRIU, ADLD, SURR)
KIANG 84 PR C30 1638 +Kumar, Nogami, VanDijk (DALH, MCMS)
MILLER 84 (LOUC)
Conf. Intersections between Particle and Nuclear Physics, p. 783
VANDIJK 84 PR D30 937 (MCMS)
VEIT 84 PL 137B 415 +Jennings, Barrett, Thomas (TRIU, SURR, CERN)
DALITZ 82 +McGinley, Belyea, Anthony (OXFTP)
Heidelberg Conf., p. 201
DALITZ 81 +McGinley (OXFTP)
Low and Intermediate Energy Kaon-Nucleon Physics, p.381
MARTIN 81B Low and Intermediate Energy Kaon-Nucleon Phys., p. 97 (DURH)
OADES 77 NC 42A 462 +Rasche (AARH, ZURI)
SHAW 73 Purdue Conf. 417 (UCI)
BARBARO-... 72 LBL-555 Barbaro-Galtieri (LBL)
DOBSON 72 PR D6 3256 +McElhaney (HAWA)
RAJASEKA... 72 PR D5 610 Rajasekaran (TATA)
Earlier papers also cited in RAJASEKARAN 72.
CLINE 71 PRL 26 1194 +Laumann, Mapp (WISC)
MARTIN 71 PL 35B 62 +Martin, Ross (DURH, LOUC, RHEL)
DALITZ 67 PR 153 1617 +Wong, Rajasekaran (OXFTP, BOMB)
DONALD 66 PL 22 711 +Edwards, Lys, Nisar, Moore (LIVP)
KADYK 66 PRL 17 599 +Oren, Goldhaber, Goldhaber, Trilling (LRL)
ABRAMS 65 PR 139B 454 +Sechi-Zorn (UMD)

$\Lambda(1520)$ D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗∗

Discovered by FERRO-LUZZI 62; the elaboration in WATSON 63 is the classic paper on the Breit-Wigner analysis of a multichannel resonance.

The measurements of the mass, width, and elasticity published before 1975 are now obsolete and have been omitted. They were last listed in our 1982 edition Physics Letters **111B** (1982).

Production and formation experiments agree quite well, so they are listed together here.

$\Lambda(1520)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1519.5 ±1.0 OUR ESTIMATE					
1519.50±0.18 OUR AVERAGE					
1517.3 ±1.5	300	BARBER	80D	SPEC	$\gamma p \rightarrow \Lambda(1520) K^+$
1519 ±1		GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1517.8 ±1.2	5k	BARLAG	79	HBC	$K^- p$ 4.2 GeV/c
1520.0 ±0.5		ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
1519.7 ±0.3	4k	CAMERON	77	HBC	$K^- p$ 0.96–1.36 GeV/c
1519 ±1		GOPAL	77	DPWA	$\overline{K}N$ multichannel
1519.4 ±0.3	2000	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Lambda(1520)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
15.6 ±1.0 OUR ESTIMATE					
15.59±0.27 OUR AVERAGE					
16.3 ±3.3	300	BARBER	80D	SPEC	$\gamma p \rightarrow \Lambda(1520) K^+$
16 ±1		GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
14 ±3	677	[1] BARLAG	79	HBC	$K^- p$ 4.2 GeV/c
15.4 ±0.5		ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
16.3 ±0.5	4k	CAMERON	77	HBC	$K^- p$ 0.96–1.36 GeV/c
15.0 ±0.5		GOPAL	77	DPWA	$\overline{K}N$ multichannel
15.5 ±1.6	2000	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Lambda(1520)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	45 ± 1%
Γ_2	$\Sigma\pi$	42 ± 1%
Γ_3	$\Lambda\pi\pi$	10 ± 1%
Γ_4	$\Sigma(1385)\pi$	
Γ_5	$\Sigma(1385)\pi (\rightarrow \Lambda\pi\pi)$	
Γ_6	$\Lambda(\pi\pi)$ S-wave	
Γ_7	$\Sigma\pi\pi$	0.9 ± 0.1%
Γ_8	$\Lambda\gamma$	0.8 ± 0.2%
Γ_9	$\Sigma^0\gamma$	

CONSTRAINED FIT INFORMATION

An overall fit to 9 branching ratios uses 24 measurements and one constraint to determine 6 parameters. The overall fit has a $\chi^2 =$ 16.5 for 19 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−63				
x_3	−32	−33			
x_7	−4	−3	−1		
x_8	−9	−8	−4	0	
x_9	−24	−21	−10	−1	−2
	x_1	x_2	x_3	x_7	x_8

$\Lambda(1520)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

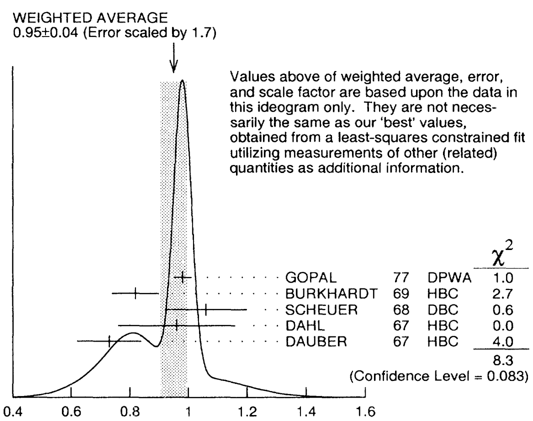
VALUE	DOCUMENT ID		TECN	COMMENT
0.45 ±0.01 OUR ESTIMATE				
0.448±0.007 OUR FIT Error includes scale factor of 1.2.				
0.455±0.011 OUR AVERAGE				
0.47 ±0.02	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.45 ±0.03	ALSTON-...	78	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.448±0.014	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.47 ±0.01	GOPAL	77	DPWA	See GOPAL 80
0.42	MAST	76	HBC	$K^- p \rightarrow \overline{K}^0 n$

$\Gamma(\Sigma\pi)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.42 ±0.01 OUR ESTIMATE				
0.421±0.007 OUR FIT Error includes scale factor of 1.2.				
0.423±0.011 OUR AVERAGE				
0.426±0.014	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.418±0.017	BARBARO-...	69B	HBC	$K^- p$ 0.28–0.45 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.46	KIM	71	DPWA	K-matrix analysis

$\Gamma(\Sigma\pi)/\Gamma(N\overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.940±0.026 OUR FIT Error includes scale factor of 1.3.				
0.95 ±0.04 OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.				
0.98 ±0.03	[2] GOPAL	77	DPWA	$\overline{K}N$ multichannel
0.82 ±0.08	BURKHARDT	69	HBC	$K^- p$ 0.8–1.2 GeV/c
1.06 ±0.14	SCHEUER	68	DBC	$K^- N$ 3 GeV/c
0.96 ±0.20	DAHL	67	HBC	$\pi^- p$ 1.6–4 GeV/c
0.73 ±0.11	DAUBER	67	HBC	$K^- p$ 2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.06 ±0.12	BERTHON	74	HBC	Quasi-2-body σ
1.72 ±0.78	MUSGRAVE	65	HBC	



$\Gamma(\Sigma\pi)/\Gamma(N\overline{K})$

$\Gamma(\Lambda\pi\pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.10 ±0.01 OUR ESTIMATE				
0.095±0.005 OUR FIT Error includes scale factor of 1.2.				
0.096±0.008 OUR AVERAGE Error includes scale factor of 1.6.				
0.091±0.006	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.11 ±0.01	[3] MAST	73B	IPWA	$K^- p \rightarrow \Lambda\pi\pi$

$\Gamma(\Lambda\pi\pi)/\Gamma(N\overline{K})$ — Γ_3/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.213±0.012 OUR FIT Error includes scale factor of 1.2.				
0.202±0.021 OUR AVERAGE				
0.22 ±0.03	BURKHARDT	69	HBC	$K^- p$ 0.8–1.2 GeV/c
0.19 ±0.04	SCHEUER	68	DBC	$K^- N$ 3 GeV/c
0.17 ±0.05	DAHL	67	HBC	$\pi^- p$ 1.6–4 GeV/c
0.21 ±0.18	DAUBER	67	HBC	$K^- p$ 2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.27 ±0.13	BERTHON	74	HBC	Quasi-2-body σ
0.2	KIM	71	DPWA	K-matrix analysis

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi\pi)$ — Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
4.42±0.25 OUR FIT Error includes scale factor of 1.2.				
3.9 ±0.6 OUR AVERAGE				
3.9 ±1.0	UHLIG	67	HBC	$K^- p$ 0.9–1.0 GeV/c
3.3 ±1.1	BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
4.5 ±1.0	ARMENTEROS	65C	HBC	

$\Gamma(\Sigma(1385)\pi)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.041±0.005	CHAN	72	HBC	$K^- p \rightarrow \Lambda\pi\pi$

$\Gamma(\Sigma(1385)\pi(\to \Lambda\pi\pi))/\Gamma(\Lambda\pi\pi)$ — Γ_5/Γ_3

The $\Lambda\pi\pi$ mode is largely due to $\Sigma(1385)\pi$. Only the values of $(\Sigma(1385)\pi)$ / $(\Lambda 2\pi)$ given by MAST 73B and CORDEN 75 are based on real 3-body partial-wave analyses. The discrepancy between the two results is essentially due to the different hypotheses made concerning the shape of the $(\pi\pi)_{S\text{-wave}}$ state.

VALUE	DOCUMENT ID		TECN	COMMENT
0.58±0.22	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.82±0.10	[4] MAST	73B	IPWA	$K^- p \to \Lambda\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.39±0.10	[5] BURKHARDT	71	HBC	$K^- p \to (\Lambda\pi\pi)\pi$

$\Gamma(\Lambda(\pi\pi)_{S\text{-wave}})/\Gamma(\Lambda\pi\pi)$ — Γ_6/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.20±0.08	CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c

$\Gamma(\Sigma\pi\pi)/\Gamma_{total}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.009 ±0.001 OUR ESTIMATE				
0.0086±0.0005 OUR FIT				
0.0086±0.0005 OUR AVERAGE				
0.007 ±0.002	[6] CORDEN	75	DBC	$K^- d$ 1.4–1.8 GeV/c
0.0085±0.0006	[7] MAST	73	MPWA	$K^- p \to \Sigma\pi\pi$
0.010 ±0.0015	BARBARO-...	69B	HBC	$K^- p$ 0.28–0.45 GeV/c

$\Gamma(\Lambda\gamma)/\Gamma_{total}$ — Γ_8/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.008 ±0.002 OUR ESTIMATE					
0.0079±0.0014 OUR FIT					
0.0080±0.0014	238	MAST	68B	HBC	Using $\Gamma(N\overline{K})/\Gamma_{total}$ = 0.45

$\Gamma(\Sigma^0\gamma)/\Gamma_{total}$ — Γ_9/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.0195±0.0034 OUR FIT				
0.02 ±0.0035	[8] MAST	68B	HBC	Not measured; see note

$\Lambda(1520)$ FOOTNOTES

[1] From the best-resolution sample of $\Lambda\pi\pi$ events only.
[2] The $\overline{K}N \to \Sigma\pi$ amplitude at resonance is $+0.46 \pm 0.01$.
[3] Assumes $\Gamma(N\overline{K})/\Gamma_{total} = 0.46 \pm 0.02$.
[4] Both $\Sigma(1385)\pi$ DS_{03} and $\Sigma(\pi\pi)$ DP_{03} contribute.
[5] The central bin (1514–1524 MeV) gives 0.74 ± 0.10; other bins are lower by 2-to-5 standard deviations.
[6] Much of the $\Sigma\pi\pi$ decay proceeds via $\Sigma(1385)\pi$.
[7] Assumes $\Gamma(N\overline{K})/\Gamma_{total} = 0.46$.
[8] Calculated from $\Gamma(\Lambda\gamma)/\Gamma_{total}$, assuming SU(3). Needed to constrain the sum of all the branching ratios to be unity.

$\Lambda(1520)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
BARBER	80D	ZPHY C7 17	+Dainton, Lee, Marshall+	(DARE, LANC, SHEF)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
BARLAG	79	NP B149 220	+Blokzijl, Jongejans+	(AMST, CERN, NIJM, OXF)
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MAST	76	PR D14 13	+Alston-Garnjost, Bangerter+	(LBL)
CORDEN	75	NP B84 306	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
MAST	73	PR D7 3212	+Bangerter, Alston-Garnjost+	(LBL) IJP
MAST	73B	PR D7 5	+Bangerter, Alston-Garnjost+	(LBL) IJP
CHAN	72	PRL 28 256	+Button-Shafer, Hertzbach, Kofler+	(MASA, YALE)
BURKHARDT	71	NP B27 64	+Filthuth, Kluge+	(HEID, CERN, SACL)
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
BARBARO-...	69B	Lund Conf. 352	Barbaro-Galtieri, Bangerter, Mast, Tripp	(LRL)
Also	70	Duke Conf. 95	Tripp	(LRL)
BURKHARDT	69	NP B14 106	+Filthuth, Kluge+	(HEID, EFI, CERN, SACL)
MAST	68B	PRL 21 1715	+Alston-Garnjost, Bangerter, Galtieri+	(LRL)
SCHEUER	68	NP B8 503	+Merrill, Verglas, DeWitt+	(SABRE Collab.)
DAHL	67	PR 163 1377	+Hardy, Hess, Kirz, Miller	(LRL)
DAUBER	67	PL 24B 525	+Malamud, Schlein, Slater, Stork	(UCLA)
UHLIG	67	PR 155 1448	+Charlton, Condon, Glasser, Yodh+	(UMD, NRL)
BIRMINGHAM	66	PR 152 1148		(BIRM, GLAS, LOIC, OXF, RHEL)
ARMENTEROS	65C	PL 19 338	+Ferro-Luzzi+	(CERN, HEID, SACL)
MUSGRAVE	65	NC 35 735	+Petmezas+	(BIRM, CERN, EPOL, LOIC, SACL)
WATSON	63	PR 131 2248	+Ferro-Luzzi, Tripp	(LRL) IJP
FERRO-LUZZI	62	PRL 8 28	+Tripp, Watson	(LRL) IJP

$\Lambda(1600)$ P_{01}

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

See also the $\Lambda(1810)$ P_{01}. There are quite possibly two P_{01} states in this region.

$\Lambda(1600)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1560 to 1700 (≈ 1600) OUR ESTIMATE				
1568± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1703±100	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1573± 25	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1596± 6	KANE	74	DPWA	$K^- p \to \Sigma\pi$
1620± 10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1572 or 1617	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1646± 7	[2] CARROLL	76	DPWA	Isospin-0 total σ
1570	KIM	71	DPWA	K-matrix analysis

$\Lambda(1600)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 250 (≈ 150) OUR ESTIMATE				
116± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
593±200	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
147± 50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
175± 20	KANE	74	DPWA	$K^- p \to \Sigma\pi$
60± 10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
247 or 271	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
20	[2] CARROLL	76	DPWA	Isospin-0 total σ
50	KIM	71	DPWA	K-matrix analysis

$\Lambda(1600)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	15–30 %
Γ_2	$\Sigma\pi$	10–60 %

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1600)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 to 0.30 OUR ESTIMATE				
0.23±0.04	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.14±0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.25±0.15	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24±0.04	GOPAL	77	DPWA	See GOPAL 80
0.30 or 0.29	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1600) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.16±0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.33±0.11	KANE	74	DPWA	$K^- p \to \Sigma\pi$
0.28±0.09	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.39 or −0.39	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$

$\Lambda(1600)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] A total cross-section bump with $(J+1/2)$ Γ_{el} / Γ_{total} = 0.04.

$\Lambda(1600)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEIDH, MPIM) IJP
KANE	74	LBL-2452		(LBL) IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP

$\Lambda(1670)$ S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

The measurements of the mass, width, and elasticity published before 1974 are now obsolete and have been omitted. They were last listed in our 1982 edition Physics Letters **111B** (1982).

$\Lambda(1670)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1660 to 1680 (≈ 1670) OUR ESTIMATE				
1670.8±1.7	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
1667 ±5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1671 ±3	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1670 ±5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1675 ±2	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
1679 ±1	KANE	74	DPWA	$K^- p \to \Sigma\pi$
1665 ±5	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1669 ±2	ABAEV	96	DPWA	$\pi^- p \to \eta n$
1664	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1670)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
25 to 50 (≈ 35) OUR ESTIMATE				
34.1± 3.7	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
29 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
29 ± 5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
45 ±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
46 ± 5	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
40 ± 3	KANE	74	DPWA	$K^- p \to \Sigma\pi$
19 ± 5	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
21 ± 4	ABAEV	96	DPWA	$\pi^- p \to \eta n$
12	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	15–25 %
Γ_2	$\Sigma\pi$	20–60 %
Γ_3	$\Lambda\eta$	15–35 %
Γ_4	$\Sigma(1385)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1670)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.15 to 0.25 OUR ESTIMATE				
0.18±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.17±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.20±0.03	GOPAL	77	DPWA	See GOPAL 80
0.15	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1670) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.26±0.02	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
−0.31±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.29±0.03	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
−0.23±0.03	LONDON	75	HLBC	$K^- p \to \Sigma^0\pi^0$
−0.27±0.02	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.13	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1670) \to \Lambda\eta$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.20±0.05	BAXTER	73	DPWA	$K^- p \to$ neutrals
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.06	ABAEV	96	DPWA	$\pi^- p \to \eta n$
0.24	KIM	71	DPWA	K-matrix analysis
0.26	ARMENTEROS	69C	HBC	
0.20 or 0.23	BERLEY	65	HBC	

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1670) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.18±0.05	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$\Lambda(1670)$ FOOTNOTES

[1] MARTIN 77 obtains identical resonance parameters from a T-matrix pole and from a Breit-Wigner fit.

$\Lambda(1670)$ REFERENCES

ABAEV	96	PR C53 385	+Nefkens	(UCLA)
KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEIDH, MPIM) IJP
LONDON	75	NP B85 289	+Yu, Boyd+	(BNL, CERN, EPOL, ORSAY, TORI)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BAXTER	73	NP B67 125	+Buckingham, Corbett, Dunn+	(OXF) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
ARMENTEROS	69C	Lund Paper 229	+Baillon+	(CERN, HEID, SACL) IJP
Values are quoted in LEVI-SETTI 69.				
BERLEY	65	PRL 15 641	+Connolly, Hart, Rahm, Stonehill+	(BNL) IJP

$\Lambda(1690)$ D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗∗

The measurements of the mass, width, and elasticity published before 1974 are now obsolete and have been omitted. They were last listed in our 1982 edition Physics Letters **111B** (1982).

$\Lambda(1690)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1685 to 1695 (≈ 1690) OUR ESTIMATE				
1695.7±2.6	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
1690 ±5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1692 ±5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1690 ±5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1690 ±3	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
1689 ±1	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1687 or 1689	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1692 ±4	CARROLL	76	DPWA	Isospin-0 total σ

$\Lambda(1690)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 70 (≈ 60) OUR ESTIMATE				
67.2± 5.6	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
61 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
64 ±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
60 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
82 ± 8	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
60 ± 4	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
62 or 62	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
38	CARROLL	76	DPWA	Isospin-0 total σ

$\Lambda(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–30 %
Γ_2	$\Sigma\pi$	20–40 %
Γ_3	$\Lambda\pi\pi$	∼ 25 %
Γ_4	$\Sigma\pi\pi$	∼ 20 %
Γ_5	$\Lambda\eta$	
Γ_6	$\Sigma(1385)\pi$, S-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1690)$ BRANCHING RATIOS

The sum of all the quoted branching ratios is more than 1.0. The two-body ratios are from partial-wave analyses, and thus probably are more reliable than the three-body ratios, which are determined from bumps in cross sections. Of the latter, the $\Sigma\pi\pi$ bump looks more significant. (The error given for the $\Lambda\pi\pi$ ratio looks unreasonably small.) Hardly any of the $\Sigma\pi\pi$ decay can be via $\Sigma(1385)$, for then seven times as much $\Lambda\pi\pi$ decay would be required. See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.2 to 0.3 OUR ESTIMATE				
0.23 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.22 ± 0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.24 ± 0.03	GOPAL	77	DPWA	See GOPAL 80
0.28 or 0.26	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.34 ± 0.02	KOISO	85	DPWA	$K^-p \to \Sigma\pi$
-0.25 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.29 ± 0.03	HEPP	76B	DPWA	$K^-N \to \Sigma\pi$
-0.28 ± 0.03	LONDON	75	HLBC	$K^-p \to \Sigma^0\pi^0$
-0.28 ± 0.02	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.30 or -0.28	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Lambda\eta$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.00 ± 0.03	BAXTER	73	DPWA	$K^-p \to$ neutrals

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Lambda\pi\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.25 ± 0.02	[2] BARTLEY	68	HDBC	$K^-p \to \Lambda\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Sigma\pi\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.21	ARMENTEROS	68C	HDBC	$K^-N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1690) \to \Sigma(1385)\pi$, S-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.27\pm0.04$	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$

$\Lambda(1690)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit. Another D_{03} Λ at 1966 MeV is also suggested by MARTIN 77, but is very uncertain.

[2] BARTLEY 68 uses only cross-section data. The enhancement is not seen by PREVOST 71.

$\Lambda(1690)$ REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEIDH, MPIM) IJP
LONDON	75	NP B85 289	+Yu, Boyd+	(BNL, CERN, EPOL, ORSAY, TORI)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BAXTER	73	NP B67 125	+Buckingham, Corbett, Dunn+	(OXF) IJP
PREVOST	71	Amsterdam Conf.		(CERN, HEID, SACL)
ARMENTEROS	68C	NP B8 216	+Baillon+	(CERN, HEID, SACL) I
BARTLEY	68	PRL 21 1111	+Chu, Dowd, Greene+	(TUFTS, FSU, BRAN) I

$\Lambda(1800)$ S_{01}

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗

This is the second resonance in the S_{01} wave, the first being the $\Lambda(1670)$.

$\Lambda(1800)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1720 to 1850 (≈ 1800) OUR ESTIMATE				
1841 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1725 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1825 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1830 ± 20	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1767 or 1842	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1780	KIM	71	DPWA	K-matrix analysis
1872 ± 10	BRICMAN	70B	DPWA	$\overline{K}N \to \overline{K}N$

$\Lambda(1800)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
200 to 400 (≈ 300) OUR ESTIMATE				
228 ± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
185 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
230 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
70 ± 15	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
435 or 473	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
40	KIM	71	DPWA	K-matrix analysis
100 ± 20	BRICMAN	70B	DPWA	$\overline{K}N \to \overline{K}N$

$\Lambda(1800)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	25–40 %
Γ_2	$\Sigma\pi$	seen
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$N\overline{K}^*(892)$	seen
Γ_5	$N\overline{K}^*(892)$, S=1/2, S-wave	
Γ_6	$N\overline{K}^*(892)$, S=3/2, D-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1800)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.25 to 0.40 OUR ESTIMATE				
0.36 ± 0.04	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.28 ± 0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.35 ± 0.15	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.37 ± 0.05	GOPAL	77	DPWA	See GOPAL 80
1.21 or 0.70	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.80	KIM	71	DPWA	K-matrix analysis
0.18 ± 0.02	BRICMAN	70B	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1800) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.08 ± 0.05	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.74 or -0.43	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.24	KIM	71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1800) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.056\pm0.028$	[2] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1800) \to N\overline{K}^*(892)$, S=1/2, S-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.17 ± 0.03	[2] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1800) \to N\overline{K}^*(892)$, S=3/2, D-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.13 ± 0.04	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Lambda(1800)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Lambda(1800)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
BRICMAN	70B	PL 33B 511	+Ferro-Luzzi, Lagnaux	(CERN) IJP

$\Lambda(1810)$ P_{01}

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

Almost all the recent analyses contain a P_{01} state, and sometimes two of them, but the masses, widths, and branching ratios vary greatly. See also the $\Lambda(1600)$ P_{01}.

$\Lambda(1810)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1750 to 1850 (≈ 1810) OUR ESTIMATE				
1841±20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1853±20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1735± 5	CARROLL	76	DPWA	Isospin-0 total σ
1746±10	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
1780±20	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1861 or 1953	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1755	KIM	71	DPWA	K-matrix analysis
1800	ARMENTEROS	70	HBC	$\overline{K}N \to \overline{K}N$
1750	ARMENTEROS	70	HBC	$\overline{K}N \to \Sigma\pi$
1690±10	BARBARO-...	70	HBC	$\overline{K}N \to \Sigma\pi$
1740	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
1745	ARMENTEROS	68B	HBC	$\overline{K}N \to \overline{K}N$

$\Lambda(1810)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
50 to 250 (≈ 150) OUR ESTIMATE				
164±20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
90±20	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
166±20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
46±20	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
120±10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
535 or 585	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
28	CARROLL	76	DPWA	Isospin-0 total σ
35	KIM	71	DPWA	K-matrix analysis
30	ARMENTEROS	70	HBC	$\overline{K}N \to \overline{K}N$
70	ARMENTEROS	70	HBC	$\overline{K}N \to \Sigma\pi$
22	BARBARO-...	70	HBC	$\overline{K}N \to \Sigma\pi$
300	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
147	ARMENTEROS	68B	HBC	

$\Lambda(1810)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–50 %
Γ_2	$\Sigma\pi$	10–40 %
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$N\overline{K}^*(892)$	30–60 %
Γ_5	$N\overline{K}^*(892)$, $S=1/2$, P-wave	
Γ_6	$N\overline{K}^*(892)$, $S=3/2$, P-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1810)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.2 to 0.5 OUR ESTIMATE				
0.24±0.04	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.36±0.05	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.21±0.04	GOPAL	77	DPWA	See GOPAL 80
0.52 or 0.49	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.30	KIM	71	DPWA	K-matrix analysis
0.15	ARMENTEROS	70	DPWA	$\overline{K}N \to \overline{K}N$
0.55	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
0.4	ARMENTEROS	68B	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1810) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.24±0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.25 or +0.23	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
< 0.01	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
0.17	KIM	71	DPWA	K-matrix analysis
+0.20	[2] ARMENTEROS	70	DPWA	$\overline{K}N \to \Sigma\pi$
−0.13±0.03	BARBARO-...	70	DPWA	$\overline{K}N \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1810) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.18±0.10	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1810) \to N\overline{K}^*(892)$, $S=1/2$, P-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.14±0.03	[2] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1810) \to N\overline{K}^*(892)$, $S=3/2$, P-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.35±0.06	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Lambda(1810)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Lambda(1810)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP
ARMENTEROS	70	Duke Conf. 123	+Baillon+	(CERN, HEID, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
BAILEY	69	Thesis UCRL 50617		(LLL) IJP
ARMENTEROS	68B	NP B8 195	+Baillon+	(CERN, HEID, SACL) IJP

$\Lambda(1820)$ F_{05}

$I(J^P) = 0(\frac{5}{2}^+)$ Status: ∗∗∗∗

This resonance is the cornerstone for all partial-wave analyses in this region. Most of the results published before 1973 are now obsolete and have been omitted. They may be found in our 1982 edition Physics Letters **111B** (1982).

Most of the quoted errors are statistical only; the systematic errors due to the particular parametrizations used in the partial-wave analyses are not included. For this reason we do not calculate weighted averages for the mass and width.

$\Lambda(1820)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1815 to 1825 (≈ 1820) OUR ESTIMATE				
1823±3	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1819±2	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1822±2	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1821±2	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1830	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
1817 or 1819	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Lambda(1820)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
70 to 90 (≈ 80) OUR ESTIMATE				
77±5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
72±5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
81±5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
87±3	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
82	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
76 or 76	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

Λ(1820) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	55–65 %
Γ_2	$\Sigma\pi$	8–14 %
Γ_3	$\Sigma(1385)\pi$	5–10 %
Γ_4	$\Sigma(1385)\pi$, *P*-wave	
Γ_5	$\Sigma(1385)\pi$, *F*-wave	
Γ_6	$\Lambda\eta$	
Γ_7	$\Sigma\pi\pi$	

The above branching fractions are our estimates, not fits or averages.

Λ(1820) BRANCHING RATIOS

Errors quoted do not include uncertainties in the parametrizations used in the partial-wave analyses and are thus too small. See also "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.55 to 0.65 OUR ESTIMATE				
0.58±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.60±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.51	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.57±0.02	GOPAL	77	DPWA	See GOPAL 80
0.59 or 0.58	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1820) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.28±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.28±0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.25 or −0.25	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1820) \to \Lambda\eta$ $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN
$-0.096^{+0.040}_{-0.020}$	RADER	73	MPWA

$\Gamma(\Sigma\pi\pi)/\Gamma_{total}$ Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
no clear signal	[2] ARMENTEROS	68C	HDBC	$K^-N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1820) \to \Sigma(1385)\pi$, *P*-wave $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.167±0.054	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$
+0.27 ±0.03	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1820) \to \Sigma(1385)\pi$, *F*-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.065±0.025	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

Λ(1820) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] There is a suggestion of a bump, enough to be consistent with what is expected from $\Sigma(1385) \to \Sigma\pi$ decay.

[3] The published sign has been changed to be in accord with the baryon-first convention.

Λ(1820) REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)
ARMENTEROS	68C	NP B8 216	+Baillon+	(CERN, HEID, SACL) I

Λ(1830) D_{05}

$I(J^P) = 0(\frac{5}{2}^-)$ Status: ∗∗∗∗

For results published before 1973 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

The best evidence for this resonance is in the $\Sigma\pi$ channel.

Λ(1830) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1810 to 1830 (≈ 1830) OUR ESTIMATE				
1831±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1825±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1825± 1	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1817 or 1818	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

Λ(1830) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 110 (≈ 95) OUR ESTIMATE				
100±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
94±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
119± 3	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
56 or 56	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

Λ(1830) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	3–10 %
Γ_2	$\Sigma\pi$	35–75 %
Γ_3	$\Sigma(1385)\pi$	>15 %
Γ_4	$\Sigma(1385)\pi$, *D*-wave	
Γ_5	$\Lambda\eta$	

The above branching fractions are our estimates, not fits or averages.

Λ(1830) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.03 to 0.10 OUR ESTIMATE				
0.08±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.02±0.02	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.04±0.03	GOPAL	77	DPWA	See GOPAL 80
0.04 or 0.04	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1830) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.17±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.15±0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.17 or −0.17	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1830) \to \Lambda\eta$ $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN
−0.044±0.020	RADER	73	MPWA

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1830) \to \Sigma(1385)\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.141±0.014	[2] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$
+0.13 ±0.03	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$

Λ(1830) FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] The CAMERON 78 upper limit on *G*-wave decay is 0.03. The published sign has been changed to be in accord with the baryon-first convention.

Λ(1830) REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)

$\Lambda(1890)$ P_{03}

$I(J^P) = 0(\frac{3}{2}^+)$ Status: ∗∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

The $J^P = 3/2^+$ assignment is consistent with all available data (including polarization) and recent partial-wave analyses. The dominant inelastic modes remain unknown.

$\Lambda(1890)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1850 to 1910 (≈ 1890) OUR ESTIMATE				
1897± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1908±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1900± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1894±10	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1856 or 1868	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1900	[2] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

$\Lambda(1890)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 200 (≈ 100) OUR ESTIMATE				
74±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
119±20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
72±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
107±10	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
191 or 193	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
100	[2] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

$\Lambda(1890)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	20–35 %
Γ_2	$\Sigma\pi$	3–10 %
Γ_3	$\Sigma(1385)\pi$	seen
Γ_4	$\Sigma(1385)\pi$, P-wave	
Γ_5	$\Sigma(1385)\pi$, F-wave	
Γ_6	$N\overline{K}^*(892)$	seen
Γ_7	$N\overline{K}^*(892)$, S=1/2, P-wave	
Γ_8	$\Lambda\omega$	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(1890)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.20 to 0.35 OUR ESTIMATE				
0.20±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.34±0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.24±0.04	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.18±0.02	GOPAL	77	DPWA	See GOPAL 80
0.36 or 0.34	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.15 or +0.14	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to \Lambda\omega$ — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
seen	BACCARI	77	IPWA	$K^- p \to \Lambda\omega$
0.032	[2] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma(1385)\pi$, P-wave — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.03	CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to \Sigma(1385)\pi$, F-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.126±0.055	[3] CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(1890) \to N\overline{K}^*(892)$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.07±0.03	[3,4] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Lambda(1890)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] Found in one of two best solutions.
[3] The published sign has been changed to be in accord with the baryon-first convention.
[4] Upper limits on the P_3 and F_3 waves are each 0.03.

$\Lambda(1890)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP

$\Lambda(2000)$

$I(J^P) = 0(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

We list here all the ambiguous resonance possibilities with a mass around 2 GeV. The proposed quantum numbers are D_3 (BARBARO-GALTIERI 70 in $\Sigma\pi$), D_3+F_5, P_3+D_5, or P_1+D_3 (BRANDSTETTER 72 in $\Lambda\omega$), and S_1 (CAMERON 78B in $N\overline{K}^*$). The first two of the above analyses should now be considered obsolete. See also NAKKASYAN 75.

$\Lambda(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2000 OUR ESTIMATE				
2030±30	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
1935 to 1971	[1] BRANDSTET...	72	DPWA	$K^- p \to \Lambda\omega$
1951 to 2034	[1] BRANDSTET...	72	DPWA	$K^- p \to \Lambda\omega$
2010±30	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$\Lambda(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
125±25	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
180 to 240	[1] BRANDSTET...	72	DPWA	(lower mass)
73 to 154	[1] BRANDSTET...	72	DPWA	(higher mass)
130±50	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$\Lambda(2000)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$
Γ_3	$\Lambda\omega$
Γ_4	$N\overline{K}^*(892)$, S=1/2, S-wave
Γ_5	$N\overline{K}^*(892)$, S=3/2, D-wave

$\Lambda(2000)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2000) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.20±0.04	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2000) \to \Lambda\omega$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.17 to 0.25	[1] BRANDSTET...	72	DPWA	(lower mass)
0.04 to 0.15	[1] BRANDSTET...	72	DPWA	(higher mass)

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2000) \to N\overline{K}^*(892)$, S=1/2, S-wave — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.12±0.03	[2] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2000) \to N\overline{K}^*(892)$, S=3/2, D-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.09±0.03	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

Λ(2000) FOOTNOTES

[1] The parameters quoted here are ranges from the three best fits; the lower state probably has $J \leq 3/2$, and the higher one probably has $J \leq 5/2$.

[2] The published sign has been changed to be in accord with the baryon-first convention.

Λ(2000) REFERENCES

CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
BRANDSTET...	72	NP B39 13	Brandstetter, Butterworth+	(RHEL, CDEF, SACL)
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

Λ(2020) F_{07}

$I(J^P) = 0(\frac{7}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

In LITCHFIELD 71, need for the state rests solely on a possibly inconsistent polarization measurement at 1.784 GeV/c. HEMINGWAY 75 does not require this state. GOPAL 77 does not need it in either $N\overline{K}$ or $\Sigma\pi$. With new $K^- n$ angular distributions included, DECLAIS 77 sees it. However, this and other new data are included in GOPAL 80 and the state is not required. BACCARI 77 weakly supports it.

Λ(2020) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2020 OUR ESTIMATE				
2140	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
2117	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
2100±30	LITCHFIELD	71	DPWA	$K^- p \to \overline{K}N$
2020±20	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

Λ(2020) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
128	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
167	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
120±30	LITCHFIELD	71	DPWA	$K^- p \to \overline{K}N$
160±30	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

Λ(2020) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$
Γ_3	$\Lambda\omega$

Λ(2020) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.05±0.02	LITCHFIELD	71	DPWA	$K^- p \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2020) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.15±0.02	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2020) \to \Lambda\omega$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.05	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$

Λ(2020) REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL)
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
LITCHFIELD	71	NP B30 125	+..., Lesquoy+	(RHEL, CDEF, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

Λ(2100) G_{07}

$I(J^P) = 0(\frac{7}{2}^-)$ Status: ****

Discovered by COOL 66 and by WOHL 66. Most of the results published before 1973 are now obsolete and have been omitted. They may be found in our 1982 edition Physics Letters **111B** (1982).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and in invariant-mass distributions around 2100 MeV used to be listed in a separate entry immediately following. It may be found in our 1986 edition Physics Letters **170B** (1986).

Λ(2100) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2090 to 2110 (≈ 2100) OUR ESTIMATE				
2104±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2106±30	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2110±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
2105±10	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
2115±10	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2094	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
2094	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
2110 or 2089	[1] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

Λ(2100) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 250 (≈ 200) OUR ESTIMATE				
157±40	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
250±30	GOPAL	77	DPWA	$\overline{K}N$ multichannel
241±30	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
152±15	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
98	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
250	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
244 or 302	[1] NAKKASYAN	75	DPWA	$K^- p \to \Lambda\omega$

Λ(2100) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	25–35 %
Γ_2	$\Sigma\pi$	∼ 5 %
Γ_3	$\Lambda\eta$	<3 %
Γ_4	ΞK	<3 %
Γ_5	$\Lambda\omega$	<8 %
Γ_6	$N\overline{K}^*(892)$	10–20 %
Γ_7	$N\overline{K}^*(892)$, S=1/2, G-wave	
Γ_8	$N\overline{K}^*(892)$, S=3/2, D-wave	

The above branching fractions are our estimates, not fits or averages.

Λ(2100) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.25 to 0.35 OUR ESTIMATE				
0.34±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.24±0.06	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
0.31±0.03	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.29	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
0.30±0.03	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.12±0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.11±0.01	KANE	74	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Lambda\eta$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.050±0.020	RADER	73	MPWA	$K^- p \to \Lambda\eta$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Xi K$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.035 ± 0.018	LITCHFIELD	71	DPWA	$K^-p \to \Xi K$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.003	MULLER	69B	DPWA	$K^-p \to \Xi K$
0.05	TRIPP	67	RVUE	$K^-p \to \Xi K$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to \Lambda\omega$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.070	[2] BACCARI	77	DPWA	GD_{37} wave
$+0.011$	[2] BACCARI	77	DPWA	GG_{17} wave
$+0.008$	[2] BACCARI	77	DPWA	GG_{37} wave
0.122 or 0.154	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to N\overline{K}^*(892)$, S=3/2, D-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.21\pm0.04$	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2100) \to N\overline{K}^*(892)$, S=1/2, G-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.04 ± 0.03	[3] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Lambda(2100)$ FOOTNOTES

[1] The NAKKASYAN 75 values are from the two best solutions found. Each has the $\Lambda(2100)$ and one additional resonance (P_3 or F_5).
[2] Note that the three for BACCARI 77 entries are for three different waves.
[3] The published sign has been changed to be in accord with the baryon-first convention. The upper limit on the G_3 wave is 0.03.

$\Lambda(2100)$ REFERENCES

PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
KANE	74	LBL-2452		(LBL) IJP
RADER	73	NC 16A 178	+Barloutaud+	(SACL, HEID, CERN, RHEL, CDEF)
LITCHFIELD	71	NP B30 125	+..., Lesquoy+	(RHEL, CDEF, SACL) IJP
MULLER	69B	Thesis UCRL 19372		(LRL)
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)
WOHL	66	PRL 17 107	+Solmitz, Stevenson	(LRL) IJP

$\Lambda(2110)$ F_{05}

$I(J^P) = 0(\frac{5}{2}^+)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982). All the references have been retained.

This resonance is in the Baryon Summary Table, but the evidence for it could be better.

$\Lambda(2110)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2090 to 2140 (≈ 2110) OUR ESTIMATE				
2092 ± 25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2125 ± 25	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
2106 ± 50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2140 ± 20	DEBELLEFON	77	DPWA	$K^-p \to \Sigma\pi$
2100 ± 50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$2112\pm\ 7$	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2137	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$
2103	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$\Lambda(2110)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 250 (≈ 200) OUR ESTIMATE				
245 ± 25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
160 ± 30	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
251 ± 50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
140 ± 20	DEBELLEFON	77	DPWA	$K^-p \to \Sigma\pi$
200 ± 50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
190 ± 30	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
132	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$
391	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$\Lambda(2110)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	5–25 %
Γ_2	$\Sigma\pi$	10–40 %
Γ_3	$\Lambda\omega$	seen
Γ_4	$\Sigma(1385)\pi$	seen
Γ_5	$\Sigma(1385)\pi$, P-wave	
Γ_6	$N\overline{K}^*(892)$	10–60 %
Γ_7	$N\overline{K}^*(892)$, S=1/2, F-wave	

The above branching fractions are our estimates, not fits or averages.

$\Lambda(2110)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.25 OUR ESTIMATE				
0.07 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.27 ± 0.06	[2] DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.07 ± 0.03	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2110) \to \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.14\pm0.01$	DEBELLEFON	77	DPWA	$K^-p \to \Sigma\pi$
$+0.20\pm0.03$	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$+0.10\pm0.03$	GOPAL	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2110) \to \Lambda\omega$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.05	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$
0.112	[1] NAKKASYAN	75	DPWA	$K^-p \to \Lambda\omega$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2110) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.071\pm0.025$	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2110) \to N\overline{K}^*(892)$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.17 ± 0.04	[4] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Lambda(2110)$ FOOTNOTES

[1] Found in one of two best solutions.
[2] The published error of 0.6 was a misprint.
[3] The CAMERON 78 upper limit on F-wave decay is 0.03. The sign here has been changed to be in accord with the baryon-first convention.
[4] The published sign has been changed to be in accord with the baryon-first convention. The CAMERON 78B upper limits on the P_3 and F_3 waves are each 0.03.

$\Lambda(2110)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
BACCARI	77	NC 41A 96	+Poulard, Revel, Tallini+	(SACL, CDEF) IJP
DEBELLEFON	77	NC 37A 175	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
NAKKASYAN	75	NP B93 85		(CERN) IJP
KANE	74	LBL-2452		(LBL) IJP

$\Lambda(2325)$ D_{03}

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

BACCARI 77 finds this state with either $J^P = 3/2^-$ or $3/2^+$ in a energy-dependent partial-wave analyses of $K^-p \to \Lambda\omega$ from 2070 to 2436 MeV. A subsequent semi-energy-independent analysis from threshold to 2436 MeV selects $3/2^-$. DEBELLEFON 78 (same group) also sees this state in an energy-dependent partial-wave analysis of $K^-p \to \overline{K}N$ data, and finds $J^P = 3/2^-$ or $3/2^+$. They again prefer $J^P = 3/2^-$, but only on the basis of model-dependent considerations.

$\Lambda(2325)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2325 OUR ESTIMATE				
2342 ± 30	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2327 ± 20	BACCARI	77	DPWA	$K^-p \to \Lambda\omega$

Λ(2325) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
177±40	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
160±40	BACCARI	77	IPWA	$K^- p \to \Lambda\omega$

Λ(2325) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\omega$

Λ(2325) BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.19±0.06	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2325) \to \Lambda\omega$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	[1] BACCARI	77	IPWA	DS_{33} wave
0.05±0.02	[1] BACCARI	77	DPWA	DD_{13} wave
0.08±0.03	[1] BACCARI	77	DPWA	DD_{33} wave

Λ(2325) FOOTNOTES

[1] Note that the three BACCARI 77 entries are for three different waves.

Λ(2325) REFERENCES

DEBELLEFON 78 NC 42A 403 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
BACCARI 77 NC 41A 96 +Poulard, Revel, Tallini+ (SACL, CDEF) IJP

Λ(2350) H_{09}

$I(J^P) = 0(\frac{9}{2}^+)$ Status: ***

DAUM 68 favors $J^P = 7/2^-$ or $9/2^+$. BRICMAN 70 favors $9/2^+$. LASINSKI 71 suggests three states in this region using a Pomeron + resonances model. There are now also three formation experiments from the College de France-Saclay group, DEBELLEFON 77, BACCARI 77, and DEBELLEFON 78, which find $9/2^+$ in energy-dependent partial-wave analyses of $\overline{K}N \to \Sigma\pi$, $\Lambda\omega$, and $N\overline{K}$.

Λ(2350) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2340 to 2370 (≈ 2350) OUR ESTIMATE				
2370±50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
2365±20	DEBELLEFON	77	DPWA	$K^- p \to \Sigma\pi$
2358± 6	BRICMAN	70	CNTR	Total, charge exchange
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2372	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
2344±15	COOL	70	CNTR	$K^- p$, $K^- d$ total
2360±20	LU	70	CNTR	$\gamma p \to K^+ Y^*$
2340± 7	BUGG	68	CNTR	$K^- p$, $K^- d$ total

Λ(2350) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
100 to 250 (≈ 150) OUR ESTIMATE				
204±50	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$
110±20	DEBELLEFON	77	DPWA	$K^- p \to \Sigma\pi$
324±30	BRICMAN	70	CNTR	Total, charge exchange
• • • We do not use the following data for averages, fits, limits, etc. • • •				
257	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$
190	COOL	70	CNTR	$K^- p$, $K^- d$ total
55	LU	70	CNTR	$\gamma p \to K^+ Y^*$
140±20	BUGG	68	CNTR	$K^- p$, $K^- d$ total

Λ(2350) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	~ 12 %
Γ_2	$\Sigma\pi$	~ 10 %
Γ_3	$\Lambda\omega$	

The above branching fractions are our estimates, not fits or averages.

Λ(2350) BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
~ 0.12 OUR ESTIMATE				
0.12±0.04	DEBELLEFON	78	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2350) \to \Sigma\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.11±0.02	DEBELLEFON	77	DPWA	$K^- p \to \Sigma\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Lambda(2350) \to \Lambda\omega$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.05	BACCARI	77	DPWA	$K^- p \to \Lambda\omega$

Λ(2350) REFERENCES

DEBELLEFON 78 NC 42A 403 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
BACCARI 77 NC 41A 96 +Poulard, Revel, Tallini+ (SACL, CDEF) IJP
DEBELLEFON 77 NC 37A 175 De Bellefon, Berthon, Billoir+ (CDEF, SACL) IJP
LASINSKI 71 NP B29 125 (EFI) IJP
BRICMAN 70 PL 31B 152 +Ferro-Luzzi, Perreau+ (CERN, CAEN, SACL)
COOL 70 PR D1 1887 +Giacomelli, Kycia, Leontic, Li+ (BNL) I
Also 66 PRL 16 1228 Cool, Giacomelli, Kycia, Leontic, Lundby+ (BNL) I
LU 70 PR D2 1846 +Greenberg, Hughes, Minehart, Mori+ (YALE)
BUGG 68 PR 168 1466 +Gilmore, Knight+ (RHEL, BIRM, CAVE) I
DAUM 68 NP B7 19 +Erne, Lagnaux, Sens, Steuer, Udo (CERN) JP

Λ(2585) Bumps

$I(J^P) = 0(?^?)$ Status: **

OMITTED FROM SUMMARY TABLE

Λ(2585) MASS (BUMPS)

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2585 OUR ESTIMATE				
2585±45	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
2530±25	LU	70	CNTR	$\gamma p \to K^+ Y^*$

Λ(2585) WIDTH (BUMPS)

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
150	LU	70	CNTR	$\gamma p \to K^+ Y^*$

Λ(2585) DECAY MODES (BUMPS)

	Mode
Γ_1	$N\overline{K}$

Λ(2585) BRANCHING RATIOS (BUMPS)

$(J+\frac{1}{2})\times\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

J is not known, so only $(J+\frac{1}{2}) \times \Gamma(N\overline{K})/\Gamma_{total}$ can be given.

VALUE	DOCUMENT ID		TECN	COMMENT
1	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
0.12±0.12	[1] BRICMAN	70	CNTR	Total, charge exchange

Λ(2585) FOOTNOTES (BUMPS)

[1] The resonance is at the end of the region analyzed — no clear signal.

Λ(2585) REFERENCES (BUMPS)

ABRAMS 70 PR D1 1917 +Cool, Giacomelli, Kycia, Leontic, Li+ (BNL) I
Also 66 PRL 16 1228 Cool, Giacomelli, Kycia, Leontic, Lundby+ (BNL) I
BRICMAN 70 PL 31B 152 +Ferro-Luzzi, Perreau+ (CERN, CAEN, SACL)
LU 70 PR D2 1846 +Greenberg, Hughes, Minehart, Mori+ (YALE)

Σ BARYONS
$(S = -1, I = 1)$

$\Sigma^+ = uus$, $\Sigma^0 = uds$, $\Sigma^- = dds$

Σ^+

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. See our earlier editions.

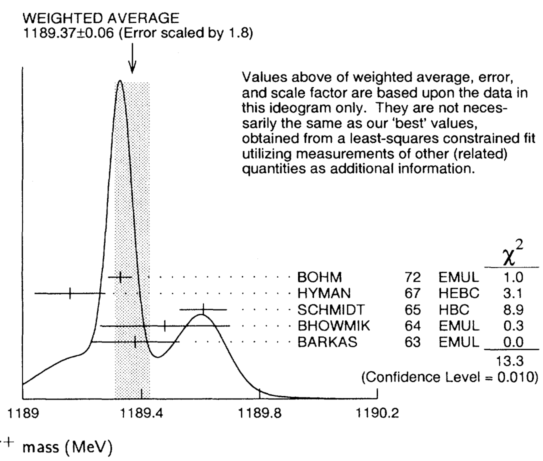
Σ^+ MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1189.37±0.07 OUR FIT Error includes scale factor of 2.2.					
1189.37±0.06 OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.					
1189.33±0.04	607	[1] BOHM	72	EMUL	
1189.16±0.12		HYMAN	67	HEBC	
1189.61±0.08	4205	SCHMIDT	65	HBC	See note with Λ mass
1189.48±0.22	58	[2] BHOWMIK	64	EMUL	
1189.38±0.15	144	[2] BARKAS	63	EMUL	

[1] BOHM 72 is updated with our 1973 K^-, π^-, and π^0 masses (Reviews of Modern Physics **45** No. 2 Pt. II (1973)).

[2] These masses have been raised 30 keV to take into account a 46 keV increase in the proton mass and a 21 keV decrease in the π^0 mass (note added 1967 edition, Reviews of Modern Physics **39** 1 (1967)).



Σ^+ MEAN LIFE

Measurements with an error $\geq 0.1 \times 10^{-10}$ s have been omitted.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.799±0.004 OUR AVERAGE					
0.798±0.005	30k	MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c
0.807±0.013	5719	CONFORTO	76	HBC	$K^- p$ 1–1.4 GeV/c
0.83 ±0.04	526	BAKKER	71	DBC	$K^- n \rightarrow \Sigma^+ \pi^- \pi^-$
0.795±0.010	20k	EISELE	70	HBC	$K^- p$ at rest
0.803±0.008	10664	BARLOUTAUD	69	HBC	$K^- p$ 0.4–1.2 GeV/c
0.83 ±0.032	1300	[3] CHANG	66	HBC	
0.80 ±0.07	381	COOK	66	OSPK	
0.84 ±0.09	181	BALTAY	65	HBC	
0.76 ±0.03	900	CARAYAN...	65	HBC	
$0.749^{+0.056}_{-0.052}$	192	GRARD	62	HBC	
0.765±0.04	456	HUMPHREY	62	HBC	

[3] We have increased the CHANG 66 error of 0.018; see our 1970 edition, Reviews of Modern Physics **42** No. 1 (1970).

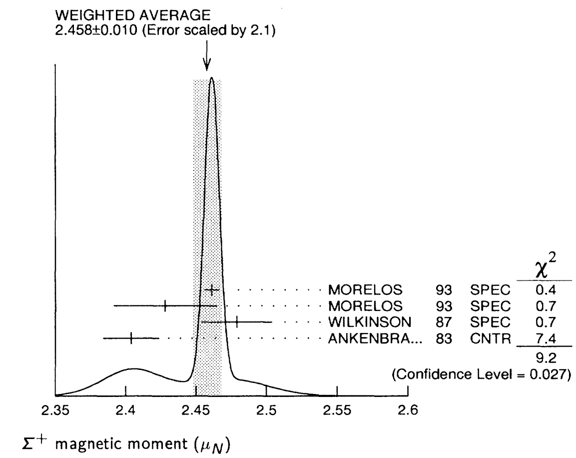
Σ^+ MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings. Measurements with an error $\geq 0.1\ \mu_N$ have been omitted.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
2.458 ±0.010 OUR AVERAGE Error includes scale factor of 2.1. See the ideogram below.					
2.4613±0.0034±0.0040	250k	MORELOS	93	SPEC	pCu 800 GeV
2.428 ±0.036 ±0.007	12k	[4] MORELOS	93	SPEC	pCu 800 GeV
2.479 ±0.012 ±0.022	137k	WILKINSON	87	SPEC	pBe 400 GeV
2.4040±0.0198	44k	[5] ANKENBRA...	83	CNTR	pCu 400 GeV

[4] We assume CPT invariance: this is (minus) the $\overline{\Sigma}^-$ magnetic moment as measured by MORELOS 93. See below for the moment difference testing CPT.

[5] ANKENBRANDT 83 gives the value 2.38 ± 0.02μ_N. MORELOS 93 uses the same hyperon magnet and channel and claims to determine the field integral better, leading to the revised value given here.



$(\mu_{\Sigma^+} - |\mu_{\overline{\Sigma}^-}|) \,/\, |\mu|_{\text{average}}$

A test of CPT invariance.

VALUE	DOCUMENT ID		TECN	COMMENT
0.014±0.015	[6] MORELOS	93	SPEC	pCu 800 GeV

[6] This is our calculation from the MORELOS 93 measurements of the Σ^+ and $\overline{\Sigma}^-$ magnetic moments given above. The statistical error on $\mu_{\overline{\Sigma}^-}$ dominates the error here.

Σ^+ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$p\pi^0$		(51.57±0.30) %	
Γ_2	$n\pi^+$		(48.31±0.30) %	
Γ_3	$p\gamma$		(1.23±0.05) × 10^{-3}	
Γ_4	$n\pi^+\gamma$	[a]	(4.5 ±0.5) × 10^{-4}	
Γ_5	$\Lambda e^+ \nu_e$		(2.0 ±0.5) × 10^{-5}	
	$\Delta S = \Delta Q$ (SQ) violating modes or $\Delta S = 1$ weak neutral current ($S1$) modes			
Γ_6	$n e^+ \nu_e$	SQ	< 5 × 10^{-6}	90%
Γ_7	$n \mu^+ \nu_\mu$	SQ	< 3.0 × 10^{-5}	90%
Γ_8	$p e^+ e^-$	$S1$	< 7 × 10^{-6}	

[a] See the Particle Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 14 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 7.7 for 12 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100	
x_3	12	−14
	x_1	x_2

Σ^+ BRANCHING RATIOS

$\Gamma(n\pi^+)/\Gamma(N\pi)$ — $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.4836±0.0030 OUR FIT				
0.4836±0.0030 OUR AVERAGE				
0.4828±0.0036	10k	[7] MARRAFFINO 80	HBC	$K^- p$ 0.42–0.5 GeV/c
0.488 ±0.008	1861	NOWAK 78	HBC	
0.484 ±0.015	537	TOVEE 71	EMUL	
0.488 ±0.010	1331	BARLOUTAUD 69	HBC	$K^- p$ 0.4–1.2 GeV/c
0.46 ±0.02	534	CHANG 66	HBC	
0.490 ±0.024	308	HUMPHREY 62	HBC	

[7] MARRAFFINO 80 actually gives $\Gamma(p\pi^0)/\Gamma(\text{total}) = 0.5172 \pm 0.0036$.

$\Gamma(p\gamma)/\Gamma(p\pi^0)$ — Γ_3/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
2.38±0.10 OUR FIT				
2.38±0.10 OUR AVERAGE				
2.32±0.11±0.10	32k	TIMM 95	E761	Σ^+ 375 GeV
$2.81\pm0.39^{+0.21}_{-0.43}$	408	HESSEY 89	CNTR	$K^- p \to \Sigma^+\pi^-$ at rest
2.52±0.28	190	[8] KOBAYASHI 87	CNTR	$\pi^+ p \to \Sigma^+ K^+$
$2.46^{+0.30}_{-0.35}$	155	BIAGI 85	CNTR	CERN hyperon beam
2.11±0.38	46	MANZ 80	HBC	$K^- p \to \Sigma^+\pi^-$
2.1 ±0.3	45	ANG 69B	HBC	$K^- p$ at rest
2.76±0.51	31	GERSHWIN 69B	HBC	$K - p \to \Sigma^+\pi^-$
3.7 ±0.8	24	BAZIN 65	HBC	$K^- p$ at rest

[8] KOBAYASHI 87 actually gives $\Gamma(p\gamma)/\Gamma(\text{total}) = (1.30 \pm 0.15) \times 10^{-3}$.

$\Gamma(n\pi^+\gamma)/\Gamma(n\pi^+)$ — Γ_4/Γ_2

The π^+ momentum cuts differ, so we do not average the results but simply use the latest value in the Summary Table.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID	TECN	COMMENT
0.93±0.10	180	EBENHOH 73	HBC	$\pi^+ < 150$ MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.27±0.05	29	ANG 69B	HBC	$\pi^+ < 110$ MeV/c
~ 1.8		BAZIN 65B	HBC	$\pi^+ < 116$ MeV/c

$\Gamma(\Lambda e^+\nu_e)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID	TECN	COMMENT
2.0±0.5 OUR AVERAGE				
1.6±0.7	5	BALTAY 69	HBC	$K^- p$ at rest
2.9±1.0	10	EISELE 69	HBC	$K^- p$ at rest
2.0±0.8	6	BARASH 67	HBC	$K^- p$ at rest

$\Gamma(ne^+\nu_e)/\Gamma(n\pi^+)$ — Γ_6/Γ_2

Test of $\Delta S = \Delta Q$ rule. Experiments with an effective denominator less than 100,000 have been omitted.

EFFECTIVE DENOM.	EVTS	DOCUMENT ID	TECN	COMMENT
< 1.1 x 10^{-5} OUR LIMIT		Our 90% CL limit = (2.3 events)/(effective denominator sum). [Number of events increased to 2.3 for a 90% confidence level.]		
111000	0	[9] EBENHOH 74	HBC	$K^- p$ at rest
105000	0	[9] SECHI-ZORN 73	HBC	$K^- p$ at rest

[9] Effective denominator calculated by us.

$\Gamma(n\mu^+\nu_\mu)/\Gamma(n\pi^+)$ — Γ_7/Γ_2

Test of $\Delta S = \Delta Q$ rule.

EFFECTIVE DENOM.	EVTS	DOCUMENT ID	TECN
< 6.2 x 10^{-5} OUR LIMIT		Our 90% CL limit = (6.7 events)/(effective denominator sum). [Number of events increased to 6.7 for a 90% confidence level.]	
33800	0	BAGGETT 69B	HBC
62000	2	[10] EISELE 69B	HBC
10150	0	[11] COURANT 64	HBC
1710	0	[11] NAUENBERG 64	HBC
120	1	GALTIERI 62	EMUL

[10] Effective denominator calculated by us.
[11] Effective denominator taken from EISELE 67.

$\Gamma(pe^+e^-)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE (units 10^{-6})	DOCUMENT ID	TECN	COMMENT
<7	[12] ANG 69B	HBC	$K^- p$ at rest

[12] ANG 69B found three pe^+e^- events in agreement with $\gamma \to e^+e^-$ conversion from $\Sigma^+ \to p\gamma$. The limit given here is for neutral currents.

$\Gamma(\Sigma^+ \to ne^+\nu_e)/\Gamma(\Sigma^- \to ne^-\overline{\nu}_e)$

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
<0.009 OUR LIMIT			Our 90% CL limit, using $\Gamma(ne^+\nu_e)/\Gamma(n\pi^+)$ above.		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.019	90	0	EBENHOH 74	HBC	$K^- p$ at rest
<0.018	90	0	SECHI-ZORN 73	HBC	$K^- p$ at rest
<0.12	95	0	COLE 71	HBC	$K^- p$ at rest
<0.03	90	0	EISELE 69B	HBC	See EBENHOH 74

$\Gamma(\Sigma^+ \to n\mu^+\nu_\mu)/\Gamma(\Sigma^- \to n\mu^-\overline{\nu}_\mu)$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<0.12 OUR LIMIT		Our 90% CL limit, using $\Gamma(n\mu^+\nu_\mu)/\Gamma(n\pi^+)$ above.		
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.06^{+0.045}_{-0.03}$	2	EISELE 69B	HBC	$K^- p$ at rest

$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\overline{\nu})$

Test of $\Delta S = \Delta Q$ rule.

VALUE	EVTS	DOCUMENT ID	TECN
<0.043 OUR LIMIT		Our 90% CL limit, using $\left[\Gamma(ne^+\nu_e) + \Gamma(n\mu^+\nu_\mu)\right]/\Gamma(n\pi^+)$.	
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<0.08	1	NORTON 69	HBC
<0.034	0	BAGGETT 67	HBC

Σ^+ DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings. A few early results have been omitted.

α_0 FOR $\Sigma^+ \to p\pi^0$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$-0.980^{+0.017}_{-0.015}$ OUR FIT				
$-0.980^{+0.017}_{-0.013}$ OUR AVERAGE				
$-0.945^{+0.055}_{-0.042}$	1259	[13] LIPMAN 73	OSPK	$\pi^+ p \to \Sigma^+$
−0.940±0.045	16k	BELLAMY 72	ASPK	$\pi^+ p \to \Sigma^+ K^+$
$-0.98\ ^{+0.05}_{-0.02}$	1335	[14] HARRIS 70	OSPK	$\pi^+ p \to \Sigma^+ K^+$
−0.999±0.022	32k	BANGERTER 69	HBC	$K^- p$ 0.4 GeV/c

[13] Decay protons scattered off aluminum.
[14] Decay protons scattered off carbon.

ϕ_0 ANGLE FOR $\Sigma^+ \to p\pi^0$ — $(\tan\phi_0 = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
36 ±34 OUR AVERAGE				
$38.1^{+35.7}_{-37.1}$	1259	[15] LIPMAN 73	OSPK	$\pi^+ p \to \Sigma^+ K^+$
22 ±90		[16] HARRIS 70	OSPK	$\pi^+ p \to \Sigma^+ K^+$

[15] Decay proton scattered off aluminum.
[16] Decay protons scattered off carbon.

α_+ / α_0

Older results have been omitted.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.069±0.013 OUR FIT				
−0.073±0.021	23k	MARRAFFINO 80	HBC	$K^- p$ 0.42–0.5 GeV/c

α_+ FOR $\Sigma^+ \to n\pi^+$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.068±0.013 OUR FIT				
0.066±0.016 OUR AVERAGE				
0.037±0.049	4101	BERLEY 70B	HBC	
0.069±0.017	35k	BANGERTER 69	HBC	$K^- p$ 0.4 GeV/c

ϕ_+ ANGLE FOR $\Sigma^+ \to n\pi^+$ — $(\tan\phi_+ = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID	TECN	COMMENT
167±20 OUR AVERAGE		Error includes scale factor of 1.1.		
184±24	1054	[17] BERLEY 70B	HBC	
143±29	560	BANGERTER 69B	HBC	$K^- p$ 0.4 GeV/c

[17] Changed from 176 to 184° to agree with our sign convention.

α_γ FOR $\Sigma^+ \to p\gamma$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
−0.76 ±0.08 OUR AVERAGE				
−0.720±0.086±0.045	35k	[18] FOUCHER 92	SPEC	Σ^+ 375 GeV
−0.86 ±0.13 ±0.04	190	KOBAYASHI 87	CNTR	$\pi^+ p \to \Sigma^+ K^+$
$-0.53\ ^{+0.38}_{-0.36}$	46	MANZ 80	HBC	$K^- p \to \Sigma^+\pi^-$
$-1.03\ ^{+0.52}_{-0.42}$	61	GERSHWIN 69B	HBC	$K^- p \to \Sigma^+\pi^-$

[18] See TIMM 95 for a detailed description of the analysis.

Σ^+ REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

TIMM	95	PR D51 4638	+Albuquerque, Bondar+	(FNAL E761 Collab.)
MORELOS	93	PRL 71 3417	+Albuquerque, Bondar, Carrigan+	(FNAL E761 Collab.)
FOUCHER	92	PRL 68 3004	+Albuquerque, Bondar+	(FNAL E761 Collab.)
HESSEY	89	ZPHY C42 175	+Booth, Fickinger, Gall+	(BNL-811 Collab.)
KOBAYASHI	87	PRL 59 868	+Haba, Homma, Kawai, Miyake+	(KYOT)
WILKINSON	87	PRL 58 855	+Handler+	(WISC, MICH, RUTG, MINN)
BIAGI	85	ZPHY C28 495	+Bourquin+	(CERN WA62 Collab.)
ANKENBRA...	83	PRL 51 863	Ankenbrandt, Berge+	(FNAL, IOWA, ISU, YALE)
MANZ	80	PL 96B 217	+Reucroft, Settles, Wolf+	(MPIM, VAND)
MARRAFFINO	80	PR D21 2501	+Reucroft, Roos, Waters+	(VAND, MPIM)
NOWAK	78	NP B139 61	+Armstrong, Davis+	(LOUC, BELG, DURH, WARS)
CONFORTO	76	NP B105 189	+Gopal, Kalmus, Litchfield, Ross+	(RHEL, LOIC)
EBENHOH	74	ZPHY 266 367	+Eisele, Engelmann, Filthuth, Hepp+	(HEIDT)
EBENHOH	73	ZPHY 264 413	+Eisele, Filthuth, Hepp, Leitner, Thouw+	(HEIDT)
LIPMAN	73	PL 43B 89	+Uto, Walker, Montgomery+	(RHEL, SUSS, LOWC)
PDG	73	RMP 45 No. 2 Pt. II	Lasinski, Barbaro-Galtieri, Kelly+	(LBL, BRAN, CERN+)
SECHI-ZORN	73	PR D8 12	+Snow	(UMD)
BELLAMY	72	PL 39B 299	+Anderson, Crawford+	(LOWC, RHEL, SUSS)
BOHM	72	NP B48 1	+	(BERL, KIDR, BRUX, IASD, DUUC, LOUC+)
Also	73	IIHE-73.2 Nov	Bohm	(BERL, KIDR, BRUX, IASD, DUUC, LOUC+)
BAKKER	71	LNC 1 37	+Hoogland, Kluyver, Massard+	(SABRE Collab.)
COLE	71	PR D4 631	+Lee-Franzini, Loveless, Baltay+	(STON, COLU)
TOVEE	71	NP B33 493	+	(LOUC, KIDR, BERL, BRUX, DUUC, WARS)
BERLEY	70B	PR D1 2015	+Yamin, Hertzbach, Kofler+	(BNL, MASA, YALE)
EISELE	70	ZPHY 238 372	+Filthuth, Hepp, Presser, Zech	(HEID)
HARRIS	70	PRL 24 165	+Overseth, Pondrom, Dettmann	(MICH, WISC)
PDG	70	RMP 42 No. 1	Barbaro-Galtieri, Derenzo, Price+	(LRL, BRAN, CERN+)
ANG	69B	ZPHY 228 151	+Ebenhoh, Eisele, Engelmann, Filthuth+	(HEID)
BAGGETT	69B	Thesis MDDP-TR-973		(UMD)
BALTAY	69	PRL 22 615	+Franzini, Newman, Norton+	(COLU, STON)
BANGERTER	69	Thesis UCRL 19244		(LRL)
BANGERTER	69B	PR 187 1821	+Alston-Garnjost, Galtieri, Gershwin+	(LRL)
BARLOUTAUD	69	NP B14 153	+DeBellefon, Granet+	(SACL, CERN, HEID)
EISELE	69	ZPHY 221 1	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
Also	64	PRL 13 291	Willis, Courant+	(BNL, CERN, HEID, UMD)
EISELE	69B	ZPHY 221 401	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
GERSHWIN	69B	PR 188 2077	+Alston-Garnjost, Bangerter+	(LRL)
Also	69	Thesis UCRL 19246	Gershwin	(LRL)
NORTON	69	Thesis Nevis 175		(COLU)
BAGGETT	67	PRL 19 1458	+Day, Glasser, Kehoe, Knop+	(UMD)
Also	68	Vienna Abs. 374	Baggett, Kehoe	(UMD)
Also	68B	Private Comm.	Baggett	(UMD)
BARASH	67	PRL 19 181	+Day, Glasser, Kehoe, Knop+	(UMD)
EISELE	67	ZPHY 205 409	+Engelmann, Filthuth, Folish, Hepp+	(HEID)
HYMAN	67	PL 25B 376	+Loken, Pewitt, McKenzie+	(ANL, CMU, NWES)
PDG	67	RMP 39 1	Rosenfeld, Barbaro-Galtieri, Podolsky+	(LRL, CERN, YALE)
CHANG	66	PR 151 1081		(COLU)
Also	65	Thesis Nevis 145	Chang	(COLU)
COOK	66	PRL 17 223	+Ewart, Masek, Orr, Platner	(WASH)
BALTAY	65	PR 140B 1027	+Sandweiss, Culwick, Kopp+	(YALE, BNL)
BAZIN	65	PRL 14 154	+Blumenfeld, Nauenberg+	(PRIN, COLU)
BAZIN	65B	PR 140B 1358	+Plano, Schmidt+	(PRIN, RUTG, COLU)
CARAYAN...	65	PR 138B 433	Carayannopoulos, Tautfest, Willmann	(PURD)
SCHMIDT	65	PR 140B 1328		(COLU)
BHOWMIK	64	NP 53 22	+Jain, Mathur, Lakshmi	(DELH)
COURANT	64	PR 136B 1791	+Filthuth+	(CERN, HEID, UMD, NRL, BNL)
NAUENBERG	64	PRL 12 679	+Marateck+	(COLU, RUTG, PRIN)
BARKAS	63	PRL 11 26	+Dyer, Heckman	(LRL)
Also	61	Thesis UCRL 9450	Dyer	(LRL)
GALTIERI	62	PRL 9 26	+Barkas, Heckman, Patrick, Smith	(LRL)
GRARD	62	PR 127 607	+Smith	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)

Σ^0

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

The spin and parity have not been measured directly. They are of course assumed to be the same as for the Σ^+ and Σ^-.

Σ^0 MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	*DOCUMENT ID*
1192.55±0.08 OUR FIT	Error includes scale factor of 1.2.

$m_{\Sigma^-} - m_{\Sigma^0}$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.88±0.08 OUR FIT	Error includes scale factor of 1.2.				
4.86±0.08 OUR AVERAGE	Error includes scale factor of 1.2.				
4.87±0.12	37	DOSCH	65	HBC	
5.01±0.12	12	SCHMIDT	65	HBC	See note with Λ mass
4.75±0.1	18	BURNSTEIN	64	HBC	

$m_{\Sigma^0} - m_{\Lambda}$

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
76.87±0.08 OUR FIT	Error includes scale factor of 1.2.				
76.55±0.25 OUR AVERAGE					
76.23±0.55	109	COLAS	75	HLBC	$\Sigma^0 \to \Lambda\gamma$
76.63±0.28	208	SCHMIDT	65	HBC	See note with Λ mass

Σ^0 MEAN LIFE

These lifetimes are deduced from measurements of the cross sections for the Primakoff process $\Lambda \to \Sigma^0$ in nuclear Coulomb fields. An alternative expression of the same information is the Σ^0-Λ transition magnetic moment given in the following section. The relation is $(\mu_{\Sigma\Lambda}/\mu_N)^2\ \tau = 1.92951 \times 10^{-19}$ s (see DEVLIN 86).

VALUE (10^{-20} s)	*DOCUMENT ID*		*TECN*	*COMMENT*
7.4±0.7 OUR EVALUATION	Using $\mu_{\Sigma\Lambda}$ (see the above note).			
$6.5^{+1.7}_{-1.1}$	[1] DEVLIN	86	SPEC	Primakoff effect
7.6±0.5±0.7	[2] PETERSEN	86	SPEC	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.8±1.3	[1] DYDAK	77	SPEC	See DEVLIN 86

[1] DEVLIN 86 is a recalculation of the results of DYDAK 77 removing a numerical approximation made in that work.
[2] An additional uncertainty of the Primakoff formalism is estimated to be < 5%.

$|\mu(\Sigma^0 \to \Lambda)|$ TRANSITION MAGNETIC MOMENT

See the note in the Σ^0 mean-life section above. Also, see the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.61±0.08 OUR AVERAGE				
$1.72^{+0.17}_{-0.19}$	[3] DEVLIN	86	SPEC	Primakoff effect
1.59±0.05±0.07	[4] PETERSEN	86	SPEC	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.82^{+0.25}_{-0.18}$	[3] DYDAK	77	SPEC	See DEVLIN 86

[3] DEVLIN 86 is a recalculation of the results of DYDAK 77 removing a numerical approximation made in that work.
[4] An additional uncertainty of the Primakoff formalism is estimated to be < 2.5%.

Σ^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\gamma$	100 %	
Γ_2	$\Lambda\gamma\gamma$	< 3 %	90%
Γ_3	$\Lambda e^+ e^-$	[a] 5×10^{-3}	

[a] A theoretical value using QED.

Σ^0 BRANCHING RATIOS

$\Gamma(\Lambda\gamma\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	*CL%*	*DOCUMENT ID*		*TECN*
<0.03	90	COLAS	75	HLBC

$\Gamma(\Lambda e^+ e^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE	*DOCUMENT ID*		*COMMENT*
0.00545	FEINBERG	58	Theoretical QED calculation

Σ^0 REFERENCES

DEVLIN	86	PR D34 1626	+Petersen, Beretvas	(RUTG)
PETERSEN	86	PRL 57 949	+Beretvas, Devlin, Luk+	(RUTG, WISC, MICH, MINN)
DYDAK	77	NP B118 1	+Navarria, Overseth, Steffen+	(CERN, DORT, HEIDH)
COLAS	75	NP B91 253	+Farwell, Ferrer, Six	(ORSAY)
DOSCH	65	PL 14 239	+Engelmann, Filthuth, Hepp, Kluge+	(HEID)
SCHMIDT	65	PR 140B 1328		(COLU)
BURNSTEIN	64	PRL 13 66	+Day, Kehoe, Zorn, Snow	(UMD)
FEINBERG	58	PR 109 1019		(BNL)

Σ^-

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Σ^- MASS

The fit uses Σ^+, Σ^0, Σ^-, and Λ mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1197.436±0.033 OUR FIT	Error includes scale factor of 1.2.				
1197.45 ±0.04 OUR AVERAGE	Error includes scale factor of 1.2.				
1197.417±0.040		GUREV	93	SPEC	Σ^- C atom, crystal diff.
1197.532±0.057		GALL	88	CNTR	Σ^- Pb, Σ^- W atoms
1197.43 ±0.08	3000	SCHMIDT	65	HBC	See note with Λ mass
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1197.24 ±0.15		[1] DUGAN	75	CNTR	Exotic atoms

[1] GALL 88 concludes that the DUGAN 75 mass needs to be reevaluated.

$m_{\Sigma^-} - m_{\Sigma^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN
8.07±0.08 OUR FIT	Error includes scale factor of 1.9.			
8.09±0.16 OUR AVERAGE				
7.91±0.23	86	BOHM	72	EMUL
8.25±0.25	2500	DOSCH	65	HBC
8.25±0.40	87	BARKAS	63	EMUL

$m_{\Sigma^-} - m_{\Lambda}$

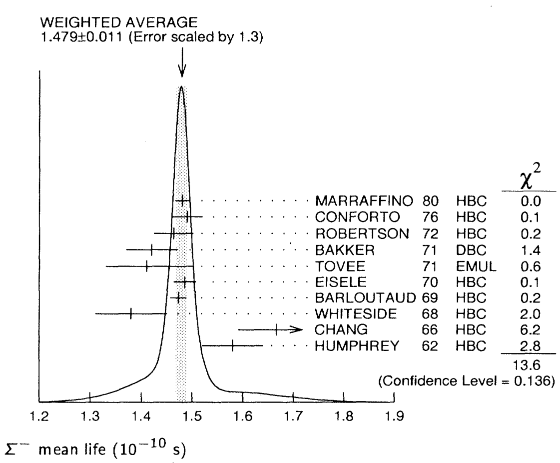
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
81.752±0.034 OUR FIT	Error includes scale factor of 1.2.				
81.69 ±0.07 OUR AVERAGE					
81.64 ±0.09	2279	HEPP	68	HBC	
81.80 ±0.13	85	SCHMIDT	65	HBC	See note with Λ mass
81.70 ±0.19		BURNSTEIN	64	HBC	

Σ^- MEAN LIFE

Measurements with an error $\geq 0.2 \times 10^{-10}$ s have been omitted.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.479±0.011 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
1.480±0.014	16k	MARRAFFINO	80	HBC	$K^- p$ 0.42–0.5 GeV/c
1.49 ±0.03	8437	CONFORTO	76	HBC	$K^- p$ 1–1.4 GeV/c
1.463±0.039	2400	ROBERTSON	72	HBC	$K^- p$ 0.25 GeV/c
1.42 ±0.05	1383	BAKKER	71	DBC	$K^- N \to \Sigma^- \pi\pi$
1.41 $^{+0.09}_{-0.08}$		TOVEE	71	EMUL	
1.485±0.022	100k	EISELE	70	HBC	$K^- p$ at rest
1.472±0.016	10k	BARLOUTAUD	69	HBC	$K^- p$ 0.4–1.2 GeV/c
1.38 ±0.07	506	WHITESIDE	68	HBC	$K^- p$ at rest
1.666±0.075	3267	[2] CHANG	66	HBC	$K^- p$ at rest
1.58 ±0.06	1208	HUMPHREY	62	HBC	$K^- p$ at rest

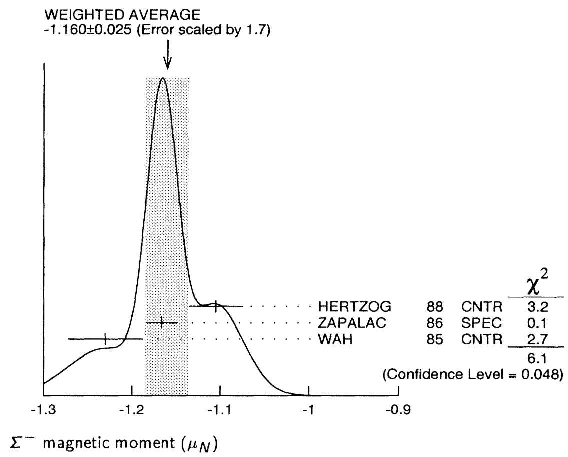
[2] We have increased the CHANG 66 error of 0.018; see our 1970 edition, Reviews of Modern Physics **42** No. 1 (1970).



Σ^- MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings. Measurements with an error $\geq 0.3\ \mu_N$ have been omitted.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
−1.160±0.025 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.				
−1.105±0.029±0.010		HERTZOG	88	CNTR	Σ^- Pb, Σ^- W atoms
−1.166±0.014±0.010	671k	ZAPALAC	86	SPEC	$ne^-\nu$, $n\pi^-$ decays
−1.23 ±0.03 ±0.03		WAH	85	CNTR	pCu $\to \Sigma^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.89 ±0.14	516k	DECK	83	SPEC	pBe $\to \Sigma^- X$



Σ^- DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$n\pi^-$	(99.848±0.005) %
Γ_2	$n\pi^-\gamma$	[a] (4.6 ±0.6) $\times 10^{-4}$
Γ_3	$ne^-\overline{\nu}_e$	(1.017±0.034) $\times 10^{-3}$
Γ_4	$n\mu^-\overline{\nu}_\mu$	(4.5 ±0.4) $\times 10^{-4}$
Γ_5	$\Lambda e^-\overline{\nu}_e$	(5.73 ±0.27) $\times 10^{-5}$

[a] See the Particle Listings below for the pion momentum range used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 16 measurements and one constraint to determine 4 parameters. The overall fit has a $\chi^2 =$ 8.7 for 13 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left<\delta x_i \delta x_j\right>/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_3	−64		
x_4	−77	0	
x_5	−5	0	0
	x_1	x_3	x_4

Σ^- BRANCHING RATIOS

$\Gamma(n\pi^-\gamma)/\Gamma(n\pi^-)$ — Γ_2/Γ_1

The π^+ momentum cuts differ, so we do not average the results but simply use the latest value for the Summary Table.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.46±0.06	292	EBENHOH	73	HBC	$\pi^+ < 150$ MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.10±0.02	23	ANG	69B	HBC	$\pi^- < 110$ MeV/c
~ 1.1		BAZIN	65B	HBC	$\pi^- < 166$ MeV/c

$\Gamma(ne^-\overline{\nu}_e)/\Gamma(n\pi^-)$ — Γ_3/Γ_1

Measurements with an error $\geq 0.2 \times 10^{-3}$ have been omitted.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.019±0.034 OUR FIT					
$1.019^{+0.031}_{-0.036}$ OUR AVERAGE					
0.96 ±0.05	2847	BOURQUIN	83C	SPEC	SPS hyperon beam
$1.09\ ^{+0.06}_{-0.08}$	601	[3] EBENHOH	74	HBC	$K^- p$ at rest
$1.05\ ^{+0.07}_{-0.13}$	455	[3] SECHI-ZORN	73	HBC	$K^- p$ at rest
0.97 ±0.15	57	COLE	71	HBC	$K^- p$ at rest
1.11 ±0.09	180	BIERMAN	68	HBC	

[3] An additional negative systematic error is included for internal radiative corrections and latest form factors; see BOURQUIN 83C.

$\Gamma(n\mu^-\overline{\nu}_\mu)/\Gamma(n\pi^-)$ — Γ_4/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.45±0.04 OUR FIT					
0.45±0.04 OUR AVERAGE					
0.38±0.11	13	COLE	71	HBC	$K^- p$ at rest
0.43±0.06	72	ANG	69	HBC	$K^- p$ at rest
0.43±0.09	56	BAGGETT	69	HBC	$K^- p$ at rest
0.56±0.20	11	BAZIN	65B	HBC	$K^- p$ at rest
0.66±0.15	22	COURANT	64	HBC	

$\Gamma(\Lambda e^-\overline{\nu}_e)/\Gamma(n\pi^-)$ — Γ_5/Γ_1

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
0.574±0.027 OUR FIT					
0.574±0.027 OUR AVERAGE					
0.561±0.031	1620	[4] BOURQUIN	82	SPEC	SPS hyperon beam
0.63 ±0.11	114	THOMPSON	80	ASPK	Hyperon beam
0.52 ±0.09	31	BALTAY	69	HBC	$K^- p$ at rest
0.69 ±0.12	31	EISELE	69	HBC	$K^- p$ at rest
0.64 ±0.12	35	BARASH	67	HBC	$K^- p$ at rest
0.75 ±0.28	11	COURANT	64	HBC	$K^- p$ at rest

[4] The value is from BOURQUIN 83B, and includes radiation corrections and new acceptance.

Σ^- DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings. Older, outdated results have been omitted.

α_- FOR $\Sigma^- \to n\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.068±0.008 OUR AVERAGE					
−0.062±0.024	28k	HANSL	78	HBC	$K^- p \to \Sigma^- \pi^+$
−0.067±0.011	60k	BOGERT	70	HBC	$K^- p$ 0.4 GeV/c
−0.071±0.012	51k	BANGERTER	69	HBC	$K^- p$ 0.4 GeV/c

ϕ ANGLE FOR $\Sigma^- \to n\pi^-$ — $(\tan\phi = \beta\ /\ \gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
10±15 OUR AVERAGE					
+ 5±23	1092	[5] BERLEY	70B	HBC	n rescattering
14±19	1385	BANGERTER	69B	HBC	$K^- p$ 0.4 GeV/c

[5] BERLEY 70B changed from −5 to +5° to agree with our sign convention.

g_A/g_V FOR $\Sigma^- \to ne^-\overline{\nu}_e$

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with our conventions, which are given in the "Note on Baryon Decay Parameters" in the neutron Listings. What is actually listed is $|g_1/f_1 - 0.237 g_2/f_1|$. This reduces to $g_A/g_V \equiv g_1(0)/f_1(0)$ on making the usual assumption that $g_2 = 0$. See also the note on HSUEH 88.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.340±0.017 OUR AVERAGE					
+0.327±0.007±0.019	50k	[6] HSUEH	88	SPEC	Σ^- 250 GeV
+0.34 ±0.05	4456	[7] BOURQUIN	83C	SPEC	SPS hyperon beam
0.385±0.037	3507	[8] TANENBAUM	74	ASPK	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.29 ±0.07	25k	HSUEH	85	SPEC	See HSUEH 88
$0.17\ ^{+0.07}_{-0.09}$	519	DECAMP	77	ELEC	Hyperon beam

[6] The sign is, *with our conventions*, unambiguously positive. The value assumes, as usual, that $g_2 = 0$. If g_2 is included in the fit, than (with our sign convention) $g_2 = -0.56 \pm 0.37$, with a corresponding reduction of g_A/g_V to $+0.20 \pm 0.08$.

[7] BOURQUIN 83C favors the positive sign by at least 2.6 standard deviations.

[8] TANENBAUM 74 gives 0.435 ± 0.035, assuming no q^2 dependence in g_A and g_V. The listed result allows q^2 dependence, and is taken from HSUEH 88.

$f_2(0)/f_1(0)$ FOR $\Sigma^- \to ne^-\overline{\nu}_e$

The signs have been changed to be in accord with our conventions, given in the "Note on Baryon Decay Parameters" in the neutron Listings.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.97±0.14 OUR AVERAGE					
+0.96±0.07±0.13	50k	HSUEH	88	SPEC	Σ^- 250 GeV
+1.02±0.34	4456	BOURQUIN	83C	SPEC	SPS hyperon beam

TRIPLE CORRELATION COEFFICIENT D for $\Sigma^- \to ne^-\overline{\nu}_e$

The coefficient D of the term $D\,\mathbf{P}\cdot(\mathbf{p}_e \times \mathbf{p}_\nu)$ in the $\Sigma^- \to ne^-\overline{\nu}$ decay angular distribution. A nonzero value would indicate a violation of time-reversal invariance.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.11±0.10	50k	HSUEH	88	SPEC	Σ^- 250 GeV

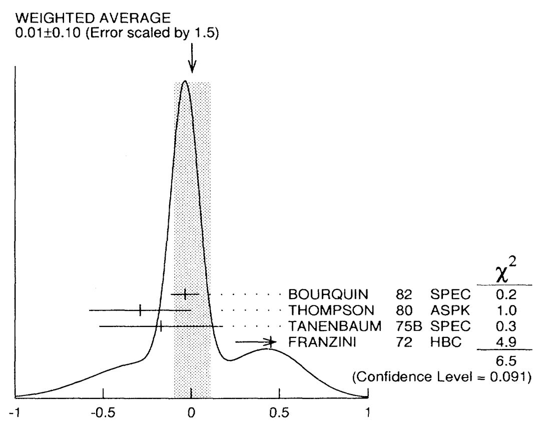
g_V/g_A FOR $\Sigma^- \to \Lambda e^-\overline{\nu}_e$

For the sign convention, see the "Note on Baryon Decay Parameters" in the neutron Listings. The value is predicted to be zero by conserved vector current theory. The values averaged assume CVC-SU(3) weak magnetism term.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.01 ±0.10 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.			
−0.034±0.080	1620	[9] BOURQUIN	82	SPEC	SPS hyperon beam
−0.29 ±0.29	114	THOMPSON	80	ASPK	BNL hyperon beam
−0.17 ±0.35	55	TANENBAUM	75B	SPEC	BNL hyperon beam
+0.45 ±0.20	186	[9,10] FRANZINI	72	HBC	

[9] The sign has been changed to agree with our convention.

[10] The FRANZINI 72 value includes the events of earlier papers.



g_V/g_A for $\Sigma^- \to \Lambda e^-\overline{\nu}_e$

g_{WM}/g_A FOR $\Sigma^- \to \Lambda e^-\overline{\nu}_e$

The values quoted assume the CVC prediction $g_V = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
2.4 ±1.7 OUR AVERAGE					
1.75±3.5	114	THOMPSON	80	ASPK	BNL hyperon beam
3.5 ±4.5	55	TANENBAUM	75B	SPEC	BNL hyperon beam
2.4 ±2.1	186	FRANZINI	72	HBC	

Σ^- REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

GUREV 93 JETPL 57 400 Gur'ev, Denisov, Zhelamkov, Ivanov+ (PNPI)
Translated from ZETFP 57 389.
GALL 88 PRL 60 186 +Austin+ (BOST, MIT, WILL, CIT, CMU, WYOM)
HERTZOG 88 PR D37 1142 +Eckhause+ (WILL, BOST, MIT, CIT, CMU, WYOM)
HSUEH 88 PR D38 2056 + (CHIC, ELMT, FNAL, IOWA, ISU, PNPI, YALE)
ZAPALAC 86 PRL 57 1526 + (EFI, ELMT, FNAL, IOWA, ISU, PNPI, YALE)
HSUEH 85 PRL 54 2399 +Muller+ (CHIC, ELMT, FNAL, ISU, PNPI, YALE)
WAH 85 PRL 55 2551 +Cardello, Cooper, Teig+ (FNAL, IOWA, ISU)
BOURQUIN 83B ZPHY C21 27 + (BRIS, GEVA, HEIDP, LALO, RL, STRB)
BOURQUIN 83C ZPHY C21 17 + (BRIS, GEVA, HEIDP, LALO, RL, STRB)
DECK 83 PR D28 1 +Beretvas, Devlin, Luk+ (RUTG, WISC, MICH, MINN)
BOURQUIN 82 ZPHY C12 307 +Brown+ (BRIS, GEVA, HEIDP, LALO, RL, STRB)
MARRAFFINO 80 PR D21 2501 +Reucroft, Roos, Waters+ (VAND, MPIM)
THOMPSON 80 PR D21 25 +Cleland, Cooper, Dris, Engels+ (PITT, BNL)
HANSL 78 NP B132 45 +Manz, Matt, Reucroft, Settles+ (MPIM, VAND)
DECAMP 77 PL 66B 295 +Badier, Bland, Chollet, Gaillard+ (LALO, EPOL)
CONFORTO 76 NP B105 189 +Gopal, Kalmus, Litchfield, Ross+ (RHEL, LOIC)
DUGAN 75 NP A254 396 +Asano, Chen, Cheng, Hu, Lidofsky+ (COLU, YALE)
TANENBAUM 75B PR D12 1871 +Hungerbuhler+ (YALE, FNAL, BNL)
EBENHOH 74 ZPHY 266 367 +Eisele, Engelmann, Filthuth, Hepp+ (HEIDT)
TANENBAUM 74 PRL 33 175 +Hungerbuhler+ (YALE, FNAL, BNL)
EBENHOH 73 ZPHY 264 413 +Eisele, Filthuth, Hepp, Leitner, Thouw+ (HEIDT)
SECHI-ZORN 73 PR D8 12 +Snow (UMD)
BOHM 72 NP B48 1 + (BERL, KIDR, BRUX, IASD, DUUC, LOUC+)
FRANZINI 72 PR D6 2417 + (COLU, HEID, UMD, STON)
ROBERTSON 72 Thesis UMI 78-00877 (IIT)
BAKKER 71 LNC 1 37 +Hoogland, Kluyver, Massard+ (SABRE Collab.)
COLE 71 PR D4 631 +Lee-Franzini, Loveless, Baltay+ (STON, COLU)
Also 69 Thesis Nevis 175 Norton (COLU)
TOVEE 71 NP B33 493 + (LOUC, KIDR, BERL, BRUX, DUUC, WARS)
BERLEY 70B PR D1 2015 +Yamin, Hertzbach, Kofler+ (BNL, MASA, YALE)

BOGERT	70	PR D2 6	+Lucas, Taft, Willis, Berley+	(BNL, MASA, YALE)
EISELE	70	ZPHY 238 372	+Filthuth, Hepp, Presser, Zech	(HEID)
PDG	70	RMP 42 No. 1	Barbaro-Galtieri, Derenzo, Price+	(LRL, BRAN, CERN+)
ANG	69	ZPHY 223 103	+Eisele, Engelmann, Filthuth+	(HEID)
ANG	69B	ZPHY 228 151	+Ebenhoh, Eisele, Engelmann, Filthuth+	(HEID)
BAGGETT	69	PRL 23 249	+Kehoe, Snow	(UMD)
BALTAY	69	PRL 22 615	+Franzini, Newman, Norton+	(COLU, STON)
BANGERTER	69	Thesis UCRL 19244		(LRL)
BANGERTER	69B	PR 187 1821	+Alston-Garnjost, Galtieri, Gershwin+	(LRL)
BARLOUTAUD	69	NP B14 153	+DeBellefon, Granet+	(SACL, CERN, HEID)
EISELE	69	ZPHY 221 1	+Engelmann, Filthuth, Fohlisch, Hepp+	(HEID)
BIERMAN	68	PRL 20 1459	+Kounosu, Nauenberg+	(PRIN)
HEPP	68	ZPHY 214 71	+Schleich	(HEID)
WHITESIDE	68	NC 54A 537	+Gollub	(OBER)
BARASH	67	PRL 19 181	+Day, Glasser, Kehoe, Knop+	(UMD)
CHANG	66	PR 151 1081		(COLU)
BAZIN	65B	PR 140B 1358	+Plano, Schmidt+	(PRIN, RUTG, COLU)
DOSCH	65	PL 14 239	+Engelmann, Filthuth, Hepp, Kluge+	(HEID)
Also	66	PR 151 1081	Chang	(COLU)
SCHMIDT	65	PR 140B 1328		(COLU)
BURNSTEIN	64	PRL 13 66	+Day, Kehoe, Zorn, Snow	(UMD)
COURANT	64	PR 136B 1791	+Filthuth+	(CERN, HEID, UMD, NRL, BNL)
BARKAS	63	PRL 11 26	+Dyer, Heckman	(LRL)
HUMPHREY	62	PR 127 1305	+Ross	(LRL)

$\Sigma(1385)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: ∗∗∗∗

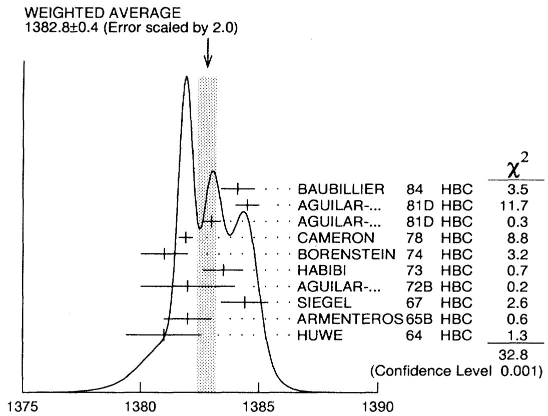
Discovered by ALSTON 60. Early measurements of the mass and width for combined charge states have been omitted. They may be found in our 1984 edition Reviews of Modern Physics **56** No. 2 Pt. II (1984).

We average only the most significant determinations. We do not average results from inclusive experiments with large backgrounds or results which are not accompanied by some discussion of experimental resolution. Nevertheless systematic differences between experiments remain. (See the ideograms in the Listings below.) These differences could arise from interference effects that change with production mechanism and/or beam momentum. They can also be accounted for in part by differences in the parametrizations employed. (See BORENSTEIN 74 for a discussion on this point.) Thus BORENSTEIN 74 uses a Breit-Wigner with energy-independent width, since a *P*-wave was found to give unsatisfactory fits. CAMERON 78 uses the same form. On the other hand HOLMGREN 77 obtains a good fit to their $\Lambda\pi$ spectrum with a *P*-wave Breit-Wigner, but includes the partial width for the $\Sigma\pi$ decay mode in the parametrization. AGUILAR-BENITEZ 81D gives masses and widths for five different Breit-Wigner shapes. The results vary considerably. Only the best-fit *S*-wave results are given here.

$\Sigma(1385)$ MASSES

$\Sigma(1385)^+$ MASS

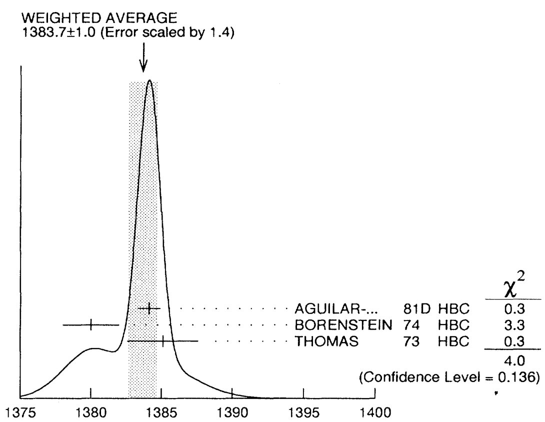
VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1382.8±0.4 OUR AVERAGE		Error includes scale factor of 2.0. See the ideogram below.		
1384.1±0.7	1897	BAUBILLIER 84	HBC	$K^- p$ 8.25 GeV/c
1384.5±0.5	5256	AGUILAR-... 81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
1383.0±0.4	9361	AGUILAR-... 81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1381.9±0.3	6900	CAMERON 78	HBC	$K^- p$ 0.96–1.36 GeV/c
1381 ±1	6846	BORENSTEIN 74	HBC	$K^- p$ 2.18 GeV/c
1383.5±0.85	2300	HABIBI 73	HBC	$K^- p \to \Lambda\pi\pi$
1382 ±2	400	AGUILAR-... 72B	HBC	$K^- p \to \Lambda\pi$'s
1384.4±1.0	1260	SIEGEL 67	HBC	$K^- p$ 2.1 GeV/c
1382 ±1	750	ARMENTEROS 65B	HBC	$K^- p$ 0.9–1.2 GeV/c
1381.0±1.6	859	HUWE 64	HBC	$K^- p$ 1.22 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1385.1±1.2	600	BAKER 80	HYBR	$\pi^+ p$ 7 GeV/c
1383.2±1.0	750	BAKER 80	HYBR	$K^- p$ 7 GeV/c
1381 ±2	7k	[1] BAUBILLIER 79B	HBC	$K^- p$ 8.25 GeV/c
1391 ±2	2k	CAUTIS 79	HYBR	$\pi^+ p/K^- p$ 11.5 GeV
1390 ±2	100	[1] SUGAHARA 79B	HBC	$\pi^- p$ 6 GeV/c
1385 ±3	22k	[1,2] BARREIRO 77B	HBC	$K^- p$ 4.2 GeV/c
1385 ±1	2594	HOLMGREN 77	HBC	See AGUILAR 81D
1380 ±2		[1] BARDADIN-... 75	HBC	$K^- p$ 14.3 GeV/c
1382 ±1	3740	[3] BERTHON 74	HBC	$K^- p$ 1263–1843 MeV/c
1390 ±6	46	AGUILAR-... 70B	HBC	$K^- p \to \Sigma\pi$'s 4 GeV/c
1383 ±8	62	[4] BIRMINGHAM 66	HBC	$K^- p$ 3.5 GeV/c
1378 ±5	135	LONDON 66	HBC	$K^- p$ 2.24 GeV/c
1384.3±1.9	250	[4] SMITH 65	HBC	$K^- p$ 1.8 GeV/c
1382.6±2.1	250	[4] SMITH 65	HBC	$K^- p$ 1.95 GeV/c
1375.0±3.9	170	COOPER 64	HBC	$K^- p$ 1.45 GeV/c
1376.0±3.9	154	[4] ELY 61	HLBC	$K^- p$ 1.11 GeV/c



$\Sigma(1385)^+$ mass (MeV)

$\Sigma(1385)^0$ MASS

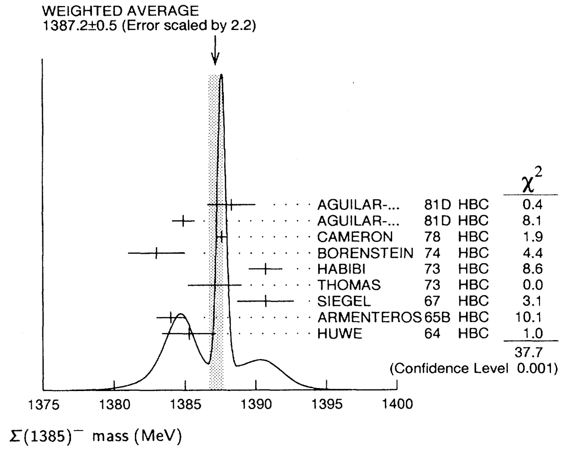
VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1383.7±1.0 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.		
1384.1±0.8	5722	AGUILAR-... 81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1380 ±2	3100	[5] BORENSTEIN 74	HBC	$K^- p \to \Lambda 3\pi$ 2.18 GeV/c
1385.1±2.5	240	[4] THOMAS 73	HBC	$\pi^- p \to \Lambda\pi^0 K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1389 ±3	500	[6] BAUBILLIER 79B	HBC	$K^- p$ 8.25 GeV/c



$\Sigma(1385)^0$ mass (MeV)

$\Sigma(1385)^-$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1387.2±0.5 OUR AVERAGE		Error includes scale factor of 2.2. See the ideogram below.		
1388.3±1.7	620	AGUILAR-... 81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
1384.9±0.8	3346	AGUILAR-... 81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
1387.6±0.3	9720	CAMERON 78	HBC	$K^- p$ 0.96–1.36 GeV/c
1383 ±2	2303	BORENSTEIN 74	HBC	$K^- p$ 2.18 GeV/c
1390.7±1.2	1900	HABIBI 73	HBC	$K^- p \to \Lambda\pi\pi$
1387.1±1.9	630	[4] THOMAS 73	HBC	$\pi^- p \to \Lambda\pi^- K^+$
1390.7±2.0	370	SIEGEL 67	HBC	$K^- p$ 2.1 GeV/c
1384 ±1	1380	ARMENTEROS 65B	HBC	$K^- p$ 0.9–1.2 GeV/c
1385.3±1.9	1086	[4] HUWE 64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1383 ±1	4.5k	[1] BAUBILLIER 79B	HBC	$K^- p$ 8.25 GeV/c
1380 ±6	150	[1] SUGAHARA 79B	HBC	$\pi^- p$ 6 GeV/c
1387 ±3	12k	[1,2] BARREIRO 77B	HBC	$K^- p$ 4.2 GeV/c
1391 ±3	193	HOLMGREN 77	HBC	See AGUILAR 81D
1383 ±2		[1] BARDADIN-... 75	HBC	$K^- p$ 14.3 GeV/c
1389 ±1	3060	[3] BERTHON 74	HBC	$K^- p$ 1263–1843 MeV/c
1389 ±9	15	LONDON 66	HBC	$K^- p$ 2.24 GeV/c
1391.5±2.6	120	[4] SMITH 65	HBC	$K^- p$ 1.8 GeV/c
1399.8±2.2	58	[4] SMITH 65	HBC	$K^- p$ 1.95 GeV/c
1392.0±6.2	200	COOPER 64	HBC	$K^- p$ 1.45 GeV/c
1382 ±3	93	DAHL 61	DBC	$K^- d$ 0.45 GeV/c
1376.0±4.4	224	[4] ELY 61	HLBC	$K^- p$ 1.11 GeV/c



$m_{\Sigma(1385)^-} - m_{\Sigma(1385)^+}$

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−2 to +6	95	[7] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
7.2±1.4		[7] HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
6.3±2.0		[7] SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
11 ±9		[7] LONDON	66	HBC	$K^- p$ 2.24 GeV/c
9 ±6		LONDON	66	HBC	$\Lambda 3\pi$ events
2.0±1.5		[7] ARMENTEROS	65B	HBC	$K^- p$ 0.9–1.2 GeV/c
7.2±2.1		[7] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
17.2±2.0		[7] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
17 ±7		[7] COOPER	64	HBC	$K^- p$ 1.45 GeV/c
4.3±2.2		[7] HUWE	64	HBC	$K^- p$ 1.22 GeV/c
0.0±4.2		[7] ELY	61	HLBC	$K^- p$ 1.11 GeV/c

$m_{\Sigma(1385)^0} - m_{\Sigma(1385)^+}$

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−4 to +4	95	[7] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c

$m_{\Sigma(1385)^-} - m_{\Sigma(1385)^0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.0±2.4	[7] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^- K^+$

Σ(1385) WIDTHS

Σ(1385)+ WIDTH

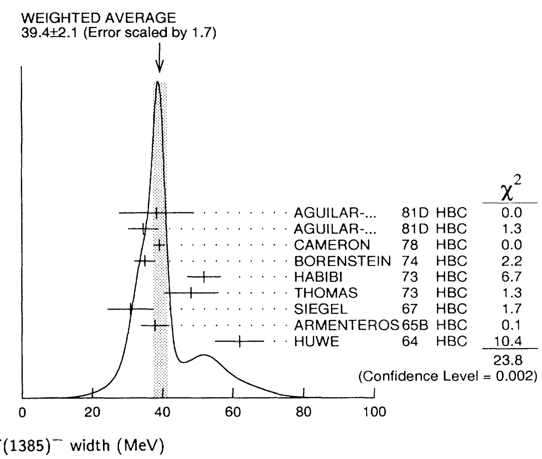
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
35.8± 0.8 OUR AVERAGE					
37.2± 2.0	1897	BAUBILLIER	84	HBC	$K^- p$ 8.25 GeV/c
35.1± 1.7	5256	AGUILAR-...	81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
37.5± 2.0	9361	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
35.5± 1.9	6900	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
34.0± 1.6	6846	[8] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
38.3± 3.2	2300	[9] HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
32.5± 6.0	400	AGUILAR-...	72B	HBC	$K^- p \to \Lambda\pi$'s
36 ± 4	1260	[9] SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
32.0± 4.7	750	[9] ARMENTEROS	65B	HBC	$K^- p$ 0.95–1.20 GeV/c
46.5± 6.4	859	[9] HUWE	64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
40 ± 3	600	BAKER	80	HYBR	$\pi^+ p$ 7 GeV/c
37 ± 2	750	BAKER	80	HYBR	$K^- p$ 7 GeV/c
37 ± 2	7k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
30 ± 4	2k	CAUTIS	79	HYBR	$\pi^+ p/K^- p$ 11.5 GeV
30 ± 6	100	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
43 ± 5	22k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
34 ± 2	2594	HOLMGREN	77	HBC	See AGUILAR 81D
40.0± 3.2		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
48 ± 3	3740	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
33 ±20	46	[9] AGUILAR-...	70B	HBC	$K^- p \to \Sigma\pi$'s 4 GeV/c
25 ±32	62	[9] BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
30.3± 7.5	250	[9] SMITH	65	HBC	$K^- p$ 1.8 GeV/c
33.1± 8.3	250	[9] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
51 ±16	170	[9] COOPER	64	HBC	$K^- p$ 1.45 GeV/c
48 ±16	154	[9] ELY	61	HLBC	$K^- p$ 1.11 GeV/c

Σ(1385)0 WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
36 ± 5 OUR AVERAGE					
34.8± 5.6	5722	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
39.3±10.2	240	[9] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^0 K^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
53 ± 8	3100	[10] BORENSTEIN	74	HBC	$K^- p \to \Lambda 3\pi$ 2.18 GeV/c
30 ± 9	106	CURTIS	63	OSPK	$\pi^- p$ 1.5 GeV/c

Σ(1385)− WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
39.4± 2.1 OUR AVERAGE Error includes scale factor of 1.7. See the ideogram below.					
38.4±10.7	620	AGUILAR-...	81D	HBC	$K^- p \to \Lambda\pi\pi$ 4.2 GeV/c
34.6± 4.2	3346	AGUILAR-...	81D	HBC	$K^- p \to \Lambda 3\pi$ 4.2 GeV/c
39.2± 1.7	9720	CAMERON	78	HBC	$K^- p$ 0.96–1.36 GeV/c
35 ± 3	2303	[8] BORENSTEIN	74	HBC	$K^- p$ 2.18 GeV/c
51.9± 4.8	1900	[9] HABIBI	73	HBC	$K^- p \to \Lambda\pi\pi$
48.2± 7.7	630	[9] THOMAS	73	HBC	$\pi^- p \to \Lambda\pi^- K^0$
31.0± 6.5	370	[9] SIEGEL	67	HBC	$K^- p$ 2.1 GeV/c
38.0± 4.1	1382	[9] ARMENTEROS	65B	HBC	$K^- p$ 0.95–1.20 GeV/c
62 ± 7	1086	HUWE	64	HBC	$K^- p$ 1.15–1.30 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
44 ± 4	4.5k	[1] BAUBILLIER	79B	HBC	$K^- p$ 8.25 GeV/c
58 ± 4	150	[1] SUGAHARA	79B	HBC	$\pi^- p$ 6 GeV/c
45 ± 5	12k	[1,2] BARREIRO	77B	HBC	$K^- p$ 4.2 GeV/c
35 ±10	193	HOLMGREN	77	HBC	See AGUILAR 81D
47 ± 6		[1] BARDADIN-...	75	HBC	$K^- p$ 14.3 GeV/c
40 ± 3	3060	[3] BERTHON	74	HBC	$K^- p$ 1263–1843 MeV/c
29.2±10.6	120	[9] SMITH	65	HBC	$K^- p$ 1.80 GeV/c
17.1± 8.9	58	[9] SMITH	65	HBC	$K^- p$ 1.95 GeV/c
88 ±24	200	[9] COOPER	64	HBC	$K^- p$ 1.45 GeV/c
40		DAHL	61	DBC	$K^- d$ 0.45 GeV/c
66 ±18	224	[9] ELY	61	HLBC	$K^- p$ 1.11 GeV/c



Σ(1385) POLE POSITIONS

Σ(1385)+ REAL PART

VALUE	DOCUMENT ID		COMMENT
1379±1	LICHTENBERG	74	Extrapolates HABIBI 73

Σ(1385)+ −IMAGINARY PART

VALUE	DOCUMENT ID		COMMENT
17.5±1.5	LICHTENBERG	74	Extrapolates HABIBI 73

Σ(1385)− REAL PART

VALUE	DOCUMENT ID		COMMENT
1383±1	LICHTENBERG	74	Extrapolates HABIBI 73

Σ(1385)− −IMAGINARY PART

VALUE	DOCUMENT ID		COMMENT
22.5±1.5	LICHTENBERG	74	Extrapolates HABIBI 73

$\Sigma(1385)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\pi$	88±2 %
Γ_2	$\Sigma\pi$	12±2 %
Γ_3	$\Lambda\gamma$	
Γ_4	$\Sigma\gamma$	
Γ_5	$N\overline{K}$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1385)$ BRANCHING RATIOS

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.135±0.011 OUR AVERAGE					
0.20 ±0.06	DIONISI	78B	HBC	±	$K^- p \to Y^* K \overline{K}$
0.16 ±0.03	BERTHON	74	HBC	+	$K^- p$ 1.26–1.84 GeV/c
0.11 ±0.02	BERTHON	74	HBC	−	$K^- p$ 1.26–1.84 GeV/c
0.21 ±0.05	BORENSTEIN	74	HBC	+	$K^- p \to \Lambda\pi^+\pi^-$, $\Sigma^0\pi^+\pi^-$
0.18 ±0.04	MAST	73	MPWA	±	$K^- p \to \Lambda\pi^+\pi^-$, $\Sigma^0\pi^+\pi^-$
0.10 ±0.05	THOMAS	73	HBC	−	$\pi^- p \to \Lambda K\pi$, $\Sigma K\pi$
0.16 ±0.07	AGUILAR-...	72B	HBC	+	$K^- p$ 3.9, 4.6 GeV/c
0.13 ±0.04	COLLEY	71B	DBC	−0	$K^- N$ 1.5 GeV/c
0.13 ±0.04	PAN	69	HBC	+	$\pi^+ p \to \Lambda K\pi$, $\Sigma K\pi$
0.08 ±0.06	LONDON	66	HBC	+	$K^- p$ 2.24 GeV/c
0.163±0.041	ARMENTEROS	65B	HBC	±	$K^- p$ 0.95–1.20 GeV/c
0.09 ±0.04	HUWE	64	HBC	±	$K^- p$ 1.2–1.7 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.04	ALSTON	62	HBC	±0	$K^- p$ 1.15 GeV/c
0.04 ±0.04	BASTIEN	61	HBC	±	

$\Gamma(\Lambda\gamma)/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.17±0.17	1	MEISNER	72	HBC	1 event only

$\Gamma(\Lambda\gamma)/\Gamma(\Lambda\pi)$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.06	90	COLAS	75	HLBC	$K^- p$ 575–970 MeV

$\Gamma(\Sigma\gamma)/\Gamma(\Lambda\pi)$ — Γ_4/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	COLAS	75	HLBC	$K^- p$ 575–970 MeV

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1385) \to \Lambda\pi$ — $(\Gamma_5\Gamma_1)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		CHG	COMMENT
+0.586±0.319	[11] DEVENISH	74B	0	Fixed-t dispersion rel.

$\Sigma(1385)$ FOOTNOTES

[1] From fit to inclusive $\Lambda\pi$ spectrum.
[2] Includes data of HOLMGREN 77.
[3] The errors are statistical only. The resolution is not unfolded.
[4] The error is enlarged to $\Gamma/\sqrt{N}$. See the note on the $K^*(892)$ mass in the 1984 edition.
[5] From a fit to $\Lambda\pi^0$ with the width fixed at 34 MeV.
[6] From fit to inclusive $\Lambda\pi^0$ spectrum with the width fixed at 40 MeV.
[7] Redundant with data in the mass Listings.
[8] Results from $\Lambda\pi^+\pi^-$ and $\Lambda\pi^+\pi^-\pi^0$ combined by us.
[9] The error is enlarged to $4\Gamma/\sqrt{N}$. See the note on the $K^*(892)$ mass in the 1984 edition.
[10] Consistent with +, 0, and − widths equal.
[11] An extrapolation of the parametrized amplitude below threshold.

$\Sigma(1385)$ REFERENCES

BAUBILLIER	84	ZPHY C23 213	+	(BIRM, CERN, GLAS, MSU, CURIN)
PDG	84	RMP 56 No. 2 Pt. II	Wohl, Cahn, Rittenberg+	(LBL, CIT, CERN)
AGUILAR-...	81D	AFIS A77 144	Aguilar-Benitez, Salicio	(MADR)
BAKER	80	NP B166 207	+Chima, Dornan, Gibbs, Hall, Miller+	(LOIC)
BAUBILLIER	79B	NP B148 18	+	(BIRM, CERN, GLAS, MSU, CURIN)
CAUTIS	79	NP B156 507	+Ballam, Bouchez, Carroll, Chadwick+	(SLAC)
SUGAHARA	79B	NP B156 237	+Ochiai, Fukui, Cooper+	(KEK, OSKC, KINK)
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC)
DIONISI	78B	PL 78B 154	+Armenteros, Diaz	(CERN, AMST, NIJM, OXF)
BARREIRO	77B	NP B126 319	+Berge, Ganguli, Blokzijl+	(CERN, AMST, NIJM)
HOLMGREN	77	NP B119 261	+Aguilar-Benitez, Kluyver+	(CERN, AMST, NIJM)
BARDADIN-...	75	NP B98 418	Bardadin-Otwinowska+	(SACL, EPOL, RHEL)
COLAS	75	NP B91 253	+Farwell, Ferrer, Six	(ORSAY)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
BORENSTEIN	74	PR D9 3006	+Kalbfleisch, Strand+	(BNL, MICH)
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LICHTENBERG	74	PR D10 3865		(IND)
Also	74B	Private Comm.	Lichtenberg	(IND)
HABIBI	73	Thesis Nevis 199		(COLU)
Also	73	Purdue Conf. 387	Baltay, Bridgewater, Cooper+	(COLU, BING)
MAST	73	PR D7 3212	+Bangerter, Alston-Garnjost+	(LBL) IJP
Also	73B	PR D7 5	Mast, Bangerter, Alston-Garnjost+	(LBL) IJP
THOMAS	73	NP B56 15	+Engler, Fisk, Kraemer	(CMU) JP
AGUILAR-...	72B	PR D6 29	Aguilar-Benitez, Chung, Eisner, Samios	(BNL)
MEISNER	72	NC 12A 62		(UNC, LBL)
COLLEY	71B	NP B31 61	+Cox, Eastwood, Fry+	(BIRM, EDIN, GLAS, LOIC)
AGUILAR-...	70B	PRL 25 58	Aguilar-Benitez, Barnes, Bassano+	(BNL, SYRA)
PAN	69	PRL 23 808	+Forman	(PENN) I
SIEGEL	67	Thesis UCRL 18041		(LRL)
BIRMINGHAM	66	PR 152 1148		(BIRM, GLAS, LOIC, OXF, RHEL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) J
ARMENTEROS	65B	PL 19 75	+	(CERN, HEID, SACL)
SMITH	65	Thesis UCLA		(UCLA)
COOPER	64	PL 8 365	+Filthuth, Fridman, Malamud+	(CERN, AMST)
HUWE	64	Thesis UCRL 11291		(LRL) JP
Also	69	PR 180 1824	Huwe	(LRL)
CURTIS	63	PR 132 1771	+Coffin, Meyer, Terwilliger	(MICH) J
ALSTON	62	CERN Conf. 311	+Alvarez, Ferro-Luzzi+	(LRL)
BASTIEN	61	PRL 6 702	+Ferro-Luzzi, Rosenfeld	(LRL)
DAHL	61	PRL 6 142	+Horwitz, Miller, Murray, White	(LRL)
ELY	61	PRL 7 461	+Fung, Gidal, Pan, Powell, White	(LRL) J
ALSTON	60	PRL 5 520	+Alvarez, Eberhard, Good, Graziano+	(LRL) I

$\Sigma(1480)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

These are peaks seen in $\Lambda\pi$ and $\Sigma\pi$ spectra in the reaction $\pi^+ p \to (Y\pi)K^+$ at 1.7 GeV/c. Also, the Y polarization oscillates in the same region.

MILLER 70 suggests a possible alternate explanation in terms of a reflection of $N(1675) \to \Lambda K$ decay. However, such an explanation for the $(\Sigma^+\pi^0)K^+$ channel in terms of $\Delta(1650) \to \Sigma K$ decay seems unlikely (see PAN 70). In addition such reflections would also have to account for the oscillation of the Y polarization in the 1480 MeV region.

HANSON 71, with less data than PAN 70, can neither confirm nor deny the existence of this state. MAST 75 sees no structure in this region in $K^- p \to \Lambda\pi^0$.

ENGELEN 80 performs a multichannel analysis of $K^- p \to p\overline{K}^0\pi^-$ at 4.2 GeV/c. They observe a 3.5 standard-deviation signal at 1480 MeV in $p\overline{K}^0$ which cannot be explained as a reflection of any competing channel.

$\Sigma(1480)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1480 OUR ESTIMATE						
1480	120	ENGELEN	80	HBC	+	$K^- p \to (p\overline{K}^0)\pi^-$
1485±10		CLINE	73	MPWA	−	$K^- d \to (\Lambda\pi^-)p$
1479±10		PAN	70	HBC	+	$\pi^+ p \to (\Lambda\pi^+)K^+$
1465±15		PAN	70	HBC	+	$\pi^+ p \to (\Sigma\pi)K^+$

$\Sigma(1480)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
80±20	120	ENGELEN	80	HBC	+	$K^- p \to (p\overline{K}^0)\pi^-$
40±20		CLINE	73	MPWA	−	$K^- d \to (\Lambda\pi^-)p$
31±15		PAN	70	HBC	+	$\pi^+ p \to (\Lambda\pi^+)K^+$
30±20		PAN	70	HBC	+	$\pi^+ p \to (\Sigma\pi)K^+$

$\Sigma(1480)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1480)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	CHG
0.82±0.51	PAN	70	HBC	+

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ — Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG
0.72±0.50	PAN	70	HBC	+

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
small	CLINE	73	MPWA	$K^- d \to (\Lambda\pi^-)p$

$\Sigma(1480)$ REFERENCES (PRODUCTION EXPERIMENTS)

ENGELEN	80	NP B167 61	+Jongejans, Dionisi+	(NIJM, AMST, CERN, OXF)
MAST	75	PR D11 3078	+Alston-Garnjost, Bangerter+	(LBL)
CLINE	73	LNC 6 205	+Laumann, Mapp	(WISC) IJP
HANSON	71	PR D4 1296	+Kalmus, Louie	(LBL) I
MILLER	70	Duke Conf. 229		(PURD)
PAN	70	PR D2 49	+Forman, Ko, Hagopian, Selove	(PENN)
Also	69	PRL 23 808	Pan, Forman	(PENN) I
Also	69B	PRL 23 806	Pan, Forman	(PENN) I

$\Sigma(1560)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

This entry lists peaks reported in mass spectra around 1560 MeV without implying that they are necessarily related.

DIONISI 78B observes a 6 standard-deviation enhancement at 1553 MeV in the charged $\Lambda/\Sigma\pi$ mass spectra from $K^- p \to (\Lambda/\Sigma)\pi K\overline{K}$ at 4.2 GeV/c. In a CERN ISR experiment, LOCKMAN 78 reports a narrow 6 standard-deviation enhancement at 1572 MeV in $\Lambda\pi^\pm$ from the reaction $pp \to \Lambda\pi^+\pi^- X$. These enhancements are unlikely to be associated with the $\Sigma(1580)$ (which has not been confirmed by several recent experiments – see the next entry in the Listings).

CARROLL 76 observes a bump at 1550 MeV (as well as one at 1580 MeV) in the isospin-1 $\overline{K}N$ total cross section, but uncertainties in cross section measurements outside the mass range of the experiment preclude estimating its significance.

See also MEADOWS 80 for a review of this state.

$\Sigma(1560)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1560 OUR ESTIMATE						
1553±7	121	DIONISI	78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$
1572±4	40	LOCKMAN	78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

$\Sigma(1560)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
79±30	121	DIONISI	78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$
15± 6	40	[1] LOCKMAN	78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

$\Sigma(1560)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\pi$	seen
Γ_2	$\Sigma\pi$	

$\Sigma(1560)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Sigma\pi)/[\Gamma(\Lambda\pi)+\Gamma(\Sigma\pi)]$ — $\Gamma_2/(\Gamma_1+\Gamma_2)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.35±0.12	DIONISI	78B	HBC	±	$K^- p \to (Y\pi)K\overline{K}$

$\Gamma(\Lambda\pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	LOCKMAN	78	SPEC	±	$pp \to \Lambda\pi^+\pi^- X$

$\Sigma(1560)$ FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] The width observed by LOCKMAN 78 is consistent with experimental resolution.

$\Sigma(1560)$ REFERENCES (PRODUCTION EXPERIMENTS)

MEADOWS	80	Toronto Conf. 283		(CINC)
DIONISI	78B	PL 78B 154	+Armenteros, Diaz	(CERN, AMST, NIJM, OXF) I
LOCKMAN	78	Saclay DPHPE 78-01	+Meyer, Rander, Poster, Schlein+	(UCLA, SACL)
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I

$\Sigma(1580)$ D_{13}

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Seen in the isospin-1 $\overline{K}N$ cross section at BNL (LI 73, CARROLL 76) and in a partial-wave analysis of $K^- p \to \Lambda\pi^0$ for c.m. energies 1560–1600 MeV by LITCHFIELD 74. LITCHFIELD 74 finds $J^P = 3/2^-$. Not seen by ENGLER 78 or by CAMERON 78C (with larger statistics in $K^0_L p \to \Lambda\pi^+$ and $\Sigma^0\pi^+$).

$\Sigma(1580)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1580 OUR ESTIMATE				
1583±4	[1] CARROLL	76	DPWA	Isospin-1 total σ
1582±4	[2] LITCHFIELD	74	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1580)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
15	[1] CARROLL	76	DPWA	Isospin-1 total σ
11±4	[2] LITCHFIELD	74	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1580)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1580)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03±0.01	[2] LITCHFIELD	74	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1580) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	CAMERON	78C	HBC	$K^0_L p \to \Lambda\pi^+$
not seen	ENGLER	78	HBC	$K^0_L p \to \Lambda\pi^+$
+0.10±0.02	[2] LITCHFIELD	74	DPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1580) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	CAMERON	78C	HBC	$K^0_L p \to \Sigma^0\pi^+$
not seen	ENGLER	78	HBC	$K^0_L p \to \Sigma^0\pi^+$
+0.03±0.04	[2] LITCHFIELD	74	DPWA	$\overline{K}N$ multichannel

$\Sigma(1580)$ FOOTNOTES

[1] CARROLL 76 sees a total-cross-section bump with $(J+1/2)\ \Gamma_{el} / \Gamma_{total} = 0.06$.
[2] The main effect observed by LITCHFIELD 74 is in the $\Lambda\pi$ final state; the $\overline{K}N$ and $\Sigma\pi$ couplings are estimated from a multichannel fit including total-cross-section data of LI 73.

Σ(1580) REFERENCES

CAMERON	78C	NP B132 189	+Capiluppi+	(BGNA, EDIN, GLAS, PISA, RHEL) I
ENGLER	78	PR D18 3061	+Keyes, Kraemer, Tanaka, Cho+	(CMU, ANL)
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
LITCHFIELD	74	PL 51B 509		(CERN) IJP
LI	73	Purdue Conf. 283		(BNL) I

$\Sigma(1620)$ S_{11}

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

The S_{11} state at 1697 MeV reported by VANHORN 75 is tentatively listed under the $\Sigma(1750)$. CARROLL 76 sees two bumps in the isospin-1 total cross section near this mass.

Production experiments are listed separately in the next entry.

Σ(1620) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1620 OUR ESTIMATE				
1600± 6	[1] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
1608± 5	[2] CARROLL	76	DPWA	Isospin-1 total σ
1633±10	[3] CARROLL	76	DPWA	Isospin-1 total σ
1630±10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
1620	KIM	71	DPWA	K-matrix analysis

Σ(1620) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
87±19	[1] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
15	[2] CARROLL	76	DPWA	Isospin-1 total σ
10	[3] CARROLL	76	DPWA	Isospin-1 total σ
65±20	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
40	KIM	71	DPWA	K-matrix analysis

Σ(1620) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

Σ(1620) BRANCHING RATIOS

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.22±0.02	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
0.05	KIM	71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1620) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.12±0.02	[1] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
not seen	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
0.15	KIM	71	DPWA	K-matrix analysis

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1620) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
not seen	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
0.40±0.06	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel
0.08	KIM	71	DPWA	K-matrix analysis

Σ(1620) FOOTNOTES

[1] MORRIS 78 obtains an equally good fit without including this resonance.
[2] Total cross-section bump with $(J+1/2)$ Γ_{el} / Γ_{total} is 0.06 seen by CARROLL 76.
[3] Total cross-section bump with $(J+1/2)$ Γ_{el} / Γ_{total} is 0.04 seen by CARROLL 76.

Σ(1620) REFERENCES

MORRIS	78	PR D17 55	+Albright, Colleraine, Kimel, Lannutti	(FSU) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEIDH, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
KIM	71	PRL 27 356		(HARV) IJP
Also	70	Duke Conf. 161	Kim	(HARV) IJP

$\Sigma(1620)$ Production Experiments

$I(J^P) = 1(?^?)$

OMITTED FROM SUMMARY TABLE

Formation experiments are listed separately in the previous entry.

The results of CRENNELL 69B at 3.9 GeV/c are not confirmed by SABRE 70 at 3.0 GeV/c. However, at 4.5 GeV/c, AMMANN 70 sees a peak at 1642 MeV which on the basis of branching ratios they do not associate with the $\Sigma(1670)$. See MILLER 70 for a review of these conflicts.

Σ(1620) MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1620 OUR ESTIMATE						
1642±12		AMMANN	70	DBC		$K^- N$ 4.5 GeV/c
1618± 3	20	BLUMENFELD	69	HBC	+	$K^0_L p$
1619± 8		CRENNELL	69B	DBC	±	$K^- N \to \Lambda\pi\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1616± 8		CRENNELL	68	DBC	±	See CRENNELL 69B

Σ(1620) WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
55±24		AMMANN	70	DBC		$K^- N$ 4.5 GeV/c
30±10	20	BLUMENFELD	69	HBC	+	
72^{+22}_{-15}		CRENNELL	69B	DBC	±	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
66±16		CRENNELL	68	DBC	±	See CRENNELL 69B

Σ(1620) DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda\pi\pi$
Γ_5	$\Sigma(1385)\pi$
Γ_6	$\Lambda(1405)\pi$

Σ(1620) BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Lambda\pi\pi)/\Gamma(\Lambda\pi)$ Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	CHG
~ 2.5	14	BLUMENFELD	69	HBC	+

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.4±0.4	AMMANN	70	DBC		$K^- p$ 4.5 GeV/c
0.0±0.1	CRENNELL	68	DBC	+	See CRENNELL 69B

$\Gamma(\Lambda\pi)/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG
large	CRENNELL	68	DBC	±

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi)$ Γ_5/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.3	95	AMMANN	70	DBC		$K^- p$ 4.5 GeV/c
0.2±0.1		CRENNELL	68	DBC	±	

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1	95	AMMANN	70	DBC	$K^- N$ 4.5 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Lambda\pi)$ Γ_6/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.7±0.4	AMMANN	70	DBC	$K^- p$ 4.5 GeV/c

$\Sigma(1620)$ REFERENCES (PRODUCTION EXPERIMENTS)

AMMANN	70	PRL 24 327	+Garfinkel, Carmony, Gutay+	(PURD, IND)
Also	73	PR D7 1345	Ammann, Carmony, Garfinkel+	(PURD, IUPU)
MILLER	70	Duke Conf. 229		(PURD)
SABRE	70	NP B16 201	Barloutaud, Merril, Schever+	(SABRE Collab.)
BLUMENFELD	69	PL 29B 58	+Kalbfleisch	(BNL) I
CRENNELL	69B	Lund Paper 183	+Karshon, Lai, O'Neil, Scarr+	(BNL, CUNY) I
Results are quoted in LEVI-SETTI 69C.				
Also	69C	Lund Conf.	Levi-Setti	(EFI)
CRENNELL	68	PRL 21 648	+Delaney, Flaminio, Karshon+	(BNL, CUNY) I

$\Sigma(1660)\ P_{11}$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

$\Sigma(1660)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1630 to 1690 (≈ 1660) OUR ESTIMATE				
1665.1±11.2	[1] KOISO	85	DPWA	$K^- p \to \Sigma\pi$
1670 ±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1679 ±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1676 ±15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1668 ±25	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1670 ±20	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1565 or 1597	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1660 ±30	[3] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1671 ± 2	[4] PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1660)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40 to 200 (≈ 100) OUR ESTIMATE				
81.5± 22.2	[1] KOISO	85	DPWA	$K^- p \to \Sigma\pi$
152 ± 20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
38 ± 10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
120 ± 20	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$230\ ^{+165}_{-\ 60}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
250 ±110	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
202 or 217	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
80 ± 40	[3] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
81 ± 10	[4] PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1660)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	10–30 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen

$\Sigma(1660)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.3 OUR ESTIMATE				
0.12±0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.10±0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.04	GOPAL	77	DPWA	See GOPAL 80
0.27 or 0.29	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1660) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$0.12^{+0.12}_{-0.04}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.10 or −0.11	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.04±0.02	[3] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.16±0.01	[4] PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1660) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.13±0.04	[1] KOISO	85	DPWA	$K^- p \to \Sigma\pi$
−0.16±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.11±0.01	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.34 or −0.37	[2] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$

$\Sigma(1660)$ FOOTNOTES

[1] The evidence of KOISO 85 is weak.
[2] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[3] From solution 1 of BAILLON 75; not present in solution 2.
[4] From solution 2 of PONTE 75; not present in solution 1.

$\Sigma(1660)$ REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEIDH, MPIM) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
PONTE	75	PR D12 2597	+Hertzbach, Button-Shafer+	(MASA, TENN, UCR) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
KANE	74	LBL-2452		(LBL) IJP

THE $\Sigma(1670)$ REGION

Production experiments: The measured $\Sigma\pi/\Sigma\pi\pi$ branching ratio for the $\Sigma(1670)$ produced in the reaction $K^- p \to \pi^-\Sigma(1670)^+$ is strongly dependent on momentum transfer. This was first discovered by EBERHARD 69, who suggested that there exist two Σ resonances with the same mass and quantum numbers: one with a large $\Sigma\pi\pi$ (mainly $\Lambda(1405)\pi$) branching fraction produced peripherally, and the other with a large $\Sigma\pi$ branching fraction produced at larger angles. The experimental results have been confirmed by AGUILAR-BENITEZ 70, ASPELL 74, ESTES 74, and TIMMERMANS 76. If, in fact, there are two resonances, the most likely quantum numbers for both the $\Sigma\pi$ and the $\Lambda(1405)\pi$ states are D_{13}. There is also possibly a third Σ in this region, the $\Sigma(1690)$ in the Listings, the main evidence for which is a large $\Lambda\pi/\Sigma\pi$ branching ratio. These topics have been reviewed by EBERHARD 73 and by MILLER 70.

Formation experiments: Two states are also observed near this mass in formation experiments. One of these, the $\Sigma(1670)D_{13}$, has the same quantum numbers as those observed in production and has a large $\Sigma\pi/\Sigma\pi\pi$ branching ratio; it may well be the $\Sigma(1670)$ produced at larger angles (see TIMMERMANS 76). The other state, the $\Sigma(1660)P_{11}$, has different quantum numbers, its $\Sigma\pi/\Sigma\pi\pi$ branching ratio is unknown, and its relation to the produced $\Sigma(1670)$ states is obscure.

$\Sigma(1670)$ D_{13}

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗∗∗

For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

Results from production experiments are listed separately in the next entry.

$\Sigma(1670)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1665 to 1685 (≈ 1670) OUR ESTIMATE				
1665.1 ± 4.1	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
1682 ± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1679 ± 10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1670 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1670 ± 6	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
1685 ± 20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$1659\ ^{+12}_{-5}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1670 ± 2	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1667 or 1668	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1650	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
1671 ± 3	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
1655 ± 2	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

$\Sigma(1670)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
40 to 80 (≈ 60) OUR ESTIMATE				
65.0 ± 7.3	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
79 ± 10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
56 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
50 ± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
56 ± 3	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
85 ± 25	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
32 ± 11	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
79 ± 6	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
46 or 46	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
80	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
44 ± 11	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
76 ± 5	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

$\Sigma(1670)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	7–13 %
Γ_2	$\Lambda\pi$	5–15 %
Γ_3	$\Sigma\pi$	30–60 %
Γ_4	$\Lambda\pi\pi$	
Γ_5	$\Sigma\pi\pi$	
Γ_6	$\Sigma(1385)\pi$	
Γ_7	$\Sigma(1385)\pi$, S-wave	
Γ_8	$\Lambda(1405)\pi$	
Γ_9	$\Lambda(1520)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1670)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.07 to 0.13 OUR ESTIMATE				
0.10 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.11 ± 0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.08 ± 0.03	GOPAL	77	DPWA	See GOPAL 80
0.07 or 0.07	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.17 ± 0.03	[2] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
0.13 ± 0.02	[2] MORRIS	78	DPWA	$K^- n \to \Lambda\pi^-$
+0.10 ± 0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.06 ± 0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.09 ± 0.02	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
+0.018 ± 0.060	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.08 or +0.08	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
+0.05	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
0.08 ± 0.01	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 1)
0.17 ± 0.01	PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$ (sol. 2)

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.20 ± 0.02	KOISO	85	DPWA	$K^- p \to \Sigma\pi$
+0.21 ± 0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.20 ± 0.01	HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
+0.21 ± 0.03	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.18 or +0.17	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Gamma(\Lambda\pi\pi)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.11	ARMENTEROS	68E	HBC	$K^- p$ (Γ_1=0.09)

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Sigma(1385)\pi$, S-wave — $(\Gamma_1\Gamma_7)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.11 ± 0.03	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.17 ± 0.02	[3] SIMS	68	DBC	$K^- N \to \Lambda\pi\pi$

$\Gamma(\Sigma\pi\pi)/\Gamma_{total}$ — Γ_5/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.14	[4] ARMENTEROS	68E	HBC	$K^- p$, $K^- d$ (Γ_1=0.09)

$\Gamma(\Lambda(1405)\pi)/\Gamma_{total}$ — Γ_8/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.06	ARMENTEROS	68E	HBC	$K^- p$, $K^- d$ (Γ_1=0.09)

$\Gamma_i\Gamma_f/\Gamma^2_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda(1405)\pi$ — $\Gamma_1\Gamma_8/\Gamma^2$

VALUE	DOCUMENT ID		TECN	COMMENT
0.007 ± 0.002	[5] BRUCKER	70	DBC	$K^- N \to \Sigma\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.03	BERLEY	69	HBC	$K^- p$ 0.6–0.82 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma(1385)\pi)$ — Γ_8/Γ_6

VALUE	DOCUMENT ID		TECN	COMMENT
0.23 ± 0.08	BRUCKER	70	DBC	$K^- N \to \Sigma\pi\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1670) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_9)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.081 ± 0.016	[6] CAMERON	77	DPWA	P-wave decay

$\Sigma(1670)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] Results are with and without an S_{11} $\Sigma(1620)$ in the fit.
[3] SIMS 68 uses only cross-section data. Result used as upper limit only.
[4] Ratio only for $\Sigma 2\pi$ system in $I = 1$, which cannot be $\Sigma(1385)$.
[5] Assuming the $\Lambda(1405)\pi$ cross-section bump is due only to $3/2^-$ resonance.
[6] The CAMERON 77 upper limit on F-wave decay is 0.03.

$\Sigma(1670)$ REFERENCES

KOISO	85	NP A433 619	+Sai, Yamamoto, Kofler	(TOKY, MASA)	
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)	
GOPAL	80	Toronto Conf. 159		(RHEL)	IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN)	IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN)	IJP
MORRIS	78	PR D17 55	+Albright, Colleraine, Kimel, Lannutti	(FSU)	IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC)	IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL)	IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS)	IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)	
Also	77C	NP B126 285	Martin, Pidcock	(LOUC)	IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF)	IJP
HEPP	76B	PL 65B 487	+Braun, Grimm, Strobele+	(CERN, HEIDH, MPIM)	IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL)	IJP
PONTE	75	PR D12 2597	+Hertzbach, Button-Shafer+	(MASA, TENN, UCR)	IJP
VANHORN	75	NP B87 145		(LBL)	IJP
Also	75B	NP B87 157	VanHorn	(LBL)	IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)	
KANE	74	LBL-2452		(LBL)	IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)	
BRUCKER	70	Duke Conf. 155	+Harrison, Sims, Albright, Chandler+	(FSU)	I
BERLEY	69	PL 30B 430	+Hart, Rahm, Willis, Yamamoto	(BNL)	
ARMENTEROS	68E	PL 28B 521	+Baillon+	(CERN, HEID, SACL)	I
SIMS	68	PRL 21 1413	+Albright, Bartley, Meer+	(FSU, TUFTS, BRAN)	

Σ(1670) Bumps

$I(J^P) = 1(?^?)$

OMITTED FROM SUMMARY TABLE

Formation experiments are listed separately in the preceding entry.

Probably there are two states at the same mass with the same quantum numbers, one decaying to $\Sigma\pi$ and $\Lambda\pi$, the other to $\Lambda(1405)\pi$. See the note in front of the preceding entry.

Σ(1670) MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1670 OUR ESTIMATE						
1670± 4		[1] CARROLL	76	DPWA		Isospin-1 total σ
1675±10		[2] HEPP	76	DBC	−	$K^- N$ 1.6–1.75 GeV/c
1665± 1		APSELL	74	HBC		$K^- p$ 2.87 GeV/c
1688± 2 or 1683 ± 5	1200	BERTHON	74	HBC	0	Quasi-2-body σ
1670± 6		AGUILAR-...	70B	HBC		$K^- p \rightarrow \Sigma\pi\pi$ 4 GeV
1668±10		AGUILAR-...	70B	HBC		$K^- p \rightarrow \Sigma 3\pi$ 4 GeV
1660±10		ALVAREZ	63	HBC	+	$K^- p$ 1.51 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1668±10	150	[3] FERRERSORIA	81	OMEG	−	$\pi^- p$ 9,12 GeV/c
1655 to 1677		TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
1665± 5		BUGG	68	CNTR		$K^- p$, d total σ
1661± 9	70	PRIMER	68	HBC	+	See BARNES 69E
1685		ALEXANDER	62C	HBC	−0	$\pi^- p$ 2–2.2 GeV/c

Σ(1670) WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
67.0± 2.4		APSELL	74	HBC		$K^- p$ 2.87 GeV/c
110 ±12		AGUILAR-...	70B	HBC		$K^- p \rightarrow \Sigma\pi\pi$ 4 GeV
$135\ ^{+40}_{-30}$		AGUILAR-...	70B	HBC		$K^- p \rightarrow \Sigma 3\pi$ 4 GeV
40 ±10		ALVAREZ	63	HBC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
90 ±20	150	[3] FERRERSORIA	81	OMEG	−	$\pi^- p$ 9,12 GeV/c
52		[1] CARROLL	76	DPWA		Isospin-1 total σ
48 to 63		TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
30 ±15		BUGG	68	CNTR		
60 ±20	70	PRIMER	68	HBC	+	See BARNES 69E
45		ALEXANDER	62C	HBC	−0	

Σ(1670) DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda\pi\pi$
Γ_5	$\Sigma\pi\pi$
Γ_6	$\Sigma(1385)\pi$
Γ_7	$\Lambda(1405)\pi$

Σ(1670) BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(N\overline{K})/\Gamma(\Sigma\pi)$ — Γ_1/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<0.03		TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
<0.10		BERTHON	74	HBC	0	Quasi-2-body σ
<0.2		AGUILAR-...	70B	HBC		
<0.26		BARNES	69E	HBC	+	$K^- p$ 3.9–5 GeV/c
0.025		BUGG	68	CNTR	0	Assuming $J = 3/2$
<0.24	0	PRIMER	68	HBC	+	$K^- p$ 4.6–5 GeV/c
<0.6		LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c
<0.19	0	ALVAREZ	63	HBC	+	$K^- p$ 1.15 GeV/c
≥ 0.5 ±0.25		SMITH	63	HBC	−0	

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi)$ — Γ_2/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.76±0.09		ESTES	74	HBC	0	$K^- p$ 2.1,2.6 GeV/c
0.45±0.15		BARNES	69E	HBC	+	$K^- p$ 3.9–5 GeV/c
0.15±0.07		HUWE	69	HBC	+	
0.11±0.06	33	BUTTON-...	68	HBC	+	$K^- p$ 1.7 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
≤ 0.45±0.07		TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
0.55±0.11		BERTHON	74	HBC	0	Quasi-2-body σ
0	0	PRIMER	68	HBC	+	See BARNES 69E
<0.6		LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c
1.2	130	ALVAREZ	63	HBC	+	$K^- p$ 1.15 GeV/c
1.2		SMITH	63	HBC	−0	

$\Gamma(\Lambda\pi\pi)/\Gamma(\Sigma\pi)$ — Γ_4/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<0.6		LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c
0.56	90	ALVAREZ	63	HBC	+	$K^- p$ 1.15 GeV/c
0.17		SMITH	63	HBC	−0	

$\Gamma(\Sigma\pi\pi)/\Gamma(\Sigma\pi)$ — Γ_5/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
largest at small angles		ESTES	74	HBC	0	$K^- p$ 2.1,2.6 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.2		[2] HEPP	76	DBC	−	$K^- N$ 1.6–1.75 GeV/c
0.56	180	ALVAREZ	63	HBC	+	$K^- p$ 1.15 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma\pi)$ — Γ_7/Γ_3

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.8 ±0.3 to 0.02 ± 0.07		[3,4] TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
largest at small angles		ESTES	74	HBC	±	$K^- p$ 2.1,2.6 GeV/c
3.0 ±1.6	50	LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.58±0.20	17	PRIMER	68	HBC	+	See BARNES 69E

$\Gamma(\Sigma\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_3/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
varies with prod. angle	[5] APSELL	74	HBC	+	$K^- p$ 2.87 GeV/c
1.39±0.16	BERTHON	74	HBC	0	Quasi-2-body σ
2.5 to 0.24	[4] EBERHARD	69	HBC		$K^- p$ 2.6 GeV/c
<0.4	BIRMINGHAM	66	HBC	+	$K^- p$ 3.5 GeV/c
0.30±0.15	LONDON	66	HBC	+	$K^- p$ 2.25 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_7/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.97±0.08	TIMMERMANS	76	HBC		$K^- p$ 4.2 GeV/c
1.00±0.02	APSELL	74	HBC		$K^- p$ 2.87 GeV/c
$0.90^{+0.10}_{-0.16}$	EBERHARD	65	HBC	+	$K^- p$ 2.45 GeV/c

$\Gamma(\Lambda(1405)\pi)/\Gamma(\Sigma(1385)\pi)$ — Γ_7/Γ_6

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.8	EBERHARD	65	HBC	+	$K^- p$ 2.45 GeV/c

$\Gamma(\Lambda\pi\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_4/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.35±0.2	BIRMINGHAM	66	HBC	+	$K^- p$ 3.5 GeV/c

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi\pi)$ — Γ_2/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.2	BIRMINGHAM	66	HBC	+	$K^- p$ 3.5 GeV/c

$\Gamma(\Lambda\pi)/[\Gamma(\Lambda\pi)+\Gamma(\Sigma\pi)]$ — $\Gamma_2/(\Gamma_2+\Gamma_3)$

VALUE	DOCUMENT ID		TECN
<0.6	AGUILAR-...	70B	HBC

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Sigma\pi)$ — Γ_6/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
≤ 0.21±0.05	TIMMERMANS	76	HBC	$K^- p$ 4.2 GeV/c

Σ(1670) QUANTUM NUMBERS (PRODUCTION EXPERIMENTS)

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$J^P = 3/2^-$	400	BUTTON-...	68	HBC	±	$\Sigma^0\pi$
$J^P = 3/2^-$		EBERHARD	67	HBC	+	$\Lambda(1405)\pi$
$J^P = 3/2^+$		LEVEQUE	65	HBC		$\Lambda(1405)\pi$

$\Sigma(1670)$ FOOTNOTES

[1] Total cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total} = 0.23$.
[2] Enhancements in $\Sigma\pi$ and $\Sigma\pi\pi$ cross sections.
[3] Backward production in the $\Lambda\pi^- K^+$ final state.
[4] Depending on production angle.
[5] APSELL 74, ESTES 74, and TIMMERMANS 76 find strong branching ratio dependence on production angle, as in earlier production experiments.

$\Sigma(1670)$ REFERENCES (PRODUCTION EXPERIMENTS)

FERRERSORIA	81	NP B178 373	+Treille, Rivet, Volte+	(CERN, CDEF, EPOL, LALO)
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
HEPP	76	NP B115 82	+Braun, Grimm, Stroebele+	(CERN, HEID, MPIM) I
TIMMERMANS	76	NP B112 77	+Engelen+	(NIJM, CERN, AMST, OXF) JP
APSELL	74	PR D10 1419	+Ford, Gourevitch+	(BRAN, UMD, SYRA, TUFTS) I
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
ESTES	74	Thesis LBL-3827		(LBL)
AGUILAR-...	70B	PRL 25 58	Aguilar-Benitez, Barnes, Bassano+	(BNL, SYRA)
BARNES	69E	BNL 13823	+Chung, Eisner, Flaminio+	(BNL, SYRA)
EBERHARD	69	PRL 22 200	+Friedman, Pripstein, Ross	(LRL)
HUWE	69	PR 180 1824		(LRL)
BUGG	68	PR 168 1466	+Gilmore, Knight+	(RHEL, BIRM, CAVE) I
BUTTON-...	68	PRL 21 1123	Button-Shafer	(MASA, LRL) JP
PRIMER	68	PRL 20 610	+Goldberg, Jaeger, Barnes, Dornan+	(SYRA, BNL)
EBERHARD	67	PR 163 1446	+Pripstein, Shively, Kruse, Swanson	(LRL, ILL) IJP
BIRMINGHAM	66	PR 152 1148		(BIRM, GLAS, LOIC, OXF, RHEL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) IJ
EBERHARD	65	PRL 14 466	+Shively, Ross, Siegal, Ficenec+	(LRL, ILL) I
LEVEQUE	65	PL 18 69	+	(SACL, EPOL, GLAS, LOIC, OXF, RHEL) JP
ALVAREZ	63	PRL 10 184	+Alston, Ferro-Luzzi, Huwe+	(LRL) I
SMITH	63	Athens Conf. 67		(LRL)
ALEXANDER	62C	CERN Conf. 320	+Jacobs, Kalbfleisch, Miller+	(LRL) I

$\Sigma(1690)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

See the note preceding the $\Sigma(1670)$ Listings. Seen in production experiments only, mainly in $\Lambda\pi$.

$\Sigma(1690)$ MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 1690 OUR ESTIMATE						
1698±20	70	[1] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
1707±20	40	[2] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
1698±20	15	ADERHOLZ	69	HBC	+	$\pi^+ p$ 8 GeV/c
1682± 2	46	BLUMENFELD	69	HBC	+	$K^0_L p$
1700±20		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
1694±24	60	[3] PRIMER	68	HBC	+	$K^- p$ 4.6–5 GeV/c
1700± 6		[4] SIMS	68	HBC	−	$K^- N \to \Lambda\pi\pi$
1715±12	30	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

$\Sigma(1690)$ WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
240± 60	70	[1] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
130^{+100}_{-60}	40	[2] GODDARD	79	HBC	+	$\pi^+ p$ 10.3 GeV/c
142± 40	15	ADERHOLZ	69	HBC	+	$\pi^+ p$ 8 GeV/c
25± 10	46	BLUMENFELD	69	HBC	+	$K^0_L p$
130± 25		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
105± 35	60	[3] PRIMER	68	HBC	+	$K^- p$ 4.6–5 GeV/c
62± 14		[4] SIMS	68	HBC	−	$K^- N \to \Lambda\pi\pi$
100± 35	30	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

$\Sigma(1690)$ DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Sigma(1385)\pi$
Γ_5	$\Lambda\pi\pi$ (including $\Sigma(1385)\pi$)

$\Sigma(1690)$ BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(N\overline{K})/\Gamma(\Lambda\pi)$ Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
small		GODDARD	79	HBC	+	$\pi^+ p$ 10.2 GeV/c
<0.2		MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
0.4±0.25	18	COLLEY	67	HBC	+	6/30 events

$\Gamma(\Sigma\pi)/\Gamma(\Lambda\pi)$ Γ_3/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
small		GODDARD	79	HBC	+	$\pi^+ p$ 10.2 GeV/c
<0.4	90	MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c
0.3±0.3		COLLEY	67	HBC	+	4/30 events

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi)$ Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.5	MOTT	69	HBC	+	$K^- p$ 5.5 GeV/c

$\Gamma(\Lambda\pi\pi(\text{including } \Sigma(1385)\pi))/\Gamma(\Lambda\pi)$ Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
2.0±0.6	BLUMENFELD	69	HBC	+	31/15 events
0.5±0.25	COLLEY	67	HBC	+	15/30 events

$\Gamma(\Sigma(1385)\pi)/\Gamma(\Lambda\pi\pi(\text{including } \Sigma(1385)\pi))$ Γ_4/Γ_5

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
large	SIMS	68	HBC	−	$K^- N \to \Lambda\pi\pi$
small	COLLEY	67	HBC	+	$K^- p$ 6 GeV/c

$\Sigma(1690)$ FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] From $\pi^+ p \to (\Lambda\pi^+)K^+$. $J > 1/2$ is not required by the data.
[2] From $\pi^+ p \to (\Lambda\pi^+)(K\pi)^+$. $J > 1/2$ is indicated, but large background precludes a definite conclusion.
[3] See the $\Sigma(1670)$ Listings. AGUILAR-BENITEZ 70B with three times the data of PRIMER 68 find no evidence for the $\Sigma(1690)$.
[4] This analysis, which is difficult and requires several assumptions and shows no unambiguous $\Sigma(1690)$ signal, suggests $J^P = 5/2^+$. Such a state would lead all previously known Y^* trajectories.

$\Sigma(1690)$ REFERENCES (PRODUCTION EXPERIMENTS)

GODDARD	79	PR D19 1350	+Key, Luste, Prentice, Yoon, Gordon+	(TNTO, BNL) IJ
AGUILAR-...	70B	PRL 25 58	Aguilar-Benitez, Barnes, Bassano+	(BNL, SYRA)
ADERHOLZ	69	NP B11 259	+Bartsch+	(AACH3, BERL, CERN, JAGL, WARS) I
BLUMENFELD	69	PL 29B 58	+Kalbfleisch	(BNL) I
MOTT	69	PR 177 1966	+Ammar, Davis, Kropac, Slate+	(NWES, ANL) I
Also	67	PRL 18 266	Derrick, Fields, Loken, Ammar+	(ANL, NWES) I
PRIMER	68	PRL 20 610	+Goldberg, Jaeger, Barnes, Dornan+	(SYRA, BNL) I
SIMS	68	PRL 21 1413	+Albright, Bartley, Meer+	(FSU, TUFTS, BRAN) I
COLLEY	67	PL 24B 489		(BIRM, GLAS, LOIC, MUNI, OXF, RHEL) I

$\Sigma(1750)\ S_{11}$

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗∗∗

For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

There is evidence for this state in many partial-wave analyses, but with wide variations in the mass, width, and couplings. The latest analyses indicated significant couplings to $N\overline{K}$ and $\Lambda\pi$, as well as to $\Sigma\eta$ whose threshold is at 1746 MeV (JONES 74).

$\Sigma(1750)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1730 to 1800 (≈ 1750) OUR ESTIMATE				
1756±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1770±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1770±15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1800 or 1813	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1715±10	[2] CARROLL	76	DPWA	Isospin-1 total σ
1730	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
1780±30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
1700±30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
1697^{+20}_{-10}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1785±12	CHU	74	DBC	Fits $\sigma(K^- n \to \Sigma^-\eta)$
1760± 5	[3] JONES	74	HBC	Fits $\sigma(K^- p \to \Sigma^0\eta)$
1739±10	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$\Sigma(1750)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 160 (≈ 90) OUR ESTIMATE				
64±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
161±20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
60±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel

• • • We do not use the following data for averages, fits, limits, etc. • • •

117 or 119	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
10	[2] CARROLL	76	DPWA	Isospin-1 total σ
110	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
140 ± 30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
160 ± 50	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
66^{+14}_{-12}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
89 ± 33	CHU	74	DBC	Fits $\sigma(K^- n \to \Sigma^-\eta)$
$92\pm\ 7$	[3] JONES	74	HBC	Fits $\sigma(K^- p \to \Sigma^0\eta)$
108 ± 20	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$\Sigma(1750)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	10–40 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	<8 %
Γ_4	$\Sigma\eta$	15–55 %
Γ_5	$\Sigma(1385)\pi$	
Γ_6	$\Lambda(1520)\pi$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1750)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.1 to 0.4 OUR ESTIMATE				
0.14 ± 0.03	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.33 ± 0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15 ± 0.03	GOPAL	77	DPWA	See GOPAL 80
0.06 or 0.05	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$0.04\ \pm0.03$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.10 or -0.09	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
-0.12	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
$-0.12\ \pm0.02$	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
$-0.13\ \pm0.03$	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
$-0.13\ \pm0.04$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
-0.120 ± 0.077	DEVENISH	74B		Fixed-t dispersion rel.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.09 ± 0.05	GOPAL	77	DPWA	$\overline{K}N$ multichannel
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$+0.06$ or $+0.06$	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.13 ± 0.02	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Sigma\eta$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.23 ± 0.01	[3] JONES	74	HBC	Fits $\sigma(K^- p \to \Sigma^0\eta)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	CLINE	69	DBC	Threshold bump

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.18\pm0.15$	PREVOST	74	DPWA	$K^- N \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1750) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.032 ± 0.021	CAMERON	77	DPWA	P-wave decay

$\Sigma(1750)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] A total cross-section bump with $(J+1/2)\ \Gamma_{el}\ /\ \Gamma_{total} = 0.30$.

[3] An S-wave Breit-Wigner fit to the threshold cross section with no background and errors statistical only.

$\Sigma(1750)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
CHU	74	NC 20A 35	+Bartley+	(PLAT, TUFTS, BRAN) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
JONES	74	NP B73 141		(CHIC) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP
CLINE	69	LNC 2 407	+Laumann, Mapp	(WISC)

$\Sigma(1770)$ P_{11}

$I(J^P) = 1(\frac{1}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

Evidence for this state now rests solely on solution 1 of BAILLON 75, (see the footnotes) but the $\Lambda\pi$ partial-wave amplitudes of this solution are in disagreement with amplitudes from most other $\Lambda\pi$ analyses.

$\Sigma(1770)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1770 OUR ESTIMATE				
1738 ± 10	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel
1770 ± 20	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1772	[3] KANE	72	DPWA	$K^- p \to \Sigma\pi$

$\Sigma(1770)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
72 ± 10	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel
80 ± 30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
80	[3] KANE	72	DPWA	$K^- p \to \Sigma\pi$

$\Sigma(1770)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1770)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.14 ± 0.04	[1] GOPAL	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1770) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.08 ± 0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1770) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.108	[3] KANE	72	DPWA	$K^- p \to \Sigma\pi$

$\Sigma(1770)$ FOOTNOTES

[1] Required to fit the isospin-1 total cross section of CARROLL 76 in the $\overline{K}N$ channel. The addition of new $K^- p$ polarization and $K^- n$ differential cross-section data in GOPAL 80 find it to be more consistent with the $\Sigma(1660)$ P_{11}.

[2] From solution 1 of BAILLON 75; not present in solution 2.

[3] Not required in KANE 74, which supersedes KANE 72.

$\Sigma(1770)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL)
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
CARROLL	76	PRL 37 806	+Chiang, Kycia, Li, Mazur, Michael+	(BNL) I
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
KANE	74	LBL-2452		(LBL) IJP
KANE	72	PR D5 1583		(LBL)

$\Sigma(1775)\ D_{15}$

$I(J^P) = 1(\frac{5}{2}^-)$ Status: ∗∗∗∗

Discovered by GALTIERI 63, this resonance plays the same role as cornerstone for isospin-1 analyses in this region as the $\Lambda(1820)$ does in the isospin-0 channel.

For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

$\Sigma(1775)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1770 to 1780 (≈ 1775) OUR ESTIMATE				
1778± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1777± 5	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
1774± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1775±10	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1774±10	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
1772± 6	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1772 or 1777	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1765	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(1775)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
105 to 135 (≈ 120) OUR ESTIMATE				
137±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
116±10	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
130±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
125±15	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
146±18	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
154±10	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
102 or 103	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
120	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(1775)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	37–43%
Γ_2	$\Lambda\pi$	14–20%
Γ_3	$\Sigma\pi$	2–5%
Γ_4	$\Sigma(1385)\pi$	8–12%
Γ_5	$\Sigma(1385)\pi$, D-wave	
Γ_6	$\Lambda(1520)\pi$	17–23%
Γ_7	$\Sigma\pi\pi$	

The above branching fractions are our estimates, not fits or averages.

CONSTRAINED FIT INFORMATION

An overall fit to 8 branching ratios uses 16 measurements and one constraint to determine 5 parameters. The overall fit has a $\chi^2 =$ 63.9 for 12 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i \delta x_j\right\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−30			
x_3	−17	−21		
x_4	−37	−49	−14	
x_6	−81	6	8	16
	x_1	x_2	x_3	x_4

$\Sigma(1775)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances. Also, the errors quoted do not include uncertainties due to the parametrization used in the partial-wave analyses and are thus too small.

$\Gamma(N\overline{K})/\Gamma_{\rm total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.37 to 0.43 OUR ESTIMATE				
0.45 ±0.04 OUR FIT Error includes scale factor of 3.1.				
0.391±0.017 OUR AVERAGE				
0.40 ±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.37 ±0.03	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.41 ±0.03	GOPAL	77	DPWA	See GOPAL 80
0.37 or 0.36	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1775) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.305±0.018 OUR FIT Error includes scale factor of 2.4.				
−0.262±0.015 OUR AVERAGE				
−0.28 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.25 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.28\ ^{+0.04}_{-0.05}$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
−0.259±0.048	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.29 or −0.28	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.30	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1775) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.105±0.025 OUR FIT Error includes scale factor of 3.1.				
0.098±0.016 OUR AVERAGE Error includes scale factor of 1.8.				
+0.13 ±0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
0.09 ±0.01	KANE	74	DPWA	$K^-p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.08 or +0.08	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1775) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.315±0.010 OUR FIT Error includes scale factor of 1.5.				
0.303±0.009 OUR AVERAGE Signs on measurements were ignored.				
−0.305±0.010	[2] CAMERON	77	DPWA	$K^-p \to \Lambda(1520)\pi^0$
0.31 ±0.02	BARLETTA	72	DPWA	$K^-p \to \Lambda(1520)\pi^0$
0.27 ±0.03	ARMENTEROS	65C	HBC	$K^-p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{\rm total}$ in $N\overline{K} \to \Sigma(1775) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.211±0.022 OUR FIT Error includes scale factor of 2.8.				
0.188±0.010 OUR AVERAGE Signs on measurements were ignored.				
−0.184±0.011	[3] CAMERON	78	DPWA	$K^-p \to \Sigma(1385)\pi$
+0.20 ±0.02	PREVOST	74	DPWA	$K^-N \to \Sigma(1385)\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.32 ±0.06	SIMS	68	DBC	$K^-N \to \Lambda\pi\pi$
0.24 ±0.03	ARMENTEROS	67C	HBC	$K^-p \to \Lambda\pi\pi$

$\Gamma(\Lambda\pi)/\Gamma(N\overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.46±0.09 OUR FIT Error includes scale factor of 2.9.				
0.33±0.05	UHLIG	67	HBC	K^-p 0.9 GeV/c

$\Gamma(\Sigma\pi\pi)/\Gamma_{\rm total}$ — Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.12	[4] ARMENTEROS	68C	HDBC	$K^-N \to \Sigma\pi\pi$

$\Gamma(\Sigma(1385)\pi)/\Gamma(N\overline{K})$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.22±0.07 OUR FIT Error includes scale factor of 3.6.				
0.25±0.09	UHLIG	67	HBC	K^-p 0.9 GeV/c

$\Gamma(\Lambda(1520)\pi)/\Gamma(N\overline{K})$ — Γ_6/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
0.49±0.11 OUR FIT Error includes scale factor of 3.5.				
0.28±0.05	UHLIG	67	HBC	K^-p 0.9 GeV/c

$\Sigma(1775)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.

[2] This rate combines P-wave- and F-wave decays. The CAMERON 77 results for the separate P-wave- and F-wave decays are -0.303 ± 0.010 and -0.037 ± 0.014. The published signs have been changed here to be in accord with the baryon-first convention.

[3] The CAMERON 78 upper limit on G-wave decay is 0.03.

[4] For about 3/4 of this, the $\Sigma\pi$ system has $I = 0$ and is almost entirely $\Lambda(1520)$. For the rest, the $\Sigma\pi$ has $I = 1$, which is about what is expected from the known $\Sigma(1775) \to \Sigma(1385)\pi$ rate, as seen in $\Lambda\pi\pi$.

$\Sigma(1775)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP

DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
PREVOST	74	NP B69 246	+Barloutaud+	(SACL, CERN, HEID)
BARLETTA	72	NP B40 45		(EFI) IJP
Also	66	PRL 17 841	Fenster, Gelfand, Harmsen+	(CHIC, ANL, CERN) IJP
ARMENTEROS	68C	NP B8 216	+Baillon+	(CERN, HEID, SACL) I
SIMS	68	PRL 21 1413	+Albright, Bartley, Meer+	(FSU, TUFTS, BRAN)
ARMENTEROS	67C	ZPHY 202 486	+Ferro-Luzzi+	(CERN, HEID, SACL)
UHLIG	67	PR 155 1448	+Charlton, Condon, Glasser, Yodh+	(UMD, NRL)
ARMENTEROS	65C	PL 19 338	+Ferro-Luzzi+	(CERN, HEID, SACL) IJP
GALTIERI	63	PL 6 296	+Hussain, Tripp	(LRL) IJ

$\Sigma(1840)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: ∗

OMITTED FROM SUMMARY TABLE

For the time being, we list together here all resonance claims in the P_{13} wave between 1700 and 1900 MeV.

$\Sigma(1840)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1840 OUR ESTIMATE				
1798 or 1802	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1720± 30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1925±200	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
1840± 10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$\Sigma(1840)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
93 or 93	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
120±30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
65^{+50}_{-20}	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
120±10	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$\Sigma(1840)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(1840)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0 or 0	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.37±0.13	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1840) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.03 or +0.03	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
+0.11 ±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
+0.06 ±0.04	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
+0.122±0.078	DEVENISH	74B		Fixed-t dispersion rel.
0.20 ±0.04	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1840) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.04 or −0.04	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.15±0.04	LANGBEIN	72	IPWA	$\overline{K}N$ multichannel

$\Sigma(1840)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] From solution 1 of BAILLON 75; not present in solution 2.

$\Sigma(1840)$ REFERENCES

MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LANGBEIN	72	NP B47 477	+Wagner	(MPIM) IJP

$\Sigma(1880)$ P_{11}

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

A P_{11} resonance is suggested by several partial-wave analyses, but with wide variations in the mass and other parameters. We list here all claims which lie well above the P_{11} $\Sigma(1770)$.

$\Sigma(1880)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 1880 OUR ESTIMATE				
1826±20	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1870±10	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
1847 or 1863	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1960±30	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1985±50	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
1898	[3] LEA	73	DPWA	Multichannel K-matrix
∼ 1850	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
1950±50	BARBARO-...	70	DPWA	$K^-N \to \Lambda\pi$
1920±30	LITCHFIELD	70	DPWA	$K^-N \to \Lambda\pi$
1850	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
1882±40	SMART	68	DPWA	$K^-N \to \Lambda\pi$

$\Sigma(1880)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
86± 15	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
80± 10	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$
216 or 220	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
260± 40	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
220±140	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
222	[3] LEA	73	DPWA	Multichannel K-matrix
∼ 30	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
200± 50	BARBARO-...	70	DPWA	$K^-N \to \Lambda\pi$
170± 40	LITCHFIELD	70	DPWA	$K^-N \to \Lambda\pi$
200	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$
222±150	SMART	68	DPWA	$K^-N \to \Lambda\pi$

$\Sigma(1880)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$N\overline{K}^*(892)$, S=1/2, P-wave
Γ_5	$N\overline{K}^*(892)$, S=3/2, P-wave

$\Sigma(1880)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.06±0.02	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.27 or 0.27	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
0.31	[3] LEA	73	DPWA	Multichannel K-matrix
0.20	ARMENTEROS	70	IPWA	$\overline{K}N \to \overline{K}N$
0.22	BAILEY	69	DPWA	$\overline{K}N \to \overline{K}N$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1880) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.24 or −0.24	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
−0.12 ±0.02	[2] BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.05\ ^{+0.07}_{-0.02}$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
−0.169±0.119	DEVENISH	74B		Fixed-t dispersion rel.
−0.30	[3] LEA	73	DPWA	Multichannel K-matrix
−0.09 ±0.04	BARBARO-...	70	DPWA	$K^-N \to \Lambda\pi$
−0.14 ±0.03	LITCHFIELD	70	DPWA	$K^-N \to \Lambda\pi$
−0.11 ±0.03	SMART	68	DPWA	$K^-N \to \Lambda\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1880) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.30 or +0.29	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	[3] LEA	73	DPWA	Multichannel K-matrix

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1880) \to N\overline{K}^*(892)$, S=1/2, P-wave — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.05±0.03	[4] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1880) \to N\overline{K}^*(892)$, S=3/2, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.11\pm0.03$	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Sigma(1880)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] From solution 1 of BAILLON 75; not present in solution 2.
[3] Only unconstrained states from table 1 of LEA 73 are listed.
[4] The published sign has been changed to be in accord with the baryon-first convention.

$\Sigma(1880)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
LEA	73	NP B56 77	+Martin, Moorhouse+	(RHEL, LOUC, GLAS, AARH) IJP
ARMENTEROS	70	Duke Conf. 123	+Baillon+	(CERN, HEID, SACL) IJP
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
LITCHFIELD	70	NP B22 269		(RHEL) IJP
BAILEY	69	Thesis UCRL 50617		(LLL) IJP
SMART	68	PR 169 1330		(LRL) IJP

$\Sigma(1915)$ F_{15}

$I(J^P) = 1(\frac{5}{2}^+)$ Status: ∗∗∗∗

Discovered by COOL 66. For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and invariant-mass distributions in this region used to be listed in in a separate entry immediately following. They may be found in our 1986 edition Physics Letters **170B** (1986).

$\Sigma(1915)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900 to 1935 (≈ 1915) OUR ESTIMATE				
1937 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
$1894\pm\ 5$	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
$1909\pm\ 5$	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
1920 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$1900\pm\ 4$	[2] CORDEN	76	DPWA	$K^- n \to \Lambda\pi^-$
1920 ± 30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1914 ± 10	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
1920^{+15}_{-20}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
$1920\pm\ 5$	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
not seen	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
1925 or 1933	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1915	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1915)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80 to 160 (≈ 120) OUR ESTIMATE				
161 ± 20	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
107 ± 14	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
85 ± 13	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
130 ± 10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
75 ± 14	[2] CORDEN	76	DPWA	$K^- n \to \Lambda\pi^-$
70 ± 20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
85 ± 15	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
102 ± 18	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
162 ± 25	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
171 or 173	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel
60	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(1915)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	5–15 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$\Sigma(1385)\pi$	<5 %
Γ_5	$\Sigma(1385)\pi$, P-wave	
Γ_6	$\Sigma(1385)\pi$, F-wave	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(1915)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.05 to 0.15 OUR ESTIMATE				
0.03 ± 0.02	[4] GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.14 ± 0.05	ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
0.11 ± 0.04	HEMINGWAY	75	DPWA	$K^- p \to \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.05 ± 0.03	GOPAL	77	DPWA	See GOPAL 80
0.08 or 0.08	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$-0.09\ \pm0.03$	GOPAL	77	DPWA	$\overline{K}N$ multichannel
$-0.10\ \pm0.01$	[2] CORDEN	76	DPWA	$K^- n \to \Lambda\pi^-$
$-0.06\ \pm0.02$	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.09\ \pm0.02$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
-0.087 ± 0.056	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.09 or -0.09	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel
-0.10	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
-0.17 ± 0.01	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
-0.15 ± 0.02	[1] CORDEN	77C		$K^- n \to \Sigma\pi$
-0.19 ± 0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
-0.16 ± 0.03	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-0.05 or -0.05	[3] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma(1385)\pi$, P-wave $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.01	CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1915) \to \Sigma(1385)\pi$, F-wave $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
$+0.039\pm0.009$	[5] CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$\Sigma(1915)$ FOOTNOTES

[1] The two entries for CORDEN 77C are from two different acceptable solutions.
[2] Preferred solution 3; see CORDEN 76 for other possibilities.
[3] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[4] The mass and width are fixed to the GOPAL 77 values due to the low elasticity.
[5] The published sign has been changed to be in accord with the baryon-first convention.

$\Sigma(1915)$ REFERENCES

PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
ALSTON-...	78	PR D18 182	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
Also	77	PRL 38 1007	Alston-Garnjost, Kenney+	(LBL, MTHO, CERN) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CORDEN	77C	NP B125 61	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)

$\Sigma(1940)$ D_{13}

$I(J^P) = 1(\frac{3}{2}^-)$ Status: ∗∗∗

For results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

Not all analyses require this state. It is not required by the GOYAL 77 analysis of $K^- n \to (\Sigma\pi)^-$ nor by the GOPAL 80 analysis of $K^- n \to K^- n$. See also HEMINGWAY 75.

$\Sigma(1940)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1900 to 1950 (≈ 1940) OUR ESTIMATE				
1920±50	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1950±30	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
1949^{+40}_{-60}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
1935±80	KANE	74	DPWA	$K^- p \to \Sigma\pi$
1940±20	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
1950±20	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1886 or 1893	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
1940	DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$, F_{17} wave

$\Sigma(1940)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 300 (≈ 220) OUR ESTIMATE				
170±25	CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$
300±80	GOPAL	77	DPWA	$\overline{K}N$ multichannel
150±75	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
160^{+70}_{-40}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
330±80	KANE	74	DPWA	$K^- p \to \Sigma\pi$
60±20	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$
70^{+30}_{-20}	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
157 or 159	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$\Sigma(1940)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	<20 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$\Sigma(1385)\pi$	seen
Γ_5	$\Sigma(1385)\pi$, S-wave	
Γ_6	$\Lambda(1520)\pi$	seen
Γ_7	$\Lambda(1520)\pi$, P-wave	
Γ_8	$\Lambda(1520)\pi$, F-wave	
Γ_9	$\Delta(1232)\overline{K}$	seen
Γ_{10}	$\Delta(1232)\overline{K}$, S-wave	
Γ_{11}	$\Delta(1232)\overline{K}$, D-wave	
Γ_{12}	$N\overline{K}^*(892)$	seen
Γ_{13}	$N\overline{K}^*(892)$, S=3/2, S-wave	

$\Sigma(1940)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.2 OUR ESTIMATE				
<0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
0.14 or 0.13	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.06 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.04 ±0.02	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$-0.05\ ^{+0.03}_{-0.02}$	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
−0.153±0.070	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.15 or −0.14	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.08±0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.14±0.04	KANE	74	DPWA	$K^- p \to \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.16 or +0.16	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda(1520)\pi$, P-wave — $(\Gamma_1\Gamma_7)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
< 0.03	CAMERON	77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
−0.11±0.04	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Lambda(1520)\pi$, F-wave — $(\Gamma_1\Gamma_8)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.062±0.021	CAMERON	77	DPWA	$K^- p \to \Lambda(1520)\pi^0$
−0.08 ±0.04	LITCHFIELD	74B	DPWA	$K^- p \to \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Delta(1232)\overline{K}$, S-wave — $(\Gamma_1\Gamma_{10})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.16±0.05	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Delta(1232)\overline{K}$, D-wave — $(\Gamma_1\Gamma_{11})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.14±0.05	LITCHFIELD	74C	DPWA	$K^- p \to \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.066±0.025	[2] CAMERON	78	DPWA	$K^- p \to \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(1940) \to N\overline{K}^*(892)$ — $(\Gamma_1\Gamma_{12})^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09±0.02	[3] CAMERON	78B	DPWA	$K^- p \to N\overline{K}^*$

$\Sigma(1940)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] The published sign has been changed to be in accord with the baryon-first convention.
[3] Upper limits on the D_1 and D_3 waves are each 0.03.

$\Sigma(1940)$ REFERENCES

PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL)
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
GOYAL	77	PR D16 2746	+Sodhi	(DELH)
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
LITCHFIELD	74B	NP B74 19	+Hemingway, Baillon+	(CERN, HEIDH) IJP
LITCHFIELD	74C	NP B74 39	+Hemingway, Baillon+	(CERN, HEIDH) IJP

$\Sigma(2000)$ S_{11}

$I(J^P) = 1(\frac{1}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

We list here all reported S_{11} states lying above the $\Sigma(1750)$ S_{11}.

$\Sigma(2000)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2000 OUR ESTIMATE				
1944±15	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
1955±15	GOPAL	77	DPWA	$\overline{K}N$ multichannel
1755 or 1834	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
2004±40	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(2000)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
215±25	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
170±40	GOPAL	77	DPWA	$\overline{K}N$ multichannel
413 or 450	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
116±40	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$

$\Sigma(2000)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$
Γ_4	$\Lambda(1520)\pi$
Γ_5	$N\overline{K}^*(892)$, S=1/2, S-wave
Γ_6	$N\overline{K}^*(892)$, S=3/2, D-wave

$\Sigma(2000)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.51±0.05	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
0.44±0.05	GOPAL	77	DPWA	See GOPAL 80
0.62 or 0.57	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.19 or −0.18	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel
not seen	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
$+0.07^{+0.02}_{-0.01}$	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.20±0.04	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.26 or +0.24	[1] MARTIN	77	DPWA	$\overline{K}N$ multichannel

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to \Lambda(1520)\pi$ — $(\Gamma_1\Gamma_4)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.081±0.021	[2] CAMERON	77	DPWA	P-wave decay

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to N\overline{K}^*(892)$, S=1/2, S-wave — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.10±0.02	[2] CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2000) \to N\overline{K}^*(892)$, S=3/2, D-wave — $(\Gamma_1\Gamma_6)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.07±0.03	CAMERON	78B	DPWA	$K^-p \to N\overline{K}^*$

$\Sigma(2000)$ FOOTNOTES

[1] The two MARTIN 77 values are from a T-matrix pole and from a Breit-Wigner fit.
[2] The published sign has been changed to be in accord with the baryon-first convention.

$\Sigma(2000)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
MARTIN	77	NP B127 349	+Pidcock, Moorhouse	(LOUC, GLAS) IJP
Also	77B	NP B126 266	Martin, Pidcock	(LOUC)
Also	77C	NP B126 285	Martin, Pidcock	(LOUC) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP

$\Sigma(2030)$ F_{17}

$I(J^P) = 1(\frac{7}{2}^+)$ Status: ∗∗∗∗

Discovered by COOL 66 and by WOHL 66. For most results published before 1974 (they are now obsolete), see our 1982 edition Physics Letters **111B** (1982).

This entry only includes results from partial-wave analyses. Parameters of peaks seen in cross sections and invariant-mass distributions around 2030 MeV may be found in our 1984 edition, Reviews of Modern Physics **56** No. 2 Pt. II (1984).

$\Sigma(2030)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2025 to 2040 (≈ 2030) OUR ESTIMATE				
2036± 5	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
2038±10	CORDEN	77B		$K^-N \to N\overline{K}^*$
2040± 5	GOPAL	77	DPWA	$\overline{K}N$ multichannel
2030± 3	[1] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
2035±15	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
2038±10	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
2042±11	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
2020± 6	KANE	74	DPWA	$K^-p \to \Sigma\pi$
2035±10	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$
2020±30	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$
2025±10	LITCHFIELD	74D	DPWA	$K^-p \to \Lambda(1820)\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2027 to 2057	GOYAL	77	DPWA	$K^-N \to \Sigma\pi$
2030	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$

$\Sigma(2030)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
150 to 200 (≈ 180) OUR ESTIMATE				
172±10	GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
137±40	CORDEN	77B		$K^-N \to N\overline{K}^*$
190±10	GOPAL	77	DPWA	$\overline{K}N$ multichannel
201± 9	[1] CORDEN	76	DPWA	$K^-n \to \Lambda\pi^-$
180±20	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
172±15	HEMINGWAY	75	DPWA	$K^-p \to \overline{K}N$
178±13	VANHORN	75	DPWA	$K^-p \to \Lambda\pi^0$
111± 5	KANE	74	DPWA	$K^-p \to \Sigma\pi$
160±20	LITCHFIELD	74B	DPWA	$K^-p \to \Lambda(1520)\pi^0$
200±30	LITCHFIELD	74C	DPWA	$K^-p \to \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
260	DECLAIS	77	DPWA	$\overline{K}N \to \overline{K}N$
126 to 195	GOYAL	77	DPWA	$K^-N \to \Sigma\pi$
160	DEBELLEFON	76	IPWA	$K^-p \to \Lambda\pi^0$
70 to 125	LITCHFIELD	74D	DPWA	$K^-p \to \Lambda(1820)\pi^0$

$\Sigma(2030)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	17–23 %
Γ_2	$\Lambda\pi$	17–23 %
Γ_3	$\Sigma\pi$	5–10 %
Γ_4	ΞK	<2 %
Γ_5	$\Sigma(1385)\pi$	5–15 %
Γ_6	$\Sigma(1385)\pi$, F-wave	
Γ_7	$\Lambda(1520)\pi$	10–20 %
Γ_8	$\Lambda(1520)\pi$, D-wave	
Γ_9	$\Lambda(1520)\pi$, G-wave	
Γ_{10}	$\Delta(1232)\overline{K}$	10–20 %
Γ_{11}	$\Delta(1232)\overline{K}$, F-wave	
Γ_{12}	$\Delta(1232)\overline{K}$, H-wave	
Γ_{13}	$N\overline{K}^*(892)$	<5 %
Γ_{14}	$N\overline{K}^*(892)$, S=1/2, F-wave	
Γ_{15}	$N\overline{K}^*(892)$, S=3/2, F-wave	
Γ_{16}	$\Lambda(1820)\pi$, P-wave	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(2030)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.17 to 0.23 OUR ESTIMATE				
0.19±0.03	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.18±0.03	HEMINGWAY	75	DPWA	$K^-p \rightarrow \overline{K}N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.15	DECLAIS	77	DPWA	$\overline{K}N \rightarrow \overline{K}N$
0.24±0.02	GOPAL	77	DPWA	See GOPAL 80

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.18 ±0.02	GOPAL	77	DPWA	$\overline{K}N$ multichannel
+0.20 ±0.01	[1] CORDEN	76	DPWA	$K^-n \rightarrow \Lambda\pi^-$
+0.18 ±0.02	BAILLON	75	IPWA	$\overline{K}N \rightarrow \Lambda\pi$
+0.20 ±0.01	VANHORN	75	DPWA	$K^-p \rightarrow \Lambda\pi^0$
+0.195±0.053	DEVENISH	74B		Fixed-t dispersion rel.
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.20	DEBELLEFON	76	IPWA	$K^-p \rightarrow \Lambda\pi^0$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.09 ±0.01	[2] CORDEN	77C		$K^-n \rightarrow \Sigma\pi$
−0.06 ±0.01	[2] CORDEN	77C		$K^-n \rightarrow \Sigma\pi$
−0.15 ±0.03	GOPAL	77	DPWA	$\overline{K}N$ multichannel
−0.10 ±0.01	KANE	74	DPWA	$K^-p \rightarrow \Sigma\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.085±0.02	[3] GOYAL	77	DPWA	$K^-N \rightarrow \Sigma\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow \Xi K$ — $(\Gamma_1\Gamma_4)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.023	MULLER	69B	DPWA	$K^-p \rightarrow \Xi K$
<0.05	BURGUN	68	DPWA	$K^-p \rightarrow \Xi K$
<0.05	TRIPP	67	RVUE	$K^-p \rightarrow \Xi K$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow \Lambda(1820)\pi$, P-wave — $(\Gamma_1\Gamma_{16})^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.14±0.02	CORDEN	75B	DBC	$K^-n \rightarrow N\overline{K}\pi^-$
0.18±0.04	LITCHFIELD	74D	DPWA	$K^-p \rightarrow \Lambda(1820)\pi^0$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow \Lambda(1520)\pi$, D-wave — $(\Gamma_1\Gamma_8)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.114±0.010	[4] CAMERON	77	DPWA	$K^-p \rightarrow \Lambda(1520)\pi^0$
0.14 ±0.03	LITCHFIELD	74B	DPWA	$K^-p \rightarrow \Lambda(1520)\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10 ±0.03	[5] CORDEN	75B	DBC	$K^-n \rightarrow N\overline{K}\pi^-$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow \Lambda(1520)\pi$, G-wave — $(\Gamma_1\Gamma_9)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.146±0.010	[4] CAMERON	77	DPWA	$K^-p \rightarrow \Lambda(1520)\pi^0$
0.02 ±0.02	LITCHFIELD	74B	DPWA	$K^-p \rightarrow \Lambda(1520)\pi^0$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow \Delta(1232)\overline{K}$, F-wave — $(\Gamma_1\Gamma_{11})^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.16±0.03	LITCHFIELD	74C	DPWA	$K^-p \rightarrow \Delta(1232)\overline{K}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.17±0.03	[5] CORDEN	75B	DBC	$K^-n \rightarrow N\overline{K}\pi^-$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow \Delta(1232)\overline{K}$, H-wave — $(\Gamma_1\Gamma_{12})^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.00±0.02	LITCHFIELD	74C	DPWA	$K^-p \rightarrow \Delta(1232)\overline{K}$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow \Sigma(1385)\pi$ — $(\Gamma_1\Gamma_5)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.153±0.026	[4] CAMERON	78	DPWA	$K^-p \rightarrow \Sigma(1385)\pi$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow N\overline{K}^*(892)$, S=1/2, F-wave — $(\Gamma_1\Gamma_{14})^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.06±0.03	[4] CAMERON	78B	DPWA	$K^-p \rightarrow N\overline{K}^*$
−0.02±0.01	CORDEN	77B		$K^-d \rightarrow NN\overline{K}^*$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2030) \rightarrow N\overline{K}^*(892)$, S=3/2, F-wave — $(\Gamma_1\Gamma_{15})^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.04±0.03	[6] CAMERON	78B	DPWA	$K^-p \rightarrow N\overline{K}^*$
−0.12±0.02	CORDEN	77B		$K^-d \rightarrow NN\overline{K}^*$

$\Sigma(2030)$ FOOTNOTES

[1] Preferred solution 3; see CORDEN 76 for other possibilities.
[2] The two entries for CORDEN 77C are from two different acceptable solutions.
[3] This coupling is extracted from unnormalized data.
[4] The published sign has been changed to be in accord with the baryon-first convention.
[5] An upper limit.
[6] The upper limit on the G_3 wave is 0.03.

$\Sigma(2030)$ REFERENCES

PDG	84	RMP 56 No. 2 Pt. II	Wohl, Cahn, Rittenberg+	(LBL, CIT, CERN)
PDG	82	PL 111B	Roos, Porter, Aguilar-Benitez+	(HELS, CIT, CERN)
GOPAL	80	Toronto Conf. 159		(RHEL) IJP
CAMERON	78	NP B143 189	+Franek, Gopal, Bacon, Butterworth+	(RHEL, LOIC) IJP
CAMERON	78B	NP B146 327	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CAMERON	77	NP B131 399	+Franek, Gopal, Kalmus, McPherson+	(RHEL, LOIC) IJP
CORDEN	77B	NP B121 365	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
CORDEN	77C	NP B125 61	+Cox, Kenyon, O'Neale, Stubbs, Sumorok+	(BIRM) IJP
DECLAIS	77	CERN 77-16	+Duchon, Louvel, Patry, Seguinot+	(CAEN, CERN) IJP
GOPAL	77	NP B119 362	+Ross, VanHorn, McPherson+	(LOIC, RHEL) IJP
GOYAL	77	PR D16 2746	+Sodhi	(DELH) IJP
CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
CORDEN	75B	NP B92 365	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
HEMINGWAY	75	NP B91 12	+Eades, Harmsen+	(CERN, HEIDH, MPIM) IJP
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
DEVENISH	74B	NP B81 330	+Froggatt, Martin	(DESY, NORD, LOUC)
KANE	74	LBL-2452		(LBL) IJP
LITCHFIELD	74B	NP B74 19	+Hemingway, Baillon+	(CERN, HEIDH) IJP
LITCHFIELD	74C	NP B74 39	+Hemingway, Baillon+	(CERN, HEIDH) IJP
LITCHFIELD	74D	NP B74 12	+Hemingway, Baillon+	(CERN, HEIDH) IJP
MULLER	69B	Thesis UCRL 19372		(LRL)
BURGUN	68	NP B8 447	+Meyer, Pauli, Tallini+	(SACL, CDEF, RHEL)
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)
COOL	66	PRL 16 1228	+Giacomelli, Kycia, Leontic, Lundby+	(BNL)
WOHL	66	PRL 17 107	+Solmitz, Stevenson	(LRL) IJP

$\Sigma(2070)$ F_{15}

$I(J^P) = 1(\frac{5}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

This state suggested by BERTHON 70B finds support in GOPAL 80 with new K^-p polarization and K^-n angular distributions. The very broad state seen in KANE 72 is not required in the later (KANE 74) analysis of $\overline{K}N \rightarrow \Sigma\pi$.

$\Sigma(2070)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2070 OUR ESTIMATE				
2051±25	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
2057	KANE	72	DPWA	$K^-p \rightarrow \Sigma\pi$
2070±10	BERTHON	70B	DPWA	$K^-p \rightarrow \Sigma\pi$

$\Sigma(2070)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
300±30	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$
906	KANE	72	DPWA	$K^-p \rightarrow \Sigma\pi$
140±20	BERTHON	70B	DPWA	$K^-p \rightarrow \Sigma\pi$

$\Sigma(2070)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Sigma\pi$

$\Sigma(2070)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.08±0.03	GOPAL	80	DPWA	$\overline{K}N \rightarrow \overline{K}N$

$(\Gamma_i\Gamma_f)^{½}/\Gamma_{total}$ in $N\overline{K} \rightarrow \Sigma(2070) \rightarrow \Sigma\pi$ — $(\Gamma_1\Gamma_2)^{½}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.104	KANE	72	DPWA	$K^-p \rightarrow \Sigma\pi$
+0.12 ±0.02	BERTHON	70B	DPWA	$K^-p \rightarrow \Sigma\pi$

$\Sigma(2070)$ REFERENCES

GOPAL	80	Toronto Conf. 159		(RHEL) IJP
KANE	74	LBL-2452		(LBL)
KANE	72	PR D5 1583		(LBL)
BERTHON	70B	NP B24 417	+Vrana, Butterworth+	(CDEF, RHEL, SACL) IJP

$\Sigma(2080)$ P_{13}

$I(J^P) = 1(\frac{3}{2}^+)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Suggested by some but not all partial-wave analyses across this region.

$\Sigma(2080)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2080 OUR ESTIMATE				
2091± 7	[1] CORDEN	76	DPWA	$K^- n \to \Lambda \pi^-$
2070 to 2120	DEBELLEFON	76	IPWA	$K^- p \to \Lambda \pi^0$
2120±40	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
2140±40	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
2082± 4	COX	70	DPWA	See CORDEN 76
2070±30	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$

$\Sigma(2080)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
186±48	[1] CORDEN	76	DPWA	$K^- n \to \Lambda \pi^-$
100	DEBELLEFON	76	IPWA	$K^- p \to \Lambda \pi^0$
240±50	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1)
200±50	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 2)
87±20	COX	70	DPWA	See CORDEN 76
250±40	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$

$\Sigma(2080)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$

$\Sigma(2080)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2080) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.10±0.03	[1] CORDEN	76	DPWA	$K^- n \to \Lambda \pi^-$
−0.10	DEBELLEFON	76	IPWA	$K^- p \to \Lambda \pi^0$
−0.13±0.04	BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$ (sol. 1 and 2)
−0.16±0.03	COX	70	DPWA	See CORDEN 76
−0.09±0.03	LITCHFIELD	70	DPWA	$K^- N \to \Lambda\pi$

$\Sigma(2080)$ FOOTNOTES

[1] Preferred solution 3; see CORDEN 76 for other possibilities, including a D_{15} at this mass.

$\Sigma(2080)$ REFERENCES

CORDEN	76	NP B104 382	+Cox, Dartnell, Kenyon, O'Neale+	(BIRM) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
Also	75	NP B90 1	De Bellefon, Berthon, Brunet+	(CDEF, SACL) IJP
BAILLON	75	NP B94 39	+Litchfield	(CERN, RHEL) IJP
COX	70	NP B19 61	+Islam, Colley+	(BIRM, EDIN, GLAS, LOIC) IJP
LITCHFIELD	70	NP B22 269		(RHEL) IJP

$\Sigma(2100)$ G_{17}

$I(J^P) = 1(\frac{7}{2}^-)$ Status: ∗

OMITTED FROM SUMMARY TABLE

$\Sigma(2100)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2100 OUR ESTIMATE				
2060±20	BARBARO-...	70	DPWA	$K^- p \to \Lambda \pi^0$
2120±30	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$\Sigma(2100)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
70±30	BARBARO-...	70	DPWA	$K^- p \to \Lambda \pi^0$
135±30	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$\Sigma(2100)$ DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$
Γ_3	$\Sigma\pi$

$\Sigma(2100)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2100) \to \Lambda\pi$ $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.07±0.02	BARBARO-...	70	DPWA	$K^- p \to \Lambda \pi^0$

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\overline{K} \to \Sigma(2100) \to \Sigma\pi$ $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.13±0.02	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$

$\Sigma(2100)$ REFERENCES

BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP

$\Sigma(2250)$

$I(J^P) = 1(?^?)$ Status: ∗∗∗

Results from partial-wave analyses are too weak to warrant separating them from the production and cross-section experiments. LASINSKI 71 in $\overline{K}N$ using a Pomeron + resonances model, and DEBELLEFON 76, DEBELLEFON 77, and DEBELLEFON 78 in energy-dependent partial-wave analyses of $\overline{K}N \to \Lambda\pi$, $\Sigma\pi$, and $N\overline{K}$, respectively, suggest two resonances around this mass.

$\Sigma(2250)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
2210 to 2280 (≈ 2250) OUR ESTIMATE				
2270±50	DEBELLEFON	78	DPWA	D_5 wave
2210±30	DEBELLEFON	78	DPWA	G_9 wave
2275±20	DEBELLEFON	77	DPWA	D_5 wave
2215±20	DEBELLEFON	77	DPWA	G_9 wave
2300±30	[1] DEBELLEFON	75B	HBC	$K^- p \to \Xi^{*0} K^0$
2251^{+30}_{-20}	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$, F_5 wave
2280±14	AGUILAR-...	70B	HBC	$K^- p$ 3.9, 4.6 GeV/c
2237±11	BRICMAN	70	CNTR	Total, charge exchange
2255±10	COOL	70	CNTR	$K^- p$, $K^- d$ total
2250± 7	BUGG	68	CNTR	$K^- p$, $K^- d$ total
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2260	DEBELLEFON	76	IPWA	D_5 wave
2215	DEBELLEFON	76	IPWA	G_9 wave
2250±20	LU	70	CNTR	$\gamma p \to K^+ Y^*$
2245	BLANPIED	65	CNTR	$\gamma p \to K^+ Y^*$
2299± 6	BOCK	65	HBC	$\overline{p}p$ 5.7 GeV/c

$\Sigma(2250)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
60 to 150 (≈ 100) OUR ESTIMATE				
120±40	DEBELLEFON	78	DPWA	D_5 wave
80±20	DEBELLEFON	78	DPWA	G_9 wave
70±20	DEBELLEFON	77	DPWA	D_5 wave
60±20	DEBELLEFON	77	DPWA	G_9 wave
130±20	[1] DEBELLEFON	75B	HBC	$K^- p \to \Xi^{*0} K^0$
192±30	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$, F_5 wave
100±20	AGUILAR-...	70B	HBC	$K^- p$ 3.9, 4.6 GeV/c
164±50	BRICMAN	70	CNTR	Total, charge exchange
230±20	BUGG	68	CNTR	$K^- p$, $K^- d$ total
• • • We do not use the following data for averages, fits, limits, etc. • • •				
100	DEBELLEFON	76	IPWA	D_5 wave
140	DEBELLEFON	76	IPWA	G_9 wave
170	COOL	70	CNTR	$K^- p$, $K^- d$ total
125	LU	70	CNTR	$\gamma p \to K^+ Y^*$
150	BLANPIED	65	CNTR	$\gamma p \to K^+ Y^*$
21^{+17}_{-21}	BOCK	65	HBC	$\bar{p}p$ 5.7 GeV/c

$\Sigma(2250)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\bar{K}$	<10 %
Γ_2	$\Lambda\pi$	seen
Γ_3	$\Sigma\pi$	seen
Γ_4	$N\bar{K}\pi$	
Γ_5	$\Xi(1530)K$	

The above branching fractions are our estimates, not fits or averages.

$\Sigma(2250)$ BRANCHING RATIOS

See "Sign conventions for resonance couplings" in the Note on Λ and Σ Resonances.

$\Gamma(N\bar{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
<0.1 OUR ESTIMATE				
0.08±0.02	DEBELLEFON	78	DPWA	D_5 wave
0.02±0.01	DEBELLEFON	78	DPWA	G_9 wave

$(J+\frac{1}{2})\times\Gamma(N\bar{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.16±0.12	BRICMAN	70	CNTR	Total, charge exchange
0.42	COOL	70	CNTR	$K^- p$, $K^- d$ total
0.47	BUGG	68	CNTR	

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\bar{K} \to \Sigma(2250) \to \Lambda\pi$ — $(\Gamma_1\Gamma_2)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
−0.16±0.03	VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$, F_5 wave
• • • We do not use the following data for averages, fits, limits, etc. • • •				
+0.11	DEBELLEFON	76	IPWA	D_5 wave
−0.10	DEBELLEFON	76	IPWA	G_9 wave
−0.18	BARBARO-...	70	DPWA	$K^- p \to \Lambda\pi^0$, G_9 wave

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\bar{K} \to \Sigma(2250) \to \Sigma\pi$ — $(\Gamma_1\Gamma_3)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
+0.06±0.02	DEBELLEFON	77	DPWA	D_5 wave
−0.03±0.02	DEBELLEFON	77	DPWA	G_9 wave
+0.07	BARBARO-...	70	DPWA	$K^- p \to \Sigma\pi$, G_9 wave

$\Gamma(N\bar{K})/\Gamma(\Sigma\pi)$ — Γ_1/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.18	BARNES	69	HBC	1 standard dev. limit

$\Gamma(\Lambda\pi)/\Gamma(\Sigma\pi)$ — Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.18	BARNES	69	HBC	1 standard dev. limit

$(\Gamma_i\Gamma_f)^{1/2}/\Gamma_{total}$ in $N\bar{K} \to \Sigma(2250) \to \Xi(1530)K$ — $(\Gamma_1\Gamma_5)^{1/2}/\Gamma$

VALUE	DOCUMENT ID		TECN	COMMENT
0.18±0.04	[1] DEBELLEFON	75B	HBC	$K^- p \to \Xi^{*0} K^0$

$\Sigma(2250)$ FOOTNOTES

[1] Seen in the (initial and final state) D_5 wave. Isospin not determined.

$\Sigma(2250)$ REFERENCES

DEBELLEFON	78	NC 42A 403	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
DEBELLEFON	77	NC 37A 175	De Bellefon, Berthon, Billoir+	(CDEF, SACL) IJP
DEBELLEFON	76	NP B109 129	De Bellefon, Berthon	(CDEF) IJP
Also	75	NP B90 1	De Bellefon, Berthon, Brunet+	(CDEF, SACL) IJP
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
VANHORN	75	NP B87 145		(LBL) IJP
Also	75B	NP B87 157	VanHorn	(LBL) IJP
LASINSKI	71	NP B29 125		(EFI) IJP
AGUILAR-...	70B	PRL 25 58	Aguilar-Benitez, Barnes, Bassano+	(BNL, SYRA)
BARBARO-...	70	Duke Conf. 173	Barbaro-Galtieri	(LRL) IJP
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
COOL	70	PR D1 1887	+Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	66	PRL 16 1228	Cool, Giacomelli, Kycia, Leontic, Lundby+	(BNL) I
LU	70	PR D2 1846	+Greenberg, Hughes, Minehart, Mori+	(YALE)
BARNES	69	PRL 22 479	+Flaminio, Montanet, Samios+	(BNL, SYRA)
BUGG	68	PR 168 1466	+Gilmore, Knight+	(RHEL, BIRM, CAVE) I
BLANPIED	65	PRL 14 741	+Greenberg, Hughes, Kitching, Lu+	(YALE, CEA)
BOCK	65	PL 17 166	+Cooper, French, Kinson+	(CERN, SACL)

$\Sigma(2455)$ Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

There is also some slight evidence for Y^* states in this mass region from the reaction $\gamma p \to K^+ X$ — see GREENBERG 68.

$\Sigma(2455)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2455 OUR ESTIMATE				
2455±10	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
2455± 7	BUGG	68	CNTR	$K^- p$, $K^- d$ total

$\Sigma(2455)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
140	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
100±20	BUGG	68	CNTR	

$\Sigma(2455)$ DECAY MODES

	Mode
Γ_1	$N\bar{K}$

$\Sigma(2455)$ BRANCHING RATIOS

$(J+\frac{1}{2})\times\Gamma(N\bar{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.39	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
0.05±0.05	[1] BRICMAN	70	CNTR	Total, charge exchange
0.3	BUGG	68	CNTR	

$\Sigma(2455)$ FOOTNOTES

[1] Fit of total cross section given by BRICMAN 70 is poor in this region.

$\Sigma(2455)$ REFERENCES

ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	67E	PRL 19 678	Abrams, Cool, Giacomelli, Kycia, Leontic+	(BNL)
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)
BUGG	68	PR 168 1466	+Gilmore, Knight+	(RHEL, BIRM, CAVE) I
GREENBERG	68	PRL 20 221	+Hughes, Lu, Minehart+	(YALE)

Σ(2620) Bumps

$I(J^P) = 1(?^?)$ Status: ∗∗

OMITTED FROM SUMMARY TABLE

Σ(2620) MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
≈ 2620 OUR ESTIMATE				
2542±22	DIBIANCA	75	DBC	$K^- N \to \Xi K \pi$
2620±15	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total

Σ(2620) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
221±81	DIBIANCA	75	DBC	$K^- N \to \Xi K \pi$
175	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total

Σ(2620) DECAY MODES

	Mode
Γ_1	$N\overline{K}$

Σ(2620) BRANCHING RATIOS

$(J+\frac{1}{2})\times\Gamma(N\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.32	ABRAMS	70	CNTR	$K^- p$, $K^- d$ total
0.36±0.12	BRICMAN	70	CNTR	Total, charge exchange

Σ(2620) REFERENCES

DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ABRAMS	70	PR D1 1917	+Cool, Giacomelli, Kycia, Leontic, Li+	(BNL) I
Also	67E	PRL 19 678	Abrams, Cool, Giacomelli, Kycia, Leontic+	(BNL)
BRICMAN	70	PL 31B 152	+Ferro-Luzzi, Perreau+	(CERN, CAEN, SACL)

Σ(3000) Bumps

$I(J^P) = 1(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Seen as an enhancement in $\Lambda\pi$ and $\overline{K}N$ invariant mass spectra and in the missing mass of neutrals recoiling against a K^0.

Σ(3000) MASS

VALUE (MeV)	DOCUMENT ID		TECN	CHG	COMMENT
≈ 3000 OUR ESTIMATE					
3000	EHRLICH	66	HBC	0	$\pi^- p$ 7.91 GeV/c

Σ(3000) DECAY MODES

	Mode
Γ_1	$N\overline{K}$
Γ_2	$\Lambda\pi$

Σ(3000) REFERENCES

EHRLICH	66	PR 152 1194	+Selove, Yuta	(PENN) I

Σ(3170) Bumps

$I(J^P) = 1(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

Seen by AMIRZADEH 79 as a narrow 6.5-standard-deviation enhancement in the reaction $K^- p \to Y^{*+}\pi^-$ using data from independent high statistics bubble chamber experiments at 8.25 and 6.5 GeV/c. The dominant decay modes are multibody, multistrange final states and the production is via isospin-3/2 baryon exchange. Isospin 1 is favored.

Not seen in a $K^- p$ experiment in LASS at 11 GeV/c (ASTON 85B).

Σ(3170) MASS (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 3170 OUR ESTIMATE					
3170±5	35	AMIRZADEH	79	HBC	$K^- p \to Y^{*+}\pi^-$

Σ(3170) WIDTH (PRODUCTION EXPERIMENTS)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
<20	35	[1] AMIRZADEH	79	HBC	$K^- p \to Y^{*+}\pi^-$

Σ(3170) DECAY MODES (PRODUCTION EXPERIMENTS)

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda K\overline{K}\pi$'s	seen
Γ_2	$\Sigma K\overline{K}\pi$'s	seen
Γ_3	$\Xi K\pi$'s	seen

Σ(3170) BRANCHING RATIOS (PRODUCTION EXPERIMENTS)

$\Gamma(\Lambda K\overline{K}\pi\text{'s})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+}\pi^-$

$\Gamma(\Sigma K\overline{K}\pi\text{'s})/\Gamma_{total}$ Γ_2/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+}\pi^-$

$\Gamma(\Xi K\pi\text{'s})/\Gamma_{total}$ Γ_3/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	AMIRZADEH	79	HBC	$K^- p \to Y^{*+}\pi^-$

Σ(3170) FOOTNOTES (PRODUCTION EXPERIMENTS)

[1] Observed width consistent with experimental resolution.

Σ(3170) REFERENCES (PRODUCTION EXPERIMENTS)

ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
AMIRZADEH	79	PL 89B 125	+	(BIRM, CERN, GLAS, MSU, CURIN, CAVE+) I
Also	80	Toronto Conf. 263	Kinson+	(BIRM, CERN, GLAS, MSU, CURIN) I

Ξ BARYONS
$(S=-2,\ I=1/2)$

$\Xi^0 = uss,\quad \Xi^- = dss$

Ξ^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity has not actually been measured, but + is of course expected.

Ξ^0 MASS

The fit uses the Ξ^0, Ξ^-, and $\overline{\Xi}^+$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN
1314.9±0.6 OUR FIT				
1314.8±0.8 OUR AVERAGE				
1315.2±0.92	49	WILQUET	72	HLBC
1313.4±1.8	1	PALMER	68	HBC

$m_{\Xi^-} - m_{\Xi^0}$

The fit uses the Ξ^0, Ξ^-, and $\overline{\Xi}^+$ mass and mass difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
6.4±0.6 OUR FIT					
6.3±0.7 OUR AVERAGE					
6.9±2.2	29	LONDON	66	HBC	
6.1±0.9	88	PJERROU	65B	HBC	
6.8±1.6	23	JAUNEAU	63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
6.1±1.6	45	CARMONY	64B	HBC	See PJERROU 65B

Ξ^0 MEAN LIFE

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
2.90±0.09 OUR AVERAGE					
2.83±0.16	6300	[1] ZECH	77	SPEC	Neutral hyperon beam
$2.88^{+0.21}_{-0.19}$	652	BALTAY	74	HBC	1.75 GeV/c $K^- p$
$2.90^{+0.32}_{-0.27}$	157	[2] MAYEUR	72	HLBC	2.1 GeV/c K^-
$3.07^{+0.22}_{-0.20}$	340	DAUBER	69	HBC	
3.0 ±0.5	80	PJERROU	65B	HBC	
$2.5\ ^{+0.4}_{-0.3}$	101	HUBBARD	64	HBC	
$3.9\ ^{+1.4}_{-0.8}$	24	JAUNEAU	63	FBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$3.5\ ^{+1.0}_{-0.8}$	45	CARMONY	64B	HBC	See PJERROU 65B

[1] The ZECH 77 result is $\tau_{\Xi^0} = [2.77-(\tau_\Lambda-2.69)] \times 10^{-10}$ s, in which we use $\tau_\Lambda = 2.63 \times 10^{-10}$ s.
[2] The MAYEUR 72 value is modified by the erratum.

Ξ^0 MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN
−1.250±0.014 OUR AVERAGE				
−1.253±0.014	270k	COX	81	SPEC
−1.20 ±0.06	42k	BUNCE	79	SPEC

Ξ^0 DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\pi^0$		(99.54±0.05) %	
Γ_2	$\Lambda\gamma$		(1.06±0.16) × 10^{-3}	
Γ_3	$\Sigma^0\gamma$		(3.5 ±0.4) × 10^{-3}	
Γ_4	$\Sigma^+ e^- \overline{\nu}_e$		< 1.1 × 10^{-3}	90%
Γ_5	$\Sigma^+ \mu^- \overline{\nu}_\mu$		< 1.1 × 10^{-3}	90%
	$\Delta S = \Delta Q$ (SQ) violating modes or $\Delta S = 2$ forbidden ($S2$) modes			
Γ_6	$\Sigma^- e^+ \nu_e$	SQ	< 9 × 10^{-4}	90%
Γ_7	$\Sigma^- \mu^+ \nu_\mu$	SQ	< 9 × 10^{-4}	90%
Γ_8	$p\pi^-$	$S2$	< 4 × 10^{-5}	90%
Γ_9	$p e^- \overline{\nu}_e$	$S2$	< 1.3 × 10^{-3}	
Γ_{10}	$p \mu^- \overline{\nu}_\mu$	$S2$	< 1.3 × 10^{-3}	

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 2 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 0.0 for 0 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\rm total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−35	
x_3	−94	0
	x_1	x_2

Ξ^0 BRANCHING RATIOS

$\Gamma(\Lambda\gamma)/\Gamma(\Lambda\pi^0)$ — Γ_2/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.06±0.16 OUR FIT					
1.06±0.12±0.11	116	JAMES	90	SPEC	FNAL hyperons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5 ±5	1	YEH	74	HBC	Effective denom.=200

$\Gamma(\Sigma^0\gamma)/\Gamma(\Lambda\pi^0)$ — Γ_3/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
3.6 ±0.4 OUR FIT						
3.56±0.42±0.10		85	TEIGE	89	SPEC	FNAL hyperons
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 8	90		BENSINGER	88	MPS2	K^- W 6 GeV/c
<65	90	0–1	YEH	74	HBC	Effective denom.=60

$\Gamma(\Sigma^+ e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^0)$ — Γ_4/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.1	90	0	YEH	74	HBC	Effective denom.=2100
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<7			HUBBARD	66	HBC	

$\Gamma(\Sigma^+ \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda\pi^0)$ — Γ_5/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.1	90	0	YEH	74	HBC	Effective denom.=2100
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<7			HUBBARD	66	HBC	

$\Gamma(\Sigma^- e^+ \nu_e)/\Gamma(\Lambda\pi^0)$ — Γ_6/Γ_1

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.9	90	0	YEH	74	HBC	Effective denom.=2500
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<6			HUBBARD	66	HBC	

$\Gamma(\Sigma^- \mu^+ \nu_\mu)/\Gamma(\Lambda\pi^0)$ — Γ_7/Γ_1

Test of $\Delta S = \Delta Q$ rule.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.9	90	0	YEH	74	HBC	Effective denom.=2500
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.5			DAUBER	69	HBC	
<6			HUBBARD	66	HBC	

$\Gamma(p\pi^-)/\Gamma(\Lambda\pi^0)$ — Γ_8/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-5})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 3.6	90		GEWENIGER	75	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<180	90	0	YEH	74	HBC	Effective denom.=1300
< 90			DAUBER	69	HBC	
<500			HUBBARD	66	HBC	

$\Gamma(p e^- \overline{\nu}_e)/\Gamma(\Lambda\pi^0)$ — Γ_9/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.3			DAUBER	69	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.4	90	0	YEH	74	HBC	Effective denom.=670
<6			HUBBARD	66	HBC	

$\Gamma(p \mu^- \overline{\nu}_\mu)/\Gamma(\Lambda\pi^0)$ — Γ_{10}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

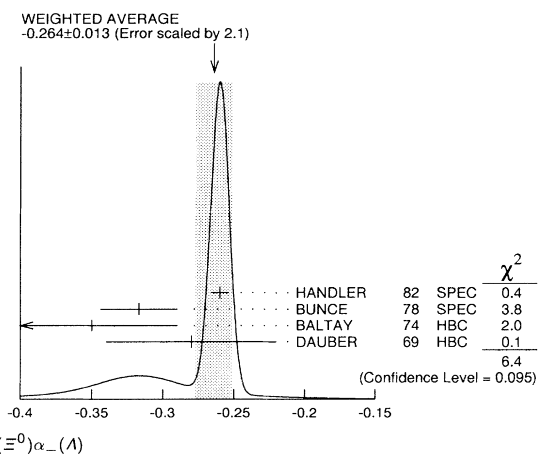
VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.3			DAUBER	69	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.5	90	0	YEH	74	HBC	Effective denom.=664
<6			HUBBARD	66	HBC	

Ξ^0 DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings.

$\alpha(\Xi^0)\ \alpha_-(\Lambda)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.264±0.013 OUR AVERAGE	Error includes scale factor of 2.1. See the ideogram below.				
−0.260±0.004±0.005	300k	HANDLER	82	SPEC	FNAL hyperons
−0.317±0.027	6075	BUNCE	78	SPEC	FNAL hyperons
−0.35 ±0.06	505	BALTAY	74	HBC	$K^- p$ 1.75 GeV/c
−0.28 ±0.06	739	DAUBER	69	HBC	$K^- p$ 1.7–2.6 GeV/c



α FOR $\Xi^0 \rightarrow \Lambda\pi^0$

The above average, $\alpha(\Xi^0)\alpha_-(\Lambda) = -0.264 \pm 0.013$, where the error includes a scale factor of 2.1, divided by our current average $\alpha_-(\Lambda) = 0.642 \pm 0.013$, gives the following value for $\alpha(\Xi^0)$.

VALUE	DOCUMENT ID
−0.411±0.022 OUR EVALUATION	Error includes scale factor of 2.1.

ϕ ANGLE FOR $\Xi^0 \rightarrow \Lambda\pi^0$ — $(\tan\phi = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
21±12 OUR AVERAGE					
16±17	652	BALTAY	74	HBC	1.75 GeV/c $K^- p$
38±19	739	[3] DAUBER	69	HBC	
− 8±30	146	[4] BERGE	66	HBC	

[3] DAUBER 69 uses $\alpha_\Lambda = 0.647 \pm 0.020$.

[4] The errors have been multiplied by 1.2 due to approximations used for the Ξ polarization; see DAUBER 69 for a discussion.

α FOR $\Xi^0 \rightarrow \Lambda\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
+0.43±0.44	87	JAMES	90	SPEC	FNAL hyperons

α FOR $\Xi^0 \rightarrow \Sigma^0\gamma$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
+0.20±0.32±0.05	85	TEIGE	89	SPEC	FNAL hyperons

Ξ^0 REFERENCES

JAMES	90	PRL 64 843	+Heller, Border, Dworkin+	(MINN, MICH, WISC, RUTG)
TEIGE	89	PRL 63 2717	+Beretvas, Caracappa, Devlin+	(RUTG, MICH, MINN)
BENSINGER	88	PL B215 195	+Fortner, Kirsch, Piekarz+	(BRAN, DUKE, NDAM, MASD)
HANDLER	82	PR D25 639	+Grobel, Pondrom+	(WISC, MICH, MINN, RUTG)
COX	81	PRL 46 877	+Dworkin+	(MICH, WISC, RUTG, MINN, BNL)
BUNCE	79	PL 86B 386	+Overseth, Cox+	(BNL, MICH, RUTG, WISC)
BUNCE	78	PR D18 633	+Handler, March, Martin+	(WISC, MICH, RUTG)
ZECH	77	NP B124 413	+Dydak, Navarria+	(SIEG, CERN, DORT, HEIDH)
GEWENIGER	75	PL 57B 193	+Gjesdal, Presser+	(CERN, HEIDH)
BALTAY	74	PR D9 49	+Bridgewater, Cooper, Gershwin+	(COLU, BING) J
YEH	74	PR D10 3545	+Gaigalas, Smith, Zendle, Baltay+	(BING, COLU)
MAYEUR	72	NP B47 333	+VanBinst, Wilquet+	(BRUX, CERN, TUFTS, LOUC)
Also	73	NP B53 268 erratum	Mayeur	
WILQUET	72	PL 42B 372	+Fliagine, Guy+	(BRUX, CERN, TUFTS, LOUC)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)
PALMER	68	PL 26B 323	+Radojicic, Rau, Richardson+	(BNL, SYRA)
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL)
HUBBARD	66	Thesis UCRL 11510		(LRL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
Also	65	Thesis	Pjerrou	(UCLA)
CARMONY	64B	PRL 12 482	+Pjerrou, Schlein, Slater, Stork+	(UCLA)
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
JAUNEAU	63	PL 4 49	+	(EPOL, CERN, LOUC, RHEL, BERG)
Also	63C	Siena Conf. 1 1	Jauneau+	(EPOL, CERN, LOUC, RHEL, BERG)

Ξ^-

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity has not actually been measured, but + is of course expected.

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Ξ^- MASS

The fit uses the Ξ^-, $\overline{\Xi}^+$, and Ξ^0 mass and mass difference measurements. It assumes the Ξ^- and $\overline{\Xi}^+$ masses are the same.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1321.32±0.13 OUR FIT					
1321.34±0.14 OUR AVERAGE					
1321.46±0.34	632	DIBIANCA	75	DBC	4.9 GeV/c $K^- d$
1321.12±0.41	268	WILQUET	72	HLBC	
1321.87±0.51	195	[1] GOLDWASSER	70	HBC	5.5 GeV/c $K^- p$
1321.67±0.52	6	CHIEN	66	HBC	6.9 GeV/c $\overline{p}p$
1321.4 ±1.1	299	LONDON	66	HBC	
1321.3 ±0.4	149	PJERROU	65B	HBC	
1321.1 ±0.3	241	[2] BADIER	64	HBC	
1321.4 ±0.4	517	[2] JAUNEAU	63D	FBC	
1321.1 ±0.65	62	[2] SCHNEIDER	63	HBC	

[1] GOLDWASSER 70 uses $m_\Lambda = 1115.58$ MeV.

[2] These masses have been increased 0.09 MeV because the Λ mass increased.

$\overline{\Xi}^+$ MASS

The fit uses the Ξ^-, $\overline{\Xi}^+$, and Ξ^0 mass and mass difference measurements. It assumes the Ξ^- and $\overline{\Xi}^+$ masses are the same.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1321.32±0.13 OUR FIT					
1321.20±0.33 OUR AVERAGE					
1321.6 ±0.8	35	VOTRUBA	72	HBC	10 GeV/c $K^+ p$
1321.2 ±0.4	34	STONE	70	HBC	
1320.69±0.93	5	CHIEN	66	HBC	6.9 GeV/c $\overline{p}p$

$(m_{\Xi^-} - m_{\overline{\Xi}^+})\ /\ m_{\rm average}$

A test of CPT invariance. We calculate it from the *average* Ξ^- and $\overline{\Xi}^+$ masses above.

VALUE	DOCUMENT ID
(1.1±2.7) x 10^{-4} OUR EVALUATION	

Ξ^- MEAN LIFE

Measurements with an error > 0.2 x 10^{-10} s or with systematic errors not included have been omitted.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.639±0.015 OUR AVERAGE					
1.652±0.051	32k	BOURQUIN	84	SPEC	Hyperon beam
1.665±0.065	41k	BOURQUIN	79	SPEC	Hyperon beam
1.609±0.028	4286	HEMINGWAY	78	HBC	4.2 GeV/c $K^- p$
1.67 ±0.08		DIBIANCA	75	DBC	4.9 GeV/c $K^- d$
1.63 ±0.03	4303	BALTAY	74	HBC	1.75 GeV/c $K^- p$
1.73 $^{+0.08}_{-0.07}$	680	MAYEUR	72	HLBC	2.1 GeV/c K^-
1.61 ±0.04	2610	DAUBER	69	HBC	
1.80 ±0.16	299	LONDON	66	HBC	
1.70 ±0.12	246	PJERROU	65B	HBC	
1.69 ±0.07	794	HUBBARD	64	HBC	
1.86 $^{+0.15}_{-0.14}$	517	JAUNEAU	63D	FBC	

$\overline{\Xi}^+$ MEAN LIFE

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.6 ±0.3	34	STONE	70	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.55^{+0.35}_{-0.20}$	35	[3] VOTRUBA	72	HBC	10 GeV/c K^+p
$1.9\ ^{+0.7}_{-0.5}$	12	[3] SHEN	67	HBC	
1.51 ± 0.55	5	[3] CHIEN	66	HBC	6.9 GeV/c $\overline{p}p$

[3] The error is statistical only.

$(\tau_{\Xi^-} - \tau_{\overline{\Xi}^+})\ /\ \tau_{\text{average}}$

A test of CPT invariance. Calculated from the Ξ^- and $\overline{\Xi}^+$ mean lives, above.

VALUE	DOCUMENT ID
0.02±0.18 OUR EVALUATION	

Ξ^- MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
−0.6507±0.0025 OUR AVERAGE					
−0.6505±0.0025	4.36M	DURYEA	92	SPEC	800 GeV p Be
−0.661 ±0.036 ±0.036	44k	TROST	89	SPEC	Ξ^- ~250 GeV
−0.69 ±0.04	218k	RAMEIKA	84	SPEC	400 GeV pBe
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.674 ±0.021 ±0.020	122k	HO	90	SPEC	See DURYEA 92
−2.1 ±0.8	2436	COOL	74	OSPK	1.8 GeV/c K^-p
−0.1 ±2.1	2724	BINGHAM	70B	OSPK	1.8 GeV/c K^-p

$\overline{\Xi}^+$ MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings.

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
+0.657±0.028±0.020	70k	HO	90	SPEC	800 GeV pBe

Ξ^- DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\pi^-$		(99.887±0.035) %	
Γ_2	$\Sigma^-\gamma$		(1.27 ±0.23) × 10^{-4}	
Γ_3	$\Lambda e^-\overline{\nu}_e$		(5.63 ±0.31) × 10^{-4}	
Γ_4	$\Lambda\mu^-\overline{\nu}_\mu$		(3.5 $^{+3.5}_{-2.2}$) × 10^{-4}	
Γ_5	$\Sigma^0 e^-\overline{\nu}_e$		(8.7 ±1.7) × 10^{-5}	
Γ_6	$\Sigma^0\mu^-\overline{\nu}_\mu$		< 8 × 10^{-4}	90%
Γ_7	$\Xi^0 e^-\overline{\nu}_e$		< 2.3 × 10^{-3}	90%
	$\Delta S = 2$ forbidden ($S2$) modes			
Γ_8	$n\pi^-$	$S2$	< 1.9 × 10^{-5}	90%
Γ_9	$ne^-\overline{\nu}_e$	$S2$	< 3.2 × 10^{-3}	90%
Γ_{10}	$n\mu^-\overline{\nu}_\mu$	$S2$	< 1.5 %	90%
Γ_{11}	$p\pi^-\pi^-$	$S2$	< 4 × 10^{-4}	90%
Γ_{12}	$p\pi^- e^-\overline{\nu}_e$	$S2$	< 4 × 10^{-4}	90%
Γ_{13}	$p\pi^-\mu^-\overline{\nu}_\mu$	$S2$	< 4 × 10^{-4}	90%
Γ_{14}	$p\mu^-\mu^-$	L	< 4 × 10^{-4}	90%

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 5 measurements and one constraint to determine 5 parameters. The overall fit has a χ^2 = 1.0 for 1 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i\delta x_j\right\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−6			
x_3	−8	0		
x_4	−99	0	−1	
x_5	−5	0	0	0
	x_1	x_2	x_3	x_4

Ξ^- BRANCHING RATIOS

A number of early results have been omitted.

$\Gamma(\Sigma^-\gamma)/\Gamma(\Lambda\pi^-)$ — Γ_2/Γ_1

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.27±0.24 OUR FIT					
1.27±0.23 OUR AVERAGE					
1.22±0.23±0.06	211	[4] DUBBS	94	E761	Ξ^- 375 GeV
2.27±1.02	9	BIAGI	87B	SPEC	SPS hyperon beam

[4] DUBBS 94 also finds weak evidence that the asymmetry parameter α_γ is positive (α_γ = 1.0 ± 1.3).

$\Gamma(\Lambda e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_3/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.564±0.031 OUR FIT					
0.564±0.031	2857	BOURQUIN	83	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.30 ±0.13	11	THOMPSON	80	ASPK	Hyperon beam

$\Gamma(\Lambda\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ — Γ_4/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$0.35^{+0.35}_{-0.22}$ OUR FIT						
0.35±0.35		1	YEH	74	HBC	Effective denom.=2859
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 2.3	90	0	THOMPSON	80	ASPK	Effective denom.=1017
< 1.3			DAUBER	69	HBC	
<12			BERGE	66	HBC	

$\Gamma(\Sigma^0 e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_5/Γ_1

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
0.087±0.017 OUR FIT					
0.087±0.017	154	BOURQUIN	83	SPEC	SPS hyperon beam

$\Gamma(\Sigma^0\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ — Γ_6/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.76	90	0	YEH	74	HBC	Effective denom.=3026
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<5			BERGE	66	HBC	

$[\Gamma(\Lambda e^-\overline{\nu}_e)+\Gamma(\Sigma^0 e^-\overline{\nu}_e)]/\Gamma(\Lambda\pi^-)$ — $(\Gamma_3+\Gamma_5)/\Gamma_1$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.651±0.031	3011	[5] BOURQUIN	83	SPEC	SPS hyperon beam
0.68 ±0.22	17	[6] DUCLOS	71	OSPK	

[5] See the separate BOURQUIN 83 values for $\Gamma(\Lambda e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ and $\Gamma(\Sigma^0 e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ above.

[6] DUCLOS 71 cannot distinguish Σ^0's from Λ's. The Cabibbo theory predicts the Σ^0 rate is about a factor 6 smaller than the Λ rate.

$\Gamma(\Xi^0 e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_7/Γ_1

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.3	90	0	YEH	74	HBC	Effective denom.=1000

$\Gamma(n\pi^-)/\Gamma(\Lambda\pi^-)$ — Γ_8/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.019	90		BIAGI	82B	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.0	90	0	YEH	74	HBC	Effective denom.=760
<1.1			DAUBER	69	HBC	
<5.0			FERRO-LUZZI	63	HBC	

$\Gamma(ne^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_9/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 3.2	90	0	YEH	74	HBC	Effective denom.=715
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<10	90		BINGHAM	65	RVUE	

$\Gamma(n\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ — Γ_{10}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<15.3	90	0	YEH	74	HBC	Effective denom.=150

$\Gamma(p\pi^-\pi^-)/\Gamma(\Lambda\pi^-)$ — Γ_{11}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.7	90	0	YEH	74	HBC	Effective denom.=6200

$\Gamma(p\pi^-e^-\overline{\nu}_e)/\Gamma(\Lambda\pi^-)$ — Γ_{12}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.7	90	0	YEH	74	HBC	Effective denom.=6200

$\Gamma(p\pi^-\mu^-\overline{\nu}_\mu)/\Gamma(\Lambda\pi^-)$ — Γ_{13}/Γ_1

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.7	90	0	YEH	74	HBC	Effective denom.=6200

$\Gamma(p\mu^-\mu^-)/\Gamma(\Lambda\pi^-)$ — Γ_{14}/Γ_1

A ΔL=2 decay, forbidden by total lepton number conservation.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<3.7	90	[7] LITTENBERG	92B	HBC	Uses YEH 74 data

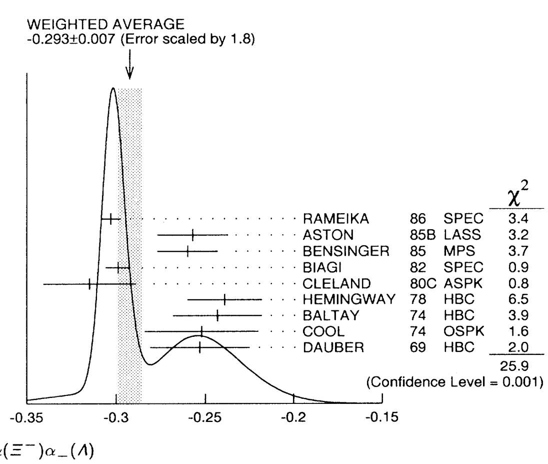
[7] This LITTENBERG 92B limit and the identical YEH 74 limits for the preceding three modes all result from nonobservance of any 3-prong decays of the Ξ^-. One could as well apply the limit to the *sum* of the four modes.

Ξ^- DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings.

$\alpha(\Xi^-)\alpha_-(\Lambda)$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.293±0.007 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram below.				
−0.303±0.004±0.004	192k	RAMEIKA	86	SPEC	400 GeV pBe
−0.257±0.020	11k	ASTON	85B	LASS	11 GeV/c K^-p
−0.260±0.017	21k	BENSINGER	85	MPS	5 GeV/c K^-p
−0.299±0.007	150k	BIAGI	82	SPEC	SPS hyperon beam
−0.315±0.026	9046	CLELAND	80C	ASPK	BNL hyperon beam
−0.239±0.021	6599	HEMINGWAY	78	HBC	4.2 GeV/c K^-p
−0.243±0.025	4303	BALTAY	74	HBC	1.75 GeV/c K^-p
−0.252±0.032	2436	COOL	74	OSPK	1.8 GeV/c K^-p
−0.253±0.028	2781	DAUBER	69	HBC	



α FOR $\Xi^- \rightarrow \Lambda\pi^-$

The above average, $\alpha(\Xi^-)\ \alpha_-(\Lambda) = -0.293 \pm 0.007$, where the error includes a scale factor of 1.8, divided by our current average $\alpha_-(\Lambda) = 0.642 \pm 0.013$, gives the following value for $\alpha(\Xi^-)$.

VALUE	DOCUMENT ID
−0.456±0.014 OUR EVALUATION	Error includes scale factor of 1.8.

ϕ ANGLE FOR $\Xi^- \rightarrow \Lambda\pi^-$ — $(\tan\phi = \beta/\gamma)$

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
4 ± 4 OUR AVERAGE					
5 ±10	11k	ASTON	85B	LASS	K^-p
14.7±16.0	21k	[8] BENSINGER	85	MPS	5 GeV/c K^-p
11 ± 9	4303	BALTAY	74	HBC	1.75 GeV/c K^-p
5 ±16	2436	COOL	74	OSPK	1.8 GeV/c K^-p
−26 ±30	2724	BINGHAM	70B	OSPK	
−14 ±11	2781	DAUBER	69	HBC	Uses $\alpha_\Lambda = 0.647 \pm 0.020$
0 ±12	1004	[9] BERGE	66	HBC	
0 ±20.4	364	[9] LONDON	66	HBC	Using $\alpha_\Lambda = 0.62$
54 ±30	356	[9] CARMONY	64B	HBC	

[8] BENSINGER 85 used $\alpha_\Lambda = 0.642 \pm 0.013$.

[9] The errors have been multiplied by 1.2 due to approximations used for the Ξ polarization; see DAUBER 69 for a discussion.

g_A / g_V FOR $\Xi^- \rightarrow \Lambda e^-\overline{\nu}_e$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.25±0.05	1992	[10] BOURQUIN	83	SPEC	SPS hyperon beam

[10] BOURQUIN 83 assumes that $g_2 = 0$. Also, the sign has been changed to agree with our conventions, given in the "Note on Baryon Decay Parameters" in the neutron Listings.

Ξ^- REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

DUBBS	94	PRL 72 808	+Albuquerque, Bondar+	(FNAL E761 Collab.)
DURYEA	92	PRL 68 768	+Guglielmo, Heller+	(MINN, FNAL, MICH, RUTG)
LITTENBERG	92B	PR D46 R892	+Shrock	(BNL, STON)
HO	90	PRL 65 1713	+Longo, Nguyen, Luk+	(MICH, FNAL, MINN, RUTG)
Also	91	PR D44 3402	Ho, Longo, Nguyen, Luk+	(MICH, FNAL, MINN, RUTG)
TROST	89	PR D40 1703	+McCliment, Newsom, Hseuh, Mueller+	(FNAL-715 Collab.)
BIAGI	87B	ZPHY C35 143	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
RAMEIKA	86	PR D33 3172	+Beretvas, Deck+	(RUTG, MICH, WISC, MINN)
ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
BENSINGER	85	NP B252 561	+	(CHIC, ELMT, FNAL, ISU, PNPI, MASD)
BOURQUIN	84	NP B241 1	+	(BRIS, GEVA, HEIDP, LALO, RAL, STRB)
RAMEIKA	84	PRL 52 581	+Beretvas, Deck+	(RUTG, MICH, WISC, MINN)
BOURQUIN	83	ZPHY C21 1	+Brown+	(BRIS, GEVA, HEIDP, LALO, RL, STRB)
BIAGI	82	PL 112B 265	+	(BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RL)
BIAGI	82B	PL 112B 277	+	(LOQM, GEVA, RL, HEIDP, CAVE, LAUS, BRIS)
CLELAND	80C	PR D21 12	+Cooper, Dris, Engels, Herbert+	(PITT, BNL)
THOMPSON	80	PR D21 25	+Cleland, Cooper, Dris, Engels+	(PITT, BNL)
BOURQUIN	79	PL 87B 297	+	(BRIS, GEVA, HEIDP, ORSAY, RHEL, STRB)
HEMINGWAY	78	NP B142 205	+Armenteros+	(CERN, ZEEM, NIJM, OXF)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
BALTAY	74	PR D9 49	+Bridgewater, Cooper, Gershwin+	(COLU, BING) J
COOL	74	PR D10 792	+Giacomelli, Jenkins, Kycia, Leontic, Li+	(BNL)
Also	72	PRL 29 1630	Cool, Giacomelli, Jenkins, Kycia, Leontic+	(BNL)
YEH	74	PR D10 3545	+Gaigalas, Smith, Zendle, Baltay+	(BING, COLU)
MAYEUR	72	NP B47 333	+VanBinst, Wilquet+	(BRUX, CERN, TUFTS, LOUC)
VOTRUBA	72	NP B45 77	+Safder, Ratcliffe	(BIRM, EDIN)
WILQUET	72	PL 42B 372	+Fliagine, Guy+	(BRUX, CERN, TUFTS, LOUC)
DUCLOS	71	NP B32 493	+Freytag, Heintze, Heinzelmann, Jones+	(CERN)
BINGHAM	70B	PR D1 3010	+Cook, Humphrey, Sander+	(UCSD, WASH)
GOLDWASSER	70	PR D1 1960	+Schultz	(ILL)
STONE	70	PL 32B 515	+Berlinghieri, Bromberg, Cohen, Ferbel+	(ROCH)
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL) J
SHEN	67	PL 25B 443	+Firestone, Goldhaber	(UCB, LRL)
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL)
CHIEN	66	PR 152 1171	+Lach, Sandweiss, Taft, Yeh, Oren+	(YALE, BNL)
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA)
BINGHAM	65	PRSL 285 202		(CERN)
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
Also	65	Thesis	Pjerrou	(UCLA)
BADIER	64	Dubna Conf. 1 593	+Demoulin, Barloutaud+	(EPOL, SACL, ZEEM)
CARMONY	64B	PRL 12 482	+Pjerrou, Schlein, Slater, Stork+	(UCLA) J
HUBBARD	64	PR 135B 183	+Berge, Kalbfleisch, Shafer+	(LRL)
FERRO-LUZZI	63	PR 130 1568	+Alston-Garnjost, Rosenfeld, Wojcicki	(LRL)
JAUNEAU	63D	Siena Conf. 4	+	(EPOL, CERN, LOUC, RHEL, BERG)
Also	63B	PL 5 261	Jauneau+	(EPOL, CERN, LOUC, RHEL, BERG)
SCHNEIDER	63	PL 4 360		(CERN)

Ξ RESONANCES

The accompanying table gives our evaluation of the present status of the Ξ resonances. Not much is known about Ξ resonances. This is because (1) they can only be produced as a part of a final state, and so the analysis is more complicated than if direct formation were possible, (2) the production cross sections are small (typically a few μb), and (3) the final states are topologically complicated and difficult to study with electronic techniques. Thus early information about Ξ resonances came entirely from bubble chamber experiments, where the numbers of events are small, and only in the 1980's did electronic experiments make any significant contributions. However, there has not been a single new piece of data on Ξ resonances since our 1988 edition.

For a detailed earlier review, see Meadows [1].

Reference

1. B.T. Meadows, in *Proceedings of the IVth International Conference on Baryon Resonances* (Toronto, 1980), ed. N. Isgur, p. 283.

Table 1. The status of the Ξ resonances. Only those with an overall status of *** or **** are included in the Baryon Summary Table.

Particle	$L_{2I\cdot 2J}$	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
Ξ(1318)	P_{11}	****					Decays weakly
Ξ(1530)	P_{13}	****	****				
Ξ(1620)		*	*				
Ξ(1690)		***		***	**		
Ξ(1820)	D_{13}	***	**	***	**	**	
Ξ(1950)		***	**	**		*	
Ξ(2030)	1	***		**	***		
Ξ(2120)		*		*			
Ξ(2250)		**					3-body decays
Ξ(2370)	1	**					3-body decays
Ξ(2500)		*		*	*		3-body decays

**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

Ξ(1530) P_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ****

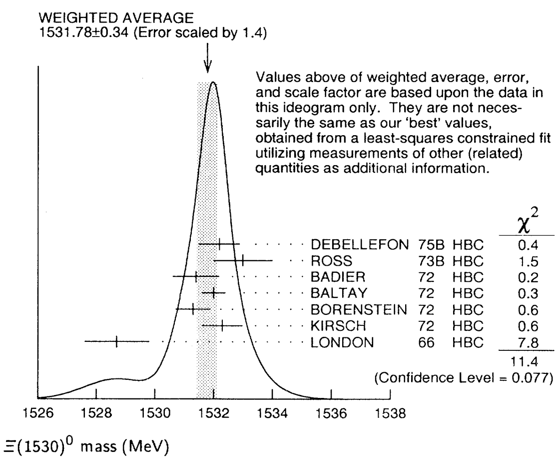
This is the only Ξ resonance whose properties are all reasonably well known. Spin-parity $3/2^+$ is favored by the data.

We use only those determinations of the mass and width that are accompanied by some discussion of systematics and resolution.

Ξ(1530) MASSES

Ξ(1530)^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1531.80±0.32 OUR FIT Error includes scale factor of 1.3.				
1531.78±0.34 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
1532.2 ±0.7		DEBELLEFON 75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
1533 ±1		ROSS 73B	HBC	$K^- p \to \Xi \overline{K} \pi(\pi)$
1531.4 ±0.8	59	BADIER 72	HBC	$K^- p$ 3.95 GeV/c
1532.0 ±0.4	1262	BALTAY 72	HBC	$K^- p$ 1.75 GeV/c
1531.3 ±0.6	324	BORENSTEIN 72	HBC	$K^- p$ 2.2 GeV/c
1532.3 ±0.7	286	KIRSCH 72	HBC	$K^- p$ 2.87 GeV/c
1528.7 ±1.1	76	LONDON 66	HBC	$K^- p$ 2.24 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1532.1 ±0.4	1244	ASTON 85B	LASS	$K^- p$ 11 GeV/c
1532.1 ±0.6	2700	[1] BAUBILLIER 81B	HBC	$K^- p$ 8.25 GeV/c
1530 ±1	450	BIAGI 81	SPEC	SPS hyperon beam
1527 ±6	80	SIXEL 79	HBC	$K^- p$ 10 GeV/c
1535 ±4	100	SIXEL 79	HBC	$K^- p$ 16 GeV/c
1533.6 ±1.4	97	BERTHON 74	HBC	Quasi-2-body σ



Ξ(1530)$^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1535.0±0.6 OUR FIT				
1535.2±0.8 OUR AVERAGE				
1534.5±1.2		DEBELLEFON 75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
1535.3±2.0		ROSS 73B	HBC	$K^- p \to \Xi \overline{K} \pi(\pi)$
1536.2±1.6	185	KIRSCH 72	HBC	$K^- p$ 2.87 GeV/c
1535.7±3.2	38	LONDON 66	HBC	$K^- p$ 2.24 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1540 ±3	48	BERTHON 74	HBC	Quasi-2-body σ
1534.7±1.1	334	BALTAY 72	HBC	$K^- p$ 1.75 GeV/c

$m_{\Xi(1530)^-} - m_{\Xi(1530)}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
3.2±0.6 OUR FIT			
2.9±0.9 OUR AVERAGE			
2.7±1.0	BALTAY 72	HBC	$K^- p$ 1.75 GeV/c
2.0±3.2	MERRILL 66	HBC	$K^- p$ 1.7–2.7 GeV/c
5.7±3.0	PJERROU 65B	HBC	$K^- p$ 1.8–1.95 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.9±1.8	[2] KIRSCH 72	HBC	$K^- p$ 2.87 GeV/c
7 ±4	[2] LONDON 66	HBC	$K^- p$ 2.24 GeV/c

$\Xi(1530)$ WIDTHS

$\Xi(1530)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
9.1±0.5 OUR AVERAGE					
9.5±1.2		DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
9.1±2.4		ROSS	73B	HBC	$K^- p \to \Xi \overline{K} \pi(\pi)$
11 ±2		BADIER	72	HBC	$K^- p$ 3.95 GeV/c
9.0±0.7		BALTAY	72	HBC	$K^- p$ 1.75 GeV/c
8.4±1.4		BORENSTEIN	72	HBC	$\Xi^- \pi^+$
11.0±1.8		KIRSCH	72	HBC	$\Xi^- \pi^+$
7 ±7		BERGE	66	HBC	$K^- p$ 1.5–1.7 GeV/c
8.5±3.5		LONDON	66	HBC	$K^- p$ 2.24 GeV/c
7 ±2		SCHLEIN	63B	HBC	$K^- p$ 1.8, 1.95 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
12.8±1.0	2700	[1] BAUBILLIER	81B	HBC	$K^- p$ 8.25 GeV/c
19 ±6	80	[3] SIXEL	79	HBC	$K^- p$ 10 GeV/c
14 ±5	100	[3] SIXEL	79	HBC	$K^- p$ 16 GeV/c

$\Xi(1530)^-$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$9.9^{+1.7}_{-1.9}$ OUR AVERAGE				
9.6±2.8	DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
8.3±3.6	ROSS	73B	HBC	$K^- p \to \Xi \overline{K} \pi(\pi)$
$7.8^{+3.5}_{-7.8}$	BALTAY	72	HBC	$K^- p$ 1.75 GeV/c
16.2±4.6	KIRSCH	72	HBC	$\Xi^- \pi^0$, $\Xi^0 \pi^-$

$\Xi(1530)$ POLE POSITIONS

$\Xi(1530)^0$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1531.6±0.4	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)^0$ IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
4.45±0.35	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)^-$ REAL PART

VALUE	DOCUMENT ID	COMMENT
1534.4±1.1	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)^-$ IMAGINARY PART

VALUE	DOCUMENT ID	COMMENT
$3.9^{+1.75}_{-3.9}$	LICHTENBERG74	Using HABIBI 73

$\Xi(1530)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Xi\pi$	100 %	
Γ_2	$\Xi\gamma$	<4 %	90%

$\Xi(1530)$ BRANCHING RATIOS

$\Gamma(\Xi\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.04	90	KALBFLEISCH	75	HBC	$K^- p$ 2.18 GeV/c

$\Xi(1530)$ FOOTNOTES

[1] BAUBILLIER 81B is a fit to the inclusive spectrum. The resolution (5 MeV) is not unfolded.

[2] Redundant with data in the mass Listings.

[3] SIXEL 79 doesn't unfold the experimental resolution of 15 MeV.

$\Xi(1530)$ REFERENCES

ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)
BAUBILLIER	81B	NP B192 1	+	(BIRM, CERN, GLAS, MSU, CURIN)
BIAGI	81	ZPHY C9 305	+	(BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RHEL)
SIXEL	79	NP B159 125	+Bottcher+	(AACH3, BERL, CERN, LOIC, VIEN)
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
KALBFLEISCH	75	PR D11 987	+Strand, Chapman	(BNL, MICH)
BERTHON	74	NC 21A 146	+Tristram+	(CDEF, RHEL, SACL, STRB)
LICHTENBERG	74	PR D10 3865		(IND)
Also	74B	Private Comm.	Lichtenberg	(IND)
HABIBI	73	Thesis Nevis 199		(COLU)
ROSS	73B	Purdue Conf. 355	+Lloyd, Radojicic	(OXF)
BADIER	72	NP B37 429	+Barrelet, Charlton, Videau	(EPOL)
BALTAY	72	PL 42B 129	+Bridgewater, Cooper, Gershwin+	(COLU, BING)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH) I
KIRSCH	72	NP B40 349	+Schmidt, Chang+	(BRAN, UMD, SYRA, TUFTS) I
BERGE	66	PR 147 945	+Eberhard, Hubbard, Merrill+	(LRL) I
LONDON	66	PR 143 1034	+Rau, Goldberg, Lichtman+	(BNL, SYRA) IJ
MERRILL	66	Thesis UCRL 16455		(LRL) JP
PJERROU	65B	PRL 14 275	+Schlein, Slater, Smith, Stork, Ticho	(UCLA)
SCHLEIN	63B	PRL 11 167	+Carmony, Pjerrou, Slater, Stork, Ticho	(UCLA) IJP

OTHER RELATED PAPERS

MAZZUCATO	81	NP B178 1	+Pennino+	(AMST, CERN, NIJM, OXF)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFTS)
BRIEFEL	75	PR D12 1859	+Gourevitch+	(BRAN, UMD, SYRA, TUFTS)
HUNGERBU...	74	PR D10 2051	Hungerbuhler, Majka+	(YALE, FNAL, BNL, PITT)
BUTTON-...	66	PR 142 883	Button-Shafer, Lindsey, Murray, Smith	(LRL) JP

$\Xi(1620)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

What little evidence there is consists of weak signals in the $\Xi\pi$ channel. A number of other experiments (e.g., BORENSTEIN 72 and HASSALL 81) have looked for but not seen any effect.

$\Xi(1620)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 1620 OUR ESTIMATE					
1624± 3	31	BRIEFEL	77	HBC	$K^- p$ 2.87 GeV/c
1633±12	34	DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
1606± 6	29	ROSS	72	HBC	$K^- p$ 3.1–3.7 GeV/c

$\Xi(1620)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
22.5	31	[1] BRIEFEL	77	HBC	$K^- p$ 2.87 GeV/c
40 ±15	34	DEBELLEFON	75B	HBC	$K^- p \to \Xi^- \overline{K} \pi$
21 ± 7	29	ROSS	72	HBC	$K^- p \to \Xi^- \pi^+ K^{*0}(892)$

$\Xi(1620)$ DECAY MODES

	Mode
Γ_1	$\Xi\pi$

$\Xi(1620)$ FOOTNOTES

[1] The fit is insensitive to values between 15 and 30 MeV.

$\Xi(1620)$ REFERENCES

HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAVE, MSU)
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFTS)
Also	70	Duke Conf. 317	Briefel+	(BRAN, UMD, SYRA, TUFTS)
Also	75	PR D12 1859	Briefel, Gourevitch+	(BRAN, UMD, SYRA, TUFTS)
DEBELLEFON	75B	NC 28A 289	De Bellefon, Berthon, Billoir+	(CDEF, SACL)
BORENSTEIN	72	PR D5 1559	+Danburg, Kalbfleisch+	(BNL, MICH) I
ROSS	72	PL 38B 177	+Buran, Lloyd, Mulvey, Radojicic	(OXF) I

OTHER RELATED PAPERS

HUNGERBU...	74	PR D10 2051	Hungerbuhler, Majka+	(YALE, FNAL, BNL, PITT)
SCHMIDT	73	Purdue Conf. 363		(BRAN)
KALBFLEISCH	70	Duke Conf. 331		(BNL) I
APSELL	69	PRL 23 884	+	(BRAN, UMD, SYRA, TUFTS)
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)

$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗∗

DIONISI 78 sees a threshold enhancement in both the neutral and negatively charged $\Sigma\overline{K}$ mass spectra in $K^- p \to (\Sigma\overline{K}) K\pi$ at 4.2 GeV/c. The data from the $\Sigma\overline{K}$ channels alone cannot distinguish between a resonance and a large scattering length. Weaker evidence at the same mass is seen in the corresponding $\Lambda\overline{K}$ channels, and a coupled-channel analysis yields results consistent with a new Ξ.

BIAGI 81 sees an enhancement at 1700 MeV in the diffractively produced ΛK^- system. A peak is also observed in the $\Lambda\overline{K}^0$ mass spectrum at 1660 MeV that is consistent with a 1720 MeV resonance decaying to $\Sigma^0\overline{K}^0$, with the γ from the Σ^0 decay not detected.

BIAGI 87 provides further confirmation of this state in diffractive dissociation of Ξ^- into ΛK^-. The significance claimed is 6.7 standard deviations.

$\Xi(1690)$ MASSES

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
1690±10 OUR ESTIMATE	This is only an educated guess; the error given is larger than the error on the average of the published values.

$\Xi(1690)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1699±5	175	[1] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c
1684±5	183	[2] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1691.1± 1.9±2.0	104	BIAGI	87	SPEC	Ξ^- Be 116 GeV
1700 ±10	150	[3] BIAGI	81	SPEC	Ξ^- H 100, 135 GeV
1694 ± 6	45	[4] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)$ WIDTHS

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
<50 OUR ESTIMATE	

$\Xi(1690)^0$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
44±23	175	[1] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c
20± 4	183	[2] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)^-$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 8	90	104	BIAGI	87	SPEC	Ξ^- Be 116 GeV
47±14		150	[3] BIAGI	81	SPEC	Ξ^- H 100, 135 GeV
26± 6		45	[4] DIONISI	78	HBC	$K^- p$ 4.2 GeV/c

$\Xi(1690)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	seen
Γ_2	$\Sigma \overline{K}$	seen
Γ_3	$\Xi \pi$	
Γ_4	$\Xi^- \pi^+ \pi^0$	
Γ_5	$\Xi^- \pi^+ \pi^-$	possibly seen
Γ_6	$\Xi(1530)\pi$	

$\Xi(1690)$ BRANCHING RATIOS

$\Gamma(\Lambda \overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
seen	104	BIAGI	87	SPEC	–	Ξ^- Be 116 GeV

$\Gamma(\Sigma \overline{K})/\Gamma(\Lambda \overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
2.7±0.9	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c
3.1±1.4	DIONISI	78	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi \pi)/\Gamma(\Sigma \overline{K})$ — Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi^- \pi^+ \pi^0)/\Gamma(\Sigma \overline{K})$ — Γ_4/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.04	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi^- \pi^+ \pi^-)/\Gamma_{total}$ — Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
possibly seen	4	BIAGI	87	SPEC	–	Ξ^- Be 116 GeV

$\Gamma(\Xi^- \pi^+ \pi^-)/\Gamma(\Sigma \overline{K})$ — Γ_5/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.03	DIONISI	78	HBC	–	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma(\Sigma \overline{K})$ — Γ_6/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.06	DIONISI	78	HBC	–	$K^- p$ 4.2 GeV/c

$\Xi(1690)$ FOOTNOTES

[1] From a fit to the $\Sigma^+ K^-$ spectrum.
[2] From a coupled-channel analysis of the $\Sigma^+ K^-$ and $\Lambda \overline{K}^0$ spectra.
[3] A fit to the inclusive spectrum from $\Xi^- N \rightarrow \Lambda K^- X$.
[4] From a coupled-channel analysis of the $\Sigma^0 K^-$ and ΛK^- spectra.

$\Xi(1690)$ REFERENCES

BIAGI 87 ZPHY C34 15 + (BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL) I
BIAGI 81 ZPHY C9 305 + (BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RHEL)
DIONISI 78 PL 80B 145 +Diaz, Armenteros+ (CERN, AMST, NIJM, OXF) I

$\Xi(1820)$ D_{13}

$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ Status: ∗∗∗

The clearest evidence is an 8-standard-deviation peak in ΛK^- seen by GAY 76. TEODORO 78 favors J=3/2, but cannot make a parity discrimination. BIAGI 87C is consistent with J=3/2 and favors negative parity for this J value.

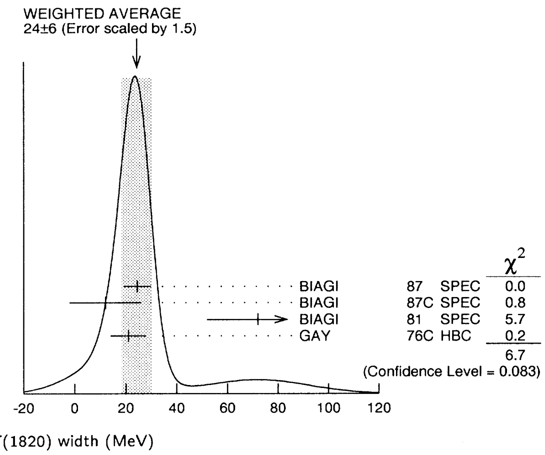
$\Xi(1820)$ MASS

We only average the measurements that appear to us to be most significant and best determined.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1823 ± 5 OUR ESTIMATE						
1823.4± 1.4 OUR AVERAGE						
1819.4± 3.1±2.0	280	[1] BIAGI	87	SPEC	0	Ξ^- Be → (ΛK^-) X
1826 ± 3 ±1	54	BIAGI	87C	SPEC	0	Ξ^- Be → $(\Lambda \overline{K}^0)$ X
1822 ± 6		JENKINS	83	MPS	–	$K^- p \rightarrow K^+$ (MM)
1830 ± 6	300	BIAGI	81	SPEC	–	SPS hyperon beam
1823 ± 2	130	GAY	76C	HBC	–	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1797 ±19	74	BRIEFEL	77	HBC	0	$K^- p$ 2.87 GeV/c
1829 ± 9	68	BRIEFEL	77	HBC	–0	$\Xi(1530)\pi$
1860 ±14	39	BRIEFEL	77	HBC	–	$\Sigma^- \overline{K}^0$
1870 ± 9	44	BRIEFEL	77	HBC	0	$\Lambda \overline{K}^0$
1813 ± 4	57	BRIEFEL	77	HBC	–	ΛK^-
1807 ±27		DIBIANCA	75	DBC	–0	$\Xi \pi \pi$, $\Xi^* \pi$
1762 ± 8	28	[2] BADIER	72	HBC	–0	$\Xi \pi$, $\Xi \pi \pi$, YK
1838 ± 5	38	[2] BADIER	72	HBC	–0	$\Xi \pi$, $\Xi \pi \pi$, YK
1830 ±10	25	[3] CRENNELL	70B	DBC	–0	3.6, 3.9 GeV/c
1826 ±12		[4] CRENNELL	70B	DBC	–0	3.6, 3.9 GeV/c
1830 ±10	40	ALITTI	69	HBC	–	Λ, $\Sigma \overline{K}$
1814 ± 4	30	BADIER	65	HBC	0	$\Lambda \overline{K}^0$
1817 ± 7	29	SMITH	65C	HBC	–0	$\Lambda \overline{K}^0$, ΛK^-
1770		HALSTEINSLID	63	FBC	–0	K^- freon 3.5 GeV/c

$\Xi(1820)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
24 $^{+15}_{-10}$ OUR ESTIMATE						
24 ± 6 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.						
24.6± 5.3	280	[1] BIAGI	87	SPEC	0	Ξ^- Be → (ΛK^-) X
12 ±14 ±1.7	54	BIAGI	87C	SPEC	0	Ξ^- Be → $(\Lambda \overline{K}^0)$ X
72 ±20	300	BIAGI	81	SPEC	–	SPS hyperon beam
21 ± 7	130	GAY	76C	HBC	–	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •						
99 ±57	74	BRIEFEL	77	HBC	0	$K^- p$ 2.87 GeV/c
52 ±34	68	BRIEFEL	77	HBC	–0	$\Xi(1530)\pi$
72 ±17	39	BRIEFEL	77	HBC	–	$\Sigma^- \overline{K}^0$
44 ±11	44	BRIEFEL	77	HBC	0	$\Lambda \overline{K}^0$
26 ±11	57	BRIEFEL	77	HBC	–	ΛK^-
85 ±58		DIBIANCA	75	DBC	–0	$\Xi \pi \pi$, $\Xi^* \pi$
51 ±13		[2] BADIER	72	HBC	–0	Lower mass
58 ±13		[2] BADIER	72	HBC	–0	Higher mass
103 $^{+38}_{-24}$		[3] CRENNELL	70B	DBC	–0	3.6, 3.9 GeV/c
48 $^{+36}_{-19}$		[4] CRENNELL	70B	DBC	–0	3.6, 3.9 GeV/c
55 $^{+40}_{-20}$		ALITTI	69	HBC	–	Λ, $\Sigma \overline{K}$
12 ± 4		BADIER	65	HBC	0	$\Lambda \overline{K}^0$
30 ± 7		SMITH	65B	HBC	–0	$\Lambda \overline{K}$
< 80		HALSTEINSLID	63	FBC	–0	K^- freon 3.5 GeV/c



Ξ(1820) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	large
Γ_2	$\Sigma \overline{K}$	small
Γ_3	$\Xi \pi$	small
Γ_4	$\Xi(1530)\pi$	small
Γ_5	$\Xi \pi \pi$ (not $\Xi(1530)\pi$)	

Ξ(1820) BRANCHING RATIOS

The dominant modes seem to be $\Lambda \overline{K}$ and (perhaps) $\Xi(1530)\pi$, but the branching fractions are very poorly determined.

$\Gamma(\Lambda \overline{K})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi \pi)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.10±0.10	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi \pi)/\Gamma(\Lambda \overline{K})$ — Γ_3/Γ_1

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.36	95	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
0.20±0.20		BADIER	65	HBC	0	$K^- p$ 3 GeV/c

$\Gamma(\Xi \pi)/\Gamma(\Xi(1530)\pi)$ — Γ_3/Γ_4

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
$1.5^{+0.6}_{-0.4}$	APSELL	70	HBC	0	$K^- p$ 2.87 GeV/c

$\Gamma(\Sigma \overline{K})/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.02	TRIPP	67	RVUE		Use SMITH 65C

$\Gamma(\Sigma \overline{K})/\Gamma(\Lambda \overline{K})$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.24±0.10	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	ASTON	85B	LASS		$K^- p$ 11 GeV/c
not seen	[5] HASSALL	81	HBC		$K^- p$ 6.5 GeV/c
<0.25	[6] DAUBER	69	HBC		$K^- p$ 2.7 GeV/c

$\Gamma(\Xi(1530)\pi)/\Gamma(\Lambda \overline{K})$ — Γ_4/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.38±0.27 OUR AVERAGE	Error includes scale factor of 2.3.				
1.0 ±0.3	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
0.26±0.13	SMITH	65C	HBC	−0	$K^- p$ 2.45–2.7 GeV/c

$\Gamma(\Xi \pi\pi$ (not $\Xi(1530)\pi))/\Gamma(\Lambda \overline{K})$ — Γ_5/Γ_1

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.30±0.20	BIAGI	87	SPEC	−	Ξ^- Be 116 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.14	[7] BADIER	65	HBC	0	1 st. dev. limit
>0.1	SMITH	65C	HBC	−0	$K^- p$ 2.45–2.7 GeV/c

$\Gamma(\Xi \pi\pi$ (not $\Xi(1530)\pi))/\Gamma(\Xi(1530)\pi)$ — Γ_5/Γ_4

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
consistent with zero	GAY	76C	HBC	−	$K^- p$ 4.2 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.3±0.5	[8] APSELL	70	HBC	0	$K^- p$ 2.87 GeV/c

Ξ(1820) FOOTNOTES

[1] BIAGI 87 also sees weak signals in the in the $\Xi^- \pi^+ \pi^-$ channel at 1782.6 ± 1.4 MeV (Γ = 6.0 ± 1.5 MeV) and 1831.9 ± 2.8 MeV (Γ = 9.6 ± 9.9 MeV).
[2] BADIER 72 adds all channels and divides the peak into lower and higher mass regions. The data can also be fitted with a single Breit-Wigner of mass 1800 MeV and width 150 MeV.
[3] From a fit to inclusive $\Xi\pi$, $\Xi\pi\pi$, and ΛK^- spectra.
[4] From a fit to inclusive $\Xi\pi$ and $\Xi\pi\pi$ spectra only.
[5] Including $\Xi\pi\pi$.
[6] DAUBER 69 uses in part the same data as SMITH 65C.
[7] For the decay mode $\Xi^- \pi^+ \pi^0$ only. This limit includes $\Xi(1530)\pi$.
[8] Or less. Upper limit for the 3-body decay.

Ξ(1820) REFERENCES

BIAGI	87	ZPHY C34 15	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)	
BIAGI	87C	ZPHY C34 175	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)	JP
ASTON	85B	PR D32 2270	+Carnegie+	(SLAC, CARL, CNRC, CINC)	
JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, MASD)	
BIAGI	81	ZPHY C9 305	+	(BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RHEL)	
HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAVE, MSU)	
TEODORO	78	PL 77B 451	+Diaz, Dionisi, Blokzijl+	(AMST, CERN, NIJM, OXF)	JP
BRIEFEL	77	PR D16 2706	+Gourevitch, Chang+	(BRAN, UMD, SYRA, TUFTS)	
Also	69	PRL 23 884	Apsell+	(BRAN, UMD, SYRA, TUFTS)	
GAY	76	NC 31A 593	+Jeanneret, Bogdanski+	(NEUC, LAUS, LIVP, CURIN)	
GAY	76C	PL 62B 477	+Armenteros, Berge+	(AMST, CERN, NIJM)	IJ
DIBIANCA	75	NP B98 137	+Endorf	(CMU)	
BADIER	72	NP B37 429	+Barrelet, Charlton, Videau	(EPOL)	
APSELL	70	PRL 24 777	+	(BRAN, UMD, SYRA, TUFTS)	I
CRENNELL	70B	PR D1 847	+Karshon, Lai, O'Neall, Scarr, Schumann	(BNL)	
ALITTI	69	PRL 22 79	+Barnes, Flaminio, Metzger+	(BNL, SYRA)	I
DAUBER	69	PR 179 1262	+Berge, Hubbard, Merrill, Miller	(LRL)	
TRIPP	67	NP B3 10	+Leith+	(LRL, SLAC, CERN, HEID, SACL)	
BADIER	65	PL 16 171	+Demoulin, Goldberg+	(EPOL, SACL, AMST)	I
SMITH	65B	Athens Conf. 251	+Lindsey	(LRL)	
SMITH	65C	PRL 14 25	+Lindsey, Button-Shafer, Murray	(LRL)	IJP
HALSTEINSLID	63	Siena Conf. 1 73	+	(BERG, CERN, EPOL, RHEL, LOUC)	I

OTHER RELATED PAPERS

TEODORO	78	PL 77B 451	+Diaz, Dionisi, Blokzijl+	(AMST, CERN, NIJM, OXF)	JP
BRIEFEL	75	PR D12 1859	+Gourevitch+	(BRAN, UMD, SYRA, TUFTS)	
SCHMIDT	73	Purdue Conf. 363		(BRAN)	
MERRILL	68	PR 167 1202	+Shafer	(LRL)	
SMITH	64	PRL 13 61	+Lindsey, Murray, Button-Shafer+	(LRL)	IJP

Ξ(1950)

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗∗

We list here everything reported between 1875 and 2000 MeV. The accumulated evidence for a Ξ near 1950 MeV seems strong enough to include a $\Xi(1950)$ in the main Baryon Table, but not much can be said about its properties. In fact, there may be more than one Ξ near this mass.

Ξ(1950) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1950±15 OUR ESTIMATE					
1944± 9	129	BIAGI	87	SPEC	Ξ^- Be → $(\Xi^-\pi^+)\pi^- X$
1963± 5±2	63	BIAGI	87C	SPEC	Ξ^- Be → $(\Lambda \overline{K}^0)$ X
1937± 7	150	BIAGI	81	SPEC	SPS hyperon beam
1961±18	139	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^- \pi^+ X$
1936±22	44	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^0 \pi^- X$
1964±10	56	BRIEFEL	77	HBC	$\Xi(1530)\pi$
1900±12		DIBIANCA	75	DBC	$\Xi\pi$
1952±11	25	ROSS	73C		$(\Xi\pi)^-$
1956± 6	29	BADIER	72	HBC	$\Xi\pi$, $\Xi\pi\pi$, YK
1955±14	21	GOLDWASSER	70	HBC	$\Xi\pi$
1894±18	66	DAUBER	69	HBC	$\Xi\pi$
1930±20	27	ALITTI	68	HBC	$\Xi^-\pi^+$
1933±16	35	BADIER	65	HBC	$\Xi^-\pi^+$

Ξ(1950) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
60±20 OUR ESTIMATE					
100±31	129	BIAGI	87	SPEC	$\Xi^- \text{Be} \to (\Xi^- \pi^+)\pi^- X$
25±15±1.2	63	BIAGI	87C	SPEC	$\Xi^- \text{Be} \to (\Lambda \overline{K}^0) X$
60± 8	150	BIAGI	81	SPEC	SPS hyperon beam
159±57	139	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^- \pi^+ X$
87±26	44	BRIEFEL	77	HBC	2.87 $K^- p \to \Xi^0 \pi^- X$
60±39	56	BRIEFEL	77	HBC	$\Xi(1530)\pi$
63±78		DIBIANCA	75	DBC	$\Xi\pi$
38±10		ROSS	73C		$(\Xi\pi)^-$
35±11	29	BADIER	72	HBC	$\Xi\pi$, $\Xi\pi\pi$, YK
56±26	21	GOLDWASSER	70	HBC	$\Xi\pi$
98±23	66	DAUBER	69	HBC	$\Xi\pi$
80±40	27	ALITTI	68	HBC	$\Xi^- \pi^+$
140±35	35	BADIER	65	HBC	$\Xi^- \pi^+$

Ξ(1950) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}$	seen
Γ_2	$\Sigma \overline{K}$	possibly seen
Γ_3	$\Xi\pi$	seen
Γ_4	$\Xi(1530)\pi$	
Γ_5	$\Xi\pi\pi$ (not $\Xi(1530)\pi$)	

Ξ(1950) BRANCHING RATIOS

$\Gamma(\Sigma\overline{K})/\Gamma(\Lambda\overline{K})$ — **Γ_2/Γ_1**

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.3	90	0	BIAGI	87C	SPEC	Ξ^- Be 116 GeV

$\Gamma(\Sigma\overline{K})/\Gamma_{\text{total}}$ — **Γ_2/Γ**

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
possibly seen	17	HASSALL	81	HBC	$K^- p$ 6.5 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Xi(1530)\pi)$ — **Γ_3/Γ_4**

VALUE	DOCUMENT ID		TECN
$2.8^{+0.7}_{-0.6}$	APSELL	70	HBC

$\Gamma(\Xi\pi\pi(\text{not}\,\Xi(1530)\pi))/\Gamma(\Xi(1530)\pi)$ — **Γ_5/Γ_4**

VALUE	DOCUMENT ID		TECN
0.0±0.3	APSELL	70	HBC

Ξ(1950) REFERENCES

BIAGI 87 ZPHY C34 15 + (BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
BIAGI 87C ZPHY C34 175 + (BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
BIAGI 81 ZPHY C9 305 + (BRIS, CAVE, GEVA, HEIDP, LAUS, LOQM, RHEL)
HASSALL 81 NP B189 397 +Ansorge, Carter, Neale+ (CAVE, MSU)
BRIEFEL 77 PR D16 2706 +Gourevitch, Chang+ (BRAN, UMD, SYRA, TUFTS)
Also 70 Duke Conf. 317 Briefel+ (BRAN, UMD, SYRA, TUFTS)
DIBIANCA 75 NP B98 137 +Endorf (CMU)
ROSS 73C Purdue Conf. 345 +Lloyd, Radojicic (OXF)
BADIER 72 NP B37 429 +Barrelet, Charlton, Videau (EPOL)
APSELL 70 PRL 24 777 + (BRAN, UMD, SYRA, TUFTS) I
GOLDWASSER 70 PR D1 1960 +Schultz (ILL)
DAUBER 69 PR 179 1262 +Berge, Hubbard, Merrill, Miller (LRL) I
ALITTI 68 PRL 21 1119 +Flaminio, Metzger, Radojicic+ (BNL, SYRA) I
BADIER 65 PL 16 171 +Demoulin, Goldberg+ (EPOL, SACL, AMST) I

Ξ(2030)

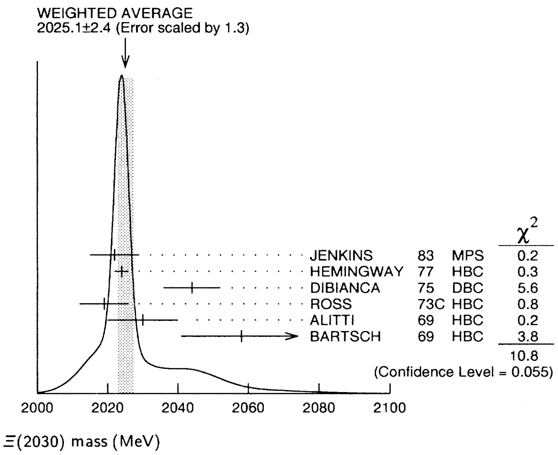
$I(J^P) = \frac{1}{2}(\geq \frac{5}{2}^?)$ Status: ∗∗∗

The evidence for this state has been much improved by HEMINGWAY 77, who see an eight standard deviation enhancement in $\Sigma\overline{K}$ and a weaker coupling to $\Lambda\overline{K}$. ALITTI 68 and HEMINGWAY 77 observe no signals in the $\Xi\pi\pi$ (or $\Xi(1530)\pi$) channel, in contrast to DIBIANCA 75. The decay $(\Lambda/\Sigma)\overline{K}\pi$ reported by BARTSCH 69 is also not confirmed by HEMINGWAY 77.

A moments analysis of the HEMINGWAY 77 data indicates at a level of three standard deviations that $J \geq 5/2$.

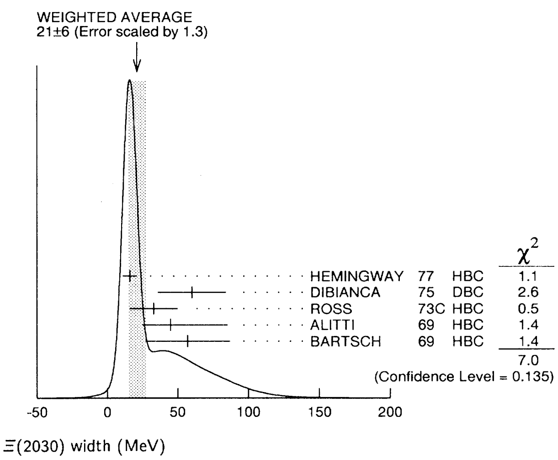
Ξ(2030) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2025 ± 5 OUR ESTIMATE						
2025.1± 2.4 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.					
2022 ± 7		JENKINS	83	MPS	−	$K^- p \to K^+$ MM
2024 ± 2	200	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c
2044 ± 8		DIBIANCA	75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
2019 ± 7	15	ROSS	73C	HBC	−0	$\Sigma\overline{K}$
2030 ±10	42	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
2058 ±17	40	BARTSCH	69	HBC	−0	$K^- p$ 10 GeV/c



Ξ(2030) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
20^{+15}_{-5} OUR ESTIMATE						
21± 6 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.					
16± 5	200	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c
60±24		DIBIANCA	75	DBC	−0	$\Xi\pi\pi$, $\Xi^*\pi$
33±17	15	ROSS	73C	HBC	−0	$\Sigma\overline{K}$
45^{+40}_{-20}		ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c
57±30		BARTSCH	69	HBC	−0	$K^- p$ 10 GeV/c



Ξ(2030) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}$	~ 20 %
Γ_2	$\Sigma\overline{K}$	~ 80 %
Γ_3	$\Xi\pi$	small
Γ_4	$\Xi(1530)\pi$	small
Γ_5	$\Xi\pi\pi$ (not $\Xi(1530)\pi$)	small
Γ_6	$\Lambda\overline{K}\pi$	small
Γ_7	$\Sigma\overline{K}\pi$	small

Ξ(2030) BRANCHING RATIOS

$\Gamma(\Xi\pi)/[\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi\pi)+\Gamma(\Xi(1530)\pi)]$ — **$\Gamma_3/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.30	ALITTI	69	HBC	−	1 standard dev. limit

$\Gamma(\Xi\pi)/\Gamma(\Sigma\overline{K})$ — **Γ_3/Γ_2**

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.19	95	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Lambda\overline{K})/[\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi\pi)+\Gamma(\Xi(1530)\pi)]$ $\Gamma_1/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.25 ± 0.15	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Lambda\overline{K})/\Gamma(\Sigma\overline{K})$ Γ_1/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.22 ± 0.09	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Sigma\overline{K})/[\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi\pi)+\Gamma(\Xi(1530)\pi)]$ $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.75 ± 0.20	ALITTI	69	HBC	−	$K^- p$ 3.9–5 GeV/c

$\Gamma(\Xi(1530)\pi)/[\Gamma(\Lambda\overline{K})+\Gamma(\Sigma\overline{K})+\Gamma(\Xi\pi)+\Gamma(\Xi(1530)\pi)]$ $\Gamma_4/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_4)$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15	ALITTI	69	HBC	−	1 standard dev. limit

$[\Gamma(\Xi(1530)\pi)+\Gamma(\Xi\pi\pi(\text{not }\Xi(1530)\pi))]/\Gamma(\Sigma\overline{K})$ $(\Gamma_4+\Gamma_5)/\Gamma_2$

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.11	95	[1] HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Lambda\overline{K}\pi)/\Gamma_{total}$ Γ_6/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BARTSCH	69	HBC	$K^- p$ 10 GeV

$\Gamma(\Lambda\overline{K}\pi)/\Gamma(\Sigma\overline{K})$ Γ_6/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.32	95	HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Sigma\overline{K}\pi)/\Gamma_{total}$ Γ_7/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
seen	BARTSCH	69	HBC	$K^- p$ 10 GeV

$\Gamma(\Sigma\overline{K}\pi)/\Gamma(\Sigma\overline{K})$ Γ_7/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<0.04	95	[2] HEMINGWAY	77	HBC	−	$K^- p$ 4.2 GeV/c

$\Xi(2030)$ FOOTNOTES

[1] For the decay mode $\Xi^-\pi^+\pi^-$ only.
[2] For the decay mode $\Sigma^\pm K^-\pi^\mp$ only.

$\Xi(2030)$ REFERENCES

JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, MASD)
HEMINGWAY	77	PL 68B 197	+Armenteros+	(AMST, CERN, NIJM, OXF) IJ
Also	76C	PL 62B 477	Gay, Armenteros, Berge+	(AMST, CERN, NIJM)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ROSS	73C	Purdue Conf. 345	+Lloyd, Radojicic	(OXF)
ALITTI	69	PRL 22 79	+Barnes, Flaminio, Metzger+	(BNL, SYRA) I
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)
ALITTI	68	PRL 21 1119	+Flaminio, Metzger, Radojicic+	(BNL, SYRA)

$\Xi(2120)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

$\Xi(2120)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 2120 OUR ESTIMATE					
2137 ± 4	18	[1] CHLIAPNIK...	79	HBC	$K^+ p$ 32 GeV/c
2123 ± 7		[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

$\Xi(2120)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
<20	18	[1] CHLIAPNIK...	79	HBC	$K^+ p$ 32 GeV/c
25 ± 12		[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

$\Xi(2120)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda\overline{K}$	seen

$\Xi(2120)$ BRANCHING RATIOS

$\Gamma(\Lambda\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	[1] CHLIAPNIK...	79	HBC	$K^+ p \to (\overline{\Lambda}K^+)$ X
seen	[2] GAY	76C	HBC	$K^- p$ 4.2 GeV/c

$\Xi(2120)$ FOOTNOTES

[1] CHLIAPNIKOV 79 does not uniquely identify the K^+ in the $(\overline{\Lambda}K^+)$ X final state. It also reports bumps with fewer events at 2240, 2540, and 2830 MeV.
[2] GAY 76C sees a 4-standard deviation signal. However, HEMINGWAY 77, with more events from the same experiment points out that the signal is greatly reduced if a cut is made on the 4-momentum u. This suggests an anomalous production mechanism if the $\Xi(2120)$ is real.

$\Xi(2120)$ REFERENCES

CHLIAPNIK...	79	NP B158 253	Chliapnikov, Gerdyukov+	(CERN, BELG, MONS)
HEMINGWAY	77	PL 68B 197	+Armenteros+	(AMST, CERN, NIJM, OXF)
GAY	76C	PL 62B 477	+Armenteros, Berge+	(AMST, CERN, NIJM)

$\Xi(2250)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

The evidence for this state is mixed. BARTSCH 69 sees a bump of not much statistical significance in $\Lambda\overline{K}\pi$, $\Sigma\overline{K}\pi$, and $\Xi\pi\pi$ mass spectra. GOLDWASSER 70 sees a narrower bump in $\Xi\pi\pi$ at a higher mass. Not seen by HASSALL 81 with 45 events/μb at 6.5 GeV/c. Seen by JENKINS 83. Perhaps seen by BIAGI 87.

$\Xi(2250)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 2250 OUR ESTIMATE						
2189 ± 7	66	BIAGI	87	SPEC	−	Ξ^- Be → $(\Xi^-\pi^+\pi^-)$ X
2214 ± 5		JENKINS	83	MPS	−	$K^- p \to K^+$ MM
2295 ± 15	18	GOLDWASSER	70	HBC	−	$K^- p$ 5.5 GeV/c
2244 ± 52	35	BARTSCH	69	HBC		$K^- p$ 10 GeV/c

$\Xi(2250)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
46 ± 27	66	BIAGI	87	SPEC	−	Ξ^- Be → $(\Xi^-\pi^+\pi^-)$ X
< 30		GOLDWASSER	70	HBC	−	$K^- p$ 5.5 GeV/c
130 ± 80		BARTSCH	69	HBC		

$\Xi(2250)$ DECAY MODES

	Mode
Γ_1	$\Xi\pi\pi$
Γ_2	$\Lambda\overline{K}\pi$
Γ_3	$\Sigma\overline{K}\pi$

$\Xi(2250)$ REFERENCES

BIAGI	87	ZPHY C34 15	+	(BRIS, CERN, GEVA, HEIDP, LAUS, LOQM, RAL)
JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, MASD)
HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAVE, MSU)
GOLDWASSER	70	PR D1 1960	+Schultz	(ILL)
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)

$\Xi(2370)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

$\Xi(2370)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 2370 OUR ESTIMATE						
2356±10		JENKINS	83	MPS	−	$K^- p \to K^+$ MM
2370	50	HASSALL	81	HBC	−0	$K^- p$ 6.5 GeV/c
2373± 8	94	AMIRZADEH	80	HBC	−0	$K^- p$ 8.25 GeV/c
2392±27		DIBIANCA	75	DBC		$\Xi 2\pi$

$\Xi(2370)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
80	50	HASSALL	81	HBC	−0	$K^- p$ 6.5 GeV/c
80±25	94	AMIRZADEH	80	HBC	−0	$K^- p$ 8.25 GeV/c
75±69		DIBIANCA	75	DBC		$\Xi 2\pi$

$\Xi(2370)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K} \pi$ Includes $\Gamma_4 + \Gamma_6$.	seen
Γ_2	$\Sigma \overline{K} \pi$ Includes $\Gamma_5 + \Gamma_6$.	seen
Γ_3	$\Omega^- K$	
Γ_4	$\Lambda \overline{K}^*(892)$	
Γ_5	$\Sigma \overline{K}^*(892)$	
Γ_6	$\Sigma(1385) \overline{K}$	

$\Xi(2370)$ BRANCHING RATIOS

$\Gamma(\Lambda \overline{K} \pi)/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	AMIRZADEH	80	HBC	−0	$K^- p$ 8.25 GeV/c

$\Gamma(\Sigma \overline{K} \pi)/\Gamma_{total}$ — Γ_2/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
seen	AMIRZADEH	80	HBC	−0	$K^- p$ 8.25 GeV/c

$[\Gamma(\Lambda \overline{K} \pi) + \Gamma(\Sigma \overline{K} \pi)]/\Gamma_{total}$ — $(\Gamma_1+\Gamma_2)/\Gamma$

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
seen	50	HASSALL	81	HBC	−0	$K^- p$ 6.5 GeV/c

$\Gamma(\Omega^- K)/\Gamma_{total}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.09±0.04	[1] KINSON	80	HBC	−	$K^- p$ 8.25 GeV/c

$[\Gamma(\Lambda \overline{K}^*(892)) + \Gamma(\Sigma \overline{K}^*(892))]/\Gamma_{total}$ — $(\Gamma_4+\Gamma_5)/\Gamma$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.22±0.13	[1] KINSON	80	HBC	−	$K^- p$ 8.25 GeV/c

$\Gamma(\Sigma(1385) \overline{K})/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.12±0.08	[1] KINSON	80	HBC	−	$K^- p$ 8.25 GeV/c

$\Xi(2370)$ FOOTNOTES

[1] KINSON 80 is a reanalysis of AMIRZADEH 80 with 50% more events.

$\Xi(2370)$ REFERENCES

JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, MASD)
HASSALL	81	NP B189 397	+Ansorge, Carter, Neale+	(CAVE, MSU)
AMIRZADEH	80	PL 90B 324	+	(BIRM, CERN, GLAS, MSU, CURIN) I
KINSON	80	Toronto Conf. 263	+	(BIRM, CERN, GLAS, MSU, CURIN) I
DIBIANCA	75	NP B98 137	+Endorf	(CMU)

$\Xi(2500)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: ∗
J, P need confirmation.

OMITTED FROM SUMMARY TABLE

The ALITTI 69 peak might be instead the $\Xi(2370)$ or might be neither the $\Xi(2370)$ nor the $\Xi(2500)$.

$\Xi(2500)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
≈ 2500 OUR ESTIMATE						
2505±10		JENKINS	83	MPS	−	$K^- p \to K^+$ MM
2430±20	30	ALITTI	69	HBC	−	$K^- p$ 4.6–5 GeV/c
2500±10	45	BARTSCH	69	HBC	−0	$K^- p$ 10 GeV/c

$\Xi(2500)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	CHG
150^{+60}_{-40}	ALITTI	69	HBC	−
59±27	BARTSCH	69	HBC	−0

$\Xi(2500)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi \pi$	
Γ_2	$\Lambda \overline{K}$	
Γ_3	$\Sigma \overline{K}$	
Γ_4	$\Xi \pi \pi$	seen
Γ_5	$\Xi(1530) \pi$	
Γ_6	$\Lambda \overline{K} \pi + \Sigma \overline{K} \pi$	seen

$\Xi(2500)$ BRANCHING RATIOS

$\Gamma(\Xi \pi)/[\Gamma(\Xi \pi) + \Gamma(\Lambda \overline{K}) + \Gamma(\Sigma \overline{K}) + \Gamma(\Xi(1530)\pi)]$ — $\Gamma_1/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.5	ALITTI	69	HBC	1 standard dev. limit

$\Gamma(\Lambda \overline{K})/[\Gamma(\Xi \pi) + \Gamma(\Lambda \overline{K}) + \Gamma(\Sigma \overline{K}) + \Gamma(\Xi(1530)\pi)]$ — $\Gamma_2/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	CHG
0.5±0.2	ALITTI	69	HBC	−

$\Gamma(\Sigma \overline{K})/[\Gamma(\Xi \pi) + \Gamma(\Lambda \overline{K}) + \Gamma(\Sigma \overline{K}) + \Gamma(\Xi(1530)\pi)]$ — $\Gamma_3/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	CHG
0.5±0.2	ALITTI	69	HBC	−

$\Gamma(\Xi(1530)\pi)/[\Gamma(\Xi \pi) + \Gamma(\Lambda \overline{K}) + \Gamma(\Sigma \overline{K}) + \Gamma(\Xi(1530)\pi)]$ — $\Gamma_5/(\Gamma_1+\Gamma_2+\Gamma_3+\Gamma_5)$

VALUE	DOCUMENT ID		TECN	COMMENT
<0.2	ALITTI	69	HBC	1 standard dev. limit

$\Gamma(\Xi \pi \pi)/\Gamma_{total}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	CHG
seen	BARTSCH	69	HBC	−0

$[\Gamma(\Lambda \overline{K} \pi) + \Gamma(\Sigma \overline{K} \pi)]/\Gamma_{total}$ — Γ_6/Γ

VALUE	DOCUMENT ID		TECN	CHG
seen	BARTSCH	69	HBC	−0

$\Xi(2500)$ REFERENCES

JENKINS	83	PRL 51 951	+Albright, Diamond+	(FSU, BRAN, LBL, CINC, MASD)
ALITTI	69	PRL 22 79	+Barnes, Flaminio, Metzger+	(BNL, SYRA) I
BARTSCH	69	PL 28B 439	+	(AACH, BERL, CERN, LOIC, VIEN)

Ω BARYONS
$(S = -3, I = 0)$

$\Omega^- = sss$

Ω^-

$I(J^P) = 0(\frac{3}{2}^+)$ Status: ∗∗∗∗

The unambiguous discovery in both production and decay was by BARNES 64. The quantum numbers have not actually been measured, but follow from the assignment of the particle to the baryon decuplet. DEUTSCHMANN 78 and BAUBILLIER 78 rule out $J = 1/2$ and find consistency with $J = 3/2$.

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Ω^- MASS

The fit assumes the Ω^- and $\overline{\Omega}^+$ masses are the same.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1672.45±0.29 OUR FIT					
1672.43±0.32 OUR AVERAGE					
1673 ±1	100	HARTOUNI	85	SPEC	80–280 GeV K^0_L C
1673.0 ±0.8	41	BAUBILLIER	78	HBC	8.25 GeV/c K^-p
1671.7 ±0.6	27	HEMINGWAY	78	HBC	4.2 GeV/c K^-p
1673.4 ±1.7	4	[1] DIBIANCA	75	DBC	4.9 GeV/c K^-d
1673.3 ±1.0	3	PALMER	68	HBC	K^-p 4.6, 5 GeV/c
1671.8 ±0.8	3	SCHULTZ	68	HBC	K^-p 5.5 GeV/c
1674.2 ±1.6	5	SCOTTER	68	HBC	K^-p 6 GeV/c
1672.1 ±1.0	1	[2] FRY	55	EMUL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1671.43±0.78	13	[3] DEUTSCH...	73	HBC	K^-p 10 GeV/c
1671.9 ±1.2	6	[3] SPETH	69	HBC	See DEUTSCHMANN 73
1673.0 ±8.0	1	ABRAMS	64	HBC	$\rightarrow \Xi^-\pi^0$
1670.6 ±1.0	1	[2] FRY	55B	EMUL	
1615	1	[4] EISENBERG	54	EMUL	

[1] DIBIANCA 75 gives a mass for each event. We quote the average.

[2] The FRY 55 and FRY 55B events were identified as Ω^- by ALVAREZ 73. The masses assume decay to ΛK^- at rest. For FRY 55B, decay from an atomic orbit could Doppler shift the K^- energy and the resulting Ω^- mass by several MeV. This shift is negligible for FRY 55 because the Ω decay is approximately perpendicular to its orbital velocity, as is known because the Λ strikes the nucleus (L.Alvarez, private communication 1973). We have calculated the error assuming that the orbital n is 4 or larger.

[3] Excluded from the average; the Ω^- lifetimes measured by the experiments differ significantly from other measurements.

[4] The EISENBERG 54 mass was calculated for decay in flight. ALVAREZ 73 has shown that the Ω interacted with an Ag nucleus to give $K^-\Xi$Ag.

$\overline{\Omega}^+$ MASS

The fit assumes the Ω^- and $\overline{\Omega}^+$ masses are the same.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1672.45±0.29 OUR FIT					
1672.5 ±0.7 OUR AVERAGE					
1672 ±1	72	HARTOUNI	85	SPEC	80–280 GeV K^0_L C
1673.1 ±1.0	1	FIRESTONE	71B	HBC	12 GeV/c K^+d

$(m_{\Omega^-} - m_{\overline{\Omega}^+})\ /\ m_{\text{average}}$

A test of CPT invariance. Calculated from the *average* Ω^- and $\overline{\Omega}^+$ masses, above.

VALUE	DOCUMENT ID
(0±5) x 10^{-4} OUR EVALUATION	

Ω^- MEAN LIFE

Measurements with an error $>$ 0.1 x 10^{-10} s have been omitted.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.822±0.012 OUR AVERAGE					
0.811±0.037	1096	LUK	88	SPEC	pBe 400 GeV
0.823±0.013	12k	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.822±0.028	2437	BOURQUIN	79B	SPEC	See BOURQUIN 84

Ω^- MAGNETIC MOMENT

VALUE (μ_N)	EVTS	DOCUMENT ID		TECN	COMMENT
−2.02 ±0.05 OUR AVERAGE					
−2.024±0.056	235k	WALLACE	95	SPEC	Ω^- 300–550 GeV
−1.94 ±0.17 ±0.14	25k	DIEHL	91	SPEC	Spin-transfer production

Ω^- DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	ΛK^-		(67.8±0.7) %	
Γ_2	$\Xi^0\pi^-$		(23.6±0.7) %	
Γ_3	$\Xi^-\pi^0$		(8.6±0.4) %	
Γ_4	$\Xi^-\pi^+\pi^-$		$(4.3^{+3.4}_{-1.3}) \times 10^{-4}$	
Γ_5	$\Xi(1530)^0\pi^-$		$(6.4^{+5.1}_{-2.0}) \times 10^{-4}$	
Γ_6	$\Xi^0 e^- \overline{\nu}_e$		$(5.6\pm2.8) \times 10^{-3}$	
Γ_7	$\Xi^-\gamma$		$< 4.6 \times 10^{-4}$	90%
	$\Delta S = 2$ forbidden ($S2$) modes			
Γ_8	$\Lambda\pi^-$	$S2$	$< 1.9 \times 10^{-4}$	90%

Ω^- BRANCHING RATIOS

The BOURQUIN 84 values (which include results of BOURQUIN 79B, a separate experiment) are much more accurate than any other results, and so the other results have been omitted.

$\Gamma(\Lambda K^-)/\Gamma_{\text{total}}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.678±0.007	14k	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.686±0.013	1920	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^0\pi^-)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.236±0.007	1947	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.234±0.013	317	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^-\pi^0)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.086±0.004	759	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.080±0.008	145	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^-\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$4.3^{+3.4}_{-1.3}$	4	BOURQUIN	84	SPEC	SPS hyperon beam

$\Gamma(\Xi(1530)^0\pi^-)/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$6.4^{+5.1}_{-2.0}$	4	[5] BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
∼ 20	1	BOURQUIN	79B	SPEC	See BOURQUIN 84

[5] The same 4 events as in the previous mode, with the isospin factor to take into account $\Xi(1530)^0 \rightarrow \Xi^0\pi^0$ decays included.

$\Gamma(\Xi^0 e^- \overline{\nu}_e)/\Gamma_{\text{total}}$ — Γ_6/Γ

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
5.6±2.8	14	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •					
∼ 10	3	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Xi^-\gamma)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 4.6	90	0	ALBUQUERQ...94		E761	Ω^- 375 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<22	90	9	BOURQUIN	84	SPEC	SPS hyperon beam
<31	90	0	BOURQUIN	79B	SPEC	See BOURQUIN 84

$\Gamma(\Lambda\pi^-)/\Gamma_{\text{total}}$ — Γ_8/Γ

ΔS=2. Forbidden in first-order weak interaction.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 1.9	90	0	BOURQUIN	84	SPEC	SPS hyperon beam
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<13	90	0	BOURQUIN	79B	SPEC	See BOURQUIN 84

Ω^- DECAY PARAMETERS

α FOR $\Omega^- \to \Lambda K^-$

Some early results have been omitted.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.026 ± 0.026 OUR AVERAGE					
-0.034 ± 0.079	1743	LUK	88	SPEC	pBe 400 GeV
-0.025 ± 0.028	12k	BOURQUIN	84	SPEC	SPS hyperon beam

α FOR $\Omega^- \to \Xi^0 \pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$+0.09 \pm 0.14$	1630	BOURQUIN	84	SPEC	SPS hyperon beam

α FOR $\Omega^- \to \Xi^- \pi^0$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$+0.05 \pm 0.21$	614	BOURQUIN	84	SPEC	SPS hyperon beam

Ω^- REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

WALLACE	95	PRL 74 3732	+Border+	(MINN, ARIZ, MICH, FNAL)
ALBUQUERQ...	94	PR D50 R18	Albuquerque, Bondar, Carrigan+	(FNAL E761 Collab.)
DIEHL	91	PRL 67 804	+Teige, Thompson, Zou+	(RUTG, FNAL, MICH, MINN)
LUK	88	PR D38 19	+Beretvas, Deck+	(RUTG, WISC, MICH, MINN)
HARTOUNI	85	PRL 54 628	+Atiya, Holmes, Knapp, Lee+	(COLU, ILL, FNAL)
BOURQUIN	84	NP B241 1	+	(BRIS, GEVA, HEIDP, LALO, RAL, STRB)
Also	79	PL 87B 297	Bourquin+	(BRIS, GEVA, HEIDP, ORSAY, RHEL, STRB)
BOURQUIN	79B	PL 88B 192	+	(BRIS, GEVA, HEIDP, LALO, RAL)
BAUBILLIER	78	PL 78B 342	+	(BIRM, CERN, GLAS, MSU, CURIN, PARIN) J
DEUTSCH...	78	PL 73B 96	Deutschmann+	(AACH3, BERL, CERN, INNS, LOIC+) J
HEMINGWAY	78	NP B142 205	+Armenteros+	(CERN, ZEEM, NIJM, OXF)
DIBIANCA	75	NP B98 137	+Endorf	(CMU)
ALVAREZ	73	PR D8 702		(LBL)
DEUTSCH...	73	NP B61 102	Deutschmann, Kaufmann, Besliv+	(ABCLV Collab.)
FIRESTONE	71B	PRL 26 410	+Goldhaber, Lissauer, Sheldon, Trilling	(LRL)
SPETH	69	PL 29B 252	+	(AACH, BERL, CERN, LOIC, VIEN)
PALMER	68	PL 26B 323	+Radojicic, Rau, Richardson+	(BNL, SYRA)
SCHULTZ	68	PR 168 1509	+	(ILL, ANL, NWES, WISC)
SCOTTER	68	PL 26B 474	+	(BIRM, GLAS, LOIC, MUNI, OXF)
ABRAMS	64	PRL 13 670	+Burnstein, Glasser+	(UMD, NRL)
BARNES	64	PRL 12 204	+Connolly, Crennell, Culwick+	(BNL)
FRY	55	PR 97 1189	+Schneps, Swami	(WISC)
FRY	55B	NC 2 346	+Schneps, Swami	(WISC)
EISENBERG	54	PR 96 541		(CORN)

$\Omega(2250)^-$

$I(J^P) = 0(?^?)$ Status: ∗∗∗

$\Omega(2250)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2252 ± 9 OUR AVERAGE					
2253 ± 13	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
$2251 \pm 9 \pm 8$	78	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2250)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
55 ± 18 OUR AVERAGE					
81 ± 38	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
48 ± 20	78	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2250)^-$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi^- \pi^+ K^-$	seen
Γ_2	$\Xi(1530)^0 K^-$	seen

$\Omega(2250)^-$ BRANCHING RATIOS

$\Gamma(\Xi(1530)^0 K^-)/\Gamma(\Xi^- \pi^+ K^-)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
~ 1.0	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
0.70 ± 0.20	49	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Omega(2250)^-$ REFERENCES

ASTON	87B	PL B194 579	+Awaji, Bienz, Bird+	(SLAC, NAGO, CINC, INUS)
BIAGI	86B	ZPHY C31 33	+	(LOQM, GEVA, RAL, HEIDP, LAUS, BRIS, CERN)

$\Omega(2380)^-$

Status: ∗∗

OMITTED FROM SUMMARY TABLE

$\Omega(2380)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 2380 OUR ESTIMATE					
$2384 \pm 9 \pm 8$	45	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
26 ± 23	45	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ DECAY MODES

	Mode
Γ_1	$\Xi^- \pi^+ K^-$
Γ_2	$\Xi(1530)^0 K^-$
Γ_3	$\Xi^- \overline{K}^*(892)^0$

$\Omega(2380)^-$ BRANCHING RATIOS

$\Gamma(\Xi(1530)^0 K^-)/\Gamma(\Xi^- \pi^+ K^-)$ — Γ_2/Γ_1

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.44	90	9	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Gamma(\Xi^- \overline{K}^*(892)^0)/\Gamma(\Xi^- \pi^+ K^-)$ — Γ_3/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.5 ± 0.3	21	BIAGI	86B	SPEC	Ξ^- Be 116 GeV/c

$\Omega(2380)^-$ REFERENCES

BIAGI 86B ZPHY C31 33 + (LOQM, GEVA, RAL, HEIDP, LAUS, BRIS, CERN)

$\Omega(2470)^-$

Status: ∗∗

OMITTED FROM SUMMARY TABLE

A peak in the $\Omega^- \pi^+ \pi^-$ mass spectrum with a signal significance claimed to be at least 5.5 standard deviations. There is no reason to seriously doubt the existence of this state, but unless the evidence is overwhelming we usually wait for confirmation from a second experiment before elevating peaks to the Summary Table.

$\Omega(2470)^-$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2474 ± 12	59	ASTON	88G	LASS	$K^- p$ 11 GeV/c

$\Omega(2470)^-$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
72 ± 33	59	ASTON	88G	LASS	$K^- p$ 11 GeV/c

$\Omega(2470)^-$ DECAY MODES

	Mode
Γ_1	$\Omega^- \pi^+ \pi^-$

$\Omega(2470)^-$ REFERENCES

ASTON 88G PL B215 799 +Awaji, Bienz, Bird+ (SLAC, NAGO, CINC, INUS)

CHARMED BARYONS
($C = +1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

CHARMED BARYONS

Figure 1 shows the SU(4) multiplets that have as their lowest levels (a) the SU(3) octet that contains the nucleon, and (b) the SU(3) decuplet that contains the $\Delta(1232)$. All the particles in a given SU(4) multiplet have the same spin and parity. The only known charmed baryons each contain one charmed quark and thus belong to the second level of an SU(4) multiplet. Figure 2 shows this level for the SU(4) multiplet of Fig. 1(a). The level splits apart into two SU(3) multiplets, a $\overline{\mathbf{3}}$ that contains the $\Lambda_c(2285)$ and the $\Xi_c(2470)$, both of which decay weakly, and a **6** that contains the $\Sigma_c(2455)$, which decays strongly to $\Lambda_c\pi$, and the $\Omega_c(2710)$, which decays weakly. A second Ξ_c remains to be discovered to fill out the **6**, and a host of other baryons with one or more charmed quarks are needed to fill out the full SU(4) multiplets. Furthermore, *every* N or Δ baryon resonance "starts" another SU(4) multiplet, so the woods are full of charmed baryons, most of which no doubt will forever remain undiscovered. The only candidates so far to belong to more massive multiplets are the $\Lambda_c(2593)$ and the $\Lambda_c(2625)$, and perhaps a $\Xi_c(2645)$; see the Listings.

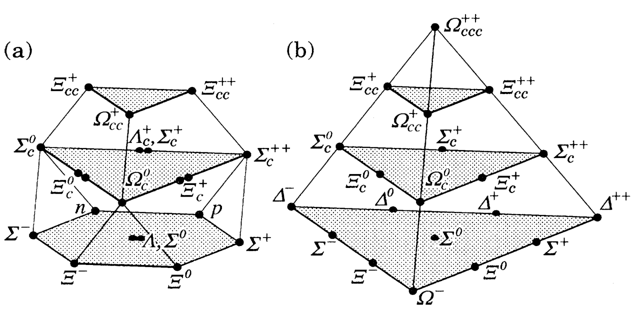


Fig. 1. SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet on the lowest level. (b) The 20-plet with an SU(3) decuplet on the lowest level.

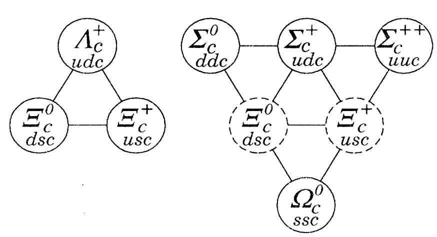


Fig. 2. The SU(3) multiplets on the second level of the SU(4) multiplet of Fig. 1(a). The particles in dashed circles have yet to be discovered.

The states of the $\overline{\mathbf{3}}$ multiplet in Fig. 2 are antisymmetric under interchange of the two light quarks (the u, d, and s quarks), whereas the states of the **6** multiplet are symmetric under interchange of these quarks. Actually, there may be some mixing between the pure $\overline{\mathbf{3}}$ and **6** Ξ_c states (they have the same I, J, and P quantum numbers) to form the physical Ξ_c states.

It need hardly be said that the flavor symmetries Fig. 1 displays are very badly broken, but the figure is the simplest way to see what charmed baryons should exist.

For a review of theory and experiment, see Ref. 1.

References

1. J.G. Körner, M. Krämer, and D. Pirjol, Prog. in Part. Nucl. Phys. **33**, 787 (1994).

Λ_c^+

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗∗

J has not actually been measured yet. Results of an analysis of $pK^-\pi^+$ decays (JEZABEK 92) are consistent with the expected $J = 1/2$. The quark content is udc.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in earlier editions.

Λ_c^+ MASS

Measurements with an error greater than 5 MeV or that are otherwise obsolete have been omitted.

The fit also uses Σ_c-Λ_c^+ and Λ_c^{*+}-Λ_c^+ mass-difference measurements.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2284.9±0.6 OUR FIT					
2284.9±0.6 OUR AVERAGE					
2284.7±0.6±0.7	1134	AVERY	91	CLEO	Six modes
2281.7±2.7±2.6	29	ALVAREZ	90B	NA14	$pK^-\pi^+$
2285.8±0.6±1.2	101	BARLAG	89	NA32	$pK^-\pi^+$
2284.7±2.3±0.5	5	AGUILAR-...	88B	LEBC	$pK^-\pi^+$
2283.1±1.7±2.0	628	ALBRECHT	88C	ARG	$pK^-\pi^+$, $p\overline{K}^0$, $\Lambda 3\pi$
2286.2±1.7±0.7	97	ANJOS	88B	E691	$pK^-\pi^+$
2281 ±3	2	JONES	87	HBC	$pK^-\pi^+$
2283 ±3	3	BOSETTI	82	HBC	$pK^-\pi^+$
2290 ±3	1	CALICCHIO	80	HYBR	$pK^-\pi^+$

Λ_c^+ MEAN LIFE

Measurements with an error $\geq 0.1 \times 10^{-12}$ s or with fewer than 20 events have been omitted.

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.206±0.012 OUR AVERAGE					
0.215±0.016±0.008	1340	FRABETTI	93D	E687	γBe, $\Lambda_c^+ \to pK^-\pi^+$
0.18 ±0.03 ±0.03	29	ALVAREZ	90	NA14	γ, $\Lambda_c^+ \to pK^-\pi^+$
0.20 ±0.03 ±0.03	90	FRABETTI	90	E687	γBe, $\Lambda_c^+ \to pK^-\pi^+$
$0.196^{+0.023}_{-0.020}$	101	BARLAG	89	NA32	$pK^-\pi^+$ + c.c.
0.22 ±0.03 ±0.02	97	ANJOS	88B	E691	$pK^-\pi^+$ + c.c.

Λ_c^+ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Hadronic modes with a p and one $\overline{K}$			
Γ_1	$p\overline{K}^0$		(2.2 ± 0.4) %	
Γ_2	$pK^-\pi^+$		(4.4 ± 0.6) %	
Γ_3	$p\overline{K}^*(892)^0$	[a]	(1.6 ± 0.4) %	
Γ_4	$\Delta(1232)^{++}K^-$		(7 ± 4) $\times 10^{-3}$	
Γ_5	$\Lambda(1520)\pi^+$	[a]	(4.0 $^{+2.0}_{-1.7}$) $\times 10^{-3}$	
Γ_6	$pK^-\pi^+$ nonresonant		(2.5 $^{+0.5}_{-0.6}$) %	
Γ_7	$p\overline{K}^0\eta$		(1.10 ± 0.29) %	
Γ_8	$p\overline{K}^0\pi^+\pi^-$		(2.1 ± 0.8) %	
Γ_9	$pK^-\pi^+\pi^0$		seen	
Γ_{10}	$pK^*(892)^-\pi^+$	[a]	(9 ± 5) $\times 10^{-3}$	
Γ_{11}	$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(3.2 ± 0.7) %	
Γ_{12}	$\Delta(1232)\overline{K}^*(892)$		seen	
Γ_{13}	$pK^-\pi^+\pi^+\pi^-$		(10 ± 7) $\times 10^{-4}$	
Γ_{14}	$pK^-\pi^+\pi^0\pi^0$		(7.0 ± 3.5) $\times 10^{-3}$	
Γ_{15}	$pK^-\pi^+\pi^0\pi^0\pi^0$		(4.4 ± 2.8) $\times 10^{-3}$	
	Hadronic modes with a p and zero or two K's			
Γ_{16}	$p\pi^+\pi^-$		(3.0 ± 1.6) $\times 10^{-3}$	
Γ_{17}	$pf_0(980)$	[a]	(2.4 ± 1.6) $\times 10^{-3}$	
Γ_{18}	$p\pi^+\pi^+\pi^-\pi^-$		(1.6 ± 1.0) $\times 10^{-3}$	
Γ_{19}	pK^+K^-		(2.0 ± 0.6) $\times 10^{-3}$	
Γ_{20}	$p\phi$	[a]	(1.06 ± 0.33) $\times 10^{-3}$	
	Hadronic modes with a hyperon			
Γ_{21}	$\Lambda\pi^+$		(7.9 ± 1.8) $\times 10^{-3}$	
Γ_{22}	$\Lambda\pi^+\pi^0$		(3.2 ± 0.9) %	
Γ_{23}	$\Lambda\rho^0$		< 4 %	CL=95%
Γ_{24}	$\Lambda\pi^+\pi^+\pi^-$		(2.9 ± 0.6) %	
Γ_{25}	$\Lambda\pi^+\eta$		(1.5 ± 0.4) %	
Γ_{26}	$\Sigma(1385)^+\eta$	[a]	(7.5 ± 2.4) $\times 10^{-3}$	
Γ_{27}	$\Lambda K^+\overline{K}^0$		(5.3 ± 1.4) $\times 10^{-3}$	
Γ_{28}	$\Sigma^0\pi^+$		(8.8 ± 2.0) $\times 10^{-3}$	
Γ_{29}	$\Sigma^+\pi^0$		(8.8 ± 2.2) $\times 10^{-3}$	
Γ_{30}	$\Sigma^+\eta$		(4.8 ± 1.7) $\times 10^{-3}$	
Γ_{31}	$\Sigma^+\pi^+\pi^-$		(3.0 ± 0.6) %	
Γ_{32}	$\Sigma^+\rho^0$		< 1.2 %	CL=95%
Γ_{33}	$\Sigma^-\pi^+\pi^+$		(1.6 ± 0.6) %	
Γ_{34}	$\Sigma^0\pi^+\pi^0$		(1.6 ± 0.6) %	
Γ_{35}	$\Sigma^0\pi^+\pi^+\pi^-$		(9.2 ± 3.4) $\times 10^{-3}$	
Γ_{36}	$\Sigma^+\pi^+\pi^-\pi^0$			
Γ_{37}	$\Sigma^+\omega$	[a]	(2.4 ± 0.7) %	
Γ_{38}	$\Sigma^+\pi^+\pi^+\pi^-\pi^-$		(2.6 $^{+3.5}_{-1.8}$) $\times 10^{-3}$	
Γ_{39}	$\Sigma^+K^+K^-$		(3.1 ± 0.8) $\times 10^{-3}$	
Γ_{40}	$\Sigma^+\phi$	[a]	(3.0 ± 1.3) $\times 10^{-3}$	
Γ_{41}	$\Sigma^+K^+\pi^-$		(5.7 $^{+5.3}_{-3.2}$) $\times 10^{-3}$	
Γ_{42}	Ξ^0K^+		(3.4 ± 0.9) $\times 10^{-3}$	
Γ_{43}	$\Xi^-K^+\pi^+$		(4.3 ± 1.1) $\times 10^{-3}$	
Γ_{44}	$\Xi(1530)^0K^+$	[a]	(2.3 ± 0.7) $\times 10^{-3}$	
	Semileptonic modes			
Γ_{45}	$\Lambda\ell^+\nu_\ell$	[b]	(2.3 ± 0.5) %	
Γ_{46}	e^+ anything		(4.5 ± 1.7) %	
Γ_{47}	pe^+ anything		(1.8 ± 0.9) %	
Γ_{48}	Λe^+ anything		(1.6 ± 0.6) %	
Γ_{49}	$\Lambda\mu^+$ anything		(1.5 ± 0.9) %	
Γ_{50}	$\Lambda\ell^+\nu_\ell$ anything			
	Inclusive modes			
Γ_{51}	p anything		(50 ±16) %	
Γ_{52}	p anything (no Λ)		(12 ±19) %	
Γ_{53}	p hadrons			
Γ_{54}	n anything		(50 ±16) %	
Γ_{55}	n anything (no Λ)		(29 ±17) %	
Γ_{56}	Λ anything		(35 ±11) %	S=1.4
Γ_{57}	$\Sigma^\pm$ anything	[c]	(10 ± 5) %	

$\Delta C = 1$ weak neutral current ($C1$) modes, or Lepton number (L) violating modes

	Mode		Fraction	Confidence level
Γ_{58}	$p\mu^+\mu^-$	$C1$	< 3.4 $\times 10^{-4}$	CL=90%
Γ_{59}	$\Sigma^-\mu^+\mu^+$	L	< 7.0 $\times 10^{-4}$	CL=90%
Γ_{60}	dummy mode used by the fit		(92.7 ± 1.0) %	

[a] This branching fraction includes all the decay modes of the final-state resonance.

[b] ℓ indicates e or μ mode, not sum over modes.

[c] The value is for the sum of the charge states of particle/antiparticle states indicated.

CONSTRAINED FIT INFORMATION

An overall fit to 3 branching ratios uses 9 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 2.0 for 7 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle\delta x_i\delta x_j\right\rangle/(\delta x_i\cdot\delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_{24}	61	
x_{60}	−90	−89
	x_2	x_{24}

Λ_c^+ BRANCHING RATIOS

Most of the modes are measured relative to the $pK^-\pi^+$ mode. A few obsolete results have been omitted.

Hadronic modes with a p and one $\overline{K}$

$\Gamma(p\overline{K}^0)/\Gamma(pK^-\pi^+)$ Γ_1/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.49±0.07 OUR AVERAGE					
0.44±0.07±0.05	133	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.55±0.17±0.14	45	ANJOS	90	E691	γ Be 70–260 GeV
0.62±0.15±0.03	73	ALBRECHT	88C	ARG	e^+e^- 10 GeV

$\Gamma(pK^-\pi^+)/\Gamma_{\text{total}}$ Γ_2/Γ

Most of the other modes are measured relative to this mode.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.044 ±0.006 OUR FIT						
0.044 ±0.006 OUR AVERAGE						
0.0594±0.0031±0.0144			BERGFELD [1]	94	CLEO	$e^+e^- \approx \Upsilon(4S)$
0.040 ±0.003 ±0.008			ALBRECHT [2]	92O	ARG	$e^+e^- \approx \Upsilon(4S)$
0.043 ±0.010 ±0.008			CRAWFORD [3]	92	CLEO	e^+e^- 10.5 GeV
0.041 ±0.024		208	ALBRECHT [4]	88E	ARG	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.044	90	6	AGUILAR-... [5]	88B	LEBC	pp 27.4 GeV

[1] BERGFELD 94 measures $\Gamma(pK^-\pi^+)/\Gamma(\Lambda\ell^+\nu_\ell) = 1.93 \pm 0.10 \pm 0.33$ and calculates $\Gamma(e^+\text{anything})/\Gamma_{\text{total}} = 0.034 \pm 0.004$ from D-meson data, assuming that all charmed hadrons have the same semileptonic width. Combined, these values give $\Gamma(pK^-\pi^+)/\Gamma_{\text{total}} = f\times(6.67\pm0.35\pm1.35)\%$, where $f \equiv \Gamma(\Lambda\ell^+\nu_\ell)/\Gamma(\ell^+\text{anything})$. Since $f \leq 1$, this gives an upper bound on $\Gamma(pK^-\pi^+)/\Gamma_{\text{total}}$. In the spectator model, the quantity corresponding to f in D-meson decay is $\Gamma(D \to (\overline{K}+\overline{K}^*)\ell^+\nu_\ell)/\Gamma(D \to \ell^+\text{anything}) = 0.89 \pm 0.12$. This value of f leads to the value of $\Gamma(pK^-\pi^+)/\Gamma_{\text{total}}$ we give here.

[2] ALBRECHT 92O uses $B(\overline{B} \to \Lambda_c^+X)\times B(\Lambda_c^+ \to pK^-\pi^+) = (0.28 \pm 0.05)\%$ plus $B(\overline{B} \to \Lambda_c^+X) = (6.8 \pm 0.5 \pm 0.3)\%$ and assumes that $\overline{B} \to \Xi_cX$ and $\overline{B} \to \Omega_cX$ decays are suppressed and negligible.

[3] CRAWFORD 92 uses $B(\overline{B} \to \Lambda_c^+X)\times B(\Lambda_c^+ \to pK^-\pi^+) = (0.273\pm0.051\pm0.039)\%$ and estimates $B(\overline{B} \to \Lambda_c^+X) = (6.4 \pm 0.8 \pm 0.8)\%$. If final states other than $\Lambda_c^+\overline{N}X$ contribute to $\overline{B}$ decay, the $\Lambda_c^+ \to pK^-\pi^+$ branching fraction would increase.

[4] ALBRECHT 88E uses their result $B(\overline{B} \to \Lambda_c^+X)\times B(\Lambda_c^+ \to pK^-\pi^+) = (0.30\pm0.12\pm0.06)\%$ plus $B(\overline{B} \to \Lambda_c^+X) = (7.4\pm2.9)\%$ from other measurements of inclusive proton and Λ yields in B decays.

[5] This AGUILAR-BENITEZ 88B limit assumes that $\tau_{\Lambda_c} = 1.2\times10^{-13}$ s, and it "decreases by 20% [to > 0.035] assuming a lifetime of 1.7×10^{-13} s instead." Our average for τ_{Λ_c} is still higher (see the mean-life section), which would further reduce the limit.

$\Gamma(p\overline{K}^*(892)^0)/\Gamma(pK^-\pi^+)$ — Γ_3/Γ_2

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.36^{+0.06}_{-0.07}$ OUR AVERAGE					
$0.35^{+0.06}_{-0.07}\pm0.03$	39	BOZEK	93	NA32	π^- Cu 230 GeV
0.42 ± 0.24	12	BASILE	81B	CNTR	$pp \rightarrow \Lambda_c^+ e^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.35 ± 0.11		BARLAG	90D	NA32	See BOZEK 93

$\Gamma(\Delta(1232)^{++}K^-)/\Gamma(pK^-\pi^+)$ — Γ_4/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.16 ± 0.10 OUR AVERAGE Error includes scale factor of 1.5.					
$0.12^{+0.04}_{-0.05}\pm0.05$	14	BOZEK	93	NA32	π^- Cu 230 GeV
0.40 ± 0.17	17	BASILE	81B	CNTR	$pp \rightarrow \Lambda_c^+ e^- X$

$\Gamma(\Lambda(1520)\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_5/Γ_2

Unseen decay modes of the $\Lambda(1520)$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.09^{+0.04}_{-0.03}\pm0.02$	12	BOZEK	93	NA32	π^- Cu 230 GeV

$\Gamma(pK^-\pi^+ \text{ nonresonant})/\Gamma(pK^-\pi^+)$ — Γ_6/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.56^{+0.07}_{-0.09}\pm0.05$	71	BOZEK	93	NA32	π^- Cu 230 GeV

$\Gamma(p\overline{K}^0\eta)/\Gamma(pK^-\pi^+)$ — Γ_7/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.25\pm0.04\pm0.04$	57	AMMAR	95	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_8/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.49 ± 0.17 OUR AVERAGE Error includes scale factor of 1.4.					
$0.43\pm0.12\pm0.04$	83	AVERY	91	CLEO	e^+e^- 10.5 GeV
$0.98\pm0.36\pm0.08$	12	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma_{total}$ — Γ_9/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	44	AMENDOLIA	87	SPEC	γGe-Si

$\Gamma(pK^*(892)^-\pi^+)/\Gamma(p\overline{K}^0\pi^+\pi^-)$ — Γ_{10}/Γ_8

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.44 ± 0.14	17	ALEEV	94	BIS2	nN 20–70 GeV

$\Gamma(p(K^-\pi^+)_{\text{nonresonant}}\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{11}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.73\pm0.12\pm0.05$	67	BOZEK	93	NA32	π^- Cu 230 GeV

$\Gamma(\Delta(1232)\overline{K}^*(892))/\Gamma_{total}$ — Γ_{12}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	35	AMENDOLIA	87	SPEC	γGe-Si

$\Gamma(pK^-\pi^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{13}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.022 ± 0.015	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{14}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.16\pm0.07\pm0.03$	15	BOZEK	93	NA32	π^- Cu 230 GeV

$\Gamma(pK^-\pi^+\pi^0\pi^0\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{15}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.10\pm0.06\pm0.02$	8	BOZEK	93	NA32	π^- Cu 230 GeV

Hadronic modes with a p and 0 or 2 K's

$\Gamma(p\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{16}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.069 ± 0.036	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pf_0(980))/\Gamma(pK^-\pi^+)$ — Γ_{17}/Γ_2

Unseen decay modes of the $f_0(980)$ are included.

VALUE	DOCUMENT ID		TECN	COMMENT
0.055 ± 0.036	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(p\pi^+\pi^+\pi^-\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{18}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.036 ± 0.023	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^+K^-)/\Gamma(pK^-\pi^+)$ — Γ_{19}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.046 ± 0.012 OUR AVERAGE Error includes scale factor of 1.2.					
$0.039\pm0.009\pm0.007$	214	ALEXANDER	96C	CLEO	$e^+e^- \approx \Upsilon(4S)$
$0.096\pm0.029\pm0.010$	30	FRABETTI	93H	E687	γBe, $\overline{E}_\gamma$ 220 GeV
0.048 ± 0.027		BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(p\phi)/\Gamma(pK^-\pi^+)$ — Γ_{20}/Γ_2

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.024\pm0.006\pm0.003$	54	ALEXANDER	96C	CLEO	$e^+e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.040 ± 0.027		BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(p\phi)/\Gamma(pK^+K^-)$ — Γ_{20}/Γ_{19}

Unseen decay modes of the ϕ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.58	90	FRABETTI	93H	E687	γBe, $\overline{E}_\gamma$ 220 GeV

Hadronic modes with a hyperon

$\Gamma(\Lambda\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_{21}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.180 ± 0.032 OUR AVERAGE						
$0.18\pm0.03\pm0.04$			ALBRECHT	92	ARG	$e^+e^- \approx 10.4$ GeV
$0.18\pm0.03\pm0.03$		87	AVERY	91	CLEO	e^+e^- 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.33	90		ANJOS	90	E691	γBe 70–260 GeV
<0.16	90		ALBRECHT	88C	ARG	e^+e^- 10 GeV

$\Gamma(\Lambda\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{22}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.73\pm0.09\pm0.16$	464	AVERY	94	CLEO	$e^+e^- \approx \Upsilon(3S),\Upsilon(4S)$

$\Gamma(\Lambda\rho^0)/\Gamma(pK^-\pi^+)$ — Γ_{23}/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.95	95	AVERY	94	CLEO	$e^+e^- \approx \Upsilon(3S),\Upsilon(4S)$

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma_{total}$ — Γ_{24}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.029 ± 0.006 OUR FIT					
$0.028\pm0.007\pm0.011$	70	[6] BOWCOCK	85	CLEO	e^+e^- 10.5 GeV

[6] See BOWCOCK 85 for assumptions made on charm production and Λ_c production from charm to get this result.

$\Gamma(\Lambda\pi^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{24}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.66 ± 0.10 OUR FIT					
0.66 ± 0.11 OUR AVERAGE					
$0.65\pm0.11\pm0.12$	289	AVERY	91	CLEO	e^+e^- 10.5 GeV
$0.82\pm0.29\pm0.27$	44	ANJOS	90	E691	γBe 70–260 GeV
$0.94\pm0.41\pm0.13$	10	BARLAG	90D	NA32	π^- 230 GeV
$0.61\pm0.16\pm0.04$	105	ALBRECHT	88C	ARG	e^+e^- 10 GeV

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(\Lambda\pi^+\pi^+\pi^-)$ — Γ_8/Γ_{24}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.3 ± 1.2	130	ALEEV	84	BIS2	nC 40–70 GeV

$\Gamma(\Lambda\pi^+\eta)/\Gamma(pK^-\pi^+)$ — Γ_{25}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.35\pm0.05\pm0.06$	116	AMMAR	95	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma(1385)^+\eta)/\Gamma(pK^-\pi^+)$ — Γ_{26}/Γ_2

Unseen decay modes of the $\Sigma(1385)^+$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.17\pm0.04\pm0.03$	54	AMMAR	95	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Lambda K^+\overline{K}^0)/\Gamma(pK^-\pi^+)$ — Γ_{27}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.12\pm0.02\pm0.02$	59	AMMAR	95	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^0\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_{28}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.20 ± 0.04 OUR AVERAGE					
$0.21\pm0.02\pm0.04$	196	AVERY	94	CLEO	$e^+e^- \approx \Upsilon(3S),\Upsilon(4S)$
$0.17\pm0.06\pm0.04$		ALBRECHT	92	ARG	$e^+e^- \approx 10.4$ GeV

$\Gamma(\Sigma^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{29}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.20\pm0.03\pm0.03$	93	KUBOTA	93	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^+\eta)/\Gamma(pK^-\pi^+)$ — Γ_{30}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.11±0.03±0.02	26	AMMAR	95	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{31}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.68±0.09 OUR AVERAGE					
0.74±0.07±0.09	487	KUBOTA	93	CLEO	$e^+e^- \approx \Upsilon(4S)$
$0.54^{+0.18}_{-0.15}$	11	BARLAG	92	NA32	π^- Cu 230 GeV

$\Gamma(\Sigma^+\rho^0)/\Gamma(pK^-\pi^+)$ — Γ_{32}/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.27	95	KUBOTA	93	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^-\pi^+\pi^+)/\Gamma(\Sigma^+\pi^+\pi^-)$ — Γ_{33}/Γ_{31}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.53±0.15±0.07	56	FRABETTI	94E	E687	γBe, $\overline{E}_\gamma$ 220 GeV

$\Gamma(\Sigma^0\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{34}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.36±0.09±0.10	117	AVERY	94	CLEO	$e^+e^- \approx \Upsilon(3S), \Upsilon(4S)$

$\Gamma(\Sigma^0\pi^+\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{35}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.21±0.05±0.05	90	AVERY	94	CLEO	$e^+e^- \approx \Upsilon(3S), \Upsilon(4S)$

$\Gamma(\Sigma^+\omega)/\Gamma(pK^-\pi^+)$ — Γ_{37}/Γ_2

Unseen decay modes of the ω are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.54±0.13±0.06	107	KUBOTA	93	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^+\pi^+\pi^+\pi^-\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{38}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.06^{+0.08}_{-0.04}}$	1	BARLAG	92	NA32	π^- Cu 230 GeV

$\Gamma(\Sigma^+K^+K^-)/\Gamma(pK^-\pi^+)$ — Γ_{39}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.070±0.011±0.011	59	AVERY	93	CLEO	$e^+e^- \approx 10.5$ GeV

$\Gamma(\Sigma^+\phi)/\Gamma(pK^-\pi^+)$ — Γ_{40}/Γ_2

Unseen decay modes of the ϕ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.069±0.023±0.016	26	AVERY	93	CLEO	$e^+e^- \approx 10.5$ GeV

$\Gamma(\Sigma^+K^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{41}/Γ_2

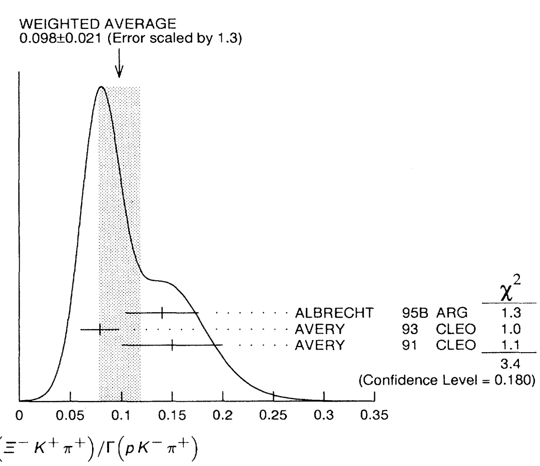
VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.13^{+0.12}_{-0.07}}$	2	BARLAG	92	NA32	π^- Cu 230 GeV

$\Gamma(\Xi^0K^+)/\Gamma(pK^-\pi^+)$ — Γ_{42}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.078±0.013±0.013	56	AVERY	93	CLEO	$e^+e^- \approx 10.5$ GeV

$\Gamma(\Xi^-K^+\pi^+)/\Gamma(pK^-\pi^+)$ — Γ_{43}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.098±0.021 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
0.14 ±0.03 ±0.02	34	ALBRECHT	95B	ARG	$e^+e^- \approx 10.4$ GeV
0.079±0.013±0.014	60	AVERY	93	CLEO	$e^+e^- \approx 10.5$ GeV
0.15 ±0.04 ±0.03	30	AVERY	91	CLEO	e^+e^- 10.5 GeV



$\Gamma(\Xi(1530)^0K^+)/\Gamma(pK^-\pi^+)$ — Γ_{44}/Γ_2

Unseen decay modes of the $\Xi(1530)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.052±0.014 OUR AVERAGE					
0.05 ±0.02 ±0.01	11	ALBRECHT	95B	ARG	$e^+e^- \approx 10.4$ GeV
0.053±0.016±0.010	24	AVERY	93	CLEO	$e^+e^- \approx 10.5$ GeV

Semileptonic modes

$\Gamma(\Lambda\ell^+\nu_\ell)/\Gamma(pK^-\pi^+)$ — Γ_{45}/Γ_2

VALUE	DOCUMENT ID		TECN	COMMENT
0.518±0.027±0.089	BERGFELD	94	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(e^+\text{anything})/\Gamma_{\text{total}}$ — Γ_{46}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.045±0.017	VELLA	82	MRK2	e^+e^- 4.5–6.8 GeV

$\Gamma(pe^+\text{anything})/\Gamma_{\text{total}}$ — Γ_{47}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.018±0.009	[7] VELLA	82	MRK2	e^+e^- 4.5–6.8 GeV

[7] VELLA 82 includes protons from Λ decay.

$\Gamma(\Lambda e^+\text{anything})/\Gamma_{\text{total}}$ — Γ_{48}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.011±0.008	[8] VELLA	82	MRK2	e^+e^- 4.5–6.8 GeV

[8] VELLA 82 includes Λ's from Σ^0 decay.

$\Gamma(\Lambda e^+\text{anything})/\Gamma(pK^-\pi^+)$ — Γ_{48}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.37±0.11±0.08	73	ALBRECHT	91G	ARG	$e^+e^- \approx 10.4$ GeV

$\Gamma(\Lambda\mu^+\text{anything})/\Gamma(pK^-\pi^+)$ — Γ_{49}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.35±0.18±0.09	30	ALBRECHT	91G	ARG	$e^+e^- \approx 10.4$ GeV

Inclusive modes

$\Gamma(p\,\text{anything})/\Gamma_{\text{total}}$ — Γ_{51}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.50±0.08±0.14	[9] CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

[9] This CRAWFORD 92 value includes protons from Λ decay. The value is model dependent, but account is taken of this in the systematic error.

$\Gamma(p\,\text{anything (no }\Lambda))/\Gamma_{\text{total}}$ — Γ_{52}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.12±0.10±0.16	CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

$\Gamma(n\,\text{anything})/\Gamma_{\text{total}}$ — Γ_{54}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.50±0.08±0.14	[10] CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

[10] This CRAWFORD 92 value includes neutrons from Λ decay. The value is model dependent, but account is taken of this in the systematic error.

$\Gamma(n\,\text{anything (no }\Lambda))/\Gamma_{\text{total}}$ — Γ_{55}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.29±0.09±0.15	CRAWFORD	92	CLEO	e^+e^- 10.5 GeV

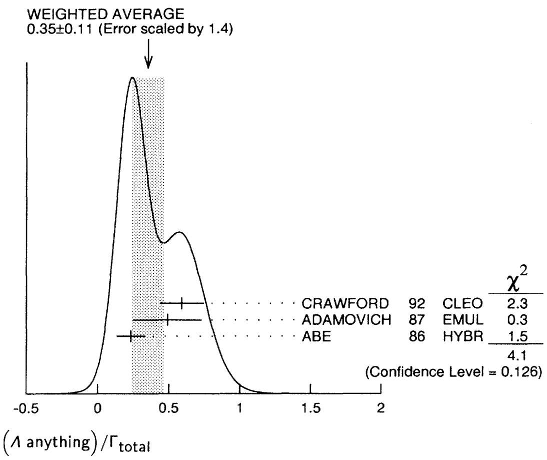
$\Gamma(p\,\text{hadrons})/\Gamma_{\text{total}}$ — Γ_{53}/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.41±0.24	ADAMOVICH	87	EMUL	γA 20–70 GeV/c

$\Gamma(\Lambda\,\text{anything})/\Gamma_{\text{total}}$ — Γ_{56}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.35±0.11 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.				
0.59±0.10±0.12		CRAWFORD	92	CLEO	e^+e^- 10.5 GeV
0.49±0.24		ADAMOVICH	87	EMUL	γA 20–70 GeV/c
0.23±0.10	8	[11] ABE	86	HYBR	20 GeV γp

[11] ABE 86 includes Λ's from Σ^0 decay.



$\Gamma(\Sigma^\pm \text{anything})/\Gamma_{total}$ — Γ_{57}/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.1 ±0.05	5	ABE	86	HYBR	20 GeV γp

Rare or forbidden modes

$\Gamma(p\mu^+\mu^-)/\Gamma_{total}$ — Γ_{58}/Γ

A test for the ΔC=1 weak neutral current. Allowed by higher-order electroweak interactions.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<3.4 × 10⁻⁴	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

$\Gamma(\Sigma^-\mu^+\mu^+)/\Gamma_{total}$ — Γ_{59}/Γ

A test of lepton-number conservation.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<7.0 × 10⁻⁴	90	0	KODAMA	95	E653	π^- emulsion 600 GeV

Λ_c^+ DECAY PARAMETERS

See the "Note on Baryon Decay Parameters" in the neutron Listings.

α FOR $\Lambda_c^+ \to \Lambda\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.98±0.19 OUR AVERAGE					
−0.94±0.21±0.12	414	[12] BISHAI	95	CLEO	$e^+e^- \approx \Upsilon(4S)$
−0.96±0.42		ALBRECHT	92	ARG	$e^+e^- \approx$ 10.4 GeV
−1.1 ±0.4	86	AVERY	90B	CLEO	$e^+e^- \approx$ 10.6 GeV

[12] BISHAI 95 actually gives $\alpha = -0.94^{+0.21}_{-0.06}{}^{+0.12}_{-0.06}$, chopping the errors at the physical limit −1.0. However, for $\alpha \approx -1.0$, some experiments should *get* unphysical values ($\alpha < -1.0$), and for averaging with other measurements such values (or errors that extend below −1.0) should *not* be chopped.

α FOR $\Lambda_c^+ \to \Sigma^+\pi^0$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.45±0.31±0.06	89	BISHAI	95	CLEO	$e^+e^- \approx \Upsilon(4S)$

α FOR $\Lambda_c^+ \to \Lambda\ell^+\nu_\ell$

The experiments don't cover the complete (or same incomplete) $M(\Lambda\ell^+)$ range, but we average them together anyway.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$-0.82^{+0.11}_{-0.07}$ OUR AVERAGE					
$-0.82^{+0.09}_{-0.06}{}^{+0.06}_{-0.03}$	700	[13] CRAWFORD	95	CLEO	$e^+e^- \approx \Upsilon(4S)$
−0.91±0.42±0.25		[14] ALBRECHT	94B	ARG	$e^+e^- \approx$ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$-0.89^{+0.17}_{-0.11}{}^{+0.09}_{-0.05}$	350	[15] BERGFELD	94	CLEO	See CRAWFORD 95

[13] CRAWFORD 95 measures the form-factor ratio $R \equiv f_2/f_1$ for $\Lambda_c^+ \to \Lambda e^+\nu_e$ events to be −0.25 ± 0.14 ± 0.08 and from this calculates α, averaged over q^2, to be the above.

[14] ALBRECHT 94B uses Λe^+ and $\Lambda\mu^+$ events in the mass range 1.85 $< M(\Lambda\ell^+) <$ 2.20 GeV.

[15] BERGFELD 94 uses Λe^+ events.

Λ_c^+ REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1992 edition (Physical Review **D45**, 1 June, Part II) or in earlier editions.

ALEXANDER	96C	PR D53 R1013	+Bebek, Berger+	(CLEO Collab.)
ALBRECHT	95B	PL B342 397	+Hamacher, Hofmann+	(ARGUS Collab.)
AMMAR	95	PRL 74 3534	+Baringer, Bean, Besson+	(CLEO Collab.)
BISHAI	95	PL B350 256	+Fast, Gerndt, Hinson+	(CLEO Collab.)
CRAWFORD	95	PRL 75 624	+Daubenmier, Fulton+	(CLEO Collab.)
KODAMA	95	PL B345 85	+Ushida, Mokhtarani+	(FNAL E653 Collab.)
ALBRECHT	94B	PL B326 320	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALEEV	94	PAN 57 1370	+Balandin+	(Serpukhov BIS-2 Collab.)
		Translated from YF 57 1443.		
AVERY	94	PL B325 257	+Freyberger, Rodriguez+	(CLEO Collab.)
BERGFELD	94	PL B323 219	+Eisenstein, Gollin, Ong+	(CLEO Collab.)
FRABETTI	94E	PL B328 193	+Cheung, Cumalat+	(FNAL E687 Collab.)
AVERY	93	PRL 71 2391	+Freyberger, Rodriguez+	(CLEO Collab.)
BOZEK	93	PL B312 247	+Barlag, Becker, Boehringer+	(CERN NA32 Collab.)
FRABETTI	93D	PRL 70 1755	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	93H	PL B314 477	+Cheung, Cumalat+	(FNAL E687 Collab.)
KUBOTA	93	PRL 71 3255	+Lattery, Nelson, Patton+	(CLEO Collab.)
ALBRECHT	92	PL B274 239	+Ehrlichmann, Hamacher, Krueger+	(ARGUS Collab.)
ALBRECHT	92O	ZPHY C56 1	+Cronstroem, Ehrlichmann+	(ARGUS Collab.)
BARLAG	92	PL B283 465	+Becker, Bozek, Boehringer+	(ACCMOR Collab.)
CRAWFORD	92	PR D45 752	+Fulton, Jensen, Johnson+	(CLEO Collab.)
JEZABEK	92	PL B286 175	+Rybicki, Rylko	(CRAC)
ALBRECHT	91G	PL B269 234	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
AVERY	91	PR D43 3599	+Besson, Garren, Yelton+	(CLEO Collab.)
ALVAREZ	90	ZPHY C47 539	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ALVAREZ	90B	PL B246 256	+Barate, Bloch, Bonamy+	(CERN NA14/2 Collab.)
ANJOS	90	PR D41 801	+Appel, Bean+	(FNAL E691 Collab.)
AVERY	90B	PRL 65 2842	+Besson, Garren, Yelton, Kinoshita+	(CLEO Collab.)
BARLAG	90D	ZPHY C48 29	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
FRABETTI	90	PL B251 639	+Bogart, Cheung, Coteus+	(FNAL E687 Collab.)
BARLAG	89	PL B218 374	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
AGUILAR-...	88B	ZPHY C40 321	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
Also	87	PL B189 254	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
Also	87B	PL B199 462	Aguilar-Benitez, Allison, Bailly+	(LEBC-EHS Collab.)
Also	88	SJNP 48 833	Begalli, Otter, Schulte, Gensch+	(LEBC-EHS Collab.)
		Translated from YAF 48 1310.		
ALBRECHT	88C	PL B207 109	+	(ARGUS Collab.)
ALBRECHT	88E	PL B210 263	+Boeckmann, Glaeser+	(ARGUS Collab.)
ANJOS	88B	PRL 60 1379	+Appel+	(FNAL E691 Collab.)
ADAMOVICH	87	EPL 4 887	+Alexandrov, Bolta+	(Photon Emulsion Collab.)
Also	87	SJNP 46 447	Viaggi, Gessaroli+	(Photon Emulsion Collab.)
		Translated from YAF 46 799.		
AMENDOLIA	87	ZPHY C36 513	+Bagliesi, Batignani, Beck+	(CERN NA1 Collab.)
JONES	87	ZPHY C36 593	+Jones, Kennedy, O'Neale+	(CERN WA21 Collab.)
ABE	86	PR D33 1	+	(SLAC Hybrid Facility Photon Collab.)
BOWCOCK	85	PRL 55 923	+Giles, Hassard, Kinoshita+	(CLEO Collab.)
ALEEV	84	ZPHY C23 333	+Arefiev, Balandin, Berdyshev+	(BIS-2 Collab.)
BOSETTI	82	PL 109B 234	+Graessler+	(AACH3, BONN, CERN, MPIM, OXF)
VELLA	82	PRL 48 1515	+Trilling, Abrams, Alam+	(SLAC, LBL, UCB)
BASILE	81B	NC 62A 14	+Romeo+	(CERN, BGNA, PGIA, FRAS)
CALICCHIO	80	PL 93B 521	+	(BARI, BIRM, BRUX, CERN, EPOL, RHEL+)

$\Lambda_c(2593)^+$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗

Seen in $\Lambda_c^+\pi^+\pi^-$ but not in $\Lambda_c^+\pi^0$, so this is indeed an excited Λ_c^+ rather than a Σ_c^+. The $\Lambda_c^+\pi^+\pi^-$ mode is largely, and perhaps entirely, $\Sigma_c\pi$, which is just at threshold; thus (assuming, as has not yet been proven, that the Σ_c has $J^P = 1/2^+$) the J^P here is almost certainly $1/2^-$. This result is in accord with the theoretical expectation that this is the charm counterpart of the strange $\Lambda(1405)$.

$\Lambda_c(2593)^+$ MASS

The value is obtained from the $m_{\Lambda_c(2593)^+} - m_{\Lambda_c^+}$ mass-difference measurement below.

VALUE (MeV)	DOCUMENT ID
2593.6±1.0 OUR FIT Error includes scale factor of 1.2.	

$m_{\Lambda_c(2593)^+} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
308.6±0.8 OUR FIT Error includes scale factor of 1.3.					
308.6±0.8 OUR AVERAGE Error includes scale factor of 1.3.					
309.2±0.7±0.3	14	[1] FRABETTI	96	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
307.5±0.4±1.0	112	[2] EDWARDS	95	CLEO	$e^+e^- \approx$ 10.5 GeV

[1] FRABETTI 96 claims a signal of 13.9 ± 4.5 events.

[2] EDWARDS 95 claims a signal of 112.5 ± 16.5 events in $\Lambda_c^+\pi^+\pi^-$.

$\Lambda_c(2593)^+$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$3.9^{+1.4}_{-1.2}{}^{+2.0}_{-1.0}$	112	EDWARDS	95	CLEO	$e^+e^- \approx$ 10.5 GeV

$\Lambda_c(2593)^+$ DECAY MODES

$\Lambda_c^+\pi\pi$ and $\Sigma_c(2455)\pi$ — the latter just barely — are the only strong decays allowed to an excited Λ_c^+ having this mass; and the $\Lambda_c^+\pi^+\pi^-$ mode seems to be largely via $\Sigma_c^{++}\pi^-$ or $\Sigma_c^0\pi^+$.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+\pi^+\pi^-$	seen
Γ_2	$\Sigma_c(2455)^{++}\pi^-$	large
Γ_3	$\Sigma_c(2455)^0\pi^+$	large
Γ_4	$\Lambda_c^+\pi^+\pi^-$ 3-body	small
Γ_5	$\Lambda_c^+\pi^0$	not seen
Γ_6	$\Lambda_c^+\gamma$	not seen

$\Lambda_c(2593)^+$ BRANCHING RATIOS

$\Gamma(\Sigma_c(2455)^{++}\pi^-)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_2/Γ_1**

VALUE	DOCUMENT ID		TECN	COMMENT
0.36±0.09±0.09	EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV

$\Gamma(\Sigma_c(2455)^0\pi^+)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_3/Γ_1**

VALUE	DOCUMENT ID		TECN	COMMENT
0.42±0.09±0.09	EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV

$[\Gamma(\Sigma_c(2455)^{++}\pi^-)+\Gamma(\Sigma_c(2455)^0\pi^+)]/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **$(\Gamma_2+\Gamma_3)/\Gamma_1$**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.51	90	[3] FRABETTI	96	E687	γBe, $\overline{E}_\gamma\approx$ 220 GeV

[3] The results of FRABETTI 96 are consistent with this ratio being 100%.

$\Gamma(\Lambda_c^+\pi^0)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_5/Γ_1**

$\Lambda_c^+\pi^0$ decay is forbidden by isospin conservation if this state is in fact a Λ_c.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.53	90	EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV

$\Gamma(\Lambda_c^+\gamma)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_6/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.98	90	EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV

$\Lambda_c(2593)^+$ REFERENCES

FRABETTI 96 PL B365 461 +Cheung, Cumalat+ (FNAL E687 Collab.)
EDWARDS 95 PRL 74 3331 +Ogg, Bellerive, Britton+ (CLEO Collab.)

$\Lambda_c(2625)^+$

$I(J^P) = 0(?^?)$ Status: ∗∗∗

Seen in $\Lambda_c^+\pi^+\pi^-$ but not in $\Lambda_c^+\pi^0$ so this is indeed an excited Λ_c^+ rather than a Σ_c^+. The spin-parity is expected to be $3/2^-$: this is presumably the charm counterpart of the strange $\Lambda(1520)$.

$\Lambda_c(2625)^+$ MASS

The fit also uses the $m_{\Lambda_c(2625)^+} - m_{\Lambda_c^+}$ mass-difference measurement below.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2626.4±0.9 OUR FIT	Error includes scale factor of 1.3.				
2626.6±0.5±1.5	42	[1] ALBRECHT	93F	ARG	$e^+e^-\approx\Upsilon(4S)$

[1] ALBRECHT 93F claims a signal of 42.4 ± 8.8 events.

$m_{\Lambda_c(2625)^+} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
341.5±0.8 OUR FIT	Error includes scale factor of 1.9.				
341.5±0.9 OUR AVERAGE	Error includes scale factor of 2.1.				
342.2±0.2±0.5	245	[2] EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV
340.4±0.6±0.3	40	[3] FRABETTI	94	E687	γBe, $\overline{E}_\gamma\approx$ 220 GeV

[2] EDWARDS 95 claims a signal of 244.6 ± 19.0 events in $\Lambda_c^+\pi^+\pi^-$.
[3] FRABETTI 94 claims a signal of 39.7 ± 8.7 events.

$\Lambda_c(2625)^+$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<1.9	90	245	EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<3.2	90		ALBRECHT	93F	ARG	$e^+e^-\approx\Upsilon(4S)$

$\Lambda_c(2625)^+$ DECAY MODES

$\Lambda_c^+\pi\pi$ and $\Sigma(2455)\pi$ are the only strong decays allowed to an excited Λ_c^+ having this mass.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+\pi^+\pi^-$	seen
Γ_2	$\Sigma_c(2455)^{++}\pi^-$	small
Γ_3	$\Sigma_c(2455)^0\pi^+$	small
Γ_4	$\Lambda_c^+\pi^+\pi^-$ 3-body	large
Γ_5	$\Lambda_c^+\pi^0$	not seen
Γ_6	$\Lambda_c^+\gamma$	not seen

$\Lambda_c(2625)^+$ BRANCHING RATIOS

$\Gamma(\Sigma_c(2455)^{++}\pi^-)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_2/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.08	90	EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV

$\Gamma(\Sigma_c(2455)^0\pi^+)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_3/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.07	90	EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV

$[\Gamma(\Sigma_c(2455)^{++}\pi^-)+\Gamma(\Sigma_c(2455)^0\pi^+)]/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **$(\Gamma_2+\Gamma_3)/\Gamma_1$**

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.36	90		FRABETTI	94	E687	γBe, $\overline{E}_\gamma$ = 220 GeV
0.46±0.14		21	ALBRECHT	93F	ARG	$e^+e^-\approx\Upsilon(4S)$

$\Gamma(\Lambda_c^+\pi^+\pi^-$ 3-body$)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_4/Γ_1**

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.54±0.14	16	ALBRECHT	93F	ARG	$e^+e^-\approx\Upsilon(4S)$

$\Gamma(\Lambda_c^+\pi^0)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_5/Γ_1**

$\Lambda_c^+\pi^0$ decay is forbidden by isospin conservation if this state is in fact a Λ_c.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.91	90	EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV

$\Gamma(\Lambda_c^+\gamma)/\Gamma(\Lambda_c^+\pi^+\pi^-)$ **Γ_6/Γ_1**

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.52	90	EDWARDS	95	CLEO	$e^+e^-\approx$ 10.5 GeV

$\Lambda_c(2625)^+$ REFERENCES

EDWARDS 95 PRL 74 3331 +Ogg, Bellerive, Britton+ (CLEO Collab.)
FRABETTI 94 PRL 72 961 +Cheung, Cumalat+ (FNAL E687 Collab.)
ALBRECHT 93F PL B317 227 +Ehrlichmann, Hamacher+ (ARGUS Collab.)

$\Sigma_c(2455)$

$I(J^P) = 1(\frac{1}{2}^+)$ Status: ∗∗∗∗

J^P is not confirmed. $1/2^+$ is the quark model prediction.

$\Sigma_c(2455)$ MASSES

The mass measurements in this section are redundant with the mass difference measurements that follow. We get the masses by adding $m_{\Sigma_c(2455)} - m_{\Lambda_c^+}$ to the Λ_c^+ mass.

$\Sigma_c(2455)^{++}$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2452.9± 0.6 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2449 ± 3	2	JONES	87	HBC	++	νp in BEBC
2480	1	ADAMOVICH	84	EMUL	++	γA (OMEGA)
2454 ± 5	1	BOSETTI	82	HBC	++	See JONES 87
2425 ±10	6	BALTAY	79	HLBC	++	ν Ne-H in 15-ft
>2439	1	BARISH	77B	DBC	++	νd in 12-ft
2426 ±12	1	CAZZOLI	75	HBC	++	νp in BNL 7-ft

$\Sigma_c(2455)^+$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2453.5±0.9 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2457 ±4	1	CALICCHIO	80	HBC	+	νp in BEBC-TST

$\Sigma_c(2455)^0$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
2452.1± 0.7 OUR FIT						
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2462 ±26	1	AMMAR	86	EMUL	0	νA
~ 2460	9	KNAPP	76	SPEC	0	γBe

$m_{\Sigma_c(2455)} - m_{\Lambda_c^+}$

$m_{\Sigma_c^{++}} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
167.95± 0.25 OUR FIT						
167.94± 0.26 OUR AVERAGE						
167.6 ± 0.6 ±0.6	56	FRABETTI	96	E687	++	γBe, $\overline{E}_\gamma \approx$ 220 GeV
168.2 ± 0.3 ±0.2	126	CRAWFORD	93	CLEO	++	$e^+e^- \approx \Upsilon(4S)$
167.8 ± 0.4 ±0.3	54	BOWCOCK	89	CLEO	++	e^+e^- 10 GeV
168.2 ± 0.5 ±1.6	92	ALBRECHT	88D	ARG	++	e^+e^- 10 GeV
167.4 ± 0.5 ±2.0	46	DIESBURG	87	SPEC	++	nA ~ 600 GeV
167 ± 1	2	JONES	87	HBC	++	νp in BEBC
168 ± 3	6	BALTAY	79	HLBC	++	ν Ne-H in 15-ft
• • • We do not use the following data for averages, fits, limits, etc. • • •						
166 ± 1	1	BOSETTI	82	HBC	++	See JONES 87
166 ±15	1	CAZZOLI	75	HBC	++	νp in BNL 7-ft

$m_{\Sigma_c^+} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
168.5±0.7 OUR FIT Error includes scale factor of 1.1.						
168 ±3	1	CALICCHIO	80	HBC	+	νp in BEBC-TST
• • • We do not use the following data for averages, fits, limits, etc. • • •						
168.5±0.4±0.2	111	[1] CRAWFORD	93	CLEO	+	$e^+e^- \approx \Upsilon(4S)$

[1] This result enters the fit through $m_{\Sigma_c^+} - m_{\Sigma_c^0}$ below.

$m_{\Sigma_c^0} - m_{\Lambda_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
167.2±0.4 OUR FIT Error includes scale factor of 1.1.						
167.2±0.9 OUR AVERAGE Error includes scale factor of 1.4.						
166.6±0.5±0.6	69	FRABETTI	96	E687	0	γBe, $\overline{E}_\gamma \approx$ 220 GeV
168.4±1.0±0.3	14	ANJOS	89D	E691	0	γBe 90–260 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
167.1±0.3±0.2	124	[2] CRAWFORD	93	CLEO	0	$e^+e^- \approx \Upsilon(4S)$
167.9±0.5±0.3	48	[2] BOWCOCK	89	CLEO	0	e^+e^- 10 GeV
167.0±0.5±1.6	70	[2] ALBRECHT	88D	ARG	0	e^+e^- 10 GeV
178.2±0.4±2.0	85	[3] DIESBURG	87	SPEC	0	nA ~ 600 GeV
163 ±2	1	AMMAR	86	EMUL	0	νA

[2] This result enters the fit through $m_{\Sigma_c^{++}} - m_{\Sigma_c^0}$ given below.

[3] See the note on DIESBURG 87 in the $m_{\Sigma_c^{++}} - m_{\Sigma_c^0}$ section below.

$\Sigma_c(2455)$ MASS DIFFERENCES

$m_{\Sigma_c^{++}} - m_{\Sigma_c^0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.79±0.33 OUR FIT Error includes scale factor of 1.2.				
0.8 ±0.4 OUR AVERAGE Error includes scale factor of 1.2.				
1.1 ±0.4 ±0.1	CRAWFORD	93	CLEO	$e^+e^- \approx \Upsilon(4S)$
− 0.1 ±0.6 ±0.1	BOWCOCK	89	CLEO	e^+e^- 10 GeV
+ 1.2 ±0.7 ±0.3	ALBRECHT	88D	ARG	e^+e^- ~ 10 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−10.8 ±2.9	[4] DIESBURG	87	SPEC	nA ~ 600 GeV

[4] DIESBURG 87 is completely incompatible with the other experiments, which is surprising since it agrees with them about $m_{\Sigma_c(2455)^{++}} - m_{\Lambda_c^+}$. We go with the majority here.

$m_{\Sigma_c^+} - m_{\Sigma_c^0}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1.4±0.6 OUR FIT				
1.4±0.5±0.3	CRAWFORD	93	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Sigma_c(2455)$ DECAY MODES

$\Lambda_c^+\pi$ is the only strong decay allowed to a Σ_c having this mass.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda_c^+\pi$	≈ 100 %

$\Sigma_c(2455)$ REFERENCES

FRABETTI	96	PL B365 461	+Cheung, Cumalat+	(FNAL E687 Collab.)
CRAWFORD	93	PRL 71 3259	+Daubenmier, Fulton+	(CLEO Collab.)
ANJOS	89D	PRL 62 1721	+Appel, Bean, Bracker, Browder+	(FNAL E691 Collab.)
BOWCOCK	89	PRL 62 1240	+Kinoshita, Pipkin, Procario, Wilson+	(CLEO Collab.)
ALBRECHT	88D	PL B211 489	+Boeckmann, Glaeser+	(ARGUS Collab.)
DIESBURG	87	PRL 59 2711	+Ladbury, Binkley+	(FNAL E400 Collab.)
JONES	87	ZPHY C36 593	+Jones, Kennedy, O'Neale+	(CERN WA21 Collab.)
AMMAR	86	JETPL 43 515	+Ammosov, Bakic, Baranov, Burnett+	(ITEP)
		Translated from ZETFP 43 401.		
ADAMOVICH	84	PL 140B 119	+Alexandrov, Bolta, Bravo+	(CERN WA58 Collab.)
BOSETTI	82	PL 109B 234	+Graessler+	(AACH3, BONN, CERN, MPIM, OXF)
CALICCHIO	80	PL 93B 521	+	(BARI, BIRM, BRUX, CERN, EPOL, RHEL+)
BALTAY	79	PRL 42 1721	+Caroumbalis, French, Hibbs+	(COLU, BNL)
BARISH	77B	PR D15 1	+Derrick, Dombeck, Musgrave+	(ANL, PURD)
KNAPP	76	PRL 37 882	+Lee, Leung, Smith+	(COLU, HAWA, ILL, FNAL)
CAZZOLI	75	PRL 34 1125	+Cnops, Connolly, Louttit, Murtagh+	(BNL)

$\Sigma_c(2530)$

Status: ∗

OMITTED FROM SUMMARY TABLE

$\Sigma_c(2530)$ MASSES

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2530±5±5	6	[1] AMMOSOV	93	HLBC	$\nu p \to \mu^- \Sigma_c(2530)^{++}$

[1] AMMOSOV 93 sees a cluster of 6 events and estimates the background to be 1 event.

$\Sigma_c(2530)$ REFERENCES

AMMOSOV	93	JETPL 58 247	+Vasil'ev, Ivanilov, Ivanov+	(SERP)
		Translated from ZETFP 58 241.		

Ξ_c^+

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

According to the quark model, the Ξ_c^+ (quark content usc) and Ξ_c^0 form an isospin doublet, and the spin-parity ought to be $J^P = 1/2^+$. None of I, J, or P has actually been measured.

Ξ_c^+ MASS

The fit uses the Ξ_c^+ and Ξ_c^0 mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2465.6± 1.4 OUR FIT					
2465.9± 1.4 OUR AVERAGE					
2467.0± 1.6± 2.0	147	EDWARDS	96	CLEO	$e^+e^- \approx \Upsilon(4S)$
2464.4± 2.0± 1.4	30	FRABETTI	93B	E687	γBe, $\overline{E}_\gamma$= 220 GeV
2465.1± 3.6± 1.9	30	ALBRECHT	90F	ARG	e^+e^- at $\Upsilon(4S)$
2467 ± 3 ± 4	23	ALAM	89	CLEO	e^+e^- 10.6 GeV
2466.5± 2.7± 1.2	5	BARLAG	89C	ACCM	π^- Cu 230 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2459 ± 5 ±30	56	[1] COTEUS	87	SPEC	nA ≃ 600 GeV
2460 ±25	82	BIAGI	83	SPEC	Σ^- Be 135 GeV

[1] Although COTEUS 87 claims to agree well with BIAGI 83 on the mass and width, there appears to be a discrepancy between the two experiments. BIAGI 83 sees a single peak (stated significance about 6 standard deviations) in the $\Lambda K^-\pi^+\pi^+$ mass spectrum. COTEUS 87 sees *two* peaks in the same spectrum, one at the Ξ_c^+ mass, the other 75 MeV lower. The latter is attributed to $\Xi_c^+ \to \Sigma^0 K^-\pi^+\pi^+ \to (\Lambda\gamma)K^-\pi^+\pi^+$, with the γ unseen. The *combined* significance of the double peak is stated to be 5.5 standard deviations. But the absence of any trace of a lower peak in BIAGI 83 seems to us to throw into question the interpretation of the lower peak of COTEUS 87.

Ξ_c^+ MEAN LIFE

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.35^{+0.07}_{-0.04}$ OUR AVERAGE					
$0.41^{+0.11}_{-0.08}\pm0.02$	30	FRABETTI	93B	E687	γBe, $\overline{E}_\gamma$= 220 GeV
$0.20^{+0.11}_{-0.06}$	6	BARLAG	89C	ACCM	π^- (K^-) Cu 230 GeV
$0.40^{+0.18}_{-0.12}\pm0.10$	102	COTEUS	87	SPEC	nA ≃ 600 GeV
$0.48^{+0.21}_{-0.15}{}^{+0.20}_{-0.10}$	53	BIAGI	85C	SPEC	Σ^- Be 135 GeV

Ξ_c^+ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda K^- \pi^+ \pi^+$	seen
Γ_2	$\Lambda \overline{K}^*(892)^0 \pi^+$	not seen
Γ_3	$\Sigma(1385)^+ K^- \pi^+$	not seen
Γ_4	$\Sigma^+ K^- \pi^+$	seen
Γ_5	$\Sigma^+ \overline{K}^*(892)^0$	seen
Γ_6	$\Sigma^0 K^- \pi^+ \pi^+$	seen
Γ_7	$\Xi^0 \pi^+$	seen
Γ_8	$\Xi^- \pi^+ \pi^+$	seen
Γ_9	$\Xi(1530)^0 \pi^+$	not seen
Γ_{10}	$\Xi^0 \pi^+ \pi^0$	seen
Γ_{11}	$\Xi^0 \pi^+ \pi^+ \pi^-$	seen
Γ_{12}	$\Xi^0 e^+ \nu_e$	seen

Ξ_c^+ BRANCHING RATIOS

$\Gamma(\Lambda K^- \pi^+ \pi^+)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	56	COTEUS	87	SPEC	$nA \simeq$ 600 GeV
seen	82	[2] BIAGI	83	SPEC	Σ^- Be 135 GeV

[2] BIAGI 85B looks for but does not see the Ξ_c^+ in $pK^- \overline{K}^0 \pi^+$ ($\Gamma(pK^- \overline{K}^0 \pi^+)$ / $\Gamma(\Lambda K^- \pi^+ \pi^+)$ <0.08 with 90% CL), $p 2K^- 2\pi^+$ ($\Gamma(p2K^- 2\pi^+)$ / $\Gamma(\Lambda K^- \pi^+ \pi^+)$ <0.03, 90% CL), $\Omega^- K^+ \pi^+$, $\Lambda K^{*0} \pi^+$, and $\Sigma(1385)^+ K^- \pi^+$.

$\Gamma(\Lambda K^- \pi^+ \pi^+)/\Gamma(\Xi^- \pi^+ \pi^+)$ — Γ_1/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.58±0.16±0.07	61	BERGFELD	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Lambda \overline{K}^*(892)^0 \pi^+)/\Gamma(\Lambda K^- \pi^+ \pi^+)$ — Γ_2/Γ_1

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.5	90	BERGFELD	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma(1385)^+ K^- \pi^+)/\Gamma(\Lambda K^- \pi^+ \pi^+)$ — Γ_3/Γ_1

Unseen decay modes of the $\Sigma(1385)^+$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.7	90	BERGFELD	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^+ K^- \pi^+)/\Gamma(\Xi^- \pi^+ \pi^+)$ — Γ_4/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.18±0.26±0.17	119	BERGFELD	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.09^{+0.13}_{-0.06}{}^{+0.03}_{-0.02}$	5	BARLAG	89C	ACCM	$2\ \Sigma^+ K^- \pi^+$, $3\ \Xi^- \pi^+ \pi^+$

$\Gamma(\Sigma^+ \overline{K}^*(892)^0)/\Gamma(\Xi^- \pi^+ \pi^+)$ — Γ_5/Γ_8

Unseen decay modes of the $\overline{K}^*(892)^0$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.92±0.27±0.14	61	BERGFELD	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	59	AVERY	95	CLEO	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Sigma^0 K^- \pi^+ \pi^+)/\Gamma(\Lambda K^- \pi^+ \pi^+)$ — Γ_6/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.84±0.36	47	[3] COTEUS	87	SPEC	$nA \simeq$ 600 GeV

[3] See, however, the note on the COTEUS 87 Ξ_c^+ mass measurement.

$\Gamma(\Xi^0 \pi^+)/\Gamma(\Xi^- \pi^+ \pi^+)$ — Γ_7/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.55±0.13±0.09	39	EDWARDS	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^- \pi^+ \pi^+)/\Gamma_{total}$ — Γ_8/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	131	BERGFELD	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$
seen	160	AVERY	95	CLEO	$e^+ e^- \approx \Upsilon(4S)$
seen	30	FRABETTI	93B	E687	γ Be, $\overline{E}_\gamma$= 220 GeV
seen	30	ALBRECHT	90F	ARG	$e^+ e^-$ at $\Upsilon(4S)$
seen	23	ALAM	89	CLEO	$e^+ e^-$ 10.6 GeV

$\Gamma(\Xi(1530)^0 \pi^+)/\Gamma(\Xi^- \pi^+ \pi^+)$ — Γ_9/Γ_8

Unseen decay modes of the $\Xi(1530)^0$ are included.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.2	90	BERGFELD	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^0 \pi^+ \pi^0)/\Gamma(\Xi^- \pi^+ \pi^+)$ — Γ_{10}/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
2.34±0.57±0.37	81	EDWARDS	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Xi(1530)^0 \pi^+)/\Gamma(\Xi^0 \pi^+ \pi^0)$ — Γ_9/Γ_{10}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.3	90	EDWARDS	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^0 \pi^+ \pi^+ \pi^-)/\Gamma(\Xi^- \pi^+ \pi^+)$ — Γ_{11}/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.74±0.42±0.27	57	EDWARDS	96	CLEO	$e^+ e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^0 e^+ \nu_e)/\Gamma(\Xi^- \pi^+ \pi^+)$ — Γ_{12}/Γ_8

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$2.3\pm0.6^{+0.3}_{-0.6}$	41	ALEXANDER	95B	CLEO	$e^+ e^- \approx \Upsilon(4S)$

Ξ_c^+ REFERENCES

BERGFELD	96	PL B365 431	+Eisenstein, Ernst+	(CLEO Collab.)
EDWARDS	96	PL B373 261	+McLean, Ogg+	(CLEO Collab.)
ALEXANDER	95B	PRL 74 3113	+Bebek, Berkelman+	(CLEO Collab.)
Also	95E	PRL 75 4155 (erratum)		
AVERY	95	PRL 75 4364	+Freyberger, Lingel+	(CLEO Collab.)
FRABETTI	93B	PRL 70 1381	+Cheung, Cumalat+	(FNAL E687 Collab.)
ALBRECHT	90F	PL B247 121	+Ehrlichmann, Harder, Kruger, Nau+	(ARGUS Collab.)
ALAM	89	PL B226 401	+Katayama, Kim, Li, Lou, Sun+	(CLEO Collab.)
BARLAG	89C	PL B233 522	+Boehringer, Bosman+	(ACCMOR Collab.)
COTEUS	87	PRL 59 1530	+Binkley+	(FNAL E400 Collab.)
BIAGI	85B	ZPHY C28 175	+Bourquin, Britten+	(CERN WA62 Collab.)
BIAGI	85C	PL 150B 230	+Bourquin, Britten+	(CERN WA62 Collab.)
BIAGI	83	PL 122B 455	+Bourquin, Britten+	(CERN WA62 Collab.)

Ξ_c^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

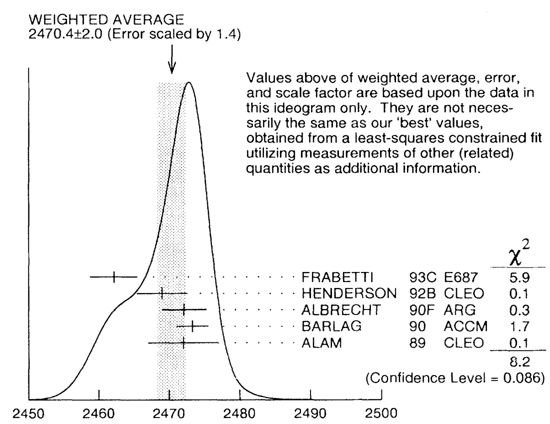
According to the quark model, the Ξ_c^0 (quark content dsc) and Ξ_c^+ form an isospin doublet, and the spin-parity ought to be $J^P = 1/2^+$. None of I, J, or P has actually been measured.

Ξ_c^0 MASS

The fit uses the Ξ_c^0 and Ξ_c^+ mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2470.3±1.8 OUR FIT Error includes scale factor of 1.3.					
2470.4±2.0 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.					
2462.1±3.1±1.4	42	[1] FRABETTI	93C	E687	γ Be, $\overline{E}_\gamma$= 220 GeV
2469 ±2 ±3	9	HENDERSON	92B	CLEO	$\Omega^- K^+$
2472.1±2.7±1.6	54	ALBRECHT	90F	ARG	$e^+ e^-$ at $\Upsilon(4S)$
2473.3±1.9±1.2	4	BARLAG	90	ACCM	π^- (K^-) Cu 230 GeV
2472 ±3 ±4	19	ALAM	89	CLEO	$e^+ e^-$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2471 ±3 ±4	14	AVERY	89	CLEO	See ALAM 89

[1] The FRABETTI 93C mass is well below the other measurements.



Ξ_c^0 mass (MeV)

$m_{\Xi_c^0} - m_{\Xi_c^+}$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
4.7±2.1 OUR FIT Error includes scale factor of 1.2.				
6.3±2.3 OUR AVERAGE				
+7.0±4.5±2.2	ALBRECHT	90F	ARG	$e^+ e^-$ at $\Upsilon(4S)$
+6.8±3.3±0.5	BARLAG	90	ACCM	π^- (K^-) Cu 230 GeV
+5 ±4 ±1	ALAM	89	CLEO	$\Xi_c^0 \to \Xi^- \pi^+$, $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$

Ξ_c^0 MEAN LIFE

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$0.098^{+0.023}_{-0.015}$ OUR AVERAGE					
$0.101^{+0.025}_{-0.017}\pm0.005$	42	FRABETTI	93C	E687	γBe, $\overline{E}_\gamma$= 220 GeV
$0.082^{+0.059}_{-0.030}$	4	BARLAG	90	ACCM	π^- (K^-) Cu 230 GeV

Ξ_c^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Lambda \overline{K}^0$	seen
Γ_2	$\Xi^- \pi^+$	seen
Γ_3	$\Xi^- \pi^+ \pi^+ \pi^-$	seen
Γ_4	$p K^- \overline{K}^*(892)^0$	seen
Γ_5	$\Omega^- K^+$	seen
Γ_6	$\Xi^- e^+ \nu_e$	seen
Γ_7	$\Xi^- \ell^+$ anything	seen

Ξ_c^0 BRANCHING RATIOS

$\Gamma(\Lambda \overline{K}^0)/\Gamma_{total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	7	ALBRECHT	95B	ARG	$e^+e^- \approx$ 10.4 GeV

$\Gamma(\Xi^-\pi^+)/\Gamma(\Xi^-\pi^+\pi^+\pi^-)$ Γ_2/Γ_3

VALUE	DOCUMENT ID		TECN	COMMENT
0.30±0.12±0.05	ALBRECHT	90F	ARG	e^+e^- at $\Upsilon(4S)$

$\Gamma(pK^-\overline{K}^*(892)^0)/\Gamma_{total}$ Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	BARLAG	90	ACCM	π^- (K^-) Cu 230 GeV

$\Gamma(\Omega^- K^+)/\Gamma(\Xi^-\pi^+)$ Γ_5/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.50±0.21±0.05	9	HENDERSON	92B	CLEO	$e^+e^- \approx$ 10.6 GeV

$\Gamma(\Xi^- e^+\nu_e)/\Gamma(\Xi^-\pi^+)$ Γ_6/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$3.1\pm1.0^{+0.3}_{-0.5}$	54	ALEXANDER	95B	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(\Xi^-\ell^+$ anything$)/\Gamma(\Xi^-\pi^+)$ Γ_7/Γ_2

The ratio is for the *average* (not the sum) of the $\Xi^- e^+$ anything and $\Xi^- \mu^+$ anything modes.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.96±0.43±0.18	18	ALBRECHT	93B	ARG	$e^+e^- \approx$ 10.4 GeV

$\Gamma(\Xi^-\ell^+$ anything$)/\Gamma(\Xi^-\pi^+\pi^+\pi^-)$ Γ_7/Γ_3

The ratio is for the *average* (not the sum) of the $\Xi^- e^+$ anything and $\Xi^- \mu^+$ anything modes.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.29±0.12±0.04	18	ALBRECHT	93B	ARG	$e^+e^- \approx$ 10.4 GeV

Ξ_c^0 REFERENCES

ALBRECHT	95B	PL B342 397	+Hamacher, Hofmann+	(ARGUS Collab.)
ALEXANDER	95B	PRL 74 3113	+Bebek, Berkelman+	(CLEO Collab.)
Also	95E	PRL 75 4155 (erratum)		
ALBRECHT	93B	PL B303 368	+Cronstroem, Ehrlichmann+	(ARGUS Collab.)
FRABETTI	93C	PRL 70 2058	+Cheung, Cumalat+	(FNAL E687 Collab.)
HENDERSON	92B	PL B283 161	+Kinoshita, Pipkin, Saulnier+	(CLEO Collab.)
ALBRECHT	90F	PL B247 121	+Ehrlichmann, Harder, Kruger, Nau+	(ARGUS Collab.)
BARLAG	90	PL B236 495	+Becker, Boehringer, Bosman+	(ACCMOR Collab.)
ALAM	89	PL B226 401	+Katayama, Kim, Li, Lou, Sun+	(CLEO Collab.)
AVERY	89	PRL 62 863	+Besson, Garren, Yelton, Bowcock+	(CLEO Collab.)

$\Xi_c(2645)$

$I(J^P) = ?(?^?)$ Status: ∗∗∗

A narrow peak seen in the $\Xi_c^+\pi^-$ mass spectrum. The natural assignment is that this is the $J^P = 3/2^+$ excitation of the Ξ_c in the same SU(4) multiplet as the $\Delta(1232)$. We advance this to the Summary Table since it has also been seen by CLEO in $\Xi_c^0\pi^+$ (CLNS 96/1394, submitted but not yet approved, so not reported below).

$\Xi_c(2645)$ MASS

VALUE (MeV)	DOCUMENT ID
2643.8±1.8 OUR FIT	

$m_{\Xi_c(2645)^0} - m_{\Xi_c^+}$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
178.2±1.1 OUR FIT					
178.2±0.5±1.0	55	AVERY	95	CLEO	$e^+e^- \approx \Upsilon(4S)$

$\Xi_c(2645)$ WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
<5.5	90	55	AVERY	95	CLEO	0	$e^+e^- \approx \Upsilon(4S)$

$\Xi_c(2645)$ DECAY MODES

$\Xi_c\pi$ is the only strong decay allowed to a Ξ_c resonance having this mass.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi_c^+\pi^-$	seen

$\Xi_c(2645)$ BRANCHING RATIOS

$\Gamma(\Xi_c^+\pi^-)/\Gamma_{total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
seen	55	AVERY	95	CLEO	0	$e^+e^- \approx \Upsilon(4S)$

$\Xi_c(2645)$ REFERENCES

AVERY 95 PRL 75 4364 +Freyberger, Lingel+ (CLEO Collab.)

Ω_c^0

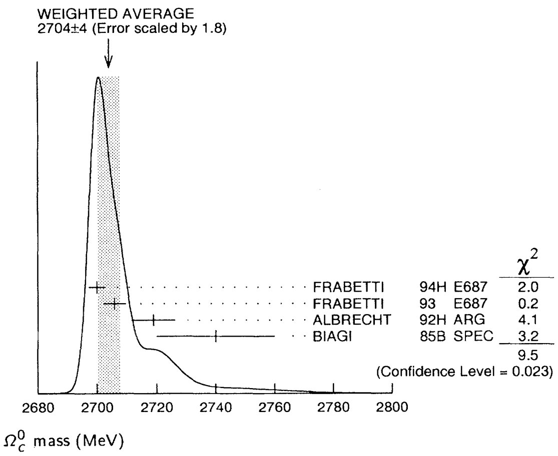
$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

The quantum numbers have not been measured, but are simply assigned in accord with the quark model, in which the Ω_c^0 is the *ssc* ground state.

Ω_c^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2704 ± 4 OUR AVERAGE		Error includes scale factor of 1.8. See the ideogram below.			
2699.9± 1.5±2.5	42	[1] FRABETTI	94H	E687	γBe, $\overline{E}_\gamma$= 221 GeV
2705.9± 3.3±2.0	10	[2] FRABETTI	93	E687	γBe, $\overline{E}_\gamma$= 221 GeV
2719.0± 7.0±2.5	11	[3] ALBRECHT	92H	ARG	$e^+e^- \approx$ 10.6 GeV
2740 ±20	3	BIAGI	85B	SPEC	Σ^- Be 135 GeV/c

[1] FRABETTI 94H claims a signal of 42.5 ± 8.8 $\Sigma^+ K^- K^- \pi^+$ events. The background is about 24 events.
[2] FRABETTI 93 claims a signal of 10.3 ± 3.9 $\Omega^-\pi^+$ events above a background of 5.8 events.
[3] ALBRECHT 92H claims a signal of 11.5 ± 4.3 $\Xi^- K^- \pi^+ \pi^+$ events. The background is about 5 events.



Ω_c^0 MEAN LIFE

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
0.064±0.020 OUR AVERAGE					
$0.055^{+0.013}_{-0.011}{}^{+0.018}_{-0.023}$	86	ADAMOVICH	95B	WA89	$\Omega^-\pi^-\pi^+\pi^+$, $\Xi^-K^-\pi^+\pi^+$
$0.086^{+0.027}_{-0.020}\pm0.028$	25	FRABETTI	95D	E687	$\Sigma^+K^-K^-\pi^+$

Ω_c^0 DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Sigma^+K^-K^-\pi^+$	seen
Γ_2	$\Xi^-K^-\pi^+\pi^+$	seen
Γ_3	$\Omega^-\pi^+$	seen
Γ_4	$\Omega^-\pi^-\pi^+\pi^+$	seen

Ω_c^0 BRANCHING RATIOS

$\Gamma(\Sigma^+K^-K^-\pi^+)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	42	FRABETTI	94H	E687	γBe, $\overline{E}_\gamma$= 221 GeV

$\Gamma(\Xi^-K^-\pi^+\pi^+)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	11	ALBRECHT	92H	ARG	$e^+e^-\approx$ 10.6 GeV
seen	3	BIAGI	85B	SPEC	Σ^- Be 135 GeV/c

$\Gamma(\Omega^-\pi^+)/\Gamma_{total}$ — Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	10	FRABETTI	93	E687	γBe, $\overline{E}_\gamma$= 221 GeV

$\Gamma(\Xi^-K^-\pi^+\pi^+)/\Gamma(\Omega^-\pi^+)$ — Γ_2/Γ_3

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.8	90	FRABETTI	93	E687	γBe, $\overline{E}_\gamma$= 221 GeV

$\Gamma(\Omega^-\pi^-\pi^+\pi^+)/\Gamma(\Omega^-\pi^+)$ — Γ_4/Γ_3

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
seen		ADAMOVICH	95B	WA89	Σ^- 340 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	90	FRABETTI	93	E687	γBe, $\overline{E}_\gamma$= 221 GeV

Ω_c^0 REFERENCES

ADAMOVICH	95B	PL B358 151	+Albertson, Alexandrov+	(CERN WA89 Collab.)
FRABETTI	95D	PL B357 678	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	94H	PL B338 106	+Cheung, Cumalat+	(FNAL E687 Collab.)
FRABETTI	93	PL B300 190	+Cheung, Cumalat, Dallapiccola+	(FNAL E687 Collab.)
ALBRECHT	92H	PL B288 367	+Cronstroem, Ehrlichmann, Hamacher+	(ARGUS Collab.)
BIAGI	85B	ZPHY C28 175	+Bourquin, Britten+	(CERN WA62 Collab.)

BOTTOM (BEAUTY) BARYONS
$(B = -1)$

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$

Λ_b^0

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗

In the quark model, a Λ_b^0 is an isospin-0 udb state. The lowest Λ_b^0 ought to have $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Λ_b^0 MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
5641± 50 OUR AVERAGE					
5640± 50±30	16	[1] ALBAJAR	91E	UA1	$p\overline{p}$ 630 GeV
5640^{+100}_{-210}	52	BARI	91	SFM	$\Lambda_b^0 \to pD^0\pi^-$
5650^{+150}_{-200}	90	BARI	91	SFM	$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
not seen		[2] ABE	93B	CDF	$p\overline{p}$ 1.8 TeV
~ 5750	4	[3] ARENTON	86	FMPS	$\Lambda K_S^0 2\pi^+ 2\pi^-$
5425^{+175}_{-75}		[4] BASILE	81	SFM	See BARI 91

[1] ALBAJAR 91E claims 16 ± 5 events above a background of 9 ± 1 events, a significance of about 5 standard deviations.
[2] ABE 93B states that, based on the signal claimed by ALBAJAR 91E, CDF should have found 30 ± 23 $\Lambda_b^0 \to J/\psi(1S)\Lambda$ events. Instead, CDF found not more than 2 events.
[3] The decay of the Λ_b^0 to the final state observed by ARENTON 86 is Cabibbo suppressed, whereas the decay of a Ξ_b^0 to this final state is allowed. ARENTON 86 thus only claims to have observed a baryon which probably has a b quark and has a D^0 among the decay products, not necessarily the Λ_b^0.
[4] The first claim to have discovered the Λ_b^0 was reported by BASILE 81. In contrast, DRIJARD 82 reported no observation of Λ_b^0, and this led to some discussion in BASILE 82 and DRIJARD 82B. Further evidence for the Λ_b^0 was again reported by the first authors in BARI 91 (see above) in a second, upgraded experiment where two different Λ_b^0 decay modes were observed.

Λ_b^0 MEAN LIFE

These are actually measurements of the average lifetime of weakly decaying b baryons weighted by generally unknown production rates, branching fractions, and detection efficiencies. Presumably, the mix is mainly Λ_b^0, with some Ξ_b^0 and Ξ_b^-.

"OUR EVALUATION" is an average of the data listed below performed by the LEP B Lifetimes Working Group as described in our review "Production and Decay of b-flavored Hadrons" in the $B^\pm$ Section of the Listings. The averaging procedure takes into account correlations between the measurements and asymmetric lifetime errors.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
1.14±0.08 OUR EVALUATION					
$1.46^{+0.22}_{-0.21}{}^{+0.07}_{-0.09}$		ABREU	96D	DLPH	Excess $\Lambda\ell^-\pi^+$, decay lengths
$1.10^{+0.19}_{-0.17}\pm0.09$		ABREU	96D	DLPH	Excess $\Lambda\mu^-$ impact parameters
$1.19^{+0.21}_{-0.18}{}^{+0.07}_{-0.08}$		ABREU	96D	DLPH	Excess $\Lambda_c\ell^-$, decay lengths
1.15±0.12±0.06		AKERS	96	OPAL	Excess $\Lambda\ell^-$, decay lengths
$1.21^{+0.15}_{-0.13}\pm0.10$		AKERS	96	OPAL	Excess $\Lambda\ell^-$, impact parameters
$1.27^{+0.35}_{-0.29}\pm0.09$		ABREU	95S	DLPH	Excess $p\mu^-$, decay lengths
$1.14^{+0.22}_{-0.19}\pm0.07$	69	AKERS	95K	OPAL	Excess $\Lambda_c\ell^-$, decay lengths
$1.05^{+0.12}_{-0.11}\pm0.09$	290	BUSKULIC	95L	ALEP	Excess $\Lambda\ell^-$, impact parameters
$1.02^{+0.23}_{-0.18}\pm0.06$	44	BUSKULIC	95L	ALEP	Excess $\Lambda_c\ell^-$, decay lengths
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.25±0.11±0.05		[5] ABREU	96D	DLPH	Combined result
1.16±0.11±0.06		[6] AKERS	96	OPAL	Combined result
$1.04^{+0.48}_{-0.38}\pm0.10$	11	[7] ABREU	93F	DLPH	Excess $\Lambda\mu^-$, decay lengths
$1.05^{+0.23}_{-0.20}\pm0.08$	157	[8] AKERS	93	OPAL	Excess $\Lambda\ell^-$, decay lengths
$1.12^{+0.32}_{-0.29}\pm0.16$	101	[9] BUSKULIC	92I	ALEP	Excess $\Lambda\ell^-$, impact parameters

[5] Combined result of the three ABREU 96D methods and ABREU 95S.
[6] Combined result of AKERS 96 impact parameter and decay length methods.
[7] ABREU 93F superseded by ABREU 96D.
[8] AKERS 93 superseded by AKERS 96.
[9] BUSKULIC 92I superseded by BUSKULIC 95L.

Λ_b^0 DECAY MODES

These branching fractions are actually an average over weakly decaying b-baryons weighted by their production rates in Z decay (or high-energy $p\overline{p}$), branching ratios, and detection efficiencies. They scale with the LEP Λ_b production fraction $B(b \to \Lambda_b)$ and are evaluated for our value $B(b \to \Lambda_b) = (13.2 \pm 4.1)\%$.

The branching fractions $B(\Lambda_b^0 \to \Lambda\ell^-\overline{\nu}_\ell\text{anything})$ and $B(\Lambda_b^0 \to \Lambda_c^+\ell^-\overline{\nu}_\ell\text{anything})$ are not pure measurements because the underlying measured products of these with $B(b \to \Lambda_b)$ were used to determine $B(b \to \Lambda_b)$, as described in the note "Production and Decay of b-Flavored Hadrons."

	Mode	Fraction (Γ_i/Γ)
Γ_1	$J/\psi(1S)\Lambda$	(1.4± 0.9) %
Γ_2	$pD^0\pi^-$	seen
Γ_3	$\Lambda_c^+\pi^+\pi^-\pi^-$	seen
Γ_4	$\Lambda K^0 2\pi^+ 2\pi^-$	
Γ_5	$p\mu^-\overline{\nu}$anything	(3.7± 1.7) %
Γ_6	$\Lambda\ell^-\overline{\nu}_\ell$anything	[a] (2.5± 0.5) %
Γ_7	$\Lambda_c^+\ell^-\overline{\nu}_\ell$anything	[a] (10.0± 3.0) %
Γ_8	$\Lambda/\overline{\Lambda}$anything	$(17\ ^{+11}_{-8})$ %

[a] Not a pure measurement. See note at head of Λ_b^0 Decay Modes.

Λ_b^0 BRANCHING RATIOS

$\Gamma(J/\psi(1S)\Lambda)/\Gamma_{total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.014±0.008±0.004	16	[10] ALBAJAR	91E	UA1	$J/\psi(1S) \to \mu^+\mu^-$

[10] ALBAJAR 91E reports 0.018 ± 0.011 for $B(b \to \Lambda_b) = 0.10$. We rescale to our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(pD^0\pi^-)/\Gamma_{total}$ Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	52	BARI	91	SFM	$D^0 \to K^-\pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen		BASILE	81	SFM	$D^0 \to K^-\pi^+$

$\Gamma(\Lambda_c^+\pi^+\pi^-\pi^-)/\Gamma_{total}$ Γ_3/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
seen	90	BARI	91	SFM	$\Lambda_c^+ \to pK^-\pi^+$

$\Gamma(\Lambda K^0 2\pi^+ 2\pi^-)/\Gamma_{total}$ Γ_4/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	4	[11] ARENTON	86	FMPS	$\Lambda K_S^0 2\pi^+ 2\pi^-$

[11] See the footnote to the ARENTON 86 mass value.

$\Gamma(p\mu^-\overline{\nu}\text{anything})/\Gamma_{total}$ Γ_5/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.037^{+0.014}_{-0.012}\pm0.012}$	125	[12] ABREU	95S	DLPH	$e^+e^- \to Z$

[12] ABREU 95S reports $[B(\Lambda_b^0 \to p\mu^-\overline{\nu}\text{anything}) \times B(b \to \Lambda_b)] = 0.0049 \pm 0.0011^{+0.0015}_{-0.0011}$. We divide by our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

$\Gamma(\Lambda\ell^-\overline{\nu}_\ell\text{anything})/\Gamma_{total}$ Γ_6/Γ

The values and averages in this section serve only to show what values result if one assumes our $B(b \to \Lambda_b)$. They cannot be thought of as measurements since the underlying product branching fractions were also used to determinine $B(b \to \Lambda_b)$ as described in the note on "Production and Decay of b-Flavored Hadrons."

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.025±0.005 OUR AVERAGE					
0.022±0.003±0.007		[13] AKERS	96	OPAL	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$
0.023±0.005±0.007	262	[14] ABREU	95S	DLPH	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$
0.046±0.009±0.014	290	[15] BUSKULIC	95L	ALEP	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
seen	157	[16] AKERS	93	OPAL	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$
0.053±0.016±0.016	101	[17] BUSKULIC	92I	ALEP	Excess of $\Lambda\ell^-$ over $\Lambda\ell^+$

[13] AKERS 96 reports $[B(\Lambda_b^0 \to \Lambda\ell^-\overline{\nu}_\ell\text{anything}) \times B(b \to \Lambda_b)] = 0.00291 \pm 0.00023 \pm 0.00025$. We divide by our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.
[14] ABREU 95S reports $[B(\Lambda_b^0 \to \Lambda\ell^-\overline{\nu}_\ell\text{anything}) \times B(b \to \Lambda_b)] = 0.0030 \pm 0.0006 \pm 0.0004$. We divide by our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[15] BUSKULIC 95L reports $[B(\Lambda_b^0 \to \Lambda \ell^- \overline{\nu}_\ell \text{anything}) \times B(b \to \Lambda_b)] = 0.0061 \pm 0.0006 \pm 0.0010$. We divide by our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.
[16] AKERS 93 superseded by AKERS 96.
[17] BUSKULIC 92I reports $[B(\Lambda_b^0 \to \Lambda \ell^- \overline{\nu}_\ell \text{anything}) \times B(b \to \Lambda_b)] = 0.0070 \pm 0.0010 \pm 0.0018$. We divide by our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Superseded by BUSKULIC 95L.

$\Gamma(\Lambda_c^+ \ell^- \overline{\nu}_\ell \text{anything})/\Gamma_{total}$ — Γ_7/Γ

The values and averages in this section serve only to show what values result if one assumes our $B(b \to \Lambda_b)$. They cannot be thought of as measurements since the underlying product branching fractions were also used to determinine $B(b \to \Lambda_b)$ as described in the note on "Production and Decay of b-Flavored Hadrons."

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.100±0.030 OUR AVERAGE					
$0.089^{+0.031}_{-0.025} \pm 0.028$	29	[18] ABREU	95S	DLPH	$e^+e^- \to Z$
$0.11 \pm 0.03 \pm 0.04$	55	[19] BUSKULIC	95L	ALEP	$e^+e^- \to Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.23 \pm 0.09 \pm 0.07$	21	[20] BUSKULIC	92E	ALEP	$\Lambda_c^+ \to pK^-\pi^+$

[18] ABREU 95S reports $[B(\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell \text{anything}) \times B(b \to \Lambda_b)] = 0.0118 \pm 0.0026^{+0.0031}_{-0.0021}$. We divide by our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.
[19] BUSKULIC 95L reports $[B(\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell \text{anything}) \times B(b \to \Lambda_b)] = 0.0151 \pm 0.0029 \pm 0.0023$. We divide by our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.
[20] BUSKULIC 92E reports $[B(\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell \text{anything}) \times B(b \to \Lambda_b)] = 0.030 \pm 0.007 \pm 0.009$. We divide by our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value. Superseded by BUSKULIC 95L.

$\Gamma(\Lambda/\overline{\Lambda}\text{anything})/\Gamma_{total}$ — Γ_8/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.17^{+0.09}_{-0.06} \pm 0.05}$	[21] ABREU	95C	DLPH	$e^+e^- \to Z$

[21] ABREU 95C reports $0.28^{+0.17}_{-0.12}$ for $B(b \to \Lambda_b) = 0.08 \pm 0.02$. We rescale to our best value $B(b \to \Lambda_b) = (13.2 \pm 4.1) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

Λ_b^0 REFERENCES

ABREU	96D	ZPHY C (submitted)	+Adam, Adye, Agasi+	(DELPHI Collab.)
CERN-PPE/96-21				
AKERS	96	ZPHY C69 195	+Alexander, Allison, Altekamp+	(OPAL Collab.)
ABREU	95C	PL B347 447	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95S	ZPHY C68 375	+Adam, Adye, Agasi+	(DELPHI Collab.)
AKERS	95K	PL B353 402	+Alexander, Allison, Altekamp+	(OPAL Collab.)
BUSKULIC	95L	PL B357 685	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ABE	93B	PR D47 R2639	+Amidei, Anway-Wiese, Apollinari+	(CDF Collab.)
ABREU	93F	PL B311 379	+Adam, Adye, Agasi+	(DELPHI Collab.)
AKERS	93	PL B316 435	+Alexander, Allison, Anderson+	(OPAL Collab.)
Also	92E	PL B281 394	Acton, Alexander, Allison, Allport+	(OPAL Collab.)
BUSKULIC	92E	PL B294 145	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
BUSKULIC	92I	PL B297 449	+Decamp, Goy, Lees+	(ALEPH Collab.)
Also	92D	PL B278 209	Decamp, Deschizeaux, Goy+	(ALEPH Collab.)
ALBAJAR	91E	PL B273 540	+Albrow, Allkofer, Ankoviak+	(UA1 Collab.)
BARI	91	NC 104A 1787	+Basile, Bruni, Cara Romeo+	(CERN R422 Collab.)
ARENTON	86	NP B274 707	+Chen, Cormell, Dieterle+	(ARIZ, NDAM, VAND)
BASILE	82	NC 68A 289	+Bonvicini, Romeo+	(CERN R415 Collab.)
DRIJARD	82	PL 108B 361	+	(CERN, CDEF, DORT, HEIDH, LAPP, WARS)
DRIJARD	82B	CERN-EP/82-31	+	(CERN, CDEF, DORT, HEIDH, LAPP, WARS)
BASILE	81	LNC 31 97	+Bonvicini, Romeo+	(CERN R415 Collab.)

Ξ_b^0, Ξ_b^-

$I(J^P) = 0(\frac{1}{2}^+)$ Status: *

OMITTED FROM SUMMARY TABLE

ABREU 95V observe an excess of same-sign $\Xi^\mp \ell^\mp$ events in jets, which they interpret as $\Xi_b \to \Xi^- \ell^- \overline{\nu}_\ell X$. They find that the probability for these events to come from non-b-baryon decays is less than 5×10^{-4} and that Λ_b decays can account for less than 10% of these events.

In the quark model, Ξ_b^0 and Ξ_b^- are an isodoublet (usb, dsb) state; the lowest Ξ_b^0 and Ξ_b^- ought to have $J^P = 1/2^+$. None of I, J, or P have actually been measured.

Ξ_b MEAN LIFE

This is actually a measurement of the average lifetime of b-baryons that decay to a jet containing a same-sign $\Xi^\mp \ell^\mp$ pair. Presumably the mix is mainly Ξ_b, with some Λ_b.

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{1.5^{+0.7}_{-0.4} \pm 0.3}$	8	ABREU	95V	DLPH	Excess $\Xi^- \ell^-$, decay lengths

Ξ_b DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\Xi^+ \ell^+ \overline{\nu}_\ell \text{anything}$	seen

Ξ_b BRANCHING RATIOS

$\Gamma(\Xi^+ \ell^+ \overline{\nu}_\ell \text{anything})/\Gamma_{total}$ — Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
seen	ABREU	95V	DLPH	Excess $\Xi^- \ell^-$ over $\Xi^- \ell^+$

Ξ_b REFERENCES

ABREU 95V ZPHY C68 541 +Adam, Adye, Agasi+ (DELPHI Collab.)

SEARCHES*

Notes in the Search Listings

* See the Boson Particle Listings for searches for Higgs bosons, other heavy bosons, and axions and other very light bosons; the Lepton Particle Listings for searches for heavy leptons and for neutrino mixing; the Quark Particle Listings for free quark searches; and the Meson Particle Listings for searches for top and fourth-generation hadrons.

SEARCHES FOR MONOPOLES, SUPERSYMMETRY, COMPOSITENESS, etc.

Magnetic Monopole Searches

MAGNETIC MONOPOLE SEARCHES

(by W.P. Trower, Virginia Polytechnic Institute and State University)

Although the usual formulation of Maxwell's equations suggests magnetic monopoles, no observed phenomenon requires them for explanation [1]. A monopole anywhere in the universe results in electric charge quantization everywhere, and leads to the prediction of a least magnetic charge $G = e/2\alpha$, the Dirac charge [2]. Recently monopoles have become indispensable in many gauge theories, which endow them with a variety of extraordinarily large masses.

Monopole detectors have predominantly used either induction or ionization. Induction experiments measure the monopole magnetic charge and are independent of monopole electric charge, mass, and velocity. Monopole candidate events (CABRERA 82, CAPLIN 86) in single semiconductor loops have been detected by this method, but no two-loop coincidence has been observed. Ionization experiments rely on a magnetic charge producing more ionization than an electrical charge with the same velocity. However, the ability to distinguish a monopole by ionization diminishes with velocity.

Cosmic rays are the most likely source of massive monopoles, since accelerator energies are insufficient to produce them. Evidence for such monopoles may also be obtained from astrophysical observations.

This compilation is only a guide to the literature, since the quoted experimental limits are often only indicative.

References

1. J.D. Jackson, CERN-77-17 (1977).
2. P.A.M. Dirac, Proc. Royal Soc. London **A133**, 60 (1931).

Monopole Production Cross Section — Accelerator Searches

X-SECT (cm^2)	MASS (GeV)	CHG (g)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
	<510			e^+e^-		[1] ACCIARRI	95C	L3
<3.E−37	<45.0	1.0	88–94	e^+e^-	0	PINFOLD	93	PLAS
<3.E−37	<41.6	2.0	88–94	e^+e^-	0	PINFOLD	93	PLAS
<7.E−35	<44.9	0.2–1.0	89–93	e^+e^-	0	KINOSHITA	92	PLAS
<2.E−34	<850	≥ 0.5	1800	$p\bar{p}$	0	BERTANI	90	PLAS
<1.2E−33	<800	≥ 1	1800	$p\bar{p}$	0	PRICE	90	PLAS
<1.E−37	<29	1	50–61	e^+e^-	0	KINOSHITA	89	PLAS
<1.E−37	<18	2	50–61	e^+e^-	0	KINOSHITA	89	PLAS
<1.E−38	<17	<1	35	e^+e^-	0	BRAUNSCH...	88B	CNTR
<8.E−37	<24	1	50–52	e^+e^-	0	KINOSHITA	88	PLAS
<1.3E−35	<22	2	50–52	e^+e^-	0	KINOSHITA	88	PLAS
<9.E−37	<4	<0.15	10.6	e^+e^-	0	GENTILE	87	CLEO
<3.E−32	<800	≥ 1	1800	$p\bar{p}$	0	PRICE	87	PLAS
<3.E−38		<3	29	e^+e^-	0	FRYBERGER	84	PLAS
<1.E−31		1,3	540	$p\bar{p}$	0	AUBERT	83B	PLAS
<4.E−38	<10	<6	34	e^+e^-	0	MUSSET	83	PLAS
<8.E−36	<20		52	pp	0	[2] DELL	82	CNTR
<9.E−37	<30	<3	29	e^+e^-	0	KINOSHITA	82	PLAS
<1.E−37	<20	<24	63	pp	0	CARRIGAN	78	CNTR
<1.E−37	<30	<3	56	pp	0	HOFFMANN	78	PLAS
			62	pp	0	[2] DELL	76	SPRK
<4.E−33			300	p	0	[2] STEVENS	76B	SPRK
<1.E−40	<5	<2	70	p	0	[3] ZRELOV	76	CNTR
<2.E−30			300	n	0	[2] BURKE	75	OSPK
<1.E−38			8	ν	0	[4] CARRIGAN	75	HLBC
<5.E−43	<12	<10	400	p	0	EBERHARD	75B	INDU
<2.E−36	<30	<3	60	pp	0	GIACOMELLI	75	PLAS
<5.E−42	<13	<24	400	p	0	CARRIGAN	74	CNTR
<6.E−42	<12	<24	300	p	0	CARRIGAN	73	CNTR
<2.E−36		1	.001	γ	0	[3] BARTLETT	72	CNTR
<1.E−41	<5		70	p	0	GUREVICH	72	EMUL
<1.E−40	<3	<2	28	p	0	AMALDI	63	EMUL
<2.E−40	<3	<2	30	p	0	PURCELL	63	CNTR
<1.E−35	<3	<4	28	p	0	FIDECARO	61	CNTR
<2.E−35	<1	1	6	p	0	BRADNER	59	EMUL

[1] ACCIARRI 95C finds a limit $B(Z \rightarrow \gamma\gamma\gamma) < 0.8 \times 10^{-5}$ (which is possible via a monopole loop) at 95% CL and sets the mass limit via a cross section model.

[2] Multiphoton events.

[3] Cherenkov radiation polarization.

[4] Re-examines CERN neutrino experiments.

Monopole Flux — Cosmic Ray Searches

FLUX (cm^{-2}sr^{-1}s^{-1})	MASS (GeV)	CHG (g)	COMMENTS ($\beta = v/c$)	EVTS	DOCUMENT ID		TECN
<5.6E−15		1	1.8E−4 < β <3.E−3	0	[5] AHLEN	94	MCRO
<2.7E−15		1	β ∼ 1 × 10^{-3}	0	[6] BECKER-SZ...	94	IMB
<8.7E−15		1	>2.E−3	0	THRON	92	SOUD
<4.4E−12		1	all β	0	GARDNER	91	INDU
<7.2E−13		1	all β	0	HUBER	91	INDU
<3.7E−15	>E12	1	β=1.E−4	0	[7] ORITO	91	PLAS
<3.2E−16	>E10	1	β > 0.05	0	[7] ORITO	91	PLAS
<3.2E−16	>E10–E12	2, 3		0	[7] ORITO	91	PLAS
<3.8E−13		1	all β	0	BERMON	90	INDU
<5.E−16		1	β <1.E−3	0	[6] BEZRUKOV	90	CHER
<1.8E−14		1	β >1.1E−4	0	[8] BUCKLAND	90	HEPT
<1E−18			3.E−4 < β <1.5E−3	0	[9] GHOSH	90	MICA
<7.2E−13		1	all β	0	HUBER	90	INDU
<5.E−12	>E7	1	3.E−4 < β <5.E−3	0	BARISH	87	CNTR
<1.E−13			1.E−5 < β <1	0	[6] BARTELT	87	SOUD
<1.E−10		1	all β	0	EBISU	87	INDU
<2.E−13			1.E−4 < β <6.E−4	0	MASEK	87	HEPT
<2.E−14			4.E−5 < β <2.E−4	0	NAKAMURA	87	PLAS
<2.E−14			1.E−3 < β <1	0	NAKAMURA	87	PLAS
<5.E−14			9.E−4 < β <1.E−2	0	SHEPKO	87	CNTR
<2.E−13			4.E−4 < β <1	0	TSUKAMOTO	87	CNTR
<5.E−14		1	all β	1	[10] CAPLIN	86	INDU
<5.E−12		1		0	CROMAR	86	INDU
<1.E−13		1	7.E−4 < β	0	HARA	86	CNTR
<7.E−11		1	all β	0	INCANDELA	86	INDU
<1.E−18			4.E−4 < β <1.E−3	0	[9] PRICE	86	MICA
<5.E−12		1		0	BERMON	85	INDU
<6.E−12		1		0	CAPLIN	85	INDU
<6.E−10		1		0	EBISU	85	INDU
<3.E−15			5.E−5 ≤ β ≤ 1.E−3	0	[6] KAJITA	85	KAMI
<2.E−21			β <1.E−3	0	[6,11] KAJITA	85	KAMI
<3.E−15			1.E−3 < β <1.E−1	0	[6] PARK	85B	CNTR
<5.E−12		1	1.E−4 < β <1	0	BATTISTONI	84	NUSX
<7.E−12		1		0	INCANDELA	84	INDU
<7.E−13		1	3.E−4 < β	0	[8] KAJINO	84	CNTR
<2.E−12		1	3.E−4 < β <1.E−1	0	KAJINO	84B	CNTR
<6.E−13		1	5.E−4 < β <1	0	KAWAGOE	84	CNTR
<2.E−14			1.E−3 < β	0	[6] KRISHNA...	84	CNTR
<4.E−13		1	6.E−4 < β <2.E−3	0	LISS	84	CNTR
<1.E−16			3.E−4 < β <1.E−3	0	[9] PRICE	84	MICA
<1.E−13		1	1.E−4 < β	0	PRICE	84B	PLAS
<4.E−13		1	6.E−4 < β <2.E−3	0	TARLE	84	CNTR
				7	[12] ANDERSON	83	EMUL
<4.E−13		1	1.E−2 < β <1.E−3	0	BARTELT	83B	CNTR
<1.E−12		1	7.E−3 < β <1	0	BARWICK	83	PLAS
<3.E−13		1	1.E−3 < β <4.E−1	0	BONARELLI	83	CNTR
<3.E−12			5.E−4 < β <5.E−2	0	[6] BOSETTI	83	CNTR
<4.E−11		1		0	CABRERA	83	INDU
<5.E−15		1	1.E−2 < β <1	0	DOKE	83	PLAS
<8.E−15			1.E−4 < β <1.E−1	0	[6] ERREDE	83	IMB
<5.E−12		1	1.E−4 < β <3.E−2	0	GROOM	83	CNTR
<2.E−12			6.E−4 < β <1	0	MASHIMO	83	CNTR
<1.E−13		1	β=3.E−3	0	ALEXEYEV	82	CNTR
<2.E−12		1	7.E−3 < β <6.E−1	0	BONARELLI	82	CNTR
6.E−10		1	all β	1	[13] CABRERA	82	INDU
<2.E−11			1.E−2 < β <1.E−1	0	MASHIMO	82	CNTR
<2.E−15			concentrator	0	BARTLETT	81	PLAS
<1.E−13	>1		1.E−3 < β	0	KINOSHITA	81B	PLAS

<5.E−11	<E17		3.E−4 < β <1.E−3	0	ULLMAN 81	CNTR
<2.E−11			concentrator	0	BARTLETT 78	PLAS
1.E−1	>200	2		1	[14] PRICE 75	PLAS
<2.E−13		>2		0	FLEISCHER 71	PLAS
<1.E−19		>2	obsidian, mica	0	FLEISCHER 69C	PLAS
<5.E−15	<15	<3	concentrator	0	CARITHERS 66	ELEC
<2.E−11		<1–3	concentrator	0	MALKUS 51	EMUL

[5] AHLEN 94 limit for dyons extends down to β=0.9E−4 and a limit of 1.3E−14 extends to β = 0.8E−4. Aso see comment by PRICE 94 and reply of BARISH 94. One loophole in the AHLEN 94 result is that in the case of monopoles catalyzing nucleon decay, relativisitic particles could veto the events. New electronics will remove this possibility.
[6] Catalysis of nucleon decay; sensitive to assumed catalysis cross section.
[7] ORITO 91 limits are functions of velocity. Lowest limits are given here.
[8] Used DKMPR mechanism and Penning effect.
[9] Assumes monopole attaches fermion nucleus.
[10] Limit from combining data of CAPLIN 86, BERMON 85, INCANDELA 84, and CABRERA 83. For a discussion of controversy about CAPLIN 86 observed event, see GUY 87. Also see SCHOUTEN 87.
[11] Based on lack of high- energy solar neutrinos from catalysis in the sun.
[12] Anomalous long-range α (^{4}He) tracks.
[13] CABRERA 82 candidate event has single Dirac charge within $\pm$5%.
[14] ALVAREZ 75, FLEISCHER 75, and FRIEDLANDER 75 explain as fragmenting nucleus. EBERHARD 75 and ROSS 76 discuss conflict with other experiments. HAGSTROM 77 reinterprets as antinucleus. PRICE 78 reassesses.

Monopole Flux — Astrophysics

FLUX ($cm^{-2}sr^{-1}s^{-1}$)	MASS (GeV)	CHG (g)	COMMENTS ($\beta = v/c$)	EVTS	DOCUMENT ID	TECN
<1.E−16	E17	1	galactic field	0	[15] ADAMS 93	COSM
<1.E−23			Jovian planets		[16] ARAFUNE 85	COSM
<1.E−16	E15		solar trapping	0	BRACCI 85B	COSM
<1.E−18		1		0	[16] HARVEY 84	COSM
<3.E−23			neutron stars		KOLB 84	COSM
<7.E−22			pulsars	0	[16] FREESE 83B	COSM
<1.E−18	<E18	1	intergalactic field	0	[16] REPHAELI 83	COSM
<1.E−23			neutron stars	0	[16] DIMOPOUL... 82	COSM
<5.E−22			neutron stars	0	[16] KOLB 82	COSM
<5.E−15	>E21		galactic halo		SALPETER 82	COSM
<1.E−12	E19	1	β=3.E−3	0	[17] TURNER 82	COSM
<1.E−16		1	galactic field	0	PARKER 70	COSM

[15] ADAMS 93 limit based on "survival and growth of a small galactic seed field" is 10^{-16} $(m/10^{17}$ GeV) $cm^{-2}s^{-1}sr^{-1}$. Above 10^{17} GeV, limit 10^{-16} (10^{17} GeV/m) $cm^{-2}s^{-1}sr^{-1}$ (from requirement that monopole density does not overclose the universe) is more stringent.
[16] Catalysis of nucleon decay.
[17] Re-evaluates PARKER 70 limit for GUT monopoles.

Monopole Density — Matter Searches

DENSITY	CHG (g)	MATERIAL	EVTS	DOCUMENT ID	TECN
<6.9E−6/gram	>1/3	Meteorites and other	0	JEON 95	INDU
<2.E−7/gram	>0.6	Fe ore	0	[18] EBISU 87	INDU
>1.E−14/gram	>1/3	iron aerosols	>1	MIKHAILOV 83	SPEC
<6.E−4/gram		air, seawater	0	CARRIGAN 76	CNTR
<5.E−1/gram	>0.04	11 materials	0	CABRERA 75	INDU
<2.E−4/gram	>0.05	moon rock	0	ROSS 73	INDU
<6.E−7/gram	<140	seawater	0	KOLM 71	CNTR
<1.E−2/gram	<120	manganese nodules	0	FLEISCHER 69	PLAS
<1.E−4/gram	>0	manganese	0	FLEISCHER 69B	PLAS
<2.E−3/gram	<1–3	magnetite, meteor	0	GOTO 63	EMUL
<2.E−2/gram		meteorite	0	PETUKHOV 63	CNTR

[18] Mass 1 × 10^{14}–1 × 10^{17} GeV.

Monopole Density — Astrophysics

DENSITY	CHG (g)	MATERIAL	EVTS	DOCUMENT ID	TECN
<1.E−9/gram	1	sun, catalysis	0	[19] ARAFUNE 83	COSM
<6.E−33/nucl	1	moon wake	0	SCHATTEN 83	ELEC
<2.E−28/nucl		earth heat	0	CARRIGAN 80	COSM
<2.E−4/prot		42cm absorption	0	BRODERICK 79	COSM
<2.E−13/m^3		moon wake	0	SCHATTEN 70	ELEC

[19] Catalysis of nucleon decay.

REFERENCES FOR Magnetic Monopole Searches

ACCIARRI 95C PL B345 609 +Adam, Adriani, Aguilar-Benitez+ (L3 Collab.)
JEON 95 PRL 75 1443 Jeon, Longo (MICH)
AHLEN 94 PRL 72 608 +Ambrosio, Antolini, Auriemma+ (MACRO Collab.)
BARISH 94 PRL 73 1306 +Giacomelli, Hong (CIT, BGNA, BOST)
BECKER-SZ... 94 PR D49 2169 Becker-Szendy, Bratton, Breault, Casper+ (IMB Collab.)
PRICE 94 PRL 73 1305 (UCB)
ADAMS 93 PRL 70 2511 +Fatuzzo, Freese, Tarle+ (MICH, FNAL)
PINFOLD 93 PL B316 407 +Du, Kinoshita, Lorazo+ (ALBE, HARV, MONT, UCB)
KINOSHITA 92 PR D46 R881 +Du, Giacomelli, Patriziili+ (HARV, BGNA, REHO)
THRON 92 PR D46 4846 +Allison, Alner, Ambats+ (SOUDAN-2 Collab.)
GARDNER 91 PR D44 622 +Cabrera, Huber, Taber (STAN)
HUBER 91 PR D44 636 +Cabrera, Taber, Gardner (STAN)
ORITO 91 PRL 66 1951 +Ichinose, Nakamura+ (ICEPP, WASCR, NIHO, ICRR)
BERMON 90 PRL 64 839 +Chi, Tsuei+ (IBM, BNL)
BERTANI 90 EPL 12 613 +Giacomelli, Mondardini, Pal+ (BGNA, INFN)
BEZRUKOV 90 SJNP 52 54 +Belolaptikov, Bugaev, Budnev+ (INRM)
Translated from YAF 52 86.
BUCKLAND 90 PR D41 2726 +Masek, Vernon, Knapp, Stronsi (UCSD)
GHOSH 90 EPL 12 25 +Chatterjea (JADA)
HUBER 90 PRL 64 835 +Cabrera, Tabor, Gardner (STAN)
PRICE 90 PRL 65 149 +Guiru, Kinoshita (UCB, HARV)
KINOSHITA 89 PL B228 543 +Fujii, Nakajima+ (HARV, TISA, KEK, UCB, GIFU)
BRAUNSCH... 88B ZPHY C38 543 Braunschweig, Gerhards, Kirschfink+ (TASSO Collab.)
KINOSHITA 88 PRL 60 1610 +Fujii, Nakajima+ (HARV, TISA, KEK, UCB, GIFU)
BARISH 87 PR D36 2641 +Liu, Lane (CIT)
BARTELT 87 PR D36 1990 +Courant, Heller+ (Soudan Collab.)
Also 89 PR D40 1701 erratum Bartelt, Courant, Heller+ (Soudan Collab.)
EBISU 87 PR D36 3359 +Watanabe (KOBE)
Also 85 JPG 11 883 Ebisu, Watanabe (KOBE)
GENTILE 87 PR D35 1081 +Haas, Hempstead+ (CLEO Collab.)
GUY 87 Nature 325 463 (LOIC)
MASEK 87 PR D35 2758 +Knapp, Miller, Stronski, Vernon, White (UCSD)
NAKAMURA 87 PL B183 395 +Kawagoe, Yamamoto+ (INUS, WASCR, NIHO)
PRICE 87 PRL 59 2523 +Guoxiao, Kinoshita (UCB, HARV)
SCHOUTEN 87 JPE 20 850 +Caplin, Guy, Hardiman+ (LOIC)
SHEPKO 87 PR D35 2917 +Gagliardi, Green, McIntyre+ (TAMU)
TSUKAMOTO 87 EPL 3 39 +Nagano, Anraku+ (ICRR)
CAPLIN 86 Nature 321 402 +Hardiman, Koratzinos, Schouten (LOIC)
Also 87 JPE 20 850 Schouten, Caplin, Guy, Hardiman+ (LOIC)
Also 87 Nature 325 463 Guy (LOIC)
CROMAR 86 PRL 56 2561 +Clark, Fickett (NBSB)
HARA 86 PRL 56 553 +Honda, Ohno+ (ICRR, KYOT, KEK, KOBE, ICEPP)
INCANDELA 86 PR D34 2637 +Frisch, Somalwar, Kuchnir+ (CHIC, FNAL, MICH)
PRICE 86 PRL 56 1226 +Salamon (UCB)
ARAFUNE 85 PR D32 2586 +Fukugita, Yanagita (ICRR, KYOTY, IBAR)
BERMON 85 PRL 55 1850 +Chaudhari, Chi, Tesche, Tsuei (IBM)
BRACCI 85B NP B258 726 +Fiorentini, Mezzorani (PISA, CAGL, INFN)
Also 85 LNC 42 123 Bracci, Fiorentini (PISA)
CAPLIN 85 Nature 317 234 +Guy, Hardiman, Park, Schouten (LOIC)
EBISU 85 JPG 11 883 +Watanabe (KOBE)
KAJITA 85 JPSJ 54 4065 +Arisaka, Koshiba, Nakahata+ (ICRR, KEK, NIIG)
PARK 85B NP B252 261 +Blewitt, Cortez, Foster+ (IMB Collab.)
BATTISTONI 84 PL 133B 454 +Bellotti, Bologna, Campana+ (NUSEX Collab.)
FRYBERGER 84 PR D29 1524 +Coan, Kinoshita, Price (SLAC, UCB)
HARVEY 84 NP B236 255 (PRIN)
INCANDELA 84 PRL 53 2067 +Campbell, Frisch+ (CHIC, FNAL, MICH)
KAJINO 84 PRL 52 1373 +Matsuno, Yuan, Kitamura (ICRR)
KAJINO 84B JPG 10 447 +Matsuno, Kitamura, Aoki, Yuan, Mitsui+ (ICRR)
KAWAGOE 84 LNC 41 315 +Mashimo, Nakamura, Nozaki, Orito (TOKY)
KOLB 84 APJ 286 702 +Turner (FNAL, CHIC)
KRISHNA... 84 PL 142B 99 Krishnaswamy, Menon+ (TATA, OSKC, INUS)
LISS 84 PR D30 884 +Ahlen, Tarle (UCB, IND, MICH)
PRICE 84 PRL 52 1265 +Guo, Ahlen, Fleischer (ROMA, UCB, IND, GESC)
PRICE 84B PL 140B 112 (CERN)
TARLE 84 PRL 52 90 +Ahlen, Liss (UCB, MICH, IND)
ANDERSON 83 PR D28 2308 +Lord, Strausz, Wilkes (WASH)
ARAFUNE 83 PL 133B 380 +Fukugita (ICRR, KYOTY)
AUBERT 83B PL 120B 465 +Musset, Price, Vialle (CERN, LAPP)
BARTELT 83B PRL 50 655 +Courant, Heller, Joyce, Marshak+ (MINN, ANL)
BARWICK 83 PR D28 2338 +Kinoshita, Price (UCB)
BONARELLI 83 PL 126B 137 +Capiluppi, Dantone (BGNA)
BOSETTI 83 PL 133B 265 +Gorham, Harris, Learned+ (AACH3, HAWA, TOKY)
CABRERA 83 PRL 51 1933 +Taber, Gardner, Bourg (STAN)
DOKE 83 PL 129B 370 +Hayashi, Hamasaki+ (WASU, RIKK, TTAM, RIKEN)
ERREDE 83 PRL 51 245 +Stone, Vander Velde, Bionta+ (IMB Collab.)
FREESE 83B PRL 51 1625 +Turner, Schramm (CHIC)
GROOM 83 PRL 50 573 +Loh, Nelson, Ritson (UTAH, STAN)
MASHIMO 83 PL 128B 327 +Orito, Kawagoe, Nakamura, Nozaki (ICEPP)
MIKHAILOV 83 PL 130B 331 (KAZA)
MUSSET 83 PL 128B 333 +Price, Lohrmann (CERN, HAMB)
REPHAELI 83 PL 121B 115 +Turner (CHIC)
SCHATTEN 83 PR D27 1525 (NASA)
ALEXEYEV 82 LNC 35 413 +Boliev, Chudakov, Makoev, Mikheyev+ (INRM)
BONARELLI 82 PL 112B 100 +Capiluppi, Dantone+ (BGNA)
CABRERA 82 PRL 48 1378 (STAN)
DELL 82 NP B209 45 +Yuan, Roberts, Dooher+ (BNL, ADEL, ROMA)
DIMOPOUL... 82 PL 119B 320 Dimopoulos, Preskill, Wilczek (HARV, UCSBT)
KINOSHITA 82 PRL 48 77 +Price, Fryberger (UCB, SLAC)
KOLB 82 PRL 49 1373 +Colgate, Harvey (LASL, PRIN)
MASHIMO 82 JPSJ 51 3067 +Kawagoe, Koshiba (INUS)
SALPETER 82 PRL 49 1114 +Shapiro, Wasserman (CORN)
TURNER 82 PR D26 1296 +Parker, Bogdan (CHIC)
BARTLETT 81 PR D24 612 +Soo, Fleischer, Hart+ (COLO, GESC)
KINOSHITA 81B PR D24 1707 +Price (UCB)
ULLMAN 81 PRL 47 289 (LEHM, BNL)
CARRIGAN 80 Nature 288 348 (FNAL)
BRODERICK 79 PR D19 1046 +Ficenec, Teplitz, Teplitz (VPI)
BARTLETT 78 PR D18 2253 +Soo, White (COLO, PRIN)
CARRIGAN 78 PR D17 1754 +Strauss, Giacomelli (FNAL, BGNA)
HOFFMANN 78 LNC 23 357 +Kantardjian, Diliberto, Meddi+ (CERN, ROMA)
PRICE 78 PR D18 1382 +Shirk, Osborne, Pinsky (UCB, HOUS)
HAGSTROM 77 PRL 38 729 (LBL)
CARRIGAN 76 PR D13 1823 +Nezrick, Strauss (FNAL)
DELL 76 LNC 15 269 +Uto, Yuan, Amaldi+ (CERN, BNL, ROMA, ADEL)
ROSS 76 LBL-4665 (LBL)
STEVENS 76B PR D14 2207 +Collins, Ficenec, Trower, Fischer+ (VPI, BNL)
ZRELOV 76 CZJP B26 1306 +Kollarova, Kollar, Lupiltsev, Pavlovic+ (JINR)
ALVAREZ 75 LBL-4260 (LBL)
BURKE 75 PL 60B 113 +Gustafson, Jones, Longo (MICH)
CABRERA 75 Thesis (STAN)
CARRIGAN 75 NP B91 279 +Nezrick (FNAL)
Also 71 PR D3 56 Carrigan, Nezrick (FNAL)
EBERHARD 75 PR D11 3099 +Ross, Taylor, Alvarez, Oberlack (LBL, MPIM)
EBERHARD 75B LBL-4289 (LBL)
FLEISCHER 75 PRL 35 1412 +Walker (GESC, WUSL)
FRIEDLANDER 75 PRL 35 1167 (WUSL)
GIACOMELLI 75 NC 28A 21 +Rossi+ (BGNA, CERN, SACL, ROMA)
PRICE 75 PRL 35 487 +Shirk, Osborne, Pinsky (UCB, HOUS)
CARRIGAN 74 PR D10 3867 +Nezrick, Strauss (FNAL)
CARRIGAN 73 PR D8 3717 +Nezrick, Strauss (FNAL)
ROSS 73 PR D8 698 +Eberhard, Alvarez, Watt (LBL, SLAC)
Also 71 PR D4 3260 Eberhard, Ross, Alvarez, Watt (LBL, SLAC)
Also 70 Science 167 701 Alvarez, Eberhard, Ross, Watt (LBL, SLAC)
BARTLETT 72 PR D6 1817 +Lahana (COLO)
GUREVICH 72 PL 38B 549 +Khakimov, Martemyanov+ (KIAE, NOVO, SERP)
Also 72B JETP 34 917 Barkov, Gurevich, Zolotorev (KIAE, NOVO, SERP)
Translated from ZETF 61 1721.
Also 70 PL 31B 394 Gurevich, Khakimov+ (KIAE, NOVO, SERP)
FLEISCHER 71 PR D4 24 +Hart, Nichols, Price (GESC)

KOLM 71 PR D4 1285 +Villa, Odian (MIT, SLAC)
PARKER 70 APJ 160 383 (CHIC)
SCHATTEN 70 PR D1 2245 (NASA)
FLEISCHER 69 PR 177 2029 +Jacobs, Schwartz, Price (GESC, FSU)
FLEISCHER 69B PR 184 1393 +Hart, Jacobs+ (GESC, UNCS, GSCO)
FLEISCHER 69C PR 184 1398 +Price, Woods (GESC)
Also 70C JAP 41 958 Fleischer, Hart, Jacobs, Price+ (GESC)
CARITHERS 66 PR 149 1070 +Stefanski, Adair (YALE, BNL)
AMALDI 63 NC 28 773 +Baroni, Manfredini+ (ROMA, UCSD, CERN)
GOTO 63 PR 132 387 +Kolm, Ford (TOKY, MIT, BRAN)
PETUKHOV 63 NP 49 87 +Yakimenko (LEBD)
PURCELL 63 PR 129 2326 +Collins, Fujii, Hornbostel, Turkot (HARV, BNL)
FIDECARO 61 NC 22 657 +Finocchiaro, Giacomelli (CERN)
BRADNER 59 PR 114 603 +Isbell (LBL)
MALKUS 51 PR 83 899 (CHIC)

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Review

Supersymmetric Particle Searches

SUPERSYMMETRY

(by H.E. Haber, Univ. of California, Santa Cruz)

A. Introduction: Supersymmetry is a generalization of the space-time symmetries of quantum field theory that transforms fermions into bosons and vice versa. It also provides a framework for the unification of particle physics and gravity, which takes place at an energy of order the Planck scale ($\approx 10^{19}$ GeV) [1–3]. However, supersymmetry is clearly not an exact symmetry of nature, and therefore must be broken. In theories of "low-energy" supersymmetry, the effective scale of supersymmetry breaking is tied to the electroweak scale [4–6]. In this way, it is hoped that supersymmetry will ultimately explain the origin of the large hierarchy between the W and Z masses and the Planck scale. At present, there are no unambiguous experimental results that require the existence of low-energy supersymmetry. However, if experimentation at future colliders uncovers evidence for supersymmetry, this would have a profound effect on the study of TeV-scale physics and the development of a more fundamental theory of mass and symmetry-breaking phenomena in particle physics.

B. Structure of the MSSM: The minimal supersymmetric extension of the Standard Model (MSSM) consists of taking the Standard Model and adding the corresponding supersymmetric partners [7]. In addition, the MSSM contains two hypercharge $Y = \pm 1$ Higgs doublets, which is the minimal structure for the Higgs sector of an anomaly-free supersymmetric extension of the Standard Model. The supersymmetric structure of the theory also requires (at least) two Higgs doublets to generate mass for both "up"-type and "down"-type quarks (and charged leptons) [8,9]. All renormalizable supersymmetric interactions consistent with (global) B–L conservation (B =baryon number and L =lepton number) are included. Finally, the most general soft-supersymmetry-breaking terms are added [10].

If supersymmetry is relevant for explaining the scale of electroweak interactions, then the mass parameters that occur in the soft-supersymmetry-breaking terms must be of order 1 TeV or below [11]. Some bounds on these parameters exist due to the absence of supersymmetric-particle production at current accelerators (see the Particle Listings following this note). Additional constraints arise from limits on the contributions of virtual supersymmetric particle exchange to a variety of Standard Model processes [12]. The impact of precision electroweak measurements at LEP and SLC on the MSSM parameter space is discussed briefly at the end of this note.

As a consequence of B–L invariance, the MSSM possesses a discrete R-parity invariance, where $R = (-1)^{3(B-L)+2S}$ for a particle of spin S [13]. Note that this formula implies that all the ordinary Standard Model particles have even R-parity, whereas the corresponding supersymmetric partners have odd R-parity. The conservation of R-parity in scattering and decay processes has a crucial impact on supersymmetric phenomenology. For example, starting from an initial state involving ordinary (R-even) particles, it follows that supersymmetric particles must be produced in pairs. In general, these particles are highly unstable and decay quickly into lighter states. However, R-parity invariance also implies that the lightest supersymmetric particle (LSP) is absolutely stable, and must eventually be produced at the end of a decay chain initiated by the decay of a heavy unstable supersymmetric particle.

In order to be consistent with cosmological constraints, the LSP is almost certainly electrically and color neutral [14]. Consequently, the LSP is weakly-interacting in ordinary matter, *i.e.* it behaves like a stable heavy neutrino and will escape detectors without being directly observed. Thus, the canonical signature for (R-parity conserving) supersymmetric theories is missing (transverse) energy, due to the escape of the LSP.

Some model builders attempt to relax the assumption of R-parity conservation. Models of this type must break B–L and are therefore strongly constrained by experiment [15]. Nevertheless, it is still important to allow for the possibility of R-parity violating processes in the search for supersymmetry. In such models, the LSP is unstable and supersymmetric particles can be singly produced and destroyed in association with B or L violation. These features lead to a phenomenology of broken-R-parity models that is very different from that of the MSSM.

In the MSSM, supersymmetry breaking is accomplished by including the soft-supersymmetry breaking terms mentioned earlier. These terms parametrize our ignorance of the fundamental mechanism of supersymmetry breaking. If this breaking occurs spontaneously, then (in the absence of supergravity) a massless Goldstone fermion called the *goldstino* ($\widetilde{G}$) must exist. The goldstino would then be the LSP and could play an important role in supersymmetric phenomenology [16]. In models that incorporate supergravity, this picture changes. If supergravity is spontaneously broken, the goldstino is absorbed ("eaten") by the *gravitino* ($g_{3/2}$), the spin-3/2 partner of the graviton [17]. By this super-Higgs mechanism, the gravitino acquires a mass ($m_{3/2}$). In many models, the gravitino mass is of order the electroweak-symmetry-breaking scale, while its couplings are gravitational in strength [1,18]. Such a gravitino would play no role in supersymmetric phenomenology at colliders.

The parameters of the MSSM are conveniently described by considering separately the supersymmetry-conserving sector and the supersymmetry-breaking sector. A careful discussion of the conventions used in defining the MSSM parameters can be found in Ref. 19. Among the parameters of the supersymmetry conserving sector are: (i) gauge couplings: g_s, g, and g', corresponding to the Standard Model gauge group SU(3)×SU(2)×U(1) respectively; (ii) Higgs-Yukawa couplings: λ_e, λ_u, and λ_d (which are 3×3 matrices in flavor space); and (iii) a supersymmetry-conserving Higgs mass parameter μ.

The supersymmetry-breaking sector contains the following set of parameters: (i) gaugino Majorana masses M_3, M_2 and M_1 associated with the SU(3), SU(2), and U(1) subgroups of the Standard Model; (ii) scalar mass matrices for the squarks and sleptons; (iii) Higgs-squark-squark trilinear interaction terms (the so-called "A-parameters") and corresponding terms involving the sleptons; and (iv) three scalar Higgs mass parameters—two diagonal and one off-diagonal mass terms for the two Higgs doublets. These three mass parameters can be re-expressed in terms of the two Higgs vacuum expectation values, v_1 and v_2, and one physical Higgs mass. Here, v_1 (v_2) is the vacuum expectation value of the Higgs field which couples exclusively to down-type (up-type) quarks and leptons. Note that $v_1^2 + v_2^2 = (246\text{ GeV})^2$ is fixed by the W mass (or equivalently by the Fermi constant G_F), while the ratio

$$\tan\beta = v_2/v_1 \tag{1}$$

is a free parameter of the model.

The supersymmetric constraints imply that the MSSM Higgs sector is automatically CP-conserving (at tree-level). Thus, $\tan\beta$ is a real parameter (conventionally chosen to be positive), and the physical neutral Higgs scalars are CP-eigenstates. Nevertheless, the MSSM does contain a number of possible new sources of CP violation. For example, gaugino-mass parameters, the A-parameters, and μ may be complex. Some combination of these complex phases must be less than of order 10^{-2}–10^{-3} (for a supersymmetry-breaking scale of 100 GeV) to avoid generating electric dipole moments for the neutron, electron, and atoms in conflict with observed data [20]. However, these complex phases have little impact on the direct searches for supersymmetric particles, and are usually ignored in experimental analyses.

C. The Higgs sector of the MSSM: Before describing the supersymmetric-particle sector, let us consider the Higgs sector of the MSSM [21]. There are five physical Higgs particles in this model: a charged Higgs pair ($H^\pm$), two CP-even neutral Higgs bosons (denoted by H_1^0 and H_2^0 where $m_{H_1^0} \le m_{H_2^0}$) and one CP-odd neutral Higgs boson (A^0). The properties of the Higgs sector are determined by the Higgs potential which is made up of quadratic terms [whose squared-mass coefficients were mentioned above Eq. (1)] and quartic interaction terms. The strengths of the interaction terms are directly related to the gauge couplings by supersymmetry (and are not affected at tree-level by supersymmetry-breaking). As a result, $\tan\beta$ [defined in Eq. (1)] and one Higgs mass determine: the Higgs spectrum, an angle α [which indicates the amount of mixing of the original $Y = \pm 1$ Higgs doublet states in the physical CP-even scalars], and the Higgs boson couplings.

When one-loop radiative corrections are incorporated, additional parameters of the supersymmetric model enter via virtual loops. The impact of these corrections can be significant [22,23]. For example, at tree-level, the MSSM predicts $m_{H_1^0} \le m_Z$ [8,9]. If true, this would imply that experiments to be performed at LEP-2 operating at its maximum energy and luminosity would rule out the MSSM if H_1^0 were not found. However, this Higgs mass bound can be violated when the radiative corrections are incorporated. For example, in Ref. 22, the following approximate upper bound was obtained for $m_{H_1^0}$ (assuming $m_{A^0} > m_Z$) in the limit of $m_Z \ll m_t \ll M_{\widetilde{t}}$ [where top-squark ($\widetilde{t}_L$–$\widetilde{t}_R$) mixing is neglected]

$$m_{H_1^0}^2 \lesssim m_Z^2 + \frac{3g^2 m_Z^4}{16\pi^2 m_W^2} \times \left\{ \ln\left(\frac{M_{\widetilde{t}}^2}{m_t^2}\right)\left[\frac{2m_t^4 - m_t^2 m_Z^2}{m_Z^4}\right] + \frac{m_t^2}{3m_Z^2}\right\}. \tag{2}$$

More refined computations (which include the effects of top-squark mixing, renormalization group improvement, and the leading two-loop contributions) yield $m_{H_1^0} \lesssim 125$ GeV for $m_t = 175$ GeV and a top-squark mass of $M_{\widetilde{t}} = 1$ TeV [24]. Clearly, the radiative corrections to the Higgs masses have a significant impact on the search for the Higgs bosons of the MSSM at LEP [25].

D. Supersymmetric-particle spectrum: Consider next the supersymmetric-particle sector of the MSSM. The supersymmetric partners of the gauge and Higgs bosons are fermions, whose names are obtained by appending "ino" at the end of the corresponding Standard Model particle name. The *gluino* is the color octet Majorana fermion partner of the gluon with mass $M_{\widetilde{g}} = |M_3|$. The supersymmetric partners of the electroweak gauge and Higgs bosons (the *gauginos* and *Higgsinos*) can mix. As a result, the physical mass eigenstates are model-dependent linear combinations of these states, called *charginos* and *neutralinos*, which are obtained by diagonalizing the corresponding mass matrices. The chargino-mass matrix depends on M_2, μ, $\tan\beta$ and m_W [26].

The corresponding chargino-mass eigenstates are denoted by $\widetilde{\chi}_1^+$ and $\widetilde{\chi}_2^+$, with masses

$$M^2_{\widetilde{\chi}_1^+,\widetilde{\chi}_2^+} = \tfrac{1}{2}\Big\{|\mu|^2 + |M_2|^2 + 2m_W^2 \mp \Big[\left(|\mu|^2 + |M_2|^2 + 2m_W^2\right)^2 - 4|\mu|^2|M_2|^2 - 4m_W^4 \sin^2 2\beta + 8m_W^2 \sin 2\beta\,\mathrm{Re}(\mu M_2)\Big]^{1/2}\Big\}, \tag{3}$$

where the states are ordered such that $M_{\widetilde{\chi}_1^+} \le M_{\widetilde{\chi}_2^+}$. If CP-violating effects are ignored (in which case, M_2 and μ are real parameters), then one can choose a convention where $\tan\beta$ and M_2 are positive. (Note that the relative sign of M_2 and μ is meaningful. The sign of μ is convention-dependent; the reader is warned that both sign conventions appear in the literature.) The sign convention for μ implicit in Eq. (3) is used by the LEP collaborations [27] in their plots of exclusion contours in the M_2 *vs.* μ plane derived from the non-observation of $Z \to \widetilde{\chi}_1^+\widetilde{\chi}_1^-$. The neutralino mass matrix depends on M_1, M_2, μ, $\tan\beta$, m_Z, and the weak mixing angle θ_W [26]. The corresponding neutralino eigenstates are usually denoted by $\widetilde{\chi}_i^0$ ($i = 1, \ldots 4$), according to the convention that $M_{\widetilde{\chi}_1^0} \le M_{\widetilde{\chi}_2^0} \le M_{\widetilde{\chi}_3^0} \le M_{\widetilde{\chi}_4^0}$. If a chargino or neutralino eigenstate approximates a particular gaugino or Higgsino state, it may be convenient to use the corresponding nomenclature. For example, if M_1 and M_2 are small compared to m_Z (and μ), then the lightest neutralino $\widetilde{\chi}_1^0$ will be nearly a pure photino, $\widetilde{\gamma}$ (the supersymmetric partner of the photon).

It is common practice in the literature to reduce the supersymmetric parameter freedom by requiring that all three gaugino-mass parameters are equal at some grand unification scale. Then, at the electroweak scale, the gaugino-mass parameters can be expressed in terms of one of them (say, M_2). The other two gaugino-mass parameters are given by

$$M_3 = (g_s^2/g^2)M_2 \ , \qquad M_1 = (5g'^2/3g^2)M_2 \ . \tag{4}$$

Having made this assumption, the chargino and neutralino masses and mixing angles depend only on three unknown parameters: the gluino mass, μ, and $\tan\beta$. However, the assumption of gaugino-mass unification could prove false and must eventually be tested experimentally.

The supersymmetric partners of the quarks and leptons are spin-zero bosons: the *squarks*, charged *sleptons*, and *sneutrinos*. For a given fermion f, there are two supersymmetric partners $\widetilde{f}_L$ and $\widetilde{f}_R$ which are scalar partners of the corresponding left and right-handed fermion. (There is no $\widetilde{\nu}_R$.) However, in general, $\widetilde{f}_L$ and $\widetilde{f}_R$ are not mass-eigenstates since there is $\widetilde{f}_L$-$\widetilde{f}_R$ mixing which is proportional in strength to the corresponding element of the scalar mass-squared matrix [28]:

$$M_{LR}^2 = \begin{cases} m_d(A_d - \mu\tan\beta), & \text{for "down"-type } f \\ m_u(A_u - \mu\cot\beta), & \text{for "up"-type } f, \end{cases} \tag{5}$$

where m_d (m_u) is the mass of the appropriate "down" ("up") type quark or lepton. Here, A_d and A_u are (unknown) soft-supersymmetry-breaking A–parameters and μ and $\tan\beta$ have been defined earlier. The signs of the A parameters are also convention-dependent; see Ref. 19. Due to the appearance of the *fermion* mass in Eq. (5), one expects M_{LR} to be small compared to the diagonal squark and slepton masses, with the possible exception of the top-squark, since m_t is large, and the bottom-squark and tau-slepton if $\tan\beta \gg 1$.

The (diagonal) L- and R-type squark and slepton masses are given by [2]

$$M^2_{\widetilde{u}_L} = M^2_{\widetilde{Q}} + m_u^2 + m_Z^2\cos 2\beta(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W) \tag{6}$$

$$M^2_{\widetilde{u}_R} = M^2_{\widetilde{U}} + m_u^2 + \tfrac{2}{3}m_Z^2\cos 2\beta\sin^2\theta_W \tag{7}$$

$$M^2_{\widetilde{d}_L} = M^2_{\widetilde{Q}} + m_d^2 - m_Z^2\cos 2\beta(\tfrac{1}{2} - \tfrac{1}{3}\sin^2\theta_W) \tag{8}$$

$$M^2_{\widetilde{d}_R} = M^2_{\widetilde{D}} + m_d^2 - \tfrac{1}{3}m_Z^2\cos 2\beta\sin^2\theta_W \tag{9}$$

$$M^2_{\widetilde{\nu}} = M^2_{\widetilde{L}} + \tfrac{1}{2}m_Z^2\cos 2\beta \tag{10}$$

$$M^2_{\widetilde{e}_L} = M^2_{\widetilde{L}} + m_e^2 - m_Z^2\cos 2\beta(\tfrac{1}{2} - \sin^2\theta_W) \tag{11}$$

$$M^2_{\widetilde{e}_R} = M^2_{\widetilde{E}} + m_e^2 - m_Z^2\cos 2\beta\sin^2\theta_W \,. \tag{12}$$

The soft-supersymmetry-breaking parameters: $M_{\widetilde{Q}}$, $M_{\widetilde{U}}$, $M_{\widetilde{D}}$, $M_{\widetilde{L}}$, and $M_{\widetilde{E}}$ are unknown parameters. In the equations above, the notation of first generation fermions has been used and generational indices have been suppressed. Further complications such as intergenerational mixing are possible, although there are some constraints from the nonobservation of flavor-changing neutral currents (FCNC) [29].

E. Reducing the MSSM parameter freedom: One way to guarantee the absence of significant FCNC's mediated by virtual supersymmetric-particle exchange is to posit that the diagonal soft-supersymmetry-breaking scalar squared-masses are universal in flavor space at some energy scale (normally taken to be at or near the Planck scale) [5,30,31]. Renormalization group evolution is used to determine the low-energy values for the scalar mass parameters listed above. This assumption substantially reduces the MSSM parameter freedom. For example, supersymmetric grand unified models with universal scalar masses at the Planck scale typically give [32] $M_{\widetilde{L}} \approx M_{\widetilde{E}} < M_{\widetilde{Q}} \approx M_{\widetilde{U}} \approx M_{\widetilde{D}}$ with the squark masses somewhere between a factor of 1–3 larger than the slepton masses (neglecting generational distinctions). More specifically, the first two generations are thought to be nearly degenerate in mass, while $M_{\widetilde{Q}_3}$ and $M_{\widetilde{U}_3}$ are typically reduced by a factor of 1–3 from the other soft-supersymmetry-breaking masses because of renormalization effects due to the heavy top quark mass.

As a result, four flavors of squarks (with two squark eigenstates per flavor) and $\widetilde{b}_R$ will be nearly mass-degenerate and somewhat heavier than six flavors of nearly mass-degenerate sleptons (with two per flavor for the charged sleptons and one per flavor for the sneutrinos). On the other hand, the $\widetilde{b}_L$ mass and the diagonal $\widetilde{t}_L$ and $\widetilde{t}_R$ masses are reduced compared to the common squark mass of the first two generations. In addition, third generation squark masses and tau-slepton masses are sensitive to the strength of the respective $\widetilde{f}_L$–$\widetilde{f}_R$ mixing as discussed below Eq. (5).

Two additional theoretical frameworks are often introduced to reduce further the MSSM parameter freedom [1,2,33]. The first involves grand unified theories (GUTs) and the desert hypothesis ($i.e$ no new physics between the TeV-scale and the GUT-scale). Perhaps one of the most compelling hints for low-energy supersymmetry is the unification of SU(3)×SU(2)×U(1) gauge couplings predicted by supersymmetric GUT models [5,34] (with the supersymmetry breaking scale of order 1 TeV or below). The unification, which takes place at an energy scale of order 10^{16} GeV, is quite robust (and depends weakly on the details of the GUT-scale theory). For example, a recent analysis [35] finds that supersymmetric GUT unification implies that $\alpha_s(m_Z) = 0.129 \pm 0.010$, not including threshold corrections due to GUT-scale particles (which could diminish the value of $\alpha_s(m_Z)$). This result is compatible with the world average of $\alpha_s(m_Z) = 0.118 \pm 0.003$ as quoted by the Particle Data Group. In contrast, gauge coupling unification in the simplest nonsupersymmetric GUT models fails by many standard deviations [36].

Grand unification can impose additional constraints through the unification of Higgs-fermion Yukawa couplings (λ_f). There is some evidence that $\lambda_b = \lambda_\tau$ leads to good low-energy phenomenology [37], and an intriguing possibility that in the MSSM (in the parameter regime where $\tan\beta \simeq m_t/m_b$) $\lambda_b = \lambda_\tau = \lambda_t$ may be phenomenologically viable [38]. However, such unification constraints are GUT-model dependent, and do not address the origin of the first and second generation fermion masses and the CKM mixing matrix. Finally, grand unification imposes constraints on the soft-supersymmetry-breaking parameters. For example, gaugino-mass unification leads to the relations given in Eq. (4). Diagonal squark and slepton soft-supersymmetry-breaking scalar masses may also be unified at the GUT scale (analogous to the unification of Higgs-fermion Yukawa couplings).

In order to further reduce the number of independent soft-supersymmetry-breaking parameters (with or without grand unification), an additional simplifying assumption is required. In the minimal supergravity theory, the soft-supersymmetry-breaking parameters are often taken to have the following simple form. Referring to the parameter list given above Eq. (1), the Planck-scale values of the soft-supersymmetry-breaking terms depend on the following minimal set of parameters: (i) a universal gaugino mass $m_{1/2}$; (ii) a universal diagonal scalar-mass parameter m_0 [whose consequences were described at the beginning of this section]; (iii) a universal A-parameter, A_0; and (iv) three scalar Higgs mass parameters—two common diagonal-squared masses given by $|\mu_0|^2 + m_0^2$ and an off-diagonal-squared mass given by $B_0\mu_0$ (which defines the Planck-scale supersymmetry-breaking parameter B_0), where μ_0 is the Planck-scale value of the μ-parameter.

As before, renormalization group evolution is used to compute the low-energy values of the supersymmetry-breaking parameters and determines the supersymmetric-particle spectrum. Moreover, in this approach, electroweak symmetry breaking is induced radiatively if one of the Higgs diagonal-squared masses is forced negative by the evolution. This occurs in models with a large Higgs-top quark Yukawa coupling ($i.e.$ large m_t). As a result, the two Higgs vacuum expectation values (or equivalently, m_Z and $\tan\beta$) can be expressed as a function of the Planck-scale supergravity parameters. The simplest procedure [32] is to remove μ_0 and B_0 in favor of m_Z and $\tan\beta$ (the sign of μ_0 is not fixed in this process). In this case, the MSSM spectrum and its interactions are determined by m_0, A_0, $m_{1/2}$, $\tan\beta$, and the sign of μ_0 (in addition to the parameters of the Standard Model). However, the minimal approach above is probably too restrictive. Theoretical considerations suggest that the universality of Planck-scale soft-supersymmetry breaking parameters is not generic [39]. In the absence of a fundamental theory of supersymmetry breaking, further progress will require a detailed knowledge of the supersymmetric-particle spectrum in order to determine the nature of the Planck-scale parameters. Of course, any of the theoretical assumptions described in this section could be wrong and must eventually be tested experimentally.

F. The MSSM and precision of electroweak data: The MSSM (with or without constraints imposed from the theory near the Planck scale) provides a framework that can be tested by precision electroweak data. The level of accuracy of the measured Z decay observables at LEP and SLC is sufficient to test the structure of the one-loop radiative corrections of the electroweak model [40], and is thus potentially sensitive to the virtual effects of undiscovered particles. Combining the most recent LEP and SLC electroweak results [41] with the recent top-quark mass measurement at the Tevatron [42], a weak preference is found [41,43] for a light Higgs boson mass of order m_Z, which is consistent with the MSSM Higgs mass upper bound previously noted. Moreover, for Z decay observables, the effects of virtual supersymmetric-particle exchange are suppressed by a factor of $m_Z^2/M_{\rm SUSY}^2$, and therefore decouple in the limit of large supersymmetric-particle masses. It follows that for $M_{\rm SUSY}^2 \gg m_Z$ (in practice, it is sufficient to have all supersymmetric-particle masses above 200 GeV) the MSSM yields an equally good fit to the precision electroweak data as compared to the Standard Model fit.

On the other hand, there are a few tantalizing hints in the data for deviations from Standard Model predictions. Indeed, if $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ is confirmed to lie above its Standard Model prediction due to the presence of new physics, then a plausible candidate for the new physics would be the MSSM with some light supersymmetric particles ($e.g.$ a light chargino and top-squark and/or a light CP-odd scalar, A^0) close in mass to their present LEP bounds [44,45]. Such a scenario would be tested by the search for supersymmetric particles at LEP-2 and the Tevatron.

G. Beyond the MSSM: Nonminimal versions of low-energy supersymmetry can also be constructed. These models add additional matter and/or gauge super-multiplets to the MSSM (at the TeV scale or below). Experimental and theoretical constraints place some restrictions on these approaches, although no comprehensive treatment has yet appeared in the literature.

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MINIMAL SUPERSYMMETRIC STANDARD MODEL ASSUMPTIONS

All results shown below (except where stated otherwise) are based on the Minimal Supersymmetric Standard Model (MSSM) as described in the Note on Supersymmetry. This includes the assumption that R-parity is conserved. In addition the following assumptions are made in most cases:

1) The $\widetilde{\chi}^0_1$ (or $\widetilde{\gamma}$) is the lightest supersymmetric particle (LSP).

2) $m_{\widetilde{f}_L} = m_{\widetilde{f}_R}$ where $\widetilde{f}_L$ and $\widetilde{f}_R$ refer to the scalar partners of left-and right-handed fermions.

Limits involving different assumptions either are identified with comments or are in the miscellaneous section.

When needed, specific assumptions of the eigenstate content of neutralinos and charginos are indicated (use of the notation $\widetilde{\gamma}$ (photino), $\widetilde{H}$ (Higgsino), $\widetilde{W}$ (w-ino), and $\widetilde{Z}$ (z-ino) indicates the approximation of a pure state was made).

$\widetilde{\chi}^0_1$ (Lightest Neutralino) MASS LIMIT

$\widetilde{\chi}^0_1$ is likely to be the lightest supersymmetric particle (LSP). See also the $\widetilde{\chi}^0_2$, $\widetilde{\chi}^0_3$, $\widetilde{\chi}^0_4$ section below.

We have divided the $\widetilde{\chi}^0_1$ listings below into three sections: 1) Accelerator limits for $\widetilde{\chi}^0_1$, 2) Bounds on $\widetilde{\chi}^0_1$ from dark matter searches, and 3) Other bounds on $\widetilde{\chi}^0_1$ from astrophysics and cosmology.

Accelerator limits for $\widetilde{\chi}^0_1$

These papers generally exclude regions in the $M_2-\mu$ parameter plane based on accelerator experiments. Unless otherwise stated, these papers assume minimal supersymmetry and GUT relations (gaugino-mass unification condition).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>23	95	[1] ACCIARRI	95E	L3	$\tan\beta > 3$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
≥ 0		[2] FRANKE	94	RVUE	$\widetilde{\chi}^0_1$ mixed with a singlet
>20	95	[3] DECAMP	92	ALEP	$\tan\beta > 3$
>18.8		[4] BAER	91	RVUE	$\tan\beta > 1.6$
>18.4	90	[5] HIDAKA	91	RVUE	
> (10–13)	90	[6] ROSZKOWSKI	90	RVUE	$\tan\beta \geq 1$
>5	90	[7] HEARTY	89	ASP	$\widetilde{\gamma}$; for $m_{\widetilde{e}} < 55$ GeV

[1] ACCIARRI 95E limit for $\tan\beta > 2$ is 20 GeV, and the bound disappears if $\tan\beta \sim 1$.
[2] FRANKE 94 reanalyzed the LEP constraints on the neutralinos in the MSSM with an additional singlet.
[3] DECAMP 92 limit for $\tan\beta > 2$ is $m > 13$ GeV.
[4] BAER 91 limit obtained from LEP and preliminary CDF results assuming $\tan\beta > 1.6$.
[5] HIDAKA 91 limit obtained from LEP and preliminary CDF limits on the gluino mass (as analyzed in BAER 91).
[6] ROSZKOWSKI 90 limit obtained from ALEPH and CDF/UA2 results assuming $\tan\beta \geq 1$.
[7] HEARTY 89 assumed pure $\widetilde{\gamma}$ eigenstate and $m_{\widetilde{e}_L} = m_{\widetilde{e}_R}$. There is no limit for $m_{\widetilde{e}} > 58$ GeV. Uses $e^+e^- \rightarrow \gamma\widetilde{\gamma}\widetilde{\gamma}$. No GUT relation assumptions are made.

Bounds on $\widetilde{\chi}^0_1$ from dark matter searches

These papers generally exclude regions in the $M_2-\mu$ parameter plane assuming that $\widetilde{\chi}^0_1$ is the dominant form of dark matter in the galactic halo. These limits are based on the lack of detection in laboratory experiments or by the absence of a signal in underground neturino detectors. The latter signal is expected if $\widetilde{\chi}^0_1$ accumlates in the Sun or the Earth and annihilates into high-energy ν's.

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[8] MORI	93	KAMI
	[9] BOTTINO	92	COSM
	[10] BOTTINO	91	RVUE
	[11] GELMINI	91	COSM
	[12] KAMIONKOW..	91	RVUE
	[13] MORI	91B	KAMI
none 4–15 GeV	[14] OLIVE	88	COSM

[8] MORI 93 excludes some region in M_2-μ parameter space depending on $\tan\beta$ and lightest scalar Higgs mass for neutralino dark matter $m_{\widetilde{\chi}0} > m_W$, using limits on upgoing muons produced by energetic neutrinos from neutralino annihilation in the Sun and the Earth.
[9] BOTTINO 92 excludes some region M_2-μ parameter space assuming that the lightest neutralino is the dark matter, using upgoing muons at Kamiokande, direct searches by Ge detectors, and by LEP experiments. The analysis includes top radiative corrections on Higgs parameters and employs two different hypotheses for nucleon-Higgs coupling. Effects of rescaling in the local neutralino density according to the neutralino relic abundance are taken into account.
[10] BOTTINO 91 excluded a region in $M_2-\mu$ plane using upgoing muon data from Kamioka experiment, assuming that the dark matter surrounding us is composed of neutralinos and that the Higgs boson.
[11] GELMINI 91 exclude a region in $M_2-\mu$ plane using dark matter searches.
[12] KAMIONKOWSKI 91 excludes a region in the M_2-μ plane using IMB limit on upgoing muons originated by energetic neutrinos from neutralino annihilation in the sun, assuming that the dark matter is composed of neutralinos and that $m_{H^0_1} \lesssim 50$ GeV. See Fig. 8 in the paper.
[13] MORI 91B exclude a part of the region in the M_2-μ plane with $m_{\widetilde{\chi}^0_1} \lesssim 80$ GeV using a limit on upgoing muons originated by energetic neutrinos from neutralino annihilation in the earth, assuming that the dark matter surrounding us is composed of neutralinos and that $m_{H^0_1} \lesssim 80$ GeV.
[14] OLIVE 88 result assumes that photinos make up the dark matter in the galactic halo. Limit is based on annihilations in the sun and is due to an absence of high energy neutrinos detected in underground experiments. The limit is model dependent.

Other bounds on $\widetilde{\chi}^0_1$ from astrophysics and cosmology

Most of these papers generally exclude regions in the $M_2-\mu$ parameter plane by requiring that the $\widetilde{\chi}^0_1$ contribution to the overall cosmological density is less than some maximal value to avoid overclosure of the Universe. Those not based on the cosmological density are indicated. Many of these papers also include LEP and/or other bounds.

VALUE	DOCUMENT ID		TECN	COMMENT
none 100 eV – 15 GeV	SREDNICKI	88	COSM	$\widetilde{\gamma}$; $m_{\widetilde{f}}$=100 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
		[15] FALK	95 COSM	*CP*-violating phases
		DREES	93 COSM	Minimal supergravity
		FALK	93 COSM	Sfermion mixing
		KELLEY	93 COSM	Minimal supergravity
		MIZUTA	93 COSM	Co-annihilation
		ELLIS	92F COSM	Minimal supergravity
		KAWASAKI	92 COSM	Minimal supergravity, m_0=A=0
		LOPEZ	92 COSM	Minimal supergravity, m_0=A=0
		MCDONALD	92 COSM	
		NOJIRI	91 COSM	Minimal supergravity
		[16] OLIVE	91 COSM	
		ROSZKOWSKI	91 COSM	
		ELLIS	90 COSM	
		[17] GRIEST	90 COSM	
		[18] GRIFOLS	90 ASTR	$\tilde{\gamma}$; SN 1987A
		KRAUSS	90 COSM	
		[16] OLIVE	89 COSM	
> 100 eV		[19] ELLIS	88B ASTR	$\tilde{\gamma}$; SN 1987A
none 100 eV – (5–7) GeV		SREDNICKI	88 COSM	$\tilde{\gamma}$; $m_{\tilde{f}}$=60 GeV
none 100 eV–5 GeV		ELLIS	84 COSM	$\tilde{\gamma}$; for $m_{\tilde{f}}$=100 GeV
		GOLDBERG	83 COSM	$\tilde{\gamma}$
		[20] KRAUSS	83 COSM	$\tilde{\gamma}$
		VYSOTSKII	83 COSM	$\tilde{\gamma}$

[15] Mass of the bino (=LSP) is limited to $m_{\tilde{B}} \lesssim$ 350 GeV for m_t = 174 GeV.

[16] Mass of the bino (=LSP) is limited to $m_{\tilde{B}} \lesssim$ 350 GeV for $m_t \leq$ 200 GeV. Mass of the higgsino (=LSP) is limited to $m_{\tilde{H}} \lesssim$ 1 TeV for $m_t \leq$ 200 GeV.

[17] Mass of the bino (=LSP) is limited to $m_{\tilde{B}} \lesssim$ 550 GeV. Mass of the higgsino (=LSP) is limited to $m_{\tilde{H}} \lesssim$ 3.2 TeV.

[18] GRIFOLS 90 argues that SN1987A data exclude a light photino ($\lesssim$ 1 MeV) if $m_{\tilde{q}} <$ 1.1 TeV, $m_{\tilde{e}} <$ 0.83 TeV.

[19] ELLIS 88B argues that the observed neutrino flux from SN 1987A is inconsistent with a light photino if 60 GeV $\lesssim m_{\tilde{q}} \lesssim$ 2.5 TeV. If m(higgsino) is O(100 eV) the same argument leads to limits on the ratio of the two Higgs v.e.v.'s. LAU 93 discusses possible relations of ELLIS 88B bounds.

[20] KRAUSS 83 finds $m_{\tilde{\gamma}}$ not 30 eV to 2.5 GeV. KRAUSS 83 takes into account the gravitino decay. Find that limits depend strongly on reheated temperature. For example a new allowed region $m_{\tilde{\gamma}}$ = 4–20 MeV exists if $m_{\text{gravitino}}$ <40 TeV. See figure 2.

$\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, $\tilde{\chi}^0_4$ (Neutralinos) MASS LIMITS

Neutralinos are unknown mixtures of photinos, z-inos, and neutral higgsinos (the supersymmetric partners of photons and of Z and Higgs bosons). The limits here apply only to $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, and $\tilde{\chi}^0_4$. $\tilde{\chi}^0_1$ is the lightest supersymmetric particle (LSP); see $\tilde{\chi}^0_1$ Mass Limits. It is not possible to quote rigorous mass limits because they are extremely model dependent; i.e. they depend on branching ratios of various $\tilde{\chi}^0$ decay modes, on the masses of decay products ($\tilde{e}$, $\tilde{\gamma}$, $\tilde{q}$, $\tilde{g}$), and on the $\tilde{e}$ mass exchanged in $e^+e^- \to \tilde{\chi}^0_i \tilde{\chi}^0_j$. Often limits are given as contour plots in the $m_{\tilde{\chi}^0} - m_{\tilde{e}}$ plane vs other parameters. When specific assumptions are made, e.g, the neutralino is a pure photino ($\tilde{\gamma}$), pure z-ino ($\tilde{Z}$), or pure neutral higgsino ($\tilde{H}^0$), the neutralinos will be labelled as such.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 52	95	[21] ACCIARRI	95E L3	$\tilde{\chi}^0_2$, tanβ >3
> 84	95	[21] ACCIARRI	95E L3	$\tilde{\chi}^0_3$, tanβ >3
>127	95	[21] ACCIARRI	95E L3	$\tilde{\chi}^0_4$, tanβ >3
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[22] ABACHI	96 D0	$p\bar{p} \to \tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2$
> 45	95	[23] DECAMP	92 ALEP	$\tilde{\chi}^0_2$, tanβ >3
> 45	95	[24] HIDAKA	91 RVUE	$\tilde{\chi}^0_2$
> 70	95	[24] HIDAKA	91 RVUE	$\tilde{\chi}^0_3$
>108	95	[24] HIDAKA	91 RVUE	$\tilde{\chi}^0_4$
		[25] ABREU	90G DLPH	$Z \to \tilde{\chi}^0 \tilde{\chi}^0$
		[26] AKRAWY	90N OPAL	$Z \to \tilde{\chi}^0 \tilde{\chi}^0$
> 57	90	[27] BAER	90 RVUE	$\tilde{\chi}^0_3$; Γ(Z); tanβ > 1
		[28] BARKLOW	90 MRK2	$Z \to \tilde{\chi}^0_1 \tilde{\chi}^0_2$, $\tilde{\chi}^0_2 \tilde{\chi}^0_2$
		[29] DECAMP	90K ALEP	$Z \to \tilde{\chi}^0 \tilde{\chi}^0$
> 41	95	[30] SAKAI	90 AMY	$e^+e^- \to \tilde{H}^0_1 \tilde{H}^0_2$ ($\tilde{H}^0_2 \to f\bar{f}\tilde{H}^0_1$)
> 31	95	[31] BEHREND	87B CELL	$e^+e^- \to \tilde{\gamma}\tilde{Z}$ ($\tilde{Z} \to q\bar{q}\tilde{\gamma}$), $m_{\tilde{e}}$ < 70 GeV
> 30	95	[32] BEHREND	87B CELL	$e^+e^- \to \tilde{\gamma}\tilde{Z}$ ($\tilde{Z} \to q\bar{q}\tilde{g}$)
> 31.3	95	[33] BEHREND	87B CELL	$e^+e^- \to \tilde{H}^0_1 \tilde{H}^0_2$ ($\tilde{H}^0_2 \to f\bar{f}\tilde{H}^0_1$)
> 22	95	[34] BEHREND	87B CELL	$e^+e^- \to \gamma\tilde{\gamma}\tilde{Z}$ ($\tilde{Z} \to \bar{\nu}\nu$)
		[35] AKERLOF	85 HRS	$e^+e^- \to \tilde{\gamma}\tilde{\chi}^0$ ($\tilde{\chi}^0 \to q\bar{q}\tilde{\gamma}$)
none 1–21	95	[36] BARTEL	85L JADE	$e^+e^- \to \tilde{H}^0_1 \tilde{H}^0_2$, $\tilde{H}^0_2 \to f\bar{f}\tilde{H}^0_1$
		[37] BEHREND	85 CELL	$e^+e^- \to$ monojet X
> 35	95	[38] ADEVA	84B MRKJ	$e^+e^- \to \gamma\tilde{Z}$ ($\tilde{Z} \to \ell\bar{\ell}\tilde{\gamma}$)
> 28	95	[39] BARTEL	84C JADE	$e^+e^- \to \gamma\tilde{Z}$ ($\tilde{Z} \to f\bar{f}\tilde{\gamma}$)
		[40] ELLIS	84 COSM	

[21] ACCIARRI 95E limits go down to 0 GeV ($\tilde{\chi}^0_2$), 60 GeV ($\tilde{\chi}^0_3$), and 90 GeV ($\tilde{\chi}^0_4$) for tanβ=1.

[22] ABACHI 96 searches for 3-lepton final states. Efficiencies are calculated using mass relations and branching ratios in the Minimal Supergravity scenario. Results are presented as lower bounds on $\sigma(\tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2) \times B(\tilde{\chi}^{\pm}_1 \to \ell\nu_\ell \tilde{\chi}^0_1) \times B(\tilde{\chi}^0_2 \to \ell^+\ell^- \tilde{\chi}^0_1)$ as a function of $m_{\tilde{\chi}^0_1}$. Limits range from 3.1 pb ($m_{\tilde{\chi}^0_1}$ = 45 GeV) to 0.6 pb ($m_{\tilde{\chi}^0_1}$ = 100 GeV).

[23] For tanβ >2 the limit is >40 GeV; and it disappears for tanβ < 1.6.

[24] HIDAKA 91 limit obtained from LEP and preliminary CDF limits on the gluino mass (as analyzed in BAER 91).

[25] ABREU 90G exclude $B(Z \to \tilde{\chi}^0_1 \tilde{\chi}^0_2) \geq 10^{-3}$ and $B(Z \to \tilde{\chi}^0_2 \tilde{\chi}^0_2) \geq 2 \times 10^{-3}$ assuming $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 f\bar{f}$ via virtual Z. These exclude certain regions in model parameter space, see their Fig. 5.

[26] AKRAWY 90N exclude $B(Z \to \tilde{\chi}^0_1 \tilde{\chi}^0_2) \gtrsim$ 3–5 × 10^{-4} assuming $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 f\bar{f}$ or $\tilde{\chi}^0_1 \gamma$ for most accessible masses. These exclude certain regions in model parameter space, see their Fig. 7.

[27] BAER 90 is independent of decay modes. Limit from analysis of supersymmetric parameter space restrictions implied by ΔΓ(Z) < 120 MeV. These result from decays of Z to all combinations of $\tilde{\chi}^{\pm}_i$ and $\tilde{\chi}^0_i$. Minimal supersymmetry with tanβ > 1 is assumed.

[28] See Figs. 4, 5 in BARKLOW 90 for the excluded regions.

[29] DECAMP 90K exclude certain regions in model parameter space, see their figures.

[30] SAKAI 90 assume $m_{\tilde{H}^0_1}$ = 0. The limit is for $m_{\tilde{H}^0_2}$.

[31] Pure $\tilde{\gamma}$ and pure $\tilde{Z}$ eigenstates. $B(\tilde{Z} \to q\bar{q}\tilde{\gamma})$ = 0.60 and $B(\tilde{Z} \to e^+e^-\tilde{\gamma})$ = 0.13. $m_{\tilde{e}_L} = m_{\tilde{e}_R}$ < 70 GeV. $m_{\tilde{\gamma}}$ < 10 GeV.

[32] Pure $\tilde{\gamma}$ and pure $\tilde{Z}$ eigenstates. $B(\tilde{Z} \to q\bar{q}\tilde{g})$ = 1. $m_{\tilde{e}_L} = m_{\tilde{e}_R}$ < 70 GeV. $m_{\tilde{\gamma}}$ = 0.

[33] Pure higgsino. The LSP is the other higgsino and is taken massless. Limit degraded if $\tilde{\chi}^0$ not pure higgsino or if LSP not massless.

[34] Pure $\tilde{\gamma}$ and pure $\tilde{Z}$ eigenstates. $B(\tilde{Z} \to \bar{\nu}\nu)$ = 1. $m_{\tilde{e}_L} = m_{\tilde{e}_R}$ = 26 GeV. $m_{\tilde{\gamma}}$ = 10 GeV. No excluded region remains for $m_{\tilde{e}}$ >30 GeV.

[35] AKERLOF 85 is e^+e^- monojet search motivated by UA1 monojet events. Observed only one event consistent with $e^+e^- \to \tilde{\gamma}+\tilde{\chi}^0$ where $\tilde{\chi}^0 \to$ monojet. Assuming that missing-p_T is due to $\tilde{\gamma}$, and monojet due to $\tilde{\chi}^0$, limits dependent on the mixing and $m_{\tilde{e}}$ are given, see their figure 4.

[36] BARTEL 85L assume $m_{\tilde{H}^0_1}$ = 0, $\Gamma(Z \to \tilde{H}^0_1 \tilde{H}^0_2) \gtrsim \frac{1}{2}\Gamma(Z \to \nu_e \bar{\nu}_e)$. The limit is for $m_{\tilde{H}^0_2}$.

[37] BEHREND 85 find no monojet at E_{cm} = 40–46 GeV. Consider $\tilde{\chi}^0$ pair production via Z^0. One is assumed as massless and escapes detector. Limit is for the heavier one, decaying into a jet and massless $\tilde{\chi}^0$. Both $\tilde{\chi}^0$'s are assumed to be pure higgsino. For these very model-dependent results, BEHREND 85 excludes m = 1.5–19.5 GeV.

[38] ADEVA 84B observed no events with signature of acoplanar lepton pair with missing energy. Above example limit is for $m_{\tilde{\gamma}}$ <2 GeV and $m_{\tilde{e}}$ <40 GeV, and assumes $B(\tilde{Z} \to \mu^+\mu^-\tilde{\gamma}) = B(\tilde{Z} \to e^+e^-\tilde{\gamma})$ = 0.10. BR = 0.05 gives 33.5 GeV limit.

[39] BARTEL 84C search for $e^+e^- \to \tilde{Z}+\tilde{\gamma}$ with $\tilde{Z} \to \tilde{\gamma}+e^+e^-$, $\mu^+\mu^-$, $q\bar{q}$, etc. They see no acoplanar events with missing-p_T due to two $\tilde{\gamma}$'s. Above example limit is for $m_{\tilde{e}}$ = 40 GeV and for light stable $\tilde{\gamma}$ with $B(\tilde{Z} \to e^+e^-\tilde{\gamma})$ = 0.1.

[40] ELLIS 84 find if lightest neutralino is stable, then $m_{\tilde{\chi}^0}$ not 100 eV – 2 GeV (for $m_{\tilde{q}}$ = 40 GeV). The upper limit depends on $m_{\tilde{q}}$ (similar to the $\tilde{\gamma}$ limit) and on nature of $\tilde{\chi}^0$. For pure higgsino the higher limit is 5 GeV.

$\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^{\pm}_2$ (Charginos) MASS LIMITS

Charginos ($\tilde{\chi}^{\pm}$'s) are unknown mixtures of w-inos and charged higgsinos (the supersymmetric partners of W and Higgs bosons). Mass limits are relatively model dependent, so assumptions concerning branching ratios need to be specified. When specific assumptions are made, e.g. the chargino is a pure w-ino ($\tilde{W}$) or pure charged higgsino ($\tilde{H}^{\pm}$), the charginos will be labelled as such.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>44.0	95	[41] ADRIANI	93M L3	$Z \to \tilde{\chi}^+\tilde{\chi}^-$, Γ($Z$)
>45.2	95	[42] DECAMP	92 ALEP	$Z \to \tilde{\chi}^+\tilde{\chi}^-$, all $m_{\tilde{\chi}^0_1}$
>47	95	[42] DECAMP	92 ALEP	$Z \to \tilde{\chi}^+\tilde{\chi}^-$, $m_{\tilde{\chi}^0_1}$ <41 GeV
>99	95	[43] HIDAKA	91 RVUE	$\tilde{\chi}^{\pm}_2$
>44.5	95	[44] ABREU	90G DLPH	$Z \to \tilde{\chi}^+\tilde{\chi}^-$, $m_{\tilde{\gamma}}$ < 20 GeV
>45	95	[45] AKRAWY	90D OPAL	$e^+e^- \to \tilde{\chi}^+\tilde{\chi}^-$; $m_{\tilde{\gamma}}$ < 20 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

		[46] ABACHI	96	D0	$p\overline{p} \to \widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$
		[47] DATTA	92	RVUE	$Z \to \widetilde{\chi}^+\widetilde{\chi}^-$, $\widetilde{\chi}^0\widetilde{\chi}^0$
>43	90	[48] DREES	91	RVUE	$\widetilde{\chi}_1^{\pm}$
>45	95	ABREU	90G	DLPH	Stable $\widetilde{\chi}^{\pm}$, $\widetilde{\chi}^+\widetilde{\chi}^-$
>28.2	95	ADACHI	90C	TOPZ	Stable $\widetilde{\chi}^{\pm}$, $\widetilde{\chi}^+\widetilde{\chi}^-$
>45	95	[49] AKESSON	90B	UA2	$p\overline{p} \to ZX$ ($Z \to \widetilde{W}^+\widetilde{W}^-$)
>37	90	[50] BAER	90	RVUE	$\Gamma(Z)$; $\tan\beta > 1$
>45	95	[51] BARKLOW	90	MRK2	$Z \to \widetilde{W}^+\widetilde{W}^-$
>42	95	[52] BARKLOW	90	MRK2	$Z \to \widetilde{H}^+\widetilde{H}^-$
>44.5	95	[53] DECAMP	90C	ALEP	$e^+e^- \to \widetilde{\chi}^+\widetilde{\chi}^-$; $m_{\widetilde{\gamma}} < 28$ GeV
>25.5	95	[54] ADACHI	89	TOPZ	$e^+e^- \to \widetilde{\chi}^+\widetilde{\chi}^-$
>44	95	[55] ADEVA	89B	L3	$e^+e^- \to \widetilde{W}^+\widetilde{W}^-$, $\widetilde{W} \to \ell\widetilde{\nu}$ or $\ell\nu\widetilde{\gamma}$
>45	90	[56] ANSARI	87D	UA2	$p\overline{p} \to ZX$ ($Z \to \widetilde{W}^+\widetilde{W}^-$, $\widetilde{W}^{\pm} \to e^{\pm}\widetilde{\nu}$)
>40		[57] BAER	87B	RVUE	$p\overline{p} \to W/ZX$ ($W/Z \to \widetilde{W}$, $\widetilde{Z}$, $\widetilde{\gamma}$)

[41] ADRIANI 93M limit from $\Delta\Gamma(Z)<$ 35.1 MeV. For pure wino, the limit is 45.5 GeV.

[42] DECAMP 92 limit is for a general $\widetilde{\chi}^{\pm}$ (all contents).

[43] HIDAKA 91 limit obtained from LEP and preliminary CDF limits on the gluino mass (as analyzed in BAER 91).

[44] ABREU 90G limit is for a general $\widetilde{\chi}^{\pm}$. They assume charginos have a three-body decay such as $\ell^+\nu\widetilde{\gamma}$.

[45] AKRAWY 90D assume charginos have three-body decay such as $\ell^+\nu\widetilde{\gamma}$ (i.e. $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^+}$). A two-body decay, $\widetilde{\chi}^+ \to \ell\widetilde{\nu}$ would have been seen by their search for acoplanar leptons. The result is independent of the hadronic branching ratio. They search for acoplanar electromagnetic clusters and quark jets.

[46] ABACHI 96 searches for 3-lepton final states. Efficiencies are calculated using mass relations and branching ratios in the Minimal Supergravity scenario. Results are presented as lower bounds on $\sigma(\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0) \times B(\widetilde{\chi}_1^{\pm} \to \ell\nu_\ell\widetilde{\chi}_1^0) \times B(\widetilde{\chi}_2^0 \to \ell^+\ell^-\widetilde{\chi}_1^0)$ as a function of $m_{\widetilde{\chi}_1^0}$. Limits range from 3.1 pb ($m_{\widetilde{\chi}_1^0} = 45$ GeV) to 0.6 pb ($m_{\widetilde{\chi}_1^0} = 100$ GeV). See Fig. 3 for some explicit mass limits as a function of parameters.

[47] DATTA 92 exclude some regions in chargino-gluino mass plane from LEP experiments.

[48] DREES 91 limit obtained from LEP results within minimal supersymmetry with gaugino-mass unification condition. They make use of DECAMP 90C analysis plus additional constraint from total Z width. The bound can only be evaded if the chargino mixes with other charged singlets or with gauginos of a right-handed gauge group.

[49] AKESSON 90B assume $\widetilde{W} \to e\widetilde{\nu}$ with B > 20% and $m_{\widetilde{\nu}} = 0$. The limit disappears if $m_{\widetilde{\nu}} > 30$ GeV.

[50] BAER 90 is independent of decay modes. Limit from analysis of supersymmetric parameter space restrictions implied by $\Delta\Gamma(Z) < 120$ MeV. These result from decays of Z to all combinations of $\widetilde{\chi}_i^{\pm}$ and $\widetilde{\chi}_i^0$. Minimal supersymmetry with $\tan\beta > 1$ is assumed.

[51] BARKLOW 90 assume 100% $\widetilde{W} \to W^*\widetilde{\chi}_1^0$. Valid up to $m_{\widetilde{\chi}_1^0} \lesssim [m_{\widetilde{W}} - 5$ GeV].

[52] BARKLOW 90 assume 100% $\widetilde{H} \to H^*\widetilde{\chi}_1^0$. Valid up to $m_{\widetilde{\chi}_1^0} \lesssim [m_{\widetilde{H}} - 8$ GeV].

[53] DECAMP 90C assume charginos have three-body decay such as $\ell^+\nu\widetilde{\gamma}$ (i.e. $m_{\widetilde{\nu}} > m_{\widetilde{\chi}^+}$), and branching ratio to each lepton is 11%. They search for acoplanar dimuons, dielectrons, and μe events. Limit valid for $m_{\widetilde{\gamma}} < 28$ GeV.

[54] ADACHI 89 assume only single photon annihilation in the production. The limit applies for arbitrary decay branching ratios with $B(\widetilde{\chi} \to e\nu\widetilde{\gamma}) + B(\widetilde{\chi} \to \mu\nu\widetilde{\gamma}) + B(\widetilde{\chi} \to \tau\nu\widetilde{\gamma}) + B(\widetilde{\chi} \to q\overline{q}\widetilde{\gamma}) = 1$ (lepton universality is *not* assumed). The limit is for $m_{\widetilde{\gamma}} = 0$ but a very similar limit is obtained for $m_{\widetilde{\gamma}} = 10$ GeV. For $B(\widetilde{\chi} \to q\overline{q}\widetilde{\gamma}) = 1$, the limit increases to 27.8 GeV.

[55] ADEVA 89B assume for $\ell\nu\widetilde{\gamma}$ ($\ell\widetilde{\nu}$) mode that $B(e) = B(\mu) = B(\tau) = 11\%$ (33%) and search for acoplanar dimuons, dielectrons, and μe events. Also assume $m_{\widetilde{\gamma}} < 20$ GeV and for $\ell\widetilde{\nu}$ mode that $m_{\widetilde{\nu}} = 10$ GeV.

[56] ANSARI 87D looks for high p_T e^+e^- pair with large missing p_T at the CERN $p\overline{p}$ collider at $E_{cm} = 546$–630 GeV. The limit is valid when $m_{\widetilde{\nu}} \lesssim 20$ GeV, $B(\widetilde{W} \to e\widetilde{\nu}_e) = 1/3$, and $B(Z \to \widetilde{W}^+\widetilde{W}^-)$ is calculated by assuming pure gaugino eigenstate. See their Fig. 3(b) for excluded region in the $m_{\widetilde{W}} - m_{\widetilde{\nu}}$ plane.

[57] BAER 87B argue that the charged heavy lepton mass limit of 41 GeV obtained by UA1 collaboration (ALBAJAR 87B) corresponds to the mass limit of 40 GeV under the assumptions that the LSP (photino) has a mass smaller than 8 GeV and that the gaugino-higgsino mixing is parametrized by the three minimal supergravity model parameters. In grand unified theories $m_{\widetilde{\gamma}} < 8$ implies $m_{\widetilde{g}} < 50$ GeV. For larger gluino masses, this limit can be evaded as discussed in BAER 88.

$\widetilde{\nu}$ (Sneutrino) MASS LIMIT

The limit depends on the number, $N(\widetilde{\nu})$, of sneutrinos assumed to be degenerate in mass. Only $\widetilde{\nu}_L$ (not $\widetilde{\nu}_R$) exist. It is possible that $\widetilde{\nu}$ could be the lightest supersymmetric particle (LSP).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 41.8	95	[58] ADRIANI	93M	L3	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=3
> 37.1	95	[58] ADRIANI	93M	L3	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
> 41	95	[59] DECAMP	92	ALEP	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=3
> 36	95	ABREU	91F	DLPH	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
> 32	95	[60] ABREU	91F	DLPH	$\Gamma(Z)$; $N(\widetilde{\nu})$=1
> 31.2	95	[61] ALEXANDER	91F	OPAL	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 46.0	95	[62] BUSKULIC	95E	ALEP	$N(\widetilde{\nu})$=1, $\widetilde{\nu} \to \nu\nu\ell\overline{\ell}'$
none 20–25000		[63] BECK	94	COSM	Stable $\widetilde{\nu}$, dark matter
<600		[64] FALK	94	COSM	$\widetilde{\nu}$ LSP, cosmic abundance
> 38.4	90	[65] DREES	91	RVUE	$\Gamma(Z)$; $N(\widetilde{\nu})$=3
> 28.9	90	[65] DREES	91	RVUE	$\Gamma(Z)$; $N(\widetilde{\nu})$=1
none 3–90	90	[66] SATO	91	KAMI	Stable $\widetilde{\nu}_e$ or $\widetilde{\nu}_\mu$, dark matter
none 4–90	90	[66] SATO	91	KAMI	Stable $\widetilde{\nu}_\tau$, dark matter
> 31.4	95	[67] ADEVA	90I	L3	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=1
> 39.4	95	[67] ADEVA	90I	L3	$\Gamma(Z \to$ invisible); $N(\widetilde{\nu})$=3
> 36.5	90	[68] BAER	90	RVUE	$\Gamma(Z)$; $N(\widetilde{\nu})$=3

[58] ADRIANI 93M limit from $\Delta\Gamma(Z)$(invisible)< 16.2 MeV.

[59] DECAMP 92 limit is from Γ(invisible)/$\Gamma(\ell\ell)$ = 5.91 ± 0.15 (N_ν = 2.97 ± 0.07).

[60] ABREU 91F limit (>32 GeV) is independent of sneutrino decay mode.

[61] ALEXANDER 91F limit is for one species of $\widetilde{\nu}$ and is derived from Γ(invisible, new)/$\Gamma(\ell\ell)$ < 0.38.

[62] BUSKULIC 95E looked for $Z \to \widetilde{\nu}\widetilde{\nu}$, where $\widetilde{\nu} \to \nu\chi_1^0$ and χ_1^0 decays via R-parity violating interactions into two leptons and a neutrino.

[63] BECK 94 limit can be inferred from limit on Dirac neutrino using $\sigma(\widetilde{\nu}) = 4\sigma(\nu)$. Also private communication with H.V. Klapdor-Kleingrothaus.

[64] FALK 94 puts an upper bound on $m_{\widetilde{\nu}}$ when $\widetilde{\nu}$ is LSP by requiring its relic density does not overclose the Universe.

[65] DREES 91 limits from $\Delta\Gamma(Z)$ (nonhadronic) < 38.3 MeV. Independent of decay modes. Minimal supersymmetry assumed.

[66] SATO 91 search for high-energy neutrinos from the sun produced by annihilation of sneutrinos in the sun. Sneutrinos are assumed to be stable and to constitute dark matter in our galaxy. SATO 91 follow the analysis of NG 87, OLIVE 88, and GAISSER 86.

[67] ADEVA 90I limit is from ΔN_ν < 0.19.

[68] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry assumed. The 95%CL bound is 35.6 GeV.

$\widetilde{e}$ (Selectron) MASS LIMIT

Limits assume $m_{\widetilde{e}_L} = m_{\widetilde{e}_R}$ unless otherwise stated.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 45	95	[69] ADRIANI	93M	L3	$m_{\widetilde{\chi}_1^0}$ <40 GeV, $\widetilde{e}^+\widetilde{e}^-$
> 45	95	[70] DECAMP	92	ALEP	$m_{\widetilde{\chi}_1^0}$ <41 GeV, $\widetilde{e}^+\widetilde{e}^-$
> 50	95	HEARTY	89	ASP	$m_{\widetilde{\gamma}}$ <5 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$

• • • We do not use the following data for averages, fits, limits, etc. • • •

> 45.6	95	[71] BUSKULIC	95E	ALEP	$\widetilde{e} \to e\nu\ell\overline{\ell}'$
> 51.9	90	HOSODA	94	VNS	$m_{\widetilde{\gamma}}$=0; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 72.6	90	[72] HOSODA	94	RVUE	$m_{\widetilde{\gamma}}$=0; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 42	95	ABREU	90G	DLPH	$m_{\widetilde{\gamma}}$ < 40 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 38	95	[73] AKESSON	90B	UA2	$m_{\widetilde{\gamma}}$ = 0; $p\overline{p} \to ZX$ ($Z \to \widetilde{e}^+\widetilde{e}^-$)
> 43.4	95	[74] AKRAWY	90D	OPAL	$m_{\widetilde{\gamma}}$ < 30 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 38.1	90	[75] BAER	90	RVUE	$\widetilde{e}_L$; $\Gamma(Z)$; $\tan\beta > 1$
> 43.5	95	[76] DECAMP	90C	ALEP	$m_{\widetilde{\gamma}}$ < 36 GeV; $\widetilde{e}^+\widetilde{e}^-$
>830		GRIFOLS	90	ASTR	$m_{\widetilde{\gamma}}$ < 1 MeV
> 29.9	95	SAKAI	90	AMY	$m_{\widetilde{\gamma}}$ < 20 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 29	95	TAKETANI	90	VNS	$m_{\widetilde{\gamma}}$ < 25 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 60		[77] ZHUKOVSKII	90	ASTR	$m_{\widetilde{\gamma}}$ = 0
> 28	95	[78] ADACHI	89	TOPZ	$m_{\widetilde{\gamma}} \lesssim 0.85 m_{\widetilde{e}}$; $\widetilde{e}^+\widetilde{e}^-$
> 41	95	[79] ADEVA	89B	L3	$m_{\widetilde{\gamma}}$ < 20 GeV; $\widetilde{e}^+\widetilde{e}^-$
> 32	90	[80] ALBAJAR	89	UA1	$p\overline{p} \to W^{\pm}X$ ($W^{\pm} \to \widetilde{e}_L\widetilde{\nu}$) ($\widetilde{e}_L \to e\widetilde{\gamma}$)
> 14	90	[81] ALBAJAR	89	UA1	$Z \to \widetilde{e}^+\widetilde{e}^-$
> 53	95	[82,83] HEARTY	89	ASP	$m_{\widetilde{\gamma}}$=0; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 65	95	[82,84] HEARTY	89	RVUE	$m_{\widetilde{\gamma}}$=0; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 35	95	HEARTY	89	ASP	$m_{\widetilde{\gamma}}$ <10 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 51.5	90	[85,86] BEHREND	88B	CELL	$m_{\widetilde{\gamma}}$ = 0 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 64	95	[85,87] BEHREND	88B	RVUE	$m_{\widetilde{\gamma}}$ = 0 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$
> 48	90	BEHREND	88B	CELL	$m_{\widetilde{\gamma}}$ < 5 GeV; $\gamma\widetilde{\gamma}\widetilde{\gamma}$

[69] ADRIANI 93M limit is for $m_{\widetilde{e}_L} \gg m_{\widetilde{e}_R}$ using acolinear di-lepton events.

[70] DECAMP 92 limit is for $m_{\widetilde{e}_L} \gg m_{\widetilde{e}_R}$; for equal masses the limit would improve. They looked for acoplanar electrons.

[71] BUSKULIC 95E looked for $Z \to \widetilde{e}_R^+\widetilde{e}_R^-$ where $\widetilde{e}_R \to e\chi_1^0$ and χ_1^0 decays via R-parity violating interactions into two leptons and a neutrino.

[72] HOSODA 94 combines the results of HOSODA 94, HEARTY 89, BEHREND 88B, and FORD 86.

[73] AKESSON 90B assume $m_{\widetilde{\gamma}} = 0$. Very similar limits hold for $m_{\widetilde{\gamma}} \lesssim 20$ GeV.

[74] AKRAWY 90D look for acoplanar electrons. For $m_{\widetilde{e}_L} \gg m_{\widetilde{e}_R}$, limit is 41.5 GeV, for $m_{\widetilde{\gamma}} < 30$ GeV.

[75] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.

[76] DECAMP 90C look for acoplanar electrons. For $m_{\widetilde{e}_L} \gg m_{\widetilde{e}_R}$ limit is 42 GeV, for $m_{\widetilde{\gamma}} < 33$ GeV.

[77] ZHUKOVSKII 90 set limit by saying the luminosity of a magnetized neutron star due to massless photino emission by electrons be small compared with its neutrino luminosity.

[78] ADACHI 89 assume only photon and photino exchange and $m_{\tilde{e}_L} = m_{\tilde{e}_R}$. The limit for the nondegenerate case is 26 GeV.
[79] ADEVA 89B look for acoplanar electrons.
[80] ALBAJAR 89 limit applies for $\tilde{e}_L$ when $m_{\tilde{e}_L} = m_{\tilde{\nu}_L}$ and $m_{\tilde{\gamma}} = 0$. See their Fig. 55 for the 90% CL excluded region in the $m_{\tilde{e}_L} - m_{\tilde{\nu}_L}$ plane. For $m_{\tilde{\nu}} = m_{\tilde{\gamma}} = 0$, limit is 50 GeV.
[81] ALBAJAR 89 assume $m_{\tilde{\gamma}} = 0$.
[82] HEARTY 89 assume $m_{\tilde{\gamma}} = 0$. The limit is very sensitive to $m_{\tilde{\gamma}}$; no limit can be placed for $m_{\tilde{\gamma}} \gtrsim 13$ GeV.
[83] The limit is reduced to 43 GeV if only one $\tilde{e}$ state is produced ($\tilde{e}_L$ or $\tilde{e}_R$ very heavy).
[84] Results of HEARTY 89, BEHREND 88B, ADEVA 87, and FORD 86 are combined. The limit is reduced to 53 GeV if only one $\tilde{e}$ state is exchanged ($\tilde{e}_L$ or $\tilde{e}_R$ very heavy).
[85] BEHREND 88B limits assume pure photino eigenstate and $m_{\tilde{e}_L} = m_{\tilde{e}_R}$.
[86] The 95% CL limit for BEHREND 88B is 47.5 GeV for $m_{\tilde{\gamma}} = 0$. The limit for $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$ is 40 GeV at 90% CL.
[87] BEHREND 88B combined their data with those from ASP (HEARTY 87), MAC (FORD 86), and MARK-J (H. Wu, Ph. D. Thesis, University of Hamburg, 1986).

$\tilde{\mu}$ (Smuon) MASS LIMIT

Limits assume $m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R}$ unless otherwise stated.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>45	95	[88] ADRIANI	93M	L3	$m_{\tilde{\chi}^0_1}$ <40 GeV, $\tilde{\mu}^+\tilde{\mu}^-$
>45	95	[89] DECAMP	92	ALEP	$m_{\tilde{\chi}^0_1}$ <41 GeV, $\tilde{\mu}^+\tilde{\mu}^-$
>43	95	[90] AKRAWY	90D	OPAL	$m_{\tilde{\gamma}} < 30$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>45.6	95	[91] BUSKULIC	95E	ALEP	$\tilde{\mu} \to \mu\nu\ell\bar{\ell}'$
>36	95	ABREU	90G	DLPH	$m_{\tilde{\gamma}} < 33$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$
>38.1	90	[92] BAER	90	RVUE	$\tilde{\mu}_L$; $\Gamma(Z)$; $\tan\beta > 1$
>42.6	95	[93] DECAMP	90C	ALEP	$m_{\tilde{\gamma}} < 34$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$
>27	95	SAKAI	90	AMY	$m_{\tilde{\gamma}} < 18$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$
>24.5	95	TAKETANI	90	VNS	$m_{\tilde{\gamma}} < 15$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$
>24.5	95	[94] ADACHI	89	TOPZ	$m_{\tilde{\gamma}} \lesssim 0.8 m_{\tilde{\mu}}$; $\tilde{\mu}^+\tilde{\mu}^-$
>41	95	[95] ADEVA	89B	L3	$m_{\tilde{\gamma}} < 20$ GeV; $\tilde{\mu}^+\tilde{\mu}^-$

[88] ADRIANI 93M limit is for $m_{\tilde{\mu}_L} \gg m_{\tilde{\mu}_R}$ using acolinear di-lepton events.
[89] DECAMP 92 limit is for $m_{\tilde{\mu}_L} \gg m_{\tilde{\mu}_R}$; for equal masses the limit would improve. They looked for acoplanar muons.
[90] AKRAWY 90D look for acoplanar muons. For $m_{\tilde{\mu}_L} \gg m_{\tilde{\mu}_R}$, limit is 41.0 GeV, for $m_{\tilde{\gamma}} < 30$ GeV.
[91] BUSKULIC 95E looked for $Z \to \tilde{\mu}^+_R\tilde{\mu}^-_R$, where $\tilde{\mu}_R \to \mu\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.
[92] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.
[93] DECAMP 90C look for acoplanar muons. For $m_{\tilde{\mu}_L} \gg m_{\tilde{\mu}_R}$ limit is 40 GeV, for $m_{\tilde{\gamma}} <$ 30 GeV.
[94] ADACHI 89 assume only photon exchange, which gives a conservative limit. $m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R}$ assumed. The limit for nondegenerate case is 22 GeV.
[95] ADEVA 89B look for acoplanar muons.

$\tilde{\tau}$ (Stau) MASS LIMIT

Limits assume $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R}$ unless otherwise stated.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>44	95	[96] ADRIANI	93M	L3	$m_{\tilde{\chi}^0_1}$ <38 GeV, $\tilde{\tau}^+\tilde{\tau}^-$
>45	95	[97] DECAMP	92	ALEP	$m_{\tilde{\chi}^0_1}$ <38 GeV, $\tilde{\tau}^+\tilde{\tau}^-$
>43.0	95	[98] AKRAWY	90D	OPAL	$m_{\tilde{\gamma}} < 23$ GeV; $\tilde{\tau}^+\tilde{\tau}^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>45.6	95	[99] BUSKULIC	95E	ALEP	$\tilde{\tau} \to \tau\nu\ell\bar{\ell}'$
>35	95	ABREU	90G	DLPH	$m_{\tilde{\gamma}} < 25$ GeV; $\tilde{\tau}^+\tilde{\tau}^-$
>38.1	90	[100] BAER	90	RVUE	$\tilde{\tau}_L$; $\Gamma(Z)$; $\tan\beta > 1$
>40.4	95	[101] DECAMP	90C	ALEP	$m_{\tilde{\gamma}} < 15$ GeV; $\tilde{\tau}^+\tilde{\tau}^-$
>25	95	SAKAI	90	AMY	$m_{\tilde{\gamma}} < 10$ GeV; $\tilde{\tau}^+\tilde{\tau}^-$
>25.5	95	TAKETANI	90	VNS	$m_{\tilde{\gamma}} < 15$ GeV; $\tilde{\tau}^+\tilde{\tau}^-$
>21.7	95	[102] ADACHI	89	TOPZ	$m_{\tilde{\gamma}}=0$; $\tilde{\tau}^+\tilde{\tau}^-$

[96] ADRIANI 93M limit is for $m_{\tilde{\tau}_L} \gg m_{\tilde{\tau}_R}$.
[97] DECAMP 92 limit is for $m_{\tilde{\tau}_L} \gg m_{\tilde{\tau}_R}$; for equal masses the limit would improve. They looked for acoplanar particles.
[98] AKRAWY 90D look for acoplanar particles. For $m_{\tilde{\tau}_L} \gg m_{\tilde{\tau}_R}$, limit is 41.0 GeV, for $m_{\tilde{\gamma}} < 23$ GeV.
[99] BUSKULIC 95E looked for $Z \to \tilde{\tau}^+_R\tilde{\tau}^-_R$, where $\tilde{\tau}_R \to \tau\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.
[100] BAER 90 limit from $\Delta\Gamma(Z)$ (nonhadronic) < 53 MeV. Independent of decay modes. Mininal supersymmetry and $\tan\beta > 1$ assumed.
[101] DECAMP 90C look for acoplanar charged particle pairs. Limit is for $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R}$. For $m_{\tilde{\gamma}} \leq 24$ GeV, the limit is 37 GeV. For $m_{\tilde{\tau}_L} \gg m_{\tilde{\tau}_R}$ and $m_{\tilde{\gamma}} < 15$ GeV, the limit is 33 GeV.
[102] ADACHI 89 assume only photon exchange, which gives a conservative limit. $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R}$ assumed.

Stable $\tilde{\ell}$ (Slepton) MASS LIMIT

Limits on scalar leptons which leave detector before decaying. Limits from Z decays are independent of lepton flavor. Limits from continuum e^+e^- annihilation are also independent of flavor for smuons and staus. However, selectron limits from continuum e^+e^- annihilation depend on flavor because there is an additional contribution from neutralino exchange that in general yields stronger limits. All limits assume $m_{\tilde{\ell}_L} = m_{\tilde{\ell}_R}$ unless otherwise stated.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>40	95	ABREU	90G	DLPH	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>26.3	95	ADACHI	90C	TOPZ	$\tilde{\mu}$, $\tilde{\tau}$
>38.8	95	AKRAWY	90O	OPAL	$\tilde{\ell}_R$
>27.1	95	[103] SAKAI	90	AMY	
>32.6	95	SODERSTROM	90	MRK2	
>24.5	95	[104] ADACHI	89	TOPZ	

[103] SAKAI 90 limit improves to 30.1 GeV for $\tilde{e}$ if $m_{\tilde{\gamma}} \approx m_{\tilde{e}}$.
[104] ADACHI 89 assume only photon (and photino for $\tilde{e}$) exchange. The limit for $\tilde{e}$ improves to 26 GeV for $m_{\tilde{\gamma}} \approx m_{\tilde{e}}$.

$\tilde{q}$ (Squark) MASS LIMIT

For $m_{\tilde{q}} >$ 60–70 GeV, it is expected that squarks would undergo a cascade decay via a number of neutralinos and/or charginos rather than undergo a direct decay to photinos as assumed by some papers. Limits obtained when direct decay is assumed are usually higher than limits when cascade decays are included. The limits from Z decay do not assume GUT relations and are more model independent.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 224	95	[105] ABE	96D	CDF	$m_{\tilde{g}} \leq m_{\tilde{q}}$; with cascade decays
> 176	95	[106] ABACHI	95C	D0	Any $m_{\tilde{g}}$ <300 GeV; with cascade decays
> 212	95	[106] ABACHI	95C	D0	$m_{\tilde{g}} \leq m_{\tilde{q}}$; with cascade decays
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[107] ABE	95T	CDF	$\tilde{q} \to \tilde{\chi}^0_2 \to \tilde{\chi}^0_1\gamma$
> 45.3	95	[108] BUSKULIC	95E	ALEP	$\tilde{q} \to q\nu\ell\bar{\ell}'$
> 239	95	[109] AHMED	94B	H1	$ep \to \tilde{q}$; R-parity violation, λ=0.30
> 135	95	[109] AHMED	94B	H1	$ep \to \tilde{q}$; R-parity violation, λ=0.1
> 35.3	95	[110] ADRIANI	93M	L3	$Z \to \tilde{u}\bar{\tilde{u}}$, $\Gamma(Z)$
> 36.8	95	[110] ADRIANI	93M	L3	$Z \to \tilde{d}\bar{\tilde{d}}$, $\Gamma(Z)$
> 90	90	[111] ABE	92L	CDF	Any $m_{\tilde{g}}$ <410 GeV; with cascade decay
> 218	90	[112] ABE	92L	CDF	$m_{\tilde{q}} = m_{\tilde{g}}$; with cascade decay
> 180	90	[111] ABE	92L	CDF	$m_{\tilde{g}} < m_{\tilde{q}}$; with cascade decay
> 100		[113] ROY	92	RVUE	$p\bar{p} \to \tilde{q}\bar{\tilde{q}}$; R-parity violating
		[114] NOJIRI	91	COSM	
> 45	95	[115] ABREU	90F	DLPH	$Z \to \tilde{q}\bar{\tilde{q}}$, $m_{\tilde{\gamma}} < 20$ GeV
> 43	95	[116] ABREU	90F	DLPH	$Z \to \tilde{d}\bar{\tilde{d}}$, $m_{\tilde{\gamma}} < 20$ GeV
> 42	95	[117] ABREU	90F	DLPH	$Z \to \tilde{u}\bar{\tilde{u}}$, $m_{\tilde{\gamma}} < 20$ GeV
> 27.0	95	ADACHI	90C	TOPZ	Stable $\tilde{u}$, $\bar{\tilde{u}}$
> 74	90	[118] ALITTI	90	UA2	Any $m_{\tilde{q}}$; $B(\tilde{q} \to q\tilde{g}$ or $q\tilde{\gamma}) = 1$
> 106	90	[118] ALITTI	90	UA2	$m_{\tilde{q}} = m_{\tilde{g}}$; $B(\tilde{q} \to q\tilde{\gamma}) = 1$
> 39.2	90	[119] BAER	90	RVUE	$\tilde{d}_L$; $\Gamma(Z)$
> 45	95	[120,121] BARKLOW	90	MRK2	$Z \to \tilde{q}\bar{\tilde{q}}$
> 40	95	[120,122] BARKLOW	90	MRK2	$Z \to \tilde{d}\bar{\tilde{d}}$
> 39	95	[120,123] BARKLOW	90	MRK2	$Z \to \tilde{u}\bar{\tilde{u}}$
>1100		GRIFOLS	90	ASTR	$m_{\tilde{\gamma}} < 1$ MeV
> 24	95	SAKAI	90	AMY	$e^+e^- \to \tilde{d}\bar{\tilde{d}} \to d\bar{d}\tilde{\gamma}\tilde{\gamma}$; $m_{\tilde{\gamma}} < 10$ GeV
> 26	95	SAKAI	90	AMY	$e^+e^- \to \tilde{u}\bar{\tilde{u}} \to u\bar{u}\tilde{\gamma}\tilde{\gamma}$; $m_{\tilde{\gamma}} < 10$ GeV
> 26.3	95	[124] ADACHI	89	TOPZ	$e^+e^- \to \tilde{q}\bar{\tilde{q}} \to q\bar{q}\tilde{\gamma}\tilde{\gamma}$
		[125] NATH	88	THEO	$\tau(p \to \nu K)$ in supergravity GUT
> 45	90	[126] ALBAJAR	87D	UA1	Any $m_{\tilde{g}} > m_{\tilde{q}}$
> 75	90	[126] ALBAJAR	87D	UA1	$m_{\tilde{g}} = m_{\tilde{q}}$

[105] ABE 96D searched for production of gluinos and five degenerate squarks in final states containing a pair of leptons, two jets, and missing E_T. The two leptons arise from the semileptonic decays of charginos produced in the cascade decays. The limit is derived for

fixed $\tan\beta = 4.0$, $\mu = -400$ GeV, and $m_{H^+} = 500$ GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario.

[106] ABACHI 95C assume five degenerate squark flavors with $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. Sleptons are assumed to be heavier than squarks. The limits are derived for fixed $\tan\beta = 2.0$ $\mu = -250$ GeV, and m_{H^+}=500 GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario. The bounds are weakly sensitive to the three fixed parameters for a large fraction of parameter space. No limit is given for $m_{\text{gluino}} >547$ GeV.

[107] ABE 95T looked for a cascade decay of five degenerate squarks into $\tilde{\chi}^0_2$ which further decays into $\tilde{\chi}^0_1$ and a photon. No signal is observed. Limits vary widely depending on the choice of parameters. For $\mu = -40$ GeV, $\tan\beta = 1.5$, and heavy gluinos, the range $50<m_{\tilde{q}}$ (GeV)<110 is excluded at 90% CL. See the paper for details.

[108] BUSKULIC 95E looked for $Z \to \tilde{q}\overline{\tilde{q}}$, where $\tilde{q} \to q\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

[109] AHMED 94B looked for squarks as s-channel resonance in ep collision via R-parity violating coupling in the superpotential $W = \lambda L_1 Q_1 d_1$. The degeneracy of all squarks Q_1 and d_1 is assumed. The squarks decay dominantly via the same R-violating coupling into eq or νq if $\lambda \gtrsim 0.2$. For smaller λ, decay into photino is assumed which subsequently decays into $eq\overline{q}$, and the bound depends on $m_{\tilde{\gamma}}$. See paper for excluded region on $(m_{\tilde{q}},\lambda)$ plane.

[110] ADRIANI 93M limit from $\Delta\Gamma(Z)<$ 35.1 MeV and assumes $m_{\tilde{q}_L} \gg m_{\tilde{q}_R}$.

[111] ABE 92L assume five degenerate squark flavors and $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. ABE 92L includes the effect of cascade decay, for a particular choice of parameters, $\mu = -250$ GeV, $\tan\beta = 2$. Results are weakly sensitive to these parameters over much of parameter space. No limit for $m_{\tilde{q}} \leq 50$ GeV (but other experiments rule out that region). Limits are 10–20 GeV higher if $B(\tilde{q} \to q\tilde{\gamma}) = 1$. Limit assumes GUT relations between gaugino masses and the gauge coupling; in particular that for $|\mu|$ not small, $m_{\tilde{\chi}^0_1} \approx m_{\tilde{g}}/6$. This last relation implies that as $m_{\tilde{g}}$ increases, the mass of $\tilde{\chi}^0_1$ will eventually exceed $m_{\tilde{q}}$ so that no decay is possible. Even before that occurs, the signal will disappear; in particular no bounds can be obtained for $m_{\tilde{g}} >$410 GeV. m_{H^+}=500 GeV.

[112] ABE 92L bounds are based on similar assumptions as ABACHI 95C. No limits for $m_{gluino} >$410 GeV.

[113] ROY 92 reanalyzed CDF limits on di-lepton events to obtain limits on squark production in R-parity violating models. The 100% decay $\tilde{q} \to q\tilde{\chi}$ where $\tilde{\chi}$ is the LSP, and the LSP decays either into $\ell q \overline{d}$ or $\ell\ell\overline{e}$ is assumed.

[114] NOJIRI 91 argues that a heavy squark should be nearly degenerate with the gluino in minimal supergravity not to overclose the universe.

[115] ABREU 90F assume six degenerate squarks and $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. $m_{\tilde{q}} <$ 41 GeV is excluded at 95% CL for $m_{\text{LSP}} < m_{\tilde{q}}-2$ GeV.

[116] ABREU 90F exclude $m_{\tilde{d}} <$ 38 GeV at 95% for $m_{\text{LSP}} < m_{\tilde{d}}-2$ GeV.

[117] ABREU 90F exclude $m_{\tilde{u}} <$ 36 GeV at 95% for $m_{\text{LSP}} < m_{\tilde{u}}-2$ GeV.

[118] ALITTI 90 searched for events having $\geq$ 2 jets with $E^1_T >$ 25 GeV, $E^2_T >$ 15 GeV, $|\eta| <$ 0.85, and $\Delta\phi <$ 160°, with a missing momentum > 40 GeV and no electrons. They assume $\tilde{q} \to q\tilde{\gamma}$ (if $m_{\tilde{q}} < m_{\tilde{g}}$) or $\tilde{q} \to q\tilde{g}$ (if $m_{\tilde{q}} > m_{\tilde{g}}$) decay and $m_{\tilde{\gamma}} \lesssim$ 20 GeV. Five degenerate squark flavors and $m_{\tilde{q}_L} = m_{\tilde{q}_R}$ are assumed. Masses below 50 GeV are not excluded by the analysis.

[119] BAER 90 limit from $\Delta\Gamma(Z) <$ 120 MeV, assuming $m_{\tilde{d}_L} = m_{\tilde{u}_L} = m_{\tilde{e}_L} = m_{\tilde{\nu}}$. Independent of decay modes. Minimal supergravity assumed.

[120] BARKLOW 90 assume 100% $\tilde{q} \to q\tilde{\gamma}$.

[121] BARKLOW 90 assume five degenerate squarks (left- and right-handed). Valid up to $m_{\tilde{\chi}^0_1} \lesssim [m_{\tilde{q}}-4$ GeV].

[122] BARKLOW 90 result valid up to $m_{\tilde{\chi}^0_1} \lesssim [m_{\tilde{d}}-5$ GeV].

[123] BARKLOW 90 result valid up to $m_{\tilde{\chi}^0_1} \lesssim [m_{\tilde{u}}-6$ GeV].

[124] ADACHI 89 assume only photon exchange, which gives a a conservative limit. The limit is only for one flavor of charge 2/3 $\tilde{q}$. $m_{\tilde{q}_L} = m_{\tilde{q}_R}$ and $m_{\tilde{\gamma}} = 0$ assumed. The limit decreases to 26.1 GeV for $m_{\tilde{\gamma}} =$ 15 GeV. The limit for nondegenerate case is 24.4 GeV.

[125] NATH 88 uses Kamioka limit of $\tau(p \to \overline{\nu}K^+) > 7\times10^{31}$ yrs to constrain squark mass $m_{\tilde{q}} >$ 1000 GeV by assuming that the proton decay proceeds via an exchange of a color-triplet Higgsino of mass $< 10^{16}$ GeV in the supersymmetric SU(5) GUT. The limit applies for $m_{\tilde{\gamma}} \equiv (8/3)\sin^2\theta_W \tilde{m}_2 >$ 10 GeV ($\tilde{m}_2$ is the SU(2) gaugino mass) and for a very conservative value of the three-quark proton wave function, barring cancellation between second and third generations. Lower squark mass is allowed if $m_{\tilde{\gamma}}$ as defined above is smaller.

[126] The limits of ALBAJAR 87D are from $p\overline{p} \to \tilde{q}\overline{\tilde{q}}X$ ($\tilde{q} \to q\tilde{\gamma}$) and assume 5 flavors of degenerate mass squarks each with $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. They also assume $m_{\tilde{g}} > m_{\tilde{q}}$. These limits apply for $m_{\tilde{\gamma}} \lesssim$ 20 GeV.

$\tilde{t}$ (Stop) MASS LIMIT

Limit depends on decay mode. In e^+e^- collisions they also depend on the mixing angle of the mass eigenstate $\tilde{t}_1 = \tilde{t}_L\cos\theta_t + \tilde{t}_R\sin\theta_t$. Coupling to Z vanishes when $\theta_t = 0.98$. In the Listings below, we use $\Delta m \equiv m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1}$. See also bound in "$\tilde{q}$ (Squark) MASS LIMIT."

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
none 61–91	95	[127] ABACHI	96B	D0	$\tilde{t} \to c\tilde{\chi}^0_1$, $m_{\tilde{\chi}^0_1}$ <30 GeV
none 6.0–41.2	95	AKERS	94K	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >2 GeV
none 5.0–46.0	95	AKERS	94K	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0, $\Delta(m)$ >5 GeV
none 11.2–25.5	95	AKERS	94K	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0.98, $\Delta(m)$ >2 GeV
none 7.9–41.2	95	AKERS	94K	OPAL	$\tilde{t} \to c\tilde{\chi}^0_1$, θ_t=0.98, $\Delta(m)$ >5 GeV
none 7.6–28.0	95	[128] SHIRAI	94	VNS	$\tilde{t} \to c\tilde{\chi}^0_1$, any θ_t, $\Delta(m)$ >10 GeV
none 10–20	95	[128] SHIRAI	94	VNS	$\tilde{t} \to c\tilde{\chi}^0_1$, any θ_t, $\Delta(m)$ > 2.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 11–41	95	[129] BUSKULIC	95E	ALEP	θ_t=0.98, $\tilde{t} \to c\nu\ell\overline{\ell}'$
		[130] BAER	91B	RVUE	$\tilde{t}$
		[131] DREES	90	RVUE	$\tilde{t}$

[127] ABACHI 96B searches for final states with 2 jets and missing E_T. Limits on $m_{\tilde{t}}$ are given as a function of $m_{\tilde{\chi}^0_1}$. See Fig. 4 for details.

[128] SHIRAI 94 bound assumes the cross section without the s-channel Z-exchange and the QCD correction, underestimating the cross section up to 20% and 30%, respectively. They assume m_c=1.5 GeV.

[129] BUSKULIC 95E looked for $Z \to \tilde{t}\overline{\tilde{t}}$, where $\tilde{t} \to c\chi^0_1$ and χ^0_1 decays via R-parity violating interactions into two leptons and a neutrino.

[130] BAER 91B argue that a top squark as light as 45 GeV may have escaped detection at the CDF detector at the Tevatron Collider (45 GeV is the limit from LEP experiments).

[131] DREES 90 argue that bounds from Z decay are not valid for $\tilde{t}$ for a certain range of $\tilde{t}_L$-$\tilde{t}_R$ mixing angle.

$\tilde{g}$ (Gluino) MASS LIMIT

For $m_{\tilde{g}} >$ 60–70 GeV, it is expected that gluinos would undergo a cascade decay via a number of neutralinos and/or charginos rather than undergo a direct decay to photinos as assumed by some papers. Limits obtained when direct decay is assumed are usually higher than limits when cascade decays are included.

There is an ongoing controversy (reflected in these Listings) about whether very light $\tilde{g}$'s ($1 \lesssim m_{\tilde{g}} \lesssim 4$ GeV) are ruled out. These papers sometimes make different assumptions and use different calculational techniques.

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
>224	95		[132] ABE	96D	CDF	$m_{\tilde{q}} = m_{\tilde{g}}$; with cascade decays
>154	95		[132] ABE	96D	CDF	$m_{\tilde{g}} < m_{\tilde{q}}$; with cascade decays
>212	95		[133] ABACHI	95C	D0	$m_{\tilde{g}} \geq m_{\tilde{q}}$; with cascade decays
>144	95		[133] ABACHI	95C	D0	Any $m_{\tilde{q}}$; with cascade decays
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[134] ABE	95T	CDF	$\tilde{g} \to \tilde{\chi}^0_2 \to \tilde{\chi}^0_1\gamma$
none 1.9–13.6	95		[135] AKERS	95R	OPAL	Z decay into a long-lived $(\tilde{g}q\overline{q})^{\pm}$
< 0.7			[136] CLAVELLI	95	RVUE	quarkonia
			[137] HEBBEKER	93	RVUE	e^+e^- jet analyses
not 3–5			[138] LOPEZ	93C	RVUE	LEP
>218	90		[139] ABE	92L	CDF	$m_{\tilde{q}} \leq m_{\tilde{g}}$; with cascade decay
>100	90		[139] ABE	92L	CDF	Any $m_{\tilde{q}}$; with cascade decay
≈ 4			[140] CLAVELLI	92	RVUE	α_s running
>100			[141] ROY	92	RVUE	$p\overline{p} \to \tilde{g}\tilde{g}$; R-parity violating
			[142] ANTONIADIS	91	RVUE	α_s running
> 1			[143] ANTONIADIS	91	RVUE	$pN \to$ missing energy
>132	90		[144] HIDAKA	91	RVUE	
			[145] NOJIRI	91	COSM	
> 79	90		[146] ALITTI	90	UA2	Any $m_{\tilde{q}}$; $B(\tilde{g} \to q\overline{q}\tilde{\gamma}) = 1$
>106	90		[146] ALITTI	90	UA2	$m_{\tilde{q}} = m_{\tilde{g}}$; $B(\tilde{g} \to q\overline{q}\tilde{\gamma}) = 1$
			[147] NAKAMURA	89	SPEC	R-Δ^{++}
none 4–53	90		[148] ALBAJAR	87D	UA1	Any $m_{\tilde{q}} > m_{\tilde{g}}$
none 4–75	90		[148] ALBAJAR	87D	UA1	$m_{\tilde{q}} = m_{\tilde{g}}$
none 16–58	90		[149] ANSARI	87D	UA2	$m_{\tilde{q}} \lesssim$ 100 GeV
> 3.8	90		[150] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \simeq A^1$
> 3.2	90		[150] ARNOLD	87	EMUL	π^- (350 GeV). $\sigma \simeq A^{0.72}$
none 0.6–2.2	90		[151] TUTS	87	CUSB	$\Upsilon(1S) \to \gamma +$ gluinonium
none 1 –4.5	90	0	[152] ALBRECHT	86C	ARG	$1\times10^{-11} \lesssim \tau \lesssim 1\times10^{-9}$s
none 1–4	90	0	[153] BADIER	86	BDMP	$1\times10^{-10} < \tau < 1\times10^{-7}$s
none 3–5			[154] BARNETT	86	RVUE	$p\overline{p} \to$ gluino gluino gluon

none		[155] VOLOSHIN	86	RVUE	If (quasi) stable; $\tilde{g}uud$
none 0.5–2		[156] COOPER-...	85B	BDMP	For $m_{\tilde{q}}$=300 GeV
none 0.5–4		[156] COOPER-...	85B	BDMP	For $m_{\tilde{q}}$ <65 GeV
none 0.5–3		[156] COOPER-...	85B	BDMP	For $m_{\tilde{q}}$=150 GeV
none 2–4		[157] DAWSON	85	RVUE	$\tau > 10^{-7}$ s
none 1–2.5		[157] DAWSON	85	RVUE	For $m_{\tilde{q}}$=100 GeV
none 0.5–4.1	90	[158] FARRAR	85	RVUE	FNAL beam dump
> 1		[159] GOLDMAN	85	RVUE	Gluononium
>1–2		[160] HABER	85	RVUE	
		[161] BALL	84	CALO	
		[162] BRICK	84	RVUE	
		[163] FARRAR	84	RVUE	
> 2		[164] BERGSMA	83C	RVUE	For $m_{\tilde{q}}$ <100 GeV
		[165] CHANOWITZ	83	RVUE	$\tilde{g}u\overline{d}$, $\tilde{g}uud$
>2–3		[166] KANE	82	RVUE	Beam dump
>1.5–2		FARRAR	78	RVUE	*R*-hadron

[132] ABE 96D searched for production of gluinos and five degenerate squarks in final states containing a pair of leptons, two jets, and missing E_T. The two leptons arise from the semileptonic decays of charginos produced in the cascade decays. The limits are derived for fixed $\tan\beta = 4.0$, $\mu = -400$ GeV, and $m_{H^+} = 500$ GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario. The bounds are weakly sensitive to the values of the three fixed parameters for a large fraction of parameter space. See Fig. 2 for the limits corresponding to different parameter choices.

[133] ABACHI 95C assume five degenerate squark flavors with with $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. Sleptons are assumed to be heavier than squarks. The limits are derived for fixed $\tan\beta = 2.0$ $\mu = -250$ GeV, and m_{H^+}=500 GeV, and with the cascade decays of the squarks and gluinos calculated within the framework of the Minimal Supergravity scenario. The bounds are weakly sensitive to the three fixed parameters for a large fraction of parameter space.

[134] ABE 95T looked for a cascade decay of gluino into $\tilde{\chi}^0_2$ which further decays into $\tilde{\chi}^0_1$ and a photon. No signal is observed. Limits vary widely depending on the choice of parameters. For $\mu = -40$ GeV, $\tan\beta = 1.5$, and heavy squarks, the range $50 < m_{\tilde{g}}$ (GeV)<140 is excluded at 90% CL. See the paper for details.

[135] AKERS 95R looked for *Z* decay into $q\overline{q}\tilde{g}\tilde{g}$, by searching for charged particles with dE/dx consistent with $\tilde{g}$ fragmentation into a state $(\tilde{g}q\overline{q})^{\pm}$ with lifetime $\tau > 10^{-7}$ sec. The fragmentation probability into a charged state is assumed to be 25%.

[136] CLAVELLI 95 updates the analysis of CLAVELLI 93, based on a comparison of the hadronic widths of charmonium and bottomonium *S*-wave states. The analysis includes a parametrization of relativisitic corrections. Claims that the presence of a light gluino improves agreement with the data by slowing down the running of α_s.

[137] HEBBEKER 93 combined jet analyses at various e^+e^- colliders. The 4-jet analyses at TRISTAN/LEP and the measured α_s at PEP/PETRA/TRISTAN/LEP are used. A constraint on effective number of quarks N=6.3 ± 1.1 is obtained, which is compared to that with a light gluino, N=8.

[138] LOPEZ 93C uses combined restraint from the radiative symmetry breaking scenario within the minimal supergravity model, and the LEP bounds on the (M_2,μ) plane. Claims that the light gluino window is strongly disfavored.

[139] ABE 92L bounds are based on similar assumptions as ABACHI 95C. Not sensitive to $m_{\rm gluino}$ <40 GeV (but other experiments rule out that region).

[140] CLAVELLI 92 claims that a light gluino mass around 4 GeV should exist to explain the discrepancy between α_s at LEP and at quarkonia (Υ), since a light gluino slows the running of the QCD coupling.

[141] ROY 92 reanalyzed CDF limits on di-lepton events to obtain limits on gluino production in *R*-parity violating models. The 100% decay $\tilde{g} \rightarrow q\overline{q}\tilde{\chi}$ where $\tilde{\chi}$ is the LSP, and the LSP decays either into $\ell q\overline{d}$ or $\ell\ell\overline{e}$ is assumed.

[142] ANTONIADIS 91 argue that possible light gluinos (< 5 GeV) contradict the observed running of α_s between 5 GeV and m_Z. The significance is less than 2 s.d.

[143] ANTONIADIS 91 intrepret the search for missing energy events in 450 GeV/c pN collisions, AKESSON 91, in terms of light gluinos.

[144] HIDAKA 91 limit obtained from LEP and preliminary CDF results within minimal supersymmetry with gaugino-mass unification condition. HIDAKA 91 limit extracted from BAER 91 analysis.

[145] NOJIRI 91 argues that a heavy gluino should be nearly degenerate with squarks in minimal supergravity not to overclose the universe.

[146] ALITTI 90 searched for events having ≥ 2 jets with $E^1_T > 25$ GeV, $E^2_T > 15$ GeV, $|\eta| < 0.85$, and $\Delta\phi < 160°$, with a missing momentum > 40 GeV and no electrons. They assume $\tilde{g} \rightarrow q\overline{q}\tilde{\gamma}$ decay and $m_{\tilde{\gamma}} \lesssim 20$ GeV. Masses below 50 GeV are not excluded by the analysis.

[147] NAKAMURA 89 searched for a long-lived ($\tau \gtrsim 10^{-7}$ s) charge-(±2) particle with mass $\lesssim$ 1.6 GeV in proton-Pt interactions at 12 GeV and found that the yield is less than 10^{-8} times that of the pion. This excludes R-Δ^{++} (a $\tilde{g}uuu$ state) lighter than 1.6 GeV.

[148] The limits of ALBAJAR 87D are from $p\overline{p} \rightarrow \tilde{g}\tilde{g}X$ ($\tilde{g} \rightarrow q\overline{q}\tilde{\gamma}$) and assume $m_{\tilde{q}} > m_{\tilde{g}}$. These limits apply for $m_{\tilde{\gamma}} \lesssim 20$ GeV and $\tau(\tilde{g}) < 10^{-10}$ s.

[149] The limit of ANSARI 87D assumes $m_{\tilde{q}} > m_{\tilde{g}}$ and $m_{\tilde{\gamma}} \approx 0$.

[150] The limits assume $m_{\tilde{q}} = 100$ GeV. See their figure 3 for limits vs. $m_{\tilde{q}}$.

[151] The gluino mass is defined by half the bound $\tilde{g}\tilde{g}$ mass. If zero gluino mass gives a $\tilde{g}\tilde{g}$ of mass about 1 GeV as suggested by various glueball mass estimates, then the low-mass bound can be replaced by zero. The high-mass bound is obtained by comparing the data with nonrelativistic potential-model estimates.

[152] ALBRECHT 86C search for secondary decay vertices from $\chi_{b1}(1P) \rightarrow \tilde{g}\tilde{g}g$ where $\tilde{g}$'s make long-lived hadrons. See their figure 4 for excluded region in the $m_{\tilde{g}} - m_{\tilde{q}}$ and $m_{\tilde{g}} - m_{\tilde{q}}$ plane. The lower $m_{\tilde{g}}$ region below ~ 2 GeV may be sensitive to fragmentation effects. Remark that the $\tilde{g}$-hadron mass is expected to be ~ 1 GeV (glueball mass) in the zero $\tilde{g}$ mass limit.

[153] BADIER 86 looked for secondary decay vertices from long-lived $\tilde{g}$-hadrons produced at 300 GeV π^- beam dump. The quoted bound assumes $\tilde{g}$-hadron nucleon total cross section of 10μb. See their figure 7 for excluded region in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane for several assumed total cross-section values.

[154] BARNETT 86 rule out light gluinos (m = 3–5 GeV) by calculating the monojet rate from gluino gluino gluon events (and from gluino gluino events) and by using UA1 data from $p\overline{p}$ collisions at CERN.

[155] VOLOSHIN 86 rules out stable gluino based on the cosmological argument that predicts too much hydrogen consisting of the charged stable hadron $\tilde{g}uud$. Quasi-stable ($\tau > 1. \times 10^{-7}$s) light gluino of $m_{\tilde{g}}$ <3 GeV is also ruled out by nonobservation of the stable charged particles, $\tilde{g}uud$, in high energy hadron collisions.

[156] COOPER-SARKAR 85B is BEBC beam-dump. Gluinos decaying in dump would yield $\tilde{\gamma}$'s in the detector giving neutral-current-like interactions. For $m_{\tilde{q}}$ >330 GeV, no limit is set.

[157] DAWSON 85 first limit from neutral particle search. Second limit based on FNAL beam dump experiment.

[158] FARRAR 85 points out that BALL 84 analysis applies only if the $\tilde{g}$'s decay before interacting, i.e. $m_{\tilde{q}} < 80 m_{\tilde{g}}^{1.5}$. FARRAR 85 finds $m_{\tilde{g}}$ <0.5 not excluded for $m_{\tilde{q}}$ = 30–1000 GeV and $m_{\tilde{g}}$ <1.0 not excluded for $m_{\tilde{q}}$ = 100–500 GeV by BALL 84 experiment.

[159] GOLDMAN 85 use nonobservation of a pseudoscalar $\tilde{g}$-$\tilde{g}$ bound state in radiative ψ decay.

[160] HABER 85 is based on survey of all previous searches sensitive to low mass $\tilde{g}$'s. Limit makes assumptions regarding the lifetime and electric charge of the lightest supersymmetric particle.

[161] BALL 84 is FNAL beam dump experiment. Observed no interactions of $\tilde{\gamma}$ in the calorimeter, where $\tilde{\gamma}$'s are expected to come from pair-produced $\tilde{g}$'s. Search for long-lived $\tilde{\gamma}$ interacting in calorimeter 56m from target. Limit is for $m_{\tilde{q}}$ = 40 GeV and production cross section proportional to $A^{0.72}$. BALL 84 find no $\tilde{g}$ allowed below 4.1 GeV at CL = 90%. Their figure 1 shows dependence on $m_{\tilde{q}}$ and A. See also KANE 82.

[162] BRICK 84 reanalyzed FNAL 147 GeV HBC data for R-$\Delta(1232)^{++}$ with $\tau > 10^{-9}$ s and $p_{\rm lab}$ >2 GeV. Set CL = 90% upper limits 6.1, 4.4, and 29 microbarns in pp, π^+p, K^+p collisions respectively. R-Δ^{++} is defined as being $\tilde{g}$ and 3 up quarks. If mass = 1.2–1.5 GeV, then limits may be lower than theory predictions.

[163] FARRAR 84 argues that $m_{\tilde{g}}$ <100 MeV is not ruled out if the lightest R-hadrons are long-lived. A long lifetime would occur if R-hadrons are lighter than $\tilde{\gamma}$'s or if $m_{\tilde{q}}$ >100 GeV.

[164] BERGSMA 83C is reanalysis of CERN-SPS beam-dump data. See their figure 1.

[165] CHANOWITZ 83 find in bag-model that charged *s*-hadron exists which is stable against strong decay if $m_{\tilde{g}}$ <1 GeV. This is important since tracks from decay of neutral *s*-hadron cannot be reconstructed to primary vertex because of missed $\tilde{\gamma}$. Charged *s*-hadron leaves track from vertex.

[166] KANE 82 inferred above $\tilde{g}$ mass limit from retroactive analysis of hadronic collision and beam dump experiments. Limits valid if $\tilde{g}$ decays inside detector.

Unstable $\tilde{\gamma}$ (Photino) MASS LIMIT

Unless stated otherwise, the limits below assume that the $\tilde{\gamma}$ decays either into $\gamma\tilde{G}$ (goldstino) or into $\gamma\tilde{H}^0$ (Higgsino).

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>40	95	[167] BUSKULIC	95E	ALEP	$e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$ ($\tilde{\chi}^0_1 \rightarrow \nu\ell\overline{\ell}'$)
		[168] BUSKULIC	95E	ALEP	$e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$ ($\tilde{\gamma} \rightarrow \nu\ell\overline{\ell}'$)
		[169] ACTON	93G	OPAL	$e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$ ($\tilde{\gamma} \rightarrow \tau^{\pm}\ell^{\mp}\nu_{\ell'}$)
		[170] ABE	89J	VNS	$e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$ ($\tilde{\gamma} \rightarrow \gamma\tilde{G}$ or $\gamma\tilde{H}^0$)
>15	95	[171] BEHREND	87B	CELL	$e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$ ($\tilde{\gamma} \rightarrow \gamma\tilde{G}$ or $\gamma\tilde{H}^0$)
		[172] ADEVA	85	MRKJ	
		[173] BALL	84	CALO	Beam dump
		[174] BARTEL	84B	JADE	
		[174] BEHREND	83	CELL	
		[175] CABIBBO	81	COSM	

[167] BUSKULIC 95E looked for $e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$, where $\tilde{\chi}^0_1$ decays via *R*-parity violating interaction into one neutrino and two opposite-charge leptons. The bound applies provided that $B(Z \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1) > 3 \times 10^{-5}\beta^3$, β being the final state $\tilde{\chi}^0_1$ velocity.

[168] BUSKULIC 95E looked for $e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$, where $\tilde{\gamma}$ decays via *R*-parity violating interaction into one neutrino and two opposite-charge leptons. They extend the domain in the $(m_{\tilde{e}}, m_{\tilde{\gamma}})$ plane excluded by ACTON 93G to $m_{\tilde{e}}$ >220 GeV/c^2 (for $m_{\tilde{\gamma}}$=15 GeV/c^2) and to $m_{\tilde{\gamma}}$ >2 GeV/c^2 (for $m_{\tilde{e}}$ <220 GeV/c^2).

[169] ACTON 93G assume *R*-parity violation and decays $\tilde{\gamma} \rightarrow \tau^{\pm}\ell^{\mp}\nu_{\ell}$ (ℓ= e or μ). They exclude $m_{\tilde{\gamma}}$ = 4–43 GeV for $m_{\tilde{e}_L}$ <42 GeV, and $m_{\tilde{\gamma}}$ = 7–30 GeV for $m_{\tilde{e}_L}$ <100 GeV (95% CL). Assumes $\tilde{e}_R$ much heavier than $\tilde{e}_L$, and lepton family number violation but L_e-L_μ conservation.

[170] ABE 89J exclude $m_{\tilde{\gamma}}$ = 0.15–25 GeV (95%CL) for d = (100 GeV)^2 and $m_{\tilde{e}}$ = 40 GeV in the case $\tilde{\gamma} \rightarrow \gamma\tilde{G}$, and $m_{\tilde{\gamma}}$ up to 23 GeV for $m_{\tilde{e}}$ = 40 GeV in the case $\tilde{\gamma} \rightarrow \gamma\tilde{H}^0$.

[171] BEHREND 87B limit is for unstable photinos only. Assumes $B(\tilde{\gamma} \rightarrow \gamma(\tilde{G}$ or $\tilde{H}^0))$ =1, $m_{\tilde{G} {\rm or} \tilde{H}^0} \ll m_{\tilde{\gamma}}$ and pure $\tilde{\gamma}$ eigenstate. $m_{\tilde{e}_L} = m_{\tilde{e}_R}$ < 100 GeV.

[172] ADEVA 85 is sensitive to $\tilde{\gamma}$ decay path <5 cm. With $m_{\tilde{e}}$ = 50 GeV, limit (CL = 90%) is $m_{\tilde{\gamma}}$ >20.5 GeV. Assume $\tilde{\gamma}$ decays to photon + goldstino and search for acoplanar photons with large missing p_T.

[173] BALL 84 is FNAL beam dump experiment. Observed no $\tilde{\gamma}$ decay, where $\tilde{\gamma}$'s are expected to come from $\tilde{g}$'s produced at the target. Three possible $\tilde{\gamma}$ lifetimes are considered. Gluino decay to goldstino + gluon is also considered.

[174] BEHREND 83 and BARTEL 84B look for 2γ events from $\widetilde{\gamma}$ pair production. With supersymmetric breaking parameter d = $(100\ \text{GeV})^2$ and $m_{\widetilde{e}}$ = 40 GeV the excluded regions at CL = 95% would be $m_{\widetilde{\gamma}}$ = 100 MeV – 13 GeV for BEHREND 83 $m_{\widetilde{\gamma}}$ = 80 MeV – 18 GeV for BARTEL 84B. Limit is also applicable if the $\widetilde{\gamma}$ decays radiatively within the detector.

[175] CABIBBO 81 consider $\widetilde{\gamma} \to \gamma +$ goldstino. Photino must be either light enough (<30 eV) to satisfy cosmology bound, or heavy enough (>0.3 MeV) to have disappeared at early universe.

Supersymmetry Miscellaneous Results

Results that do not appear under other headings or that make nonminimal assumptions.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[176] BARBER	84B	RVUE	
	[177] HOFFMAN	83	CNTR	$\pi p \to n(e^+ e^-)$

[176] BARBER 84B consider that $\widetilde{\mu}$ and $\widetilde{e}$ may mix leading to $\mu \to e\widetilde{\gamma}\widetilde{\gamma}$. They discuss mass-mixing limits from decay dist asym in LBL-TRIUMF data and e^+ polarization in SIN data.

[177] HOFFMAN 83 set CL = 90% limit $d\sigma/dt$ B(e^+e^-) < 3.5×10^{-32} cm^2/GeV^2 for spin-1 partner of Goldstone fermions with 140 < m < 160 MeV decaying → e^+e^- pair.

REFERENCES FOR Supersymmetric Particle Searches

ABACHI 96 PRL 76 2228 +Abbott, Abolins, Acharya+ (D0 Collab.)
ABACHI 96B PRL 76 2222 +Abbott, Abolins, Acharya+ (D0 Collab.)
ABE 96D PRL 76 2006 +Akimoto, Akopian, Albrow+ (CDF Collab.)
ABACHI 95C PRL 75 618 +Abbott, Abolins, Acharya+ (D0 Collab.)
ABE 95T PRL 75 613 +Albrow, Amidei, Anway-Wiese+ (CDF Collab.)
ACCIARRI 95E PL B350 109 +Adam, Adraiani, Aguilar-Benitez+ (L3 Collab.)
AKERS 95R ZPHY C67 203 +Alexander, Allison, Ametewee, Anderson+ (OPAL Collab.)
BUSKULIC 95E PL B349 238 +Casper, DeBonis, Decamp+ (ALEPH Collab.)
CLAVELLI 95 PR D51 1117 +Coulter (ALAT)
FALK 95 PL B354 99 +Olive, Srednicki (MINN, UCSB)
AHMED 94B ZPHY C64 545 +Aid, Andreev, Andrieu, Appuhn, Arpagaus+ (H1 Collab.)
AKERS 94K PL B337 207 +Alexander, Allison, Anderson+ (OPAL Collab.)
BECK 94 PL B336 141 +Bensch, Bockholt+ (MPIH, KIAE, SASSO)
FALK 94 PL B339 248 +Olive, Srednicki (UCSB, MINN)
FRANKE 94 PL B336 415 +Fraas, Bartl (WURZ, WIEN)
HOSODA 94 PL B331 211 +Abe, Amako, Arai+ (VENUS Collab.)
SHIRAI 94 PRL 72 3313 +Ohmoto, Abe, Amako+ (VENUS Collab.)
ACTON 93G PL B313 333 +Akers, Alexander, Allison, Anderson+ (OPAL Collab.)
ADRIANI 93M PRPL 236 1 +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ (L3 Collab.)
CLAVELLI 93 PR D47 1973 +Coulter, Yuan (ALAT)
DREES 93 PR D47 376 +Nojiri (DESY, SLAC)
FALK 93 PL B318 354 +Madden, Olive, Srednicki (UCB, UCSB, MINN)
HEBBEKER 93 ZPHY C60 63 (CERN)
KELLEY 93 PR D47 2461 +Lopez, Nanopoulos, Pois, Yuan (TAMU, ALAH)
LAU 93 PR D47 1087 (HOUS)
LOPEZ 93C PL B313 241 +Nanopoulos, Wang (TAMU, HARC, CERN)
MIZUTA 93 PL B298 120 +Yamaguchi (TOHO)
MORI 93 PR D48 5505 +(KEK, NIIG, TOKY, TOKA, KOBE, OSAK, TINT, GIFU)
ABE 92L PRL 69 3439 +Amidei, Anway-Wiese, Apollinari, Atac+ (CDF Collab.)
BOTTINO 92 MPL A7 733 +DeAlfaro, Fornengo, Morales, Puimedon+ (TORI, ZARA)
Also 91 PL B265 57 Bottino, de Alfaro, Fornengo, Mignola+ (TORI, INFN)
CLAVELLI 92 PR D46 2112 (ALAT)
DATTA 92 ZPHY C54 513 +Guchait, Raychaudhuri (JADA, CALC)
DECAMP 92 PRPL 216 253 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
ELLIS 92F PL B283 252 +Roszkowski (CERN)
KAWASAKI 92 PR D46 1634 +Mizuta (OSU, TOHO)
LOPEZ 92 NP B370 445 +Nanopoulos, Yuan (TAMU)
MCDONALD 92 PL B283 80 +Olive, Srednicki (LISB, MINN, UCSB)
ROY 92 PL B283 270 (CERN)
ABREU 91F NP B367 511 +Adam, Adami, Adye, Akesson+ (DELPHI Collab.)
AKESSON 91 ZPHY C52 219 +Almehed, Angelis, Atherton, Aubry+ (HELIOS Collab.)
ALEXANDER 91F ZPHY C52 175 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)
ANTONIADIS 91 PL B262 109 +Ellis, Nanopoulos (EPOL, CERN, TAMU, HARC)
BAER 91 PR D44 207 +Tata, Woodside (FSU, HAWA, ISU)
BAER 91B PR D44 725 +Drees, Godbole+ (FSU, DESY, BOMB, UCD, HAWA)
BOTTINO 91 PL B265 57 +de Alfaro, Fornengo, Mignola+ (TORI, INFN)
DREES 91 PR D43 2971 +Tata (CERN, HAWA)
GELMINI 91 NP B351 623 +Gondolo, Roulet (UCLA, TRST)
HIDAKA 91 PR D44 927 (TGAK)
KAMIONKOW... 91 PR D44 3021 Kamionkowski (CHIC, FNAL)
MORI 91B PL B270 89 +Nojiri, Oyama, Suzuki+ (Kamiokande Collab.)
NOJIRI 91 PL B261 76 (KEK)
OLIVE 91 NP B355 208 +Srednicki (MINN, UCSB)
ROSZKOWSKI 91 PL B262 59 (CERN)
SATO 91 PR D44 2220 +Hirata, Kajita, Kifune, Kihara+ (Kamioka Collab.)
ABREU 90F PL B247 148 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ABREU 90G PL B247 157 +Adam, Adami, Adye, Alekseev+ (DELPHI Collab.)
ADACHI 90C PL B244 352 +Aihara, Doser, Enomoto+ (TOPAZ Collab.)
ADEVA 90I PL B249 341 +Adriani, Aguilar-Benitez, Akbari, Alcarez+ (L3 Collab.)
AKESSON 90B PL B238 442 +Alitti, Ansari, Ansorge+ (UA2 Collab.)
AKRAWY 90D PL B240 261 +Alexander, Allison, Allport+ (OPAL Collab.)
AKRAWY 90N PL B248 211 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 90O PL B252 290 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALITTI 90 PL B235 363 +Ansari, Ansorge, Bagnaia, Bareyre+ (UA2 Collab.)
BAER 90 PR D41 3414 +Drees, Tata (FSU, CERN, HAWA)
BARKLOW 90 PRL 64 2984 +Abrams, Adolphsen, Averill, Ballam+ (Mark II Collab.)
DECAMP 90C PL B236 86 +Deschizeaux, Lees, Minard, Crespo+ (ALEPH Collab.)
DECAMP 90K PL B244 541 +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
DREES 90 PL B252 127 +Hikasa (CERN, KEK)
ELLIS 90 PL B245 251 +Nanopoulos, Roszkowski, Schramm (CERN, HARC, TAMU)
GRIEST 90 PR D41 3565 +Kamionkowski, Turner (UCB, CHIC, FNAL)
GRIFOLS 90 NP B331 244 +Masso (BARC)
KRAUSS 90 PRL 64 999 (YALE)
ROSZKOWSKI 90 PL B252 471 (TAMU, HARC)
SAKAI 90 PL B234 534 +Gu, Low, Abe, Fujii+ (AMY Collab.)
SODERSTROM 90 PRL 64 2980 +McKenna, Abrams, Adolphsen, Averill+ (Mark II Collab.)
TAKETANI 90 PL B234 202 +Odaka, Abe, Amako+ (VENUS Collab.)
ZHUKOVSKII 90 SJNP 52 931 +Eminov (MOSU)
Translated from YAF 52 1473.
ABE 89J ZPHY C45 175 +Amako, Arai, Fukawa+ (VENUS Collab.)
ADACHI 89 PL B218 105 +Aihara, Dijkstra, Enomoto, Fujii+ (TOPAZ Collab.)
ADEVA 89B PL B233 530 +Adriani, Aguilar-Benitez, Akbari+ (L3 Collab.)
ALBAJAR 89 ZPHY C44 15 +Albrow, Allkofer, Arnison, Astbury+ (UA1 Collab.)
HEARTY 89 PR D39 3207 +Rothberg, Young, Johnson, Whitaker+ (ASP Collab.)
Also 87 PRL 58 1711 Hearty, Rothberg, Young, Johnson+ (ASP Collab.)
Also 86 PRL 56 685 Bartha, Burke, Extermann+ (ASP Collab.)
NAKAMURA 89 PR D39 1261 +Kobayashi, Konaka, Imai, Masaike+ (KYOT, TMTC)
OLIVE 89 PL B230 78 +Srednicki (MINN, UCSB)
BAER 88 PR D38 1485 +Hagiwara, Tata (FSU, KEK, WISC)
Also 89B PR D39 989 erratum Baer, Hagiwara, Tata (FSU, KEK, WISC)
BEHREND 88B PL B215 186 +Criegee, Dainton, Field+ (CELLO Collab.)
ELLIS 88B PL B215 404 +Olive, Sarkar, Sciama (CERN, MINN, RAL, CAMB)
NATH 88 PR D38 1479 +Arnowitt (NEAS, TAMU)
OLIVE 88 PL B205 553 +Srednicki (MINN, UCSB)
SREDNICKI 88 NP B310 693 +Watkins, Olive (MINN, UCSB)
ADEVA 87 PL B194 167 +Anderhub, Ansari, Becker+ (Mark-J Collab.)
ALBAJAR 87B PL B185 241 +Albrow, Allkofer, Arnison+ (UA1 Collab.)
ALBAJAR 87D PL B198 261 +Albrow, Allkofer+ (UA1 Collab.)
ANSARI 87D PL B195 613 +Bagnaia, Banner+ (UA2 Collab.)
ARNOLD 87 PL B186 435 +Barth+ (BRUX, DUUC, LOUC, BARI, AICH, CERN+)
BAER 87B PR D35 1598 +Hagiwara, Tata (KEK, ANL, WISC)
Also 86 PRL 57 294 Baer, Hagiwara, Tata (ANL, DESY, WISC)
BEHREND 87B ZPHY C35 181 +Buerger, Criegee, Dainton+ (CELLO Collab.)
HEARTY 87 PRL 58 1711 +Rothberg, Young, Johnson+ (ASP Collab.)
NG 87 PL B188 138 +Olive, Srednicki (MINN, UCSB)
TUTS 87 PL B186 233 +Franzini, Youssef, Zhao+ (CUSB Collab.)
ALBRECHT 86C PL 167B 360 +Binder, Harder+ (ARGUS Collab.)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
BARNETT 86 NP B267 625 +Haber, Kane (LBL, UCSC, MICH)
FORD 86 PR D33 3472 +Qi, Read+ (MAC Collab.)
GAISSER 86 PR D34 2206 +Steigman, Tilav (BART, DELA)
VOLOSHIN 86 SJNP 43 495 +Okun (ITEP)
Translated from YAF 43 779.
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
Also 84C PRPL 109 131 Adeva, Barber, Becker+ (Mark-J Collab.)
AKERLOF 85 PL 156B 271 +Bonvicini, Chapman, Errede+ (HRS Collab.)
BARTEL 85L PL 155B 288 +Becker, Cords, Felst, Hagiwara+ (JADE Collab.)
BEHREND 85 PL 161B 182 +Burger, Criegee, Fenner+ (CELLO Collab.)
COOPER-... 85B PL 160B 212 Cooper-Sarkar, Parker, Sarkar+ (WA66 Collab.)
DAWSON 85 PR D31 1581 +Eichten, Quigg (LBL, FNAL)
FARRAR 85 PRL 55 895 (RUTG)
GOLDMAN 85 Physica 15D 181 +Haber (LANL, UCSC)
HABER 85 PRPL 117 75 +Kane (UCSC, MICH)
ADEVA 84B PRL 53 1806 +Barber, Becker, Berdugo+ (Mark-J Collab.)
BALL 84 PRL 53 1314 +Coffin, Gustafson+ (MICH, FIRZ, OSU, FNAL, WISC)
BARBER 84B PL 139B 427 +Shrock (STON)
BARTEL 84B PL 139B 327 +Becker, Bowdery, Cords+ (JADE Collab.)
BARTEL 84C PL 146B 126 +Becker, Bowdery, Cords+ (JADE Collab.)
BRICK 84 PR D30 1134 + (BROW, CAVE, IIT, IND, MIT, MONS, NIJM+)
ELLIS 84 NP B238 453 +Hagelin, Nanopoulos, Olive, Srednicki (CERN)
FARRAR 84 PRL 53 1029 (RUTG)
BEHREND 83 PL 123B 127 +Chen, Fenner, Gumpel+ (CELLO Collab.)
BERGSMA 83C PL 121B 429 +Dorenbosch, Jonker+ (CHARM Collab.)
CHANOWITZ 83 PL 126B 225 +Sharpe (UCB, LBL)
GOLDBERG 83 PRL 50 1419 (NEAS)
HOFFMAN 83 PR D28 660 +Frank, Mischke, Moir, Schardt (LANL, ARZS)
KRAUSS 83 NP B227 556 (HARV)
VYSOTSKII 83 SJNP 37 948 (ITEP)
Translated from YAF 37 1597.
KANE 82 PL 112B 227 +Leveille (MICH)
CABIBBO 81 PL 105B 155 +Farrar, Maiani (ROMA, RUTG)
FARRAR 78 PL 76B 575 +Fayet (CIT)
Also 78B PL 79B 442 Farrar, Fayet (CIT)

Quark and Lepton Compositeness, Searches for

SEARCHES FOR QUARK AND LEPTON COMPOSITENESS

If quarks and leptons are made of constituents, then at the scale of constituent binding energies, there should appear new interactions among quarks and leptons. At energies much below the compositeness scale (Λ), these interactions are suppressed by inverse powers of Λ. The dominant effect should come from the lowest dimensional interactions with four fermions (contact terms), whose most general chirally invariant form reads [1]

$$L = \frac{g^2}{2\Lambda^2}\left[\eta_{LL}\,\overline{\psi}_L\,\gamma_\mu\,\psi_L\,\overline{\psi}_L\,\gamma^\mu\,\psi_L + \eta_{RR}\,\overline{\psi}_R\,\gamma_\mu\,\psi_R\,\overline{\psi}_R\,\gamma^\mu\,\psi_R + 2\eta_{LR}\,\overline{\psi}_L\,\gamma_\mu\,\psi_L\,\overline{\psi}_R\,\gamma^\mu\,\psi_R\right] \; . \qquad (1)$$

Chiral invariance provides a natural explanation why quark and lepton masses are much smaller than their inverse size Λ. We may determine the scale Λ unambiguously by using the above form of the effective interactions; the conventional method [1] is to fix its scale by setting $g^2/4\pi = g^2(\Lambda)/4\pi = 1$ for the new strong interaction coupling and by setting the largest magnitude of the coefficients $\eta_{\alpha\beta}$ to be unity. In the following, we denote

$$\begin{aligned} \Lambda &= \Lambda^\pm_{LL} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1,\,0,\,0)\;, \\ \Lambda &= \Lambda^\pm_{RR} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (0,\,\pm1,\,0)\;, \\ \Lambda &= \Lambda^\pm_{VV} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1,\,\pm1,\,\pm1)\;, \\ \Lambda &= \Lambda^\pm_{AA} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1,\,\pm1,\,\mp1)\;, \end{aligned} \qquad (2)$$

as typical examples. Such interactions can arise by constituent interchange (when the fermions have common constituents, e.g., for $ee \to ee$) and/or by exchange of the binding quanta (whenever binding quanta couple to constituents of both particles).

Another typical consequence of compositeness is the appearance of excited leptons and quarks (ℓ^* and q^*). Phenomenologically, an excited lepton is defined to be a heavy lepton which shares leptonic quantum number with one of the existing leptons (an excited quark is defined similarly). For example, an excited electron e^* is characterized by a nonzero transition-magnetic coupling with electrons. Smallness of the lepton mass and the success of QED prediction for g–2 suggest chirality conservation, *i.e.*, an excited lepton should not couple to both left- and right-handed components of the corresponding lepton.

Excited leptons may be classified by SU(2)×U(1) quantum numbers. Typical examples are:

1. Sequential type

$$\begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_L\;, \qquad [\nu^*_R]\;, \qquad \ell^*_R\;.$$

ν^*_R is necessary unless ν^* has a Majorana mass.

2. Mirror type

$$[\nu^*_L]\;, \qquad \ell^*_L\;, \qquad \begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_R\;.$$

3. Homodoublet type

$$\begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_L\;, \qquad \begin{pmatrix}\nu^*\\ \ell^*\end{pmatrix}_R\;.$$

Similar classification can be made for excited quarks.

Excited fermions can be pair produced via their gauge couplings. The couplings of excited leptons with Z are listed in the following table (for notation see Eq. (1) in "Standard Model of Electroweak Interactions"):

	Sequential type	Mirror type	Homodoublet type
V^{ℓ^*}	$-\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}+2\sin^2\theta_W$	$-1+2\sin^2\theta_W$
A^{ℓ^*}	$-\frac{1}{2}$	$+\frac{1}{2}$	0
$V^{\nu^*_D}$	$+\frac{1}{2}$	$+\frac{1}{2}$	+1
$A^{\nu^*_D}$	$+\frac{1}{2}$	$-\frac{1}{2}$	0
$V^{\nu^*_M}$	0	0	—
$A^{\nu^*_M}$	+1	−1	—

Here ν^*_D (ν^*_M) stands for Dirac (Majorana) excited neutrino. The corresponding couplings of excited quarks can be easily obtained. Although form factor effects can be present for the gauge couplings at $q^2 \neq 0$, they are usually neglected.

In addition, transition magnetic type couplings with a gauge boson are expected. These couplings can be generally parametrized as follows:

$$\begin{aligned}\mathcal{L} = {} & \frac{\lambda_\gamma^{(f^*)} e}{2m_{f^*}}\,\overline{f}^*\sigma^{\mu\nu}(\eta_L\tfrac{1-\gamma_5}{2}+\eta_R\tfrac{1+\gamma_5}{2})fF_{\mu\nu} \\ & + \frac{\lambda_Z^{(f^*)} e}{2m_{f^*}}\,\overline{f}^*\sigma^{\mu\nu}(\eta_L\tfrac{1-\gamma_5}{2}+\eta_R\tfrac{1+\gamma_5}{2})fZ_{\mu\nu} \\ & + \frac{\lambda_W^{(\ell^*)} g}{2m_{\ell^*}}\,\overline{\ell}^*\sigma^{\mu\nu}\tfrac{1-\gamma_5}{2}\nu W_{\mu\nu} \\ & + \frac{\lambda_W^{(\nu^*)} g}{2m_{\nu^*}}\,\overline{\nu}^*\sigma^{\mu\nu}(\eta_L\tfrac{1-\gamma_5}{2}+\eta_R\tfrac{1+\gamma_5}{2})\ell\, W^\dagger_{\mu\nu} \\ & + \text{h.c.}\;, \end{aligned} \qquad (3)$$

where $g = e/\sin\theta_W$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the photon field strength, $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$, *etc.* The normalization of the coupling is chosen such that

$$\max(|\eta_L|, |\eta_R|) = 1\;.$$

Chirality conservation requires

$$\eta_L\eta_R = 0\;. \qquad (4)$$

These couplings can arise from SU(2)×U(1)-invariant higher-dimensional interactions. A well-studied model is the interaction of homodoublet type ℓ^* with the Lagrangian [2,3]

$$\mathcal{L} = \frac{1}{2\Lambda}\overline{L}^*(gf\tfrac{\tau^a}{2}W^a_{\mu\nu} + g'f'YB_{\mu\nu})\tfrac{1-\gamma_5}{2}L + \text{h.c.}\;, \qquad (5)$$

where L denotes the lepton doublet (ν, ℓ), Λ is the compositeness scale, g, g' are SU(2) and U(1)$_Y$ gauge couplings, and $W^a_{\mu\nu}$ and $B_{\mu\nu}$ are the field strengths for SU(2) and U(1)$_Y$ gauge fields. The same interaction occurs for mirror-type excited leptons. For sequential-type excited leptons, the ℓ^* and ν^* couplings become unrelated, and the couplings receive the extra suppression of (250 GeV)/Λ or m_{L^*}/Λ. In any case, these couplings satisfy the relation

$$\lambda_W = -\sqrt{2}\sin^2\theta_W(\lambda_Z \cot\theta_W + \lambda_\gamma) \; . \tag{6}$$

Additional coupling with gluons is possible for excited quarks:

$$\mathcal{L} = \frac{1}{2\Lambda}\overline{Q}^*\sigma^{\mu\nu}\left(g_s f_s \tfrac{\lambda^a}{2}G^a_{\mu\nu} + g\, f\tfrac{\tau^a}{2}W^a_{\mu\nu} + g'\, f' Y B_{\mu\nu}\right) \times \tfrac{1-\gamma_5}{2}Q + \text{h.c.} \; , \tag{7}$$

where Q denotes a quark doublet, g_s is the QCD gauge coupling, and $G^a_{\mu\nu}$ the gluon field strength.

Some experimental analyses assume the relation $\eta_L = \eta_R = 1$, which violates chiral symmetry. We encode the results of such analyses if the crucial part of the cross section is proportional to the factor $\eta_L^2 + \eta_R^2$ and the limits can be reinterpreted as those for chirality conserving cases $(\eta_L, \eta_R) = (1,0)$ or $(0,1)$ after rescaling λ.

Several different conventions are used by LEP experiments to express the transition magnetic couplings. To facilitate comparison, we reexpress these in terms of λ_Z and λ_γ using the following relations and taking $\sin^2\theta_W = 0.23$. We assume chiral couplings, *i.e.*, $|c| = |d|$ in the notation of Ref. 2.

1. ALEPH (charged lepton and neutrino)

$$\lambda_Z^{\text{ALEPH}} = \frac{1}{2}\lambda_Z \quad \text{(1990 papers)} \tag{8a}$$

$$\frac{2c}{\Lambda} = \frac{\lambda_Z}{m_{\ell^*}[\text{or } m_{\nu^*}]} \quad (\text{for } |c| = |d|) \tag{8b}$$

2. ALEPH (quark)

$$\lambda_u^{\text{ALEPH}} = \frac{\sin\theta_W\cos\theta_W}{\sqrt{\frac{1}{4} - \frac{2}{3}\sin^2\theta_W + \frac{8}{9}\sin^4\theta_W}}\,\lambda_Z = 1.11\lambda_Z \tag{9}$$

3. L3 and DELPHI (charged lepton)

$$\lambda^{\text{L3}} = \lambda_Z^{\text{DELPHI}} = -\frac{\sqrt{2}}{\cot\theta_W - \tan\theta_W}\,\lambda_Z = -1.10\lambda_Z \tag{10}$$

4. L3 (neutrino)

$$f_Z^{\text{L3}} = \sqrt{2}\lambda_Z \tag{11}$$

5. OPAL (charged lepton)

$$\frac{f^{\text{OPAL}}}{\Lambda} = -\frac{2}{\cot\theta_W - \tan\theta_W}\,\frac{\lambda_Z}{m_{\ell^*}} = -1.56\,\frac{\lambda_Z}{m_{\ell^*}} \tag{12}$$

6. OPAL (quark)

$$\frac{f^{\text{OPAL}}c}{\Lambda} = \frac{\lambda_Z}{2m_{q^*}} \quad (\text{for } |c| = |d|) \tag{13}$$

7. DELPHI (charged lepton)

$$\lambda_\gamma^{\text{DELPHI}} = -\frac{1}{\sqrt{2}}\,\lambda_\gamma \tag{14}$$

If leptons are made of color triplet and antitriplet constituents, we may expect their color-octet partners. Transitions between the octet leptons (ℓ_8) and the ordinary lepton (ℓ) may take place via the dimension-five interactions

$$\mathcal{L} = \frac{1}{2\Lambda}\sum_\ell \left\{ \overline{\ell}_8^\alpha\, g_S\, F^\alpha_{\mu\nu}\,\sigma^{\mu\nu}\left(\eta_L\, \ell_L + \eta_R\, \ell_R\right) + h.c. \right\} \tag{15}$$

where the summation is over charged leptons and neutrinos. The leptonic chiral invariance implies $\eta_L\, \eta_R = 0$ as before.

References

1. E.J. Eichten, K.D. Lane, and M.E. Peskin, Phys. Rev. Lett. **50**, 811 (1983).
2. K. Hagiwara, S. Komamiya, and D. Zeppenfeld, Z. Phys. **C29**, 115 (1985).
3. N. Cabibbo, L. Maiani, and Y. Srivastava, Phys. Lett. **139B**, 459 (1984).

SCALE LIMITS for Contact Interactions: $\Lambda(eeee)$

Limits are for $\Lambda^\pm_{LL}$ only. For other cases, see each reference.

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>1.6		95	[1,2] BUSKULIC	93Q	RVUE	
	>3.6	95	[3] KROHA	92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>1.6	>2.0	95	[2] BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
	>2.2	95	BUSKULIC	93Q	RVUE	
>1.3		95	[3] KROHA	92	RVUE	
>0.7	>2.8	95	BEHREND	91C	CELL	E_{cm}=35 GeV
>1.3	>1.3	95	KIM	89	AMY	E_{cm}=50–57 GeV
>1.4	>3.3	95	[4] BRAUNSCH...	88	TASS	E_{cm}=12–46.8 GeV
>1.0	>0.7	95	[5] FERNANDEZ	87B	MAC	E_{cm}=29 GeV
>1.1	>1.4	95	[6] BARTEL	86C	JADE	E_{cm}=12–46.8 GeV
>1.17	>0.87	95	[7] DERRICK	86	HRS	E_{cm}=29 GeV
>1.1	>0.76	95	[8] BERGER	85B	PLUT	E_{cm}=34.7 GeV

[1] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[2] BUSKULIC 93Q uses the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[3] KROHA 92 limit is from fit to BERGER 85B, BARTEL 86C, DERRICK 86B, FERNANDEZ 87B, BRAUNSCHWEIG 88, BEHREND 91B, and BEHREND 91C. The fit gives $\eta/\Lambda^2_{LL} = +0.230 \pm 0.206$ TeV^{-2}.

[4] BRAUNSCHWEIG 88 assumed $m_Z = 92$ GeV and $\sin^2\theta_W = 0.23$.

[5] FERNANDEZ 87B assumed $\sin^2\theta_W = 0.22$.

[6] BARTEL 86C assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

[7] DERRICK 86 assumed $m_Z = 93$ GeV and $g_V^2 = (-1/2+2\sin^2\theta_W)^2 = 0.004$.

[8] BERGER 85B assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

SCALE LIMITS for Contact Interactions: $\Lambda(ee\mu\mu)$

Limits are for $\Lambda^\pm_{LL}$ only. For other cases, see each reference.

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>2.6	**>1.9**	95	[9,10] BUSKULIC	93Q	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>1.7	>2.2	95	[10] VELISSARIS	94	AMY	E_{cm}=57.8 GeV
>1.3	>1.5	95	[10] BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
>2.3	>2.0	95	HOWELL	92	TOPZ	E_{cm}=52–61.4 GeV
	>1.7	95	[11] KROHA	92	RVUE	
>2.5	>1.5	95	BEHREND	91C	CELL	E_{cm}=35–43 GeV
>1.6	>2.0	95	[12] ABE	90I	VNS	E_{cm}=50–60.8 GeV
>1.9	>1.0	95	KIM	89	AMY	E_{cm}=50–57 GeV
>2.3	>1.3	95	BRAUNSCH...	88D	TASS	E_{cm}=30–46.8 GeV
>4.4	>2.1	95	[13] BARTEL	86C	JADE	E_{cm}=12–46.8 GeV
>2.9	>0.86	95	[14] BERGER	85	PLUT	E_{cm}=34.7 GeV

[9] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[10] BUSKULIC 93Q and VELISSARIS 94 use the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[11] KROHA 92 limit is from fit to BARTEL 86C, BEHREND 87C, BRAUNSCHWEIG 88D, BRAUNSCHWEIG 89C, ABE 90I, and BEHREND 91C. The fit gives $\eta/\Lambda^2_{LL} = -0.155 \pm 0.095$ TeV^{-2}.

[12] ABE 90I assumed m_Z =91.163 GeV and $\sin^2\theta_W = 0.231$.

[13] BARTEL 86C assumed m_Z = 93 GeV and $\sin^2\theta_W = 0.217$.

[14] BERGER 85 assumed m_Z = 93 GeV and $\sin^2\theta_W = 0.217$.

SCALE LIMITS for Contact Interactions: $\Lambda(ee\tau\tau)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>1.9	**>2.9**	95	[15] KROHA	92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>1.4	>2.0	95	[16] VELISSARIS	94	AMY	E_{cm}=57.8 GeV
>1.0	>1.5	95	[16] BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
>1.8	>2.3	95	[16,17] BUSKULIC	93Q	RVUE	
>1.9	>1.7	95	HOWELL	92	TOPZ	E_{cm}=52–61.4 GeV
>1.6	>2.3	95	BEHREND	91C	CELL	E_{cm}=35–43 GeV
>1.8	>1.3	95	[18] ABE	90I	VNS	E_{cm}=50–60.8 GeV
>2.2	>3.2	95	[19] BARTEL	86	JADE	E_{cm}=12–46.8 GeV

[15] KROHA 92 limit is from fit to BARTEL 86C BEHREND 89B, BRAUNSCHWEIG 89C, ABE 90I, and BEHREND 91C. The fit gives $\eta/\Lambda^2_{LL} = +0.095 \pm 0.120$ TeV^{-2}.

[16] BUSKULIC 93Q and VELISSARIS 94 use the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[17] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[18] ABE 90I assumed m_Z =91.163 GeV and $\sin^2\theta_W = 0.231$.

[19] BARTEL 86 assumed m_Z = 93 GeV and $\sin^2\theta_W = 0.217$.

SCALE LIMITS for Contact Interactions: $\Lambda(\ell\ell\ell\ell)$

Lepton universality assumed. Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>3.5	**>2.8**	95	[20,21] BUSKULIC	93Q	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>3.0	>2.3	95	[21,22] BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
>2.5	>2.2	95	[23] HOWELL	92	TOPZ	E_{cm}=52–61.4 GeV
>3.4	>2.7	95	[24] KROHA	92	RVUE	

[20] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[21] BUSKULIC 93Q uses the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[22] From $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, and $\tau^+\tau^-$.

[23] HOWELL 92 limit is from $e^+e^- \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$.

[24] KROHA 92 limit is from fit to most PEP/PETRA/TRISTAN data. The fit gives $\eta/\Lambda^2_{LL} = -0.0200 \pm 0.0666$ TeV^{-2}.

SCALE LIMITS for Contact Interactions: $\Lambda(eeqq)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 2.3	> 1.0	95	[25] AID	95	H1	$(eeqq)$ (u, d quarks)
> 1.7	**> 2.2**	95	[26] ABE	91D	CDF	$(eeqq)$ (u, d quarks)
>1.2		95	[27] ADACHI	91	TOPZ	$(eeqq)$ (flavor-universal)
	>1.7	95	[28] ABE	89L	VNS	$(eeqq)$ (flavor-universal)
• • • We do not use the following data for averages, fits, limits, etc. • • •						
	>1.6	95	[27] ADACHI	91	TOPZ	$(eeqq)$ (flavor-universal)
>0.6	>1.7	95	[29] BEHREND	91C	CELL	$(eecc)$
>1.1	>1.0	95	[29] BEHREND	91C	CELL	$(eebb)$
>0.9		95	[28] ABE	89L	VNS	$(eeqq)$ (flavor-universal)
>1.05	>1.61	95	[30] HAGIWARA	89	RVUE	$(eecc)$
>1.21	>0.53	95	[31] HAGIWARA	89	RVUE	$(eebb)$

[25] AID 95 limits are from the Q^2 spectrum measurement of $ep \rightarrow eX$.

[26] ABE 91D limits are from e^+e^- mass distribution in $p\overline{p} \rightarrow e^+e^-X$ at E_{cm} = 1.8 TeV.

[27] ADACHI 91 limits are from differential jet cross section. Universality of $\Lambda(eeqq)$ for five flavors is assumed.

[28] ABE 89L limits are from jet charge asymmetry. Universality of $\Lambda(eeqq)$ for five flavors is assumed.

[29] BEHREND 91C is from data at E_{cm} = 35–43 GeV.

[30] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurements of D/D^* mesons by ALTHOFF 83C, BARTEL 84E, and BARINGER 88.

[31] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurement of b hadrons by BARTEL 84D.

SCALE LIMITS for Contact Interactions: $\Lambda(\mu\mu qq)$

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>1.4	**>1.6**	95	ABE	92B	CDF	$(\mu\mu qq)$ (isosinglet)

SCALE LIMITS for Contact Interactions: $\Lambda(\ell\nu\ell\nu)$

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>3.10	90	[32] JODIDIO	86	SPEC	$\Lambda^{\pm}_{LR}(\nu_\mu\nu_e\mu e)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>3.8		[33] DIAZCRUZ	94	RVUE	$\Lambda^+_{LL}(\tau\nu_\tau e\nu_e)$
>8.1		[33] DIAZCRUZ	94	RVUE	$\Lambda^-_{LL}(\tau\nu_\tau e\nu_e)$
>4.1		[34] DIAZCRUZ	94	RVUE	$\Lambda^+_{LL}(\tau\nu_\tau\mu\nu_\mu)$
>6.5		[34] DIAZCRUZ	94	RVUE	$\Lambda^-_{LL}(\tau\nu_\tau\mu\nu_\mu)$

[32] JODIDIO 86 limit is from $\mu^+ \rightarrow \overline{\nu}_\mu e^+\nu_e$. Chirality invariant interactions $L = (g^2/\Lambda^2)$ $[\eta_{LL}\,(\overline{\nu}_{\mu L}\gamma^\alpha\mu_L)\,(\overline{e}_L\gamma_\alpha\nu_{eL}) + \eta_{LR}\,(\overline{\nu}_{\mu L}\gamma^\alpha\nu_{eL})\,(\overline{e}_R\gamma_\alpha\mu_R)]$ with $g^2/4\pi = 1$ and $(\eta_{LL},\eta_{LR}) = (0,\pm1)$ are taken. No limits are given for $\Lambda^{\pm}_{LL}$ with $(\eta_{LL},\eta_{LR}) = (\pm1,0)$. For more general constraints with right-handed neutrinos and chirality nonconserving contact interactions, see their text.

[33] DIAZCRUZ 94 limits are from $\Gamma(\tau \rightarrow e\nu\nu)$ and assume flavor-dependent contact interactions with $\Lambda(\tau\nu_\tau e\nu_e) \ll \Lambda(\mu\nu_\mu e\nu_e)$.

[34] DIAZCRUZ 94 limits are from $\Gamma(\tau \rightarrow \mu\nu\nu)$ and assume flavor-dependent contact interactions with $\Lambda(\tau\nu_\tau\mu\nu_\mu) \ll \Lambda(\mu\nu_\mu e\nu_e)$.

SCALE LIMITS for Contact Interactions: $\Lambda(qqqq)$

Limits are for $\Lambda^{\pm}_{LL}$ with color-singlet isoscalar exchanges among u_L's and d_L's only. See EICHTEN 84 for details.

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
		[35] ABE	96	CDF	$p\overline{p} \rightarrow$ jets inclusive
>1.4	95	[36] ABE	92D	CDF	$p\overline{p} \rightarrow$ jets inclusive
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1.3	95	[37] ABE	93G	CDF	$p\overline{p} \rightarrow$ dijet mass
>1.0	99	[38] ABE	92M	CDF	$p\overline{p} \rightarrow$ dijet angl.
>0.825	95	[39] ALITTI	91B	UA2	$p\overline{p} \rightarrow$ jets inclusive
>0.700	95	[36] ABE	89	CDF	$p\overline{p} \rightarrow$ jets inclusive
>0.330	95	[40] ABE	89H	CDF	$p\overline{p} \rightarrow$ dijet angl.
>0.400	95	[41] ARNISON	86C	UA1	$p\overline{p} \rightarrow$ jets inclusive
>0.415	95	[42] ARNISON	86D	UA1	$p\overline{p} \rightarrow$ dijet angl.
>0.370	95	[43] APPEL	85	UA2	$p\overline{p} \rightarrow$ jets inclusive
>0.275	95	[44] BAGNAIA	84C	UA2	Repl. by APPEL 85

[35] ABE 96 finds that the inclusive jet cross section for E_T >200 GeV is significantly higher than the $\mathcal{O}(\alpha_s^3)$ perturbative QCD prediction. This could be interpreted as the effect of a contact interaction with $\Lambda_{LL} \sim 1.6$ TeV. However, ABE 96 state that uncertainty in the parton distribution functions, higher-order QCD corrections, and the detector calibration may possibly account for the effect.

[36] Limit is from inclusive jet cross-section data in $p\overline{p}$ collisions at E_{cm} = 1.8 TeV. The limit takes into account uncertainties in choice of structure functions and in choice of process scale.

[37] ABE 93G limit is from dijet mass distribution in $p\overline{p}$ collisions at E_{cm} = 1.8 TeV. The limit is the weakest from several choices of structure functions and renormalization scale.

[38] ABE 92M limit is from dijet angular distribution for m_{dijet} >550 GeV in $p\overline{p}$ collisions at E_{cm}=1.8 TeV.

[39] ALITTI 91B limit is from inclusive jet cross section in $p\overline{p}$ collisions at E_{cm} = 630 GeV. The limit takes into account uncertainties in choice of structure functions and in choice of process scale.

[40] ABE 89H limit is from dijet angular distribution for m_{dijet} > 200 GeV at the Fermilab Tevatron Collider with E_{cm} = 1.8 TeV. The QCD prediction is quite insensitive to choice of structure functions and choice of process scale.

[41] ARNISON 86C limit is from the study of inclusive high-p_T jet distributions at the CERN $\overline{p}p$ collider (E_{cm} = 546 and 630 GeV). The QCD prediction renormalized to the low-p_T region gives a good fit to the data.

[42] ARNISON 86D limit is from the study of dijet angular distribution in the range 240 < m(dijet) < 300 GeV at the CERN $\overline{p}p$ collider (E_{cm} = 630 GeV). QCD prediction using EHLQ structure function (EICHTEN 84) with Λ_{QCD} = 0.2 GeV for the choice of $Q^2 = {p_T}^2$ gives the best fit to the data.

[43] APPEL 85 limit is from the study of inclusive high-p_T jet distributions at the CERN $\overline{p}p$ collider (E_{cm} = 630 GeV). The QCD prediction renormalized to the low-p_T region gives a good description of the data.

[44] BAGNAIA 84C limit is from the study of jet p_T and dijet mass distributions at the CERN $\overline{p}p$ collider (E_{cm} = 540 GeV). The limit suffers from the uncertainties in comparing the data with the QCD prediction.

MASS LIMITS for Excited e (e^*)

Most e^+e^- experiments assume one-photon or Z exchange. The limits from some e^+e^- experiments which depend on λ have assumed transition couplings which are chirality violating ($\eta_L = \eta_R$). However they can be interpreted as limits for chirality-conserving interactions after multiplying the coupling value λ by $\sqrt{2}$; see Note.

Excited leptons have the same quantum numbers as other ortholeptons. See also the searches for ortholeptons in the "Searches for Heavy Leptons" section.

Limits for Excited e (e^*) from Pair Production

These limits are obtained from $e^+e^- \to e^{*+}e^{*-}$ and thus rely only on the (electroweak) charge of e^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the e^* coupling is assumed to be of sequential type. Possible t channel contribution from transition magnetic coupling is neglected. All limits assume $e^* \to e\gamma$ decay except the limits from $\Gamma(Z)$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45,** 1 June, Part II (1992)).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>45.6	95	ADRIANI	93M	L3	$Z \to e^*e^*$
>45.6	95	ABREU	92C	DLPH	$Z \to e^*e^*$
>46.1	95	DECAMP	92	ALEP	$Z \to e^*e^*$
>44.9	95	AKRAWY	90I	OPAL	$Z \to e^*e^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>29.8	95	[45] BARDADIN-...	92	RVUE	$\Gamma(Z)$
>26.1	95	[46] DECAMP	92	ALEP	$Z \to e^*e^*$; $\Gamma(Z)$
>33	95	[46] ABREU	91F	DLPH	$Z \to e^*e^*$; $\Gamma(Z)$
>45.0	95	[47] ADEVA	90F	L3	$Z \to e^*e^*$
>44.6	95	[48] DECAMP	90G	ALEP	$e^+e^- \to e^*e^*$
>30.2	95	ADACHI	89B	TOPZ	$e^+e^- \to e^*e^*$
>28.3	95	KIM	89	AMY	$e^+e^- \to e^*e^*$
>27.9	95	[49] ABE	88B	VNS	$e^+e^- \to e^*e^*$

[45] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)$<36 MeV.
[46] Limit is independent of e^* decay mode.
[47] ADEVA 90F is superseded by ADRIANI 93M.
[48] Superseded by DECAMP 92.
[49] ABE 88B limits assume $e^+e^- \to e^{*+}e^{*-}$ with one photon exchange only and $e^* \to e\gamma$ giving $ee\gamma\gamma$.

Limits for Excited e (e^*) from Single Production

These limits are from $e^+e^- \to e^*e$, $W \to e^*\nu$, or $ep \to e^*X$ and depend on transition magnetic coupling between e and e^*. All limits assume $e^* \to e\gamma$ decay except as noted. Limits from LEP, UA2, and H1 are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m_{e^*}$ plane. See the original papers.

For limits prior to 1987, see our 1992 edition (Physical Review **D45,** 1 June, Part II (1992)).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>89	95	ADRIANI	93M	L3	$Z \to ee^*$, $\lambda_Z > 0.5$
>88	95	ABREU	92C	DLPH	$Z \to ee^*$, $\lambda_Z > 0.5$
>91	95	DECAMP	92	ALEP	$Z \to ee^*$, $\lambda_Z > 1$
>87	95	AKRAWY	90I	OPAL	$Z \to ee^*$, $\lambda_Z > 0.5$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[50] DERRICK	95B	ZEUS	$ep \to e^*X$
		[51] ABT	93	H1	$ep \to e^*X$
>86	95	ADRIANI	93M	L3	$\lambda_\gamma > 0.04$
		[52] DERRICK	93B	ZEUS	Superseded by DERRICK 95B
>86	95	ABREU	92C	DLPH	$e^+e^- \to ee^*$, $\lambda_\gamma > 0.1$
>88	95	[53] ADEVA	90F	L3	$Z \to ee^*$, $\lambda_Z > 0.5$
>86	95	[53] ADEVA	90F	L3	$Z \to ee^*$, $\lambda_Z > 0.04$
>81	95	[54] DECAMP	90G	ALEP	$Z \to ee^*$, $\lambda_Z > 1$
>50	95	ADACHI	89B	TOPZ	$e^+e^- \to ee^*$, $\lambda_\gamma > 0.04$
>56	95	KIM	89	AMY	$e^+e^- \to ee^*$, $\lambda_\gamma > 0.03$
none 23–54	95	[55] ABE	88B	VNS	$e^+e^- \to ee^*$ $\lambda_\gamma > 0.04$
>75	95	[56] ANSARI	87D	UA2	$W \to e^*\nu$; $\lambda_W > 0.7$
>63	95	[56] ANSARI	87D	UA2	$W \to e^*\nu$; $\lambda_W > 0.2$
>40	95	[56] ANSARI	87D	UA2	$W \to e^*\nu$; $\lambda_W > 0.09$

[50] DERRICK 95B search for single e^* production via $e^*e\gamma$ coupling in ep collisions with the decays $e^* \to e\gamma$, eZ, νW. See their Fig. 13 for the exclusion plot in the $m_{e^*}-\lambda\gamma$ plane.
[51] ABT 93 search for single e^* production via $e^*e\gamma$ coupling in ep collisions with the decays $e^* \to e\gamma$, eZ, νW. See their Fig. 4 for exclusion plot in the $m_{e^*}-\lambda_\gamma$ plane.
[52] DERRICK 93B search for single e^* production via $e^*e\gamma$ coupling in ep collisions with the decays $e^* \to e\gamma$, eZ, νW. See their Fig. 3 for exclusion plot in the $m_{e^*}-\lambda_\gamma$ plane.
[53] Superseded by ADRIANI 93M.
[54] Superseded by DECAMP 92.
[55] ABE 88B limits use $e^+e^- \to ee^*$ where t-channel photon exchange dominates giving $e\gamma(e)$ (quasi-real compton scattering).
[56] ANSARI 87D is at E_{cm} = 546–630 GeV.

Limits for Excited e (e^*) from $e^+e^- \to \gamma\gamma$

These limits are derived from indirect effects due to e^* exchange in the t channel and depend on transition magnetic coupling between e and e^*. All limits are for $\lambda_\gamma = 1$. All limits except ABE 89J are for nonchiral coupling with $\eta_L = \eta_R = 1$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45,** 1 June, Part II (1992)).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>146	95	ACCIARRI	95G	L3	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[57] BUSKULIC	93Q	ALEP	
>127	95	[58] ADRIANI	92B	L3	
>114	95	[59] BARDADIN-...	92	RVUE	
> 99	95	DECAMP	92	ALEP	
		[60] SHIMOZAWA	92	TOPZ	
>100	95	ABREU	91E	DLPH	
>116	95	AKRAWY	91F	OPAL	
> 83	95	ADEVA	90K	L3	
> 82	95	AKRAWY	90F	OPAL	
> 68	95	[61] ABE	89J	VNS	η_L=1, η_R=0
> 90.2	95	ADACHI	89B	TOPZ	
> 65	95	KIM	89	AMY	

[57] BUSKULIC 93Q obtain Λ^+ >121 GeV (95%CL) from ALEPH experiment and Λ^+ >135 GeV from combined TRISTAN and ALEPH data. These limits roughly correspond to limits on m_{e^*}.
[58] ADRIANI 92B superseded by ACCIARRI 95G.
[59] BARDADIN-OTWINOWSKA 92 limit from fit to the combined data of DECAMP 92, ABREU 91E, ADEVA 90K, AKRAWY 91F.
[60] SHIMOZAWA 92 fit the data to the limiting form of the cross section with $m_{e^*} \gg E_{cm}$ and obtain m_{e^*} >168 GeV at 95%CL. Use of the full form would reduce this limit by a few GeV. The statistically unexpected large value is due to fluctuation in the data.
[61] The ABE 89J limit assumes chiral coupling. This corresponds to $\lambda_\gamma = 0.7$ for nonchiral coupling.

Indirect Limits for Excited e (e^*)

These limits make use of loop effects involving e^* and are therefore subject to theoretical uncertainty.

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[62] DORENBOS...	89	CHRM	$\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ and $\nu_\mu e \to \nu_\mu e$
	[63] GRIFOLS	86	THEO	$\nu_\mu e \to \nu_\mu e$
	[64] RENARD	82	THEO	$g-2$ of electron

[62] DORENBOSCH 89 obtain the limit $\lambda_\gamma^2 \Lambda_{cut}^2 / m_{e^*}^2 < 2.6$ (95% CL), where Λ_{cut} is the cutoff scale, based on the one-loop calculation by GRIFOLS 86. If one assumes that Λ_{cut} = 1 TeV and $\lambda_\gamma = 1$, one obtains m_{e^*} > 620 GeV. However, one generally expects $\lambda_\gamma \approx m_{e^*}/\Lambda_{cut}$ in composite models.
[63] GRIFOLS 86 uses $\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ data from CHARM Collaboration to derive mass limits which depend on the scale of compositeness.
[64] RENARD 82 derived from $g-2$ data limits on mass and couplings of e^* and μ^*. See figures 2 and 3 of the paper.

MASS LIMITS for Excited μ (μ^*)

Limits for Excited μ (μ^*) from Pair Production

These limits are obtained from $e^+e^- \to \mu^{*+}\mu^{*-}$ and thus rely only on the (electroweak) charge of μ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the μ^* coupling is assumed to be of sequential type. All limits assume $\mu^* \to \mu\gamma$ decay except for the limits from $\Gamma(Z)$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45,** 1 June, Part II (1992)).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>45.6	95	ADRIANI	93M	L3	$Z \to \mu^*\mu^*$
>45.6	95	ABREU	92C	DLPH	$Z \to \mu^*\mu^*$
>46.1	95	DECAMP	92	ALEP	$Z \to \mu^*\mu^*$
>44.9	95	AKRAWY	90I	OPAL	$Z \to \mu^*\mu^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>29.8	95	[65] BARDADIN-...	92	RVUE	$\Gamma(Z)$
>26.1	95	[66] DECAMP	92	ALEP	$Z \to \mu^*\mu^*$; $\Gamma(Z)$
>33	95	[66] ABREU	91F	DLPH	$Z \to \mu^*\mu^*$; $\Gamma(Z)$
>45.3	95	[67] ADEVA	90F	L3	$Z \to \mu^*\mu^*$
>44.6	95	[68] DECAMP	90G	ALEP	$e^+e^- \to \mu^*\mu^*$
>29.9	95	ADACHI	89B	TOPZ	$e^+e^- \to \mu^*\mu^*$
>28.3	95	KIM	89	AMY	$e^+e^- \to \mu^*\mu^*$

[65] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)$<36 MeV.
[66] Limit is independent of μ^* decay mode.
[67] Superseded by ADRIANI 93M.
[68] Superseded by DECAMP 92.

Limits for Excited μ (μ^*) from Single Production

These limits are from $e^+e^- \rightarrow \mu^*\mu$ and depend on transition magnetic coupling between μ and μ^*. All limits assume $\mu^* \rightarrow \mu\gamma$ decay. Limits from LEP are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m_{\mu^*}$ plane. See the original papers.

For limits prior to 1987, see our 1992 edition (Physical Review **D45**, 1 June, Part II (1992)).

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>89	95	ADRIANI 93M	L3	$Z \rightarrow \mu\mu^*$, $\lambda_Z > 0.5$
>88	95	ABREU 92C	DLPH	$Z \rightarrow \mu\mu^*$, $\lambda_Z > 0.5$
>91	95	DECAMP 92	ALEP	$Z \rightarrow \mu\mu^*$, $\lambda_Z > 1$
>87	95	AKRAWY 90I	OPAL	$Z \rightarrow \mu\mu^*$, $\lambda_Z > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>85	95	[69] ADEVA 90F	L3	$Z \rightarrow \mu\mu^*$, $\lambda_Z > 1$
>75	95	[69] ADEVA 90F	L3	$Z \rightarrow \mu\mu^*$, $\lambda_Z > 0.1$
>80	95	[70] DECAMP 90G	ALEP	$e^+e^- \rightarrow \mu\mu^*$, $\lambda_Z = 1$
>50	95	ADACHI 89B	TOPZ	$e^+e^- \rightarrow \mu\mu^*$, $\lambda_\gamma = 0.7$
>46	95	KIM 89	AMY	$e^+e^- \rightarrow \mu\mu^*$, $\lambda_\gamma = 0.2$

[69] Superseded by ADRIANI 93M.
[70] Superseded by DECAMP 92.

Indirect Limits for Excited μ (μ^*)

These limits make use of loop effects involving μ^* and are therefore subject to theoretical uncertainty.

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[71] RENARD 82	THEO	$g-2$ of muon

[71] RENARD 82 derived from $g-2$ data limits on mass and couplings of e^* and μ^*. See figures 2 and 3 of the paper.

MASS LIMITS for Excited τ (τ^*)

Limits for Excited τ (τ^*) from Pair Production

These limits are obtained from $e^+e^- \rightarrow \tau^{*+}\tau^{*-}$ and thus rely only on the (electroweak) charge of τ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the τ^* coupling is assumed to be of sequential type. All limits assume $\tau^* \rightarrow \tau\gamma$ decay except for the limits from $\Gamma(Z)$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45**, 1 June, Part II (1992)).

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>45.6	95	ADRIANI 93M	L3	$Z \rightarrow \tau^*\tau^*$
>45.3	95	ABREU 92C	DLPH	$Z \rightarrow \tau^*\tau^*$
>46.0	95	DECAMP 92	ALEP	$Z \rightarrow \tau^*\tau^*$
>44.9	95	AKRAWY 90I	OPAL	$Z \rightarrow \tau^*\tau^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>29.8	95	[72] BARDADIN-... 92	RVUE	$\Gamma(Z)$
>26.1	95	[73] DECAMP 92	ALEP	$Z \rightarrow \tau^*\tau^*$; $\Gamma(Z)$
>33	95	[73] ABREU 91F	DLPH	$Z \rightarrow \tau^*\tau^*$; $\Gamma(Z)$
>45.5	95	[74] ADEVA 90L	L3	$Z \rightarrow \tau^*\tau^*$
>41.2	95	[75] DECAMP 90G	ALEP	$e^+e^- \rightarrow \tau^*\tau^*$
>29.0	95	ADACHI 89B	TOPZ	$e^+e^- \rightarrow \tau^*\tau^*$

[72] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)$<36 MeV.
[73] Limit is independent of τ^* decay mode.
[74] Superseded by ADRIANI 93M.
[75] Superseded by DECAMP 92.

Limits for Excited τ (τ^*) from Single Production

These limits are from $e^+e^- \rightarrow \tau^*\tau$ and depend on transition magnetic coupling between τ and τ^*. All limits assume $\tau^* \rightarrow \tau\gamma$ decay. Limits from LEP are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m_{\tau^*}$ plane. See the original papers.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>88	95	ADRIANI 93M	L3	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 0.5$
>87	95	ABREU 92C	DLPH	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 0.5$
>90	95	DECAMP 92	ALEP	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 0.18$
>86.5	95	AKRAWY 90I	OPAL	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>88	95	[76] ADEVA 90L	L3	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 1$
>59	95	[77] DECAMP 90G	ALEP	$Z \rightarrow \tau\tau^*$, $\lambda_Z = 1$
>40	95	[78] BARTEL 86	JADE	$e^+e^- \rightarrow \tau\tau^*$, $\lambda_\gamma = 1$
>41.4	95	[79] BEHREND 86	CELL	$e^+e^- \rightarrow \tau\tau^*$, $\lambda_\gamma = 1$
>40.8	95	[79] BEHREND 86	CELL	$e^+e^- \rightarrow \tau\tau^*$, $\lambda_\gamma = 0.7$

[76] Superseded by ADRIANI 93M.
[77] Superseded by DECAMP 92.
[78] BARTEL 86 is at E_{cm} = 30–46.78 GeV.
[79] BEHREND 86 limit is at E_{cm} = 33–46.8 GeV.

MASS LIMITS for Excited Neutrino (ν^*)

Limits for Excited ν (ν^*) from Pair Production

These limits are obtained from $Z \rightarrow \nu^*\nu^*$ decay and thus rely only on the (electroweak) charge of ν^*. Form factor effects are ignored unless noted. The ν^* coupling is assumed to be of sequential type. Limits assume $\nu^* \rightarrow \nu\gamma$ decay except for the $\Gamma(Z)$ measurement which makes no assumption about decay mode.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>47	95	[80] DECAMP 92	ALEP	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>43.7	95	[81] BARDADIN-... 92	RVUE	$\Gamma(Z)$
>42.6	95	[82] DECAMP 92	ALEP	$\Gamma(Z)$
>35.4	95	[83,84] DECAMP 90O	ALEP	$\Gamma(Z)$
>46	95	[84,85] DECAMP 90O	ALEP	

[80] Limit is based on $B(Z \rightarrow \nu^*\overline{\nu}^*) \times B(\nu^* \rightarrow \nu\gamma)^2 < 5 \times 10^{-5}$ (95%CL) assuming Dirac ν^*, $B(\nu^* \rightarrow \nu\gamma) = 1$.
[81] BARDADIN-OTWINOWSKA 92 limit is for Dirac ν^*. Based on $\Delta\Gamma(Z)$<36 MeV. The limit is 36.4 GeV for Majorana ν^*, 45.4 GeV for homodoublet ν^*.
[82] Limit is for Dirac ν^*. The limit is 34.6 GeV for Majorana ν^*, 45.4 GeV for homodoublet ν^*.
[83] DECAMP 90O limit is from excess $\Delta\Gamma(Z) < 89$ MeV. The above value is for Dirac ν^*; 26.6 GeV for Majorana ν^*; 44.8 GeV for homodoublet ν^*.
[84] Superseded by DECAMP 92.
[85] DECAMP 90O limit based on $B(Z \rightarrow \nu^*\nu^*) \cdot B(\nu^* \rightarrow \nu\gamma)^2 < 7 \times 10^{-5}$ (95%CL), assuming Dirac ν^*, $B(\nu^* \rightarrow \nu\gamma) = 1$.

Limits for Excited ν (ν^*) from Single Production

These limits are from $Z \rightarrow \nu\nu^*$ or $ep \rightarrow \nu^*X$ and depend on transition magnetic coupling between ν/e and ν^*. Assumptions about ν^* decay mode are given in footnotes.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>91	95	ADRIANI 93M	L3	$\lambda_Z > 1$, $\nu^* \rightarrow \nu\gamma$
>89	95	ADRIANI 93M	L3	$\lambda_Z > 1$, $\nu_e^* \rightarrow eW$
>91	95	[86] DECAMP 92	ALEP	$\lambda_Z > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[87] DERRICK 95B	ZEUS	$ep \rightarrow \nu^*X$
		[88] ABT 93	H1	$ep \rightarrow \nu^*X$
>87	95	ADRIANI 93M	L3	$\lambda_Z > 0.1$, $\nu^* \rightarrow \nu\gamma$
>74	95	ADRIANI 93M	L3	$\lambda_Z > 0.1$, $\nu_e^* \rightarrow eW$
		[89] BARDADIN-... 92	RVUE	
>74	95	[86] DECAMP 92	ALEP	$\lambda_Z > 0.034$
>91	95	[90,91] ADEVA 90O	L3	$\lambda_Z > 1$
>83	95	[91] ADEVA 90O	L3	$\lambda_Z > 0.1$, $\nu^* \rightarrow \nu\gamma$
>74	95	[91] ADEVA 90O	L3	$\lambda_Z > 0.1$, $\nu_e^* \rightarrow eW$
>90	95	[92,93] DECAMP 90O	ALEP	$\lambda_Z > 1$
>74.7	95	[92,93] DECAMP 90O	ALEP	$\lambda_Z > 0.06$

[86] DECAMP 92 limit is based on $B(Z \rightarrow \nu^*\overline{\nu}) \times B(\nu^* \rightarrow \nu\gamma) < 2.7 \times 10^{-5}$ (95%CL) assuming Dirac ν^*, $B(\nu^* \rightarrow \nu\gamma) = 1$.
[87] DERRICK 95B search for single ν^* production via ν^*eW coupling in ep collisions with the decays $\nu^* \rightarrow \nu\gamma$, νZ, eW. See their Fig. 14 for the exclusion plot in the $m_{\nu^*} - \lambda\gamma$ plane.
[88] ABT 93 search for single ν^* production via ν^*eW coupling in ep collisions with the decays $\nu^* \rightarrow \nu\gamma$, νZ, eW. See their Fig. 4 for exclusion plot in the $m_{\nu^*} - \lambda_W$ plane.
[89] See Fig. 5 of BARDADIN-OTWINOWSKA 92 for combined limit of ADEVA 90O, DECAMP 90O, and DECAMP 92.
[90] Limit is either for $\nu^* \rightarrow \nu\gamma$ or $\nu^* \rightarrow eW$.
[91] Superseded by ADRIANI 93M.
[92] DECAMP 90O limit based on $B(Z \rightarrow \nu\nu^*) \cdot B(\nu^* \rightarrow \nu\gamma) < 6 \times 10^{-5}$ (95%CL), assuming $B(\nu^* \rightarrow \nu\gamma) = 1$.
[93] Superseded by DECAMP 92.

MASS LIMITS for Excited q (q^*)

Limits for Excited q (q^*) from Pair Production

These limits are obtained from $e^+e^- \rightarrow q^*\overline{q}^*$ and thus rely only on the (electroweak) charge of the q^*. Form factor effects are ignored unless noted. Assumptions about the q^* decay are given in the comments and footnotes.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>45.6	95	[94] ADRIANI 93M	L3	u or d type, $Z \rightarrow q^*q^*$
>45	95	[95] DECAMP 92	ALEP	u or d type, $Z \rightarrow q^*q^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[96] ADRIANI 92F	L3	$Z \rightarrow q^*q^*$
>41.7	95	[97] BARDADIN-... 92	RVUE	u-type, $\Gamma(Z)$
>44.7	95	[97] BARDADIN-... 92	RVUE	d-type, $\Gamma(Z)$
>40.6	95	[98] DECAMP 92	ALEP	u-type, $\Gamma(Z)$
>44.2	95	[98] DECAMP 92	ALEP	d-type, $\Gamma(Z)$
>45	95	[98] ABREU 91F	DLPH	u-type, $\Gamma(Z)$
>45	95	[98] ABREU 91F	DLPH	d-type, $\Gamma(Z)$
>21.1	95	[99] BEHREND 86C	CELL	$e(q^*) = -1/3$, $q^* \rightarrow qg$
>22.3	95	[99] BEHREND 86C	CELL	$e(q^*) = 2/3$, $q^* \rightarrow qg$
>22.5	95	[99] BEHREND 86C	CELL	$e(q^*) = -1/3$, $q^* \rightarrow q\gamma$
>23.2	95	[99] BEHREND 86C	CELL	$e(q^*) = 2/3$, $q^* \rightarrow q\gamma$

[94] ADRIANI 93M limit is valid for $B(q^* \to qg) > 0.25$ (0.17) for up (down) type.

[95] Limit is for $B(q^* \to qg)+B(q^* \to q\gamma)=1$.

[96] ADRIANI 92F search for $Z \to q^* \overline{q}^*$ followed with $q^* \to q\gamma$ decays and give the limit $\sigma_Z \cdot B(Z \to q^* \overline{q}^*) \cdot B^2(q^* \to q\gamma) < 2$ pb at 95%CL. Assuming five flavors of degenerate q^* of homodoublet type, $B(q^* \to q\gamma) < 4\%$ is obtained for $m_{q^*} < 45$ GeV.

[97] BARDADIN-OTWINOWSKA 92 limit based on $\Delta\Gamma(Z) < 36$ MeV.

[98] These limits are independent of decay modes.

[99] BEHREND 86C search for $e^+e^- \to q^* \overline{q}^*$ for $m_{q^*} > 5$ GeV. But $m < 5$ GeV excluded by total hadronic cross section. The limits are for point-like photon couplings of excited quarks.

Limits for Excited q (q^*) from Single Production

These limits are from $e^+e^- \to q^* \overline{q}$ or $p\overline{p} \to q^* X$ and depend on transition magnetic couplings between q and q^*. Assumptions about q^* decay mode are given in the footnotes and comments.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>570 (CL = 95%) OUR EVALUATION					
none 80–570	95	[100] ABE	95N	CDF	$p\overline{p} \to q^* X$, $q^* \to qg$, $q\gamma$, qW
>288	90	[101] ALITTI	93	UA2	$p\overline{p} \to q^* X$, $q^* \to qg$
> 88	95	[102] DECAMP	92	ALEP	$Z \to qq^*$, $\lambda_Z > 1$
> 86	95	[102] AKRAWY	90J	OPAL	$Z \to qq^*$, $\lambda_Z > 1.2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[103] DERRICK	95B	ZEUS	$ep \to q^* X$
none 80–540	95	[104] ABE	94	CDF	$p\overline{p} \to q^* X$, $q^* \to q\gamma$, qW
> 79	95	[105] ADRIANI	93M	L3	λ_Z(L3)> 0.06
		[106] ABREU	92D	DLPH	$Z \to qq^*$
		[107] ADRIANI	92F	L3	$Z \to qq^*$
> 75	95	[105] DECAMP	92	ALEP	$Z \to qq^*$, $\lambda_Z > 1$
		[108] ALBAJAR	89	UA1	$p\overline{p} \to q^* X$, $q^* \to qW$
> 39	95	[109] BEHREND	86C	CELL	$e^+e^- \to q^* \overline{q}$ ($q^* \to qg, q\gamma$), $\lambda_\gamma=1$

[100] ABE 95N assume a degenerate u^* and d^* with $f_s=f=f'=\Lambda/m_{q^*}$. See their Fig. 4 for the excluded region in $m_{q^*} - f$ plane.

[101] ALITTI 93 search for resonances in the two-jet invariant mass. The limit is for $f_s = f = f' = \Lambda/m_{q^*}$. u^* and d^* are assumed to be degenerate. If not, the limit for u^* (d^*) is 277 (247) GeV if $m_{d^*} \gg m_{u^*}$ ($m_{u^*} \gg m_{d^*}$).

[102] Assumes $B(q^* \to q\gamma) = 0.1$.

[103] DERRICK 95B search for single q^* production via $q^* q\gamma$ coupling in ep collisions with the decays $q^* \to qW$, qZ, qg, $q\gamma$. See their Fig. 15 for the exclusion plot in the $m_{q^*}-\lambda\gamma$ plane.

[104] ABE 94 search for resonances in jet-γ and jet-W invariant mass in $p\overline{p}$ collisions at $E_{cm} = 1.8$ TeV. The limit is for $f_s = f = f' = \Lambda/m_{q^*}$ and u^* and d^* are assumed to be degenerate. See their Fig. 4 for the excluded region in m_{q^*}-f plane.

[105] Assumes $B(q^* \to qg) = 1$.

[106] ABREU 92D give $\sigma(e^+e^- \to Z \to q^* \overline{q}$ or $q\overline{q}^*) \times B(q^* \to q\gamma) < 15$ pb (95% CL) for $m_{q^*} < 80$ GeV.

[107] ADRIANI 92F search for $Z \to qq^*$ with $q^* \to q\gamma$ and give the limit $\sigma_Z \cdot B(Z \to qq^*) \cdot B(q^* \to q\gamma) <$ (2–10) pb (95%CL) for $m_{q^*} =$ (46–82) GeV.

[108] ALBAJAR 89 give $\sigma(q^* \to W + \text{jet})/\sigma(W) < 0.019$ (90% CL) for $m_{q^*} > 220$ GeV.

[109] BEHREND 86C has $E_{cm} = 42.5$–46.8 GeV. See their Fig. 3 for excluded region in the $m_{q^*}-(\lambda_\gamma/m_{q^*})^2$ plane. The limit is for $\lambda_\gamma = 1$ with $\eta_L = \eta_R = 1$.

MASS LIMITS for Color Sextet Quarks (q_6)

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>84	95	[110] ABE	89D	CDF	$p\overline{p} \to q_6 \overline{q}_6$

[110] ABE 89D look for pair production of unit-charged particles which leave the detector before decaying. In the above limit the color sextet quark is assumed to fragment into a unit-charged or neutral hadron with equal probability and to have long enough lifetime not to decay within the detector. A limit of 121 GeV is obtained for a color decuplet.

MASS LIMITS for Color Octet Charged Leptons (ℓ_8)

$\lambda \equiv m_{\ell_8}/\Lambda$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>86	95	[111] ABE	89D	CDF	Stable ℓ_8: $p\overline{p} \to \ell_8 \overline{\ell}_8$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[112] ABT	93	H1	e_8: $ep \to e_8 X$
none 3.0–30.3	95	[113] KIM	90	AMY	e_8: $e^+e^- \to ee$ + jets
none 3.5–30.3	95	[113] KIM	90	AMY	μ_8: $e^+e^- \to \mu\mu$ + jets
		[114] KIM	90	AMY	e_8: $e^+e^- \to gg$; R
>19.8	95	[115] BARTEL	87B	JADE	e_8, μ_8, τ_8: e^+e^-; R
none 5–23.2	95	[115] BARTEL	87B	JADE	μ_8: $e^+e^- \to \mu\mu$ + jets
		[116] BARTEL	85K	JADE	e_8: $e^+e^- \to gg$; R

[111] ABE 89D look for pair production of unit-charged particles which leave the detector before decaying. In the above limit the color octet lepton is assumed to fragment into a unit-charged or neutral hadron with equal probability and to have long enough lifetime not to decay within the detector. The limit improves to 99 GeV if it always fragments into a unit-charged hadron.

[112] ABT 93 search for e_8 production via e-gluon fusion in ep collisions with $e_8 \to eg$. See their Fig. 3 for exclusion plot in the m_{e_8}–Λ plane for $m_{e_8} = 35$–220 GeV.

[113] KIM 90 is at $E_{cm} = 50$–60.8 GeV. The same assumptions as in BARTEL 87B are used.

[114] KIM 90 result $(m_{e_8}\Lambda_M)^{1/2} > 178.4$ GeV (95%CL, $\alpha_s = 0.16$ used) is subject to the same restriction as for BARTEL 85K.

[115] BARTEL 87B is at $E_{cm} = 46.3$–46.78 GeV. The limits assume ℓ_8 pair production cross sections to be eight times larger than those of the corresponding heavy lepton pair production.

[116] In BARTEL 85K, R can be affected by $e^+e^- \to gg$ via e_q exchange. Their limit $m_{e_8} > 173$ GeV (CL=95%) at $\lambda = m_{e_8}/\Lambda_M = 1$ ($\eta_L = \eta_R = 1$) is not listed above because the cross section is sensitive to the product $\eta_L\eta_R$, which should be absent in ordinary theory with electronic chiral invariance.

MASS LIMITS for Color Octet Neutrinos (ν_8)

$\lambda \equiv m_{\ell_8}/\Lambda$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>110	90	[117] BARGER	89	RVUE	ν_8: $p\overline{p} \to \nu_8 \overline{\nu}_8$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 3.8–29.8	95	[118] KIM	90	AMY	ν_8: $e^+e^- \to$ acoplanar jets
none 9–21.9	95	[119] BARTEL	87B	JADE	ν_8: $e^+e^- \to$ acoplanar jets

[117] BARGER 89 used ABE 89B limit for events with large missing transverse momentum. Two-body decay $\nu_8 \to \nu g$ is assumed.

[118] KIM 90 is at $E_{cm} = 50$–60.8 GeV. The same assumptions as in BARTEL 87B are used.

[119] BARTEL 87B is at $E_{cm} = 46.3$–46.78 GeV. The limit assumes the ν_8 pair production cross section to be eight times larger than that of the corresponding heavy neutrino pair production. This assumption is not valid in general for the weak couplings, and the limit can be sensitive to its $SU(2)_L \times U(1)_Y$ quantum numbers.

MASS LIMITS for W_8 (Color Octet W Boson)

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[120] ALBAJAR	89	UA1	$p\overline{p} \to W_8 X$, $W_8 \to Wg$

[120] ALBAJAR 89 give $\sigma(W_8 \to W + \text{jet})/\sigma(W) < 0.019$ (90% CL) for $m_{W_8} > 220$ GeV.

Limits on $ZZ\gamma$ Coupling

Limits are for the electric dipole transition form factor for $Z \to \gamma Z^*$ parametrized as $f(s') = \beta(s'/m_Z^2 - 1)$, where s' is the virtual Z mass. In the Standard Model $\beta \sim 10^{-5}$.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.80	95	ADRIANI	92J	L3	$Z \to \gamma\nu\overline{\nu}$

REFERENCES FOR Searches for Quark and Lepton Compositeness

ABE	96	PRL (submitted)	+Akimoto, Akopian, Albrow+	(CDF Collab.)
CDF/ANAL/JET/CDFR/2995				
ABE	95N	PRL 74 3538	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ACCIARRI	95G	PL B353 136	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
AID	95	PL B353 578	+Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
DERRICK	95B	ZPHY C65 627	+Krakauer, Magill, Musgrave, Repond+	(ZEUS Collab.)
ABE	94	PRL 72 3004	+Albrow, Amidei, Anway-Wiese, Apollinari+	(CDF Collab.)
DIAZCRUZ	94	PR D49 R2149	Diaz Cruz, Sampayo	(CINV)
VELISSARIS	94	PL B331 227	+Lusin, Chung, Park, Cho, Bodek, Kim+	(AMY Collab.)
ABE	93G	PRL 71 2542	+Albrow, Akimoto, Amidei, Anway-Wiese+	(CDF Collab.)
ABT	93	NP B396 3	+Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ALITTI	93	NP B400 3	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
BUSKULIC	93Q	ZPHY C59 215	+Decamp, Goy, Lees, Minard, Mours+	(ALEPH Collab.)
DERRICK	93B	PL B316 207	+Krakauer, Magill, Musgrave, Repond+	(ZEUS Collab.)
ABE	92B	PRL 68 1463	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	92D	PRL 68 1104	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	92M	PRL 69 2896	+Amidei, Anway-Wiese, Apollinari, Atac+	(CDF Collab.)
ABREU	92C	ZPHY C53 41	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ABREU	92D	ZPHY C53 555	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ADRIANI	92B	PL B288 404	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
ADRIANI	92F	PL B292 472	+Aguilar-Benitez, Ahlen, Akbari, Alcarez+	(L3 Collab.)
ADRIANI	92J	PL B297 469	+Aguilar-Benitez, Ahlen, Alcarez, Aloisio+	(L3 Collab.)
BARDADIN-...	92	ZPHY C55 163	Bardadin-Otwinowska	(CLER)
DECAMP	92	PRPL 216 253	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
HOWELL	92	PL B291 206	+Koltick, Tauchi, Miyamoto, Kichimi+	(TOPAZ Collab.)
KROHA	92	PR D46 58		(ROCH)
PDG	92	PR D45, 1 June, Part II	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
SHIMOZAWA	92	PL B284 144	+Fujimoto, Abe, Adachi, Doser+	(TOPAZ Collab.)
ABE	91D	PRL 67 2418	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	91E	PL B268 296	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ABREU	91F	NP B367 511	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ADACHI	91	PL B255 613	+Anazawa, Doser, Enomoto+	(TOPAZ Collab.)
AKRAWY	91F	PL B257 531	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALITTI	91B	PL B257 232	+Ansari, Autiero, Bareyre, Blaylock+	(UA2 Collab.)
BEHREND	91B	ZPHY C51 143	+Criegee, Field, Franke, Jung+	(CELLO Collab.)
BEHREND	91C	ZPHY C51 149	+Criegee, Field, Franke, Jung, Meyer+	(CELLO Collab.)
Also	91B	ZPHY C51 143	Behrend, Criegee, Field, Franke, Jung+	(CELLO Collab.)
ABE	90I	ZPHY C48 13	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ADEVA	90F	PL B247 177	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90K	PL B250 199	+Adriani, Aguilar-Benitez, Akbari, Alcarez+	(L3 Collab.)
ADEVA	90L	PL B250 205	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90O	PL B252 525	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	90F	PL B241 133	+Alexander, Allison, Allport+	(OPAL Collab.)

AKRAWY 90I PL B244 135 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
AKRAWY 90J PL B246 285 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
DECAMP 90G PL B236 501 +Deschizeaux, Lees, Minard+ (ALEPH Collab.)
DECAMP 90O PL B250 172 +Deschizeaux, Goy, Lees+ (ALEPH Collab.)
KIM 90 PL B240 243 +Breedon, Ko, Lander, Maeshima, Malchow+(AMY Collab.)
ABE 89 PRL 62 613 +Amidei, Apollinari, Ascori, Atac+ (CDF Collab.)
ABE 89B PRL 62 1825 +Amidei, Apollinari, Ascoli, Atac+ (CDF Collab.)
ABE 89D PRL 63 1447 +Amidei, Apollinari, Ascoli, Atac+ (CDF Collab.)
ABE 89H PRL 62 3020 +Amidei, Apollinari, Ascoli, Atac+ (CDF Collab.)
ABE 89J ZPHY C45 175 +Amako, Arai, Fukawa+ (VENUS Collab.)
ABE 89L PL B232 425 +Amako, Arai, Asano, Chiba+ (VENUS Collab.)
ADACHI 89B PL B228 553 +Aihara, Doser, Enomoto, Fujii+ (TOPAZ Collab.)
ALBAJAR 89 ZPHY C44 15 +Albrow, Allkofer, Arnison, Astbury+ (UA1 Collab.)
BARGER 89 PL B220 464 +Hagiwara, Han, Zeppenfeld (WISC, KEK)
BEHREND 89B PL B222 163 +Criegee, Dainton, Field, Franke+ (CELLO Collab.)
BRAUNSCH... 89C ZPHY C43 549 Braunschweig, Gerhards, Kirschfink+ (TASSO Collab.)
DORENBOS... 89 ZPHY C41 567 Dorenbosch, Udo, Allaby, Amaldi+ (CHARM Collab.)
HAGIWARA 89 PL B219 369 +Sakuda, Terunuma (KEK, DURH, HIRO)
KIM 89 PL B223 476 +Kim, Kang, Lee, Myung, Bacala (AMY Collab.)
ABE 88B PL B213 400 +Amako, Arai, Asano, Chiba, Chiba+ (VENUS Collab.)
BARINGER 88 PL B206 551 +Bylsma, De Bonte, Koltick, Low+ (HRS Collab.)
BRAUNSCH... 88 ZPHY C37 171 Braunschweig, Gerhards+ (TASSO Collab.)
BRAUNSCH... 88D ZPHY C40 163 Braunschweig, Gerhards, Kirschfink+ (TASSO Collab.)
ANSARI 87D PL B195 613 +Bagnaia, Banner+ (UA2 Collab.)
BARTEL 87B ZPHY C36 15 +Becker, Felst+ (JADE Collab.)
BEHREND 87C PL B191 209 +Buerger, Criegee, Dainton+ (CELLO Collab.)
FERNANDEZ 87B PR D35 10 +Ford, Qi, Read, Smith, Camporesi+ (MAC Collab.)
ARNISON 86C PL B172 461 +Albrow, Allkofer+ (UA1 Collab.)
ARNISON 86D PL B177 244 +Albajar, Albrow+ (UA1 Collab.)
BARTEL 86 ZPHY C31 359 +Becker, Felst, Haidt+ (JADE Collab.)
BARTEL 86C ZPHY C30 371 +Becker, Cords, Felst, Haidt+ (JADE Collab.)
BEHREND 86 PL 168B 420 +Buerger, Criegee, Fenner+ (CELLO Collab.)
BEHREND 86C PL B181 178 +Buerger, Criegee, Dainton+ (CELLO Collab.)
DERRICK 86 PL 166B 463 +Gan, Kooijman, Loos+ (HRS Collab.)
Also 86B PR D34 3286 Derrick, Gan, Kooijman, Loos, Musgrave+ (HRS Collab.)
DERRICK 86B PR D34 3286 +Gan, Kooijman, Loos, Musgrave+ (HRS Collab.)
GRIFOLS 86 PL 168B 264 +Peris (BARC)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
APPEL 85 PL 160B 349 +Bagnaia, Banner+ (UA2 Collab.)
BARTEL 85K PL 160B 337 +Becker, Cords, Eichler+ (JADE Collab.)
BERGER 85 ZPHY C28 1 +Genzel, Lackas, Pielorz+ (PLUTO Collab.)
BERGER 85B ZPHY C27 341 +Deuter, Genzel, Lackas, Pielorz+ (PLUTO Collab.)
BAGNAIA 84C PL 138B 430 +Banner, Battiston+ (UA2 Collab.)
BARTEL 84D PL 146B 437 +Becker, Bowdery, Cords+ (JADE Collab.)
BARTEL 84E PL 146B 121 +Becker, Bowdery, Cords, Felst+ (JADE Collab.)
EICHTEN 84 RMP 56 579 +Hinchliffe, Lane, Quigg (FNAL, LBL, OSU)
ALTHOFF 83C PL 126B 493 +Fischer, Burkhardt+ (TASSO Collab.)
RENARD 82 PL 116B 264 (CERN)

Other Particle Searches

OMITTED FROM SUMMARY TABLE

OTHER PARTICLE SEARCHES

We collect here those searches which do not appear in any of the above search categories. These are listed in the following order:

1. Concentration of stable particles in matter
2. Galactic WIMP (weakly-interacting massive particle) searches
3. Limits on neutral particle production at accelerators
4. Limits on jet-jet resonance in hadron collisions
5. Limits on charged particles in e^+e^- collisions
6. Limits on charged particles in hadron reactions
7. Limits on charged particles in cosmic rays

Note that searches appear in separate sections elsewhere for Higgs bosons (and technipions), other heavy bosons (including W_R, W', Z', leptoquarks, axigluons), axions (including pseudo-Goldstone bosons, Majorons, familons), heavy leptons, heavy neutrinos, free quarks, monopoles, supersymmetric particles, and compositeness. We include specific WIMP searches in the appropriate sections when they yield limits on hypothetical particles such as supersymmetric particles, axions, massive neutrinos, monopoles, *etc.*

We omit papers on CHAMP's, millicharged particles, and other exotic particles. We no longer list for limits on tachyons and centauros. See our 1994 edition for these limits.

CONCENTRATION OF STABLE PARTICLES IN MATTER

Concentration of Heavy (Charge +1) Stable Particles in Matter

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-17}$	95	[1] YAMAGATA	93	SPEC	Deep sea water, m=5–1600m_p
$<6 \times 10^{-15}$	95	[2] VERKERK	92	SPEC	Water, $m = 10^5$ to 3×10^7 GeV
$<7 \times 10^{-15}$	95	[2] VERKERK	92	SPEC	Water, $m = 10^4$, 6×10^7 GeV
$<9 \times 10^{-15}$	95	[2] VERKERK	92	SPEC	Water, $m = 10^8$ GeV
$<3 \times 10^{-23}$	90	[3] HEMMICK	90	SPEC	Water, $m = 1000m_p$
$<2 \times 10^{-21}$	90	[3] HEMMICK	90	SPEC	Water, $m = 5000m_p$
$<3 \times 10^{-20}$	90	[3] HEMMICK	90	SPEC	Water, $m = 10000m_p$
$<1. \times 10^{-29}$		SMITH	82B	SPEC	Water, m=30–400m_p
$<2. \times 10^{-28}$		SMITH	82B	SPEC	Water, m=12–1000m_p
$<1. \times 10^{-14}$		SMITH	82B	SPEC	Water, m >1000 m_p
$<(0.2–1.) \times 10^{-21}$		SMITH	79	SPEC	Water, m=6–350 m_p

[1] YAMAGATA 93 used deep sea water at 4000 m since the concentration is enhanced in deep sea due to gravity.
[2] VERKERK 92 looked for heavy isotopes in sea water and put a bound on concentration of stable charged massive particle in sea water. The above bound can be translated into into a bound on charged dark matter particle (5×10^6 GeV), assuming the local density, ρ=0.3 GeV/cm^3, and the mean velocity $\langle v \rangle$=300 km/s.
[3] See HEMMICK 90 Fig. 7 for other masses 100–10000 m_p.

Concentration of Heavy (Charge −1) Stable Particles

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-20}$	90	[4] HEMMICK	90	SPEC	C, $M = 100m_p$
$<8 \times 10^{-20}$	90	[4] HEMMICK	90	SPEC	C, $M = 1000m_p$
$<2 \times 10^{-16}$	90	[4] HEMMICK	90	SPEC	C, $M = 10000m_p$
$<6 \times 10^{-13}$	90	[4] HEMMICK	90	SPEC	Li, $M = 1000m_p$
$<1 \times 10^{-11}$	90	[4] HEMMICK	90	SPEC	Be, $M = 1000m_p$
$<6 \times 10^{-14}$	90	[4] HEMMICK	90	SPEC	B, $M = 1000m_p$
$<4 \times 10^{-17}$	90	[4] HEMMICK	90	SPEC	O, $M = 1000m_p$
$<4 \times 10^{-15}$	90	[4] HEMMICK	90	SPEC	F, $M = 1000m_p$
$< 1.5 \times 10^{-13}$/nucleon	68	[5] NORMAN	89	SPEC	^{206}PbX^-
$< 1.2 \times 10^{-12}$/nucleon	68	[5] NORMAN	87	SPEC	^{56,58}FeX^-

[4] See HEMMICK 90 Fig. 7 for other masses 100–10000 m_p.
[5] Bound valid up to $m_{X^-} \sim$ 100 TeV.

GALACTIC WIMP SEARCHES

Cross-Section Limits for Dark Matter Particles (X^0) on Nuclei

These limits are for weakly-interacting stable particles which may constitute the invisible mass in the Galaxy with a local mass density of 0.3 GeV/cm^3. See each paper for assumptions on the velocity distribution. In the papers the limit is given as a function of the X^0 mass. Here we list limits only for typical mass values of 20 GeV, 100 GeV, and 1 TeV. Specific limits on supersymmetric dark matter particles may be found in the Supersymmetry section.

For m_{X^0} = 20 GeV

VALUE (nb)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.05	95	[6] GARCIA	95	CNTR	Natural Ge
< 0.1	95	QUENBY	95	CNTR	Na
<90	90	[7] SNOWDEN-...	95	MICA	^{16}O
$< 4 \times 10^3$	90	[7] SNOWDEN-...	95	MICA	^{39}K
< 0.7	90	BACCI	92	CNTR	Na
< 0.12	90	[8] REUSSER	91	CNTR	Natural Ge
< 0.06	95	CALDWELL	88	CNTR	Natural Ge

[6] GARCIA 95 limit is from the event rate. A weaker limit is obtained from searches for diurnal and annual modulation.
[7] SNOWDEN-IFFT 95 look for recoil tracks in an ancient mica crystal. Similar limits are also given for ^{27}Al and ^{28}Si.
[8] REUSSER 91 limit here is changed from published (0.04) after reanalysis by authors. J.L. Vuilleumier, private communication, March 29, 1996.

For m_{X^0} = 100 GeV

VALUE (nb)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.35	95	[9] GARCIA	95	CNTR	Natural Ge
<0.6	95	QUENBY	95	CNTR	Na
<3	95	QUENBY	95	CNTR	I
$<1.5 \times 10^2$	90	[10] SNOWDEN-...	95	MICA	^{16}O
$<4 \times 10^2$	90	[10] SNOWDEN-...	95	MICA	^{39}K
<0.08	90	[11] BECK	94	CNTR	^{76}Ge
<2.5	90	BACCI	92	CNTR	Na
<3	90	BACCI	92	CNTR	I
<0.9	90	[12] REUSSER	91	CNTR	Natural Ge
<0.7	95	CALDWELL	88	CNTR	Natural Ge

[9] GARCIA 95 limit is from the event rate. A weaker limit is obtained from searches for diurnal and annual modulation.
[10] SNOWDEN-IFFT 95 look for recoil tracks in an ancient mica crystal. Similar limits are also given for ^{27}Al and ^{28}Si.
[11] BECK 94 uses enriched ^{76}Ge (86% purity).
[12] REUSSER 91 limit here is changed from published (0.3) after reanalysis by authors. J.L. Vuilleumier, private communication, March 29, 1996.

For $m_{\chi^0} = 1$ TeV

VALUE (nb)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 6	95	[13] GARCIA	95	CNTR	Natural Ge
< 8	95	QUENBY	95	CNTR	Na
<50	95	QUENBY	95	CNTR	I
< 7 × 10^2	90	[14] SNOWDEN-...	95	MICA	^{16}O
< 1 × 10^3	90	[14] SNOWDEN-...	95	MICA	^{39}K
< 0.8	90	[15] BECK	94	CNTR	^{76}Ge
<30	90	BACCI	92	CNTR	Na
<30	90	BACCI	92	CNTR	I
<15	90	[16] REUSSER	91	CNTR	Natural Ge
< 6	95	CALDWELL	88	CNTR	Natural Ge

[13] GARCIA 95 limit is from the event rate. A weaker limit is obtained from searches for diurnal and annual modulation.
[14] SNOWDEN-IFFT 95 look for recoil tracks in an ancient mica crystal. Similar limits are also given for ^{27}Al and ^{28}Si.
[15] BECK 94 uses enriched ^{76}Ge (86% purity).
[16] REUSSER 91 limit here is changed from published (5) after reanalysis by authors. J.L. Vuilleumier, private communication, March 29, 1996.

LIMITS ON NEUTRAL PARTICLE PRODUCTION

Heavy Particle Production Cross Section

VALUE (cm^2/N)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 10^{-36}–10^{-33}	90		[17] GALLAS	95	TOF	m= 0.5–20 GeV
<(4–0.3) × 10^{-31}	95		[18] AKESSON	91	CNTR	m = 0–5 GeV
<2 × 10^{-36}	90	0	[19] BADIER	86	BDMP	τ = (0.05–1.) × 10^{-8}s
<2.5 × 10^{-35}		0	[20] GUSTAFSON	76	CNTR	$\tau > 10^{-7}$ s

[17] GALLAS 95 limit is for a weakly interacting neutral particle produced in 800 GeV/c pN interactions decaying with a lifetime of 10^{-4}–10^{-8} s. See their Figs. 8 and 9. Similar limits are obtained for a stable particle with interaction cross section 10^{-29}–10^{-33} cm^2. See Fig. 10.
[18] AKESSON 91 limit is from weakly interacting neutral long-lived particles produced in pN reaction at 450 GeV/c performed at CERN SPS. Bourquin-Gaillard formula is used as the production model. The above limit is for $\tau > 10^{-7}$ s. For $\tau > 10^{-9}$ s, $\sigma < 10^{-30}$ cm^{-2}/nucleon is obtained.
[19] BADIER 86 looked for long-lived particles at 300 GeV π^- beam dump. The limit applies for nonstrongly interacting neutral or charged particles with mass >2 GeV. The limit applies for particle modes, $\mu^+\pi^-$, $\mu^+\mu^-$, $\pi^+\pi^-$X, $\pi^+\pi^-\pi^\pm$ etc. See their figure 5 for the contours of limits in the mass-τ plane for each mode.
[20] GUSTAFSON 76 is a 300 GeV FNAL experiment looking for heavy (m >2 GeV) long-lived neutral hadrons in the M4 neutral beam. The above typical value is for m = 3 GeV and assumes an interaction cross section of 1 mb. Values as a function of mass and interaction cross section are given in figure 2.

Production of New Penetrating Non-ν Like States in Beam Dump

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[21] LOSECCO	81	CALO	28 GeV protons

[21] No excess neutral-current events leads to σ(production) × σ(interaction)×acceptance < 2.26 × 10^{-71} cm^4/nucleon^2 (CL = 90%) for light neutrals. Acceptance depends on models (0.1 to 4. × 10^{-4}).

LIMITS ON JET-JET RESONANCES

Heavy Particle Production Cross Section in $p\overline{p}$

Limits are for a particle decaying to two hadronic jets.

Units(pb)	CL%	Mass(GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2603	95	200	[22] ABE	93G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2jets
< 44	95	400	[22] ABE	93G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2jets
< 7	95	600	[22] ABE	93G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2jets

[22] ABE 93G gives cross section times branching ratio into light (d, u, s, c, b) quarks for Γ = 0.02 M. Their Table II gives limits for M = 200–900 GeV and Γ = (0.02–0.2) M.

LIMITS ON CHARGED PARTICLES IN e^+e^-

Heavy Particle Production Cross Section in e^+e^-

Ratio to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ unless noted. See also entries in Free Quark Search and Magnetic Monopole Searches.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2 × 10^{-5}	95		[23] AKERS	95R	OPAL	Q=1, m= 5–45 GeV
<1 × 10^{-5}	95		[23] AKERS	95R	OPAL	Q=2, m= 5–45 GeV
<2 × 10^{-3}	90		[24] BUSKULIC	93C	ALEP	Q=1, m=32–72 GeV
<(10^{-2}–1)	95		[25] ADACHI	90C	TOPZ	Q = 1, m = 1–16, 18–27 GeV
<7 × 10^{-2}	90		[26] ADACHI	90E	TOPZ	Q = 1, m = 5–25 GeV
<1.6 × 10^{-2}	95	0	[27] KINOSHITA	82	PLAS	Q=3–180, m <14.5 GeV
<5.0 × 10^{-2}	90	0	[28] BARTEL	80	JADE	Q=(3,4,5)/3 2–12 GeV

[23] AKERS 95R is a CERN-LEP experiment with $W_{cm} \sim m_Z$. The limit is for the production of a stable particle in multihadron events normalized to $\sigma(e^+e^- \rightarrow$ hadrons). Constant phase space distribution is assumed. See their Fig. 3 for bounds for $Q = \pm2/3$, $\pm4/3$.
[24] BUSKULIC 93C is a CERN-LEP experiment with $W_{cm} = m_Z$. The limit is for a pair or single production of heavy particles with unusual ionization loss in TPC. See their Fig. 5 and Table 1.
[25] ADACHI 90C is a KEK-TRISTAN experiment with W_{cm} = 52–60 GeV. The limit is for pair production of a scalar or spin-1/2 particle. See Figs. 3 and 4.
[26] ADACHI 90E is KEK-TRISTAN experiment with W_{cm} = 52–61.4 GeV. The above limit is for inclusive production cross section normalized to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)\cdot\beta(3-\beta^2)/2$, where $\beta = (1 - 4m^2/W_{cm}^2)^{1/2}$. See the paper for the assumption about the production mechanism.
[27] KINOSHITA 82 is SLAC PEP experiment at W_{cm} = 29 GeV using lexan and ^{39}Cr plastic sheets sensitive to highly ionizing particles.
[28] BARTEL 80 is DESY-PETRA experiment with W_{cm} = 27–35 GeV. Above limit is for inclusive pair production and ranges between 1. × 10^{-1} and 1. × 10^{-2} depending on mass and production momentum distributions. (See their figures 9, 10, 11).

Branching Fraction of Z^0 to a Pair of Stable Charged Heavy Fermions

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<5 × 10^{-6}	95	[29] AKERS	95R	OPAL	m= 40.4–45.6 GeV
<1 × 10^{-3}	95	AKRAWY	90O	OPAL	m = 29–40 GeV

[29] AKERS 95R give the 95% CL limit $\sigma(X\overline{X})/\sigma(\mu\mu) < 1.8\times10^{-4}$ for the pair production of singly- or doubly-charged stable particles. The limit applies for the mass range 40.4–45.6 GeV for $X^\pm$ and < 45.6 GeV for $X^{\pm\pm}$. See the paper for bounds for $Q = \pm2/3$, $\pm4/3$.

LIMITS ON CHARGED PARTICLES IN HADRONIC REACTIONS

Heavy Particle Production Cross Section

VALUE (nb)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.05	95		[30] ABE	92J	CDF	m=50–200 GeV
<30–130			[31] CARROLL	78	SPEC	m=2–2.5 GeV
<100		0	[32] LEIPUNER	73	CNTR	m=3–11 GeV

[30] ABE 92J look for pair production of unit-charged particles which leave detector before decaying. Limit shown here is for m=50 GeV. See their Fig. 5 for different charges and stronger limits for higher mass.
[31] CARROLL 78 look for neutral, $S = -2$ dihyperon resonance in $pp \rightarrow 2K^+$X. Cross section varies within above limits over mass range and p_{lab} = 5.1–5.9 GeV/c.
[32] LEIPUNER 73 is an NAL 300 GeV p experiment. Would have detected particles with lifetime greater than 200 ns.

Heavy Particle Production Differential Cross Section

VALUE (cm^{2}sr^{-1}GeV^{-1})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<2.6 × 10^{-36}	90	0	[33] BALDIN	76	CNTR	−	Q= 1, m=2.1–9.4 GeV
<2.2 × 10^{-33}	90	0	[34] ALBROW	75	SPEC	±	Q= ±1, m=4–15 GeV
<1.1 × 10^{-33}	90	0	[34] ALBROW	75	SPEC	±	Q= ±2, m=6–27 GeV
<8. × 10^{-35}	90	0	[35] JOVANOV...	75	CNTR	±	m=15–26 GeV
<1.5 × 10^{-34}	90	0	[35] JOVANOV...	75	CNTR	±	Q= ±2, m=3–10 GeV
<6. × 10^{-35}	90	0	[35] JOVANOV...	75	CNTR	±	Q= ±2, m=10–26 GeV
<1. × 10^{-31}	90	0	[36] APPEL	74	CNTR	±	m=3.2–7.2 GeV
<5.8 × 10^{-34}	90	0	[37] ALPER	73	SPEC	±	m=1.5–24 GeV
<1.2 × 10^{-35}	90	0	[38] ANTIPOV	71B	CNTR	−	Q=−, m=2.2–2.8
<2.4 × 10^{-35}	90	0	[39] ANTIPOV	71C	CNTR	−	Q=−, m=1.2–1.7, 2.1–4
<2.4 × 10^{-35}	90	0	BINON	69	CNTR	−	Q=−, m=1–1.8 GeV
<1.5 × 10^{-36}		0	[40] DORFAN	65	CNTR		Be target m=3–7 GeV
<3.0 × 10^{-36}		0	[40] DORFAN	65	CNTR		Fe target m=3–7 GeV

[33] BALDIN 76 is a 70 GeV Serpukhov experiment. Value is per Al nucleus at θ = 0. For other charges in range −0.5 to −3.0, CL = 90% limit is (2.6 × 10^{-36})/|(charge)| for mass range (2.1–9.4 GeV) × |(charge)|. Assumes stable particle interacting with matter as do antiprotons.
[34] ALBROW 75 is a CERN ISR experiment with E_{cm} = 53 GeV. θ = 40 mr. See figure 5 for mass ranges up to 35 GeV.

[35] JOVANOVICH 75 is a CERN ISR 26+26 and 15+15 GeV pp experiment. Figure 4 covers ranges $Q = 1/3$ to 2 and m = 3 to 26 GeV. Value is per GeV momentum.
[36] APPEL 74 is NAL 300 GeV pW experiment. Studies forward production of heavy (up to 24 GeV) charged particles with momenta 24–200 GeV (−charge) and 40–150 GeV (+charge). Above typical value is for 75 GeV and is per GeV momentum per nucleon.
[37] ALPER 73 is CERN ISR 26+26 GeV pp experiment. p >0.9 GeV, $0.2 < \beta < 0.65$.
[38] ANTIPOV 71B is from same 70 GeV p experiment as ANTIPOV 71C and BINON 69.
[39] ANTIPOV 71C limit inferred from flux ratio. 70 GeV p experiment.
[40] DORFAN 65 is a 30 GeV/c p experiment at BNL. Units are per GeV momentum per nucleus.

Long-Lived Heavy Particle Invariant Cross Section

VALUE (cm^2/GeV^2/N)	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$< 5 \times 10^{-35}$–7×10^{-33}	90	0	[41] BERNSTEIN	88	CNTR		
$< 5 \times 10^{-37}$–7×10^{-35}	90	0	[41] BERNSTEIN	88	CNTR		
$<2.5 \times 10^{-36}$	90	0	[42] THRON	85	CNTR	−	Q= 1, m=4–12 GeV
$<1. \times 10^{-35}$	90	1	[42] THRON	85	CNTR	+	Q= 1, m=4–12 GeV
$<6. \times 10^{-33}$	90	0	[43] ARMITAGE	79	SPEC		m=1.87 GeV
$<1.5 \times 10^{-33}$	90	0	[43] ARMITAGE	79	SPEC		m=1.5–3.0 GeV
		0	[44] BOZZOLI	79	CNTR	±	Q = (2/3, 1, 4/3, 2)
$<1.1 \times 10^{-37}$	90	0	[45] CUTTS	78	CNTR		m=4–10 GeV
$<3.0 \times 10^{-37}$	90	0	[46] VIDAL	78	CNTR		m=4.5–6 GeV

[41] BERNSTEIN 88 limits apply at $x = 0.2$ and $p_T = 0$. Mass and lifetime dependence of limits are shown in the regions: m = 1.5–7.5 GeV and $\tau = 10^{-8}$–2×10^{-6} s. First number is for hadrons; second is for weakly interacting particles.
[42] THRON 85 is FNAL 400 GeV proton experiment. Mass determined from measured velocity and momentum. Limits are for $\tau > 3 \times 10^{-9}$ s.
[43] ARMITAGE 79 is CERN-ISR experiment at E_{cm} = 53 GeV. Value is for $x = 0.1$ and $p_T = 0.15$. Observed particles at m = 1.87 GeV are found all consistent with being antideuterons.
[44] BOZZOLI 79 is CERN-SPS 200 GeV pN experiment. Looks for particle with τ larger than 10^{-8} s. See their figure 11–18 for production cross-section upper limits vs mass.
[45] CUTTS 78 is pBe experiment at FNAL sensitive to particles of $\tau > 5 \times 10^{-8}$ s. Value is for $-0.3 < x < 0$ and $p_T = 0.175$.
[46] VIDAL 78 is FNAL 400 GeV proton experiment. Value is for $x = 0$ and $p_T = 0$. Puts lifetime limit of $< 5 \times 10^{-8}$ s on particle in this mass range.

Long-Lived Heavy Particle Production (σ(Heavy Particle) / $\sigma(\pi)$)

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<10^{-8}$		[47] NAKAMURA	89	SPEC	±	Q= (−5/3,±2)
	0	[48] BUSSIERE	80	CNTR	±	Q= (2/3,1,4/3,2)

[47] NAKAMURA 89 is KEK experiment with 12 GeV protons on Pt target. The limit applies for mass $\lesssim$ 1.6 GeV and lifetime $\gtrsim 10^{-7}$ s.
[48] BUSSIERE 80 is CERN-SPS experiment with 200–240 GeV protons on Be and Al target. See their figures 6 and 7 for cross-section ratio vs mass.

Production and Capture of Long-Lived Massive Particles

VALUE (10^{-36} cm^2)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<20 to 800	0	[49] ALEKSEEV	76	ELEC	τ=5 ms to 1 day
<200 to 2000	0	[49] ALEKSEEV	76B	ELEC	τ=100 ms to 1 day
<1.4 to 9	0	[50] FRANKEL	75	CNTR	τ=50 ms to 10 hours
<0.1 to 9	0	[51] FRANKEL	74	CNTR	τ=1 to 1000 hours

[49] ALEKSEEV 76 and ALEKSEEV 76B are 61–70 GeV p Serpukhov experiment. Cross section is per Pb nucleus.
[50] FRANKEL 75 is extension of FRANKEL 74.
[51] FRANKEL 74 looks for particles produced in thick Al targets by 300–400 GeV/c protons.

Long-Lived Particle Search at Hadron Collisions

Limits are for cross section times branching ratio.

VALUE (pb/nucleon)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2	90	0	[52] BADIER	86	BDMP	$\tau = (0.05$–$1.) \times 10^{-8}$s

[52] BADIER 86 looked for long-lived particles at 300 GeV π^- beam dump. The limit applies for nonstrongly interacting neutral or charged particles with mass >2 GeV. The limit applies for particle modes, $\mu^+\pi^-$, $\mu^+\mu^-$, $\pi^+\pi^-$X, $\pi^+\pi^-\pi^\pm$ etc. See their figure 5 for the contours of limits in the mass-τ plane for each mode.

Long-Lived Heavy Particle Cross Section

VALUE (pb/sr)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<34	95	[53] RAM	94	SPEC	$1015 < m_{X^{++}} < 1085$ MeV
<75	95	[53] RAM	94	SPEC	$920 < m_{X^{++}} < 1025$ MeV

[53] RAM 94 search for a long-lived doubly-charged fermion X^{++} with mass between m_N and $m_N + m_\pi$ and baryon number +1 in the reaction $pp \rightarrow X^{++} n$. No candidate is found. The limit is for the cross section at 15° scattering angle at 460 MeV incident energy and applies for $\tau(X^{++}) \gg 0.1\,\mu$s.

LIMITS ON CHARGED PARTICLES IN COSMIC RAYS

Heavy Particle Flux in Cosmic Rays

VALUE (cm^{-2}sr^{-1}s^{-1})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$\sim 6 \times 10^{-9}$		2	[54] SAITO	90			$Q \simeq 14$, $m \simeq 370 m_p$
$< 1.4 \times 10^{-12}$	90	0	[55] MINCER	85	CALO		$m \geq 1$ TeV
			[56] SAKUYAMA	83B	PLAS		$m \sim 1$ TeV
$< 1.7 \times 10^{-11}$	99	0	[57] BHAT	82	CC		
$< 1. \times 10^{-9}$	90	0	[58] MARINI	82	CNTR	±	Q= 1, $m \sim 4.5 m_p$
$2. \times 10^{-9}$		3	[59] YOCK	81	SPRK	±	Q= 1, $m \sim 4.5 m_p$
		3	[59] YOCK	81	SPRK		Fractionally charged
3.0×10^{-9}		3	[60] YOCK	80	SPRK		$m \sim 4.5\ m_p$
$(4 \pm 1) \times 10^{-11}$		3	GOODMAN	79	ELEC		$m \geq 5$ GeV
$< 1.3 \times 10^{-9}$	90		[61] BHAT	78	CNTR	±	m >1 GeV
$< 1.0 \times 10^{-9}$		0	BRIATORE	76	ELEC		
$< 7. \times 10^{-10}$	90	0	YOCK	75	ELEC	±	Q >7e or < −7e
$> 6. \times 10^{-9}$		5	[62] YOCK	74	CNTR		m >6 GeV
$< 3.0 \times 10^{-8}$		0	DARDO	72	CNTR		
$< 1.5 \times 10^{-9}$		0	TONWAR	72	CNTR		m >10 GeV
$< 3.0 \times 10^{-10}$		0	BJORNBOE	68	CNTR		m >5 GeV
$< 5.0 \times 10^{-11}$	90	0	JONES	67	ELEC		m=5–15 GeV

[54] SAITO 90 candidates carry about 450 MeV/nucleon. Cannot be accounted for by conventional backgrounds. Consistent with strange quark matter hypothesis.
[55] MINCER 85 is high statistics study of calorimeter signals delayed by 20–200 ns. Calibration with AGS beam shows they can be accounted for by rare fluctuations in signals from low-energy hadrons in the shower. Claim that previous delayed signals including BJORNBOE 68, DARDO 72, BHAT 82, SAKUYAMA 83B below may be due to this fake effect.
[56] SAKUYAMA 83B analyzed 6000 extended air shower events. Increase of delayed particles and change of lateral distribution above 10^{17} eV may indicate production of very heavy parent at top of atmosphere.
[57] BHAT 82 observed 12 events with delay $> 2. \times 10^{-8}$ s and with more than 40 particles. 1 eV has good hadron shower. However all events are delayed in only one of two detectors in cloud chamber, and could not be due to strongly interacting massive particle.
[58] MARINI 82 applied PEP-counter for TOF. Above limit is for velocity = 0.54 of light. Limit is inconsistent with YOCK 80 YOCK 81 events if isotropic dependence on zenith angle is assumed.
[59] YOCK 81 saw another 3 events with $Q = \pm 1$ and m about $4.5 m_p$ as well as 2 events with $m > 5.3 m_p$, $Q = \pm 0.75 \pm 0.05$ and $m > 2.8 m_p$, $Q = \pm 0.70 \pm 0.05$ and 1 event with $m = (9.3 \pm 3.) m_p$, $Q = \pm 0.89 \pm 0.06$ as possible heavy candidates.
[60] YOCK 80 events are with charge exactly or approximately equal to unity.
[61] BHAT 78 is at Kolar gold fields. Limit is for $\tau > 10^{-6}$ s.
[62] YOCK 74 events could be tritons.

Superheavy Particle (Quark Matter) Flux in Cosmic Rays

VALUE (cm^{-2}sr^{-1}s^{-1})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<1.8 \times 10^{-12}$	90		[63] ASTONE	93	CNTR	$m \geq 1.5 \times 10^{-13}$gram
$<1.1 \times 10^{-14}$	90		[64] AHLEN	92	MCRO	$10^{-10} < m < 0.1$ gram
$<3.2 \times 10^{-11}$	90	0	[65] NAKAMURA	85	CNTR	$m > 1.5 \times 10^{-13}$gram
$<3.5 \times 10^{-11}$	90	0	[66] ULLMAN	81	CNTR	Planck-mass 10^{19}GeV
$<7. \times 10^{-11}$	90	0	[66] ULLMAN	81	CNTR	$m \leq 10^{16}$ GeV

[63] ASTONE 93 searched for quark matter ("nuclearites") in the velocity/c range = 10^{-3}–1. Their Table 1 gives a compilation of searches for nuclearites.
[64] AHLEN 92 searched for quark matter ("nuclearites"). The bound applies to velocity/c $< 2.5 \times 10^{-3}$. See their Fig. 3 for other velocity/c and heavier mass range.
[65] NAKAMURA 85 at KEK searched for quark-matter. These might be lumps of strange quark matter with roughly equal numbers of u, d, s quarks. These lumps or nuclearites were assumed to have velocity/c of 10^{-4}–10^{-3}.
[66] ULLMAN 81 is sensitive for heavy slow singly charge particle reaching earth with vertical velocity 100–350 km/s.

Highly Ionizing Particle Flux

VALUE (m^{-2}yr^{-1})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.4	95	0	KINOSHITA	81B	PLAS	Z/β 30–100

REFERENCES FOR Other Particle Searches

AKERS 95R ZPHY C67 203 +Alexander, Allison, Ametewee, Anderson+ (OPAL Collab.)
GALLAS 95 PR D52 6 +Abolins, Brock, Cobau+ (MSU, FNAL, MIT, FLOR)
GARCIA 95 PR D51 1458 +Morales, Morales, Sarsa+ (ZARA, SCUC, PNL)
QUENBY 95 PL B351 70 +Sumner+ (LOIC, RAL, SHEF, BIRK, NOTT, RHBL)
SNOWDEN-... 95 PRL 74 4133 Snowden-Ifft, Freeman, Price (UCB)
BECK 94 PL B336 141 +Bensch, Bockholt+ (MPIH, KIAE, SASSO)
RAM 94 PR D49 3120 +Abegg, Ashery, Frekers, Helmer+ (TELA, TRIU)
ABE 93G PRL 71 2542 +Albrow, Akimoto, Amidei, Anway-Wiese+ (CDF Collab.)
ASTONE 93 PR D47 4770 +Bassan, Bonifazi, Coccia+(ROMA, ROMAI, CATA, FRAS)
BUSKULIC 93C PL B303 198 +Decamp, Goy, Lees, Minard+ (ALEPH Collab.)
YAMAGATA 93 PR D47 1231 +Takamori, Utsunomiya (KONAN)
ABE 92J PR D46 R1889 +Amidei, Anway-Weiss+ (CDF Collab.)
AHLEN 92 PRL 69 1860 +Ambrosio, Antolini, Auriemma, Baker+ (MACRO Collab.)
BACCI 92 PL B293 460 +Belli, Bernabei+ (Beijing-Roma-Saclay Collab.)
VERKERK 92 PRL 68 1116 +Grynberg, Pichard, Spiro, Zylberajch+(ENSP, SACL, PAST)
AKESSON 91 ZPHY C52 219 +Almehed, Angelis, Atherton, Aubry+ (HELIOS Collab.)
REUSSER 91 PL B255 143 +Treichel, Boehm, Broggini+ (NEUC, CIT, PSI)
ADACHI 90C PL B244 352 +Aihara, Doser, Enomoto+ (TOPAZ Collab.)
ADACHI 90E PL B249 336 +Anazawa, Doser, Enomoto, Fujii+ (TOPAZ Collab.)
AKRAWY 90O PL B252 290 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
HEMMICK 90 PR D41 2074 +Elmore+ (ROCH, MICH, OHIO, RAL, LANL, STON)
SAITO 90 PRL 65 2094 +Hatano, Fukada, Oda (ICRR, KOBE)
NAKAMURA 89 PR D39 1261 +Kobayashi, Konaka, Imai, Masaike+ (KYOT, TMTC)
NORMAN 89 PR D39 2499 +Chadwick, Lesko, Larimer, Hoffman (LBL)
BERNSTEIN 88 PR D37 3103 +Shea, Winstein, Cousins, Greenhalgh+ (STAN, WISC)
CALDWELL 88 PRL 61 510 +Eisberg, Grumm, Witherell+ (UCSB, UCB, LBL)
NORMAN 87 PRL 58 1403 +Gazes, Bennett (LBL)
BADIER 86 ZPHY C31 21 +Bemporad, Boucrot, Callot+ (NA3 Collab.)
MINCER 85 PR D32 541 +Freudenreich, Goodman+ (UMD, GMAS, NSF)
NAKAMURA 85 PL 161B 417 +Horie, Takahashi, Tanimori (KEK, INUS)
THRON 85 PR D31 451 +Cardello, Cooper, Teig+ (YALE, FNAL, IOWA)
SAKUYAMA 83B LNC 37 17 +Nuzuki (MEIS)
Also 83 LNC 36 389 Sakuyama, Watanabe (MEIS)
Also 83D NC 78A 147 Sakuyama, Watanabe (MEIS)
Also 83C NC 6C 371 Sakuyama, Watanabe (MEIS)
BHAT 82 PR D25 2820 +Gupta, Murthy, Sreekantan+ (TATA)
KINOSHITA 82 PRL 48 77 +Price, Fryberger (UCB, SLAC)
MARINI 82 PR D26 1777 +Peruzzi, Piccolo+ (FRAS, LBL, NWES, STAN, HAWA)
SMITH 82B NP B206 333 +Bennett, Homer, Lewin, Walford, Smith (RAL)
KINOSHITA 81B PR D24 1707 +Price (UCB)
LOSECCO 81 PL 102B 209 +Sulak, Galik, Horstkotte+ (MICH, PENN, BNL)
ULLMAN 81 PRL 47 289 (LEHM, BNL)
YOCK 81 PR D23 1207 (AUCK)
BARTEL 80 ZPHY C6 295 +Canzler, Lords, Drumm+ (JADE Collab.)
BUSSIERE 80 NP B174 1 +Giacomelli, Lesquoy+ (BGNA, SACL, LAPP)
YOCK 80 PR D22 61 (AUCK)
ARMITAGE 79 NP B150 87 +Benz, Bobbink+ (CERN, DARE, FOM, MCHS, UTRE)
BOZZOLI 79 NP B159 363 +Bussiere, Giacomelli+ (BGNA, LAPP, SACL, CERN)
GOODMAN 79 PR D19 2572 +Ellsworth, Ito, Macfall, Siohan+ (UMD)
SMITH 79 NP B149 525 +Bennett (RHEL)
BHAT 78 Pramana 10 115 +Murthy (TATA)
CARROLL 78 PRL 41 777 +Chiang, Johnson, Kycia, Ki+ (BNL, PRIN)
CUTTS 78 PRL 41 363 +Dulude+ (BROW, FNAL, ILL, BARI, MIT, WARS)
VIDAL 78 PL 77B 344 +Herb, Lederman+ (COLU, FNAL, STON, UCB)
ALEKSEEV 76 SJNP 22 531 +Zaitsev, Kalinina, Kruglov+ (JINR)
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ALEKSEEV 76B SJNP 23 633 +Zaitsev, Kalinina, Kruglov+ (JINR)
Translated from YAF 23 1190.
BALDIN 76 SJNP 22 264 +Vertogradov, Vishnevsky, Grishkevich+ (JINR)
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GUSTAFSON 76 PRL 37 474 +Ayre, Jones, Longo, Murthy (MICH)
ALBROW 75 NP B97 189 +Barber+ (CERN, DARE, FOM, LANC, MCHS, UTRE)
FRANKEL 75 PR D12 2561 +Frati, Resvanis, Yang, Nezrick (PENN, FNAL)
JOVANOV... 75 PL 56B 105 Jovanovich+ (MANI, AACH, CERN, GENO, HARV+)
YOCK 75 NP B86 216 (AUCK, SLAC)
APPEL 74 PRL 32 428 +Bourquin, Gaines, Lederman+ (COLU, FNAL)
FRANKEL 74 PR D9 1932 +Frati, Resvanis, Yang, Nezrick (PENN, FNAL)
YOCK 74 NP B76 175 (AUCK)
ALPER 73 PL 46B 265 + (CERN, LIVP, LUND, BOHR, RHEL, STOH, BERG+)
LEIPUNER 73 PRL 31 1226 +Larsen, Sessoms, Smith, Williams+ (BNL, YALE)
DARDO 72 NC 9A 319 +Navarra, Penengo, Sitte (TORI)
TONWAR 72 JPA 5 569 +Naranan, Sreekantan (TATA)
ANTIPOV 71B NP B31 235 +Denisov, Donskov, Gorin, Kachanov+ (SERP)
ANTIPOV 71C PL 34B 164 +Denisov, Donskov, Gorin, Kachanov+ (SERP)
BINON 69 PL 30B 510 +Duteil, Kachanov, Khromov, Kutyin+ (SERP)
BJORNBOE 68 NC B53 241 +Damgard, Hansen+ (BOHR, TATA, BERN, BERG)
JONES 67 PR 164 1584 (MICH, WISC, LBL, UCLA, MINN, COSU, COLO+)
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†In memoriam: Gary S. Wagman, 1954–1995