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 2000 new measurements from 610 papers, in addition to the 16,800 measurements from 4850 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 1999 (and, in some areas, well into 2000). 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

Particle Data Group, MS 50-308
Lawrence Berkeley National Laboratory
Berkeley, CA 94720, USA

or send e-mail to `PDG@LBL.GOV`.

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Switzerland

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(`http://www.cern.ch/library`)
`Publications`

2. Authors and consultants

The authors' main areas of responsibility are shown below:
* Asterisk indicates the person to contact with questions or comments

Gauge and Higgs bosons

γ	D.E. Groom*
Gluons	R.M. Barnett,* A.V. Manohar
Graviton	D.E. Groom*
W, Z	C. Caso,* A. Gurtu*
Higgs bosons	K. Hikasa, M.L. Mangano*
Heavy bosons	C. Kolda,* M. Tanabashi, T.G. Trippe*
Axions	M.L. Mangano,* H. Murayama, K.A. Olive

Leptons

Neutrinos	M. Goodman, D.E. Groom,* K. Nakamura, K.A. Olive, A. Piepke, P. Vogel
e, μ	C. Grab, D.E. Groom*
ν_τ, τ	D.E. Groom, K.G. Hayes, K. Mönig*

Quarks

Quarks	R.M. Barnett,* A.V. Manohar
Top quark	J.L. Feng, K. Hagiwara, T.G. Trippe*
b'	J.L. Feng, K. Hagiwara, T.G. Trippe*
Free quark	D.E. Groom*

Mesons

π, η	C. Grab, D.E. Groom,* C.G. Wohl
Unstable mesons	M. Aguilar-Benitez, C. Amsler, M. Doser,* S. Eidelman, J.J. Hernández, A. Masoni, S. Navas, M. Roos, N.A. Törnqvist
K (stable)	G. Conforto, T.G. Trippe*
D (stable)	P.R. Burchat, C.G. Wohl*
B (stable)	L. Gibbons, K. Honscheid, W.-M. Yao*

Baryons

Stable baryons	C. Grab, C.G. Wohl*
Unstable baryons	C.G. Wohl,* R.L. Workman
Charmed baryons	P.R. Burchat, C.G. Wohl*
Bottom baryons	L. Gibbons, K. Honscheid, W.-M. Yao*

Miscellaneous searches

Monopole	D.E. Groom*
Supersymmetry	M.L. Mangano,* H. Murayama, K.A. Olive, L. Pape
Technicolor	C. Kolda,* T.G. Trippe*
Compositeness	C.D. Carone, M. Tanabashi, T.G. Trippe*
WIMPs and Other	J.L. Feng, K. Hikasa, K.A. Olive, T.G. Trippe*

Reviews, tables, figures, and formulae

R.M. Barnett, D.E. Groom,* T.G. Trippe, C.G. Wohl, W.-M. Yao

Technical support

B. Armstrong,* J.L. Casas Serradilla, B.B. Filimonov,
P.S. Gee, S.B. Lugovsky, S. Mankov

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P. Bloch (CERN), Chair
A. Ali (DESY)
T. Kondo (KEK)
P. Kreitz (SLAC)
Z. Kunszt (ETH Zurich)
J. LoSecco (Notre Dame)

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- L. Addis (SLAC)
- S.I. Alekhin (COMPAS Group, IHEP, Serpukhov)
- A. Ali (DESY)
- J. Annala (Fermilab)
- T. Appelquist (Yale University)
- M. Artuso (Syracuse University)
- R. Bailey (CERN)
- E. Barberio (CERN)
- A.R. Barker (University of Colorado)
- T. Barnes (University of Tennessee)
- J.-L. Basdevant (University of Paris)
- M. Battaylia (University of Helsinki)
- M. Berg (University of Texas)
- E. Berger (ANL)
- S. Bethke (CERN)
- I.I. Bigi (Notre Dame University)
- S. Bilenky (Joint Inst. for Nuclear Research, Dubna)
- M. Billing (Cornell University)
- E. Blucher (University of Chicago)
- R.A. Briere (Harvard University)
- D. Bryman (TRIUMF)
- A. Buras (Tech. University of Munich)
- S.V. Burdin (Budker Inst. of Nuclear Physics)
- M. Carena (Fermilab)
- S. Catani (CERN)

- D. Chakraborty (SUNY, Stony Brook)
- M. Chanowitz (LBNL)
- M. Chertok (Texas A&M University)
- R. Clare (MIT)
- E.D. Commins (University of California, Berkeley)
- J. Conway (Rutgers University)
- G. Cowan (University of Siegen)
- P. Coyle (CPP, Marseille)
- R.L. Crawford (Glasgow)
- R.H. Dalitz (Oxford University)
- S.E. Deustua (LBNL)
- L. Di Ciaccio (LAPP, Annecy)
- S. Dittmaier (CERN)
- J. Donoghue (University of Massachusetts, Amherst)
- K. Ecklund (Cornell University)
- R.K. Ellis (Fermilab)
- J. Ellison (University of California, Riverside)
- A. Falk (Johns Hopkins University)
- A. Favara (California Institute of Technology)
- T. Feldmann (RWTH Aachen)
- T. Ferbel (Rochester University)
- R. Fleischer (DESY)
- G. Fogli (University of Bari)
- S.J. Freedman (LBNL)
- H. Fritzsch (University of Munich)
- F. Gabbiani (Duke University)
- J.-F. Genat (LPHNE, Paris)
- A. Goldhaber (Stony Brook)
- A. Goussiou (SUNY, Stony Brook)
- H. Greenlee (Fermilab)
- J.-F. Grivax (INPNP, Univeristy of Paris, Sud)
- E.M. Gullikson (LBNL)
- R. Hagstrom (ANL)
- L. Hall (LBNL)
- F. Halzen (University of Wisconsin)
- D.L. Hartill (Cornell University)
- R. Harris (Fermilab)
- R. Hawkings (CERN)
- W.C. Haxton (University of Washington)
- J. Hewett (SLAC)
- J. Huston (Michigan State University)
- J. Imazato (KEK)
- G. Isidori (INFN, Frascati)
- P.M. Ivanov (Budker Inst. of Nuclear Physics)

- Yu.M. Ivanov (Petersburg Nuclear Physics Inst.)
- F. James (CERN)
- P. Janot (CERN)
- T. Junk (Carleton University)
- J.A. Kadyk (LBNL)
- R.W. Kenney (LBNL)
- B. Klima (Fermilab)
- I. Koop (Budker Inst. of Nuclear Physics)
- P.P. Krokovny (Budker Inst. of Nuclear Physics)
- S. Kurokawa (KEK)
- M. Lancaster (Bristol University)
- G. Landsberg (Brown University)
- K. Lane (Boston University)
- P. Lefevre (CERN)
- Z. Ligeti (LBNL)
- S. Loucatos (Saclay)
- J. Lykken (FNAL)
- G.R. Lynch (LBNL)
- W.C. Martin (NIST)
- P. Meyers (Princeton University)
- A. Milsztajn (DAPNIA, Saclay)
- P.J. Mohr (NIST)
- D. Morgan (Rutherford Appleton Lab)
- H.-G. Moser (Max-Planck-Inst. für Physik, München)
- H.N. Nelson (University of California at Santa Barbara)
- Y. Nir (Weizmann Institutute)
- H. O'Connell (SLAC)
- F. Paige (Brookhaven National Lab)
- V. Parkhomchuk (Budker Inst. of Nuclear Physics)
- F. Parodi (University of Genova)
- R. Partridge (Brown University)
- M. Paulini (Carnegie Mellon University)
- R. Peccei (University of California, Los Angeles)
- M.R. Pennington (University of Durham)
- E. Perevedentsev (Budker Inst. of Nuclear Physics)
- N. Phinney (SLAC)
- B.V.P. Polishchuk (COMPAS Group, IHEP, Serpukhov)
- H.B. Prosper (Florida State University)
- I. Protopopov (Budker Inst. of Nuclear Physics)
- J. Qian (Michigan University)
- A. Quadt (CERN)
- J. Richman (University of California, Santa Barbara)
- T. Rizzo (SLAC)
- B.L. Roberts (Boston University)

- R.G.H. Robertson (University of Washington)
- B.P. Roe (Univeristy of Michigan)
- R. Roser (Fermilab)
- J.L. Rosner (University of Chicago)
- P. Roudeau (LAL, Orsay)
- G. Rudolph (University of Innsbruck)
- V. Ruhlmann-Kleider (DAPNIA, CEA-Saclay)
- O. Schneider (University of Lausanne)
- J. Seeman (SLAC)
- Yu. Shatunov (Budker Inst. of Nuclear Physics)
- C. Shepherd-Themistocleous (University of Cambridge)
- M. Shochet (University of Chicago)
- A. Sirlin (New York University)
- T. Stelzer (University of Illinois, Urbana)
- S.L. Stone (Syracuse University)
- S.I. Striganov (COMPAS Group, IHEP, Serpukhov)
- Yu. G. Stroganov (COMPAS Group, IHEP, Serpukhov)
- M. Strovink (LBNL)
- C.W. Stubbs (University of Washington)
- M. Swartz (Johns Hopkins University)
- B.N. Taylor (NIST)
- K.A. Ter-Martirosian (Moscow, ITEP)
- J.L. Tonry (University of Hawaii)
- W. Venus (RAL)
- G. Vignola (Frascati)
- C. Wagner (CERN)
- H. Wahl (CERN)
- A. Warburton (Cornell University)
- C. Weiser (CERN)
- M. Whalley (University of Durham)
- M. White (Harvard University
- C.M. Will (Washington U., St. Louis)
- F. Willeke (DESY)
- G. Wilson (DESY)
- C. Woody (Brookhaven National Lab)
- M.P. Worah (LBNL)
- M. Zeller (Yale University)
- P. Zerwas (DESY)
- C. Zhang (IHEP, Beijing)

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 $c\overline{c}$ or $b\overline{b}$ mesons (we do, however, now use χ_c for the $c\overline{c}$ 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. 1) 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 multiparameter 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

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

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. Figure 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.

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 $R = P_iP_j$ and $R = (P_iP_j)^{1/2}$ are also allowed.] Further assume that *each* ratio R has been measured by N_k experiments (we designate

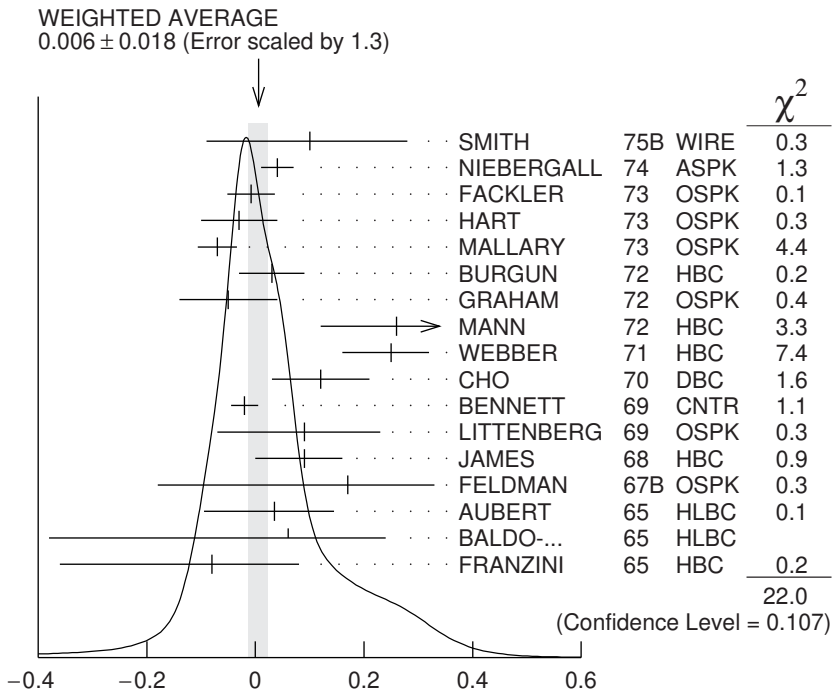

Figure 1: A typical ideogram. The arrow at the top shows the position of the weighted average, while the width of the shaded pattern shows the error in the average after scaling by the factor S. The column on the right gives the χ^2 contribution of each of the experiments. Note that the next-to-last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

each 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 $\chi^2 = \sum \chi^2_r$. 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 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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