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Combined Preliminary Results on the Mass and Width of the W Boson Measured by the LEP Experiments

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Abstract

The combinations of the preliminary W mass and width measurements of the LEP experiments are presented. Measurements of the W mass obtained from data corresponding to a total integrated luminosity of approximately 2500 pb^{-1} are combined to give:

$M_{\mathrm{W}} = 80.450 \pm 0.039$ GeV/c^2.

This result includes the LEP W mass determination from the threshold cross section measurement. The separate results from the $\mathrm{W^+W^-}\to\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{W^+W^-}\to\mathrm{q\overline{q}q\overline{q}}$ decay channels are consistent, with a difference in the masses obtained from the two channels of

$\Delta M_{\mathrm{W}}(\mathrm{q\overline{q}q\overline{q}} - \mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = +9 \pm 44$ MeV/c^2.

A direct measurement of the width of the W boson gives:

$\Gamma_{\mathrm{W}} = 2.150 \pm 0.091$ GeV/c^2.

These results include all LEP published and preliminary measurements which were available in June 2001.

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WWW access at `http://www.cern.ch/LEPEWWG/wmass/`

1 W Mass Measurements

The W boson mass results presented in this note are obtained from data recorded over a range of centre-of-mass energies, $\sqrt{s} = 161 - 209$ GeV, during the 1996-2000 operation of the LEP collider. The results reported by the ALEPH, DELPHI and L3 collaborations include an analysis of the year 2000 data, and have an integrated luminosity per experiment of about 700 pb^{-1}. The OPAL collaboration has analysed the data up to and including 1999 and has an integrated luminosity of approximately 450 pb^{-1}.

The results on the W mass and width quoted below correspond to a definition based on a Breit-Wigner denominator with an s-dependent width, $|(s - {M_{\mathrm{W}}}^2) + is\Gamma_{\mathrm{W}}/M_{\mathrm{W}}|$.

Since 1996 the LEP $\mathrm{e^+e^-}$ collider has been operating above the threshold for $\mathrm{W^+W^-}$ pair production. Initially, 10 pb^{-1}of data were recorded close to the $\mathrm{W^+W^-}$ pair production threshold. At this energy the $\mathrm{W^+W^-}$ cross section is sensitive to the W boson mass, M_{W}. Table 1 summarises the W mass results from the four LEP collaborations based on these data [1–4].

THRESHOLD ANALYSIS	
Experiment	M_{W}(threshold) GeV/c^2
ALEPH [1]	80.14 ± 0.35
DELPHI [2]	80.40 ± 0.45
L3 [3]	$80.80^{+0.48}_{-0.42}$
OPAL [4]	$80.40^{+0.46}_{-0.43}$

Table 1: W mass measurements from the $\mathrm{W^+W^-}$ threshold cross section at $\sqrt{s} = 161$ GeV. The errors include statistical and systematic contributions.

Subsequently LEP has operated at energies significantly above the $\mathrm{W^+W^-}$ threshold, where the $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$ cross section has little sensitivity to M_{W}. For these higher energy data M_{W} was measured through the direct reconstruction of the W boson's invariant mass from the observed jets and leptons. Table 2 summarises the W mass results from the four LEP experiments using the direct reconstruction method. The combined values of M_{W} from each collaboration take into account the correlated systematic uncertainties between the decay channels and between the different years of data taking. In addition to the combined numbers, each experiment presents mass measurements from $\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}q\overline{q}}$ channels separately. The DELPHI and OPAL collaborations provide results from independent fits to the data in the $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{q\overline{q}q\overline{q}}$ decay channels separately and hence account for correlations between years but are unaffected by correlations between the two channels. The $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{q\overline{q}q\overline{q}}$ results quoted by the ALEPH and L3 collaborations are obtained from a simultaneous fit to all data which, in addition to other correlations, takes into account the correlated systematic uncertainties between the two channels. The L3 result is unchanged when determined through separate fits. The large variation in the systematic uncertainties in the $\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}q\overline{q}}$ channel are caused by differing estimates of the possible effects of Colour Reconnection (CR) and Bose-Einstein Correlations (BEC), this is discussed below. The systematic errors in the $\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ channel are dominated by uncertainties from hadronisation, with estimates ranging from 15-30 MeV/c^2.

Experiment	DIRECT RECONSTRUCTION		
	$W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$	$W^+W^- \to q\overline{q}q\overline{q}$	Combined
	M_W GeV/c^2	M_W GeV/c^2	M_W GeV/c^2
ALEPH [5–7]	$80.456 \pm 0.051 \pm 0.032$	$80.507 \pm 0.054 \pm 0.045$	$80.477 \pm 0.038 \pm 0.032$
DELPHI [8–11]	$80.414 \pm 0.074 \pm 0.048$	$80.384 \pm 0.053 \pm 0.065$	$80.399 \pm 0.045 \pm 0.049$
L3 [12–16]	$80.314 \pm 0.074 \pm 0.045$	$80.478 \pm 0.063 \pm 0.069$	$80.389 \pm 0.048 \pm 0.051$
OPAL [17–21]	$80.516 \pm 0.067 \pm 0.030$	$80.408 \pm 0.066 \pm 0.100$	$80.491 \pm 0.053 \pm 0.038$

Table 2: **PRELIMINARY** W mass measurements from direct reconstruction ($\sqrt{s} = 172 - 209$ GeV). The first error is statistical and the second systematic. Results are given for the semi-leptonic, fully-hadronic channels and the combined value. The $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ results from the ALEPH and OPAL collaborations include mass information from the $W^+W^- \to \ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$ channel.

2 Combination Procedure

A combined LEP W mass measurement has been obtained from the results of the four experiments. In order to perform a reliable combination of the measurements, a more detailed input than that given in Table 2 was required. Each experiment provided a W mass measurement for both the $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ and $W^+W^- \to q\overline{q}q\overline{q}$ channels for each of the data taking years (1996-2000) that it had analysed. In addition to the four threshold measurements a total of 36 direct reconstruction measurements were supplied: ALEPH and DELPHI provided 10 results (1996-2000), L3 gave 8 results (1996-2000) having already combined the 1996 and 1997 results and OPAL provided 8 measurements (1996-1999). The $W^+W^- \to \ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$ channel has also been analysed by the ALEPH(1997-2000) and OPAL(1997-2000) collaborations; the lower precision results obtained from this channel were combined by the experiments with their $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ channel mass determinations.

Subdividing the results by data-taking years enables a proper treatment of the correlated systematic uncertainty from the LEP beam energy and other dependences on the centre-of-mass energy or data-taking period. A detailed breakdown of the sources of systematic uncertainty were provided for each result and the correlations specified. The inter-year, inter-channel and inter-experiment correlations are included in the combination. The main sources of correlated systematic errors are: colour reconnection, Bose-Einstein correlations, hadronisation, the LEP beam energy, and uncertainties from initial and final state radiation. The full correlation matrix for the LEP beam energy is employed [22]. The combination was performed and the evaluation of the components of the total error assessed using the best linear unbiassed estimate technique, see [23].

The four LEP collaborations gave different estimates of the systematic errors arising from final state interactions: these varied from 30-66 MeV/c^2 for colour reconnection and from 20-67 MeV/c^2 for Bose-Einstein correlations. This range of estimates could be due to different experimental sensitivities to these effects or, alternatively, simply a reflection of the different phenomenological models used to assess the uncertainties. This question has been resolved by comparing the results of the experiments when analysing simulation samples with and without CR effects in the SK-I model [24]. Studies of these samples demonstrate that the four experiments are equally sensitive to colour reconnection effects, *i.e.* when looking at the same CR model similar biases are seen by all experiments. This is shown in Figure 1 as a function of the fraction of reconnected events, a reconnection fraction of 30% of events is typically assumed by

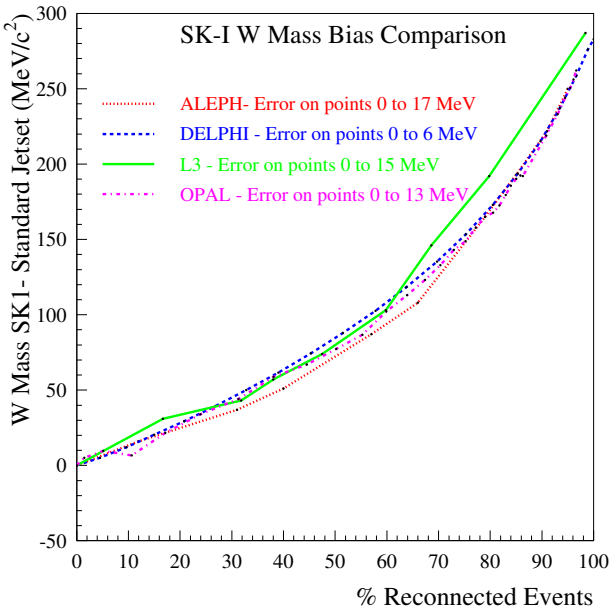

Figure 1: W Mass bias in the SK-I model of colour reconnection at a centre of mass energy of 189 GeV. The fully-hadronic decay channel analyses of the four LEP experiments show similar sensitivity to this effect.

the experiments for the assesment of systematic uncertainities.

For this reason a common value of the CR systematic uncertainty was used in the combination. For Bose-Einstein Correlations, no similar test has been made of the respective experimental sensitivities. However, in the absence of evidence that the experiments have different sensitivities to the effect, a common value of the systematic uncertainty from BEC was assumed. In the combination a common colour reconnection error of 40 MeV/c^2 and a common Bose-Einstein systematic uncertainty of 25 MeV/c^2 were used. These values were chosen as they result in the same final error on M_{W} as obtained when using the BEC and CR estimates of the experiments. Applying this procedure changes the value of M_{W} from the fit by 7 MeV/c^2.

3 LEP Combined W Boson Mass

The combined W mass from direct reconstruction is

$$M_{\mathrm{W}}(\mathrm{direct}) = 80.450 \pm 0.026(\mathrm{stat.}) \pm 0.030(\mathrm{syst.})\ \mathrm{GeV}/c^2,$$

with a χ^2/d.o.f. of 31.1/35, corresponding to a χ^2 probability of 66%. The weight of the fully-hadronic channel in the combined fit is 0.27. This reduced weight is a consequence of the relatively large size of the current estimates of the systematic errors from CR and BEC. Table 3 gives a breakdown of the contribution to the total error of the various sources of systematic errors. The largest contribution to the systematic error comes from hadronisation uncertainties, which are conservatively treated as correlated between the two channels, between experiments and between years. In the absence of systematic effects the current LEP statistical precision

Source	Systematic Error on M_{W} (MeV/c^2)		
	$\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$	$\mathrm{q\overline{q}q\overline{q}}$	Combined
ISR/FSR	8	9	8
Hadronisation	19	17	17
Detector Systematics	12	8	10
LEP Beam Energy	17	17	17
Colour Reconnection	–	40	11
Bose-Einstein Correlations	–	25	7
Other	4	4	3
Total Systematic	29	54	30
Statistical	33	30	26
Total	44	62	40
Statistical in absence of Systematics	32	29	22

Table 3: Error decomposition for the combined LEP W mass results. Detector systematics include uncertainties in the jet and lepton energy scales and resolution. The 'Other' category refers to errors, all of which are uncorrelated between experiments, arising from: simulation statistics, background estimation, four-fermion treatment, fitting method and event selection. The error decomposition in the $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{q\overline{q}q\overline{q}}$ channels refers to the independent fits to the results from the two channels separately.

on M_{W} would be 22 MeV/c^2: the statistical error contribution in the LEP combination is larger than this (26 MeV/c^2) due to the significantly reduced weight of the fully-hadronic channel.

In addition to the above results, the W boson mass has been measured at LEP from the 10 pb^{-1} per experiment of data recorded at threshold for W pair production:

$$M_{\mathrm{W}}(\mathrm{threshold}) = 80.40 \pm 0.20(\mathrm{stat.}) \pm 0.07(\mathrm{syst.}) \pm 0.03(\mathrm{LEP})\ \mathrm{GeV}/c^2.$$

When the threshold measurements are combined with the much more precise results obtained from direct reconstruction one achieves a W mass measurement of

$$M_{\mathrm{W}} = 80.450 \pm 0.026(\mathrm{stat.}) \pm 0.030(\mathrm{syst.})\mathrm{GeV}/c^2.$$

The LEP beam energy uncertainty is the only correlated systematic error source between the threshold and direct reconstruction measurements. The threshold measurements have a weight of only 0.02 in the combined fit. This LEP combined result is compared with the results (threshold and direct reconstruction combined) of the four LEP experiments in Figure 2.

4 Consistency Checks

The mass difference between the W boson mass measurements obtained from the fully-hadronic and semi-leptonic channels, $\Delta M_{\mathrm{W}}(\mathrm{q\overline{q}q\overline{q}} - \mathrm{q\overline{q}}\ell\overline{\nu}_\ell)$, has been determined:

$$\Delta M_{\mathrm{W}}(\mathrm{q\overline{q}q\overline{q}} - \mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = +9 \pm 44\ \mathrm{MeV}/c^2.$$

A significant non-zero value for ΔM_{W} could indicate that FSI effects are biasing the value of M_{W} determined from $\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}q\overline{q}}$ events. Since ΔM_{W} is primarily of interest as a check

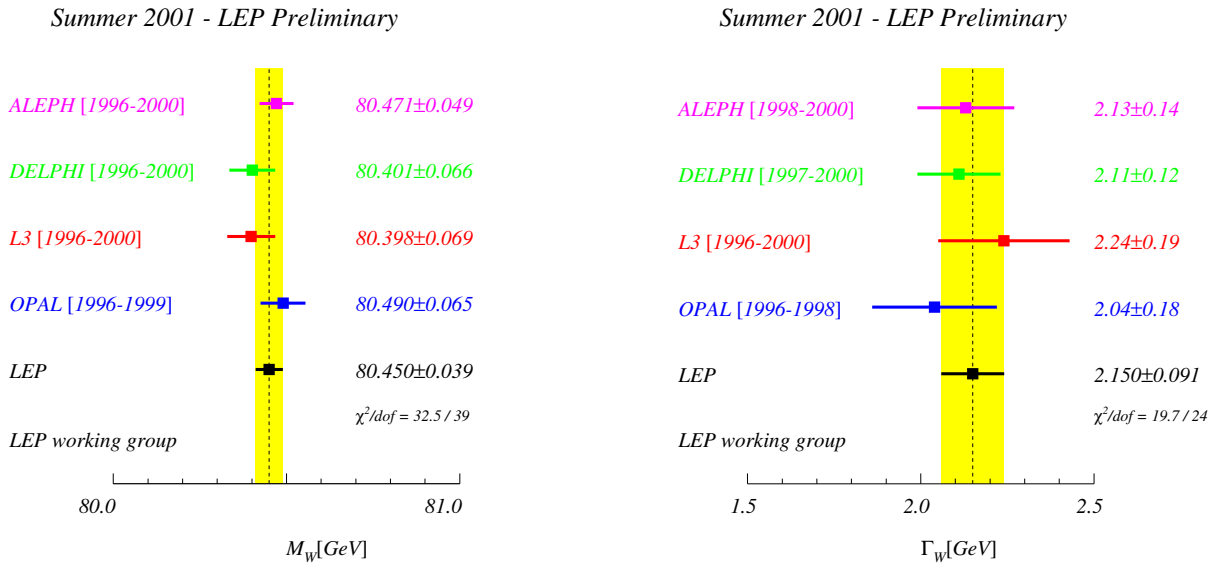

Figure 2: **Summer 2001 Preliminary** The combined results for the measurements of the W mass and W width compared to the results obtained by the four LEP collaborations. The combined values take into account correlations between experiments and years and hence, in general, do not give the same central value as a simple average. In the LEP combination of the $\mathrm{q\overline{q}q\overline{q}}$ results common values (see text) for the CR and BEC errors have been used. The individual and combined M_{W} results include the measurements from the threshold cross section.

of the possible effects of final state interactions, the errors from CR and BEC are set to zero in its determination. The result was obtained from a fit where the imposed correlations were the same as those for the results given in the previous sections. This result is almost unchanged if the systematic part of the error on Mw from hadronisation effects is considered as uncorrelated between channels, although the uncertainty increases by 16%. In section 2 a study of the W mass bias in the SK-I colour reconnection model is reported. This study and the equivalent analysis for the W width are not used to place limits on colour reconnection as only one model is considered and, taken in isolation, the results are not sufficiently precise.

The masses from the two channels obtained from this fit with the BEC and CR errors now included are:

$$M_{\mathrm{W}}(\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = 80.448 \pm 0.033(\mathrm{stat.}) \pm 0.028(\mathrm{syst.})\ \mathrm{GeV}/c^2,$$
$$M_{\mathrm{W}}(\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}q\overline{q}}) = 80.457 \pm 0.030(\mathrm{stat.}) \pm 0.054(\mathrm{syst.})\ \mathrm{GeV}/c^2.$$

These two results are correlated and have a correlation coefficient of 0.28. The value of χ^2/d.o.f is 31.1/34, corresponding to a χ^2 probability of 62%. These results and the correlation between them can be used to combine the two measurements or to form the mass difference. The LEP combined results from the two channels are compared with those quoted by the individual experiments in Figure 3.

Experimentally, separate M_{W} measurements were obtained from the $\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}q\overline{q}}$ channels for each of the years of data. The combination using only the $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ measurements yields:

$$M_{\mathrm{W}}^{\mathrm{indep}}(\mathrm{W^+W^-}\rightarrow\mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = 80.448 \pm 0.033(\mathrm{stat.}) \pm 0.029(\mathrm{syst.})\ \mathrm{GeV}/c^2.$$

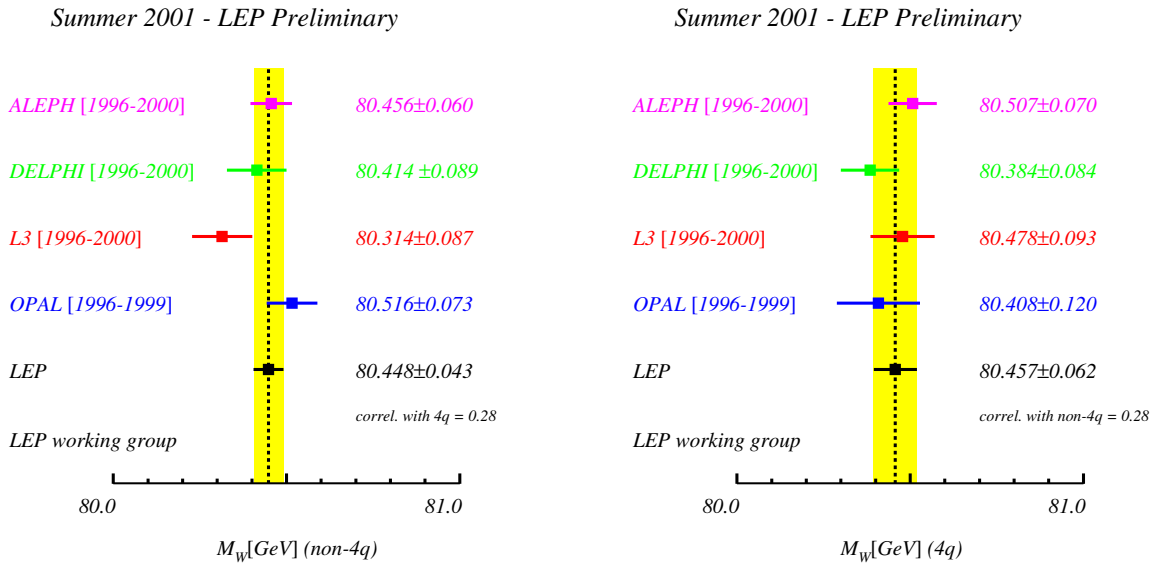

Figure 3: **Summer 2001 Preliminary**. The W mass measurements from the $W^+W^-\to q\bar{q}\ell\bar{\nu}_\ell$ and $W^+W^-\to q\bar{q}q\bar{q}$ channels obtained by the four LEP collaborations compared to the combined value. The combined values take into account correlations between experiments, years and the two channels. In the LEP combination of the $q\bar{q}q\bar{q}$ results common values (see text) for the CR and BEC errors have been used. The ALEPH and L3 $q\bar{q}\ell\bar{\nu}_\ell$ and $q\bar{q}q\bar{q}$ results are correlated since they are obtained from a fit to both channels taking into account inter-channel correlations.

The systematic error is dominated by hadronisation uncertainties (± 19 MeV/c^2) and the uncertainty in the LEP beam energy (± 17 MeV/c^2). The combination using only the $q\bar{q}q\bar{q}$ measurements gives:

$$M_{\mathrm{W}}^{\mathrm{indep}}(\mathrm{W^+W^-}\to q\bar{q}q\bar{q}) = 80.447 \pm 0.030(\mathrm{stat.}) \pm 0.054(\mathrm{syst.})\ \mathrm{GeV}/c^2.$$

where the dominant contributions to the systematic error arise from BEC/CR (± 47 MeV/c^2), hadronisation (± 17 MeV/c^2) and from the uncertainty in the LEP beam energy (± 17 MeV/c^2).

5 LEP Combined W Boson Width

The method of direct reconstruction is also well suited to the direct measurement of the width of the W boson. The results of the four LEP experiments are shown in Table 4 and in Figure 2.

Each experiment provided a W width measurement for both $W^+W^-\to q\bar{q}\ell\bar{\nu}_\ell$ and $W^+W^-\to q\bar{q}q\bar{q}$ channels for each of the data taking years (1996-2000) that it had analysed. A total of 25 measurements were supplied: ALEPH provided 3 $W^+W^-\to q\bar{q}q\bar{q}$ results (1998-2000) and two $W^+W^-\to q\bar{q}\ell\bar{\nu}_\ell$ results (1998-1999), DELPHI 8 measurements (1997-2000), L3 8 measurements (1996-2000) having already combined the 1996 and 1997 results and OPAL provided 4 measurements (1996-1998) where for the first two years the $W^+W^-\to q\bar{q}\ell\bar{\nu}_\ell$ and $W^+W^-\to q\bar{q}q\bar{q}$ results had already been combined.

A common colour reconnection error of 65 MeV/c^2 and a common Bose-Einstein correlation error of 35 MeV/c^2 were used in the combination. This procedure resulted in the same error

Experiment	Γ_{W} GeV/c^2
ALEPH	$2.13 \pm 0.11 \pm 0.09$
DELPHI	$2.11 \pm 0.10 \pm 0.07$
L3	$2.24 \pm 0.11 \pm 0.15$
OPAL	$2.04 \pm 0.16 \pm 0.09$

Table 4: **PRELIMINARY** W width measurements ($\sqrt{s} = 172-209$ GeV) from the individual experiments. The first error is statistical and the second systematic.

on Γ_{W} as obtained using the BEC/CR errors supplied by the experiments. The change in the value of the width was only 2 MeV/c^2.

A simultaneous fit to the results of the four LEP collaborations was performed in the same way as for the M_{W} measurement. Correlated systematic uncertainties are taken into account and the combination gives:

$$\Gamma_{\mathrm{W}} = 2.150 \pm 0.068(\mathrm{stat.}) \pm 0.060(\mathrm{syst.})\ \mathrm{GeV}/c^2,$$

with a χ^2/d.o.f. of 19.7/24, corresponding to a χ^2 probability of 71%.

6 Summary

The results of the four LEP experiments on the mass and width of the W boson have been combined taking into account correlated systematic uncertainties, giving:

$$\begin{aligned} M_{\mathrm{W}} &= 80.450 \pm 0.039\ \mathrm{GeV}/c^2, \\ \Gamma_{\mathrm{W}} &= 2.150 \pm 0.091\ \mathrm{GeV}/c^2. \end{aligned}$$

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