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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:

$$m_{\mathrm{W}} = 80.412 \pm 0.042 \text{ GeV}.$$

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

$$\Delta m_{\mathrm{W}}(\mathrm{q\overline{q}q\overline{q}} - \mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = +22 \pm 43 \text{ MeV}.$$

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

$$\Gamma_{\mathrm{W}} = 2.150 \pm 0.091 \text{ GeV}.$$

These results include all LEP published and preliminary measurements which were available in February 2003.

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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 ALEPH result does not include an analysis of the small amount of data (about 10 pb^{-1}) collected in 1996 at a centre-of-mass energy of 172 GeV.

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].

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

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} is 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 presented individually by 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 do not include 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 to 30 MeV.

The results presented in this note differ from those in the previous combination [2] due to revised measurements from the ALEPH Collaboration [3] the results are otherwise identical. The ALEPH measurements have been revised due to a change in their event reconstruction algorithm. This change makes the analysis less sensitive to detector simulation inaccuracies which were not taken into account in the previous preliminary result.

	DIRECT RECONSTRUCTION		
	$W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$	$W^+W^- \to q\bar{q}q\bar{q}$	Combined
Experiment	m_W/GeV	m_W/GeV	m_W/GeV
ALEPH [3]	80.375 ± 0.062	80.431 ± 0.117	80.385 ± 0.058
DELPHI [4–7]	80.414 ± 0.089	80.374 ± 0.119	80.402 ± 0.075
L3 [8–12]	80.314 ± 0.087	80.485 ± 0.127	80.367 ± 0.078
OPAL [13–17]	80.516 ± 0.073	80.407 ± 0.120	80.495 ± 0.067

Table 2: Preliminary W mass measurements from direct reconstruction ($\sqrt{s} = 172 - 209$ GeV). Results are given for the semi-leptonic, fully-hadronic channels and the combined value. The $W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$ results from the OPAL collaboration include mass information from the $W^+W^- \to \ell\bar{\nu}_\ell\ell\bar{\nu}_\ell$ channel. The results given here differ from those in the publications of the individual experiments as they have been recalculated imposing common FSI uncertainties.

2 Combination Procedure

A combined LEP W mass measurement is 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 is required. Each experiment provided a W mass measurement for both the $W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$ and $W^+W^- \to q\bar{q}q\bar{q}$ channels for each of the data taking years (1996-2000) that it had analysed. In addition to the four threshold measurements a total of 36 direct reconstruction measurements are supplied: DELPHI provided 10 measurements (1996-2000), L3 gave 8 measurements (1996-2000) having already combined the 1996 and 1997 results, ALEPH provided 8 measurements (1997-2000) and OPAL also gave 8 measurements (1996-1999). The $W^+W^- \to \ell\bar{\nu}_\ell\ell\bar{\nu}_\ell$ channel is also analysed by the OPAL(1997-1999) collaboration; the lower precision results obtained from this channel are combined with the $W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$ 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 are 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 [18]. The combination is performed and the evaluation of the components of the total error assessed using the Best Linear Unbiased Estimate (BLUE) technique, see Reference 19.

A preliminary study of colour reconnection has been made by the LEP experiments using the particle flow method [20] on a sample of fully-hadronic WW events. These results are

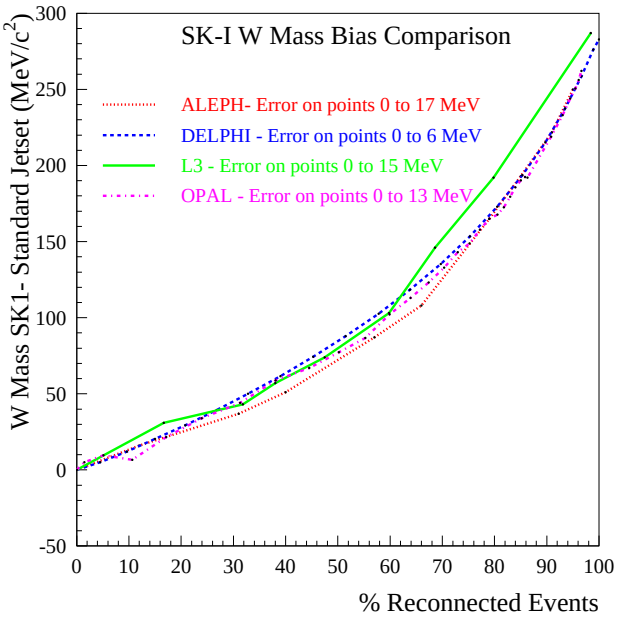

Figure 1: W mass bias obtained in the SK-I model of colour reconnection relative to a simulation without colour reconnection as a function of the fraction of events reconnected for the fully-hadronic decay channel at a centre of mass energy of 189 GeV. The analyses of the four LEP experiments show similar sensitivity to this effect. The points connected by the lines have correlated uncertainties increasing to the right in the range indicated.

interpreted in terms of the reconnection parameter k_i of the SK-I model [21] and yield a 68% confidence level range of :

$$0.39 < k_i < 2.13$$

The method was found to be insensitive to the HERWIG and ARIADNE II models of colour reconnection.

Studies of simulation samples have demonstrated 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 for the SKI model as a function of the fraction of reconnected events. For this reason a common value for all experiments of the CR systematic uncertainty is used in the combination.

For this combination, no offset has been applied to the central value of m_{W} due to colour reconnection effects and a symmetric systematic error has been imposed. The m_{W} error is set from a linear extrapolation of simulation results obtained at $k_i = 2.13$, the values used were: 74 MeV shift for the 1996 data at a centre-of-mass energy of 172 GeV, 84 MeV for 1997 at 183 GeV, 90 MeV for 1998 at 189 GeV, 95 MeV for 1999 at 195 GeV and 105 MeV for 2000 at 207 GeV, they are shown in Figure 2. Previous m_{W} combinations have relied upon theoretical expectations of colour reconnection effects, in which there is considerable uncertainty. This new data driven approach achieves a more robust uncertainty estimate at the expense of a significantly increased colour reconnection uncertainty. The ARIADNE II and HERWIG models of colour reconnection have also been studied and the W Mass shift was found to be lower than that from SK1 with $k_i = 2.13$.

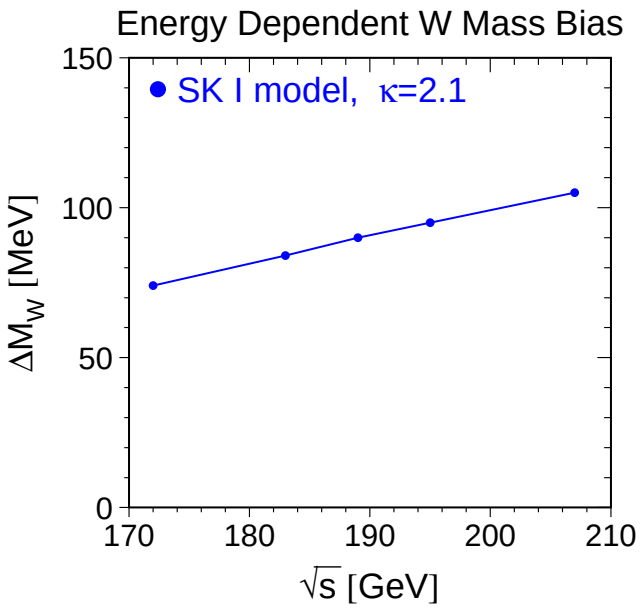

Figure 2: The values used in the W Mass combination for the uncertainty due to colour reconnection are shown as a function of the centre of mass energy. These values were obtained from a linear fit to simulation results obtained with the SK1 model of colour reconnection at $k_i = 2.13$.

For Bose-Einstein Correlations, a similar test has been made of the respective experimental sensitivities with the LUBOEI [22] model: the experiments observed compatible mass shifts. A common value of the systematic uncertainty from BEC is assumed of 35 MeV from studies of the LUBOEI model. Again, this value may be compared with recent direct measurements from LEP of this effect [23, 24], where the observed effect was of considerably smaller magnitude than in the LUBOEI model. Hence, the currently ascribed 35 MeV uncertainty is considered a conservative estimate.

3 LEP Combined W Boson Mass

The combined W mass from direct reconstruction is

$$m_{\mathrm{W}}(\mathrm{direct}) = 80.412 \pm 0.029(\mathrm{stat.}) \pm 0.031(\mathrm{syst.})\ \mathrm{GeV},$$

with a χ^2/d.o.f. of 28.2/33, corresponding to a χ^2 probability of 70%. The weight of the fully-hadronic channel in the combined fit is 0.10. 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 on m_{W} would be 21 MeV: the statistical error contribution in the LEP combination is larger than this (29 MeV) due to the significantly reduced weight of the fully-hadronic channel.

Source	Systematic Error on m_{W} (MeV)		
	$\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$	$\mathrm{q\overline{q}q\overline{q}}$	Combined
ISR/FSR	8	8	8
Hadronisation	19	18	18
Detector Systematics	14	10	14
LEP Beam Energy	17	17	17
Colour Reconnection	–	90	9
Bose-Einstein Correlations	–	35	3
Other	4	5	4
Total Systematic	31	101	31
Statistical	32	35	29
Total	44	107	43
Statistical in absence of Systematics	32	28	21

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.

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

$$m_{\mathrm{W}}(\mathrm{threshold}) = 80.40 \pm 0.20(\mathrm{stat.}) \pm 0.07(\mathrm{syst.}) \pm 0.03(\mathrm{E_{beam}})\ \mathrm{GeV}.$$

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

$$m_{\mathrm{W}} = 80.412 \pm 0.029(\mathrm{stat.}) \pm 0.031(\mathrm{syst.})\mathrm{GeV}.$$

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 0.03 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 3.

4 Consistency Checks

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

$$\Delta m_{\mathrm{W}}(\mathrm{q\overline{q}q\overline{q}} - \mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = +22 \pm 43\ \mathrm{MeV}.$$

A significant non-zero value for Δm_{W} could indicate that CR and BEC 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 of the possible effects of final state interactions, the errors from CR and BEC are set to zero in its determination. The result is obtained from a fit where the imposed correlations

are 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 m_{W} from hadronisation effects is considered as uncorrelated between channels, although the uncertainty increases by 16%.

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

$$m_{\mathrm{W}}(\mathrm{W^+W^-}\rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = 80.411 \pm 0.032(\mathrm{stat.}) \pm 0.030(\mathrm{syst.})\ \mathrm{GeV},$$
$$m_{\mathrm{W}}(\mathrm{W^+W^-}\rightarrow \mathrm{q\overline{q}q\overline{q}}) = 80.420 \pm 0.035(\mathrm{stat.}) \pm 0.101(\mathrm{syst.})\ \mathrm{GeV}.$$

These two results are correlated and have a correlation coefficient of 0.18. The value of χ^2/d.o.f is 28.2/32, corresponding to a χ^2 probability of 66%. 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 4, where the common CR and BEC errors have been imposed.

Experimentally, separate m_{W} measurements are 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:

$$m_{\mathrm{W}}^{\mathrm{indep}}(\mathrm{W^+W^-}\rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = 80.413 \pm 0.032(\mathrm{stat.}) \pm 0.031(\mathrm{syst.})\ \mathrm{GeV}.$$

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

$$m_{\mathrm{W}}^{\mathrm{indep}}(\mathrm{W^+W^-}\rightarrow \mathrm{q\overline{q}q\overline{q}}) = 80.411 \pm 0.035(\mathrm{stat.}) \pm 0.107(\mathrm{syst.})\ \mathrm{GeV}.$$

where the dominant contributions to the systematic error are from CR (±90 MeV) and BEC (±35 MeV).

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 3.

Experiment	Γ_{W} (GeV)
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.

Each experiment provided a W width measurement for both $\mathrm{W^+W^-}\rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{W^+W^-}\rightarrow \mathrm{q\overline{q}q\overline{q}}$ channels for each of the data taking years (1996-2000) that it has analysed. A total of 25 measurements are supplied: ALEPH provided 3 $\mathrm{W^+W^-}\rightarrow \mathrm{q\overline{q}q\overline{q}}$ results (1998-2000) and two $\mathrm{W^+W^-}\rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ 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 are already combined.

A common colour reconnection error of 65 MeV and a common Bose-Einstein correlation error of 35 MeV are used in the combination. These common errors were determined such that the same error was obtained on Γ_W as when using the BEC/CR errors supplied by the experiments. The change in the value of the width is only 2 MeV. The BEC and CR values supplied by the experiments were based on studies of phenomenolgical models of these effects, the uncertainty has not yet been determined from the particle flow measurements of colour reconnection.

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

$$\Gamma_W = 2.150 \pm 0.068(\text{stat.}) \pm 0.060(\text{syst.}) \text{ GeV},$$

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

The statistical correlation between mass and width is small and neglected. Their correlation due to common systematic effects is under study.

6 Summary

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

$$\begin{aligned} m_W &= 80.412 \pm 0.042 \text{ GeV}, \\ \Gamma_W &= 2.150 \pm 0.091 \text{ GeV}. \end{aligned}$$

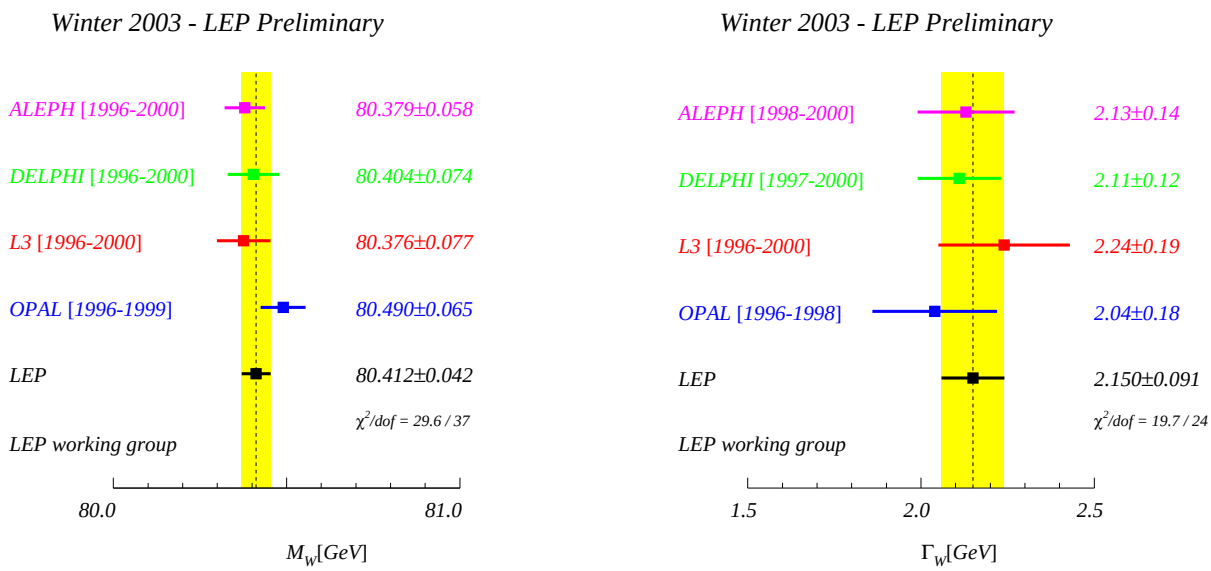

Figure 3: The combined results for the measurements of the W mass (left) and W width (right) compared to the results obtained by the four LEP collaborations. The combined values take into account correlations between experiments and years and hence, in general, do not give the same central value as a simple average. In the LEP combination of the $\mathrm{q\bar{q}q\bar{q}}$ results common values (see text) for the CR and BEC errors are used. The individual and combined m_{W} results include the measurements from the threshold cross section. The m_{W} values from the experiments have been recalculated for this plot including the common LEP CR and BEC errors.

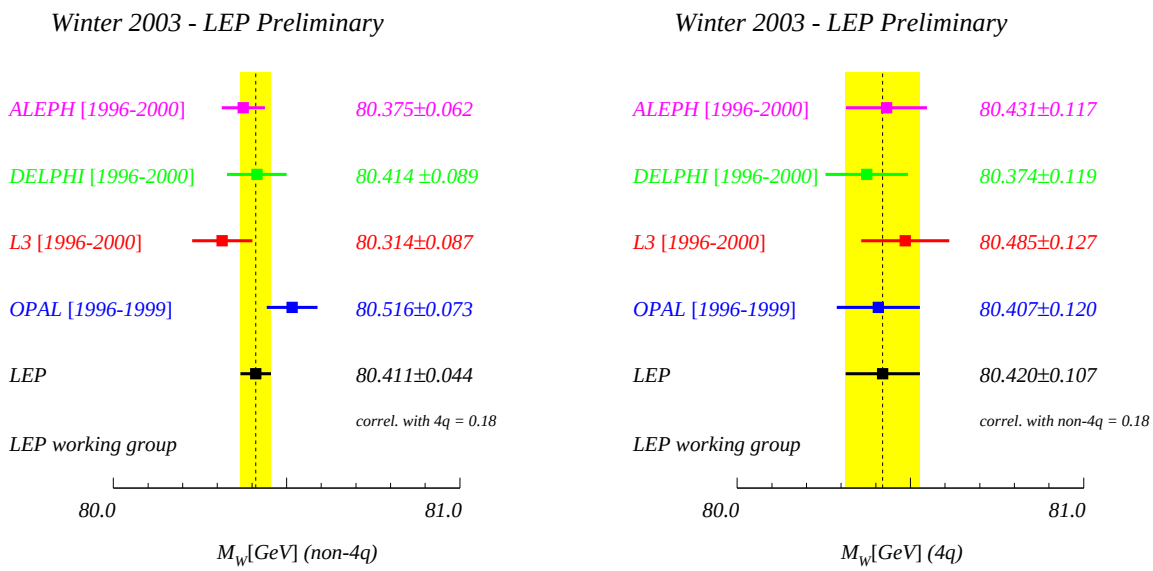

Figure 4: The W mass measurements from the $W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$ (left) and $W^+W^- \to q\bar{q}q\bar{q}$ (right) channels obtained by the four LEP collaborations compared to the combined value. The combined values take into account correlations between experiments, years and the two channels. In the LEP combination of the $q\bar{q}q\bar{q}$ results common values (see text) for the CR and BEC errors are 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 m_W values from the experiments have been recalculated for this plot including the common LEP CR and BEC errors.

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