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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 LEP W mass and width measurements are presented. Measurements of the W mass obtained from data corresponding to an integrated luminosity of approximately 460 pb^{-1} per experiment are combined to give:

$$M_{\mathrm{W}} = 80.427 \pm 0.046 \text{ GeV}.$$

This result includes the LEP W mass measurement 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

$$\Delta M_{\mathrm{W}}(\mathrm{q\overline{q}q\overline{q}} - \mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = +5 \pm 51 \text{ MeV}.$$

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

$$\Gamma_{\mathrm{W}} = 2.12 \pm 0.11 \text{ GeV}.$$

The above results include all LEP preliminary and published measurements which were available at the time of July 2000.

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The collaborations each take responsibility for the preliminary data of their own experiment.
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, $\sqrt{s} = 161 - 202$ GeV during the 1996-1999 operation of the LEP collider. These data correspond to an integrated luminosity of approximately 460 pb^{-1} per experiment. No results from the year 2000 LEP running are included. The results on the W mass quoted below correspond to a mass definition based on a Breit-Wigner denominator with an s-dependent width, $|s - {M_{\rm W}}^2 + is\Gamma_{\rm W}/M_{\rm W}|$.

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

THRESHOLD CROSS SECTION	
Experiment	$M_{\rm W}$(threshold) /GeV
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 W^+W^- threshold cross section at $\sqrt{s} = 161$ GeV. The errors include statistical and systematic contributions.

Subsequently LEP has operated well above the W^+W^- threshold, delivering 450 pb^{-1} per experiment (excluding the operation in 2000). Above threshold, the $e^+e^- \rightarrow W^+W^-$ cross section has little sensitivity to $M_{\rm W}$. For these data the W boson mass is measured using the method of direct reconstruction where the measured four-momenta of the reconstructed jets and leptons are used to reconstruct the invariant mass on an event-by-event basis. Table 2 summarises the W mass results from the four LEP experiments using the method of direct reconstruction. In addition to the combined numbers, each experiment presents mass measurements from $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$ and $W^+W^- \rightarrow q\overline{q}q\overline{q}$ channels separately. The DELPHI, L3 and OPAL collaborations obtain results for the $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$ channels using independent fits to data from each channel, taking into account correlated systematic errors. The $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$ results quoted by the ALEPH collaboration 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 large variation in the systematic uncertainties in the $W^+W^- \rightarrow q\overline{q}q\overline{q}$ channel are caused by differing estimates of the possible effects of Colour Reconnection (CR) and Bose-Einstein Correlations (BEC), discussed below. The systematic errors in the $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$ channel are dominated by uncertainties from hadronisation, with estimates ranging from 20-40 MeV.

Experiment	DIRECT RECONSTRUCTION $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ M_W/GeV	$W^+W^- \to q\overline{q}q\overline{q}$ M_W/GeV	Combined M_W/GeV
ALEPH[5-7]	$80.435 \pm 0.063 \pm 0.048$	$80.467 \pm 0.064 \pm 0.057$	$80.449 \pm 0.045 \pm 0.047$
DELPHI[8-11]	$80.381 \pm 0.088 \pm 0.048$	$80.372 \pm 0.064 \pm 0.063$	$80.380 \pm 0.053 \pm 0.047$
L3[12-15]	$80.273 \pm 0.089 \pm 0.046$	$80.461 \pm 0.077 \pm 0.069$	$80.362 \pm 0.058 \pm 0.052$
OPAL[16-20]	$80.510 \pm 0.067 \pm 0.031$	$80.408 \pm 0.066 \pm 0.100$	$80.486 \pm 0.053 \pm 0.039$

Table 2: **PRELIMINARY** W mass measurements from direct reconstruction ($\sqrt{s} = 172 - 202$ GeV). Results are given for the semi-leptonic, fully-hadronic channels and the combined value. The errors are statistical and systematic respectively. The combined values of M_W from each collaboration take into account the correlated systematic uncertainties between the two channels and between the different years of data taking. 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 LEP combined W mass measurement has been obtained from the results of the four experiments. To combine the measurements, a more detailed input than that given in Table 2 is required. Each experiment provides a W mass measurement for both $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ and $W^+W^- \to q\overline{q}q\overline{q}$ channels for each of the four years data taking (1996-1999), a total of 30 measurements (the L3 Collaboration provides results from the 1996 and 1997 data already combined). The subdivision into years enables a proper treatment of the correlated systematic uncertainty from the LEP beam energy and allows for the possibility that the systematic uncertainties depend on the centre-of-mass energy and/or data-taking period. For each result a detailed breakdown of the sources of systematic uncertainty is provided and the correlations are specified. In the combination these inter-year, inter-channel and inter-experiment correlations are included. 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 [21]. All the information used in the W mass combination is given in `http://lepewwg.web.cern.ch/LEPEWWG/protected/wmass/Summer00/mw2000input.ps`.

The four LEP collaborations give different estimates of the systematic errors arising from final state interactions, ranging from 30-66 MeV for Colour Reconnection and from 20-67 MeV for Bose-Einstein Correlations. This 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 addressed using common Monte Carlo samples with and without CR effects. These were passed through the full detector simulations of each of the four experiments. 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. 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 is assumed. In the combination a common Colour Reconnection error of 50 MeV and a common Bose-Einstein systematic uncertainty of 25 MeV are used. These

uncertainties are representative of the numbers estimated by the four LEP collaborations.

3 LEP Combined W Boson Mass

The combined W mass from direct reconstruction, taking into account all correlations including those between the $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ and $W^+W^- \to q\overline{q}q\overline{q}$ channels, years and experiments gives

$$M_W(direct) = 80.428 \pm 0.030(\text{stat.}) \pm 0.036(\text{syst.}) \text{ GeV},$$

with a χ^2/d.o.f. of 27.1/29, corresponding to a χ^2 probability of 57%. The weight of the fully hadronic channel in the combined fit is 0.27. The 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 systematic errors from different sources and the contribution to total error from statistics. The largest contribution to the systematic error comes from hadronisation uncertainties, which are treated as correlated between the two channels. It should be noted that in the absence of systematic effects the current LEP statistical precision on M_W would be 25 MeV. The statistical error contribution to the total error from the LEP combination is larger than this (30 MeV) due to the significantly reduced weight of the fully-hadronic channel. Table 3 also shows the error breakdown for W mass measurements from the two channels separately (described in the following section).

Source	Systematic Error on M_W (MeV)		
	$q\overline{q}\ell\overline{\nu}_\ell$	$q\overline{q}q\overline{q}$	Combined
ISR/FSR	8	10	8
Hadronisation	26	23	24
Detector Systematics	11	7	10
LEP Beam Energy	17	17	17
Colour Reconnection	–	50	13
Bose-Einstein Correlations	–	25	7
Other	5	5	4
Total Systematic	35	64	36
Statistical	38	34	30
Total	51	73	47

Table 3: Error decomposition for the combined 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: Monte Carlo statistics, background, four-fermion treatment, fitting and event selection. The error decomposition in the $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$ channels refers to the independent fits to the results from the two channels separately.

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

$$M_W(threshold) = 80.40 \pm 0.20(\text{stat.}) \pm 0.07(\text{syst.}) \pm 0.03(\text{LEP}) \text{ GeV}.$$

When this is combined with the much more precise results obtained from direct reconstruction one obtains a W mass measurement of

$$M_{\mathrm{W}} = 80.427 \pm 0.046 \text{ GeV}.$$

In combining the threshold and direct reconstruction measurements the only correlated systematic uncertainty is that from the LEP beam energy. This LEP combined result is compared with the results (threshold and direct reconstruction combined) of the four LEP experiments in Figure 1.

4 Consistency Checks

In addition to fitting for the combined W mass from the $\mathrm{W^+W^-}\to\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{W^+W^-}\to\mathrm{q\overline{q}q\overline{q}}$ channels, the mass difference bewteen the W boson mass measurements obtained from the fully-hadronic and semi-leptonic channels, $\Delta M_{\mathrm{W}}(\mathrm{q\overline{q}q\overline{q}} - \mathrm{q\overline{q}}\ell\overline{\nu}_\ell)$, can be determined. A significant non-zero value for ΔM_{W} could indicate that FSI effects are biasing the value of M_{W} determined from $\mathrm{W^+W^-}\to\mathrm{q\overline{q}q\overline{q}}$ 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, giving:

$$\Delta M_{\mathrm{W}}(\mathrm{q\overline{q}q\overline{q}} - \mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = +5 \pm 51 \text{ MeV}.$$

This result is obtained from a fit to the results of the four experiments taking into account correlations between: the experiments, the two channels and different years. This result is almost unchanged if the systematic part of the error on Mw from fragmentation effects is considered as uncorrelated between experiments, although the uncertainty increases by about 17%. The masses from the two channels obtained from this fit are

$$M_{\mathrm{W}}(\mathrm{W^+W^-}\to\mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = 80.427 \pm 0.038(\text{stat.}) \pm 0.035(\text{syst.}) \text{ GeV},$$
$$M_{\mathrm{W}}(\mathrm{W^+W^-}\to\mathrm{q\overline{q}q\overline{q}}) = 80.432 \pm 0.034(\text{stat.}) \pm 0.064(\text{syst.}) \text{ GeV}.$$

These two results are correlated having a correlation coefficient of 0.29. The value of χ^2/d.o.f is 27.1/28, corresponding to a χ^2 probability of 52%. 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 2.

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

$$M_{\mathrm{W}}^{indep}(\mathrm{W^+W^-}\to\mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = 80.429 \pm 0.038(\text{stat.}) \pm 0.035(\text{syst.}) \text{ GeV}.$$

This result is independent of the measurements in the $\mathrm{W^+W^-}\to\mathrm{q\overline{q}q\overline{q}}$ channel. The systematic error is dominated by fragmentation uncertainties (±26 MeV) and the uncertainty in the LEP centre-of-mass energy (±17 MeV). The independent average over all qqqq measurements only gives

$$M_{\mathrm{W}}^{indep}(\mathrm{W^+W^-}\to\mathrm{q\overline{q}q\overline{q}}) = 80.424 \pm 0.034(\text{stat.}) \pm 0.064(\text{syst.}) \text{ GeV}.$$

where the dominant contributions to the systematic error arise from BE/CR (±56 MeV), fragmentation (±23 MeV) and from the uncertainty in the LEP centre-of-mass energy (±17 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 1.

Experiment	Γ_{W}/GeV
Aleph	$2.17 \pm 0.16 \pm 0.12$
Delphi	$2.09 \pm 0.12 \pm 0.09$
L3	$2.19 \pm 0.14 \pm 0.16$
Opal	$2.04 \pm 0.16 \pm 0.09$
Combined	$2.12 \pm 0.08 \pm 0.07$

Table 4: **PRELIMINARY** W width measurements ($\sqrt{s} = 172-202$ GeV) from the individual experiments. The first error is statistical and the second systematic. The ALEPH results at 192-202 GeV do not use the $\mathrm{W^+W^-}\to\mathrm{q\overline{q}q\overline{q}}$ channel and the OPAL results do not include data recorded at centre-of-mass energies greater than 189 GeV. Only OPAL and L3 include data from 172 GeV.

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 to give:

$$\Gamma_{\mathrm{W}} = 2.12 \pm 0.08(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})\ \mathrm{GeV},$$

with a χ^2/d.o.f. of 13.7/17. Currently no LEP combined value for Γ_{W} is obtained from the $\mathrm{W^+W^-}\to\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{W^+W^-}\to\mathrm{q\overline{q}q\overline{q}}$ channels separately.

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:

$$\begin{aligned} M_{\mathrm{W}} &= 80.427 \pm 0.046\ \mathrm{GeV}, \\ \Gamma_{\mathrm{W}} &= 2.12 \pm 0.11\ \mathrm{GeV}. \end{aligned}$$

References

[1] The ALEPH Collaboration, Phys. Lett. **B401** (1997) 347.

[2] The DELPHI Collaboration, Phys. Lett. **B397** (158) 1997.

[3] The L3 Collaboration, Phys. Lett. **B398** (1997) 223.

[4] The OPAL Collaboration, Phys. Lett. **B389** (1996) 416.

[5] The ALEPH Collaboration, Phys. Lett. **B453** (1999) 121.

[6] The ALEPH Collaboration, CERN-EP/00-045.

[7] The ALEPH Collaboration, "Measurement of the W Mass and Width in e^+e^- Collisions at $\sqrt{s} \sim 192 - 202$GeV", ALEPH 2000-018, CONF 2000-015.

[8] The DELPHI Collaboration, Eur. Phys. J. **C2** (581) 1998.

[9] The DELPHI Collaboration, Phys. Lett. **B462** (410) 1999.

[10] The DELPHI Collaboration, "Measurement of the mass and width of the W Boson in e^+e^- collisions at $\sqrt{s} = 189$GeV", DELPHI 2000-144 CONF 443, Contributed paper for ICHEP 2000.

[11] The DELPHI Collaboration, "Measurement of the mass and width of the W Boson in e^+e^- collisions at $\sqrt{s} = 192 - 202$GeV", DELPHI 2000-149 CONF 446, Contributed paper for ICHEP 2000.

[12] The L3 Collaboration, Phys. Lett. **B407** (1997) 419.

[13] The L3 Collaboration, Phys. Lett. **B454** (1999) 386.

[14] The L3 Collaboration, "Preliminary Results on the Measurement of the Mass and Width of the W Boson at LEP", L3 Note 2377, March 1999.

[15] The L3 Collaboration, "Preliminary Results on the Measurement of the Mass and Width of the W Boson at LEP", L3 Note 2575, July 2000.

[16] The OPAL Collaboration, Eur. Phys. J. **C1** (1998) 395.

[17] The OPAL Collaboration, Phys. Lett. **B453** (1999) 138.

[18] The OPAL Collaboration, Opal Paper PR320, submitted to Physics Letters.

[19] The OPAL Collaboration, "Measurement of the Mass of the W Boson in e^+e^- annihilations at 192-202 GeV", Opal Physics Note PN422 (updated July 2000).

[20] The OPAL Collaboration, "Determination of the W mass in the fully leptonic channel", Opal Physics Note PN447, July 2000.

[21] LEP Energy Working Group, LEPEWG 00/01, June 2000.

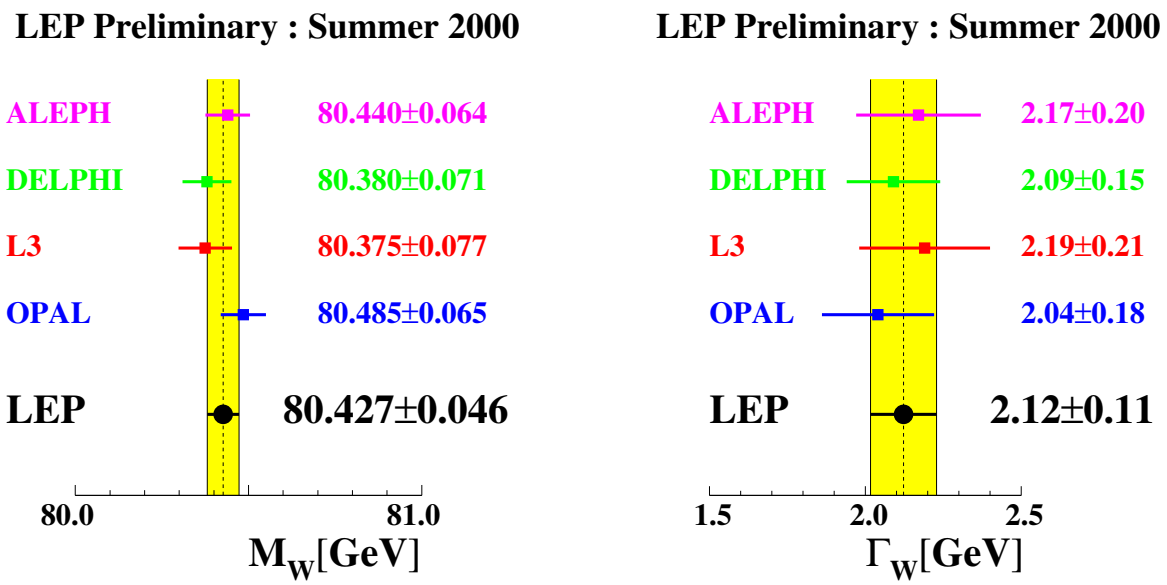

Figure 1: **Summer 2000 Preliminary** The combined results for the measurements of the W mass and W width compared to the results obtained by the four LEP collaborations. The combined values take into account correlations between experiments and years and hence, in general, do not give the same central value as a simple average. In the combination of the $q\bar{q}q\bar{q}$ results the common values for the CR and BEC errors have been used. The individual and combined M_W results include the measurements from the threshold cross section (161 GeV).

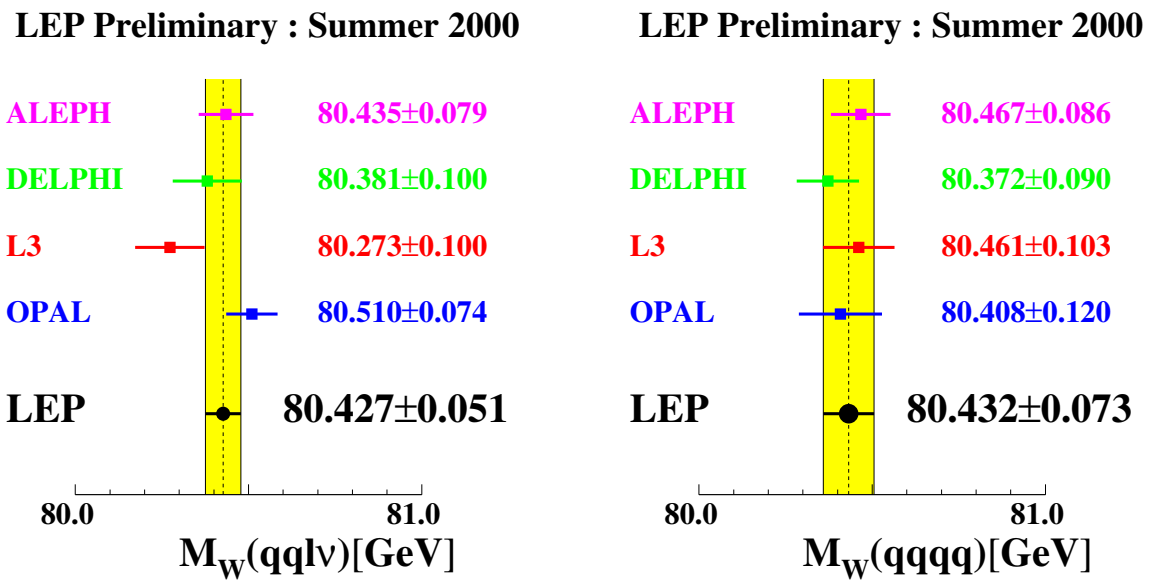

Figure 2: **Summer 2000 Preliminary**. The W mass measurements from the $W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$ and $W^+W^- \to q\bar{q}q\bar{q}$ channels obtained by the four LEP collaborations compared to the combined value. The combined values take into account correlations between experiments, years and the two channels. In the combination of the $q\bar{q}q\bar{q}$ results common CR (50 MeV) and BEC (25 MeV) systematic errors are used. The ALEPH $q\bar{q}\ell\bar{\nu}_\ell$ 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.