# MEASUREMENT OF THE $W$ MASS AT LEP2 FROM THE $WW$ CROSS-SECTION.

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## Abstract

In 1996, the LEP $e^+e^-$ collider at CERN was operated for the first time above the kinematic threshold for the production of pairs of $W$ bosons, at center-of-mass energies of 161 and 172 GeV. The $W$ mass was determined from the measurement of the $W$ pair cross-section at threshold, yielding

$$M_W = 80.40^{+0.22}_{-0.21} \text{ GeV}$$

for the average of the four LEP experiments. The first direct measurement of $W$ leptonic and hadronic branching ratios was also performed: in the assumption of lepton universality, a value of

$$B(W \rightarrow hadrons) = 67.0 \pm 2.0\%$$

was obtained.

## 1 Introduction.

In 1996, the LEP $e^+e^-$ collider at CERN was operated at center-of-mass energies of 161.33±0.05 GeV and 172.11±0.06 GeV, above the kinematic threshold for the process $e^+e^- \to W^+W^-$. This allowed to observe for the first time the production of pairs of $W$ bosons in $e^+e^-$ interactions [1, 2, 3, 4].

The measurements presented in the following are based upon rather limited data samples. The average integrated luminosities delivered by LEP to each experiment at 161 and 172 GeV were 12.1 and 11.3 $\text{pb}^{-1}$: these correspond to approximately 40 and 130 expected $W$ pair events per experiment at the two energies. The results we will quote for the 161 GeV run have already been published, while those obtained on 172 GeV data are preliminary and were prepared especially for this conference.

Close to threshold, the cross-section for $W$-pair production is very sensitive to the mass of the $W$ boson, which can therefore be determined directly from the cross-section measurement. The center-of-mass energy of 161 GeV was chosen precisely because it is the energy which minimizes the expected error on the measurement of the $W$ mass by the threshold cross-section method [5].

At 172 GeV, the cross-section is higher than at 161 GeV, but it is less sensitive to the $W$ mass. A better method to measure $M_W$ consists in this case in the direct reconstruction of the mass of the $W$ from its decay products [6]. On the other hand, the higher event statistics available at 172 GeV allows the determination of the leptonic and hadronic branching ratios of the $W$, from the cross-section measurements in the individual decay channels. This constitutes the first direct measurement of the $W$ branching ratios, with a resolution which compares well with that obtained in previous indirect measurements [7].

## 2 Event selection.

We will concentrate here on the analyses developed for the 161 GeV data. The procedures used for the selection of $WW$ events at 172 GeV were very similar to those used at threshold: apart from a simple rescaling of some cuts to the increased center-of-mass energy, the main changes introduced were meant to take advantage of the increased signal over background ratio, which makes event selection relatively easier at 172 GeV than at 161 GeV. All standard $WW$ decay channels have been separately analysed. We will briefly describe event selection in the following three channels: the fully leptonic channel, where both $W$ bosons decay into leptons; the semileptonic channel, where one $W$ decays into leptons and the other into hadrons; the fully hadronic channel, where both $W$ bosons decay into hadrons. The branching fractions for these three channels are 11%, 44% and 45% respectively.

The fully leptonic channel, $WW \to \ell\nu\ell\nu$, is characterized by two acollinear and acoplanar energetic leptons, and large missing energy corresponding to the two undetected neutrinos. Electrons and muons from $W$ decays have an energy of approximately 40 GeV at threshold; if the lepton is a tau, its decay products give rise to a softer and narrow jet. The main backgrounds come from leptonic two-photon interactions, dileptons from $Z/\gamma*$ decays or Bhabha scattering, and $e^+e^- \to ZZ \to \ell\ell\nu\nu$ four-fermion events. The selection procedures were optimised according to the flavours of the two leptons.

Semileptonic events, $WW \to \ell\nu q\bar{q}$, were identified thanks to the presence of large missing momentum, two hadronic jets and either an energetic electron or muon or a narrow tau jet. At threshold, where $W$ boost is low, the lepton can be efficiently identified from its property of being approximatyely antiparallel to the direction of the missing momentum. The main backgrounds to this channel are $q\bar{q}$ events with energetic leptons from heavy flavour decays, and $e^+e^- \to ZZ$, $Zee$ four-fermion events.

Hadronic events, $WW \to q\bar{q}q\bar{q}$, have no missing energy and are characterized by a large multiplicity of charged and neutral particles, distributed in space with a spherical four-jet topology. The two jets coming from the decay of either $W$ have an invariant mass close to $M_W$ and are approximately back-to-back because of low $W$ boost. This channel is the most difficult to select because of the very large background coming from $e^+e^- \to q\bar{q}$ events with hard QCD gluon radiation, which may also have a spherical four-jet topology. Figure 1 shows the distributions of two typical variables used to discriminate the $WW$ signal from the QCD background. This example indicates that no individual variable provides a good discrimination of the two processes if taken alone; a better separation of the signal from the background can instead be obtained by combining more than one such observable into a single discriminating variable, after a loose preselection. Various multivariable methods of this kind were employed. Figure 2, for instance, shows the output of the neural network used by ALEPH. To measure the cross-section, and determine the $W$ mass at threshold, there is no need to select signal events explicitly. Instead of cutting on the discriminating variable, the cross-section can be determined from a fit to the signal and background content in the sample of preselected events.

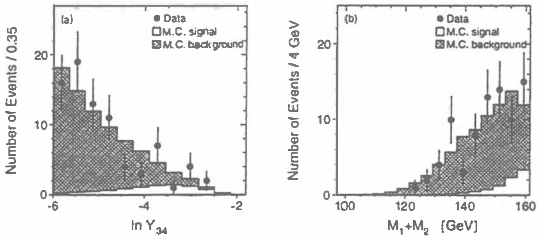

*Figure 1: Distributions used by L3 in the $WW \to q\bar{q}q\bar{q}$ neural network analysis, after preselection: (a) the jet separation parameter, $Y_{34}$, i.e. the value of $Y_{\rm cut}$ at which the transition from three to four jets occurs in the Durham jet algorithm, which is a measure of the minimum relative transverse momentum between any two of the four jets; (b) the sum of the two jet-jet invariant masses, $M_1+M_2$.*

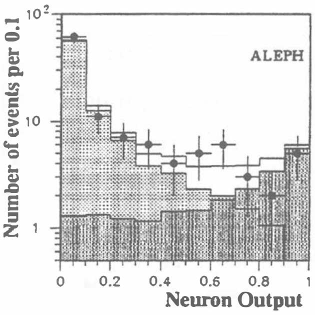

*Figure 2: Output of the neural net used by ALEPH in the $WW \to q\bar{q}q\bar{q}$ analysis, after preselection. Points with error bars are data. The dark shadowed, light shadowed and open histograms represent the MC expectation for the signal, the background and their sum.*

## 3 $WW$ total cross-sections and $W$ mass.

In all four experiments, the total cross-sections were determined from those measured in the individual channels by means of a maximum likelihood fit, assuming the $W$ branching ratios expected in the Standard Model. The results at 161 and 172 GeV are given in tables 1 and 2, respectively. The first error on each result is statistical, the second one systematic; if only one error is quoted, it includes both contributions. The errors on the cross-sections are largely dominated by statistics; conservatively, the smallest systematic error was taken as 100% correlated between the four experiments when combining the results. The combination of the four LEP cross-sections was performed using the expected statistical error on each result instead of the measured one, which is subject to

| Experiment | $\sigma_{WW}$/pb (161 GeV) | $M_W$/GeV |
|---|---|---|
| ALEPH | $4.23 \pm 0.73 \pm 0.19$ | $80.14 \pm 0.34 \pm 0.09$ |
| DELPHI | $3.67^{+0.97}_{-0.85} \pm 0.19$ | $80.40 \pm 0.44 \pm 0.09$ |
| L3 | $2.89^{+0.81}_{-0.70} \pm 0.14$ | $80.80^{+0.48}_{-0.42}$ |
| OPAL | $3.62^{+0.93}_{-0.82} \pm 0.16$ | $80.40^{+0.44}_{-0.41}\,^{+0.09}_{-0.10}$ |
| LEP comb. | $3.69 \pm 0.45$ | $80.40^{+0.22}_{-0.21}$ |

*Table 1: Summary of WW cross-section and W mass measurements at 161 GeV for the LEP experiments.*

| Experiment | $\sigma_{WW}$/pb (172 GeV) |
|---|---|
| ALEPH | $11.65\ ^{+1.29}_{-1.24} \pm 0.25$ |
| DELPHI | $11.38\ ^{+1.54}_{-1.43} \pm 0.32$ |
| L3 | $12.92\ ^{+1.50}_{-1.41} \pm 0.38$ |
| OPAL | $12.3 \pm 1.3 \pm 0.3$ |
| LEP comb. | $12.05 \pm 0.73$ |

*Table 2: Summary of WW cross-section measurements at 172 GeV.*

large fluctuations because of the low event statistics. Systematics come mainly from the hadronic channel, where they are larger than in the selection of leptonic and semileptonic events: the most important contributions arise from the uncertainty in the subtraction of the QCD background, and from the assessment of the agreement of data and Monte Carlo for the variables used as input to the multivariable analyses. The resulting LEP average measured cross-sections at 161 and 172 GeV are compatible with the theoretical expectation, as shown in figure 3; the curve is calculated using the program GENTLE [9], assuming the previous world average value of the $W$ mass, $M_W = 80.356$ GeV.

The cross-sections we have presented are all to be interpreted as "CC03" cross-sections: in other words, they are defined to correspond to the production of four-fermion final states through the three diagrams involving a pair of resonating $W$ bosons [8]. These are the diagrams responsible for the large sensitivity of the threshold cross-section to the $W$ mass. Many other diagrams, involving at most one resonating $W$ boson, lead to the same four-fermion final states and interfere with the CC03 diagrams. The effect of these extra diagrams is taken into account by additive (ALEPH, OPAL) or multiplicative (DELPHI, L3) correction factors, calculated by comparing Monte Carlo simulations including only CC03 processes or the full set of four fermion diagrams.

The $W$ mass was then extracted from the average 161 GeV cross-section for the four LEP experiments. To do this, the theoretical prediction for the $WW$ cross-section as a function of the $W$ mass was calculated using the program GENTLE [9], at the average center-of-mass energy for the four experiments, $\sqrt{s} = 161.33 \pm 0.05$ GeV. This is plotted in figure 4. The result of the measurement is

$$M_W = 80.40^{+0.22}_{-0.21} \text{ GeV}; \tag{1}$$

it is shown in table 1, where the individual mass measurements performed by the four experiments are also indicated. The quoted error, dominated by statistics, includes the beam energy calibration uncertainty and the systematic error of approximately 70 MeV which originates from the common error on the average LEP cross-section. It also includes the 30 MeV uncertainty coming from the 2% error in the GENTLE theoretical calculations.

The sensitivity of the cross-section to the $W$ mass at 172 GeV is not as pronounced as at threshold. If the LEP average cross-section at 172 GeV is used to extract the $W$ mass, one finds $M_W = 80.8^{+0.8}_{-1.0}$ GeV.

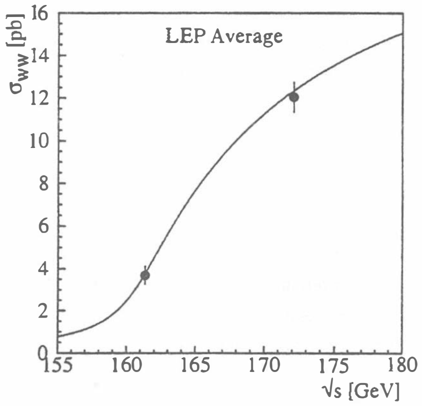

*Figure 3: Comparison of LEP average cross-section measurements at 161 GeV and 172 GeV to the GENTLE theoretical prediction for the previous world average W mass of 80.356 GeV.*

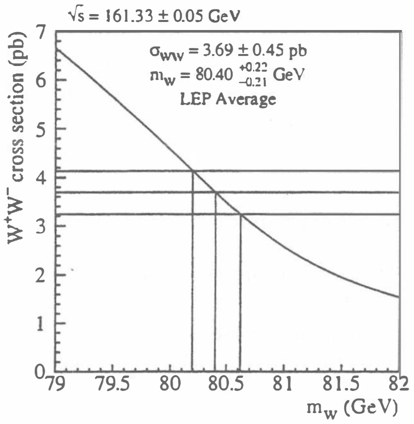

*Figure 4: The WW cross-section at threshold as a function of the W mass, calculated using GENTLE. The yellow band indicates the LEP combined result.*

## 4 $W$ branching ratios.

The cross-sections measured in the individual $WW$ decay channels can be expressed in terms of the total $WW$ cross-section and the $W$ branching ratios,

$$\begin{aligned}
\sigma(WW \rightarrow q\bar{q}q\bar{q}; \sqrt{s}) &= \sigma(\sqrt{s}) B(W \rightarrow hadrons)^2, && (2)\\
\sigma(WW \rightarrow \ell_i\nu_i q\bar{q}; \sqrt{s}) &= 2\sigma(\sqrt{s}) B(W \rightarrow hadrons) B(W \rightarrow \ell_i\nu_i), && (3)\\
\sigma(WW \rightarrow \ell\nu\ell\nu; \sqrt{s}) &= \sigma(\sqrt{s})[1 - B(W \rightarrow hadrons)]^2, && (4)
\end{aligned}$$

where the constraint $B(W \rightarrow hadrons) + \sum_{i=1..3} B(W \rightarrow \ell_i\nu_i) = 1$ is imposed. The results presented in the following were obtained using the measurements of: the hadronic and inclusive fully leptonic cross-sections at 161 and 172 GeV for ALEPH, DELPHI and L3; the inclusive semileptonic cross-section for ALEPH at 161 GeV and for DELPHI at both energies; the exclusive semileptonic cross-sections in the $e\nu q\bar{q}$, $\mu\nu q\bar{q}$ and $\tau\nu q\bar{q}$ channels for ALEPH at 172 GeV and for L3 at both energies.

If the $W$ leptonic branching ratios are not required to be equal, the above formulas may be used to derive the branching ratios for $W$ decays to electrons, muons and taus, as well as the 161 GeV and 172 GeV total cross-sections, from a five-parameter fit to the partial cross-section measurements. The leptonic branching ratios from this fit are

$$\begin{aligned}
B(W \rightarrow e\nu_e) &= 12.0 \pm 2.0\%, && (5)\\
B(W \rightarrow \mu\nu_\mu) &= 10.3 \pm 1.7\%, && (6)\\
B(W \rightarrow \tau\nu_\tau) &= 10.7 \pm 2.2\%, && (7)
\end{aligned}$$

from which one may derive the hadronic branching ratio

$$B(W \rightarrow hadrons) = 67.0 \pm 2.5\%. \qquad (8)$$

Alternatively, one may assume lepton flavour coupling universality and derive the $W$ leptonic branching ratio, as well as the 161 and 172 GeV total cross-sections, from a three-parameter fit to the measured partial cross-sections. In this case, a more precise determination of the hadronic branching ratio is possible,

$$B(W \to hadrons) = 67.0 \pm 2.0\%. \qquad (9)$$

## 5 Conclusions.

The successful upgrade of LEP energy above the $W$ pair threshold has allowed the observation of the first $W$ pairs in $e^+e^-$ collisions. All standard $WW$ decay channels have been analysed. The $W$ mass has been determined from the measurement of the $WW$ cross-section at threshold; a resolution of 220 MeV has been achieved on a sample of data limited to fewer than 200 events in total. The first direct measurement of $W$ branching ratios has been performed. The 1997 LEP run is expected to provide more than 50 pb$^{-1}$ luminosity at a center-of-mass energy of 184 GeV: this will allow major improvements in the measurement of the $W$ mass by the direct reconstruction method and in the measurement of the $W$ branching ratios.

## Acknowledgements.

I would like to thank my colleagues from the four LEP Collaborations, and especially the members of the LEP Electroweak Working Group, for their help in preparing this talk. I also wish to express my gratitude to the organisers of these Rencontres for providing such a stimulating and friendly atmosphere. My participation to this Euroconference was partly supported by the European Commission.

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