OPAL-CR313
10^{th} June 1997.

DIRECT RECONSTRUCTION OF M_W AT LEP *

Mark A. Thomson
CERN, European Organisation for Particle Physics
1211 Geneva 23
Switzerland.

Abstract

This paper describes the first measurements of the W boson mass at LEP from direct reconstruction of the invariant mass of W^+W^- decay products. From an integrated luminosity of ~10 pb^{-1} per experiment a combined value of $M_W = 80.37 \pm 0.19$ GeV is obtained.

*Invited talk at the XXXIInd Rencontres de Moriond, Electroweak Interactions and Unified Theories, March 15-22, 1997.

Introduction

In the first part of 1996 the LEP accelerator produced e^+e^- collisions at a centre-of-mass energy of 161 GeV, just above the threshold for W boson pair production. In the second half of the year the centre-of-mass energy was increased to 172 GeV. Each of the four LEP experiments recorded approximately 10 pb^{-1} of data at each of these energies.

Figure 1 shows the OPAL measurements of the W pair cross section (CC03) at 161 GeV[1)] and 172 GeV[2)]. The solid curve shows the predicted[3)] cross section for $M_W = 80.33$ GeV. The dashed curves indicated the effect on the expected cross section for $M_W = 80.33 \pm 0.5$ GeV. Near to threshold, the cross section is very sensitive to M_W and this enabled the four LEP experiments to measure the mass from the 161 GeV data[1, 4, 5, 6)]. The combined LEP result from the threshold cross section measurement is $M_W = 80.44 \pm 0.22$ GeV[7)]. Above threshold, the sensitivity of the cross section to the mass is greatly reduced. For the 172 GeV data the W mass was determined by direct reconstruction of the invariant mass W^+W^- decay products.

This paper will briefly discuss the methods employed by the LEP experiments in their first preliminary measurements of the W mass from direct reconstruction. The discussion will concentrate on the OPAL measurement which will be used as an overview of the experimental procedure. The discussion of the other three LEP experiments will be limited to the differences in the fitting techniques employed.

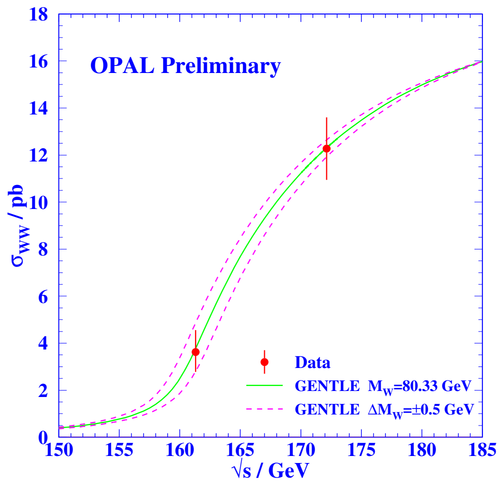

Figure 1: The OPAL measurement of the W^+W^- production cross section (CC03) at 161 GeV and 172 GeV.

Experimental Procedure

Event Selection

Both fully hadronic ($q\bar{q}q\bar{q}$) and semi-leptonic ($q\bar{q}l\nu$) final states have been used in the M_W reconstruction. The fully leptonic final states ($l\nu l\nu$) have not been included in the current analyses since the presence of the two neutrinos greatly reduces the mass sensitivity. The event selections used by the LEP experiments are not necessarily the same as used for the 172 GeV W^+W^- cross section measurements[7)]. In particular, for the cross section determination both ALEPH and OPAL used multivariate selections for the $q\bar{q}q\bar{q}$ channel. For the W mass reconstruction cut based selections were preferred. Table 1 summarizes the efficiencies and purities for the $q\bar{q}q\bar{q}$ channel and the combined $q\bar{q}e\nu$ and $q\bar{q}\mu\nu$ channel for the selections used for the mass determination.

Table 1: Efficiencies and purities for the selections used for the direct reconstruction the W mass.

Expt	$q\bar{q}q\bar{q}$ Selection		$q\bar{q}l\nu$ Selection	
	Effic.	Purity	Effic.	Purity
ALEPH	70%	74%	82%	95%
DELPHI	78%	64%	69%	97%
L3	76%	74%	78%	96%
OPAL	72%	70%	87%	98%

Jet Pairing

In the $q\bar{q}q\bar{q}$ channel selected events are first forced into 4 jets and the jets are then grouped into pairs. There are three different ways of assigning jet pairs to the two Ws in the events *i.e.* (12)(34), (13)(24) and (14)(23). This combinatorial ambiguity is an additional complication. Different experiments have used different procedures in choosing the combination most likely to correspond to the correct pairing.

Mass reconstruction

For each selected W^+W^- event an invariant mass is reconstructed. There are a number of ways of reconstructing the invariant mass of the two Ws in the event from the chosen jet pairing:

- The four momenta of the jets can be used directly to calculate the invariant masses.
- The energy of each of the pairs of jets are scaled to the beam energy, E_{beam}.
- A 4 Constraint (4C) kinematic fit using the measured jet 4-momenta and errors on the 4-momenta imposing energy and momentum conservation. The two reconstructed W masses are highly anti-correlated and to benefit, in terms of resolution, these are averaged.
- A 5 Constraint (5C) kinematic fit with the additional constraint that the two reconstructed masses are equal.

The three latter methods result in a similar mass resolution which is approximately a factor of 4 better than using the measured four momenta. In addition to the gain in mass resolution, the kinematic fit gives a probability that the event is consistent with the fit hypothesis. Small probabilities, indicating poor fits, can be used to reject background. All LEP experiments used kinematic fits to improve the mass resolution.

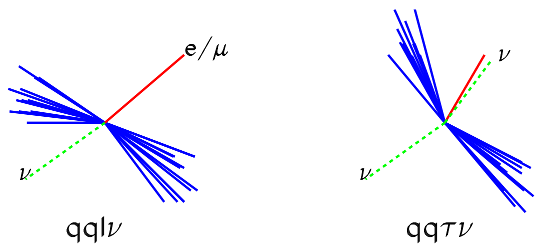

Figure 2: $q\bar{q}l\nu$ and $q\bar{q}\tau\nu$ final state.

For semi-leptonic events, shown in figure 2, a different procedure is used. For $q\bar{q}l\nu$ (l =e,μ) events the best mass resolution is obtained using a 2C kinematic fit. This is identical to the 5C fit described above except that three of the constraints are taken up by the unobserved neutrino momentum. For $q\bar{q}\tau\nu$ events the mass is determined by scaling the energy of the jet-jet system to the beam energy (ignoring the tau decay products).

Fit to the Mass Distribution

The distribution of the masses from selected events is expected to have a Breit-Wigner like structure with its peak at the W mass. A number of methods have been used to extract M_{W} from the mass distribution. Both ALEPH and OPAL used the Monte Carlo calibration procedure, L3 used the reweighting method and DELPHI used the convolution method. These fitting procedures are all described in the report of the LEP2 workshop[8)].

Comparison of Sensitivities

Different final states have different sensitivities to the W mass. It is useful to define a quantity which expresses the inherent statistical sensitivity to the W mass per selected *signal* event. Defining the sensitivity of one selected signal event as :

$$s = \Delta(M_{\mathrm{W}})\sqrt{(N_{sel}^{sig})}$$

where $\Delta(M_{\mathrm{W}})$ is the error on M_{W} obtained from an event sample containing N_{sel}^{sig} selected $\mathrm{W^+W^-}$ events. Using this definition the error on M_{W} is proportional to $s/\sqrt{\epsilon}$, where ϵ is the selection efficiency. Table 2 shows a comparison between the statistical power of different $\mathrm{W^+W^-}$ final states. The efficiencies and purities are 'typical' values. The $\mathrm{q\bar{q}}\tau\nu$ values are from OPAL (so far the only experiment to analyse this channel separately). It is interesting to note that the $\mathrm{q\bar{q}e}\nu$ and $\mathrm{q\bar{q}}\mu\nu$ channels have more statistical power per selected $\mathrm{W^+W^-}$ event than the $\mathrm{q\bar{q}q\bar{q}}$ channel. The lower sensitivity for the $\mathrm{q\bar{q}q\bar{q}}$ selection reflects is the ambiguities in the jet-pairing and the higher background level. Both the combined leptonic and fully hadronic channels give expected errors of approximately 500 MeV per experiment for 10 pb^{-1}.

Table 2: A comparison of the sensitivities of the different channels.

	cross sec.	Effic.	Purity	s	$\Delta(M_{\mathrm{W}})(10\ \mathrm{pb}^{-1})$
$\mathrm{q\bar{q}q\bar{q}}$	5.6 pb	75%	70%	3.3 GeV	510 MeV
$\mathrm{q\bar{q}e}\nu$	1.8 pb	85%	96%	2.5 GeV	640 MeV
$\mathrm{q\bar{q}}\mu\nu$	1.8 pb	87%	98%	2.5 GeV	630 MeV
$\mathrm{q\bar{q}}\tau\nu$	1.8 pb	60%*	90%*	3.4 GeV*	1.0 GeV*

OPAL Results

OPAL used $\mathrm{q\bar{q}q\bar{q}}$, $\mathrm{q\bar{q}e}\nu$, $\mathrm{q\bar{q}}\mu\nu$ and $\mathrm{q\bar{q}}\tau\nu$ final states in the direct reconstruction of the W mass[9)]. In the case of the $\mathrm{q\bar{q}q\bar{q}}$ channel only one of the three possible jet-jet combinations contains any useful information on M_{W}. The choice of which combination to use is based on the 5C kinematic fit probabilities. The fit with the highest probability gives the correct association of the jet pairs to the parent W bosons in ~68% of cases. The mass from this combination is used if the fit probability is $> 1\%$. The 2nd highest probability fit gives the correct association ~25% of the time. The mass from this combination is also used if the fit has a probability of $> 1\%$ and if this probability is within a factor of three of that of the best fit. For some $\mathrm{q\bar{q}q\bar{q}}$ events two masses are reconstructed and used in the mass fit. The other LEP experiments used different methods to deal with the jet pairing ambiguity. A 2C kinematic fit is used to reconstruct the mass in $\mathrm{q\bar{q}e}\nu$ and $\mathrm{q\bar{q}}\mu\nu$ events. Events with a fit probability of $> 0.1\%$ were retained. For selected $\mathrm{q\bar{q}}\tau\nu$ events the mass was determined by scaling the jet energies to the beam energy. In total 115 events were used in the mass determination with two different jet-pairings being used in 17 of the 67 observed $\mathrm{q\bar{q}q\bar{q}}$ events.

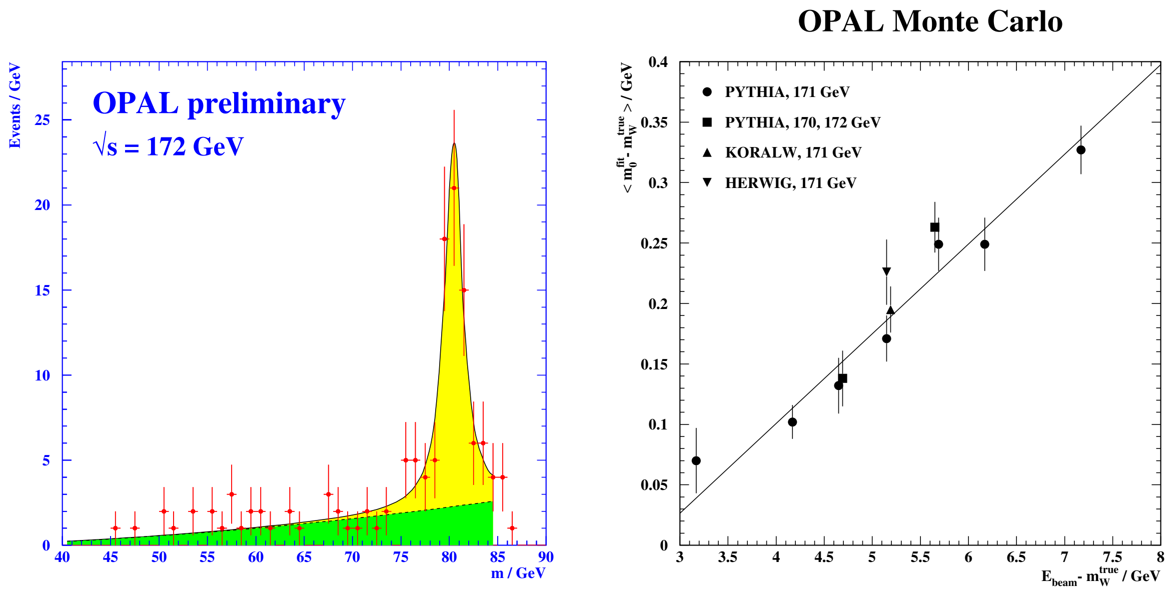

Figure 3: OPAL: a) Mass distribution of the data and b) Monte Carlo calibration curve.

Due to the low statistics of the event sample the masses from all channels were combined into one distribution, shown in figure 3a. In order to extract M_{W} from this distribution parametrizations of expected signal shape (as a function of M_{W}) and background shape are used. The shape of the signal distribution will be a convolution of relativistic Breit-Wigner (the underlying distribution), the (Gaussian) experimental resolution, the effect of phase space and any biases from the kinematic fit and the event selection. Nevertheless, it is found from Monte Carlo that the mass distribution for accepted signal events is well described relativistic Breit-Wigner (in the region $m < 84$ GeV) and the background by a quadratic. The fit of a relativistic Breit-Wigner plus quadratic background term to the combined data of Figure 3a gives: $m_{\mathrm{FIT}} = 80.41 \pm 0.21$ GeV and $\Gamma_{\mathrm{FIT}} = 2.21 \pm 0.58$ GeV . The fitted width of the Breit-Wigner distribution, Γ_{FIT}, is only slightly larger than Γ_{W}, and considerably smaller than the expected value 3.8 GeV. As a consequence the error on the mass is smaller than the expected value. Monte Carlo studies indicate that the probability of getting such a small error is $\sim 10\%$. Further Monte Carlo studies indicate that for these low statistics samples, the error from the fit is not a good estimate of the true uncertainty on the mass. For this reason the expected statistical error is used for these preliminary results rather than the fit error. Both ALEPH and L3 also quote the expected statistical error which is larger than the fitted error. DELPHI use the error from the fit, again the conservative choice since it is larger than the expected error.

A number of effects introduce a shift between the expectation value of the fitted mass and the true value of M_{W}. Such shifts can arise from; the effect of initial state radiation, the event selection, the kinematic fit and fit to the mass distribution. Monte Carlo samples generated at different masses are used to determine the calibration curve between the fitted value and the true value, shown in Figure 3b. A straight line fit to the different Monte Carlo samples gives: $\langle m_{\mathrm{fit}} - M_{\mathrm{W}} \rangle = -0.196 + 0.0742(E_{\mathrm{beam}} - M_{\mathrm{W}})$. Correcting the fitted mass for the bias gives

$$M_{\mathrm{W}} = 80.16 \pm 0.34 \mathrm{GeV},$$

where the error is the expected statistical error. The magnitude of the correction is 240 MeV. How well this correction is understood is one of the main contributions to the systematic error.

The systematic uncertainties on the OPAL measurement of M_{W} are listed in table 3. The Monte

Carlo models used in the $q\bar{q}q\bar{q}$ analysis assume independent fragmentation for the two $q\bar{q}$ pairs from the different W-decays. A number of effects, such as colour reconnection[8] and Bose-Einstein correlations[8] can invalidate this assumption and distort the reconstructed mass spectra. Currently a 100 MeV systematic uncertainty is assigned to this effect, but this figure requires further theoretical and experimental investigation. The systematic uncertainties from detector effects, hadronization and the fit procedure uncertainties all relate to how well the Monte Carlo correction to the fitted mass is currently understood.

Table 3: OPAL: Systematic uncertainties

Error Source	M_W Uncertainty / MeV
Detector Effects	64
Colour Recon./Bose-Einstein	50
Hadronization	44
Fit Procedure	43
Initial State Radiation	27
Beam Energy	25

ALEPH results

The ALEPH analysis[10] is similar to that used by OPAL, *i.e.* reconstruction of the mass distribution, fit to a Breit-Wigner and then application of a correction obtained from a Monte Carlo calibration curve. One of the main differences is that the $q\bar{q}l\nu$ and $q\bar{q}q\bar{q}$ mass distributions are fitted separately with separate bias correction applied to each result. In the $q\bar{q}q\bar{q}$ channel only the best jet pairing combination is used. This is determined (mainly) by minimising

$$\sum_{events} (m_{jj1} - m_{ref})^2 + (m_{jj2} - m_{ref})^2$$

where the m_{jj} are the jet pair masses from a 4C fit and m_{ref} is a a reference mass (the measured mass). The jet pair assignment works iteratively with the reference mass set equal to the measured mass from the previous iteration. This method selects the correct pairing for 79 % of selected events. The results of the are from $q\bar{q}l\nu$: $M_W = 80.51 \pm 0.51 \pm 0.06$ GeV and from $q\bar{q}q\bar{q}$: $M_W = 80.64 \pm 0.45 \pm 0.18$ GeV.

L3 Results

L3 use the reweighting method[8] to fit the mass distribution[11]. With a large enough number of high statistics Monte Carlo samples each generated a different values of M_W, the reconstructed mass distribution in the data could be compared to each of the Monte Carlo samples. A χ^2 could be calculated for each sample giving a χ^2 versus M_W curve, from which the mass for the data could be determined. The disadvantage of this method is the requirement of many Monte Carlo samples. The reweighting method employed by L3 avoids the need for such a large number of simulated events. Only one Monte Carlo sample is generated with $({M_W}^{MC}, \Gamma_W^{MC})$. Event-by-event reweighting based on the generator level invariant masses (m_1, m_2) enables the predicted distribution for a different mass and width to be determined $({M_W}^0, \Gamma_W^0)$. In this method no bias correction (Monte Carlo calibration curve) is required, provided all biases in the reconstructed mass distribution are well described by the Monte Carlo). The resulting fit to the L3 172 GeV data sample gives $M_W = 80.72 \pm 0.34 \pm 0.11$ GeV.

DELPHI Results

Delphi used the convolution method[8] to reconstruct M_W[12]. In this method one attempts to extract the maximal information from each event. The methods described above made no use of the event-by-event mass errors from the kinematic fit; poorly measured events are treated on the same basis as those with smaller errors on the reconstructed event mass.

Due to the limitations of space only the $q\bar{q}l\nu$ aanalysis will described here. It is found that there is a large variation on event-by-event mass error from the kinematic fit. The error from the mass kinematic fit is used as an estimate of the event mass resolution. The use of the mass error information is believed to reduce the statistical error on measurement of M_W by 15%. For each event the probability of observing the measured mass was calculated (as a function of M_W) from the convolution of two distributions. The first being a Breit-Wigner (plus a phase space factor) and the second being Gaussian function with a width given by the error on the mass from the kinematic fit. For each event a likelihood versus M_W curve is obtained. The sum, over selected events, of the log-likelihood curves was used to determine M_W for the event sample. $q\bar{q}e\nu$ and $q\bar{q}\mu\nu$ events were treated separately. The mass from the likelihood curve is then corrected for biases using a Monte Carlo calibration curve. The $q\bar{q}q\bar{q}$ fit is more complex because of the jet pairing ambiguity, but in essence follows that described above. The combined result of the $q\bar{q}q\bar{q}$ and $q\bar{q}l\nu$ fits is $M_W = 80.51 \pm 0.51 \pm 0.06$ GeV.

Combined LEP Results

Table 4 shows the results from the direct reconstruction M_W measurement from the 172 GeV data recorded in 1996. For the combined LEP number a common systematic uncertainty of 30 MeV from beam energy has been included as has a common uncertainty of 50 MeV from possible biases in the $q\bar{q}q\bar{q}$ channel from colour reconnection and Bose-Einstein effects.

Table 4: Preliminary M_W results from the direct reconstruction.

Expt.	M_W	Stat.	Sys.
ALEPH	80.59	± 0.34	± 0.1 GeV
DELPHI	79.95	± 0.38	± 0.06 GeV
L3	80.72	± 0.34	± 0.11 GeV
OPAL	80.16	± 0.34	± 0.11 GeV
LEP 172 GeV	80.37	± 0.17	± 0.08 GeV

Table 5 shows the current combined LEP value for $M_W$from both the cross section measurement at threshold and the direct reconstruction measurement using the 172 GeV data. A common systematic uncertainty of 30 MeV due to beam energy calibration has been included.

Table 5: Preliminary combined M_W results from the LEP 1996 run.

Threshold (161 GeV)	$M_W = 80.40 \pm 0.22$ GeV
Direct Recon. (172 GeV	$M_W = 80.37 \pm 0.19$ GeV
Combined	$M_W = 80.38 \pm 0.14$ GeV

World Average

Figure 4 shows the current world average value of M_W from the direct measurements at both LEP and pp-colliders (including the Tevatron results presented at this conference) compared to the indirect Standard Model value from measurements of electroweak parameters at LEP and SLD. The error from the combination of direct measurements is 80 MeV compared to 40 MeV from the indirect measurements.

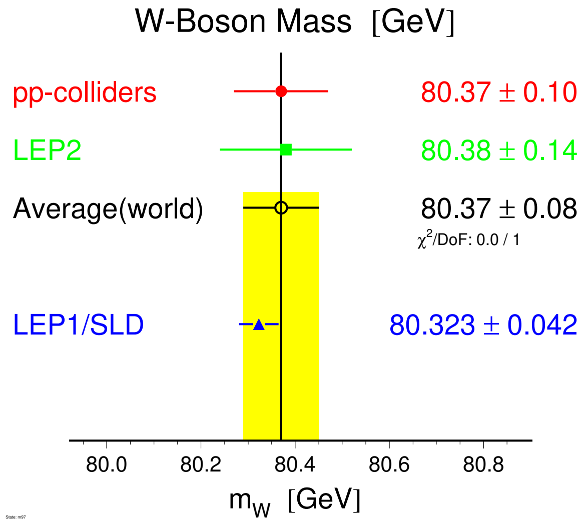

Figure 4: Current world average values of M_W for direct and indirect measurements..

Conclusions

The first attempts at direct reconstruction of M_W by the four LEP collaborations have been successful. From an integrated luminosity of $\sim$10 pb^{-1} per LEP experiment a combined value of $M_W = 80.37 \pm 0.19$ GeV has been obtained. A number of different approaches to fitting the reconstructed mass distribution have been implemented. A statistical precision of $\sim$500 MeV expt^{-1} has be obtained for both the hadronic and semi-leptonic final states. With the projected 500 pb^{-1} LEP 2 data the combined statistical precision for *both* hadronic and semi-leptonic final states will be $<$ 50 MeV.

Acknowledgements

I would like to thank the four LEP experiments and their representatives in the LEP Electroweak Working Group for their assistance in preparing this contribution.

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