W mass measurement at LEP

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In 1998, the four experiments of LEP, i.e. ALEPH, DELPHI, L3 and OPAL, collected data of about 175 pb^{-1} per experiment at the center-of-mass energy of 189 GeV. Using these data, the mass of W boson was directly measured by reconstructing the decay products of two W bosons from the e+e- collisions. The W mass measurement was combined personally with the results obtained from data at 161, 172, and 183 GeV. This yielded the private LEP2 average of $M_\mathrm{W} = 80.350 \pm 0.056$ GeV.

1 Introduction

In June 1996, the LEP2 started with the center-of-mass energy (CME) of 161 GeV, just above the threshold of pair-production of W bosons. This allowed the four experiments of LEP, i.e. ALEPH, DELPHI, L3 and OPAL, to collect data of about 10 pb^{-1} per experiment and to measure the mass of W boson from cross-section measurement of WW events. In October 1996, and in 1997 and 1998, the CME's were raised to significantly above the threshold, 172, 183 and 189 GeV, and the recorded data per experiment were about 10, 55 and 175 pb^{-1}, respectively. Using these data, the mass of W boson was directly measured by reconstructing decay products of W boson pair.

2 Selection

WW events are produced through three doubly resonant diagrams (s-channel γ and Z^0 exchange and t-channel ν exchange), called "CC03 diagrams", where each W can decay into quark pair or lepton-nutorino pair. This leads to the classification of WW events into three channels, i.e. fully hadronic, semileptonic, and fully leptonic channels. WW events are selected with good efficiency and high purity in the analysis, utilising corresponding event-topology to the three channels.

Hadronic $\mathrm{W}^+\mathrm{W}^-\to\mathrm{q\bar{q}q\bar{q}}$ decays comprise 46% of the total $\mathrm{W}^+\mathrm{W}^-$ cross-section. The typical final state of the fully hadronic events is specified by four hadronic jets whose energy sum is consistent with the center-of-mass energy. The background is dominated by electron-positron annihilation to $q\bar{q}(\gamma)$. Semileptonic final states, $\mathrm{W}^+\mathrm{W}^-\to\mathrm{q\bar{q}}\,l\bar{\nu}_l$, are expected to comprise 44% of $\mathrm{W}^+\mathrm{W}^-$ decays. $\mathrm{W}^+\mathrm{W}^-\to\mathrm{q\bar{q}e}\bar{\nu}_e$ and $\mathrm{W}^+\mathrm{W}^-\to\mathrm{q\bar{q}}\mu\bar{\nu}_\mu$ events are characterised by two well-separated hadronic jets, a high momentum lepton and sizable missing momentum due to the unobserved neutrino. The signature for $\mathrm{W}^+\mathrm{W}^-\to\mathrm{q\bar{q}}\tau\bar{\nu}_\tau$ events is two well separated jets from the hadronic W decay and one low multiplicity jet typically consisting of one or three tracks due to the decay of tau. The dominant backgrounds are $Z^0/\gamma \to q\overline{q}$ and four-fermion processes such as $e^+e^- \to We\overline{\nu}_e$ and $(Z^0/\gamma)^*(Z^0/\gamma)^* \to q\overline{q}l^+l^-$. Fully leptonic $W^+W^- \to l^+\nu l^-\overline{\nu}$ decays comprise 10% of the total W^+W^- cross-section. The typical fully leptonic WW events consist of two acoplanar energetic leptons with significant missing energy in detectors. Typical efficiency and purity of WW event selection and expected and observed numbers of events in each channel, from ALEPH at 189 GeV, are shown in table 1.

Table 1: WW event selection of ALEPH at 189 GeV.

	Efficiency (%)	Purity (%)	Exp. N evts	Obs. N evts
$q\overline{q}q\overline{q}$	71.4	84.7	1173	1068
$q\overline{q}e\overline{\nu}_e$	81.3	92.7	371	358
$q\overline{q}\mu\overline{\nu}_\mu$	84.1	96.6	365	363
$q\overline{q}\tau\overline{\nu}_\tau$	41.5	95.4	176	159

3 Extraction of W mass

As to the actual procedure to measure M_W from W-pair production, two methods are advocated. One procedure requires a measurement of the total W-pair cross-section close to the threshold, where the size of σ_{tot} is most sensitive to the W mass. This method is adopted at the CME of 161 GeV and the result of W mass measurements is 80.40 ± 0.22 GeV [1,2] with combining four experiments.

The other one is called the direct mass reconstruction method, which is adopted at the CME's of 172, 183 and 189 GeV. In this method, the measurement of the W mass can be made by direct reconstruction of the invariant mass of the fermion pairs from each W decay, using a kinematic fit technique with some constraints. Incorporating the constraints of energy and momentum conservation into a kinematic fit significantly improves the invariant mass resolution and is adopted by all experiments. Specific combinations of additional constraints and techniques, for example, a constraint of equal mass of two W bosons, a technique of beam energy rescaling and so on, are employed by some experiments.

Events of the fully hadronic and semileptonic decay channels are used in the analysis. In the fully hadronic channel, four jets in an event can be divided into two di-jets in three different ways. It is not obvious which of these partitions is correct and so this ambiguity leads to a combinatorial background. Four experiments employed different pairing schemes to optimise the sensitivity to the W mass. In a $W^+W^- \to q\overline{q}\, l\overline{\nu}_l$ event (l =e or μ), a kinematic fit is performed including two jets and one lepton, imposing the constraints mentioned above. For $W^+W^- \to q\overline{q}\tau\overline{\nu}_\tau$ events, ALEPH employed a kinematic fit, L3 and OPAL utilised a technique of beam energy rescaling. Fig. 1 shows the distributions of the reconstructed invariant mass from L3 for (a) semileptonic and (b) fully hadronic channels, where a larger amount of background in fully hadronic channel than the semileptonic channel is due to the above mentioned jet-pairing combinatorial background.

The invariant mass distributions obtained from the event sample have a Breit-Wigner like shape but distorted due to several effects such as phase space restrictions, detector resolution, initial state radiation, background contamination, selection algorithms, etc... A possible way of extracting M_W is fitting directly to the data the invariant mass distribution predicted by the Monte Carlo (MC) including all distortions. In this method, MC events for some specific input values of ${M_W}^{MC}$ are generated, and by reweighting technique, a MC sample with an arbitrary input value of ${M_W}^{MC}$ is produced. Then one can find the best matching MC sample to the data, where that ${M_W}^{MC}$ yields the measurement of M_W. ALEPH, L3 and OPAL employed this method to extract the W mass [3,4].

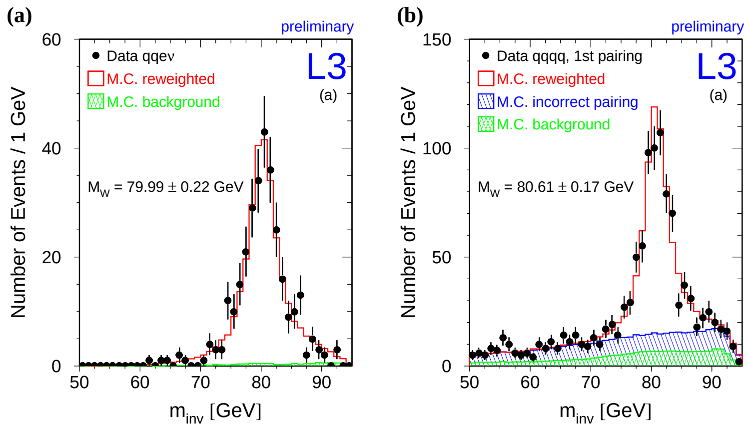

Figure 1: The invariant mass distributions from L3 at 189 GeV.

On the other hand, DELPHI developed a different method in which the information on the W mass is extracted from the likelihood of observing each individual event [5]. The event-by-event likelihood as a function of M_{W} is calculated by the convolution of a Gaussian resolution function with a mean of fitted invariant mass and a width of its error, and a relativistic Breit-Wigner function of M_{W} including the phase space effect, taking into account the efficiency, purity, background, all jet-pairing combinations in $\mathrm{q\bar{q}q\bar{q}}$ channel and so on. The combined likelihood for observing all the events is expressed as the product of all the event-by-event likelihoods. The maximum of this combined likelihood then yields the measurement of the W mass.

4 Results

Table 2: Official and private averages of LEP M_{W} measurements by direct reconstruction method.

W mass results (GeV)	Mw ± (stat.) ± (syst.) ± (FSI) ± (LEP)	Data
Official average	80.368 ± 0.044 ± 0.039 ±0.023 ± 0.018	A+L 172-189 GeV D+O 172-183 GeV
Private average	80.347 ± 0.036 ± 0.036 ±0.020 ± 0.017	A+D+L+O 172-189 GeV

The official average of measured M_{W}'s from ALEPH and L3 using 172 - 189 GeV data and DELPHI and OPAL using 172 - 183 GeV data is shown in table 2. The first, second, third and fourth errors are the statistical and systematic uncertainties, and the uncertainties from the final state interactions (FSI) and the LEP beam energy (LEP), respectively. During this conference, on 23 March 1999, the results of DELPHI and OPAL at 189 GeV were approved and I privately averaged all these results. This private combined results of LEP four experiments is also shown in table 2. The systematic error and uncertainty from FSI will be mentioned in next section.

Recently ALEPH released a new analysis in which M_{W} is extracted from $\mathrm{W} \to l\bar{\nu}_l$ decays using 57 pb^{-1} data at 183 GeV. The result is M_{W}= 80.142 ± 0.192 ± 0.089 GeV combining results from $l^+\nu l^-\bar{\nu}$ and $\mathrm{q\bar{q}}\,l\bar{\nu}_l$ channels, where the first and second errors are statistical and systematic uncertainties, respectively.

5 Systematic errors

Typical systematic errors on M_{W} measurement from OPAL at 183 GeV are shown in table 3 for $\mathrm{q\overline{q}q\overline{q}}$, $\mathrm{q\overline{q}}\,l\overline{\nu}_l$ and combined results. The uncertainties of M_{W} measurement are from LEP beam energy precision, theoretical uncertainty of initial state radiation, hadronization model dependence in MC's, effects of not including interference terms between CC03 and other four-fermion diagrams in reweighting procedure, detector effects, reweighting fit procedure, uncertainties of normalization and shape of background distributions in MC samples, finite statistics of used MC samples, Bose-Einstein (BE) correlations and Colour Reconnection (CR) effects.

BE correlations and CR effects are simply called final state interactions and then abbreviated as FSI. Uncertainty from BE correlations happens only in $\mathrm{q\overline{q}q\overline{q}}$ channel, because BE correlations between decay products from different W's might distort the invariant mass spectrum. Two MC samples with and without this effect are compared, and the difference of measured M_{W}'s is assigned as systematic error. Uncertainty from CR effects also happens only in $\mathrm{q\overline{q}q\overline{q}}$ channel. In normal MC's, fragmentation is implemented only within each W, but fragmentation between two W's might distorts the invariant mass spectrum. Various MC models including CR effects are checked using 183 GeV data and the Ellis-Geiger model VNI was excluded [6]. In OPAL, ARIADNE model is used to assign the systematic error by comparing it with a normal MC sample [4].

Table 3: Summary of the systematic uncertainties from OPAL at 183 GeV.

Systematic errors (MeV)	M_{W} $\mathrm{q\overline{q}q\overline{q}}$	M_{W} $\mathrm{q\overline{q}}\,l\overline{\nu}_l$	M_{W} comb.
Beam Energy	22	22	22
Initial State Radiation	10	10	10
Hadronization	21	21	16
Four-fermion	30	28	21
Detector Effects	38	31	26
Fit Procedure	15	15	15
Background	25	10	10
MC statistics	15	15	11
Sub-total	67	58	49
Bose-Einstein Correlations	32	0	11
Colour Reconnection	49	0	16
Total systematic error	89	58	53

6 Conclusions

The four experiments of LEP collected data successfully at the CME's of 161, 172, 183 and 189 GeV. The official average of M_{W} using the data of (A+L 172 - 189 GeV) and (D+O 172 - 183 GeV) is 80.368$\pm$0.044(stat.) $\pm$0.039(syst.) $\pm$0.023(FSI) $\pm$0.018(LEP) GeV. If combining it with results at 161 GeV, the official LEP2 average is $M_{\mathrm{W}} = 80.370 \pm 0.063$ GeV. Including DELPHI and OPAL results at 189 GeV, the private average of M_{W}, where the data is (A+D+L+O 172 -189 GeV), is 80.347 $\pm$ 0.036(stat.) $\pm$0.036(syst.) $\pm$0.020 (FSI) $\pm$0.017(LEP) GeV. If this is combined with results at 161 GeV, the private LEP2 average is

$$M_{\mathrm{W}} = 80.350 \pm 0.056 \text{ GeV}.$$

Because the systematic error on $M_{\rm W}$ measurement is now less than the statistical error, more studies are needed on sytematic errors from BE correlations, CR effects, LEP beam energy, detector effects and so on. Also important is utilizing W $\rightarrow l\overline{\nu}_l$ decays to reduce the error on $M_{\rm W}$ measurement.

The private world average of W mass direct measurements combining the private LEP2 average and results of direct measurements from Tevatron [7] is shown in figure 2 (a). In the same figure, the private world average of $M_{\rm W} = 80.394 \pm 0.042$ GeV is compared with the indirect W mass measurements from TuTeV/CCFR and LEP1/SLD/νN/$m_{\rm t}$ [8]. The direct and indirect measurements are in agreement within errors. The comparison of the indirect measurements of $m_{\rm W}$ and $m_{\rm t}$ (LEP+SLD+νN data) [8] (solid contour) and the direct measurements (Tevatron [7] and LEP2 official averages) (dashed contour) is shown in figure 2 (b). Also shown in the figure are the Standard Model relationship for the masses as a function of the Higgs mass, and the private world average of W mass in three dashed lines with a width of the measurement error.

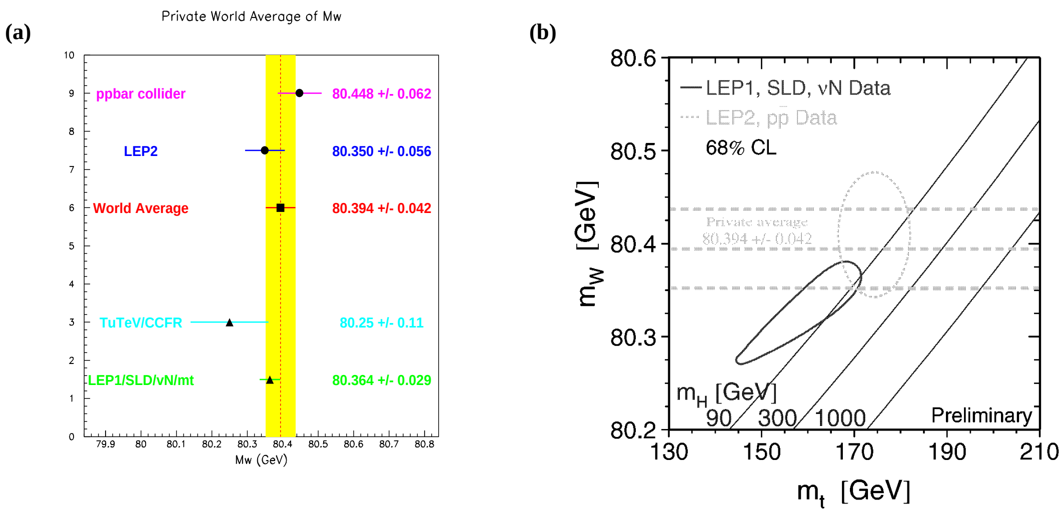

Figure 2: (a) the private world average of W mass direct measurements and comparison with indirect W mass measurements, and (b) the comparison of the indirect measurements of $m_{\rm W}$ and $m_{\rm t}$ (LEP+SLD+νN data) (solid contour) and the direct measurements (Tevatron and LEP2 official averages) (dashed contour). In both cases the 68% C.L. contours are plotted.

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