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MEASUREMENT OF THE W-BOSON MASS AT LEP

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In 1997 each LEP experiment recorded approximately 55 pb^{-1} of data at mean centre-of-mass energy of 183 GeV. The experimental details of the measurement of the mass of the W-boson in the fully hadronic final state ($W^+W^- \to q\overline{q}q\overline{q}$) are described. This result is combined with the measurement obtained from $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ events. The LEP combined result, obtained from all data recorded above the W-pair production threshold, assuming the Standard Model relation between the W-boson decay width and mass, is $M_W = 80.37 \pm 0.07(\text{exp}) \pm 0.04(\text{FSI}) \pm 0.02(E_\text{beam})$. This result is consistent with the indirect determination of M_W from fits to Z^0 data obtained at LEP and SLC.

1 Introduction

The aim of the LEP 2 program is to deliver 500 pb^{-1} of data[a] above the W-pair production threshold. These data will be used to study the properties of the W-boson: mass, production cross section, decay branching ratios and triple gauge couplings. The consistency of the direct measurement of M_W from LEP 2 and from the Tevatron with the indirect determination from fits to LEP 1 and SLC Z^0 electroweak data provides an interesting test of the the Standard Model (SM). Furthermore, precise measurements of M_W and M_top can be interpreted as an indirect measurement of the Higgs mass, m_H.

In the first two years of LEP 2 running, approximately 75 pb^{-1} of data have been recorded by each LEP experiment. Of these data, 10 pb^{-1} were recorded at $\sqrt{s}$ = 161 GeV just above W^+W^- production threshold. At this energy, the W^+W^- production cross section is sensitive to the W-boson mass (see Figure 1). This dependence was used to obtain [1]:

$$M_W = 80.40 \pm 0.20(\text{exp}) \pm 0.03(E_\text{beam}) \text{ GeV},$$

where the errors are experimental (combined statistical and systematic) and due to the uncertainty in the LEP beam energy. Above threshold, the sensitivity of the W^+W^- production cross section to M_W is diminished and an alternative method to measure M_W, direct reconstruction, is employed.

The method of direct reconstruction as applied to $W^+W^- \to q\overline{q}q\overline{q}$ channels is described below. The results are then combined with those obtained from the $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ final state (described elsewhere in these proceedings [2]). Finally the combined LEP measurement is compared to data from other experiments.

[a]all luminosities are quoted for a single LEP experiment.

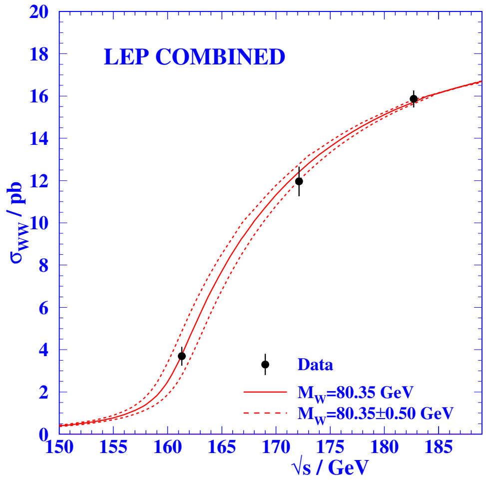

Figure 1: σ_{WW} versus $\sqrt{s}$. The points show the LEP combined data, the solid line shows the standard model expectation assuming M_W = 80.35 GeV and the dashed lines show the variation in the cross section corresponding to a ±500 MeV variation in M_W.

2 M_W from $W^+W^- \to q\overline{q}q\overline{q}$

2.1 Event Selection

The ALEPH, L3 and OPAL collaborations use multivariate techniques to separate $W^+W^- \to q\overline{q}q\overline{q}$ events from the main background process, $Z^0/\gamma \to q\overline{q} \to 4$ jets. DELPHI use a cut based selection optimised for high efficiency for those $W^+W^- \to q\overline{q}q\overline{q}$ events which have useful mass information. A comparison of the performances of the event selections [3,4] used by the four LEP collaborations is given in Table 1.

2.2 $W^+W^- \to q\overline{q}q\overline{q}$ *versus* $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$

Before describing the details of the determination of M_W from $W^+W^- \to q\overline{q}q\overline{q}$ events, it is interesting to contrast

Table 1: Comparison of selection efficiencies and purities of the $W^+W^- \to q\overline{q}q\overline{q}$ event samples used in the determination of M_W. The numbers for the DELPHI collaboration are not directly comparable to the others since in the determination of M_W events are weighted according to how likely they are to be $W^+W^- \to q\overline{q}q\overline{q}$.

	Efficiency	Purity
ALEPH	89%	82%
DELPHI	85%	65%
L3	88%	80%
OPAL	85%	79%

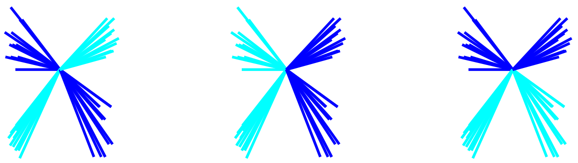

Figure 2: The three possible jet pairings.

the $W^+W^- \to q\overline{q}q\overline{q}$ channel with the $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ channel. The branching fractions for W^+W^- decaying into the fully-hadronic and semi-leptonic final states are similar $\sim 45\%$, as are the selection efficiencies, both $\sim 85\%$. As a result the numbers of W^+W^- events selected in each channel are comparable. For the semi-leptonic channel there is at least one neutrino in the final state (two or three in the case of $W^+W^- \to q\overline{q}\tau\overline{\nu}_\tau$ events). One might expect the fully hadronic channel to have approximately twice the statistical power as the semi-leptonic channel since the decay products of both Ws are observed. However, there are a number of disadvantages with fully-hadronic final state:

- there is an ambiguous assignment of tracks and clusters to jets;
- there is a three-fold ambiguity in the assignment of jets to Ws (see figure 2) resulting in a combinatoric background;
- there is a larger background fraction (mainly $Z^0/\gamma \to q\overline{q} \to 4$ jets).

As a result of the above effects, the statistical sensitivity of the $W^+W^- \to q\overline{q}q\overline{q}$ channel is degraded to a level which is very similar to that obtained from the $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ channel. In addition, in the $W^+W^- \to q\overline{q}q\overline{q}$ channel, there are potentially large systematic uncertainties arising from possible final state interactions (FSI) between the jets from different W-decays, *e.g.* colour reconnection (CR) and Bose-Einstein correlations (BEC).

2.3 *Mass reconstruction*

Selected $W^+W^- \to q\overline{q}q\overline{q}$ events are forced into four jets using the Durham algorithm [5] (DELPHI also use 5-jet configurations). From four jets there are three ways of choosing which two pairs of jets correspond to the two W-bosons. Experimentally the jet angles are much better determined than the jet energies and significant gains in mass resolution can be obtained by using an energy constraint. In W^+W^- production in e^+e^- colliders, the sum the energies of the final state fermions is equal to $\sqrt{s}$, apart from the effects of initial state radiation (ISR). This energy constraint results in a significant improvement in the event-by-event mass resolution. For a given choice of jet-pairing, there are a several methods for reconstructing the invariant mass of each W-boson from its decay products:

- **Raw mass**; the masses are determined from the measured jet energies and momenta, $M^{raw}_{q\overline{q}} = \sqrt{2E_1E_2}(1-\cos\theta_{12})$, where θ_{12} is the angle between the two jets and E_i is the energy of the ith jet.
- **Scaled mass**; the energy of the jet-jet system is scaled to the beam energy, $E_{\rm beam}$, giving $M^{scaled}_{q\overline{q}} = M^{raw}_{q\overline{q}} \frac{E_{\rm beam}}{(E_1+E_2)}$
- **4C Kinematic fit**; imposing the constraints of energy and momentum conservation, $\sum(E,\mathbf{p}) = (\sqrt{s},\mathbf{0})$, yielding two reconstructed masses, corresponding to the two W-bosons in the event. After the kinematic fit, the sum of the two masses is better determined than the difference due to the energy constraint and the fact that the jet energies are relatively poorly determined. Another consequence is that the two 4C fit masses are highly anti-correlated.
- **Rescaled 4C fit**; ALEPH re-scale the two 4C masses using the measured jet energies, $M^{\rm rescaled}_{ij} = M^{4C}_{ij} \frac{E_{\rm beam}}{(E_i+E_j)}$. This removes the anti-correlation between the two 4C fit masses and has the advantage that certain systematic effects cancel.
- **5C Kinematic fit**; in addition to the four constraints of the 4C fit, the finite width of the W-boson is ignored and the two reconstructed masses are required to be equal, yielding a single fitted mass per event.

Figure 3 shows a comparison of the mass resolution of the first three methods described above. Since jet directions are better determined than the jet energies, even the relatively simple use of an energy constraint as employed in the scaled mass method yields a significant improvement compared to the raw mass.

For the measurement of the W-boson mass, DELPHI use the two masses from the 4C kinematic fit, ALEPH use the two rescaled 4C fit masses and L3 and OPAL use the 5C fit mass.

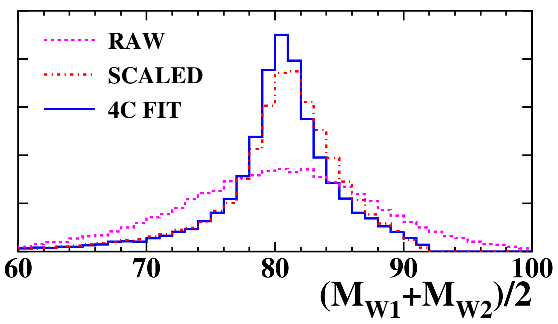

Figure 3: A comparison of the mass resolution obtained using the raw mass, the scaled mass and the 4C fit mass. In each case the average of the reconstructed masses of the two W-bosons is plotted.

2.4 *Selecting the correct jet pairing*

For each event, one has the results from three different kinematic fits corresponding to the three jet pairings of Figure 2. Only the correct pairing, *i.e.* the one with the correct association of jets to the two W-bosons, contains information useful for extracting $M_{\rm W}$. The inclusion of incorrect pairings will result to a combinatoric background. To avoid this combinatoric background a number of algorithms have been developed to select the correct jet pairing. For example, OPAL and L3 use probability of 5C fit. This probability can be viewed as the consistency of a particular jet pairing with the hypothesis of that the jets come from the decays of two particles of equal mass. The jet-pairings are placed in descending order of 5C fit probability[b], $P_1 > P_2 > P_3$. Figure 4 shows Monte Carlo 5C fit mass distributions ordered by fit probability, *i.e.* the first plot shows the distribution for the 5C fit giving with the highest probability, *etc.* For events where the correct jet-pairing gives an acceptable kinematic fit, the correct pairing corresponds to the highest probability fit in $80-85\%$ of cases. Nevertheless, there is significant mass information in the second highest probability fit. Both L3 and OPAL use the highest and second highest probability fits in their determination of $M_{\rm W}$. The reconstructed 5C mass distribution for $\rm W^+W^- \rightarrow q\overline{q}q\overline{q}$ obtained by L3 is shown in Figure 5. In this distribution the fitted 5C masses from the highest and second highest probability fits are used. In the case of the OPAL experiment, the masses from the second best fit enter the reconstructed mass distribution with a weight given by $P_2/(P_1+P_2)$.

The ALEPH collaboration use only one jet pairing per event. The algorithm to decide which combination is used is based on the difference between the two fitted masses reconstructed using the rescaled 4C fit. The efficiency for identifying the correct combination is $\sim 87\%$. This procedure has the advantage that only one combination per event is used. In the DELPHI fit to $M_{\rm W}$, described below, all jet pairings are used.

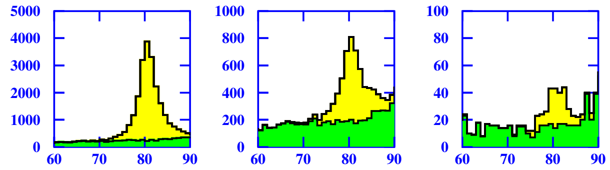

Figure 4: Monte Carlo reconstructed mass distributions from a 5C fit ordered by fit probability, *i.e.* the first plot shows the distribution for the fit giving the highest probability, *etc.* In each plot, the lightly shaded histogram shows the component from the correct jet pairing and the combinatoric background is shown as the dark histogram.

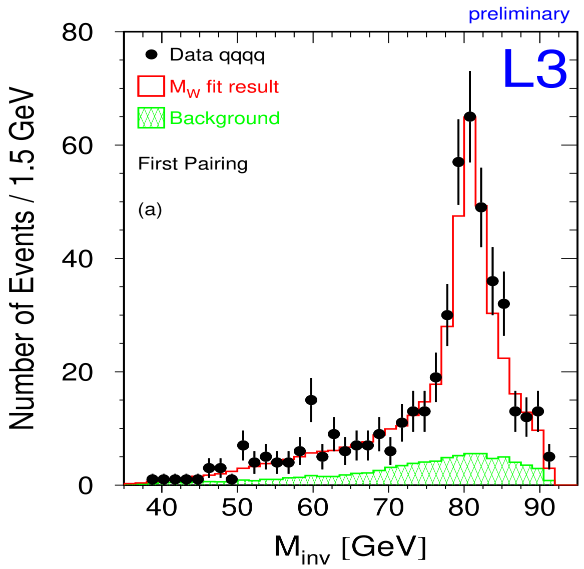

Figure 5: Reconstructed mass distribution for the $\rm W^+W^- \rightarrow q\overline{q}q\overline{q}$ channel from the L3 collaboration.

2.5 *W-mass determination*

There are a number of possible techniques to extract $M_{\rm W}$ from the reconstructed mass distribution. As in their previous analyses[6], ALEPH, L3 and OPAL use a likelihood fit comparing the measured distribution to Monte Carlo spectra corresponding to different values of $M_{\rm W}$. This procedure has the advantage that all biases in the reconstructed mass distribution (*i.e.* event selection, ISR, detector resolution, *etc.*) are included in the Monte Carlo spectra. In order to minimise the necessary Monte Carlo statistics the reweighting method is used. L3 fit the 1-dimensional distribution of reconstructed masses (shown in Figure 5). OPAL perform a similar fit. ALEPH

[b]It should be noted that not all jet-pairings result in a kinematic fit with an acceptable χ^2 probability. In particular, for incorrect jet pairings the fit will often fail to converge.

fit the 2-dimensional distribution of the rescaled 4C fit masses of each event. DELPHI employs a convolution method based on that used for previous data [7]. This method uses all jet pairing combinations as well the errors on the fitted masses. The results of the 4C fit are interpreted as a 2-dimensional probability density function (PDF). The convolution of this function with a 2-dimensional Breit-Wigner distribution $\mathcal{BW}(M_{\mathrm{W}})$ is used to calculate the event likelihood as a function of M_{W}; $\mathcal{L}(M_{\mathrm{W}}) = \mathrm{PDF}_i \otimes \mathcal{BW}(M_{\mathrm{W}})$. Unlike in the reweighting fit, experimental biases and the effects of ISR are not implicitly included and corrections need to be applied. These corrections are determined using Monte Carlo.

To summarise: L3 and OPAL use MC reweighting technique to fit the 5C mass distribution (1 or 2 jet pairings per event); ALEPH use a MC reweighting fit to the 2-dimensional distribution of rescaled 4C masses (one jet pairing per event); and DELPHI use the convolution method using the 4C fit results (all jet pairings).

2.6 Systematic Uncertainties

Table 2: Typical systematic uncertainties on M_{W} from the $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ channel quoted by the four LEP collaborations.

Source	ΔM_{W} (MeV)
QCD background	10
MC statistics	10
Initial state radiation	15
Beam energy	20
Hadronization	30
Detector calibration	30
Final State Interactions	90
Total	**110**

Table 2 lists typical values of the main sources of systematic uncertainty in the determination of M_{W} from the $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ channel. The dominant uncertainty arises from possible "final state interactions" (FSI) between the jets from different W-bosons. The standard Monte Carlo generators assume independent fragmentation of the two W bosons in $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ events. If this is not the case, biases in the reconstructed mass distribution can occur. Since W-bosons decay within a distance of < 0.1 fm, smaller than the hadronization scale ~ 1.0 fm, the fragmentation process for the two hadronic decay products from the two W-bosons in the event is not necessarily independent. Two main sources of possible interconnection between the decay products of the two W-bosons have been considered; Bose-Einstein correlations (BEC) and colour reconnection (CR), both reviewed at this conference [8,9].

The phenomena of BEC in multi-particle final states is a quantum mechanical effect which results in a tendency for like-sign pions to be produced close together in phase space. The effect of BEC in $\mathrm{Z^0}$ decays has been unambiguously observed at LEP [10] and undoubtedly exists in hadronic W-decays. The question of relevance to the determination of M_{W} is whether BEC exist between pions from the decays of *different* W-bosons. If so, then a bias in the mass measurement could be introduced. Currently the measurements of BEC in $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ events are not of sufficient statistical sensitivity to establish or revoke the existence of BEC between pions from different W-bosons [8].

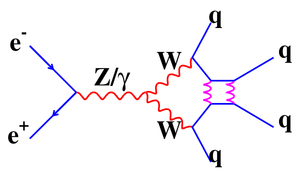

Figure 6: Perturbative colour interconnection.

The other class of possible FSI is colour reconnection. In the perturbative phase (QCD), colour connection between the quarks from different W-decays can occur via diagrams such as that shown in figure 6. However, such diagrams are suppressed by colour factors and the need to exchange two gluons. These perturbative effects are believed to be small $<$ 10 MeV. In addition to reconnection phenomena in the perturbative phase, possible effects could arise in the non-perturbative hadronization phase. Here, one has to rely on fragmentation models (sting, cluster, *etc.*) to assess the possible influence on the determination of M_{W}. A variety of models implementing interconnection effects have been proposed. Different models predict different biases in the measurement of the M_{W} from the $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ channel, with predictions ranging from $0 - 300$ MeV. Currently, no evidence for colour interconnection effects have been observed in $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ events [9].

In the absence of any experimental demonstration of the existence or non-existence of FSI between the decay products of different W-bosons, the systematic uncertainty from such effects is estimated by comparing the mass biases observed from a variety of Monte Carlo models. The current situation is summarised in Table 3. It has been noted that the current implementation of the VNI model [11] does not reproduce the properties of $\mathrm{Z^0}$ hadronic decays and is not used for the estimate of the size of possible colour reconnection effects. DELPHI, L3 and OPAL quote a systematic uncertainty on M_{W} from the $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ channel of 100 MeV for BEC and CR. ALEPH quote 25 MeV for CR and 50 MeV for BEC.

If FSI significantly influenced the M_{W} determination in the $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ channel then one might observe differences between M_{W} obtained from the

$W^+W^- \rightarrow q\bar{q}\ell\overline{\nu}_\ell$ and $W^+W^- \rightarrow q\bar{q}q\bar{q}$ channels. Currently consistent values are obtained, $M_W^{q\bar{q}q\bar{q}} - M_W^{q\bar{q}\ell\overline{\nu}_\ell} = 80 \pm 140$ MeV (statistical error only).

Table 3: Some typical values for mass biases predicted by different colour reconnection and BEC models.

Model	Effect	Mass shift
Herwig	CR	$\sim$ 10-30 MeV
Pythia	CR	$\sim$ 20-50 MeV
Ariadne	CR	$\sim$ 50-150 MeV
VNI	CR	$\sim$ O(100) MeV
Pythia	BEC	$\sim$ 20-50 MeV
KoralW	BEC	$\sim$ 20-50 MeV

2.7 Results

Table 4 summarises the measurements of M_W using the $W^+W^- \rightarrow q\bar{q}q\bar{q}$ channel. For each experiment, the result is the combination of that obtained from 10 pb^{-1} of data recorded at $\sqrt{s}$ =172 GeV and the *preliminary* results from 55 pb^{-1} of data recorded at $\sqrt{s}$ =183 GeV. For the LEP combination, a 90 MeV common systematic uncertainty for FSI was assigned. A common systematic of 40 MeV accounted for hadronization and ISR. The beam energy uncertainty was taken to be 100% correlated between the four experiments.

3 Combined LEP M_W

The results from direct reconstruction of the fully hadronic channel are combined with the mass obtained from the semi-leptonic channel [2] $M_W^{q\bar{q}\ell\overline{\nu}_\ell} = 80.31 \pm 0.11$ GeV where the systematic errors arising from ISR and the LEP beam energy are taken to be 100 % correlated. The results from the combination of the $W^+W^- \rightarrow q\bar{q}\ell\overline{\nu}_\ell$ and the $W^+W^- \rightarrow q\bar{q}q\bar{q}$ channels (172 GeV and 183 GeV) from the four LEP experiments are compared in figure 3. This combined result from direct reconstruction, $80.36 \pm 0.08(\text{exp}) \pm 0.05(\text{FSI}) \pm 0.02(\text{E}_{\text{beam}})$ is combined with the threshold measurement (from data recorded at $\sqrt{s} \sim 161$ GeV), 80.40±0.22 GeV,

Table 4: M_W determination from the $W^+W^- \rightarrow q\bar{q}q\bar{q}$ channel using data recorded at $\sqrt{s} \sim 172$ GeV and $\sqrt{s} \sim 183$ GeV.

	stat. sys. FSI E_{beam}
ALEPH	$80.53 \pm 0.17 \pm 0.05 \pm 0.05 \pm 0.02$
DELPHI	$80.01 \pm 0.19 \pm 0.04 \pm 0.10 \pm 0.03$
L3	$80.59 \pm 0.19 \pm 0.08 \pm 0.10 \pm 0.03$
OPAL	$80.40 \pm 0.20 \pm 0.08 \pm 0.10 \pm 0.03$
COMBINED	$80.39 \pm 0.093 \pm 0.05 \pm 0.09 \pm 0.03$

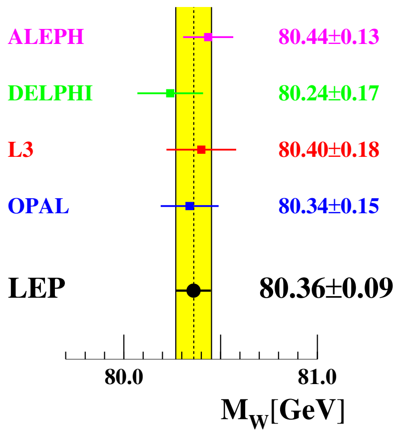

Figure 7: Determination of M_W from direct reconstruction of the W-boson decay products. Each value is the average of the results from the fully-hadronic and semi-leptonic channels from data recorded at $\sqrt{s} \sim 172$ GeV and $\sqrt{s} \sim 183$ GeV.

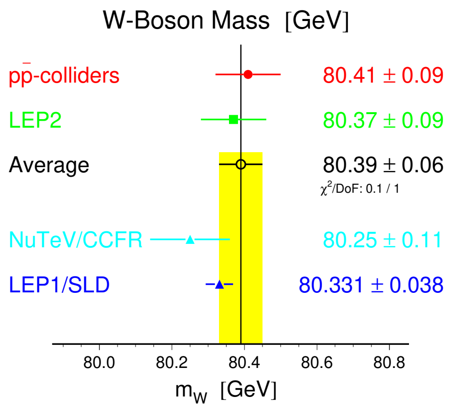

Figure 8: Comparison of direct and indirect determinations of M_W.

to give the current LEP estimate of the W-boson mass: $\mathbf{80.37 \pm 0.07(exp) \pm 0.04(FSI) \pm 0.02(E_{beam})\ GeV}$.

4 Comparison with other data

Figure 4 compares the *direct* measurement of M_W from LEP with the *direct* measurement of M_W from $p\bar{p}$-colliders (dominated by the measurements at the Tevatron [12]). The LEP and the Tevatron measurements of M_W are of comparable precision, 90 MeV. Combining these two measurements gives a current (preliminary) world average value for the direct determination of the W-boson mass of $M_W = 80.39 \pm 0.06$ GeV. Also shown in Figure 4 are the indirect determinations of M_W from fits to LEP 1 and SLD electroweak data and from neutrino scattering experiments. Good agreement is observed.

Figure 9 shows the sensitivity of measurements of (M_W, M_{top}) to the Higgs mass, m_H, within the context of the Standard Model defined by (M_Z, G_μ, α). In the global

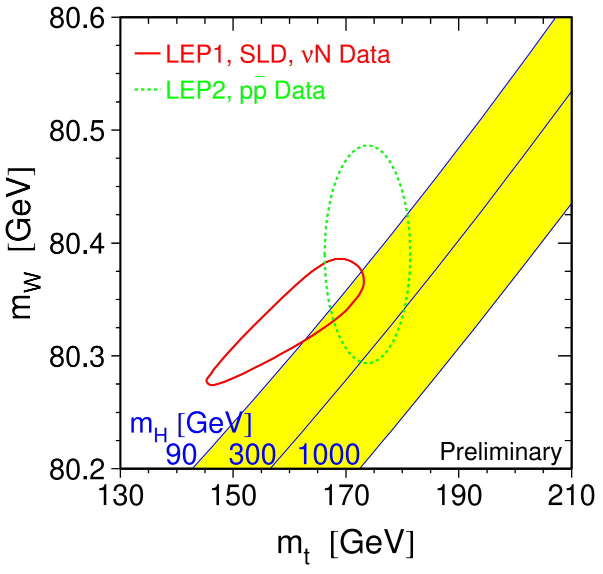

Figure 9: Direct determination of M_{W} and M_{top} compared to the indirect determination from LEP1, SLD and neutrino scattering data. In each case the regions shown correspond to 68 % C.L. contours. The diagonal band shows the Standard Model prediction for a range of Higgs masses.

fits to electroweak data [13], the limits on the SM Higgs mass is determined mainly by the LEP and SLD asymmetry measurements, $\mathrm{A}^{l}_{\mathrm{FB}}$, $\mathrm{A}^{b}_{\mathrm{FB}}$, A_{LR}, A_{τ}, *etc.*, which determine $\sin^2\theta_{eff}$. The uncertainty in $\alpha(M_{\mathrm{Z}^0})$ is an important contribution to the uncertainty on m_{H} derived from $\sin^2\theta_{eff}$. In the global fits to the electroweak data the second strongest constraint on the Higgs mass comes from the direct measurements of $(M_{\mathrm{W}}, M_{\mathrm{top}})$ which alone gives:

$$m_{\mathrm{H}} = 80^{+160}_{-70}\mathrm{GeV}.$$

This statistically limited measure of m_{H} has little sensitivity to $\alpha(M_{\mathrm{Z}^0})$. Future reductions in the uncertainties on the direct measurements of M_{W} and M_{top} will further probe the Higgs sector.

5 Outlook

From 75 pb^{-1} of LEP data recorded above the $\mathrm{W}^+\mathrm{W}^-$ production threshold, M_{W} has been determined with a statistical error of 70 MeV. If the LEP 2 target luminosity of 500 pb^{-1} is achieved, the statistical errors on M_{W} will be $\sim$35 MeV from $\mathrm{W}^+\mathrm{W}^- \to \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ channel and $\sim$35 MeV from $\mathrm{W}^+\mathrm{W}^- \to \mathrm{q\overline{q}q\overline{q}}$ channel. At this level of statistical precision there are a number of systematic effects which need to be much better understood. In particular, for the $\mathrm{W}^+\mathrm{W}^- \to \mathrm{q\overline{q}q\overline{q}}$ channel to contribute to the final value of M_{W}, the systematic uncertainties from final state interactions need to be significantly reduced. Understanding these effects represents a considerable experimental and theoretical challenge.

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