Proceedings of the DIS'2004, Štrbské Pleso, Slovakia

DETERMINATION OF THE W-MASS AND THE WW AND ZZ CROSS-SECTION AT LEP

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We review the precision measurement of the mass of the W-boson at LEP. We discuss the techniques used by the four LEP experiments to determine the mass of the W-boson as well as the major sources of systematic uncertainty. The measurement of the W^+W^- and ZZ cross-sections are presented.

1 Introduction

In 1996 the center-of-mass energy of the electron-positron collider LEP was increased above the threshold of two times the W-boson mass (M_{W}) which made it possible to produce pairs of W-bosons in e^+e^- collisions and thus opened the opportunity for a precision determination of the W-boson mass and measurements of its couplings and decay branching ratios. A detailed review of measurements of the W-boson mass and its couplings can be found e.g. in [1].

2 Motivation

In the electroweak Standard Model, the properties of the Z^0- and W-boson depend on a few fundamental parameters only. The comparison of the directly measured W-boson mass with Standard Model predictions based on precision measurements of Z^0-boson properties is therefore an important test of the Standard Model. In the lowest order calculation (at tree level), M_{W} only depends on the Fermi constant G_μ, which is accurately known from muon decays, the fine structure constant α and the mass of the Z^0-boson M_Z. Loop corrections lead to a quadratic dependence of M_{W}^2 on the top mass and a logarithmic dependence on the Higgs mass. As an example, Figure 1 shows 1-loop contributions to the W propagator including a top quark and a Higgs boson. Figure 2 shows the prediction for the W-boson and top quark mass from a fit to all data excluding the direct measurements of M_{W} and M_{top} [2]. The figure also shows the Standard Model prediction for M_{W} as function of M_{top} for three different Higgs masses. The predictions are compared to direct measurements of the top quark mass and the W-boson mass at the LEP and Tevatron colliders. This comparison is an important test of the electroweak Standard Model.

The measurement of W-pair and other four-fermion cross sections can be used to study triple gauge boson couplings. Any deviations from the Standard Model predictions can be interpreted as a sign for physics beyond the Standard Model.

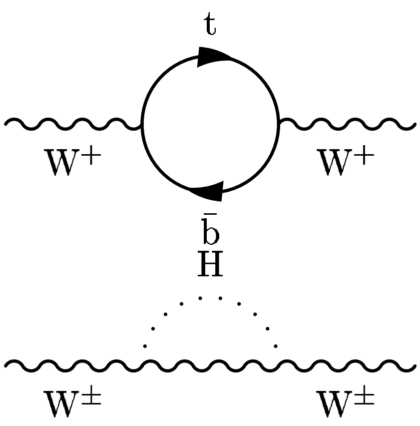

Figure 1. Feynman diagram of 1-loop corrections to the W propagator.

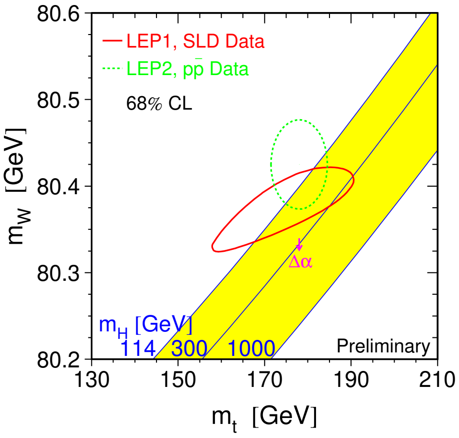

Figure 2. Result of a Standard Model fit to the electroweak data and the Standard Model prediction of the W-boson mass as function of the top mass.

3 W-Pair Production and Decay

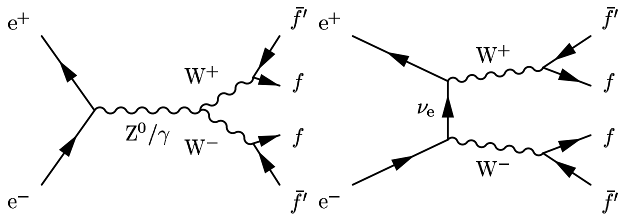

Figure 3. Feynman diagrams for W-pair production.

Above the center-of-mass energy threshold of $2 \cdot M_{\mathrm{W}}$, W-boson pairs can be produced in e^+e^- annihilation. Figure 3 shows the tree level Feynman diagrams contributing to the W-pair production (called CC03). The Feynman diagrams for the W-pair production via a virtual Z or photon contain a triple gauge boson coupling which can therefore be studied by measuring the pair production cross section.

The W-boson decays in 68.5% hadronically into a quark-antiquark pair, which will be observed in the detector as two jets, and in 31.5% leptonically into a charged lepton and a neutrino. Depending on the decay of the two W-bosons this leads to three distinct signatures. In 46% of the events, both W-bosons decay hadronically (hadronic decays). For these events, one expects four jets. In 44% of the events, one W decays hadronically and the other leptonically (semileptonic decay), leading to events with two jets, a high energetic lepton and missing energy due to the unobserved neutrino. For the 10% of events in which both W-bosons decay leptonically, the event only contains two high energetic leptons and a large amount of missing energy. In order to study the different W-boson pair decays, it is important to be able to precisely measure the momentum and direction of the leptons and jets.

4 W- and Z- Pair cross-section

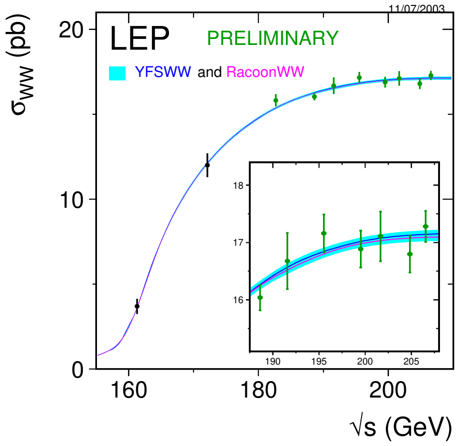

Figure 4. W-pair cross-section as function of center-of-mass energy.

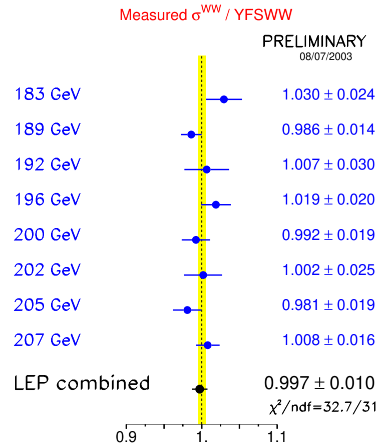

Figure 5. Ratio of the measured cross-section to the prediction.

In Figures 4 and 5 the measured W-pair cross-section is compared to predictions of RACOONWW [3] and YFSWW [4]. The LEP measurements have reached a precision of 1% and agree with the predictions.

Figure 6 shows the tree level Feynman diagrams contributing to the Z-pair production (called NC02). Figure 7 shows that the Z-pair cross-section agrees well with the theoretical predictions of ZZTO [5] and YFSZZ [6].

5 W-mass determination

In principle the invariant mass of two jets coming from the same hadronic W decay could be used to determine the most likely W-mass in a given event. This would however result in a poor mass resolution of about 10%. This resolution is dominated by the jet energy resolution. The mass resolution can be greatly improved by a kinematic fit in which the directions and energies of the jets and the charged lepton (in the case of semileptonic W-pair events) are allowed to vary within there uncertainties while requiring energy and momentum conservation. Due to the constrain of energy conservation the relative uncertainty in the determination of the beam energy will result in a corresponding relative uncertainty on the W-boson mass.

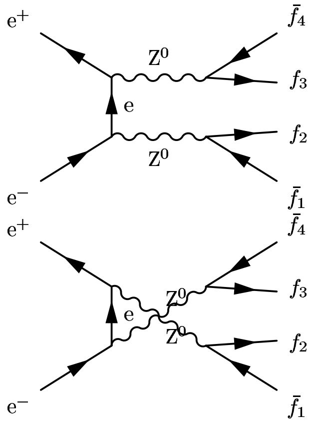

Figure 6. Feynman diagrams for Zpair production.

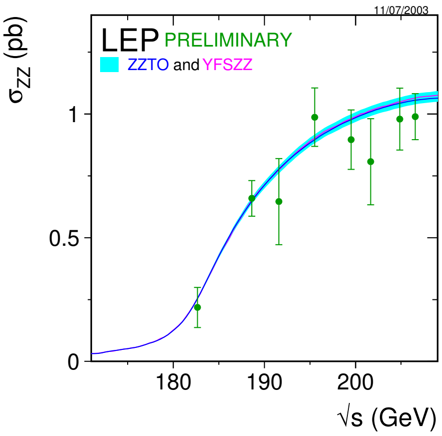

Figure 7. Z pair cross-section as function of center of mass energy.

The mass of the W-boson can be determined by comparing the reconstructed mass distribution in data with Monte Carlo templates corresponding to different W-boson masses and by minimizing the difference between data and Monte Carlo distribution. The comparison can be extended to several dimensions using e.g. the results from different kinematic fits or both the fitted mass and its uncertainty.

The optimal use of the information can be made by using event probabilities. The event probabilities are calculated by the convolution of a resolution function with a physics function. The physics function expresses the probability to produce an event where the two produced W-bosons have masses m_{W_1} and m_{W_2} for a given value of the W-boson mass. The physics function is basically given by a Breit-Wigner function for the W decay modified by phase space effects. The resolution function parametrises the probability for the observation of a certain kinematic event topology, given that the produced W-bosons have masses m_{W_1} and m_{W_2}. The resolution function is in the simplest case a Gaussian with the central value and width determined by the kinematic fit. The mass of the W-boson is obtaind by maximising the total likelihood which is given by the product of the event probabilties.

6 Systematic errors

The major systematic errors are summarized in Table 1 [2]. For the W-mass measurement an excellent understanding of the detector response is important. The energy scale and resolution, the angular resolution and their uncertainties have to be determined from the data. One important sample for the calibration of the detector are events which were collected at the Z^0 resonance each year. The jet or lepton pairs from the Z^0 decay are back to back and the total energy is equal to the beam energy. In order to obtain information for jets and leptons with energies different than half the Z^0 mass, 3-jet events and events with an identified initial

Source	Systematic Error on M_W (MeV)		
	$q\bar{q}l\nu$	$q\bar{q}q\bar{q}$	Combined
Detector Systematics	14	10	14
Hadronisation	19	18	18
LEP Beam Energy	17	17	17
Colour Reconnection	–	90	9
Bose-Einstein Correlations	–	35	3

Table 1. Major errors for the combined LEP W-mass results.

state photon were used as well.

The hadronisation of coloured quarks and gluons into observable hadrons can only be described with models. Despite energy and momentum conservation in the hadronisation process this leads to a systematic uncertainty due to the following effects: In the detector only particles with momenta larger than a given threshold are observed; the energy resolution for neutral hadrons like K_L and neutrons is quite low; and for all charged particles the pion mass is assumed in the calculation of the particle energy. The systematic uncertainty due to hadronisation is estimated by comparing different Monte Carlo Models (and sets of Monte Carlo parameters) which all describe the high statistics Z^0 data well. It is important that, the parameter sets do not only describe inclusive distributions but also reflect our knowledge on exclusive rates like baryon and kaon fractions.

In the case that both W-bosons decay hadronically the uncertainty due to possible final state interactions between the decay products of the two W-bosons is by far the largest source of systematic uncertainty. The possible bias on the reconstructed W-mass due to Bose-Einstein Correlations between identical bosons from the decay of different W-bosons and of colour reconnections between partons from different W-bosons can only be estimated with phenomenological models. Measurements of the correlations between identical bosons and measurements of multiplicities, energy and particle flows (which are effected by possible colour reconnections) are used to estimated the possible size of finale state interactions. Thereby limiting the range of models and model parameters used to estimate the systematic uncertainty on the W-boson mass. The final state interactions predominately effect low momentum particles far away from jets. The exclusion of this particles in the calculation of the jet direction can greatly reduce the effect of final state interactions while the statistical power of the mass determination is only slightly deteriorated. This approach has not been yet used for the preliminary results shown is this presentation but it will be used in the final publications of the W-mass measurements.

7 Results

Figure 8 shows the preliminary results for the mass of the W-boson from the four LEP collaborations. The combined result including the threshold measurements is [2]:

$$M_W = 80.412 \pm 0.042 \text{ GeV}.$$

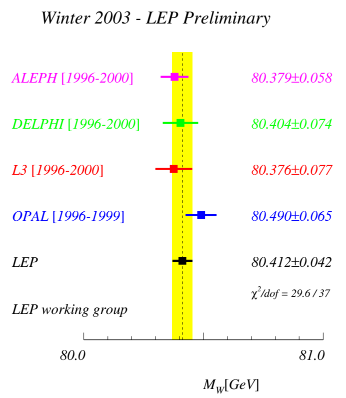

Figure 8. Preliminary results for the measurement of the W-boson mass by the LEP collaborations

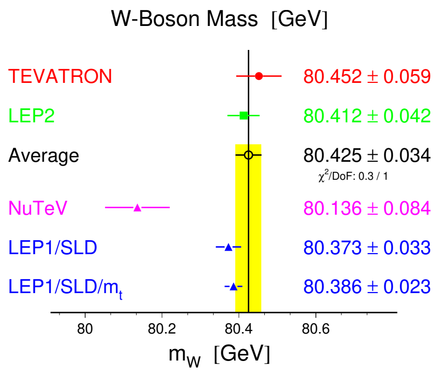

Figure 9. Comparison of the direct measurements with indirect predictions from electroweak precision measurements.

The results of the direct measurements are compared in Figure 9 and Figure 2 with indirect predictions from the fit to electroweak precision measurements. One can see that the direct measurements have reached the same precision as the indirect predictions. Since no significant discrepancies are found the Standard Model predictions are confirmed at the level of loop corrections.

Acknowledgements

I thank the LEP Electroweak WG for providing much of the information presented here and the CERN accelerator devison for the efficent operation of the LEP accelerator.

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