

# W boson mass and properties at LEP

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**Abstract.** The current status of the measurements and the combination of the W mass and width from the LEP experiments is presented, with a focus on systematics effects, in particular Color Reconnection. The latest published WW cross-section and W spin density matrix measurements at LEP are also shown.

## 1. Introduction

At LEP, W bosons are produced in pairs in the process  $e^+e^- \rightarrow W^+W^-$ , with a subsequent decay of the W bosons into quark/antiquark pairs,  $q\bar{q}$ , or lepton-neutrino pairs,  $\ell\nu$ . The presented measurements are based on the data collected at the LEP experiments ALEPH, DELPHI, L3 and OPAL in the years 1996-2000 [1]. The data have been collected at center-of-mass energies of  $\sqrt{s} = 161\text{-}209$  GeV, using an integrated luminosity of about  $700\text{ pb}^{-1}$  per experiment, corresponding to about 40000 W boson pairs in total.

## 2. Measurement of the W boson mass and width

There are two different ways to measure the W boson mass and width, both of which have been used at LEP. At production threshold,  $\sqrt{s} \approx 2M_W$ , the W mass can be easily measured from the W pair cross-section by comparison with the theoretically calculated cross-section for different W mass hypotheses.

The direct reconstruction measurement is used at higher energies. The invariant masses of the W bosons are reconstructed from the observed jets and leptons. From the measured spectra the W mass is derived.

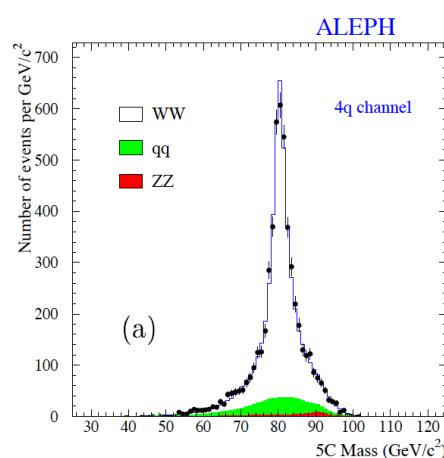
The W mass analyses at the four LEP experiments start with a standard selection of  $W^+W^- \rightarrow \ell\nu q\bar{q}$  and  $W^+W^- \rightarrow q\bar{q}q\bar{q}$  events. A kinematic fit is applied to improve the resolution. Four momentum conservation is used in the fit, where the velocity of the jets is fixed to the measured value. A further constraint is made by requiring the masses of the two W bosons to be equal. Figure 1 shows the mass distribution in the  $q\bar{q}q\bar{q}$  channel for data, non-WW background and signal+background Monte Carlo with  $M_W$  set to the one fitted.

The W boson mass and width are henceforth extracted using a maximum likelihood fit comparing data to Monte Carlo samples with different underlying masses. Here, the W mass variation is implemented using either Monte Carlo reweighting or convolution techniques. A more sophisticated approach is taken by DELPHI collaboration, using ideograms. These are 2 dimensional likelihood functions that include terms from each potential jet pairing, three jet clustering algorithms and possible ISR emission to represent the reconstructed mass information from the event kinematics.

### 2.1. Systematic effects

Generally, for the W mass measurements, the systematics is dominated by uncertainties from hadronisation.

Uncertainties of the LEP beam energy (contribution to the total systematics: 9 MeV) play a role due to the usage of the beam energy as a constraint in kinematic fits. Uncertainties due to Monte Carlo modelling include electroweak radiation (7 MeV), detector modelling (10 MeV), which is uncorrelated between experiments, hadronisation modelling (14 MeV) and the modelling of Final State Interactions - Bose-Einstein-Correlations (2 MeV) and Color Reconnection (8 MeV). To reduce uncertainties from radiative corrections, full  $\mathcal{O}(\alpha)$  electroweak calculations are included in the Monte Carlo description. To estimate uncertainties from the modelling of hadronisation, the descriptions of the hadronisation from different Monte Carlo programs are compared.



**Figure 1.** Mass distribution in the  $q\bar{q}q\bar{q}$  channel for data and MC with  $M_W$  set to the one fitted (ALEPH).

singlets between partons from different W bosons. As the momentum of the hadrons is rearranged, the energy-momentum is not any more conserved in each of the W bosons. Several phenomenological models exist to describe CR. The LEP collaborations have chosen the SK-I model as a benchmark for the measurements and the estimation of systematics for the W boson mass measurements.

To determine the size of CR in data, the DELPHI, L3 and OPAL collaborations use an approach based on particle flow, which is measured as a function of a rescaled angle with respect to the quark jets in the WW event. The full SK-I model predicts a lower particle flow between the decay products of a single W (intra-W) and a higher particle flow between the decay products of the two W bosons (inter-W). Figure 2 shows the particle flow distribution as a function of the rescaled angle measured by L3.

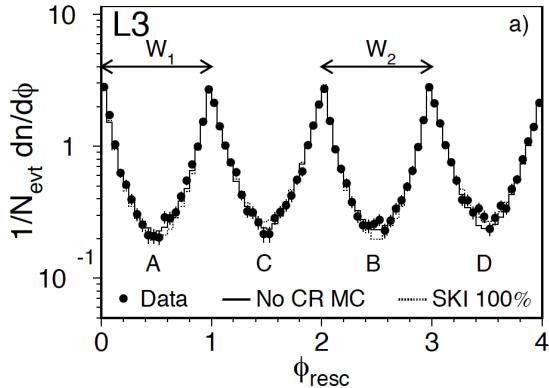
Another approach, taken by ALEPH, DELPHI and OPAL, is based on the W boson mass measurement itself. Here, a standard  $M_W$  analysis is compared with a modified analysis that is either using weights or even cutting on a certain type of particles. Several different analyses are used: a *pcut* analysis of the W mass uses only particles that have momentum above a certain threshold,  $p_{cut}$ , and a *cone* analysis of the W mass that uses only those particles for the jet 3-momentum reconstruction which are inside a cone with opening angle  $R$ . A convolution analysis, as used by OPAL, assigns weights  $p^\kappa$  to the momenta of all particles used in the jet direction reconstruction. From the comparison of the particular analyses, a bias in the W mass

For  $W^+W^- \rightarrow q\bar{q}q\bar{q}$  events, the influence of the Final State Interactions is reduced by using only those particles which have momentum above a certain threshold, determined by each experiment separately. The systematics in the fully hadronic final state is dominated by uncertainties from FSI: Bose-Einstein-Correlations (7 MeV) and particularly Color Reconnection (35 MeV).

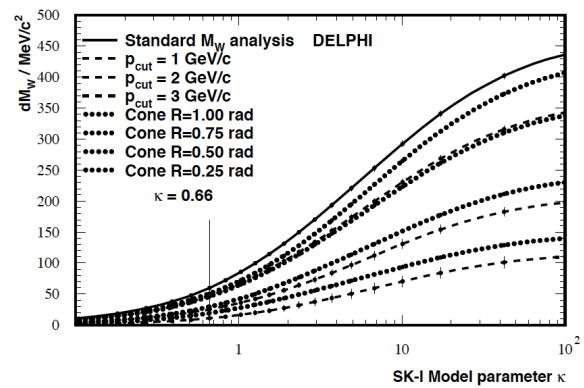
Bose-Einstein-Correlations (BEC) are the enhanced probability of the production of pairs of identical mesons (mostly pions and kaons) close together in phase space. The presence of these correlations can affect the direct reconstruction of the invariant W mass, especially in the case of BEC between hadrons originating from different W bosons. BEC have been measured by all LEP experiments. The particular measurements as well as their combination is compatible with the absence of BEC [1]. The upper limit on this effect is used to derive a systematics uncertainty on the W mass.

Color Reconnection (CR) is the exchange of color

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**Figure 2.** Particle-flow distribution as a function of the rescaled angle for data and for PYTHIA MC predictions without CR, and with the SKI 100% model as measured by L3.



**Figure 3.** The difference  $dM_W(\kappa) = M_W(\kappa) - M_W(\kappa = 0)$  as a function of  $\kappa$ , for different  $M_W$  estimators as obtained by DELPHI. The vertical line indicates the value of  $\kappa$  preferred by the SK-I authors.

measurement is determined. This bias is compared to the biases determined using the same analyses using Monte Carlo events simulated assuming different CR scenarios. Figure 3 shows the differences in terms of  $M_W$  between the standard analysis and the various  $pcut$  and  $cone$  analyses with different threshold  $p_{cut}$  and cone opening angle,  $R$ , values.

The LEP data are compatible with the absence of CR and an upper limit is derived on the model parameter  $\kappa$  which describes the strength of the CR. For the LEP combination of the  $W$  mass, a common combined upper limit for CR of  $\kappa < 2.13$  is used to estimate the systematics for CR and to determine the cuts in the  $W^+W^- \rightarrow q\bar{q}q\bar{q}$  analysis which each experiment uses to obtain its  $W$  mass. This value does not yet include the latest CR combination which is being performed.

## 2.2. $W$ mass and width results and LEP combination

All four LEP experiments have published their final analyses. The LEP combined values for the  $W$  mass and width, combined taking into account correlated systematics, are:

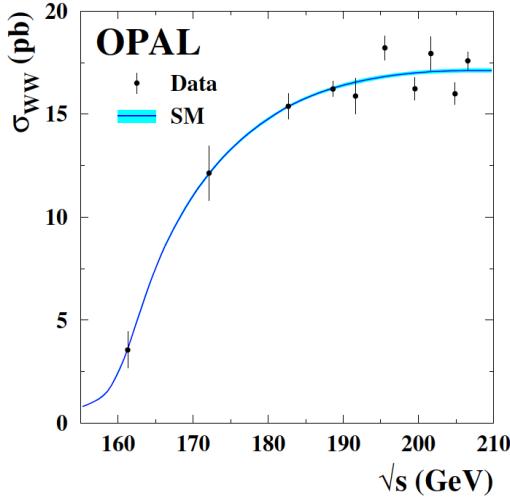
$$M_W = 80.376 \pm 0.025(\text{stat.}) \pm 0.022(\text{syst.}), \quad \Gamma_W = 2.196 \pm 0.063(\text{stat.}) \pm 0.055(\text{syst.})$$

The LEP combination is still preliminary due to the need of including a final LEP-combination of the CR. It compares well to the  $W$  mass value of  $M_W = 80.361 \pm 0.020$  derived from all electroweak measurements without the direct measurement. This constitutes an important test of the Standard Model and can be used to better constrain parameters like the Higgs mass.

## 3. Properties of the $W$ boson

### 3.1. $WW$ cross-section and branching ratio

The  $WW$  cross-section and branching ratios (BR) of the  $W$  decay have been measured to a great detail at LEP [1]. Taking into account all LEP data, the ratio of data to Standard Model predictions for the BR is  $R = 0.994 \pm 0.009$ . The OPAL collaboration has recently obtained their final results [2]. Figure 4 shows the  $WW$  cross-section as a function of energy for OPAL data and SM Monte Carlo. The  $WW$  cross-section as well as the branching ratio of the  $W$  decay are in agreement with the SM and separate measurements of the BR for each leptonic final state are consistent with lepton universality.



**Figure 4.** The measured WW cross sections (OPAL) from fits assuming SM W decay branching fractions from OPAL for data (points) and SM expectation (line). The shaded region shows the 0.5% theoretical error.

### 3.2. W spin density matrix

The L3 collaboration has recently finalised their W spin density matrix measurement [3]. The massive W bosons have an additional spin degree of freedom w.r.t. massless photons, and thus the three possible helicity states  $-1, +1$  and  $0$ . The longitudinal polarised (helicity 0) state is of particular interest due to its connection with the Higgs sector in the Standard Model.

The W pair production process is described entirely in terms of helicities by the two-particle joint Spin Density Matrix (SDM) elements. The single-particle SDM elements,  $\rho_{\tau_1 \tau_1}^{W^-}$ , with  $\tau_1(\tau_2)$  the helicity of the  $W^-$  ( $W^+$ ), are obtained by summation over all possible helicity states of one of the W bosons.

For the analysis, projection operators are used which isolate the corresponding SDM elements. The reconstructed SDM is corrected for detector acceptance, resolution effects and background contamination. As an example, Figure 5 shows the SDM elements measured by L3 at  $\sqrt{s} = 189 - 209$  GeV as a function of the W boson polar angle, combined for  $e\nu q\bar{q}$  and  $\mu\nu q\bar{q}$  data. For all analyses, good agreement with the Standard Model prediction is found. Also good agreement with the previously published analysis from OPAL [4] is observed.

The imaginary parts of the off-diagonal SDM elements are used to perform a test of CP and CPT invariance at tree level. The data confirm the absence of CPT and CP violation at tree level as predicted by the Standard Model.

### References

- [1] ALEPH, DELPHI, L3, OPAL Collab. and the LEP Electroweak Working Group, *A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model*, CERN-PH-EP/2006-042, December 14, 2006, and references therein.
- [2] OPAL Collab., *Measurement of the  $e^+e^- \rightarrow W^+W^-$  cross section and W decay branching fractions at LEP*, CERN-PH-EP-2007-027, Submitted to Eur Phys J C.
- [3] L3 Collab., *Measurement of the W-boson Spin-Density Matrix at LEP*, in preparation.
- [4] OPAL Collab., *W Boson Polarisation at LEP2*, Phys.Lett. **B585** (2004) 223.