A review of the Triple Gauge Boson Couplings and the W mass measurements at LEP2

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Abstract

During 1998 LEP took data at a centre-of-mass energy of 189 GeV. At this energy, significantly above threshold for W boson pair production, a more precise measurement of the W mass and Triple Gauge Boson Couplings could be obtained. A description of the charged couplings and the ongoing analyses at LEP2 is given and preliminary results from the four LEP experiments are shown. The measurement of the mass of the W boson with the different reconstruction methods is discussed and preliminary results, obtained by the four LEP experiments, are presented.

1 Introduction

Since the start of the LEP2 program in 1996 each experiment collected data equivalent to $\sim 250pb^{-1}$ at several centre-of-mass energies, ranging from 161 GeV up to 189 GeV. This results in about 3500 produced W pairs per experiment.
At LEP W pair production occurs at Born level via three diagrams [1]. In the s-channel the exchange of a photon or a Z boson is possible. The third diagram is a t-channel diagram with neutrino ν_e exchange. The W particles are short lived, and the pair production gives rise to three different topologies at detector level, each with specific characteristics:

- SEMILEPTONIC CHANNEL ($q\bar{q}l\nu_l$, BR $\sim$40%):
  - isolated high momentum lepton(μ or e);
  - in case of a τ lepton: isolated low multiplicity jet;
  - the hadronic part consists of two well separated jets;
  - large missing momentum coming from the neutrino;
- HADRONIC CHANNEL ($q\bar{q}q\bar{q}$, BR $\sim$50%):
  - no missing energy;
  - four or more well separated jets;
  - high multiplicity;
- LEPTONIC CHANNEL ($l\nu_l l\nu_l$, BR $\sim$10%):
  - two acoplanar leptons;
  - large missing energy coming from the undetected neutrinos.

According to these specific topologies, selection procedures have been developed.

2 Triple Gauge Boson Couplings

One of the goals of LEP2 is to carry out an accurate study of the WWV (V $\equiv \gamma$/Z) vertex [2]. The Standard Model(SM), being a non-Abelian theory, gives an exact prediction of the trilinear interactions of the gauge bosons W, Z and γ, and a key question is whether the form of their interaction follows this SM prediction precisely. Observing a possible deviation from this prediction is very interesting as this might indicate new physics.

[1] On behalf of the four LEP collaborations.

2.1 Theoretical framework of the WWV interaction.

If we ask ourselves how two W bosons and a photon or Z boson may interact, we can write down all possible interaction terms which describe these processes in an effective Lagrangian, obeying certain rules such as Lorentz invariance, as an extension to the SM:

$$\begin{aligned} i\mathcal{L}_{eff}^{WWV} = & \; g_{WWV}[g_V^1 V^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \\ & \frac{\lambda_V}{M_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^- \\ & + i g_5^V \epsilon_{\mu\nu\rho\sigma}((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})) V^\sigma \\ & + i g_4^V W_\mu^- W_\nu^+ (\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} \\ & - \frac{\tilde{\lambda}_V}{2M_W^2} W_{\rho\mu}^- W_\nu^{+\mu} \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}] \end{aligned} \tag{1}$$

where the field-strength tensors $V_{\mu\nu}$ and $W_{\mu\nu}^\pm$ are defined from the corresponding vector fields $V_\mu (\equiv A_\mu$, Z_μ, $W_\mu^\pm$ respectively) as $(\partial_\mu V_\nu - \partial_\nu V_\mu)$. The overall couplings are defined as $g_{WW\gamma} = e$ and $g_{WWZ} = e \cot\theta_W$. Here θ_W is the Weinberg electroweak mixing angle. The couplings related to the $WW\gamma$ vertex correspond to the lowest order terms of a multipole expansion of the $W\gamma$ interaction:

$$\begin{aligned} Q_W &= e g_\gamma^1, \\ \mu_W &= \frac{e}{2M_W}(g_\gamma^1 + \kappa_\gamma + \lambda_\gamma,) \\ q_W &= -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma), \end{aligned}$$

with Q_W the charge, μ_W the magnetic dipole momentum and q_W the electric quadrupole momentum of the W^+ boson.
The parametrisation in the Lagrangian equation (1) involves 14 TGC parameters; ie. 7 independent operators for each vertex. Three parameters (g_1^V, κ_V and λ_V) conserve C and P individually, one (g_5^V) violates C and P but conserves CP, and the remaining (g_4^V, $\tilde{\kappa}_V$ and $\tilde{\lambda}_V$) couplings parametrise a possible CP violation in the bosonic sector. Within the SM, at tree level, the couplings are given by

$$g_Z^1 = g_\gamma^1 = \kappa_Z = \kappa_\gamma = 1$$

with all other couplings in (1) vanishing.
On rather general grounds [3] CP violating couplings can be ignored since they are not likely to produce observable effects at LEP2; as a consequence only C and P conserving couplings will be considered. Furthermore no deviations of the overall coupling strength γWW, given by the electric charge, is expected. This leaves us with five coupling parameters. We would like to study deviations from the SM, so the set of parameters obtained is the following:

$$\begin{aligned} \Delta g_Z^1 = & \; g_Z^1 - 1, \\ \Delta\kappa_\gamma = & \; \kappa_\gamma - 1, \\ \Delta\kappa_Z = & \; \kappa_Z - 1, \\ & \lambda_\gamma, \lambda_Z. \end{aligned}$$

In the SM all these parameters take zero value. Since statistics at LEP2 is limited, it is quite impossible to set up a multidimensional fit to retrieve the complete parameter information with reasonable accuracy. Hence it is favourable to reduce even further the number of parameters on the basis of theoretical arguments.
Where do we have to look for new physics? Let there be some new physics scale at high energy called Λ. The terms contributing to this new physics enter in the Lagrangian (1) suppressed by factors like $1/\Lambda^{N-4}$, with N the dimension of the operators. Since lower dimension operators are more likely to produce observable effects, we only include dimension 4 and 6 operators. Furthermore we have tested

the SM extensively and we would like the W and Z bosons to obey SU(2) $\times$ U(1) invariance from the electroweak theory. So if we imply this invariance and we consider only couplings which are not excluded by LEP1 measurements ("blind directions" [3, 4]), we further reduce the parameter set to (Δg_Z^1, $\Delta\kappa_\gamma$, λ_γ) in which the obtained results will be quoted, with the following constraints coming from SU(2) $\times$ U(1):

$$\begin{aligned} \Delta\kappa_Z &= \Delta g_Z^1 - \Delta\kappa_\gamma \tan^2\theta_W\,, \\ \lambda_Z &= \lambda_\gamma. \end{aligned}$$

These blind directions correspond to the set of three parameters $\alpha_{W\Phi}$, $\alpha_{B\Phi}$ and α_W, in which results obtained earlier by the four LEP collaborations [5], were quoted. The relationship between this set of parameters and the set in which the obtained results will be quoted, is as follows:

$$\begin{aligned} \Delta g_Z^1 &= \alpha_{W\Phi}/c_W^2\,, \\ \Delta\kappa_\gamma &= \alpha_{W\Phi} + \alpha_{B\Phi}\,, \\ \lambda_\gamma &= \alpha_W. \end{aligned}$$

As a final comment, it should be mentioned that by reducing the number of free TGC parameters a test of the SM is possible. But these reductions cannot substitute a general fit in case deviations are observed. In that case a multi-parameter fit has to be done to determine which direction the new physics prefers and sort out what kind of new physics we are dealing with.

2.2 Access to Triple Gauge Boson Couplings

At LEP the main channel for the study of TGCs is the W pair production process. As we have seen in section 1 this production goes through three Feynman diagrams, and the WWV(V$\equiv$ Z or γ) vertex can be probed in the s-channel. This channel allows us to set limits on the parameter set (Δg_Z^1, λ_γ, $\Delta\kappa_\gamma$). In addition, through the single photon and single W production channels, one has access to the WWγ vertex, setting extra limits on the couplings $\Delta\kappa_\gamma$ and λ_γ. Results of the latter channels will not be presented in this talk.

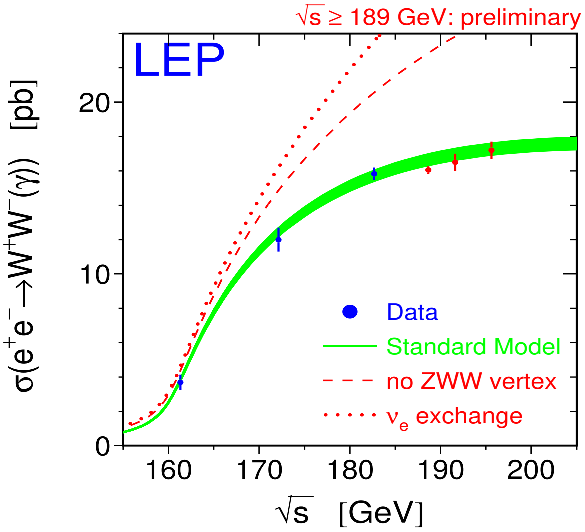

Figure 1: The excitation curve for the process $e^+e^- \to W^+W^-$.

The production helicity amplitudes for the process $e^+e^- \to W^+W^-$ depend on the couplings [6]. As a consequence the total WW production cross-section also depends on the TGCs. By measuring the excitation curve one can conclude if the WWV vertices exist and are necessary for the gauge cancellations.

In fig. 1 this excitation curve is presented [7]: the data points represent the WW pair cross-section measured by the four LEP experiments at different energies, the full line is the SM prediction, the dashed line the prediction in absence of a the WWZ vertex and the dotted line the prediction when no WWV vertex is present. One can clearly see that with the present data the SM is favoured, giving a clear indication of the existence of the WWV vertex.

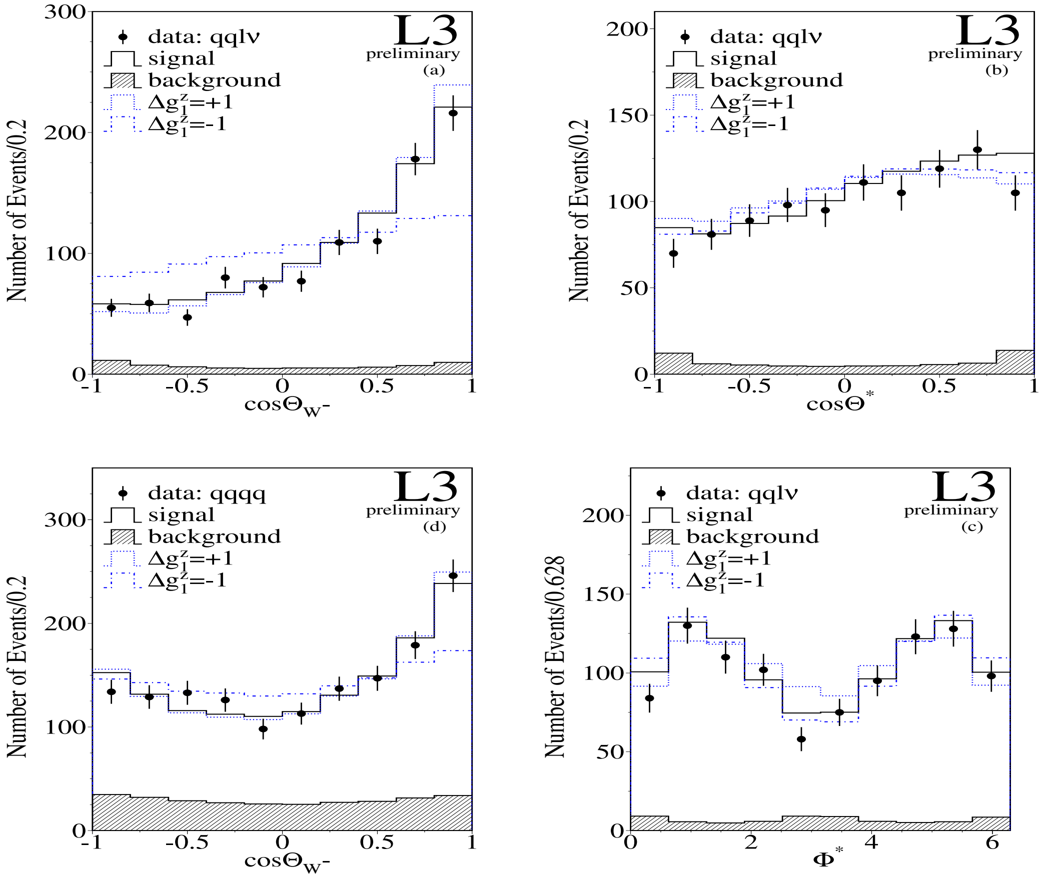

Figure 2: Angular distributions for different channels. For the semileptonic channel we see the observed distributions of (a) the production angle of the W^-, (b) the polar decay angle of the W^- and (c) (on the right) the phi decay angle of the W^-. Fig. (d), on the left, shows the observed distribution of the production angle of the W^- for the hadronic channel. The data at 189 GeV are shown by points, and the predicted distributions for SM couplings and for $\Delta g_1^z = \pm 1$ are indicated.

The shape of the differential cross-section as a function of the W production angle is also sensitive to the TGCs as are the distributions of the W decay products. The most important is the W^- production angle $\cos\theta_{W^-}$. The other four are the decay angles (Φ^* and $\cos\theta^*$) of the W bosons in their rest frames with respect to the W flight direction. Example of these angular distributions are shown in fig. 2.
In the next two sections the two main analysis methods used by the LEP experiments [8], one based on the accurate measurement of the angles and one based on the optimal observables, are presented.

2.2.1 Angular distributions

The maximum kinematic information that is available in an event and which is of particular use for TGC analyses is a set of five angles. The amount of kinematic information that can be accessed from the experimental data depends strongly on the channel used. As one needs to know the charge and direction of the measured W, it is clear that the ideal channel is the semileptonic decay mode with its clear lepton

signature and straightforward measurement of the W direction. This information is less easy to obtain for the fully hadronic channel, as there is no clear charge signature. This can be seen in fig. 2(d). As can also be clearly seen from these figures, the decay angles add less information than the production angle where the biggest deviation from the SM for a given anomalous coupling can be observed in the forward direction. It is also clear that the semileptonic channel is more sensitive to TGCs than the fully hadronic channel, for the reason explained above. However a major disadvantage of an analysis of the data in terms of these 5-dimensional angular distributions is the integration in many dimensions of complicated detector response functions. Consequently for the analyses a subsample of kinematic variables has usually been used.
The differential cross-section as a function of the parameter to be fitted is expressed by an analytical function. The Triple Gauge Boson Couplings are then determined in a maximum likelihood fit.

2.2.2 Optimal Observables

The theory of optimal observable methods and their application to TGC measurements is given in reference [9]. For a one parameter fit the differential cross-section, depending on the parameter α, can be expressed as

$$\frac{d\sigma}{d\Omega} = c_0(\Omega) + c_1(\Omega)\alpha + c_2(\Omega)\alpha^2, \tag{2}$$

with Ω the available kinematic information(see previous section). This expression can also be seen as a Taylor expansion around the SM cross-section value c_0.
In a popular application of this optimal observable technique, the estimation of the anomalous couplings is performed by means of a likelihood fit of the data to the predicted distributions of the optimal observables $\xi_1 = \frac{c_1}{c_0}$ and $\xi_2 = \frac{c_2}{c_0}$, obtained from Monte Carlo (MC) simulation with the reweighting technique(see section 3.1.1). These optimal variables ξ_1 and ξ_2 contain all available kinematic information from the event. In this way one can easily include detector effects. The direction which is most sensitive to the couplings is picked out by the optimal observables in the five dimensional angular space, so optimal use of the available angular information is made.
In the case of a two parameter fit the expression (2) becomes more complicated, and five optimal variables are needed to retain all the TGC information of the event. In this case an iterative procedure may be used to determine the couplings.

2.3 Results and comparison

The results of the analyses are presented as likelihood curves, as can be seen in fig. 3 [7]. In this figure the results of the one parameter fits to the couplings $\Delta\kappa_\gamma$ and λ_γ are presented. For the one parameter fit, the coupling concerned is left free while the other two couplings are set to their SM value, ie. zero. The combined LEP results are computed by the LEP electroweak working group as described in [10]. Preliminary results for data taken by the four LEP experiments at centre-of-mass energies up to 189 GeV are:

$$\Delta\kappa_\gamma = +0.06^{+0.09}_{-0.09}, \tag{3}$$
$$\Delta g_Z^1 = -0.01^{+0.03}_{-0.03}, \tag{4}$$
$$\lambda_\gamma = -0.03^{+0.04}_{-0.04}. \tag{5}$$

As there exist correlations between the parameters, it is better to perform a three parameter fit. This technique is quite complicated and with the limited statistics taken until now not very accurate. Therefore two parameter fits are performed, where two parameters are varied simultaneously while the third one is left at its SM value. In fig. 4 [7] the 95% and 68% confidence level contour plots are shown for the combined results of the four LEP collaborations.
Fig. 3 [7] shows the results on the couplings $\Delta\kappa_\gamma$ and λ_γ measured by LEP and those of the D0 collaboration in $q\overline{q}$ reactions at the Tevatron. In all these measurements the statistical errors are still dominating, as the systematic errors are typically a factor 10 smaller. But already some systematic error contributions coming from cross-sections, backgrounds and efficiencies are taken into account in the total error.

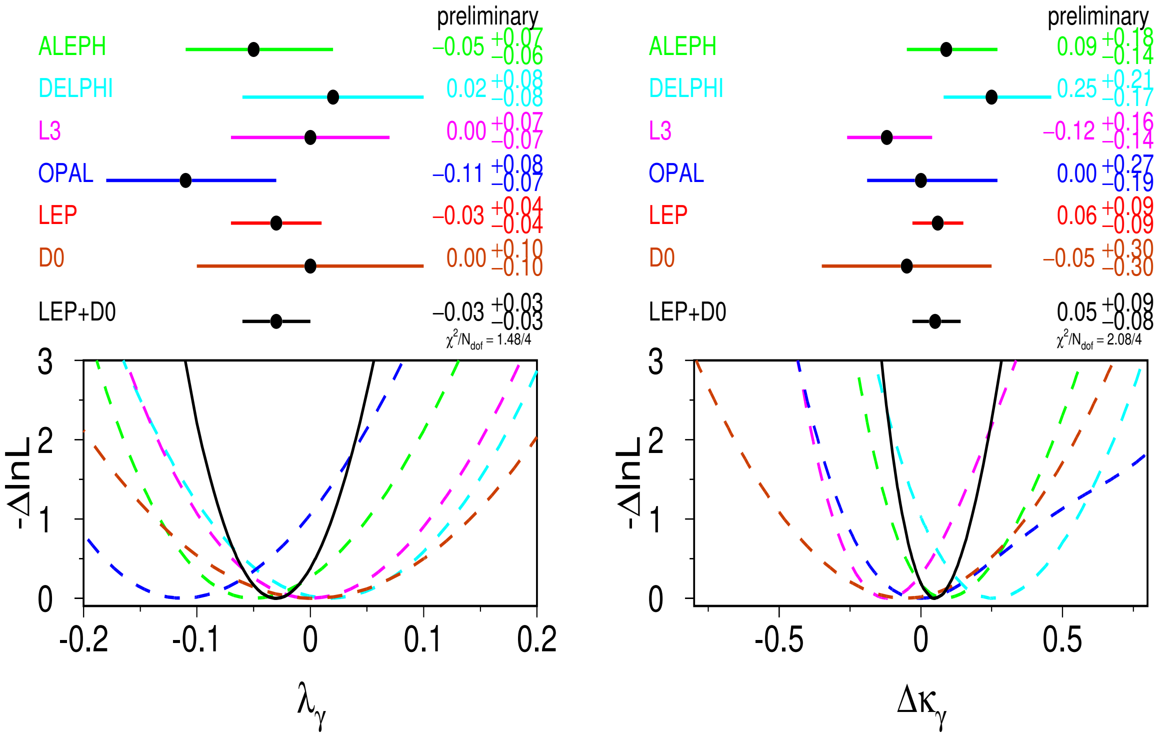

Figure 3: The results, separately and combined for the four LEP experiments and D0 for the one parameter fits of $\Delta\kappa_\gamma$ and λ_γ.

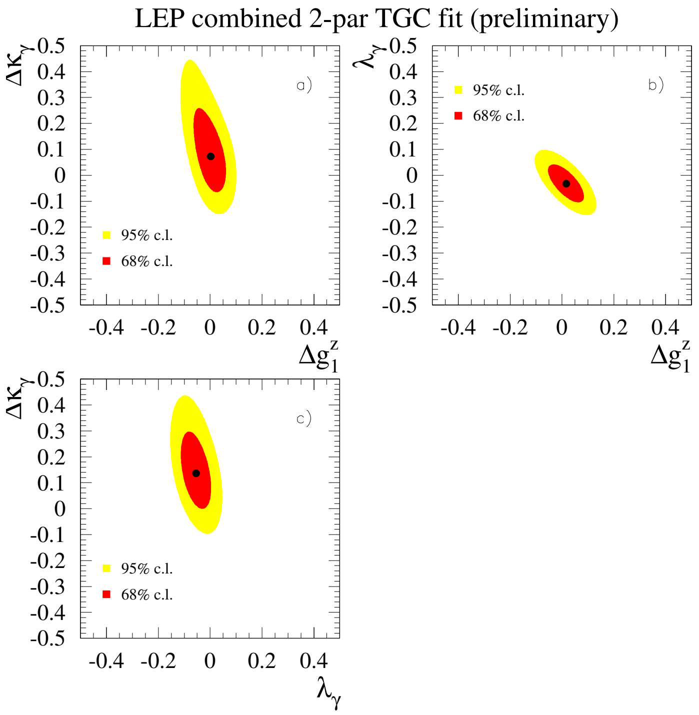

Figure 4: The LEP combined results for various two parameter TGC fits.

For the future a reduction of the statistical error is expected, as higher energies and more statistics will reduce the error. The final expected precision at LEP2 on the measurement of the TGC parameters will be of the order of .03 (at 68% CL) with the worst absolute precision on $\Delta\kappa_\gamma$, and Δg_Z^1 the most accurately measured.

3 Measurement of the W mass

The measurement of the W boson mass is very important, as it enters in the Standard Model relation

$$\sin^2\theta_W = (1 - (M_W/M_Z)^2)(1 - \Delta r), \tag{6}$$

where the radiative corrections Δr depend on the mass of the top quark and to a certain extent on the mass of the Higgs boson.
With the present centre-of-mass energies being well above threshold the W decay products can be used for direct reconstruction of the W mass. The two channels where this measurement is done are the fully hadronic and the semileptonic channel, both with their specific challenges.
In the fully hadronic channel there is a combinatorial problem as four reconstructed jets give rise to three jet pair combinations. In the case of five jets (treated by the DELPHI collaboration as a separate case) it even goes up to 10 pairing possibilities. Different algorithms have been developed to identify the best solution based on the lowest mass difference between the two jet pairs or on the highest fit probability, imposing energy and momentum conservation and an equal mass constraint. In the ideogram technique (used by DELPHI) all pairing solutions are taken into account as will be shown later.
In the semileptonic channel 1C or 2C kinematic fits have to be carried out in order to reconstruct the neutrino momentum and the W masses.

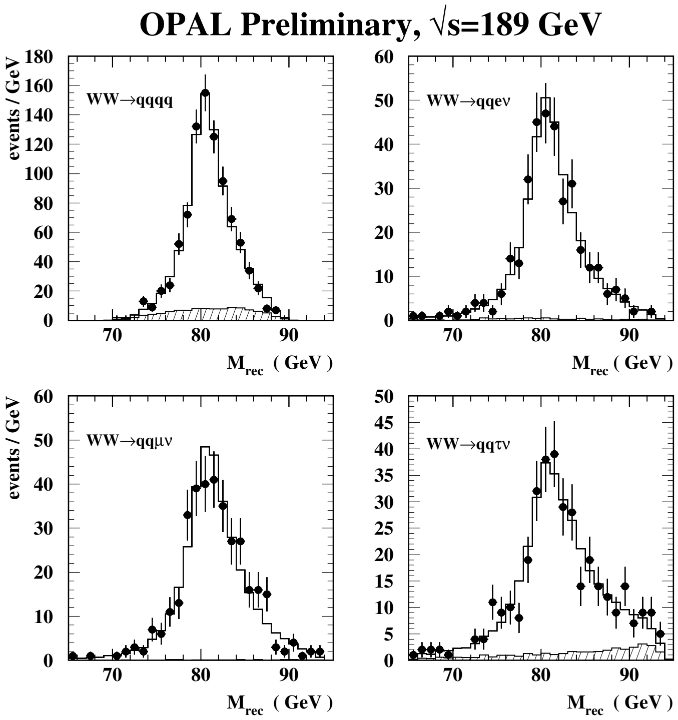

Figure 5: Mass spectra obtained from the data taken at 189 GeV for the different decay channels.The full curve represents the spectrum taken from MC simulations with the best fitted value used as W boson mass.

3.1 Techniques for extraction

Out of the reconstructed mass spectra the mass of the W boson M_W is extracted. Two techniques [11, 12], each with different advantages and disadvantages, are used and will be briefly reviewed in the next sections.

3.1.1 The reweighting technique

The idea behind the reweighting technique [13] is the comparison of the shape of the reconstructed (from data) mass spectrum with the shape obtained from MC samples at different values of M_W. An example of such mass spectra at 189 GeV can be found in fig. 5 for the different decay channels. This technique requires a lot of MC events to be generated and simulated, which quickly becomes time-consuming from a computational point of view. With the reweighting procedure it is possible to construct MC samples which correspond to different values of the W mass M_W out of one single simulated sample. Every MC event is assigned a weight as a function of the variable parameter M_W. The weight will be the ratio of the probabilities to observe the given event respectively with the new and the original value of the W boson mass. The weight assigned to each event can be expressed as the ratio of the squared matrix elements $|\mathcal{M}|^2$ of the evaluated process respectively with the new and the original value of the W mass:

$$\mathcal{R}_{weight} = \frac{|\mathcal{M}(p_1, p_2, p_3, p_4, m_W)|^2}{|\mathcal{M}(p_1, p_2, p_3, p_4, m_W^{MC})|^2}. \tag{7}$$

In a next step a probability density function is constructed as a function of the W boson mass M_W and finally the value of M_W is obtained with a likelihood fitting technique.
The main advantages of this technique are that selection and resolution are easily taken into account, Initial State Radiation is on average included and the method is bias free as long as the MC describes these effects correctly. The main disadvantage is that this method is limited by simulation statistics, which limits the amount of information which can be included in such analyses.

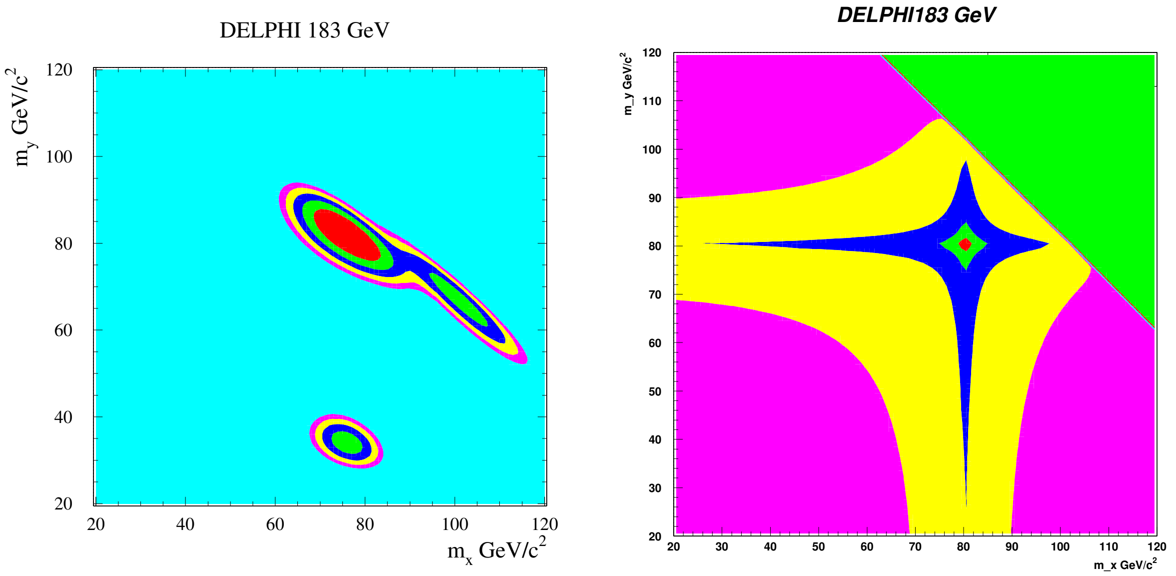

Figure 6: These are examples of two-dimensional ideograms : the experimental ideogram(on the left) and the theoretical ideogram (on the right hand side). Up to five sigma contours are shown in both cases.

3.1.2 The ideogram technique

This technique [14] can be best explained in three steps. The first step contains the construction of an experimental probability ideogram. With the given kinematics of an event the probability that two

heavy objects with corresponding masses m_x and m_y were produced is calculated. In this calculation the detector resolution function is taken into account. An example of such an ideogram for the three jet pairing solutions can be found in fig. 6.
The second step consists of the construction of a theoretical ideogram as the complement of the experimental ideogram. Here the production probability of the signal, which is a two-dimensional Breit-Wigner, and the production probability of the background processes, which can be taken from simulation, are convoluted. An example of the two-dimensional Breit-Wigner distribution can be found in fig. 6. A contour plot with up to five standard deviations is shown and the phase space cut-off at the kinematic limit is indicated.
In the last and third step an event-by-event likelihood is constructed. This is done by making a two-dimensional convolution of all these relative probabilities. The likelihood obtained in this way is then a function of M_W.
The main advantage of this method is that more kinematic information of the event is taken into account as all jet pairings are included. In this two-dimensional fit both masses m_x and m_y vary. In addition the five-jet events are treated separately. These events are produced when hard non-collinear gluon radiation occurs at an early stage and hence the event cannot be clustered in a natural way into four jets.
This ideogram method has been devised and used by DELPHI and enables the inclusion of complicated detector response functions. This method is not bias free, but this can be corrected for after the bias has been estimated from simulation.

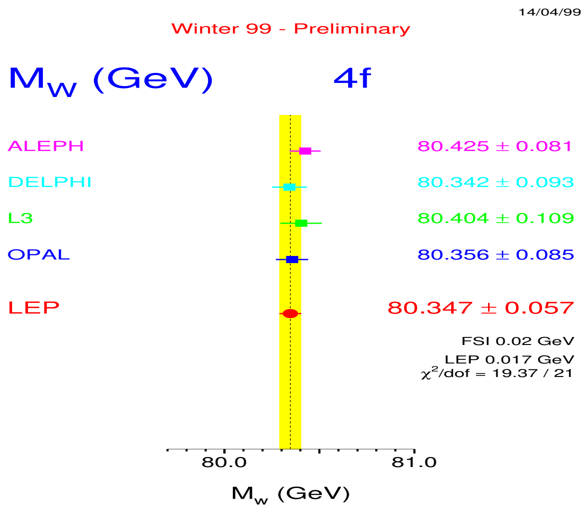

Figure 7: The measured W mass for each experiment individually and combined for the four LEP experiments. These are the results for the hadronic and semileptonic channel with data taken from 172 GeV up to 189 GeV.

3.2 Results and comparison

In fig. 7 [7] the combined results [15, 16] from the semileptonic and hadronic channel are presented for centre-of-mass energies ranging from 172 GeV up to 189 GeV. The results are given for each experiment separately. The combined LEP result, evaluated by the LEP electroweak working group [16], is also given.
At 189 GeV the statistical error on the combined result, for both channels (semileptonic and hadronic) was ∼33 MeV. In comparison with the results obtained in 1997 this is a factor two better. If we look forward to the end of LEP the statistical error is expected to reduce even to 25 MeV. It is clear that systematic errors start dominating the total precision. In the semileptonic channel the statistical error

is still dominating but the main contribution in the combined systematic error is coming from the LEP beam energy. Already now efforts are made by the LEP energy working group to improve and reduce the error on the measurement of the beam energy. The preliminary error for 1998 on this measurement is 40 MeV, which yields an error of 17 MeV on the W mass.
In the hadronic channel, on the contrary, the biggest contribution in the error is already that from systematics. The largest contribution comes from Final State Interactions(FSI), because both W almost decay on top of each other. By FSI we understand the two phenomena of Bose Einstein Correlations and Colour Reconnection [17]. To estimate the possible effects of these Final State Interactions on the W mass, phenomenological models are used. Some aspects in these models are not well understood, and studies are being performed. For this reason the present quoted systematics may be a too conservative estimate.
In the combination of both semileptonic and hadronic channels, a weighted average is used, so the latter contributes less to the total error.
The W mass is also measured at $p\overline{p}$ colliders (Tevatron [18]); these results combined with the one from LEP gives the average

$$M_W = 80.394 \pm .042\, GeV/c^2. \tag{8}$$

4 Summary and conclusions

Currently the measurements on the Triple Gauge Boson Couplings and the determination of the W boson mass are the most accurate and in agreement with the SM model expectation. The statistical errors will be reduced on both measurements as LEP is taking data each time at higher centre-of-mass energies and an estimated $300pb^{-1}$ is still to be delivered. A lot of effort is now put in the study of the systematics.

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