The analyses and results on WW physics obtained in the first year of running of LEP2 are summarized. The determination of the W mass, both through the measurement of the WW production cross section at a center-of-mass energy of 161 GeV and through the study of the invariant mass distribution of W decay products in the 172 GeV run are described first. Preliminary results on searches for anomalous triple gauge-boson vertices are also presented.

1 Introduction

The LEP accelerator at CERN is just in the middle of an energy upgrade that will bring its energy to about 195 GeV in year 1998, with peak luminosities close to $10^{32}\text{ cm}^{-2}\text{s}^{-1}$.

The main reason to double the energy of the LEP machine is to be able to produce pairs of W’s. Their mass can be accurately measured, providing a new constraint on the Minimal Standard Model (MSM) fundamental parameters. A very precise measurement of the W mass could provide useful information on the mass of the MSM Higgs boson. The W couplings to the other vector bosons in the electroweak theory (photon and Z), which come from the non-abelian nature of the gauge group, can be studied with great detail and constraints on new physics can be derived from their determination.

This article summarizes the first results on WW physics obtained with the 1996 data sample and will analyse also the prospects for precise measurements of both the W mass and its couplings to Z and photon when the whole data sample will be collected around year 2000.

The 1996 LEP2 run was splitted into two parts. The first run, between June and August 1996 collected 11 pb$^{-1}$ of data per experiment at a center-of-mass energy $\sqrt{s} = 161.3\text{ GeV}$, that is about 0.5 GeV above the nominal WW production threshold. The second run, in October and November 1996, was at $\sqrt{s} = 172\text{ GeV}$ and accumulated 10 pb$^{-1}$. Final results from the WW analyses for the first set are available from all four LEP experiments and will be reviewed here. At the time of writing, only preliminary results were
available from the 172 GeV run. They will also be discussed here, although with less detail, due to their volatility.

The current LEP2 schedule includes running in years 1997–1999 with center-of-mass energies increasing from 184 GeV in 1997 to 194 GeV in 1998 and 1999. The expected luminosities are around 100 pb$^{-1}$ for 1997 and about 180 pb$^{-1}$ in each of 1998 and 1999. Together with the 21 pb$^{-1}$ collected in 1996, this would bring the total close to 500 pb$^{-1}$, which will be taken in the following as ultimate LEP2 luminosity per experiment.

Section 2 discusses some generalities about W production and decay, selection and background in $e^+e^-$ collisions. The W mass determination done with 1996 data taken near the WW production threshold is presented in section 3. The measurement done with the 1996 data at higher energy (172 GeV) and the prospects using all data up to 1999 are the subject of section 4. Section 5 contains the first results and future capabilities of LEP2 in the measurement of the trilinear gauge-boson couplings. Finally, section 6 contains a brief summary with the conclusions of the paper.

2 WW production and decay

Pairs of $W^+$s and $W^-$s are produced at LEP2 based on the three tree-level diagrams depicted in fig. 1. The t-channel exchange diagram dominates the resulting amplitude by having a factor $\beta = (1 - 4M_W^2/s)^{1/2}$ less. Therefore, the Ws tend to be produced in the forward direction. More so near threshold, where $\beta$ is indeed very small. The other two diagrams, whose existence is needed in order to preserve unitarity, include the non-abelian couplings between two Ws and either a photon or a Z. Since the t-channel diagram dominates near threshold, it is clear that the experimental sensitivity to trilinear
gauge-boson couplings will be higher for higher center-of-mass energies.

Neglecting flavour-mixing, the W boson decays to each pair of available up-antidown fermions with the same strength. Therefore, its branching ratios are 1/3 to lepton and neutrino and 2/3 to quark-antiquark. Because of the large mass of the top quark, decays to top-bottom pair are not allowed and, therefore, neglecting bottom-strange and bottom-down mixing, no $b$ quarks are produced in W decays.

Considering now W pairs, there are three possible final states:

- $ll\nu\nu$ (10.5% of the total WW sample). There are at least two neutrinos (more if $l = \tau$). The complete reconstruction of the event is possible only if the value of the W mass is assumed. These events can be used in the determination of the anomalous couplings.

- $l\nu$ jet jet (44%). With one neutrino ($l = e, \mu, 30\%$) the complete kinematical reconstruction is possible. These are clean events, with the two Ws clearly separated. They can be used in any study presented below.

- jet jet jet jet (45.5%). Often with a fifth jet due to gluon radiation. These are messy, unclear events, with important QCD backgrounds. The task of assigning particles to jets and jets to Ws is not easy. While the possibility of using the four-jet events for the determination of the W mass is by now firmly established, it still remains to be seen whether they can be used effectively in the anomalous couplings analysis.

The two main topics of interest in W physics at LEP2 are the precise determination of the W mass and the study of the non-abelian couplings between two Ws and Z or $\gamma$. They will be discussed in turn in the following.

### 3 W mass measurement at threshold

The current best determination of $M_W$ comes from the CDF and D0 experiments at the Tevatron, which get the W mass through a fit to the “transverse mass” distribution measured in W leptonic decays from the lepton momentum and the missing transverse momentum. Their current averaged value is

$$M_W = 80.37 \pm 0.10 \text{ GeV}.$$  

This number makes use of all available CDF and D0 data. By the end of run II, expected to start in 1999, the error could go down to 30–40 MeV.

An indirect $M_W$ determination can be obtained from the Standard Model fits to all electroweak data, mainly LEP1 results. Once the free parameters of
The minimal standard model, like $m_t$ or $M_H$ are obtained from the fit, they can be used to predict any other observable like $M_W$. The current best value, not using the direct $M_W$ and $m_t$ information, is

$$M_W = 80.323 \pm 0.042 \text{ GeV},$$

in excellent agreement with the direct measurement.

A strong consistency check of the theory can be obtained by comparing both numbers. The uncertainty in the indirect determination is going to decrease only slightly in the near future (thanks to the continuing $\sin^2 \theta_W$ measurements at SLAC). Therefore a crucial goal for the direct $M_W$ determinations is to bring down the error to the 30–40 MeV level, comparable to the error of the indirect measurement.

Two very different methods exist for the measurement of the W mass at LEP2:

- Measuring the total WW production cross section near the threshold region allows the determination of the kinematical threshold and, therefore, the W mass. The advantages of this method is that only involves counting events, it is clean and uses all decay channels. However, it needs data very close to threshold, where the cross section is small and, therefore, signal to background ratios are low and the number of events (for other measurements) is minimal.

- The direct reconstruction of the invariant mass of hadronic and leptonic decays uses about 90% of the events (all but the ones with two leptonic decays) and it works equally well at any LEP2 energy above about 170 GeV. However, it is very involved, especially for four-jet events, and it can be sensitive to soft QCD effects, also for the four-jet channel.

Both methods rely on the knowledge of the beam energy, the second because some sort of kinematical fit assuming four-momentum conservation is needed in order to improve the invariant mass resolution. In both cases, the error on the beam energy, $\Delta E_b$, translates almost directly into an error on the W mass:

$$\Delta M_W(\text{beam}) \simeq \Delta E_b.$$

The main problem for the measurement of the WW cross section near threshold is that the background is much larger than the signal, in particular for the fully hadronic channel. While the cross section for WW production and subsequent decay to hadrons is about 1.6 pb at 161 GeV, the cross section for hadron production through photon and/or Z reaches about 150 pb, or 100 times more.
Studies previous to the start-up of LEP2 showed that for a luminosity of 100 pb\(^{-1}\), the overall statistical error on \(M_W\) could be of order 134 MeV. Systematic errors were thought to be considerably smaller, leading to a total uncertainty around 144 MeV, when considering four experiments collecting 25 pb\(^{-1}\) each.

3.1 The \(WW \rightarrow l\nu l\nu\) channel at 161 GeV

The events in which both Ws decay leptonically are very simple indeed. All experiments select these events based on their low charge and neutral multiplicity, high missing transverse momentum (due to the neutrinos) and high acoplanarity (since there is more than one invisible particle). The overall efficiency varies with experiment, from about 40\% to almost 70\%. Differences amongst experiments have to do with their different solid angle coverage for track measurements and their diverse capabilities in tau identification. Indeed, a big fraction of the inefficiency comes from events were at least one of the Ws decay into tau.

Backgrounds are estimated to be very low, around 50 fb, to be compared with a signal cross section around 400 fb. The four experiments together have collected 12 events of this type. Clearly, with this level of statistics, it is not surprising that systematic errors are negligibly small, compared to the statistical error.

3.2 The \(WW \rightarrow l\nu qq\) channel at 161 GeV

The selection of \(WW \rightarrow l\nu qq\) when \(l = e, \mu\) is also very simple. All experiments select these events requiring large charged-particle multiplicity, large missing energy and momentum and trying to identify an isolated electron or muon opposite to the direction of the missing momentum. Efficiencies in this channel range from 70 to 90\%, the differences coming essentially from the different lepton coverage of the experiments. Background is very low, around 20 fb for a signal cross section close to 1.1 pb.

When the lepton is a tau, instead, the analysis is substantially more difficult. The selections differ for each experiment. The most common version selects events with two broad jets (\(q\bar{q}\)), one narrow jet (tau) and missing energy. Efficiencies are substantially lower, 40–55\%, and background from \(q\bar{q}\) production is rather large at about 150 fb, with signal cross section around 550 fb. Figure 2 shows two distributions used by the OPAL collaboration to select \(\tau\nu qq\) events, involving the missing energy and the direction of the missing momentum.
Figure 2: Distributions of direction of missing momentum and of amount of missing energy as used in the selection of the $\tau \nu qq$ final state by the OPAL collaboration. The arrows show the location of the selection cuts.
The total number of $l\nu qq$ events with $l = e, \mu, \tau$ selected in the 161 GeV run by the four collaborations is 51. Systematic errors are still small compared to the statistical errors and are dominated by the subtraction of the $q\bar{q}$ background to the $\tau\nu qq$ channel.

3.3 The $WW \rightarrow qqqq$ channel at 161 GeV

Although WW events in which both Ws decay hadronically at $\sqrt{s} = 161$ GeV do have a characteristic look as clear four-jet events with two pairs of back-to-back jets, their selection is much more involved, due to the huge background from $e^+e^- \rightarrow q\bar{q}$ production. DELPHI and OPAL have used standard cut techniques and get efficiencies around 60% and signal to background ratios between two and three. L3 and, especially, ALEPH have chosen more sophisticated methods based on multivariate analysis.

L3 has used a neural network with 12 variables, which include, among others:

- $y_{34}$, the value of the clustering parameter $y_{ij}$ for which the event changes from having four jets to having three jets;
- sphericity;
- the sum and difference between the two reconstructed W masses (after choosing one particular pairing among jets);
- the minimum and maximum jet energies.

The ALEPH collaboration has investigated several multivariate techniques for the $qqqq$ selection, which have been combined at the end. In all the analyses, loose preselections are applied to the data to get rid of clear $e^+e^- \rightarrow \gamma Z \rightarrow \gamma q\bar{q}$ radiative return events, two-photon initiated events and two-jet like events. After preselection, the efficiency is still very high, about 90%, but the signal to background ratio is still only around 0.1–0.3.

Then, signal is separated from background by using simultaneously several variables, most of them close to those used by L3 with the addition of two more discriminating quantities: the value of the four-jet QCD matrix element squared evaluated with each event kinematic variables, and the sum of the transverse momentum of all particles with respect to their nearest jet.

Four different statistical techniques have been used to combine the information on all those variables: a linear discriminant variable, a rarity variable, a weight technique and, finally, a neural network. Detailed information on all four techniques can be found in ref. [4]. The results of the four analyses are
then combined taking into account the correlations between them, which are found to be around 0.5–0.6, and a cross section for the $qqqq$ channels is obtained, $\sigma_{qqqq} = 1.80 \pm 0.50 \pm 0.19$ pb. The systematic error is larger than for the other two channels and has several components dealing with detector modeling, background subtraction, etc.

Finally, the results coming from the three channels are combined using a maximum likelihood method with inputs given by the number of observed events in the purely leptonic and the lepton-hadron channel and the cross section measured in the fully hadronic channel. The combination of the WW cross sections measured by the four experiments, assuming the Standard Model $W$ branching ratios, gives the final result

$$\sigma_{WW}(161.3 \text{ GeV}) = (3.69 \pm 0.45) \text{ pb}.$$  

The error is dominated by statistics. The systematic error (0.15 pb, included in the 0.45 pb) is dominated by the contribution from the $qqqq$ channel.

From the total WW cross section at threshold, the $W$ mass is obtained by using a Standard Model calculation that relates the WW cross section near threshold to its mass. Most of the $W$ mass sensitivity comes really from phase space restrictions and is, therefore, independent of many of the Standard Model assumptions. The resulting $W$ mass obtained from the threshold cross section measurement at 161 GeV is:

$$M_W = (80.40^{+0.22}_{-0.21} \pm 0.03) \text{ GeV},$$

where the last error reflects the current uncertainty on the LEP beam energy. Figure 3 shows the relationship between the measured cross section and mass.

4 W mass measurement above threshold

Above the WW production threshold, the WW cross sections is no longer very sensitive to the $W$ mass. The best method to measure the $W$ mass at energies above 170 GeV is to measure directly the invariant mass distribution of the $W$ decay products, $M_{jj}$ and $M_{l\nu}$, in $qqqq$ and $l\nu qq$ events. In the semileptonic events, the momentum of the neutrino can be obtained imposing four-momentum conservation. The fully leptonic events cannot be used because of the two missing neutrinos.
$m_W$ from $\sigma_{WW}$ at 161 GeV

$\sqrt{s} = 161.33 \pm 0.05$ GeV

$\sigma_{WW} = 3.69 \pm 0.45$ pb

$m_W = 80.40^{+0.22}_{-0.21}$ GeV

LEP Average

Final LEP 161 GeV W mass
LEP EW Working Group

Figure 3: WW cross section at $\sqrt{s} = 161.3$ GeV as a function of W mass. The band represents the experimental measurement.
Once the invariant mass distribution is measured, a fit to an appropriate function that will depend on the W mass will give the best estimate for this parameter, which will be approximately equal to the mean of the invariant mass distribution.

The detector resolution being far too poor to obtain a reasonably narrow invariant mass distribution, energy and momentum conservation have to be imposed in all channels to improve the resolution. Perfect resolution would result in a distribution close to a Breit-Wigner with the width given by the W decay width.

The intrinsic resolution of the method does not change very much with the center-of-mass energy, and, therefore, the method works best at the point with highest cross section, which for the LEP2 range is the point with highest energy, around 194 GeV. However, the method works similarly well at all energies above about 170 GeV.

Since the WW cross section increases sharply when moving away from threshold, while the $q\bar{q}$ cross section decreases slightly, the background problem in the fully hadronic channel discussed in the previous section is much less of a problem already at 172 GeV.

However, for this same channel, $qqqg$, other difficulties arise in the jet finding process and in the jet pairing into Ws, for which there are three possible combinations that will produce a total of six invariant masses per event, of which only two have anything to do with the W mass.

An example of what the analysis chain could look like in the four-jet channel will clearly show the fact that this is not, indeed, a simple analysis:

1. Event selection: based on large number of tracks or calorimeter clusters, large visible energy and momentum balance. Efficiencies in excess of 70% can be obtained with low levels of background.

2. Jet reconstruction: using the Durham or Jade algorithms with a value for $y_{cut}$ that has to be optimized for maximum jet-pair mass resolution.

3. Jet assignment to Ws: decide which jet goes to which W based on some $\chi^2$ value, or rough mass estimate. Or just take all possible combinations.

4. Kinematical fit: fit all jet energies and angles imposing four-momentum conservation and, optionally, an additional constraint on the difference of the two W masses. If this is not down, one will obtain two masses per event, which will, in general, be highly anticorrelated.

5. W mass fit: fit the resulting invariant mass distribution with a formula that has to represent a Breit-Wigner with threshold effects and
include initial state radiation, biases due to the method, correlations if two masses per event are used, etc.

Based on analyses of this kind made on Monte Carlo events, the authors of ref. concluded that the statistical error on \( M_W \) that could be expected after 500 \( \text{pb}^{-1} \) would be around 75 MeV for each of the channels, \( l\nu qq \) and \( qqqq \), increasing slightly when moving from a center-of-mass energy of 175 GeV to 192 GeV.

Systematic errors were also considered. Due to the use of four-momentum conservation, the beam energy uncertainty translates directly into an uncertainty on the \( W \) mass. Experimental systematical errors were evaluated as affecting \( M_W \) at the level of 20 MeV or so, while theoretical uncertainties in the initial state radiation calculation were estimated as 10 MeV. Putting all four experiments together, the expected final error, for a luminosity per experiment of 500 \( \text{pb}^{-1} \) was estimated to be 45 MeV for the \( qqqq \) channel, 44 MeV for the \( l\nu qq \) channel, and 34 MeV when combining both, roughly independent of the center-of-mass energy in the range between 170 GeV and 195 GeV.

A possibly important source of systematic error not included in the above estimate can come from soft QCD effects. The exchange of soft gluons between quarks from different \( W \) decays can lead to substantial momentum transfer between the two \( W \)s in a fully hadronic event. This, in turn, would modify the invariant mass distributions of the two \( W \)s. The effect has been called “color reconnection”, because in an extreme case, can lead to the formation of a color singlet with a quark and an antiquark coming from different \( W \)s.

Several models have been built to try to assess the size of the effect on \( M_W \). The estimates range from essentially no effect, to shifts of order 50–70 MeV. These are large numbers but, on the other hand, the effect is small enough so that it can be very difficult to measure it in any other distribution available at LEP2.

Bose-Einstein correlation effects between identical particles (for example, pions) from the decay of the two \( W \)s, can also lead to momentum exchange between the two \( W \)s. For the moment, to take all these possible shifts into account, a systematic error of order 50 MeV should probably be added to the error estimate for \( M_W \) obtained from direct reconstruction in the \( qqqq \) channel.

4.1 The \( WW \rightarrow l\nu qq \) channel at 172 GeV

The selection of semileptonic events at \( \sqrt{s} = 172 \) GeV proceeds in a similar way as at 161 GeV. The efficiencies are slightly higher, 70–80\%, and the background lower.
The event kinematics is reconstructed using a 1-C kinematic fit, as explained above, or, in some experiments, a 2-C fit, in which the two invariant masses are taken as equal: $m_{l\nu} = m_{jj}$. The resulting invariant mass distribution is then fitted using a simple Breit-Wigner formula. This introduces a shift on $M_W$ of order 100 MeV, which is corrected for by using Monte Carlo generated events.

4.2 The $WW \rightarrow qqqq$ channel at 172 GeV

The selection in the fully hadronic channel at 172 GeV is much simpler than at 161 GeV because of the much larger ratio of signal to background. All experiments have chosen to do a standard cut selection, with efficiencies around 70–80%.

Most experiments then use a 5-C kinematical fit to improve their mass resolution, imposing four-momentum conservation and equality of the two $W$ masses. The assignment of jets to pairs is done either according to some $\chi^2$ obtained from the 5-C fit or according to the distance of the invariant mass obtained to some reference value, although this last technique probably introduces some bias in the result.

Finally the fit is made with a Breit-Wigner formula, in some cases including a polynomial background. One of such fits, from DELPHI, can be seen in fig. 4.

There are still quite a number of issues that have to be better understood in all analyses: the optimization of the jet pairing, the use of a fit formula more complete than a simple Breit-Wigner, the problem of the soft QCD corrections... The 1997 data will both allow making more studies to solve these issues and will bring a decrease in statistical error that will indeed make all these points very relevant.

For the moment, the combination of the four preliminary $W$ mass measurements with the direct reconstruction method at 172 GeV (including both semileptonic and totally hadronic events) gives

$$M_W = (80.37 \pm 0.18_{\text{exp}} \pm 0.05_{\text{thco}} \pm 0.03_{\text{beam}}) \text{ GeV}$$

$$= (80.37 \pm 0.19) \text{ GeV}.$$}

The dominant error includes statistical and purely experimental errors, the second one is the estimate of the uncertainty due to soft QCD effects and the third comes from the beam energy uncertainty.

This result can be combined with the final $M_W$ determination using the WW production cross section measured at 161 GeV to give the preliminary $W$
Figure 4: Average W mass in $qqqq$ events at $\sqrt{s} = 172$ GeV as measured by the DELPHI collaboration (preliminary). The points represent data, while the shaded histograms are expectations from WW signal and background.
mass result from the first year of running of LEP2:

\[ M_W = (80.38 \pm 0.14) \text{ GeV}. \]

This value is compared in fig. 5 with the other measurements of \( M_W \), both direct at the Tevatron and indirect at LEP1 and SLD. The agreement of all measurements is perfect. The current LEP2 error is already quite good but still much larger than the 40 MeV uncertainty in the indirect measurement. To get a direct determination of \( M_W \) with this sort of accuracy and to compare it against the indirect measurement, which assumes the Minimal Standard Model, is the next challenge for both LEP2 and the Tevatron.

5 Triple gauge boson vertices

Measuring directly the strength of the non-abelian coupling between three vector bosons is an important test of the validity of the Minimal Standard Model. Direct measurements at the Tevatron using \( W \gamma \) and \( W Z \) production are not very precise, while some existing very stringent bounds on deviations from the MSM predictions obtained using LEP1 data are both model dependent and not comprehensive.

The most general Lagrangian involving interactions of two Ws and a photon or Z which is Lorentz invariant and preserves U(1) gauge invariance and parity and charge conjugation in the electromagnetic sector can be written as:

\[
\mathcal{L} = -ieA_\mu \left( W^{-\mu\nu} W^+_{\nu} - W^{+\mu\nu} W^-_{\nu} \right) -ie\kappa_\omega F_{\mu\nu} W^{+\mu} W^{-\nu} -ie g_{ZW} Z_\mu \left( W^{-\mu\nu} W^+_{\nu} - W^{+\mu\nu} W^-_{\nu} \right) -ie\cot\theta_W \kappa_Z Z_{\mu\nu} W^{+\mu} W^{-\nu} + ie \frac{\lambda_\gamma}{M_W^2} F^{\nu\lambda} W_{\mu\nu} W^{+\mu} + ie \cot\theta_W \frac{\lambda_Z}{M_W^2} Z^{\mu\lambda} W_{\lambda\mu} W^{+\nu} + e \frac{z}{M_W^2} Z_{\rho\sigma} \left( \partial^\rho W^{-\sigma} W^{+\alpha} - \partial^\rho W^{-\alpha} W^{+\sigma} + \partial^\rho W^{+\sigma} W^{-\alpha} - \partial^\rho W^{+\alpha} W^{-\sigma} \right) + ie \cot\theta_W \kappa'_{Z\rho} \hat{Z}_{\mu\nu} W^{+\mu} W^{-\nu} + ie \cot\theta_W \lambda'_{Z\rho} \hat{Z}^{\nu\lambda} W_{\lambda\mu} W^{+\nu} -\mu + ie \cot\theta_W \kappa''_{Z\rho} \left( \partial^\rho Z^{\nu} + \partial^\rho Z^{\nu} \right) W_{\mu\nu} W^{-\nu},
\]
$m_W$ [GeV]

- **pp-colliders**: $80.37 \pm 0.10$
- **LEP2**: $80.38 \pm 0.14$
- **Average(world)**: $80.37 \pm 0.08$ \(\chi^2/\text{DoF}: 0.0 / 1\)
- **LEP1/SLD**: $80.323 \pm 0.042$

Figure 5: Comparison of the direct $W$ mass measurements at the Tevatron and LEP2 and the indirect determination using LEP1 and SLD data.
where

\[ V_{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu \]

\[ \hat{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma} \]

for \( V = F, W, Z \).

There are ten terms in total, with nine free parameters, the fixed one being \( e \), the W charge. The first six terms conserve both \( P \) and \( C \) separately. They include the (electromagnetic and weak) anomalous dipole magnetic moment and quadrupole electric moment of the W, and the point-like coupling of two Ws to one Z. The anapole term, the one with the \( z \) parameter, violates both \( P \) and \( C \) while conserving \( CP \). The last three terms violate \( CP \). In the MSM, the only non-zero parameters are \( \kappa_\gamma \) and \( \kappa_Z \), which both are equal to 1, and \( g_{ZW} \), which is \( \cot \theta_W \) in the MSM.

Normally one assumes \( C \) and \( P \) invariance of the whole lagrangian, which eliminates the last four terms and leaves five free parameters. The next step in simplification consists in imposing \( SU(2)_L \times U(1)_Y \) invariance to the whole lagrangian. Then one can use the effective lagrangian approach and expand the lagrangian in inverse powers of the square of the scale for new physics. The numerator is given by the combinations of the available operators which have the right dimensions and which are gauge-invariant. If one makes use of the light Higgs field to construct the operators and furthermore the expansion is terminated at the first non-trivial term (that is, \( M_W^4/\Lambda_{NP}^2 \) is assumed to be small), it is found that the five non-zero parameters left can be expressed in terms of only three independent parameters:

\[
\begin{align*}
g_{ZW} - \cot \theta_W &= \frac{\alpha_{W\Phi}}{\sin \theta_W \cos \theta_W} \\
\kappa_\gamma - 1 &= \cot^2 \theta_W (\kappa_Z - 1) + \cot \theta_W (g_{ZW} - \cot \theta_W) \\
&= \alpha_{W\Phi} + \alpha_{B\Phi} \\
\lambda_\gamma = \lambda_Z &= \alpha_W.
\end{align*}
\]

Therefore, there are only three free parameters, which can be chosen as \( g_{ZW} \), \( \kappa_\gamma \), \( \kappa_Z \) or as \( \alpha_{W\Phi}, \alpha_{B\Phi}, \alpha_W \). This is the approach that has been followed by the LEP experiments.

If no light Higgs is assumed, then \( \lambda_\gamma \) and \( \lambda_Z \) are both of order \( M_W^4/\Lambda_{NP}^2 \) and one is left, again, with only three free parameters, \( g_{ZW}, \kappa_\gamma, \kappa_Z \), which are reduced to only two if global \( SU(2) \) symmetry is assumed in the limit \( g' \rightarrow 0 \).

The present direct limits to \( |\kappa_\gamma - 1| \) and \( |\lambda_\gamma| \) from the Tevatron experiments stand both at around 0.5. Limits on the parameters \( \alpha_{W\Phi}, \alpha_{B\Phi}, \alpha_W \) from LEP1
loop effects are also in the same range 0.1–1. However, other terms which appear in the expansion of the lagrangian and which do not contribute to three-point functions (vertices) but do contribute to two-point functions (or vacuum polarizations, which are very well measured at LEP1), like $\alpha_{BW}$, are strongly constrained by LEP1 measurements to be below 0.01. It has been argued\cite{15} that, naturally, most models for new physics would tend to predict

$$\alpha_{BW} \sim \alpha_{W\Phi} \sim \alpha_{B\Phi} \sim \alpha_W,$$

and that, therefore, only effects of order $10^{-2}$ could be visible at LEP2. While this looks indeed a natural assumption, a truly model-independent study of the trilinear couplings cannot be based on these assumptions, which, on top, could be triggered by some peculiar cancellation being at work for $\alpha_{BW}$.

The experimental information that can be used for the measurement of the couplings is all contained in the five-fold differential distribution

$$\frac{d^5\sigma}{d \cos \theta_W d \cos \theta_+^* d \cos \Theta^- d \phi_+^* d \phi_-^*},$$

where $\theta_W$ is the $W$ production angle and $\theta_+^*$ and $\phi_{+(-)}^*$ are the decay angles of the $W^{+(-)}$ in its rest frame. Not all information is available for all $W$ decay channels. In the fully hadronic channel, since it is very difficult to know which jet is a quark and which is an antiquark, which is the $W^+$ and which is the $W^-$, one only has access to folded distributions of the five angles. In the fully leptonic channel, the kinematics can be solved by assuming a certain value for the $W$ mass. However one obtains two different solutions for the five angles. Finally, no problem arises in the $l\nu qq$ channel.

The method for obtaining the values of the trilinear couplings can be summarized as follows:

- Select $W^+W^-$ events using standard cut techniques.
- Use a kinematical fit to improve angular reconstruction.
- For the fully hadronic channel, choose jet pairing to form $W$s.
- Get the angles $\theta_W, \theta_+^*, \theta_-^*, \phi_+^*, \phi_-^*$.
- Perform a maximum likelihood fit to the five-dimensional distribution, having as free parameters one, two or three of the $\alpha_i$ variables introduced above.
Monte Carlo studies show that in fits with only one free parameter, $\alpha_W$, (the other two are set to zero), limits around 0.05–0.10 can be obtained, depending on the center-of-mass energy, with luminosity around 500 pb$^{-1}$. The sensitivity increases substantially at $\sqrt{s} = 190$ GeV with respect to $\sqrt{s} = 176$ GeV. Furthermore, the semileptonic channel performs substantially better than the fully hadronic channel, and both do better than the fully leptonic one, because of its reduced branching fraction. Systematic uncertainties are expected to be substantially smaller than the statistical error, even with the full LEP2 data sample.

With the small WW data sample collected at 161 GeV, all LEP experiments have chosen to put limits to only one parameter, $\alpha_W$, and assume all other anomalous couplings are zero. ALEPH, DELPHI and L3 have used only their measured total cross section and the W mass determination at the Tevatron to derive limits, which are in the range $|\alpha_W| < 1.5 - 2.0$, at 95% confidence level. OPAL has also analyzed the kinematics of their $l\nu qq$ events to get a similar limit.

In the 172 GeV run, there are already enough events to do a full kinematic study. At the time of this writing the four LEP experiments had all presented very preliminary results using only the “golden” channel $l\nu qq$. The resulting limits are $|\alpha_W| < 0.5 - 1.0$. Once the information from fully hadronic and fully leptonic events will be included the limit will start becoming interesting, compared to the Tevatron ones. Already now, the L3 collaboration has combined their measurements at 161 and 172 GeV to conclude that they can exclude at 95% confidence level the case of no coupling between Z and W, $g_{ZW} = 0$. Figure 6 shows the DELPHI measurement of the W production angle and their fit to $\alpha_W$. It is clear that this measurement will especially benefit from higher energy and luminosity, as expected for the 1997 run.

6 Summary

The LEP2 machine has very rich capabilities in WW physics. The W mass will be determined with total error around 30–40 MeV. And the couplings of photon and Z to two Ws will be determined to a few per cent accuracy.

The first LEP2 run in 1996, with only a total of 21 pb$^{-1}$ of data, has produced already some very interesting results, like the determination of the W mass with 140 MeV uncertainty or the first limits on $\alpha_W$, of order 0.5.
Figure 6: Measurement of the W production angle distribution in semileptonic events by the DELPHI collaboration and fit to $\alpha_{W,\Phi}$.
Higher energies and luminosities in the period 1997 to 1999 or 2000 will certainly produce more precise results, providing precise tests of the Minimal Standard Model and, maybe, unveiling some of its weaknesses.

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