W boson physics at LEP2

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The precision study of W boson properties is one of the most important goals of the LEP2 physics programme This paper provides an overview of the measurements performed by the four LEP experiments, with particular emphasis on the extraction of the W mass. A review of the results obtained with the data collected until 1999 is also presented

1. INTRODUCTION

The LEP e^+e^- collider at CERN has been operated at centre-of-mass energies above the W-pair production threshold since 1996, when the so-called LEP2 phase started. The energy was gradually raised to reach 204 GeV in 1999. A total integrated luminosity of about 450 pb^{-1}, corresponding to nearly 7000 WW events, has been collected by each of the four LEP experiments. LEP2 data taking is currently going on at energies of 206-208 GeV, and will continue until the end of the year 2000.

WW production gives origin to a four-fermion final state. $qqqq$ (B.R.=45.9%), characterised by a four-jet topology, $qql\nu$ (43.7%), with one energetic lepton isolated from the hadronic system and missing energy due to the undetected neutrino, and $l\nu l\nu$ (10.4%), with two acoplanar leptons and missing energy. Other processes, involving either two, one or no W bosons, can result in the same four-fermion final states, with a number of contributing Feynmann diagrams depending on the final state. Each measurement implies the choice of a subset of contributing diagrams which is defined as the signal.

2. WW CROSS-SECTIONS AND BRANCHING RATIOS

The set of contributing Feynmann diagrams for the cross-section measurement is the "CC03" set, including the production of two resonant W bosons via t-channel neutrino exchange, or via s-channels γ or Z exchange.

All the final states resulting from W pair production are used for the cross-section measurement. Dedicated event selections have been developed for each final state, based either on sequential cuts, or on the use of multivariate techniques (neural networks, iterative discriminant analysis, likelihood ratio). Very similar event selection criteria are used also for the other analyses described below. Detailed descriptions of these criteria can be found in the quoted references.

The efficiency and purity of the selection are very high, typically around 80-90%, with worse performance for final states including one or more τ leptons.

The cross-section for the individual final states, the total W-pair production cross-section and the W decay branching ratios are extracted by maximising the Poisson probability of observing the detected number of events in each channel, with the expected number computed from the integrated luminosity, the selection efficiency and the expected background The effect of the cross-talk between different signal channels is taken into account in the efficiency computation while the contribution of Feynmann diagrams other than the CC03 set is corrected by comparing Montecarlo samples including all the diagrams or the CC03 set only.

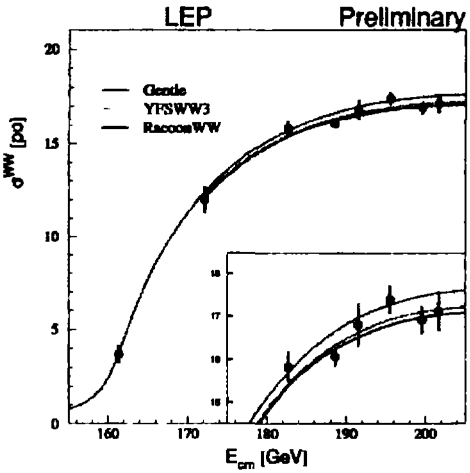


Figure 1. *W-pair production cross-section*

The results of the individual experiments [1] are in good agreement. The combined LEP measurement of the total W pair production cross-section at the different centre-of-mass energies is shown in figure 1. The experimental error is at the level of 1%. This is smaller than the uncertainty on the prediction from the GENTLE program (about 2%), which has been used so far to obtain the theoretical estimates. More recent calculations [2], including a better treatment of non-factorizable radiative corrections with the DPA technique, have a much smaller uncertainty (about 0.5%) and a predicted central value lower than the GENTLE one by 2-2.5%. These predictions are compared with the experimental results in the figure.

The combined LEP measurements of the W decay branching ratios into leptons are reported in table 1. These values are consistent with the hypothesis of lepton universality in charged current weak interactions. If this is assumed to hold, the decay ratio of the W into hadrons can be extracted.

$BR(W \to e\bar{\nu}_e)$	$10.63 \pm 0.20\%$
$BR(W \to \mu\bar{\nu}_\mu)$	$10.56 \pm 0.19\%$
$BR(W \to \tau\bar{\nu}_\tau)$	$11.02 \pm 0.26\%$
$BR(W \to q\bar{q}')$	$67.85 \pm 0.33\%$

Table 1
W decay branching ratios.

3. SINGLE-W CROSS-SECTIONS

The measurement of the cross-section for single W boson production provides a critical test for Gauge invariance in the Standard Model For the first time on occasion of the 2000 Winter Conferences, the four LEP experiments have agreed on a common definition of the signal for the $e^+e^- \to We\nu_e$ process, represented by the gauge-invariant subset of t-channel Feynmann diagrams contributing to the $We\nu_e$ final state, and have thus provided the first LEP combined measurement of the single-W production cross-section. The results [3] are shown in figure 2, in comparison with the theoretical predictions from two different calculations. The measurement is statistically limited, and its error is much larger than the uncertainty on the theoretical prediction.

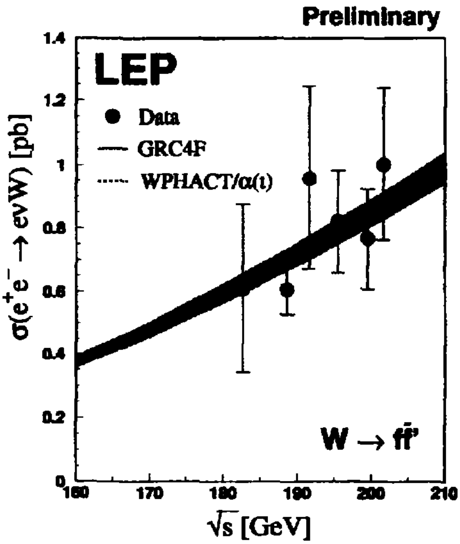


Figure 2. Single-W production cross-section.

4. TRILINEAR GAUGE BOSON COUPLINGS (TGCs)

Couplings among gauge bosons are a distinctive feature of non-abelian theories, such as the Standard Model. A direct measurement of the WWV ($V = Z,\gamma$) vertices allows for a test of the predicted form of the interaction. The observation of deviations from the Standard Model could be a hint for new physics.

In the most general Lorenz-invariant lagrangian, 7 independent parameters describe each of the two vertices. Assuming C, P and CP conservation, gauge invariance and $SU(2)\times U(1)$ constraints, the number of free parameters is reduced to 3, indicated as κ_γ, g_Z^1 and λ_γ. These are directly related to the electric dipole and magnetic quadrupole moments of the W boson [4]. Deviations from the Standard Model values are quoted:

$$\Delta\kappa_\gamma = \kappa_\gamma - 1 \;\; ; \;\; \Delta g_Z^1 = g_Z^1 - 1 \;\; ; \;\; \lambda_\gamma$$

At LEP2, WWV vertices can be explored directly in several processes, where they contribute at tree level: W-pair production, single-W ($e^+e^- \to We\nu_e$) and single photon ($e^+e^- \to \nu\bar{\nu}\gamma$) events.

Anomalous contributions to the WWV vertices would alter both the total production rate and the relative weight of different W helicity amplitudes. Sensitive observables are the total cross-sections for the above mentioned processes, and the differential distributions of W production and decay angles (in $e^+e^- \to W^+W^-$ only).

The kinematical variables used for TGC analyses in WW events are the polar angle of W^- production in the lab frame and the polar and azimuthal angles of the W^+ and W^- decay products in the rest system of the respective parent boson.

Not all these variables can be measured in general: the accessible information depends on the WW decay channel. Furthermore, the loss of information introduced by detector effects must be taken into account. Constrained fits based on four-momentum conservation are used to improve the resolution on the observables.

Several statistical techniques are used to determine TGCs. Maximum likelihood fits require the choice of a subset of the kinematical variables, due to the limited statistics available. With the method of Optimal Observables [5], based on the quadratic dependence of any differential cross-section on any of the couplings, the five kinematical variables are reduced to two, retaining maximal information on the TGCs; one clear advantage is that detector effects are much easier to include.

Combining the data from all the LEP experiments [6], and allowing for one free parameter at a time, with the other ones fixed to their Standard Model values, the results reported in table 2 are obtained.

No evidence is seen for deviations from the null values expected in the Standard Model. TGC measurements will specially profit from the future LEP2 data both because of the larger statistics (the systematic error is smaller than the statistical one), and because the sensitivity increases at higher energy.

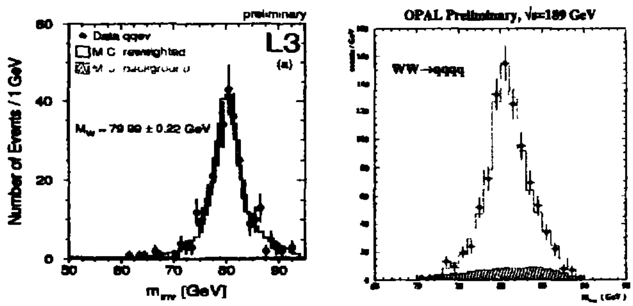
5. MEASUREMENT OF THE W BOSON MASS

The precision measurement of the W boson mass (m_W) is one of the most important goals of the LEP2 physics programme. Its interest lies both in the test of the Standard Model

$\Delta\kappa_\gamma$	$0.021^{+0.063}_{-0.059}$
Δg_1^Z	-0.024 ± 0.024
λ_γ	-0.016 ± 0.026

Table 2
Combined LEP results on TGCs.

expectations by comparing with the "indirect measurement" from radiative corrections, and in the prediction on the mass of the Higgs boson



(a) (b)

Figure 3. Reconstructed invariant mass distribution in $qqe\nu_e$ and $qqqq$ events

Direct reconstruction of the invariant mass of the W decay products is the most accurate method to perform the measurement The experimental resolution on the invariant mass is improved by means of kinematic fits exploiting the constraint of four-momentum conservation in the clean environment of e^+e^- collisions and the (approximate) equality of the masses of the two Ws in the same event. The typical mass resolution after the kinematic fit is about 3 GeV. Examples of reconstructed mass distributions are shown in figure 3

5.1. Statistical methods for the extraction of m_W

The statistical methods to extract the W mass are based on maximum likelihood fits to the data. Two techniques are used by the different experiments:

- Reweighting (A,L,O): the generated simulation events are reweighted as a function of m_W using the matrix elements from a full four-fermion calculation. All biases in the reconstruction are taken into account, but the inclusion of event-by-event information is not straightforward. An example of the comparison of data with reweighted simulation events is shown in figure 3(a)

- Convolution (D,O): a semi-analytical fit is performed with a function describing the reconstructed mass distribution, for example the theoretical excitation curve (a Breit-Wigner modified by the effects of phase space and initial state radiation) convoluted with a detector resolution function. This is illustrated in figure 3(b). Event quality information is included in the resolution function (χ^2 and mass error from the kinematic fit). However, biases must be calibrated on the simulation.

The two techniques have been shown to give consistent statistical precision. Possible differences in the sensitivity to systematic effects are under investigation.
The statistical sensitivity of the two WW decay channels used for mass reconstruction, $qqqq$ and $qql\nu$, are comparable. When all the results from the four experiments on the data available fro the 2000 Winter conferences are combined, the overall statistical error on m_W amounts to 27 MeV.
The total systematic error, on the other hand, is 41 MeV, and is largely dominating. Systematics are going to limit the precision on the measurement of m_W, and the efforts of the four experiments are focusing on understanding and possible reducing them, as explained in the next section.

5.2. Systematic errors

Table 3 summarises the contributions of the main sources of systematic uncertainty on m_W, as quoted by the individual experiments. Correlations between experiments, channels and years of data taking must be studied and carefully taken into account in the combination of results. The most relevant sources of systematic error will be briefly discussed in this section.

Systematic error source	Δm_W (MeV)	Correlations		
		Experiments	Channels	Years
LEP beam energy	17	X	X	X
ISR (and EW corrections)	2-15	X	X	X
Fragmentation	10-60	?	?	X
FSI: Colour Reconnection	30-55	X		X
FSI: Bose-Einstein Correl.	20-50	?		X
Detector effects	5-60		X	X

Table 3
Impact of the different sources of systematic error on the measurement of the W mass, as quoted by the different experiments. The correlations taken into account in the combination are also indicated. See the text for details.

The LEP beam energy is applied as a constraint in the kinematic fit used for mass reconstruction, therefore its fractional error translates directly to the same fractional error on m_W. The current preliminary measurement of the LEP beam energy [7] uses resonant depolarization techniques at low energy and extrapolation to high energy with integral

methods (flux loop) and with local NMR probes. A new measurement technique based on the precise measurement of the beam deflection in a known magnetic field should improve the beam energy error to 10 MeV.
Systematic errors due to fragmentation are evaluated by comparing different Montecarlo models (ARIADNE, JETSET and HERWIG), with the parameters tuned to describe the data at the Z peak. The four experiments quote different values for fragmentation error because they use different models and parameter values and different evaluation methods. Furthermore, most of the error estimates suffer from limited simulation statistics. A joint effort is ongoing to compare the evaluation methods and evaluate the correlations by analysing common samples of Montecarlo events.
Final State Interactions could affect the mass measurement in $qqqq$ events since the cross-talk between the decay products of the two Ws could alter the invariant mass reconstruction. Interconnection effects can occur both in the hadronization phase (Colour Reconnection) or at the level of final state particles (Bose-Einstein correlations). A dedicated presentation on BEC has been given in this conference [8]. Systematic effects from CR phenomena on the W mass measurement are estimated by comparing several phenomenological models describing QCD interconnection between the two Ws. A more valuable insight could be obtained by studying FSI directly from the data. However, only the most extreme CR models predict effects on global event variables, and are excluded by the data. A method based on the study of the local particle density around the jet axis is currently under development, and is expected to provide good sensitivity to CR effects, once the data from all the experiments are combined.

Experiment	m_W (GeV)
ALEPH	80.449 ± 0.065
DELPHI	80.308 ± 0.091
L3	80.353 ± 0.088
OPAL	80.446 ± 0.064
LEP combined	80.401 ± 0.049

Table 4
W mass measurements by the four LEP experiments and their combination.

5.3. Results

Table 4 summarises the preliminary results obtained by the four LEP experiments, including the collected until 1999 (except DELPHI, using data until 1998). The combined LEP measurement

$$m_W^{(LEP)} = 80.401(\mathrm{stat}) \pm 0.027(\mathrm{syst}) \pm 0.041 \quad \mathrm{GeV}$$

is currently the world's most precise direct measurement of the W mass.
With the data collected in the year 2000, the final integrated luminosity will amount to about 650 pb^{-1} per experiment, and the aim is for a final error on m_W lower than

40 MeV. Furthermore, we expect to be able to observe or exclude Colour Reconnection and Bose-Einstein Correlations directly from the data.

6. CONCLUSIONS

During the LEP2 data taking, each of the four LEP experiments has collected several thousands of events with W bosons. They have been used for precision test of the Standard Model: the W-pair and single-W production have been measured, and found to be in good agreement with the most accurate theoretical predictions. Limits have been set on anomalous couplings in the non-abelian WWZ and $WW\gamma$ vertices.
The most important goal of the LEP2 physics programme is the precise measurement of the W boson mass. The efforts of the four experiments are focusing on understanding and reducing systematic errors, which are going to be the limiting factor on the accuracy of the measurement. The combined LEP result is at present the world's most accurate direct measurement of m_W.
LEP2 data taking is going on until the end of the year 2000. With the further accumulated statistics and the improvements in the experimental analyses, we're looking forward to even better precision on all the measurements described above.

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