In five years of operation (1996-2000) the four LEP2 experiments collected roughly 3 fb$^{-1}$ of data from $e^+e^-$ collisions at centre-of-mass energies between 161 and 207 GeV, yielding a total of about 40000 W-pair events. The analysis of the LEP2 W-pair production rates and kinematics has allowed fundamental new measurements of the electroweak model to be performed, most notably: (i) the first determination of gauge boson self couplings, (ii) direct measurements of W decay couplings to all fermions, and (iii) a direct measurement of the W mass with a 40 MeV/$c^2$ precision, comparable to hadron collider and indirect determinations.

1 W-pair cross section

Pair-production of W bosons is of great importance in the Standard Model (SM) of electroweak interactions, where the non-abelian nature of the SU(2) group leads to three-line (TGC) boson vertices that play a crucial role in the W-pair production. The LEP2 data sample of 700 pb$^{-1}$ per experiment at $\sqrt{s}=161$-207 GeV allowed to collect about $10^4$ W-pairs per experiment, identifying these events in all their final states, leptonic and hadronic. The results for the total W-pair cross sections as a function of the centre-of-mass energy are shown in Fig. 1 and are in overall agreement with SM predictions at the level of 1%. As it can be seen, the LEP2 W-pair cross section measurement alone represents a stunning proof of the presence of both the WWZ and WW$\gamma$ couplings dictated by the electroweak SU(2)$\otimes$U(1) gauge structure.

2 W couplings to gauge bosons

The structure and magnitude of WWZ and WW$\gamma$ couplings are measured fitting the W-pair event rates and the angular distributions of the W production and decay axes. The most general Lorentz-invariant WWV vertex ($V=\gamma,Z$) can have seven complex couplings

$$g_1^V \kappa_V \lambda_V, g_5^V \tilde{\kappa}_V \tilde{\lambda}_V.$$
making up a total of 28 parameters for both WWZ and WWγ vertices. In the SU(2)⊗U(1) model we expect \( g_1^V = \kappa_V = 1 \) for both \( V=\gamma \) and \( V=Z \), while all other real and imaginary parts are expected to vanish. A fit to ALEPH data only to all 28 parameters leads to

\[
\begin{align*}
\text{Re}(g_1^\gamma) &= 1.123 \pm 0.091 \\
\text{Re}(\kappa_\gamma) &= 1.071 \pm 0.062 \\
\text{Re}(g_1^Z) &= 1.066 \pm 0.073 \\
\text{Re}(\kappa_Z) &= 1.065 \pm 0.061
\end{align*}
\]

and all other 24 coupling parameters consistent with zero, within uncertainties ranging from 0.035 to 0.250. The result of this fit shows how clearly the W-pair data has revealed the SU(2)⊗U(1) structure of the gauge self-couplings.

A more constrained fit of all LEP2 data, in search of anomalous contributions to TGC, to the three couplings that conserve separately C and P, \( U(1)_{\text{em}} \), and global SU(2)_L⊗U(1)_Y, yields

\[
\kappa_\gamma = 0.984 \pm 0.045 \quad \lambda_\gamma = -0.016 \pm 0.022 \quad g_1^Z = 0.991 \pm 0.021,
\]

revealing again no deviation from the SM expectations.

### 3 W decay couplings

Given the possibility to classifying all W decays modes, the LEP2 W-pair sample has allowed the first direct measurement of all leptonic and hadronic W decay branching ratios, as

- \( \text{B}(W \rightarrow q\bar{q}) = 67.49 \pm 0.28\% \)
- \( \text{B}(W \rightarrow e\nu) = 10.66 \pm 0.18\% \)
- \( \text{B}(W \rightarrow \mu\nu) = 10.60 \pm 0.15\% \)
- \( \text{B}(W \rightarrow \tau\nu) = 11.41 \pm 0.22\% \)
where the hadronic decay fraction $B(W \to qq)$ is determined under the assumption of lepton coupling universality $B(W \to e\nu) = B(W \to \mu\nu) = B(W \to \tau\nu) = (1 - B(W \to qq)) / 3$. In the case of lepton non-universality, it can be noticed that the tau decay fraction is currently about three sigmas larger than the electron-muon average.

The above results can be interpreted as a test of the lepton-quark universality of charged currents ($g_q/g_\ell = 1.000 \pm 0.006$), and of the lepton family universality of charged currents ($g_\mu/g_e = 0.997 \pm 0.010$, $g_\tau/g_e = 1.034 \pm 0.015$, $g_\tau/g_\mu = 1.037 \pm 0.014$). The $W$ hadronic decay fraction can also be interpreted as a test of the unitarity of the CKM quark mixing matrix, in the first two families as $\sum |V_{ij}|^2(i = u, c; j = d, s, b) = 2.000 \pm 0.026$, and from this extract the $W_{cs}$ coupling amplitude $|V_{cs}| = 0.976 \pm 0.014$, without CKM unitarity assumptions.

4 W mass

4.1 $W$ mass from threshold cross section

At the start of LEP2 about 10 pb$^{-1}$ of data per experiment were recorded near the $W$-pair production threshold ($\sqrt{s} \simeq 161$ GeV), where the production cross section alone is very sensitive to the $m_W$ value. From the cross section determination an independent measurement of the $W$ mass has been obtained to be $m_W = 80.40 \pm 0.20$ GeV/$c^2$, where the large uncertainty is due to the limited statistics of the data sample.

4.2 $W$ mass from kinematic reconstruction

The $W$ invariant mass is reconstructed event-by-event in all $qqqq$ and $qq\ell\nu$ decays of $W$-pairs, from the kinematics of the visible decay particles. The resolution of the $W$ mass peak is improved by applying a kinematic fit imposing energy-momentum conservation constraints, leading to mass distributions as those shown in Fig. 2.

![ALEPH Preliminary qqqq](image1.png) ![ALEPH Preliminary $\mu\nuqq$](image2.png)

Figure 2: ALEPH reconstructed $W$ mass distributions after applying energy-momentum conservation constraints, in the fully hadronic channel (left), and in the semi-leptonic muon channel (right).

The $m_W$ value is extracted from the $W$ mass distributions with different methods as fits with a probability density function (p.d.f.) calibrated with Monte Carlo simulations, or Monte Carlo re-weighting techniques using the measured masses and their errors as inputs. The $m_W$ values
and systematic uncertainties are evaluated separately for each W-pair decay topology, (qqqq, eνqq, µνqq and τνqq) and the final $m_W$ values is obtained by combining the measurement from the individual channels. The most recent combined result from the LEP2 data is

$$m_W = 80.412 \pm 0.042 \text{ GeV}/c^2$$

where the weight of the fully hadronic (qqqq) channel is only 10% because of large uncertainties coming from possible final state interactions (FSI) effects between the two W hadronic decay products. Recent prospects to reduce the FSI uncertainty on $m_W$ in the hadronic channel from 100 to 40-50 MeV/$c^2$ should bring down the combined error on $m_W$ from 42 to 35-38 MeV/$c^2$.

The current LEP2 determination and other direct and indirect measurements of $m_W$ are shown in Fig. 3.

| W-Boson Mass [GeV] |
|---------------------|
| TEVATRON            |
| LEP2                |
| Average             |
| NuTeV               |
| LEP1/SLD            |
| LEP1/SLD/m_t        |

| $m_W$ [GeV] | Value     |
|-------------|-----------|
| 80.452      | ±0.059    |
| 80.412      | ±0.042    |
| 80.425      | ±0.034    |
| 80.136      | ±0.084    |
| 80.368      | ±0.032    |
| 80.379      | ±0.023    |

Figure 3: Comparison of W mass measurements. Results from the direct measurements from TEVATRON and LEP2 data are shown on the top. Indirect constraints from other electroweak measurements are shown on the bottom. Separately, the NuTeV determination is 2.8 sigmas lower than the direct determinations.

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