Results on W-pair productions at LEP2 are reviewed and their consistency with standard electroweak expectations is summarised. Special interest is given to measurements of W polarisation, and to new studies of spin and decay-plane correlations among the W pairs.

**1. Introduction**

During the data taking years from 1996 to 2000 the LEP2 program has delivered $e^+e^-$ interactions at centre of mass energies ranging from 161 to 207 GeV. In this period the four LEP experiments (ALEPH, DELPHI, L3, OPAL) have collected a total integrated luminosity of almost 3 fb$^{-1}$. The LEP2 data yielded about 40,000 W pair events, reconstructed in all their decay channels. Event rates allowed measurements of the W pair partial and total cross sections at different energies, as well as of W decay branching fractions. Further, the study of the W pair decay products kinematics allowed determinations of the W polarisation states, and of correlations among the two W bosons.

**2. W pair production rates**

Depending on the decay channels, different techniques allowed to select W pairs with efficiencies in the 50-90% range and background contamination in the 5-20% range$^{1,2,3,4}$. The combined results for the total W pair cross section at LEP2 energies are shown in figure 1 where the combined experimental precision is at the level of 1%. The total cross section results represent the first clear proof of the electroweak SU(2)$\otimes$U(1) gauge structure, through the gauge cancellations that ensure the W pair tree level scattering unitarity and the theory renomalizability.

The cross section measurement near the W pair production kinematic threshold at $\sqrt{s}=161$ GeV, has allowed a determination of the W boson mass, $m_W = 80.40 \pm 0.21$ GeV/$c^2$, that is completely independent from the methods based on the kinematics of the decay products. The overall experimental precision of the cross section measurements has also allowed to establish the presence of Standard Model radiative corrections.
to the tree level CC03 diagrams involved in the W pair production. Depending on the energy, these radiative corrections decrease the total cross section at the 2-3% level, and modify the shapes of some differential cross section distributions.

The W pair data has also allowed measurements of the W decay branching fractions at the 1% level. Combined results are in good agreement with the Standard Model expectations, except for the tau leptonic branching fraction that appears to exceed both the electron and muon fractions by more than two standard deviations leading to \( \frac{g_\tau}{(g_e + g_\mu)} = 1.036 \pm 0.014 \), an overall excess of 2.6 standard deviations.

3. W Polarisation

The helicity of the produced W can be measured using the polar and azimuthal decay angles (\( \theta^*, \phi^* \)) of the decay fermion in the W rest frame. In the case of a leptonic decay, where the charge of the fermion can be determined, the W boson fractions of helicity states are given by

\[
\frac{1}{N} \frac{dN}{d \cos \theta^*_\ell} = f_- \frac{3}{8} (1 + \cos \theta^*_\ell)^2 + f_+ \frac{3}{8} (1 - \cos \theta^*_\ell)^2 + f_0 \frac{3}{4} \sin^2 \theta^*_\ell,
\]

where \( f_- \), \( f_0 \), \( f_+ \) are the fractions of the \( \lambda = -1, 0, +1 \) helicity states for a W\(^-\), and of the \( \lambda = 1, 0, -1 \) helicity states for a W\(^+\). In the case of hadronic decays, since the charge can’t be determined clearly, only the absolute value \( |\cos \theta^*_q| \) is measurable and the differential distribution becomes

\[
\frac{1}{N} \frac{dN}{d |\cos \theta^*_q|} = f_\pm \frac{3}{4} (1 + |\cos \theta^*_q|^2) + f_0 \frac{3}{4} (1 - |\cos \theta^*_q|^2),
\]

where \( f_\pm = f_+ + f_- \) is the sum of both transverse helicity fractions.

In the case of LEP pair productions, the helicity state will be a function of the centre of mass energy \( s \) and of the angle \( \theta_{W^-} \) of the W\(^-\) direction with respect to the e\(^+\)e\(^-\) axis. To measure the helicity fractions, the interference terms and possible CP or CPT violating effects, the formalism of the Spin Density Matrix (SDM) is used, defined as

\[
\sigma_{\tau\tau'}^W(s, \cos \theta_{W^-}) = F^{W^-}_{\tau}(F^{W^-}_{\tau'})^*/\sum_{\tau} |F^{W^-}_{\tau}|^2
\]

where \( F^{W^-}_{\tau} \) is the amplitude to produce a W\(^-\) with helicity \( \tau = -1, 0, +1 \). The SDM is a Hermitian matrix with unit trace, the diagonal elements are the probabilities to observe a W in one of the three helicity states and the off diagonal terms represent the interference between helicity amplitudes.

![Fig. 2. Measurements of the Spin Density Matrix elements from DELPHI](image-url)

LEP experiments have measured SDM elements at different energies and in different \( \cos \theta_W \) bins \(^5,6,7\), by measuring the average values of projection operators \( \Lambda_{\tau\tau'}^W \) that are analytical functions of the \( \theta^* \) and \( \phi^* \) angles. An example of SDM measurements is shown...
Invariance under CPT would ensure that 
\[ \sigma_{W}^{f} = \left( \sigma_{-f}^{f} \right)^{T} \]
while additional CP invariance implies \( \sigma_{W}^{f} = \sigma_{W}^{-f} \), so that the matrix would be real. Therefore effects that do not conserve CP or CPT have been searched for by comparing the \( W^{+} \) and \( W^{-} \) SMD elements, and by searching for off diagonal imaginary parts. No significant deviation from the Standard Model expectation has been seen in the data so that both the CP and CPT violating effects in the SDM should be at a level smaller that \( 10^{-1} \).

Focusing on the diagonal SDM elements, the overall fraction of longitudinally polarised \( W \) bosons at LEP2 can be extracted averaging \( \sigma_{00} \) over all data samples. The average of current results \(^{5,6,7} \) yields

\[ f_{L} = \frac{\sigma_{00}}{\sigma_{\text{tot}}} = 23.6 \pm 1.6\%. \]

4. Spin and Decay-Plane Correlations

Recent studies address the possibility to measure correlations between the spin states of the two \( W \) bosons in \( W \) pair events, and more in general correlations in the decay kinematics of the two \( W \) bosons \(^{8} \).

The electroweak model predicts that the helicity combinations of the two \( W \) bosons depend strongly on the direction of the production axis \( \cos \theta_{W^{\pm}} \) as shown in figure 3. The forward \( \cos \theta_{W^{\pm}} \) direction is where the maximum of \( W \) pairs, both with transverse helicity \( (\lambda_{W^{\pm}} = -1, \lambda_{W^{\pm}} = +1) \) is found, and selecting \( 0.3 < \cos \theta_{W^{\pm}} < 0.9 \), 68% of the \( W \) pairs are expected to be produced in the \((+-)\) state. Conversely in the backward \( \cos \theta_{W^{\pm}} \) direction the maximum of \( W \) pairs, with double longitudinal helicity \( (\lambda_{W^{\pm}} = 0, \lambda_{W^{\pm}} = -1) \) is expected, in particular a fraction of 28% in the \(-0.9 < \cos \theta_{W^{\pm}} < -0.3 \) region.

Spin correlations have been searched for in semileptonic \( W^{+}W^{-} \rightarrow q\ell\nu \) decays. For the \( W \) decaying hadronically a cut \( |\cos \theta_{\ell^{\pm}}| > 0.66 \) on the polar decay angle distribution allows to select a sample enriched in \( \lambda = \pm 1 \) transverse spin while a cut \( |\cos \theta_{\ell^{\pm}}| < 0.33 \) selects a sample of hadronic decays enriched in longitudinal \( \lambda = 0 \) spin. For both samples a fit to the lepton \( \cos \theta_{\ell^{\pm}} \) distribution determines the helicity fractions of the leptonic \( W \), and differences in the fitted fractions can reveal the correlations among the two spin states.

In the forward \( \cos \theta_{W^{\pm}} \) region, enriching the hadronic transverse spin states should enhance the leptonic transverse spin fractions, while in the backward \( \cos \theta_{W^{\pm}} \) region the enrichment of hadronic longitudinal states should enhance the leptonic longitudinal spin fraction. Data results are shown in figure 4 where the expected effects are visible in the forward \( \cos \theta_{W^{\pm}} \) data, which benefits from quite larger statistics.

With the forward \( \cos \theta_{W^{\pm}} \) data, enrich-
The hadronic W transverse spin, with the two $|\cos \theta_W^*|$ selections, changes the leptonic W helicity fractions by $\Delta f_+ = +0.32 \pm 0.10 \pm 0.06$, $\Delta f_- = -0.03 \pm 0.07 \pm 0.05$ and $\Delta f_0 = -0.28 \pm 0.14 \pm 0.08$, clearly enhancing the transverse helicities, in reasonable agreement with the Standard Model expectations.

In a more general approach both semileptonic and fully hadronic W pair decays have been used to determine possible correlations between the two W bosons decay planes. Given the angle $|\Delta \phi|$ between the planes of the decay products of the two W bosons, the differential distribution of $|\Delta \phi|$ is given by:

$$\frac{1}{N} \frac{dN}{d|\Delta \phi|} = 1 + D \cos |\Delta \phi|$$

where $D$ measures the strength of the correlation. The data distributions of $|\Delta \phi|$ are shown in figure 5. The combined result of the fits of the two distributions gives $D = 0.012 \pm 0.021 \pm 0.012$, in agreement with the Standard Model Monte Carlo prediction of $D_{MC} = 0.010 \pm 0.002$, but not revealing any significant correlation effect.

5. Conclusions

The LEP2 data has brought the first precision confirmation of the SU(2)$\otimes$U(1) electroweak gauge structure through the W pair productions rates and decay kinematics. Results are in good agreement with the Standard Model expectations, with the $W\tau\nu_\tau$ coupling 2.6 standard deviations larger than expected. The W polarization fractions have been measured accurately and no anomalous interference terms, CP or CPT violating contributions have been found in the Spin Density matrix determinations. Spin correlations have also been established between the two W bosons, in agreement with expectations.

References

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