MEASUREMENT OF W POLARISATION WITH L3 AT LEP

RADOSLAW A. OFIERZYNSKI

CERN, EP Division, 1211 Geneva 23, Switzerland
E-mail: Radoslaw.Ofierzynski@cern.ch

The three different helicity states of W bosons produced in the reaction $e^+e^- \rightarrow W^+W^- \rightarrow \ell\nu q\bar{q}'$ at LEP are studied using leptonic and hadronic W decays. Data at centre-of-mass energies $\sqrt{s} = 183 - 209$ GeV are used to measure the polarisation of W bosons, and its dependence on the W boson production angle. The fraction of longitudinally polarised W bosons is measured to be $0.218 \pm 0.027 \pm 0.016$ where the first uncertainty is statistical and the second systematic, in agreement with the Standard Model expectation. The helicity information is used to determine spin correlations between W bosons w.r.t. the W flight direction. Combining all data, WW spin correlations are seen with a significance of up to 3 standard deviations in the forward and backward scattering regions. The difference between data and the Standard Model is at the 2 standard deviation level.

1. Introduction

In the Standard Model, the masses of the W and the Z boson are generated by the Higgs mechanism. The massless W, which has only two spin degrees of freedom, becomes massive through the combination with a scalar Goldstone boson. At the same time, the third spin degree of freedom appears, corresponding to longitudinal polarisation. Still the unphysical Goldstone boson controls the amplitude for emission or absorption of the longitudinal W boson. At high energy, this amplitude becomes equal to the amplitude for emission or absorption of the Goldstone boson [1]. Hence the measurement of the fractions of longitudinally and transversely polarised W bosons constitutes an important test of the Standard Model.

In this analysis, semileptonic W pair events generated at LEP are studied, *i.e.* events of the type $e^+e^- \rightarrow W^+W^- \rightarrow \ell\nu q\bar{q}'$, with ℓ denoting either an electron or a muon [2].

The W helicity states are extracted in a model independent way from the shape of the distributions of the polar decay angle, θ^*_ℓ, which is the angle in the W rest frame between the charged lepton and the W flight direction. Transversely polarised W bosons have angular distributions $(1 \mp \cos\theta^*_\ell)^2$

for a W^- with helicity ± 1, and $(1 \pm \cos\theta^*_\ell)^2$ for a W^+ with helicity ± 1. For longitudinally polarised W bosons, a $\sin^2\theta^*_\ell$ dependence is expected. For simplicity, we refer in the following only to the fractions f_-, f_+ and f_0 of the helicity states -1, $+1$ and 0 of the W^- boson, respectively. Assuming CP invariance these equal the fractions of the corresponding helicity states $+1$, -1 and 0 of the W^+ boson.

The differential distribution of leptonic W^- decays at Born level is:

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

For hadronic W decays, the quark charge is difficult to reconstruct experimentally and only the absolute value of the cosine of the decay angle, $|\cos\theta^*_{\mathrm{q}}|$, is used:

$$\frac{1}{N}\frac{dN}{d|\cos\theta^*_{\mathrm{q}}|} = (f_+ + f_-)\frac{3}{4}(1+|\cos\theta^*_{\mathrm{q}}|^2) + f_0\frac{3}{2}(1-|\cos\theta^*_{\mathrm{q}}|^2). \quad (2)$$

After correcting the data for selection efficiencies and background, the different fractions of W helicity states are obtained from a fit to these distributions.

A total of 685 pb^{-1} of data, collected at different centre-of-mass energies between 183 GeV and 209 GeV, is analysed. After a simple selection, which ensures a good angular resolution, we obtain 1088 $W^+W^-\to e\nu q\bar{q}'$ candidates and 922 $W^+W^-\to\mu\nu q\bar{q}'$ candidates, with an efficiency of 65.7% and a contamination from $W^+W^-\to\tau\nu q\bar{q}'$ and $e^+e^-\to q\bar{q}(\gamma)$ of 3.7%. For the selected events, the rest frames of the W bosons are calculated from the lepton and neutrino momenta, the latter being approximated by the missing momentum vector of the event. The polar decay angles θ^*_ℓ and θ^*_{q} of the lepton and the quarks are then determined. The angle θ^*_{q} is approximated by the polar angle of the thrust axis with respect to the W direction in the rest frame of the hadronically decaying W.

The fractions of the W helicity states are obtained from the event distributions, $dN/d\cos\theta^*_\ell$ and $dN/d|\cos\theta^*_{\mathrm{q}}|$. These distributions are corrected at each energy point for background and selection efficiencies. The corrected distributions at the different centre-of-mass energies are combined into single distributions for leptonic and hadronic decays. A binned fit to the functions (1) and (2) is performed on the normalised distributions. For leptonic decays, f_- and f_0 are used as the fit parameters and f_+ is obtained by constraining the sum of all three parameters to unity. For hadronic decays, f_0 is used as the fit parameter and the sum of f_+ and f_- is obtained from the unity constraint. The fit results are corrected for a small bias

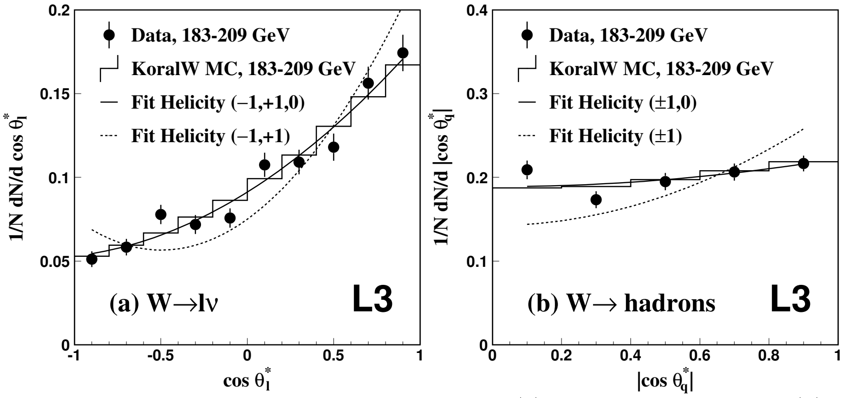

Figure 1. Corrected decay angle distributions for (a) leptonic W decays and (b) for hadronic W decays at $\sqrt{s} = 183 - 209$ GeV. Fit results for the different W helicity hypotheses are also shown.

due to migration effects introduced by detector resolution. The Standard Model predictions for f_-, f_+ and f_0 are obtained from Monte Carlo samples by fitting the generated decay angular distributions for each value of $\sqrt{s}$. The expected fraction of longitudinally polarised W bosons depends on the centre-of-mass energy, *e.g.* it changes from 0.271 at $\sqrt{s} = 183$ GeV to 0.223 at $\sqrt{s} = 206$ GeV.

2. Polarisations of the Individual W Bosons.

Figure 1 shows the results of the fits to the normalised decay angle distributions for leptonic and hadronic W decays. The data are well described only if all three W helicity states are used. For leptonic W decays, if the helicity 0 state is omitted the χ^2 of the fit increases from 12.7 for eight degrees of freedom to 56.2 for nine degrees of freedom. For hadronic decays, the χ^2 increases from 6.6 for four degrees of freedom to 59.1 for 5 degrees of freedom if we use only ±1 helicities.

Table 1. W^- helicity fractions, measured combining leptonic and hadronic decays. All the helicities are converted to W^- parameters using CP invariance. The first uncertainty is statistical, the second systematic. The corresponding Standard Model expectations are also given with their statistical uncertainties.

	f_-	f_+	f_0
W^- Data	0.555±0.037±0.016	0.200±0.026±0.015	0.245±0.038±0.016
W^+ Data	0.634±0.038±0.016	0.181±0.024±0.015	0.185±0.039±0.016
$W^\pm$ Data	0.592±0.027±0.016	0.190±0.017±0.015	0.218±0.027±0.016
Monte Carlo	0.590 ± 0.003	0.169 ± 0.002	0.241 ± 0.003

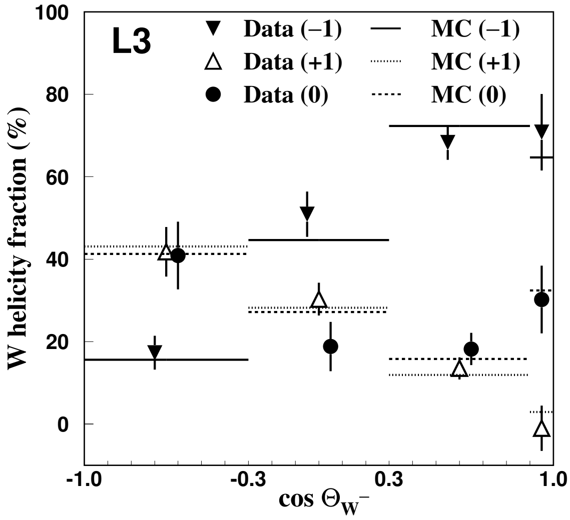

Figure 2. W helicity fractions f_-, f_+ and f_0 and their statistical uncertainties for four different bins of $\cos\Theta_{W^-}$ in the combined data sample and in the KORALW Monte Carlo for $\sqrt{s} = 183 - 209$ GeV.

The measured helicity fractions, at an average centre-of-mass energy $\sqrt{s} = 196.7$ GeV, are presented together with the Standard Model expectations in Table 1. The measured W helicity fractions agree well with the expectations. We observe longitudinal W polarisation with a significance of seven standard deviations, including systematic uncertainties.

Because of CP symmetry, the helicity fractions f_+, f_- and f_0 for the W^+ are expected to be identical to the fractions f_-, f_+ and f_0 for the W^-, respectively. We test CP invariance by measuring the helicity fractions for W^+ and W^- separately. The charge of the W bosons is obtained from the charge of the lepton. We select 1020 $W^+ \to \ell^+ \nu$, and 990 $W^- \to \ell^- \bar{\nu}$ events. Table 1 shows the results for separate fits to the W^+ and W^- distributions. The results are consistent with CP invariance.

To test the variation of the helicity fractions w.r.t. the W^- production angle, Θ_{W^-}, the data have been grouped into four bins of $\cos\Theta_{W^-}$. The ranges have been chosen such that large and statistically significant variations of the different helicity fractions are expected. The fit results combining leptonic and hadronic W decays are shown in Figure 2 together with the Standard Model expectations. The results are in agreement with the Standard Model expectation and demonstrate a strong variation of the W helicity fractions with the W^- production angle.

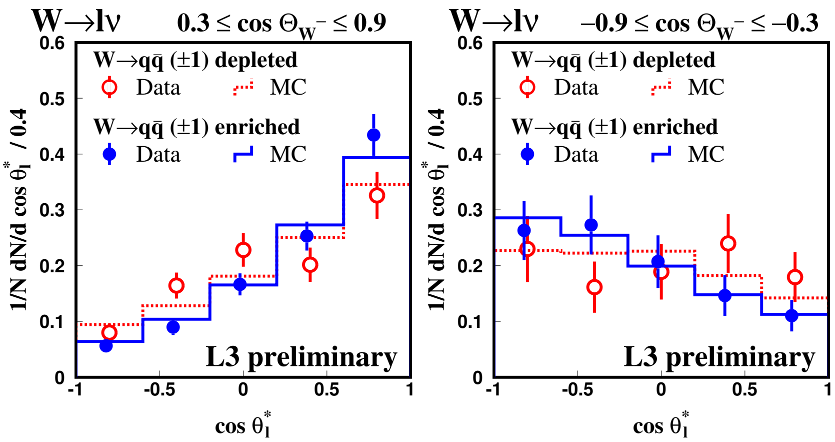

Figure 3. Corrected $\cos\theta^*_\ell$ distributions for $\mathrm{W}\rightarrow\ell\nu$ decays for data and the KORALW Monte Carlo in the intervals $0.3 < \cos\Theta_{\mathrm{W}^-} < 0.9$ (left) and $-0.9 < \cos\Theta_{\mathrm{W}^-} < -0.3$ (right) at $\sqrt{s}$=183–209 GeV. The distributions are shown for the subsamples with ±1 helicities depleted and enriched in W→hadron decays.

3. Spin Correlations between W Bosons. (or: does one of the W bosons scream when we squeeze the other one ?)

To answer this question, we consider two subsamples of W pair events: in the first the fraction of hadronically decaying W bosons with helicity ±1 is enlarged, in the second reduced. This enrichment and depletion is performed by cuts on the angular distribution of the hadronically decaying W bosons. For small polar decay angles (as follows from Eq. (2)), the sample consists of much fewer ±1 states, while for large polar decay angles the opposite is the case. For our analysis the slices $0 < |\cos\theta^*_{\mathrm{q}}| < 0.33$ for ±1 depleted and $0.66 < |\cos\theta^*_{\mathrm{q}}| < 1.0$ for ±1 enriched samples were chosen. The corresponding leptonically decaying W boson samples are compared to determine the correlation effect.

In order to enlarge possible effects the W^- scattering angle, $\cos\Theta_{\mathrm{W}^-}$, is used. As was shown in the first part, the W helicities vary with $\cos\Theta_{\mathrm{W}^-}$, as do the helicity combinations. One can thus use this angle to select particular W pair helicities. For this analysis, two intervals of the W scattering angle are used: In the forward bin, $0.3 < \cos\Theta_{\mathrm{W}^-} < 0.9$, the fraction of the helicity combination $\lambda_{\mathrm{W}^-} = -1, \lambda_{\mathrm{W}^+} = +1$ is increased to about 63% of all W pairs compared to 43% average over the whole $\cos\Theta_{\mathrm{W}^-}$ range. In the backward bin, $-0.9 < \cos\Theta_{\mathrm{W}^-} < -0.3$, the fraction of the helicity combination $\lambda_{\mathrm{W}^-} = 0, \lambda_{\mathrm{W}^+} = 0$ is increased to about 25% compared to the average value of 9%. In each of these two $\cos\Theta_{\mathrm{W}^-}$ bins, the proce-

Table 2. The W helicity fractions measured with leptonic W decays for different intervals of $\cos\Theta_{W^-}$. The results are shown for different subsamples with enriched or depleted helicity ±1 component of the hadronically decaying W boson.

	$0.3 < \cos\Theta_{W^-} < 0.9$: W$\to \ell\nu$ helicity fractions		
W$\to q\bar{q}$	f_-	f_+	f_0
±1 depleted	0.456±0.086±0.060	0.097±0.058±0.036	0.448±0.117±0.069
±1 enriched	0.832±0.061±0.004	0.092±0.033±0.030	0.076±0.081±0.030
difference data	-0.376±0.105±0.060	0.005±0.067±0.047	0.372±0.142±0.075
difference MC	-0.120	0.048	0.072
	$-0.9 < \cos\Theta_{W^-} < -0.3$: W$\to \ell\nu$ helicity fractions		
W$\to q\bar{q}$	f_-	f_+	f_0
±1 depleted	0.327±0.112±0.089	0.296±0.112±0.076	0.377±0.259±0.112
±1 enriched	0.134±0.075±0.075	0.472±0.107±0.104	0.394±0.197±0.136
difference data	0.193±0.135±0.116	-0.176±0.155±0.129	-0.017±0.325±0.176
difference MC	0.039	-0.163	0.124

dure of enrichment/depletion of the hadronically decaying W bosons with helicity ±1 is performed and the helicity composition of the corresponding leptonically decaying W bosons is compared.

The polar decay angle distributions of the leptonically decaying W bosons in the data and the Monte Carlo, combined for all centre-of-mass energies, are shown in Figure 3. We see a clear difference between the distributions for ±1 depleted and enriched samples. The results of the fits to these distributions are summarised in Table 2. The data demonstrate the existence of WW spin correlations along the W flight direction, with a significance of up to 3 standard deviations in the forward and backward scattering regions, 2 standard deviations stronger than expected.

4. Conclusions

Studies of W polarisation in the reaction $e^+e^-\to W^+W^-\to\ell\nu q\bar{q}'$ have been presented. All three possible W helicity states are required to describe the data. The helicity fractions and their variations as a function of $\cos\Theta_{W^-}$ are in agreement with the Standard Model expectation. The helicity fractions of W^+ and W^- considered separately are in agreement with CP invariance. The data also show significant correlations between W^+ and W^- helicities, 2 standard deviations stronger than the Standard Model expectation.

References

1. see *e.g.* M.E.Peskin, D.V.Schroeder, *An Introduction to Quantum Field Theory*, Addison-Wesley, 1995.
2. L3 Collab., P. Achard *et al.*, Phys. Lett. **B 557** (2003) 147.