EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

L3 Note 2755
June 26, 2002

Measurement of W Polarisation and WW Spin Correlations in $e^+e^- \to W^+W^-$ events at LEP

The L3 Collaboration

Abstract

The three different helicity states of W bosons, produced in the reaction $e^+e^- \to W^+W^- \to \ell\nu q\bar{q}$, are studied using leptonic and hadronic W decays at $\sqrt{s} = 183$–208 GeV. The W polarisation is measured for W^+ and W^- bosons, and as a function of the W boson scattering angle. Combining the results from all center–of–mass energies, the fraction of longitudinally polarised W bosons is measured to be $0.228 \pm 0.027(\text{stat.}) \pm 0.012(\text{syst.})$ in agreement with the expectation from the Standard Model.

The helicity information is used to determine WW spin correlations with respect to the W flight direction. Combining all data, WW spin correlations are seen with a significance of up to 2.6 standard deviations in the forward and backward scattering regions.

Submitted to the 31st *International Conference on High Energy Physics*
Amsterdam, Netherlands, 24-31 July 2002.

Introduction

In the Standard Model [1], the existence of all three W helicity states, $+1, -1$ and 0, is directly related to the mechanism of electroweak symmetry breaking. The measurement of the fraction of longitudinally polarised W bosons is therefore a crucial test for the Standard Model.

The analysis presented in this paper is based on the whole data set collected during the years 1997–2000 with the L3 detector. It supersedes our previous results [2] based on lower center-of-mass energies. In total, a luminosity of 684.8 pb^{-1} of data is analysed, with an average center-of-mass energy of $\sqrt{s} = 196.7$ GeV.

A detailed description of the L3 detector and its performance is given in reference [4]. The signal ($\mathrm{e^+e^-}\to\mathrm{W^+W^-}\to\mathrm{e}(\mu)\nu\mathrm{q\bar{q}}$) is simulated by means of the Monte Carlo generators KORALW [5] and EEWW [6]. Background processes are simulated using the following Monte Carlo programs: KORALW for leptonic decays of $\mathrm{W^+W^-}\to\tau\nu\mathrm{q\bar{q}}$, PYTHIA [7] and KK2F [8] for the process $\mathrm{e^+e^-}\to$ hadrons. The L3 detector response is simulated with the GEANT–based L3 detector simulation program [9].

Analysis Strategy

The W helicity states are derived in a model independent approach from the angular differential distributions of the polar decay angle θ^*, which is the angle between the charged lepton and the W in the W rest frame. According to the V-A structure of electroweak interactions, the angle θ^* of transversely polarised W bosons shows a distribution with a $(1 \mp \cos\theta^*)^2$ shape for a $\mathrm{W^-}$ with helicity ±1 , and a $(1 \pm \cos\theta^*)^2$ distribution for a $\mathrm{W^+}$ with helicity ±1. For longitudinally polarised W bosons (helicity 0) the distribution is proportional to $\sin^2\theta^*$, *i.e.* the decay products are distributed symmetrically. For simplification we refer in the following only to the fractions f_-, f_+ and f_0 of the $\mathrm{W^-}$ helicities, which includes the corresponding $\mathrm{W^+}$ states with f_+, f_- and f_0, respectively, assuming CP invariance. The differential distribution can be written at Born level as follows:

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

To determine the W helicity fractions, events of the type $\mathrm{W^+W^-}\to\ell\nu\mathrm{q\bar{q}}$ are used with ℓ being either electron or muon. These events are essentially background free and allow a measurement with good accuracy of the W momentum vector, the W charge and the polar decay angle θ^* in the W rest frame.

After correction for background and efficiencies, the fractions of the W helicity states are obtained from a fit to the $\cos\theta^*$ distributions with the additional constraint of the sum of the three fractions being unity.

For hadronic W decays the quark charge is not well identified, therefore only the absolute value of the decay angle, $|\cos\theta^*_\mathrm{q}|$, is used. Equation (1) hence becomes:

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

with $f_\pm$=f_++f_-.

The fractions f_-, f_+ and f_0 are calculated for both the full sample, referred to as inclusive measurement, and as a function of the $\mathrm{W^-}$ scattering angle $\Theta_{\mathrm{W^-}}$ in the laboratory frame. The

Standard Model prediction is obtained from the KORALW Monte Carlo program [5], for both the inclusive measurements and for the measurement of the W scattering angle dependence. The predictions are obtained from simulated event samples, for each center-of-mass energy point separately and combined according to the collected luminosity. The expected fraction of longitudinally polarised W bosons changes from 0.271 at $\sqrt{s}$ = 183 GeV to 0.223 at $\sqrt{s}$ = 206 GeV. The fractions are obtained from a fit to the distributions of the simulated decay angles. The Standard Model expectations at an average center-of-mass energy of $\sqrt{s}$ = 196.7 GeV for the inclusive W helicity fractions f_-, f_+ and f_0 are obtained to be 0.590, 0.169 and 0.241, respectively.

A large sample of events has been simulated using also the EEWW Monte Carlo program [6]. This program assigns, differently from KORALW, W helicities on an event by event basis but uses zero total W width approximation and does not include radiative corrections and interference terms. The fractions obtained by a fit to the simulated decay angle distributions agree within the Monte Carlo statistical errors with the generated W helicity fractions. A comparison of the fractions obtained with EEWW with the fractions obtained from KORALW shows good agreement.

Selection of $\mathrm{W^+W^-} \rightarrow \mathrm{e}(\mu)\nu\mathrm{q\bar{q}}$ events

The selection of $\mathrm{W^+W^-}\rightarrow\mathrm{e}(\mu)\nu\mathrm{q\bar{q}}$ events is essentially as described in the previous publication on the longitudinal polarisation [2] and assures well measured W production and decay angles.

Charged leptons are identified using their characteristic signatures. Electrons are identified as isolated energy depositions in the electromagnetic calorimeter with electromagnetic shower shape which are matched in azimuth to a track reconstructed in the central tracking chamber. The energy and direction of electrons are measured using the electromagnetic calorimeter, while the charge is obtained from the associated track. Muons are identified and measured with tracks reconstructed in the muon chambers which point back to the interaction vertex. All other energy depositions in the calorimeters are assumed to originate from the hadronic W decay. The neutrino momentum vector is assumed to be the total missing momentum vector of the event. In addition the following criteria are used for the selection of $\mathrm{W^+W^-} \rightarrow \mathrm{e}(\mu)\nu\mathrm{q\bar{q}}$ events:

- The reconstructed momentum must be greater than 20 GeV for electrons and 15 GeV for muons. Only events which contain exactly one electron or one muon candidate are accepted.
- The momentum of the neutrino must be greater than 10 GeV and its polar angle, θ_ν, has to satisfy $|\cos\theta_\nu| < 0.95$.
- The invariant mass of the $\ell\nu$ system has to be greater than 60 GeV.
- The invariant mass of the hadronic system has to be between 50 and 110 GeV.

The number of events obtained using these selection criteria are shown in Table 1 for the different center-of-mass energies and separately for $\mathrm{W^+W^-}\rightarrow\mathrm{e}\nu\mathrm{q\bar{q}}$ and $\mathrm{W^+W^-}\rightarrow\mu\nu\mathrm{q\bar{q}}$, together with the collected luminosity. In total, 2010 events are selected as candidates. These samples have a purity of 96.3%; the background from $\mathrm{W^+W^-}\rightarrow\tau\nu\mathrm{q\bar{q}}$, with leptonic τ decays, contributes 2.4% and the background from $\mathrm{e^+e^-}\rightarrow$ hadrons 1.3%. For the selected events the rest frames of the W bosons are calculated. The decay angles θ^*_ℓ and θ^*_q of the lepton and the quarks are determined in the corresponding frame. In this procedure the angle $\theta^*_{\rm q}$ is approximated by the angle $\theta^*_{\rm Thrust}$ of the thrust axis in the rest frame of the hadronically decaying W with respect to the W direction.

Analysis of the W helicity states

The analysis is performed as described in [2]. The fractions of the W helicity states are obtained from the distributions $dN/d\cos\theta^*_\ell$ and $dN/d|\cos\theta^*_{\rm q}|$ for the leptonic and hadronic decay angle, respectively. For each energy point, background as obtained from Monte Carlo simulations is subtracted from the data, and the resulting distributions are corrected for selection efficiencies. Selection efficiencies are obtained from large samples of fully simulated KORALW Monte Carlo events as a function of the polar decay angle, taking into account detector inefficiencies.

The corrected $\cos\theta^*$ distributions at the different center-of-mass energies are combined into one distribution for each of the studied samples. These combined distributions are fitted using the functions (1) and (2).

The bias and sensitivity loss as a function of the generated helicity fractions and due to the efficiency corrections and the θ^* resolution have been studied with fully simulated and reconstructed EEWW Monte Carlo events. The correction functions are found to be dependent on the center-of-mass energy, on the ratio of the remaining two helicity fractions, and on the $\rm W^-$ scattering angle. For the center-of-mass energy dependence, the correction function is obtained from a luminosity weighted event sample using Monte Carlo events simulated at $\sqrt{s} = 189$, 200 and 206 GeV. The dependence of the correction function on the helicity fraction is found to be linear in good approximation for a constant ratio of the remaining two fractions, within the statistical errors. For the correction of f_0 in the hadronic W decay the ratio of f_-/f_+ is taken from the measurement in the leptonic W decay. Correction functions are also determined for each of the $\rm W^-$ scattering angle bins separately.

Results and systematics

The results of the binned χ^2 fits to the $\cos\theta^*$ distributions for leptonic and hadronic W decays are shown in Figure 1 for the energy combined data. The data is well described by the fit only if all three W helicity states are used. Fits omitting the 0 helicity fail to describe the data. The χ^2 increases from 13.1 for seven degrees of freedom if all helicity states are included to 56.2 for eight degrees of freedom if only helicities $+1$ and -1 are used in the fit. For hadronic W decays the χ^2 increases from 20.4 for eight degrees of freedom if all helicity states are included to 80.7 for nine degrees of freedom if only helicities ±1 are used.

The measured fractions of the W helicity states in data, at an average center-of-mass energy $\sqrt{s} = 196.7$ GeV, are shown together with the Standard Model expectation in Table 2, for leptonic and hadronic W decays separately, and in Table 3 combining both decay modes. The measured W helicity fractions agree with the Standard Model expectation. The longitudinal W polarisation is observed with a significance of 8 standard deviations.

To test the variation of the helicity fractions with the $\rm W^-$ scattering angle, $\Theta_{\rm W^-}$, the data have been grouped into four subsamples of $\Theta_{\rm W^-}$. The ranges have been chosen such that large variations of the different helicity fractions are expected, yet keeping a sufficient statistical significance. The background and efficiency corrected $\cos\theta^*$ distributions have been fitted for leptonic and hadronic W decays separately. Figure 2 shows the four $\cos\theta^*$ distributions for the leptonic W decays. The fit results, corrected for bias and combining leptonic and hadronic W decays, are shown in Table 4 and Figure 3 together with the Standard Model expectations from the KORALW Monte Carlo. Within the errors, the results agree with the Standard Model expectation and demonstrate a strong variation of the W helicity fractions with the W^- scattering angle.

Within the Standard Model, CP is conserved in the reaction $e^+e^- \to W^+W^-$ and the helicity fractions f_+, f_- and f_0 for the W^+ are expected to be identical to the fractions f_-, f_+ and f_0, respectively, for the W^-. The CP invariance can be then tested by measuring the helicity fractions for W^+ and W^- separately. The charge of the W bosons is obtained from the leptonically decaying W boson, the hadronically decaying W getting the opposite charge. Using this assignment, 1020 $W^+ \to \ell^+\nu$ and 990 $W^- \to \ell^-\bar{\nu}$ are identified in the whole data sample. Using the corresponding background and efficiency corrected $\cos\theta^*$ distributions the W helicity fractions are obtained from the fits and corrected for bias. The quantitative results are given in Table 2 for leptonic and hadronic decays separately, and in Table 3 combining both decay modes. The results agree well with the assumption of CP invariance.

A number of systematic studies have been performed to verify the stability of the obtained W helicity fractions. These studies include uncertainties due to backgrounds, selection criteria, efficiencies and bias. Backgrounds have been varied by $\pm 50\%$ for both the hadronic background and for misidentified $W \to \tau\nu$ decays. Selection cuts have been varied over a range of one standard deviation of the corresponding simulated reconstruction accuracy. Efficiency and bias systematics effects are very small due to the large Monte Carlo event sample.

Study of WW spin correlations

WW spin correlations are investigated by measuring the W helicity fractions from leptonically decaying W bosons as a function of $|\cos\theta^*_{\mathrm{q}}|$ as measured in the hadronically decaying W boson of the same event. Without the knowledge of the quark charge one can only enrich or deplete the fractions of hadronically decaying W with helicity ± 1.

Spin correlations between the W^+ and W^- produced in the reaction $e^+e^- \to W^+W^-$ are searched as helicity fractions, measured in the leptonically decaying W bosons, varying with the helicity of hadronically decaying W bosons.

Within the Standard Model and at center–of–mass energies around 200 GeV one expects that about 50% of the W^-W^+ events are produced in the helicity combination $(-1, +1)$ and about 10% with the helicity combination $(0, 0)$. In addition, one expects substantial contributions from other helicity combinations. The relative contributions for these helicity combinations are expected to depend strongly on the W^- polar scattering angle, Θ_{W^-}. For example, the fraction of W^-W^+ events with helicity $(-1, +1)$ is largest for $0.3 < \cos\Theta_{W^-} < 0.9$. Consequently, not only the inclusive fraction of W^- (W^+) bosons with helicity -1 $(+1)$ increases, but in particular, the fraction of W^-W^+ pairs where the W^- boson is found with helicity -1 and the W^+ with $+1$.

To study WW spin correlations, we analyse the distribution of the charged lepton decay angle in the reference frame of the W, $\cos\theta^*_\ell$, as a function of $|\cos\theta^*_h|$. Within the limited statistics three subsamples for $|\cos\theta^*_h|$, $0\div0.33$, $0.33\div0.66$ and $0.66\div1.0$ are used. This separation results in a depletion ($0 < |\cos\theta^*_h| < 0.33$) or an enrichment ($0.66 < |\cos\theta^*_h| < 1.0$) of W bosons with the helicity ± 1.

To enhance possible effects, the event sample is further divided into three intervals for the W^- scattering angle, $\cos\Theta_{W^-}$, with respect to the beam direction. The intervals $-0.9 <$

$\cos\Theta_{W^-} < -0.3$, $-0.3 < \cos\Theta_{W^-} < 0.3$ and $0.3 < \cos\Theta_{W^-} < 0.9$ are used. Within the Standard Model one expects variations of the different WW helicity combinations for these intervals. After correcting for background contamination and selection efficiency, the measured leptonic decay angle distributions, $\cos\theta^*_\ell$, in data and in KORALW Monte Carlo are analysed. An additional correction for bias is performed on the helicity fractions resulting from the fit.

The measured W helicity fractions for the different data samples are summarised in Table 5. The same systematics studies as for the inclusive measurement have been performed, additionally the uncertainty coming from the choice of the $|\cos\theta^*_\mathrm{q}|$ slices has been studied.

Adding all contributions, the systematic uncertainties are found to be in the order of half of the size of the statistical errors. The distributions and fits to the combined data for the three intervals of the W^- scattering angle are shown in Figures 4 and 5.

The combined data demonstrate WW spin correlations along the W flight direction, with a significance of up to 2.6 standard deviations in the forward and backward scattering regions, 1.8 standard deviations stronger than expected.

References

[1] S.L. Glashow, Nucl. Phys. **22** (1961) 579;
S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264;
A. Salam, “Elementary Particle Theory”, Ed. N. Svartholm, Stockholm, “Almquist and Wiksell” (1968), 367.

[2] L3 Collab., M. Acciarri *et al.*, Phys. Let. **B474** (2000) 194 .

[3] K. Hagiwara, K. Hikasa, R. D. Peccei and D. Zeppenfeld, Nucl. Phys. **B282** (1987) 253.

[4] L3 Collab., B. Adeva *et al.*, Nucl. Inst. Meth. **A 289** (1990) 35;
L3 Collab., O. Adriani *et al.*, Physics Reports **236** (1993) 1;
I. C. Brock *et al.*, Nucl. Instr. and Meth. **A 381** (1996) 236;
M. Chemarin *et al.*, Nucl. Inst. Meth. **A 349** (1994) 345;
M. Acciarri *et al.*, Nucl. Inst. Meth. **A 351** (1994) 300;
A. Adam *et al.*, Nucl. Inst. Meth. **A 383** (1996) 342;
G. Basti *et al.*, Nucl. Inst. Meth. **A 374** (1996) 293.

[5] M. Skrzypek, S. Jadach, W. Placzek and Z. Wąs, Comput. Phys. Commun. **94** (1996) 216;
M. Skrzypek, S. Jadach, M. Martinez, W. Placzek and Z. Wąs, Phys. Lett. **B372** (1996) 289.

[6] J. Fleischer, F. Jegerlehner, K. Kolodziej and G. J. van Oldenborgh, Comput. Phys. Commun. **85** (1995) 29.

[7] PYTHIA versions 5.722 and 6.1 are used.
T. Sjöstrand, *PYTHIA 5.7 and JETSET 7.4 Physics and Manual*,
CERN-TH/7112/93 (1993), revised August 1995; Comp. Phys. Comm. **82** (1994) 74; hep-ph/0001032.

[8] S. Jadach, B.F.L. Ward and Z. Wąs, Phys. Lett. **B 449** (1999) 97.

[9] The L3 detector simulation is based on GEANT Version 3.15, R. Brun *et al.*, *GEANT 3*, CERN-DD/EE/84-1 (Revised), 1987; and on the GEISHA program to simulate hadronic interactions, H. Fesefeldt, RWTH Aachen Report PITHA 85/2, 1985.

$\sqrt{s}$ [GeV]	integrated luminosity [pb^{-1}]	$\mathrm{e}\nu\mathrm{q}\bar{\mathrm{q}}$ candidates	$\mu\nu\mathrm{q}\bar{\mathrm{q}}$ candidates
183	55.5	82	67
189	176.8	293	255
192	29.8	59	43
196	84.1	133	110
200	83.3	110	99
202	37.2	56	59
206	218.1	355	289

Table 1: Average center-of-mass energies, corresponding integrated luminosities collected with the L3 detector and number of selected events.

	Helicity fractions for $\mathrm{W} \to \ell\nu$		
	-1	$+1$	0
$\mathrm{W}^{\pm}$ Data	$0.590 \pm 0.033 \pm 0.016$	$0.190 \pm 0.019 \pm 0.015$	$0.220 \pm 0.036 \pm 0.013$
MC	0.592	0.170	0.238
	-1	$+1$	0
W^{-} Data	$0.555 \pm 0.047 \pm 0.012$	$0.202 \pm 0.027 \pm 0.013$	$0.243 \pm 0.052 \pm 0.006$
	$+1$	-1	0
W^{+} Data	$0.629 \pm 0.048 \pm 0.022$	$0.179 \pm 0.024 \pm 0.014$	$0.192 \pm 0.050 \pm 0.022$
	Helicity fractions for $\mathrm{W}\to$ hadrons		
	± 1		0
$\mathrm{W}^{\pm}$ Data	$0.762 \pm 0.043 \pm 0.028$		$0.238 \pm 0.042 \pm 0.028$
MC	0.756		0.244
W^{-} Data	$0.731 \pm 0.058 \pm 0.040$		$0.269 \pm 0.056 \pm 0.040$
W^{+} Data	$0.817 \pm 0.065 \pm 0.022$		$0.183 \pm 0.064 \pm 0.022$

Table 2: Measured W helicity fractions for the leptonic and hadronic W decays for the combined data sample. The corresponding helicity fractions in the Standard Model as implemented in the KORALW Monte Carlo program are also given.

	Helicity fractions for W $\rightarrow \ell\nu$ and W$\rightarrow$ hadrons combined		
	-1	$+1$	0
$W^{\pm}$ Data	$0.585 \pm 0.033 \pm 0.016$	$0.188 \pm 0.018 \pm 0.015$	$0.228 \pm 0.027 \pm 0.012$
MC	0.590	0.169	0.241
	-1	$+1$	0
W^{-} Data	$0.547 \pm 0.046 \pm 0.012$	$0.198 \pm 0.027 \pm 0.013$	$0.255 \pm 0.038 \pm 0.006$
	$+1$	-1	0
W^{+} Data	$0.631 \pm 0.048 \pm 0.023$	$0.180 \pm 0.024 \pm 0.014$	$0.189 \pm 0.039 \pm 0.015$

Table 3: Measured W helicity fractions, combining leptonic and hadronic W decays, for the combined data sample. The corresponding helicity fractions in the Standard Model as implemented in the KORALW Monte Carlo program are also given.

$\sqrt{s} = 183 - 208$ GeV Data			
	Helicity fractions for W $\rightarrow \ell\nu$ and W$\rightarrow$ hadrons combined		
$\cos\Theta_{W^-}$	-1	$+1$	0
$-0.9 \div -0.3$	$0.182 \pm 0.050 \pm 0.027$	$0.368 \pm 0.075 \pm 0.046$	$0.450 \pm 0.091 \pm 0.026$
$-0.3 \div 0.3$	$0.521 \pm 0.065 \pm 0.022$	$0.307 \pm 0.043 \pm 0.028$	$0.172 \pm 0.062 \pm 0.017$
$0.3 \div 0.9$	$0.684 \pm 0.054 \pm 0.022$	$0.136 \pm 0.027 \pm 0.026$	$0.181 \pm 0.039 \pm 0.020$
$0.9 \div 1.0$	$0.684 \pm 0.135 \pm 0.051$	$0.000 \pm 0.057 \pm 0.018$	$0.316 \pm 0.086 \pm 0.046$
$\sqrt{s} = 183 - 208$ GeV KORALW MC			
	Helicity fractions for W $\rightarrow \ell\nu$ and W$\rightarrow$ hadrons combined		
$\cos\Theta_{W^-}$	-1	$+1$	0
$-0.9 \div -0.3$	0.172	0.429	0.399
$-0.3 \div 0.3$	0.446	0.282	0.272
$0.3 \div 0.9$	0.723	0.119	0.158
$0.9 \div 1.0$	0.671	0.000	0.329

Table 4: The W helicity fractions measured as a function of $\cos\Theta_{W^-}$, combining hadronic and leptonic W decays, for $\sqrt{s} = 183 - 208$ GeV in data and SM Monte Carlo. The first error is statistical, the second systematic.

$\sqrt{s} = 183 - 208$ GeV Data				
		$W \to \ell\nu$ helicity fractions		
$\cos\Theta_{W^-}$	$W \to q\bar{q}$	-1	$+1$	0
$-0.9 \div -0.3$	±1 depleted	$0.327 \pm 0.123 \pm 0.089$	$0.287 \pm 0.122 \pm 0.076$	$0.386 \pm 0.253 \pm 0.112$
$-0.9 \div -0.3$	±1 enriched	$0.135 \pm 0.073 \pm 0.075$	$0.482 \pm 0.122 \pm 0.104$	$0.383 \pm 0.207 \pm 0.136$
$-0.9 \div -0.3$	difference	$0.192 \pm 0.143 \pm 0.116$	$-0.195 \pm 0.173 \pm 0.129$	$0.003 \pm 0.327 \pm 0.176$
$-0.3 \div 0.3$	±1 depleted	$0.615 \pm 0.117 \pm 0.051$	$0.385 \pm 0.086 \pm 0.017$	$0.000 \pm 0.166 \pm 0.040$
$-0.3 \div 0.3$	±1 enriched	$0.498 \pm 0.115 \pm 0.085$	$0.335 \pm 0.069 \pm 0.071$	$0.167 \pm 0.132 \pm 0.138$
$-0.3 \div 0.3$	difference	$0.117 \pm 0.164 \pm 0.099$	$0.050 \pm 0.110 \pm 0.073$	$-0.167 \pm 0.212 \pm 0.144$
$0.3 \div 0.9$	±1 depleted	$0.455 \pm 0.103 \pm 0.060$	$0.105 \pm 0.059 \pm 0.036$	$0.440 \pm 0.115 \pm 0.069$
$0.3 \div 0.9$	±1 enriched	$0.833 \pm 0.086 \pm 0.004$	$0.092 \pm 0.033 \pm 0.030$	$0.076 \pm 0.077 \pm 0.030$
$0.3 \div 0.9$	difference	$-0.378 \pm 0.134 \pm 0.060$	$0.013 \pm 0.068 \pm 0.047$	$0.364 \pm 0.138 \pm 0.075$
$\sqrt{s} = 183 - 208$ GeV KORALW MC				
		$W \to \ell\nu$ helicity fractions		
$\cos\Theta_{W^-}$	$W \to q\bar{q}$	-1	$+1$	0
$-0.9 \div -0.3$	±1 depleted	0.187	0.363	0.450
$-0.9 \div -0.3$	±1 enriched	0.148	0.526	0.326
$-0.9 \div -0.3$	difference	0.039	-0.163	0.124
$-0.3 \div 0.3$	±1 depleted	0.465	0.251	0.284
$-0.3 \div 0.3$	±1 enriched	0.430	0.313	0.257
$-0.3 \div 0.3$	difference	0.035	-0.062	0.027
$0.3 \div 0.9$	±1 depleted	0.660	0.142	0.198
$0.3 \div 0.9$	±1 enriched	0.780	0.094	0.126
$0.3 \div 0.9$	difference	-0.120	0.048	0.072

Table 5: 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. Both data and Monte Carlo results are reported.

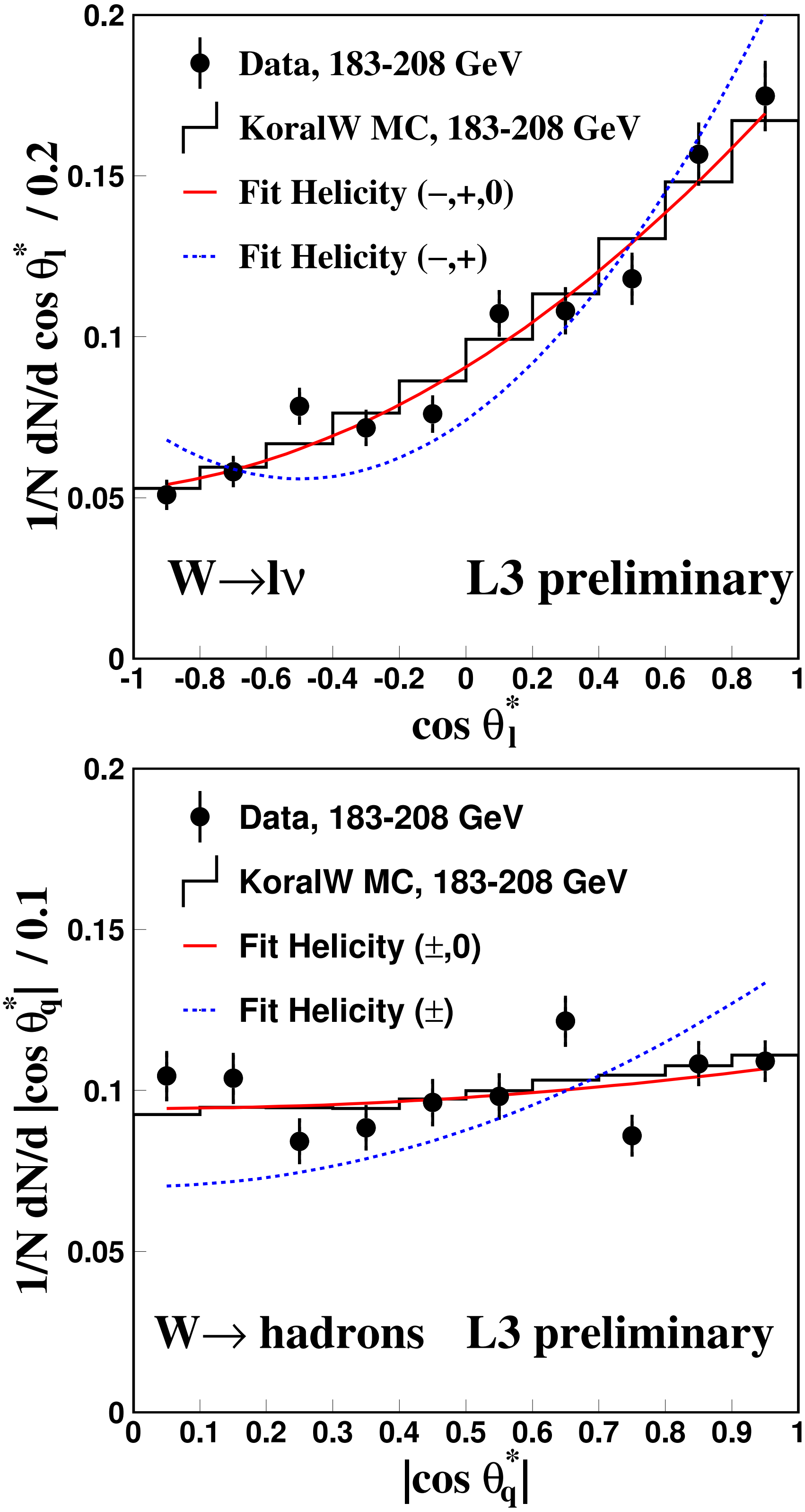

Figure 1: Corrected $\cos\theta^*$ distributions for leptonic W decays (top) and for hadronic W decays (bottom) at $\sqrt{s} = 183$–208 GeV. The fit results for the different W helicity hypotheses are also shown.

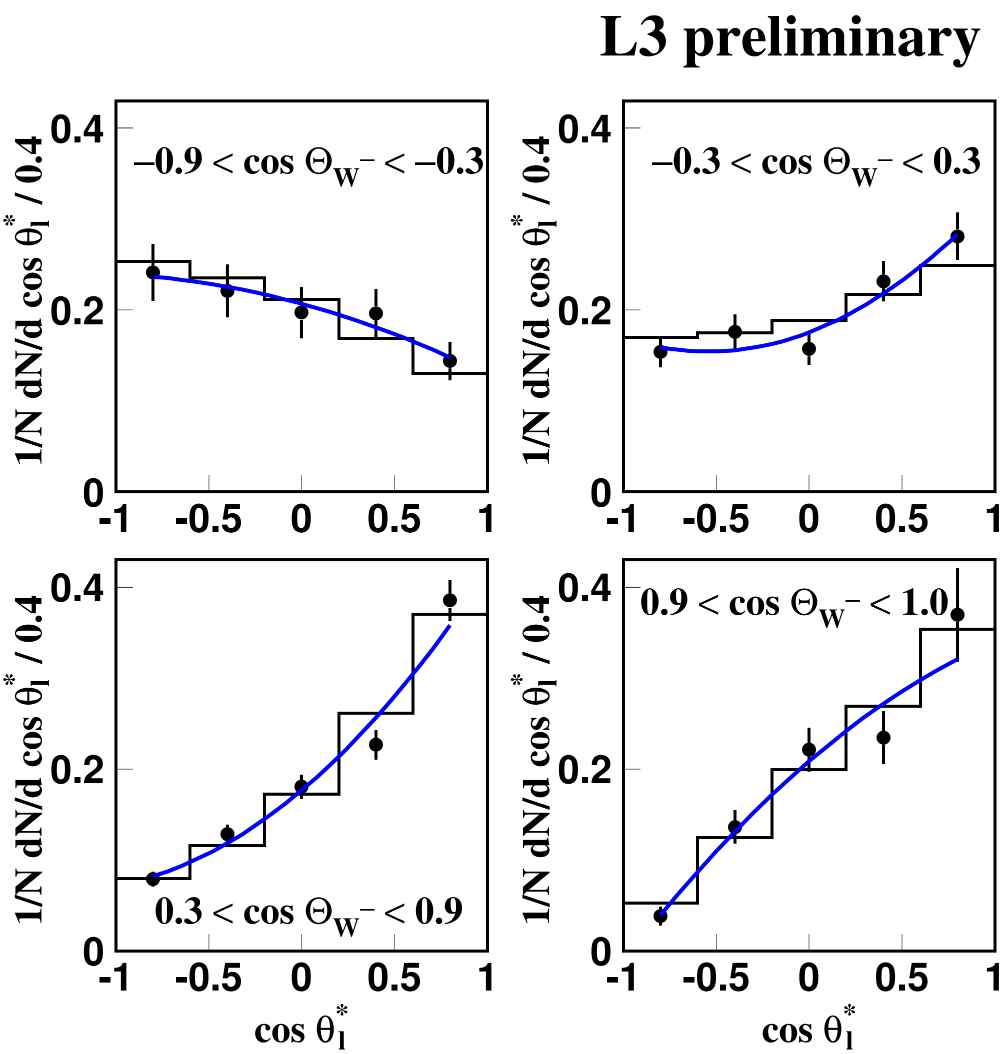

Figure 2: Corrected $\cos\theta^{*}_{\ell}$ distributions for leptonic W decays separated into four different W^{-} scattering angle ranges, together with KORALW expectation. The fit results using all three W helicities are also shown.

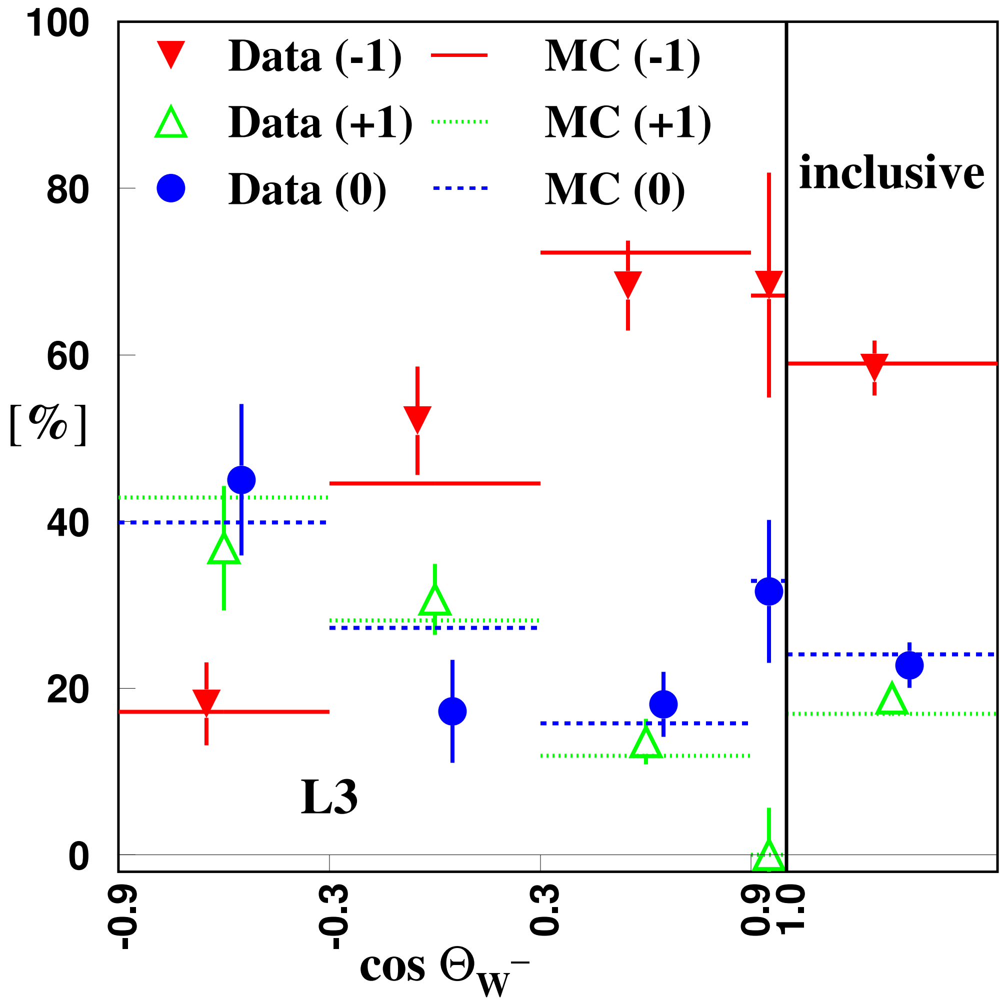

Figure 3: W helicity fractions f_-, f_+ and f_0 and their statistical errors for four different bins of $\cos\Theta_{W^-}$ in the combined data sample and in the KORALW Monte Carlo for $\sqrt{s}$=183–208GeV. On the right hand side the inclusive fractions are also shown.

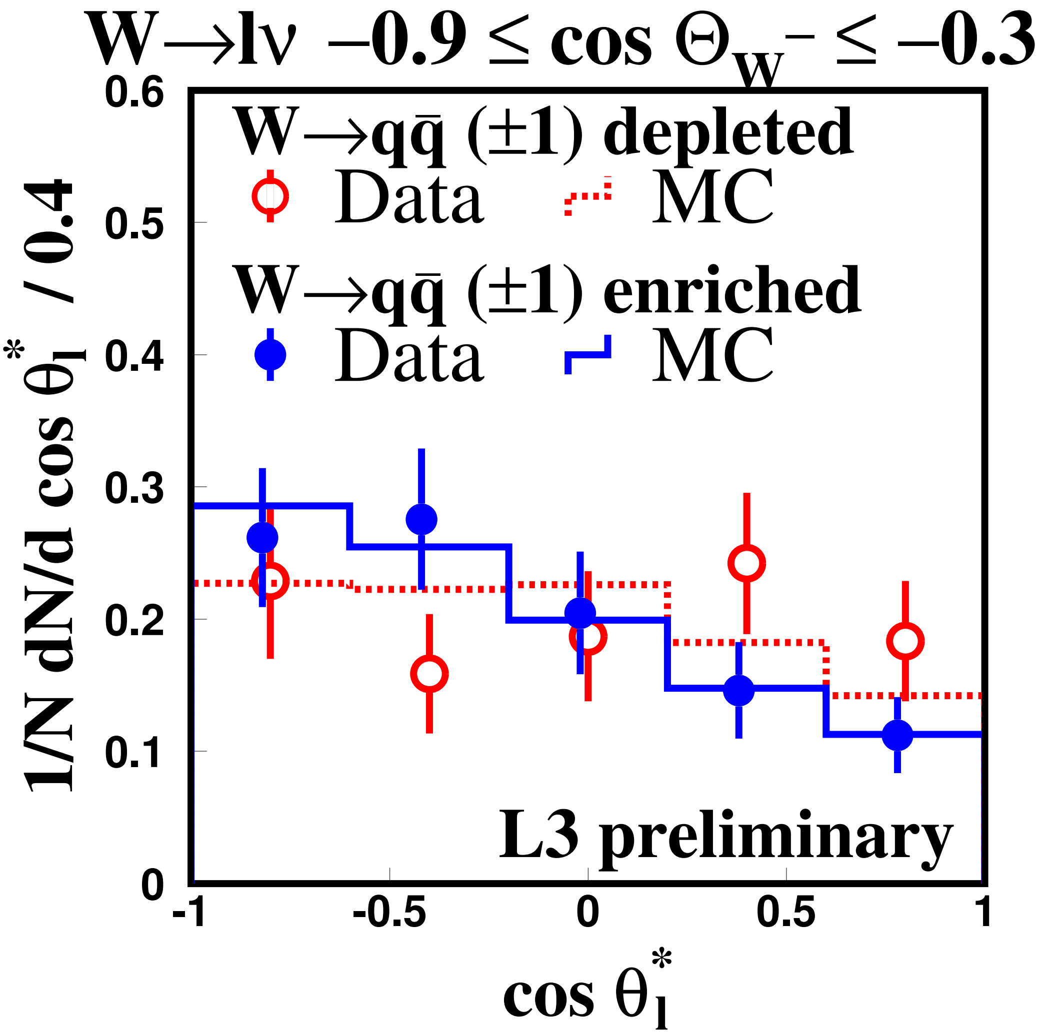

Figure 4: Corrected $\cos\theta^*_\ell$ distributions for $\mathrm{W}\to\ell\nu$ decays for data and the KORALW Monte Carlo in the interval $-0.9 < \cos\Theta_{\mathrm{W^-}} < -0.3$ at $\sqrt{s}$=183–208 GeV. The distributions are shown for the subsamples with ±1 helicities, in W→hadron decays, depleted and enriched.

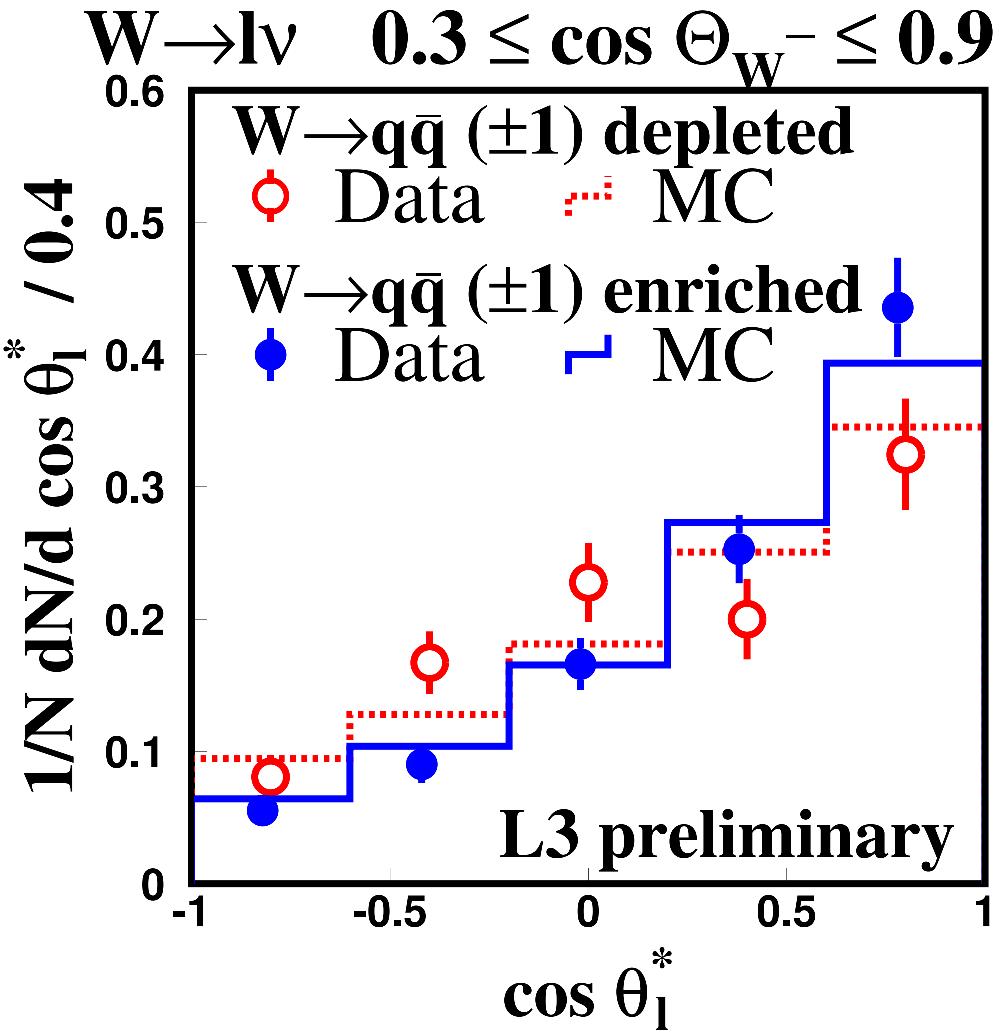

Figure 5: Corrected $\cos\theta^*_\ell$ distributions for $W \to \ell\nu$ decays for data and the KORALW Monte Carlo in the interval $0.3 < \cos\Theta_{W^-} < 0.9$ at $\sqrt{s}$=183–208 GeV. The distributions are shown for the subsamples with ±1 helicities, in W→hadron decays, depleted and enriched.