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W polarisation studies at LEP2

Radoslaw Ofierzynski[a]

ETH Zürich, 8093 Zürich

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Abstract. Studies of W boson polarisation properties performed using the W pair production process at LEP2 are presented. Measurements of the Spin Density Matrix elements and of the polarised cross sections are performed yielding good agreement with the Standard Model and no evidence for CP or CPT violation. The fraction of longitudinally polarised W bosons has been measured to be in agreement with the Standard Model prediction. Indications for W spin correlations are presented as well as a measurement of decay plane correlations.

PACS. 13.66.Fg Gauge and Higgs boson production in e^-e^+ interactions – 14.70.Fm W bosons

1 Introduction

The massive W bosons have an additional spin degree of freedom w.r.t. massless photons, and thus the three possible helicity states -1, $+1$ and 0. The longitudinal polarised (helicity 0) state is of particular interest due to its connection with the Higgs sector in the Standard Model. The polarisation properties of W bosons are studied at LEP2 in the W pair production process

$$e^+(\lambda')e^-(\lambda) \to W^+(\tau_2)W^-(\tau_1) \qquad (1)$$

with $\lambda(\lambda')$ denoting the helicity of the electron (positron) and $\tau_1(\tau_2)$ the helicity of the W^- (W^+).

2 Spin Density Matrix (SDM) elements and polarised cross-sections

The W pair production process is described entirely in terms of helicities by the two-particle joint Spin Density Matrix (SDM) elements:

$$\rho_{\tau_1\tau_1'\tau_2\tau_2'}(s,\cos\Theta_{W^-}) = \frac{\sum_\lambda F^\lambda_{\tau_1\tau_2}\left(F^\lambda_{\tau_1'\tau_2'}\right)^*}{\sum_{\lambda,\tau_1,\tau_2}\left|F^\lambda_{\tau_1\tau_2}\right|^2} \qquad (2)$$

where s is the center-of-mass energy and $F^\lambda_{\tau_1\tau_2}$ is the helicity amplitude for the production of a W pair with helicities τ_1 and τ_2. The single-particle SDM elements $\rho^{W^-}_{\tau_1\tau_1'}$ are obtained by summation over all possible helicity states of one of the W bosons.

Table 1 shows the data sample investigated at the LEP experiments [1,2,3]. For the analysis, projection operators are used which isolate the corresponding SDM elements.

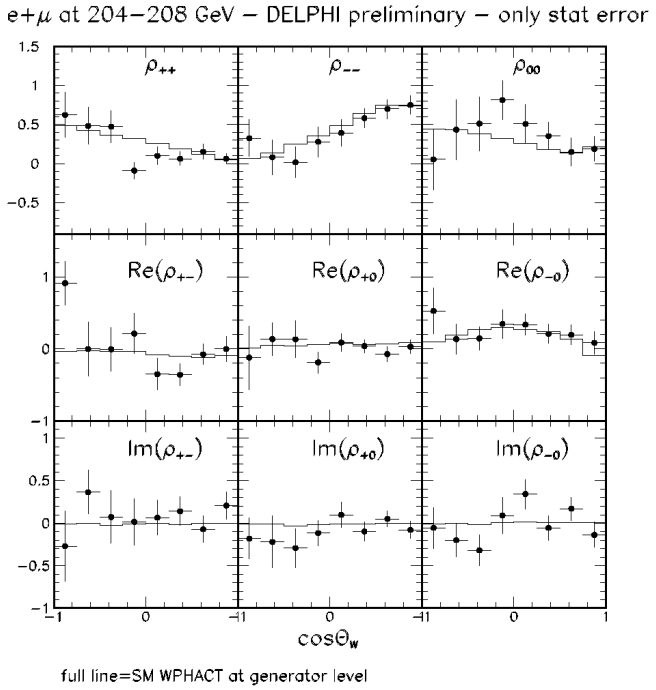

Fig. 1. SDM elements $\rho^{W^-}_{\tau_1\tau_1'}$ as a function of the W scattering angle at $\sqrt{s} = 204-208$ GeV for data as measure by DELPHI and Monte Carlo (full line). In each bin the data from W bosons decaying into leptons and into hadrons have been combined assuming CP-invariance. The errors are statistical only

The reconstructed SDM is corrected for detector acceptance, resolution effects and background contamination. As an example, Fig. 1 shows the SDM elements measured by DELPHI at $\sqrt{s} = 204-208$ GeV. For all analyses good agreement with the Standard Model prediction is found.

[a] *Present address:* CERN, EP Div., CH – 1211 Geneva 23

Table 1. Data samples used for the SDM analyses by the LEP experiments

	$\sqrt{s}$	luminosity	event types
DELPHI	189-209 GeV	520 pb^{-1}	W→e/$\mu\nu$
L3	189-209 GeV	629 pb^{-1}	W→e/$\mu\nu$
OPAL	183-209 GeV	678.5 pb^{-1}	W→e/$\mu/\tau\nu$, W→q$\bar{\text{q}}$

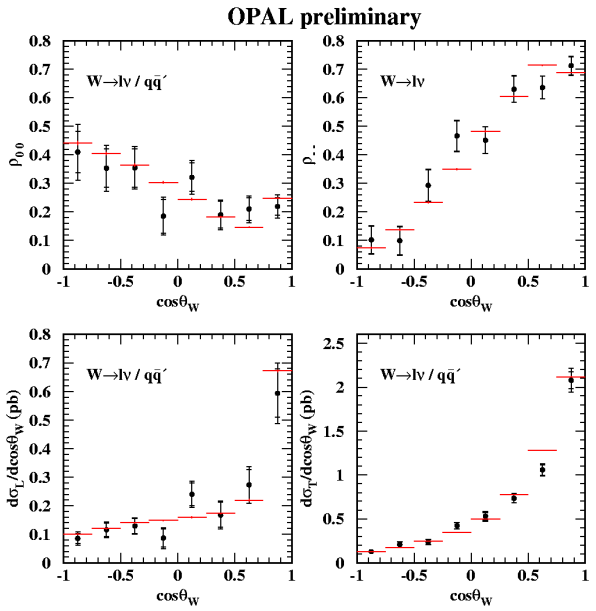

Fig. 2. OPAL SDM analysis: Luminosity averaged fraction of longitudinally polarised W bosons (upper left) and fraction of W bosons in helicity -1 state (upper right) as a function of $\cos\Theta_{\mathrm{W}^-}$. The lower plots show the longitudinally polarised (left) and transversely polarised (right) cross section. The Standard Model prediction is also shown

In DELPHI and OPAL, the diagonal SDM elements are used to measure the cross sections for transversely and longitudinally polarised W bosons. Figure 2 shows the diagonal SDM elements ρ_{00} and ρ_{--} together with the polarised differential cross sections measured by OPAL. The data is in good agreement with the Standard Model prediction.

The imaginary parts of the off-diagonal SDM elements are used at L3 and OPAL to perform a test of CP and CPT invariance at tree level. The data confirm the absence of CPT and CP violation at tree level as predicted by the Standard Model.

3 W polarisation

The W polarisation fractions are measured in L3 in $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \ell\nu\mathrm{q\bar{q}}$ events ($\ell = e, \mu$) using 685pb^{-1}of data collected at $\sqrt{s} = 183 - 209$ GeV [4]. An inclusive method is used which extracts the helicity fractions 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. Denoting the fractions of the helicity states -1, $+1$ and 0 of the W^- boson by f_-, f_+ and f_0, respectively [1] , the differential distribution of leptonic W^- decays at Born level is:

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

For hadronic W decays, only the absolute value of the cosine of the decay angle is accessible, and a folded distribution is used. After correcting the data for selection efficiencies and background, the different fractions of W helicity states are obtained separately for W bosons decaying into leptons and into hadrons from a fit of the corrected data distributions with 3, constraining the sum of all three parameters to unity. As a test for the existence of longitudinal polarisation, the data are also fitted omitting the helicity 0 state. The results of the fits show that the data are well described only if all three W helicity states are used.

In DELPHI and OPAL, the helicity 0 fraction is obtained by integration of the longitudinal differential cross sections and divided by the total cross section. Table 2 shows the results from the LEP experiments for the fraction of longitudinal polarisation. Good agreement between the experiments and with the Standard Model prediction is observed.

L3 measures the W helicity fractions also in four bins of the scattering angle Θ_{W^-}. Figure 3 shows the results for the combined data sample together with the Standard Model expectations. The results are in agreement with the expectation and demonstrate a strong variation of the W helicity fractions with the W^- scattering angle.

Table 2. Fractions of longitudinal polarisation, f_0, measured at the LEP experiments, with their statistical and systematic (L3 and OPAL only) uncertainties. The Standard Model prediction is also given

DELPHI, 189–209 GeV	0.249 ± 0.033
L3, 183–209 GeV	$0.218 \pm 0.027 \pm 0.016$
OPAL, 183–209 GeV	$0.238 \pm 0.021 \pm 0.014$
Standard Model, 183–209 GeV	0.240

4 W spin and decay plane correlations

L3 performs a search for W spin correlations in $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \ell\nu\mathrm{q\bar{q}}$ events ($\ell = e, \mu$) using 630pb^{-1} of data collected at $\sqrt{s} = 189 - 209$ GeV [5]. For the analysis, two samples of $\mathrm{W^+W^-} \to \ell\nu\mathrm{q\bar{q}}$ events are compared: enriched in and depleted of the fraction of W^- bosons decaying into hadrons with helicity $\tau_1 = \pm 1$. The helicity composition of the corresponding W bosons decaying into leptons is then analysed. For small values of $|\cos\theta^*_{\mathrm{q}}|$, the sample is

[1] The charge conjugate state W^+ is also included assuming CP conservation.

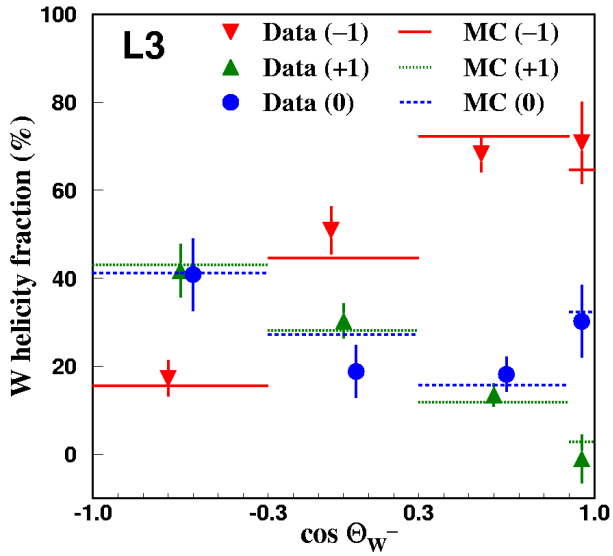

Fig. 3. W helicity fractions f_-, f_+ and f_0 and their statistical uncertainties for four different bins of $\cos\Theta_{\mathrm{W}^-}$ in the combined L3 data sample and in the KORALW Monte Carlo for $\sqrt{s} = 183 - 209$ GeV

Table 3. Differences between the helicity fractions measured with ±1 depleted and enriched samples in L3 data and Monte Carlo

$0.3 < \cos\Theta_{\mathrm{W}^-} < 0.9$: $(\tau_1, \tau_2) = (-1, +1)$ enriched		
τ	Δf_τ Data	Δf_τ MC
-1	$-0.318 \pm 0.103 \pm 0.059$	-0.111 ± 0.011
$+1$	$0.034 \pm 0.067 \pm 0.050$	0.057 ± 0.007
0	$0.284 \pm 0.137 \pm 0.082$	0.054 ± 0.015

$-0.9 < \cos\Theta_{\mathrm{W}^-} < -0.3$: $(\tau_1, \tau_2) = (0, 0)$ enriched		
τ	Δf_τ Data	Δf_τ MC
-1	$0.235 \pm 0.159 \pm 0.117$	0.028 ± 0.020
$+1$	$-0.132 \pm 0.158 \pm 0.107$	-0.181 ± 0.023
0	$-0.103 \pm 0.382 \pm 0.168$	0.153 ± 0.035

depleted of helicity ±1 states, while for large polar decay angles the sample is enriched in helicity ±1 states. The interval $|\cos\theta^*_{\mathrm{q}}| < 0.33$ is chosen for the $\tau_1 = \pm1$ depleted sample and the interval $|\cos\theta^*_{\mathrm{q}}| > 0.66$ for the $\tau_1 = \pm1$ enriched sample. After correcting the data for selection efficiencies and background, the helicity fractions of the W^- bosons decaying into leptons are obtained from a fit of 3 to the distribution of $\cos\theta^*_\ell$. The W^- scattering angle, $\cos\Theta_{\mathrm{W}^-}$, is also used to select particular W-pair helicities, as the helicity combinations vary with $\cos\Theta_{\mathrm{W}^-}$. Two intervals are considered: the forward bin, $0.3 < \cos\Theta_{\mathrm{W}^-} < 0.9$, where the fraction of the helicity combination $(\tau_1, \tau_2) = (-1, +1)$ is enriched; and the backward bin, $-0.9 < \cos\Theta_{\mathrm{W}^-} < -0.3$, where the fraction of the helicity combination $(\tau_1, \tau_2) = (0, 0)$ is enriched.

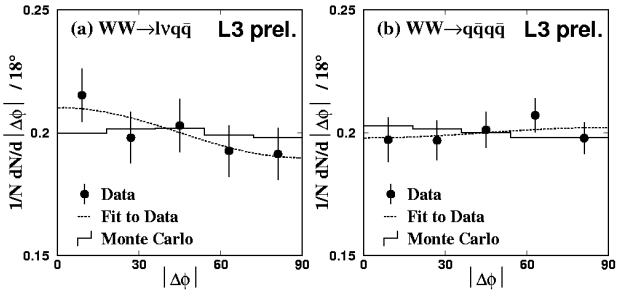

Fig. 4. Corrected $|\Delta\phi|$ distributions for (a) $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \ell\nu\mathrm{q\bar{q}}$ and (b) $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ events for L3 data and the KORALW Monte Carlo. The fit results are also shown

The results of the fits are summarised as differences between the helicity fractions measured in ±1 depleted and enriched samples in Table 3. The obtained numbers show some variations for the selected subsamples of hadronically decaying W bosons and are thus indications for W spin correlations. Considering both investigated intervals the confidence level for the data ±1 depleted samples being compatible with the data ±1 enriched samples is 1.2%. The confidence level for compatibility of the data with the KORALW Monte Carlo prediction is 34.7%.

Decay plane correlations are studied in L3 in both $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \ell\nu\mathrm{q\bar{q}}$ and $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$ events at $\sqrt{s} = 189 - 209$ GeV [5] using the absolute value of the angle, $|\Delta\phi|$, between the planes defined by the decay products of the two W bosons in the rest frame of the W-pair system. The strength of the correlation is measured by the parameter D of the differential distribution:

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\,|\Delta\phi|} = 1 + D\cos 2\,|\Delta\phi|\,. \qquad (4)$$

After correcting the data for selection efficiencies and background, the experimental distribution of $|\Delta\phi|$ is fitted to obtain the parameter D. Figure 4 shows the obtained distributions. For $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \ell\nu\mathrm{q\bar{q}}$, a value $D = 0.051 \pm 0.033 \pm 0.019$ is obtained in data, in agreement with the prediction from KORALW Monte Carlo of $D = 0.006 \pm 0.004$. For $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$, the resulting value of D is found to be $-0.011 \pm 0.023 \pm 0.016$, in agreement with the KORALW prediction of $D = 0.013 \pm 0.003$. The combined value for data of $D = 0.011 \pm 0.019 \pm 0.012$ is compatible with zero and the combined value from the KORALW Monte Carlo of $D = 0.010 \pm 0.002$.

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