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Spin Density Matrix Analysis in W-pair Production at $\sqrt{s} = 189$ GeV

The L3 Collaboration

Abstract

We report on the measurement of the Spin Density Matrix (SDM) elements using the L3 data collected with the LEP collider at a center-of-mass energy of 189 GeV, corresponding to a total integrated luminosity of 176 pb^{-1}. The data sample consists of leptonically decaying W bosons in the $e^+e^- \to W^+W^- \to q\bar{q}e\nu$ and $e^+e^- \to W^+W^- \to q\bar{q}\mu\nu$ reactions. The single W SDM elements are calculated as a function of the W polar angle. They are derived from the angular distributions of the lepton in the W rest frame using projection operators which assume a V-A coupling of the W boson to fermions. Tests of CPT- and CP- invariance at tree level are also performed. All results are preliminary.

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1 Introduction

We report on the analysis of the W polarisation properties in W-pair production using the data taken by the L3 experiment at a center-of-mass energy of 189 GeV.

The data sample consists of the leptonically decaying W bosons in the $e^+e^- \to W^+W^- \to q\bar{q}e\nu$ and $e^+e^- \to W^+W^- \to q\bar{q}\mu\nu$ reactions and correponds to a total integrated luminosity of 176 pb^{-1}. The polar and the azimuthal angle of the lepton (anti-lepton) in the W^- (W^+) rest frame is measured and projection operators [1,2] are applied to extract the Spin Density Matrix elements as a function of the W^- polar angle.

The study of the imaginary parts of the off-diagonal SDM elements, which are predicted to be zero in the Standard Model [3], provides a sensitive test of CPT- and CP-invariance at tree level [4,5].

Section 2 introduces the single W SDM elements. It is followed by the description of the data and Monte Carlo samples and the experimental results for the measured single SDM elements in section 3. Also results on CPT- and CP-violation are presented.

2 The Spin Density Matrix

Considering the helicity, the W-pair production process is written as

$$e^+(\lambda')\ e^-(\lambda) \to W^+(\tau_2)\ W^-(\tau_1)\ , \tag{1}$$

where $\lambda(\lambda') = \pm 1/2$ represents the helicity of the electron (positron).
The helicities of the W^- and the W^+, denoted by τ_1 and τ_2 respectively, take the value $\tau = \pm 1$ for transversely polarised W bosons and the value $\tau = 0$ for W bosons with a longitudinal polarisation. The two-particle joint SDM elements are then defined as [1]

$$\rho_{\tau_1\tau_1'\tau_2\tau_2'}(s, cos\theta_W) \equiv \frac{\sum_\lambda F^\lambda_{\tau_1\tau_2}\ (F^\lambda_{\tau_1'\tau_2'})^\star}{\sum_{\lambda,\tau_1,\tau_2} |F^\lambda_{\tau_1\tau_2}|^2}\ , \tag{2}$$

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 are obtained by summation over all possible helicities of one of the W's

$$\rho^{W^-}_{\tau_1\tau_1'}(s, cos\theta_{W^-}) \equiv \sum_{\tau_2} \rho_{\tau_1\tau_1'\tau_2\tau_2}(s, cos\theta_{W^-})\ . \tag{3}$$

The SDM elements are constrained by Hermiticity and are normalised to unity $\sum_\tau \rho^{W^-}_{\tau\tau} = 1$. The diagonal elements of the SDM matrix are real and express the probability to produce a W^- with helicity τ_1. The off-diagonal elements are complex and provide a test of CP-violation [4].

In the Standard Model W-pairs production is assumed to be a CPT- and CP- invariant interaction, hence the following relations are satisfied

$$CPT - invariance : \rho_{\tau\tau'}^{W^-} = (\rho_{-\tau-\tau'}^{W^+})^* \tag{4}$$

$$CP - invariance : \rho_{\tau\tau'}^{W^-} = (\rho_{-\tau-\tau'}^{W^+}) \; . \tag{5}$$

When decomposing in real and imaginary parts, CP- and CPT-invariance imply

$$CPT - invariance : \mathcal{I}m(\rho_{\tau\tau'}^{W^-}) + \mathcal{I}m(\rho_{-\tau-\tau'}^{W^+}) = 0 \tag{6}$$

$$CP - invariance : \mathcal{I}m(\rho_{\tau\tau'}^{W^-}) - \mathcal{I}m(\rho_{-\tau-\tau'}^{W^+}) = 0 \; , \tag{7}$$

while the real parts have to be equal.
This leads to an unambiguous signature for CPT- and CP-invariance: the imaginary part of all SDM elements has to be zero.

3 Experimental Results

3.1 Data and Monte Carlo Samples

This analysis uses the W-pair events recorded with the L3 detector at LEP at a center-of-mass energy of 189 GeV. A detailed description of the L3 detector and its performance is given in reference [6]. Only the W bosons from semi-leptonic W-pair events which decay into a $q\bar{q}e\nu_e$ or $q\bar{q}\mu\nu_\mu$ final state are studied. These events are characterised by two hadronic jets, an isolated lepton (electron or muon), and missing momentum due to the presence of a neutrino. More details on the selection criteria are given in Reference [7].

The selection efficiency, evaluated with the Standard Model Monte Carlo KORALW [8], is $74\% \pm 0.2$ for the $q\bar{q}e\nu_e$ final state and $71\% \pm 0.2$ for the $q\bar{q}\mu\nu_\mu$ final state, extrapolated to the full phase space. A cut on the reconstructed polar angle of the electron, $|\cos\theta_e| < 0.92$, is applied to reduce the single W component. The remaining four-fermion (non doubly resonant) background, estimated to be of the order of percent, is not included.

The background is mainly due to the $q\bar{q}\tau\nu_\tau$ final state. The non-WW backgrounds in decreasing order of importance are: $q\bar{q}\gamma$ (Pythia MC [9,10]), ZZ (Pythia MC) and Zee (Pythia MC). The two-photon background is found to be negligible. A purity of about 94% is obtained for the $q\bar{q}e\nu_e$ final state, and 95% for the $q\bar{q}\mu\nu_\mu$ final state.

A total of 334 $q\bar{q}e\nu_e$ events and 303 $q\bar{q}\mu\nu_\mu$ events are selected while 334 $q\bar{q}e\nu_e$ and 315 $q\bar{q}\mu\nu_\mu$ events are expected from the Monte Carlo simulation.

3.2 Measurement of the Single SDM Elements

The SDM elements are experimentally derived from the angular distributions of the polar angle of the W boson (θ_W), the polar angle of the lepton (θ_l^*) and its azimuthal angle (ϕ_l^*) in the corresponding W rest frame. They are shown in Figure 1 for the $q\bar{q}e\nu_e$ final state and in Figure 2 for the $q\bar{q}\mu\nu_\mu$ final state.

For the $W^- \to l^-\bar{\nu}$ decay, the single SDM elements are related to the 3-fold differential cross section by

$$\frac{d^3\sigma(e^+e^- \to W^+W^- \to W^+\, l^-\bar{\nu})}{dcos\theta_{W^-}\; dcos\theta^*_{l^-}\; d\phi^*_{l^-}} = (\frac{3}{8\pi})^2\, \frac{d\sigma(e^+e^- \to W^+W^-)}{dcos\theta_{W^-}}$$

$$\times \sum_{\tau\tau'} \rho^{W^-}_{\tau\tau'}(s, cos\theta_{W^-})\; D_{\tau\tau'}(\theta^*_{l^-}, \phi^*_{l^-}) \tag{8}$$

where $D_{\tau\tau'}(\theta^*_{l^-}, \phi^*_{l^-})$ is a function of the polar and the azimuthal angle of the lepton in the W^- rest frame and describes the dependence of the angular distribution of the lepton on the W-helicity assuming a V-A decay of the W boson into leptons.
The W-decay functions $D_{\tau\tau'}$ can be inverted to give the helicity as function of the angular distribution. The correponding projection operators [2], $\Lambda^{W^-}_{\tau\tau'}$, are applied to the angular distribution of the lepton to project out the information about the helicities of the W boson and the corresponding SDM element $\rho^{W^-}_{\tau\tau'}$ is given by

$$\rho^{W^-}_{\tau\tau'}(s, cos\theta_{W^-}) \;=\; \frac{1}{\frac{d\sigma(e^+e^- \to W^+W^- \to W^+\, l^-\bar{\nu})}{dcos\theta_{W^-}}}$$

$$\int \frac{d^3\sigma(e^+e^- \to W^+W^- \to W^+\, l^-\bar{\nu})}{dcos\theta_{W^-}\; dcos\theta^\star_{l^-}\; d\phi^\star_{l^-}}\;\; \Lambda^{W^-}_{\tau\tau'}(\theta^\star_{l^-}, \phi^\star_{l^-})\; dcos\theta^\star_{l^-}\; d\phi^\star_{l^-} \tag{9}$$

A similar relation is obtained for the $W^+ \to l^+\nu$ decay.
The projection operators are given by

$$\Lambda^{W^-}_{\pm\pm} = \Lambda^{W^+}_{\mp\mp} = \frac{1}{2}(5\; cos^2\theta^\star_l \mp 2\; cos\theta^\star_l - 1) \tag{10}$$

$$\Lambda^{W^-}_{00} = \Lambda^{W^+}_{00} = 2 - 5\; cos^2\theta^\star_l \tag{11}$$

$$\Lambda^{W^-}_{+-} = \Lambda^{W^+}_{+-} = 2e^{-2i\phi^\star_l} \tag{12}$$

$$\Lambda^{W^-}_{\pm 0} = -(\Lambda^{W^+}_{\mp 0})^\star = \frac{-8}{3\pi\sqrt{2}}(1 \mp 4\; cos\theta^\star_l)e^{\mp i\phi^\star_l}. \tag{13}$$

The SDM elements are calculated in bins of $\cos\theta_{W^-}$

$$\rho^{W^-}_{\tau\tau'}(k) = \frac{1}{N_k}\sum_{i=1}^{N_k} \Lambda^{W^-}_{\tau\tau'}(\theta^\star_{l^-}, \phi^\star_{l^-})_i\;, \tag{14}$$

where N_k is the number of events in the k-th bin and where $\Lambda^{W^-}_{\tau\tau'}$ is the projection operator, applied event per event.

The reconstructed SDM elements need to be corrected for detector acceptance, resolution effects and background contamination for a direct comparison with the theoretical expectation. Therefore each event is weighted by a correction factor ω

$$\rho^{W^-}_{\tau\tau'}(k) = \frac{1}{\omega_{tot}(k)} \sum_{i=1}^{N_k} \Lambda^{W^-}_{\tau\tau'}(\theta^\star_{l^-}, \phi^\star_{l^-})_i \; \omega_i(k) \;, \tag{15}$$

where $\omega_{tot} = \sum_{i=1}^{N_k} \omega_i$. An analogue expression is obtained for the $W^+ \to l^+\nu$ decay.
To combine the results from both W^+ and W^- decays, CPT-invariance is assumed and the SDM elements in the $\cos\theta_{W^-}$-bin k are given by

$$\rho^{W^-}_{\tau\tau'}(k) = \frac{1}{\omega_{tot}(k)} [\sum_{i=1}^{N_k^{W^-}} \Lambda^{W^-}_{\tau\tau'}(\theta^\star_{l^-}, \phi^\star_{l^-})_{\;i} \; \omega_i(k) + \sum_{j=1}^{N_k^{W^+}} (\Lambda^{W^+}_{-\tau-\tau'}(\theta^\star_{l^+}, \phi^\star_{l^+}))^\star{}_j \; \omega_j(k) \;] \;, \tag{16}$$

where $\omega_{tot} = \sum_{i=1}^{N_k^{W^-}} \omega_i + \sum_{j=1}^{N_k^{W^+}} \omega_j$.

The study of the efficiency yields a dependence on all three angles, $\cos\theta_W$, $\cos\theta^*_l$ and ϕ^*_l, defining a 3-dimensional space which completely describes each event. A bin-to-bin correction factor is derived in this 3-dimensional space to correct for purity, detector acceptance and resolution effects and is used to weight the events.
The $\cos\theta_W$-distribution is devided into 8 equal bins. The typical resolution on the measured $\cos\theta_W$ pointed out to be 0.07 for more than 80 % of the events, which lies well within the bin width (0.25). The probability of misreconstruction (migration) of $\cos\theta_W$ is of the order of 10% and is taken into account in the correction. The SDM elements measured with the $q\bar{q}e\nu_e$ and $q\bar{q}\mu\nu_\mu$ samples are presented in Figure 3, Figure 4 respectively. The results from the leptonically decaying W^+ and W^- are combined assuming CPT-invariance. A good agreement is found with the Standard Model prediction.

3.3 Test of CPT- and CP-invariance

The test of CPT- and CP-invariance at tree level consists in the measurement of the equations (6) and (7), respectively, and is presented in Figure 5 for the $q\bar{q}e\nu_e$ final state and in Figure 6 for the $q\bar{q}\mu\nu_\mu$ final state. Within the statistical error, the sum as well as the differences of the imaginary parts are compatible with zero and confirm the absence of CP- and CPT-violation at tree level as predicted by the Standard Model.

All results are preliminary and contain statistical errors only. The correlations between SDM elements in different $\cos\theta_W$-bins are supposed to be small and consequently, the resulting statistical errors in the different bins are assumed to be uncorrelated.

4 Conclusions

The L3 data taken at a center-of-mass energy of 189 GeV is used to obtain a sample of 334 events selected as $e^+e^- \to q\bar{q}e\nu_e$ and 305 events selected as $e^+e^- \to q\bar{q}\mu\nu_\mu$.
The single SDM elements were extracted using the leptonically decaying W bosons only, and results for W^- and W^+ boson were combined. Within the statistical errors, the off-diagonal elements show a good agreement with CPT- and CP-invariance at tree level as predicted by the Standard Model.

References

[1] M.Bilenky, J.L. Knuer, F.M. Renard and D. Schildknecht, Nucl. Phys. B409 (1993) 22; B419 (1994) 240

[2] G.Gournaris, J.Layssac, G.Moultaka and F.M.Renard, Int. J. Mod. Phys. **A8** (1993) 3285

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

[4] G.Gournaris, D.Schildknecht and F.M.Renard, Phys. Lett. **B263** (1991) 291

[5] K.Hagiwara *et al.*, Nucl. Phys. **B282** (1987) 253

[6] L3 Collab., B.Adeva *et al.*, Nucl. Inst. and Method. **A 289** (1990) 35;
M.Chemarin *et al.*, Nucl. Inst. and Method. **A 349** (1994) 345;
M.Acciarri *et al.*, Nucl. Inst. and Method. **A 351** (1994) 300:
G.Basti *et al.*, Nucl. Inst. and Method. **A 374** (1996) 293:
I.C.Brock *et al.*, Nucl. Inst. and Method. **A 381** (1996) 236:
A.Adam *et al.*, Nucl. Inst. and Method. **A 383** (1996) 342:

[7] L3 note 2638 submitted to the 2002 Summer Conferences

[8] KORALW version 1.42 is used
M.Skrzypek, S.Jadach, W.Placzek and Z.Was, Comp. Phys. Comm. **94** (1996) 216;
M.Skrzypek, S.Jadach, M.Martinez, W.Placzek and Z.Was, Phys. Lett. **B 372** (1996) 289;
S.Jadach, W.Placzek, M.Skrzypek and B.F.L. Ward and Z.Was, CERN-TH/98-242

[9] Physics at LEP2, Report CERN 96-01(1996), G. Altarelli, T. Sjöstrand, F. Zwirner, Vol.1.

[10] Pythia version 5.722 is used
T.Sjöstrand, *PYTHIA 5.7/JETSET 7.4 Physics Manual*, CERN-TH/7112/93 (1993), revised August 1995; Comp. Phys. Comm. **82** (1994) 74

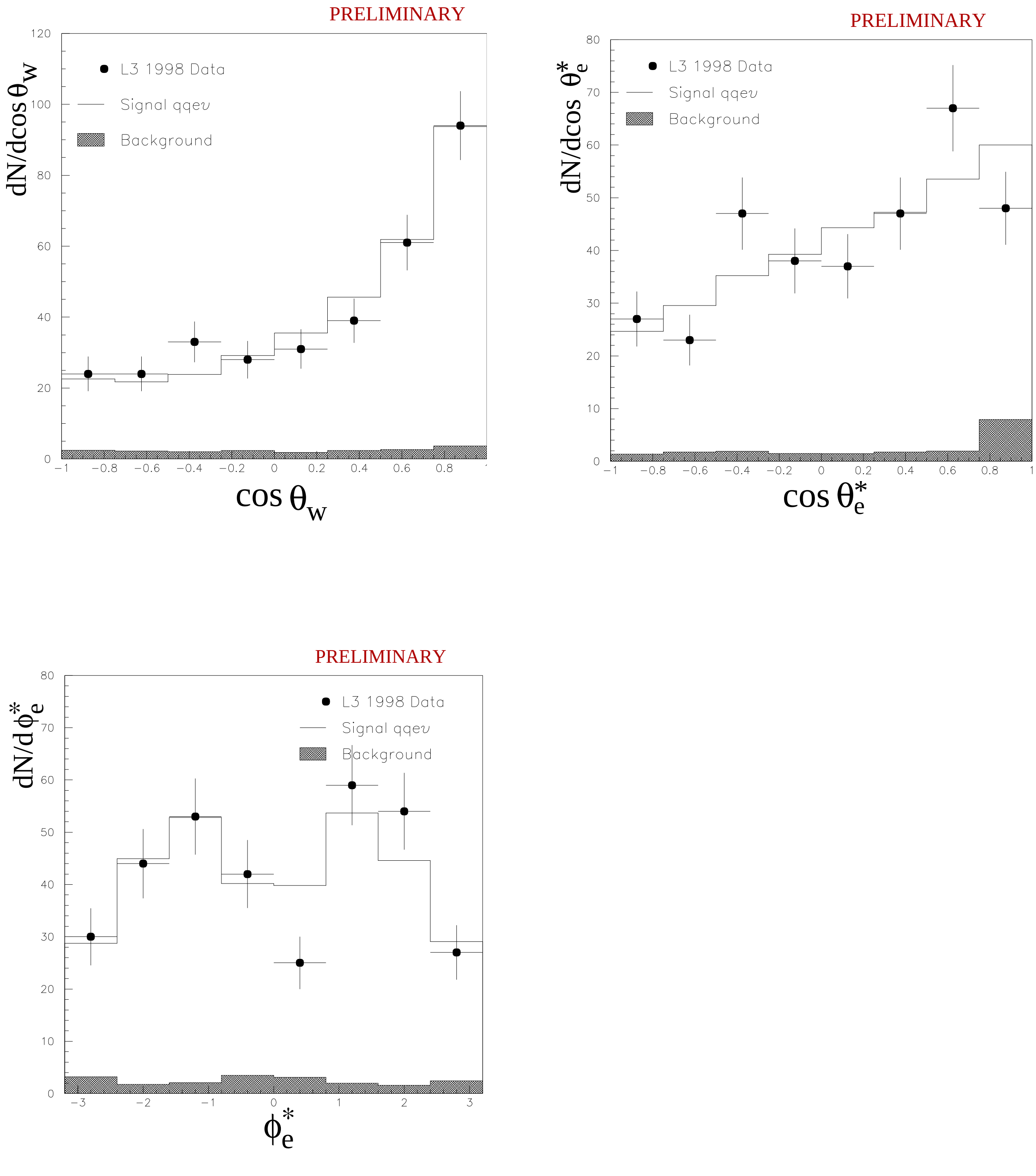

Figure 1: The distributions of the polar angle of the W boson, the polar angle and the azimutal angle of the electron in the W rest frame. The dots represent the data taken by L3 at a center-of-mass energy of 189 GeV. The solid line shows the $q\bar{q}e\nu_e$ signal calculated with Standard Model KORALW Monte Carlo and the black area the background.

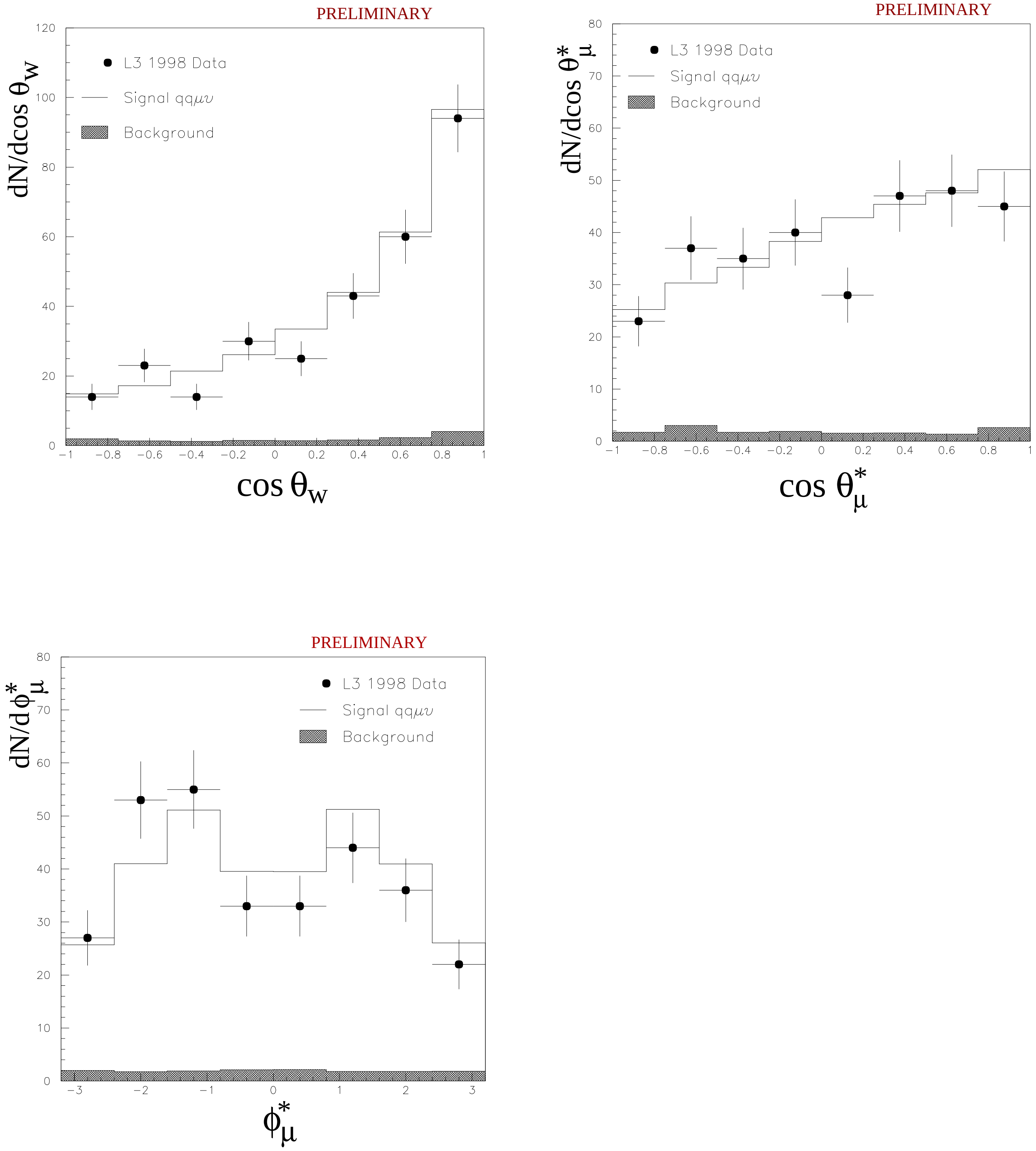

Figure 2: The distributions of the polar angle of the W boson, the polar angle and the azimutal angle of the muon in the W rest frame. The dots represent the data taken by L3 at a center-of-mass energy of 189 GeV. The solid line shows the $q\bar{q}\mu\nu_\mu$ signal calculated with Standard Model KORALW Monte Carlo and the black area the background.

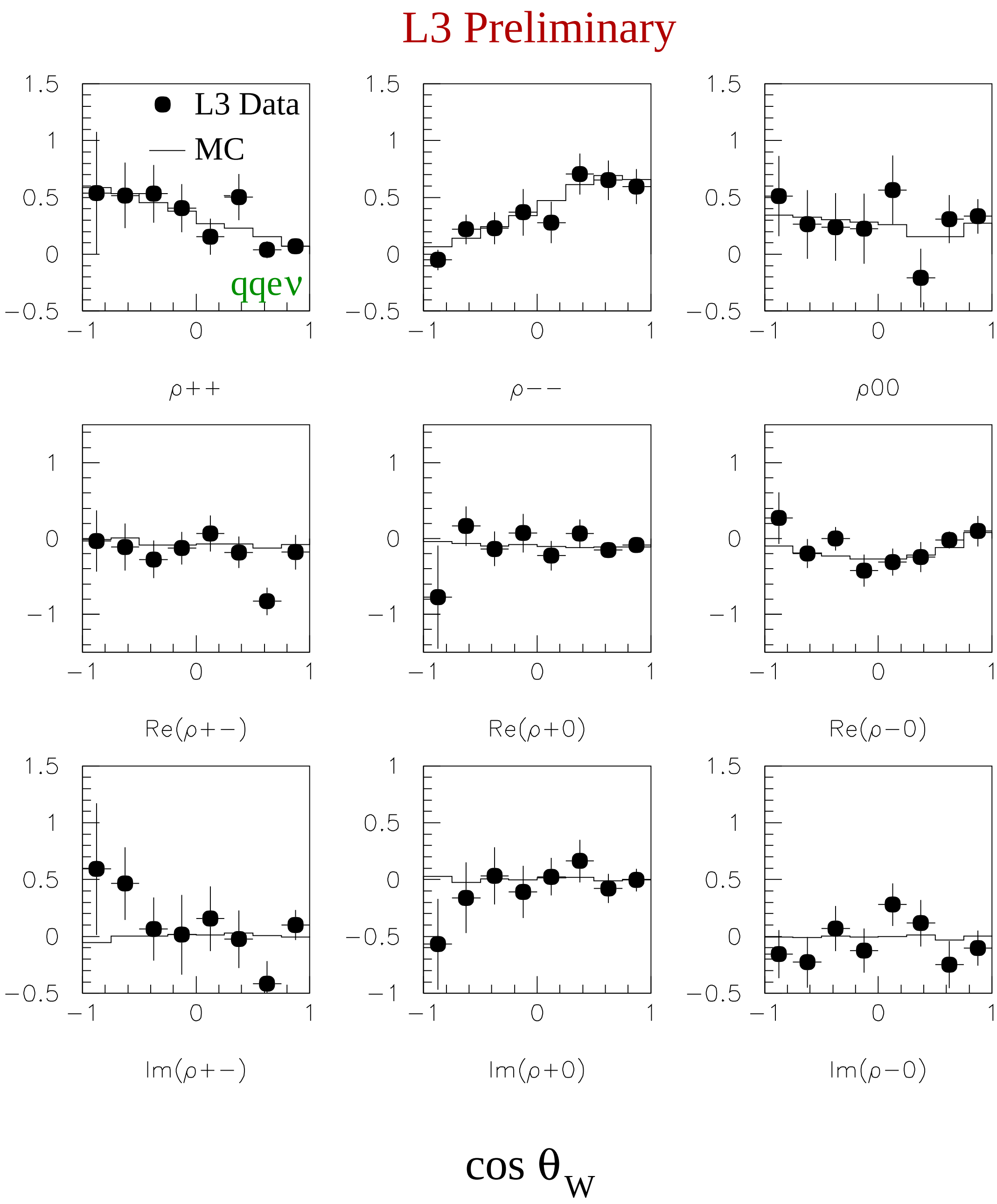

Figure 3: The nine single SDM elements, $\rho^{W^-}_{\tau\tau'}$, as a function of $\cos\theta_W$. The dots represent the $q\bar{q}e\nu_e$ events selected by L3 at a center-of-mass energy of 189 GeV. The solid line shows the Standard Model prediction calculated with the KORALW Monte Carlo at generator level. The results from leptonically decaying W^+ and W^- were combined assuming CPT-invariance. The errors are statistical only.

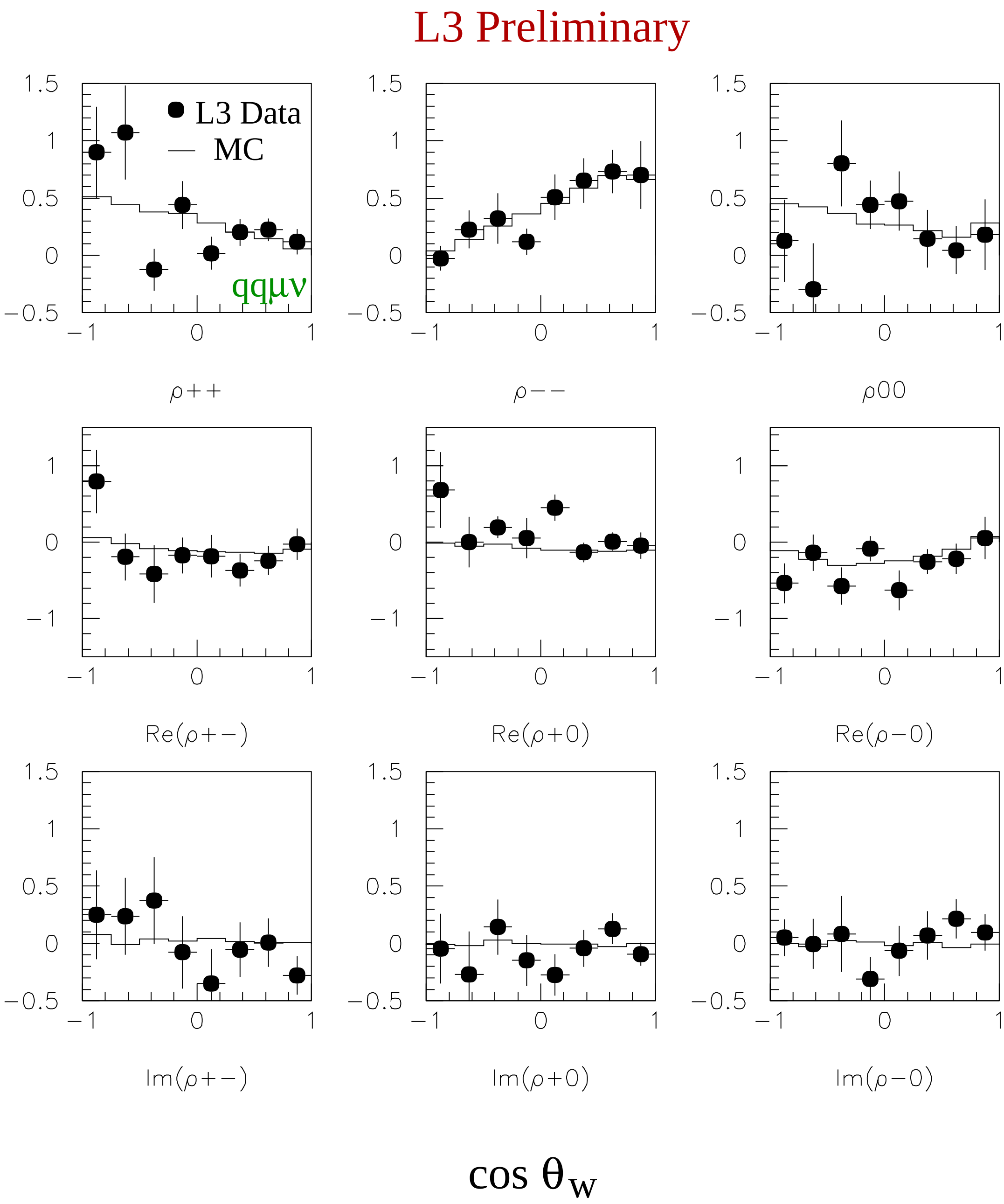

Figure 4: The nine single SDM elements, $\rho^{W^-}_{\tau\tau'}$, as a function of $\cos\theta_W$. The dots represent the $q\bar{q}\mu\nu_\mu$ events selected by L3 at a center-of-mass energy of 189 GeV. The solid line shows the Standard Model prediction calculated with the KORALW Monte Carlo at generator level. The results from leptonically decaying W^+ and W^- were combined assuming CPT-invariance. The errors are statistical only.

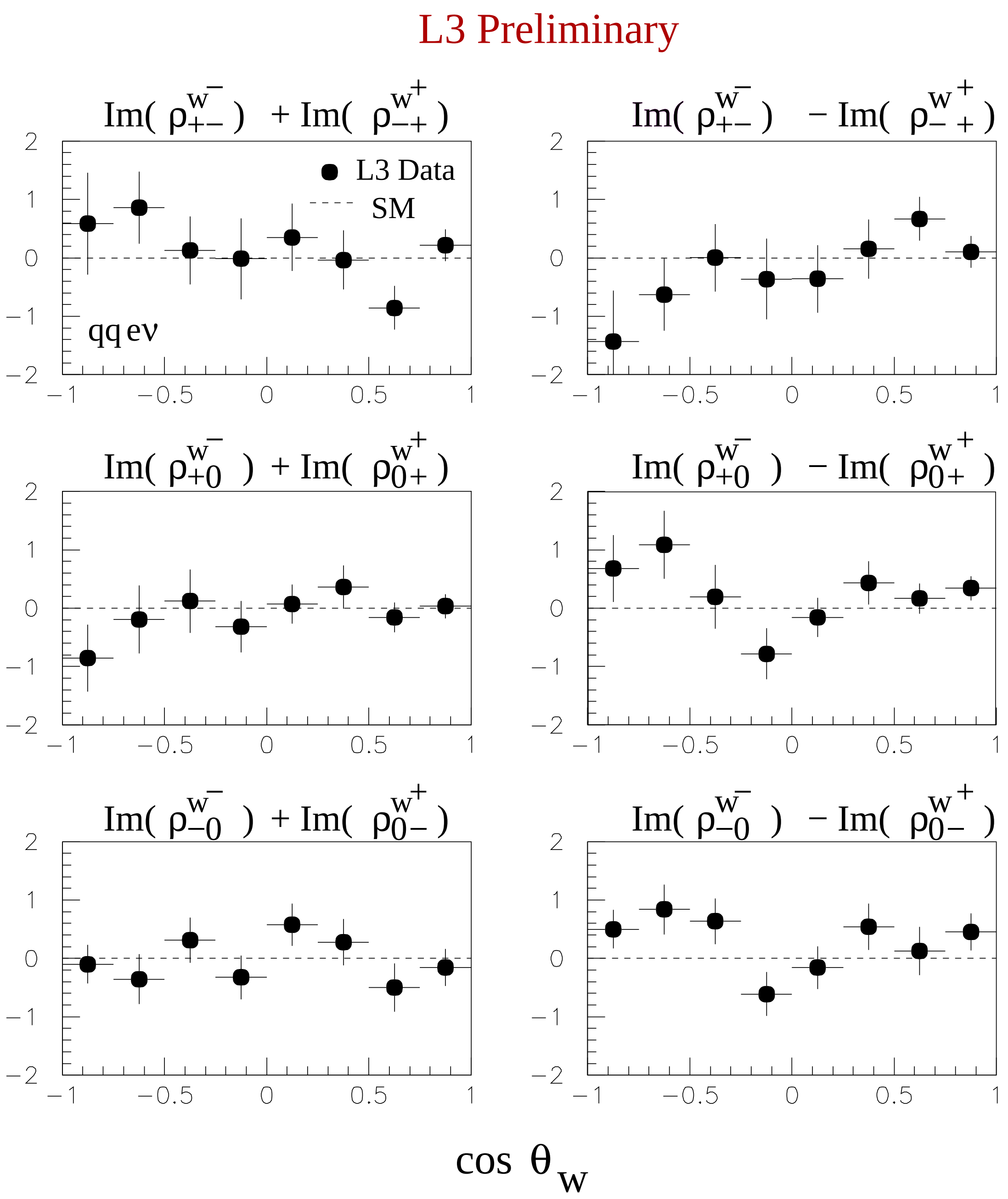

Figure 5: The sum of the imaginary parts of the off-diagonal elements, sensitive to CPT-violation at tree level (left), and the difference, sensitive to CP-violation at tree level (right). The dots represent the $q\bar{q}e\nu_e$ events selected by L3 at a center-of-mass energy of 189 GeV. The dashed line shows the Standard Model prediction. The errors are statistical only.

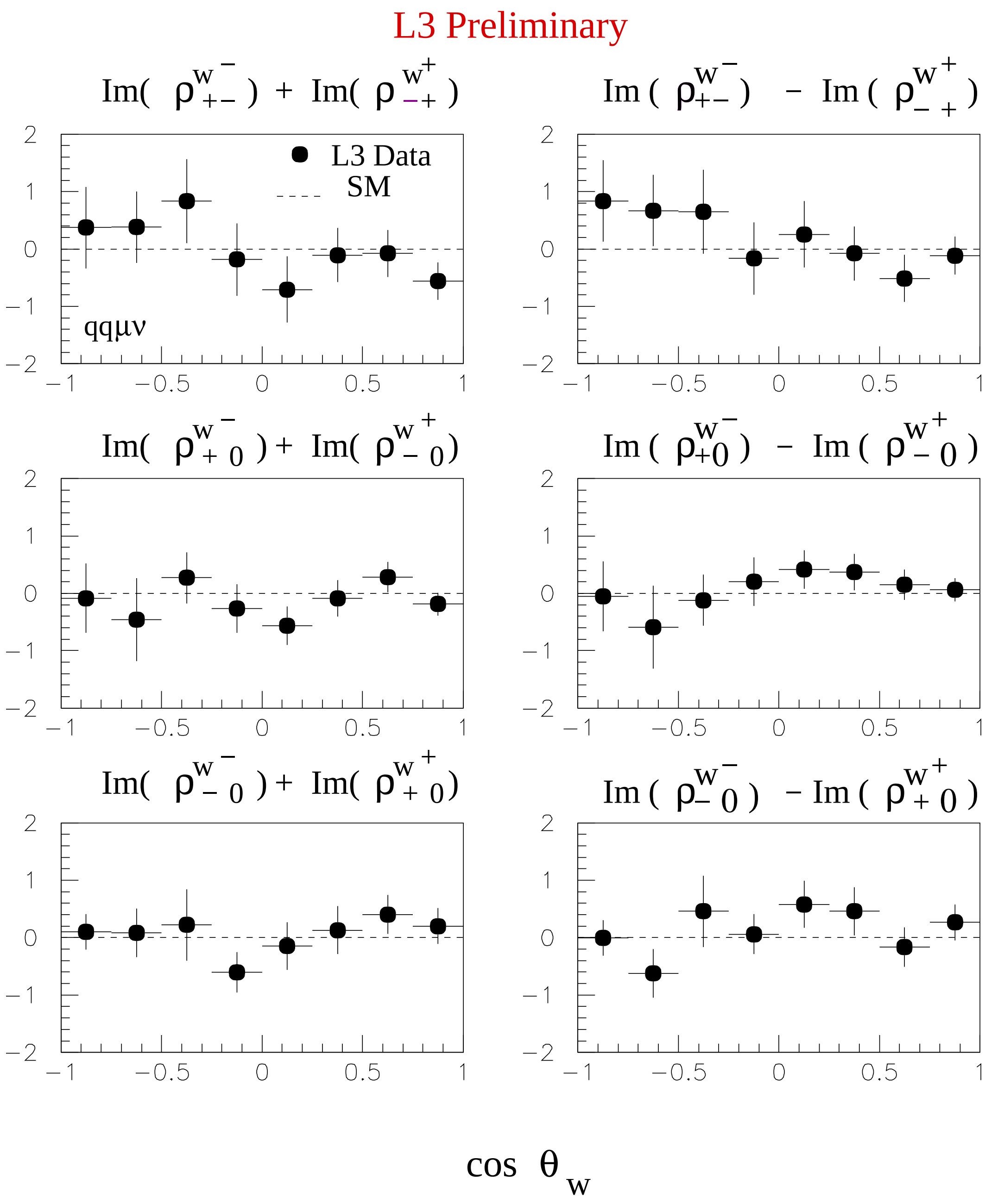

Figure 6: The sum of the imaginary parts of the off-diagonal elements, sensitive to CPT-violation at tree level (left), and the difference, sensitive to CP-violation at tree level (right). The dots represent the $q\bar{q}\mu\nu_\mu$ events selected by L3 at a center-of-mass energy of 189 GeV. The dashed line shows the Standard Model prediction. The errors are statistical only.