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Test of CP Invariance in $Z \to \mu^+\mu^-\gamma$ decay

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Abstract

We report on the first test of CP invariance in Z decays with hard photon radiation. The data recorded with the L3 detector at centre-of-mass energies near the Z resonance are used to search for CP violation in the reaction $e^+e^- \to \mu^+\mu^-\gamma$. No evidence for CP violation is found and limits on the CP-violating form factors f^μ_A and f^μ_V are derived.

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Introduction

Violation of CP invariance in Z decays would point to new physics beyond the Standard Model [1]. In the Standard Model the CP-violating contributions to the Z decay amplitude are of the order of 10^{-7} at most [2]. They are therefore not measureable at current experiments. At LEP experimental tests of the CP symmetry have been performed analysing the decays $\mathrm{Z} \rightarrow \tau^+\tau^-$ [3] and $\mathrm{Z} \rightarrow \mathrm{b\bar{b}g}$ [4]. Recently the authors of Reference [5] proposed to test the CP invariance of the radiative decays $\mathrm{Z} \rightarrow \mu^+\mu^-\gamma$ and $\mathrm{Z} \rightarrow \tau^+\tau^-\gamma$. The angular correlations of the three particle final state allow a measurement of chirality-conserving 4-particle couplings, which could be induced by CP-violating interactions beyond the Standard Model [6].

CP violation in the decays $\mathrm{Z} \rightarrow \mu^+\mu^-\gamma$ and $\mathrm{Z} \rightarrow \tau^+\tau^-\gamma$ can be described using the following effective Lagrangian

$$\begin{aligned}\mathcal{L}(x) = \sum_{\ell} \Bigg\{ \quad & \Big[f_{\mathrm{V}}^{\ell}\bar{\ell}(x)\gamma^{\nu}\ell(x) + f_{\mathrm{A}}^{\ell}\bar{\ell}(x)\gamma^{\nu}\gamma_5\ell(x)\Big] Z^{\mu}(x)\Big[\partial_{\mu}A_{\nu}(x) - \partial_{\nu}A_{\mu}(x)\Big] \\ & -\frac{i}{2}d_{\gamma}^{\ell}\bar{\ell}(x)\sigma^{\mu\nu}\gamma_5\ell(x)\Big[\partial_{\mu}A_{\nu}(x) - \partial_{\nu}A_{\mu}(x)\Big] \\ & -\frac{i}{2}d_{\mathrm{Z}}^{\ell}\bar{\ell}(x)\sigma^{\mu\nu}\gamma_5\ell(x)\Big[\partial_{\mu}Z_{\nu}(x) - \partial_{\nu}Z_{\mu}(x)\Big] \quad \Bigg\}\,,\end{aligned} \tag{1}$$

where d_{γ}^{ℓ} and d_{Z}^{ℓ} are the electric and weak dipole moments of the lepton ($\ell = \mu, \tau$), respectively. The real coupling constants f_{V}^{ℓ} and f_{A}^{ℓ} correspond to a CP-violating, but chirality-conserving $\mathrm{Z}\ell\ell\gamma$ vertex.

The electric dipole moment of the muon is known to be smaller than 10^{-18} $e$cm [7], a limit which cannot be improved by using LEP data. For the weak dipole moment only indirect limits exist [5], which use the partial width of $\mathrm{Z} \rightarrow \mu^+\mu^-(\gamma)$. It is found to be smaller than 10^{-17} $e$cm. For the tau lepton a better limit [8] has been obtained from LEP data by analysing the topology of tau decays. This kind of analysis cannot be performed using muons, as the spin-analysing muon decay occurs outside the detector.

Therefore, we concentrate on the measurement of the real coupling constants f_{V}^{μ} and f_{A}^{μ}, which are of mass dimension -2 and parametrise an anomalous, CP-violating, but chirality-conserving $\mathrm{Z}\mu\mu\gamma$ vertex (see Figure 1). Following Reference [2] we introduce the dimensionless parameters $\hat{f}_{\mathrm{V}}^{\mu}$ and $\hat{f}_{\mathrm{A}}^{\mu}$ defined by

$$f_{\mathrm{V/A}}^{\mu} \;=\; \frac{e^2}{\sin\theta_w \cos\theta_w m_{\mathrm{Z}}^2}\,\hat{f}_{\mathrm{V/A}}^{\mu} \;=\; 2.62 \cdot 10^{-5}\ \mathrm{GeV}^{-2}\ \hat{f}_{\mathrm{V/A}}^{\mu}\,. \tag{2}$$

We measure these parameters from the rate of $\mu^+\mu^-\gamma$ final states and by investigating CP-odd observables in our $\mathrm{e^+e^-} \rightarrow \mu^+\mu^-\gamma$ sample obtained at centre-of-mass energies around the Z resonance.

Event Selection and Data Sample

The L3 detector is described elsewhere [9]. The selection of muon pair events requires either two reconstructed tracks in the muon spectrometer or one muon track and the signature of a minimum ionising particle in the inner sub-detectors. Details of the muon identification are presented in Reference [10].

The two muons should be in the polar angle region $|\cos\theta| < 0.8$. The sum of the energies of the two muons and all photons in the event must exceed 80% of the centre-of-mass energy. In order to reject cosmic ray muons at least one scintillator hit is required with a time measurement that coincides within ±3ns with the beam crossing. Additionally at least one track in the vertex chamber is required with a distance of closest approach to the beam axis of less than 5 mm. We apply no acollinearity or acoplanarity cut.

The data were taken in the years from 1991 to 1995, when LEP was operated at centre-of-mass energies in the vicinity of the Z resonance. From these data, corresponding to a total integrated luminosity of 133 pb^{-1}, we select 92072 muon-pair events.

Analysis of the Event Topologies

Energy and momentum conservation implies that the kinematics of the $\mu^+\mu^-\gamma$ final state is fully determined by measuring the directions of the three particles. In the following we denote the direction of the muons by the unit vectors $\hat{\mathbf{k}}_{\mu^+}$ and $\hat{\mathbf{k}}_{\mu^-}$. For the search for CP violation the following CP-odd observables were found to be useful [5]

$$\begin{aligned} T &= (\hat{\mathbf{k}}_{\mu^+} - \hat{\mathbf{k}}_{\mu^-}) \cdot \hat{\mathbf{p}}_{\mathrm{e}^+} \, (\hat{\mathbf{k}}_{\mu^+} \times \hat{\mathbf{k}}_{\mu^-}) \cdot \hat{\mathbf{p}}_{\mathrm{e}^+} \,, \\ V &= (\hat{\mathbf{k}}_{\mu^+} \times \hat{\mathbf{k}}_{\mu^-}) \cdot \hat{\mathbf{p}}_{\mathrm{e}^+} \,, \end{aligned} \tag{3}$$

were $\hat{\mathbf{p}}_{\mathrm{e}^+}$ is the direction of the incoming positron. In this context T is the component of a tensor and V of a vector observable.

Figure 2 shows the distributions of the observables T and V for the data and events generated with the KORALZ [11] Monte-Carlo program and including full detector simulation using the GEANT [13] detector simulation program. KORALZ simulates the radiation of up to two hard photons in the initial or final state and includes photon exponentiation according to the Yennie-Frautschi-Suura ansatz [12]. Good agreement is observed over the full ranges of the two variables. Above all no asymmetry between negative and positive values, *i.e.* no sign of CP violation, is observed.

To compare the data with the prediction from CP-violating $\mathrm{Z}\mu\mu\gamma$ couplings we use a Monte-Carlo program [14]. For the calculation of the observables T and V, it is convenient to replace the parameters $\hat{f}^{\mu}_{\mathrm{V}}$ and $\hat{f}^{\mu}_{\mathrm{A}}$ by the linear combinations

$$\begin{aligned} \hat{f}^{\mu}_1 &= g^{\mu}_{\mathrm{V}} \hat{f}^{\mu}_{\mathrm{A}} - g^{\mu}_{\mathrm{A}} \hat{f}^{\mu}_{\mathrm{V}} \,, \\ \hat{f}^{\mu}_2 &= g^{\mu}_{\mathrm{V}} \hat{f}^{\mu}_{\mathrm{V}} - g^{\mu}_{\mathrm{A}} \hat{f}^{\mu}_{\mathrm{A}} \,, \end{aligned} \tag{4}$$

where $g^{\mu}_{\mathrm{V}} = 2\sin^2\theta_w - \frac{1}{2}$ and $g^{\mu}_{\mathrm{A}} = -\frac{1}{2}$ are the neutral current coupling constants of the muon. As $\hat{f}^{\mu}_1$ influences only tensor observables and $\hat{f}^{\mu}_2$ is related to vector observables, these two parameters can be measured independently by using either the observable T or V. The sensitivity of these observables on the electric and weak dipole moment of the muon is two orders of magnitude smaller [5] and therefore neglected.

In Figure 3 the relative asymmetries between negative and positive values of the observables T and V are shown for intervals in $|T|$ and $|V|$, respectively. Within their statistical errors all measurements are consistent with zero. Also included are the theoretical expectations for $\hat{f}^{\mu}_1 = \pm 1$ and $\hat{f}^{\mu}_2 = \pm 1$, which corresponds to a CP-violating coupling on the order of the Fermi constant. The expected effect of the anomalous CP-violating couplings is larger for the events with large values of $|T|$ or $|V|$. The events at $|T| = |V| = 0$ are those without photon radiation,

$Z \to \mu^+\mu^-$. In this two-particle final state it is impossible to measure CP violation without information on the muon spin. But these events can be used to test the CP invariance of the detector and of the acceptance cuts. From Figure 3 we conclude that such effects that could mimic CP violation are not present in the data.

To extract limits on the parameters $\hat{f}_1^\mu$ and $\hat{f}_2^\mu$, two sub-samples with $|T| > 0.025$ and $|V| > 0.1$ are considered, containing in total 3680 and 1586 events, respectively. To predict the number of events in each $|T|$ or $|V|$ bin according to the Standard Model, $N_i^{\rm SM}$, we use the events that were generated with the KORALZ program and include the full simulation of the L3 detector. The Monte-Carlo program [14] is used to calculate the expected change of the number of events in the different bins, $N_i(\hat{f}^\mu)/N_i(0)$, and to predict the relative asymmetry, $A_i(\hat{f}^\mu)$, which is shown in Figure 3. With this procedure the detector effects and radiative corrections calculated with the KORALZ Monte Carlo are taken into account.

The difference between the number of events with positive T or V and negative T or V in bin number i is predicted as

$$N_i^{\rm SM} \cdot \frac{N_i(\hat{f}^\mu)}{N_i(0)} \cdot A_i(\hat{f}^\mu) \ .$$

The calculated asymmetry is shown in Figure 4 for data and theory. It is proportional to the interference term between the Standard Model amplitude and the anomalous CP-odd amplitude. Varying the anomalous couplings not only changes the asymmetry, but also the total number of radiative events in the different bins, which is proportional to the absolute square of the CP-odd amplitude and therefore CP even. The number of events in bin number i is calculated as

$$N_i^{\rm SM} \cdot \frac{N_i(\hat{f}^\mu)}{N_i(0)} \ .$$

We compare our data and the predictions for different values of $\hat{f}_1^\mu$ and $\hat{f}_2^\mu$, using a χ^2 fit for different ranges of T and V, as indicated by the arrow in Figure 4. Using the asymmetries the parameters are measured to be

$$\hat{f}_1^\mu = 0.08 \pm 0.64 \qquad \text{and} \qquad \hat{f}_2^\mu = -1.61 \pm 1.34 \ .$$

Exploiting in addition the spectra of radiative events improves the measurement. We then get

$$\hat{f}_1^\mu = 0.03 \pm 0.19 \qquad \text{and} \qquad \hat{f}_2^\mu = -0.12^{+0.34}_{-0.21} \ ,$$

both consistent with zero.

In our event sample the average invariant mass of the muon photon pair, $m_{\mu\gamma}$, and therefore the mass of the radiating virtual muon, is about 15 GeV. The ratio between the CP-violating Z decay amplitude and the Standard Model amplitude coming from bremsstrahlung amounts to $\hat{f}^\mu \, (m_{\mu\gamma}/m_{\rm Z})^2$. Our measurement constrains this ratio to values below 10^{-2} at the 95% confidence level.

For the CP-violating coupling constants $f_{\rm V}^\mu$ and $f_{\rm A}^\mu$ we get limits of

$$\begin{array}{ll} -1.7 \cdot 10^{-5}\ {\rm GeV}^{-2} < f_{\rm V}^\mu < 1.9 \cdot 10^{-5}\ {\rm GeV}^{-2} & \qquad \text{and} \\ -2.4 \cdot 10^{-5}\ {\rm GeV}^{-2} < f_{\rm A}^\mu < 2.2 \cdot 10^{-5}\ {\rm GeV}^{-2} & \end{array}$$

at the 95% confidence level.

Following Reference [2] the measurements of $f_{\rm V}^\mu$ and $f_{\rm A}^\mu$ are used to set a lower limit on the scale parameter for CP-violating interactions, $\Lambda_{\rm CP}$, of 229 GeV and 204 GeV, respectively.

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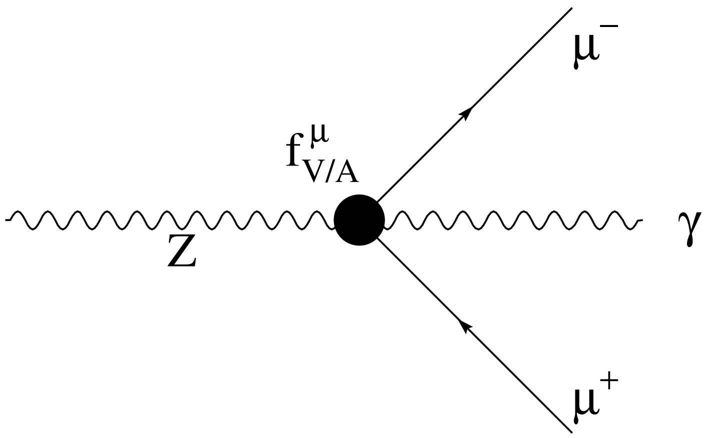

Figure 1: CP-violating and chirality-conserving $Z\mu\mu\gamma$ vertex.

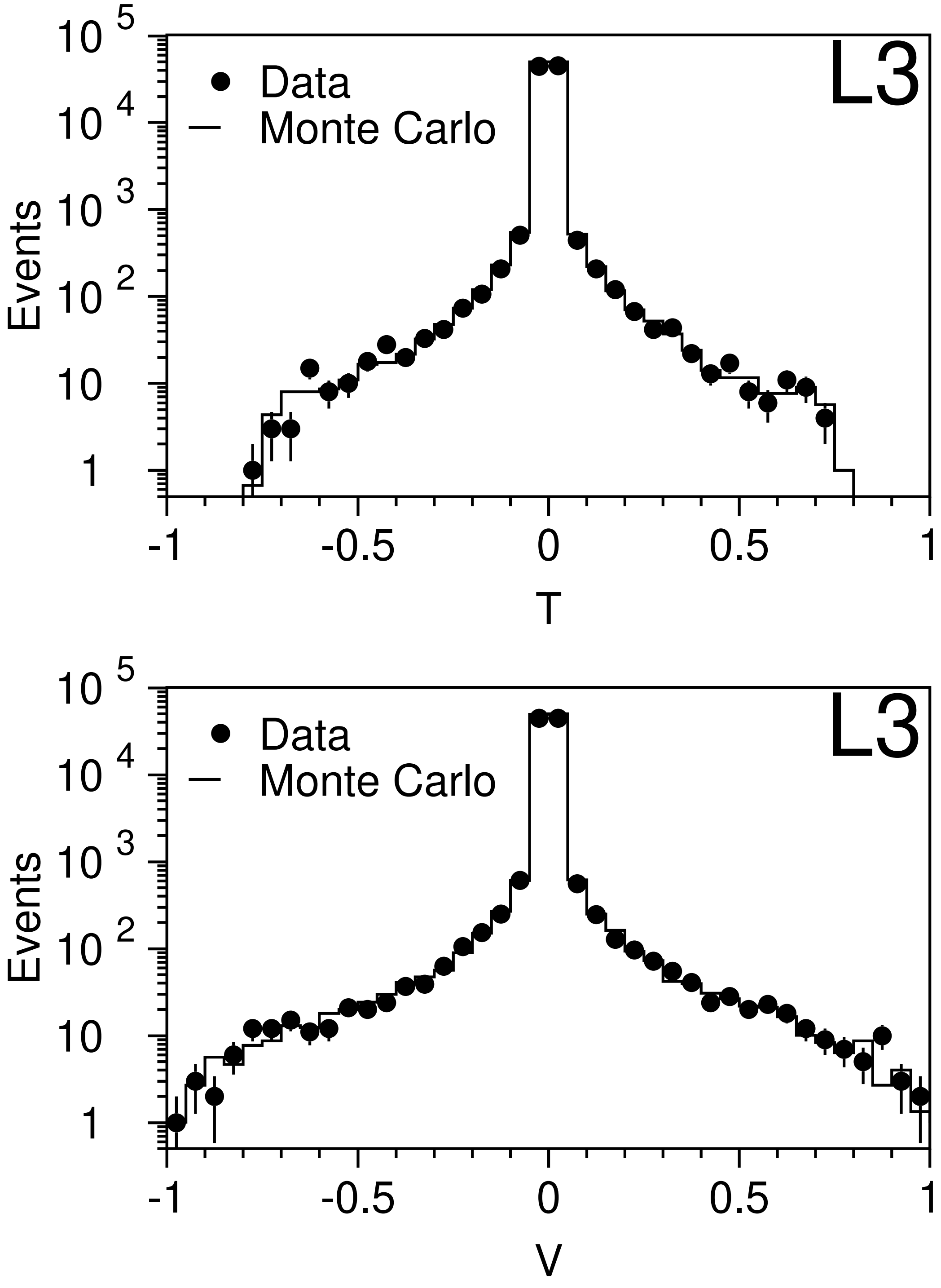

Figure 2: Distributions of the CP-odd observables T and V in data (points) and Monte Carlo (histogram).

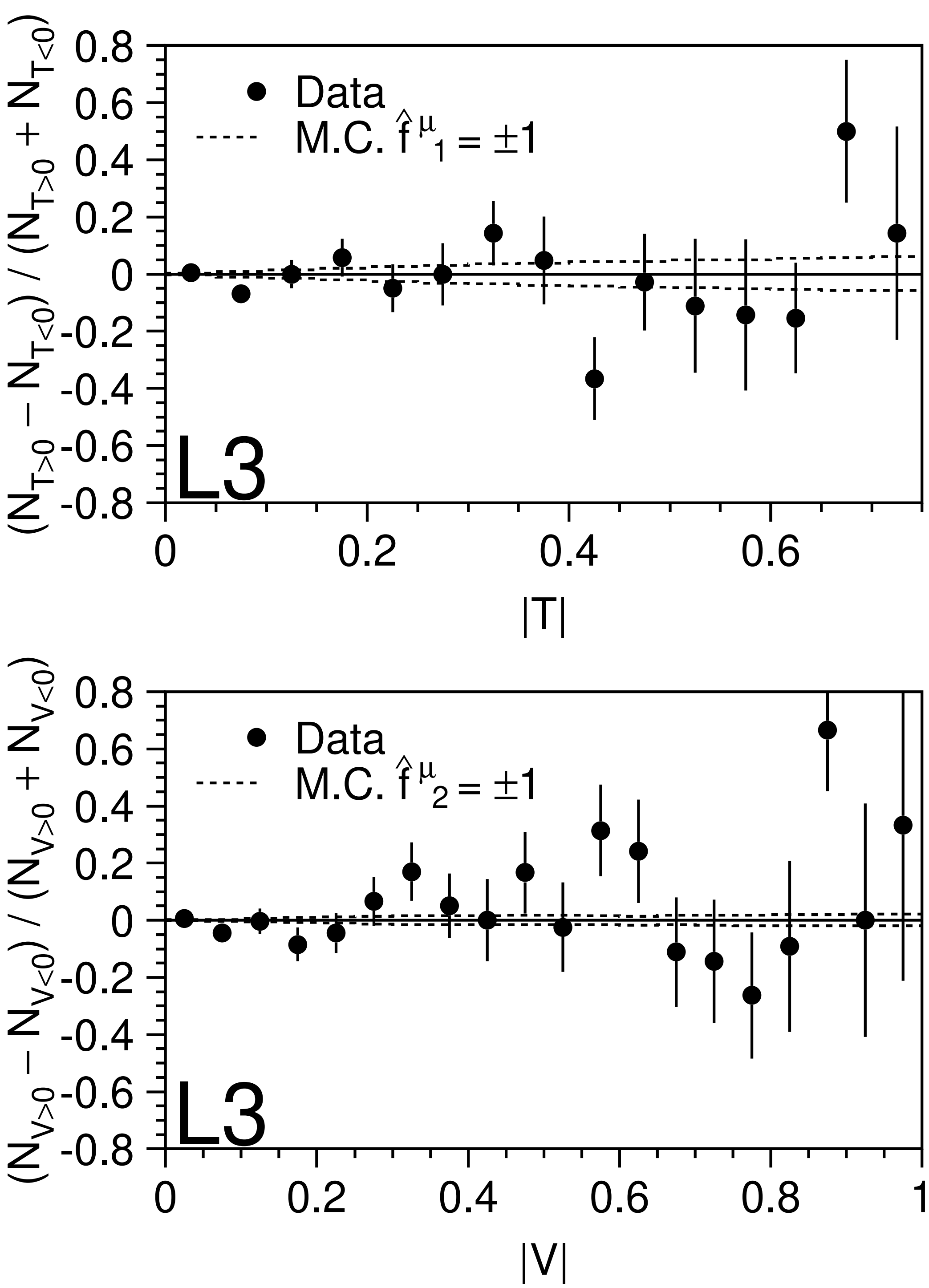

Figure 3: Measurement of the relative asymmetry for T and V. The dashed line shows the theory prediction for a variation of ± 1 of the CP-violating parameters $\hat{f}_1^{\mu}$ and $\hat{f}_2^{\mu}$.

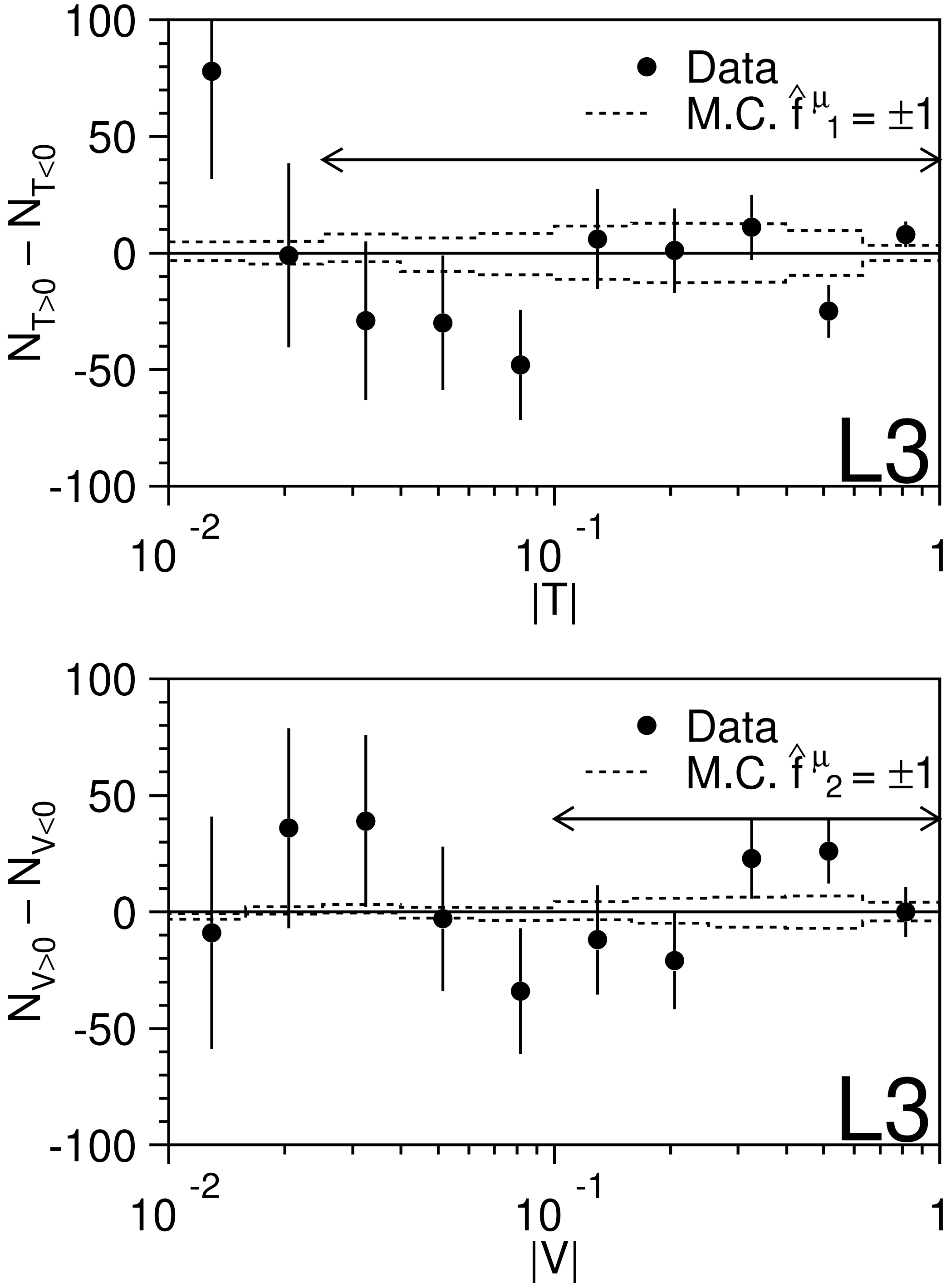

Figure 4: Measurement of the absolute asymmetry for T and V. The dashed line shows the theory prediction for a variation of the CP-violating parameters as in Figure 3. The fit range for the determination of the CP-violating parameters $\hat{f}_1^{\mu}$ and $\hat{f}_2^{\mu}$ is indicated by the arrow.