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Search for CP Violation in $Z \rightarrow \tau\tau$

The ALEPH Collaboration[1]

Abstract

Using the $18.8 pb^{-1}$ of data accumulated at LEP in 1990 and 1991 with the ALEPH detector, a direct test of neutral current CP-invariance is performed by a search for CP-odd correlations in Z decays to τ pairs where both τ decay modes are identified. No evidence for CP-violation is observed. The weak dipole moment of the τ has been measured to be $d_\tau(m_Z) = (1.3 \pm 1.4 \pm 0.1) \times 10^{-17} e \cdot cm$ which results in an upper limit on the weak dipole moment of $|d_\tau(m_Z)| \leq 3.7 \times 10^{-17} e \cdot cm$ with 95% confidence level.

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1 Introduction

It has been pointed out that various decay modes of the Z boson can be used to search for CP-violating effects beyond the Kobayashi-Maskawa mechanism [1]. The measurements involve appropriate CP-odd correlations which provide direct information about CP-odd form factors [2]. CP-odd quantities for the leptonic Z boson decays, $Z \to l\bar{l}$, are accessible by measuring the correlation between the spins of the leptons. Due to parity violation in τ decays, the energy spectra and angular distributions of the decay products reflect the τ polarization allowing momentum correlations between the τ^+ and τ^- decay products to be used to measure CP-odd effects. With unpolarized beams, only two CP-odd form factors contribute to CP-odd correlation functions in $e^+e^- \to \tau^+\tau^-$. These are the electromagnetic and weak dipole moments, d_τ^{em} and d_τ^w, of the τ and lead to non-vanishing values for the correlation functions. Observation of a non-zero dipole moment would indicate physics beyond the Standard Model.

The CP violating Lagrangian for the $\tau\tau$ production vertex is

$$\mathcal{L}_{CP} = -\frac{1}{2} i\bar{\tau}\gamma_5\sigma^{\mu\nu}\tau(d_\tau^{em}(q^2)F_{\mu\nu} + d_\tau^w(q^2)Z_{\mu\nu}) \qquad , \qquad (1)$$

where $F_{\mu\nu}$ and $Z_{\mu\nu}$ are the electromagnetic and weak field tensors. In the nonrelativistic limit, the corresponding interaction Hamiltonian, H_I, is given by $H_I = -d\vec{\sigma}\cdot\vec{E}$ where d and E stand for the electric or weak dipole moments and the field strengths respectively. As this analysis is performed at $q^2 = m_Z^2$ the contribution of the weak dipole moment, written as $d_\tau(m_Z)$, will be enhanced due to the Z resonance and it is assumed that any electric dipole moment contribution can be neglected. Visible CP violating correlations appear due to interference between the CP violating amplitude, A_{CP}, from (1) and the CP conserving Standard Model amplitude resulting in a term approximately proportional to $d_\tau(\vec{s}_+ - \vec{s}_-)$ where $\vec{s}_+(\vec{s}_-)$ is the polarisation vector of the $\tau^+(\tau^-)$.

The CP-even contribution, $|A_{CP}|^2$, to the cross section increases the partial width $\Gamma(Z \to \tau\tau)$ and therefore an indirect measurement of the dipole moment can be obtained from the Z partial width. The width has a quadratic dependence on the dipole moment which gives a contribution of $\Delta\Gamma_\tau \approx |d_\tau(m_Z)|^2 m_Z^3/(24\pi)$ [2]. Using the data accumulated at LEP the width has been measured to be $\Gamma_\tau = (82.76 \pm 1.02)MeV$ [3]. This can be compared with the theoretical prediction $\Gamma_\tau^{SM} = (83.7 \pm 0.4)MeV$ of the Standard Model [4] or with the measured partial width $\Gamma_{e,\mu} = (83.24 \pm 0.42)MeV$ [3] for $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$, assuming the weak dipole moment of light leptons to be zero[1]. For Γ_τ^{SM} the top and Higgs masses are varied in a correlated way in the intervals $90GeV < m_t < 200GeV$ and $50GeV < m_H < 1000GeV$ as is described in ref. [4]. Taking into account correlations between data one obtains $\Delta\Gamma_\tau^{SM} = (-0.94 \pm 1.10)MeV$ and $\Delta\Gamma_\tau^{e,\mu} = (-0.48 \pm 1.10)MeV$ respectively, which correspond, for both cases, to an indirect limit on the weak dipole moment of $|d_\tau(m_Z)| < 0.7 \cdot 10^{-17} e\cdot cm$ at 95% confidence level. However, the contribution of a non-zero dipole moment to the partial width could be compensated for by other unknown physical effects.

[1] In many models the magnitude of the lepton dipole moment increases with mass at least linearly[1].

2 Analysis Procedure

The weak dipole moment is measured directly from a CP-odd correlation between the momenta of the τ^+ and τ^- decay products in a similar manner to the recent analysis of the OPAL collaboration [5]. In this analysis the sensitivity is improved by exclusively identifying the specific τ decay modes.

Various correlation functions have been proposed [1] with one basic difference which is their behaviour under time reversal [6, 7]. Observables which are CP-odd and CPT-even are required. For the decays $\tau^- \to A^- X$, $\tau^+ \to B^+ Y$ the following quantity is chosen [6]

$$T_{A\bar{B}\ i,j} = \quad (\hat{P}_A - \hat{P}_{\bar{B}})_i \frac{(\hat{P}_A \times \hat{P}_{\bar{B}})_j}{|\hat{P}_A \times \hat{P}_{\bar{B}}|} \quad + \quad (i \leftrightarrow j)\ , \tag{2}$$

where $\hat{P}_A(\hat{P}_{\bar{B}})$ is the momentum direction of the charged decay products of the negative (positive) τ-lepton. The indices i and j refer to the Cartesian coordinates where the third components are taken to be along the beam axis. The expectation value $\langle T_{A\bar{B}\ i,j}\rangle$ changes sign under a CP transformation, but not under CPT.

For unpolarized beams CP-odd form factors at the eeZ vertex cannot contribute to $T_{A\bar{B}\ i,j}$, so the mean value of $T_{A\bar{B}\ i,j}$ is directly related to the dipole moment of the τ [6]:

$$\frac{\langle T_{A\bar{B}\ i,j}\rangle + \langle T_{B\bar{A}\ i,j}\rangle}{2} = \frac{m_Z}{e} d_\tau(m_Z) \cdot C_{AB} \cdot diag(-1/6, -1/6, 1/3)_{i,j} \quad . \tag{3}$$

By the term $diag$ is meant a diagonal matrix with diagonal elements as given above. The $T_{A\bar{B}\ i,i}$ $(i = 1, 2)$ have less analyzing power than $T_{A\bar{B}\ 3,3}$ due to the factor 2 and as they are also highly correlated to $T_{A\bar{B}\ 3,3}$, only this quantity is used in this analysis. The linear dependence of the expectation value $\langle T_{A\bar{B}\ i,j}\rangle + \langle T_{B\bar{A}\ i,j}\rangle$ on $d_\tau(m_Z)$ is due to the interference between the CP-odd form factor and the Standard Model contribution. In addition there are terms quadratic in $d_\tau(m_Z)$, resulting from the normalization of $\langle T_{A\bar{B}\ i,j}\rangle$, but these can be neglected for $d_\tau(m_Z) \ll e/m_Z$.

The proportionality constants C_{AB} depend on the τ decay mode and are listed in ref. [6, 8][2]. As the interference term has the approximate form, $d_\tau(\vec{s}_+ - \vec{s}_-)$, the proportionality constants can be written as $C_{AB} \approx C_A + C_B$ where $C_A(C_B)$ are proportional to the analyzing power of the $\tau^+(\tau^-)$ decay modes used as a polarimeter. Experimental cuts do not invalidate the choice of CP-odd correlation functions as long as they are CP blind which is the case in this analysis. However, they cause changes to the proportionality constants leading to effective constants C_{AB}^{eff}. The calculation of these effective constants using a Monte Carlo program written by the authors of ref. [6, 8] is discussed in section 5.

For the ρ decay mode there are in principle three different definitions of $T_{A\bar{B}\ i,j}$; one can use the momentum of the charged pion only, the neutral pion only, or the sum of both, resulting in differences in sensitivity up to a factor of 20 [8]. In the case of $\pi\rho$

[2]To obtain the above formula the V–A interaction was assumed in the τ decays. It can be shown that to lowest order in the Standard Model couplings, $\langle T_{A\bar{B}\ i,j}\rangle$ does not receive contributions from possible CP-violating effects in the τ decay amplitudes [9].

and $\rho\rho$ modes the best sensitivity is achieved by calculating the correlation using the reconstructed ρ momenta. For the $e\rho$ and $\mu\rho$ correlation, however, the lowest error on the dipole moment is obtained if the $\pi^{\pm}$ momentum is used. This is due to a cancelation of the sensitivities C_l and C_ρ which are approximately equal but opposite in sign.

Two methods can be used to select the events. It is possible to either exclusively identify all the τ decay modes, or to only make the distinction between leptonic and hadronic decay modes as in ref. [5, 10]. However, with the latter, inclusive, method the sum is over rather different C_{AB} values leading to a lower analyzing power. In addition, the ρ decay modes cannot be treated as described above. This analysis therefore uses the exclusive method resulting in a gain of around 1.6 in the statistical error on the dipole moment.

3 The Detector

The ALEPH detector is described in detail elsewhere [11]. The detector components from the beam pipe outwards are:

• The Vertex Detector (VDET), two layers of silicon strip detectors with double-sided readout. The spatial resolution in $r\phi$ and z is $12\mu m$ for perpendicularly traversing particles.

• The Inner Tracking Chamber (ITC), an 8–layer cylindrical drift chamber with sense and field wires parallel to the beam axis from 13cm to 29cm in radius. Particles with polar angles from 14° to 166° traverse all 8 layers.

• The large cylindrical Time Projection Chamber (TPC), extending to an outer radius of 180cm. Together with the ITC it provides an angular resolution of 0.3$mrad$ depending on the momentum and the polar angle of the particle and a momentum resolution of $\delta p/p^2 = 0.0008 GeV^{-1}$.

• The highly granular Electromagnetic Calorimeter (ECAL), a lead/proportional wire chamber sandwich covering the polar angular range from 11° to 169°. Cathode pads are arranged in towers of approximately $0.8° \times 0.8°$ solid angle and read out in three storeys of 4, 9 and 9 radiation lengths. The signals from the 45 wire planes of each module are also read out, allowing an additional energy measurement.

• The Hadron Calorimeter (HCAL), consisting of 23 layers of streamer tubes interleaved in the iron return yoke of the magnet system. The coverage in polar angle is from 6° to 174°. Digital signals from each of the $1 \times 1 cm^2$ tubes are read out. In addition, analogue signals are recorded from pads, which are arranged in towers and cover solid angles of about $3.7° \times 3.7°$.

• The muon chambers, two double layers of streamer tubes with orthogonal strips surrounding the HCAL.

The momenta of the particles are defined by the tracking chambers and the ECAL. Particle identification involves TPC, ECAL, HCAL and muon chambers.

4 Event Selection

This analysis uses the τ decay modes with only one charged track $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi(K)\nu$ and $\tau \to \rho(K^*)\nu$. The data were accumulated at LEP during 1990 and 1991. The integrated luminosity represents $18.8pb^{-1}$ distributed in energy around the Z mass and corresponds to 21,600 $\tau\tau$ events.

In an event, two particles were required with opposite charge and each with a momentum greater than $3GeV$. The scattering angle was restricted to be within $|\cos\theta| < 0.9$ and the cosine of the acollinearity to be less than -0.95. Particle identification techniques similar to those described in ref. [12] were applied.

Electrons are identified using the transverse and longitudinal profile of the shower in ECAL and the difference between the observed and expected track ionisation. The estimator sensitive to the transverse profile also requires a balance between the ECAL energy and the TPC track momentum measurement.

Muons are identified from hits in the muon chambers and by their penetration and characteristic shower pattern in HCAL.

Pions are positively identified on the basis of the depth and width of showers in HCAL and the energy deposited in ECAL. To reject ρ, pion candidates must have no photon within 60 degrees of the track direction; a photon is defined as a cluster of energy of more than $400MeV$ in ECAL separated from the track impact position by more than $5cm$ and having at least 70% of its energy in the first 13 radiation lengths.

For $\rho^\pm \to \pi^\pm\pi^0$ candidates, a track is required which does not enter the electron or muon classes described above, and which is accompanied by one or two photons. If only one photon is found its energy must be larger than $4GeV$, whereas in the case of two photons, their invariant mass must be within $60MeV$ of the π^0 mass. Furthermore, the invariant mass of the charged track and the photons must be between $0.5GeV$ and $1.2GeV$. The ρ momentum is calculated by adding the charged pion momentum and the reconstructed photon momenta using the ECAL storey information. If only one photon is reconstructed then its momentum is taken to be the π^0 momentum [12].

With these selection criteria the efficiencies for particle identification are 75% for electrons, 92% for muons, 74% for pions and 56% for ρ candidates.

Bhabha events and $e^+e^- \to \mu^+\mu^-$ events are rejected as follows. If both charged particles are identified as muons, it is required that the higher (lower) particle momentum be less than 85% (60%) of the beam energy and that there is no photon with an energy above $1GeV$. For $\mu\pi$ events the muon momentum must be less than 90% of the beam energy. In the case of $e\pi$ $(e\rho)$ pairs the total energy deposited in the electromagnetic calorimeter must be lower than $0.65(0.8)\sqrt{s}$.

Bhabha background causes a non-zero expectation value of $T_{A\bar{B}\ 3,3}$ due to bremsstrahlung (cf. section 5), therefore electron pairs are not used in this analysis.

Table 1 shows the number of selected pairs, the detection efficiency and the back-

mode	events	efficiency	background	br. ratio
$e\mu$	601	$(51.4 \pm 1.4)\%$	$(2.6 \pm 0.4)\%$	$(5.27 \pm 0.27)\%$
$e\pi$	414	$(37.4 \pm 1.7)\%$	$(10.0 \pm 1.2)\%$	$(4.61 \pm 0.32)\%$
$e\rho$	486	$(28.0 \pm 1.2)\%$	$(3.0 \pm 0.6)\%$	$(7.79 \pm 0.50)\%$
$\mu\mu$	481	$(63.9 \pm 2.0)\%$	$(13.2 \pm 1.2)\%$	$(3.02 \pm 0.18)\%$
$\mu\pi$	417	$(45.4 \pm 1.7)\%$	$(10.1 \pm 1.1)\%$	$(3.82 \pm 0.25)\%$
$\mu\rho$	663	$(35.5 \pm 1.2)\%$	$(8.2 \pm 0.8)\%$	$(7.93 \pm 0.43)\%$
$\pi\pi$	128	$(36.2 \pm 2.8)\%$	$(11.0 \pm 2.0)\%$	$(1.46 \pm 0.18)\%$
$\pi\rho$	365	$(26.2 \pm 1.5)\%$	$(12.4 \pm 1.4)\%$	$(5.65 \pm 0.46)\%$
$\rho\rho$	290	$(21.7 \pm 1.6)\%$	$(11.4 \pm 1.6)\%$	$(5.48 \pm 0.54)\%$
sum	3845			

Table 1. The number of selected decay modes, their efficiencies, backgrounds, and the measured branching ratios.

ground. The non-τ background for all decay modes is less than 1%, except for the $\mu\mu$ class, which has an $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ background of 10.5%. From the number of selected pairs the branching ratio for $\tau^+\tau^- \rightarrow X^+Y^-\nu\bar{\nu}$ is calculated as shown in table 1. The branching ratios are in agreement with ref. [13], with a global χ^2 of 13.4 with eight degrees of freedom.

5 Corrections and Systematic Errors

Systematic errors are classified in two ways. Firstly there are errors on $T_{A\bar{B}\ 3,3}$ coming from experimental biases faking a CP-odd form factor. For instance, if one of the TPC end plates is rotated around the beam axis by a twist angle of $\omega_{TPC} = 1mrad$, then there would be a contribution to $\langle T_{A\bar{B}\ 3,3}\rangle$ of 0.01. Secondly, errors on the effective proportionality constants C_{AB}^{eff} arise from background and experimental cuts; these are only significant for a non-zero dipole moment.

5.1 Systematic Errors on $T_{A\bar{B}\ 3,3}$

Radiation in the material of the detector causes a systematic shift in the acoplanarity measured in the plane perpendicular to the beam axis. This leads to a shift in $T_{A\bar{B}\ 3,3}$, equal in magnitude but opposite in sign, for forward and backward scattering. Since the forward-backward asymmetry in τ pair production is relatively small, this effect can be neglected. The Bhabha background causes a non-zero expectation value due to the large forward-backward asymmetry and the high degree of radiation in the detector material. Values of $\langle T_{A\bar{B}\ 3,3}\rangle$ between 0.10 and 0.25 are obtained depending upon the cuts. Therefore the ee correlation was not used.

The twist angle ω_{TPC} was measured to be less than $0.4mrad$ using μ pair events. This leads to a shift in $\langle T_{A\bar{B}\ 3,3}\rangle$ of 0.004 resulting in a fake dipole moment between

$-0.020e/m_Z$ and $0.035e/m_Z$, depending on the decay modes. The different sign of the various decay modes enables this source of systematic error to be eliminated.

A constant shift, ΔT, for all decay modes can be measured by inspecting the dipole moments d_+ and d_- derived from decay modes with positive or negative C_{AB}^{eff} respectively. These two moments are functions of the shift, ΔT, and the dipole moment $d_\tau(m_Z)$:

$$d_\pm = d_\tau(m_Z) \pm 3\Delta T|c_\pm| \tag{4}$$

where $c_\pm$ is given by the weighted sums of $1/C_{AB}^{eff}$. The difference between these two moments depends only on the shift but not on the physical dipole moment. Conversely, an appropriately weighted sum of these moments depends on the physical dipole moment alone. The weighted mean value of the dipole moments d_+ and d_- for positive and negative C_{AB}^{eff} are measured, using the results of table 3, to be:

$$d_+ = 0.017 \pm 0.128 \qquad d_- = 0.112 \pm 0.074 \qquad \left[\frac{e}{m_Z}\right] \quad , \tag{5}$$

leading to a shift ΔT of

$$\Delta T = -0.016 \pm 0.019 \quad . \tag{6}$$

This is observed to be compatible with zero.

For the $\pi\rho$ and $\rho\rho$ correlation, the electromagnetic calorimeter is used to reconstruct the ρ momentum. Therefore a different twist of the TPC and ECAL end plates can still fake a non-zero dipole moment. The dependence of the dipole moment on the twist angles ω_{TPC} and ω_{ECAL} was studied by adding rotations of the end plates into the Monte Carlo program. This yields:

$$\frac{\Delta d}{[e/m_Z]} \approx 4\, \frac{\omega_{TPC} - \omega_{ECAL}}{[rad]} \quad . \tag{7}$$

The twist angles, ω_{TPC} and ω_{ECAL}, measured using μ-pair events are compatible with zero and results in an error on the dipole moment of $0.003e/m_Z$. Several other sources of systematic errors, like a tilt or a displacement, were also studied and found to be one order of magnitude lower than the error due to a possible twist.

5.2 Corrections and Systematic Errors on the Sensitivity

The ratio between C_{AB}^{eff} and C_{AB} is a result of both the background and the kinematical cuts (cf. table 2). Systematic errors from the former arise from both experimental uncertainties and a lack of knowledge of C_{AB} for some types of background. Errors resulting from the cuts are negligible. The error from the experimental uncertainty in the background is estimated by varying the background by a relative amount of 50%. In the second case, where C_{AB} is unknown the error is estimated by varying C_{AB} from -1 to 1. The separate errors are shown in table 2. To evaluate the systematic error on C_{AB}^{eff} induced by cuts on kinematical variables like acollinearity, lowest allowed momentum of the track, and polar angle these cuts were varied over a wide range compared to the

mode	background	kin. cuts	C_{AB}^{eff}
$e\mu$	$0.984 \pm 0.008 \pm 0.005$	1.17	$+0.713 \pm 0.014$
$e\pi$	$0.876 \pm 0.062 \pm 0.058$	1.13	-0.614 ± 0.053
$e\rho$	$0.956 \pm 0.022 \pm 0.107$	1.04	$+0.338 \pm 0.038$
$\mu\mu$	$0.865 \pm 0.054 \pm 0.012$	1.15	$+0.615 \pm 0.035$
$\mu\pi$	$0.868 \pm 0.066 \pm 0.034$	1.11	-0.597 ± 0.045
$\mu\rho$	$0.962 \pm 0.019 \pm 0.061$	1.04	$+0.340 \pm 0.024$
$\pi\pi$	$0.942 \pm 0.029 \pm 0.005$	1.09	-1.869 ± 0.056
$\pi\rho$	$0.900 \pm 0.050 \pm 0.050$	1.05	-1.455 ± 0.103
$\rho\rho$	$0.886 \pm 0.057 \pm 0.134$	1.01	-0.816 ± 0.119

Table 2. The contribution to the ratio between C_{AB}^{eff} and C_{AB} caused by background and cuts on the kinematics of the event. The last column shows the final proportionality constant C_{AB}^{eff}. The first and second error on the background are due to experimental and theoretical uncertainties, respectively. The errors arising from the cuts are negligible. The error on C_{AB}^{eff} combines the errors due to background estimation and the statistics of the Monte Carlo sample.

errors on these variables. This caused insignificant changes to C_{AB}^{eff}. According to Monte Carlo studies, the momentum and angular resolutions have a negligible influence on the proportionality constants. An error caused by a wrong definition of the z-axis also belongs to the first group of errors, because the measured $T_{A\bar{B}\ 3,3}$ is then a linear combination of the various $T_{A\bar{B}\ i,j}$. The error is negligibly small because the geometry is known to $1 mrad$.

6 Results

Table 3 shows the measured dipole moment in units of e/m_Z. In the case of the $e\rho$ and $\mu\rho$ correlation the highest analyzing power is given by the lepton and charged pion momentum as discussed above, so this definition of $T_{A\bar{B}\ 3,3}$ for the lepton-ρ correlation was used.

As pointed out in section 4, an appropriately weighted sum of d_+ and d_- results in a weak dipole moment which is independent of a constant shift of $T_{A\bar{B}\ 3,3}$. The mean value of $d_\tau(m_Z)$ as well as the statistical error on $d_\tau(m_Z)$ receive an additional error due to the error on C_{AB}^{eff}. Propagation of the errors, assuming them to be gaussian and non-correlated, results in a relative error on the mean value of $d_\tau(m_Z)$ of 5.6% and on the statistical error of 2.9%. One obtains

$$d_\tau(m_Z) = 0.062 \pm 0.064 \pm 0.005 \qquad \left[\frac{e}{m_Z}\right] \qquad , \tag{8}$$

where the systematic error coming from the measurement of $T_{A\bar{B}\ 3,3}$ is $0.003 e/m_Z$, the rest arising from uncertainties in the C_{AB}^{eff}. Comparison with table 3 shows that the

mode	$d_\tau(m_Z)[e/m_Z]$
$e\mu$	0.378 ± 0.190
$e\pi$	0.262 ± 0.249
$e\rho$	-0.056 ± 0.414
$\mu\mu$	-0.251 ± 0.222
$\mu\pi$	0.375 ± 0.255
$\mu\rho$	-0.450 ± 0.362
$\pi\pi$	0.212 ± 0.146
$\pi\rho$	0.071 ± 0.107
$\rho\rho$	-0.289 ± 0.238
mean	0.085 ± 0.064

Table 3. The measured dipole moments and the statistical errors in units of e/m_Z for the various decay modes.

weighting procedure adopted to reduce the systematic error has minimal effect on the statistical error.

In units of $e \cdot cm$ the result reads

$$d_\tau(m_Z) = (1.3 \pm 1.4 \pm 0.1) \cdot 10^{-17} e \cdot cm$$

and yields a limit on the weak dipole moment of

$$|d_\tau(m_Z)| < 3.7 \cdot 10^{-17} e \cdot cm$$

at a confidence level of 95%.

7 Conclusion

The limit on the weak dipole moment of the τ lepton has been determined to be $|d_\tau(m_Z)| < 3.7 \cdot 10^{-17} e \cdot cm$. The results here benefit from treating the τ decay channels exclusively because the proportionality constants, C_{AB}, between the measured quantities $T_{A\bar{B}\ 3,3}$ and the weak dipole moment differ in magnitude and sign for the various decay modes. The increased sensitivity results in a reduction of the statistical errors by a factor of around 1.6 compared to the inclusive method and an appropriately weighted sum of the dipole moments with positive and negative proportionality constants leads to a cancellation of systematic errors.

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