Measurement of the Tau Dipole Moments at LEP

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From the analysis of $e^+e^- \to \tau^+\tau^-(\gamma)$ events collected by the four experiments at LEP between 1990 and 1995, a measurement of the electromagnetic and weak dipole moments of the tau lepton (τ) has been performed. No indication of CP violation or new physics beyond the Standard Model has been observed.

1 Introduction

In the Standard Model [1] (SM) leptons are assumed to be pointlike particles. This has been proved experimentally for electrons and muons [2]. Before LEP, precise data were missing about the heaviest lepton, the tau (τ), and only limits on its anomalous magnetic moments were given at $q^2 \neq 0$ [3] and, with very low statistics in the first stages of LEP, at $q^2 = 0$ [4].

At LEP, high statistics data samples of $e^+e^- \to Z \to \tau^+\tau^-(\gamma)$ processes allow to measure the electromagnetic and weak dipole moments of the τ.

The electromagnetic anomalous magnetic and electric dipole moments are measured at $q^2 = 0$ from the radiation of real photons by the τ in $Z \to \tau\tau\gamma$ events. Weak dipole moments are obtained from spin measurements using the τ decay products in $Z \to \tau^+\tau^-$ events.

Large anomalous magnetic dipole moments would be a signal for substructure of the τ. A measurement of non-zero electric (electromagnetic or weak) dipole moments is an unambiguous signal of CP violation [5].

In this paper, I review the measurements of the electromagnetic and weak dipole moments of the τ lepton performed by the LEP experiments. I will introduce the fundamental concepts of the topic and will outline the basic ideas of the respective analyses. The results hereby quoted include the full statistics collected in the first phase of running of the LEP collider.

2 Electromagnetic Dipole Moments

In general a photon may couple to a τ lepton through its electric charge, magnetic dipole moment or electric dipole moment. This coupling may be parametrised using a matrix element in which the usual γ^μ is replaced by a more general Lorentz-invariant form [6],

$$\Gamma^\mu = F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i}{2m_\ell}\sigma^{\mu\nu}q_\nu - F_3(q^2)\sigma^{\mu\nu}\gamma^5 q_\nu .$$

The q^2-dependent form-factors, $F_i(q^2)$, have familiar interpretations for $q^2 = 0$: $F_1(0) \equiv Q_\tau$ is the electric charge; $F_2(0) \equiv a_\tau$ is the anomalous magnetic moment ($a_\tau \equiv (g_\tau - 2)/2$); and $F_3(0) \equiv d_\tau/Q_\tau$, where d_τ is the electric dipole moment. In the SM a_τ is non-zero due to loop diagrams and is predicted to be $a_\tau^{\rm SM} = 0.001\,177\,3(3)$ [7]. A non-zero value of d_τ is forbidden by both P invariance and T invariance. Assuming CPT invariance, observation of a non-zero value of d_τ would imply CP violation.

2.1 Data Analysis

Anomalous electromagnetic moments would influence the production of high energy isolated photons in $e^+e^- \to \tau^+\tau^-\gamma$ events, compared to the SM initial and final state radiation processes [8] (figure 1). In this calculation, the cross section contains terms linear and quadratic in a_τ, which come from the interference with the SM amplitude.

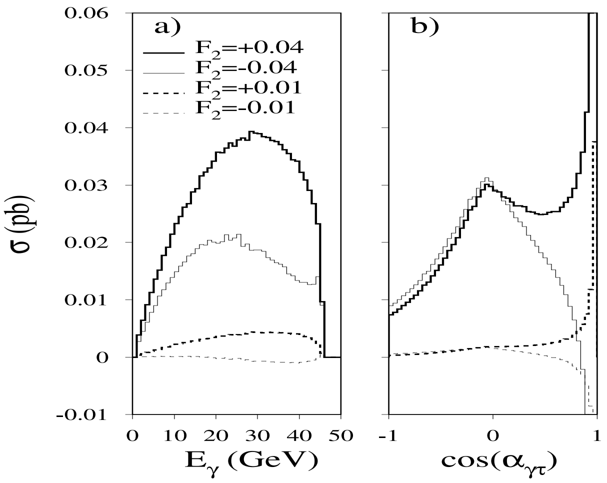

Figure 1: Effect of the additional contribution to the Standard Model cross section of the process $e^+e^- \to \tau^+\tau^-\gamma$, due to non zero values of F_2, in the a) photon energy and b) $\tau\gamma$ opening angle distributions.

The OPAL [9] and L3 [10] experiments selected $e^+e^- \to \tau^+\tau^-\gamma$ events containing at least one high energy isolated photon. The samples used in the analysis collected during the 1990-1995 LEP runs at the Z peak, corresponding to an integrated luminosity of about 100 pb^{-1} per experiment, consisted of 1429 events for OPAL and 1590 for L3. A typical $\tau\tau\gamma$ event is shown in figure 2.

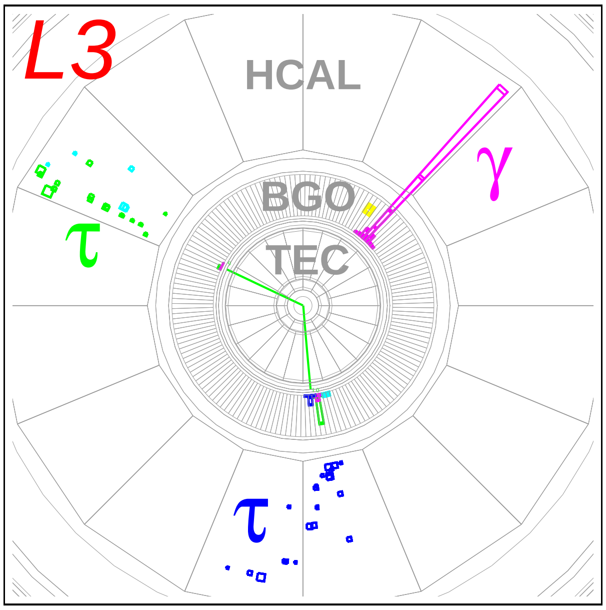

Figure 2: Cross view of a typical $e^+e^- \to \tau^+\tau^-\gamma$ event as seen in the L3 Detector. The Vertex chamber (TEC) and the calorimeters (BGO, HCAL) are also drawn.

The anomalous moments were determined from fits to the distributions of the photon energy (OPAL, L3) and isolation angle (L3), allowing for the SM backgrounds. Figure 3 shows the energy and angular photon spectra from L3 data, together with the SM expectation and the expected signal for a $a_\tau = 0.1$ contribution.

2.2 Results

The LEP results on electric and anomalous magnetic dipole moments are summarised in figure 4.

Detailed studies on the possible systematic uncertainties were performed by the two collaborations [9,10]. The most important sources of systematic error are those affecting the normalisation of the $\tau\tau\gamma$ sample: uncertainty in the $e^+e^- \to \tau^+\tau^-$ cross section, event selection cut and photon reconstruction efficiencies. Studies were performed on the effect of multiple photon radiation and of the theoretical modelling of the $e^+e^- \to \tau^+\tau^-\gamma$ process in the fitted distributions. They were shown to have a negligible effect on the result of the fit. The overall systematic uncertainty is at the level of the statistical error.

A limit is established by combining the individual likelihood functions, taking appropriate care of the correlated systematic errors. The LEP limits at the 95% CL on electric and anomalous magnetic dipole moments are:

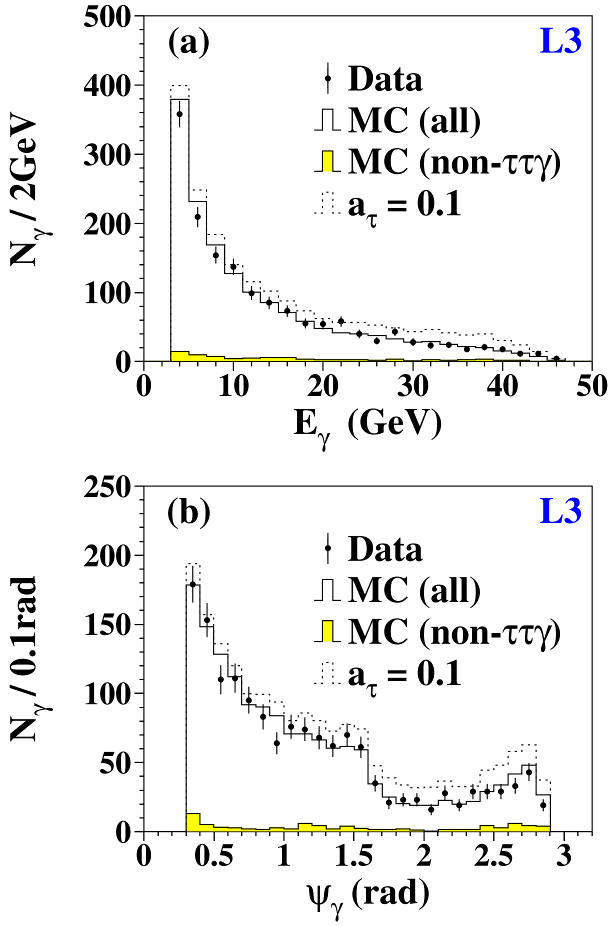

Figure 3: The number N_γ of photon candidates in the $e^+e^- \to \tau^+\tau^-\gamma$ sample (L3) as a function of (a) photon energy E_γ and (b) the isolation angle Ψ_γ with respect to the τ. The points with error bars denote the data and the solid histograms denote the Monte Carlo predictions, assuming the SM values of a_τ and d_τ. For illustration, the dashed histograms show how the distributions would appear for $a_\tau = 0.1$. Both the increase in the total cross section and the relatively greater importance of photons with large E_γ and Ψ_γ are evident.

$$
\begin{array}{l}
-0.05 < a_\tau < 0.05 \\
(\ -3 < d_\tau < 3\ ) \times 10^{-16} \quad e \cdot cm.
\end{array}
$$

The SM predictions are consistent with the measured values. Therefore, these give no indication of either CP violation or new physics beyond the SM.

3 Weak Dipole Moments

To be sensitive a to CP asymmetry in $Z \to f\bar{f}$ production, access to the spin of the final state fermions is required. At LEP, this can be done by exploiting the kinematics of the decay products of the short lived τ leptons.

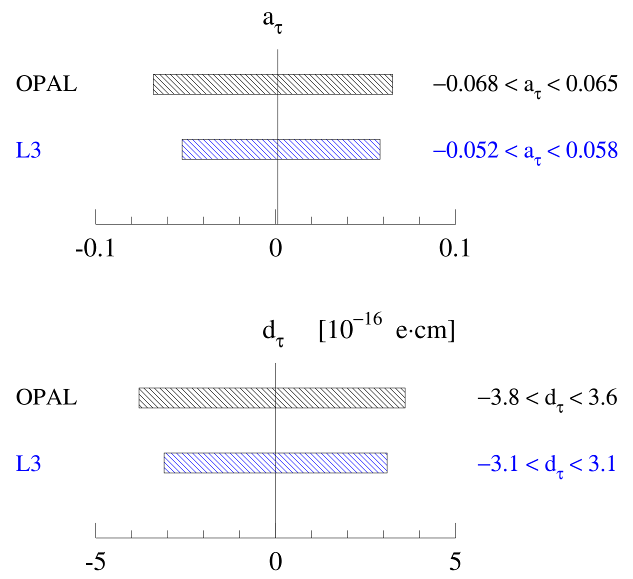

Figure 4: LEP results on the electromagnetic dipole moments a_τ and d_τ.

Different analysis methods were used by the different experiments. L3[11] based its measurement in the analysis of the spin of single τ decays. ALEPH[12], DELPHI[13] and OPAL[14] used the spin correlations of both τ decays.

All the experiments selected $e^+e^- \to \tau^+\tau^-$ events applying standard cuts. The analysis of L3 was restricted to π and ρ final states. The other collaborations used most of the available τ decay channels. A list of the data samples and the τ decay channels analysed by each experiment is shown in table 1.

Table 1: Data samples and τ decay channels analysed by the LEP experiments.

Experiment	Data	#decays	Decay channels
ALEPH	1990–95	83 000	e, μ, π, ρ, a_1
DELPHI	1992–95	22 000	e, μ, π, ρ, a_1 (3pr)
OPAL	1991–95	70 000	e, μ, π, ρ, a_1 (3pr)
L3	1991–95	9 000	π, ρ

3.1 L3 Method

This analysis exploited the polarisation of single τ decays. Events containing only $\tau \to \pi\nu$ and/or $\tau \to \rho\nu$ decays were used. The τ flight direction was reconstructed in these final states. Special azimuthal asymmetries were defined which were sensitive to the transverse and normal components of the polarisation of each single τ[15], allowing for the measurement of both d_τ^w and a_τ^w. The results on a_τ^w are:

$$\begin{aligned} \mathrm{Re}\,(a_\tau^w) &= (\quad 0.0 \pm 1.6 \pm 2.3\ ) \times 10^{-3} \\ \mathrm{Im}\,(a_\tau^w) &= (\,-1.0 \pm 3.6 \pm 4.3\ ) \times 10^{-3}. \end{aligned}$$

This is the first measurement of a_τ^w. Results on d_τ^w are summarised, together with the other LEP results, in section 3.3. Details of the analysis can be found elsewhere[11,16].

3.2 ALEPH, DELPHI and OPAL Method

These experiments tested the CP invariance of τ pair production using CP-odd observables constructed from the measured momenta and energies of the τ decay products. The optimal observables are given by:

$$\mathcal{O}^{\mathrm{Re}} = \frac{\mathcal{M}_{\mathrm{CP}}^{\mathrm{Re}}}{\mathcal{M}_{\mathrm{SM}}} \quad , \quad \mathcal{O}^{\mathrm{Im}} = \frac{\mathcal{M}_{\mathrm{CP}}^{\mathrm{Im}}}{\mathcal{M}_{\mathrm{SM}}} \ ,$$

where $\mathcal{M}_{\mathrm{SM}}$ is the squared SM matrix element of the $e^+e^- \to \tau^+\tau^-$ process and $\mathcal{M}_{\mathrm{CP}}^{\mathrm{Re}}$ and $\mathcal{M}_{\mathrm{CP}}^{\mathrm{Im}}$ are the CP violating contributions to the squared amplitude[17]. These matrix elements are computed from an estimation of the τ spin and flight directions.

The mean value of the optimal observables can be expressed in terms of d_τ^w as follows:

$$\begin{aligned} \langle \mathcal{O}^{\mathrm{Re}} \rangle_{AB} &= \frac{m_{\mathrm{Z}}}{e} \cdot c_{AB} \cdot \mathrm{Re}\,(d_\tau^w) \\ \langle \mathcal{O}^{\mathrm{Im}} \rangle_{AB} &= \frac{m_{\mathrm{Z}}}{e} \cdot f_{AB} \cdot \mathrm{Im}\,(d_\tau^w)\ , \end{aligned}$$

where c_{AB} and f_{AB} are the sensitivities for a given final state $\tau^+\tau^- \to \mathrm{A\,B} + \mathrm{n}\nu$. They are calculated performing detailed Monte Carlo studies, including a complete simulation of the detectors.

With this definition of optimal observables, any significant observed deviation from zero points unambiguously to CP violation. As an example, the values of $\mathrm{Re}\,(d_\tau^w)$ measured by the OPAL collaboration for the different final states are shown in figure 5. Details of the analyses from the different experiments can be found elsewhere[12,13,14].

3.3 Results

The LEP results on the weak electric dipole moment are summarised in figure 6. The OPAL and L3 results are final, while those of ALEPH and DELPHI are preliminary. The L3 results on the weak anomalous magnetic moment are given in section 3.1.

Detailed studies on the possible systematic uncertainties were performed by all the collaborations. The

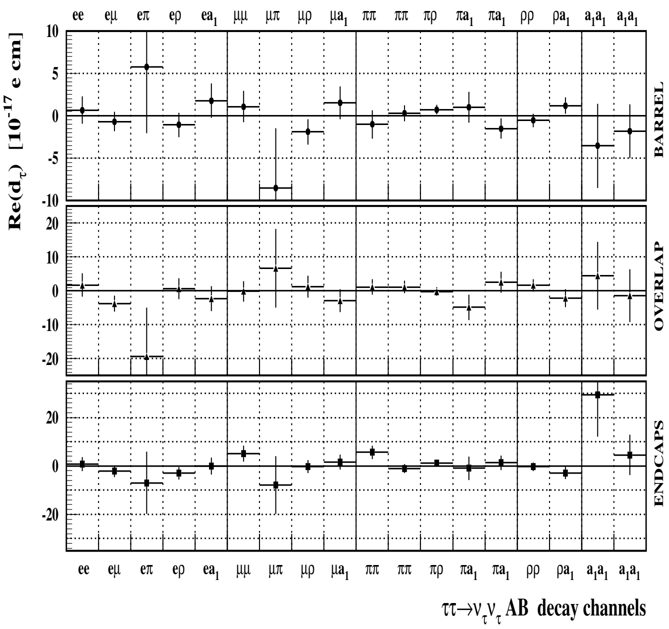

Figure 5: Real part of the weak dipole moment for the different decay topologies and detector regions (OPAL). Decay topologies which appear twice refer to different data periods (1991–92 and 1993–95, respectively).

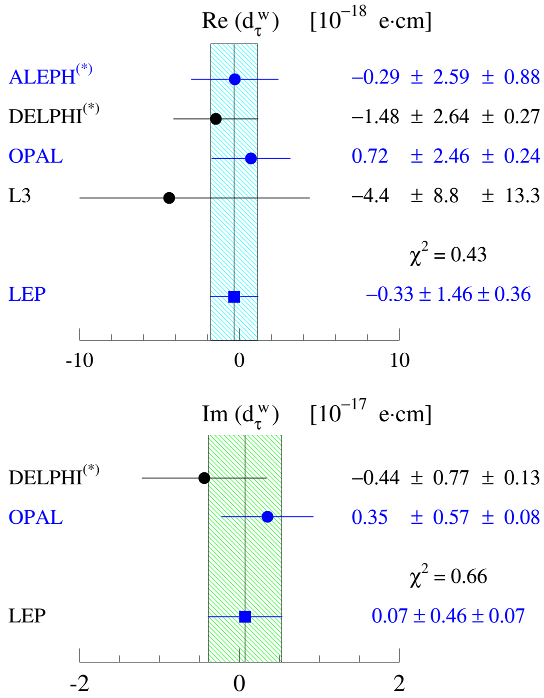

Figure 6: LEP results on the weak electric dipole moment d_τ^w. The OPAL and L3 results are final, the ALEPH and DELPHI ones are preliminary$^{(*)}$.

most important sources of systematic error are the alignment, homogeneity and CP invariance of the detectors. The latter has been checked to be at the level of 10^{-19} e·cm by artificially destroying the spin correlations of the final state in an event by event basis. The overall systematic uncertainty is well below the statistical error.

A limit is established by combining the individual values assuming gaussian errors and considering the systematic errors completely uncorrelated. The LEP limits at the 95% CL on the real and imaginary parts of the weak electric dipole moment are:

$$\begin{aligned} (-3.3 < \mathrm{Re}\ (d_\tau^w) < 2.7\ ) &\times 10^{-18} \quad e\cdot cm \\ (-0.9 < \mathrm{Im}\ (d_\tau^w) < 1.0\ ) &\times 10^{-17} \quad e\cdot cm \\ |d_\tau^w| \quad < 0.7 \quad &\times 10^{-17} \quad e\cdot cm. \end{aligned}$$

The SM predictions are consistent with the measured values both of a_τ^w and d_τ^w. As a consequence, no indication of either CP violation or new physics beyond the SM has been found.

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