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Abstract

Tests of CP invariance in the reaction $e^+e^- \rightarrow \tau^+\tau^-$ on the Z^0 and measurements of the weak and electric (magnetic) dipole moments of the τ lepton are reviewed. The relative importance of the measurements in terms of several models are discussed. Averaging the present LEP measurements, upper limits on the real and imaginary parts of the weak dipole moment of the τ lepton of $|Re(d_\tau^w(M_Z^2))| < 3.6 \cdot 10^{-18}$ ecm and $|Im(d_\tau^w(M_Z^2))| < 1.1 \cdot 10^{-17}$ ecm with 95% c.l. are obtained. Results on measurements on the weak magnetic moment and the anomalous (electric) magnetic moment are also reported.

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CP Tests and Dipole Moments in τ -Pair Production Experiments

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Tests of $\mathcal{CP}$ invariance in the reaction $e^+e^- \rightarrow \tau^+\tau^-$ on the Z^0 and measurements of the weak and electric (magnetic) dipole moments of the τ lepton are reviewed. The relative importance of the measurements in terms of several models are discussed. Averaging the present LEP measurements, upper limits on the real and imaginary parts of the weak dipole moment of the τ lepton of $|\text{Re}(d_\tau^w(M_Z^2))| < 3.6 \cdot 10^{-18}$ ecm and $|\text{Im}(d_\tau^w(M_Z^2))| < 1.1 \cdot 10^{-17}$ ecm with 95% c.l. are obtained. Results on measurements on the weak magnetic moment and the anomalous (electric) magnetic moment are also reported.

1. Motivation

The understanding of $\mathcal{CP}$ violation [1] is one of the most burning issues of particle physics today. Particularly interesting is the question whether the description of $\mathcal{CP}$ violation as being offered by the Standard Model of electroweak interactions is sufficient to describe all related phenomena including the apparent baryon asymmetry in the universe [2]. With respect to the latter it has been argued [3] that additional sources of $\mathcal{CP}$ violation need to be invoked. This motivates the experimental search for new $\mathcal{CP}$ violating interactions, for instance $\mathcal{CP}$ violating couplings in neutral current processes such as $e^+e^- \rightarrow \tau^+\tau^-$. These couplings are usually parametrized by dipole form factors, which - at a fixed Q^2 - are called electric ($Q^2 = 0$) or weak ($Q^2 = M_Z^2$) dipole moments.

Classically, an electric dipole moment occurs when the centre of a charge distribution does not coincide with its mass centre. In the case of an elementary particle the (polar) dipole moment vector $\vec{d}$ must be proportional to the only (axial) vector available, the spin $\vec{S}$. Because of the different transformation properties of $\vec{d}$ and $\vec{S}$ a non-vanishing dipole moment implies $\mathcal{P}$ and $\mathcal{T}$ violation [4]. At the field theory level, dipole moment interactions arise from quantum loop effects

parametrized by chirality flipping form factors [5] which naturally introduce a mass dependence.

Searches for *electric* and *weak* dipole moment interactions in the reaction $e^+e^- \rightarrow \tau^+\tau^-$, on the other hand, are true $\mathcal{CP}$ tests [7-9] because the e^+e^- initial state is $\mathcal{CP}$ symmetric. *Weak magnetic* moments can, in principle, also be extracted from this reaction as was shown at this conference [10]. The *anomalous* (electric) *magnetic* and the *electric* dipole moment of the τ is searched for at LEP at the $\tau\tau\gamma$ vertex of the reaction $e^+e^- \rightarrow \tau^+\tau^-\gamma$. Note, that magnetic moment interactions do not violate $\mathcal{CP}$.

In this talk, I shall mainly review the experimental situation on weak dipole moment measurements and $\mathcal{CP}$ tests using results obtained by the LEP experiments. At the end of this writeup I will also mention new analyses on the anomalous magnetic moment and will summarize the present LEP results on all dipole moment measurements.

2. Models

Within the framework of the Standard Model $\mathcal{CP}$ violation in $e^+e^- \rightarrow \tau^+\tau^-$ requires to invoke CKM phases in higher order corrections. Such contributions [13,11] can be estimated to be at most of the order $(g^2/4\pi)^2 \cdot c_1 c_2 c_3 s_1^2 s_2 s_3 s_4 \cdot T_{SM} \approx 10^{-7} T_{SM}$ [7], where T_{SM} is a typical Standard Model amplitude at the Born level and c_i, s_i denote elements of the CKM matrix [12]. An observation of $\mathcal{CP}$ violation in $Z^0 \rightarrow f\bar{f}$ would there-

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fore indicate physics beyond the Standard Model.

Many models exist (for a review see [14]) which predict $\mathcal{CP}$ violation by means of dipole moment interactions introduced by radiative corrections. Two examples of diagrams which contribute to $\mathcal{CP}$ violating interactions are given in fig. 1 showing vertex corrections involving the exchange of a virtual scalar field (fig. 1(a)) without defined $\mathcal{CP}$ symmetry in a multi-Higgs model [6,7,17], and the exchange of a lepto-quark in fig. 1(b) which occurs in lepto-quark models [16,11,15].

Figure 1. $\mathcal{CP}$ violating diagrams contributing in multi-Higgs models (a) and lepto-quark models (b). Additional contributions are not shown.

The strength d of such couplings is at the level of a radiative correction at the 1-loop level and may be of the order $d \sim \alpha/\pi \cdot 1/M_Z$. Because d is chirality flipping it depends also on the external or internal fermion loop mass. In some cases, for example in multi-Higgs models, additional mass dependences arise from the proportionality of the Higgs coupling to the fermion mass. In these models the electric and weak dipole moments of heavy fermions scale like m_f^3 [17]², rep-

²For light fermions the dominant contribution to d in these models is a 2-loop effect [18].

dering τ lepton production a particularly well suited reaction to study. A second advantage of the τ pair production process will be given in the next section. In the case of some lepto-quark models (fig. 1(b)) the mass dependence includes the mass of the quark partner at the vertex [17]: $d_\tau : d_\mu : d_e = m_\tau m_t^2 : m_\mu m_c^2 : m_e m_u^2$. Table 1 summarizes the mass dependence expected from various models and the expected values for dipole moments. The ratio of weak to electric dipole moments is expected in these models to be in the range 1/3 to 1/4 [17].

Table 1 sets the target for experimental measurements of electric or weak dipole moments: 10^{-19} ecm. However, limits in the range of 10^{-17} to 10^{-18} ecm are already considered as sensitive tests for surprises originating from physics beyond the standard model.

In a recent publication [19] it has been argued that measurements which search for $\mathcal{CP}$ violating amplitudes in the production of τ pairs are a waste of time because dipole moment interactions would expose themselves most strongly at low energies. I believe that this argument is incorrect because in most models the dipole form factors contain a high mass threshold, for instance the $t\bar{t}$ threshold in the lepto-quark model of fig. 1(b). As a result the magnitude of the form factors grows in fact with increasing c.m. energy until this threshold is reached. Only beyond that threshold the form factors fall off with the c.m. energy. This fact is nicely explained and shown in fig. 1 of ref. [17].

3. Methodology

$\mathcal{CP}$ violating physics beyond the Standard Model can be parametrized by electric and weak dipole form factors using an effective, model independent Lagrangian ansatz as suggested by Bernreuther and Nachtmann [7]. This assumes that the new interaction scale is much larger than the Z mass. The strength of the new interaction is governed by the dipole form factors which are, most generally, complex. Neglecting the contribution from one-photon annihilation at the Z^0 peak this ansatz has only one "parameter", $d_\tau^w(M_Z^2)$, the weak dipole moment of the τ lepton. At the Born

Table 1

The range of expectations from some classes of models for d_τ^w

model	m_τ dependence	maximum expectation for d_τ^w (ecm)
multi-Higgs	m_τ^3	2×10^{-20}
SUSY	m_τ	$few \times 10^{-20}$
lepto-quark	$m_i^2 m_\tau$	$(2-3) \times 10^{-19}$
Majorana $\hat{\nu}$	$m_{\hat{\nu}}^2 m_\tau$	$few \times 10^{-20}$

level only the interference of the SM amplitude T_{SM} with the $\mathcal{CP}$ violating amplitude $T_{\mathcal{CP}}$ is $\mathcal{CP}$ -odd. The $\mathcal{CP}$ -even squared amplitude $|T_{\mathcal{CP}}|^2$ is of order $|d_\tau^w|^2$ and contributes to the partial width $Z \rightarrow \tau^+ \tau^-$ [7]. While this constitutes a measurement of $|d_\tau^w|$ it is not a test of $\mathcal{CP}$ invariance. Using the actual experimental values [21] of $\Gamma_{\tau\tau}$ and M_Z and the relation

$$\begin{aligned} \Delta\Gamma_{Z \rightarrow \tau\tau} &= \frac{|d_\tau^w|^2}{24\pi} M_Z^3 \left(1 - \frac{4m_\tau^2}{M_Z^2}\right)^{3/2} \\ &= 0.237 \times 10^{31} |d_\tau(ecm)|^2 \text{ GeV} \quad (1) \end{aligned}$$

one obtains³

$$|d_\tau^w| < 1.8 \times 10^{-17} \text{ ecm} \quad (2)$$

The $\mathcal{CP}$ -odd interference term can be split into two parts, $2\text{Re}(T_{SM}^* T_{\mathcal{CP}}) = \text{Re}(d_\tau^w) \cdot M_{\mathcal{CP}}^{Re} + \text{Im}(d_\tau^w) \cdot M_{\mathcal{CP}}^{Im}$, which are proportional to the real and imaginary parts of the weak dipole moment, respectively. The squared matrix elements, $M_{\mathcal{CP}}^{Re}$ and $M_{\mathcal{CP}}^{Im}$ are functions [24] of the direction and the spin orientation of the taus, which are transferred to the τ decay products. This is the second important reason why τ -pair production is a favourable reaction for these kind of measurements. Contributions to the imaginary part of d_τ^w are related to absorptive parts in the $\mathcal{CP}$ violating interaction. In general $\text{Im}(d_\tau^w)$ is expected to be smaller than $\text{Re}(d_\tau^w)$ because for a number of models such absorptive parts develop only as ≥ 2 -loop effects [5].

³The value for $\Gamma_{\tau\tau}$ to be used is $\Gamma_{tot} \cdot B_{\tau\tau}$, where $\Gamma_{tot} = 2496.3 \pm 3.2 \text{ MeV}$ is the total width as determined from a global SM fit (ref. [21], p. 91). The Standard Model value is $\Gamma_{SM} = (83.97 \pm 0.01 \pm 0.06) \text{ MeV}$ [21].

4. $\mathcal{CP}$ -odd observables

Direct tests of $\mathcal{CP}$ invariance in $e^+e^- \rightarrow \tau^+\tau^-$ exploiting the interference term as explained in section 3 have been performed by the LEP experiments since 1992 using $\mathcal{CP}$ -odd observables [7,20]. In the early analyses [22,23] the tensor variable

$$T_{ij} = (\vec{q}_+ - \vec{q}_-)_i \cdot (\vec{q}_+ \times \vec{q}_-)_j + (i \leftrightarrow j) \quad (3)$$

where $\vec{q}_+$ and $\vec{q}_-$ are the momenta of the τ decay products, has been used. This observable has the advantage that it employs only directly measured quantities and has the same form independent of the τ decay channel considered. However, it is not optimally sensitive to $\text{Re}(d_\tau^w)$ and not at all sensitive to $\text{Im}(d_\tau^w)$.

Optimal observables [29], in the sense that the signal to noise ratio attains a maximum, have then been employed [25–28] since 1995 and are defined as

$$\mathcal{O}^{Re} = \frac{M_{\mathcal{CP}}^{Re}}{M_{SM}} \quad ; \quad \mathcal{O}^{Im} = \frac{M_{\mathcal{CP}}^{Im}}{M_{SM}} \quad , \quad (4)$$

where M_{SM} is the squared Standard Model matrix element. They allow to measure real and imaginary parts of d_τ^w (M_Z^2) separately. The calculation of the observables for every event requires however the measurement of the τ flight direction and spin, for which different formulae must be employed for every decay channel considered (see for instance [28]). The reward is an increased sensitivity by a factor of about two with respect to using eq. (3). L3 has used a different (asymmetry) method as reported on this conference [10]. The experimental signature is shown in fig. 2 using simulated events. A non-vanishing d_τ^w causes the otherwise symmetric distribution of the $\mathcal{CP}$ observable (fig. 2(a)) to become asymmetric

(fig. 2(b)). For values of $|d_\tau^w| < 5 \times 10^{-17}$ ecm, which is already measured to be the case (see eq. (2)), $|T_{CP}|^2$ can be neglected and the mean value of the observables is directly proportional to d_τ^w as

$$\begin{aligned} \langle T_{ij} \rangle &= \frac{M_Z}{e} \cdot s_{AB} \cdot \text{Re}(d_\tau^w) \cdot \text{diag}\left(-\frac{1}{6}, -\frac{1}{6}, \frac{1}{3}\right) \\ \langle \mathcal{O}^{Re} \rangle &= \frac{M_Z}{e} \cdot c_{AB} \cdot \text{Re}(d_\tau^w) \\ \langle \mathcal{O}^{Im} \rangle &= \frac{M_Z}{e} \cdot f_{AB} \cdot \text{Im}(d_\tau^w) . \end{aligned} \quad (5)$$

Here $e/M_Z = 2.16 \cdot 10^{-16}$ ecm and diag denotes a diagonal matrix with all off-diagonal elements being zero. The proportionality constants s_{AB} , c_{AB} , and f_{AB} are the "sensitivities" for a given final state $ee \rightarrow \tau\bar{\tau} \rightarrow A\nu_\tau + B\bar{\nu}_\tau$. They must be determined by Monte Carlo simulation including detector effects and backgrounds.

5. Experimental Peculiarities

Sensitive CP tests and precise measurements of d_τ^w require the identification of as many τ decay channels as possible. After selecting τ pairs all LEP experiments use identification methods of high efficiency and purity. Straight cut selection methods have been employed by ALEPH [26], DELPHI [27] and L3 [10], a channel likelihood selection is used by OPAL [25,28]. The τ decay modes to lepton (e, μ) and hadron (π, ρ, a_1) channels (ALEPH, DELPHI, OPAL) have been identified and used in the CP analyses. L3 [10] has employed the π and ρ hadronic decay modes.

A challenging experimental task is the reconstruction of the τ flight direction. The fact that for back-to-back produced taus the true flight direction must point to one of the two possible intersections of the two cones shaped around the direction of the measured decay products with known (calculable) opening angle, has meanwhile been widely exploited by most experiments. With excellent vertex detection capability provided by microstrip vertex detectors, it is also possible to resolve the remaining twofold ambiguity [30]. This requires to determine the relative impact parameter between the decay products of the two decays in space. Figure 3 shows the angle between

reconstructed and true τ flight direction using simulated events for the cases with completely resolved ambiguity (fig. 3(a)) and those where an average between the two possible solutions has been assumed (fig. 3(b)). Typically, for the easiest decay topologies with only charged hadrons in the final state, both directions can be reconstructed for about 80% of the events. Of those for another 80% also the sign, i.e. the correct solution, can be determined. For decays with one or more neutral hadrons in the final state the

Figure 2. A CP violating signature resulting from $d_\tau^w = 5 \times 10^{-17}$ ecm (middle) compared to a vanishing dipole moment (top) obtained from a Monte Carlo simulation. The difference distribution is shown at the bottom.

precision of the flight direction reconstruction is substantially diminished.

An estimator for the τ spin direction is derived from the knowledge that the differential decay width can generally be expressed as [31]

$$d\Gamma(\tau \rightarrow A\nu_\tau) \propto 1 + \vec{h} \cdot \vec{S}_\tau \quad (6)$$

where $\vec{h}$ is the so-called polarimeter vector which must be calculated for every decay. The best estimator for the τ spin direction $\vec{S}_\tau$ then is the direction of $\vec{h}$, i.e. the direction with respect to which $d\Gamma$ is maximal.

Using the information accessible from the detectors the optimal observables (eq. (4)) are constructed for every event. The sensitivities c_{AB} and f_{AB} must be calculated. The ideal sensitivity decreases when acceptance cuts are applied. They further decrease due to detector resolution and background contamination. The values for c_{AB} after correcting for detector effects and backgrounds range from about 0.25 for channels with only charged particles in the final state to about 0.05 for lepton channels and channels including neutral pions. The relative sensitivity increase obtained from the reconstruction of the τ flight direction is about 20%. Table 2 summarizes the analyses of the four LEP experiments to date.

6. $\mathcal{CP}$ Symmetry of the Detectors

Systematic uncertainties arising from (a) overall background contamination and (b) contamination and correlations among decay channels as well as (c) detector resolution and (d) detection efficiency are estimated using simulated events and included in the error on the sensitivities. Detector effects are determined using events generated from the full amplitude including $\mathcal{CP}$ violation and processed through the full detector MC (ALEPH) or alternatively are deduced from standard MC events with no $\mathcal{CP}$ violation applying a reweighting technique.

The main systematic limitation, however, is the level up to which the detectors themselves are $\mathcal{CP}$ symmetric. A $\mathcal{CP}$ unsymmetric detector can artificially produce an effect interpreted as a dipole moment amplitude or - even worse - a true $\mathcal{CP}$ effect could be obscured by such a detector. $\mathcal{CP}$ violation can be faked by measuring particle directions systematically wrong, caused for example by a misalignment of detector components such as a possible systematic rotation of the drift chamber end flanges or the endcaps or by systematically biased reconstruction algorithms. Other sources, which may lead to systematic shifts of the expectation values, are local detector defects or charge dependent identification probabilities. In order to assess the level of $\mathcal{CP}$ symmetry of the LEP detectors, data events are studied for which non-vanishing expectation

Figure 3. Angle between the true and the reconstructed τ flight direction for simulated events for which the ambiguity has been resolved (a), and events for which the average between the two possible directions is taken (b). Note that both histograms use the same events.

Table 2

Summary of the main features of the most recent analyses on d_τ^w by the LEP Experiments

	Aleph [26]	Delphi [27]	L3 [10]	Opal [25,28]
years	90 - 95	92 - 95	91 - 94	91 - 95
$\tau\tau$ produced	200.000	170.000	170.000	190.000
no. of events	83.000	18.000	4.100	70.000
reconstr. of τ direction	yes	yes	yes	yes
ambiguity resolved	yes	no	no	yes
method	opt. obs.	opt. obs.	asymmetry	opt. obs.
$ \cos\theta $ range	0.95	0.73	0.7	0.95
decay channels	$e, \mu, \pi, \rho, a_1^{ch}, a_1^{neut}$	$e, \mu, \pi, \rho, a_1^{ch}$	π, ρ	$e, \mu, \pi, \rho, a_1^{ch}$

values of $\mathcal{O}$ arising from true $\mathcal{CP}$ violation are believed to not exist, e.g. $Z \rightarrow \mu\mu$ and 2-track combinations from multi-hadron events. It is, however, premature to conclude from these reactions that the detector is $\mathcal{CP}$ symmetric if no effect is observed, because $\mathcal{CP}$ violating effects are easily averaged over. The best method, in my opinion, is to use τ data, for which the spin correlations are purposely destroyed by combining two τ decay cones from different events (event mixing) with very similar topologies. For example, a 1-prong tau decay (decay no. 1) in a given event is combined with the cone recoiling against another 1-prong tau decay of a different event (decay no. 2) if and only if the tracks of decays no. 1 and no. 2 coincide within an angle of 3° and have the same charge. It has been verified [28] that the spin correlations are indeed destroyed by this procedure using simulated events generated with a non-vanishing dipole moment. A systematic, detector induced $\mathcal{CP}$ asymmetry, however, survives the same treatment [28].

The LEP experiments have verified that their detectors are $\mathcal{CP}$ symmetric to a level of about $|Re(d_\tau^w)| < 0.5 \cdot 10^{-18} \text{ ecm}$ and $|Im(d_\tau^w)| < 1.0 \times 10^{-18} \text{ ecm}$, respectively.

7. Results

Figures 4 (a) and (b) summarize the measurements obtained by the LEP experiments on the weak dipole moments. Combining the results of the most recent analyses which include the full data samples obtained at LEP-I the 95% c.l. li-

mits are

$$\begin{aligned} |Re(d_\tau^w)| &< 3.6 \cdot 10^{-18} \text{ ecm} \\ |Im(d_\tau^w)| &< 1.1 \cdot 10^{-17} \text{ ecm} \end{aligned}$$

resulting in a limit on $|d_\tau^w|$ of

$$|d_\tau^w| < 1.11 \cdot 10^{-17} \text{ ecm}$$

which can be compared to the limit derived from the partial width of eq. (2). Under the assumption that $Im(d_\tau^w)$ is negligible the limit on $|d_\tau^w|$ is of course determined by $Re(d_\tau^w)$ and is thus much more stringent.

8. Anomalous magnetic moment

The radiative decay $e^+e^- \rightarrow \tau^+\tau^-\gamma$ allows to probe the electromagnetic interaction of the τ with the photon. Writing the electromagnetic vector current in the general form

$$\begin{aligned} j_{elm}^\mu &= e\bar{\tau}\gamma^\mu\tau \\ &+ e\bar{\tau}\left\{\left(\frac{i}{2m_\tau}F_{mag} + \gamma^5 F_{el}\right)\sigma^{\mu\nu}q_\nu\right\}\tau \end{aligned} \quad (7)$$

and defining

$$\begin{aligned} a_\tau^{el} &= \left(\frac{g_\tau - 2}{2}\right) = F_{mag}(Q^2 = 0) \\ d_\tau^{el} &= eF_{el}(Q^2 = 0) \end{aligned} \quad (8)$$

as the anomalous (electric) magnetic and electric dipole moments, respectively, one can experimentally look for an excess of photons due to the existence of non-vanishing form factors F_{mag} and F_{el} . L3 [33] and ALEPH have reported such measurements at this conference. A limit on the

number of excess photons in the measured photon energy spectrum is obtained from fitting the data to the expected signal shape and the events from known sources, i.e. standard ($g_\tau = 2$) $\tau\tau\gamma$ production plus backgrounds. The number of excess photons can be interpreted either as a limit on the magnetic or the electric dipole moment, assuming the respective other formfactor to vanish. The numerical result from L3 [33] is reported in the summary below.

9. Conclusions

Using the full data samples obtained at LEP sensitive $\mathcal{CP}$ tests have been performed and limits on the *weak dipole moment*

$$\begin{aligned} |Re(d_\tau^w)| &< 3.6 \cdot 10^{-18} \text{ ecm} \\ |Im(d_\tau^w)| &< 1.1 \cdot 10^{-17} \text{ ecm} \\ |d_\tau^w| &< 1.11 \cdot 10^{-17} \text{ ecm} \end{aligned} \quad (9)$$

have been obtained with 95% confidence level. The limit on $|d_\tau^w|$ can be compared to

$$|d_\tau^w| < 1.8 \cdot 10^{-17} \text{ ecm}$$

obtained from a measurement of the partial width $\Gamma_{\tau\tau}$ only.

In a different analysis L3 [10] has presented a measurement also on the *weak magnetic moment*

$$|a_\tau^w| < 0.014 \quad \text{at } 95\% \text{ c.l.}$$

Theoretical estimates here lie in the order of 10^{-6} [13,32].

Limits on the *electric* and the *anomalous magnetic* dipole moments have been studied by L3 and ALEPH in the reaction $e^+e^- \rightarrow \tau^+\tau^-\gamma$. The L3 result with 90% c.l. is [33]

$$\begin{aligned} |d_\tau^{el}| &< 2.7 \cdot 10^{-16} \text{ ecm} \\ \text{and/or} \\ |a_\tau^{el}| &< 0.049 \end{aligned}$$

The pure QED prediction for a_τ^{el} is [34] $a_\tau^{QED} = 1.17319 \times 10^{-3}$ which receives however additional weak and strong interaction contributions [34,35].

Various models predict values for d_τ^w in the order of 10^{-19} to 10^{-21} ecm. Although the present limits are already very precise there is still an order of magnitude missing before certain models can be ruled out.

Figure 4. Summary of measurements of (top) $Re(d_\tau^w)$ and (bottom) $Im(d_\tau^w)$ obtained by the LEP experiments. The values high-lighted by the shaded band are the present best measurements and have been used for the average.

In order to assess the relative importance of the results one may consider models with a $\mathcal{CP}$ violating Higgs sector [6,7] or with lepto-quarks [17]. Assuming that weak and electric dipole moments can be directly compared and are expected in these models to have roughly the same order of magnitude [7], the above result on $|d_\tau^w|$ has been scaled in table 3 with the ratio of the fermion masses⁴ as described in section 2. For the case of the electron this simple scaling has to be taken with a grain of salt. Other models also exist [36]

Table 3

Comparison of measured limits on dipole moments from direct measurements with scaled limits from d_τ^w in multi-Higgs (MH) and lepto-quark (LQ) models. All units in (ecm).

	meas. limit on d_f^{el} [37]	MH $d_f \propto m_f^3$	LQ $d_f \propto m_f m_q^2$
e	4×10^{-27}	2×10^{-28}	2×10^{-30}
μ	1.0×10^{-18}	1×10^{-24}	3×10^{-23}

which predict a weaker dependence on the mass of the fermion. Table 3 nevertheless indicates that in terms of certain model expectations the present limits on d_τ^w can well cope with existing measurements on the electric dipole moment of electron and muon, respectively.

Another useful comparison is obtained by defining a $\mathcal{CP}$ parameter ϵ_τ as

$$\begin{aligned} \epsilon_\tau &= \frac{\Delta\Gamma(Z \rightarrow \tau\tau)}{\Gamma_{\tau\tau}} \\ &= 0.237 \times 10^{31} |d_\tau(ecm)|^2 \cdot \frac{1}{\Gamma_{\tau\tau}} \end{aligned}$$

where $\Delta\Gamma(Z \rightarrow \tau\tau)$ is the change in the τ partial width due to the new $\mathcal{CP}$ violating interaction.

Using the limits quoted in eq. (9) for $|d_\tau^w|$ and for $|Re(d_\tau^w)|$ (i.e. assuming $Im(d_\tau^w) = 0$), respectively, and $\Gamma_{\tau\tau} = (83.88 \pm 0.39)$ MeV (c.f. foot-

note to eq. (2)) one obtains

$$\begin{aligned} \epsilon_\tau &< 3.5 \cdot 10^{-3} \quad \text{using } |d_\tau^w| \\ &\text{and} \\ \epsilon_\tau &< 3.7 \cdot 10^{-4} \quad \text{assuming } Im(d_\tau^w) = 0 \end{aligned}$$

While ϵ_τ cannot be directly compared to the K^0 system parameters [21] $\epsilon_K = 2.3 \cdot 10^{-3}$ and $\epsilon'_K \leq 2 \cdot 10^{-6}$, which are defined through amplitude ratios, it gives an indication that the present sensitivity to $\mathcal{CP}$ violation in the neutral current reaction $Z \rightarrow \tau^+\tau^-$ is of a similar order of magnitude as the observed $\mathcal{CP}$ violation in the $\Delta S = 2$, $K^0\bar{K}^0$ mixing amplitude.

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REFERENCES

1. J. H. Christensen et al., *Phys. Rev. Lett.* **13**, 138 (1964).
2. A. D. Sakharov, *JETP Lett.* **5** (1967) 24.
3. P. Huet, E. Sather, *Phys. Rev. D* **51**, 279 (1995); M. B. Gavela et al., *Nucl. Phys. B* **430**, 345 (1994); P. Huet, A.E. Nelson, *Phys.Rev. D* **53** (1996) 4578.
4. S.M. Barr, W.J. Marciano, 'Electric Dipole Moments', in C. Jarlskog (ed.) *Proceedings $\mathcal{CP}$ violation 1990*, 455-499.
5. W. Bernreuther, O. Nachtmann, 'Some Remarks on the Search for $\mathcal{CP}$ Violation in Z-decays', Univ. of Heidelberg and RWTH Aachen preprints HD-THEP-96-03 and PITHA 96/03 (1996).

⁴For the quark masses the values $m_u = 5$ MeV, $m_c = 1.3$ GeV, $m_t = 180$ GeV have been used.

6. S. Weinberg, *Phys. Rev. Lett.* **37** (1976) 657; N.G. Deshpande, E. Ma, *Phys. Rev. D* **16** (1977) 1583; C.Q. Geng, J.N. Ng, *Phys. Rev. Lett* **62** (1989) 2645.
7. W. Bernreuther, O. Nachtmann, *Phys. Rev. Lett.* **63** (1989) 2787 and references therein.
8. C.A. Nelson, SUNY preprint SUNY-BING-4-30-94 (1994); C.A. Nelson, H.S. Friedman, S. Goozovat, J.A. Klein, L.R. Kneller, W.J. Perry, S.A. Ustin, *Phys. Rev. D* **50** (1994) 4544.
9. C.A. Nelson, Proceedings of the 3rd Workshop of Tau Physics, Montreux 1994.
10. E. Sanchez, L3 Collaboration, talk given at this conference.
11. U. Mahanta, *Phys. Rev. D* **54** (1996) 3377; M.J. Booth, University of Chicago report EFI-93-02 (1993).
12. M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).
13. J. Bernabeu, G.A. Gonzalez-Sprinberg and J. Vidal, 'Weak Dipole Moments at e^+e^- colliders', Univ. Valencia and IFIC preprint FTUV/95-15, IFIC/95-15 (1995); J. Bernabeu, G.A. Gonzalez-Sprinberg and J. Vidal, *Phys. Lett. B* **326** (1994) 168.
14. Proceedings, CP violation 1990, C. Jarlskog (ed.), 35-57.
15. S. Barr, A. Masiero, *Phys. Rev. Lett* **58** (1987) 187; W. Bernreuther, *Z. Phys. (Proc. Suppl.) C* **56** (1992) 97.
16. W. Bernreuther, T. Schröder, T.N. Pham, *Phys. Lett. B* **279** (1992) 389.
17. W. Bernreuther, A. Brandenburg and P. Overmann 'CP Violation Beyond the SM and Tau Pair Production in e^+e^- Collisions', PITHA-96-26 (1996).
18. S. Barr and A. Zee, *Phys. Rev. Lett.* **65** (1990) 21.
19. Y.S. Tsai, *Phys. Lett. B* **378** (1996) 272.
20. G. Valencia and A. Soni, *Phys. Lett. B* **263** (1991) 517.
21. Particle Data Group, R. M. Barnett et al., *Phys. Rev. D* **54** (1996) 1.
22. OPAL Collaboration, P. D. Acton et al., *Phys. Lett. B* **281** (1992) 405.
23. ALEPH Collaboration, D. Buskulic et al., *Phys. Lett. B* **297** (1992) 459.
24. W. Bernreuther, O. Nachtmann, P. Overmann, *Phys. Rev. D* **48** (1993) 78.
25. OPAL Collaboration, R. Akers et al., *Z. Phys. C* **66** (1995) 31.
26. ALEPH Collaboration, D. Buskulic et al., *CERN-PPE (94-175)* (1994); *ICHEP'96*, Ref. PA08-030 (1996)
27. DELPHI Collaboration, M.C. Chen et al., *Brussels*, 95-113 Phys 548 (1995); DELPHI Collaboration, M.C. Chen et al., *ICHEP'96*, Ref. PA07-014 (1996).
28. OPAL Collaboration, R. Akers et al., OPAL Physics Note No. 259 (1996), data presented to this conference, submitted to *Z. Phys.* (1997).
29. D. Atwood, A. Soni, *Phys. Rev. D* **45** (1992) 2405; M. Davier, L. Duflot, F. Le Diberder, A. Rougé, *Phys. Lett. B* **306** (1993) 411; P. Overmann, *Univ. of Dortmund preprint DO-TH 93-24*, (1993); P. Overmann, *Dissertation, Inst. f. theor. Physik, Heidelberg* (1992); M. Diehl, O. Nachtmann, *Z. Phys. C* **62** (1994) 397.
30. J. H. Kühn, *Phys. Lett. B* **313** (1993) 458.
31. Y. S. Tsai, *Phys. Rev. D* **4** (1971) 2821.
32. J. Bernabeu, G.A. Gonzalez-Sprinberg, M. Tung, J. Vidal, *Nucl. Phys. B* **436** (1995) 474.
33. L. Taylor (L3), talk presented at this conference.
34. M.A. Samuel, G. Li, R. Mendel, *Phys. Rev. Lett.* **67** (1991) 668.
35. F. Hamzeh, N.F. Nasrallah, *Phys. Lett. B* **373** (1996) 211.
36. Hai-Yang Cheng, *Phys. Rev. D* **28** (1983) 150.
37. E.D. Commins et al., *Phys. Rev. A* **50** (1994) 2960.