Electric and Magnetic Tau Dipole Moments Revisited

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Abstract

Precise measurements of magnetic and electric dipole moments are important tests of the Standard Model and beyond Standard Model physics, particularly for the electron and the muon. However, the situation presents distinctive challenges when dealing with the tau lepton due to its very short lifetime and relatively high mass. Here, we review the theoretical predictions and experimental measurements of both the anomalous magnetic and electric dipole moments of the tau lepton.

Contents

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1 Introduction: Tau Dipole Moments

Tau dipole moments (DM) have been investigated since the discovery of this high-mass lepton [1]. It was speculated that the DMs could play a role similar to those the electron and the muon DMs were playing in the Standard Model (SM) and beyond the SM physics (BSM). However, the measurements for both the magnetic and electric DMs of the tau slowly evolved, and the measurements are still very far from the SM predictions, in particular for the former [2]. In contrast, the electron magnetic moment is one of the highest precision measurements in physics and the theory for this DM provides a strong test for QED. Additionally, the result reported by J. Schwinger [3] for the electron laid the foundations for quantum field theory as a tool for understanding nature at small scales. We begin presenting the electric DM in the next section, followed by the magnetic DM, and, finally, some conclusions in the current experimental and theoretical prospects.

2 Tau Electric Dipole Moment

Electric dipole moments (EDM) were introduced as a probe of parity and time reversal invariance in particle physics [4]. In quantum field theory, time reversal violation also implies CP violation. For a lepton, the EDM is the first-order CP-odd interaction with the photon field:

$$H_{EDM} = \frac{i}{2} d\, \bar{l} \gamma^5 \sigma^{\mu\nu} l\, F_{\mu\nu}, \tag{1}$$

where l is the lepton field, and $F_{\mu\nu}$ is the electromagnetic field tensor. This equation, in the non-relativistic limit, gives the usual first-order interaction with an electric field:

$$H_{EDM} = -\vec{d} \cdot \vec{E}. \tag{2}$$

For the tau, the high $m_\tau = (1776.86 \pm 0.12)\, MeV$ may be advantageous because the EDM tensor structure flips chirality and then it is proportional to the chirality flipping particle's mass. Moreover, many BSM predictions for the tau EDM are proportional to some power n of the particle mass over the scale of new physics, *i.e.* $(m_\tau/m_\Lambda)^n$. When compared to the electron and muon, being that $(m_\tau/m_e)^2 \simeq 10^7$ and $(m_\tau/m_\mu)^2 \simeq 300$, tau physics looks like a promising scenario for searching for EDM signals from BSM physics. On the other hand, the very short lifetime $(2.903 \pm 0.005) \times 10^{-13}\, s$ poses an experimental challenge, necessitating a completely different approach to searching for the tau EDM should be followed. Recently, stringent bounds on the electron and muon EDM were obtained in experiments [2] from CP-odd observables. Besides, many BSM models were ruled out or their space parameter was strongly limited when confronted with the experiments. The PDG bounds [2] for the leptons EDM are:

$$|d_e| < 1.1 \times 10^{-29}\ e\ cm\ at\ CL{=}90.0\%\ ,\ |d_\mu| < 1.8 \times 10^{-19}\ e\ cm\ at\ CL{=}95\%, \tag{3}$$

$$-1.85 \times 10^{-17}\ ecm < Re(d_\tau) < 6.1 \times 10^{-18}\ ecm, \tag{4}$$

$$-1.03 \times 10^{-17}\ ecm < Im(d_\tau) < 2.30 \times 10^{-18}\ ecm. \tag{5}$$

Tau bounds are much weaker, particularly when compared to the electron one. Limits of the tau EDM slowly evolved over the past decades, with the present bounds (4) and (5) derived from the work of K.Inami *etal* at BELLE [5]. Additionally, due to the tiny value of the EDM for leptons in the SM, arising from three-loop diagrams [6], any non-zero signal should indicate new physics. The EDM depends on the underlying mechanisms of CP-violation of the BSM physics and can be obtained by a one-loop vertex correction in these models [7]. In the effective lagrangian approach, the EDM is represented by a dimension six operator [8]. By naively scaling the EDM by mass, and considering the SM computation for the electron EDM, for example, one might expect $d_\tau = \frac{m_\tau}{m_e} d_e$, where the latter is expected to be on the order of 10^{-38} [7]. Note that this value is 21 orders of magnitude below the current experimental bounds (see (4) and (5)).
Note that both CP-odd and CP-even observables may receive an EDM contribution. However, for CP-even observables, contributions are proportional to $|d_\tau|^2$. This is the case for the contributions coming from the leading diagrams for these kind of observables, shown in Fig. 1 for some processes. These correspond to cross sections, angular distributions, and

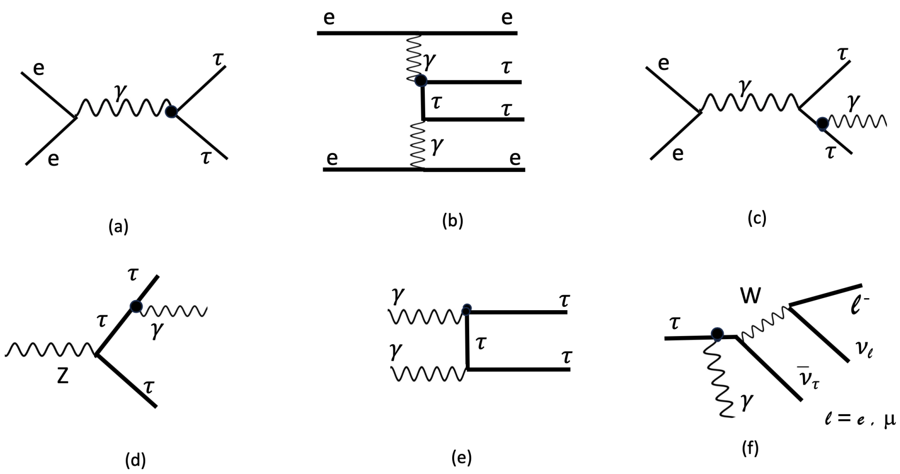

Figure 1: Some processes where the τ dipole moments may contribute.

decay widths, shown in this figure in (a) $\sigma(e^+e^- \to \tau^+\tau^-)$, (b) $\sigma(e^+e^- \to \tau^+\tau^-e^+e^-)$, (c) $\sigma(e^+e^- \to \tau^+\tau^-\gamma)$, (d) $\Gamma(Z \to \tau^+\tau^-\gamma)$, (e) $\sigma(\gamma\gamma \to \tau^+\tau^-)$, (f) $\Gamma(\tau \to l^+\nu_\tau\bar{\nu}_l\gamma)$ for example. These were studied or proposed for experiments at PETRA, LEP, LEP2, BABAR, BELLE, BELLE2, and the LHC (see, for example, [9–11]). On the other hand, CP-odd observables proportional to the tau-EDM can be studied in tau-pair production by a s-channel photon diagram. These can be analyzed in the spin terms (spin linear or spin-spin correlation terms) that modify the angular distributions of the decay products, or in expectation values of triple spin-momentum observables. The latter were used by K.Imani at BELLE following the ideas in [9]. It is expected that the high statistics from B-factories will allow for better bounds on the tau EDM, potentially reaching levels where some BSM physics might be detectable.

3 Tau Magnetic Dipole Moment

The first-order leading contribution in QED [3] for the electron magnetic moment anomaly, leads to the flavor-independent expression:

$$a = \frac{g-2}{2} = \frac{\alpha}{2\pi} \simeq 0.00116. \tag{6}$$

This computation was updated in [12] for the tau, including weak and hadronic contributions:

$$a_\tau = 117721(5) \times 10^{-8}. \tag{7}$$

The PDG bound for the tau anomaly is $-0.052 < a_\tau < 0.013\,(95\%\,CL)$. This value, taken from [13] more than two decades ago, was obtained from total cross-section data, such as the one in fig. 1 (a) for DELPHI. Other processes, as shown in fig. 1, were also considered by other authors to set bounds on the tau anomaly. In [14], a global and model-independent analysis through effective lagrangians of SLD and LEP data shows that a stringent bound for BSM contributions to the tau magnetic anomaly can be obtained: $-0.007 < a_\tau^{BSM} < 0.005\,(2\sigma)$. The case for the tau anomaly is very different from that of the electron or muon. While the SM theoretical prediction is also well-known, the experimental precision for the tau anomaly is still lacking, and even the sign is unknown. The tau promptly decays, and it is through the angular distribution of the secondary particles of the decay that the anomaly can be traced back. Generally, total cross-section may provide an indirect bound on the anomaly. Moreover, spin or spin-spin correlations terms in the final tau pairs could serve as sensitive observables for detecting the tau anomaly. Several of the studied observables do not have all three particles on-shell. This means that what is actually being measured or bound is not the SM prediction, where both τ and photon are on-shell, but a bound on possible BSM contributions to the form factor of this off-shell vertex. Furthermore, it is usually assumed that not all the form factors that parameterize this off-shell vertex are considered. More recently, proposals for many colliders, particularly for B-factories experiments have been put forward. For example, in [15,16], it was shown that the QED magnetic form factor for $q^2 = M_\Upsilon^2$ can be obtained from asymmetries constructed with longitudinal and transverse polarizations of the produced taus for polarized beams. All these studies have been considered in [17], which shows that feasible BSM values of the tau anomaly at the level 10^{-6} could be probed with a polarization upgrade of SuperKEKB.

4 Conclusion

Tau DMs remain an attractive area of research, with potential new results expected in the near future. Recent experiments related to the electric DM have shown improvement due to the high-statistics data from B-factories. For the tau magnetic anomaly, the experimental limits are still orders of magnitude above the SM prediction, and even the sign of the tau anomaly remains unknown. The magnetic DM experiments are making progress, and new experimental ideas are emerging. Accessing the $q^2 = 0$ SM prediction is challenging due to the very short lifetime of the tau-lepton. However, for $q^2 \simeq M_\Upsilon^2$ at B-factories, some promising ideas may help to establish bounds on the magnetic form factor at B-factories at levels where BSM effects could appear. As Martin Perl [18] stated many decades ago in *Dreams and odd ideas in tau research*: "... It would be very nice to measure μ_τ with enough precision to check this (*the Schwinger term* $\alpha/2\pi$), as it was checked for the e and the μ years ago. At present such precision is a dream." The tau DMs may still yield impressive results due to the BSM physics sensitivity to this high-mass lepton and to the high statistics available from colliders experiments.

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