Sensitivity on the electromagnetic dipole moments of the tau-lepton at the CLIC

M. A. Hernández-Ruíz[1*], A. A. Billur[2], M. Köksal[3] and A. Gutiérrez-Rodríguez[4]

1 Unidad Académica de Ciencias Químicas, Universidad Autónoma de Zacatecas,
Apartado Postal C-585, 98060 Zacatecas, México.
2 Deparment of Physics, Cumhuriyet University, 58140, Sivas, Turkey.
3 Deparment of Optical Engineering, Cumhuriyet University, 58140, Sivas, Turkey.
4 Unidad Académica de Física, Universidad Autónoma de Zacatecas,
Apartado Postal C-580, 98060 Zacatecas, México.
* mahernan@uaz.edu.mx

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Abstract

In this paper we established model independent bounds on the anomalous magnetic and electric dipole moments of the tau-lepton using the process $\gamma\gamma \to \tau^+\tau^-$. We use data collected with the future e^+e^- linear collider such as the CLIC at $\sqrt{s} = 380, 1500, 3000$ GeV, and we consider systematic uncertainties of $\delta_{\rm sys} = 0\%, 3\%, 5\%$. The theory predictions are a very good prospect for probing the dipole moments of the tau-lepton at the future e^+e^- linear collider at the $\gamma\gamma$ mode.

Contents

1 Introduction

In this work, using $\gamma\gamma \to \tau^+\tau^-$ reaction we establish model independent sensitivity estimates on the dipole moments a_τ and d_τ of the tau-lepton. The high center-of-mass energies what has been proposed for the Compact Linear Collider (CLIC) make it an appropriate machine to probe the anomalous magnetic (MM) and electric dipole (EDM) moments which are more sensitive to the high energy and high luminosity of the collider. The CLIC is a proposed future e^+e^- collider, designed to fulfill e^+e^- collision at center-of-mass energies of 0.35 TeV, 1.4 TeV and 3 TeV planned to be constructed with a three main stage research region. This enables the investigation of de $\gamma\gamma$ and $e\gamma$ interactions by converting the original e^- or e^+ beam into a photon beam through the Compton back-scattering mechanism.

For our study we consider the following parameters of the CLIC: $\sqrt{s} = 380, 1500, 3000$ GeV, $\mathcal{L} = 10, 50, 100, 300, 500, 1000, 1500, 2000, 3000$ fb^{-1}, with systematic uncertainties of $\delta_{sys} = 0\%, 3\%, 5\%$. We obtain strong sensitivity in comparison to the bounds given by the DELPHI, L3, OPAL, BELLE, and ARGUS Collaborations [1, 2, 3, 4, 5].

This paper is organized as follows: In Section 2, we present the total cross section and the electromagnetic dipole moments of the tau-lepton for the $\gamma\gamma \to \tau^+\tau^-$ reaction. In section 3, the results. In section 4, we give our conclusion.

2 The process $\gamma\gamma \to \tau^+\tau^-$

To calculate the $\gamma\gamma \to \tau^+\tau^-$ total cross section, the corresponding Feynman diagrams are given in Fig. 1. We determine sensitivity estimates on the electromagnetic dipole moments of the tau-lepton a_τ and d_τ via the two-photon process [6]. The future Collider CLIC can produce very hard photons at high luminosity in Compton backscattering of laser light off high energy e^+e^- beams.

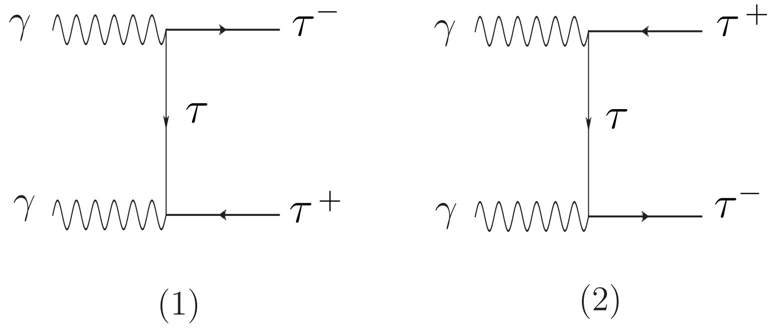

Figure 1: The Feynman diagrams for the process $\gamma\gamma \to \tau^+\tau^-$.

The electromagnetic current between on-shell tau-lepton and the photon is given by [7, 8, 9, 10]

$$\begin{aligned}\Gamma^\alpha_\tau &= eF_1(q^2)\gamma^\alpha + \frac{ie}{2m_\tau}F_2(q^2)\sigma^{\alpha\mu}q_\mu + \frac{e}{2m_\tau}F_3(q^2)\sigma^{\alpha\mu}q_\mu\gamma_5 \\ &\quad + eF_4(q^2)\gamma_5\left(\gamma^\alpha - \frac{2q^\alpha m_\tau}{q^2}\right), \end{aligned} \tag{1}$$

where the q^2-dependent form factors $F_{1,2,3,4}(q^2)$ have interpretations for $q^2 = 0$: $F_1(0) =$

Q_τ is the electric charge; $F_2(0) = a_\tau$ is anomalous MM and $F_3(0) = \frac{2m_\tau}{e} d_\tau$ with d_τ the EDM. $F_4(q^2)$ is the anapole form factor. Here, e is the charge of the electron, m_τ is the mass of the tau-lepton, $\sigma^{\alpha\mu} = \frac{\mathbf{i}}{\mathbf{2}}[\gamma^\alpha, \gamma^\mu]$ represents the spin 1/2 angular momentum tensor, and $q = p' - p$ is the momentum transfer.

The spectrum of Compton backscattered photons to the process $\gamma\gamma \to \tau^+\tau^-$ is given by

$$f_\gamma(y) = \frac{1}{g(\zeta)}[1 - y + \frac{1}{1-y} - \frac{4y}{\zeta(1-y)} + \frac{4y^2}{\zeta^2(1-y)^2}], \tag{2}$$

where

$$g(\zeta) = (1 - \frac{4}{\zeta} - \frac{8}{\zeta^2}) \log{(\zeta + 1)} + \frac{1}{2} + \frac{8}{\zeta} - \frac{1}{2(\zeta+1)^2}, \tag{3}$$

and

$$y = \frac{E_\gamma}{E_e}, \qquad \zeta = \frac{4E_0 E_e}{M_e^2}. \tag{4}$$

E_0 is energy of the incoming laser photon while for E_e is initial energy of the electron beam before Compton backscattering, and E_γ is the energy of the backscattered photon.

The total cross section can be written as,

$$\sigma = \int f_\gamma(x) f_\gamma(x) d\hat{\sigma} dE_1 dE_2, \tag{5}$$

where E_1 and E_2 is the energy of the particles of the final state.

Now, we present the total cross section as a polynomial in powers of F_2 and F_3 for the process $\gamma\gamma \to \tau^+\tau^-$. The formulas have been obtained with the help of the package CALCHEP [11], which can computate the Feynman diagrams, integrate over multiparticle face space and event simulation.

- For $\sqrt{s} = 380\, GeV$.

$$\begin{aligned} \sigma(F_2) &= \big[(9914034)F_2^4 + (81889)F_2^3 + (81382)F_2^2 + (111)F_2 + 38.75\big](pb), \\ \sigma(F_3) &= \big[(9736246)F_3^4 + (82619)F_3^2 + 38.75\big](pb). \end{aligned} \tag{6}$$

- For $\sqrt{s} = 1500\, GeV$.

$$\begin{aligned} \sigma(F_2) &= \big[(1.54 \times 10^8)F_2^4 + (84288)F_2^3 + (88058)F_2^2 + (17.5)F_2 + 6\big](pb), \\ \sigma(F_3) &= \big[(1.54 \times 10^8)F_3^4 + (88124)F_3^2 + 6\big](pb). \end{aligned} \tag{7}$$

- For $\sqrt{s} = 3000\, GeV$.

$$\begin{aligned} \sigma(F_2) &= \big[(6.17 \times 10^8)F_2^4 + (91348)F_2^3 + (87216)F_2^2 - (1.21)F_2 + 1.97\big](pb), \\ \sigma(F_3) &= \big[(6.17 \times 10^8)F_3^4 + (88327)F_3^2 + 1.97\big](pb). \end{aligned} \tag{8}$$

3 Bounds on the a_τ and d_τ through $\gamma\gamma \to \tau^+\tau^-$ at the CLIC

We now proceed with our numerical analysis of the total cross section $\sigma_{NP}(\gamma\gamma \to \tau^+\tau^-) = \sigma_{NP}(\sqrt{s},\ F_2,\ F_3)$, as well as of the electromagnetic dipole moments of the tau-lepton, here the free parameters are $\sqrt{s}$, $\mathcal{L}$, F_2 and F_3. For this purpose, we use the usual formula for the χ^2 function [12, 13, 14, 15]:

$$\chi^2 = \left(\frac{\sigma_{SM} - \sigma_{NP}(\sqrt{s}, F_2, F_3)}{\sigma_{SM}\delta}\right)^2, \tag{9}$$

$\sigma_{NP}(\sqrt{s}, F_2, F_3)$ is the total cross section which includes contributions to the SM and new physics, $\delta = \sqrt{(\delta_{st})^2 + (\delta_{sys})^2}$, $\delta_{st} = \frac{1}{\sqrt{N_{SM}}}$ is the statistical error, δ_{sys} is the systematic error and N_{SM} is the number of signal expected events $N_{SM} = \mathcal{L}_{int} \times BR \times \sigma_{SM}$, $\mathcal{L}_{int}$ is the integrated CLIC luminosity.

4 Results

In this section we presented a set of figures, which illustrate our results. The total cross sections $\sigma_{\gamma\gamma\to\tau^+\tau^-}(\sqrt{s}, F_2, F_3)$ are calculated as a function of the anomalous couplings F_2 and F_3 with the center-of-mass energies of $\sqrt{s} = 380$ GeV, $\sqrt{s} = 1500$ GeV and $\sqrt{s} = 3000$ GeV. The total cross section shows a strong dependence on the anomalous paramaters F_2, F_3, and the center-of-mass energy of the collider $\sqrt{s}$ as they are show in Figures 2-4.

Figures 5-7 indicate allowed regions at 95% C.L. in the plane $(F_2 - F_3)$ for the process $\gamma\gamma \to \tau^+\tau^-$ during the first, second and third stage of operation of the CLIC, where assumed fixed center-of-mass energies are $\sqrt{s} = 380$ GeV, $\sqrt{s} = 1500$ GeV, and $\sqrt{s} = 3000$ GeV with luminosities $\mathcal{L} = 10\, fb^{-1}$, $\mathcal{L} = 100\, fb^{-1}$, and $\mathcal{L} = 500\, fb^{-1}$, in Figure 5; likewise $\mathcal{L} = 100 fb^{-1}$, $\mathcal{L} = 500 fb^{-1}$, and $\mathcal{L} = 1500 fb^{-1}$ in Figure 6; while, $\mathcal{L} = 100 fb^{-1}$, $\mathcal{L} = 500 fb^{-1}$, $\mathcal{L} = 3000 fb^{-1}$ in Figure 7, and systematic uncertainties of $\delta_{sys} = 0\%, 3\%, 5\%$ [1, 16].

These results that we get for the process $\gamma\gamma \to \tau^+\tau^-$ at the CLIC indicate the improved sensitivity on anomalous electromagnetic dipole moments of tau-lepton with respect to the existing experimental bounds by two orders of magnitude. The best sensitivities obtained on a_τ and d_τ are $-0.00012 \leq a_\tau \leq 0.00014$ and $|d_\tau(ecm)| = 7.445 \times 10^{-19}$ [6].

Furthermore, there has been extensive theoretical work done in new physics beyond de Standard Model that contributes to dipole moments of tau-lepton: Left-right symmetric model [17], E_6 superstring models [18], simplest little Higgs model [19], and 331 model [20]. Other limits on the MM and EDM of the τ-lepton are reported in Refs. [12, 13, 14, 21, 22, 23, 24, 25].

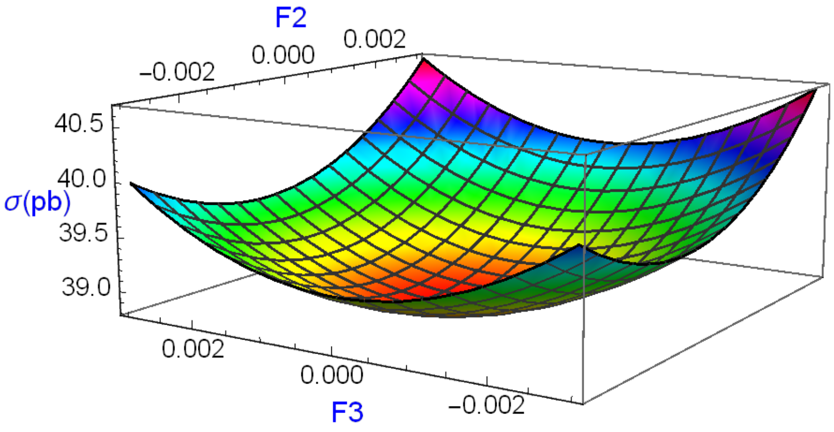

Figure 2: The total cross sections of the process $\gamma\gamma \to \tau^+\tau^-$ as a function of F_2 and F_3 for center-of-mass energy of $\sqrt{s} = 380$ GeV.

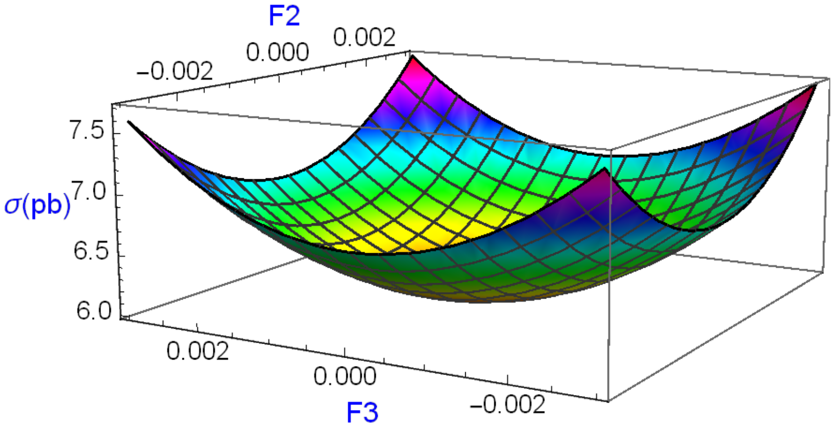

Figure 3: The same as in Figure 2, now for $\sqrt{s} = 1500$ GeV.

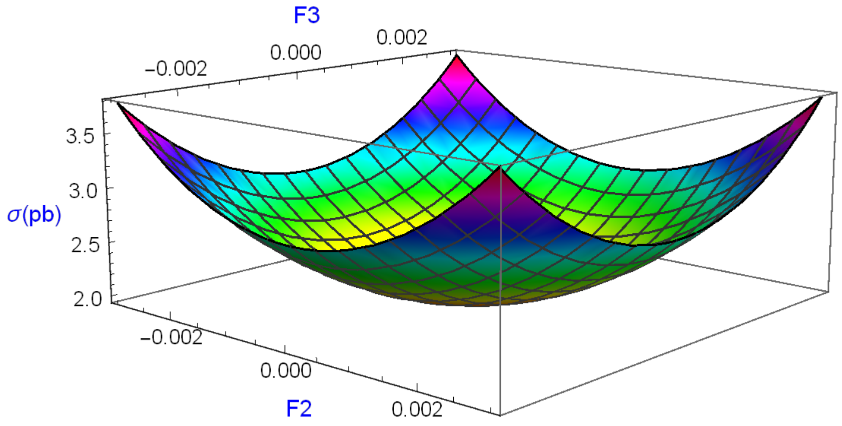

Figure 4: The same as in Figure 3, now for $\sqrt{s} = 3000$ GeV.

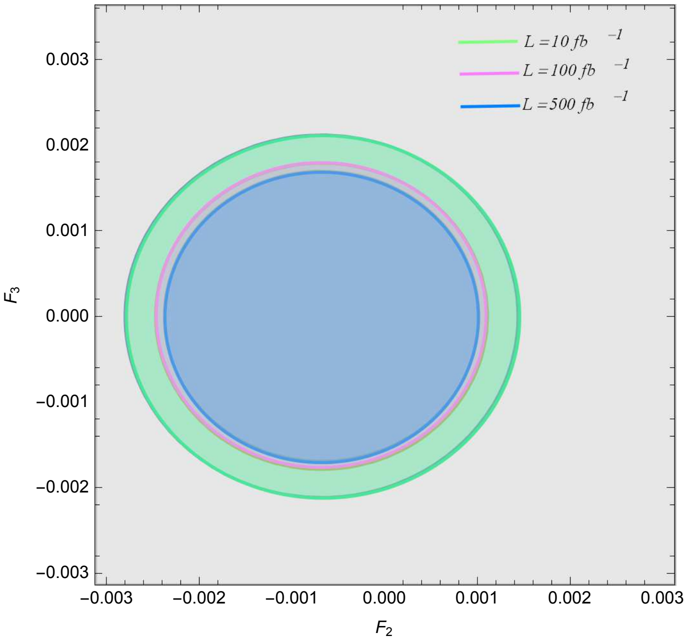

Figure 5: Bounds contours at the 95% C.L. in the $(F_2 - F_3)$ plane for the process $\gamma\gamma \to \tau^+\tau^-$ with the $\mathcal{L} = 10, 100, 500\, bf^{-1}$ and for center-of-mass energy of $\sqrt{s} = 380$ GeV.

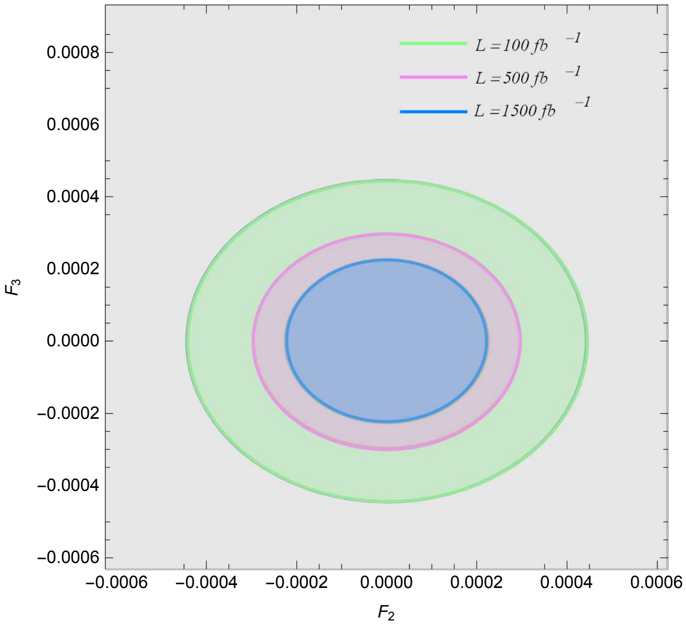

Figure 6: The same as in Figure 5, now for $\mathcal{L} = 100, 500, 1500\, bf^{-1}$ and for center-of-mass energy of $\sqrt{s} = 1500$ GeV.

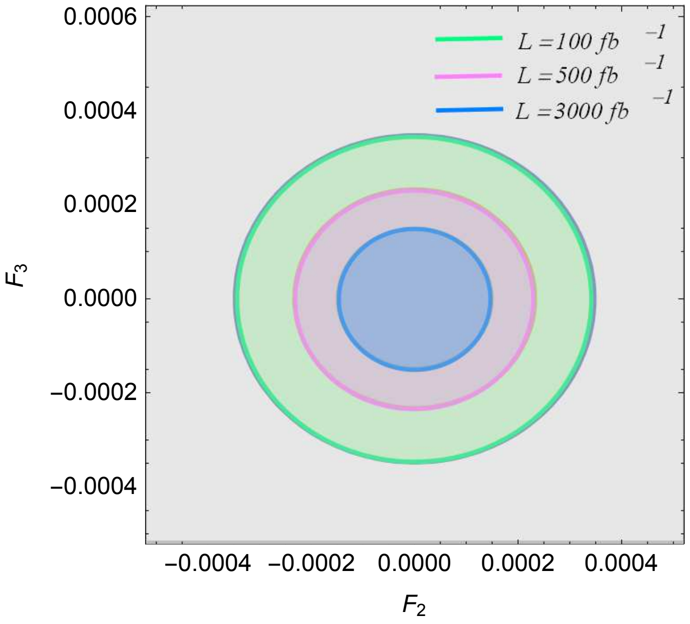

Figure 7: The same as in Figure 6, now for $\mathcal{L} = 100, 500, 3000\, bf^{-1}$ and for center-of-mass energy of $\sqrt{s} = 3000$ GeV.

5 Conclusion

In conclusion, we have shown that the $\gamma\gamma \to \tau^+\tau^-$ process at the CLIC leads to an improvement in the existing sensitivity estimates on the a_τ and d_τ. We present an optimistic scenario regarding the potencial precision, energy, and luminosity that may be achievable at the future e^+e^- colliders. Our results for the process $\gamma\gamma \to \tau^+\tau^-$ at the CLIC could improve the sensitivity on anomalous electromagnetic dipole moments of τ-lepton with respect to the existing experimental bounds (see Table I in Ref. [6]) by 2 orders of magnitude. The best sensitivities obtained on $\tilde{a}_\tau$ and $\tilde{d}_\tau$ were $-0.00015 \leq \tilde{a}_\tau \leq 0.00017$ and $|\tilde{d}_\tau| = 9.040 \times 10^{-19}$, respectively, as shown in Tables III-V in Ref. [6]. These are compared with experimental results of earlier studies for a linear collider as published by the DELPHI and BELLE Collaborations [1, 4].

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