Possibility of Determining $\tau$ Lepton Electromagnetic Moments in $\gamma\gamma \rightarrow \tau^+\tau^-$ Process at the CERN-LHC

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Abstract: Potential of the LHC to determine the electromagnetic couplings of the $\tau$ lepton is discussed via the process $\gamma\gamma \rightarrow \tau^+\tau^-$. Highly improved constraints of the anomalous magnetic and electric dipole moments have been obtained compared to the LEP sensitivity.

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1. Introduction

The magnetic moment of the electron which is responsible for the interaction with the magnetic field in the Born approximation can be written in the standard form

\[ \vec{\mu} = g \left( \frac{e \hbar}{2 m c} \right) \vec{s} \]  

(1.1)

where \( \vec{s} \), \( e \) and \( m \) is the spin, electric charge and mass of the electron. The coefficient \( g \) is called the Lande g-factor or gyromagnetic factor. Standard prediction of the Dirac equation gives \( g = 2 \). Deviation from the Dirac value

\[ a_e = \left( g - 2 \right)/2 \]  

(1.2)

is known as the anomalous magnetic moment. The first result for the anomalous magnetic moment of the electron was calculated from Quantum Electrodynamics (QED) using radiative corrections by Schwinger in 1948 as \( a_e = \frac{\alpha}{2\pi} \). From that time, physicists have improved successively the accuracy of this quantity both in the theoretical and experimental point of views. These works have provided the stringent tests of QED and have lead to the precise determination of the fine structure constant \( \alpha \) based on the fact that \( a_e \) is insensitive to the weak and strong interactions. Similar studies have been done for muons. Since the higher loop corrections are mass dependent, the \( a_\mu \) is expected to include weak and hadronic contributions. This offers a sensitivity to new physics by a relative enhancement factor of \( (m_\mu/m_e)^2 \sim 4 \times 10^4 \) than to the case of \( a_e \). Several detailed Standard Model tests have been done using the accurate value of the anomalous magnetic moment of the muon \([3]\). Anomalous magnetic moment \( a_\tau \) of \( \tau \) lepton would be much better to constrain the new physics due to its large mass. However, spin precession experiment is not convenient to make a direct measurement for \( a_\tau \) at present because of its short lifetime. So we need collider experiments with high accuracy to produce \( \tau \) lepton. Latest QED contribution to the anomalous magnetic moment \( a_\tau \) from higher loop corrections is given by the following theoretical result \([3]\).
\[ a_\tau^{QED} = 117324 \times 10^{-8} \]  

with the uncertainty \( 2 \times 10^{-8} \). The experimental limits at 95\% CL were obtained by L3 and OPAL collaborations in radiative \( Z \rightarrow \tau\tau\gamma \) events at LEP \footnote{4, 5}.

\[-0.052 < a_\tau < 0.058 \quad \text{(L3)} \]  
\[-0.068 < a_\tau < 0.065 \quad \text{(OPAL)} \]  

and later by DELPHI Collaborations \footnote{6} based on the process \( e^+e^- \rightarrow e^+e^-\tau^+\tau^- \)

\[-0.052 < a_\tau < 0.013 \quad \text{(1.6)} \]  

It is clear that we need at least one order of magnitude improvement to determine \( a_\tau \).

In the coupling of \( \tau \) lepton to a photon, another interesting contribution is the CP violating effects which create electric dipole moment. CP violation has been observed in the system of \( K^0 \) mesons \footnote{9}. This phenomenon has been described within the SM by the complex couplings in the Cabibbo-Kobayashi-Maskawa (CKM) matrix of the quark sector \footnote{10}. Actually, there is no CP violation in the leptonic couplings in the SM. In spite of that, CP violation in the quark sector induces electric dipole moment of the leptons in the three loop level \footnote{11}. This contribution of the SM to the electric dipole moment of the leptons can be shown to be too small to detect. Another source of CP violating coupling of leptons comes from the neutrino mixing if neutrinos are massive \footnote{12}. It is also shown that this kind of CP violation is undetectable through the electric dipole moment of the \( \tau \) lepton. Supersymmetry (SUSY) \footnote{13}, more Higgs multiplets \footnote{14}, left-right symmetric models \footnote{15} and leptoquarks \footnote{16} are expected to be the sources of the CP violation. Some loop diagrams are proportional to the fermion masses which make the \( \tau \) the most sensitive lepton to the CP violation. Therefore, larger effects may arise from the physics beyond the SM. Only upper limits on the electric dipole moment of the \( \tau \) lepton have been obtained so far from the experiments at 95\%CL \footnote{4, 5, 6}.

\[ |d_\tau| < 3.1 \times 10^{-16} \text{ e cm (L3)} \]  
\[ |d_\tau| < 3.7 \times 10^{-16} \text{ e cm (OPAL)} \]  
\[ |d_\tau| < 3.7 \times 10^{-16} \text{ e cm (DELPHI)} \]  

More stringent limits were set by BELLE \footnote{17}.

\[-0.22 < Re(d_\tau) < 0.45 \times 10^{-16} \text{ e cm} \]  
\[-0.25 < Im(d_\tau) < 0.08 \times 10^{-16} \text{ e cm} \]  

There are more articles providing limits from previous LEP results \footnote{7} or obtained by using some indirect methods and early study in heavy ion collision \footnote{8}.
Couplings of τ lepton to a photon can be parametrized by replacing the pointlike factor $\gamma^\mu$ by $\Gamma^\mu$ as follows \[18\]

$$\Gamma^\mu = F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i}{2m_\tau}\sigma^{\mu\nu} q_\nu + F_3(q^2)\frac{1}{2m_\tau}\sigma^{\mu\nu} q_\nu \gamma^5$$

where $F_1(q^2)$, $F_2(q^2)$ and $F_3(q^2)$ are form factors related to electric charge, anomalous magnetic dipole moment and electric dipole moment. $q$ is defined as the momentum transfer to the photon and $\sigma^{\mu\nu} = \frac{i}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$. Asymptotic values of the form factors, in the limiting case $q^2 \rightarrow 0$, are called moments describing the static properties of the fermions

$$F_1(0) = 1, \quad a_\tau = F_2(0), \quad d_\tau = \frac{e}{2m_\tau}F_3(0)$$ \[1.13\]

In the next section, we give some details of the equivalent photon approximation and forward detector physics at LHC. Then we study the sensitivity of the process $pp \rightarrow pp\tau^+\tau^-$ to the anomalous electromagnetic moments of the τ lepton via the subprocess $\gamma\gamma \rightarrow \tau^+\tau^-$. 

2. $\gamma\gamma$ Scattering at LHC

Two photon scattering physics at Large Hadron Collider (LHC) is becoming interesting as an additional tool to search for physics in Standard Model (SM) or beyond it. Forward detectors at ATLAS and CMS are developed to detect the particles not detected by the central detectors with a pseudorapidity $\eta$ coverage 2.5 for tracking system and 5.0 for calorimetry. In many cases, the elastic scattering and ultraperipheral collisions are out of the central detectors. According to the program of ATLAS and CMS Collaborations forward detectors will be installed in a region nearly 100m-400m from the interaction point \[19\]. With these new equipments, it is aimed to investigate soft and hard diffraction, low-x dynamics with forward jet studies, high energy photon induced interactions, large rapidity gaps between forward jets, and luminosity monitoring \[19, 20, 21\]. These dedicated detectors may tag protons with energy fraction loss $\xi = E_{\text{loss}}/E_{\text{beam}}$ far away from the interaction point. This nice property allows for high energy photon induced interactions with exclusive final states in the central detectors. In the recent program of ATLAS and CMS, the positions of the forward detectors are planned to give an overall acceptance region of $0.0015 < \xi < 0.5$ \[22, 23\]. Closer location of the forward detectors to interaction point leads to higher $\xi$. Almost real photons are emitted by each proton and interact each other to produce exclusive final states. In this work, we are interested in the τ lepton pair in the final states $\gamma\gamma \rightarrow \tau^+\tau^-$. Deflected protons and their energy loss will be detected by the forward detectors far away from the interaction point as mentioned above. Final τ leptons with rapidity $|\eta| < 2.5$ and $p_T > 20$GeV will be identified by the central detector. Photons emitted with small angles by the protons show a spectrum of virtuality $Q^2$ and energy $E_\gamma$. In order to handle this kind of processes equivalent photon approximation \[24, 23\] is used. The proton-proton case differs from the pointlike electron-positron case by including the electromagnetic form factors in the equivalent photon spectrum and effective $\gamma\gamma$ luminosity.
$$dN = \frac{\alpha}{\pi} \frac{dE_\gamma}{E_\gamma} \frac{dQ^2}{Q^2} [ (1 - \frac{E_\gamma}{E})(1 - \frac{Q^2_{\text{min}}}{Q^2}) ] F_E + \frac{E^2}{2E^2} F_M$$  \hspace{1cm} (2.1)$$

where

$$Q^2_{\text{min}} = \frac{m_p^2 E^2_\gamma}{E(E - E_\gamma)} , \quad F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2}  \hspace{1cm} (2.2)$$

$$G_E^2 = \frac{G_M^2}{\mu_p^2} = (1 + \frac{Q^2}{Q_0^2})^{-4}, \quad F_M = G_M^2, \quad Q_0^2 = 0.71 \text{GeV}^2  \hspace{1cm} (2.3)$$

Here $E$ is the energy of the proton beam which is related to the photon energy by $E_\gamma = \xi E$ and $m_p$ is the mass of the proton. The magnetic moment of the proton is $\mu_p^2 = 7.78$, $F_E$ and $F_M$ are functions of the electric and magnetic form factors. The integration of the subprocess $\gamma\gamma \rightarrow \tau^+\tau^-$ over the photon spectrum is needed

$$d\sigma = \int dL_{\gamma\gamma} d\sigma_{\gamma\gamma \rightarrow \tau\tau}(W) dW$$  \hspace{1cm} (2.4)$$

where the effective photon luminosity $dL_{\gamma\gamma}/dW$ is given by

$$dL_{\gamma\gamma}/dW = \int_{Q^2_{\text{min}}}^{Q^2_{\text{max}}} dQ_1^2 \int_{Q^2_{\text{min}}}^{Q^2_{\text{max}}} dQ_2^2 \int_{y_{\text{min}}}^{y_{\max}} dy \frac{W}{2y} f_1 \left( \frac{W^2}{4y}, Q_1^2 \right) f_2(y, Q_2^2).  \hspace{1cm} (2.5)$$

with

$$y_{\text{min}} = \text{MAX}(W^2/(4\xi_{\text{max}} E), \xi_{\text{min}} E), \quad y_{\max} = \xi_{\text{max}} E, \quad f = \frac{dN}{dE_\gamma dQ^2}.  \hspace{1cm} (2.6)$$

Here $W$ is the invariant mass of the two photon system $W = 2E\sqrt{\xi_1 \xi_2}$ and $Q^2_{\text{max}}$ is the maximum virtuality. Behaviour of the effective $\gamma\gamma$ luminosity is shown in Fig.4 as a function of the invariant mass of the two photon system. $Q^2_{\text{max}}$ dependence of the effective $\gamma\gamma$ luminosity will not be separable in Fig.4 between $Q^2_{\text{max}} = (1 - 4)$ GeV$^2$. This is due to electromagnetic dipole form factors of the protons which are steeply falling as a function of $Q^2$. This causes very slow increase in $\gamma\gamma$ luminosity as $Q^2_{\text{max}}$ increases. This is explicitly shown in Table 4 where the cross sections are calculated in the next section. From Table 4 we see that $Q^2_{\text{max}}$ dependence does not create considerable uncertainty. Thus, it is reasonable to take $Q^2_{\text{max}}$ as (1-2)GeV$^2$.

There are experimental uncertainties in the dipole form factors in Eq. (2.3). In Ref. 20 these uncertainties are given for the region $Q^2 = 0.007 - 5.850 \text{ GeV}^2$. The change in the photon flux $f(E_\gamma, Q^2)$ from the uncertainties in the electric and magnetic form factors can be calculated with the help of the expression below
Figure 1: Effective $\gamma\gamma$ luminosity as a function of the invariant mass of the two photon system.

![Graph showing $\gamma\gamma$ luminosity vs. W(GeV)](image)

Table 1: $Q^2_{max}$ dependence of the cross sections with equivalent photon approximation for the process $pp \rightarrow p\tau^+\tau^-p$ without anomalous couplings of tau lepton. Two intervals of forward detector acceptance $\xi$ are considered. For $Q^2_{max} = (1 - 4) GeV^2$ the cross sections do not change appreciably.

| $Q^2_{max}$ (GeV$^2$) | $\sigma^0$(fb) | $\sigma^0$(fb) |
|-----------------------|----------------|----------------|
|                       | $0.0015 < \xi < 0.5$ | $0.01 < \xi < 0.15$ |
| 0.5                   | 167.6          | 10.4           |
| 0.8                   | 171.3          | 10.7           |
| 1.0                   | 172.3          | 10.8           |
| 1.5                   | 173.3          | 10.9           |
| 1.8                   | 173.5          | 10.9           |
| 2.0                   | 173.6          | 10.9           |
| 3.0                   | 173.8          | 11.0           |
| 4.0                   | 173.8          | 11.0           |

Table 1: $Q^2_{max}$ dependence of the cross sections with equivalent photon approximation for the process $pp \rightarrow p\tau^+\tau^-p$ without anomalous couplings of tau lepton. Two intervals of forward detector acceptance $\xi$ are considered. For $Q^2_{max} = (1 - 4) GeV^2$ the cross sections do not change appreciably.

$$\delta f = \sqrt{\left(\frac{\partial f}{\partial G_E}\delta G_E\right)^2 + \left(\frac{\partial f}{\partial G_M}\delta G_M\right)^2}$$  \hspace{1cm} (2.7)$$

Using some of the uncertainties in Ref. [26] we obtain relative changes in the photon flux $\delta f/f$. The results are shown in Table 2 for two photon energies. The uncertainty in the photon flux from both protons leads to the relative uncertainty in the cross section $\delta\sigma/\sigma$ around 0.03 on the average depending on the photon energy for the process $pp \rightarrow p\tau^+\tau^-p$ with $Q^2_{max} = 2 GeV^2$. 


Let us discuss briefly bremsstrahlung lepton pair production which is one of the possible backgrounds to the equivalent photon approximation. In this process, there are a virtual photon exchange between the two protons and one bremsstrahlung photon emitted by one of the protons. The bremsstrahlung photon creates a lepton pair. The square of the matrix element includes electromagnetic form factors in each of the photon-proton vertex which are given in Ref. [27]

\[ |M_{ij}|^2 \rightarrow |M_{ij}|^2 |F_A(q_1^2)|^2 |F_B(q_1^2)|^2 |F_T(q_2^2)|^2 \]

(2.8)

where \( q_1 \) is the momentum transfer between two protons and \( q_2 \) is identical to the momentum of the lepton pair. \( F_A(q_1^2), F_B(q_1^2) \) are elastic form factors in the space-like region and \( F_T(q_2^2) \) is the form factor in the time-like region. If we have high \( q_2^2 \) the form factor \( |F_T(q_2^2)|^2 \) will suppress the cross section based on the fact that the large \( q^2 \) form factors behave like \( 1/q^4 \). In our work, as will be seen in the next section, each tau lepton in the final state has \( p_T > 20 \text{ GeV} \). Therefore the minimum \( q_2^2 \) value is \( 4(m_\tau^2 + p_T^2) = 1612 \text{ GeV}^2 \) which makes the cross section for the bremsstrahlung tau pair production completely negligible.

Two photon exchange interactions with invariant diphoton mass \( W > 1 \text{ TeV} \) are highly interesting to probe more accurate values of the SM parameters and also deviations from SM with available luminosity.

3. Cross Sections And Sensitivity

There are t and u channels Feynman diagrams of the subprocess \( \gamma\gamma \rightarrow \tau^+\tau^- \) where both vertices contain anomalous couplings. The squared amplitude can be written in terms of the following reduced amplitudes,

\[
A_1 = \frac{1}{2m^4} \left[ 48F_1^3 F_2 (m^2 - \hat{t})(m^2 + \hat{s} - \hat{t})m^4 - 16F_1^4 (3m^4 - \hat{s}m^2 + \hat{t}(\hat{s} + \hat{t}))m^4 
+ 2F_2^2 (m^2 - \hat{t})(F_2^2 (17m^4 + (22\hat{s} - 26\hat{t}))m^2 + \hat{t}(9\hat{t} - 4\hat{s})) \right]
\]

Table 2: Relative change in the photon flux \( \delta f/f \) due to the experimental uncertainties in dipole form factors. Values in the middle three columns are taken from Ref. [26].
\[ + F_3^2(17m^2 + 4s - 9t)(m^2 - t)m^2 + 12F_1F_2(F_2^2 + F_3^2)s(m^3 - mt) - (F_2^2 + F_3^2)^2(m^2 - t)^2(m^2 - s - t) \] (3.1)

\[ A_2 = \frac{1}{2m_t} \left[ 48F_1^3F_2(m^4 + (s - 2t)m^2 + t(s + t))m^4 + 16F_1^4(7m^4 - (3s + 4t)m^2 + t(s + t))m^4 + 2F_1^2(m^2 - t)(F_2^2(m^4 + (17s - 10t)m^2 + 9t(s + t)) + F_2^2(m^2 - 9t)(m^2 - t - s)m^2 + (F_2^2 + F_3^2)^2(m^2 - t)^3(m^2 - s - t) \right] \] (3.2)

\[ A_{12} = \frac{1}{m^2} \left[ -16F_1^4(4m^6 - m^4) + 8F_1^3F_2m^2(6m^4 - 6m^2(s + 2t) - s)^2 + 6t)^2 + 6st \right] + F_2^2(16m^6 - m^4)(15s + 32t) + m^2(-15s^2 + 14ts + 16t^2) + 6t(s + t) + F_3^2(16m^6 - m^4)(15s + 32t) + m^2(-5s^2 + 14ts + 16t^2) + 6t(s + t)) - 4F_1F_2(F_2^2 + F_3^2)s(m^4 + m^2(s - 2t) + 6t(s + t)) - 4F_3(F_2^2 + F_3^2)(2m^2 - s - 2t)\epsilon_{\mu\nu\rho\sigma}\rho_\mu\rho_\nu\rho_\sigma\rho_\nu - 2(F_2^2 + F_3^2)^2s(m^4 - 2tm^2 + 6(s + t)) \] (3.3)

where \( p_1, p_2, p_3 \) and \( p_4 \) are the momenta of the incoming photons and final \( \tau \) leptons. Mandelstam variables are defined as \( s = (p_1 + p_2)^2, t = (p_1 - p_3)^2 \) and \( u = (p_1 - p_4)^2 \). \( m \) is the \( \tau \) lepton mass. The squared amplitudes are

\[ |M_1|^2 = \frac{16\pi^2\alpha^2}{(t - m^2)^2}A_1 \] (3.4)

\[ |M_2|^2 = \frac{16\pi^2\alpha^2}{(u - m^2)^2}A_2 \] (3.5)

\[ |M_{12}|^2 = \frac{16\pi^2\alpha^2}{(t - m^2)(u - m^2)}A_{12} \] (3.6)

The cross section for the process \( pp \to pp\tau^+\tau^- \) without anomalous couplings is given in Table 3 at the LHC energy \( \sqrt{s} = 14 \text{ TeV} \) for rapidity \( \eta < 2.5 \) and transverse momentum \( p_T > 20 \text{ GeV} \) of the final \( \tau \) leptons.

The possible background is the diffractive double pomeron exchange (DPE) production of tau pairs created via Drell-Yan process. The DPE production cross section can be obtained within the factorized Ingelman-Schlein \[ 28 \] model where the concept of diffractive parton distribution function (DPDF) is introduced. The convolution integral for the subprocess \( q\bar{q} \to \tau\tau \) is given by

\[ \sigma = \int dx_1dx_2d\beta_1d\beta_2f_{\gamma/p}(x_1,t)f_{\gamma/p}(x_2,t) \]

\[ \sum_{i,j=1}^3 [f_i(\beta_1,Q^2)f_j(\beta_2,Q^2) + f_j(\beta_1,Q^2)f_i(\beta_2,Q^2)] \tilde{\sigma}(q\bar{q} \to \tau\tau) \] (3.7)
where \( f_{P/p}(x_1, t) \) is the pomeron flux emitted by one of the protons and \( f_i(\beta_1, Q^2) \) is the light quark distribution function coming from the structure of the pomeron. \( x_1, x_2 \) denote the momentum fractions of the protons carried by the pomeron fluxes and \( \beta_1, \beta_2 \) represent the longitudinal momentum fractions of the pomeron carried by the struck quarks. Double pomeron exchange production cross section should be multiplied by gap survival probability 0.03 for LHC. The measurements of pomeron flux and DPDF were performed at HERA with their uncertainties [29, 30]. The uncertainty in DPDF was obtained as (5-10)% for light quarks in Fig.11 of Ref. [30]. We have determined the uncertainty in the pomeron flux as (8-10)% using the uncertainties of the flux parameters which were given in Ref. [29].

Taking the maximum values of the each uncertainties above, the combined uncertainty due to both DPDF and pomeron flux from one proton is estimated by 14%. The overall uncertainty related to pomerons arising from both protons is estimated to be 20% using a root sum-of-the-squares approach.

![Table 3: Cross sections \( \sigma^p \) obtained by double pomeron exchange production of tau pairs multiplied by gap survival probability 0.03. For comparison, the cross sections \( \sigma^0 \) for the same subprocess obtained by equivalent photon approximation at tree level (without anomalous couplings) are given. In both cases the LHC energy \( \sqrt{s} = 14 \) TeV, transverse momentum and rapidity cuts \( p_T > 20 \) GeV and \( |\eta| < 2.5 \) are taken into account for each final \( \tau \) lepton. The uncertainty in the \( \sigma^p \) is due to pomeron flux and DPDF. The uncertainty in the \( \sigma^0 \) is related to the dipole form factors in the equivalent photon spectrum.](image)

\[
\chi^2 = \frac{(\sigma(F_2) - \sigma^0)^2}{(\sigma^0 + \sigma^p)^2 \delta^2} \tag{3.8}
\]

\[
\delta = \sqrt{(\delta_{st})^2 + (\delta_{sys})^2} \tag{3.9}
\]

\[
\delta_{st} = \frac{1}{\sqrt{N^0}} \tag{3.10}
\]

\[
N^0 = L_{int}(\sigma^0 + \sigma^p)BR \tag{3.11}
\]
where $\sigma^0$, $N^0$ and $\delta$ are the cross section, number of events and uncertainty without anomalous couplings. $L_{int}$ is the integrated luminosity of LHC. The contributions of pomeron background do not appear in the numerator because of cancellation of each other. Thus, the pomeron contribution in the denominator is not expected to be so effective even if it has large 20% uncertainty. Now let us determine the effect of uncertainties due to $\sigma(F_2)$, $\sigma^0$ and pomeron backgrounds on the $\chi^2$ function. The sources of uncertainties of $\sigma(F_2)$ and $\sigma^0$ are connected to the dipole form factors in the equivalent photon spectrum, as explained before. The change in the $\chi^2$ function from the 3% uncertainty of $\sigma(F_2)$ and $\sigma^0$ lead to the $\delta^{sys}$ values shown in Table 4. Total systematic uncertainty can be formed by combining individual contributions in quadrature given in the last column of the Table 4. In our calculations, the individual uncertainties have been kept maximum and have been considered to be uncorrelated to get larger systematic uncertainty $\delta^{sys}$.

| $L_{int}(fb^{-1})$ | $\xi$  | $\delta^{sys}(\sigma(F_{2,3}))$ | $\delta^{sys}(\sigma^0)$ | $\delta^{sys}(\sigma^p)$ | $\delta^{sys}$ |
|-------------------|--------|-----------------|-----------------|-----------------|----------------|
| 50                | 0.0015-0.5 | 0.016             | 0.016             | 0.002             | 0.02              |
| 100               | 0.0015-0.5 | 0.014             | 0.014             | <0.002            | 0.02              |
| 200               | 0.0015-0.5 | 0.012             | 0.012             | <0.002            | <0.02             |
| 50                | 0.0015-0.15 | 0.016             | 0.016             | 0.002             | 0.02              |
| 100               | 0.0015-0.15 | 0.014             | 0.014             | <0.002            | 0.02              |
| 200               | 0.0015-0.15 | 0.012             | 0.012             | <0.002            | <0.02             |
| 50                | 0.01-0.15  | 0.025             | 0.025             | 0.007             | 0.04              |
| 100               | 0.01-0.15  | 0.020             | 0.020             | 0.006             | 0.03              |
| 200               | 0.01-0.15  | 0.018             | 0.018             | 0.005             | <0.03             |

Table 4: Systematic uncertainties in the $\chi^2$ function depending on luminosity and acceptance region $\xi$. The last column represents the combined uncertainties in quadrature. The values with $<$ character defines the uncertainties less than the specified values.

In this work all computations are done in the laboratory frame of the two protons. For the signal we consider one of the tau leptons decays hadronically and the other leptonically with branching ratios 65% and 35%. Then joint branching ratio of the tau pairs becomes BR=0.46.

Table 5 and Table 6 show the constraints on the anomalous magnetic moment and electric dipole moment of the tau lepton that we obtain using different systematic uncertainties in $\chi^2$ function for comparison. The acceptance region $\xi = 0.01 - 0.15$ seems more sensitive to anomalous couplings. The limits are improved by one order of magnitude when compared to DELPHI results. Electric dipole moment limits are slightly better than those of BELLE. At this point a remark is in order. Experimentally, the anomalous magnetic and electric dipole moments can be extracted by comparing the measured cross section with QED expectations. At LEP [3], for example, the fits to the measured cross section were performed taking $a_\tau$ and $d_\tau$ as parameters based on the $\tau\tau\gamma$ vertex parametrization given by (1.12). However, our predictions for the cross sections in the $\chi^2$ function are theoretical. When comparing our limits with those of LEP this distinction should be taken into account. The quadratic and quartic terms according to $F_3$ are not CP violating except the
term with Levi-Civita tensor in the interference amplitude $A_{12}$. However its contribution to the cross section is zero. That is why the magnitudes of negative and positive parts of the limits on $d_\tau$ are the same. This leads to the fact that it may be possible to measure tau anomalous magnetic moment when efficient tau identification is available.

Tau is the heaviest charged lepton which decays into lighter leptons, electron, muon and lighter hadrons such as $\pi$’s and $K$’s with a lifetime of $3.0 \times 10^{-13}$ s. Primary decay channels can be given with one charged particle (one prong decay)

$$\tau \rightarrow \nu_\tau + \ell + \bar{\nu}_\ell, \quad \ell = e, \mu \quad (3.12)$$

$$\tau \rightarrow \nu_\tau + \pi^\pm \quad (3.13)$$

$$\tau \rightarrow \nu_\tau + \pi^\pm + \pi^0 \quad (3.14)$$

$$\tau \rightarrow \nu_\tau + \pi^\pm + \pi^0 + \pi^0 \quad (3.15)$$

### Table 5: Sensitivity of the process $pp \rightarrow p\tau^+\tau^-p$ to tau anomalous magnetic moment $a_\tau$ and electric dipole moment $d_\tau$ at 95% C.L. for $\sqrt{s} = 14$ TeV, integrated luminosities $L_{int} = 50, 100, 200$ fb$^{-1}$ and three intervals of forward detector acceptance $\xi$. Only one of the moments is assumed to deviate from zero at a time. Total systematic uncertainty used in $\chi^2$ function has been taken $\delta^{sys} = 0.01$.

| $L_{int}(fb^{-1})$ | $\xi$     | $a_\tau$      | $|d_\tau|$(e cm) |
|---------------------|-----------|---------------|----------------|
| 50                  | 0.0015-0.5| -0.0062, 0.0042| $0.23 \times 10^{-16}$ |
| 100                 | 0.0015-0.5| -0.0057, 0.0037| $0.21 \times 10^{-16}$ |
| 200                 | 0.0015-0.5| -0.0054, 0.0034| $0.19 \times 10^{-16}$ |
| 50                  | 0.0015-0.15| -0.0063, 0.0043| $0.23 \times 10^{-16}$ |
| 100                 | 0.0015-0.15| -0.0058, 0.0037| $0.22 \times 10^{-16}$ |
| 200                 | 0.0015-0.15| -0.0055, 0.0034| $0.20 \times 10^{-16}$ |
| 50                  | 0.01-0.15 | -0.0048, 0.0045| $0.19 \times 10^{-16}$ |
| 100                 | 0.01-0.15 | -0.0042, 0.0038| $0.16 \times 10^{-16}$ |
| 200                 | 0.01-0.15 | -0.0036, 0.0032| $0.14 \times 10^{-16}$ |

### Table 6: The same as the Table 5 but for the systematic uncertainties shown in the third column.

| $L_{int}(fb^{-1})$ | $\xi$     | $\delta^{sys}$ | $a_\tau$      | $|d_\tau|$(e cm) |
|---------------------|-----------|----------------|---------------|----------------|
| 50                  | 0.0015-0.5| 0.02           | -0.0071, 0.0051| $0.28 \times 10^{-16}$ |
| 100                 | 0.0015-0.5| 0.02           | -0.0068, 0.0048| $0.26 \times 10^{-16}$ |
| 200                 | 0.0015-0.5| 0.02           | -0.0066, 0.0046| $0.26 \times 10^{-16}$ |
| 50                  | 0.0015-0.15| 0.02           | -0.0073, 0.0051| $0.28 \times 10^{-16}$ |
| 100                 | 0.0015-0.15| 0.02           | -0.0070, 0.0048| $0.27 \times 10^{-16}$ |
| 200                 | 0.0015-0.15| 0.02           | -0.0067, 0.0048| $0.27 \times 10^{-16}$ |
| 50                  | 0.01-0.15 | 0.04           | -0.0054, 0.0050| $0.21 \times 10^{-16}$ |
| 100                 | 0.01-0.15 | 0.03           | -0.0046, 0.0042| $0.18 \times 10^{-16}$ |
| 200                 | 0.01-0.15 | 0.03           | -0.0043, 0.0038| $0.17 \times 10^{-16}$ |
and with three charged particle (three prong decay)
\[ \tau \to \nu_\tau + 3\pi^\pm + n\pi^0 \] (3.16)

85% of all the tau decays are the one prong decays and 15% of them are the three prong decays. Produced particles from tau decays are called tau jets due to the fact that number of daughter particles is always greater than one. One prong lepton jets are identified by similar algorithms used by direct electron and muon. Identification of hadronic jets is more complicated than leptonic modes because of the QCD jets as background. However, tau jets are highly collimated and are distinguished from background due to its topology. Dedicated algorithms have been developed for hadronic tau jets by ATLAS [31] and CMS [32] groups. Use of these algorithms allows for good separation between tau jets and fake jets for some LHC process. Nevertheless, tau identification efficiency depends of a specific process, background processes, some kinematic parameters and luminosity. Studies of tau identification have not been finalized yet for LHC detectors. In every case, identification efficiency can be determined as a function of transverse momentum and rapidity. In our study we have considered \( p_T > 20 \text{ GeV} \) and \( \eta < 2.5 \) for a good \( \tau \) selection as used in most ATLAS and CMS studies. For a realistic efficiency we need a detailed study based on our specific process including properties of both central and forward detectors of ATLAS and CMS experiments. We expect highly efficient \( \tau \) identification due to clean final state in the process \( \gamma\gamma \to \tau^+\tau^- \) when compared to the LHC itself.

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461

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