ANOMALOUS ELECTROMAGNETIC MOMENTS OF τ LEPTON FROM $\gamma\gamma \to \tau^+\tau^-$ PROCESSES IN ULTRAPHERIPHERAL Pb+Pb COLLISIONS AT THE LHC*

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We discuss the sensitivity of the $\gamma\gamma \to \tau^+\tau^-$ process in ultraperipheral Pb+Pb collisions at LHC energies to the anomalous magnetic moment of τ lepton (a_τ). We derive the corresponding cross sections considering semi-leptonic decays of both leptons in the fiducial volume of ATLAS and CMS detectors. The expected limits on a_τ with the existing Pb+Pb dataset are better than the DELPHI experimental limit and can be further improved by a factor of two at the High Luminosity LHC. Our analysis provides a novel theoretical probe of the τ anomalous magnetic moment using ultraperipheral heavy-ion collisions at the LHC. The verification of our theoretical results with the latest ALICE and CMS experimental data will be also presented.

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1. Introduction

The physics of the ultraperipheral collisions (UPC) of heavy ions gives a good opportunity to study several QED processes [1]. The Feynman diagram for the Pb+Pb $\to$ Pb+Pb+$\tau^+\tau^-$ process in Fig. 1 includes two $\gamma\tau\tau$ vertices providing an enhanced sensitivity to the anomalous magnetic moment of the τ lepton.

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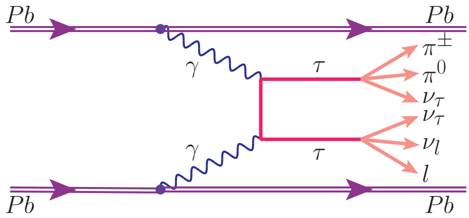

Fig. 1. Diagram for the di-taon production in ultraperipheral lead–lead collisions. Main τ decay channels presented in the figure, $\tau^\pm \to \nu_\tau + \ell^\pm + \nu_\ell$ ($\ell = e,\ \mu$) and $\tau^\pm \to \nu_\tau + \pi^\pm + n\pi^0$, give approximately 80% of all τ decays.

The DELPHI Collaboration at LEP2 [2, 3] obtained the limit: $-0.052 < a_\tau < 0.013$ (95% C.L.). The experimental limits on a_τ were also derived by the L3 and OPAL collaborations in radiative $Z \to \tau^+\tau^-\gamma$ events at LEP [4, 5], but they are typically weaker by a factor of two comparing to the DELPHI limits. For comparison, the theoretical Standard Model (SM) value of a_τ [6] is: $a_\tau^{\text{th}} = 0.00117721 \pm 0.00000005$. Recently (the results were presented for the first time at the QM2022), the CMS [7] and ATLAS collaborations [8] showed the first measurement made at the LHC.

2. Theoretical background

Cross section for two-lepton production in heavy-ion collision is the convolution of the elementary cross section for $\gamma\gamma \to \tau^+\tau^-$ and photon fluxes. Due to the large charge, ions are surrounded by a strong electromagnetic field. In our approach, photon fluxes depend not only on photon energy but also on the impact parameter [9]. The amplitude for the elementary cross section for the $\gamma\gamma \to \ell^+\ell^-$ reaction in the t- and u-channels was derived in [10]

$$\mathcal{M} = (-i)\,\epsilon_{1\mu}\epsilon_{2\nu}\,\bar{u}(p_3)\Bigg(i\Gamma^{(\gamma\ell\ell)\,\mu}(p_3,p_t)\frac{i(\not{p}_t + m_\ell)}{t - m_\ell^2 + i\epsilon}i\Gamma^{(\gamma\ell\ell)\,\nu}(p_{t'} - p_4) + i\Gamma^{(\gamma\ell\ell)\,\nu}(p_3,p_u)\frac{i(\not{p}_u + m_\ell)}{u - m_\ell^2 + i\epsilon}i\Gamma^{(\gamma\ell\ell)\,\mu}(p_{u'} - p_4)\Bigg)v(p_4)\,. \tag{1}$$

Designating p' and p as momenta of incoming and outgoing lepton, respectively, and defining $q = p' - p$ as the momentum transfer, a photon–lepton vertex function can be written as

$$i\Gamma_\mu^{(\gamma\ell\ell)}\left(p',p\right) = -ie\left[\gamma_\mu F_1\left(q^2\right) + \frac{i}{2m_\ell}\sigma_{\mu\nu}q^\nu F_2\left(q^2\right) + \frac{1}{2m_\ell}\gamma^5\sigma_{\mu\nu}q^\nu F_3\left(q^2\right)\right], \tag{2}$$

where $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$, $F_1(q^2)$ and $F_2(q^2)$ are the Dirac and Pauli form factors, $F_3(q^2)$ is the electric dipole form factor. The asymptotic values of the form factors, in the $q^2 \to 0$ limit, are the moments describing the electromagnetic properties of the lepton: $F_1(0) = 1$, $F_2(0) = a_\ell$, and $F_3(0) = d_\ell \frac{2m_\ell}{e}$.

To study the experimental sensitivity to a_τ in the $\gamma\gamma \to \tau^+\tau^-$ processes at the LHC, one has to detect UPC events containing two reconstructed τ leptons and no further activity in the detector. Since τ lepton is the heaviest lepton with a lifetime of 3×10^{-13} s, it decays into lighter leptons ($\tau^\pm \to \nu_\tau + \ell^\pm + \nu_\ell,\ \ell = e,\ \mu$) or hadrons ($\tau^\pm \to \nu_\tau + \pi^\pm + n\pi^0$, $\tau^\pm \to \nu_\tau + \pi^\pm + \pi^\mp + \pi^\pm + n\pi^0$) that happens before any direct interaction with the detector material. Therefore, the reconstruction of τ candidates depends on identifying their unique decay signatures. Approximately 80% of all τ decays are one charged particle type, and 20% of them are three-prong decays.

The nuclear cross section for the $\mathrm{Pb} + \mathrm{Pb} \to \mathrm{Pb} + \mathrm{Pb} + \tau^+\tau^-$ process is calculated in the equivalent photon approximation. Next, the PYTHIA 8.243 program is used to model τ decays. PYTHIA 8 also simulates the QED effect of the final-state radiation from outgoing leptons. The $\gamma\gamma \to \tau^+\tau^-$ candidate events are selected by requiring at least one τ lepton to decay leptonically, as this allows that existing triggering algorithms of the ATLAS or CMS detector can be used [11, 12]. We take into account the events with the limits for the leading electron or muon: $p_{\mathrm{T}} > 4$ GeV and $|\eta| < 2.5$. This operation allows for an efficient reconstruction and identification by the LHC detectors.

It is worth noting that most produced τ-lepton pairs have relatively low energy (equivalent to low transverse momentum). Therefore, the standard τ identification tools, developed by the ATLAS and CMS collaborations [13, 14], are not expected to be applicable. We propose, therefore, to categorize the $\gamma\gamma \to \tau^+\tau^-$ candidate events by their decay mode. All charged-particle tracks from one- or three-prong decays must have a transverse momentum of $p_{\mathrm{T}} > 0.2$ GeV and a pseudo-rapidity of $|\eta| < 2.5$.

The number of events for Pb+Pb$\to$Pb+Pb+$\tau^+\tau^-$ process [15] for different a_τ values can be translated into expected sensitivity to limiting a_τ. We treat SM results ($a_\tau = 0$) as the background and the difference between $a_\tau = 0$ and $a_\tau = X$ distributions as a signal. We use two values of expected systematic uncertainty (5% and 1%) and two assumptions on Pb+Pb integrated luminosity (2 nb^{-1} for the existing ATLAS/CMS dataset or 20 nb^{-1} for the HL-LHC). The expected significance can be directly transformed into expected 95% C.L. limits on a_τ. Smaller systematic uncertainty or larger luminosity value allows for predicting a narrower limit on a_τ [15].

3. SM expectation

Table 1 summarises the integrated fiducial cross sections at $\sqrt{s_{NN}} = 5.02$ TeV for different a_τ values. There is an enumeration of the expected number of reconstructed events in ATLAS or the CMS. We assume 80% reconstruction efficiency within the fiducial region and two values of integrated luminosity (L_{int}). The first one corresponds to the existing LHC Pb+Pb dataset: $L_{\mathrm{int}} = 2$ nb^{-1}, and the second one relates to expected High Luminosity LHC dataset: $L_{\mathrm{int}} = 20$ nb^{-1}. With the existing Pb+Pb dataset, we expect each experiment to reconstruct about 5000 $\gamma\gamma \to \tau^+\tau^-$ events ($a_\tau = 0$). The expected number of reconstructed τ pairs grows to about 50 000 at the HL-LHC.

Table 1. Integrated fiducial cross sections for $\mathrm{Pb+Pb} \to \mathrm{Pb+Pb}\tau^+\tau^-$ process for different values of anomalous electromagnetic moments. The expected number of events assuming 80% selection efficiency and $L_{\mathrm{int}} = 2$ nb^{-1} or $L_{\mathrm{int}} = 20$ nb^{-1} are also shown.

a_τ value	σ_{fid} [nb]	Expected events ($L_{\mathrm{int}} = 2$ nb^{-1}, $C = 0.8$)	Expected events ($L_{\mathrm{int}} = 20$ nb^{-1}, $C = 0.8$)
−0.1	4 770	7 650	76 500
−0.05	3 330	5 350	53 500
−0.02	3 060	4 900	49 000
0 (SM)	3 145	5 050	50 500
+0.02	3 445	5 500	55 000
+0.05	4 350	6 950	69 500
+0.1	7 225	11 550	115 500

The number of events from Table 1 can be translated into expected sensitivity for probing a_τ. We use the RooFit toolkit for the statistical analysis of the results. We perform fits to $R_\ell(p_{\mathrm{T}}^{\text{lead lepton}})$ distribution by treating SM results ($a_\tau = 0$) as the background and the difference between $a_\tau = 0$ and $a_\tau = X$ distributions as a signal. The procedure exploits both normalization and $p_{\mathrm{T}}^{\text{lead lepton}}$ shape differences, providing extra sensitivity to a_τ measurement. We use two values of expected systematic uncertainty (5% and 1%) and two assumptions on Pb+Pb integrated luminosity (2 nb^{-1} for existing ATLAS/CMS dataset or 20 nb^{-1} for the HL-LHC).

Figure 2 (left) shows the expected signal significance as a function of a_τ. The observed asymmetry for the positive and negative a_τ values reflects the destructive interference between SM and the anomalous τ coupling. The expected significance can be directly transformed into expected 95% C.L.

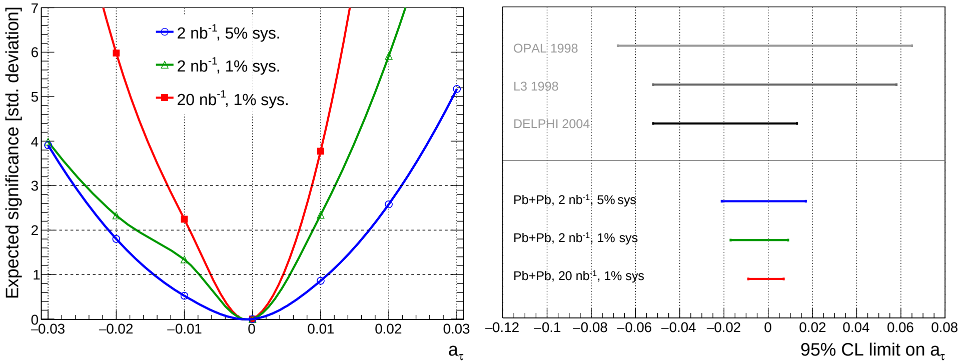

Fig. 2. Left: Expected signal significance as a function of anomalous τ moment for different values of the Pb+Pb integrated luminosity and total systematic uncertainty. Right: Expected 95% C.L. limits on a_τ measurement for different values of the Pb+Pb integrated luminosity and total systematic uncertainty. The comparison is also made to the existing limits from OPAL [5], L3 [4], and DELPHI [2] experiments at LEP.

limits on a_τ, shown in Fig. 2 (right). Assuming 2 nb^{-1} of the integrated Pb+Pb luminosity and 5% systematic uncertainty, the expected limits are $-0.021 < a_\tau < 0.017$, approximately two times better than the DELPHI limits [2]. By collecting more data (20 nb^{-1}) and improving systematic uncertainties, these limits can be further improved by another factor of two. The expected results by studying ultraperipheral collisions at the LHC can significantly improve the existing limits on a_τ.

4. Conslusion

Here, we presented a prediction on the cross section of the $\gamma\gamma \to \tau^+\tau^-$ process and its dependence on anomalous electromagnetic couplings of the τ lepton in ultraperipheral Pb+Pb collisions at the LHC. We also investigated the expected sensitivity to a_τ, assuming standard LHC detectors using the currently available and future datasets. We proposed to use cross section ratios of the $\gamma\gamma \to \tau^+\tau^-$ and $\gamma\gamma \to e^+e^-(\mu^+\mu^-)$ processes to probe a_τ, as several systematic uncertainties cancel and the experimental knowledge of a_e and a_μ is several orders of magnitude more precise than a_τ itself.

Our studies suggested that the currently available datasets of the LHC experiments are already sufficient to improve the sensitivity to a_τ by a factor of two. The ATLAS and CMS collaborations have very recently measured τ-lepton pair production in UPC, Pb+Pb $\to$ Pb+Pb+$(\gamma\gamma \to \tau^+\tau^-)$, for the collision energy of 5.02 TeV. ATLAS observed that event yield is compatible with our predictions within uncertainties. The observed 95% confidence-level intervals for a_τ are $a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$ [8]. The CMS experiment estimated a model-dependence value of the anomalous magnetic moment of τ lepton of $a_\tau = 0.001^{+0.055}_{-0.089}$ at 68% C.L.

REFERENCES

[1] A.J. Baltz, *Phys. Rep.* **458**, 1 (2008).

[2] DELPHI Collaboration, *Eur. Phys. J. C* **35**, 159 (2004).

[3] F. Cornet, J.I. Illana, *Phys. Rev. D* **53**, 1181 (1996).

[4] L3 Collaboration (M. Acciarri *et al.*), *Phys. Lett. B* **434**, 169 (1998).

[5] OPAL Collaboration (K. Ackerstaff *et al.*), *Phys. Lett. B* **431**, 188 (1998).

[6] S. Eidelman, M. Passera, *Mod. Phys. Lett. A* **22**, 159 (2007).

[7] CMS Collaboration, CMS-HIN-21-009, CERN-EP-2022-098, June 2022.

[8] ATLAS Collaboration, CERN-EP-2022-079, April 2022.

[9] M. Kłusek-Gawenda, A. Szczurek, *Phys. Rev. C* **82**, 014904 (2010).

[10] M. Kłusek-Gawenda, P. Lebiedowicz, O. Nachtmann, A. Szczurek, *Phys. Rev. D* **96**, 094029 (2017).

[11] ATLAS Collaboration (G. Aad *et al.*), *J. Instrum.* **3**, S08003 (2008).

[12] CMS Collaboration (S. Chatrchyan *et al.*), *J. Instrum.* **3**, S08004 (2008).

[13] ATLAS Collaboration (G. Aad *et al.*), *Eur. Phys. J. C* **76**, 295 (2016).

[14] CMS Collaboration (A.M. Sirunyan *et al.*), *J. Instrum.* **13**, P10005 (2018).

[15] M. Dyndal, M. Klusek-Gawenda, M. Schott, A. Szczurek, *Phys. Lett. B* **809**, 135682 (2020).