PROCEEDINGS OF SCIENCE

Limits for anomalous magnetic and electric dipole moments of τ leptons from heavy-ion UPCs

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We discuss sensitivity of the $\gamma\gamma \to \tau^+\tau^-$ process in ultraperipheral Pb+Pb collisions at LHC energies on the anomalous magnetic moment of τ lepton (a_τ). We derive the corresponding cross sections considering semileptonic 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 found to be better by a factor of two comparing to current best experimental limits and can be further improved by another factor of two at High Luminosity LHC. In addition, our results for τ lepton electric dipole moment, d_τ, can be competitive with the current best limits obtained by the Belle experiment.

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1. Theoretical framework and calculation details

The measurements of ultraperipheral collisions (UPC) of heavy ions give opportunity to study several QED processes [1]. The Feynman diagram for the Pb+Pb→Pb+Pb+$\tau^+\tau^-$ process in Fig. 1 includes two $\gamma\tau\tau$ vertices providing an enhanced sensitivity to the anomalous magnetic (a_τ) and electric (d_τ) moments of the τ lepton.

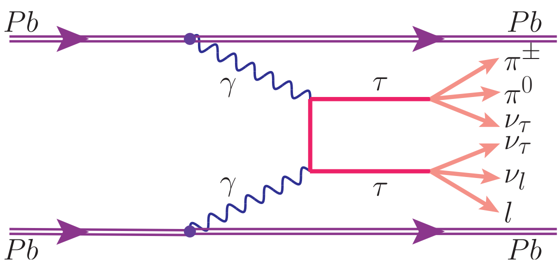

Figure 1: Diagram for the di-taon production in ultraperipheral lead-lead collisions. Main τ decay channels presented on the graphic, $\tau^\pm \to \nu_\tau + \ell^\pm + \nu_\ell$ ($\ell = e,\ \mu$) and $\tau^\pm \to \nu_\tau + \pi^\pm + n\pi^0$, give approximately 80% of all τ decays.

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 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 [2]. The amplitude for the elementary cross section for the $\gamma\gamma \to \ell^+\ell^-$ reaction in the t- and u-channel was derived in [3]:

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

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

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

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 $F_3(0) = d_\ell \frac{2m_\ell}{e}$.

The nuclear cross section for the Pb+Pb→Pb+Pb+$\tau^+\tau^-$ process is calculated in the equivalent photon approximation. Next, the Pythia8.243 program is used to model τ decays. The QED effect of the final state radiation from outgoing leptons is also simulated by Pythia8. 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 [4, 5]. We take into account the events with the limits for the leading electron or muon: $p_T > 4$ GeV and $|\eta| < 2.5$. This range allows for an efficient reconstruction and identification by the LHC detectors.

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The number of events for Pb+Pb→Pb+Pb+$\tau^+\tau^-$ process [6] for different a_τ values can be translated into expected sensitivity for limiting a_τ. We treat SM results ($a_\tau = 0$) as 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 existing ATLAS/CMS dataset or 20 nb^{-1} for HL-LHC). The expected significance can be directly transformed into expected 95% CL limits on a_τ. Smaller systematic uncertainty or larger luminosity value allows predicting a narrower limit on a_τ [6].

2. Results and conclusions

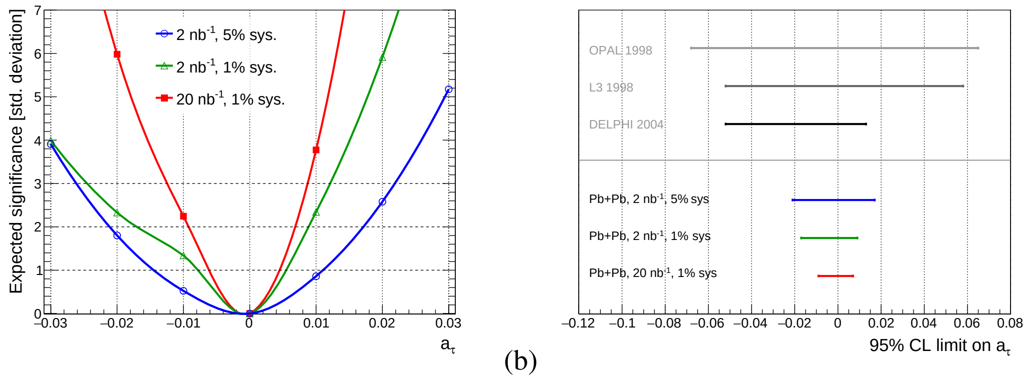
a_τ value	σ_{fid} [nb]	Expected events (L_{int} = 2 nb^{-1}, C = 0.8)	Expected events (L_{int} = 20 nb^{-1}, C = 0.8)
−0.1	4770	7650	76 500
−0.05	3330	5350	53 500
−0.02	3060	4900	49 000
0 (SM)	3145	5050	50 500
+0.02	3445	5500	55 000
+0.05	4350	6950	69 500
+0.1	7225	11550	115 500

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

The DELPHI collaboration at LEP2 [7, 8] obtained the limit: $-0.052 < a_\tau < 0.013$ (95% CL). 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 [9, 10], but they are typically weaker by a factor of two compared to the DELPHI limits. For comparison, the theoretical Standard Model (SM) value of a_τ [11] is: $a_\tau^{\text{th}} = 0.00117721 \pm 0.00000005$.

Table 1 contains a summary of 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 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_{int} = 2 nb^{-1}, and the second one relates to expected High Luminosity LHC dataset: L_{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.

Figure 2(a) shows the expected signal significance as a function of a_τ. The observed asymmetry for 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% CL limits on a_τ, shown in Fig. 2(b). Assuming 2 nb^{-1} of integrated Pb+Pb luminosity and 5% systematic uncertainty, the expected limits are $-0.021 < a_\tau < 0.017$, approximately two times



(a) (b)

Figure 2: (a) Expected signal significance as a function of anomalous τ moment for different values of Pb+Pb integrated luminosity and total systematic uncertainty. (b) Expected 95% CL limits on a_τ measurement for different values of the Pb+Pb integrated luminosity and total systematic uncertainty. Comparison is also made to the existing limits from OPAL [10], L3 [9] and DELPHI [7] experiments at LEP.

better than the DELPHI limits [7]. By collecting more data (20 nb^{-1}) and with improved systematic uncertainties, these limits can be further improved by another factor of two. The expected results for ultraperipheral collisions at the LHC can significantly improve the existing limits on a_τ.

Concluding, our studies suggest that the currently available datasets of the LHC experiments are already sufficient to improve the sensitivity to a_τ by a factor of two. Hence, we consider experimental analysis as highly interesting and worthwhile to be done in the future. Future Belle-II experiment should give much better constraints on $|a_\tau| < 1.75 \cdot 10^{-5}$ and $|d_\tau| < 2.04 \cdot 10^{-19}\ e \cdot \mathrm{cm}$ [12]. We have also studied the sensitivity of τ lepton electric dipole moment, d_τ. Our expected 95% CL sensitivity to $|d_\tau|$ assuming $a_\tau = 0$ is: $|d_\tau| < 6.3\ (4.4) \cdot 10^{-17}\ e \cdot \mathrm{cm}$ at the LHC with 5% (1%) systematic uncertainty and $|d_\tau| < 3.5 \cdot 10^{-17}\ e \cdot \mathrm{cm}$ at HL-LHC (1% systematic uncertainty). For comparison, the current best limits are measured by Belle experiment [13]: $-2.2 < Re(d_\tau) < 4.5\ (10^{-17}\ e \cdot \mathrm{cm})$ and $-2.5 < Im(d_\tau) < 0.8\ (10^{-17}\ e \cdot \mathrm{cm})$. Our projected results on d_τ can be therefore competitive with the Belle limits.

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