Anomalous electromagnetic moments of \( \tau \) lepton in \( \gamma\gamma \rightarrow \tau^+\tau^- \) reaction in Pb+Pb collisions at the LHC

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Abstract

We discuss the sensitivity of the \( \gamma\gamma \rightarrow \tau^+\tau^- \) process in ultraperipheral Pb+Pb collisions on the anomalous magnetic (\( a_\tau \)) and electric (\( d_\tau \)) moments of \( \tau \) lepton at LHC energies. We derive the corresponding cross sections by folding the elementary cross section with the heavy-ion photon fluxes and considering semi-leptonic decays of both \( \tau \) leptons in the fiducial volume of ATLAS and CMS detectors. We present predictions for total and differential cross sections, and for the ratios to \( \gamma\gamma \rightarrow e^+e^- (\mu^+\mu^-) \) process. These ratios allow to cancel theoretical and experimental uncertainties when performing precision measurement of \( a_\tau \) at the LHC. The expected limits on \( a_\tau \) with 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.

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I. INTRODUCTION

Ultraperipheral collisions (UPC) of heavy-ions provide a very clean environment to study various two-photon induced processes \cite{1,2}. Most recent examples include the production of electron pairs \cite{3–6}, muon pairs \cite{7} and light-by-light scattering \cite{8–10}. These reactions can also give rise to the production of tau lepton pairs, which provides a highly interesting opportunity to study the electromagnetic properties of the $\tau$ lepton via the $\text{Pb+Pb} \rightarrow \text{Pb+Pb} + \tau^+\tau^-$ process using data from the Large Hadron Collider (LHC).

The presence of $\gamma\tau\tau$ vertex in this reaction gives sensitivity to the anomalous electromagnetic couplings of the tau lepton. Since the $\gamma\gamma \rightarrow \tau^+\tau^-$ subprocess diagram contains two such vertices, this reaction provides even an enhanced sensitivity to the anomalous magnetic ($a_\tau$) and electric ($d_\tau$) moments of the $\tau$ lepton.

The strongest experimental constraints on $a_\tau$ come from the kinematics of the similar production process, $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$, measured by the DELPHI collaboration at the LEP2 collider \cite{11} yielding a limit of

$$-0.052 < a_\tau < 0.013 \ (95\% \ CL).$$

The experimental limits on $a_\tau$ were also derived by the L3 and OPAL collaborations in radiative $Z \rightarrow \tau\tau\gamma$ events at LEP \cite{12,13}, but they are typically weaker by a factor of two comparing to the DELPHI limits. For comparison, the theoretical Standard Model (SM) value of $a_\tau$ is \cite{14,15}:

$$a_\tau^{\text{th}} = 0.00117721 \pm 0.00000005 ,$$

i.e. significantly smaller than the currently available experimental bounds.

Measuring $a_\tau$ with improved precision tests the $\tau$ lepton compositeness \cite{16} and can be sensitive to physics beyond the Standard Model (BSM), including supersymmetric scenarios \cite{17}, left-right symmetric models \cite{18} and unparticle physics \cite{19}.

In the $\gamma\tau\tau$ coupling, another interesting contribution is the CP-violating effects which create electric dipole moment, $d_\tau$. The $d_\tau$ arises only at three-loop in SM and is therefore highly suppressed: $|d_\tau^{\text{th}}| < 10^{-34} \ e \cdot cm$ \cite{20}; the most stringent limits on $d_\tau$ were set by Belle \cite{21}. The presence of electric dipole moment of $\tau$ could be investigated via studying so-called CP-odd observables in $e^+e^- \rightarrow \tau^+\tau^-$ reaction \cite{22,23}.

There are many existing proposals how to improve the experimental sensitivity on $a_\tau$ and $d_\tau$ using lepton beams and future datasets of Belle-II \cite{24–26}, CLIC \cite{27,28}, and LHeC \cite{28,29}. The LHC feasibility studies focus on the usage of proton–proton collisions \cite{28,30–34} and more recently also on heavy-ion UPC \cite{35}.

In this article we study the sensitivity of the $\gamma\gamma \rightarrow \tau^+\tau^-$ process on $a_\tau$ and $d_\tau$ in Pb+Pb collisions at the LHC. We present calculations of the cross sections for the nuclear reaction, including outgoing $\tau$ decays and explicit dependence on $a_\tau$, and considering fiducial volumes of the ATLAS \cite{36} and CMS \cite{37} detectors. While the authors of \cite{35} rely on an Effective Field Theory (EFT) approach to perform predictions on the sensitivity of LHC UPC data on $a_\tau$, we provide a first independent calculation for the $\text{Pb+Pb} \rightarrow \text{Pb+Pb} + \tau^+\tau^-$ process for different $a_\tau$ values. We also discuss the strategy to suppress the impact of systematic uncertainties by exploiting the ratio to the $\gamma\gamma \rightarrow e^+e^- (\mu^+\mu^-)$ processes.
II. THEORETICAL FRAMEWORK

The calculation of the process \( \text{Pb} + \text{Pb} \rightarrow \text{Pb} + \text{Pb} + \tau^+ \tau^- \) requires the convolution of the two-photon luminosity with the elementary \( \gamma \gamma \rightarrow \tau^+ \tau^- \) cross section. In our study, the nuclear cross section for the production of \( \ell^+ \ell^- \) pair in ultraperipheral heavy ion collision is calculated in the impact parameter space \([38]\) and expressed via the formula:

\[
\sigma (AA \rightarrow AA \ell^+ \ell^-; \sqrt{s_{AA}}) = \int \sigma (\gamma \gamma \rightarrow \ell^+ \ell^-; W_{\gamma \gamma}) N(\omega_1, b_1) N(\omega_2, b_2) S_{abs}^2(b) \times \frac{W_{\gamma \gamma}}{2} dW_{\gamma \gamma} dY_{\ell \ell} d\vec{b}_x d\vec{b}_y d^2b. \tag{2.1}
\]

Here \( b \) denotes the impact parameter, i.e. the distance between colliding nuclei in the plane perpendicular to their direction of motion. \( W_{\gamma \gamma} = \sqrt{4\omega_1 \omega_2} \) is the invariant mass of the \( \gamma \gamma \) system and \( \omega_i, i = 1,2, \) is the energy of the photon which is emitted from the first or second nucleus, respectively. \( Y_{\ell \ell} \) is the rapidity of the \( \ell^+ \ell^- \) system. The quantities \( \vec{b}_x = (b_{1x} + b_{2x})/2, \vec{b}_y = (b_{1y} + b_{2y})/2 \) are given in terms of \( b_{1x} \) and \( b_{1y} \) which are the components of the \( b_1 \) and \( b_2 \) vectors that mark the point (distance from the first and second nucleus) where photons collide and particles are produced. The diagram illustrating these quantities in the impact parameter space can be found in \([38]\), where also the dependence of the photon flux \( N(\omega, b_i) \) on the charge form factor is presented.

Our main calculations rely on the realistic form factor, defined as the Fourier transform of the charge distribution in the nucleus. However, more sophisticated calculations are required for differential cross section predictions as well as for predictions in certain fiducial volumes which are typically imposed by experimental constrains. For those predictions, we introduce an additional kinematic parameter related to angular distribution for the subprocess into the underlying integration. A more detailed discussion of the nuclear cross section for the \( \text{Pb} + \text{Pb} \rightarrow \text{Pb} + \text{Pb} + \ell^+ \ell^- \) reaction that includes kinematic variables of outgoing leptons is given in \([39]\).

In general, we study the \( \gamma \gamma \rightarrow \ell^+ \ell^- \) subprocess where the momenta of the incoming photons are denoted by \( p_1 \) and \( p_2 \), while \( p_3 \) and \( p_4 \) denote the positively and negatively charged lepton momenta, respectively. In addition, we define \( p_t = p_2 - p_4 = p_3 - p_1 \) and \( p_u = p_1 - p_4 = p_3 - p_2 \). The amplitude for the \( \gamma \gamma \rightarrow \ell^+ \ell^- \) reaction in the \( t \)- and \( u \)-channel was previously derived \([40]\) and is given by the formula:

\[
\mathcal{M} = (-i) \varepsilon_{1 \mu} \varepsilon_{2 \nu} \bar{u}(p_3) \left( i\Gamma(\gamma \ell \ell)(p_3, p_1) i\left( p_t + m_\ell \right) \frac{i}{l - m_\ell^2 + i\varepsilon} i\Gamma(\gamma \ell \ell)(p_4) \right) v(p_4) \tag{2.2}
\]

Here a photon-lepton vertex function is introduced that depends on the momentum transfer, \( q = p' - p \). Denoting \( p' \) and \( p \) as momenta of incoming and outgoing lepton, respectively, this can be written as:

\[
\frac{i}{2 \sqrt{2}} \left[ \gamma_\mu F_1(q^2) + \frac{i}{2m_\ell} \gamma_\mu q^\nu F_2(q^2) + \frac{1}{2m_\ell^2} \gamma^5 \gamma_\mu q^\nu F_3(q^2) \right], \tag{2.3}
\]

where \( \gamma_{\mu \nu} = \frac{i}{2} [\gamma_\mu, \gamma_\nu] \) is the spin tensor that is proportional to the commutator of the gamma matrices, \( F_1(q^2) \) and \( F_2(q^2) \) are the Dirac and Pauli form factors, \( F_3(q^2) \) is the
electric dipole form factor. The last term violates CP symmetry and its non-zero value can be evidence of physics BSM. 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 $F_3(0) = d_\ell^{2m_\ell} e^{2m_\ell}$. Since the virtualities of exchanged photons for ultraperipheral Pb+Pb collisions at the LHC are very small (typically $Q_{1,2}^2 < 0.001 \text{ GeV}^2$), this asymptotic condition is well fulfilled.

Finally, the differential elementary cross section for the dilepton production in the $\gamma\gamma$-fusion reaction is given as follows:

$$\frac{d\sigma(\gamma\gamma \to \ell^+\ell^-)}{dz} = \frac{2\pi}{64\pi^2s} \left| p_{\text{out}} \right| \left| p_{\text{in}} \right| \frac{1}{4} \sum_{\text{spin}} |M|^2,$$

(2.4)

where $z = \cos \theta$ and $\theta$ is an angle of the outgoing leptons relative to the beam direction in the photon–photon center-of-mass frame, $s$ is the invariant mass squared of the $\gamma\gamma$ system, $p_{\text{out}}$ and $p_{\text{in}}$ are the 3-momenta of outgoing (lepton) and initial particle (photon), respectively.

The elementary $\gamma\gamma \to \tau^+\tau^-$ cross section strongly depends on the value of anomalous magnetic moment of $\tau$ lepton. Figure 1 illustrates the impact of non-zero $a_\tau$ value on the elementary cross section for $\gamma\gamma \to \tau^+\tau^-$ process as a function of $W_{\gamma\gamma} (= m_{\tau\tau})$ and $\cos \theta$ at $W_{\gamma\gamma} = 15 \text{ GeV}$. Shown are the results for three representative values of the anomalous magnetic moment, $a_\tau = +0.1$ (green dotted line), $a_\tau = 0$ (red solid line) and $a_\tau = -0.1$ (black dashed line), respectively.

![Figure 1: Elementary cross section for $\gamma\gamma \to \tau^+\tau^-$ process as a function of $W_{\gamma\gamma} = m_{\tau\tau}$ (left) and as a function of $z = \cos \theta$ for $W_{\gamma\gamma} = 15 \text{ GeV}$ (right).](image)

Fig. 1 shows the ratio of the total (integrated) nuclear cross section for $\tau$ pair production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ with respect to the results with $a_\tau = 0$ (SM). We show the results both for the full momentum space (black solid line) and with extra requirement of $p_T^\tau > 1 \text{ GeV}$ (blue dashed line). The total cross section values for $a_\tau = 0$ are: $\sigma(\text{Pb+Pb} \to \text{Pb+Pb+}\tau^+\tau^-; p_T^\tau > 0 \text{ GeV}) = 1.06 \text{ mb}$ and $\sigma(\text{Pb+Pb} \to \text{Pb+Pb+}$
FIG. 2: Ratio of the total nuclear cross sections for Pb+Pb→Pb+Pb+τ⁺τ⁻ production at the LHC energies as a function of $a_τ$, relative to SM ($a_τ = 0$). The ratio of the cross sections with extra $p_T^\tau > 1 \text{ GeV}$ requirement applied is also shown.

$\tau^+\tau^-; p_T^\tau > 1 \text{ GeV}) = 0.73 \text{ mb}$. The relative cross section changes significantly with $a_τ$, while its dependence on the $p_T^\tau$ cut value is relatively small for $|a_τ| < 0.1$.

FIG. 3: Total cross section for Pb+Pb→Pb+Pb+τ⁺τ⁻ production at the LHC energies as a function of ditau invariant mass (left) and ditau rapidity (right). Our results are compared with the results obtained from the STARLIGHT MC generator.

We also compare our results ($a_τ = 0$) with STARLIGHT Monte Carlo generator [41], which is commonly used to describe ultraperipheral heavy-ion collision data. Figure 3 shows the comparison of total cross section for Pb+Pb→Pb+Pb+τ⁺τ⁻ production as a function of $m_{\tau\tau}$ and $Y_{\tau\tau}$. In general, the predictions from STARLIGHT are systematically lower by about 20% in comparison to the results of the calculations described above. The overall shape of the $m_{\tau\tau}$ distribution is also slightly different between the two cal-
culations. This is mainly because STARLIGHT applies extra $|b_1| > R_{Pb}$ and $|b_2| > R_{Pb}$ requirements in the modelling of photon fluxes (see Eq. (2.1)). However, as it will be shown in Sec. [IV] the modeling uncertainty of incoming photon fluxes cancel out to a large extent, once the ratio of various $\gamma\gamma \rightarrow \ell^+\ell^- (\ell = e, \mu, \tau)$ cross sections is used.

### III. FIDUCIAL SELECTION AND $\tau$ DECAYS

In order to study the experimental sensitivity on $a_\tau$ in the $\gamma\gamma \rightarrow \tau^+\tau^-$ processes at the LHC, one has to record UPC events, which contain two reconstructed tau candidates and no further activity in the detector. Since the tau is the heaviest lepton with a lifetime of $3 \times 10^{-13}$ s, it decays into lighter leptons (electron or muon) or hadrons (mainly pions and kaons) before any direct interaction with the detector material. The reconstruction of tau candidates depends therefore on the identification of its unique decay signatures. The primary $\tau$ decay channels produce one charged particle in the final state, denoted as $1ch$, or one-prong decays in the following:

$$
\tau^\pm \rightarrow \nu_\tau + \ell^\pm + \nu_\ell \quad (\ell = e, \mu),
$$

or three charged particles, denoted as $3ch$, or three-prong decays, i.e.

$$
\tau^\pm \rightarrow \nu_\tau + \pi^\pm + n\pi^0,
$$

or three-prong decays, i.e.

$$
\tau^\pm \rightarrow \nu_\tau + \pi^\pm + \pi^\mp + \pi^\pm + n\pi^0.
$$

Approximately 80% of all $\tau$ decays are the one-prong decays and 20% of them are the three-prong decays.

While the differential cross sections of $Pb+Pb\rightarrow Pb+Pb+\tau^+\tau^-$ at the LHC are based on the previous calculations, the PYTHIA8.243 program [42] is used to model $\tau$ decays for our studies, as it simulates all known $\tau$ decay channels with a branching fraction greater than 0.04%, including large number of 2- to 6-body decay modes [43]. The effect of QED final state radiation (FSR) from outgoing leptons is also simulated by PYTHIA8. However, the spin correlations for $\tau$ decays are not taken into account, as this feature is currently not supported for the $\gamma\gamma \rightarrow \tau^+\tau^-$ process within PYTHIA8.

We propose that the $\gamma\gamma \rightarrow \tau^+\tau^-$ candidates events are selected by requiring at least one $\tau$ lepton to decay leptonically, as this allows that existing triggering algorithms of the ATLAS or CMS detector can be used [36, 37]. The leading electron or muon is further required to have a transverse momentum of $p_T > 4$ GeV and $|\eta| < 2.5$ to allow for an efficient reconstruction and identification by the LHC detectors. The correlation between the $p_T$ of one tau and its charged decay lepton is shown in Figure 4, indicating a broad smearing of the decay lepton $p_T$ due to the presence of neutrinos. On the contrary, there is a good correlation between the rapidity of $\tau^+\tau^-$ system and the rapidity of the final-state charged-particle system, as shown in Fig. 4 (right).

It should be noted that the majority of produced $\tau$ lepton pairs have relatively low energy/transverse momentum. Therefore, the standard $\tau$ identification tools, developed by the ATLAS and CMS collaborations [44, 45] are not expected to be applicable. We propose therefore to categorize the $\gamma\gamma \rightarrow \tau^+\tau^-$ candidate events by their decay mode:
FIG. 4: (left) Correlation between $p_T$ of the $\tau$ lepton and $p_T$ of the electron (muon) from its decay for both event categories. (right) Correlation between the rapidity of $\tau^+\tau^-$ system and the rapidity of the final-state charged-particle system for $\tau_1\tau_{3ch}$ category. The results are obtained for SM scenario ($\alpha_\tau = 0$) with full set of fiducial cuts applied.

$\tau_1\tau_{1ch}$ or $\tau_1\tau_{3ch}$. All charged-particle tracks from $\tau_{1ch}$ or $\tau_{3ch}$ decays are required to have a transverse momentum of $p_T > 0.2$ GeV and a pseudo-rapidity of $|\eta| < 2.5$.

Possible background processes which could fake the $\gamma\gamma \rightarrow \tau^+\tau^-$ signal are: the two-photon quark-antiquark production ($\gamma\gamma \rightarrow q\bar{q}$) and the (semi)exclusive production of electron/muon pairs. As demonstrated already in Ref. [35], the $\gamma\gamma \rightarrow q\bar{q}$ have a significantly larger charged-particle multiplicity than the signal and hence this background is fully reducible by exclusivity requirements.

On the other hand, the $\gamma\gamma \rightarrow \ell^+\ell^-$ production can become an irreducible background for the $\tau_1\tau_{1ch}$ category. To suppress this background, additional requirements on $p_T$ of the lepton+track system ($p_T^{\ell, ch} > 1$ GeV) have to be applied for this event category. As presented in Figure 5, an increased $p_T^{\ell, ch} > 1$ GeV cut removes only 10% of signal events, however, suppresses at the same time significantly back-to-back $\gamma\gamma \rightarrow e^+e^- (\mu^+\mu^-)$ processes and leading therefore to negligible background contribution from this process.

A further possible source of background is the semi-coherent dilepton production, i.e. $\gamma^* \gamma \rightarrow \ell^+\ell^-$. Here, the $p_T$ of the dilepton system can be as large as $p_T^{\ell, ch}$ in the signal process. Due to relatively large momentum transfer from $\gamma^*$, the outgoing ion dissociates, emitting forward neutrons detectable in ZDC systems [46]. Thus a requirement of zero neutrons in both ion directions provides a straightforward way to estimate and even fully suppress this background. Since the neutrons can be occasionally emitted also in the signal process due to extra Coulomb exchanges [47], a full neutron veto can lead to 20–30% reduction of the cross sections. The study of the neutron emissions is, however, beyond the scope of this paper.

The differential fiducial cross section as a function of leading lepton $p_T$ for all event categories is also shown in Figure 5. The majority of selected events have a single charged pion in the final state due to the relatively large branching fraction. These events are followed by fully leptonic decays of both $\tau$ leptons. The $\tau_1\tau_{1ch}$ category has the lowest cross

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1 due to the presence of soft lepton tracks, experimentally these leptons cannot be easily distinguished from pions, hence fully leptonic decays of both $\tau$ are kept as a part of a more generic $\tau_1\tau_{1ch}$ category.
sections. The integrated fiducial cross section values are 2630 nb for $\tau_l\tau_{1ch}$ category (including 1650 nb for $\ell^\pm\pi^\mp$ decays, 980 nb for $\ell^\pm\ell^\mp$ decays) and 515 nb for $\tau_l\tau_{3ch}$ category, assuming Pb+Pb collision energy of $\sqrt{s_{NN}} = 5.02$ TeV.

IV. RESULTS AND DISCUSSION

Figure 6 summarizes the fiducial cross section for Pb+Pb $\rightarrow$ Pb+Pb+$\tau^+\tau^-$ process as a function of the leading lepton $p_T^{lead \, lepton}$ for SM scenario ($a_\tau = 0$) as well as other representative values of $a_\tau$ ($a_\tau = -0.1, -0.05, -0.02, 0.02, 0.05, 0.1$). In addition to the overall cross section enhancement, induced by non-zero $a_\tau$, there is an interesting change in the shape of $p_T^{lead \, lepton}$ distribution visible. This is due to the fact that the anomalous $\tau$ couplings are more sensitive to higher $\tau$ energies, based on the term $\sigma^{\mu\nu} q_\nu$ in Eq. (2.3). There is also an asymmetry between the cross sections for positive and negative $a_\tau$ values, which is due to interference between the SM part and the anomalous $\tau$ coupling (see Fig. 2).

The integrated fiducial cross sections for different $a_\tau$ values are summarized in Table I. This table also lists the expected number of reconstructed events in ATLAS or CMS, assuming 80% reconstruction efficiency within the fiducial region and two values of integrated luminosity ($L_{int}$): $L_{int} = 2$ nb$^{-1}$ (existing LHC Pb+Pb dataset) or $L_{int} = 20$ nb$^{-1}$ (expected High Luminosity LHC, HL-LHC, dataset) at $\sqrt{s_{NN}} = 5.02$ TeV. With the existing Pb+Pb dataset we expect each experiment to reconstruct about 5000 $\gamma\gamma \rightarrow \tau^+\tau^-$ events ($a_\tau = 0$). The expected number of reconstructed $\tau$ pairs grows to about 50 000 at the HL-LHC.

Figure 7 shows the ratio (denoted as $R_\ell$) of fiducial cross sections presented in Fig. 6 to the fiducial cross sections from the standard candle process $\gamma\gamma \rightarrow \ell^+\ell^-$ ($\ell = e$ or $\mu$). To calculate these cross sections, the same theoretical framework described in Sec. III is used. The QED FSR effect is modeled by PYTHIA8. To match the fiducial selection of
FIG. 6: Fiducial cross section as a function of $p_T$ of the leading lepton for all event categories summed together and various $a_\tau$ values: $a_\tau = -0.1$, $-0.05$, $-0.02$, $0$ (left) and $a_\tau = 0$, $0.02$, $0.05$, $0.1$ (right). The last bin denotes integrated fiducial cross section above $p_T^{\text{lead lepton}} = 20$ GeV.

| $a_\tau$ value | $\sigma_{\text{fid}}$ [nb] | Expected events $(L_{\text{int}} = 2 \text{ nb}^{-1}, C = 0.8)$ | Expected events $(L_{\text{int}} = 20 \text{ nb}^{-1}, C = 0.8)$ |
|-----------------|----------------|-------------------------------------------------|-------------------------------------------------|
| $-0.1$          | 4770          | 7650                                      | 7650                                      |
| $-0.05$         | 3330          | 5350                                      | 5350                                      |
| $-0.02$         | 3060          | 4900                                      | 4900                                      |
| 0 (SM)          | 3145          | 5050                                      | 5050                                      |
| $+0.02$         | 3445          | 5500                                      | 5500                                      |
| $+0.05$         | 4350          | 6950                                      | 6950                                      |
| $+0.1$          | 7225          | 11550                                     | 11550                                     |

TABLE I: Integrated fiducial cross sections for Pb+Pb→Pb+Pb+$\tau^+\tau^-$ process for different $a_\tau$ values. The expected number of events assuming 80% selection efficiency and $L_{\text{int}} = 2 \text{ nb}^{-1}$ (current LHC Pb+Pb dataset) or $L_{\text{int}} = 20 \text{ nb}^{-1}$ (expected HL-LHC dataset) are also shown.

The advantage of studying the cross section ratios is the cancellation of several systematic uncertainties, such as the error on integrated luminosity, uncertainties related to lepton reconstruction, but also theoretical uncertainties, e.g. those that are associated with modeling of the initial photon fluxes.

The fiducial cross sections for $\gamma\gamma \rightarrow e^+e^-$ and $\gamma\gamma \rightarrow \mu^+\mu^-$ processes are found to be identical, hence one can equally use either of the process. Experimentally, one can match $\tau_\ell\tau_{1(3)ch}$ channels with $e^+e^-$ events and $\tau_\mu\tau_{1(3)ch}$ channels with $\mu^+\mu^-$ events to maximize cancellation of systematic uncertainties.

The sensitivity of the $a_\tau$ measurement on modeling of initial photon fluxes can be tested by repeating the analysis using the photon–photon luminosity prediction from the STARLIGHT program. As already demonstrated in Sec. II, the differences in the cross sections between STARLIGHT and the results presented in this work can be as large as 20%, mainly due to extra requirements applied in the modelling of single photon flux in
FIG. 7: Ratio of the fiducial cross sections between $\gamma\gamma \rightarrow \tau^+\tau^-$ and $\gamma\gamma \rightarrow \ell^+\ell^-$ ($\ell = e$ or $\mu$) processes as a function of $p_T$ of the leading lepton for all event categories summed together and different $a_\tau$ values: $a_\tau = -0.1, -0.05, -0.02, 0$ (left) and $a_\tau = 0, 0.02, 0.05, 0.1$ (right). The last bin denotes the ratio of integrated fiducial cross sections above $p_T^{\text{lead lepton}} = 20$ GeV.

STARlight.

FIG. 8: Fiducial cross section for the $\gamma\gamma \rightarrow \tau^+\tau^-$ process (left) and the ratio of fiducial cross sections between $\gamma\gamma \rightarrow \tau^+\tau^-$ and $\gamma\gamma \rightarrow \ell^+\ell^-$ ($\ell = e$ or $\mu$) processes (right) as a function of $p_T$ of the leading lepton for all event categories summed together and various photon fluxes. The red curve shows the results with extra $m_{\ell\ell}$ shape reweighting as described in the text. The last bin denotes integrated fiducial cross section (or the ratio) above $p_T^{\text{lead lepton}} = 20$ GeV.

Figure 8 shows the fiducial cross section for $\gamma\gamma \rightarrow \tau^+\tau^-$ process in Pb+Pb UPC at the LHC and its ratio ($R_\gamma$) to the fiducial cross section from $\gamma\gamma \rightarrow \ell^+\ell^-$ ($\ell = e$ or $\mu$) process for the two choices of initial photon fluxes. As expected, the difference in the absolute value of the fiducial cross sections is about 20%. However, after taking the ratio to $\gamma\gamma \rightarrow \ell^+\ell^-$ process, the difference becomes suppressed to 5%. The remaining difference can be explained by the $m_{\ell\ell}$ shape difference between two implementations (as demonstrated already in Figure 5) and the fact that the $p_T$ of the lepton from $\tau$ decay does not necessarily correspond to the $p_T$ of lepton from $\gamma\gamma \rightarrow \ell^+\ell^-$ process. It is also demon-
strated in Figure 8 that an extra reweighting of the shape of $m_{\ell\ell}$ distribution would lead
to differences in the ratio that are less than 1%. However, it should be noted that in reality
the $m_{\ell\ell}$ spectrum can be reweighted directly to the experimental data, thus reducing
significantly the impact of theory modelling uncertainties on the measurement.

The expected number of events from Table I can be translated into expected sensitivity
for probing $a_\tau$. We use the ROOFIT toolkit \cite{48} for the statistical analysis of the results. We
perform fits to $R_\ell(p_T^{lead\;lepton})$ distribution by treating SM results ($a_\tau = 0$) as background
and the difference between $a_\tau = 0$ and $a_\tau = X$ distributions as signal. A test statistic
based on the profile likelihood ratio \cite{49} is used under the Asimov approximation. The
procedure exploits both normalization and $p_T^{lead\;lepton}$ shape differences, providing extra
sensitivity on $a_\tau$ measurement. We use two values of expected systematic uncertainty
(5% and 1%) and two assumptions on Pb+Pb integrated luminosity (2 nb$^{-1}$ to reflect
existing ATLAS/CMS dataset, or 20 nb$^{-1}$ for HL-LHC expectations).

![Figure 9](image1)

**Figure 9**: Expected signal significance as a function of $a_\tau$ for various assumptions on Pb+Pb integrated luminosity (2 nb$^{-1}$ or 20 nb$^{-1}$) and total systematic uncertainty (5% or 1%).

![Figure 10](image2)

**Figure 10**: Expected 95% CL limits on $a_\tau$ measurement for various assumptions on Pb+Pb integrated luminosity (2 nb$^{-1}$ or 20 nb$^{-1}$) and total systematic uncertainty (5% or 1%). Comparison is also made to the existing limits from OPAL \cite{13}, L3 \cite{12} and DELPHI \cite{11} experiments at LEP.

Figure 9 shows expected signal significance as a function of $a_\tau$. The observed asymmety
in sensitivity between positive and negative $a_\tau$ values reflects the destructive interference between SM and the anomalous $\tau$ coupling.

The expected significance can be directly transformed into expected 95% CL limits on
$a_\tau$, shown in Fig. 10. 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 better
than DELPHI limits \cite{11}. 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 by studying ultraperipheral collisions at the LHC have therefore the potential to
significantly improve the existing limits on $a_\tau$.

In addition, using the same methods we study the sensitivity on tau lepton electric dipole moment, $d_\tau$. Our expected 95% CL sensitivity on $|d_\tau|$ assuming $a_\tau = 0$
is: $|d_\tau| < 6.3 \times (4.4) \cdot 10^{-17} \, e \cdot cm$ at the LHC with 5% (1%) systematic uncertainty and $|d_\tau| < 3.5 \cdot 10^{-17} \, e \cdot cm$ at HL-LHC (1% systematic uncertainty). For comparison, the current best limits are measured by Belle experiment [21]: $-2.2 < Re(d_\tau) < 4.5 \times (10^{-17} \, e \cdot cm)$ and $-2.5 < Im(d_\tau) < 0.8 \times (10^{-17} \, e \cdot cm)$. Our projected results on $d_\tau$ can be therefore competitive with Belle limits.

The expected limits on $a_\tau$ and $d_\tau$ are found to be approximately factor of two weaker than those reported in Ref. [35]. This likely points to the issue with EFT approach and the conversion used between the relevant EFT operators and $a_\tau$ when calculating elementary $\gamma\gamma \to \tau^+\tau^-$ cross section.

V. CONCLUSIONS

In this paper, we derived a prediction on the differential cross section of the $\gamma\gamma \to \tau^+\tau^-$ process and its dependence on anomalous electromagnetic couplings of the tau lepton in ultraperipheral Pb+Pb collisions at the LHC. In contrast to previous calculations, which are based on an effective field theory approach, our calculation is derived from first principles and yields a significantly different inclusive cross section dependence on $a_\tau$ than previously reported [35]. We also investigated the expected sensitivity on $a_\tau$ and $d_\tau$, assuming standard LHC detectors using the currently available as well as future datasets. In particular we propose to use cross section ratios of the $\gamma\gamma \to \tau^+\tau^-$ and $\gamma\gamma \to e^+e^- (\mu^+\mu^-)$ processes to probe $a_\tau$, as several systematic uncertainties cancel and the experimental knowledge of $a_e$ and $a_\mu$ is several orders of magnitude more precise than $a_\tau$ itself. Our studies suggest that the currently available datasets of the LHC experiments are already sufficient to improve the sensitivity on $a_\tau$ by a factor of two, hence, we consider this analysis as highly interesting and worthwhile to be done in the future. Future Belle-II experiment should give much better constraints on $|a_\tau| < 1.75 \times 10^{-5}$ and $|d_\tau| < 2.04 \times 10^{-19} \, e \cdot cm$ [26].

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