Feasibility of tau g-2 measurements in ultra-peripheral collisions of heavy ions

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Abstract

The anomalous magnetic moment of the tau lepton, $a_\tau = (g_\tau - 2)/2$, is a sensitive probe of new physics but is extremely difficult to measure precisely in contrast to electron and muon moments. The best experimental limits were set by the DELPHI collaboration more than 15 years ago in studies of the ditau production in the $ee \to ee\tau\tau$ process. Ultra-peripheral collisions (UPCs) of heavy ions at the LHC may provide a unique opportunity to improve the a_τ constraints in the studies of $\mathrm{Pb}+\mathrm{Pb} \to \mathrm{Pb}+\mathrm{Pb}+\tau\tau$ process. We review recent proposals to study ditau production via semi-leptonic tau decays in Pb-Pb UPC with the available ATLAS and CMS data and discuss the feasibility to explore this process down to low transverse momenta of decay leptons with the ALICE and LHCb experiments.

Contents

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1 Introduction

Precision measurements of the tau anomalous magnetic moment $a_\tau = (g_\tau - 2)/2$ are important for verification of QED predictions and searches for physics beyond the Standard Model (BSM), such as lepton compositeness and various supersymmetric scenarios [1]. Experimental a_τ measurements are scarce since the standard spin precession methods are not applicable for a_τ measurements due to the very short τ lifetime. The best limits on a_τ were set by the DELPHI collaboration in the studies of the ditau production in the $ee \to ee\tau\tau$ process [2]:

$$-0.052 < a_\tau < 0.013\,(95\%\,\mathrm{CL}). \tag{1}$$

However there was no progress on experimental measurements of a_τ for more than 15 years.

Latest results of the Muon $g-2$ Collaboration show a significant discrepancy of four standard deviations of the measured muon anomalous magnetic moment a_μ from the Standard Model predictions revealing possible signs of BSM contributions [3]. The tau anomalous magnetic moment is expected to be $m_\tau^2/m_\mu^2 \sim 280$ times more sensitive to BSM physics compared to muon $g-2$, therefore precision measurements of the τ anomalous magnetic moment acquired particular interest.

Ultra-peripheral collisions (UPCs) of heavy ions may provide a unique opportunity to improve the existing limits of the τ anomalous magnetic moment [4, 5]. UPCs are characterized by impact parameters larger than the sum of radii of incoming nuclei [6, 7] therefore electromagnetic processes, such as photon-photon interactions, become dominant in these collisions. Electromagnetic fields of incoming heavy ions can be described in terms of an equivalent photon flux which intensity is proportional to the squared nuclear charge Z^2. Therefore photon-photon interactions in UPCs scale as Z^4 resulting in high cross sections for dilepton pair production and other processes.

In this contribution, we review recent proposals on the tau anomalous magnetic moment measurement via ditau production studies in UPCs with ATLAS and CMS experiments and discuss the feasibility to explore this process down to low transverse momenta of the decay leptons with ALICE and LHCb detectors.

2 Event selection strategy

The process of ditau pair production in Pb–Pb UPCs is illustrated in Fig. 1. Tau leptons are produced in the photon fusion process $\gamma\gamma \to \tau\tau$ with photon-tau vertices being sensitive to the value of the tau anomalous magnetic moment. Sensitivity of the $\gamma\gamma \to \tau\tau$ cross section to the a_τ value is illustrated in Fig. 2.

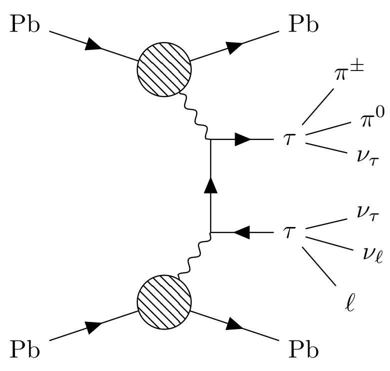

Figure 1: Production and typical decays of tau lepton pairs in Pb–Pb UPC.

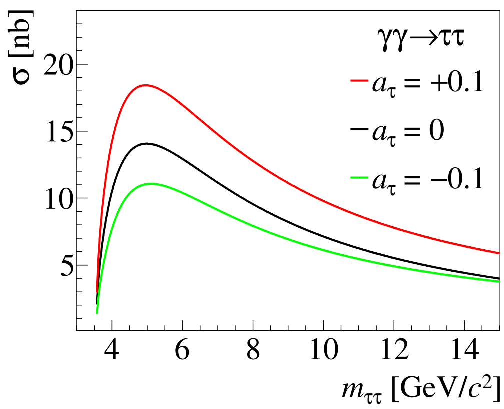

Figure 2: Elementary $\gamma\gamma\to\tau\tau$ cross sections as functions of the ditau invariant mass for different a_τ values. Figure from [8].

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Due to the short lifetime, taus decay into lighter leptons or hadrons before any direct interaction with the detector material. Therefore, in order to study tau pair production process in UPCs, one has to record events with a few charged decay products of tau leptons in an otherwise empty detector. In 35% of cases a tau decays into a lighter lepton accompanied by neutrinos: $\tau^\pm \to \ell^\pm + \nu_\ell + \nu_\tau$ [9]. Taus can also decay into one or three charged pions accompanied by neutrals with the following branching ratios: BR$(\tau^\pm \to \pi^\pm + n\pi^0 + \nu_\tau) = 45.6\%$, BR$(\tau^\pm \to \pi^\pm + \pi^\mp + \pi^\pm + n\pi^0 + \nu_\tau) = 19.4\%$.

The UPC event selection strategy in LHC experiments usually relies on online trigger requirements such as the presence of one or several leptons with $p_\mathrm{T} \gtrsim 1$ GeV/c. Therefore, possible ditau selection strategy can be based on the requirement of a leading lepton from one tau decay accompanied by one or three charged tracks from the other tau.

3 ATLAS and CMS potential

The feasibility of a_τ measurements in the ATLAS [10] and CMS [11] experiments were studied by two groups [4, 5]. L. Beresford and J. Liu [4] performed calculations within the standard model effective field theory (SMEFT), while M. Dyndał et al. [5] used a more conservative approach based on the generalized photon-lepton vertex function. Both groups considered a possibility to measure p_T distributions of leading leptons with high p_T thresholds ($p_\mathrm{T} \gtrsim 4$ GeV/c), accompanied by one or three charged tracks, and provided projections on a_τ limits which can be achieved by ATLAS and CMS in Pb–Pb UPCs at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV with the data sample collected in Run 2 and corresponding to the integrated luminosity of $L = 2$ nb^{-1}. According to estimates performed by M. Dyndał et al. under assumption of 5% systematic uncertainties, ATLAS and CMS will be able to set the following limits on a_τ: $-0.021 \lesssim a_\tau \lesssim 0.017$ (95% CL). SMEFT-based projections by Beresford and Liu appear to be more optimistic. In spite of these differences in the projections, one can expect at least a factor of 2 improvement of DELPHI results. Higher statistics foreseen in LHC Run 3 and 4 and reduced systematic uncertainties will allow ATLAS and CMS to push the limits further.

Typical tau decay products have low transverse momenta, therefore most of the ditau events are inaccessible for reconstruction in ATLAS and CMS at least with existing trigger thresholds. The low transverse momentum region can be accessed by the ALICE and LHCb experiments discussed in the following sections.

4 ALICE potential

The ALICE experiment provides an opportunity to extend the measurement of ditau events down to low transverse momenta of decay leptons in the pseudorapidity range $|\eta| < 0.9$ [12]. During the LHC Run 3 and Run 4, ALICE is going to collect data in the continuous readout mode and accumulate an integrated luminosity of about 2.7 nb^{-1} per one month of Pb–Pb data taking [13]. Energy loss measurements in the ALICE Time Projection Chamber (TPC) can be used for charged particle identification and selection of leading electrons with $p_\mathrm{T} > 0.3$ GeV/c from one tau decay accompanied by one pion or muon from another tau decay. The triggerless data taking will allow ALICE to explore the kinematic region, which is difficult to access in ATLAS and CMS.

In order to study the sensitivity of leading electron p_T-differential yields to the value of the a_τ value, we performed Monte Carlo simulations of the $\mathrm{Pb}+\mathrm{Pb} \to \mathrm{Pb}+\mathrm{Pb}+\tau\tau$ process at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV with a dedicated Upcgen generator [8] that allows one to simulate dilepton pair production in UPCs with an arbitrary value of the magnetic moment. The Upcgen generator is based on the generalized vertex approach used by M. Dyndał et al. [5]. In this approach, the amplitude of the $\gamma\gamma \to \ell\ell$ process is expressed as:

$$\mathcal{M} = (-i)\,\epsilon_{1\mu}\epsilon_{2\nu}\bar{u}(p_3)\Big(i\Gamma^{(\gamma\ell\ell)\,\mu}(p_1)\tfrac{i(\not{p}_t+m_\ell)}{p_t^2-m_\ell^2+i\epsilon}i\Gamma^{(\gamma\ell\ell)\,\nu}(p_2) \\ +i\Gamma^{(\gamma\ell\ell)\,\nu}(p_2)\tfrac{i(\not{p}_u+m_\ell)}{p_u^2-m_\ell^2+i\epsilon}i\Gamma^{(\gamma\ell\ell)\,\mu}(p_1)\Big)v(p_4)\,. \tag{2}$$

Here, p_1 and p_2 are the four-momenta of the photons, p_3 and p_4 are the four-momenta of the produced leptons, $\epsilon_{1\mu}$ and $\epsilon_{2\nu}$ are the polarization vectors of the photons, $p_t = p_2 - p_4$, $p_u = p_1 - p_4$, $\Gamma^{(\gamma\ell\ell)}$ is the generalized vertex function [5], which depends on the magnitude of the momentum transfer q:

$$i\Gamma_\mu^{(\gamma\ell\ell)}(q) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\ell}\sigma_{\mu\nu}q^\nu F_2(q^2)\right], \tag{3}$$

where m_ℓ is the lepton mass, $F_1(q^2)$ and $F_2(q^2)$ are the Dirac and Pauli form factors equal to $F_1(0) = 1$ and $F_2(0) = a_\ell$ in the asymptotic limit $q^2 \to 0$. Photons emitted by relativistic heavy ions are close to this limit since the photon virtuality is of the order of $(\hbar c/R_A)^2 \sim 10^{-3}$ GeV^2 where R_A is the nuclear radius.

The cross section of the dilepton production process $\mathrm{Pb}+\mathrm{Pb} \to \mathrm{Pb}+\mathrm{Pb}+\ell\ell$ is then obtained by convolution of the elementary $\gamma\gamma\to\ell\ell$ cross section and the two-photon luminosity $\mathrm{d}N^2_{\gamma\gamma}/\mathrm{d}Y\mathrm{d}M$:

$$\frac{\mathrm{d}^2\sigma(\mathrm{Pb{+}Pb{\to}Pb{+}Pb{+}}\ell\ell)}{\mathrm{d}Y\mathrm{d}M} = \frac{\mathrm{d}^2N_{\gamma\gamma}}{\mathrm{d}Y\mathrm{d}M}\sigma(\gamma\gamma\to\ell\ell), \tag{4}$$

where Y and M are the rapidity and invariant mass of the dilepton pair. Tau decays into final state products were performed with the Pythia8 decayer [14].

Fig. 3 illustrates an example of leading electron p_T distributions for three different values of a_τ in $\mathrm{Pb}+\mathrm{Pb} \to \mathrm{Pb}+\mathrm{Pb}+\tau\tau$ events at $\sqrt{s_\mathrm{NN}} = 5.02$ TeV corresponding to the integrated luminosity of $L = 2.7\ \mathrm{nb}^{-1}$ that is expected in the first year of the LHC Run 3. According to this figure, the ALICE experiment will be able to accumulate about 70000 ditau event candidates, an order of magnitude higher than the number of ditau events collected by ATLAS and CMS in the LHC Run 2 [4, 5].

One can also notice that the leading electron p_T dependence on a_τ is different at low and high transverse momenta. At electron p_T above 3 GeV/c, the distributions for $a_\tau = 0.1$ and $a_\tau = -0.1$ lie above the distribution corresponding to $a_\tau = 0$, while at lower transverse momenta the spectrum for $a_\tau = -0.1$ is below the $a_\tau = 0$ reference. This nontrivial behaviour

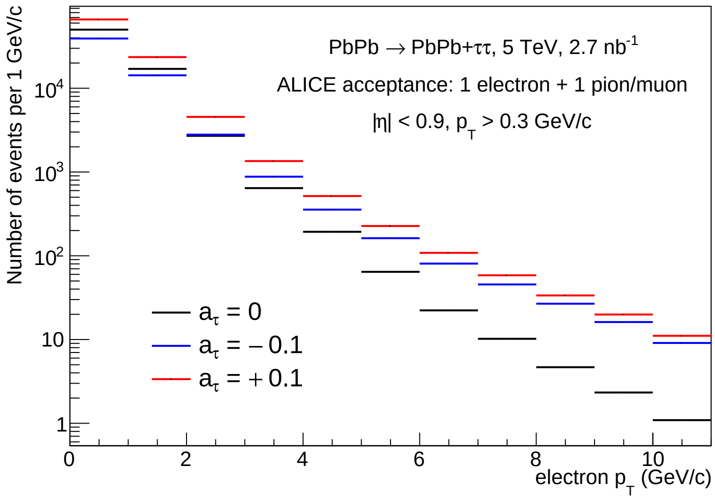

Figure 3: Leading electron p_{T} distributions for three different values of a_τ in $\mathrm{Pb}+\mathrm{Pb}\to\mathrm{Pb}+\mathrm{Pb}+\tau\tau$ events at $\sqrt{s_{\mathrm{NN}}}=5.02$ TeV corresponding to the integrated luminosity of $L=2.7\ \mathrm{nb}^{-1}$.

of the electron spectra for different a_τ values allows to increase the sensitivity to a_τ via p_{T}-differential measurements.

The sensitivity to a_τ can be studied in more detail using the ratios of electron p_{T} yields as a function of a_τ relative to the $a_\tau=0$ reference in several p_{T} intervals. These ratios are shown in Fig. 4 for three p_{T} ranges in which the statistical uncertainty of the yield is expected to be about 1% for the data sample that will be collected by ALICE in the first year of Run 3. These ratios reveal a parabolic dependence on a_τ in the vicinity of $a_\tau=0$ with higher p_{T} ratios showing a steeper raise. In particular, higher p_{T} intervals appear to be more sensitive to positive a_τ values while low p_{T} intervals ensure better sensitivity for negative a_τ.

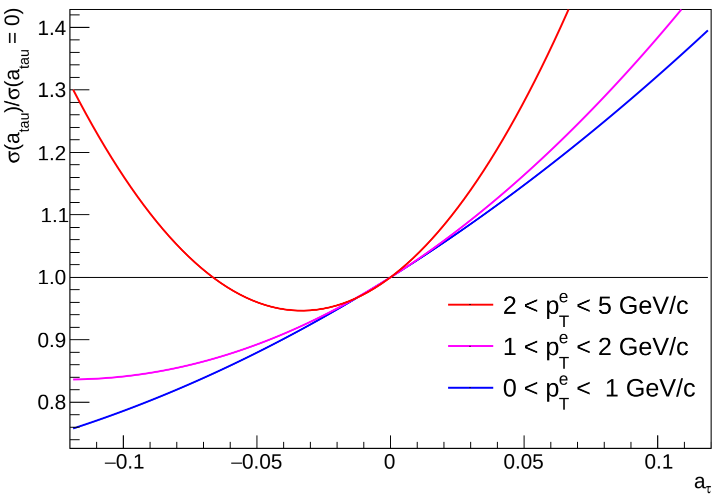

Figure 4: The ratios of electron p_{T} yields as a function of a_τ relative to the yields at $a_\tau=0$ in several p_{T} intervals.

Possible limits on a_τ, which can be set by the ALICE collaboration with the data sample from the first year of Run 3, were estimated using the following χ^2 definition:

$$\chi^2(a_\tau)=\sum_{i,\mathrm{bins}}\frac{[S_i(a_\tau)-S_i(0)]^2}{S_i(0)+\zeta S_i^2(0)} \tag{5}$$

where $S_i(a_\tau)$ is the yield of electrons in the p_T range i, ζ is the expected level of the relative systematic uncertainty. Expected limits on a_τ at 68% and 95% CL are shown in Fig. 5 for three different assumptions on the systematic uncertainty ζ (1%, 3%, 5%) in comparison with DELPHI results and SMEFT predictions corresponding to the range of confinement scales in a composite τ scenario [4].

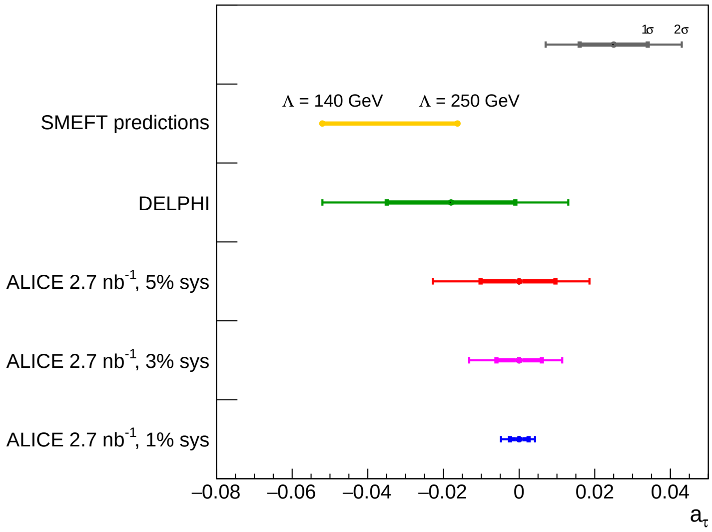

Figure 5: Expected 68% and 95% CL limits on a_τ measurements with the ALICE experiment for three different assumptions on systematic uncertainty (1%, 3%, 5%) in comparison with DELPHI results [2] and SMEFT predictions for a composite τ scenario from [4].

The obtained projections indicate that the ALICE experiment will be able to improve DELPHI limits by at least a factor of 2 for the most pessimistic scenario of 5% systematic uncertainties. Moreover, the level of systematic uncertainties appears to be decisive for the ALICE case. In order to reduce the impact of systematic uncertainties, one can consider the measurement of the p_T–differential electron yields relative to the dilepton production cross section $\gamma\gamma \to \ell\ell$ in the same UPC data sample as was proposed in [5].

5 LHCb potential

The LHCb detector is a single-arm spectrometer covering the forward pseudorapidity range $2 < \eta < 4.5$ and allowing for isolation of electrons from charged hadrons at momenta above 2 GeV/c and reconstruction of muons with momenta above 6 GeV/c [15]. Though the LHCb experiment is not designed to cope with high occupancy of central PbPb collisions, it was able to record UPC events using a dedicated trigger on muons with $p_T > 0.9$ GeV/c [16].

We repeated the analysis described in the previous section for the LHCb case considering a possibility to reconstruct ditau event candidates with one muon ($p > 6$ GeV/c) accompanied by one electron ($p > 2$ GeV/c) in the pseudorapidity range $2 < \eta < 4.5$ and assuming minimum muon p_T threshold of 0.9 GeV/c. These kinematic constraints and typical integrated luminosity of 2 nb^{-1} would allow LHCb to record about 7000 ditau event candidates. The expected limits on a_τ for this statistics are shown in Fig. 6 for different assumptions on the total systematic uncertainty.

Though possible constraints on a_τ are expected to be weaker compared to other LHC experiments, the LHCb experiment will be able to perform the analysis in the clean electron-muon

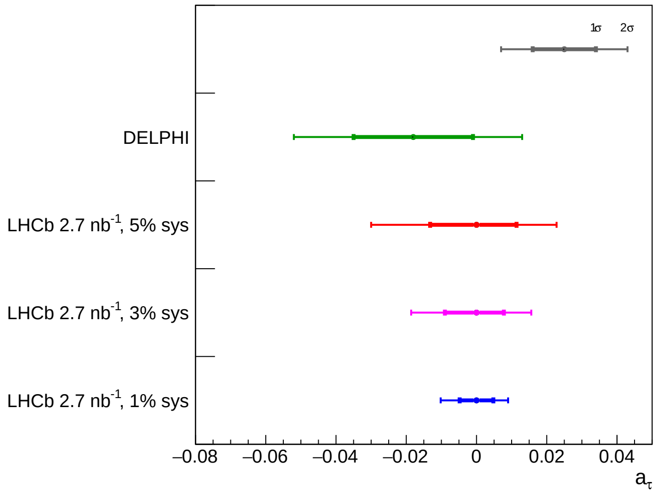

Figure 6: Expected 68% and 95% CL limits on a_τ measurements with the LHCb experiment for three different assumptions on systematic uncertainty (1%, 3%, 5%) in comparison with DELPHI results [2].

channel and in the complimentary rapidity region thus providing a possibility to reduce uncertainties of a cross-experimental measurement.

6 Conclusion

In conclusion, ultra-peripheral collisions at the LHC provide a promising tool to measure the anomalous magnetic moment of the τ lepton. We reviewed recent proposals for the a_τ measurement in ATLAS and CMS with the available $\mathrm{Pb}+\mathrm{Pb} \to \mathrm{Pb}+\mathrm{Pb}+\tau\tau$ event sample and provided our projections for ALICE and LHCb experiements.

The obtained results indicate that the currently recorded dataset in ATLAS and CMS and future ALICE and LHCb data can surpass DELPHI limits by at least a factor of two. The ALICE experiment has a potential to extend the transverse momentum reach of leading electrons from τ decays down to low p_T of about 0.3 GeV/c while the LHCb experiment may provide a measurement in the complimentary rapidity region not accessible by other experiments.

The a_τ measurement via ditau production in UPCs requires careful evaluation of various theoretical uncertainties related to higher order effects [17,18] and precision of the equivalent photon approximation used to calculate the effective two-photon luminosity in ultra-peripheral collisions. These uncertainties will be addressed in the future studies.

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