EPJ Web of Conferences **262**, 01021 (2022) https://doi.org/10.1051/epjconf/202226201021
EXA2021

Feasibility study of tau-lepton anomalous magnetic moment measurements with ultra-peripheral collisions at the LHC

Paul Bühler[1,*], *Nazar* Burmasov[2], *Roman* Lavička[1], and *Evgeny* Kryshen[2]

[1]Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, Vienna, Austria
[2]Petersburg Nuclear Physics Institute named by B. P. Konstantinov of National Research Center «Kurchatov Institute», Gatchina, Russia

Abstract.
Precision measurements of the anomalous electromagnetic moment of leptons (a_l) may serve as one of the most promising directions in the search for new physics beyond the Standard Model. While the experimental value of the electron magnetic moment agrees with theoretical predictions with up to 11 significant digits, the muon magnetic moment shows deviations from the Standard Model value at the level of 4.2 sigma, indicating the possible occurrence of new physics effects. Although the a_τ of the tau lepton with its heavy mass is expected to be $m_\tau^2/m_\mu^2 \approx 280$ times more sensitive to new physics effects than a_μ, measurements of this quantity are rare. This is because the standard spin precession methods are not suitable for a_τ measurements due to the very short tau lifetime.
Ultra-peripheral collisions of heavy ions at the LHC may serve as an alternative tool to measure a_τ. In ultra-peripheral collisions, hadronic interactions are strongly suppressed and long-distance electromagnetic processes dominate, providing an environment to study the electromagnetic properties of the tau lepton. The di-tau production process PbPb $\rightarrow$ PbPb$\gamma\gamma$ $\rightarrow$ PbPb$\tau\tau$ contains two gamma-tau vertices and hence provides enhanced sensitivity to the anomalous magnetic and electric moments.
In this contribution we discuss the feasibility of the a_τ measurement in ultra-peripheral collisions with the ALICE experiment and present projections of the sensitivity of the measurement for the upcoming heavy ion run in 2022 at LHC.

1 Introduction

The magnetic moment $\vec{\mu}_S$ of a charged elementary particle is related to its spin $\vec{S}$ by $\vec{\mu}_S = g \cdot \mu_B \cdot \vec{S}$, where g is the dimensionless g-factor and μ_B the Bohr magneton. The measurement of the lepton magnetic moments μ_l, with $l = e, \mu, \tau$ provides a sensitive test of the Standard Model (SM). A precision measurement is of interest because their SM values can be calculated with high precision and any deviation of the experimental value from the predicted SM values would be an indication for effects of Beyond the Standard Model (BSM) physics. Traditionally, the comparison is made in terms of the anomalous magnetic moment

*e-mail: paul.buehler@oeaw.ac.at

a_l, which is defined as $a_l = \frac{g_l-2}{2}$. Since g_l is approximately 2, a_l is expected to have a value close to 0.

The SM values of the lepton anomalous magnetic moments can be calculated with high precision. In general, they contain contributions from all domains of the SM, from QED, the weak, and the strong interaction. State-of-the-art calculations are discussed in Refs. [1] (electron), [2] (muon), and [3] (tau). Whereas for the electron the "anomaly" is determined by QED effects, contributions by the weak and strong forces are important in the case of the muon and tau. In addition so far unknown BSM particles could contribute as well. Not only in the SM, but also in many new physics models, additional particles with mass M contribute to the theory with terms typically proportional to m_l^2/M^2. For the three charged leptons this implies a relative sensitivity ϵ_l to BSM effects of $\epsilon_e : \epsilon_\mu : \epsilon_\tau = 1 : 42'754 : 12'092'970$, which is a strong motivation for a detailed study of a_τ.

One common method to measure the magnetic moment of a charged particle is by observing its precession in a magnetic field, of which the frequency is directly proportional to the magnetic moment. In order to perform the measurements the leptons must be stored for a long enough time to be able to measure its precession frequency. Such experiments have been realized for electrons [4] and muons [5] with remarkable precision. Within the achieved precision of 11 significant digits the value determined for a_e is in agreement with the SM value and in case of the a_μ it is still to be clarified weather the difference of 4.2 standard deviations between the currently most precise measurement and theory value is an indication of BSM physics or weather this tension is solved by refined calculations [6] or improved measurements [7].

Due to the short lifetime of the tau lepton, the precession method is not suitable to determine its anomalous magnetic moment. For this, however, the fact that the coupling strength of a tau to a pair of photons, $\Gamma_\mu^{\gamma ll}$ depends on a_τ can be exploited. Hence cross sections of reactions including such a vertex are sensitive to the value of a_τ and their precise determination allows to test for deviations of a_τ from its SM value. The photon-lepton vertex function can be parameterized as [8]

$$\Gamma_\mu^{\gamma ll}(q) \propto \gamma_\mu F_1(q^2) + \frac{1}{2m_\tau}(iF_2(q^2) + \gamma_5 F_3(q^2))\sigma_{\mu\nu}q^\nu, \quad (1)$$

where q is the momentum transfer $p' - p$, where p and p' are the four-momenta of the incoming and outgoing leptons, respectively. $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$ is the spin $1/2$ angular momentum tensor, and the γ_k are the Dirac-Matrices. In the static limit where $q = 0$ the form factors $F_{1,2,3}$ are related to the electromagnetic properties of the lepton by $q_l = F_1(q^2 = 0)$, $a_l = F_2(q^2 = 0)$, and $d_l = 2m_l/eF_3(q^2 = 0)$, where q_l is the charge in units of e and d_l the electric dipole moment of the lepton. This results in a quite sizable a_τ dependence of the elementary $\gamma\gamma \to \tau^+\tau^-$ cross sections as shown in Figure 1.

The best measurement of a_τ has been made by the DELPHI collaboration by measuring the cross section of the reaction $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\tau^+\tau^-$ at LEP2 [10]. The experimental and theoretical values of the lepton anomalous magnetic moments are summarized in Table 1. Whereas in the case of the electron and muon the precision of the experimental and theoretical value are of the same order of magnitude, this is different in the case of the tau lepton, where the measured value lacks precision.

A number of proposals for improvement of the experimental limits have been put forward including measurements at Belle-II [11], LHC [12] and future facilities like CLIC [13], LHeC and FCC-he [14] or high-luminosity B factories [15]. The possibility to determine a_τ in heavy-ion ultra-peripheral collisions (UPCs) was pointed out by del Aguila et al. [16] already in 1991. Recently, this idea has been taken up and feasibility studies to perform this measurement at LHC with the CMS and ATLAS experiments have been presented [17, 18].

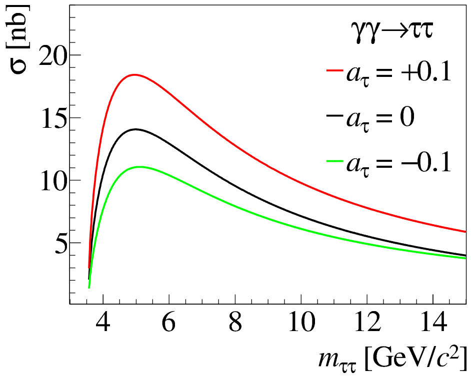

Figure 1. Cross section of the $\gamma\gamma \to \tau^+\tau^-$ reaction as function of the 2τ invariant mass $m_{\tau\tau}$ for different values of the tau anomalous magnetic moment a_τ [9].

Table 1. Theoretical and experimental values of the lepton anomalous magnetic moments.

lepton	theory		experiment	
electron	$1159652181.606(11) \times 10^{-12}$	[1]	$1159652180.91(26) \times 10^{-12}$	[20]
muon	$116591810(43) \times 10^{-11}$	[2]	$116592061(41) \times 10^{-11}$	[5]
tau	$117721(5) \times 10^{-8}$	[3]	$-0.052 < a_\tau < 0.013$ (95%C.L.)	[10]

In the remaining of this paper we will discuss the method and the possibility to measure a_τ with the ALICE experiment in UPCs.

2 Measurement of a_τ with UPCs

Ultra Peripheral Collisions are collisions of heavy ions in which the impact parameter b is larger than the sum of the radii of the colliding projectiles. Due to the large impact parameter hadronic reactions are heavily suppressed and electromagnetic interactions dominate. In UPCs, the ions flying past each other, produce strong electromagnetic fields that effectively form intense fluxes of energetic photons. The flux of photons $n(w)$ of a given energy w can be calculated using the equivalent photon approximation (EPA) [19]. The photons are almost real ($q^2 \sim 0$) and the spectrum is rather soft, making UPCs an ideal place to study the electromagnetic properties of the tau lepton.

Here we consider the photoproduction of di-tau in the reaction PbPb $\to$ PbPb$\tau^+\tau^-$ which is depicted in Figure 2. Since the photon flux from an ion scales with Z^2, where Z is the charge of the ion, the related cross section is expected to scale with Z^4. The UPC cross section, σ_{PbPb}, is given by the convolution of the photon spectra with the elementary photon-photon cross section $\sigma_{\gamma\gamma}$ by[1]

$$\sigma_{PbPb} = \int_0^\infty \int_0^\infty \sigma_{\gamma\gamma} \cdot n_{Pb}(w_1) \cdot n_{Pb}(w_2)\, dw_1 dw_2. \quad (2)$$

In order to measure the cross section of the above reaction one needs to detect the decay products of the outgoing taus. The dominating decay channels of the tau are listed in Table 2 together with the respective branching ratios. All decay channels include neutrinos which are not detected with the apparatus at LHC. The analysis strategy is thus not the exclusive

[1]A more precise approach takes into account the impact parameter dependence of the photon fluxes and the probabilitiy of hadronic interactions between colliding nuclei [9].

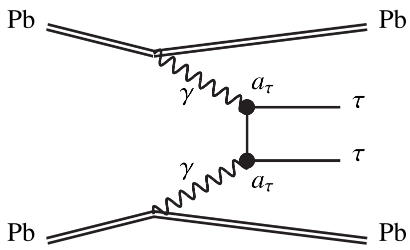

Figure 2. Pair production of tau leptons in Pb–Pb UPCs. The cross section for this process depends on the value of the anomalous magnetic moment a_τ.

reconstruction of the events but the detection of events with a lepton (electron or muon) plus one or three additional charged particles and otherwise empty detectors. Possible background reactions from hadronic interactions are effectively suppressed by the few-prong condition. Exclusive production of di-electron/muon pairs, an other potential source of background, is distinguished by the back-to-back emission of the two leptons. Semi-coherent di-lepton production in which the momentum transfer from a gamma to an ion leads to the dissociation of the ion, is accompanied by emission of forward neutrons, which are detectable in the Zero Degree Calorimeters (ZDC) of the systems.

Table 2. Dominating decay channels of tau leptons [20].

Decay channel	Branching ratio [%]
$\tau^\pm \to e^\pm \nu_e \nu_\tau$	17.8
$\tau^\pm \to \mu^\pm \nu_\mu \nu_\tau$	17.4
$\tau^\pm \to \pi^\pm \nu_\tau + n\pi^0$	45.6
$\tau^\pm \to$ 3 prong	~ 20

3 ALICE potential for Run 3

ALICE has gained quite some experience with UPC physics during Run 1 & 2 and its detector is well equipped for this (see e.g. [22]). During the last three years, during the long shutdown at LHC, the ALICE experiment has been upgraded to cope with a continuous data acquisition mode for Run 3 & 4 [21] which will allow to acquire Pb–Pb collisions at a maximum rate of 50 kHz. For the analysis of UPCs, ALICE profits of many of its sub-detectors. The Inner Tracking System (ITS) and Time Projection Chamber (TPC) are the central tracking detectors. They allow to identify charged particles with transverse momenta down to a few hundred MeV in the pseudorapidity range of $|\eta| < 0.9$. The region at $-4 < \eta < -2.5$ is covered by a muon arm. With the recently installed Muon Forward Tracker a precise determination of the production vertex will be possible allowing to discriminate muons produced in secondary vertices. The Fast Interaction Trigger detector (FIT) consists of several sub-detectors which are not only important for luminosity measurements, but also allow to veto additional activity over a large η range. Whereas the electrons can be well identified in the central region of ALICE, it is more difficult to distinguish muons from pions due to their similar mass and hence similar energy deposit in the sensitive parts of the detector. In the range covered by the muon arm, muons can be identified. Hence in ALICE two types of events will be considered for this measurement - events with an identified electron (leading electron) and an additional charged track in the central barrel (central event type) and events with a muon in forward direction plus a charged track in the central barrel (semi-forward event type).

It is planed that in Fall 2022 ALICE will accumulate an integrated luminosity of 2.7 nb^{-1} of Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV. In order to study the ALICE potential to measure a_τ with this data we performed simulations with the event generator Upcgen [9]. The estimated yield of central events in the ALICE fiducial acceptance is estimated to be around 35′000 and the yield of semi-forward events, approximately 2′000. In Figure 3 the yield of central events is plotted as function of p_T of the leading electron for different values of a_τ.

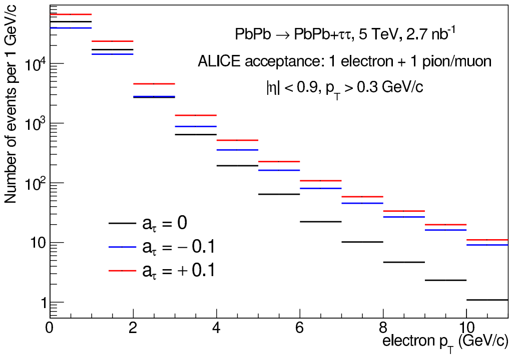

Figure 3. Number of PbPb → PbPb$\tau^+\tau^-$ events expected to be seen by the ALICE detector during the Fall 2022 Pb–Pb run at LHC. Here at least one of the taus is assumed to decay to $e^\pm \nu_e \nu_\tau$. The yield is plotted as function of the leading electron p_T for three different values of a_τ. Both, the absolute value and the slope of the yield function are sensitive to a_τ.

The p_T spectrum does not only simply scale with the value of a_τ but also changes slope. This is demonstrated with Figure 4 where the relative changes of the yields are plotted as function of a_τ for three different p_T bins of the leading electron. Whereas the a_τ dependence at low p_T is approximately linear, it becomes parabolic at higher momenta. This complex p_T-differential behavior of the a_τ dependence can be exploited to enhance the sensitivity of the measurement.

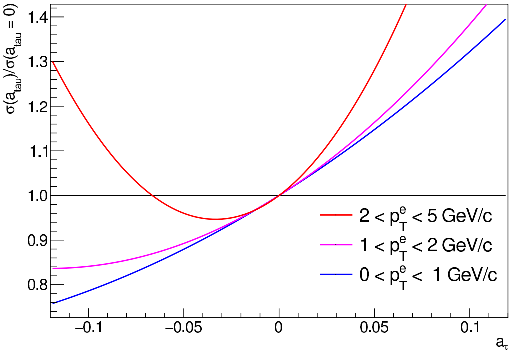

Figure 4. Relative change of central events as function of a_τ in three distinct bins of the leading electron p_T. Whereas the a_τ dependence at low p_T is approximately linear, it becomes parabolic at higher momenta.

The upper limit on a_τ, which can be set by the ALICE collaboration with the data sample from the first year of Run 3, are estimated using the following definition of χ^2

$$\chi^2(a_\tau) = \sum_i \frac{(S_i(a_\tau) - S_i(0))^2}{S_i(0) + \zeta S_i^2(0)}, \tag{3}$$

where $S_i(a_\tau)$ is the yield of leading electrons in the p_T bin i and ζ is the expected level of the relative systematic uncertainty. Background contributions are neglected here. Expected limits on a_τ at 68% and 95% CL are shown in Figure 5 for three different assumptions about the systematic uncertainty ζ (1%, 3%, 5%). The systematic errors will be dominated by the uncertainty of the luminosity determination and track reconstruction. For comparison, the DELPHI results and Standard Model Effective Field Theory (SMEFT) predictions corresponding to the range of confinement scales in a composite tauon scenario [17] are also included in the figure.

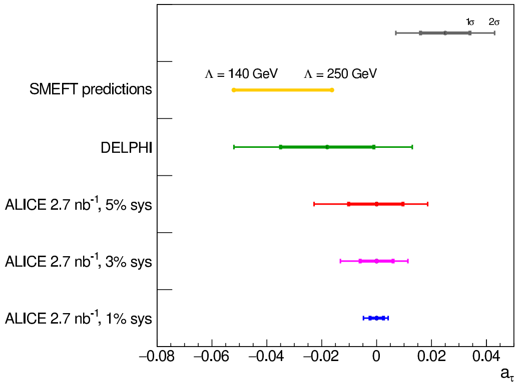

Figure 5. Comparison of the limits on a_τ from DELPHI and expected from the first year of Run 3 data taking with ALICE. The final value from ALICE will depend on the value of the achieved systematic errors. The SMEFT limits correspond to the range of confinement scales in a composite tau scenario.

4 Conclusion

UPCs at LHC provide a unique opportunity to study electromagnetic processes. In particular, with data from Run 3 limits of the anomalous magnetic moment of the tau lepton can be determined by measuring the cross section of the di-tau photoproduction in the PbPb $\to$ PbPb$\tau\tau$ process. Depending on the systematic errors which will be achieved, the data accumulated in the first year of Run 3 will allow ALICE to set new limits which are significantly below the existing best value published by the DELPHI collaboration in 2004.

Acknowledgments
This work is supported by the Austrian Science Fund (FWF, I 5277-N) and the Russian Foundation for Basic Research (RFBR, project No. 21-52-14006).

References

[1] T. Aoyama, T. Kinoshita, and M. Nio, Atoms **7**, 28 (2019).
[2] T. Aoyama et al., Physics Reports **887**, 1 (2020).
[3] S. Eidelman and M. Passera, Mod. Phys. Lett. A **22**, 159 (2007).
[4] D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, Phys. Rev. A **83**, 052122 (2011).
[5] B. Abi et al., Phys. Rev. Lett. **126**, 141801 (2021).
[6] Sz. Borsanyi et al., Nature **593** (2021) 51.
[7] M. Abe et al., Prog. Theor. Exp. Phys. **2019** (2019) 053C02.
[8] M. E. Peskin and D. V. Schroeder, CRC Press, ISBN-13: 978-0-201-50397-5 (1995).
[9] N. Burmasov et al., arXiv:2111.11383 (2021).
[10] The DELPHI collaboration, Eur. Phys. J. C **35**, 159 (2004).
[11] X. Chen and Y. Wu, J. High.Ener.Phys. **2019**, 10 (2019).
[12] A. S. Fomin et al., J. High.Ener.Phys. **2019**, 3 (2019).
[13] A.A. Billur et al., Phys. Rev. D **98**, 095013 (2018).

[14] M. Köksal, J. Phys. G **46**, 065003 (2019).
[15] A. Crivellin, M. Hoferichter, and J. M. Roney, arXiv:2111.10378 [hep-ph] (2021).
[16] F. del Aguila, F. Cornet, and J.I. Illana, Phys. Lett. B **271**, 256 (1991).
[17] L. Beresford and J. Liu, Phys. Rev. D **102**, 11 (2020).
[18] M. Dyndał et al., Phys. Lett. B **809**, 135682 (2020).
[19] C. F. V. Weizsäcker, Z.Physik **88**, 612 (1934); E. J. Williams, Kgl. Danske Vidensk. Selskab. Mat.-Fiz. Medd. **13**, 4 (1935).
[20] P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and (2021) update.
[21] ALICE collaboration, J. Phys. G **41** 087001 (2014).
[22] ALICE collaboration, Eur. Phys. J. C **79** 5 (2019), Phys. Lett. B **798** 134926 (2019), JHEP **6** 35 (2020), Phys. Lett. B **817** 136280 (2021), Eur. Phys. J. C **81** 712 (2021).