TAU ANOMALOUS MAGNETIC MOMENT MEASUREMENT AT ATLAS AND CMS*

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on behalf of the ATLAS and CMS collaborations

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This paper outlines results from the measurement of the anomalous magnetic dipole moment of the τ lepton (a_τ) using $\gamma\gamma \to \tau^+\tau^-$ events from ultra-peripheral Pb+Pb collisions recorded by CMS in 2015 and by ATLAS in 2018 at the LHC. The first and most stringent experimental constraints on a_τ were established by the DELPHI Collaboration in 2004, during their investigations of the ditau production in the $e^+e^- \to e^+e^-\tau^+\tau^-$ process. Relativistic heavy-ion beams at the LHC are accompanied by a substantial flux of equivalent photons, which lead to photon-induced processes. This paper describes two analyses of the photon-induced production of tau pairs and constraints on the tau lepton's anomalous magnetic dipole moment analysing ultra-peripheral Pb+Pb collisions.

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1. Introduction

In recent decades, the exploration of photon-induced processes in heavy-ion (HI) collisions has emerged as a promising avenue for understanding physics beyond the Standard Model (BSM). The ATLAS [1] and CMS [2] experiments at the Large Hadron Collider (LHC) allocate part of their operational time to study these processes, particularly in ultra-peripheral collisions (UPC). UPCs are distinguished by the distance between two incoming nuclei that is greater than the sum of their ion radius which facilitates photon–photon interactions due to the significant electromagnetic fields generated by relativistic ions. Such strong photon–photon interactions can be described by the Equivalent Photon Approximation [3, 4]. These

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interactions, specifically in $\mathrm{Pb}+\mathrm{Pb} \to \mathrm{Pb}(\gamma\gamma \to \tau\tau)\mathrm{Pb}$, exhibit a substantial increase in cross sections owing to the Z^2 scaling of photon fluxes (with Z being 82 for Pb). Moreover, the low hadronic pile-up in HI collisions enables the identification of exclusive events and the triggering on low-p_{T} particles, making UPC a valuable tool for investigating rare processes and probing BSM phenomena.

An essential focus of research lies in measuring the anomalous magnetic moments of leptons, denoted as $a_l = \frac{1}{2}(g_l - 2)$, which serve as fundamental tests of the Standard Model (SM) and offer insights into potential BSM physics, such as lepton compositeness [5] or supersymmetry [6]. While the anomalous magnetic moments of electrons and muons are extensively studied and precisely measured, the τ lepton's a_τ remains less constrained due to experimental challenges arising from its short lifetime. The ATLAS and CMS collaborations published two independent measurements, see Refs. [7, 8], respectively, on the first observation of tau-lepton pair production in UPC HI collisions with a significance exceeding five standard deviations in both experiments. These measurements hold significant promise for detecting BSM effects and advancing our understanding of particle physics beyond the SM.

2. Experimental ATLAS and CMS setups

2.1. ATLAS realisation

Analysis conducted by the ATLAS Collaboration presents the observation of the $\gamma\gamma \to \tau^+\tau^-$ process using data recorded from Pb+Pb UPC in 2018 at $\sqrt{s_{NN}} = 5.02$ TeV, with an integrated luminosity of 1.44 nb^{-1}, see Ref. [7]. The analysis strategy is to use the cross-section dependence of the $\gamma\gamma \to \tau^+\tau^-$ and the dependence of the muon shape p_{T} on a_τ. Due to the extremely low-p_{T} values of the signal τ-leptons, the identification techniques used by standard ATLAS analyses cannot be used. Instead, this analysis requires the presence of one muon from τ-lepton decay and either an electron or charged-particle track(s) from the decay of the other τ-lepton. The analysis defines three different signal regions (SR): muon and electron (μe-SR), muon and one track (μ1T-SR), and muon and three tracks (μ3T-SR). The muons selected for the analysis must have transverse momentum $p_{\mathrm{T}} > 4$ GeV and pseudorapidity $|\eta| < 2.4$, while the selected electrons must have $p_{\mathrm{T}} > 4$ GeV and $|\eta| < 2.47$, and selected tracks should have $p_{\mathrm{T}} > 100$ MeV and $|\eta| < 2.5$. Events containing additional low-p_{T} tracks are discarded. To guarantee the exclusivity of the selected events, a veto was imposed on the forward neutron activity in the Zero Degree Calorimeter. Since different background processes contribute differently to each signal category, the additional requirements specified in μ1T-SR, p_{T} of the muon-track pair $p_{\mathrm{T}}^{\mathrm{trk}} > 1$ GeV, and for μ3T-SR, the mass of the three-track system must satisfy $m_{3\mathrm{trk}} < 1.7$ GeV.

The signal data sets were generated via simulation with the STARlight 2.0 Monte Carlo (MC) generator [9], interfaced with TAUOLA [10] for the decay of τ-leptons and PYTHIA 8.245 [11].

The main sources of background contributions stem from the exclusive production of dimuons ($\gamma\gamma \rightarrow \mu^+\mu^-$) and diffractive photonuclear interactions. The first relies on STARlight and PYTHIA8 MC generators (MadGraph [12] used specifically for radiative dimuon background) with the photon flux distribution reweighted to SuperChic 3.05 [13]. Estimating the second contribution involves employing a data-driven approach implementing the additional dimuon control region (2μCR), requiring two opposite-charge muons with the invariant mass above 11 GeV to suppress quarkonia backgrounds and no additional tracks separated from the muons by $\Delta R_{\mu,\mathrm{trk}} > 0.1$. A fitting procedure to the muon p_{T} distribution in the SRs and CR is executed to extract the value of a_τ.

2.2. CMS realisation

The CMS experiment was conducted to measure the exclusive production of ditau particles. This was carried out using data from Pb+Pb collisions based on 404 $\mu\mathrm{b}^{-1}$, recorded in 2015 at a collision energy of $\sqrt{s_{NN}} =$ 5.02 TeV, see Ref. [8] for more details. The τ-leptons reconstruction involved identifying one muon and three charged hadrons, assumed to be pions, within a defined phase space characterized by their p_{T} and η. This approach aimed to optimize both the purity of the signal and the efficiency of the detector acceptance. Event selection was performed in real-time, requiring a single muon with no specific p_{T} threshold, at least one-pixel track, and a minimum level of event activity above the noise threshold in the forward hadron (HF) calorimeter. To ensure the events were UPC and to further minimize background interference, the energy deposition in the leading tower of HF must be lower than 4 GeV.

One muon and exactly three charged tracks are required in the phase-space region of the signal. The muon pseudorapidity must be $|\eta| < 2.4$, the muon transverse momentum is $p_{\mathrm{T}} > 3.5$ GeV for $|\eta| < 1.2$ and $p_{\mathrm{T}} > 2.5$ GeV for $|\eta| < 1.2$. The three paths identified as charged hadrons (pions) and forming the "3-prong" τ-lepton candidate [14] must be within the acceptance range of the tracker ($|\eta| < 2.5$), and their common vertex must be within 2.5 mm of the primary vertex in the z direction. The p_{T} must be greater than 0.5 and 0.3 GeV for the leading- and subleading-p_{T} pions, respectively. The selected tracks must also be identified as "high-purity" tracks [15]. The 3-prong hadronic τ candidate must have the opposite charge to the selected τ_μ candidate and have $p_{\mathrm{T}}^{\mathrm{vis}} > 2$ GeV, where $p_{\mathrm{T}}^{\mathrm{vis}}$ is the vector sum p_{T} of the three pions. In addition, the invariant mass of the 3-prong τ candidate must be between 0.2 and 1.5 GeV.

The signal is simulated using a specific $\gamma\gamma \to \tau^+\tau^-$ MC sample generated through MadGraph5_aMC@NLO (v2.6.5) [16]. For hadronization and decay processes, PYTHIA8 (v2.1.2) [11] is employed, while Geant4 [17] is used to simulate detector effects such as resolution, tracking, and trigger efficiency. These effects are adjusted by comparing them with the experimental data. Signal distributions are normalized to align with the QED predictions from Ref. [16]. Background estimation follows a data-driven approach, utilizing CRs of phase space with either a higher-number of charged-hadron tracks per event or higher energy deposition in the HF. Comparing observed data with both simulated signal and background estimated by data-driven method showed good agreement.

3. Fitting of a_τ

In the analysis conducted by ATLAS, a total of 656 data events were recorded across three signal regions following event selection criteria. The significance is the highest in the μ1T-SR, while the largest signal-to-background ratio is observed in the μe-SR. To measure a_τ, a profile likelihood fit in the three SRs and 2μ-CR is used, in which a_τ is the only free parameter. The distribution of muon p_{T} is chosen due to its high sensitivity to a_τ. Various templates are used with differing a_τ values, while in the standard signal instance, a_τ is set to the SM value ($a_\tau^{\mathrm{SM}} = 0.00117721(5)$) [18]. Samples reflecting various a_τ hypotheses are generated by adjusting the nominal sample across three dimensions (ditau invariant mass, rapidity, and difference in pseudorapidity between the two τ-leptons) [19]. This approach is consistent with the methodology used in the earlier LEP studies [20–22]. As a result, 14 samples covering the full range of a_τ values ($-0.1, -0.06, -0.05, -0.04, -0.03, -0.02, -0.01, +0.01, +0.02, +0.03, +0.04, +0.05, +0.06, +0.1$) were used. The muon p_{T} after fitting in different signal regions (SR) and control regions (CR) are shown in figure 1. The fit effectively reproduces the data, and the post-fit distributions show a noticeable reduction in uncertainty (as shown in the ratio panel). The discrepancies between SM and BSM a_τ values depend on the muon p_{T}.

In the analysis performed by CMS, the signal is extracted using a binned maximum likelihood fit of signal and background components. The fit is performed on the binned distribution of the difference in azimuthal opening angle between the τ_μ and the 3-prong τ candidates, $\Delta\phi(\tau_\mu, \tau_{3\mathrm{prong}})$. The signal distribution is derived from simulation, while that of the background is obtained from a data-driven method. The pre-fit number of signal events is scaled to match the QED prediction of Ref. [16]. The chosen criteria resulted in the identification of 91 candidate events corresponding to the $\gamma\gamma \to \tau^+\tau^-$ process. Systematic uncertainties may affect both the normalization and the

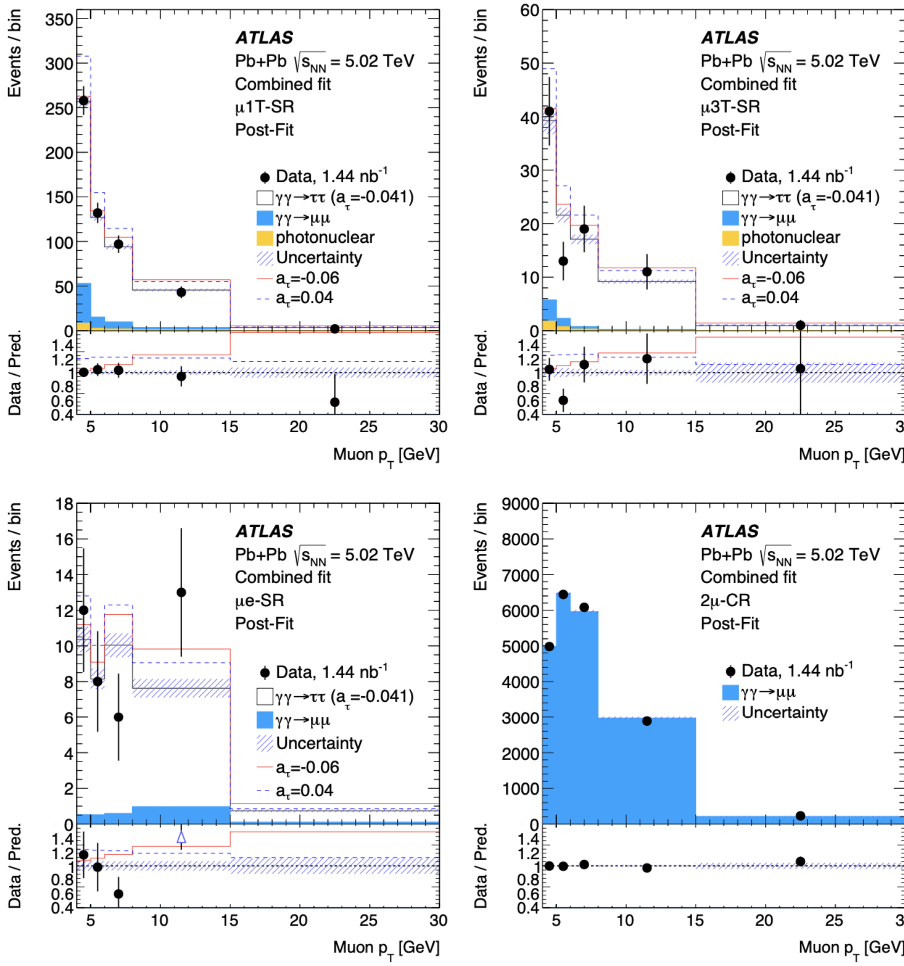

Fig. 1. (Colour on-line) Data points are represented by black markers, while the stacked histograms show the different components contributing to each region. The post-fit distributions show the signal contribution corresponding to the best-fit value of a_τ ($a_\tau = -0.041$). In addition, the signal contributions with alternative values of a_τ are illustrated as continuous red ($a_\tau = -0.06$) or dashed blue ($a_\tau = 0.04$) lines for comparison. The bottom panel shows the ratio of data to predictions after fitting and vertical bars indicating uncertainties due to a finite number of data events. The hatched bars indicate the systematic uncertainties as $\pm 1\sigma$ of the predictions, considering the limitations due to fitting. Use permitted from Ref. [7] under the Creative Commons Attribution License CC BY 4.0.

shape of the $\Delta\phi(\tau_{\mu}, \tau_{3\text{prong}})$ distributions. These uncertainties, in addition to the bin-by-bin variations of the signal and background templates, are represented by nuisance parameters in the fit. The negative log-likelihood is minimized by varying the nuisance parameters according to their uncertainties and by scaling the signal by a multiplicative factor μ.

The best-fit value of the signal strength is given by the minimization of the negative log-likelihood and corresponds to $\mu = 0.99^{+0.16}_{-0.14}$ with $N^{\tau\tau}_{\text{sig}} = 77 \pm 12$ signal events in the integral of the post-fit signal component. The fit result is shown in figure 2, where the signal template is represented by the magenta/dark grey histogram, the background by the green/light grey histogram, and the data by the black points. The contributions are stacked with their total uncertainty represented by the blue hatched area. The fiducial cross section is found to be $\sigma(\gamma\gamma \to \tau^-) = 4.8 \pm 0.6(\text{stat.}) \pm 0.5(\text{syst.})$ μb.

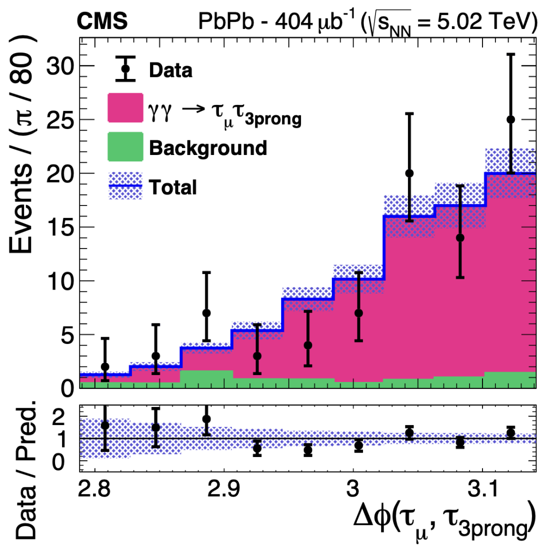

Fig. 2. (Colour on-line) The discrepancy in the azimuthal dilation angle between the candidates $\tau\mu$ and 3-prong τ candidates is shown. Data points are marked with vertical bars representing statistical uncertainties. The signal (background) contribution is illustrated by the magenta/dark grey (green/light grey) histogram after fitting. The overall distribution is indicated by the blue/black line and the hatched area indicates the combined statistical and systematic uncertainties. The bottom panel shows the ratio of data to signal and background predictions, with the hatched band representing the total uncertainty in the predictions after fitting. Use permitted from Ref. [8] under the Creative Commons Attribution License CC BY 4.0.

CMS and ATLAS use variations of the total $\sigma(\gamma\gamma \to \tau^+\tau^-)$ to place model-dependent first limits on a_τ at the LHC. These limits are $(-0.088 < a_\tau < 0.056)$ at 68% confidence level (C.L.) obtained by CMS. ATLAS measured the best-fit a_τ value as $a_\tau = -0.041$ with the corresponding 68% and 95% C.L. being $(-0.050, -0.029)$ and $(-0.057, 0.024)$, respectively, while the most stringent limits on a_τ are currently provided by the DELPHI experiment at LEP: $-0.052 < a_\tau < 0.013$ (95% C.L.) [20]. The precision of both measurements is limited by statistical uncertainty and competitive with DELPHI results.

4. Summary

This paper highlighted the significance of UPC in exploring rare SM processes and searching for BSM phenomena. The $\gamma\gamma \to \tau^+\tau^-$ process has been observed for the first time in Pb+Pb UPC by the ATLAS and CMS experiments, exceeding a 5σ significance. Signal strengths provided by both measurements are consistent with SM expectations. The new constraints on the τ-lepton anomalous magnetic dipole moment are competitive to the best limits obtained during the LEP era and could be improved with a larger data set collected in future LHC runs.

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