First measurement of the $\gamma\gamma \to \tau^+\tau^-$ production in PbPb collisions with the CMS experiment*

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The observation of the τ lepton pair production in ultraperipheral nucleus-nucleus collisions, a pure quantum electrodynamics (QED) process, is presented. The measurement is based on a data sample collected by the CMS experiment at a per nucleon center-of-mass energy of 5.02 TeV, and corresponding to an integrated luminosity of $404\,\mu\mathrm{b}^{-1}$. The photon-induced $\gamma\gamma \to \tau^+\tau^-$ production is observed with a statistical significance of at least five standard deviations in a decay process involving one muon and three particles identified as charged pions in the final state. The cross section is measured in a fiducial phase space region, and is found to be $\sigma(\gamma\gamma \to \tau^+\tau^-) = 4.8 \pm 0.6\,(\mathrm{stat}) \pm 0.5\,(\mathrm{syst})\,\mu\mathrm{b}$, in agreement with leading-order QED predictions. The $\sigma(\gamma\gamma \to \tau^+\tau^-)$ measurement is used to determine for the first time the anomalous magnetic moment of the τ lepton a_τ, which is currently poorly constrained. This approach can be used to produce constraints on a_τ that surpass the current best from previous lepton-lepton colliders.

1. Introduction

One of the contributing factors in the couplings of leptons (ℓ) with photons (γ) is the anomalous magnetic moments $a_\ell = (g-2)_\ell/2$, with the g-factor being the proportionality constant that relates the magnetic moment to the spin of the lepton. Ultraperipheral collisions (UPC) of heavy ions provide an extremely clean environment [1] to probe a_τ [2] at the LHC, and hence offering ample room for searching for physics beyond the standard model.

Here, we present [3] an observation of photoproduction of pairs of τ leptons in lead-lead (PbPb) collisions $\mathrm{PbPb}\,(\gamma\gamma) \to \mathrm{Pb}^{(*)}+\mathrm{Pb}^{(*)}\,\tau^+\tau^-$ (hereafter referred to as $\gamma\gamma \to \tau^+\tau^-$). As shown in Fig. 1, the τ leptons are

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reconstructed in a decay process involving in the final state one muon and three particles ("prongs") identified as charged pions (π) over a fiducial phase space region defined by the muon and pion transverse momenta (p_{T}) and their pseudorapidities (η). The ATLAS Collaboration has also reported a measurement of $\gamma\gamma \to \tau^+\tau^-$ using a larger PbPb data sample with an integrated luminosity of $1.44\,\mathrm{nb}^{-1}$ [4, 5].

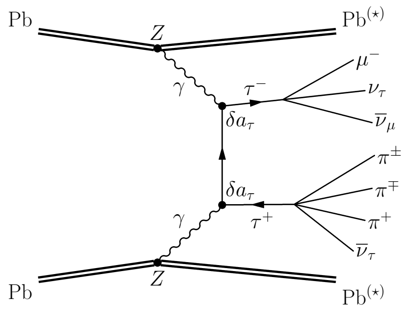

Fig. 1. Leading-order QED diagram for the photoproduction of a pair of τ leptons $\gamma\gamma \to \tau^+\tau^-$ in ultraperipheral PbPb collisions. The presence of $\gamma\tau\tau$ vertices gives enhanced sensitivity to the anomalous electromagnetic couplings of the τ lepton; here, the anomalous magnetic moment a_τ is highlighted [3].

2. Event selection, signal and background estimation

The analysis is based on a data sample collected by the CMS experiment [6] at a per nucleon center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ in 2015, and corresponding to an integrated luminosity of $404\,\mu\mathrm{b}^{-1}$. We filter UPC events by requiring in real time ("online") a single muon with no p_{T} threshold requirement and minimum event activity above the noise threshold in the forward hadron (HF) calorimeter ($3.0 < |\eta| < 5.2$). For the "τ_μ" candidate, an offline cut is applied on its pseudorapidity to be $|\eta| < 2.4$ and is required to be labeled as "soft" [7]. The requirement on the transverse momentum varies, depending on its $|\eta|$, and is $p_{\mathrm{T}} > 3.5\,\mathrm{GeV}$ for $|\eta| < 1.2$ and $p_{\mathrm{T}} > 2.5\,\mathrm{GeV}$ for $|\eta| \geq 1.2$. The tracks forming the "τ_{3prong}" candidate are identified as charged pions by the particle-flow algorithm, required to be within the tracker acceptance ($|\eta| < 2.5$), and close longitudinally and vertically to the primary vertex. The minimum transverse momentum is 0.5 (0.3) GeV for the leading- and subleading-p_{T} pions, respectively. The selected tracks are also required to be labeled as "high-purity" [8] tracks. The τ_{3prong} candidate is then required to be of opposite charge relative to the selected τ_μ, and to have $p_T^{vis} > 2$ GeV, where p_T^{vis} is the vector sum p_T of the three pions. Additionally, the visible invariant mass of τ_{3prong} candidate is required to be less than 1.5 GeV.

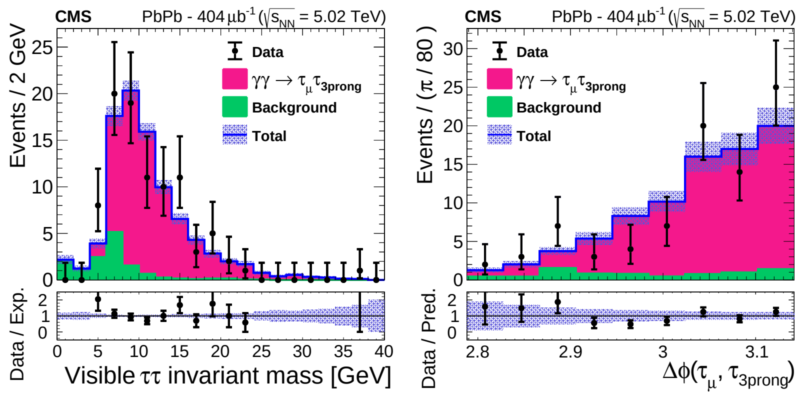

Fig. 2. Left: Invariant mass of the three pions forming the τ_{3prong} candidate. Right: Difference in azimuthal opening angle between the τ_μ and τ_{3prong} candidates. In both cases, the signal component (magenta histogram) is stacked on top of the background component (green histogram), considering their prefit (left) or postfit (right) normalizations. The sum of signal and background is displayed by a blue line and the shaded area shows the statistical uncertainty (left) or the total uncertainty in the postfit prediction (right. The data are represented with black points and the uncertainty is statistical only. The lower panels show the ratios of data to the signal-plus-background prediction, and the shaded bands represent the statistical uncertainty in the prefit expectation (left) or postfit prediction (right).

A dedicated $\gamma\gamma \to \tau^+\tau^-$ [9] Monte Carlo (MC) sample is generated with MadGraph5_aMC@NLO (v2.6.5) [10], decayed and hadronized with PYTHIA8 (v2.1.2) [11], and simulated by Geant4 [12] to study the detector effects. Background contamination is estimated in a data-driven way, using the so-called "ABCD method", in which the four uncorrelated phase space regions are defined based on the number of tracks per event and the HF activity. In all cases, good agreement is observed between the measured distributions and the sum of the signal simulation and background estimation, *e.g.*, as shown in Fig. 2 (left) for the invariant mass of the τ_{3prong} candidate.

3. Results

A binned maximum likelihood method is used for the signal extraction. The difference in opening azimuthal angle between the τ_μ and τ_{3prong}

leptons, $\Delta\phi(\tau_\mu, \tau_{3\text{prong}})$, is used as the final discriminant. Systematic uncertainties may affect the normalization and the shape of the $\Delta\phi(\tau_\mu, \tau_{3\text{prong}})$ distribution and these uncertainties are represented by nuisance parameters in the fit. The total uncertainty, found to be 9.7%, is their sum in quadrature taking into account correlations in the fit procedure. To compare the compatibility of the data with the background-only and signal plus background hypotheses, where the signal is allowed to be scaled by some factor r, we construct a test statistic based on the profile likelihood ratio. The best fit value of the signal strength is given by the minimum, which corresponds to $r = 0.99^{+0.16}_{-0.14}$ and the signal events of $N_{\text{sig}} = 77 \pm 12$. The post-fit $\Delta\phi(\tau_\mu, \tau_{3\text{prong}})$ distribution is shown in Fig. 2 (right).

The cross section $\sigma(\gamma\gamma \to \tau^+\tau^-)$ is measured in the fiducial phase space region, following the kinematic requirements previously described. The formula used is $\sigma(\gamma\gamma \to \tau^+\tau^-) = N_{\text{sig}}/(2\epsilon\,\mathcal{L}_{\text{int}}\,\mathcal{B}_{\tau_\mu}\,\mathcal{B}_{\tau_{3\text{prong}}})$, where N_{sig} is the number of signal events estimated by the fit process, $\epsilon = (78.5 \pm 0.8)\%$ is the total signal efficiency, $\mathcal{L}_{\text{int}} = 404 \pm 20\,\mu\text{b}^{-1}$ the total integrated luminosity, and $\mathcal{B}_{\tau_\mu} = (17.39 \pm 0.04)\%$ and $\mathcal{B}_{\tau_{3\text{prong}}} = (14.55 \pm 0.06)\%$ [2] the branching fractions for the two τ lepton decay modes. Combining all of the above, the fiducial cross section is found to be $\sigma(\gamma\gamma \to \tau^+\tau^-) = 4.8 \pm 0.6\,(\text{stat}) \pm 0.5\,(\text{syst})\,\mu\text{b}$. The result, summarized in Fig. 3, is compared to leading-order QED predictions [9, 13]. Further assuming the correction factor of Ref. [9] to extrapolate the fiducial cross section measurement to the full phase space region, we then use the dependence of the total $\sigma(\gamma\gamma \to \tau^+\tau^-)$ as a function of a_τ to extract the model-dependent value of $a_\tau = 0.001^{+0.055}_{-0.089}$.

4. Summary

In summary, the observation of the τ lepton pair production in ultraperipheral nucleus-nucleus collisions is reported. Events with one muon and three particles identified as charged pions in the final state are reconstructed from a lead-lead data sample collected by the CMS experiment at $\sqrt{s_{\text{NN}}} = 5.02\,\text{TeV}$ in 2015, and corresponding to an integrated luminosity of $404\,\mu\text{b}^{-1}$. This measurement introduces a novel experimental strategy using heavy ion data recorded by the LHC in order to measure the τ lepton magnetic moment a_τ. This approach can be used to produce constraints on a_τ that surpass the current best from previous lepton-lepton colliders.

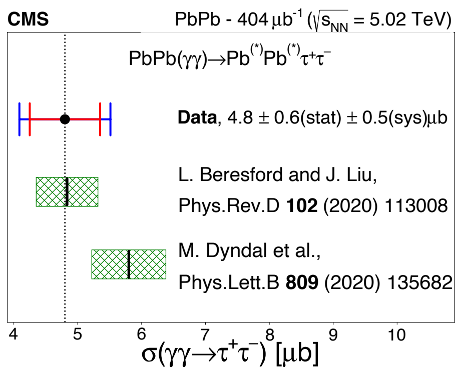

Fig. 3. The cross section, $\sigma(\gamma\gamma \to \tau^+\tau^-)$, measured in a fiducial phase space region at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$. The theoretical predictions [9, 13] are computed with leading-order accuracy in QED and are represented by the vertical solid lines that can be compared with the vertical dotted line representing this measurement. The outer blue (inner red) error bars surrounding the data point indicate the total (statistical) uncertainties, whereas the green hatched bands correspond to the uncertainty in the theoretical predictions as described in the main text. The potential electromagnetic excitation of the outgoing Pb ions is denoted by $(^*)$.

Acknowledgements

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