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

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The observation of the $\tau$ 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 $404 \mu b^{-1}$. The photon-induced $\gamma \gamma \rightarrow \tau^+\tau^-$ 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 $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = 4.8 \pm 0.6 \text{ (stat)} \pm 0.5 \text{ (syst)} \mu b$, in agreement with leading-order QED predictions. The $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)$ measurement is used to determine for the first time the anomalous magnetic moment of the $\tau$ lepton $a_\tau$, which is currently poorly constrained. This approach can be used to produce constraints on $a_\tau$ that surpass the current best from previous lepton-lepton colliders.

1. Introduction

One of the contributing factors in the couplings of leptons ($\ell$) with photons ($\gamma$) 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 $a_\tau$ [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 $\tau$ leptons in lead-lead (PbPb) collisions PbPb ($\gamma\gamma \rightarrow \text{Pb}^{(n)} + \text{Pb}^{(n)} \tau^+\tau^-$ (hereafter referred to as $\gamma\gamma \rightarrow \tau^+\tau^-$). As shown in Fig. 1, the $\tau$ 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 (\(\pi\)) over a fiducial phase space region defined by the muon and pion transverse momenta (\(p_T\)) and their pseudorapidities (\(\eta\)). The ATLAS Collaboration has also reported a measurement of \(\gamma\gamma \rightarrow \tau^+\tau^-\) using a larger PbPb data sample with an integrated luminosity of 1.44 nb\(^{-1}\) [4, 5].

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 \(\sqrt{s_{NN}} = 5.02\) TeV in 2015, and corresponding to an integrated luminosity of 404 \(\mu\)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 \("\tau_\mu\"\) 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 \(p_T > 3.5\) GeV for \(|\eta| < 1.2\) and \(p_T > 2.5\) GeV for \(|\eta| \geq 1.2\). The tracks forming the \("\tau_\text{3prong}\"\) 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 \("\tau_\text{3prong}\"\) candidate is then required to be of opposite charge relative to
the selected $\tau_\mu$, 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 $\tau_{3\text{prong}}$ candidate
is required to be less than 1.5 GeV.

![Graph](image1.png)

Fig. 2. Left: Invariant mass of the three pions forming the $\tau_{3\text{prong}}$ candidate. Right:
Difference in azimuthal opening angle between the $\tau_\mu$ and $\tau_{3\text{prong}}$ 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 $\gamma\gamma \rightarrow \tau^+\tau^-$ [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 estima-
tion, e.g., as shown in Fig. 2 (left) for the invariant mass of the $\tau_{3\text{prong}}$
candidate.

3. Results

A binned maximum likelihood method is used for the signal extrac-
tion. The difference in opening azimuthal angle between the $\tau_\mu$ and $\tau_{3\text{prong}}$
leptons, $\Delta \phi (\tau, \tau_{3\text{prong}})$, is used as the final discriminant. Systematic uncertainties may affect the normalization and the shape of the $\Delta \phi (\tau, \tau_{3\text{prong}})$ 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 $\Delta \phi (\tau, \tau_{3\text{prong}})$ 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 $\sigma (\gamma\gamma \to \tau^+ \tau^-) = \frac{N_{\text{sig}}}{2 \epsilon L_{\text{int}} B_{\tau \mu} B_{\tau_{3\text{prong}}}}$, where $N_{\text{sig}}$ is the number of signal events estimated by the fit process, $\epsilon = (78.5 \pm 0.8)\%$ is the total signal efficiency, $L_{\text{int}} = 404 \pm 20 \mu b^{-1}$ the total integrated luminosity, and $B_{\tau \mu} = (17.39 \pm 0.04)\%$ and $B_{\tau_{3\text{prong}}} = (14.55 \pm 0.06)\%$ [2] the branching fractions for the two $\tau$ lepton decay modes. Combining all of the above, the fiducial cross section is found to be $\sigma (\gamma\gamma \to \tau^+ \tau^-) = 4.8 \pm 0.6 \text{ (stat)} \pm 0.5 \text{ (syst)} \mu b$. 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 $a_\tau$ to extract the model-dependent value of $a_\tau = 0.001^{+0.055}_{-0.089}$.

4. Summary

In summary, the observation of the $\tau$ lepton pair production in ultra-peripheral 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 $\sqrt{s_{NN}} = 5.02$ TeV in 2015, and corresponding to an integrated luminosity of 404 $\mu b^{-1}$. This measurement introduces a novel experimental strategy using heavy ion data recorded by the LHC in order to measure the $\tau$ lepton magnetic moment $a_\tau$. This approach can be used to produce constraints on $a_\tau$ that surpass the current best from previous lepton-lepton colliders.
Fig. 3. The cross section, $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)$, measured in a fiducial phase space region at $\sqrt{s_{\text{NN}}} = 5.02$ 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 (*)

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