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Evidence for light-by-light scattering in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Abstract

Evidence for light-by-light (LbL) scattering, $\gamma\gamma \to \gamma\gamma$, in ultraperipheral PbPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV is reported. LbL scattering processes are selected in events with just two photons produced, with transverse energy $E_T^\gamma > 2$ GeV, pseudorapidity $|\eta^\gamma| < 2.4$; and diphoton invariant mass $m^{\gamma\gamma} > 5$ GeV, transverse momentum $p_T^{\gamma\gamma} < 1$ GeV, and acoplanarity $(1 - \Delta\phi^{\gamma\gamma}/\pi) < 0.01$. After all selection criteria, 14 events are observed, compared to 11.1 ± 1.1 (theo) and 3.8 ± 1.3 (stat) events expected for signal and background processes respectively. The significance of the signal excess over the background-only hypothesis is 4.1σ. The measured fiducial LbL scattering cross section, $\sigma_{fid}(\gamma\gamma \to \gamma\gamma) = 122 \pm 46$ (stat) ± 29 (syst) ± 4 (theo) nb is consistent with the standard model prediction.

Keywords: Light-by-light scattering, Heavy ions, Ultraperipheral collisions, CMS, LHC

1. Introduction

Elastic light-by-light (LbL) scattering, $\gamma\gamma \to \gamma\gamma$, is a pure quantum mechanical process that proceeds, at leading order in the quantum electrodynamics (QED) coupling α, via virtual box diagrams containing charged particles (Fig. 1, left). In the standard model (SM), the box diagram involves leptons, quarks, and $W^\pm$ bosons. Its direct observation in the laboratory remains elusive still today due to a very suppressed production cross section proportional to $\alpha^4 \approx 3 \times 10^{-9}$. In Ref. [1], it was proposed to observe the LbL process at the LHC via ultraperipheral heavy-ion interactions, with impact parameters larger than twice the radius of the nuclei, exploiting the very large fluxes of quasi-real photons emitted by the nuclei accelerated at TeV energies [2]. For lead (Pb) nuclei with radius $R \approx 7$ fm, the quasi-real photon beams have virtualities $-Q^2 \approx 1/R < 10^{-3}$ GeV^2, and since each photon flux scales as the square of the ion charge Z^2, $\gamma\gamma$ scattering cross sections in PbPb collisions are enhanced by a factor of $Z^4 \simeq 5 \times 10^7$ compared to similar proton-proton (pp) or e^+e^- interactions. A first evidence of $\gamma\gamma \to \gamma\gamma$ has been reported by the ATLAS experiment [3] with a signal significance of 4.4σ (3.8σ expected). The study of the $\gamma\gamma \to \gamma\gamma$ process at the LHC has also been proposed for searches of physics beyond the SM, such as axions [4], or Born–Infeld extensions of QED [5].

The final-state signature of interest is the exclusive production of two photons, PbPb $\to \gamma\gamma \to$ Pb$^{(*)}\gamma\gamma$Pb$^{(*)}$, where the diphoton final state is measured in an otherwise empty detector, and the outgoing Pb ions escape

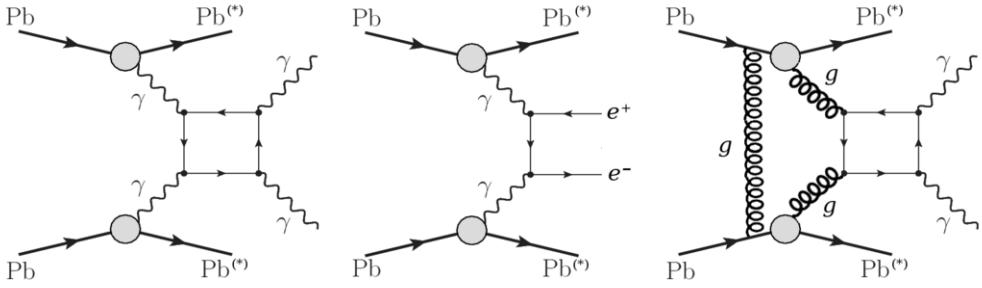Fig. 1. Diagrams of light-by-light scattering ($\gamma\gamma \to \gamma\gamma$, left), QED dielectron ($\gamma\gamma \to e^+e^-$, center), and central exclusive diphoton ($gg \to \gamma\gamma$, right) production in ultraperipheral PbPb collisions (with potential electromagnetic excitation $^{(*)}$ of the outgoing Pb ions).

undetected at very low angles (Fig. 1, left). The dominant backgrounds are the QED production of an exclusive electron-positron pair ($\gamma\gamma \to e^+e^-$, Fig. 1 center) where the $e^\pm$ are misidentified as photons, and gluon-induced central exclusive production (CEP) [6] of a pair of photons (Fig. 1, right). Simulations of the light-by-light signal are generated with MADGRAPH v.5 [7] Monte Carlo (MC) generator, modified [1, 8] to include the nuclear γ fluxes and the elementary LbL scattering cross section [9]. Background QED e^+e^- events are generated with STARLIGHT v2.76 [10]. The CEP process, $gg \to \gamma\gamma$, is simulated with SUPERCHIC 2.0 [11], where the computed pp cross section [6] is conservatively scaled to the PbPb case by multiplying it by $A^2 R_g^4$, where $A = 208$ is the lead mass number and $R_g \approx 0.7$ is a gluon shadowing correction in the relevant kinematical range [12], and where the rapidity gap survival factor is taken as 100%. Given the large theoretical uncertainty of the CEP process for PbPb collisions, the absolute normalization of this MC contribution is directly determined from a control region in the data.

2. Experimental measurement

The measurement is carried out using the following detectors of the CMS experiment [13]: (i) the silicon pixel and strip tracker measures charged particles within pseudorapidities $|\eta| < 2.5$ inside the 3.8 T magnetic field, (ii) the lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass and scintillator hadron calorimeter (HCAL) reconstruct γ, $e^\pm$, and hadrons respectively over $|\eta| = 3$, and (iii) the hadron forward calorimeters (HF) measure particle production up to $|\eta| = 5.2$. Exclusive diphoton candidates are selected with a dedicated level-1 trigger that requires at least two electromagnetic (e.m.) clusters with E_T above 2 GeV and at least one HF detector with total energy below the noise threshold. Offline, photons and electrons are reconstructed with the particle flow algorithm [14]. In the case of photons, to keep to a minimum the $e^\pm$ contamination, we require them to be fully unconverted. Additional particle identification (ID) criteria are applied to remove γ from high-p_T π^0 decays, based on a shower shape analysis. Electron candidates are identified by the association of a charged-particle track from the primary vertex with clusters of energy deposits in the ECAL. Additional $e^\pm$ ID criteria discussed in Ref. [15] are applied.

Charged and neutral exclusivity requirements are applied to reject events with any charged particles with $p_T > 0.1$ GeV over $|\eta| < 2.4$, and neutral particles above detector noise thresholds over $|\eta| < 5.2$. Nonexclusive backgrounds, characterized by a final state with larger transverse momenta and larger diphoton acoplanarities, $A_\phi = (1 - \Delta\phi^{\gamma\gamma}/\pi)$, than the back-to-back exclusive $\gamma\gamma$ events, are eliminated by requiring the transverse momentum of the diphoton system to be $p_T^{\gamma\gamma} < 1$ GeV, and the acoplanarity of the pair to be $A_\phi < 0.01$. The same analysis carried out for the LbL events is done first on exclusive e^+e^- candidates, with the exception that exactly two opposite-sign electrons, instead of exactly two photons, are exclusively reconstructed. Figure 2 (top left) shows the acoplanarity distribution measured in exclusive QED e^+e^- events passing all selection criteria (circles) compared to the STARLIGHT MC expectation (histogram). A good

data-simulation agreement is found, thereby confirming the quality of the e.m. particle reconstruction, of the exclusive event selection criteria, as well as of the UPC MC predictions [1, 10]. Small data–MC differences seen in the $m^{e^+e^-}$ tail –due to the presence of slightly acoplanar events in data, likely from $\gamma\gamma \to e^+e^-$ events where one (or both) electrons radiate an extra soft photon, that are not explicitly simulated– have no impact on the final extracted cross sections integrated over the whole distribution. The QED dielectron background
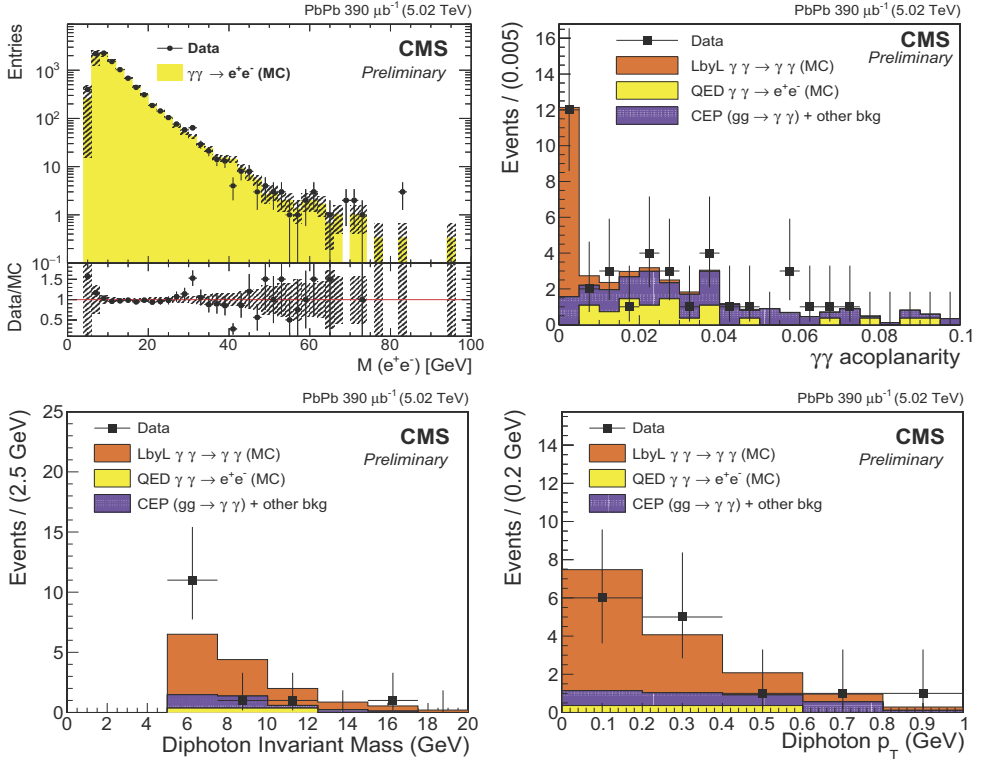

Fig. 2. Top-left: Invariant mass distribution for exclusive e^+e^- events in data (circles) and STARLIGHT MC expectation (histogram, hashed bands indicate systematic and MC statistical uncertainties in quadrature). Top-right: Diphoton acoplanarity for exclusive $\gamma\gamma$ events in data (squares) compared to the expected LbL scattering signal (orange histogram), QED e^+e^- (yellow histogram), and the CEP+other (violet histogram, scaled to match the data in the $A_\phi > 0.02$ region) backgrounds. Bottom: Distributions of $m^{\gamma\gamma}$ (left) and $p_T^{\gamma\gamma}$ (right) for exclusive $\gamma\gamma$ events in data (squares) and MC (histograms). Error bars indicate statistical uncertainties [16].

is then directly estimated from the STARLIGHT MC simulation by counting the number of e^+e^- events that pass all LbL scattering selection criteria. The charged exclusivity condition, requiring no track in the event above the $p_T = 0.1$ GeV threshold, is successful in removing it almost entirely (Fig. 2, top-right). The simulated CEP $gg \to \gamma\gamma$ events, with large theoretical uncertainties, plus any other residual backgrounds resulting in non-fully back-to-back photons for which we do not have a simulated sample available, are normalized to match the data in the region $A_\phi > 0.02$, where the contribution from $\gamma\gamma \to \gamma\gamma$ is negligible (Fig. 2, top-right). The CEP MC background normalization factor is $f_{\text{nonacoplanar}}^{\text{norm}} = 0.95 \pm 0.36$ (stat). The final requirement on diphoton acoplanarity ($A_\phi < 0.01$) leads to a significant reduction of CEP photon pairs that are produced in diffractive-like processes [6, 11] with larger momentum exchanges, leading to a pair distribution peaking at $p_T^{\gamma\gamma} \approx 0.5$ GeV, and have moderately large tails in their azimuthal acoplanarity.

   After all cuts, we observe 14 LbL scattering candidates, to be compared with 11.1 ± 1.1 (theo) expected from the LbL scattering signal, 2.7 ± 1.1 (stat) from CEP plus any residual $\gamma\gamma$ backgrounds, and 1.1 ± 0.6 (stat) from misidentified QED e^+e^- events. Figure 2 (bottom) shows the $\gamma\gamma$ invariant mass (left) and $p_T^{\gamma\gamma}$ (right)

measured in data (squares) compared to MC expectations. Both the measured total yields and kinematic distributions are in accord with the combination of the LbL scattering signal plus exclusive QED e^+e^- and CEP+other backgrounds. The compatibility of the data with a background-only hypothesis is evaluated from the measured acoplanarity distribution (Fig. 2, top-right), using a profile-likelihood ratio as a test statistic. The observed (expected) signal significance is 4.1 (4.4) standard deviations. The ratio R of cross sections of the light-by-light scattering over the QED e^+e^- processes is determined from the expression:

$$R = \frac{\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma)}{\sigma(\gamma\gamma \to e^+e^-, m^{e^+e^-} > 5\,\text{GeV})} = \frac{N^{\gamma\gamma,\text{data}} - N^{\gamma\gamma,\text{bkg}}}{C^{\gamma\gamma}} \times \frac{C^{e^+e^-} \times \text{Acc}^{e^+e^-}}{N^{e^+e^-,\text{data}} \times \mathcal{P}}, \tag{1}$$

where $\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma)$ is the LbL scattering fiducial cross section; $\sigma(\gamma\gamma \to e^+e^-, m^{e^+e^-} > 5\,\text{GeV})$ is the total QED e^+e^- cross section for masses above 5 GeV; $\text{Acc}^{e^+e^-} = N^{\text{gen}}(p_T^{\text{gen}} > 2\,\text{GeV}, |\eta^{\text{gen}}| < 2.4, m^{e^+e^-} > 5\,\text{GeV})/N^{\text{gen}}(m^{e^+e^-} > 5\,\text{GeV}) = 0.058 \pm 0.001\,(\text{stat})$ is the dielectron acceptance for the fiducial single-$e^\pm$ kinematic cuts determined from the STARLIGHT MC generator; $N^{\gamma\gamma(e^+e^-),\text{data}}$ is the number of diphoton (dielectron) events passing the data selection; $N^{\gamma\gamma,\text{bkg}}$ is the estimated number of background events passing all selection criteria; $\mathcal{P}$ is the purity of the fraction of QED e^+e^- events passing the selection; and $C^{\gamma\gamma(e^+e^-)}$ are overall trigger/reconstruction/exclusivity efficiency correction factors for $\gamma\gamma$ (e^+e^-) that are determined from the simulation and confirmed with data-driven studies in control regions. The ratio of the fiducial LbL scattering to the total QED e^+e^- cross sections is $R = (25.4 \pm 9.6\,(\text{stat}) \pm 6.0\,(\text{syst})) \times 10^{-6}$ where statistical uncertainties dominate (the systematic ones are associated to trigger, reconstruction, and identification efficiencies). From the theoretical STARLIGHT prediction of $\sigma(\gamma\gamma \to e^+e^-, m^{ee} > 5\text{GeV}) = 4.82 \pm 0.15\,(\text{theo})$ mb, we finally obtain $\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 122 \pm 46\,(\text{stat}) \pm 29\,(\text{syst}) \pm 4\,(\text{theo})$ nb, in good agreement with the theoretical LbL prediction [1] of $\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 138 \pm 14$ nb in the fiducial region considered.

3. Summary

Evidence for light-by-light (LbL) scattering, $\gamma\gamma \to \gamma\gamma$, in ultraperipheral PbPb collisions at a center-of-mass energy per nucleon pair of 5.02 TeV has been reported. Fourteen LbL scattering candidate-events with just two photons produced have been observed passing all kinematical selection requirements: single-photon $E_T^\gamma > 2$ GeV, pseudorapidity $|\eta^\gamma| < 2.4$; and diphoton invariant mass $m^{\gamma\gamma} > 5$ GeV, transverse momentum $p_T^{\gamma\gamma} < 1$ GeV, and acoplanarity $(1 - \Delta\phi^{\gamma\gamma}/\pi) < 0.01$. Both the measured total yields and kinematic distributions are in accord with the expectations from the LbL scattering signal plus small residual backgrounds, mostly from misidentified exclusive dielectron, $\gamma\gamma \to e^+e^-$, and gluon-induced central exclusive, $gg \to \gamma\gamma$, processes. The observed (expected) significance of the LbL scattering signal over the background-only expectation is 4.1 (4.4) standard deviations. The measured fiducial light-by-light scattering cross section, $\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 122 \pm 46\,(\text{stat}) \pm 29\,(\text{syst}) \pm 4\,(\text{theo})$ nb, is consistent with the standard model prediction.

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