PROCEEDINGS OF SCIENCE

Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV

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Evidence for the light-by-light scattering process, $\gamma\gamma \rightarrow \gamma\gamma$, in ultraperipheral PbPb collisions at a centre-of-mass energy per nucleon pair of 5.02 TeV is reported. The analysis is conducted using a data sample corresponding to an integrated luminosity of 390 μb^{-1} recorded by the CMS experiment at the LHC. Light-by-light scattering processes are selected in events with two photons exclusively produced, each with transverse energy $\mathrm{E_T} > 2$ GeV, pseudorapidity $abs(\eta) < 2.4$, diphoton invariant mass $m^{\gamma\gamma} > 5$ GeV, diphoton transverse momentum $\mathrm{p}_T^{\gamma\gamma} < 1$ GeV, and diphoton acoplanarity below 0.01. After all selection criteria are applied, 14 events are observed, compared to expectations of 11.1$\pm$1.1 (theo) events for the signal and 4.0$\pm$1.2 (stat) for the background processes. The excess observed in data relative to the background-only expectation corresponds to a significance of 4.1 standard deviations, and has properties consistent with those expected for the light-by-light scattering signal. The $m^{\gamma\gamma}$ distribution is used to set new exclusion limits on the production of pseudoscalar axion-like particles, via the $\gamma\gamma \rightarrow \mathrm{a} \rightarrow \gamma\gamma$ process, in the mass range m_a = 5-90 GeV.

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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. In the standard model (SM), the box diagram of LbL process (Fig.1(left)) involves the contributions from charged fermions (leptons and quarks) or bosons. Despite its simplicity, LbL scattering was unobserved before LHC because of its tiny cross section $\sigma_{\gamma\gamma} \propto \mathscr{O}(\alpha^4) \approx 3 \times 10^{-9}$. However, by exploiting very high photon fluxes in ultra-peripheral interactions of heavy ions, the process can be experimentally observed [1]. Since the photon flux scales as the square of the ion charge Z^2, $\gamma\gamma$ scattering cross-sections are enhanced by factor of Z^4 in PbPb collisions. The LbL scattering process is sensitive channel to study the physics beyond SM. In the extension of SM, the loop can contain new heavy particles, such as magnetic monopoles, vector-like fermions or other new spin-even particles, such as axion-like particles (ALPs) or gravitons.This report presents an evidence for LbL scattering and new exclusion limits on axion-like particles (ALPs) production, using PbPb collision data recorded by the CMS experiment [2] in 2015 at $\sqrt{s_{\rm NN}}$ =5.02 TeV with integrated luminosity of 390 μb^{-1} [3].

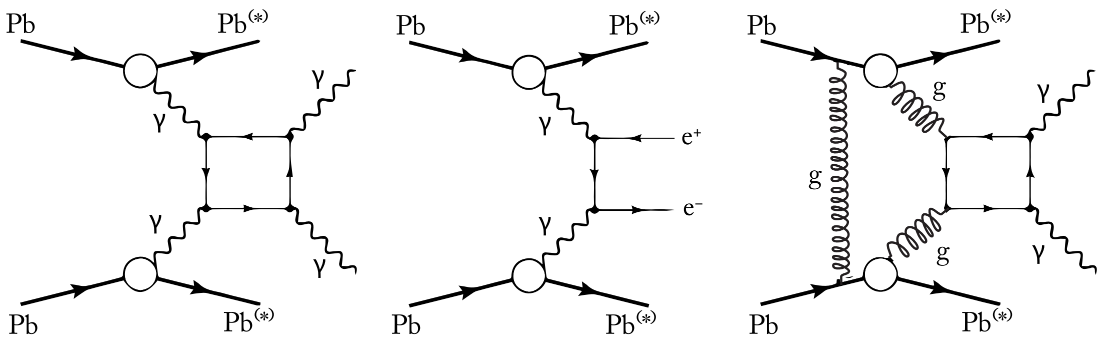

Figure 1: Schematic diagrams of light-by-light scattering ($\gamma\gamma \to \gamma\gamma$, left), QED dielectron ($\gamma\gamma \to e^+e^-$, centre), and central exclusive diphoton ($gg \to \gamma\gamma$, right) production in ultra-peripheral PbPb collisions.

2. Event selection and background estimation

The ligt-by-light signal is generated with the Madgraph v5 [4] Monte Carlo (MC) event generator, with the modifications discussed in Ref. [1]. Exclusive $\gamma\gamma \to e^+e^-$ events can be misidentified as LbL scattering if neither electron track is reconstructed or if both electrons undergo hard bremsstrahlung. This QED process is generated using the STARLIGHT [5] event generator. The central exclusive production process, gg$\to \gamma\gamma$, is simulated using Superchic 2.0 [6] event generator, where the computed proton-proton cross section is scaled to the PbPb case by multiplying it by $A^2R_{\rm g}^4$, where $A = 208$ is the mass number of lead and $R_{\rm g} \approx 0.7$ is a gluon shadowing correction. Given the large theoretical uncertainty of the CEP process for PbPb collisions, the absolute normalisation of this MC contribution is determined from a control region in the data, as explained later. All generated events are passed through the Geant detector simulation, and the events are reconstructed with the same software as for collision data. Photons and electrons are reconstructed using an algorithm based on the particle flow global event description (GED).

The exclusive diphoton candidates are selected at the trigger level by requiring at least two electromagnetic showers above $E_T > 2$ GeV and one of the Hadron Forward calorimeter empty. As the photons of interest possess very low E_T (2-10 GeV), the standard CMS high E_T ($E_T > 10$ GeV) electron/photon reconstruction algorithm was retuned for this analysis. At the offline level, events with exactly two photons with $E_T > 2$ GeV and $|\eta| < 2.4$ are selected. Further, events reconstructed with charged-particle tracks with $p_T > 0.1$ GeV and with calorimeter activity above noise thresholds are rejected. The non-exclusive diphoton background is eliminated by selecting events with diphoton acoplanarity $A_\phi < 0.01$ and diphoton transverse momentum $p_T^{\gamma\gamma} < 1$GeV.

In order to have a full control of the QED background in the LbL scattering signal region, the same analysis is carried on exclusive dielectron candidates, applying the same event selection criteria. Fig 2 shows the dielecton p_T and invariant mass distribution for events passing the exclusivity criteria. A good agreement is found between data and MC which confirms quality of the electromagnetic particle reconstruction, and of the exclusive event selection criteria, as well as of the MC predictions. The QED dielectron in the LbL signal region is estimated by counting the number of QED e^+e^- events from the STARLIGHT MC passing all LbL scattering selection criteria.

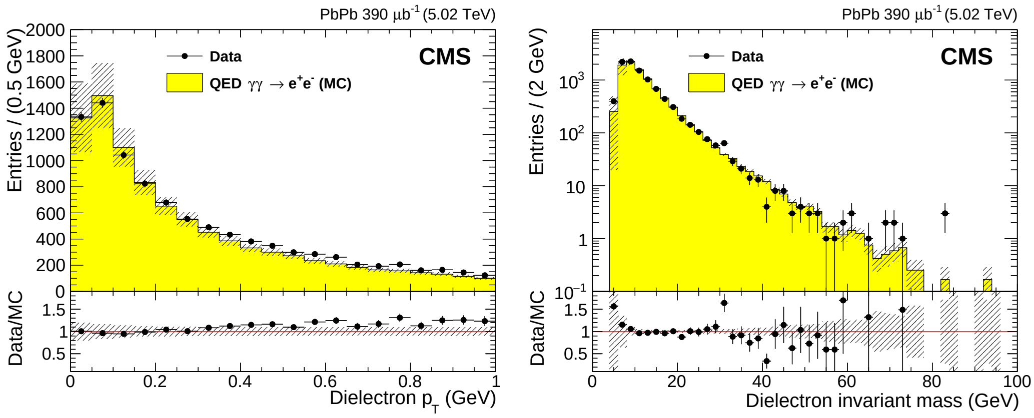

Figure 2: Dielectron p_T and invariant mass distributions compared for data and STARLIGHT MC expectation for the exclusive e^+e^- events passing all selection criteria [3].

Since the MC prediction for CEP $gg \to \gamma\gamma$ has large theoretical uncertainties, and in order to account for any other remaining backgrounds, the CEP MC prediction was normalized to match the data in the region $A_\phi > 0.02$. The number of events due to CEP plus any residual backgrounds is thus estimated to be 3.0 ± 1.1 (stat).

After applying all LbL event selection criteria, we observe 14 LbL scattering candidates, to be compared with 11.1 ± 1.1 (theo) expected from the LbL scattering signal, 3.0 ± 1.1 (stat) from CEP, and 1.0 ± 0.3 (stat) from QED e^+e^- background events. Fig. 3 shows the comparison of the measured and simulated diphoton acoplanarity and invariant mass distributions. Both the measured yields and kinematic distributions are in accord with the combination of the LbL signal plus QED e^+e^- and CEP+other background expectations. The compatibility of the data with the background-only hypothesis has been evaluated from the measured acoplanarity distribution. The

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significance of the excess at low diphoton acoplanarity is 4.1 standard deviations (4.4 standard deviations expected).

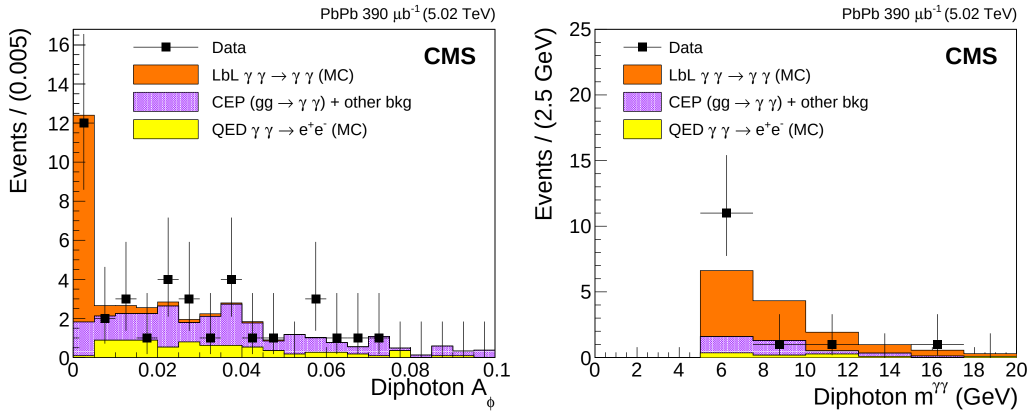

Figure 3: Diphoton acoplanarity and invariant mass distributions for exclusive $\gamma\gamma$ events in data (squares) compared to MC expectations [3].

3. Results

3.1 Light-by-light cross section

The fiducial cross-section for LbL process was obtained by measuring the ratio R of cross sections of the LbL scattering over the QED $\mathrm{e^+e^-}$ processes. Measuring the ratio reduced the uncertainties related to trigger and reconstruction efficiencies, and integrated luminosity. The ratio R is defined as,

$$R = \frac{\sigma_{\mathrm{fid}}(\gamma\gamma \to \gamma\gamma)}{\sigma(\gamma\gamma \to \mathrm{e^+e^-}, \mathrm{m^{e^+e^-}} > 5\mathrm{GeV})} = \frac{N^{\gamma\gamma,\mathrm{data}} - N^{\gamma\gamma,\mathrm{bkg}}}{C^{\gamma\gamma}} \frac{C^{\mathrm{ee}}\,\mathrm{Acc^{ee}}}{N^{\mathrm{ee,data}}\,\mathscr{P}}. \tag{3.1}$$

Here $\sigma_{\mathrm{fid}}(\gamma\gamma \to \gamma\gamma)$ is the LbL scattering fiducial cross section (passing all the aforementioned p_T, η, $m^{\gamma\gamma}$ kinematic selection criteria for the single photons and for the photon pair); $\sigma(\gamma\gamma \to \mathrm{e^+e^-}, \mathrm{m^{e^+e^-}} > 5\mathrm{GeV})$ is the total cross section for the QED $\mathrm{e^+e^-}$ process for masses above 5GeV; $\mathrm{Acc^{ee}}$ is the dielectron acceptance for single-electron kinematic selections determined from the MC generator; $N^{\gamma\gamma,\mathrm{data}}$ is the number of diphoton events passing the selection in data; $N^{\gamma\gamma,\mathrm{bkg}}$ is the estimated number of background events passing all selection criteria; $N^{\mathrm{ee,data}}$ is the number of dielectron events passing our selection in data; $\mathscr{P}$ is the purity of the estimated fraction of QED $\mathrm{e^+e^-}$ signal among these dielectron events; and $C^{\gamma\gamma}$ and C^{ee} are the overall efficiency correction factors, for the $\gamma\gamma$ and $\mathrm{e^+e^-}$ selections, respectively. The ratio R amounts to $R = (25.0 \pm 9.6(\mathrm{stat}) \pm 5.8(\mathrm{syst})) \times 10^{-6}$. The LbL fiducial cross section is obtained from the theoretical prediction of $\sigma(\gamma\gamma \to \mathrm{e^+e^-}, \mathrm{m^{ee}} > 5\mathrm{GeV}) = 4.82 \pm 0.15(\mathrm{theo})$ mb and estimated to be $\sigma_{\mathrm{fid}}(\gamma\gamma \to \gamma\gamma) = 120 \pm 46(\mathrm{stat}) \pm 28(\mathrm{syst}) \pm 4(\mathrm{theo})$ nb, which is in good agreement with the theoretical LbL prediction, $\sigma_{\mathrm{fid}}(\gamma\gamma \to \gamma\gamma) = 138 \pm 14$ nb.

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3.2 Exclusion limits on axion-like particle production

The measured invariant mass distribution (Fig.3) is used to search for pseudoscalar ALPs produced in the process $\gamma\gamma \to \mathrm{a} \to \gamma\gamma$. The LbL, QED, and CEP+other processes are considered as a background in this search. The ALPs samples were generated using Starlight generator for masses ranging from 5-90 GeV. Limits on $\sigma(\gamma\gamma \to \gamma\gamma)$ cross sections for axion-like particles are set in the 1500-20 nb range. These cross section limits is used to set exclusion limits in the $g_{a\gamma}$ vs, m_{a} plane, where $g_{a\gamma} \equiv 1/\Lambda$ is the ALP coupling to photons or also to hypercharge. Fig. 4 shows the exclusion limits for ALPs coupling to photons only (left) or also to hypercharge (right). For an ALPs coupling to the photons only, the exclusion limits are best so far over the $\mathrm{m_a}$ = 5-50 GeV. For ALPs coupling to the photons and hypercharge, the results provide new constraints in the region m_{a} = 5-10 GeV .

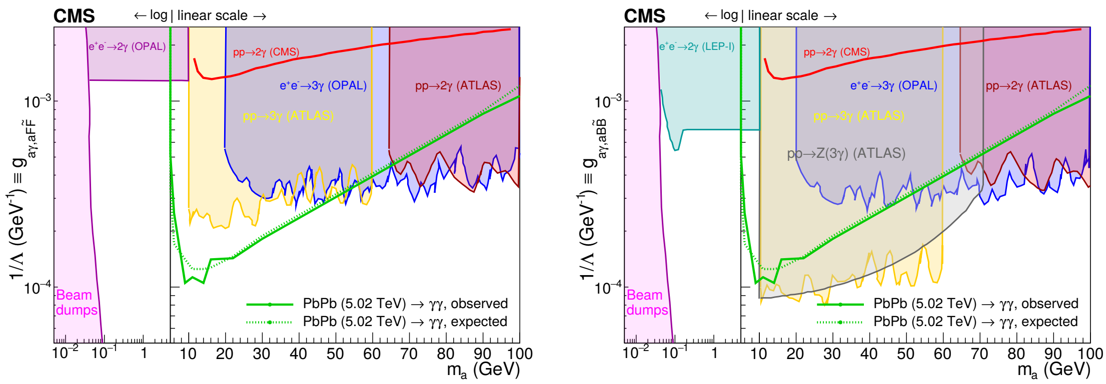

Figure 4: Exclusion limits at 95% CL in coupling vs mass plane for (a) ALPs coupling to photons only (b) including also the hypercharge coupling [3].

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