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

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A measurement of light-by-light scattering, $\gamma\gamma \to \gamma\gamma$, 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 $E_T > 2$ GeV, pseudorapidity $|\eta| < 2.4$, diphoton invariant mass $m_{\gamma\gamma} > 5$ GeV, diphoton transverse momentum $p_T < 1$ GeV, and diphoton acoplanarity below 0.01. After all selection criteria are applied, 14 events are observed, compared to expectations of 11.1 ± 1.1 (th) events for the signal and 4.0 ± 1.2 (stat) for the background processes. The significance of the light-by-light signal hypothesis against the background-only hypothesis is 4.1 standard deviations. The measured fiducial light-by-light scattering cross section, $\sigma_{fid}(\gamma\gamma \to \gamma\gamma) = 120 \pm 46$ (stat) ± 29 (syst) ± 4 (th) nb is consistent with the Standard Model prediction. The present results allow also to place new competitive limits, reported for the first time, on the production of pseudoscalar axion-like particles, produced in the process $\gamma\gamma \to a \to \gamma\gamma$, over the mass range $m_a = 5 - 50$ GeV.

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1. Introduction

Elastic light-by-light (LbL) scattering is a fundamental quantum-mechanical process, in which two photons interact through a loop containing charged Standard Model (SM) particles and results in two photons in the final state (Fig. 1). The $\gamma\gamma \to \gamma\gamma$ process could also proceed through a loop of new charged particles (e.g. supersymmetric, monopoles), or through s-channel (pseudo)scalar resonances such as axions. Despite its importance, this process still remains unobserved. The only similar process that has been experimentally confirmed is the Delbrück scattering, in which a photon is deflected in the magnetic field of a nucleus [2]. This however is an indirect LbL measurement with only one photon in the final state.

The sensitivity of LbL process to the physics beyond the SM makes it an important tool in searches for new particles. One example of such particle is an axion, arising from the Peccei-Quinn mechanism [3]. The original axions with small masses and symmetry-breaking scale similar to the electroweak scale, being natural candidates for the dark matter particles, have been ruled out. A more general class of elementary pseudoscalar particles, for which the mass-coupling relation is not fixed (called axion-like particles or ALPs), occurs in many extensions of the SM.

The difficulty to observe LbL scattering comes from a very low cross section, which scales as $\alpha^4 \approx 10^{-9}$. Several experimental approaches were proposed to probe this process: Compton backscattered photons against laser photons [4], $\gamma\gamma$ collisions from microwave wave-guides [5], cavities of high-power lasers [6], scattering laser light off two e^+e^- beams [7], as well as ultra-peripheral collisions (UPC) of protons or lead beams at the LHC [8]. In the latter process, two passing nuclei interact electromagnetically, generating huge fields ($\sim 10^{14}$ T) and amplifying LbL cross section by a factor Z^4, where $Z = 82$ for lead ions. Thanks to this enhancement, $\sigma_{\gamma\gamma\to\gamma\gamma}$ is $5 \cdot 10^7$ times higher than in proton-proton or e^+e^- interactions. The interacting photons have very low virtuality ~ 0.06 GeV and a maximum energy of ~ 80 GeV.

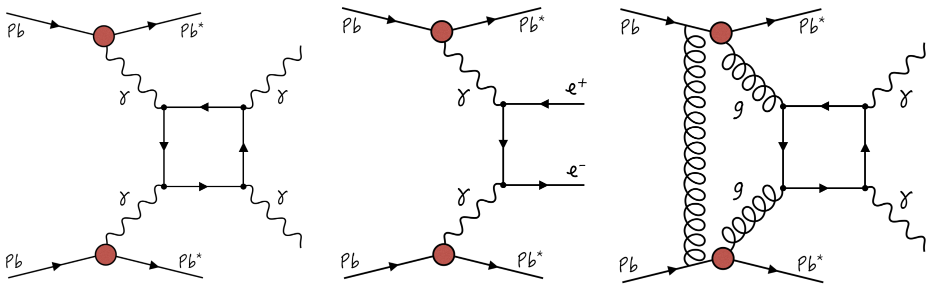

Figure 1: Diagrams of the light-by-light scattering (left), exclusive e^+e^- production (middle) and Central Exclusive Production (right) in ultraperipheral collision of lead ions.

2. CMS detector

The CMS detector [9] consists of a tracking detector and central calorimeter system, embedded in a superconducting solenoid magnet providing a field of 3.8 T, and muon detectors located outside of the solenoid, in the flux-return yoke. The central calorimeter system contains a barrel (EB) with two endcaps (EE) of the electromagnetic calorimeter (ECAL) built of scintillating $PbWO_4$ crystals, as well as a barrel (HB) and endcaps (HE) of a brass and plastic scintillator hadron calorimeter

(HCAL). Both ECAL and HCAL provide a coverage up to $|\eta| = 3.0$. The range in the forward region is extended by a steel and quartz forward hadron calorimeters (HF) with pseudorapidity coverage $2.9 < |\eta| < 5.2$. Photons resulting from LbL scattering can be measured by the CMS detector over pseudorapidity range $|\eta| < 2.4$ (due to the tracker acceptance, required for background estimation), with exclusivity conditions over $|\eta| < 5.2$.

3. Event selection and background estimation

The data sample comes from the PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, registered by the CMS detector at the LHC, with a total integrated luminosity $L_{\rm int} = 390\ \mu b^{-1}$. The trigger was set to accept events with at least two γ/electron towers in ECAL with transverse energy $E_T > 2$ GeV each and at least one of HF empty. As the photons of interest are in the low E_T region (2–10 GeV), the standard CMS high E_T electron/photon reconstruction ($E_T > 10$ GeV) was retuned for this analysis. Events with exactly two photons were pre-selected. In order to remove γ's from π^0 and η meson decays, the size of the shower along η was required to be smaller than 0.02 (0.06) in EB (EE). Anomalous signals coming from the direct ionization of the photodiode were removed requiring four neighboring hits to contain at least 5% of the highest energy hit.

The main backgrounds for LbL are the exclusive e^+e^- production (QED) and Central Exclusive Production (CEP), shown in Fig. 1. In the QED process (generated with STARLIGHT [10]), two electrons coming from a $\gamma\gamma$ interaction are misidentified as photons when they undergo hard bremsstrahlung. The CEP background (generated with SUPERCHIC 2.0 [11]) comes from a color-singlet gluon-gluon interaction resulting in two exclusive photons in the final state.

A series of selection criteria was applied. First, events with towers above the noise threshold in HCAL or HF, as well as those with any activity in ECAL far from the photon candidates: $|\Delta\eta| > 0.15$, $|\Delta\phi| > 0.7(0.4)$ in EB (EE), were rejected. Events with any charged particles with $p_T > 0.1$ GeV were removed. To reduce non-exclusive backgrounds, a cut was applied on diphoton momentum $p_{\gamma\gamma} < 1$ GeV. Finally, an acoplanarity (where $A_\phi = 1 - \Delta\phi_{\gamma\gamma}/\pi$) cut was introduced to suppress CEP and QED backgrounds. The LbL signal has very low A_ϕ, while CEP and QED backgrounds have a flatter distribution (Fig. 2), therefore A_ϕ was required to be below 0.01.

To have a full control of the QED background, the same analysis as for LbL was performed, but requiring an exclusive e^+e^- pair instead of $\gamma\gamma$. The kinematic distributions are well reproduced by STARLIGHT (except a rising A_ϕ tail from the non-generated $\gamma\gamma \to e^+e^-(\gamma)$ process, with insignificant impact in the final cross section). The estimated background from QED processes after applying the $\gamma\gamma$ selection criteria is 1.0 ± 0.3 events. The CEP background was normalized from the acoplanarity measured in the data for $A_\phi > 0.02$, where LbL signal contribution in negligible. The expected background from CEP is 3.0 ± 1.1 events.

4. Measured yields and cross section

In the signal region ($|\eta| < 2.4$, $E_T > 2$ GeV, $m_{\gamma\gamma} > 5$ GeV), 14 LbL events were observed, in comparison with the expected value of $11.1 \pm 1.1(\text{th})$ signal and $4.0 \pm 1.2(\text{stat})$ background events. The observed (expected) signal significance derived from the A_ϕ distribution is $4.1(4.4)\sigma$.

The ratio of LbL to QED cross sections was extracted taking into account efficiencies of the trigger, γ/electron reconstruction and identification, as well as statistical uncertainties on MC back-

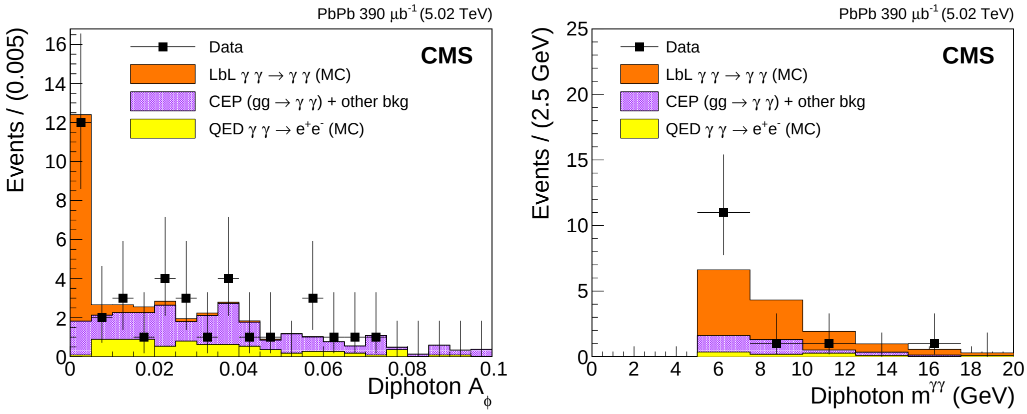

Figure 2: Left: Acoplanarity distribution for LbL, QED and CEP processes. Right: Invariant mass distribution for LbL, QED and CEP. [1]

Photon reconstruction and identification	$(2\cdot 9)\%$
Electron reconstruction and identification	$(2\cdot 2.5)\%$
Trigger	12%
MC backgrounds (stat)	8%
Total	24%

Table 1: Summary of the uncertainties of LbL to QED cross sections ratio measurement.

grounds estimation (Table 1). The exclusivity selection uncertainties cancel out from nominator and denominator. The obtained ratio is $\sigma_{\gamma\gamma\to\gamma\gamma}/\sigma_{\gamma\gamma\to e^+e^-} = 25.0 \pm 9.6(\text{stat}) \pm 5.8(\text{syst}) \cdot 10^{-6}$.

The fiducial cross section (in the signal region defined above) was calculated using the measured ratio and the QED cross section generated with STARLIGHT. The observed LbL cross section is $120 \pm 46(\text{stat}) \pm 28(\text{syst}) \pm 4(\text{th})$ nb, in comparison with the expected 138 ± 14 nb.

5. Limits on axion-like particles

In searches for ALPs, LbL, QED and CEP are treated as a background. The ALP samples were generated with STARLIGHT for masses from 5 to 90 GeV and analyzed applying full detector simulation and the same reconstruction procedure as in the LbL analysis. The distributions were compared with the measured invariant mass spectrum (Fig. 2), in which no significant excess above the SM prediction was observed. The 95% confidence limits (assuming 100% $a \to \gamma\gamma$ branching ratio) in the cross section were derived and then recast into the coupling ($g_{a\gamma}$) vs. mass (m_a) plane. The results are presented in Fig. 3: on the left assuming coupling to photons only, with operator $1/(4\Lambda)aF\tilde{F}$ and on the right including coupling to the hypercharge, with operator $1/(4\Lambda cos^2\theta_W)aB\tilde{B}$. The results obtained in this analysis provide new limits on ALPs for masses from 5 to 50 GeV.

6. Summary

The light-by-light scattering was studied in ultraperipheral collisions of lead ions at $\sqrt{s_{NN}} =$ 5.02 TeV measured by the CMS detector at the LHC. The analysis was performed taking into

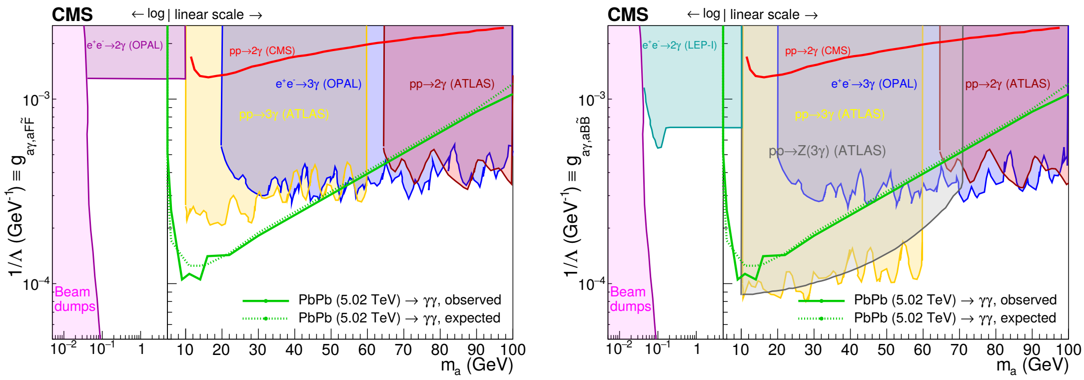

Figure 3: 95% confidence-level limits on the production of ALPs in the mass-coupling plane in e^+e^-, pp and PbPb collisions, with ALP coupling to photons (left), and to photons and the hypercharge (right). [1]

account the main backgrounds, coming from the exclusive e^+e^- production and the Central Exclusive Production. In the signal region ($|\eta| < 2.4$, $E_T > 2$ GeV, $m_{\gamma\gamma} > 5$ GeV), 14 LbL events were observed (at 4.1σ significance level). The fiducial cross section of the LbL process for $m_{\gamma\gamma} > 5$ GeV of $120 \pm 46(\text{stat}) \pm 28(\text{syst}) \pm 4(\text{th})$ nb was measured. Both the yield and the cross section are consistent with the SM prediction. No significant excess in the invariant mass spectrum was observed and improvement of existing limits was obtained for the production of axion-like particles with masses from 5 to 50 GeV.

References

[1] CMS Collaboration, *Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at* $\sqrt{s_{NN}} = 5.02$ *TeV*, [arXiv:1810.04602 [hep-ex]].

[2] A. I. Milstein and M. Schumacher, *Present status of Delbruck scattering*, *Phys. Rept.* **243** (1994) 183.

[3] R. D. Peccei and H. R. Quinn, *CP Conservation in the Presence of Instantons*, *Phys. Rev. Lett.* **38** (1977) 1440.

[4] K. O. Mikaelian, *Detection of elastic light by light scattering at SLAC*, *Phys. Lett. B* **115** (1982) 267.

[5] G. Brodin, M. Marklund and L. Stenflo, *Proposal for Detection of QED Vacuum Nonlinearities in Maxwell's Equations by the Use of Waveguides*, *Phys. Rev. Lett.* **87** (2001) 171801.

[6] D. Bernard *et al.*, *Search for Stimulated Photon-Photon Scattering in Vacuum*, *Eur. Phys. J. D* **10** (2000) 141 [arXiv:1007.0104 [physics.optics]].

[7] I. Ginzburg, G. Kotkin, V. Serbo and V. Telnov, *Production of High-Energy Colliding gamma gamma and gamma e Beams with a High Luminosity at Vlepp Accelerators*, *JETP Lett.* **34** (1981) 491.

[8] D. d'Enterria and G. G. da Silveira, *Observing light-by-light scattering at the Large Hadron Collider*, *Phys. Rev. Lett.* **111** (2013) 080405 [arXiv:1305.7142 [hep-ph]].

[9] CMS Collaboration, *The CMS Experiment at the CERN LHC*, *JINST* **3** (2008) S08004.

[10] S. R. Klein, J. Nystrand, J. Seger, Y. Gorbunov and J. Butterworth, *STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions*, *Comput. Phys. Commun.* **212** (2017) 258 [arXiv:1607.03838 [hep-ph]].

[11] L. A. Harland-Lang, V. A. Khoze and M. G. Ryskin, *Exclusive physics at the LHC with SuperChic 2*, *Eur. Phys. J. C* **76** (2016) no.1, 9 [arXiv:1508.02718 [hep-ph]].