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Light-by-Light Scattering and Axion Like-Particle Searches in Pb+Pb Collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV in ATLAS Experiment at LHC

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The ultra-peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV recorded by the ATLAS experiment are used to study a rare light-by-light scattering process, $\gamma\gamma \to \gamma\gamma$, allowed in quantum electrodynamics via a loop diagram. The report summarises recent light-by-light measurements conducted using a combination of 2015 and 2018 Pb+Pb data sets collected by the ATLAS experiment, corresponding to an integrated luminosity of 2.2 nb^{-1}. The light-by-light event candidates are required to consist of only two photons produced exclusively, each with transverse energy $E_T > 2.5$ GeV, pseudorapidity $|\eta| < 2.4$, diphoton invariant mass $m_{\gamma\gamma} > 5$ GeV, and with diphoton transverse momentum $p_{T\gamma\gamma} < 1$ GeV and acoplanarity below 0.01. The diphoton invariant mass distribution is used to set limits on the production of axion-like particles.

topics: light-by-light scattering, axion-like particles, ATLAS

1. Introduction

Light-by-light (LbyL) scattering, $\gamma\gamma \to \gamma\gamma$, is a very rare phenomenon, predicted by Euler and Heisenberg in the early 1930s, in which two photons — particles of light — interact, scattering off each other like particles of matter. The interaction is mediated via a quantum loop of virtual charged particles: fermions (leptons or quarks) or bosons $W^\pm$ at the order of α_{em}^4, where α_{em}^4 is the fine-structure constant. This is visualized in Fig. 1. A small probability of such a process to occur makes it very challenging to observe experimentally. Over the years, the LbyL process was indirectly studied in measurements of the anomalous magnetic moments of leptons [2, 3] as well as in the Delbrück scattering [4] and in the photon splitting [5]. Nonetheless, it took more than 80 years until the first direct evidence of LbyL scattering was reported by the ATLAS [6] and CMS [7] Collaborations, followed by the observation of this process published by ATLAS with a significance of 8.2 standard deviations in 2019 [8].

The ATLAS experiment [9] is one of two general-purpose experiments at the Large Hadron Collider (LHC) at CERN in Geneva. It was designed very precisely to search for the Higgs boson in proton–proton collisions, which according to the Standard Model predictions, among a variety of decay channels, may also decay into two photons. The Higgs boson was discovered by ATLAS and CMS Collaborations in 2012. The ATLAS experiment also participates in the heavy-ion physics program of the LHC and collects lead–lead (Pb+Pb)collision data for about a month per year. Lead beams can act as an intense source of high-energy photon fluxes.

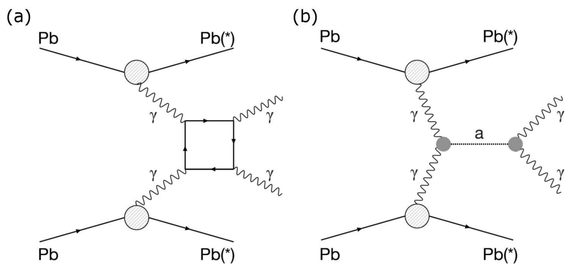

Fig. 1. Feynman diagrams for (a) LbyL scattering and (b) axion-like particle production [1].

The amount of data collected in 2015 allowed to conduct a search for LbyL scattering for the first time at the LHC [6]. After data analysis, it was found that from almost four billion strongly-interacting events, only 13 diphoton candidates were observed with 2 events originating from background processes. The result is in line with the Standard Model predictions and thus it is the first direct measurement of photon–photon scattering with a significance of 4.4 standard deviations.

In November 2018, there was another period of Pb+Pb data taking with a factor of 3.5 more integrated luminosity recorded by ATLAS. Such an enhancement in the event statistics, together with the improvement of measurement techniques, allowed to analyse LbyL scattering more precisely. In total, 59 events were observed in which only two photons were reconstructed in the detector [8]. The observation was established with a significance of 8.2 standard deviations. This new measurement performed by ATLAS Collaboration [1] paves the way for searches of New Physics, i.e., for discovering new particles and phenomena that the Standard Model fails to describe. In particular, the measurement of the LbyL process is sensitive to contributions beyond the Standard Model. It may provide insight into the production of axion-like particles (ALP). ALPs are hypothetical neutral particles that may decay to a diphoton system, as shown in Fig. 1b. Therefore, the measured diphoton invariant mass distribution can be used to search for ALP production via the process $\gamma\gamma \to a \to \gamma\gamma$, where a denotes the ALP.

2. Signature of interest

Heavy-ion or proton beams accelerated to relativistic TeV energies are sources of huge electromagnetic fields which can be equivalently described as a flux of quasi-real photons. Photon fluxes associated with the beams scale as Z^4 with the beam charge making it extremely enhanced in Pb+Pb in comparison to proton–proton collisions ($Z = 82$ for Pb, and $Z = 1$ for proton beams). Thus, Pb+Pb collisions are experimentally preferred to study LbyL scattering.

Heavy-ion collisions are mostly dominated by the strong interaction except for ultra-peripheral collisions (UPC), where the impact parameter is larger than twice the radius of the nucleus. Such collisions provide a very clean environment to study the LbyL process as hadronic interactions are strongly suppressed leaving the electromagnetic interaction to play a main role.

The signature of interest is the exclusive production of two photons, each with transverse energy $E_T^{\gamma} > 2.5$ GeV, pseudorapidity $|\eta_\gamma| < 2.37$ and diphoton invariant mass $m_{\gamma\gamma} > 5$ GeV with transverse momentum $p_{T\gamma\gamma} < 1$ GeV. Any extra activity in the detector is vetoed, in particular no reconstructed tracks originating from the nominal interaction point with $p_T > 100$ MeV are accepted. The final state of photons is expected to be aligned in the azimuthal angle ϕ. Back-to-back topology is studied using diphoton acoplanarity defined as‘ $A_\phi = 1 - \frac{|\Delta\phi|}{\pi}$. Event candidates are expected to have $A_\phi < 0.01$. Figure 2a shows the acoplanarity distribution of candidate events, where $A_\phi = 0$ corresponds to two photons ideally aligned in azimuth.

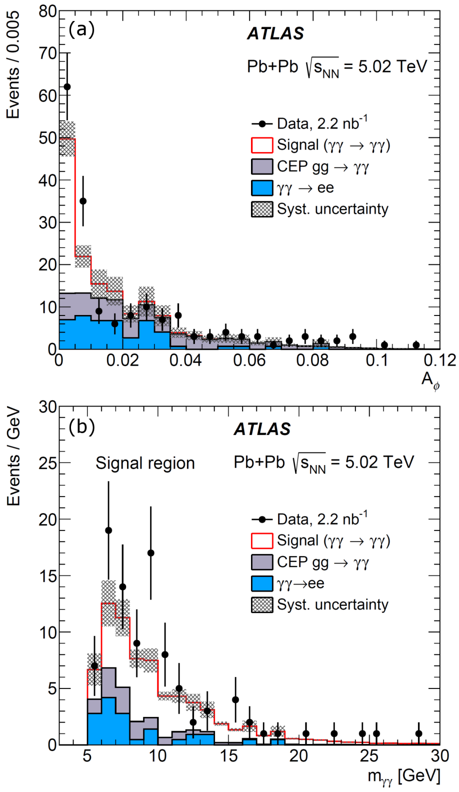

Fig. 2. The acoplanarity (a) and invariant mass (b) distributions of the selected diphoton events [1].

A main background contribution originates from exclusive production of electron–positron pairs ($\gamma\gamma \to e^+e^-$), whose cross-section is α_{em}^2 times higher as compared to LbyL. In the measurement, the $\gamma\gamma \to e^+e^-$ background is suppressed with the requirement of no tracks and pixel-tracks reconstructed in the Inner Detector. A remaining dielectron contribution is evaluated using a data-driven method.

The second significant background source is gluon-induced central exclusive production of photon pairs (CEP, gg$\to \gamma\gamma$). The gluonic initial state has an identical signature as the LbyL process but with larger initial transverse momentum which results in a broader shape of diphoton acoplanarity, as is shown in Fig. 2a. The CEP background is evaluated using a dedicated control region in data ($A_\phi > 0.01$) and then extrapolated to the LbyL signal region.

3. Results

With high statistics of 2015 and 2018 Pb+Pb data amounting to an integrated luminosity of 2.2 nb^{-1}, ATLAS established the observation of a total of 97 candidate events with 45 expected signal events and 27 ± 5 events expected from background processes [8]. This can be translated into a cross-section using an expression

$$\sigma_{\rm fid} = \frac{N_{\rm data} - N_{\rm bkg}}{C \int L {\rm d}t}, \tag{1}$$

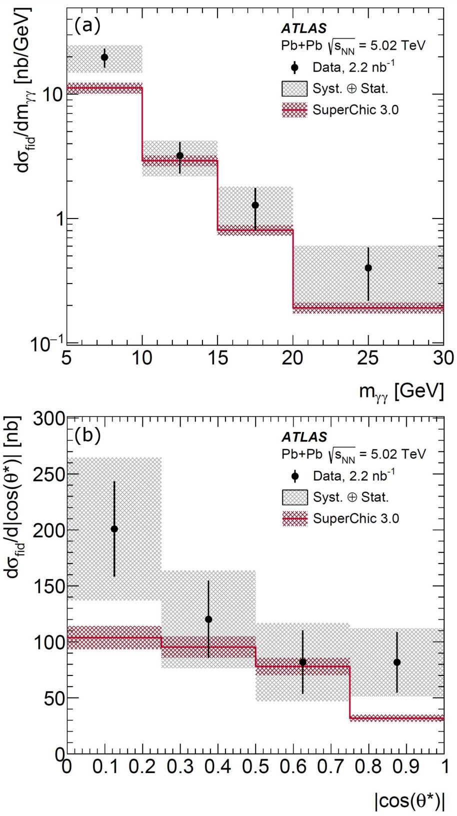

Fig. 3. Differential cross-sections of $\gamma\gamma \to \gamma\gamma$ scattering as a function of (a) diphoton invariant mass and (b) the cosine of the scattering angle in the photon–photon centre-of-mass frame [1].

where $N_{\rm data}$ and $N_{\rm bkg}$ stand for the total number of events in data and the number of background events in the signal region, respectively. Denominator expression $\int L {\rm d}t$ is the integrated luminosity of the data sample, and C is the correction factor obtained by analysing $\gamma\gamma \to \gamma\gamma$ events simulated by SuperChic v3.0 [10]. This correction is applied to account for detector efficiencies and resolution effects.

The integrated cross-section measured in the fiducial phase space defined in Sect. 2 is $\sigma_{\rm fid} = 120 \pm 17({\rm stat.}) \pm 13({\rm syst.}) \pm 4({\rm lumi})$ nb. The presented value can be compared with two theoretical predictions considered to be (i) 78 ± 8 nb from the SuperChic v3.0 MC generator [10] and (ii) 80 ± 8 nb from [11].

Comparison of the measured diphoton invariant mass and expected yields with predicted signal and background distributions is shown in Fig. 2b. The distributions have not been corrected for detector effects. Overall good agreement between the Standard Model prediction and the data is found. In addition to the integrated fiducial cross-section, ATLAS measured $\gamma\gamma \to \gamma\gamma$ differential cross-sections involving four kinematic variables of the final-state photons.

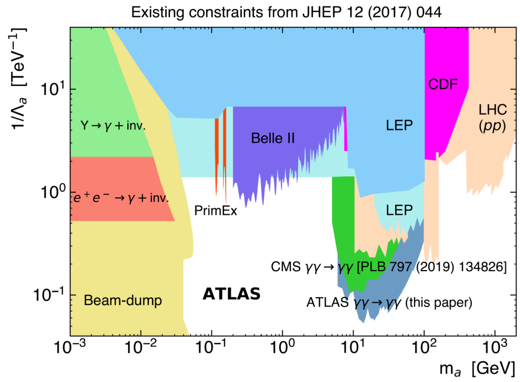

Fig. 4. Summary of exclusion limits at 95 CL in the ALP-photon coupling $1/\Lambda_a$ versus ALP mass m_a from different experiments. The new limit obtained by ATLAS is marked with label: ATLAS $\gamma\gamma \to \gamma\gamma$ [1].

Figure 3 shows examples of measured differential cross-sections as a function of diphoton invariant mass and the $|\cos(\Theta^*)|$, where Θ^* is the scattering angle in the photon–photon centre-of-mass frame. In general, a good agreement between the measurement and Standard Model predictions is found.

4. Search for ALP production

Axions, or more broadly axion-like particles (ALP), are hypothetical (pseudo-) scalar particles with typically weak interactions with Standard Model particles. They may be produced in the photon–photon fusion, $\gamma\gamma \to a \to \gamma\gamma$, followed by the decay to the diphoton pair. Thus, a diphoton invariant mass distribution may be interpreted for ALP searches. The ALP production would result in a resonance peak with diphoton mass equal to the mass of a.

The diphoton mass distribution was examined for a mass range between 6 and 100 GeV. No significant excess of events over expected background was found in the analysis. The 95% confidence level limit was derived for ALP production cross-section and ALP coupling to photons $\frac{1}{\Lambda_a}$ as a function of ALP mass. A summary of exclusion limits from different experiments together with the new ATLAS constraints is shown in Fig. 4. The new ATLAS analysis places the strongest limits on the ALP production in the intermediate mass region to date.

5. Summary

The report summarises recent results on light-by-light scattering measured in ultra-peripheral lead–lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV obtained by the ATLAS experiment at the LHC. A combined 2015+2018 data sample of 2.2 nb^{-1} is used. Integrated fiducial and differential cross-sections are measured and compared with Standard Model predictions. Overall good agreement is found between data and expectations. Furthermore, the measured invariant mass of the diphoton system is used to set new exclusion limits on axion-like particles. This measurement provides the strongest limits on the ALP production in the mass region of 6–100 GeV to date.

Acknowledgments

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