Light-by-light scattering in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector

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Abstract

Light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$) is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics. This reaction is accessible for the first time at the Large Hadron Collider thanks to the large electromagnetic field strengths generated by ultra-relativistic colliding lead (Pb) ions. Using $480 \mu\text{b}^{-1}$ of Pb+Pb collision data recorded at a centre-of-mass energy per nucleon pair of 5.02 TeV by the ATLAS detector, we report evidence for the $\gamma\gamma \rightarrow \gamma\gamma$ process. A total of 13 candidate events are observed with a background expectation of 2.6 ± 0.7 events. After background subtraction and analysis corrections, the fiducial cross-section of the process $\text{Pb} + \text{Pb} (\gamma\gamma) \rightarrow \text{Pb}^{(*)} + \text{Pb}^{(*)} \gamma\gamma$ has been measured to be 70 ± 24 (stat.) ± 17 (syst.) nb, which is in agreement with the Standard Model predictions.

Keywords:

Heavy Ion, UPC, Light-by-light

1. Introduction

One of the key features of Maxwell's Equations is their linearity, from which follows the superposition principle. This forbids effects like light-by-light (LbyL) scattering, $\gamma\gamma \rightarrow \gamma\gamma$, which is a pure quantum-mechanical process. In QED, the $\gamma\gamma \rightarrow \gamma\gamma$ reaction proceeds at lowest order in the fine structure constant via virtual one-loop box diagrams involving fermions, which is an $O(\alpha_{\text{em}}^4) \approx 3 \times 10^{-9}$ process. However, in various extensions of the Standard Model (SM), extra virtual contributions are possible, making the measurement of LbyL scattering sensitive to new physics [1, 2, 3, 4]. Such interactions can occur in relativistic heavy-ion collisions at large impact parameters, i.e. larger than twice the radius of the ions. Relativistic ions generate strong electromagnetic (EM) fields, e.g. 10^{14} T from the coherent action of the lead nucleus with atomic number $Z = 82$ protons, which can be described in the equivalent photon approximation (EPA) [5, 6]. Here, the EM-fields are interpreted as beam of quasi-real photons with

a virtuality of $-Q^2 < 1/R^2$, where R is the radius of the charge distribution and so $Q^2 < 4 \times 10^{-3} \text{GeV}^2$ for nuclei with atomic mass numbers $A \gtrsim 16$. The cross-section of the photon–photon interactions scales with $\sim Z^4$, i.e. is enhanced for ion beams. In this measurement, the final-state signature of interest is the exclusive production of two photons, $\text{Pb} + \text{Pb} \rightarrow \text{Pb}^{(*)} + \text{Pb}^{(*)} + \gamma + \gamma$ where the diphoton final-state is measured in the central detector, and the incoming lead ions (Pb) survive the EM interaction, with a possible EM excitation [7]. Hence, it is expected to detect two low-energy photons and no further activity in the detector, in particular no reconstructed charged-particle tracks coming from an interaction region.

2. Event Selection

Candidate diphoton events were recorded by the ATLAS detector [8] in the Pb+Pb run in 2015 using a dedicated trigger for events with moderate activity in the calorimeter but little additional activity elsewhere. The

total E_T registered in the calorimeter after noise subtraction was required to be above 5 GeV and below 200 GeV. Then a requirement on no activity in the forward direction was imposed and minimal activity in the tracker.

To separate signal photons from background processes a new photon identification (PID) working point, optimised for low- E_T photons is used. In addition to improving signal efficiency it is designed to maximise expected signal significance. It gives a constant photon PID efficiency as a function of η with respect to reconstructed photon candidates. At the same time, photons coming from various background sources (e.g. from clusters induced by cosmic-ray muons) are rejected with 95% efficiency.

To reduce real photon background from central exclusive production (CEP) $gg \rightarrow \gamma\gamma$ reactions, an additional requirement on acoplanarity, $A_{co} = (1 - \frac{\Delta\phi_{\gamma\gamma}}{\pi})$, is used. Therefore the final acoplanarity requirement is optimised to retain high signal efficiency and reduce the CEP background significantly. Figure 1 shows the comparison of acoplanarity shapes between signal and CEP $gg \rightarrow \gamma\gamma$ in simulation. Indeed the signal events are mostly concentrated at very low acoplanarities ($A_{co} < 0.008$), whereas $gg \rightarrow \gamma\gamma$ is relatively flat in the range $0 < A_{co} < 0.05$. The optimal acoplanarity requirement is chosen to maximise the value of $N_{sig}/\sqrt{N_{sig} + N_{gg \rightarrow \gamma\gamma}}$, where N_{sig} is the expected number of signal events and $N_{gg \rightarrow \gamma\gamma}$ is the expected background. This is obtained for $A_{co,max} = 0.01$ and therefore this value is taken as a final diphoton acoplanarity requirement.

Figure 1: The reconstructed diphoton acoplanarity distribution for signal and CEP $gg \rightarrow \gamma\gamma$ processes in MC simulation [9]. Both distributions are normalised to unity.

The fiducial volume of the diphoton final state is defined using the following requirements:

- Two photons with $E_T > 3$ GeV and $|\eta| < 2.4$
- Diphoton invariant mass, $m_{\gamma\gamma} > 6$ GeV
- Diphoton transverse momentum, $p_T^{\gamma\gamma} < 2$ GeV
- Diphoton acoplanarity, $1 - \frac{\Delta\phi_{\gamma\gamma}}{\pi} < 0.01$

3. Background Estimations

Contributions from different background sources are taken into account: CEP $gg \rightarrow \gamma\gamma$, $\gamma\gamma \rightarrow e^+e^-$, $gg \rightarrow q\bar{q}$, exclusive two-meson production and other backgrounds that could fake the diphoton signatures (cosmic-ray muons, EM calorimeter noise).

Electron final states

Due to its relatively high rate, the exclusive production of electron pairs ($\gamma\gamma \rightarrow e^+e^-$) could be a source of fake diphoton events. The electron→photon misidentification can occur when the electron track is not reconstructed or the electron emits a hard bremsstrahlung photon. A contribution from fake dielectron backgrounds is estimated using $\gamma\gamma \rightarrow e^+e^-$ MC simulation to be 1.3 events. In order to cross-check the simulation, two control regions are defined that are expected to be dominated by $\gamma\gamma \rightarrow e^+e^-$ backgrounds. The first control region is defined for events with exactly one reconstructed charged-particle track and two identified photons that pass the same preselection criteria as for the signal definition. This mostly corresponds to a scenario when one photon is induced by the presence of one of the electrons (for which a track is not reconstructed) and the other photon is emitted in hard bremsstrahlung (the electron track survives). The second control region is defined similarly to the first one except exactly two tracks are required. This enhances the contribution from events where both electron tracks fail to be matched to their relevant EM clusters. Good agreement is observed between data and MC, however the precision is limited by the number of events in data.

Quark and gluon final states

Low- p_T dijet events can produce multiple π^0 mesons which could potentially mimic diphoton events. The event selection requirements are efficient at rejecting such events, and based on studies performed with a supporting trigger, the background from hadronic processes is estimated to be 0.3 ± 0.3 events. MC simulation studies show the background from $\gamma\gamma \rightarrow q\bar{q}$ processes is negligible.

Central exclusive production of meson pairs

Exclusive two-meson production can be a potential source of background for LbyL events, mainly due to their similar back-to-back topology. Mesons can fake photons either by their intermediate decay to photons (neutral mesons: π^0 , η , η') or by misreconstructed charged-particle tracks for charged mesons ($\pi^+\pi^-$ states). Exclusive meson pairs are usually produced via resonant production at low invariant masses (e.g. $\rho^0(770) \rightarrow \pi^+\pi^-$) and the cross sections are suppressed for invariant masses above 5 GeV [10], where only continuum processes are involved. The $\sigma(gg \rightarrow \pi^0\pi^0)/\sigma(gg \rightarrow \gamma\gamma)$ ratio is calculated to be below 1% for $p_T^\pi > 3$ GeV and $|\eta^\pi| < 2.5$ [11]. The CEP ratio of $\sigma(gg \rightarrow \eta^{(\prime)}\eta^{(\prime)} \rightarrow 4\gamma)$ to $\sigma(gg \rightarrow \gamma\gamma)$ is estimated in Ref. [12] to be below 10% for mesons with $p_T > 2.5$ GeV. Since the cross sections for neutral exclusive two-meson production are estimated to be very small as compared to diphoton CEP, these processes are considered to have a negligible contribution to the signal region.

Other fake photon backgrounds

Other fake diphoton events can occur due to noise in the calorimeter or cosmic-ray muons that do not cross the tracker (no reconstructed charged-particle tracks). The contribution from such events in the signal region, is estimated using a data driven method to be 0.1 ± 0.1 and is considered negligible.

Central exclusive diphoton production

The requirement on diphoton acoplanarity ($A_{co} < 0.01$) reduces the possible CEP $gg \rightarrow \gamma\gamma$ background. However, the MC expectation of the exclusive $gg \rightarrow \gamma\gamma$ background has a large theoretical uncertainty, $\mathcal{O}(50\%)$, hence additional normalisation of this process is performed in the region $A_{co} > b$, where b is a value that can be chosen to be greater than 0.01. Three values of $b = 0.01, 0.02, 0.03$ are used, where the mean value $b = 0.02$ is chosen to derive the nominal background prediction and the values $b = 0.01$ and $b = 0.03$ to define the systematic uncertainty. The normalisation is performed using the condition:

$$f_{gg \rightarrow \gamma\gamma}^b = \frac{N_{\text{data}} - N_{\text{sig}} - N_{\gamma\gamma \rightarrow e^+e^-}}{N_{gg \rightarrow \gamma\gamma}}, \quad (1)$$

for each value of b , where N_{data} is the number of observed events, N_{sig} is the expected number of signal events and $N_{gg \rightarrow \gamma\gamma}$ is the expected background. The normalisation factors are found to be $f_{gg \rightarrow \gamma\gamma}^{b=0.01} = 0.3 \pm 0.2$ (stat.) for $b = 0.01$, $f_{gg \rightarrow \gamma\gamma}^{b=0.02} = 0.5 \pm 0.3$ (stat.) for

$b = 0.02$ and $f_{gg \rightarrow \gamma\gamma}^{b=0.03} = 0.6 \pm 0.5$ (stat.) for $b = 0.03$. The background due to CEP is thus estimated to be 0.9 ± 0.5 counts.

4. Results

Kinematic distributions

Photon kinematic distributions for events satisfying all selection criteria are shown in Figure 2. In total, 13 events were observed in data where 7.3 signal events and 2.6 background events are expected. In general, a good agreement between data and MC is observed.

Figure 2: Kinematic distributions for $\gamma\gamma \rightarrow \gamma\gamma$ event candidates: diphoton invariant mass (top) and diphoton rapidity (bottom) [9]. Data (points) are compared to MC expectations (histograms).

Cross section measurement

The cross section for the $\gamma\gamma \rightarrow \gamma\gamma$ process is measured in a fiducial phase space, defined by requirements on the diphoton final state, reflecting the selection at

reconstruction level. Experimentally, the fiducial cross section is given by

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C \cdot \int L dt} \quad (2)$$

where N_{data} is a number of selected events in data and N_{bkg} is the number of background events surviving the signal selection. The factor C is a correction factor reflecting the various detector level inefficiencies and resolution effects and is only affected to a small extent by theoretical uncertainties. The value of C is found to be: $C = 0.31 \pm 0.07$. The uncertainty on C is estimated by varying the Data/MC correction factors within their uncertainties. The measured fiducial cross section is $\sigma_{\text{fid}} = 70 \pm 20$ (stat.) ± 17 (syst.) nb, which is in agreement with the predicted value of 49 ± 10 nb [13] within statistical uncertainties.

Significance

A test statistic, t_μ , based on the asymptotic approximation of the profile likelihood ratio [14] is used to evaluate the signal strength parameter, μ (defined as the scaling of the signal histogram which produces the best agreement with data). The scan of the profile likelihood $-2\Delta \ln L$ is plotted in Figure 3 as a function of μ for both the observed data and the SM expectation (from MC). This procedure results in an estimate of $\mu = 1.4 \pm 0.6$, compatible with the SM expectation of 1.0. The p-value for the null (background-only) hypothesis is 4.8×10^{-6} , which corresponds to $\mu = 0$ and a significance of 4.4σ . The expected p-value and significance (obtained before the fit of the signal-plus-background hypothesis to the data) are 7.5×10^{-5} and 3.8σ , respectively.

5. Summary

This note presents evidence for light-by-light scattering signatures in quasi-real photon interactions from ultra-peripheral Pb+Pb collisions at centre-of-mass energy per nucleon pair of 5.02 TeV by the ATLAS experiment. After final selection criteria are applied to the data, 13 events pass, while 7.3 signal events are expected from predictions. The dominant background processes, i.e. CEP $gg \rightarrow \gamma\gamma$, $\gamma\gamma \rightarrow e^+e^-$ as well as other fake-photon backgrounds, are estimated using data-driven methods. After accounting for all of these sources, 2.6 background events are expected, with an uncertainty of 0.7. The significance is determined to be 4.4σ . After background subtraction and analysis corrections, the cross section of the $\gamma\gamma \rightarrow \gamma\gamma$ process is measured to be 70 ± 20 (stat.) ± 17 (syst.) nb, which is

Figure 3: Scan of the profile likelihood as a function of the signal strength, μ , relative to the expectation for the process $\gamma\gamma \rightarrow \gamma\gamma$. The observed significance for the background only hypothesis ($\mu = 0$) is 4.4σ , whilst the expected significance is 3.8σ [9].

compatible with the SM prediction of 49 ± 10 nb. This work was supported in part by the National Science Center, Poland grant DEC-2015/18/M/ST2/00087, and by PL-Grid Infrastructure.

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