Observation of Light-by-Light scattering in ATLAS

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These proceedings describe the observation of the light-by-light scattering process, $\gamma\gamma \rightarrow \gamma\gamma$, in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The analysis is conducted using a data sample corresponding to an integrated luminosity of $1.73$ nb$^{-1}$ collected in November 2018 by the ATLAS experiment at the LHC. After event selection 59 candidate events are observed for a background expectation of $12 \pm 3$ events. This establishes the $\gamma\gamma \rightarrow \gamma\gamma$ process with an observed significance of 8.2 standard deviations. The measured fiducial cross section is $78 \pm 13$ (stat.) $\pm 7$ (syst.) $\pm 3$ (lumi.) nb.

1 Introduction

With the development of Dirac’s theory and the discovery of anti-particles in the early 1930s it became evident the photons could scatter off each other. This process, forbidden in classical electrodynamics, is mediated via the box-diagram shown in Fig. 1 (left) at order $\alpha^{4}_{em}$, where $\alpha_{em}$ is the fine-structure constant. It took more than 80 years until the first direct evidence of the process $\gamma\gamma \rightarrow \gamma\gamma$ was seen by the ATLAS, and CMS collaborations, followed by the observation of this process which is discussed in the following.

The relativistic heavy ion beams of the LHC provide an intense photon source. The electromagnetic (EM) field of relativistic charged particles can be equivalently described as a flux of quasi-real photons. Since the photon flux scales quadratically with the nucleus charge it is strongly enhanced using Pb+Pb beams compared to proton-proton. Whenever the Pb nuclei do not collide, the surrounding photon fields may still interact while the Pb nuclei stay intact. Those interactions are called ultra peripheral collisions and are exploited in the presented measurement. The maximum energy of the photons is given by the Lorentz boost of the beam particles divided by their radius $\gamma/R$ and is about 80 GeV for Pb beams at 2.51 TeV per nucleon. Both the photon flux as well as the $\gamma\gamma$ cross section are exponentially falling with increasing photon energy. Hence this analysis focuses on low energy photons, starting at a transverse energy of $E_{T} > 3$ GeV.

Section 2 will present the details of the analysis including the uncertainties. Results and a brief outlook will be presented in section 3.

2 The analysis

The signature of interest is the exclusive production of two photons, where the Pb ions survive the EM interaction: $Pb + Pb(\gamma\gamma) \rightarrow Pb^{(*)} + Pb^{(*)}\gamma\gamma$. A possible EM excitation is indicated by $^{(*)}$. The final state photons from this reaction are expected to be aligned back-to-back in the azimuth angle $\phi$, as the initial state photons have negligible transverse momentum. No other

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activity is expected in the detector, in particular no reconstructed tracks originating from the interaction point.

The SuperChic v3.0.7 Monte Carlo (MC) generator was used to simulate the $\gamma\gamma \rightarrow \gamma\gamma$ and central exclusive production processes. In addition the Starlight 2.0.8 MC generator was used to simulate an alternative signal sample as well as a sample of $\gamma\gamma \rightarrow e^+e^-$. The theoretical uncertainty of the cross section is mainly due to limited knowledge of the nuclear form factors and initial photon fluxes and estimated to be 10% within the fiducial volume of the analysis.

2.1 Event selection

A two level trigger system was used to select events online. The first level required either at least one EM cluster with $E_T > 1$ GeV in coincidence with a total $E_T$ of 4−200 GeV measured in the calorimeter, or at least two EM clusters with $E_T > 1$ GeV with the total $E_T$ measured in the calorimeter below 50 GeV. The upper threshold on the total $E_T$ is designed to reject events from non-peripheral Pb+Pb collisions. This selection is performed in custom-built hardware allowing to analyse events at full collisions rate. At the second trigger level, which is implemented in software, requirements to select exclusive $\gamma\gamma$ final states are imposed: the number of hits in the pixel detector is limited to 15 at most and the transverse energy measured in the forward calorimeters on either side is required to be consistent with noise, i.e. $< 3$ GeV.

The efficiency of the first level trigger selection is determined using events with exclusive $e^+e^-$ final states which are triggered by independent support triggers. Those events are expected to also fire the analysis trigger. The efficiency is shown in Fig. 2 and found to be above 70% in the kinematic regime of the analysis.

Photons are reconstructed using the default ATLAS algorithm. The photon identification is performed in a second step using a neural net that is trained to identify low energy photons with high efficiency, dedicated to this analysis. The corresponding efficiencies, shown in Fig. 2(middle, right) are estimated using $e^+e^-$ final states where one of the leptons emitted a hard bremsstrahlung photon. These events are tagged by requiring one well reconstructed electron with $p_T > 4$ GeV plus one additional track with $p_T < 1.5$ GeV. As both leptons have to be balanced in $p_T$ an additional photon with $E_T > 2.5$ GeV must be present in the event which is used to determine the efficiencies.

Events are selected by requiring exactly two photons with $E_T > 3$ GeV within $|\eta| < 2.37$, excluding the crack in the EM calorimeter between $1.37 < |\eta| < 1.52$. The invariant mass of the di-photon system is required to be above 6 GeV. Cosmic muons are rejected by requiring the transverse momentum of the di-photon system to be small, $p_T^{\gamma\gamma} < 2$ GeV. To ensure the photons are back-to-back an upper limit on the reduced acoplanarity is imposed, $R_{ac} = (1 - \Delta \phi_{\gamma\gamma}/\pi) < 0.01$. Finally, no extra activity is allowed in the detector. Events containing any tracks with $p_T$ above 100 MeV as well as events having a reconstructed track in the pixel detector with...
The heavy ion collision data recorded in 2018 at a center-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02$ TeV amounts to 1.7 nb$^{-1}$. Analysing this data 59 candidate events are observed. The distribution of events in reduced acoplanarity is shown in Fig. 3.

2.2 Background estimation

Two main background processes contribute to the selected events: exclusive production of $e^+e^-$ pairs $\gamma\gamma \rightarrow e^+e^-$ and central exclusive production of two photons (CEP) $gg \rightarrow \gamma\gamma$. The corresponding Feynman diagrams are shown in Fig. 1.

Exclusive $ee$ production has a large cross section. In case both leptons are mis-identified as photons the events will pass the analysis selection. However, as the charged leptons are bent in the magnetic field of the tracker, the $R_{\text{aco}}$ distribution will be broader compared to that of photons from the signal process. The $R_{\text{aco}}$ shape as well as the normalisation of this background process is estimated from data. For this two control regions are defined by allowing one or two pixel tracks in addition to the nominal selection. Using the probability to miss a pixel track of an electron if the full track is not reconstructed, which is measured to be 47% at 0.9, the $R_{\text{aco}}$ distribution from the two control regions is extrapolated to the signal region, yielding 7 ± 3 background events. The uncertainty is dominated by the statistical uncertainty in the control regions.

The second largest source of background events, CEP, has a coloured initial state. As the gluons carry significant transverse momentum, the $R_{\text{aco}}$ distribution of the resulting photons is significantly broader than the one from the signal photons. Hence a tight cut on $R_{\text{aco}}$ removes most of this background. The number of background events in the signal region is estimated by normalizing the $R_{\text{aco}}$ distribution obtained from simulation to the measured data in a control region. This is defined by requiring $R_{\text{aco}} > 0.01$, yielding 4 ± 1 expected events in the signal region. As before the dominating uncertainty on this background is the limited statistics in the normalisation region. Due to the larger momentum transfer on a single parton in this process the Pb nuclei are expected to dissociate, releasing neutrons. Those are detected with high efficiency in the zero degree calorimeters of ATLAS allowing to cross check the rate of CEP events in the signal sample. Good agreement with the initial estimate is observed.

All other studied backgrounds, among them $\gamma\gamma \rightarrow gg$, exclusive di-meson production as well as bottomonia production $\gamma\gamma \rightarrow \eta_b \rightarrow \gamma\gamma$, are negligible.
3 Results and Outlook

Analysing 1.7 nb\(^{-1}\) of LHC Pb+Pb collision data recorded with ATLAS 59 candidate events are observed and 12 ± 3 background events expected, establishing the light-by-light scattering signal with a significance of 8.2 \(\sigma\). This translates into a measured cross section of 78 ± 13(stat.) ± 8(sys.) nb which lies within 1.8 standard deviations of the expected standard model cross section of 59 ± 5 nb. The invariant mass distribution is shown in Fig. 3.

The result from this measurement can further be transformed into limits on specific models beyond the standard model (BSM). One topic receiving particular attention at present is so called axion-like particles (ALPs). Those are (pseudo)-scalar particles that are too heavy to solve the strong CP problem, but nevertheless are likely to appear in various BSM theories. ALPs will couple to photons, and may couple to anything else, and can hence contribute to the light-by-light scattering cross section at the mass of the ALP. The early analysis result from ATLAS on 0.4 nb\(^{-1}\) recorded in 2015 observing 13 candidate events was recast into limits on the ALP coupling parameter 1/\(\Lambda\) in \(10\). The obtained limits, shown in Fig. 3 (right), have a unique sensitivity to a phase space which is not covered by other experiments. Similarly, in \(11\) results from the same ATLAS analysis were used to set limits on the mass scale appearing in the Born-Infeld theory \(12\).

The discussed BSM interpretations are based upon the 0.4 nb\(^{-1}\) dataset collected in 2015. Updates may be be expected using results from the presented analysis of 1.7 nb\(^{-1}\) Pb+Pb data collected in 2018.

References