

Electromagnetic processes in ultra-peripheral Pb+Pb collisions with ATLAS

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Abstract

The large equivalent-photon fluxes accompanying Pb ion beams at the LHC initiate photon–photon interactions, which occur when the colliding nuclei have large impact parameter (ultra-peripheral collisions). The ATLAS collaboration has carried out a range of measurements related with two-photon interactions at high energies using recently recorded Pb+Pb collision data taken at $\sqrt{s_{NN}} = 5.02$ TeV.

1. Introduction

Collisions of lead nuclei at ultrarelativistic energies are usually studied for cases where the nucleons interact hadronically, producing large multiplicities and a large volume of hot, dense quark-gluon matter. The strong electromagnetic (EM) fields of the nuclei, however, can also induce interactions at large impact parameters where the strong interaction is heavily suppressed. The nuclei can produce high-energy nearly-real photons coherently from the entire nucleus, leading to photon–photon interaction (Figure 1). Since the photon flux associated with each nucleus scales as Z^2 , the photon–photon luminosities are enhanced by a factor of $Z^4 = 4.5 \times 10^7$ when using Pb+Pb collisions instead of pp collisions provided by the Large Hadron Collider (LHC).

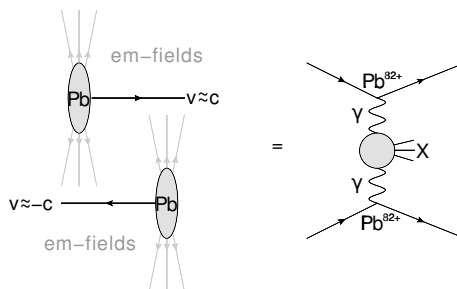


Fig. 1. Illustration of an ultra-peripheral collision of two lead ions [1]. Electromagnetic interaction between the ions can be described as an exchange of photons that can couple to form a given final-state X.

The ATLAS experiment [2] is one of the four large experiments at the LHC. The ATLAS detector is a general purpose particle physics detector with forward-backward symmetric cylindrical geometry. During the year 2015, ATLAS recorded Pb+Pb collision data corresponding to an integrated luminosity of 0.5 nb^{-1} at the center-of-mass energy per nucleon-pair of 5.02 TeV. Using this data, ATLAS has performed a range of measurements related with two-photon interactions, which are reviewed in these proceedings.

2. Measurement of high-mass dimuon pairs

ATLAS has measured the cross sections for exclusive dimuon production ($\gamma\gamma \rightarrow \mu\mu$) in ultra-peripheral Pb+Pb collisions for large dimuon invariant masses, $m_{\mu\mu} > 10 \text{ GeV}$ [3]. The cross sections are extracted by selecting events using a single-muon trigger, in association with an otherwise low-multiplicity event. The events are required to have a primary vertex formed solely from two oppositely-charged muons, each having transverse momentum $p_T > 4 \text{ GeV}$ and pseudorapidity $|\eta| < 2.4$. The events are then corrected for muon trigger and reconstruction efficiency, and for vertex efficiency.

The nuclear EM form factors ensure that the muons are emitted back-to-back ($\Delta\phi \sim \pi$), resulting in a small acoplanarity, defined as $\text{Aco} = 1 - \Delta\phi/\pi$. The simulation based on STARlight shows that over 99.9% of pairs have $\text{Aco} < 0.008$, while in the data substantial dimuon acoplanarity tails are also observed. The fraction of measured events with $\text{Aco} \geq 0.008$ is around 5%. Two assumptions – that the acoplanarity tail is all background, and that it is all signal due to higher-order QED effects – are tested. Assuming the events with $\text{Aco} \geq 0.008$ are primarily background, the data distributions are fit to a functional form comprised of two exponentials, as demonstrated in Figure 2. The final result is calculated including the average of the two scenarios and the systematic uncertainties associated with this procedure are defined as half the difference between the two results, such that both extremes are covered.

The results are compared with calculations from STARlight MC generator [4], as a function of the dimuon pair mass and pair rapidity, as presented in Figure 3. Good agreement between the data and the leading-order QED predictions from STARlight is found, which suggests that the nuclear EM fields are reasonably described by the equivalent photon approximation and that the nuclear EM form factors are adequately implemented in STARlight.

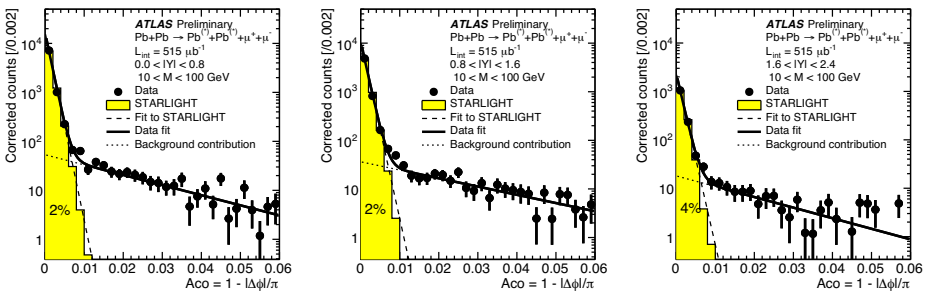


Fig. 2. Acoplanarity distributions for different selections in pair rapidity ($0 < |y_{\mu\mu}| < 0.8$, $0.8 < |y_{\mu\mu}| < 1.6$ and $1.6 < |y_{\mu\mu}| < 2.4$) [3]. The region under the dotted line gives the fraction of the data which is estimated to be background by extrapolating the background contribution down to $\text{Aco} = 0$.

3. Search for light-by-light scattering

A search for $\gamma\gamma \rightarrow \gamma\gamma$ process (light-by-light scattering) is performed by ATLAS using Pb+Pb collision data [1]. Candidate diphoton events were recorded using a dedicated trigger for events with moderate activity in the calorimeter (covering the pseudorapidity range $|\eta| < 4.9$) but little additional activity in the

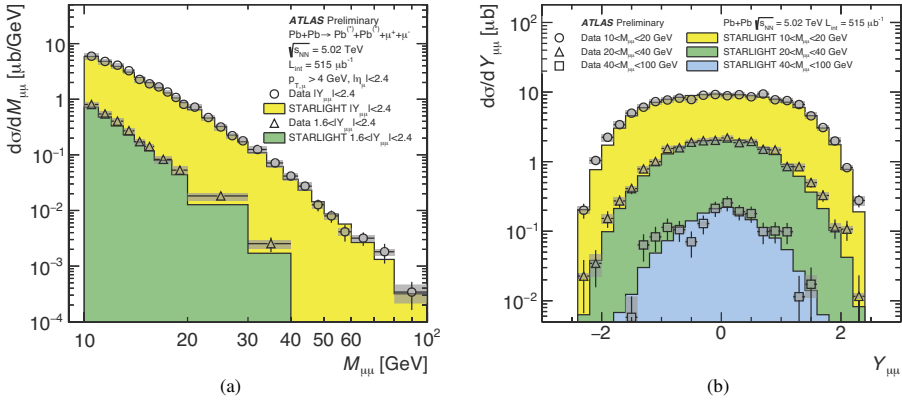


Fig. 3. The cross-sections for exclusive dimuon production, $Pb+Pb(\gamma\gamma) \rightarrow Pb^{(*)}+Pb^{(*)}\mu\mu$, as a function of (a) pair mass and (b) pair rapidity [3]. A possible EM excitation of the outgoing ions is denoted by (*). The data are indicated by the symbols while the MC predictions are shown by solid histograms. Error bars indicate statistical uncertainties while the grey bands indicate the combined systematic uncertainties.

entire detector. Events are then required to have exactly two photons with transverse energy greater than 3 GeV, pseudorapidity $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$, and a diphoton invariant mass greater than 6 GeV.

Since the analysis requires the presence of low-energy photons, which are not typically used in ATLAS analyses, detailed studies of photon reconstruction and calibration are also performed. In particular, exclusive dielectron pairs from the reaction $\gamma\gamma \rightarrow ee$ are used for various aspects of the analysis, for example to validate the EM calorimeter energy scale and resolution. Figure 4 presents the transverse momentum of the exclusive dielectron system for selected ee pairs, where a good agreement between the data and simulation is observed.

Possible backgrounds can arise mainly from misidentified electrons from the $\gamma\gamma \rightarrow ee$ process, as well as from the central exclusive production of two photons from the fusion of two gluons ($CEP\ gg \rightarrow \gamma\gamma$). In order to reduce the $\gamma\gamma \rightarrow ee$ background, a veto on the presence of any charged-particle tracks is imposed. To reduce other fake-photon backgrounds (for example, cosmic-ray muons), the transverse momentum of the diphoton system is required to be below 2 GeV. Diphoton acoplanarity distribution for events satisfying abovementioned selection criteria is shown in Figure 5a. The shape of this distribution is different for the signal and background processes, therefore an additional requirement on diphoton acoplanarity ($A_{co} < 0.01$) is imposed.

Diphoton invariant mass distribution for events satisfying all selection criteria is shown in Figure 5b. In total, 13 events are observed in data whereas 7.3 signal events and 2.6 background events are expected. The statistical significance against the background-only hypothesis is found to be 4.4 standard deviations.

After background subtraction and detector corrections, the cross section for the $Pb+Pb(\gamma\gamma) \rightarrow Pb^{(*)}+Pb^{(*)}\gamma\gamma$ process is measured in a fiducial phase space defined by the photon transverse energy $E_T > 3$ GeV, photon absolute pseudorapidity $|\eta| < 2.4$, diphoton invariant mass greater than 6 GeV, diphoton transverse momentum lower than 2 GeV and diphoton acoplanarity below 0.01. The measured fiducial cross section is $\sigma_{fid} = 70 \pm 24$ (stat.) ± 17 (syst.) nb, which is in agreement with the predicted values of 45 ± 9 nb [5] and 49 ± 10 nb [6] within uncertainties.

4. Conclusion

Using 0.5 nb^{-1} of Pb+Pb collision data recorded at $\sqrt{s_{NN}} = 5.02$ TeV by the ATLAS detector, the ATLAS collaboration has performed a study of the processes $\gamma\gamma \rightarrow \mu\mu$ and $\gamma\gamma \rightarrow \gamma\gamma$. The cross sections for $Pb+Pb(\gamma\gamma) \rightarrow Pb^{(*)}+Pb^{(*)}\mu\mu$ production are measured as a function of dimuon invariant mass and

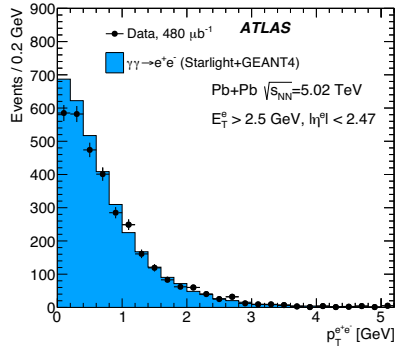


Fig. 4. Dielectron transverse momentum distribution for Pb+Pb ($\gamma\gamma$) \rightarrow Pb $^{(*)}$ +Pb $^{(*)}$ ee event candidates [7]. Electrons are required to have a transverse energy $E_T > 2.5$ GeV and pseudorapidity $|\eta| < 2.47$ with the calorimeter transition region $1.37 < |\eta| < 1.52$ excluded. Data (points) are compared to simulation (histograms). The statistical uncertainties on the data are shown as vertical bars.

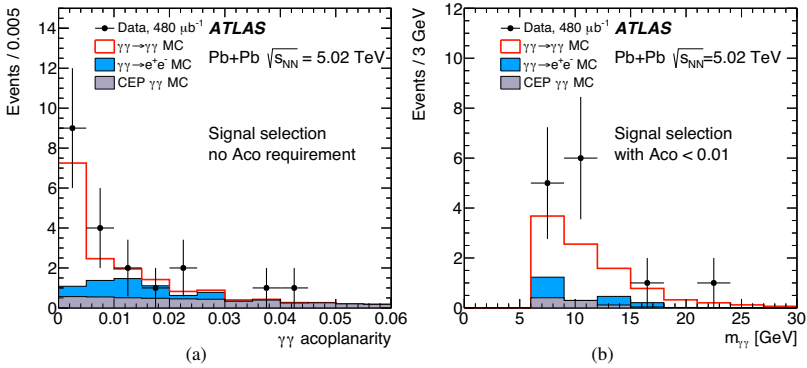


Fig. 5. Kinematic distributions for Pb+Pb ($\gamma\gamma$) \rightarrow Pb $^{(*)}$ +Pb $^{(*)}$ $\gamma\gamma$ event candidates [1]. (a) Diphoton acoplanarity before applying $A_{co} < 0.01$ requirement. (b) Diphoton invariant mass after applying $A_{co} < 0.01$ requirement. Data (points) are compared to MC predictions (histograms). The statistical uncertainties on the data are shown as vertical bars.

dimuon rapidity, and are found to be in agreement with leading-order QED calculations. The Pb+Pb ($\gamma\gamma$) \rightarrow Pb $^{(*)}$ +Pb $^{(*)}$ $\gamma\gamma$ process is evidenced with a significance of 4.4 standard deviations, and the corresponding fiducial cross section is also found to be in agreement with QED predictions.

References

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