LIGHT-BY-LIGHT SCATTERING IN LEAD–LEAD COLLISIONS IN THE ATLAS EXPERIMENT* **

Agnieszka Ogrodnik

on behalf of the ATLAS Collaboration

AGH University of Science and Technology
Faculty of Physics and Applied Computer Science
al. Mickiewicza 30, 30-059 Kraków, Poland

(Received March 26, 2019)

Light-by-light (LbyL) scattering, $\gamma\gamma \to \gamma\gamma$, is a quantum-mechanical process, forbidden by the classical theory of electrodynamics, but possible in Quantum Electrodynamics via a loop diagram. Despite the small cross section, it is theoretically possible to observe this process in ultra-peripheral high-energy heavy-ion collisions. Based on 0.48 nb^{-1} of 2015 Pb+Pb data, a first direct evidence of LbyL scattering was established by the ATLAS Collaboration in 2017. In total, 13 events were found in the signal region with a background expectation of 2.6 ± 0.7 events. The excess corresponds to 4.4σ significance over the background-only hypothesis. In November 2018, the new dataset of Pb+Pb collisions was collected by the ATLAS experiment with an integrated online luminosity of 1.7 nb^{-1}. This recent dataset has been employed to perform a preliminary study using the control sample from $\gamma\gamma \to e^+e^-$ process.

DOI:10.5506/APhysPolB.50.1159

1. Introduction

The ATLAS experiment [1] at the Large Hadron Collider (LHC) collects data not only from proton–proton (pp) collisions, which constitute the main physics program, but also from heavy-ion (HI) collisions. One special category of events are HI data is ultra-peripheral collisions, which are characterized by large impact parameters, *i.e.* larger than twice the radius of the ions. In these collisions, the interaction proceeds via electromagnetic (EM)

* Presented at the Cracow Epiphany Conference on Advances in Heavy Ion Physics, Kraków, Poland, January 8–11 2019.

** This work was supported in part by the National Science Centre, Poland (NCN) grant DEC-2016/23/B/ST2/01409 and by PL-Grid Infrastructure.

fields associated to the relativistic ion beams. In the equivalent photon approximation [2, 3], the EM fields are considered as fluxes of photons with small virtuality. Each photon flux scales with the Z^2 (where Z is the atomic number of the colliding ion), which provides a Z^4 enhancement in $\gamma\gamma$ luminosities in lead–lead (Pb+Pb) collisions with respect to the pp system. Thus, it is possible to observe very rare processes involving two photons, such as light-by-light (LbyL) scattering, in the ultra-peripheral HI collisions.

Figure 1 shows the Feynmann diagram of the LbyL scattering, $\gamma\gamma \to \gamma\gamma$. This process proceeds via the virtual one-loop box diagram involving fermions or $W^{\pm}$ bosons. In various extentions of the Standard Model (SM), also contributions from non-SM particles are possible, thus measurement of the LbyL scattering is sensitive to the new physics.

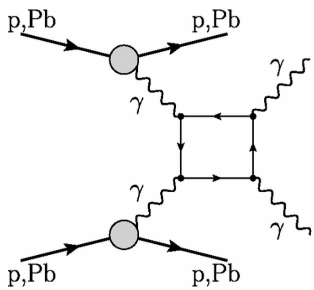

Fig. 1. Feynmann diagram of the LbyL scattering.

2. First evidence of LbyL scattering

The LbyL scattering signature consists of two photons having transverse energy, E_{T}, of the order of a few GeV. These photons have correlated E_{T} and are in back-to-back configuration in azimuth[1], what is described by the acoplanarity variable, $\mathrm{Aco} = 1 - |\Delta\phi|/\pi$, which for the signal photons is less than 0.01. First direct evidence of the LbyL scattering was reported by the ATLAS Collaboration in 2017 [4], and was followed by the CMS measurement [5]. They were based on $\sim 0.4\ \mathrm{nb}^{-1}$ of 2015 Pb+Pb data.

A dedicated unprescaled trigger was used, requiring low activity in the EM calorimeter (total E_{T} at Level-1 between 5 and 200 GeV), minimal activity in the tracker and no activity in the forward direction of the ATLAS detector. The Level-1 trigger efficiency, presented in the left panel of Fig. 2

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

was measured as a function of the sum of transverse energies of the two clusters ($E_{\rm T}^{\rm cluster1} + E_{\rm T}^{\rm cluster2}$) corresponding to electron pairs from exclusive $\gamma\gamma \to e^+e^-$ process. This process has a signature very similar to the signal events (especially at Level-1), but a much higher cross section. Therefore, the exclusive e^+e^- events can be used in trigger efficiency evaluation. The efficiency grows from around 70% for $E_{\rm T}^{\rm cluster1} + E_{\rm T}^{\rm cluster2} = 7$ GeV to 100% for $E_{\rm T}^{\rm cluster1} + E_{\rm T}^{\rm cluster2} > 9$ GeV. The parametrized error function fit to data points representing efficiency was used to reweight the MC simulations.

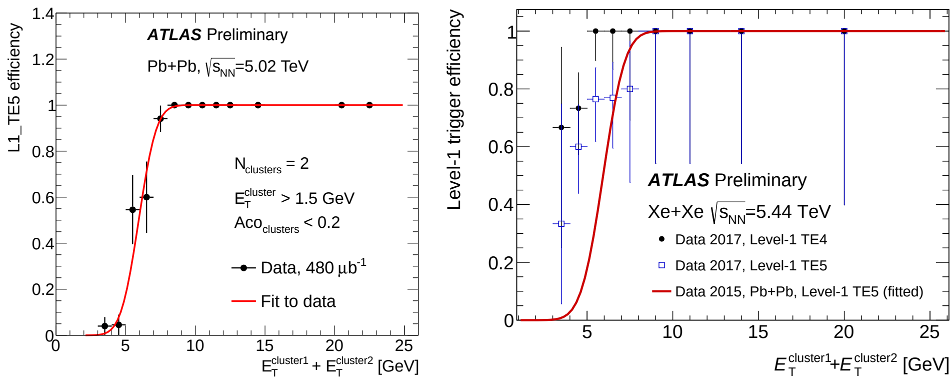

Fig. 2. Efficiency of Level-1 triggers: TE5 as a function of the sum of transverse energies of two EM clusters satisfying the exclusive e^+e^- event selection in 2015 Pb+Pb data [7] (left) and efficiency of TE4 (circles) and TE5 (squares) for exclusive e^+e^- events in 2017 Xe+Xe data [6] (right). Triggers TE4 and TE5 have 4 GeV and 5 GeV thresholds on total transverse energy at Level-1, respectively. The fit represents an L1 TE5 trigger efficiency measured in 2015 Pb+Pb data.

The default photon identification (ID) working points in the ATLAS experiment are designed to be maximally efficient for photons with $E_{\rm T} >$ 20 GeV and are not suitable for low-$E_{\rm T}$ photons originating from the LbyL scattering. Therefore, photon ID was optimized to increase efficiency in the low-$E_{\rm T}$ region. It was based on three shower shape variables and aimed to separate signal photons from background processes. The efficiency of the new photon ID is maintained constant at the level of 95% as a function of η, with respect to reconstructed photon candidates.

The trigger efficiency, photon reconstruction and ID efficiencies put the lower limit on a single photon $E_{\rm T}$ requirement used in the signal event selection: a candidate event is required to have two photons with $E_{\rm T} >$ 3 GeV and $|\eta| < 2.4$, and diphoton invariant mass above 6 GeV (hereafter $c = 1$). Other requirements serve to exclude potential background sources. The veto on presence of any charged-particle tracks reduced the background from the $\gamma\gamma \to e^+e^-$ process. The contribution from fakes, *e.g.* originating from cosmic-ray muons, is reduced by the requirement of diphoton transverse momentum to be below 2 GeV. Finally, the Aco < 0.01 requirement reduces background from Central Exclusive Production (CEP) $gg \to \gamma\gamma$ reactions.

In Fig. 3, the invariant mass distribution for signal selection is shown on the left, and the diphoton acoplanarity distribution before the Aco < 0.01 cut is presented on the right. The contributions from different background sources were taken into account: CEP $gg \to \gamma\gamma$, $\gamma\gamma \to e^+e^-$, hadronic fakes and other backgrounds that could mimic the diphoton signatures (cosmic-ray muons, EM calorimeter noise). In total, 13 events were found in the signal region with a background expectation of 2.6 ± 0.7 events. The excess corresponds to 4.4σ significance of signal presence with respect to the background-only hypothesis.

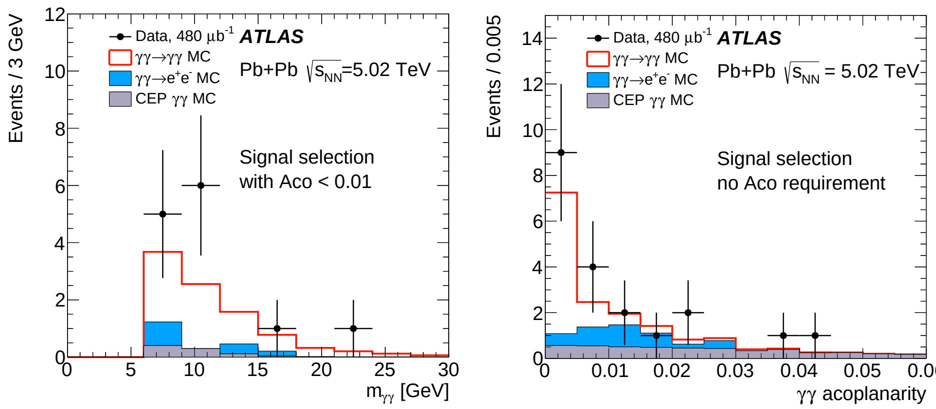

Fig. 3. Kinematic distributions for $\gamma\gamma \to \gamma\gamma$ event candidates [4]: diphoton invariant mass after applying Aco < 0.01 requirement (left) and diphoton acoplanarity before applying the Aco < 0.01 requirement (right). Data (points) are compared to MC predictions (histograms). The statistical uncertainties on the data are shown as vertical bars.

3. First look at 2018 Pb+Pb data

In November 2018, the LHC provided HI collisions with a factor of 3.5 more integrated luminosity with respect to the 2015 data sample. In preparation to 2018 HI data taking, a few improvements have been incorporated to the trigger definition. They include optimization of calorimeter noise settings as well as lowering of the total E_{T} requirement at Level-1. The optimization was performed using the 2017 xenon–xenon (Xe+Xe) data. The obtained trigger efficiency is presented in the right panel of Fig. 2. Other minor changes at the High Level Trigger introduced prior to 2018 HI data taking included redefinition of the veto of activity in forward direction and relaxing the requirement on activity in the tracker.

Validation of the trigger performance in 2018 Pb+Pb data was conducted using events from the $\gamma\gamma \to e^+e^-$ process. The control distributions are shown in Fig. 4. The track acoplanarity distribution for data, which is in good agreement with the MC simulation, is presented on the left. The difference observed in the tail is expected due to lack of radiative corrections in STARlight [8] MC generator. A strong correlation between transverse energy of two clusters associated to e^+e^- candidate events is shown in the right panel of Fig. 4. Given the good performance of tracking and EM cluster reconstruction for event candidates from the $\gamma\gamma \to e^+e^-$ process and improvement in an integrated luminosity (1.7 nb^{-1} in 2018 compared with 0.48 nb^{-1} in 2015), the new dataset looks promising for future analyses of ultra-peripheral collisions.

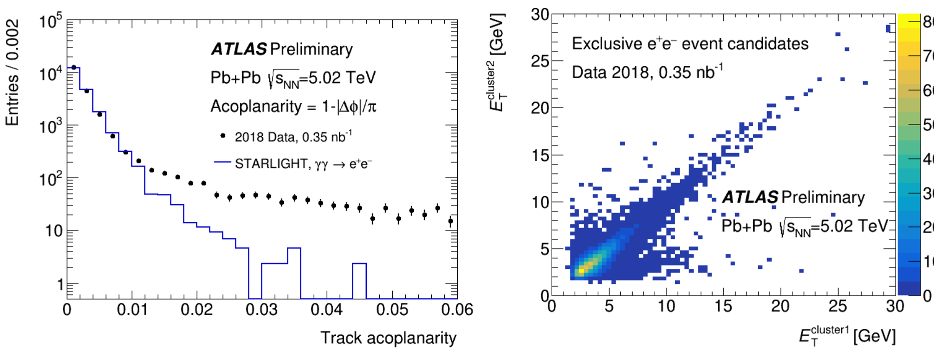

Fig. 4. Control distributions for e^+e^- candidate events in 0.35 nb^{-1} of 2018 Pb+Pb data [9]: track acoplanarity distribution for data compared with the MC simulation (left) and correlation between transverse energy of two clusters associated to exclusive e^+e^- candidate events (right).

4. Summary

The first direct evidence of light-by-light scattering has already been reported by the ATLAS Collaboration in 2017 and corresponded to 4.4σ excess over background-only hypothesis. The new dataset of 1.7 nb^{-1} from Pb+Pb collisions collected in 2018 looks promising for future analyses of ultra-peripheral collisions.

REFERENCES

[1] ATLAS Collaboration, *JINST* **3**, S08003 (2008).

[2] E. Fermi, *Nuovo Cim.* **2**, 143 (1925) [`arXiv:hep-th/0205086`].

[3] E.J. Williams, *Phys. Rev.* **45**, 729 (1934).

[4] ATLAS Collaboration, *Nature Phys.* **13**, 852 (2017).

[5] CMS Collaboration, `arXiv:1810.04602 [hep-ex]`.

[6] ATLAS Collaboration, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonTriggerPublicResults

[7] ATLAS Collaboration, ATLAS-CONF-2016-111, http://cdsweb.cern.ch/record/2220773

[8] S.R. Klein *et al.*, *Comput. Phys. Commun.* **212**, 258 (2017).

[9] ATLAS Collaboration, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/HION-2018-001/