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Measurements of dileptons and photon pairs from two-photon scattering in ultra-peripheral and hadronic Pb+Pb collisions with the ATLAS detector

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Abstract

In ultra-relativistic heavy-ion collisions, one expects copious rates of $\gamma + \gamma$ processes through the interaction of the large electromagnetic fields of the nuclei, which can produce new particles (e.g. leptons) or even lead to light-by-light scattering via loop diagrams. The latter process is a notable prediction of QED and was only recently observed by ATLAS using the full 2018 dataset of Pb+Pb collisions at LHC. In ultra-peripheral collisions (UPCs), characterized by the large impact parameter between the nuclei, the outgoing leptons and photons are produced exclusively, and exhibit a strong back-to-back momentum correlation, with long tails induced by higher-order QED effects. This work presents measurements of dilepton production and light-by-light scattering performed by the ATLAS collaboration. The angular correlations as well as differential production cross sections in UPCs are measured and compared to theoretical models, including final state QED radiation. Muon pairs produced by the same two-photon scattering process in hadronic Pb+Pb collisions also potentially provide a sensitive probe of the quark gluon plasma. First measurements by ATLAS and STAR of dileptons produced via two-photon scattering in non-ultra-peripheral (non-UPC) nucleus-nucleus collisions showed an unexpected centrality-dependent broadening of the angular correlation between the two leptons and/or of the two-lepton p_T distribution. ATLAS has recently measured dimuons produced via two-photon scattering in non-UPC Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using data collected during the 2015 & 2018 runs at LHC, corresponding to an integrated luminosity of 1.9 nb^{-1} . This data set represents a factor of 4 increase in statistics over the 2015 data set used for the first ATLAS measurement. The increased statistics allow new features to be observed in the data, as well as differential studies of the dependence of the pair-distribution on the transverse-momentum and pseudorapidity of the two muons. The results of the new measurement and the possible physics implications will be discussed.

Keywords: UPC, light-by-light, ATLAS experiment

1. Measurement of light-by-light scattering in ultra-peripheral collisions

In heavy-ion collisions, apart from direct collisions between the two nuclei, we also have ultra-peripheral collisions (UPCs) where two nuclei pass very close to each other. These passing by nuclei carry an elec-

tromagnetic (EM) field, which is the source of quasi-real photons. These photons can interact with each other giving rise to light-by-light scattering, shown in Figure 1 (left). The light-by-light scattering, $\gamma\gamma \rightarrow \gamma\gamma$ is a fundamental quantum mechanical process that proceeds via virtual one-loop box diagrams containing charged fermions (leptons and quarks) or $W^\pm$ bosons. Along with the light-by-light scattering we can also have other processes, such as Central Exclusive Production (CEP) of diphotons, QED dielectron production and photon induced quark anti-quark pair production shown in Figure 1.

Fig. 1. From left to right: light-by-light scattering, Central Exclusive Production, QED dielectron, and photon induced quark pair.

First evidence for the light-by-light scattering process in Pb+Pb collisions at the Large Hadron Collider (LHC) was given by the ATLAS collaboration [1] with observed significance of 4.4σ [2], followed by CMS results [3]. In this work, new light-by-light scattering results obtained using integrated luminosity of 1.73 nb^{-1} of Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ with the ATLAS detector are discussed [4]. Events are selected with exactly two photons, each satisfying $E_T > 3 \text{ GeV}$ and $|\eta| < 2.37$ (excluding the crack region $1.37 < |\eta| < 1.52$). Moreover, the diphoton invariant mass ($m_{\gamma\gamma}$) is required to be greater than 6 GeV. Photons are reconstructed from EM clusters in the calorimeter, and tracking information provided by the Inner Detector (ID) is used to identify photon conversions. The photon particle identification (PID) is done using shower-shape variables from the EM calorimeter, optimised for the signal events.

Fig. 2. From left to right: acoplanarity, invariant mass, and transverse momentum of the diphoton system from the data are compared with the signal and background expectations at the detector level [4].

The most dominant background to light-by-light scattering comes from the $\gamma\gamma \rightarrow e^+e^-$ process due to misidentification of electrons as photons when two electron tracks are not reconstructed. Next largest contribution to background comes from the CEP $gg \rightarrow \gamma\gamma$ process shown in Figure 1. To reduce this background, we impose a requirement on the acoplanarity, $A_\phi < 0.01$ (where $A_\phi = 1 - \frac{|\Delta\phi|}{\pi}$) on the selected signal events. A background contribution from the quark-antiquark pair process ($\gamma\gamma \rightarrow q\bar{q}$) is evaluated using the HERWIG++ Monte Carlo (MC) generator [5] and it is found to be negligible. The acoplanarity distribution for the diphoton system is shown in Figure 2(a). A signal and control regions are defined by imposing $A_\phi < 0.01$ and $A_\phi > 0.01$, respectively, to evaluate the CEP background contribution in the signal region, which is estimated to be 4 ± 1 events. Figures 2(b) and 2(c) show invariant mass and transverse momentum for the diphoton system in data compared with the signal expectations from SUPERCHIC 3.0 MC generator [6]. Background expectations for $\gamma\gamma \rightarrow e^+e^-$ is calculated using a data-driven method and simulated using STARLIGHT 2.0 MC [7] and that for the CEP $gg \rightarrow \gamma\gamma$ process was simulated by SUPERCHIC 3.0 MC. Systematic uncertainties of the signal and background processes are shown as shaded bands. The measured fiducial cross section is $78 \pm 13 \text{ (stat)} \pm 7 \text{ (syst)} \pm 3 \text{ (lumi)} \text{ nb}$, which is compared with the predicted values of $45 \pm 5 \text{ nb}$ from ref. [8], $51 \pm 5 \text{ nb}$ from ref. [9], and $50 \pm 5 \text{ nb}$ from SUPERCHIC 3.0 MC.

2. Measurement of dilepton production in non-ultra-peripheral Pb+Pb collisions

It is shown in previous works that dilepton production via $\gamma\gamma$ scattering in non-UPC heavy-ion collisions can be used as EM probes of the quark-gluon plasma [10, 11]. The ATLAS measurements of the centrality dependence of dimuon acoplanarity in non-UPC Pb+Pb collisions have shown a systematic broadening of the acoplanarity distribution that is consistent with expectations of EM scattering of one or both of the muons in the quark-gluon plasma [10]. In this work, measurement of $\gamma\gamma \rightarrow \mu^+\mu^-$ production in non-UPC Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using a combination of 2015 and 2018 data with a total integrated luminosity of 1.9 nb^{-1} is discussed [12]. Muon pairs are selected based on the pair acoplanarity ($\alpha = 1 - \frac{|\Delta\phi|}{\pi}$), asymmetry ($A = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$), and momentum kick ($k_{\perp} = \frac{p_{T1} + p_{T2}}{2}(\pi - |\Delta\phi|)$), where $\Delta\phi$ is the difference of the azimuthal angles ϕ_1 and ϕ_2 and p_{T1} and p_{T2} represent the transverse momenta of the two outgoing muons. Selected events must have at least two oppositely charged muons with average- p_T defined as $\bar{p}_T = (p_{T1} + p_{T2})/2 > 4 \text{ GeV}$, $|\eta| < 2.4$, and dimuon invariant mass ($m_{\mu\mu}$) required to be in the range 4–45 GeV. A main contribution to the background for this measurement comes from muons produced in semi-leptonic decays of heavy quarks. It is estimated using a template fit method. To reduce heavy-flavor backgrounds, requirements are placed on the $d_{0pair} \equiv \sqrt{d_{01}^2 + d_{02}^2}$ and $(z_0 \sin(\theta))_{pair} \equiv \sqrt{(z_{01}\sin(\theta_1))^2 + (z_{02}\sin(\theta_2))^2}$ variables. These requirements are $d_{0pair} < 0.1 \text{ mm}$ and $(z_0 \sin(\theta))_{pair} < 0.2 \text{ mm}$. Template fits to the d_{0pair} distributions for three centrality intervals for muons with $\bar{p}_T > 4 \text{ GeV}$ are shown in Figure 3. The template fits are performed over the $d_{0pair} < 0.3 \text{ mm}$ region. In all centrality intervals, template fits well reproduce the data.

Fig. 3. Template fits to the d_{0pair} distributions in the data for three different centrality interval compared with signal and background. The fits are performed over the range $d_{0pair} < 0.3 \text{ mm}$ [12].

The background-subtracted acoplanarity and $k_{\perp}$ distributions for three centrality intervals and for three $\bar{p}_T$ ranges i.e. $\bar{p}_T > 4, 5$, and 6 GeV are shown in Figure 4. The α distributions change shape with $\bar{p}_T$, peaking

Fig. 4. Top panel shows α distributions after the background subtraction for three $\bar{p}_T$ intervals and for three different centrality interval. Bottom panel shows similar plots but for the $k_{\perp}$ distributions [12].

towards $\alpha = 0$ at higher $\bar{p}_T$. This effect was also evident from the previous α broadening results [10] which was assumed to be resulted from physics processes that transfer a transverse momentum to the muons in the final state. On the other hand, $k_\perp$ distributions (shown in the bottom panel of Figure 4) are more stable and show no significant variation with $\bar{p}_T$. Hence $k_\perp$ variable is used over α for further studies due to its weak $\bar{p}_T$ dependence and its flexibility to observe and quantify the centrality dependent trends. The UPC $k_\perp$ distribution is fit using a sum of two Gauss functions centered at $k_\perp = 0$. The fit results describe both the central peak and the tail of the distribution. The most probable $k_\perp$ peak positions obtained from the fit are shown in Figure 5 as a function of centrality. The amplitude of the peak position increases systematically between peripheral and central collisions. In the most central events, the peak in the $k_\perp$ distribution is shifted by 36 ± 1 MeV.

Fig. 5. Most probable $k_\perp$ peak position from the shifted-UPC fits [12].

3. Summary

Using the new 2018 data and improved measurement techniques, we have discovered light-by-light scattering at LHC in Pb+Pb collisions with 8.2σ observed significance. We have observed total of 59 events with a contribution of 12 background events. A more precise measurement of dimuon photo-production in non-UPC is done with a factor of four higher statistics of data with respect to previous ATLAS results. The α distributions change shape with $\bar{p}_T$ where as the $k_\perp$ distribution shows no significant variation with $\bar{p}_T$. Moreover, the peak position of $k_\perp$ shows centrality dependence.

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