PROCEEDINGS OF SCIENCE

Measurements of dilepton production from photon fusion processes in ultra-peripheral Pb+Pb collisions with the ATLAS detector

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Relativistic heavy-ion beams at the LHC are accompanied by a large flux of nearly-real photons, leading to a variety of photon-induced processes. This note presents a series of measurements of dilepton production from photon-fusion processes performed by the ATLAS Collaboration. Recent measurements of exclusive dielectron production in ultra-peripheral collisions are presented. These processes provide strong constraints on the nuclear-photon flux and its dependence on the impact parameter and photon energy. Comparisons of the measured cross-sections to QED predictions from the STARlight and SuperChic models are also presented. Tau-pair production measurements can constrain the tau lepton anomalous magnetic dipole moment, and a recent ATLAS measurement using muonic decays of tau leptons in association with electrons and tracks provides one of the most stringent limits available to date.

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1. Introduction

Ultra-peripheral collisions (UPC) involve collisions of relativistic nuclei with impact parameters larger than twice the nuclear radius, where the ions interact electromagnetically (EM): either via photonuclear or two-photon production mechanisms [1]. Such EM interactions between the ions can be described as an exchange of photons with small virtuality of $Q < 1/R \approx 30$ MeV and a maximum energy of approximately $E = \gamma/R \approx 80$ GeV for Pb ions at the LHC.

The nuclear cross-section for a two-photon induced reaction can be calculated by convolving the respective photon flux with the elementary cross-section for the $\gamma\gamma \to X$ subprocess. Since the photon flux associated with each hadron scales with its electric charge squared, the cross-section in heavy ion (Pb+Pb) collisions at the LHC is extremely enhanced as compared to proton–proton (pp) collisions.

The experimental signature of two-photon interactions is very striking: in the $2 \to 2$ exclusive processes the object pairs are typically produced without any other activity in the central detectors (exclusive production). The two objects are also produced back-to-back in azimuth, and have little total transverse momentum. This allows the good separation of signal and various background processes.

The large Pb+Pb dataset of about 2.2 nb^{-1} collected by the ATLAS experiment [2] during LHC Run 2 (2015–2018) allows the precise study of various two-photon interaction processes with leptonic final states.

2. Measurement of $\gamma\gamma \to ee$ process

ATLAS has measured the cross-sections for exclusive dielectron production ($\gamma\gamma \to ee$) in UPC Pb+Pb collisions for dielectron invariant masses (m_{ee}) above 5 GeV [3]. This extends the previous ATLAS dimuon measurement in Pb+Pb UPC, where the minimum invariant dilepton mass was set at 10 GeV [4].

The cross-sections are extracted by selecting events having two oppositely-charged electrons, each having transverse momentum $p_{\mathrm{T}}^{e} > 2.5$ GeV and pseudorapidity $|\eta| < 2.5$, with dielectron transverse momentum below 2 GeV. The background, dominated by dissociative dielectron production where one photon is emitted by charged constituents of a nucleon, is estimated using template fits to dielectron acoplanarity (defined as $\alpha = 1 - |\Delta\phi|/\pi$).

Calculations from the STARlight 2.0 MC generator [5] and from the SuperChic3 MC generator [6], both corrected for QED final-state radiation (FSR) effects using Pythia 8 [7], are compared with the measurements. The fiducial cross-section for exclusive dielectron production is measured to be: $\sigma = 215 \pm 1(\text{stat.}) \pm 23(\text{syst.}) \pm 4(\text{lumi.})\ \mu$b, whereas the predictions from STARlight and SuperChic yield 196.9 μb and 235.1 μb, respectively. Differential cross-sections are measured as functions of m_{ee}, average p_{T}^{e}, absolute dielectron rapidity, $|y_{ee}|$, and scattering angle in the dielectron rest frame. Figure 1 shows examples of measured cross-sections. On average, the STARlight predictions underestimate the data by about 10–15%, while the SuperChic predictions are higher by about the same amount. The Starlight and SuperChic predictions tend to have very similar shapes, except for the dielectron rapidity dependence where SuperChic tends to describe the shape

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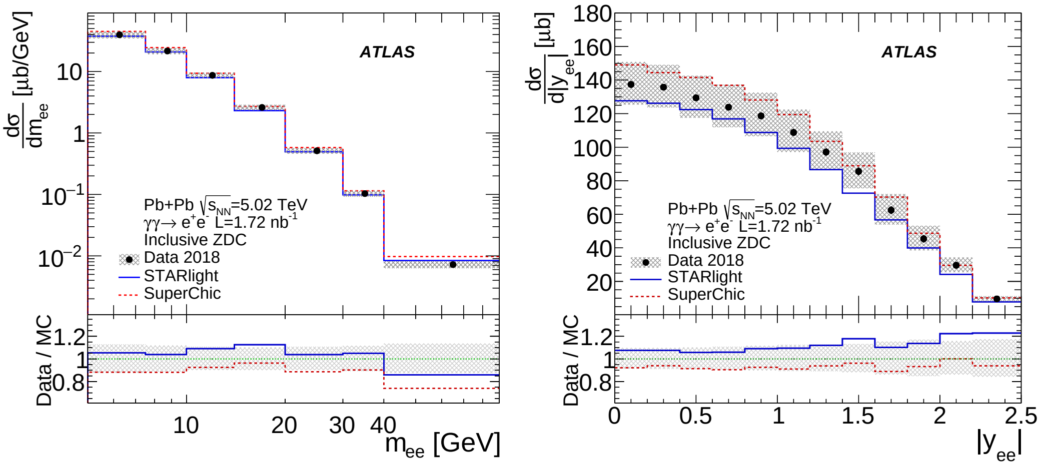

Figure 1: Measured differential fiducial cross-sections of $\gamma\gamma \to ee$ production in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV for two observables: dielectron invariant mass (left) and dielectron absolute rapidity (right) [3]. The measured cross-section values are shown as points with error bars giving the statistical uncertainty and grey bands indicating the size of the total uncertainty. For comparison, the predictions from various theory models are also included (lines).

better than STARlight. The difference in the absolute normalisation of the two predictions is due to different approaches in the calculation of the initial photon flux.

The events are also categorised using the energy deposits in the Zero Degree Calorimeters (ZDC); these energy deposits are sensitive to neutrons emitted as a result of Pb ion excitation due to multiple Coulomb interactions accompanying the $\gamma\gamma \to ee$ process. Differential cross-sections in a sample with a requirement of no activity in the forward direction (0n0n) are measured, which is shown in Fig. 2, where similar trends as for the inclusive sample (Figure 1) are seen.

3. Measurement of $\gamma\gamma \to \tau\tau$ process and constrains on $(g-2)_\tau$

The ATLAS Collaboration measured the exclusive $\gamma\gamma \to \tau\tau$ process in Pb+Pb UPC [8]. Selected events contain one muon from a τ-lepton decay, an electron or charged-particle track(s) from the other τ-lepton decay, hence three signal regions (SR) are used in the analysis: μe-SR requires exactly one additional electron and no other tracks, whereas the μ1T-SR (μ3T-SR) SR requires exactly one (three) additional tracks separated from the muon by $\Delta R_{\mu\ \mathrm{trk}} > 0.1$. In addition, to suppress the background, little additional central-detector activity, and no forward neutrons (0n0n category) are required. After applying the full event selection, a total of 656 data events are observed in all SRs. The dominant source of background is radiative dimuon ($\gamma\gamma \to \mu\mu\gamma$) production. To constrain systematic uncertainties, primarily due to photon flux modeling, a dimuon control region (CR) is defined by requiring two reconstructed muons.

The $\gamma\gamma \to \tau\tau$ process is observed with a significance exceeding five standard deviations, and a signal strength of $\mu_{\tau\tau} = 1.03 \pm 0.06$. Figure 3(left) shows the measured $\mu_{\tau\tau}$, which is extracted from the fit based on the information from the SRs and the CR.

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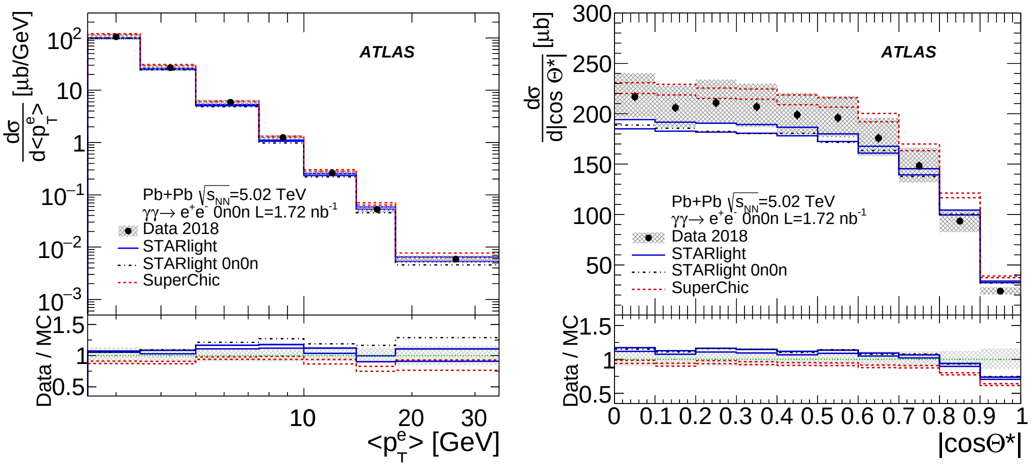

Figure 2: Measured differential fiducial cross-sections of $\gamma\gamma \to ee$ production in Pb+Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV for the 0n0n category and for two observables: electron average $p_{\rm T}$ (left) and scattering angle in the dielectron rest frame (right) [3]. The measured cross-section values are shown as points with error bars giving the statistical uncertainty and grey bands indicating the size of the total uncertainty. For comparison, the predictions from various theory models are also included (lines).

The measurement of production from ATLAS provides also constraints on the tau lepton anomalous magnetic dipole moment, $(g-2)_\tau$. To constrain $(g-2)_\tau$, a profile-likelihood fit to the measured muon $p_{\rm T}$ distribution is performed in the three SRs and CR, with $a_\tau = (g-2)_\tau/2$ being the only free parameter. Figure 3(right) shows the a_τ measurement from ATLAS together with previous results obtained at LEP. The precision of this measurement is similar to the most precise single-experiment measurement by the DELPHI Collaboration [9].

4. Future directions

To extend the ATLAS UPC physics program with leptons in the final state, more efficient triggers at very low lepton transverse momenta (below 2.5 GeV) are required. To provide such capabilities, the Level 1 trigger based on the ATLAS Transition Radiation Tracker, known as the L1 TRT FastOR, is adapted for use in a recent 2023 heavy-ion collision run [11]. Figure 4(left) shows the L1 TRT FastOR trigger efficiency for exclusive 2-track events as a function of leading track transverse momentum. The trigger reaches the efficiency of 80%-90% for tracks with $p_{\rm T}$ as low as 300 MeV. The two-track invariant mass in the J/ψ mass region for events selected by the L1 TRT FastOR trigger is shown in Figure 4(right). The number of coherent J/ψ candidates recorded using this trigger in 2023 is about 100 times higher than the number of candidates recorded in LHC Run 2 ATLAS data, demonstrating that this trigger is capable of efficient recording of exclusive UPC processes with soft leptons.

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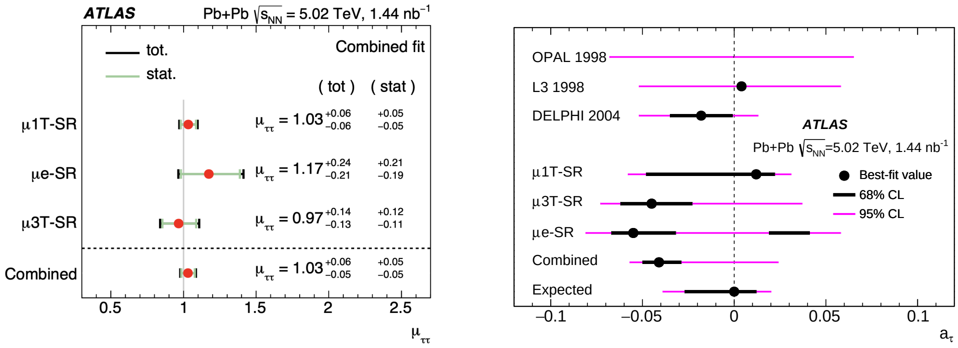

Figure 3: (left) Best-fit values of the signal strength parameter, extracted from the fit based on the individual SRs (denoted as μ1T-SR, μ3T-SR and μe-SR) [10]. The result of the global fit is also included. Statistical uncertainties are shown as green bars, whereas the total uncertainties are shown as black bars. (right) Measurements of $a_\tau = (g-2)_\tau/2$ from fits to individual SRs, and from the combined fit [8]. Measurements from the experiments at LEP are also included. A dot denotes the best-fit a_τ value for each measurement if available, while thick black (thin magenta) lines show 68% CL (95% CL) intervals. The expected interval from the ATLAS combined fit is also shown.

5. Summary

Production of exclusive lepton pairs ($\gamma\gamma \rightarrow \ell\ell$) in ultra-peripheral Pb+Pb collisions is measured by ATLAS in dielectron and $\tau\tau$ final states, complementing the previous ATLAS dimuon measurement. These measurements are sensitive to the modeling of incoming photon fluxes, and can probe EM properties of the tau lepton, via the measurement of its anomalous magnetic moment. Thanks to the trigger improvements, future planned measurements with leptons can probe lower invariant masses and hence be sensitive to the production of coherent vector mesons (like J/ψ meson) in UPC.

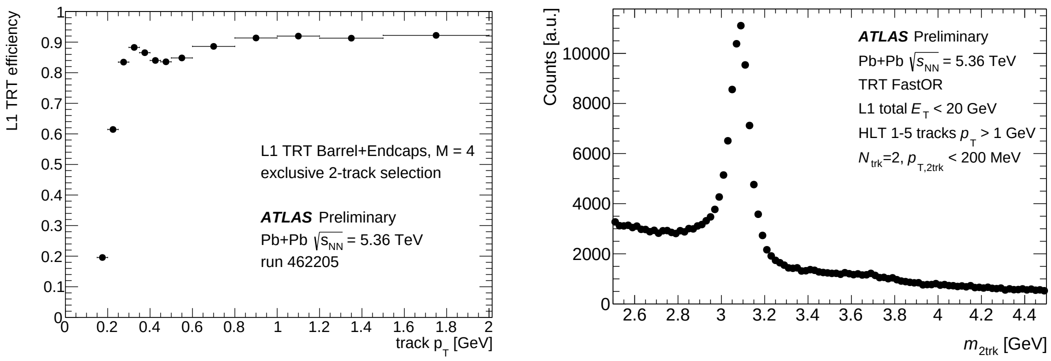

Figure 4: (left) Measured L1 TRT FastOR trigger efficiency for exclusive 2-track events as a function of leading track transverse momentum, for events passing alternative (unbiased) control triggers [12]. (right) Two-track invariant mass in the J/ψ mass region for events selected by the L1 TRT FastOR trigger [13].

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6. Acknowledgements

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