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Results on photon-photon scattering processes in ultra-peripheral Pb+Pb collisions with ATLAS

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In ultra-relativistic heavy-ion collisions, large rates of $\gamma\gamma$ processes occur through the interaction of the large electromagnetic fields of the nuclei. These interactions enable the study of processes potentially sensitive to physics beyond the Standard Model. In ultra-peripheral collisions, characterized by large impact parameter between the nuclei, the outgoing particles exhibit back-to-back production in the transverse plane, which provides precise and efficient identification. This document presents an overview of recent ATLAS measurements potentially sensitive to physics beyond the Standard Model, including the production of tau leptons, and the production of magnetic monopoles. Measurements of tau lepton production help to constrain its anomalous magnetic moment, a quantity potentially sensitive to physics beyond the Standard Model. Also presented is a more recent search for monopole-pair production in ultra-peripheral collisions, with monopole masses ranging from 20 GeV to 150 GeV. The results are compared with recently developed semi-classical models that include non-perturbative cross section calculations.

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1. Introduction

Ultra-peripheral collisions (UPC) involve collisions of relativistic nuclei with impact parameters larger than twice the nuclear radius (R), where the ions interact electromagnetically (EM): either via photonuclear or two-photon ($\gamma\gamma$) 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, where Q denotes the momentum transfer and γ is the relativistic Lorentz factor.

The experimental signature of $\gamma\gamma$ interactions is very striking: in the $2 \rightarrow 2$ 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 datasets collected by the ATLAS experiment [2] during LHC Run 2 (2015–2018) and Run 3 (2022–ongoing), corresponding to integrated luminosities of 2.2 nb^{-1} and 3.4 nb^{-1}, respectively, enable precise studies of various two-photon interaction processes.

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

ATLAS has measured the cross-sections for exclusive dielectron production ($\gamma\gamma \rightarrow ee$) in UPC Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV 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 $p_{\text{T}}^{e} > 2.5$ 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: $\sigma = 215 \pm 1(\text{stat.}) \pm 23(\text{syst.}) \pm 4(\text{lumi.})$ μb, 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 differential cross-sections. On average, the STARlight predictions underestimate the data by about 10–15%, while the SuperChic predictions are higher than data 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 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 $\gamma\gamma \rightarrow ee$ process. In particular, differential

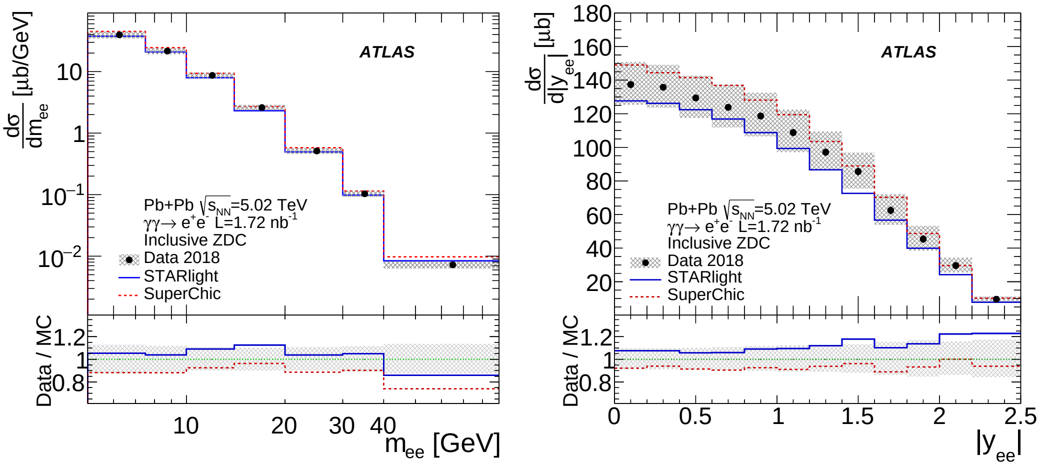

Figure 1: Measured differential fiducial cross-sections of $\gamma\gamma \to ee$ production in Pb+Pb UPC at $\sqrt{s_{\rm NN}}$ = 5.02 TeV for the two observables: dielectron invariant mass (left) and dielectron absolute rapidity (right) [3]. The measured cross-section values are shown as points with 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).

cross-sections in a sample with a requirement of no activity in the forward direction (0n0n) are measured, where similar trends as for the inclusive sample (Figure 1) are observed.

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

The ATLAS Collaboration also measured the exclusive $\gamma\gamma \to \tau\tau$ process in Pb+Pb UPC at 5.02 TeV [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 $\Delta R_{\mu\ \rm trk} > 0.1$. 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 production ($\gamma\gamma \to \mu\mu\gamma$). 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 $\mu_{\tau\tau} = 1.03 \pm 0.06$. The measurement of $\gamma\gamma \to \tau\tau$ 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, yielding $-0.057 < a_\tau < 0.024$ at 95% confidence level. The precision of this measurement is similar to the most precise single-experiment measurement by the DELPHI Collaboration at LEP [9].

4. Search for magnetic monopoles in Pb+Pb UPC

Magnetic monopoles are hypothetical particles that carry isolated magnetic charge. The interaction of strong magnetic fields in Pb+Pb UPC could give rise to the production of hypothetical magnetic monopole–antimonopole pairs. Recently, ATLAS performed a search for these elusive particles using Pb+Pb collisions at 5.36 TeV from Run-3 of the LHC [10].

The analysis employs a non-perturbative model to estimate monopole production rate [11]. Traditional perturbative models, which rely on Feynman diagrams, are inadequate due to the large coupling constant of magnetic monopoles. Instead, the study uses a model based on the Schwinger mechanism, adapted for magnetic fields, to predict monopole production in the UPC strong magnetic fields.

The analysis uses a different way of detecting low-mass monopoles in heavy-ion collisions, complementary to the trapping technique used by the MoEDAL experiment [12]. The targeted monopole signature is based on high ionization in the ATLAS Pixel Detector. The background is mainly beam-induced, and its yield is estimated using a data-driven procedure. No excess of events over the expected background is observed. As shown in Figure 2, the derived upper limits on monopole pair-production cross-sections, are more stringent than the recently reported limits from MoEDAL [12], also using Pb+Pb collisions. Based on the non-perturbative FPA model [11], monopoles with a single Dirac magnetic charge and mass below 120 GeV are excluded.

5. 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

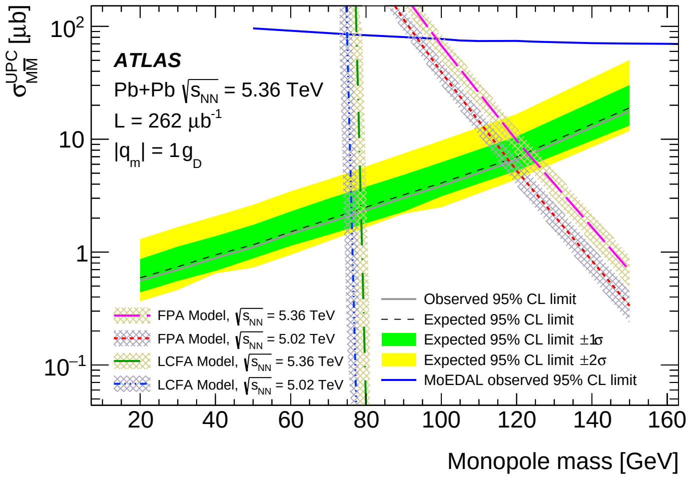

Figure 2: 95% confidence upper limits on the monopole pair-production cross-section in Pb+Pb UPC at 5.36 TeV [10]. The limits are compared with model predictions and the observed limits by the MoEDAL experiment.

L1 TRT FastOR, is adapted for use in a recent 2023 heavy-ion collision run [13]. The trigger reaches the efficiency of 80%-90% for exclusive events having tracks with p_{T} as low as 300 MeV, demonstrating that the full system is capable of efficient recording of UPC processes with soft leptons.

6. Summary

Production of exclusive lepton pairs ($\gamma\gamma \to \ell\ell$) 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 probe EM properties of the tau lepton, via the measurement of its anomalous magnetic moment. A search for highly ionising magnetic monopoles was conducted as well, based on a non-perturbative production model. The search significantly improves on the previous cross-section limits for production of low-mass monopoles in ultra-peripheral Pb+Pb collisions. Improvements in trigger-system capabilities for detecting low-momentum leptons in UPC will enhance future measurements.

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