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

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Abstract. In ultra-relativistic heavy-ion collisions, copious rates of photon-induced processes are expected through the interaction of the large electromagnetic fields of the nuclei, which enables the production of particles such as inclusive hadrons, lepton pairs, or hypothetical magnetic monopoles. This talk presents recent measurements of processes in such ultra-peripheral collisions with the ATLAS experiment at the LHC.

1 Introduction

Collisions of hadrons at high energies are usually studied for cases where the hadrons interact strongly to produce multiple particles. The electromagnetic fields of the hadrons, however, can also induce interactions at large impact parameters where the strong interaction is inactive (ultra-peripheral collisions, UPCs). In the 1930s it was found that the electromagnetic fields produced by the colliding charged particles can be treated as a beam of nearly-real photons emitted coherently [1]. This can give rise to photon–nucleus and photon–photon interactions.

The large Pb+Pb dataset collected by the ATLAS experiment [2] during LHC Run 2 (2015–2018) and LHC Run 3 (2023–2024) allows the precise study of various photon-induced interaction processes.

2 Characterising photonuclear γ+Pb collisions

Two-particle azimuthal correlations have been studied in photo-nuclear (γ+Pb) events by ATLAS [3] at the LHC. These results indicate significant non-zero elliptic and triangular flow coefficients, which are interpreted in terms of hydrodynamical models. In Ref. [4], the authors make the specific prediction that the radial flow, one of the signatures of the Quark-Gluon Plasma, is similar in γ+Pb and p+Pb collisions, and can be measured via the mean transverse momentum (p_{T}) of produced hadrons. Hence, inclusive yields of primary charged hadrons as a function of pseudorapicity (η) and p_{T}, are measured by ATLAS in γ+Pb and in p+Pb collisions [5].

Figure 1 shows the mean p_{T} of charged hadrons, extrapolated to $p_{\mathrm{T}} = 0$ GeV, as a function of charged particle multiplicity ($N_{\mathrm{ch}}^{\mathrm{rec}}$) in two η regions, $[-1.6,\ -0.8]$ and $[0.8,\ 1.6]$, for both γ+Pb and p+Pb collision systems. At negative values of η, the mean p_{T} between the two

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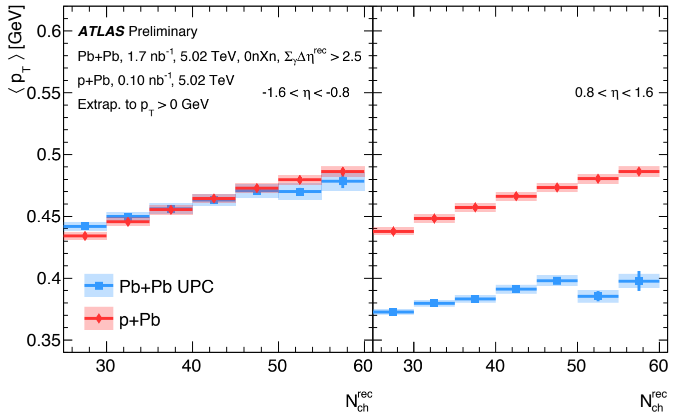

Figure 1. Mean p_T of charged-hadron yields (extrapolated to $p_T > 0$ GeV) as a function of N_{ch}^{rec} in γ+Pb and p+Pb collisions in two different pseudorapidity slices: (left) $[-1.6, -0.8]$ and (right) $[0.8, 1.6]$) [5]. Vertical lines denote statistical uncertainties and shaded boxes denote systematic uncertainties.

collision systems is fairly comparable. However, for the photon-going side ($\eta > 0$), there is a substantial difference in the mean p_T between the two collision systems for all N_{ch}^{rec} values. The substantially larger mean p_T at negative η in Pb+Pb UPC, and its comparable magnitude in p+Pb, may already hint at a contribution from radial flow, as discussed above. Further tests measuring the N_{ch}^{rec} of identified hadrons are required to better check this hypothesis, for example, by measuring baryon-to-meson ratios that are sensitive to radial flow.

3 $\gamma\gamma \to \tau\tau$ production in Pb+Pb UPC

The ATLAS Collaboration measured the exclusive $\gamma\gamma \to \tau\tau$ process in Pb+Pb UPC [6]. 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 photon flux modeling is assessed by using alternative MC generator (STARlight [7] instead of SuperChic [8]) to model the initial photon fluxes.

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 2 (left) shows the measured $\mu_{\tau\tau}$, which is extracted from the fit based on the information from the SRs and the CR.

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_T distribution is performed in the three SRs and CR, with $a_\tau = (g-2)_\tau/2$ being the only free parameter. Figure 2 (right) shows the a_τ measurement from ATLAS together with previous results obtained at LEP. The precision of this measurement is comparable to the most precise single-experiment measurement by the DELPHI Collaboration [9].

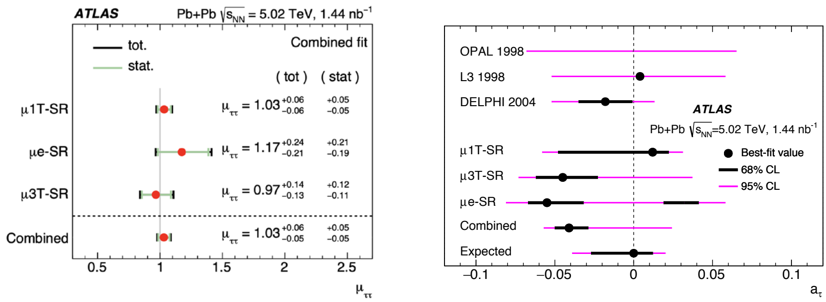

Figure 2. (left) Best-fit values of the signal strength parameter, extracted from the fit based on the individual SRs (denoted as μ1T-SR, μ3T-SR and μe-SR) [10]. The result of the global fit is also included. Statistical uncertainties are shown as green bars, whereas the total uncertainties are shown as black bars. (right) Measurements of $a_\tau = (g-2)_\tau/2$ from fits to individual SRs, and from the combined fit [6]. 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.

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 [11].

The analysis employs a non-perturbative FPA model to estimate monopole production rate [12]. 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 [13, 14]. 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 3, the derived upper limits on monopole pair-production cross-sections, are more stringent than the recently reported limits from MoEDAL [13, 14], also using Pb+Pb collisions. Based on the non-perturbative FPA model [12], 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

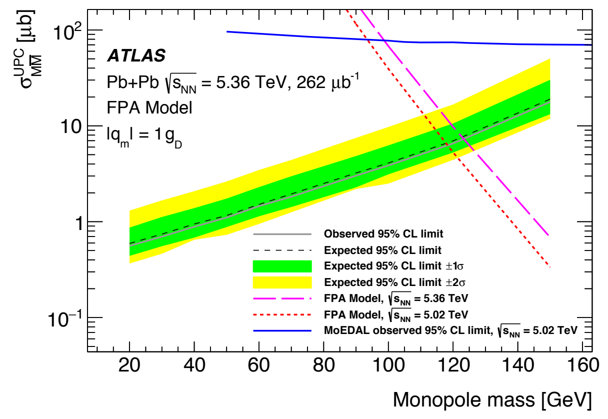

Figure 3. 95% confidence upper limits on the monopole pair-production cross-section in Pb+Pb UPC at 5.36 TeV [11]. The limits are compared with model predictions and the observed limits by the MoEDAL experiment.

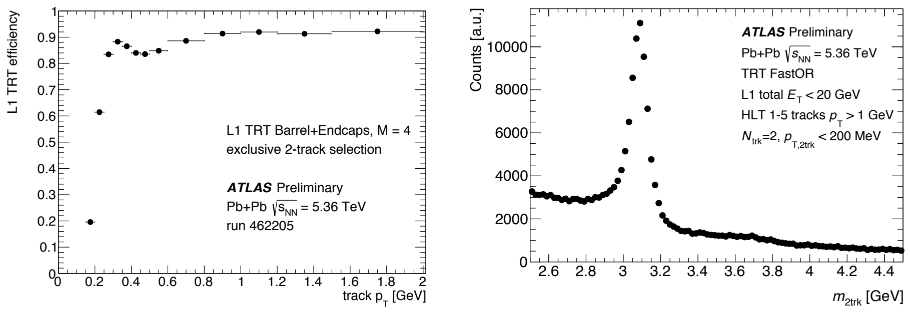

Figure 4. (left) Measured L1 TRT FastOR trigger efficiency for exclusive 2-track events as a function of leading track transverse momentum, for events passing alternative (unbiased) control triggers [16]. (right) Two-track invariant mass in the J/ψ mass region for events selected by the L1 TRT FastOR trigger [17].

as the L1 TRT FastOR, is adapted for use in a recent 2023 heavy-ion collision run [15]. 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_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.

6 Conclusions

A summary of recent results from the ATLAS experiment on photon-induced processes in ultra-peripheral Pb+Pb collisions is provided. The studies include measurements of basic properties of inclusive photo-nuclear (γ+Pb) collisions, revealing collective-like behavior in this system. Additionally, ATLAS observed τ-lepton pair production ($\gamma\gamma \rightarrow \tau\tau$) and set constraints on the anomalous magnetic moment of the τ lepton that are competitive with previous LEP results. 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. Future studies aim to enhance trigger-system capabilities for detecting low-momentum leptons in UPC.

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References

[1] E. J. Williams, Nature of the high-energy particles of penetrating radiation and status of ionization and radiation formulae, Phys. Rev. **45** (1934), 729-730, https://doi.org/10.1103/PhysRev.45.729.

[2] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST **3** (2008), S08003, https://doi.org/10.1088/1748-0221/3/08/S08003.

[3] ATLAS Collaboration, Two-particle azimuthal correlations in photonuclear ultraperipheral Pb+Pb collisions at 5.02 TeV with ATLAS, Phys. Rev. C **104** (2021) 014903, https://doi.org/10.1103/PhysRevC.104.014903.

[4] W. Zhao, C. Shen and B. Schenke, Collectivity in Ultraperipheral Pb+Pb Collisions at the Large Hadron Collider, Phys. Rev. Lett. **129** (2022) 252302, https://doi.org/10.1103/PhysRevLett.129.252302.

[5] ATLAS Collaboration, Charged-hadron yield measurements in photo-nuclear collisions using 5.02 TeV Pb+Pb data with ATLAS, ATLAS-CONF-2023-059, https://cds.cern.ch/record/2871729.

[6] ATLAS Collaboration, Observation of the $\gamma\gamma\rightarrow\tau\tau$ Process in Pb+Pb Collisions and Constraints on the τ-Lepton Anomalous Magnetic Moment with the ATLAS Detector, Phys. Rev. Lett. **131** (2023) 151802, https://doi.org/10.1103/PhysRevLett.131.151802.

[7] S. R. Klein et al., STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions, Comput. Phys. Commun. **212** (2017) 258, https://doi.org/10.1016/j.cpc.2016.10.016.

[8] L. A. Harland-Lang, V. A. Khoze and M. G. Ryskin, Exclusive LHC physics with heavy ions: SuperChic 3, Eur. Phys. J. C **79** (2019) 39 https://doi.org/10.1140/epjc/s10052-018-6530-5.

[9] DELPHI Collaboration, Study of tau-pair production in photon-photon collisions at LEP and limits on the anomalous electromagnetic moments of the tau lepton, Eur. Phys. J. C **35** (2004) 159, https://doi.org/10.1140/epjc/s2004-01852-y.

[10] ATLAS Collaboration, Auxiliary material: Observation of the $\gamma\gamma\rightarrow\tau\tau$ Process in Pb+Pb Collisions and Constraints on the τ-Lepton Anomalous Magnetic Moment

with the ATLAS Detector, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2019-19/

[11] ATLAS Collaboration, Search for Magnetic Monopole Pair Production in Ultraperipheral Pb+Pb Collisions at $\sqrt{s_{\rm NN}}$ = 5.36 TeV with the ATLAS Detector at the LHC, Phys. Rev. Lett. **134** (2025) 061803, https://doi.org/10.1103/PhysRevLett.134.061803.

[12] O. Gould, D. L. J. Ho and A. Rajantie, Towards Schwinger production of magnetic monopoles in heavy-ion collisions, Phys. Rev. D **100** (2019) 015041, https://doi.org/10.1103/PhysRevD.100.015041.

[13] MoEDAL Collaboration, Search for magnetic monopoles produced via the Schwinger mechanism, Nature **602** (2022) 63, https://doi.org/10.1038/s41586-021-04298-1

[14] MoEDAL Collaboration, MoEDAL Search in the CMS Beam Pipe for Magnetic Monopoles Produced via the Schwinger Effect, Phys. Rev. Lett. **133** (2024) 071803, https://doi.org/10.1103/PhysRevLett.133.071803.

[15] P. Rybczynski, Performance of the ATLAS L1 Transition Radiation Tracker Trigger in Heavy-ion Collisions at the LHC, Acta Phys. Pol. B Proc. Suppl. **17** (2024) 5-A34, https://doi.org/10.5506/APhysPolBSupp.17.5-A34.

[16] ATLAS Collaboration, Performance of TRT Fast-OR trigger in 2023 HI run, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDET-2023-01/.

[17] ATLAS Collaboration, Performance plots from 2023 Pb+Pb collisions at 5.36 TeV, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/HION-2023-001/.