

ATLAS OVERVIEW OF PHYSICS OF ULTRAPERIPHERAL COLLISIONS*

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Ultrapерipheral heavy-ion collisions (UPC) at the Large Hadron Collider (LHC) provide a unique environment to study photon-induced processes. This overview highlights recent ATLAS measurements of UPC in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 5.36 TeV. The measurements address important physics questions on nuclear parton structure, onset of quark–gluon plasma formation, and multiple photon-induced processes.

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1. Introduction

The relativistic heavy-ion collisions at the Large Hadron Collider (LHC) [1] provide a wide range of unique measurement opportunities. A significant part of the LHC heavy-ion programme consists of measuring ultraperipheral collisions (UPC) of nuclei, where impact parameter is larger than the sum of the nuclei radii and large enough that there is no hadronic interaction between the nuclei, providing an extremely clean environment for studying various photon-induced processes [2]. The ATLAS Collaboration has measured UPC photon–photon collision events, where exclusive lepton pairs are produced [3–5], as well as UPC photonuclear collisions, which can result in production of charged hadrons [6], jets [7], or J/ψ meson [8]. Coincident photon-initiated processes in UPC, where lepton pair and vector meson production, has also been measured [9].

The ATLAS [10] experiment is a general-purpose particle detector at the Large Hadron Collider. The ATLAS detector consists of the Inner Detector, immersed in 2 T axial magnetic field and providing charged-particle tracking

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in pseudorapidity range $|\eta| < 2.5$, electromagnetic and hadronic calorimeters, covering pseudorapidity range $|\eta| < 4.9$, and a muon spectrometers, that allows for measuring the deflection of muons in a magnetic field of the superconducting air-core toroid magnet. ATLAS is also equipped with zero-degree calorimeters (ZDC) [11], located at approximately ± 140 m from the interaction point, detecting forward neutral particles, such as neutrons, originating from the interacting nuclei.

2. Photonuclear jet production in UPC

UPC collisions provide an opportunity to study nuclear parton distribution functions (nPDFs) using photons associated with one of the colliding nuclei as an electromagnetic probe of the other nucleus [12–14]. In the leading order (LO), the photon can either scatter directly off the parton from the nucleus (“direct” mechanism), or fluctuate into a partonic or hadronic state that undergoes hard-scattering with the nucleus (“resolved” mechanism). Such photonuclear collisions typically produce two or more detected jets that can be used to reconstruct the kinematics of the incoming particle, thus providing a probe of lead nPDFs. The kinematics of the jets can be expressed using the nuclear parton momentum fraction (x_A), the parton momentum fraction in the photon direction (z_γ), and the scalar sum of the p_T of the jets (H_T), which can be viewed as a proxy for the momentum transfer.

The events selected for this measurement [7] are required to have large rapidity gaps on photon-going side, energy deposited in exactly one ZDC, and at least two jets with $p_T > 15$ GeV. The template fits of the gap distributions are used to constrain the background hadronic Pb+Pb interactions, while at the same time allowing the fraction of events resulting from “direct” or “resolved” photon processes to be estimated.

The UPC dijet differential cross sections are measured as a function of x_A , z_γ , and H_T , and are compared to four different nPDF sets. The subset of the obtained results are presented in figure 1. All four nPDF sets used tend to underpredict the data in the shadowing region, while having the better agreement in the anti-shadowing and EMC regions. Results from this measurement provide substantially improved coverage of the intermediate- Q^2 region over a wide range of x values and have substantial constraining power for nPDFs.

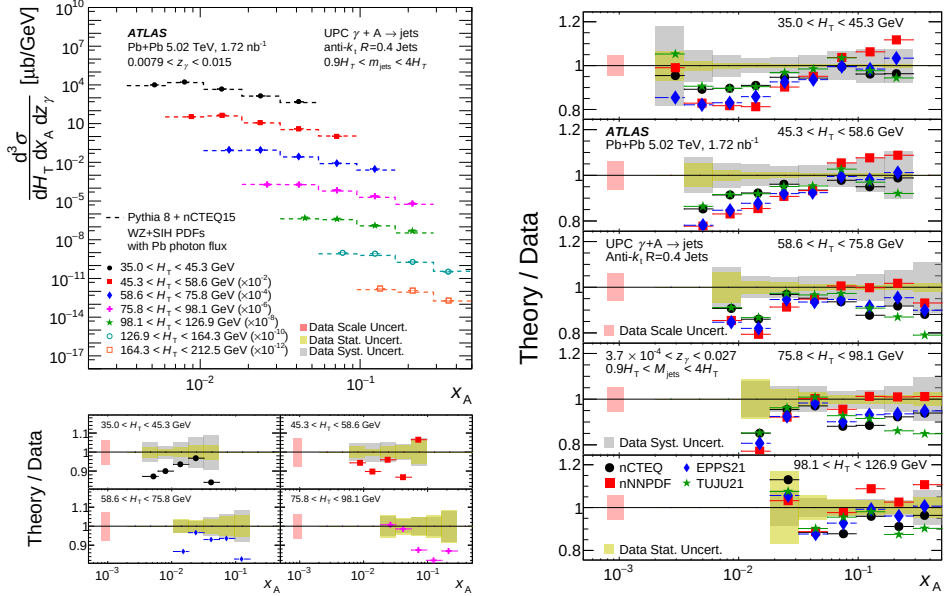


Fig. 1. Left: Triple-differential cross sections $\frac{d^3\sigma}{dH_T dx_A dz_\gamma}$ as a function of x_A for different bins of H_T for events with emitted photon energies in the kinematic range $0.0079 < z_\gamma < 0.015$. Right: Ratios of the triple-differential cross sections $\frac{d^3\sigma}{dH_T dx_A dz_\gamma}$ to theoretical predictions using several nPDF models as a function of x_A for different bins of H_T for events with struck parton energies in the kinematic range $3.7 \times 10^{-4} < z_\gamma < 0.027$ [7].

3. Charged-hadron and identified-hadron yields in $\gamma + A$

The signatures of quark–gluon plasma (QGP) include the strangeness enhancement, an abundance of $gg \rightarrow s\bar{s}$ process, and elliptic and radial flow, which are indicators of collectivity. This collective behaviour was observed in systems of various sizes, from Pb+Pb [15] down to the smallest systems such as p +Pb and pp [16]. The recent measurement of charged-hadron and identified-hadron yields by ATLAS [6] looks for signs of QGP formation in photonuclear Pb+Pb collisions.

The events selected for this measurement are required to have large pseudorapidity gaps on photon-going side, $\sum \Delta\eta > 2.5$, and energy in exactly one ZDC, with at least 15 reconstructed charged-particle tracks. For the charged-hadron analysis, tracks are required to have $p_T > 100$ MeV, pass further track quality selection criteria, and are corrected for reconstruction and selection inefficiencies and contributions of secondaries and fakes. For the identified-hadron (K_s^0 , Λ , Ξ^-) analysis, the tracks are additionally required to have opposite charges and are fitted to a common secondary vertex.

The average charged-particle p_T over all events, $\langle p_T \rangle$, is calculated as a function of charged-particle track multiplicity for charged- and identified-hadrons, as shown in figure 2. The results are compared with a hybrid hydrodynamic model [17]. The higher $\langle p_T \rangle$ for charged hadrons is observed in the lead-going direction, while for the photon-going side, lower $\langle p_T \rangle$ is observed. This can be interpreted as an indication of larger and smaller radial flow, respectively. By taking the ratio of identified-hadrons yields to charged-hadron yields, the increase of strange hadron yields relative to charged hadrons between lead-going and photon-going rapidity is observed.

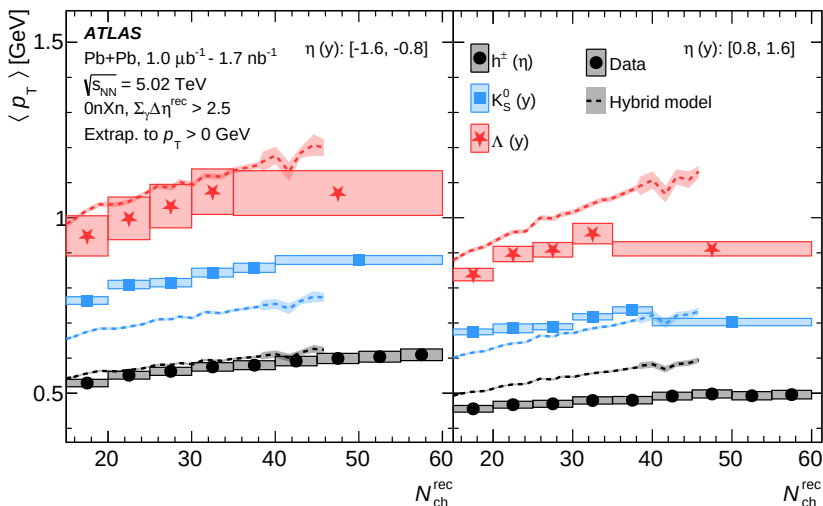


Fig. 2. The $\langle p_T \rangle$ for charged hadrons, K_S^0 , and Λ (dot, square, and star markers respectively) in Pb+Pb photo-nuclear collisions as a function of N_{ch}^{rec} . The left (right) panels are for a lead-going (photon-going) rapidity selection. The comparisons to the hybrid hydrodynamic model (dashed lines) are shown [6].

4. Coherent exclusive J/ψ production in UPC

Exclusive vector meson production in photonuclear collisions can proceed in two ways: coherent or incoherent. In coherent process, the colour-neutral exchanged object, the “Pomeron”, is emitted coherently by all the nucleons in the nucleus and does not directly resolve the nuclear structure. This process is particularly interesting because, at LO in quantum chromodynamics (QCD), the cross section is predicted to scale approximately with the square of the gluon PDF in the target. ATLAS performed the measurement of exclusive $J/\psi \rightarrow \mu^+\mu^-$ in UPC Pb+Pb collisions at medium and low rapidities [8].

At the trigger level, the events were selected using the combination of TRT “FastOR” [18] with a veto on total transverse energy $E_T < 20$ GeV, with additional requirement on forward calorimeter $E_T < 5$ GeV, up to 15 reconstructed charged-particle tracks with $p_T > 100$ MeV, and between one to five tracks with $p_T > 1$ GeV. For the offline event selection, exactly two opposite-charge tracks, each with $p_T > 1$ GeV and passing further quality selection criteria, are required. In addition, the invariant mass of each two-track systems must be within J/ψ mass window, $2.9 < m_{\mu^+\mu^-} < 3.2$ GeV, and the pair’s transverse momentum must satisfy $p_T^{\mu\mu} < 0.2$ GeV. $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$ mass shapes are described by double-sided Crystal Ball functions and their parameters are fixed using fits to simulated events. A fit to the measured invariant mass is performed to extract the yields and give the constraints on $\gamma\gamma \rightarrow ll$ background. Fit to p_T allows one to differentiate between coherent and incoherent J/ψ . Extracted yields are corrected for efficiencies, acceptance, branching ratios, and luminosity to extract the cross sections.

Figure 3 shows the differential J/ψ cross section, measured in five rapidity bins in the range $|y| < 2.5$. The results are compared with model predictions from: STARlight 2.0 [19] and two versions of a colour glass condensate (CGC) model [20, 21]. The CGC-based model including the effect of nucleon shape fluctuations is found to provide the best description of the data.

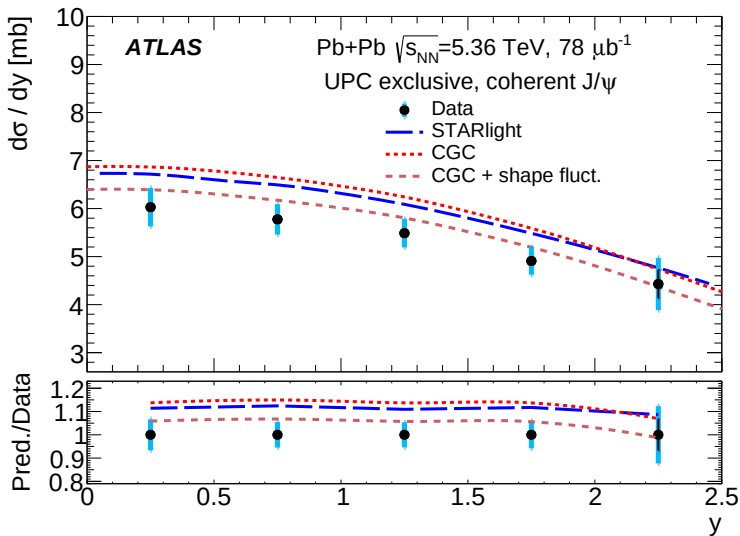


Fig. 3. Measured differential cross section for coherent exclusive J/ψ meson production in Pb+Pb UPC at $\sqrt{s_{NN}} = 5.36$ TeV as a function of J/ψ rapidity (averaged over both sides). Data (points) are compared with several model predictions: STARlight 2.0, and two versions of a color glass condensate (CGC) model [8].

5. Coincident photon-initiated processes in UPC

Any UPC scattering process, including lepton pair production, may have a non-negligible probability of producing a vector meson in the same Pb+Pb collision [22]. The probability for coincident ρ^0 production via γ -pomeron scattering in a typical UPC Pb+Pb collision can be of $O(1\%)$. ATLAS has measured the relative rate for the coincident occurrence of the $\gamma\gamma \rightarrow \mu^+\mu^-$ and $\gamma + A \rightarrow \rho^0 + A$ processes in UPC Pb+Pb collisions [9].

The events selected for this measurement are required to have exactly two opposite-charge, back-to-back muons with $p_T > 3.7$ GeV, and $|\eta| < 2.4$. The presence of two extra charged-particle tracks, which are assumed to be charged pions from ρ^0 decay, is also required. A fit to the measurement mass distribution of pion track pair using Monte Carlo simulated signal ($\rho^0 \rightarrow \pi\pi$) and backgrounds ($\gamma\gamma \rightarrow ll$), and a data-driven background template (pairs of tracks in data events with multiplicity between five and ten tracks) allows for $\rho^0 \rightarrow \pi\pi$ yield extraction. The analysis is performed in five ZDC event topologies: $0n0n$, $0nXn$, $XnXn$, $0nAn$, and $AnAn$, where $0n$ — no neutrons, Xn — at least one neutron, and An — any number of neutrons detected at given ZDC side.

The relative rate of ρ^0 production in the $\gamma\gamma \rightarrow \mu^+\mu^-$ process is shown in figure 4, in the intervals of ZDC activity, and with selection for dimuon mass, rapidity, and energy of the leading photon. Increase in relative rate is observed with increasing ZDC activity and with increasing dimuon mass. An increase of both observables can be viewed as a proxy for a decreasing impact parameter. Studies of coincident lepton pair and ρ^0 -meson production could provide an insight into the nuclear gluon distribution functions and provide constraints on photon fluxes or nuclear charge form factors.

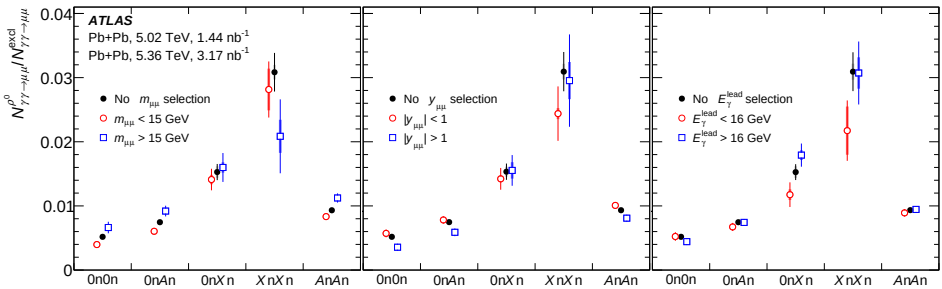


Fig. 4. The ratio of the coincident ρ^0 production in $\gamma\gamma \rightarrow \mu^+\mu^-$ events to the number of exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ events for different ZDC selections. The left, centre, and right panels compare different $m_{\mu\mu}$, $y_{\mu\mu}$, and E_{γ}^{lead} (energy of the leading photon) intervals, respectively [9].

6. Summary

Using the LHC as a photon collider provides multiple new measurement opportunities. ATLAS has recently published interesting results on the physics of the UPC collisions, which can address important physics questions on nuclear parton structure, onset of quark–gluon plasma formation and multiple photon-induced processes.

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