

MEASUREMENT OF COHERENT EXCLUSIVE J/ψ PRODUCTION IN ULTRAPERIPHERAL Pb+Pb COLLISIONS AT $\sqrt{s_{NN}} = 5.36$ TeV WITH THE ATLAS DETECTOR*

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The ATLAS heavy-ion physics program includes the study of ultra-peripheral collisions. In these interactions, the ions serve as a source of high-energy quasi-real photons. These photons can interact with another nucleus, giving rise to a variety of photon-induced processes. One of these is exclusive vector meson production. This process allows for the study of the spatial and momentum structure of the nuclear parton distribution functions and may provide insight into low Bjorken- x phenomena such as nuclear shadowing and parton saturation. This study shows the first ATLAS measurement of coherent exclusive J/ψ production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV. The differential cross section for this process is measured as a function of J/ψ rapidity.

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1. Introduction

Ultraperipheral collisions (UPCs) and vector meson photoproduction are reviewed in Refs. [1, 2]. In UPCs, a virtual photon emitted by one of the nuclei can fluctuate into a charm–anticharm ($c\bar{c}$) quark pair. This quark pair can form a real J/ψ vector meson through scattering off another nucleus. The mechanism of this interaction is described by various theoretical models. To discriminate between them, charmonium photoproduction has been extensively measured in UPCs at RHIC [3] and the LHC by ALICE [4, 5], CMS [6], and LHCb [7]. These measurements were performed across a wide range of rapidity.

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Exclusive vector meson production proceeds via a coherent or an incoherent processes. In coherent photoproduction, the $c\bar{c}$ pair couples to a colorless object (Pomeron) that is emitted coherently by all the nucleons in the nucleus, rendering the process sensitive to nuclear parton distribution functions. In incoherent production, the Pomeron is emitted either by individual nucleons or their constituents, leading to the dissociation of the nucleus. Coherent and incoherent processes can be distinguished experimentally through the transverse momentum (p_T) of the produced vector meson. Coherent production is characterized by low p_T (tens of MeV) of the mesons, while incoherent processes tend to result in mesons with significantly larger p_T .

This study presents the first ATLAS measurement of coherent exclusive J/ψ photoproduction in Pb+Pb UPCs at $\sqrt{s_{NN}} = 5.36$ TeV using Run 3 data [8]. The J/ψ cross section is measured differentially as a function of rapidity for $|y| < 2.5$, covering a previously-unmeasured region of $0.8 < |y| < 1.6$. The measurement is performed in the $J/\psi \rightarrow \mu^+\mu^-$ decay channel. The final-state muons are expected to have transverse momenta of $p_T \sim 1.5$ GeV and to lose most of their energy in the calorimeter material before reaching the muon detectors. As a result, explicit muon identification is not feasible, and the analysis relies on information from the ATLAS Inner Detector (ID) [9].

The measured cross sections are compared with theoretical predictions, particularly those that incorporate parton saturation [10, 11]. The results are compared with other measurements [4–7], performed at $\sqrt{s_{NN}} = 5.02$ TeV, after a model-dependent extrapolation to account for the beam energy difference.

2. Data and Monte Carlo simulation samples

This analysis uses data recorded by the ATLAS detector in 2023 during Pb+Pb heavy-ion collisions at $\sqrt{s_{NN}} = 5.36$ TeV.

The trigger decision relies on a positive signal from the Transition Radiation Tracker (TRT) FastOR trigger, together with a veto on total transverse energy in calorimeters above 20 GeV. This selection rejects events with large hadronic activity, while ensuring some activity in the ID. Further trigger selection consists of a veto on transverse energy in forward calorimeters (above 5 GeV) and a veto on events with more than 15 reconstructed tracks. The data set collected with these requirements corresponds to an integrated luminosity of $78 \mu\text{b}^{-1}$.

Simulated Monte Carlo (MC) events for the signal and background processes were generated using STARlight [12] interfaced with Pythia 8 for the simulation of QED final-state radiation.

3. Event selection

In the event selection, exactly two opposite-charge tracks are required. The event is rejected if there are more than two tracks with $p_T > 0.1$ GeV and $|\eta| < 2.5$ that pass a loose track-quality selection [13]. Both selected tracks are required to have $p_T > 1$ GeV and a transverse impact parameter $|d_0| < 2$ mm. The muon mass hypothesis is used for the tracks. The signal-region selection requires the dimuon system to have an invariant mass in the range $2.9 < m_{\mu^+\mu^-} < 3.2$ GeV, and a dimuon transverse momentum of $p_T^{\mu^+\mu^-} < 0.2$ GeV.

4. Yield extraction

The main backgrounds to the coherent $J/\psi \rightarrow \mu^+\mu^-$ process are $J/\psi \rightarrow e^+e^-$, $\gamma\gamma \rightarrow \ell^+\ell^-$, incoherent $J/\psi \rightarrow \ell^+\ell^-$, feed-down $\psi(2S)$ and inelastic photonuclear processes. The contribution from $\psi(2S)$ feed-down is constrained through a normalization factor extracted from a four-track control region.

Due to the low transverse momenta of the observed particles ($p_T \sim 1.5$ GeV), standard muon identification is not feasible. However, the $J/\psi \rightarrow \mu^+\mu^-$ process can be distinguished from $J/\psi \rightarrow e^+e^-$ using a fit to the invariant-mass distribution. Due to energy losses and radiative processes in the ID material, the peak of the $J/\psi \rightarrow e^+e^-$ process is widened and shifted towards lower invariant masses with respect to the $J/\psi \rightarrow \mu^+\mu^-$ peak. A fit of a Crystal Ball function to each peak allows one to extract the $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$ yields from data without explicit muon identification. Furthermore, an exponential function is added to the fit to constrain the $\gamma\gamma \rightarrow \ell^+\ell^-$ background.

The coherent contribution to the J/ψ yield is separated from the incoherent one using fits to the $p_T^{\mu^+\mu^-}$ spectrum. The fit uses templates from Monte Carlo simulation samples to model each contribution except the inelastic photonuclear background, where a data-driven template is used, and the incoherent dissociative $J/\psi \rightarrow \ell^+\ell^-$, which is parametrized with a power-law function $d\sigma/dp_T \approx p_T(1+(b_{pd}/n)p_T^2)^{-n}$. The parameters are set to $n = 3.58$ and $b_{pd} = 1.79$ GeV⁻².

5. Results

The differential cross section for the coherent exclusive $J/\psi \rightarrow \mu^+\mu^-$ process in UPCs is calculated from obtained yields. Several sources of systematic uncertainty to the measurement are considered. The most significant sources of systematic uncertainty are luminosity, TRT trigger efficiency, ID

material modeling, the methodology used in fits, the shape of the $p_T^{\mu^+\mu^-}$ spectrum for signal, and the definition of exclusivity. The sensitivity of the exclusivity selection to the measured result is estimated by relaxing the track veto requirement to allow up to four tracks. Results of the measurement are presented in figure 1. The left plot shows measured cross sections compared with several model predictions: STARlight 2.0 and Color Glass Condensate (CGC) models with and without shape fluctuations. All three models use HERA $\gamma p \rightarrow J/\psi p$ data as input. The CGC-based model including the additional shape fluctuations is found to provide the best description of the data (with a p -value of 0.8, calculated from the chi-square statistic). In the right plot of figure 1, the results of this measurement are extrapolated to $\sqrt{s_{NN}} = 5.02$ TeV and compared with measurements from ALICE [4, 5], CMS [6], and LHCb [7]. The extrapolation is performed using STARlight predictions. The result of this measurement agrees well with other measurements at higher absolute rapidities. A significant tension between this measurement and the ALICE result is observed at mid-rapidity ($0 < y < 0.8$).

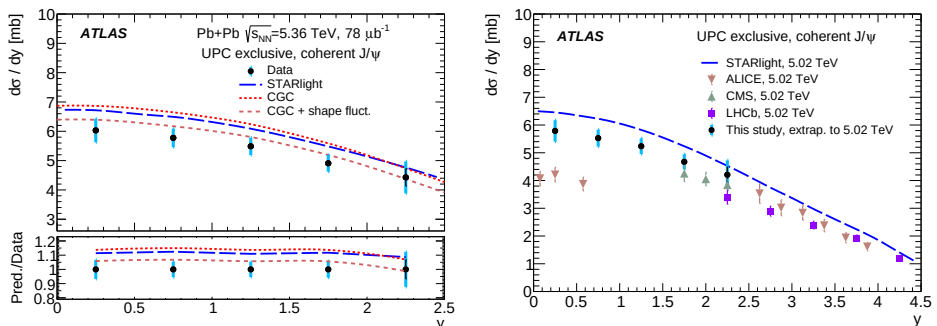


Fig. 1. The left plot shows the differential cross section for coherent exclusive J/ψ meson production in Pb+Pb UPCs at $\sqrt{s_{NN}} = 5.36$ TeV as a function of J/ψ rapidity (averaged over both sides) [8]. Data (points) are compared with several model predictions: STARlight 2.0, and two versions of a Color Glass Condensate (CGC) model [10, 11] (different dashed lines). For each data point, the thin black vertical bar represents the statistical uncertainty, and the thick blue bar represents the total uncertainty (with statistical and systematic uncertainties added in quadrature). The right plot shows the differential cross section for coherent J/ψ meson production in Pb+Pb UPCs at $\sqrt{s_{NN}} = 5.02$ TeV as a function of J/ψ rapidity [8]. Displayed are previous results from the ALICE [4, 5], CMS [6], and LHCb [7] experiments, together with the result of this analysis extrapolated to 5.02 TeV. Data (points) are compared with STARlight predictions (dashed line).

6. Conclusions

The first measurement of coherent exclusive J/ψ production in ultra-peripheral heavy-ion collisions with the ATLAS detector at the LHC is presented. It uses $78 \mu\text{b}^{-1}$ of Pb+Pb data recorded in 2023 at $\sqrt{s_{NN}} = 5.36 \text{ TeV}$. Events were selected with a special trigger requiring a signal from the ATLAS TRT at Level 1. The differential cross section for photonuclear J/ψ production is measured within the $|y| < 2.5$ rapidity interval in the $J/\psi \rightarrow \mu^+\mu^-$ decay channel. After extrapolating the results to $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, they are compared with theoretical predictions and with previous LHC Run 2 measurements. A model based on the Color Glass Condensate with nucleon shape fluctuations is found to be compatible with the measured cross sections. Significant tension with ALICE data is observed at mid-rapidity ($0 < y < 0.8$).

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