PROCEEDINGS OF SCIENCE

J/ψ production and polarization in photon-induced reactions in Pb–Pb collisions with ALICE

Roman Lavička[a,*] **for the ALICE collaboration**

[a] *Stefan Meyer Institute for Subatomic Physics of Austrian Academy of Sciences, Wiesingerstraße 4, 1010 Vienna, Austria*

E-mail: roman.lavicka@cern.ch

Intense electromagnetic fields from ultrarelativistic heavy ions can trigger photonuclear reactions, which are used to probe the nuclear gluon distribution and gluonic fluctuations over a large range of Bjorken-x. Our study examines ultra-peripheral and nuclear-overlap collisions, reporting on the photoproduction of J/ψ in peripheral Pb–Pb collision. In particular, the rapidity-dependence of the measured cross section and the measured polarization. We present new Run 2 measurements, including spectra of incoherent J/ψ in Pb–Pb UPCs at both forward and midrapidity, revealing the substructure of the lead nucleus. Additionally, we observe J/ψ photoproduction with proton dissociation in p–Pb collisions, offering fresh insights into proton sub-nucleonic fluctuations. Combining forward and midrapidity data offers a robust test of theoretical models.

42^{nd} *International Conference on High Energy Physics*
17-24 July 2024
Prague Congress Centre, Prague, Czechia

*Speaker

PoS(ICHEP2024)595

1. Introduction

Photonuclear interactions at the Large Hadron Collider (LHC) play an essential role in deepening our understanding of quantum chromodynamics (QCD). Initiated by strong electromagnetic fields generated by ultrarelativistic heavy ions, these interactions facilitate studies of gluon density within nuclei at low Bjorken-x. The ALICE detector has excellent particle tracking and identification capabilities, serving to studying a wide variety of physics processes. The knowledge of quarks and gluon distributions in nuclei is poorly known. A careful investigation is important to study hadronic structure and the high-energy limit of QCD. This exploration is vital for deciphering the microstructure of nuclear matter and enhancing the accuracy of high-energy hadron collision predictions.

Photon-induced reactions produced in Ultra-Peripheral Collisions (UPCs) enable the study of QCD phenomena, suppressing the hadronic backgrounds. In these reactions, heavy ions typically pass each other at large impact parameters. Instead, the interaction is dominated by the electromagnetic field, which is produced by the travelling ions, enabling the study of photon-induced processes. These collisions offer a unique environment to investigate the structure of hadrons through photon-gluon interactions by exploring phenomena such as vector meson production.

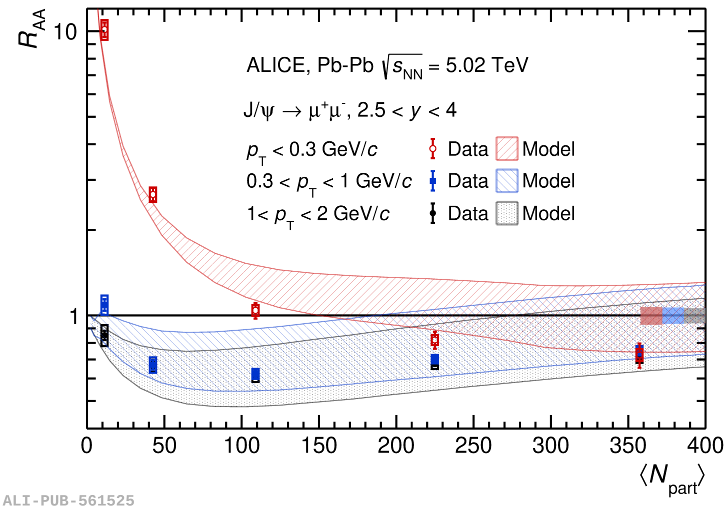

Figure 1: Nuclear modification factor R_{AA} as a function of number of collision participants N_{part} for different p_T intervals. Taken from Ref. [1].

Recently, an excess on the yield of low p_T J/ψ in collisions with nuclear overlap was observed [1]. Figure 1 shows the yield is most pronounced for peripheral collisions, decreasing as the centrality of the collision increases. A model that considers two combined mechanisms — coherent J/ψ photoproduction and hadroproduction with quark-gluon plasma effects (colour screening and c-quark recombination) [2] — provides a good description of the data. Hence, the enhancement was interpreted as coherent photoproduction.

2. Exclusive and dissociative J/ψ in proton–lead UPCs

QCD provides differential equations describing how the structure of hadrons changes with the energy and the resolution of the probe. The full equations have not been solved (we use approximations), nor have all the possibilities offered by the solutions been explored. The distribution of quarks and gluons depends on their energy which can be translated to variable called Bjorken-x. This variable describes the fraction of proton momentum the parton is carrying; to see small Bjorken-x partons, the hadron must be probed at high energies. From results at HERA [3], we can read that at high Bjorken-x, valence and sea quarks dominate over gluons; however, at smaller Bjorken-x, the number of gluons is rising. This behaviour is attributed to a unique characteristic of gluons within QCD; they can interact with each other. This allows for a gluon to split into two gluons with smaller energy, which leads to the rise of gluons at small Bjorken-x. There is a competing process, that is when two gluons recombine into one. At small, but not too small, Bjorken-x, splitting dominates. QCD predicts that at smaller Bjorken-x, the rate of these two processes reaches a dynamical equilibrium, leading to the number of gluons in the hadron to stop increasing. This is called gluon saturation. QCD cannot predict the value of Bjorken-x where this phenomenon sets in, and its experimental determination is one of the main goals of current and future facilities like the LHC and EIC. The latest findings from ALICE on the search for saturation off proton targets

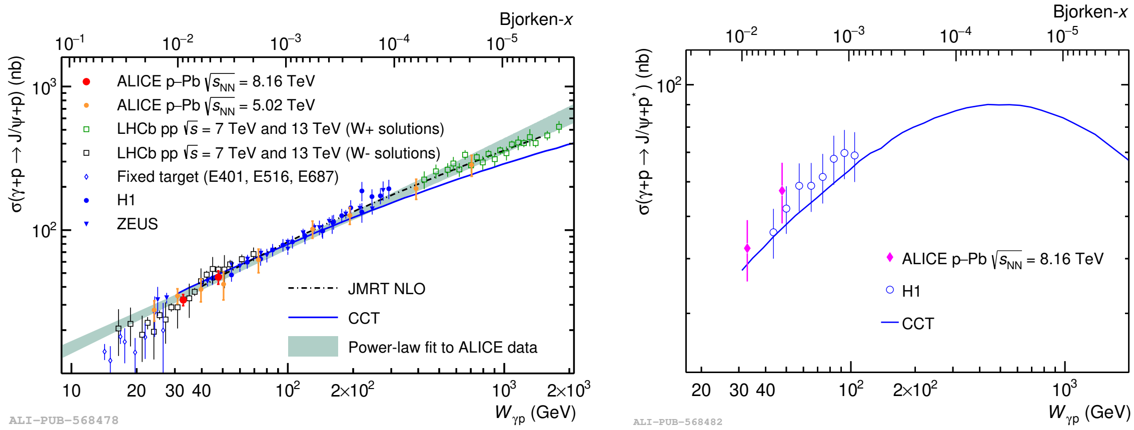

Figure 2: Exclusive (left) and dissociative (right) cross section for the $\gamma + \text{p} \rightarrow \text{J}/\psi + \text{p}$ process; both as a function of $W_{\gamma\text{Pb,n}}$ (lower axis) or Bjorken-x (upper axis). Current data are compatible with power-law growth. Taken from Ref. [4].

are illustrated in Fig. 2. Two additional data points at Bjorken-$x \approx 10^{-2}$ were obtained through the study of both exclusive and dissociative J/ψ photoproduction in proton-lead (p-Pb) collisions at an energy of $\sqrt{s_{\text{NN}}} = 8.16$ TeV. This is the first measurement of dissociative J/ψ photoproduction in hadronic colliders. These findings align well with existing HERA data, supporting a model of power-law growth. Furthermore, the CCT model [5] accurately encompasses all observed data. According to this model, the threshold for saturation is anticipated at Bjorken-$x \approx 5 \times 10^{-5}$ specifically in the context of dissociative production. While this saturation point has been attained in exclusive production scenarios, additional data from dissociative production is imperative for a more comprehensive understanding.

Table 1: Meaning of specific set of polarization parameters in terms of J/ψ polarization.

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})$	(0,0,0)	(+1,0,0)	(-1,0,0)
polarization	no	transverse	longitudinal

3. J/ψ photoproduction in Pb–Pb collisions with nuclear overlap

A stringent test of the existence of vector meson photoproduction in collisions with nuclear overlap is the polarization conservation hypothesis. Due to the s-channel helicity conservation [6], the produced vector meson keeps the polarization of the incoming photon. The source of the photons, the lead ion, is accelerated to ultrarelativistic energies and the electromagnetic field it generates is Lorentz-contracted. As a result, photons are transversely polarized. If the measured vector meson is also transversely polarized, it was produced by photoproduction. The polarization

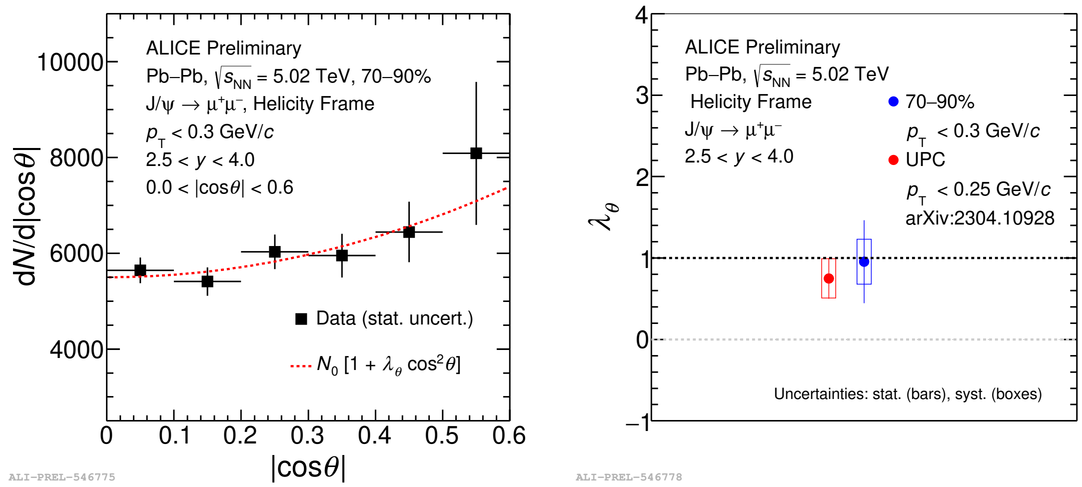

Figure 3: Left: Preliminary results on inclusive J/ψ photoproduction in collisions with nuclear overlap as a function of angular angle $\cos\theta$. Right: Comparison of polarization parameter λ_θ for results from UPCs (red) and peripheral collisions (blue).

of the J/ψ decaying into a pair of leptons is measured via the dilepton decay angular distribution [7]. This distribution is described in Eq. (1)

$$W(\cos\theta, \phi) \propto \frac{1}{3+\lambda_\theta} \cdot \left(1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi\right), \qquad (1)$$

where θ and ϕ are the angles in the helicity frame (frame with respect to the momentum of the vector meson) and $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ are three polarization parameters which are related to J/ψ polarization states. Table 1 summarises the connections between the polarization parameters values and the J/ψ polarization states. Fixing the parameters $\lambda_\phi, \lambda_{\theta\phi}$ to zero in a fit to the data simplifies the situation, as this was employed in Fig. 3. The fit result is compatible with $\lambda_\theta = +1$ which hints at transverse polarization. This is consistent with results from UPCs [8]. Hence, the ALICE results strongly suggest the successful isolation of photoproduction in collisions with nuclear overlap, an environment with a high presence of hadronic interactions.

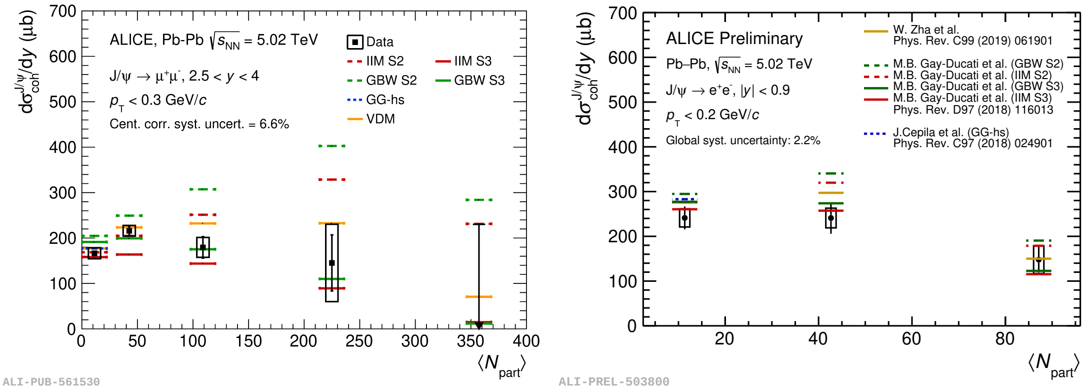

Figure 4: Coherent J/ψ photoproduction centrality dependence at forward rapidity (left) and midrapidity (right). The left plot is taken from Ref. [1], the right is preliminary.

An estimation of the hadronic contribution in events with $p_T < 0.3$ GeV/c allows the extraction of photoproduced J/ψ in collisions with nuclear overlap. A cross section dependency on collision centrality is calculated for the first time at forward rapidity [1], and preliminary results at midrapidity were presented in this contribution. The distributions with comparisons to various models are shown in Fig. 4. A mild centrality dependence within uncertainties compatible with no variation at (semi-)peripheral centralities is observed. The models used to describe data differ in the constraints on a range of photon flux and photonuclear cross section. Results agree with models that assume that only the spectators act as targets. Hence, the more central the collision is, the smaller the target is probed.

4. Summary

The results from the ALICE Collaboration at the LHC are presented reporting on exclusive and dissociative J/ψ photoproduction in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The results support a model of power-law growth in gluon distribution and suggest a saturation threshold in the context of dissociative production.

Additionally, the study delves into the realm of Pb–Pb collisions, examining the phenomenon of vector meson photoproduction in nuclear overlap scenarios. A key point of investigation is the meson's polarization, which tests the hypothesis of s-channel helicity conservation. Preliminary results hint at transverse polarization of the photoproduced J/ψ. This is consistent with theories positing photoproduction as a distinct mechanism in collisions featuring nuclear overlap.

Finally, by analyzing the coherent J/ψ photoproduction in Pb–Pb collisions at different rapidities, the research provides insights into the dependence of the cross section on collision centrality. The findings suggest a mild centrality dependence, aligning with models that consider only the spectators as the primary targets in the photoproduction process.

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