Coherent J/ψ photoproduction cross section and polarization in peripheral Pb-Pb collisions

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Photonuclear reactions are induced by the strong electromagnetic field generated by ultrarelativistic heavy-ion collisions. These processes have been extensively studied in ultraperipheral collisions, in which the impact parameter is larger than twice the nuclear radius. In recent years, the observation of coherent J/ψ photoproduction has been claimed in nucleus–nucleus (A–A) collisions with nuclear overlap, based on the measurement of an excess (with respect to hadroproduction expectations) in the yield of very low transverse momentum (p_{T}) J/ψ . Such quarkonium measurements can help constraining the nuclear gluon distributions at low Bjorken-x and high energy. In addition, they can shed light on the theory behind photon induced reactions in A–A collisions with nuclear overlap, including possible interactions of the measured probes with the formed and fast expanding quark-gluon plasma. In order to confirm the photoproduction origin of the very low p_{T} J/ψ yield excess, polarization measurement is a golden observable. It is indeed expected that the produced quarkonium would keep the polarization of the incoming photon due to s-channel helicity conservation. ALICE can measure inclusive and exclusive quarkonium production down to zero transverse momentum, at forward rapidity ($2.5 < y < 4$) and midrapidity ($|y| < 0.9$). In this contribution, we will report on the new preliminary measurement of the y-differential cross section and the first polarization analysis at LHC of coherently photoproduced J/ψ in peripheral Pb–Pb collisions. Both measurements are conducted at forward rapidity in the dimuon decay channel. Comparison with models will be shown when available.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

[*] Speaker

1. Introduction

Photon-induced processes play an important role in ultra-peripheral collisions (UPCs), i.e., collisions in which nuclei are separated by an impact parameter (b) larger than the sum of their radii. In such collisions, hadronic interactions are strongly suppressed, and the cross section of produced vector mesons (VM, e.g., J/ψ) is expected to be large due to the strong electromagnetic field of the nuclei [1]. In this process, a photon emitted by one of the colliding nuclei fluctuates into a $q\bar{q}$ pair (acts as a color dipole), which can interact with the second nucleus via two gluon exchange at Leading Order (LO). The color dipole finally recombines into a VM. The J/ψ photoproduction is one of the cleanest experimental tools, allowing to probe the gluon distributions inside the nucleus [2], which are poorly known at low Bjorken-x [3]. Photonuclear reactions in UPCs have been extensively studied (see for instance a recent measurement from ALICE in Ref. [4]).

The first experimental signature of photonuclear reactions in Pb–Pb collisions with nuclear overlap in peripheral collisions (PCs) at $\sqrt{s_{\rm NN}}$ = 2.76 TeV was reported by the ALICE Collaboration via the measurement of an excess in the J/ψ yield at very low transverse momentum ($p_{\rm T}$) with respect to expectations from hadroproduction [5]. Similar observations were confirmed by other experiments in Ref. [6, 7]. This excess was interpreted as a demonstration of the presence of a coherent J/ψ photoproduction mechanism occurring in Pb–Pb collisions with nuclear overlap. Recently, more precise measurements were performed in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV by the ALICE Collaboration. A significant J/ψ yield excess at low $p_{\rm T} < 0.3$ GeV/c was observed in collisions with nuclear overlap, down to the 30–50% centrality range [8]. A set of theoretical calculations are able to describe coherent photoproduction in UPC, and in heavy-ion collisions with nuclear overlap, where the effect of an effective photon flux and an effective photonuclear cross section are considered. These results were compared with the measurements [9–12].

Polarization measurements of coherently photoproduced VM are also of huge interest, because the produced VM is expected to retain the same polarization as that of the photon interacting with the target nucleus, according to the s-channel helicity conservation hypothesis (SCHC) [13]. The VM is expected to be transversely polarized if it obeys SCHC as the photon is transversely polarized. Recently, the polarization measurement of the coherently photoproduced J/ψ in UPCs was performed and was found to be consistent with the SCHC [14]. In these proceedings, we present the first rapidity(y) differential cross section measurement of coherent J/ψ photoproduction, and the first polarization measurement of inclusive J/ψ for $p_{\rm T} < 0.3$ GeV/c, at forward rapidity (2.5 $< y <$ 4.0) in the 70–90% centrality class in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV.

2. Analysis details

A detailed description of the ALICE detector setup and its performance are discussed in Ref. [15]. In this analysis, the J/ψ production is measured at forward rapidity using opposite-sign (OS) dimuon pairs in the centrality range 70–90%, for Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. The data samples used were collected in 2015 and 2018, and correspond to an integrated luminosity of 756 $\pm 19 \mu$b^{-1}. The event and track selection criteria are similar to the ones used in Ref. [8]. The J/ψ polarization is studied with the angular distribution of OS dimuon pairs. Here, the polarization

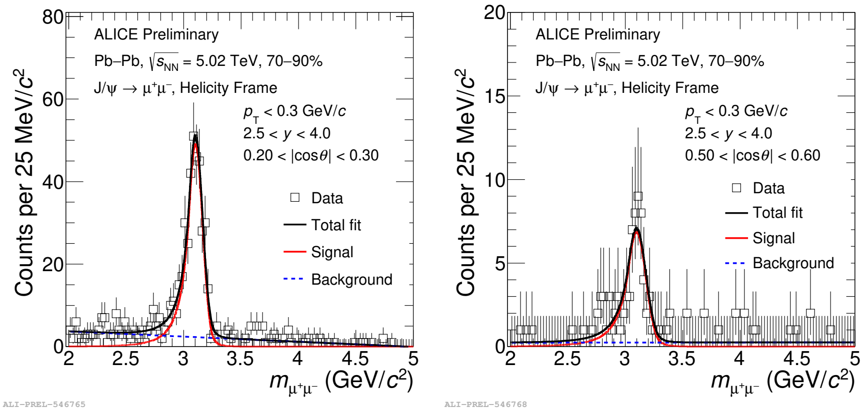

Figure 1: Opposite sign (OS) dimuon invariant mass distributions for $p_T < 0.3$ GeV/c in the centrality class (70–90)% for two cosθ intervals in the helicity frame, at forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

is measured in the helicity frame, and dimuon angular distribution can be expressed as (see Eq. 1 from Ref. [16]):

$$W(cos\theta, \phi) \propto \frac{1}{3+\lambda_\theta}[1 + \lambda_\theta cos^2\theta + \lambda_\phi sin^2\theta cos(2\phi) + \lambda_{\theta\phi} sin(2\theta) cos(\phi)] \quad (1)$$

where λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ are three parameters that are related to the particle polarization properties. If (λ_θ, λ_ϕ, $\lambda_{\theta\phi}$) = (0, 0, 0), the particle is unpolarized, if (λ_θ, λ_ϕ, $\lambda_{\theta\phi}$) = (-1, 0, 0), the particle has a longitudinal polarization, and if (λ_θ, λ_ϕ, $\lambda_{\theta\phi}$) = (1, 0, 0), the particle is transversely polarized. In both the y-differential cross section and polarization analyses, the J/ψ is reconstructed from the invariant mass distribution of OS dimuon pairs. The signal extraction is performed by fitting the invariant mass distribution with a combined fit function that describes the signal and background components. A likelihood approach is adopted during the signal extraction due to the low statistics, in order to correctly consider the empty bins in the fit procedure. Figure 1 shows an example of OS dimuon invariant mass distributions for two cosθ intervals for $p_T < 0.3$ GeV/c in the 70–90% centrality class, in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

3. Results and discussion

The raw J/ψ p_T spectra for six rapidity intervals in the centrality range 70–90% for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 2 left. An excess in the J/ψ raw yield is observed for $p_T < 0.3$ GeV/c in all y intervals w.r.t hadroproduction yield. The low p_T J/ψ excess can also be quantified by the nuclear modification factor, R_{AA} [1]. The J/ψ R_{AA} as a function of p_T for various y intervals is shown in Fig. 2 right, for peripheral Pb–Pb events. A significant increase in the R_{AA} is observed with a hierarchy in y for $p_T < 0.3$ GeV/c , becoming more pronounced towards $y = 2.5$. The J/ψ raw yield excess and the large R_{AA} values for $p_T < 0.3$ GeV/c suggest

[1] $R_{AA} = Y^{AA}_{J/\psi} / \langle T_{AA} \rangle \sigma^{pp}_{J/\psi}$ where $Y^{AA}_{J/\psi}$ *is the* J/ψ *yield in Pb–Pb collisions,* $\langle T_{AA} \rangle$ *is the average nuclear overlap function and* $\sigma^{pp}_{J/\psi}$ *is the* J/ψ *cross section in pp collisions at the same center-of-mass energy as the Pb–Pb one*

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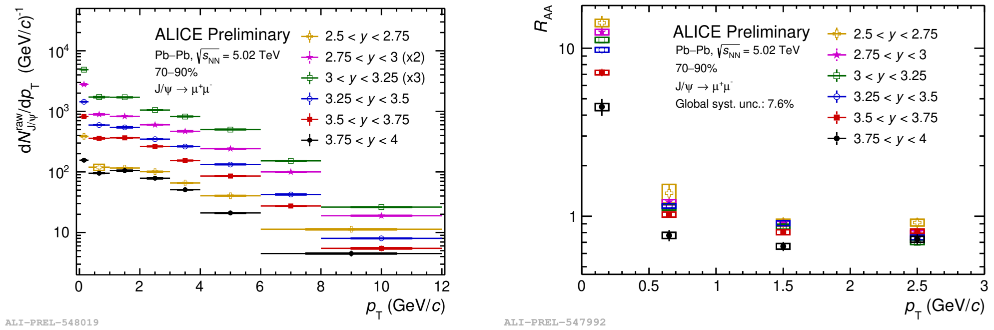

Figure 2: Raw J/ψ yield (left) and nuclear modification factor (right) as a function of p_T for different forward rapidity intervals in the centrality range 70–90% in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

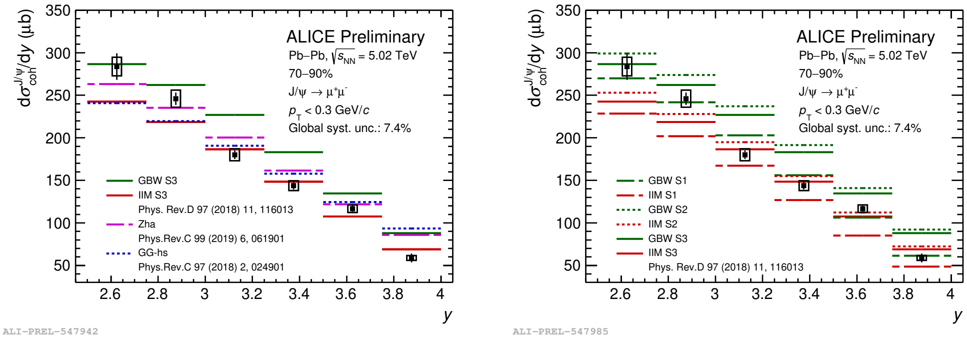

Figure 3: The cross section of coherently photoproduced J/ψ as a function of y in the centrality range 70–90% for p_T < 0.3 GeV/c in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Results are compared with different model predictions from Refs. [10–12].

that coherent J/ψ photoproduction in peripheral Pb–Pb collisions with nuclear overlap is the dominant mechanism in this kinematic region. The contribution from hadronically produced J/ψ is subtracted using a data-driven model, which takes as input the p_T-differential J/ψ cross section in pp collisions, the J/ψ R_{AA} , and the hadronic J/ψ Acceptance × Efficiency extracted from MC. Then, the coherent J/ψ yield is obtained by correcting the excess yield for the fraction of incoherently photoproduced J/ψ and the fraction of coherently photoproduced $\psi(2S)$ decaying to J/ψ estimated in UPC [17] for the kinematic range p_T < 0.3 GeV/c . This procedure was also employed in Ref. [8]. Figure 3 shows the coherent photoproduction cross section as a function of y for p_T < 0.3 GeV/c in the centrality range 70–90% in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The results are compared with available model predictions. In the left panel of Fig. 3, data are compared with GG-hs (i.e., an energy dependent hot-spot model in which photon-lead cross sections are calculated using a Gribov-Glauber approach, GG) [10], Zha (a model with assumptions on the photon-pomeron coupling scenario, in which the Nucleus (N) acts as a photon emitter and the Spectactor (S) acts as a pomeron emitter) [11], and GBW/IIM (a light-cone color dipole formalism based-model in which the calculation of the photon flux and the photonuclear cross section takes

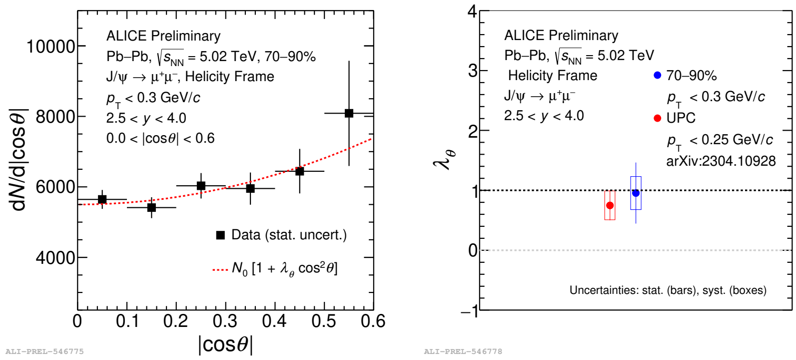

Figure 4: Left: angular cosθ distribution of J/ψ using the helicity frame at $2.5 < y < 4.0$ for the $p_{\rm T}$ range < 0.3 GeV/c in the centrality 70–90% for Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. The angular distribution is fitted with Eq. 1 for extraction of λ_θ. Right: comparison of the λ_θ from UPCs (red marker) and PCs (blue marker) using the helicity frame in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV.

into account the effective interaction area) [12]. In the right panel of Fig. 3, three scenarios of the GBW/IIM calculations are compared to data. In S1, there is no significant modification of the calculation with respect to UPCs; in S2, the effective photon flux is considering only the photons reaching the geometrical region of the target nucleus outside of the overlap region, while keeping the photonuclear cross section unchanged; and in S3 the same photon flux as S2 is used and a change in the effective photonuclear cross section to disregard the nuclear overlap region is performed). All the model predictions qualitatively reproduce the order of magnitude of the measurements but fail to describe the y-dependence. Similar conclusions also hold for the UPC measurement [17]. Figure 4 shows the cosθ angular distribution of J/ψ for $p_{\rm T} < 0.3$ GeV/c in the centrality range 70–90% in Pb–Pb collisions. A cosθ dependence is observed and the distribution is fitted with Eq. 1 to extract the λ_θ parameter. The λ_θ value in PCs is compared to the value obtained in UPCs, as shown in the right panel of Fig. 4. The results suggest that inclusive J/ψ with $p_{\rm T} < 0.3$ GeV/c have a transverse polarization and would therefore obey the SCHC hypothesis as observed in UPC (see Ref. [14]). Despite the absence of subtraction for the hadronic J/ψ contribution, this polarization measurement can be considered as a proxy of the photoproduced J/ψ polarization, as it is established from Ref. [17] that coherent J/ψ photoproduction constitutes 78% of the inclusive J/ψ yield in this kinematic region. This polarization measurement serves as an additional method to test the J/ψ production mechanisms at very low $p_{\rm T}$, and it is consistent with the picture of a coherent photoproduction origin for the measured J/ψ yield excess.

4. Summary

We report on the first measurement of the y-differential coherent J/ψ photoproduction cross section and the polarization of inclusive photoproduced J/ψ for $p_{\rm T} < 0.3$ GeV/c at forward rapidity in the centrality range 70–90% and in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. An excess of the J/ψ raw yield with respect to expectation from hadronic production and a remarkably large J/ψ $R_{\rm AA}$ value for all rapidity ranges are observed for $p_{\rm T} < 0.3$ GeV/c in peripheral Pb–Pb collisions. This J/ψ yield excess is interpreted as coherent photoproduction in heavy-ion collisions with nuclear overlap. The y-dependence of the J/ψ coherent photoproduction cross section is measured. The results are compared with various models incorporating the effect of nuclear overlap on the J/ψ photoproduction cross section calculations. All the model results qualitatively describe the measurement but fail at describing the data in the entire y range. In the same kinematic range, the inclusive J/ψ polarization measurement using the helicity frame is performed. An angular cosθ dependence is observed, and the λ_θ value is compatible with unity within larger statistical uncertainties. This result is consistent with a transverse polarization scenario and with the UPC measurements. These measurements remain a challenge for theoretical studies since the implementation of coherent photoproduction in nuclear collisions is complex and all the aspects should be considered. The J/ψ cross section measurements as a function of y in UPCs and PCs, will be used for the understanding of the photon energy ambiguity as discussed in Ref. [18]. In Run 3 more differential and precise measurements of the coherent J/ψ photoproduction cross section (as well as other VMs) will be achieved in more central collisions, together with polarization measurements.

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