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Recent ALICE results on coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions

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The strong electromagnetic fields of Pb nuclei, accelerated at the LHC, can be used to measure photon-induced interactions in a new kinematic regime. Photon-induced processes are usually studied in ultra-peripheral Pb–Pb collisions where hadronic interactions are strongly suppressed. Coherent charmonium photoproduction is of particular interest since it is sensitive to the nuclear modification of the gluon distribution function (shadowing), which is poorly known. In this contribution, recent ALICE results on the coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions from LHC Run 2 will be presented. The implications for the study of nuclear gluon shadowing will be discussed. In addition, projections for heavy vector meson photoproduction measurements in LHC Run 3 and 4 will be presented.

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1. Introduction

Accelerated lead nuclei are sources of strong electromagnetic fields, which are equivalent to a flux of quasi-real photons, thus Pb–Pb collisions at the LHC can be used to measure $\gamma\gamma$ and γPb interactions in a new kinematic regime. These interactions are usually studied in ultra-peripheral collisions (UPC), characterized by impact parameters larger than the sum of the radii of the incoming nuclei, in which hadronic interactions are strongly suppressed [1]. J/ψ photoproduction measurements in ultra-peripheral Pb–Pb collisions at the LHC are of particular interest because, at LO in perturbative QCD, the coherent J/ψ photoproduction cross section is proportional to the square of the gluon density in nuclei. The acceptance coverage of the ALICE experiment corresponds to a Bjorken-x range from $\sim 10^{-2}$ to $\sim 10^{-5}$, while the heavy-quark mass serves as a hard scale justifying perturbative calculations. Therefore, coherent charmonium photoproduction in Pb–Pb UPC provides a direct tool to probe poorly known gluon distributions and their modification in nuclei known as nuclear shadowing [2], which play a crucial role in the initial stages of heavy-ion collisions.

The UPC analysis strategy relies on the selection of events with only few tracks in an otherwise empty detector, therefore large pseudorapidity coverage is essential to guarantee the event emptiness. Almost continuous angular acceptance in ALICE is ensured with a central barrel covering the pseudorapidity range $|\eta| < 0.9$, a muon spectrometer in the forward direction ($-4 < \eta < -2.5$) and a set of forward detectors, the VZERO-A ($2.8 < \eta < 5.1$) and the VZERO-C ($-3.7 < \eta < -1.7$) used also for triggering and multiplicity measurements. The Zero-Degree Calorimeters (ZDC), located at ± 112.5 m from the interaction point and covering $|\eta| > 8.8$, are used to detect neutrons from the electromagnetic dissociation or hadronic interactions of Pb nuclei. Since 2015, ALICE has been also equipped with the ADA and the ADC detectors covering very forward ($4.9 < \eta < 6.3$) and backward ($-7 < \eta < -4.8$) rapidity ranges. UPC events are selected with dedicated triggers based on vetoes in the forward and backward directions and trigger inputs from the central barrel and the muon spectrometer. Further details on the ALICE experimental setup and performance can be found in [3, 4].

2. J/ψ photoproduction in Pb–Pb UPC

First ALICE results from Run 1 on the coherent J/ψ photoproduction cross section in Pb–Pb UPC at a center-of-mass energy per nucleon pair $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV are shown in Fig. 1, left [5, 6]. The measured cross section was found to be in good agreement with models based on the gluon shadowing from the EPS09 global fit [7]. ALICE data have been used to extract the gluon shadowing factor [2], see Fig. 1, right, indicating that coherent charmonium photoproduction in Pb–Pb UPC may serve as a promising tool to constrain gluon shadowing uncertainties.

ALICE also got first results on the coherent J/ψ photoproduction at forward rapidity in Pb–Pb UPC at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV from Run 2 [8]. The invariant mass distribution for selected unlike-sign muon pairs with $p_{\mathrm{T}} < 0.25$ GeV/c is shown in Fig. 2, left. The invariant mass distribution was fitted with a function modeling the background and two Crystal Ball functions for the J/ψ and the ψ' peaks. The obtained coherent J/ψ yield is a factor 200 higher compared to Run 1 results [5]

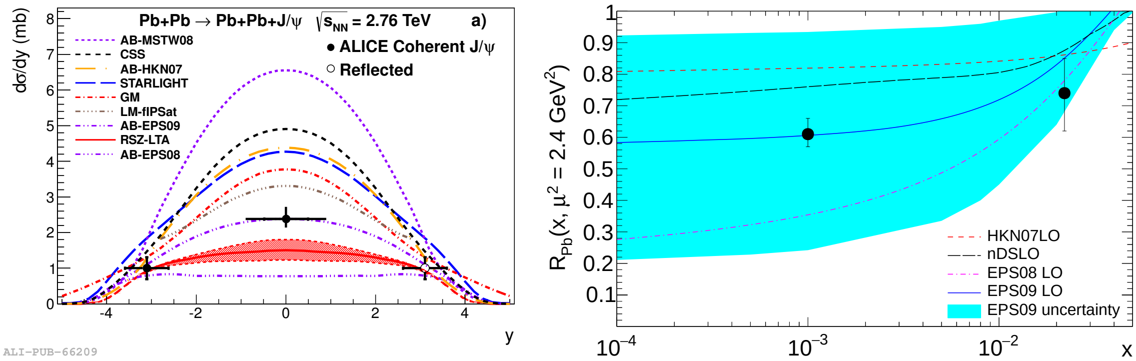

Figure 1: Left: coherent J/ψ photoproduction cross section in Pb–Pb UPC at $\sqrt{s_{NN}}$ = 2.76 TeV measured by ALICE [6]. Right: Gluon shadowing factor extracted from the ALICE measurements [2].

thanks to the much higher integrated luminosity, improved trigger logic, wider rapidity range and increased beam energy.

The raw inclusive J/ψ yields obtained from invariant mass fits contain contributions from the coherent and incoherent J/ψ photoproduction processes, which can be separated in the fits of transverse momentum spectra. The transverse momentum distribution for dimuons around the J/ψ mass fitted summing six different Monte Carlo templates is shown in Fig. 2, right. Coherent J/ψ photoproduction, when a photon interacts coherently with the whole nucleus, is characterized by a narrow transverse momentum distribution with $\langle p_T \rangle \sim 60$ MeV/c. In the incoherent case the photon couples to a single nucleon. If the target nucleon stays intact, the charmonium p_T distribution is driven by the nucleon form factor, resulting in $\langle p_T \rangle \sim 400$ MeV/c. The templates for these processes were produced with the Starlight event generator [9]. J/ψ photoproduction on a single nucleon can be also accompanied by nucleon dissociation resulting in a high-p_T tail that was fitted with the H1 parameterization [10]. Contributions from continuum dimuon production and feed-down from ψ′ decays were also taken into account in the fits.

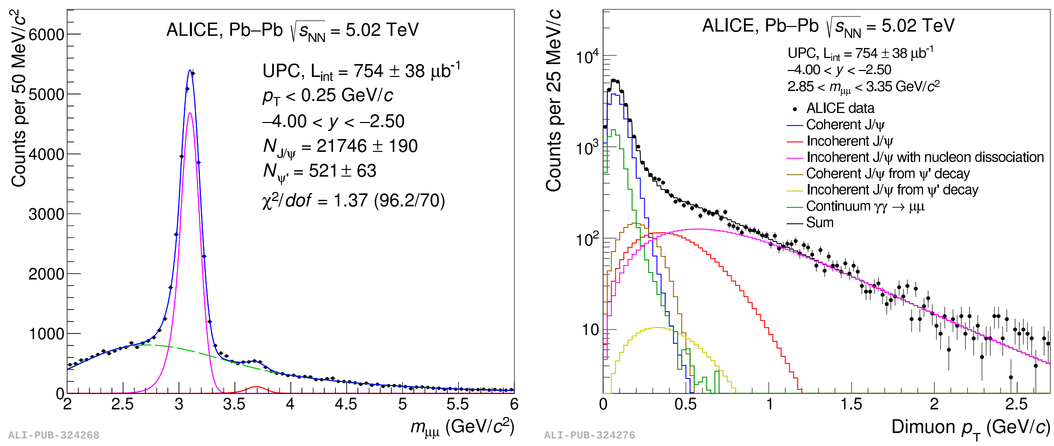

Figure 2: Invariant mass (left) and transverse momentum distribution (right) for unlike-sign dimuons with rapidity $-4.0 < y < -2.5$ in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (see text for details).

The resulting coherent J/ψ photoproduction cross section at forward rapidity in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV is compared to several theoretical predictions in Fig. 2. The covered rapidity range corresponds to a Bjorken-x of gluons either in the range $1.1 \cdot 10^{-5} < x < 5.1 \cdot 10^{-5}$ or $0.7 \cdot 10^{-2} < x < 3.3 \cdot 10^{-2}$ depending on which nucleus emitted the photon. According to models [11], the fraction of high Bjorken-x gluons ($x \sim 10^{-2}$) is dominant at forward rapidities and ranges from $\sim$60% at $y = -2.5$ to $\sim$95% at $y = -4$. A comparison of the ALICE data with the impulse approximation, based on the data from the exclusive J/ψ photoproduction off protons neglecting all nuclear effects, allows one to derive the nuclear gluon shadowing factor of about 0.8 at Bjorken-x values around 10^{-2} under assumption that the contribution from low Bjorken $x \sim 10^{-5}$ can be neglected [2].

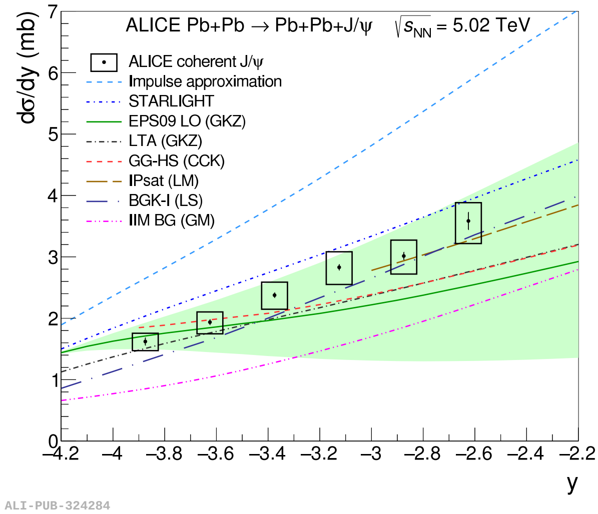

Figure 3: Measured coherent differential cross section of J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The error bars correspond to the statistical uncertainties, the open boxes to the systematic uncertainties. Results from various models are also shown [8].

This data sample was also used to extract the ratio of coherent ψ' and J/ψ photoproduction cross sections at forward rapidity:

$$R = \frac{\sigma(\psi')}{\sigma(\mathrm{J}/\psi)} = 0.150 \pm 0.018(\mathrm{stat.}) \pm 0.021(\mathrm{syst.}) \pm 0.007(\mathrm{BR}), \qquad (2.1)$$

The ratio was found to be in reasonable agreement both with the ratio of photoproduction cross sections off protons measured by the H1 Collaboration in ep collisions [12], by the LHCb Collaboration in pp collisions [13] and with LTA predictions for Pb–Pb UPC.

3. Projections for vector meson photoproduction in Pb–Pb UPC in Run 3 and 4

High statistics data in Run 3 and 4 may help to decouple low-x and high-x contributions in vector meson production cross sections measured in UPC using differential cross-section measurements with and without additional neutron activity in the Zero Degree Calorimeters [14]. The expected experimental uncertainties in Run 3 and 4 were evaluated in [15] in terms of the nuclear suppression factor $R_{\rm Pb}$ which is defined as the root square of the ratio of the photoproduction cross section $\sigma_{\gamma\rm Pb}$ measured in Pb–Pb UPC and the photoproduction cross section in the impulse approximation ($\sigma_{\rm IA}$) calculated as a reference photoproduction cross section off protons scaled by the

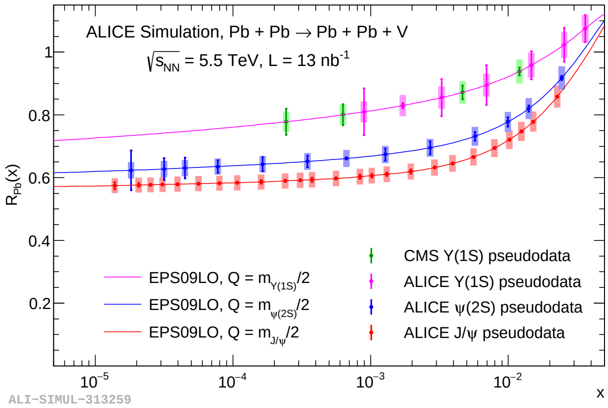

Figure 4: Pseudodata projections for the nuclear suppression factor measured with photoproduction of J/ψ, ψ' and Υ mesons in Pb–Pb UPC collisions at different scales [15].

integral over the squared Pb form factor [2]:

$$R_{\rm Pb}(x) = \left(\frac{\sigma_{\gamma \rm Pb}(x)}{\sigma_{\rm IA}(x)}\right)^{1/2}, \qquad \text{where} \qquad x = \frac{m_V}{\sqrt{s_{\rm NN}}}\exp(-y). \tag{3.1}$$

Here m_V and y are the mass and rapidity of the produced vector meson. Under the assumption that the coherent photoproduction cross section is proportional to the squared gluon density at the scale $Q = m_V/2$ this nuclear suppression factor can be used to constrain nuclear shadowing at different scales. The resulting pseudodata projections, based on EPS09 LO central values, are shown in Fig. 4.

4. J/ψ photoproduction in peripheral Pb–Pb collisions

Although photon-induced reactions are typically measured in UPCs, they have also been observed in hadronic collisions of heavy ions. A strong excess in the yield of J/ψ at forward rapidities at very low transverse momenta $p_{\rm T} < 0.3$ GeV/c, measured by ALICE in peripheral Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, results in a large nuclear modification factor $R_{AA} \sim 7$ in this $p_{\rm T}$ range [16]. A similar excess has also been observed by ALICE for J/ψ at central and forward rapidity in peripheral Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, see Fig. 5. This excess is commonly interpreted as a signal of coherent J/ψ photoproduction off heavy-ion remnants, see e.g. [17, 18]. The combination of coherent J/ψ photoproduction cross sections in peripheral and ultra-peripheral collisions have been used to extract the coherent J/ψ photoproduction cross section $\sigma_{\gamma \rm Pb}(x)$ and the nuclear suppression factor $R_{\rm Pb}(x)$ using Run 1 data [19].

5. Conclusions

Vector meson photoproduction in ultra-peripheral collisions at the LHC has shown to be particularly useful as a probe of nuclear structure. ALICE results on the coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions, measured in Run 1 and 2, are a clear demonstration of moderate nuclear gluon shadowing. Future studies on coherent heavy vector meson photoproduction

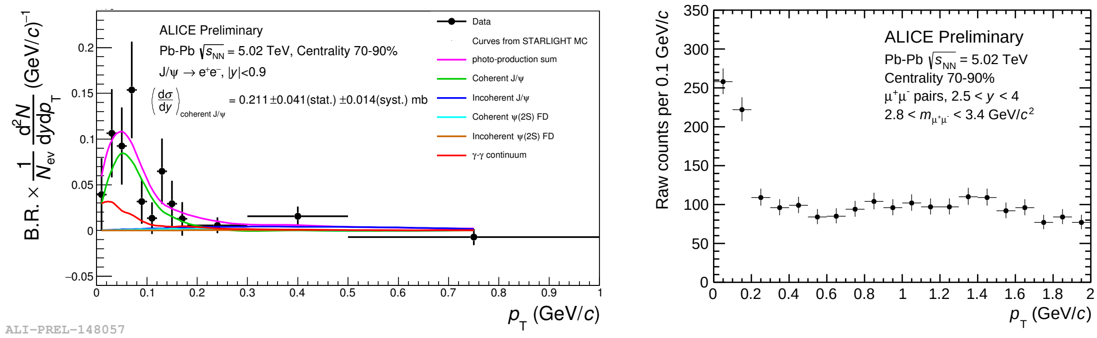

Figure 5: Transverse momentum spectrum for dimuons around J/ψ mass at central rapidity (left) and forward rapidity (right) in peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

accompanied by neutron emission may help to decouple low-x and high-x contributions in UPC measurements and provide valuable constraints on poorly known gluon shadowing effects down to Bjorken $x \sim 10^{-5}$.

Photon-induced processes may also contribute in hadronic collisions of heavy ions. The ALICE Collaboration discovered a strong excess of J/ψ at low transverse momentum in peripheral Pb–Pb collisions that is commonly interpreted as a signal of coherent J/ψ photoproduction off heavy-ion remnants. The upcoming high-luminosity LHC era will bring much more precise measurements and hopefully new exciting discoveries in photon-induced physics.

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