Coherent J/$\psi$ photoproduction in ultra-peripheral Pb–Pb collisions with ALICE at the LHC

Roman Lavicka on behalf of the ALICE collaboration
Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
E-mail: roman.lavicka@cern.ch

Abstract. There are several predictions for the behaviour of the gluon distribution in nuclei at small Bjorken-$x$ and experimental data are needed to choose among them. This is achieved by measuring the cross section of processes specially sensitive to this parton distribution.

The high flux of photons from lead ions at the LHC allows us to study photon-induced reactions in ultra-peripheral collisions of Pb–Pb nuclei, in particular of those producing a J/$\psi$ meson exclusively. The study of these collisions, where projectiles do not overlap, provides information about the initial state of nuclei.

The newest ALICE results on vector meson photoproduction are presented. The increased statistics and higher collision energy of $\sqrt{s_{NN}}=5.02$ TeV of Run 2 allow us to put new constraints on available models.

1. Introduction

Parton density functions (PDFs) of gluons and quarks inside the proton were measured with high precision at small Bjorken-$x$ at HERA [1]. The LHC facility allows one to study the gluon PDF of heavy ions, particularly lead ions, in a new kinematic range.

According to the equivalent photon approximation, a large flux of quasi-real photons accompanies the electrically charged lead ions circulating at the LHC during Pb–Pb data taking opening the possibility to use ultra-peripheral collisions (UPC) of lead ions to study photon-induced processes. The impact parameter of these collisions is larger than the sum of the nuclei radii. Therefore, hadronic processes are suppressed and only photons remain to interact with a target nucleus. In the infinite momentum frame where the photons live a long time, when the quasi-real photon emitted by one of the lead ions approaches the vicinity of the target nucleus, it may fluctuate into a quark-antiquark pair. This pair interacts strongly with the target and fluctuates into a vector meson — a J/$\psi$ in the case described here. If all nucleons in the target ion interact coherently as one body, this process is called coherent J/$\psi$ photoproduction.

A measurement of the kinematics of the meson and the cross section of this process [2] is sensitive in a leading-order approach in perturbative QCD to the gluon distribution function of the nucleus [3]. The comparison of this cross section to that from photon–proton collisions provides information about the gluon shadowing in the nucleus [4], i.e. the suppression of gluon densities in the nucleus with respect to the proton. Measurements of J/$\psi$ photoproduction in UPC with the ALICE detector [5] allow us to reach Bjorken-$x$ of $10^{-2}$ in forward and $10^{-3}$ in central rapidity. Potentially, we can reach even smaller Bjorken-$x$ with measurements of coherent J/$\psi$ photoproduction in peripheral collisions [6].
2. \(J/\psi\) photoproduction in ultra-peripheral collisions

Collisions of two lead ion beams at \(\sqrt{s_{NN}} = 2.76\) TeV were delivered to ALICE by the LHC in Autumn 2011. ALICE recorded \(J/\psi\) decays in UPC in the forward rapidity region \(-3.6 < y < -2.6\) and at mid-rapidity \(|y| < 0.9\) [7]. The events described here have a clear signal consisting of \(J/\psi\) decaying into two leptons and nothing else. The pair of leptons is measured at mid-rapidity with the ITS and the TPC and at forward rapidities with the muon spectrometer (details on the ALICE setup and performance can be found in [5, 7]). The analysed samples correspond to an integrated luminosity of about 55 \(\mu b^{-1}\) and 23 \(\mu b^{-1}\), respectively. The measured cross sections are \(d\sigma_{\text{UPC}}^{\text{coh}}/dy = (1.00\pm0.18(\text{sta.})^{+0.24}_{-0.26}(\text{sys.}))\) mb [8] and \(d\sigma_{\text{coh}}^{\text{J}/\psi}/dy = (2.38^{+0.34}_{-0.24}(\text{sta.}+\text{sys.}))\) mb [9].

The measured cross sections are compared with theoretical models in Fig. 1. The AB-EPS09 describes correctly the measurement. In this model the prescription for nuclear shadowing is based on the EPS09 parametrisation. A model which does not include any shadowing (AB-MSTW08) is excluded by the measured data. Models incorporating strong shadowing are below data. Other models (see [8, 9] and references therein) overshot the data at mid-rapidity.

These cross sections are used by Guzey, Kryshen, Strikman, and Zhalov [10] to put new constraints on the gluon nuclear distribution. They discuss the nuclear suppression factor \(S_{Pb}\).

The factor is defined in Eq. 1, where the measured UPC cross section is put into the nominator and a cross section calculated from the impulse approximation is used in the denominator. The relation between Bjorken-\(x\), the mass of the \(J/\psi\), \(M_{J/\psi}\) and the transferred energy \(W_{\gamma p}\) is also shown.

\[
S_{Pb}(W_{\gamma p}) = \left[ \frac{\sigma_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})^{\text{exp}}}{\sigma_{\gamma Pb\to J/\psi Pb}(W_{\gamma p})^{\text{IA}}} \right]^{1/2}, \quad x = \frac{M_{J/\psi}^{2}}{W_{\gamma p}^{2}}.
\]

The impulse approximation is based on photon–proton data and then scaled by the integral over squared lead form-factor. The nuclear suppression factor \(S_{Pb}(W_{\gamma p})\) can be directly compared to the nuclear shadowing on the gluon distribution at corresponding Bjorken-\(x\) values. The extracted \(S_{Pb}\) factor favours the EPS09 parametrisation and in addition it agrees with the model based on the leading twist approximation (LTA).

Additional collisions at \(\sqrt{s_{NN}} = 5.02\) TeV were measured in 2015 during LHC Run 2. Higher energy, much higher integrated luminosity, improved trigger logic and a wider rapidity range increased the statistics of the recorded sample by a factor of 50. The preliminary results on the coherent \(J/\psi\) cross section measurements are shown in Fig. 2. The increase in the sample size allows us to measure the cross sections in three forward rapidity regions. The results reaffirm the conclusion found in Fig. 1 about the EPS09 parametrisation. In addition, the LTA model, models based on the Color Glass Condensate (CGC) and GG-HS and GS-HS models using sub-nucleon degrees-of-freedom [11] are compared to data. Although it seems that CGC (LM IPsat) describes the best the measured data, the other models cannot be excluded in the forward rapidity region. A new more precise measurement in the central rapidity, which is underway, will decide between models.

3. \(J/\psi\) excess in peripheral collisions

An unexpected observation was made in data from peripheral collisions: the nuclear modification factor, \(R_{AA}\), exceeds unity by a factor of 7 for low-\(p_{T}\) \(J/\psi\) at the forward rapidity range \(-4 < y < -2.5\) in peripheral Pb–Pb collisions in the 70–90% centrality class, as shown in Fig. 3. Normally, nuclear effects are weak in peripheral collisions, therefore the \(R_{AA}\) is expected to be close to one. The observed excess suggests the existence of an additional process, which enhances the production of the \(J/\psi\) vector meson. Fig. 4 shows the measured \(p_{T}\) spectrum compared with the coherent \(J/\psi\) photoproduction template from STARlight [13]. Normally, the spectrum of
opposite-sign (OS) dimuons would decrease at low-$p_T$. The STARlight simulation here fits well the observed increase. This, in combination with other signatures, led to the interpretation that coherent $J/\psi$ photoproduction is responsible for the enhancement. The cross section was determined to be $d\sigma_{70-90}/dy = (59 \pm 11 \text{(sta.)}^{+10.6}_{-12.8} \text{(sys.)}) \, \mu b$ [12].

This result is used in [6] to extend the measurement of the nuclear gluon shadowing to smaller Bjorken-$x$. The author extracts three coherent $J/\psi$ photoproduction cross sections in $\gamma$–Pb collisions and corresponding nuclear suppression factors based on ALICE measurements in UPC and peripheral collisions. These cross sections are compared to LTA models with different parton parametrisations and fit them well at small Bjorken-$x$. Current data have large uncertainties which are propagated to the extraction of the $\gamma$–Pb cross section. Newer measurements with smaller uncertainties — some of them already available in preliminary form — will allow for a more precise extraction of the nuclear suppression factor using Eq. 1.

4. Conclusion and outlook

The results of Run 1 measurements of $J/\psi$ photoproduction in UPC and peripheral lead–lead collisions by ALICE were presented. The calculations of nuclear suppression factors at different Bjorken-$x$ based on measured data were also shown. Comparison of these measurements with different models and the calculations of $S_{Pb}$ lying below unity are a direct evidence of moderate gluon shadowing in lead nucleus. However, the available data are not precise enough to distinguish amongst the different mechanisms used in the variety of presented models.

The new lead–lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV were recorded in 2015 and are followed by additional measurement in Autumn 2018 in the so-called Run 2. These data are currently being analysed by ALICE and promise an increase of integrated luminosity up to $\sim 1 \, \text{nb}^{-1}$ together with better systematic uncertainties. Next, ALICE will be upgraded to be able to collect data at higher intensities after 2020 in Run 3 and Run 4. The integrated luminosity is expected to reach $\sim 13 \, \text{nb}^{-1}$ by the end of Run 4 and also the systematic uncertainties should decrease due to greatly improved detector performance.

Acknowledgments

This work has been partially supported by the grant 18-07880S of the Czech Science Foundation (GACR).
Figure 3. Nuclear modification factor $R_{AA}$ for different centralities and $p_T$ regions in forward rapidity as measured in Run 1. Taken from [12].

Figure 4. $p_T$ spectrum of peripheral collisions at forward rapidity as measured in Run 1 compared to coherently photoproduced $J/\psi$ predicted by STARlight [13]. Figure taken from [12].

References

[1] Abramowicz H et al. (H1 and ZEUS Collaborations) 2015 Eur. Phys. J. C 75 580 Preprint 1506.06042 [hep-ex]
[2] Contreras J G and Tapia Takaki J D 2015 Int. J. Mod. Phys. A 30 1542012
[3] Ryskin M G 1993 Z. Phys. C 57 89
[4] Armesto N 2006 J. Phys. G 32 R367 Preprint hep-ph/0604108
[5] Aamodt K et al. (LICE Collaboration) 2008 JINST 3 S08002
[6] Contreras J G 2017 Phys. Rev. C 96 015203
[7] Abelev B B et al. (ALICE Collaboration) 2014 Int. J. Mod. Phys. A 29 1430044 Preprint 1402.4476 [nucl-ex]
[8] Abelev B et al. (ALICE Collaboration) 2013 Phys. Lett. B 718 1273 Preprint 1209.3715 [nucl-ex]
[9] Abbas E et al. (ALICE Collaboration) 2013 Eur. Phys. J. C 73 2617 Preprint 1305.1467 [nucl-ex]
[10] Guzey V, Kryshen E, Strikman M and Zhalov M 2013 Phys. Lett. B 726 290 Preprint 1305.1724 [hep-ph]
[11] Cepila J, Contreras J G and Krelinka M 2018 Phys. Rev. C 97 024901 Preprint 1711.01855 [hep-ph]
[12] Adam J et al. (ALICE Collaboration) 2016 Phys. Rev. Lett. 116 222301 Preprint 1509.08802 [nucl-ex]
[13] Klein S and Nystrand J 1999 Phys. Rev. C 60 014903 Preprint hep-ph/9902259