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LHCb measurements of Quarkonia Production in Ultraperipheral PbPb collisions and Z production in pPb collisions

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Measurements of quarkonia production in ultra-peripheral heavy-ion collisions are of important value to study photon-photon and photon-nucleus interactions, the partonic structure of nuclei, and mechanisms of vector-meson production. LHCb has studied both coherent J/ψ and $\psi(2S)$ mesons in ultra-peripheral collisions using PbPb data at forward rapidity with the highest precision currently accessible. In addition, measurements of Z production in pPb collisions provide new constraints on the partonic structure of nucleons bound inside nuclei. Here will present these measurements of quarkonia and Z production, along with comparisons with the latest theoretical models.

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1. Introduction

The LHCb detector [1, 2] is a fully instrumented single-arm spectrometer in the forward region covering a pseudorapidity acceptance of $2 < \eta < 5$, providing precise vertex reconstruction and excellent tracking momentum resolution down to a very low transverse momentum (p_{T}). The heavy ion program at LHCb includes both proton-lead (pPb) and lead-lead (PbPb) collisions. Forward acceptance at LHCb allows to study parton distribution functions in protons and nuclei in both small ($x < 10^{-3}$) and large ($10^{-1} < x < 1$) Bjorken-x regions. The coherent (exclusive) photo-production of charmonium in PbPb ultra-peripheral collisions (UPC) provides an ideal laboratory to probe the nuclear gluon distribution functions at a momentum transfer of $Q^2 \approx m^2/4$, where m is the mass of the meson. The electroweak Z-boson production and its leptonic decay products once produced do not participate in hadronic interactions, are ideal probes of the nuclear modifications in the non-perturbative initial-state. Two recent results are presented in this article, the measurement of coherent J/ψ and $\psi(2S)$ production in PbPb UPC [3] and the measurement of the Z production in pPb collisions [4].

2. Charmonium production in ultra-peripheral PbPb collisions

The coherent J/ψ and $\psi(2S)$ production are measured in PbPb UPC at a nucleon-nucleon centre-of-mass energy of 5.02 TeV using a data sample corresponding to an integrated luminosity of $228 \pm 10\,\mu\mathrm{b}^{-1}$, collected by the LHCb experiment in 2018 [3].

The integrated cross-sections of coherent J/ψ and $\psi(2S)$ production in PbPb collisions are measured in the rapidity region $2.0 < y^* < 4.5$ as

$$\sigma^{\mathrm{coh}}_{J/\psi} = 5.965 \pm 0.059 \pm 0.232 \pm 0.262\,\mathrm{mb}\,,$$
$$\sigma^{\mathrm{coh}}_{\psi(2S)} = 0.923 \pm 0.086 \pm 0.028 \pm 0.040\,\mathrm{mb}\,,$$

where the first listed uncertainty is statistical, the second is systematic and the third is due to the luminosity determination. The ratio of the coherent $\psi(2S)$ to J/ψ production cross-sections is measured to be

$$\sigma^{\mathrm{coh}}_{\psi(2S)}/\sigma^{\mathrm{coh}}_{J/\psi} = 0.155 \pm 0.014 \pm 0.003\,,$$

where the first uncertainty is statistical and the second is systematic. The luminosity uncertainty cancels in the ratio measurement.

The measured differential cross-sections as a function of y^* and p^*_{T} for coherent J/ψ and $\psi(2S)$ are shown in Figs. 1 and 2, respectively. The cross-section ratio of coherent $\psi(2S)$ to J/ψ production as a function of rapidity is measured for the first time and shown in Fig. 3. These results are compared to several theoretical predictions which can be grouped into models based on perturbative-QCD (pQCD) [5, 6] and colour-glass-condensate (CGC) calculations [7–14] [1].

The models provided by Guzey *et al.* [5, 6] are based on pQCD calculations under the leading-logarithm approximation. They are compatible with the data, with excellent agreement at high

[1]New theoretical developments after the Conference talk are not yet included in the figures, but they are well noticed and acknowledged.

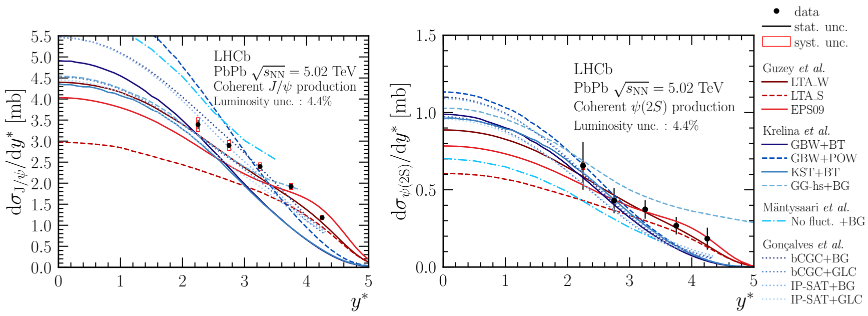

Figure 1: Differential cross-section as a function y^* for coherent (left) J/ψ and (right) $\psi(2S)$ production, compared to theoretical predictions. These models are grouped as (red lines) perturbative-QCD calculations and (blue lines) colour-glass-condensate models.

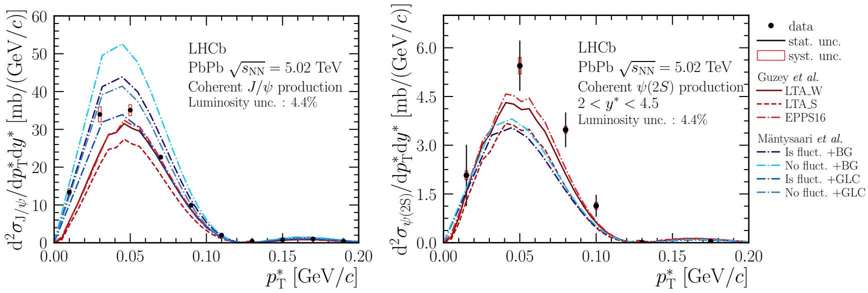

Figure 2: Differential cross-section as a function of p_{T}^* within the rapidity range $2 < y^* < 4.5$ for coherent (left) J/ψ and (right) $\psi(2S)$ production compared to theoretical predictions.

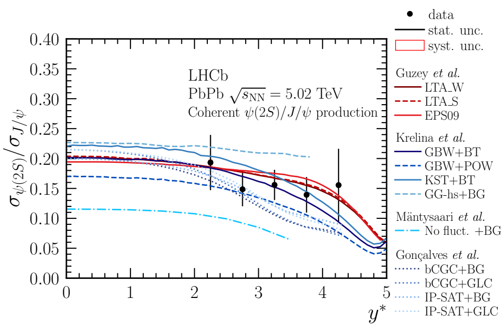

Figure 3: Differential cross-section ratio of $\psi(2S)$ to J/ψ as a function of y^*, compared to theoretical predictions. These models are separated into (red lines) perturbative QCD calculations and (blue lines) colour-glass-condensate models.

rapidity and a slight trend of underestimation at low rapidity for both J/ψ and $\psi(2S)$, as shown in Fig. 1. The underestimation at low rapidity results in an overall lower prediction in the differential cross-section as a function of p_{T}^*, shown in Fig. 2. However, excellent agreement between the prediction and data for the $\psi(2S)$ to J/ψ ratio measurement can be observed in Fig. 3.

The models by Krelina *et al.* [8, 9], Mäntysaari *et al.* [12–14], and Gonçalves *et al.* [10, 11] can be considered as variations of the colour-dipole model based on CGC theory. These models are compatible with the data, with large variations between different models. Better agreement can be seen at low rapidity than at high rapidity. A relatively larger underestimation at high rapidity and as a function of p_{T}^{*} can be seen for the $\psi(2S)$ meson in Figs. 1 and 2. This can be understood as causing by higher theoretical uncertainty, since the wave function of the $\psi(2S)$ meson has a more complicated structure than that of the J/ψ [12, 14, 15].

3. Production of Z-boson in pPb collisions

The $\mathrm{Z} \rightarrow \mu^{+}\mu^{-}$ production is measured [4] using pPb collision dataset collected at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ in 2016 by the LHCb detector corresponding to an integrated luminosity of $12.2 \pm 0.3\,\mathrm{nb}^{-1}$ for forward collisions and $18.6 \pm 0.5\,\mathrm{nb}^{-1}$ for backward collisions. The differential cross-section, the forward-backward ratio (R_{FB}) of the production cross-sections and the nuclear modification factors ($R_{p\mathrm{Pb}}$) are measured for the first time as a function of the rapidity of the Z boson in the centre-of-mass frame (y_{Z}^{*}), the transverse momentum ($p_{\mathrm{T}}^{\mathrm{Z}}$) and an angular variable ϕ^{*} [16].

The measured inclusive fiducial cross-section, forward-backward ratio (R_{FB}), and nuclear modification factors ($R_{p\mathrm{Pb}}$) are shown in Fig. 4, together with the comparisons to the PowhegBox prediction using CTEQ6.1, EPPS16 and nCTEQ15 (n)PDF sets, for forward and backward collisions, respectively. For forward collisions, the measured cross-section shown in Fig. 4(a) appears to have a good agreement with the PowhegBox calculations, with a smaller uncertainty for the two intervals of $2.0 < y_{\mathrm{Z}}^{*} < 3.0$ compared to the theoretical calculations, which can be used to further constrain the nPDFs. For backward collisions, the uncertainty of the measurement is larger than that of the PowhegBox calculation, and the measured central value is higher than the prediction especially for the $-3.5 < y_{\mathrm{Z}}^{*} < -3.0$ interval by about 2σ. However, the measurement and calculation are compatible. The measured value of R_{FB} shown in Fig. 4(b) is below unity, which is a reflection of the suppression due to, *e.g.*, nuclear shadowing at small Bjorken-x, together with an average enhancement at large Bjorken-x. The data is in agreement with the EPPS16 and nCTEQ15 predictions. The uncertainty of the measurement is smaller than the theoretical uncertainties using EPPS16 and nCTEQ15 nPDFs, showing a constraining power on the nPDFs. The measured overall $R_{p\mathrm{Pb}}$ values are shown in Fig. 4(c) and are compared to the PowhegBox predictions using the EPPS16 and nCTEQ15 nPDF sets. The overall $R_{p\mathrm{Pb}}$ results show good compatibility between measurements and theoretical predictions. The backward rapidity result shows larger uncertainty compared to that of the nPDF sets. The measured central value is consistent with the prediction at a 2σ level. The forward rapidity result gives a higher precision than the EPPS16 and nCTEQ15 nPDF sets, and the central value is larger than the prediction, which shows a constraining power on the current nPDF sets.

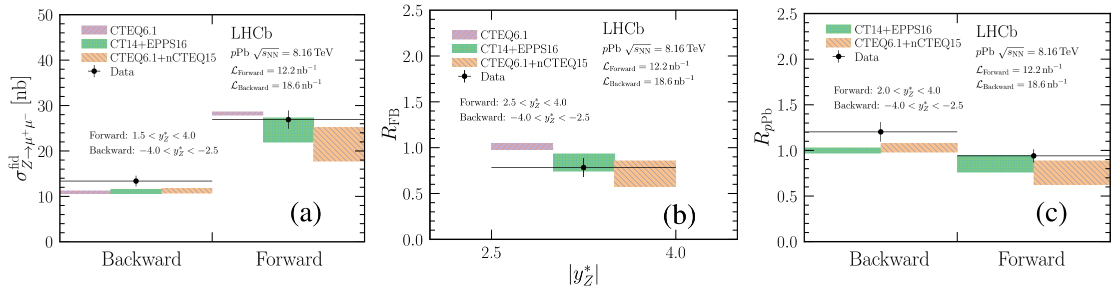

Figure 4: The measured inclusive (a) $\mathrm{Z} \rightarrow \mu^{+}\mu^{-}$ production fiducial cross-section, (b) forward-backward ratio (R_{FB}), and (c) nuclear modification factors ($R_{p\mathrm{Pb}}$), compared to theoretical predictions.

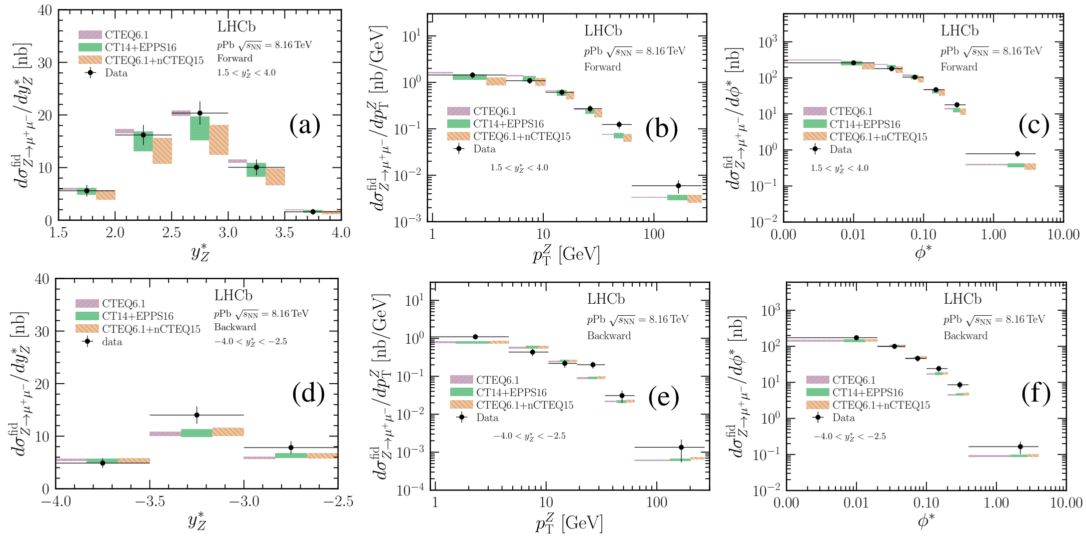

Figure 5: Differential cross-section as a function of (left column) y^*_Z, (middle column) p_T^Z and (right column) ϕ^*, together with the theoretical predictions, where the top row is for forward collisions and the bottom row is for backward collisions.

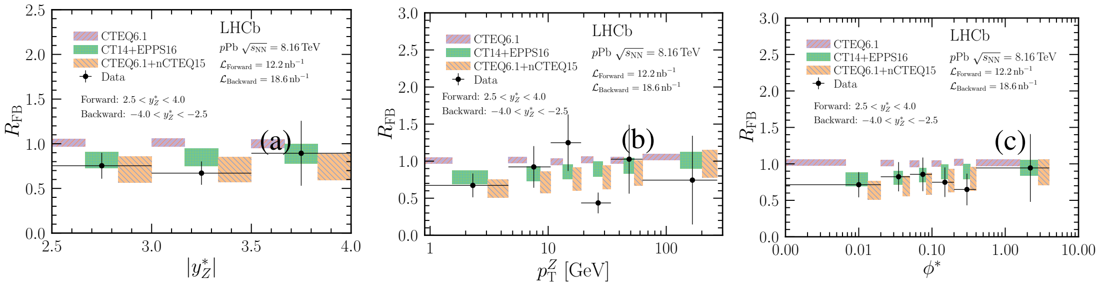

Figure 6: Forward-backward ratio ($R_{\rm FB}$) as a function of (left column) y^*_Z, (middle column) p_T^Z and (right column) ϕ^*, together with the theoretical predictions, where the top row is for forward collisions and the bottom row is for backward collisions.

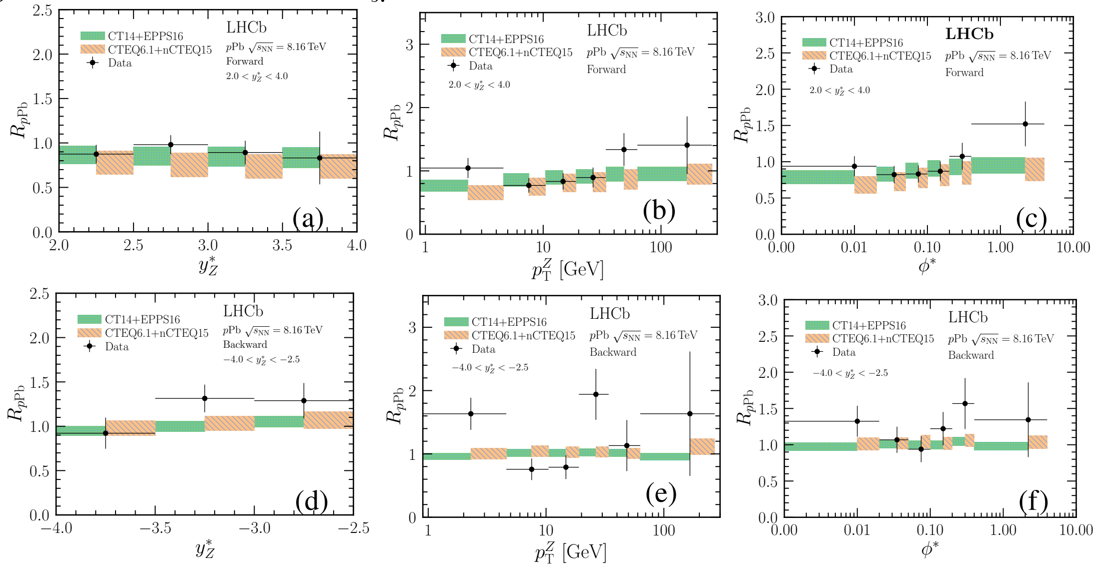

Figure 7: Nuclear modification factors ($R_{p\rm Pb}$) as a function of (left column) y^*_Z, (middle column) p_T^Z and (right column) ϕ^*, together with theoretical predictions, where the top row is for forward collisions and the bottom row is for backward collisions.

The differential measurements of the production cross-sections, R_{FB} and $R_{p\mathrm{Pb}}$ are shown in Figs. 5, 6 and 7, respectively. In general, these results are compatible with nPDF predictions. For the results of the cross-section and $R_{p\mathrm{Pb}}$, larger uncertainties compared to the current nPDF predictions appear in the backward collisions for all three observables. However, for forward rapidity the large dataset gives a higher precision for certain intervals compared to the nPDF predictions. For the measured $R_{p\mathrm{Pb}}$ results, an overall suppression below unity as expected can be observed. However, given the current large uncertainties of the measurements, no conclusive statement can be made.

4. Summary

The exclusive coherent J/ψ and $\psi(2S)$ production and their cross-section ratio in UPC PbPb collisions are newly measured using 2018 dataset collected by the LHCb detector. This is the most precise coherent J/ψ production measurement at the moment, the first coherent $\psi(2S)$ measurement, and the first ratio measurement between $\psi(2S)$ and J/ψ productions, in forward rapidity region for UPC at LHC. The differential cross-section of coherent J/ψ and $\psi(2S)$ production in PbPb UPC is also measured as a function of p_{T}^{*} for the first time. The measurements are compatible with various theoretical predictions, the high precision of the data is of great value for the fine-tuning of theoretical models. The Z-boson production is measured at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ using pPb collision dataset collected by the LHCb detector. The differential cross-section, R_{FB} and $R_{p\mathrm{Pb}}$ as a function of y_{Z}^{*}, $p_{\mathrm{T}}^{\mathrm{Z}}$, and ϕ^{*} are measured for the first time in the forward region at LHCb. The new results are compatible with nCTEQ15 or EPPS16 nPDFs calculations. Forward (small Bjorken-x) results show strong constraining power on the nPDFs.

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