Coherent photoproduction of $\psi$ and $\Upsilon$ mesons in ultraperipheral pPb and PbPb collisions at the CERN LHC

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Exclusive photoproduction of vector mesons in the perturbative two-gluon exchange formalism depends significantly on nucleon and nuclear gluon distributions. In the present study we calculate total cross sections and rapidity distributions of $J/\psi(1s), \psi(2s), \Upsilon(1s), \Upsilon(2s),$ and $\Upsilon(3s)$ in ultraperipheral proton-lead (pPb) and lead-lead (PbPb) collisions at the CERN Large Hadron Collider (LHC) at $\sqrt{s_{NN}} = 5$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV respectively. Effects of gluon shadowing are investigated and potentials for constraining nuclear gluon modifications are discussed.

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Photoproduction of heavy quarkonia in ultraperipheral collisions can help elucidate several aspects of strong interaction dynamics at high energies. It is an important part of current experimental efforts at the CERN Large Hadron Collider (LHC). All four of the large LHC experiments, ALICE, ATLAS, CMS and LHCb, have the capability to measure heavy quarkonia and first results on coherent photoproduction of $J/\psi(1s)$ in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have recently been presented by the ALICE Collaboration [1]. On the theory front it has been extensively studied at various energies and for different collision systems (see for instance [2–18]). Diverse approaches ranging from models based on perturbative Quantum Chromodynamics (pQCD) to Color Dipole models and $k_T$ factorization have been used to study coherent and incoherent photoproduction of heavy mesons. The characteristics of some of the currently employed models is discussed in [1].

In previous works [6–8] we have considered coherent photoproduction of $J/\psi(1s)$ and $\Upsilon(1s)$ at various energies in pPb and PbPb collisions at the LHC. The calculations were carried out in the framework of perturbative two-gluon exchange formalism with different nuclear gluon distributions and a detailed exposition can be found in [6] (see also [14, 20]). In the current article we extend these previous studies by considering, in addition to $J/\psi(1s)$ and $\Upsilon(1s)$, the exclusive photoproduction of $\psi(2s)$, $\Upsilon(2s)$, and $\Upsilon(3s)$ in ultraperipheral pPb (at $\sqrt{s_{NN}} = 5$ TeV) and PbPb (at $\sqrt{s_{NN}} = 2.76$ TeV) collisions at the LHC. For brevity we will refer to $J/\psi(1s)$ and $\psi(2s)$ collectively as $\psi$ mesons, and $\Upsilon(1s), \Upsilon(2s),$ and $\Upsilon(3s)$ as $\Upsilon$ mesons. The calculation framework remains essentially unchanged; the only additional assumption is that the multiplicative correction factor $\zeta_V$ introduced in [6] and determined for $J/\psi(1s)$ is applicable to $\psi(2s)$. The requisite input masses and widths of these mesons are taken from [21] and are shown in Table I. As in previous studies we use gluon distributions from MSTW08 [22], EPS08 [23], EPS09 [24], and HKN07 [25]. The characteristics of these distributions, especially the disparities in the strength of the nuclear modifications of their gluon content, have been treated in detail in [6]. Summarily, in terms of gluon shadowing strength, the progression is from zero effects (MSTW08) to weak effects (HKN07), moderate effects (EPS09), and strong effects (EPS08). From the collision energies involved, the current work can be regarded as a natural extension of the study reported in [2], and some similarities in features are thus to be expected.

Let us now present the cross sections and rapidity distributions of $J/\psi(1s)$ and $\psi(2s)$ in ultraperipheral pPb and PbPb collisions. Upper panel of Table II shows the total cross sections in $\mu$b for elastic photoproduction of these mesons in ultraperipheral pPb collisions while the lower panel displays the corresponding cross sections in $\text{mb}$ for PbPb collisions. The cross sections for each meson

| TABLE I. Masses $M_V$ and leptonic decay widths $\Gamma_{ee}$ of $\psi$ and $\Upsilon$ mesons. Data taken from [21]. |
|----------------------------------|-------------|---------------|
| $J/\psi(1s)$ | 3.906916   | 5.55          |
| $\psi(2s)$  | 3.868108   | 2.33          |
| $\Upsilon(1s)$ | 9.4603  | 1.34          |
| $\Upsilon(2s)$ | 10.0232  | 0.612         |
| $\Upsilon(3s)$ | 10.3352  | 0.443         |

| TABLE II. Total cross sections for elastic photoproduction of $J/\psi(1s)$ and $\psi(2s)$ in ultraperipheral pPb (in $\mu$b; upper panel) and PbPb (in mb; lower panel) collisions at the LHC. |
|----------------------------------|-------------|---------------|-------------|---------------|
| $J/\psi(1s)$ | MSTW08 | EPS08 | EPS09 | HKN07 |
| $\psi(2s)$  | 18.6    | 14.6  | 15.8  | 17.0  |
| $J/\psi(1s)$ | 34.3    | 6.3   | 14.6  | 23.3  |
| $\psi(2s)$  | 7.1     | 1.9   | 3.5   | 5.0   |
reflect the trend in gluon shadowing strength: those from MSTW08 are the largest while the EPS08 cross sections are the smallest. A quantitative measure of the overall effect of gluon shadowing on total photoproduction cross section can be obtained by defining, for each meson $V$ and nuclear gluon distribution NGD, a shadowing factor, $S_F$, given by

$$S_F = \frac{\sigma_V^{MSTW08} - \sigma_V^{NGD}}{\sigma_V^{MSTW08}}$$

(1)

As defined, $S_F$ scales linearly with severity of shadowing, i.e. larger values of $S_F$ translate to larger shadowing effects. When multiplied by 100 the resulting product gives the percentage by which the no-shadowing MSTW08 cross section is reduced by the shadowing in the specified nuclear gluon distribution. $S_F$ for both mesons and all three nuclear gluon distributions are shown in Fig. 1 for pPb collisions (left panel) and PbPb collisions (right panel) respectively.

![FIG. 1. (Color online) Shadowing factor $S_F$ for photoproduction of $J/\psi(1s)$ and $\psi(2s)$ in (a) pPb and (b) PbPb collisions at the LHC. Dashed lines are for visual clarity.](image)

Let us first consider pPb collisions (left panel). Shadowing effects are most pronounced for EPS08 and least pronounced for HKN07 and almost the same for both mesons. As can be seen from Fig. 1 there is approximately a 20\% reduction of the MSTW08 cross section by the shadowing effects in EPS08, 14\% by EPS09 and 7\% by HKN07 respectively.

Shadowing effects are significantly stronger in PbPb collisions as evidenced by the larger values of $S_F$ and follow the usual trend: they are largest for EPS08 and smallest for HKN07. Also $J/\psi(1s)$ exhibit greater sensitivity to shadowing effects than $\psi(2s)$, especially for EPS08. For $J/\psi(1s)$ the reduction ranges from about 32\% (HKN07) to about 80\% (EPS08) while for $\psi(2s)$ it ranges from 30\% to 72\%.

In Table III we show the ratio $\sigma^{\psi(2s)} / \sigma^{J/\psi(1s)}$ from all four gluon distributions for pPb and PbPb collisions. It is $\approx 0.21$ for pPb collisions and between 0.21 and 0.29 for PbPb collisions, in line with the trend seen in $S_F$.

![FIG. 2. (Color online) Rapidity distributions of exclusive photoproduction of $J/\psi(1s)$ and $\psi(2s)$ in (a) and (c)) and $\psi(2s)$ in (b) and (d) in pPb (upper panels) and PbPb (lower panels) collisions at the LHC. Dashed (MSTW08), dash-double-dotted (HKN07), solid (EPS09), and dash-dotted (EPS08) lines correspond to rapidity distributions with no shadowing, weak shadowing, moderate shadowing, and strong shadowing respectively. The $\psi(2s)$ distributions have been magnified for clarity.](image)

We now consider rapidity distributions. Fig. 2 shows the rapidity distributions for $J/\psi(1s)$ and $\psi(2s)$ in pPb (upper panel) and PbPb (lower panel) collisions. For pPb collisions the distributions shown are the sum of the $\gamma p$ and $\gamma Pb$ contributions and are manifestly asymmetric in line with the convention adopted in [6]. The rapidity distributions exhibit clearly the influence of gluon shadowing in the interval $-4 \lesssim y \lesssim 2$, and especially in the narrow rapidity window $-3 \lesssim y \lesssim -1$ where the differences reflect the relative strength of gluon shadowing in the respective nuclear parton distribution. Also the shapes are similar for both mesons. Thus it seems feasible that a consideration of especially $J/\psi(1s)$ production in pPb collisions in this rapidity interval offers some potential in constraining gluon shadowing.

The rapidity distributions in PbPb collisions are symmetric about midrapidity and also similar in structure except for EPS08. The influence of the significantly stronger nuclear effects in PbPb collisions is demonstrated by the remarkable distinctions in the rapidity...
distributions predicted by the different gluon distributions over an appreciable range of rapidity. Shadowing is the relevant nuclear effect in the rapidity interval $-3 < y < 3$ and the rapidity distributions mimic the shadowing strength of the various distributions. In particular the rapidity window $-2 < y < 2$ manifestly depicts the significant distinctions between the various gluon distributions. This interval is thus suitable for probing gluon shadowing. The influence of antishadowing is manifested in the intervals $-4.5 < y < -3.5$ and $3.5 < y < 4.5$ but the effect is relatively slight.

Let us now turn to $\Upsilon$ mesons in ultraperipheral pPb and PbPb collisions. The ensuing treatment parallels closely that of the $\psi$ mesons in many respects due to the same underlying production mechanism.

### TABLE IV. Total cross sections for elastic photoproduction of $\Upsilon$ mesons in ultraperipheral pPb (in nb; upper panel) and PbPb (in $\mu$b; lower panel) collisions at the LHC.

| Meson | MSTW08 | EPS08 | EPS09 | HKN07 |
|-------|--------|-------|-------|-------|
| $\Upsilon(1s)$ | 291.0 | 207.5 | 236.1 | 254.9 |
| $\Upsilon(2s)$ | 94.2 | 66.8 | 76.2 | 82.3 |
| $\Upsilon(3s)$ | 56.1 | 39.7 | 45.4 | 49.0 |
| $\Upsilon(1s)$ | 52.1 | 32.7 | 39.5 | 41.9 |
| $\Upsilon(2s)$ | 15.9 | 10.3 | 12.3 | 12.9 |
| $\Upsilon(3s)$ | 9.2 | 6.0 | 7.2 | 7.5 |

Upper panel of Table IV shows the total cross sections in nb for elastic photoproduction of $\Upsilon$ mesons in ultraperipheral pPb collisions while the lower panel displays the corresponding cross sections in $\mu$b for PbPb collisions. As in the case of $\psi$ mesons the effect of gluon shadowing on total cross sections is reflected in the plot of $S_F$ as shown in Fig. 3 for pPb collisions (left panel) and PbPb collisions (right panel) respectively.

As is apparent from left panel of Fig. 3, $S_F$ is approximately constant for all three distributions in pPb collisions. Thus the no-shadowing (MSTW08) cross sections are reduced by about 29%, 19%, and 12% respectively by the shadowing in EPS08, EPS09, and HKN07. This appreciable magnitude of the effect of shadowing indicates that $\Upsilon$ photoproduction cross section in ultraperipheral pPb collisions offers some promising potential in constraining nuclear gluon shadowing.

For PbPb collisions $S_F$ is almost constant for HKN07 and decreases with increasing mass for EPS08 and EPS09. For HKN07 the reduction is approximately 19% while for EPS08 and EPS09 it is between 37% and 34% and between 24% and 22% respectively. These reductions are quite significant and thus the cross sections for photoproduction of $\Upsilon$ mesons offer good constraining ability for gluon shadowing determination.

### TABLE V. Ratio of cross sections for pPb (upper panel) and PbPb (lower panel) collisions.

| Ratio | MSTW08 | EPS08 | EPS09 | HKN07 |
|-------|--------|-------|-------|-------|
| $\sigma(1s)/\sigma(1s)$ | 0.324 | 0.322 | 0.323 | 0.323 |
| $\sigma(2s)/\sigma(1s)$ | 0.193 | 0.191 | 0.192 | 0.192 |
| $\sigma(3s)/\sigma(1s)$ | 0.305 | 0.315 | 0.311 | 0.308 |
| $\sigma(2s)/\sigma(1s)$ | 0.177 | 0.183 | 0.182 | 0.179 |

Table V shows the ratios $\sigma(2s)/\sigma(1s)$ and $\sigma(3s)/\sigma(1s)$ for pPb and PbPb collisions. Similar ratios in the hadroproduction of $\Upsilon$ in PbPb collisions have been reported in [24, 27]. The ratios for both collision systems considered are to a good approximation independent of shadowing effects.

We now turn to rapidity distributions. Fig. 4 shows the rapidity distributions for $\Upsilon$ mesons in pPb (upper panel) and PbPb (lower panel) collisions. Again for pPb collisions the distributions shown are the sum of the $\gamma p$ and $\gamma Pb$ contributions.

Let us consider the upper panel. At negative rapidities the distributions are relatively more prominent than for $\psi$ production, due to the relatively larger influence of the $\gamma Pb$ contribution to the total rapidity distributions. Nuclear effects are clearly discernible in the interval $-5 \lesssim y \lesssim 0$, and for $-4 \lesssim y \lesssim -1$ quite distinctly reflect the effect of the varying shadowing strength in the gluon distributions used. Thus in the rapidity interval $-4 \lesssim y \lesssim -1$ the total distributions show good sensitivity to gluon shadowing, and therefore afford good potential for constraining purposes.

The rapidity distributions for $\Upsilon$ mesons in PbPb collisions are symmetric about midrapidity, and are structurally similar. The stronger nuclear effects in PbPb collisions again lead to clear cut differences in the rapidity distributions predicted by the different gluon parametrizations considered over a significant rapidity range. Shadowing is the relevant nuclear effect in the rapidity interval $-2 < y < 2$ and in particular the rapidity window $-1 < y < 1$ shows clearly the distinc-
FIG. 4. (Color online) Rapidity distributions of exclusive photoproduction of \( \Upsilon(1s) \) ((a) and (d)), \( \Upsilon(2s) \) ((b) and (e)), and \( \Upsilon(3s) \) ((c) and (f)) in pPb (upper panels) and PbPb (lower panels) collisions at the LHC. Dashed (MSTW08), dash-double-dotted (HKN07), solid (EPS09), and dash-dotted (EPS08) lines correspond to rapidity distributions with no shadowing, weak shadowing, moderate shadowing, and strong shadowing respectively. The \( \Upsilon(2s) \) and \( \Upsilon(3s) \) distributions have been magnified for clarity.

In conclusion we have considered elastic photoproduction of \( \psi \) and \( \Upsilon \) mesons in ultraperipheral pPb and PbPb collisions at LHC. The production mechanism involves nuclear gluon distributions and different sets of nuclear parton distributions with varying severity of gluon shadowing have been utilized. Cross sections, rapidity distributions, and cross section ratios for both collision systems have been presented.

The significant dependence on gluon distribution implies that elastic photoproduction of vector mesons in ultraperipheral collisions could potentially be useful in constraining modifications such as shadowing in nuclear gluon distributions. The cross sections and rapidity distributions for \( \psi \) and \( \Upsilon \) photoproduction in PbPb collisions exhibit significant sensitivity to gluon shadowing. Thus both offer good potential in constraining the shadowing component of nuclear gluon distributions. In the case of pPb collisions \( \Upsilon \), and to a lesser extent \( \psi \) production, also display appreciable sensitivity and could thus be of use in constraining purposes.

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