On theoretical uncertainty of color dipole phenomenology in the $J/\psi$ and $\Upsilon$ photoproduction in $pA$ and $AA$ collisions at the CERN Large Hadron Collider

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We investigate the theoretical uncertainty on the predictions for the photoproduction of $J/\psi$ and $\Upsilon$ states in the proton-nucleus and nucleus-nucleus collisions at the LHC within the color dipole formalism. Predictions for the rapidity distributions are presented and the dependence on the meson wavefunction, heavy quark mass as well as the models for the dipole cross section are analyzed. We compare directly the theoretical results to the recent data from ALICE collaboration on $J/\psi$ production in $pPb$ collisions at energy of 5.02 TeV. Predictions are also performed for $\Upsilon$ state in PbPb collisions at the LHC energies, including the coherent and incoherent contributions.

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I. INTRODUCTION

The recent measurements of the exclusive quarkonium photoproduction by ALICE and LHCb collaborations at the LHC have imposed serious constraints to the theoretical models for the vector meson production. The forward and central rapidities regions are mapping the dynamics at very small Bjorken-$x$ values, $x \approx (M_V/\sqrt{s})e^{\pm y}$. For instance, for the $J/\psi$ this means values of $x \approx 10^{-4} (10^{-3})$ at central rapidity in proton-proton collisions at 7 TeV (in lead-lead collisions at 2.76 TeV). Accordingly, the theoretical uncertainty in these cases is very large as the underlying models basically depend on the gluons distribution squared, which is uncertain at the small-$x$ regime. The situation is more complicated in the nuclear case, where there is the additional problem of determining the nuclear gluon distribution function. A very promising approach is given by the color dipole framework, where the inclusive and exclusive processes can be treated simultaneously. Moreover, the dipole framework allows to include in a simple way the corrections associated to the parton saturation phenomenon and to introduce information on dynamics beyond the leading logarithmic QCD approach.

As a summary on our recent works in the subject, in Ref. [1] the photoproduction of $\psi(1S)$ and $\psi(2S)$ states were computed in color dipole formalism and the results are in good agreement with LHCb data on $pp$ collisions at 7 TeV. On the other hand, in Ref. [2] the same states were analyzed in the lead-lead collisions at 2.76 TeV, including the coherent and incoherent contributions. The predictions are somehow consistent with the ALICE data. [1] It was verified that the theoretical uncertainty is very large compared to the proton case, mostly at central rapidities. The quarkonium production, i.e. the $J/\psi$ and $\Upsilon$ states, in proton-lead collisions were investigated in Ref. [11]. There, it was included predictions for the rapidity distribution in backward and forward regions in the process $Pb+p \rightarrow Pb+p+V$. In the proton-lead case it is possible to investigate at the same time the dynamics on the photon-proton cross section and on the photon-nucleus cross section. The dominant contribution comes from the photon-proton interaction as the photon flux due to the nucleus is higher compared to that due to the proton. It was shown in [11] that the photon-nucleus contribution is relevant at large rapidities and increasingly important for the $\Upsilon$ states. The present work is an extension of Ref. [11], where now we consider the process $p+Pb \rightarrow p+Pb+V$, which has recently been measured by ALICE collaboration in 5.02 TeV energy. The focus is on the investigation of the theoretical uncertainties associated to the models for the dipole cross section and meson wavefunction. Furthermore, we provide predictions for the exclusive $\Upsilon$ production in coherent and incoherent lead-lead collisions at the LHC including their theoretical uncertainties.

II. THEORETICAL FRAMEWORK AND MAIN RESULTS

Let us summarize the main expressions from the theoretical approach considered in present study. For proton-nucleus interaction at large impact parameter ($b > R_p + R_q$) and at ultra-relativistic energies it is expected that the electromagnetic interaction to be dominant. In this case, the exclusive meson photoproduction in hadron-target collisions can be factorized in terms of the equivalent flux of photons of the hadron projectile and photon-target production cross section $[12]$. The photon energy spectrum for protons and nuclei, $dN_\gamma^p/d\omega$ and $dN_\gamma^A/d\omega$, which depend on the photon energy $\omega$, are well understood (see details for the photon flux on protons or nuclei in Ref. [12]). For proton-lead collisions at the LHC energies, where the meson rapidity is positive in the proton beam direction, the quarkonium rapidity distribution reads as $[12]$

$$
\frac{d\sigma}{d\gamma} (p + Pb \rightarrow p + Pb + V) = \frac{dN_p^p(-y)}{d\omega} \sigma_{\gamma p \rightarrow V + p}(-y) + \frac{dN_p^A(y)}{d\omega} \sigma_{\gamma Pb \rightarrow V + p} \gamma(y),
$$
where \( \frac{dN_c(y)}{dy} \) is the corresponding photon flux and \( y = \ln(2\omega/m_V^2) \), with \( \omega \) being the photon energy. The case for the inverse beam direction is straightforward. Similarly, the rapidity distribution \( y \) in nucleus-nucleus collisions has the same factorized form,

\[
\frac{d\sigma}{dy}(AA \rightarrow A \otimes V \otimes Y) = \left[ \omega \frac{dN^A_\gamma}{d\omega} \sigma(\gamma A \rightarrow V + Y) \right] + (y \rightarrow -y),
\]

where the photon flux in nucleus is denoted by \( dN^A_\gamma/d\omega \) and \( Y = A \) (coherent case) or \( Y = A^* \) (incoherent case).

Here, the photon-Pomeron interaction will be described within the light-cone dipole frame, where the probing projectile fluctuates into a quark-antiquark pair with transverse separation \( r \) and momentum fraction \( z \) long after the interaction, which then scatters off the hadron. The cross section for exclusive photoproduction of vector meson off a nucleon target is given by \[7\],

\[
\sigma(\gamma p \rightarrow V p) = \frac{1}{16\pi B_V} \left| \int dz \, d^2r \, \Phi_T^{V*} \sigma_{dip} \right|^2,
\]

where \( \Psi^\gamma(z,r,m_q) \) and \( \Psi^V(z,r,m_q) \) are the light-cone wavefunction of the photon and of the vector meson, respectively. The Bjorken variable is denoted by \( x = M_V^2/(W^2_{\gamma p} - m_V^2) \), the dipole cross section by \( \sigma_{dip}(x,r) \) and the diffractive slope parameter by \( B_V \). Here, we consider the energy dependence of the slope using the Regge motivated expression, \( B_V(W_{\gamma p}) = B_0 + 4\alpha' \log(W_{\gamma p}/W_0) \) (the values of parameters for \( \psi(1S) \) and \( \Upsilon(1S) \) can be found in Refs. \[9\]-\[11\]).

Accordingly, the exclusive photoproduction off nuclei for coherent and incoherent processes can be simply computed in high energies where the large coherence length \( l_c \gg R_A \) is fairly valid. The expressions for both cases are given by \[12\],

\[
\sigma(\gamma A \rightarrow VA) = \left| \int d^2b \, \langle \Psi^V | 1 - \exp \left[ -\frac{1}{2} \sigma_{dip} T_A \right] | \Psi^\gamma \rangle \right|^2,
\]

\[
\sigma(\gamma A \rightarrow VA^*) = \frac{1}{16\pi B_V} \left| \int d^2b \, T_A \langle \Psi^V | \sigma_{dip}(x,r) \rangle \right| \exp \left[ -\frac{1}{2} \sigma_{dip} T_A(h) \right] | \Psi^\gamma \rangle^2,
\]

where \( T_A(h) = \int dz \rho_A(b,z) \) is the nuclear thickness function. The notation \( \langle \Psi^V | (\ldots) | \Psi^\gamma \rangle \) represents the overlap over the wavefunctions.

On source of theoretical uncertainty in such predictions is related to the choice for the meson wavefunction. In order to investigate this, we considered the Boosted Gaussian \[14\] (BG) and the Light-Cone Gaussian \[13\] (LCG). The expressions for the overlap functions we have used appropriately summed over the helicity and flavor indices

| common parameters | BG parameters | LCG parameters |
|-------------------|---------------|---------------|
| \( V \) \( M_V \) \( m_f \) \( \epsilon_f \) \( R^2 \) \( N_T \) \( R_T^2 \) \( N_T \) |
| \( \psi(1S) \) \( 3.097\ 1.4\ 1.27 \) \( 2/3 \) \( 2.44 \) \( 0.572 \) \( 6.5 \) \( 1.23 \) |
| \( \Upsilon(1S) \) \( 9.46\ 4.2\ 4.2 \) \( 1/3 \) \( 0.567 \) \( 0.481 \) \( 1.91 \) \( 0.78 \) |

The parameters \( R \) and \( N_T \) are constrained by unitarity of the wavefunction as well as by the electronic decay widths. They are given in Table \[11\]. On the other hand, for LCG wavefunction \[13\] one has the following expression:

\[
\phi_T = N_T z(1-z) \exp \left[ -r^2/(2R_T^2) \right],
\]

with the parameters also given in Table \[11\]. The parameters for the meson wavefunctions shown in Table correspond to fixed heavy quark masses of \( m_c = 1.4 \) GeV and \( m_b = 4.2 \) GeV. See Refs. \[16\]-\[20\] for similar determinations of wavefunction parameters for J/\( \psi \) and \( \Upsilon \) states.

Another source of theoretical uncertainty is the model for the dipole-target cross section. We considered two sets of parameters for the IIM parameterization \[21\] (including charm quark in fits). In this case, the dipole cross section is parameterized as follows,

\[
\sigma_{dip}(x,r) = \sigma_0 \left[ \begin{array}{ll}
0.7 (\frac{x}{\bar{x}})^{\gamma_{sat}(x,r)} & , \quad \text{for } \bar{x} \leq 2, \\
1 - \exp \left[ -a \ln^2 (b\bar{x}) \right] & , \quad \text{for } \bar{x} > 2,
\end{array} \right]
\]

where \( \bar{x} = r Q_{sat}(x) \). For the color transparency region near saturation border (\( \bar{x} \leq 2 \)), the behavior is driven by the effective anomalous dimension \( \gamma_{eff}(x,r) = \gamma_{sat} + \ln(2/\bar{x})/\kappa_{\lambda,\gamma} \) with \( \kappa = 9.9 \). The saturation scale is defined as \( Q_{sat}(x) = (\frac{x}{\bar{x}})^{\lambda} \) and \( \sigma_0 = 2\pi R_T^2 \).

The first set (labeled by IIM-old \[22\]) considers the previous DESY-HERA data and the values for parameters are \( \gamma_{sat} = 0.7376 \), \( \lambda = 0.2197 \), \( x_0 = 0.1632 \times 10^{-4} \) and \( R_T = 3.344 \) GeV\(^{-1} \) (\( \sigma_0 = 27.33 \) mb). For IIM-old, the charm quark mass is fixed as \( m_c = 1.4 \) GeV. The second set (labeled IIM-new \[23\]) considered the extremely
small error bars on the recent ZEUS and H1 combined results for inclusive DIS. In this case, the parameters are $\gamma_{\text{sat}} = 0.762$, $\lambda = 0.2319$, $x_0 = 0.6266 \times 10^{-4}$ and $\sigma_0 = 21.85$ mb. For IIM-new, the charm quark mass is fixed as $m_c = 1.27$ GeV. In order to compare the dependence on distinct models, we also consider the simple GBW parameterization \cite{24} (fit including charm quark).

As a final note on the details of the present calculation, we discuss the threshold correction, the real part of amplitude and skewness effects. In all numerical calculations, we multiply the dipole cross sections above by a threshold correction factor $(1 - x)^n$, where $n = 7$ for the heavy ones (the value for $n$ is estimated using quark counting rules). The cross section in Eq. (2) has been computed including the real part of amplitude contribution and skewness correction in the following way,

$$
\hat{\sigma}_{\gamma p \rightarrow Vp} = R_g^2 \sigma(\gamma p \rightarrow Vp)(1 + \beta^2),
$$

with

$$
\beta = \tan\left(\frac{\pi \epsilon}{2}\right),
R_g(\epsilon) = \frac{\pi^{2\epsilon+3}}{\sqrt{\pi}} \frac{\Gamma(\epsilon+5/2)}{\Gamma(\epsilon+4)},
$$

$$
\epsilon \equiv \frac{\partial \ln(A_{\gamma p \rightarrow Vp})}{\partial \ln(1/x)},
$$

where the factor $(1 + \beta^2)$ takes into account the missing real part of amplitude, with $\beta$ being the ratio of real to imaginary parts of the scattering amplitude. The factor $R_g$ incorporates the skewness effect, coming from the fact that the gluons attached to the $q\bar{q}$ can carry different light-front fractions $x, x'$ of the proton. The skewness factor given in Eq. (7) was obtained at NLO level, in the limit that $x' \ll x \ll 1$ and at small $t$ assuming that the diagonal gluon density of target has a power-law form \cite{25}. Similar corrections have been introduced also for the photonuclear cross section.

As a comment on the reliability of the present calculation, the non-forward wavefunction \cite{26} was not considered as the dipole cross sections used have not explicit impact-parameter or $t$-dependence. There are few phenomenological models in literature considering $b$-dependence (IP-saturation model \cite{27} and CGC impact parameter model (b-CGC) \cite{28}) and they basically take into account Gaussian-like behavior associated to the proton wavefunction (this is enough to describe the small-$t$ region from data on $ep$ exclusive processes). The same comment applies to the Marquet-Peschanski-Soyez (MPS) model \cite{29}, where explicit $t$-dependence for dipole cross section is considered. In any case, the IIM dipole
cross section considered in our calculation is a limit case \((t \to 0)\) for both CGC impact parameter and MPS models. The more complex question of b-dependence coming from the evolution equations for the dipole amplitude is work in progress and it is an open question by now (see, e.g. Ref. [30]). We considered a simpler approach, where the \(B\) wave function is taken from a parameterization for the measured values at HERA and we consider only the forward dipole amplitude (this diminishes the theoretical uncertainty associated to the specific model for the b-dependence in dipole amplitude). It would be opportune to compare our calculation to the results from Ref. [27], where the photoproduction of \(J/\psi\) has been considered using both the IP-saturation and the b-CGC models. Concerning the expression for the dipole-nucleus cross section, we are using the Glauber-Gribov (smooth nucleus) approach which has been tested against small-x data for nuclear structure functions (see, e.g. Ref. [31]). A more refined treatment of nuclear effects has been done in Ref. [28], where the gluons form a lumpy distribution within the nucleus. To account for this correlation among the gluons those authors generalize the smooth nucleus model. It was shown that only if the atomic mass number \(A\) is large and dipole size \(r\) is small the smooth nucleus formula is recovered. This is the case for the calculation we are considering: lead nucleus and heavy meson production with typical dipole sizes given by \(r \sim 1/(Q^2 + m_c^2)\).

We are now ready to obtain the rapidity distribution for \(\psi(1S)\) production in proton-lead collisions at the energy of 5.02 TeV at the LHC (an analysis for \(\Upsilon(1S)\) has been done in Refs. [11]). In Fig. 1(a) is presented the results for \(J/\psi\) taking into account the Boosted Gaussian (BG) wavefunction and some samples of phenomenological models for the dipole cross section as discussed before. The solid curve stands for the IIM-old dipole cross section, whereas the dotted-dashed line represents the result using the new fit, IIM-new. The dashed curve stands for the GBW parametrisation. The behavior at very large rapidities tends to be similar for the distinct models. However, towards midi-rapidity at mid-rapidities there is an evident model dependence. The IIM-old and GBW parameterization deliver quite similar results, whereas IIM-new produces a overall normalization large than the others. This is mainly due the smaller values of the charm quark mass considered \((m_c = 1.27\) GeV in contrast to \(m_c = 1.4\) GeV for IIM-old and GBW). We have introduced also the ALICE data [3] for forward rapidities: the wide range \(2.5 < y < 4.0\) (filled square) and three sub-bins \(y = [3.5,4.0], [3.0,4.0]\) and \([2.5,3.0]\) (filled circles). Using the BG wavefunction, GBW seems to be mode consistent considering the error bars. In Fig. 1(b), the results are now presented for the Light Cone Gaussian (LCG) wavefunction and the notation is the same as for the previous plot. Now, the IIM-new option does the better job in data description and it is observed a smaller deviation between IIM-old and IIM-new for the LCG wavefunction. This is due the difference in the \(\phi_T\) function, which does not depend explicitly on \(m_c\) in the LCG case. The predictions using the LCG wavefunction are in general smaller than the BG wavefunction case. The ALICE collaboration has also measured the rapidity cross section for the case \(Pb + p \to Pb + J/\psi + p\) in the region \(-3.6 < y < -2.6\), where \(d\sigma/dy(-3.6 < y < -2.6) = 2.46 \pm 0.31\) (stat) \(\pm 0.23\) (syst) \(\mu b\). We compute the corresponding cross section using the same rapidity cut and obtain \(d\sigma/dy = 8.7 \pm 1.5\) \(\mu b\) (for BG wavefunction) and \(d\sigma/dy = 6.8 \pm 0.76\) \(\mu b\) (for LCG wavefunction). The error is related to the theoretical uncertainty in the dipole cross section. The origin of this clear discrepancy could for instance be traced back in the expressions for the photon flux for nucleus, \(dN^L_{\gamma}(y)/d\omega\). It was shown in Ref. [32] that the strong proton-nucleus interaction reduces drastically the photon flux at large rapidities.

Let us now investigate the photnuclear production of \(\Upsilon\) in nucleus-nucleus collisions at the LHC. We will consider PbPb collisions at the energy of 2.76 TeV. In Fig. 2 we present the results for the rapidity distributions for the coherent \(\Upsilon\) production, \(Pb + Pb \to Pb + \Upsilon(1S) + Pb\), considering the BG wavefunction (without nuclear break up). The thick curves correspond to the result using BG wavefunction and the thin curves are for LCG wavefunction (multiplied by a factor 0.5 for better visualization). The theoretical uncertainty associated to the model for wavefunction is different compared to the pA case and now the results are similar. The main reason is that we are considering the same mass for the bottom quark , \(m_b = 4.2\) in both parameterizations. It is verified that the deviation is significant concerning the distinct models for the dipole cross section mostly at large rapidities. In Fig. 3 one presents the results for the incoherent production of \(\Upsilon\), \(Pb + Pb \to Pb + \Upsilon(1S) + Pb^*\) taking into account the BG and LCG wavefunctions. The notation in figure is the same as for Fig. 2. As for the coherent case, the deviation is quite small when comparing the dependence on the meson wavefunction. We notice that we are not introduced the effect of nuclear break up as we are considering here events with no neutron emitted in any direction \((0n0n)\). The strong fields associated with heavy-ions lead to large probabilities for exchanging additional photons when a \(\Upsilon\) meson is produced at small impact parameters and they will excite one or both of the nuclei and lead to break up.

Finally, we discuss the possible limitations of current approach. Here, we ignore the important problem with simultaneous description of the ALICE data on \(J/\psi\) photoproduction in coherent and incoherent Pb-Pb UPCs in the dipole approach. It was shown in Ref. [10] that the color dipole model dramatically overestimates the \(y = 0\) ALICE data point on coherent \(J/\psi\) photoproduction in Pb-Pb UPCs at 2.76 TeV and that the agreement can be achieved only by introducing an \(ad\ hoc\) the gluon shadowing factor of \(R_G\). At the same time, the \(y = 0\) ALICE data point on incoherent \(J/\psi\) photoproduction in Pb-Pb UPCs at 2.76 TeV is reproduced by the dipole formalism assuming \(R_G = 1\). However, in Ref. [19] only the
BG wavefunction and IIM-old dipole model have been considered. As discussed before, when the LCG wavefunction is considered the results are smaller than the BG case. Thus, there is some space to account for the discrepancy between data and dipole approach results in the theoretical uncertainties associated to the choices for the wavefunctions, the model for the dipole cross section and the values of heavy quark masses. In fact, we have shown in [11] that for pA collisions the effect of an additional $R_G$ contribution is negligible for practical situations. In addition, while in pp and AA UPCs, the photon flux is known rather well, the case of pA UPCs is less clear since the photon flux at large photon energies is significantly suppressed by soft pA interactions at small impact parameters as discussed in Ref. [32]. We have not considered this uncertainty in the present calculation.

Summarizing, an investigation was done on the photoproduction of $J/\psi$ and $\Upsilon(1S)$ meson states in the proton-nucleus and nucleus-nucleus collisions in the LHC energies. It was included both contributions of photon-proton and proton-nucleus interactions within the color dipole formalism. Predictions for the rapidity distributions are presented using the color dipole formalism and including saturation effects that are expected to be relevant at high energies. Predictions for the rapidity distributions are presented and the dependence on the meson wavefunction, heavy quark mass as well as the models for the dipole cross section are analyzed. We compare directly the theoretical results to the recent data from ALICE collaboration on $J/\psi$ production in pPb collisions at energy of 5.02 TeV. Predictions are also performed for $\Upsilon(1S)$ state in PbPb collisions at the LHC energies, including the coherent and incoherent contributions.

FIG. 3: (Color online) Predictions for the rapidity distribution of incoherent photonuclear production of $\Upsilon(1S)$ in PbPb collisions at LHC ($\sqrt{s} = 2.76$ TeV) for the case of Boosted Gaussian (thick curves) and Light-Cone Gaussian (thin curves) wavefunctions and several models for the dipole cross section (see text).
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