J/Ψ production in ultraperipheral Pb+Pb and p+Pb collisions at energies available at the CERN Large Hadron Collider

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We compute cross sections for incoherent and coherent diffractive J/Ψ production in ultraperipheral nucleus-nucleus and proton-nucleus collisions using two different dipole models fitted to HERA data. We obtain a reasonably good description of the available ALICE data for coherent J/Ψ production and present our prediction for the incoherent cross section. We also find that while the normalization of the cross section depends quite strongly on the dipole model and vector meson wave function used, the rapidity dependence is very well constrained.

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I. INTRODUCTION

The color glass condensate (CGC) provides a convenient way to describe strongly interacting systems in the high energy limit, where nonlinear phenomena, such as gluon recombination, become important. Because the gluon density scales as \( A^{1/3} \), these nonlinearities are enhanced when the target is changed from a proton to a heavy nucleus.

The structure of a hadron can be studied accurately in deep inelastic scattering (DIS) where a (virtual) photon scatters off the target nucleus. The dipole model is valid when \( x < x_0 \), where \( x \) is the usual Bjorken variable of DIS in a diffractive event. The dipole amplitude \( N(r_T, b_T, x) \) satisfies the BK [11] evolution equation, and ideally one would want to fit the initial condition of the BK evolution to the available DIS data (as done in Ref. [1]), solve the BK equation and use the obtained dipole amplitude when computing other observables, such as diffractive vector meson production.

However, computing diffractive events requires knowledge about the impact parameter dependence of the dipole amplitude. Straightforwardly including impact parameter dependence into the BK equation leads to an

\[
d\sigma_{\text{dif}}^p(b_T, r_T, x_P) = 2N(r_T, b_T, x_P),
\]

where \( N \) is the imaginary part of the forward dipole-proton scattering amplitude, \( r_T \) is the transverse size of the dipole, \( b_T \) is the impact parameter of the \( \gamma-p \) collision and \( x_P \) is the usual Bjorken variable of DIS in a diffractive event. The dipole amplitude \( N \) satisfies the BK [11] evolution equation, and ideally one would want to fit the initial condition of the BK evolution to the available DIS data (as done in Ref. [1]), solve the BK equation and use the obtained dipole amplitude when computing other observables, such as diffractive vector meson production.
unphysical growth of the size of the proton with the evolution [12] unless this is regulated by hand at the confinement scale [13, 14]. Because of this complication we use in this work two phenomenological dipole cross section parametrizations that include a realistic impact parameter dependence. One is the IIM [15] dipole cross section which is a parametrization including the most important features of BK evolution. The detailed expression for the dipole cross section can be found in Ref. [15]; we use here the values of the parameters from the newer fit to HERA data including charm from Ref. [16]. The second parametrization used here is a factorized approximation of the IPSat model with an eikonalized DGLAP-evolved gluon distribution [17, 18].

In the IIM model the impact parameter dependence is explicitly factorized as

$$\frac{d\sigma_{\text{dip}}^p}{d^2b_T}(b_T, r_T, x) = 2T_p(b_T)N(r_T, x),$$  \hspace{1cm} (2)

We take, following Ref. [19], a Gaussian profile for the proton impact parameter profile function: $T_p(b_T) = \exp\left(-b_T^2/2B_p\right)$ with $B_p = 5.59 \text{ GeV}^{-2}$.

In the IPSat model the impact parameter dependence is included in the saturation scale as

$$\frac{d\sigma_{\text{dip}}^p}{d^2b_T}(b_T, r_T, x) = 2\left[1 - \exp\left(-r^2F(x, r)T_p(b_T)\right)\right],$$  \hspace{1cm} (3)

denoting $r = |r_T|$. Here $T_p(b_T)$ is the same impact parameter profile function as above, but the fitted value for the proton shape is $B_p = 4.0 \text{ GeV}^2$ (see Ref. [20] for a discussion about the different numerical value) and $F$ is proportional to the DGLAP evolved gluon distribution [21],

$$F(x, r) = \frac{1}{2\pi B_p} \frac{\pi^2}{2N_c} \alpha_s \left(\mu_0^2 + \frac{C}{r^2}\right) x g \left(x, \mu_0^2 + \frac{C}{r^2}\right),$$  \hspace{1cm} (4)

with $C$ chosen as 4 and $\mu_0^2 = 1.17 \text{ GeV}^2$ resulting from the fit [18]. Following Ref. [20] we replace Eq. (3) by the factorized approximation

$$\frac{d\sigma_{\text{dip}}^p}{d^2b_T}(b_T, r_T, x) \approx 2T_p(b_T) \left[1 - \exp\left(-r^2F(x, r)\right)\right],$$  \hspace{1cm} (5)

using the same $F(x, r)$ defined in Eq. (4). This approximation, denoted here as “fIPsat”, brings the IPSat parametrization to the form Eq. (2) with $N(r_T, x) = \left[1 - \exp\left(-r^2F(x, r)\right)\right]$. It was shown in Ref. [20] that the fIPsat parametrization also describes the HERA $J/\Psi$ data accurately.

III. DIFFRACTIVE CROSS SECTION IN ULTRAPERIPHERAL COLLISIONS

In this work we consider both coherent and incoherent diffractive vector meson production. In a coherent process the nucleus off which the photon scatters remains intact, whereas in incoherent diffraction the nucleus is allowed to break up. The event is still diffractive (there is a rapidity gap) as long as there is no exchange of color charge.

The cross section for quasielastic (coherent+incoherent) vector meson production in nuclear DIS is (see, e.g., [18])

$$\frac{d\sigma_{\gamma^* A \rightarrow VA}}{dt} = \frac{R_g^2(1 + \beta^2)}{16\pi} \langle |\mathcal{A}(x_F, Q^2, \Delta T)|^2 \rangle_N,$$  \hspace{1cm} (6)

where $-Q^2$ is the virtuality of the photon. The coherent cross section is obtained by averaging the amplitude before squaring it, $|\langle \mathcal{A} \rangle_N|^2$, and the incoherent one is given by the variance $\langle |\mathcal{A}|^4 \rangle_N - |\langle \mathcal{A} \rangle_N|^2$, (see Refs. [20, 22]) where

$$\langle \mathcal{O}(|b_T|) \rangle_N = \int \prod_{i=1}^A \left[ d^2b_T, T_A(b_T_i) \right] \mathcal{O}(|b_T_i|)$$  \hspace{1cm} (7)

is the average over the positions of the nucleons in the nucleus. Here $T_A$ is the Woods-Saxon distribution with nuclear radius $R_A = (1.12A^{1/3} - 0.86A^{-1/3})$ fm and surface thickness $d = 0.54$ fm.

The factor $1 + \beta^2$ accounts for the real part of the scattering amplitude and the factor $R_g^2$ corrects for the skewedness effect, i.e. that the gluons in the target are probed at slightly different $x_F$ [23]. For these corrections we follow the prescription of Ref. [24], taking them as

$$\beta = \tan \frac{\pi \lambda}{2}$$  \hspace{1cm} (8)

$$R_g = \frac{2^{2\lambda+3} \Gamma(\lambda + 5/2)}{\sqrt{\pi} \Gamma(\lambda + 4)}$$ \hspace{1cm} (9)

$$\lambda = \frac{\partial \ln \mathcal{A}}{\partial \ln 1/x_F}.$$  \hspace{1cm} (10)

We calculate, as in Ref. [20], the correction terms from the energy dependence of the nucleon scattering amplitudes and use the same values for the nucleus at the same $Q^2, x_F$. The real part and skewedness corrections, especially $R_g$, are a significant factor in the absolute normalization of the cross section and are necessary for an agreement with HERA data.

The imaginary part of the scattering amplitude, $\mathcal{A}$, is the Fourier-transform of the dipole-target cross section $\sigma_{\text{dip}}$ from impact parameter $b_T$ to momentum transfer $\Delta T$, contracted with the overlap between the vector meson and virtual photon wave functions:

$$\mathcal{A}(x_F, Q^2, \Delta T) = \int d^2r_T d\frac{dz}{4\pi} \int d^2b_T \times [\Psi_T^+(r, Q^2, z)e^{-ib_T\cdot \Delta T} \frac{d\sigma_{\text{dip}}^p}{d^2b_T}(b_T, r_T, x_F)],$$  \hspace{1cm} (11)

where we have followed the normalization convention of Ref. [18]. For the virtual photon–vector meson wavefunction overlap we use the “boosted Gaussian” and “gau-LC” parametrizations from Ref. [18].
Assuming a large and smooth nucleus the averaged amplitude required to compute coherent $J/\Psi$ production reads [17]

$$
\langle \mathcal{A}(x_P,Q^2,\Delta_T) \rangle_N = \int_0^{\Delta_T} \frac{dz}{4\pi} d^2 \mathbf{r}_T d^2 \mathbf{b}_T e^{-\mathbf{b}_T \cdot \Delta_T} \times [\Psi^*_T \Psi^*(r,Q^2,z) 2V(r,Q^2,z) (1 - \exp \{- 2\pi B_p A T A (b) \mathcal{N}(r,x_P)\}] .
$$

(12)

At large $-t = \Delta_T^2$ the cross section is almost purely incoherent. Thus the incoherent cross section can at large $|t|$ be computed as the total quasielastic cross section, by first squaring and then averaging the amplitude. The result is derived, e.g., in Ref. [20] and reads

$$
\left\langle |A_{qq}|^2 \right\rangle_\Delta T = 16\pi B_P A \int d^2 \mathbf{b}_T \times \int d^2 \mathbf{r}_T d^2 \mathbf{r}_T' \frac{dz}{4\pi} \frac{dz'}{4\pi} \left[\Psi^*_T \Psi^*(r,Q^2,z) [\Psi^*_T \Psi^*(r',Q^2,z') x e^{-B_p \Delta_T^2} e^{-2\pi B_p A T A (b) [\mathcal{N}(r') + N(r')]} \times \left( \frac{\pi B_p N(r) N(r') T_A(b)}{1 - 2\pi B_p T_A(b) [N(r) + N(r')]} \right) .
$$

(13)

Following Ref. [25] we factorize the diffractive vector meson production cross section in nucleus-nucleus (or proton-nucleus) collisions to the product of the equivalent photon flux generated by one of the nuclei and the photon-nucleus cross section:

$$
\sigma^{AA \rightarrow J/\Psi A} = \int d\omega \frac{n(\omega)}{\omega} \sigma^{\gamma A \rightarrow J/\Psi A}(\omega).
$$

(14)

Here $\sigma^{\gamma A \rightarrow J/\Psi A}$ is the diffractive photon-nucleus cross section, $\omega = (M_V/2)e^y$ is the energy of the photon in the collider frame and $M_V$ and $y$ are the vector meson mass and rapidity. The explicit expression for the photon flux $n(\omega)$ (integrated over the impact parameter of the AA-collision $b_{AA} > 2R_A$) can be found in Ref. [25]. In nucleus-nucleus collisions both nuclei can act as a source of photons that scatter off the other nucleus:

$$
\frac{d\sigma^{A_1 A_2 \rightarrow J/\Psi A}}{dy} = n^{A_2}(y) \sigma^{\gamma A_1}(y) + n^{A_1}(-y) \sigma^{\gamma A_2}(-y).
$$

(15)

In proton-nucleus collisions the photon flux generated by a nucleus is computed requiring that the impact parameter is larger than $R_A$. The proton can also act as a photon source, and the photon flux generated by a proton is computed as in Ref. [25]. As the photon flux is proportional to the charge squared, the process where the photon is emitted from the nucleus dominates.

The kinematics of diffractive vector meson production is such that the gluon $x_P$ probed by the real photon is $x_P = M_V e^{-y}/\sqrt{s_{NN}}$. At forward and backward rapidities we have two different contributions: either a small-x photon scatters off a large-x gluon or vice versa. At midrapidity we only probe small-x structure of the nucleus. Our results should be most reliable in that region. At the LHC $\sqrt{s_{NN}} = 2.76$ TeV, and for $J/\Psi$ production $x_P \approx 0.001$ at $y = 0$. 

![Graph 1: The coherent diffractive $J/\Psi$ photoproduction cross section in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV computed using fIPsat and IIM parametrizations and Boosted Gaussian (thin blue lines) and Gaus-LC (thick black lines) wavefunctions compared with the ALICE data [10, 26].](image1)

![Graph 2: The incoherent diffractive $J/\Psi$ photoproduction cross section in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV computed using fIPsat and IIM parametrizations and Boosted Gaussian (thin blue lines) and Gaus-LC (thick black lines) wavefunctions.](image2)
FIG. 3: The coherent (thick lines) and incoherent (thin lines) diffractive $J/\Psi$ photoproduction cross section in lead-lead collision at $\sqrt{s_{NN}} = 2.76$ TeV as a function of momentum transfer $t$ at midrapidity $y = 0$ using the Gaus-LC wave function.

FIG. 4: The diffractive $J/\Psi$ photoproduction cross section in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV computed using fIPsat and IIM parametrizations and boosted Gaussian (thin blue lines) and Gaus-LC (thick black lines) wave functions. The proton is moving in the negative $y$ direction.

IV. RESULTS AND DISCUSSION

The ALICE Collaboration has measured the coherent $J/\Psi$ photoproduction cross section $d\sigma/dy$ at a relatively large rapidity $|y| \sim 3$ [10]. Recently preliminary results at midrapidity $y = 0$ were also published [26]. The comparison between our results and the ALICE data is shown in Fig. 1. The PHENIX Collaboration has also measured the ultraperipheral $J/\Psi$ cross section in gold-gold collisions at $\sqrt{s_{NN}} = 200$ GeV and $y = 0$. For these kinematics the fIPsat dipole cross section with the gaus-LC wavefunction gives the result $10.9 \mu b$, compared to $76 \pm 34 \mu b$ measured by PHENIX [27]. The ALICE data seems to favor the fIPsat over the IIM model. This is perhaps not surprising. The most important difference between the two dipole models for this purpose is the different impact parameter dependence. The IIM value $B_p = 5.59$ GeV$^{-2}$ comes from a fit to inclusive data and is close to the measured value for inclusive diffraction. The HERA data for diffractive $J/\Psi$ production [28, 29] has, however, a smaller $B_p$, which is reflected in the IPsat parametrization. Thus we consider results obtained using the fIPsat model more reliable.

Our results slightly overshoot the data, but the rapidity dependence comes out correctly. For example the fIPsat model with Gaus-LC wavefunction is above all data points by a factor $\sim 1.4$. We consider the agreement relatively good given the simplicity of the parametrizations and the fact that no nuclear data was used to constrain the models. We emphasize that the parametrizations used are exactly the same as in Ref. [20], which predates the ALICE data. Recall that both dipole models and wavefunctions used here give good descriptions of the HERA data. We suspect that the main reason for the larger normalization lies in the skewedness correction. The correction is larger here than for HERA kinematics because of the larger $x$ probed, making it less reliable.

The difference between the two wavefunctions is largest at $Q^2 = 0$ which is the case here. The ALICE data seems to favor the Gaus-LC wavefunction, and thus we consider the fIPsat dipole model and the Gaus-LC
wavefunction to be the most reliable combination. At $|y| \geq 2$, $\sqrt{s_{NN}} = 2.76$ TeV, we are probing gluons with $x_F \lesssim 0.01$, and in that region our parametrizations for the dipole amplitude are not valid any more. In addition, the real part and skewness corrections in total become of the order 2, making them less reliable. Nevertheless, all wavefunctions and dipole models consistently give $\sigma/dy|_{y=0}/\sigma/dy|_{y=2} = 1.41–1.46$. Thus the prediction for the rapidity dependence is much more robust than for the absolute normalization.

We then present our predictions for the incoherent diffractive vector meson cross section in Fig. 2. Again the different models give a quite different overall normalization, but a very similar rapidity dependence. Notice that now the absolute normalization is larger in the fIPsat model. This is due to the different different impact parameter profiles, we refer the reader to Ref. [20] for a more detailed discussion. Again most of the difference cancels in the ratio $\sigma/dy|_{y=0}/\sigma/dy|_{y=2}$ which is now $1.35–1.43$, so the energy dependence is very similar in coherent and incoherent scattering.

Our result for the incoherent vector meson production from Ref. [20] is not valid at small $|t|$. However, we expect to get a realistic estimate for the total incoherent cross section by integrating the differential cross section starting from the value of $|t|$ where incoherent and coherent cross sections are equal. The error made is small, parametrically a factor $\sim e^{-|t_{min}|B_F}$ with $|t_{min}| \sim 1/R_A^2$ and numerically $\lesssim 10\%$.

In Fig. 3 we present predictions for the $t$ distribution of diffractive $J/\Psi$ photoproduction at midrapidity where $x_F \approx 0.001$. Note that the $t$ slope of the incoherent cross section directly measures the spatial distribution of gluons inside a nucleon, because the $t$-dependence of the incoherent cross section is $\sim \exp(B_F t)$ [20].

Our pA results are shown in Figs. 4 and 5. In Fig. 4 we show the rapidity dependence of the diffractive $J/\Psi$ cross section (the photon-nucleus scattering is required to be coherent). Now the difference between the models is reduced as the dominant process is photon-proton scattering where the models are constrained by HERA data. Finally, in Fig. 5 we compute the incoherent $J/\Psi$ photoproduction cross section in $AA$ collisions divided by $A$ times the diffractive $J/\Psi$ production cross section in pA collisions at the same $\sqrt{s_{NN}}$. Since ultraperipheral proton-nucleus collisions are mostly photon-proton collisions, this is a “nuclear transparency” ratio that measures the absorption of the dipole as it propagates through the nucleus, see, e.g., [20, 30].

V. CONCLUSIONS

We have computed coherent and incoherent diffractive $J/\Psi$ photoproduction cross sections in ultraperipheral heavy ion collisions. The only inputs to our calculation come from fits to HERA data and standard nuclear geometry. Especially the rapidity dependence agrees relatively well with the published ALICE result, considering the rather large dependence on the details of the dipole model and the vector meson light cone wavefunction. The normalization of the data favors the fIPsat parametrization, where the proton diffractive slope is constrained by the HERA diffractive $J/\Psi$ data. We also find that the different parametrizations, each known to fit HERA data well, yield significantly different normalizations for the cross section leaving the overall rapidity dependence very similar, with $\sigma/dy|_{y=0}/\sigma/dy|_{y=2} = 1.41–1.46$ for the coherent and $\sigma/dy|_{y=0}/\sigma/dy|_{y=2} = 1.35–1.43$ for the incoherent scattering. A similar conclusion was found in Ref. [20] for photon-nucleus scattering. We also present predictions for diffractive $J/\Psi$ production in pA collisions.

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