DIPOLE APPROACH TO EXCLUSIVE J/ψ PHOTOPRODUCTION AND THE PUTATIVE GLUON SHADOWING*

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We discuss the role of $c\bar{c}g$-Fock states in the diffractive photoproduction of J/ψ-mesons as probed in ultraperipheral nuclear collisions. We build on our earlier description of the process in the color–dipole approach, where we took into account the rescattering of $c\bar{c}$ pairs using a Glauber–Gribov form of the dipole–nucleus amplitude. We compare the results of our calculations to recent data on the photoproduction of J/ψ by the ALICE, CMS, and LHCb collaborations. We also comment on the possible relation to gluon shadowing and compare to data on the ratio $R_g = \sqrt{\sigma(\gamma A \to J/\psi A)/\sigma_{\rm IA}}$, where $\sigma_{\rm IA}$ is the result in impulse approximation.

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1. Color–dipole approach to vector-meson photoproduction

The exclusive diffractive photoproduction of J/ψ in ultraperiphaeral heavy-ion collisions (UPCs) has recently been measured by the LHC experiments [1–5]. These data provide information on the interaction of small color dipoles with nuclei.

We start the discussion of our work [6, 7] with the well-known expression of the forward photoproduction amplitude in terms of color–dipole amplitude/cross section

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$$\mathrm{Im}\, m\mathcal{A}(\gamma A \to VA; W, \boldsymbol{q}=0) = \int_0^1 \mathrm{d}z \int \mathrm{d}^2\boldsymbol{r}\, \Psi_V^*(z,\boldsymbol{r})\Psi_\gamma(z,\boldsymbol{r}) \times \underbrace{2\int \mathrm{d}^2\boldsymbol{b}\, \Gamma_A(x,\boldsymbol{b},\boldsymbol{r})}_{\sigma(x,\boldsymbol{r})} . \tag{1}$$

Here, $x = M_V^2/W^2$, where W is the γp-cms energy. Ψ_γ, Ψ_V stand for the light-front wave functions (LFWFs) of the (virtual) photon and J/ψ meson, respectively. Now, the small-r behaviour of the dipole cross section

$$\sigma(x,\boldsymbol{r}) = \frac{\pi^2}{N_c}\alpha_\mathrm{s}\left(\mu^2\right) r^2\, xg\left(x,\mu^2\right) , \qquad \mu^2 = \frac{A}{r^2} + \mu_0^2 \tag{2}$$

leads to the proportionality of the diffractive cross section to the square of the target's gluon density

$$\sigma(\gamma p \to J\psi p) = \frac{1}{16\pi B}\Big|\mathrm{Im}\, A(W,\boldsymbol{q}=0)\Big|^2 \propto \sigma^2(x,r_s) \propto \left[xg\left(x,\mu^2\right)\right]^2 .$$

This motivates the study of photoproduction on nuclei as a probe of the nuclear glue. Notice that for $c\bar{c}$ bound states, the overlap of wave functions enforces an effective dipole size $r_\mathrm{eff} \sim 1/m_c$, which translates to a rather lowish "hard scale" of $\mu^2 \sim M_{J/\psi}^2/4$. Here, the expectation is that the glue in a bound nucleon is subject to a suppression due to shadowing corrections. Let us briefly discuss how shadowing of nuclear partons is generated in the color–dipole approach [8]. On a deuteron, which is a weakly bound state of proton and neutron, the shadowing correction $\delta\sigma$ to the virtual photoabsorption cross section is defined by the relation

$$\sigma_{\gamma^* D} = \sigma_{\gamma^* p} + \sigma_{\gamma^* n} - \delta\sigma .$$

It can be calculated from Gribov's formula for the inelastic shadowing correction [9]

$$\delta\sigma = \int \mathrm{d}M_X^2 \frac{\mathrm{d}\sigma(\gamma^* p \to Xp)}{\mathrm{d}t\,\mathrm{d}M_X^2}\Big|_{t=0} \cdot \underbrace{\mathcal{F}_D\left(4q_z^2\right)}_{\text{Deuteron form factor}} , \quad q_z = \frac{Q^2+M_X^2}{2E_\gamma} . \tag{3}$$

It is, therefore, directly related to the cross section for diffractive dissociation of a virtual photon on a free nucleon. In general, we distinguish "low mass" diffraction with $M_X^2 \sim Q^2$ from the triple Pomeron regime of large diffractive masses $M_X^2 \gg Q^2$, where we expect

$$\frac{\mathrm{d}\sigma\left(\gamma^* p \to Xp\right)}{\mathrm{d}t\,\mathrm{d}M_X^2}\Big|_{t=0} = \frac{G_{3\mathbb{P}}}{M_X^2} , \tag{4}$$

with $G_{3\mathbb{P}}$ being the triple-Pomeron coupling. The former, low-mass diffraction in the dipole approach, is described by diffractive dissociation $\gamma^* p \to q\bar{q}p$

$$\frac{\mathrm{d}\sigma\left(\gamma^* p \to q\bar{q}p\right)}{\mathrm{d}t\,\mathrm{d}M_X^2}\Big|_{t=0} = \frac{1}{16\pi}\int\limits_0^1 \mathrm{d}z\,\mathrm{d}^2\boldsymbol{r}\,\left|\Psi_{\gamma^*}(z,\boldsymbol{r})\right|^2 \sigma^2(x,\boldsymbol{r})\,, \tag{5}$$

while the triple-Pomeron regime is governed by the diffractive excitation of $q\bar{q}g$-states, $\gamma^* p \to q\bar{q}gp$. Phenomenologically, diffractive structure functions at HERA can be described with $q\bar{q}, q\bar{q}g$ excitation (see *e.g.* [10, 11]). We therefore restrict ourselves to these two contributions. The above direct unitarity relation between nuclear shadowing and diffractive final states applies only to the double scattering contribution. Regarding the $q\bar{q}$ contribution, the Glauber–Gribov ansatz

$$\Gamma(x,\boldsymbol{b},\boldsymbol{r}) = 1 - \exp\left[-\tfrac{1}{2}\sigma(x,\boldsymbol{r})T_A(\boldsymbol{b})\right] \tag{6}$$

sums up all multiple scatterings of the $q\bar{q}$ color dipole. One would readily recognize in the second-order term $\propto \sigma^2(x,\boldsymbol{r})T_A^2(\boldsymbol{b})$ the shadowing correction due to $q\bar{q}$ diffractive excitation. Furthermore, the large opacity of a heavy nucleus gives rise to the saturation scale

$$Q_A^2(x,\boldsymbol{b}) = \frac{4\pi^2}{N_c}\alpha_\mathrm{s}\left(Q_A^2\right)xg\left(x,Q_A^2\right)T_A(\boldsymbol{b})\,. \tag{7}$$

Therefore, $r_A = 2\sqrt{2}/Q_A$ separates hard processes with $r_\mathrm{eff} \ll r_A$, for which the leading twist pQCD factorization works from processes in the strongly absorptive saturation regime $r_\mathrm{eff} \lesssim r_A$.

At very high energies/small-x ($x \ll x_A \sim 0.01$), we need to take into account also the contribution of the $q\bar{q}g$-Fock state and possibly higher $q\bar{q}g_1g_2\ldots g_n$ states. Their summation gives rise to the color dipole form of BFKL. The dipole cross section for the $q\bar{q}g$ state on the nucleon is [12]

$$\sigma_{q\bar{q}g}(x,\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\boldsymbol{r}) = \frac{C_A}{2C_F}\left(\sigma(x,\boldsymbol{\rho}_1)+\sigma(x,\boldsymbol{\rho}_2)-\sigma(x,\boldsymbol{r})\right)+\sigma(x,\boldsymbol{r})\,. \tag{8}$$

Using this form of the $q\bar{q}g$ cross section in the large-N_c limit, where $C_A/2C_F \to 1$ one can obtain that

$$\Gamma_A(x,\boldsymbol{r},\boldsymbol{b}) = \Gamma_A(x_A,\boldsymbol{r},\boldsymbol{b}) + \log\left(\frac{x_A}{x}\right)\Delta\Gamma(x_A,\boldsymbol{r},\boldsymbol{b})\,, \tag{9}$$

with

$$\Delta\Gamma(x_A, \boldsymbol{r}, \boldsymbol{b}) = \int d^2\boldsymbol{\rho}_1 |\psi(\boldsymbol{\rho}_1) - \psi(\boldsymbol{\rho}_2)|^2 \Big\{ \Gamma_A\left(x_A, \boldsymbol{\rho}_1, \boldsymbol{b} + \frac{\boldsymbol{\rho}_2}{2}\right) + \Gamma_A\left(x_A, \boldsymbol{\rho}_2, \boldsymbol{b} + \frac{\boldsymbol{\rho}_1}{2}\right) - \Gamma_A(x_A, \boldsymbol{r}, \boldsymbol{b}) - \Gamma_A\left(x_A, \boldsymbol{\rho}_1, \boldsymbol{b} + \frac{\boldsymbol{\rho}_2}{2}\right)\Gamma_A\left(x_A, \boldsymbol{\rho}_2, \boldsymbol{b} + \frac{\boldsymbol{\rho}_1}{2}\right)\Big\} . \quad (10)$$

Here, we employ a infrared regularization for large dipoles

$$\psi(\boldsymbol{\rho}) = \frac{\sqrt{C_F \alpha_s(\min(\rho, r))}}{\pi} \frac{\boldsymbol{\rho}}{\rho R_c} K_1\left(\frac{\rho}{R_c}\right), \quad \text{with} \quad R_c \sim 0.2 \div 0.3 \text{ fm} \quad (11)$$

together with the freezing of $\alpha_s(r)$ for $r > R_c$. One would recognize in Eq. (10), up to our treatment of large dipoles, one iteration of the Balitsky–Kovchegov equation, including its *nonlinear term*.

1.1. Results and summary

In Fig. 1, we show the total cross section $\sigma(\gamma A \to J/\psi A)$ for the ^{208}Pb nucleus as a function of γA-cm energy W. The impulse approximation shown by the dotted line fails dramatically, illustrating the scale of nuclear effects. A large part of the nuclear suppression can be explained by the Glauber–Gribov rescattering of the $c\bar{c}$ state alone. The calculations including the effect of the $c\bar{c}g$ state show an additional suppression of the nuclear cross section, as required by experimental data. In these calculations, we used a Golec–Biernat–Wüsthoff dipole cross section. For the $c\bar{c}g$ state, we used the nonperturbative parameter $R_c = 0.28$ fm. For more details, please refer

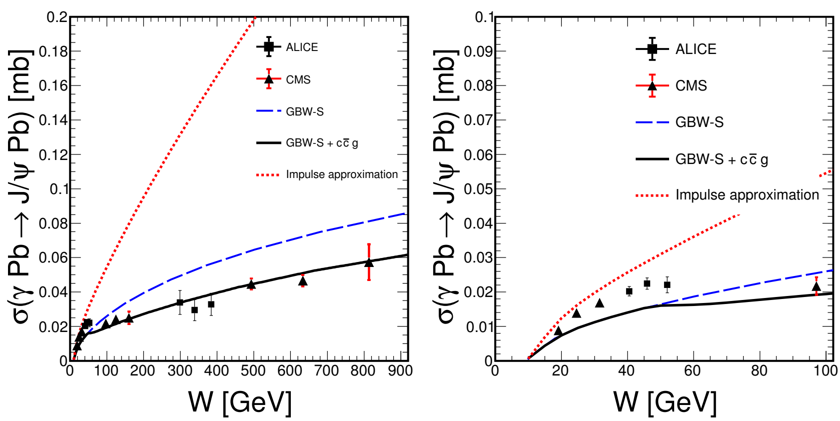

Fig. 1. Plot of the diffractive photoproduction cross section $\sigma(\gamma\text{Pb} \to J/\psi\text{Pb})$. The right panel shows a zoom on a region of lower energies.

to Refs. [6, 7]. Next, in Fig. 2, we show

$$R_g(x) = \sqrt{\frac{\sigma\left(\gamma\mathrm{Pb} \to J/\psi\mathrm{Pb}\right)}{\sigma_{\mathrm{IA}}\left(\gamma\mathrm{Pb} \to J/\psi\mathrm{Pb}\right)}} \text{``}=\text{''} \frac{g_A\left(x, m_c^2\right)}{A g_N\left(x, m_c^2\right)} \,. \tag{12}$$

Here, for the impulse approximation σ_{IA} baseline, we use a parametrization of Ref. [13]. As we indicated, $R_g(x)$ is supposed to quantify the suppression (shadowing) of the per-nucleon glue in the nucleus at small-x.

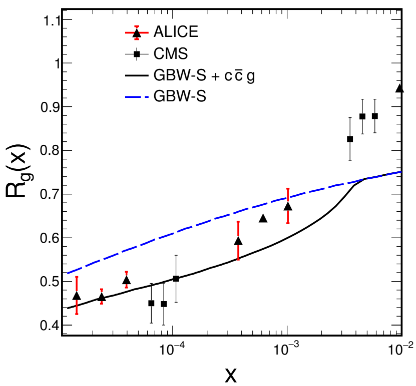

Fig. 2. Plot of the putative gluon shadowing ratio as a function of x.

We also have applied our results to the rapidity-dependent cross section of exclusive J/ψ production in heavy-ion (lead–lead) collisions at the energies $\sqrt{s_{NN}} = 2.76$ GeV and $\sqrt{s_{NN}} = 5.02$ GeV, which we show in Fig. 3 — overall the description of data can be regarded satisfactory. The Glauber–Gribov approach including only rescattering of the $c\bar{c}$ dipole works reasonably well in the forward region (large rapidities) although one observes an overprediction of nuclear suppression. In the central rapidity region, the inclusion of the $c\bar{c}g$ state introduces additional shadowing which is needed to describe the data.

The coherently scattering gluon can be viewed as a gluon shared by all nucleons. Therefore, shadowing due to the $c\bar{c}g$ state can be (roughly) identified with gluon shadowing of the nuclear PDF. It will be very interesting to investigate virtual photoproduction at electron–ion colliders where we will have a large Q^2 and studies of the Q^2 evolution of the gluon shadowing are possible.

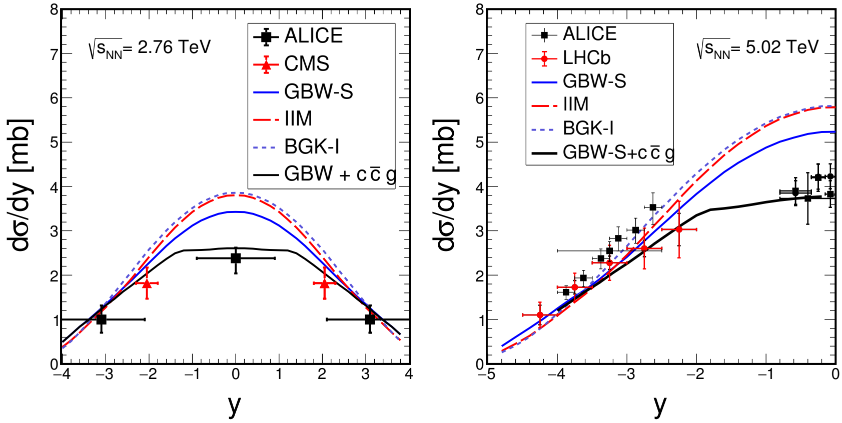

Fig. 3. Plot of the rapidity-dependent cross section for exclusive J/ψ production in Pb–Pb UPC.

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