Dipole approach to exclusive J/ψ photoproduction and the putative gluon shadowing

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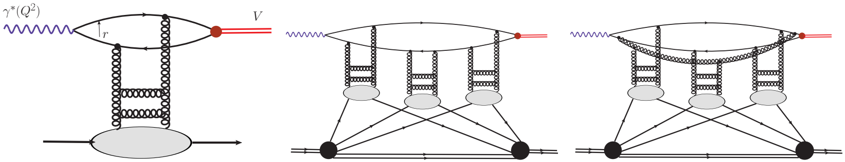
Introduction

- We discuss the role of $c\bar{c}g$-Fock states in the diffractive photoproduction of J/ψ-mesons. 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.
- The color dipole approach to coherent photoproduction on the nucleus, is a variant of Glauber-Gribov multiple scattering theory. It sums up multiple scatterings of a color-dipole within the nucleus, as on a typical diagram:



- We test a number of dipole cross sections fitted to inclusive F_2-data against the total cross section of exclusive J/ψ-production on the free nucleon and calculate the diffractive amplitude on the nuclear target.
- We compare our results to recent data on exclusive J/ψ production in ultraperipheral lead-lead collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ and $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$.

- In the dipole approach the imaginary part of the diffractive production amplitude in the forward direction $\boldsymbol{q}=0$ takes the form (Nikolaev, Kopeliovich, Zakharov):

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

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 the virtual photon and J/ψ meson respectively.

- The small-r dehaviour of the dipole cross section

$$\sigma(x,\boldsymbol{r}) = \frac{\pi^2}{N_c}\alpha_s(\mu^2) r^2\, xg(x,\mu^2), \quad \mu^2 = \frac{A}{r^2} + \mu_0^2 .$$

leads to the proportionality of the cross section to the **square of the gluon density** (Ryskin's formula):

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

- This motivates the study of photoproduction on **nuclei** as a probe of the **nuclear glue**. The "hard scale" is expected to be $\mu^2 \sim M_{J/\psi}^2/4$.

Predictions for J/ψ production on the proton target

- For the GBW and IIM dipole cross sections, we calculate the total cross section from:

$$\sigma(\gamma p \to J/\psi p; W) = \frac{1+\rho_N^2}{16\pi B}\, R^2_{\rm skewed}\, |\langle V|\sigma(x,r)|\gamma\rangle|^2$$

- The diffraction slope: $B = B_0 + 4\alpha' \log(W/W_0)$, with $B_0 = 4.88\,\mathrm{GeV}^{-2}$, $\alpha' = 0.164\,\mathrm{GeV}^{-2}$, and $W_0 = 90\,\mathrm{GeV}$.
- For the BGK type of parametrizations, it proves to be more stable numerically to substitute the "skewed glue" in the exponent:

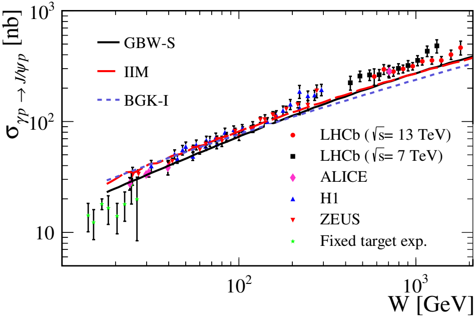
$$\sigma(x,r) = \sigma_0 \left(1 - \exp\left[-\frac{\pi^2 r^2 \alpha_s(\mu^2) R_{\rm skewed}\, xg(x,\mu^2)}{3\sigma_0}\right]\right),$$

- For gluons exchanged in the amplitude carry different longitudinal momenta, at small $x = M_V^2/W^2$ we have typically, say $x_1 \sim x, x_2 \ll x_1$. In such a situation, the corresponding correction which multiplies the amplitude is Shuvaev's factor:

$$R_{\rm skewed} = \frac{2^{2\Delta_{\mathbf{P}}+3}}{\sqrt{\pi}} \cdot \frac{\Gamma(\Delta_{\mathbf{P}}+5/2)}{\Gamma(\Delta_{\mathbf{P}}+4)}$$

Predictions for J/ψ production on the proton target

A.Łuszczak, W. S., Phys. Rev. C **99***, no.4, 044905 (2019)*



- Total cross section for the exclusive photoproduction $\gamma p \to J/\psi p$ as a function of γp-cms energy W
- We observe that the range of $30 \lesssim W \lesssim 300\text{GeV}$ is reasonably well described by all dipole cross sections.

Formalism: Nuclear target

- For the nuclear targets color dipoles can be regarded as **eigenstates of the interaction** in the sense of Good–Walker or Miettinen–Pumplin, and we can apply the standard rules of Glauber theory.
- The Glauber form of the dipole scattering amplitude for $l_c \gg R_A$ (the coherence length is much larger than the nuclear size) is:

$$\Gamma_A(x, \boldsymbol{b}, \boldsymbol{r}) = 1 - \exp[-\tfrac{1}{2}\sigma(x, r) T_A(\boldsymbol{b})]$$

- The dipole amplitude corresponds to a rescattering of the dipole in a purely absorptive medium. The real part of the dipole-nucleon amplitude is often neglected. It induces the refractive effects and instead of first eq. we should take:

$$\Gamma_A(x, \boldsymbol{b}, \boldsymbol{r}) \quad = \quad 1 - \exp[-\tfrac{1}{2}\sigma(x, r)(1 - i\rho_N) T_A(\boldsymbol{b})]$$

- The optical thickness $T_A(\boldsymbol{b})$ is calculated from a Wood-Saxon distribution $n_A(\vec{r})$:

$$T_A(\boldsymbol{b}) = \int_{-\infty}^{\infty} dz\, n_A(\vec{r})\,;\ \vec{r} = (\boldsymbol{b}, z),\ \int d^2\boldsymbol{b}\, T_A(\boldsymbol{b}) = A$$

- The diffractive amplitude in $\boldsymbol{b}$-space is:

$$\mathcal{A}(\gamma A \to VA; W, \boldsymbol{b}) \quad = \quad 2i\, \langle V | \Gamma_A(x, \boldsymbol{b}, \boldsymbol{r}) | \gamma \rangle\, \mathcal{F}_A(q_z)$$

- The nuclear form factor $\mathcal{F}_A(q) = \exp[-R^2_{\rm ch} q^2/6]$ depends on the finite longitudinal momentum transfer $q_z = x m_N$. It "switches off" the diffractive production if the coherence length becomes too small.

- The total cross section for the $\gamma A \to VA$ reaction is obtained as:

$$\sigma(\gamma A \to VA; W) = \frac{1}{4} \int d^2\boldsymbol{b} \left| \mathcal{A}(\gamma A \to VA; W, \boldsymbol{b}) \right|^2$$

Saturation scale

- The overlap of LFWFs of photon and J/ψ leads to the dominance of dipole sizes around the "scanning radius" $r_s \sim 0.1\mathrm{fm}$. (Kopeliovich, Nikolaev, Zakharov)
- The large opacity of a heavy nucleus introduces the **saturation scale**:

$$Q_A^2(x, \boldsymbol{b}) = \frac{4\pi^2}{N_c} \alpha_s(Q_A^2) x g(x, Q_A^2) T_A(\boldsymbol{b}),$$

in terms of which the dipole-nucleus S-matrix takes the form (Mueller):

$$S_A(x, \boldsymbol{r}, \boldsymbol{b}) = 1 - \Gamma_A(x, \boldsymbol{r}, \boldsymbol{b}) = \exp\left[-\frac{1}{8} Q_A^2(x, \boldsymbol{b}) r^2 \right].$$

- Therefore the scale

$$r_A = \frac{2\sqrt{2}}{Q_A},$$

separates standard **hard processes** with $r_s \ll r_A$, for which the leading twist pQCD factorization works, from processes in the strongly absorptive saturation regime $r_s \gtrsim r_A$.

- We estimated $\langle Q_A^2(\boldsymbol{b}) \rangle \sim 0.9\,\mathrm{GeV}^2$ for $A^{1/3} = 6$ and $x \sim 0.01$. Compare this to the hard scale $Q^2 = M_{J/\psi}^2/4 \sim 2.25\,\mathrm{GeV}^2$. For diffractive J/ψ photoproduction on lead we are therefore in a regime ,where we may regard the rescatterings included in the Glauber-Gribov form as a summation of higher-twist corrections, r_s^2/r_A^2.

Nuclear shadowing and diffraction in the dipole picture Nikolaev, Zakharov 1990

- On a deuteron, where we can have at most have double scattering, nuclear shadowing can be calculated (following Gribov) from the diffractive cross section:

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

with

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

- in the dipole approach **small mass** diffraction ($M_X^2 \sim Q^2$) is described by diffractive dissociation $\gamma^* p \to q\bar{q}p$:

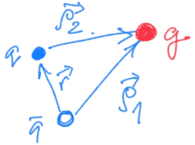
$$\frac{d\sigma(\gamma^* p \to q\bar{q}p)}{dt dM_X^2}\Big|_{t=0} = \frac{1}{16\pi} \int_0^1 dz d^2\boldsymbol{r} \, |\Psi_\gamma^*(z, \boldsymbol{r})|^2 \, \sigma^2(x, \boldsymbol{r}) \, .$$

  while **large mass** diffraction $M_X^2 \gg Q^2$ ("triple Pomeron regime")

$$\frac{d\sigma(\gamma^* p \to Xp)}{dt dM_X^2}\Big|_{t=0} = \frac{G_{3\mathbb{P}}}{M_X^2}$$

  is described by $\gamma^* p \to q\bar{q}gp$.

- Diffractive structure functions at HERA can be described with $q\bar{q}, q\bar{q}g$ excitation. (Bartels, Ellis, Kowalski, Wüsthoff (1999), Golec-Biernat, Łuszczak (2009))



- at 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 $q\bar{q}g_1 g_2 \dots g_n$ states. This gives rise to the color dipole form of BFKL.

- The dipole cross section for the $q\bar{q}g$ state on the nucleon is **Nikolaev, Zakharov, Zoller '93**

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

- integrating over dz_g/z_g spectrum of the gluon, the dipole cross section changes as

$$\sigma(x, \boldsymbol{r}) = \sigma(x_0, \boldsymbol{r}) + \log\left(\frac{x_0}{x}\right) \int d^2\boldsymbol{\rho}_1 |\psi(\boldsymbol{\rho}_1) - \psi(\boldsymbol{\rho}_2)|^2 \Big\{\sigma_{q\bar{q}g}(x_0, \boldsymbol{\rho}_1, \boldsymbol{\rho}_2, \boldsymbol{r}) - \sigma(x_0, \boldsymbol{r})\Big\}$$

- infrared "regularization" for large dipoles

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

- freezing of $\alpha_s(r)$ for $r > R_c$.

Contribution of $c\bar{c}g$ Fock-state to the nuclear amplitude

- Integrating over all variables but the dipole size $\boldsymbol{r}$, the effect of the gluon is a change of the $q\bar{q}$ dipole amplitude ($x_A \sim 0.01$):

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

$q\bar{q}g$-contribution:

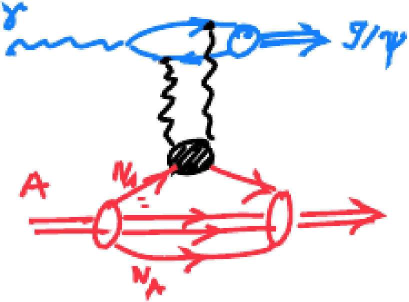
$$\begin{aligned}\Delta\Gamma(x_A, \boldsymbol{r}, \boldsymbol{b}) \quad = \quad & \int d^2\boldsymbol{\rho}_1 |\psi(\boldsymbol{\rho}_1) - \psi(\boldsymbol{\rho}_2)|^2 \Big\{\Gamma_A(x_A, \boldsymbol{\rho}_1, \boldsymbol{b} + \frac{\boldsymbol{\rho}_2}{2}) + \Gamma_A(x_A, \boldsymbol{\rho}_2, \boldsymbol{b} + \frac{\boldsymbol{\rho}_1}{2}) \\ & -\Gamma_A(x_A, \boldsymbol{r}, \boldsymbol{b}) - \Gamma_A(x_A, \boldsymbol{\rho}_1, \boldsymbol{b} + \frac{\boldsymbol{\rho}_2}{2})\Gamma_A(x_A, \boldsymbol{\rho}_2, \boldsymbol{b} + \frac{\boldsymbol{\rho}_1}{2})\Big\}\end{aligned}$$

- This is, up to our treatment of large dipoles, one iteration of the Balitsky-Kovchegov equation, including the *nonlinear term*.

$c\bar{c}g$ contribution to the diffractive amplitude

- The nuclear effect is best quantified by the ratio of the cross section including all nuclear modification effects to the impulse approximation.

$$\sigma_{IA}(\gamma A \to J/\psi A; W) = 4\pi \frac{d\sigma(\gamma p \to J/\psi p)}{dt}|_{t=0} \int d^2\boldsymbol{b} T_A^2(\boldsymbol{b})\, F^2(q_z^2)\,.$$



- We calculate the ratio

$$R_{\rm coh} = \frac{\sigma(\gamma A \to J/\psi A; W)}{\sigma_{IA}(\gamma A \to J/\psi A; W)}$$

including $c\bar{c}$ and $c\bar{c}g$ contributions, but in the IA we switch off the nonlinear piece in the $c\bar{c}g$ amplitude.

cross section:

$$\sigma(\gamma A \to J/\psi A) = R_{\rm coh}\, 4\pi B(W)\, \sigma(\gamma p \to J/\psi p) \int d^2\boldsymbol{b} T_A^2(\boldsymbol{b})\, F_A(q_z^2)\,.$$

Calculating the total cross section without and with $c\bar{c}g$ state

- the calculation without $c\bar{c}g$ states is simply the Glauber–Gribov exponential

$$\Gamma_A(x, \boldsymbol{b}, \boldsymbol{r}) = 1 - \exp[-\tfrac{1}{2}\sigma(x, r) T_A(\boldsymbol{b})]$$

- We include the $c\bar{c}g$ state by adding

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

- in **impulse approximation**, we use for the $c\bar{c}$ state

$$\Gamma_{IA}(x, \boldsymbol{b}, \boldsymbol{r}) = \tfrac{1}{2}\sigma(x, r) T_A(\boldsymbol{b})$$

  and **omit the nonlinear term** in $\Delta\Gamma_A$.
- We use the parameter $\mu_G = 0.7\,\mathrm{GeV} \Leftrightarrow \mathrm{R_c} = 0.28\,\mathrm{fm}$. The running coupling is parametrized as

$$\alpha_s(r) = \frac{4\pi}{9}\frac{1}{\log\left(\frac{C}{r^2\Lambda^2}\right)}, \quad C = 1.5, \Lambda = 0.3\,\mathrm{GeV}\,.$$

  and is **frozen for** $r \geq R_c$.
- We then add both contributions to obtain a smooth total cross section as

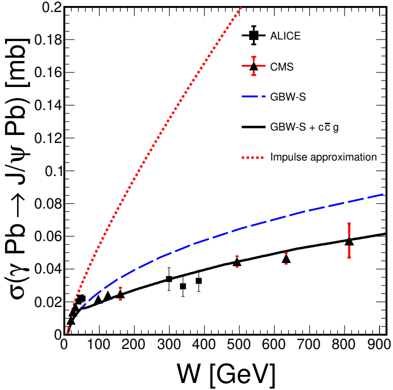
$$\sigma(\gamma A \to J/\psi A; W) = (1 - f(W))\sigma_{c\bar{c}}(\gamma A \to J/\psi A; W) + f(W)\sigma_{c\bar{c}+c\bar{c}g}(\gamma A \to J/\psi A; W)$$

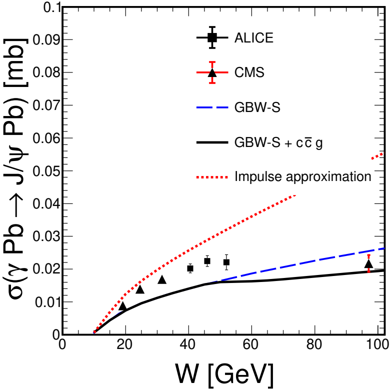
  with

$$f(W) = \tfrac{1}{2}\left\{1 + \tanh\left(\frac{W - W_0}{W_1}\right)\right\},$$

  with $W_0 = 50\,\mathrm{GeV},\ W_1 = 5\,\mathrm{GeV}.$

A.Łuszczak, W. S., Phys. Lett. B 856 138917 (2024)

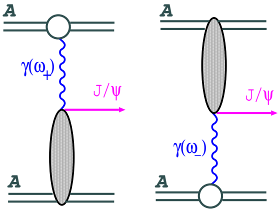




- The total cross section $\sigma(\gamma A \to J/\psi A)$ for the $^{208}\mathrm{Pb}$ nucleus as a function of γA-cm energy W.
- The impulse approximation fails dramatically, which illustrates the scale of nuclear effects. A large part of the nuclear suppression can be explained by Glauber-Gribov rescattering 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. We used the GBW dipole cross section.

Photoproduction in ultraperipheral collisions

- Exclusive photoproduction in ultraperipheral heavy-ion collisions: the left-moving ion serves as the photon source, and the right-moving one serves as the target.



- The rapidity-dependent cross section for exclusive J/ψ production from the Weizsäcker-Williams fluxes of quasi-real photons $n(\omega)$ as:

$$\frac{d\sigma(AA \to AAJ/\psi; \sqrt{s_{NN}})}{dy} = n(\omega_+)\sigma(\gamma A \to J/\psi A) + n(\omega_-)\sigma(\gamma A \to J/\psi A)$$

- We use the standard form of the Weizsäcker-Williams flux for the ion moving with boost γ:

$$n(\omega) = \frac{2Z^2\alpha_{\rm em}}{\pi}\left[\xi K_0(\xi)K_1(\xi) - \frac{\xi^2}{2}(K_1^2(\xi) - K_0^2(\xi))\right]$$

- ω is the photon energy, and $\xi = 2R_A\omega/\gamma$

Energies available for photoproduction

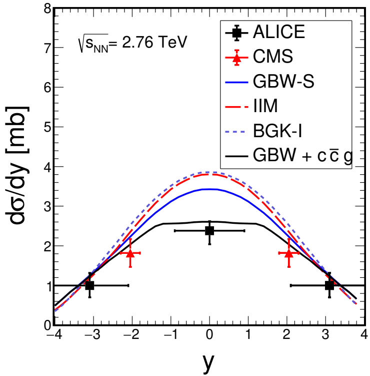
$\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$						
y	$W_+[\mathrm{GeV}]$	$W_-[\mathrm{GeV}]$	x_+	x_-	$n(\omega_+)$	$n(\omega_-)$
0.0	92.5	92.5	$1.12 \cdot 10^{-3}$	$1.12 \cdot 10^{-3}$	69.4	69.4
1.0	152	56.1	$4.13 \cdot 10^{-4}$	$3.05 \cdot 10^{-3}$	39.5	100
2.0	251	34.0	$1.52 \cdot 10^{-4}$	$8.29 \cdot 10^{-3}$	14.5	132
3.0	414	20.6	$5.59 \cdot 10^{-5}$	$2.25 \cdot 10^{-2}$	1.68	163
3.8	618	13.8	$2.51 \cdot 10^{-5}$	$5.02 \cdot 10^{-2}$	0.03	188

Table: Subenergies $W_\pm$ and Bjorken-x values $x_\pm$ for $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ for a given rapidity y. Also shown are photon fluxes $n(\omega_\pm)$.

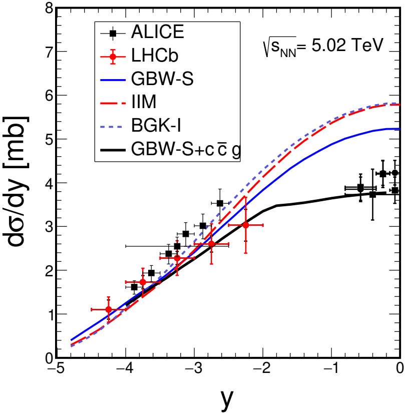
$\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$						
y	$W_+[\mathrm{GeV}]$	$W_-[\mathrm{GeV}]$	x_+	x_-	$n(\omega_+)$	$n(\omega_-)$
0.0	125	125	$6.17 \cdot 10^{-4}$	$6.17 \cdot 10^{-4}$	87.9	87.9
1.0	206	75.6	$2.27 \cdot 10^{-4}$	$1.68 \cdot 10^{-3}$	57.2	119
2.0	339	45.9	$8.35 \cdot 10^{-5}$	$4.56 \cdot 10^{-3}$	28.5	150
3.0	559	27.8	$3.07 \cdot 10^{-5}$	$1.24 \cdot 10^{-2}$	7.5	181
4.0	921	16.9	$1.13 \cdot 10^{-5}$	$3.37 \cdot 10^{-2}$	0.35	213
4.8	1370	11.3	$5.08 \cdot 10^{-6}$	$7.50 \cdot 10^{-2}$	0.001	238

Table: Subenergies $W_\pm$ and Bjorken-x values $x_\pm$ for $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$ for a given rapidity y.

A. Łuszczak, W. S., Phys. Rev. C **99***, no.4, 044905 (2019), and work in progress*

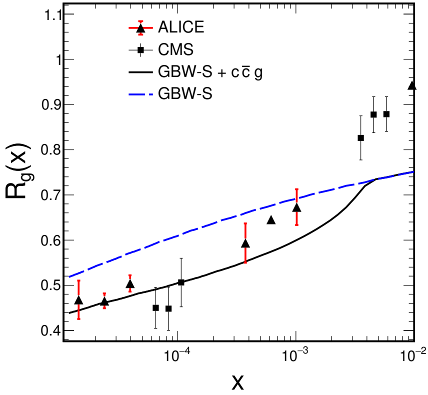


- Rapidity-dependent cross sections $d\sigma/dy$ for exclusive production of J/ψ in $^{208}\mathrm{Pb}^{208}\mathrm{Pb}$ collisions at per-nucleon c.m system energy $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$.
- For the $c\bar{c}g$ state we used the np. parameter $R_c = 0.28$ fm.



- Rapidity-dependent cross sections $d\sigma/dy$ for exclusive production of J/ψ in $^{208}\mathrm{Pb}^{208}\mathrm{Pb}$ collisions at per-nucleon c.m system energy $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$.

A.Łuszczak, W. S., Phys. Lett. B 856 138917 (2024), for GBW dipole cross section:



$$R_g(x) = \sqrt{\frac{\sigma(\gamma Pb \to J/\psi Pb)}{\sigma_{\rm IA}(\gamma Pb \to J/\psi Pb)}}$$
$$" = " \quad \frac{g_A(x, m_c^2)}{A g_N(x, m_c^2)}$$

- $R_g(x)$: is supposed to quantify the suppression (shadowing) of the per-nucleon glue in the nucleus at small-x.
- Impulse approximation baseline from a parametrization of Guzey et al. (2013) as this was also done in the analysis of the CMS collaboration (2023).
- CMS, [arXiv:2303.16984 [nucl-ex]]; ALICE, JHEP **10** (2023), 119.

Summary

- We base our approach on dipole cross sections that describe the total elastic photoproduction of J/ψ on the free nucleon.
- We have applied our results to the exclusive J/ψ production in heavy-ion (lead-lead) collisions at the energies $\sqrt{s_{NN}} = 2.76\,\mathrm{GeV}$ and $\sqrt{s_{NN}} = 5.02\,\mathrm{GeV}$, overall the description of data can be regarded satisfactory.
- Glauber-Gribov approach including only rescattering of the $c\bar{c}$ dipole works reasonably well in the forward region(large rapidities) when compared to LHCb data, but overpredicts suppression for ALICE data.
- In the central rapidity region inclusion of the $c\bar{c}g$ state indroduces 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. Extraction of the leading twist piece is a problem for the future. It depends on the infrared regulator, the gluon propagation radius R_c, and is not a prediction of perturbation theory alone.
- It will be very interesting to investigate virtual photoproduction at electron-ion colliders where we will have a large Q^2 and a studies of the Q^2 evolution of the gluon shadowing are possible.