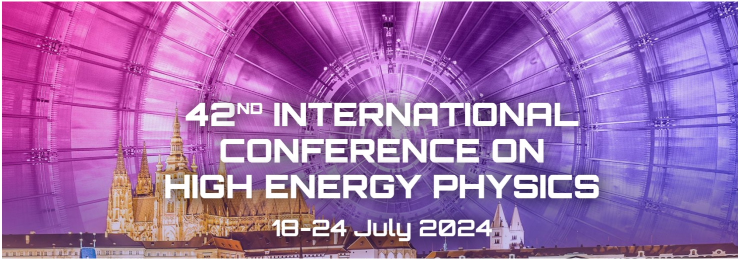
Coherent diffractive production of J/ψ in gamma-nucleus collisions

Agnieszka Łuszczak

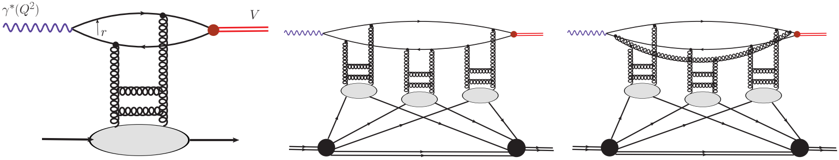
Cracow University of Technology

in collaboration with Wolfgang Schäfer INP PAS Cracow



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 $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$.

Formalism: Nucleon Target

- The coherent diffractive amplitude on the free nucleon then takes a form:

$$\begin{aligned}
\mathcal{A}(\gamma N \to VN; W, \boldsymbol{q}) &= 2(i+\rho_N)\int d^2\boldsymbol{b}\exp[i\boldsymbol{b}\boldsymbol{q}]\langle V|\exp[i(1-2z)\boldsymbol{r}\boldsymbol{q}/2] \\
&* \quad \Gamma_N(x,\boldsymbol{b},\boldsymbol{r})|\gamma\rangle \\
&= (i+\rho_N)\int d^2\boldsymbol{r}\,\rho_{V\leftarrow\gamma}(\boldsymbol{r},\boldsymbol{q})\sigma(x,\boldsymbol{r},\boldsymbol{q}) \\
&\approx (i+\rho_N)\int d^2\boldsymbol{r}\,\rho_{V\leftarrow\gamma}(\boldsymbol{r},0)\sigma(x,r)\,\exp[-B\boldsymbol{q}^2/2]
\end{aligned}$$

Here $x = M_V^2/W^2$, where W is the γp -cms energy. The amplitude is normalized such that the differential cross section is obtained from:

$$\frac{d\sigma(\gamma N \to VN; W)}{dt} = \frac{d\sigma(\gamma N \to VN; W)}{d\boldsymbol{q}^2} = \frac{1}{16\pi}\Big|\mathcal{A}(\gamma^* N \to VN; W, \boldsymbol{q})\Big|^2$$

The overlap of light-front wave functions of photon and the vector meson is:

$$\rho_{V\leftarrow\gamma}(\boldsymbol{r},\boldsymbol{q}) = \int_0^1 dz\Psi_V(z,\boldsymbol{r})\Psi_\gamma(z,\boldsymbol{r})\exp[i(1-2z)\boldsymbol{r}\boldsymbol{q}/2]$$

Formalism: Nucleon Target

- For the dipole cross section we assume a factorized form:

$$\sigma(x, \boldsymbol{r}, \boldsymbol{q}) = \sigma(x, r) \exp[-B\boldsymbol{q}^2/2]$$

- The overlap of vector meson and photon light-cone wave function, obtained from the γ_μ-vertex for the $Q\bar{Q} \to V$ vertex is given by:

$$\Psi_V^*(z, \boldsymbol{r})\Psi_\gamma(z, \boldsymbol{r}) = \frac{e_Q\sqrt{4\pi\alpha_{\mathrm{em}}}N_c}{4\pi^2 z(1-z)}\Big\{m_Q^2 K_0(m_Q r)\psi(z, r) - [z^2 + (1-z)^2] m_Q K_1(m_Q r)\frac{\partial\psi(z, r)}{\partial r}\Big\}$$

- Parameters of wave function are taken from *Kowalski, Motyka, Watt, Phys. Rev. D74, 2006.*

Formalism: Nuclear target

- For the nuclear targets color dipoles can be regarded as eigenstates of the interaction 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 $n_A(\vec{r})$:

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

Formalism: Nuclear target

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

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

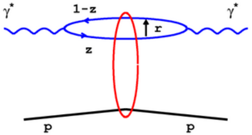
- The nuclear form factor $\mathcal{F}_A(q) = \exp[-R_{\rm ch}^2 q^2/6]$ depends on the finite longitudinal momentum transfer $q_z = x m_N$.

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

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

Dipole model of DIS

- Dipole picture of DIS at small x in the proton rest frame



r - dipole size

z - longitudinal momentum fraction of the quark/antiquark

- Factorization: dipole formation + dipole interaction

$$\sigma^{\gamma p} = \frac{4\pi^2\alpha_{em}}{Q^2} F_2 = \sum_f \int d^2r \int_0^1 dz \, |\Psi^\gamma(r,z,Q^2,m_f)|^2 \;\; \hat{\sigma}(r,x)$$

- Dipole-proton interaction

$$\hat{\sigma}(r,x) = \sigma_0 \left(1 - \exp\{-\hat{r}^2\}\right) \qquad\qquad \hat{r} = r/R_s(x)$$

Dipole cross section: GBW(Golec-Biernat-Wüsthoff)

- GBW parametrization with heavy quarks:
  $f = u, d, s, c$

$$\hat{\sigma}(r,x) = \sigma_0 \left(1 - \exp(-r^2/R_s^2)\right), \qquad R_s^2 = Q_0^2 \cdot (x/x_0)^\lambda \ \mathrm{GeV}^2$$

- The dipole scattering amplitude in such a case reads:

$$\hat{N}(\mathbf{r}, \mathbf{b}, x) = \theta(b_0 - b)\left(1 - \exp(-r^2/R_s^2)\right)$$

where

$$\hat{\sigma}(r,x) = 2\int d^2b\, \hat{N}(\mathbf{r}, \mathbf{b}, x)$$

- Parameters b_0, x_0 and λ from fits of $\hat{N}$ to F_2 data

$$\lambda = 0.288 \qquad x_0 = 4 \cdot 10^{-5} \qquad 2\pi b_0^2 = \sigma_0 = 29\ \mathrm{m}b$$

Dipole cross section: BGK (Bartels-Golec-Kowalski)

- BGK parametrization

$$\hat{\sigma}(r,x) = \sigma_0 \left\{1 - \exp\left[-\pi^2 r^2 \alpha_s(\mu^2) x g(x,\mu^2)/(3\sigma_0)\right]\right\}$$

from the xFitter QCD fit framework: https://gitlab.cern.ch/fitters/xfitter

- $\mu^2 = C/r^2 + \mu_0^2$ is the scale of the gluon density
- μ_0^2 is a starting scale of the QCD evolution. $\mu_0^2 = Q_0^2$
- gluon density is evolved according to the LO or NLO DGLAP eq.
- soft gluon:

$$xg(x,\mu_0^2) = A_g\, x^{\lambda_g}\, (1-x)^{C_g}$$

- soft + hard gluon:

$$xg(x,\mu_0^2) = A_g\, x^{\lambda_g}\, (1-x)^{C_g} (1 + D_g x + E_g x^2)$$

- A slighty different choice of the scale μ : (*Golec-Biernat, Sapeta, JHEP 03, 2018*)

$$\mu^2 = \frac{\mu_0^2}{1 - exp(-\mu_0^2 r^2/C)}$$

- which interpolates smoothly between the C/r^2 behaviour for small r and the constant behaviour, $\mu^2 = \mu_0^2$ for $r \to \infty$

Dipole cross section: IIM (Iancu, Itakura, Munier)

- The GBW and BGK models use for saturation the eikonal approximation, the IIM model uses a simplified version of the Balitsky-Kovchegov equation
- The dipole cross section is parametrized as:

$$\sigma(r,x) = 2\pi R_p^2 \begin{cases} N_0 \exp[-2\gamma L - \frac{L^2}{\kappa\lambda Y}] & \text{if } L \geq 0, \\ 1 - \exp[-a(L-L_0)^2] & \text{else,} \end{cases}$$

where

$$L = \log\left(\frac{2}{rQ_s}\right),\ Q_s^2 = \left(\frac{x_0}{x}\right)^{\lambda} \mathrm{GeV}^2,\ Y = \log\left(\frac{1}{x}\right)$$

and

$$L_0 = \frac{1-N_0}{\gamma N_0} \log\left(\frac{1}{1-N_0}\right),\ a = \frac{1}{L_0^2} \log\left(\frac{1}{1-N_0}\right)$$

We take the numerical values found in the xFitter code:

$$N_0 = 0.7, R_p = 3.44\,\mathrm{GeV}^{-1},\ \gamma = 0.737, \kappa = 9.9\,, \lambda = 0.219,\ x_0 = 1.632 \cdot 10^{-5}$$

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:

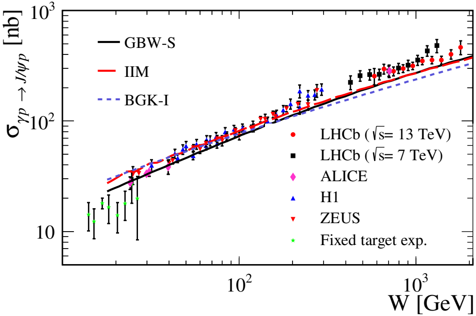
$$\sigma(x,r) = \sigma_0 \left(1 - \exp\left[-\frac{\pi^2 r^2 \alpha_s(\mu^2) R_{\rm skewed} xg(x,\mu^2)}{3\sigma_0}\right]\right),$$

- 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:

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

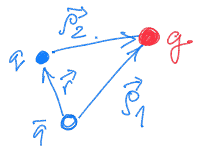
Predictions for J/ψ production on the proton target

A.Łuszczak, W. Schäfer, 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. The very high-energy domain is covered by data extracted from the $pp \to ppJ/\psi$ reaction by the LHCb, the models does a good job.

Contribution of $q\bar{q}g$ Fock-state



- 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

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

- 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:

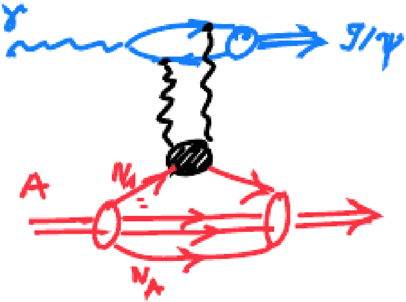
$$\begin{aligned}\Delta\Gamma(x_A, \boldsymbol{r}, \boldsymbol{b}) \quad = \quad & \int d^2\boldsymbol{\rho}_1 |\psi(\boldsymbol{\rho}_1) - \psi(\boldsymbol{\rho}_2)|^2 \Big\{ \Gamma_A(x_A, \boldsymbol{\rho}_1, \boldsymbol{b} + \frac{\boldsymbol{\rho}_2}{2}) + \Gamma_A(x_A, \boldsymbol{\rho}_2, \boldsymbol{b}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

- 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

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

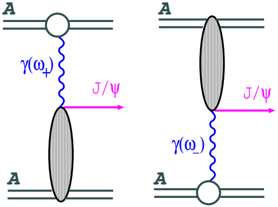
including $c\bar{c}$ and $c\bar{c}g$ contributions, but in the IA we switch off the nonlinear piece in the $c\bar{c}g$ amplitude.

cross section:

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

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:

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

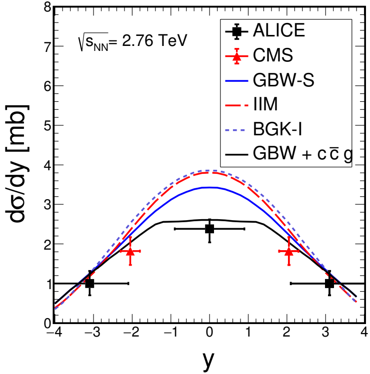
- We use the standard form of the Weizsäcker-Williams flux for the ion moving with boost γ:

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

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

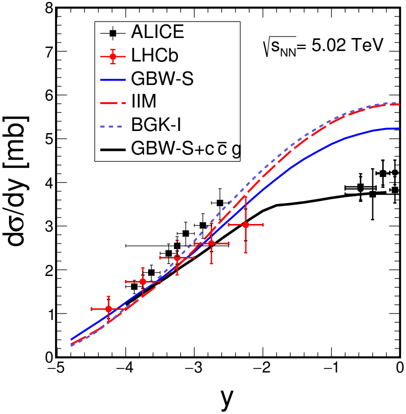
Results for photoproduction in ultraperipheral collisions

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



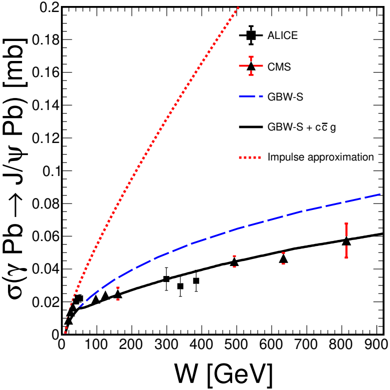
- Rapidity-dependent cross sections $d\sigma/dy$ for exclusive production of J/ψ in $^{208}\mathrm{Pb}^{208}\mathrm{Pb}$ collisions at per-nucleon c.m system energy $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$.
- For the $c\bar{c}g$ state we used the np. parameter $R_c = 0.28$ fm.

Results for photoproduction with $c\bar{c}g$ contribution



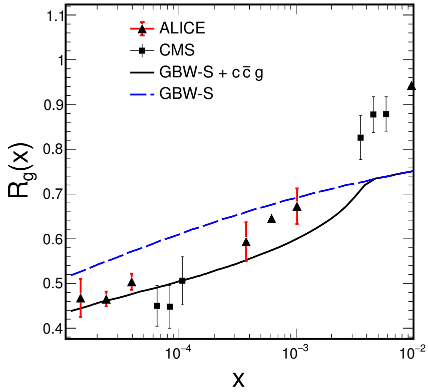
- Rapidity-dependent cross sections $d\sigma/dy$ for exclusive production of J/ψ in $^{208}\mathrm{Pb}^{208}\mathrm{Pb}$ collisions at per-nucleon c.m system energy $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$.

Results for photoproduction with $c\bar{c}g$ contribution



- 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.

The putative "gluon shadowing"



$$R_g(x) = \sqrt{\frac{\sigma(\gamma Pb \to J/\psi Pb)}{\sigma_{\rm IA}(\gamma Pb \to J/\psi Pb)}}$$

$$\text{"} = \text{"} \quad \frac{g_A(x, m_c^2)}{A g_N(x, m_c^2)}$$

- $R_g(x)$: 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 calculated the total elastic photoproduction of J/ψ on the free nucleon and compared to the data available from fixed-target epxeriments, as well as to data extracted from pp or pA collisions by the LHCb and ALICE
- 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 $\sqrt{s_{NN}} = 5.02\,\mathrm{GeV}$, the description of data can be regarded satisfactory.
- Glauber-Gribov theory including only rescattering of the $c\bar{c}$ dipole works well in the forward region(large rapidities).
- In the central rapidity region inclusion of the $c\bar{c}g$ state indroduces additional shadowing which is needed to describe the data.
- Shadowing due to the $c\bar{c}g$ state can be (roughly) identified with gluon shadowing of the nuclear pdf. 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 photoproduction in ultraperipheral collisions at the electron-ion collider where we will have a large Q^2 and a studies of the Q^2 evolution of the gluon shadowing are possible.

Energies available for photoproduction

$\sqrt{s_{NN}} = 2.76\,\text{TeV}$						
centrality	$W_+[\text{GeV}]$	$W_-[\text{GeV}]$	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 $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ for a given rapidity y. Also shown are photon fluxes $n(\omega_\pm)$.

$\sqrt{s_{NN}} = 5.02\,\text{TeV}$						
y	$W_+[\text{GeV}]$	$W_-[\text{GeV}]$	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 $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ for a given rapidity y.