

# Coherent photoproduction of $J/\psi$ in nucleus -nucleus collisions in the color dipole approach -an update

Agnieszka Łuszczak

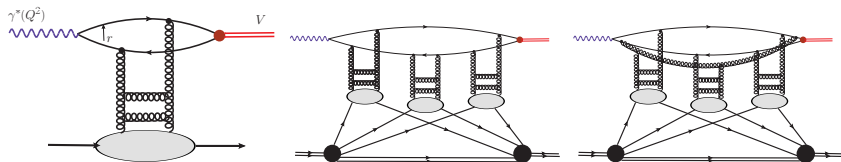
Cracow University of Technology, Krakow, Poland



XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects  
Virtual Event at Stony Brook University, April 12-16, 2021

- Introduction
- Formalism for nucleon and nuclear target
- Dipole models
- Predictions for  $J/\psi$  production on the proton target
- An update of results for photoproduction in ultraperipheral collisions
- Summary

- We investigate the exclusive photoproduction of  $J/\psi$ -mesons in heavy ion collisions in the color dipole approach.
- The color dipole approach to coherent photoproduction on the nucleus, is a variant of Glauber-Gribov multiple scattering theory.



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

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

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

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

$$\frac{d\sigma(\gamma N \rightarrow VN; W)}{dt} = \frac{d\sigma(\gamma N \rightarrow VN; W)}{d\mathbf{q}^2} = \frac{1}{16\pi} \left| \mathcal{A}(\gamma^* N \rightarrow VN; W, \mathbf{q}) \right|^2$$

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

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

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

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

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

$$\begin{aligned} \Psi_V^*(z, \mathbf{r}) \Psi_\gamma(z, \mathbf{r}) = & \frac{e_Q \sqrt{4\pi\alpha_{\text{em}} N_c}}{4\pi^2 z(1-z)} \left\{ m_Q^2 K_0(m_Q r) \psi(z, r) \right. \\ & \left. - [z^2 + (1-z)^2] m_Q K_1(m_Q r) \frac{\partial \psi(z, r)}{\partial r} \right\} \end{aligned}$$

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

- 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:

$$\Gamma_A(x, \mathbf{b}, \mathbf{r}) = 1 - \exp\left[-\frac{1}{2}\sigma(x, r)T_A(\mathbf{b})\right]$$

- 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:

$$\Gamma_A(x, \mathbf{b}, \mathbf{r}) = 1 - \exp\left[-\frac{1}{2}\sigma(x, r)(1 - i\rho_N)T_A(\mathbf{b})\right]$$

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

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

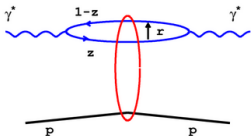
- The diffractive amplitude in  $\mathbf{b}$ -space is:

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

- The nuclear form factor  $\mathcal{F}_A(q) = \exp[-R_{\text{ch}}^2 q^2 / 6]$  depends on the finite longitudinal momentum transfer  $q_z = x m_N$ .
- The total cross section for the  $\gamma A \rightarrow VA$  reaction is obtained as:

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

- 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

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



- GBW parametrization with heavy quarks:

$$f = u, d, s, c$$

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

- The dipole scattering amplitude in such a case reads:

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

where

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

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

$$\lambda = 0.288 \quad x_0 = 4 \cdot 10^{-5} \quad 2\pi b_0^2 = \sigma_0 = 29 \text{ mb}$$

# 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
- $\mu_0^2$  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:

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

- A slightly different choice of the scale  $\mu$ : (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  $r \rightarrow \infty$

## 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

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

and

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

We take the numerical values found in the xFitter code:

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

# Predictions for $J/\psi$ production on the proton target

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

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

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

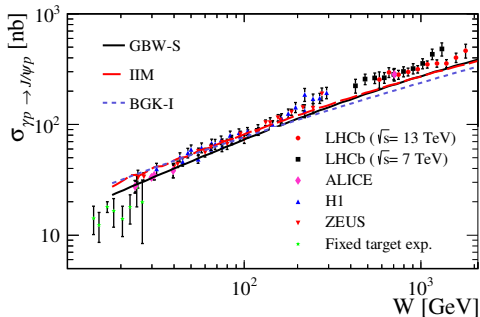
$$\sigma(x, r) = \sigma_0 \left( 1 - \exp \left[ - \frac{\pi^2 r^2 \alpha_s(\mu^2) R_{\text{skewed}} x g(x, \mu^2)}{3\sigma_0} \right] \right),$$

- 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:

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

# Predictions for $J/\psi$ production on the proton target

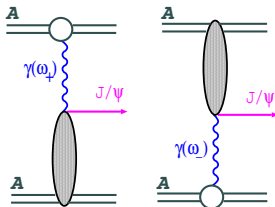
A. Łuszczak, W. Schaefer, *Phys. Rev. C* **99**, no.4, 044905 (2019)



- Total cross section for the exclusive photoproduction  $\gamma p \rightarrow J/\psi p$  as a function of  $\gamma p$ -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  $pp \rightarrow ppJ/\psi$  reaction by the LHCb, the models do a good job.

# 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  $J/\psi$  production from the Weizsäcker-Williams fluxes of quasi-real photons  $n(\omega)$  as:

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

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

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

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

# Contribution of $c\bar{c}g$ 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  $c\bar{c}g$ -Fock state. The dipole cross section for the  $q\bar{q}g$  state on the nucleon is

Nikolaev, Zakharov, Zoller '94

$$\sigma_{q\bar{q}g}(x, \rho_1, \rho_2, \mathbf{r}) = \frac{C_A}{2C_F} \left( \sigma(x, \rho_1) + \sigma(x, \rho_2) - \sigma(x, \mathbf{r}) \right) + \sigma(x, \mathbf{r})$$

Here  $\rho_{1,2}$  are the transverse  $q-g$  and  $\bar{q}-g$  distances, while  $\mathbf{r}$  refers to the  $q\bar{q}$  separation.

- Integrating over all variables but the dipole size  $\mathbf{r}$ , the effect of the gluon is a change of the  $q\bar{q}$  dipole amplitude:

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

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

$$\begin{aligned} \Delta\Gamma(x_A, \mathbf{r}, \mathbf{b}) = & \int d^2\rho_1 |\psi(\rho_1) - \psi(\rho_2)|^2 \left\{ \Gamma_A(x_A, \rho_1, \mathbf{b} + \frac{\rho_2}{2}) + \Gamma_A(x_A, \rho_2, \mathbf{b} + \frac{\rho_1}{2}) \right. \\ & \left. - \Gamma_A(x_A, \mathbf{r}, \mathbf{b}) - \Gamma_A(x_A, \rho_1, \mathbf{b} + \frac{\rho_2}{2}) \Gamma_A(x_A, \rho_2, \mathbf{b} + \frac{\rho_1}{2}) \right\} \end{aligned}$$

see also BK-equation Balitsky '96, Kovchegov '99

$$\psi(\rho) = \frac{\sqrt{C_F\alpha_s}}{\pi} \frac{\rho}{\rho R_c} K_1(\rho/R_c) \text{ with } R_c \sim 0.2 \div 0.3 \text{ fm.}$$

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

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

- We calculate the ratio

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

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.

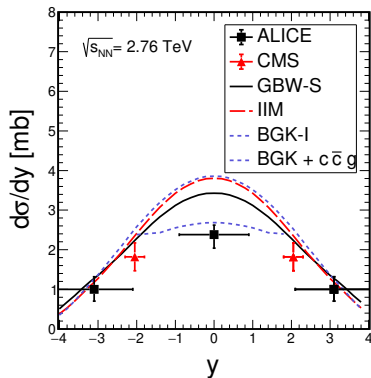
## cross section:

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



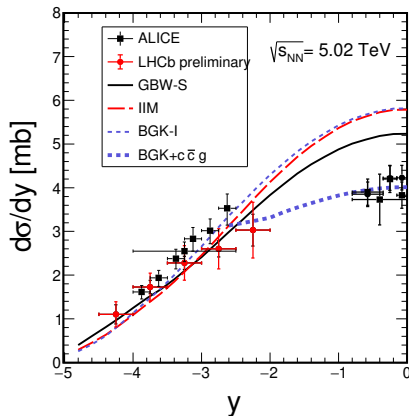
# Results for photoproduction in ultraperipheral collisions

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



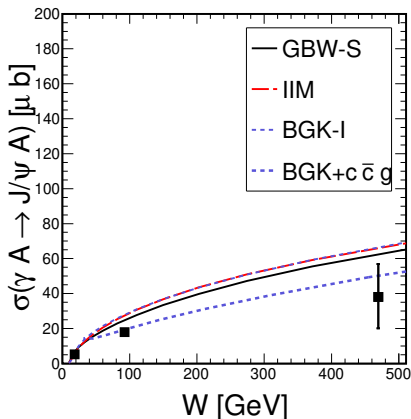
- Rapidity-dependent cross sections  $d\sigma/dy$  for **exclusive production of  $J/\psi$**  in  $^{208}\text{Pb}-^{208}\text{Pb}$  collisions at per-nucleon c.m system energy  $\sqrt{s_{NN}} = 2.76$  TeV.

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



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

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



- The total cross section  $\sigma(\gamma A \rightarrow J/\psi A)$  for the  $^{208}\text{Pb}$  nucleus as a function of  $\gamma A$ -cm energy  $W$ . Data extracted by J. G. Contreras, *Phys. Rev. C* 96, 015203 (2017).

- We calculated the total elastic photoproduction of  $J/\psi$  on the free nucleon and compared to the data available from fixed-target experiments, from the H1 and ZEUS collaborations at HERA as well as to data extracted from  $pp$  or  $pA$  collisions by the LHCb and ALICE
- We have applied our results to the exclusive  $J/\psi$  production in heavy-ion (lead-lead) collisions at the energies  $\sqrt{s_{NN}} = 2.76 \text{ GeV}$  and  $\sqrt{s_{NN}} = 5.02 \text{ GeV}$ , 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 introduces 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.