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Gluon shadowing in nuclei and the role of the $c\bar{c}g$ state in the coherent photoproduction of J/ψ in nucleus–nucleus collisions

Agnieszka Łuszczak[a,*] **and Wolfgang Schäfer**[b]

[a] *T. Kościuszko Cracow University of Technology, PL-30-084 Cracow, Poland*

[b] *Institute of Nuclear Physics Polish Academy of Sciences, ul. Radzikowskiego 152, PL-31-342 Cracow, Poland*

E-mail: agnieszka.luszczak@pk.edu.pl, Wolfgang.Schafer@ifj.edu.pl

Coherent J/ψ photoproduction in ultraperipheral nucleus–nucleus collisions is widely used as a proxy for small-x nuclear gluon shadowing. In the color-dipole picture, multiple scatterings of the $c\bar{c}$ dipole in the nuclear medium generate a sizable suppression already at $x \sim 10^{-2}$. At higher energies, however, inelastic (Gribov) shadowing associated with higher Fock states becomes important. We summarize a dipole calculation in which the leading $c\bar{c}g$ state is included on top of Glauber–Gribov rescattering, and we show that it provides the additional suppression required by the LHC data at small x.

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*Speaker

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1. Motivation

Exclusive J/ψ production in ultraperipheral heavy-ion collisions (UPCs) at the LHC provides precision access to coherent photonuclear reactions at small Bjorken-x. Recent measurements by ALICE and CMS (e.g. [1–4]) have stimulated renewed interest in the interpretation of nuclear suppression effects in terms of "gluon shadowing".

A convenient theoretical framework is the color-dipole picture. The incoming photon fluctuates into partonic Fock states which scatter off the nuclear color field, and the exclusive amplitude follows from the overlap of photon and vector-meson light-front wave functions with the dipole–nucleus scattering amplitude. For heavy nuclei, multiple elastic rescatterings of a dipole on nucleons are resummed in the familiar Glauber–Gribov form. This mechanism already produces a large suppression and gives a good description of UPC data in a broad range of rapidities in dipole-based studies.

At higher energies, the coherence length becomes large also for higher Fock states. In a nucleus, these states induce inelastic (Gribov) shadowing corrections. In this contribution we focus on the leading $c\bar{c}g$ state and discuss its impact on coherent J/ψ photoproduction on lead, which turns out to be essential at the smallest x.

2. From photonuclear to UPC observables

In UPCs, the measured rapidity distribution for the coherent process $AA \to A\,J/\psi\,A$ receives contributions from photons emitted by either nucleus. In the equivalent photon approximation one writes schematically

$$\frac{d\sigma^{AA}_{\rm coh}}{dy} = n_A(\omega_+)\,\sigma(\gamma A \to J/\psi A; W_+) + n_A(\omega_-)\,\sigma(\gamma A \to J/\psi A; W_-)\,, \tag{1}$$

where $n_A(\omega)$ is the photon flux. For a vector meson of mass M_V,

$$\omega_\pm \simeq \frac{M_V}{2}\,e^{\pm y}\,, \qquad W^2_\pm \simeq 2\,\omega_\pm\,\sqrt{s_{NN}}\,, \qquad x_\pm \simeq \frac{M_V^2}{W^2_\pm}\,. \tag{2}$$

Experimental extractions of the photonuclear cross section $\sigma(\gamma A \to J/\psi A)$ from UPC data (see e.g. [5]) often present results in terms of an effective "gluon shadowing ratio" discussed below.

3. Dipole amplitude and Glauber–Gribov rescattering

In the dipole approach the forward diffractive amplitude for $\gamma A \to J/\psi\,A$ reads

$$\Im m\,\mathcal{A}(\gamma A \to J/\psi\,A; W, \vec{q}=0) = 2\int_0^1 dz \int d^2\vec{r}\,\Psi^*_{J/\psi}(z,\vec{r})\,\Psi_\gamma(z,\vec{r}) \int d^2\vec{b}\,\Gamma_A(x,\vec{b},\vec{r})\,. \tag{3}$$

For not too small x (of order $x_A \sim 10^{-2}$), the dipole–nucleus S-matrix takes the Glauber form

$$\Gamma_A(x,\vec{b},\vec{r}) = 1 - S_A(x,\vec{b},\vec{r}), \qquad S_A(x,\vec{b},\vec{r}) = \exp\left[-\frac{1}{2}\,\sigma(x,\vec{r})\,T_A(\vec{b})\right], \tag{4}$$

with the nuclear thickness $T_A(\vec{b})$ normalized to $\int d^2b\, T_A(b) = A$. The impulse approximation corresponds to switching off nonlinear rescattering terms,

$$\Gamma_{\rm IA}(x,\vec{b},\vec{r}) = \frac{1}{2}\,\sigma(x,\vec{r})\,T_A(\vec{b})\,. \tag{5}$$

The coherent nuclear suppression factor can be defined at the amplitude level,

$$R_{\rm coh}(x) = \frac{\displaystyle\int d^2\vec{b}\,\left|\langle J/\psi|\Gamma_A(x,\vec{b},\vec{r})|\gamma\rangle\right|^2}{\displaystyle\int d^2\vec{b}\,\left|\langle J/\psi|\Gamma_{\rm IA}(x,\vec{b},\vec{r})|\gamma\rangle\right|^2}\,, \tag{6}$$

and the coherent cross section is then obtained as

$$\sigma(\gamma A\to J/\psi A;W) = R_{\rm coh}(x)\,\sigma(\gamma p\to J/\psi p;W)\,. \tag{7}$$

In phenomenological applications, $\sigma(\gamma p\to J/\psi p;W)$ is taken from a dipole description of the proton baseline (see e.g. [6]).

4. Inelastic shadowing from the $c\bar{c}g$ state

At smaller x the Glauber form (4) is incomplete because higher Fock states become coherent over the nuclear size. The leading correction is generated by the $c\bar{c}g$ component, which represents high-mass diffractive intermediate states (inelastic shadowing) in the Gribov picture. Following the dipole formulation of inelastic shadowing in [7], one may write the dipole amplitude as an expansion around x_A,

$$\Gamma_A(x,\vec{b},\vec{r}) = \Gamma_A(x_A,\vec{b},\vec{r}) + \ln\!\left(\frac{x_A}{x}\right)\,\Delta\Gamma_A(x_A,\vec{b},\vec{r})\,, \tag{8}$$

where $\Delta\Gamma_A$ is obtained from the difference between the rescattering of the $c\bar{c}g$ system and the rescattering of the parent $c\bar{c}$ dipole. The transverse separation of the emitted gluon is weighted by the $q\to qg$ light-front wave function. Since the correction involves integration over all transverse sizes, including the infrared domain, an effective gluon correlation length $R_c\simeq 1/\mu_G$ is introduced to suppress long-distance contributions, and the coupling is frozen for distances larger than R_c.

In the numerical implementation used here, the $c\bar{c}g$ contribution is smoothly switched on at high energies, reflecting the growing phase space for gluon emission. The key numerical inputs are summarized in Table 1.

5. Comparison to LHC data

Figure 1 shows the coherent $\gamma\,^{208}\mathrm{Pb}\to J/\psi\,^{208}\mathrm{Pb}$ cross section as a function of the photon–nucleus energy W, compared to ALICE and CMS photonuclear results (see [2, 4] and the compilation in [5]). The impulse approximation overshoots the data, illustrating the scale of nuclear effects. Glauber–Gribov rescattering of the $c\bar{c}$ dipole accounts for a substantial part of the suppression, but at the highest energies the inclusion of the $c\bar{c}g$ state provides the additional reduction preferred by the data.

Table 1: Representative numerical inputs used to model the onset of the $c\bar{c}g$ contribution. The parameter μ_G controls the gluon correlation length $R_c = 1/\mu_G$ and regulates the infrared part of the $c \to cg$ wave function.

parameter	value
reference point for Glauber form	$x_A \simeq 10^{-2}$
infrared regulator	$\mu_G = 0.7$ GeV
switch-on center	$W_0 = 50$ GeV
switch-on width	$W_1 = 5$ GeV

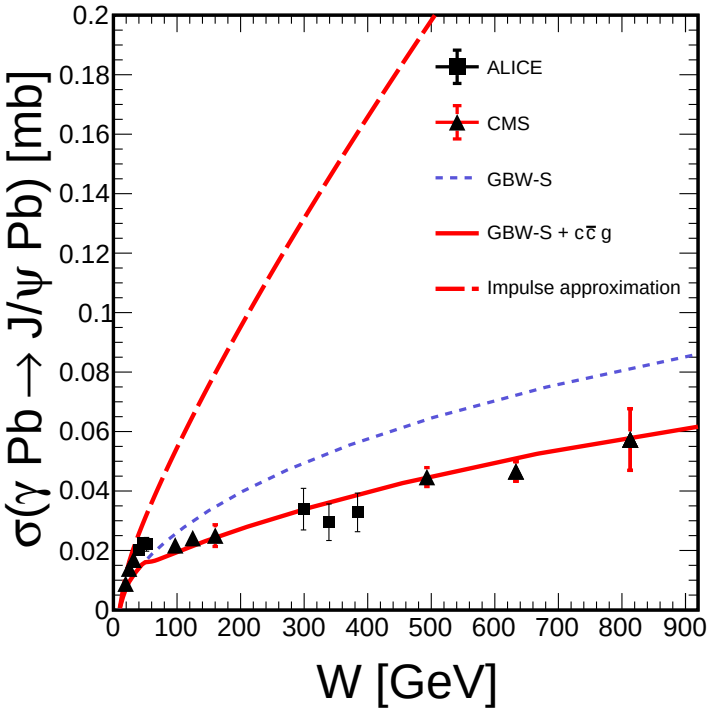

Figure 1: Coherent photoproduction cross section $\sigma(\gamma\,^{208}\mathrm{Pb} \to J/\psi\,^{208}\mathrm{Pb})$ as a function of the photon–nucleus energy W, illustrating the impact of the impulse approximation, $c\bar{c}$ rescattering and the additional $c\bar{c}g$ shadowing contribution.

A commonly used representation of the nuclear suppression is the "gluon shadowing ratio"

$$R_g(x) = \sqrt{\frac{\sigma(\gamma A \to J/\psi A; W)}{\tilde{\sigma}_{\mathrm{IA}}(\gamma A \to J/\psi A; W)}}\,, \tag{9}$$

where the reference $\tilde{\sigma}_{\mathrm{IA}}$ is taken from a phenomenological parametrization used in experimental analyses [11]. In the leading-twist limit one expects $R_g(x) \propto g_A(x,\mu^2)/(A\,g(x,\mu^2))$ with $\mu^2 \sim M_{J/\psi}^2/4$, motivating its interpretation in terms of nuclear gluon shadowing.

Figure 2 displays $R_g(x)$ for lead. Including the $c\bar{c}g$ state leads to an extra suppression at small x and improves the agreement with the experimental extraction at the smallest x values. At larger

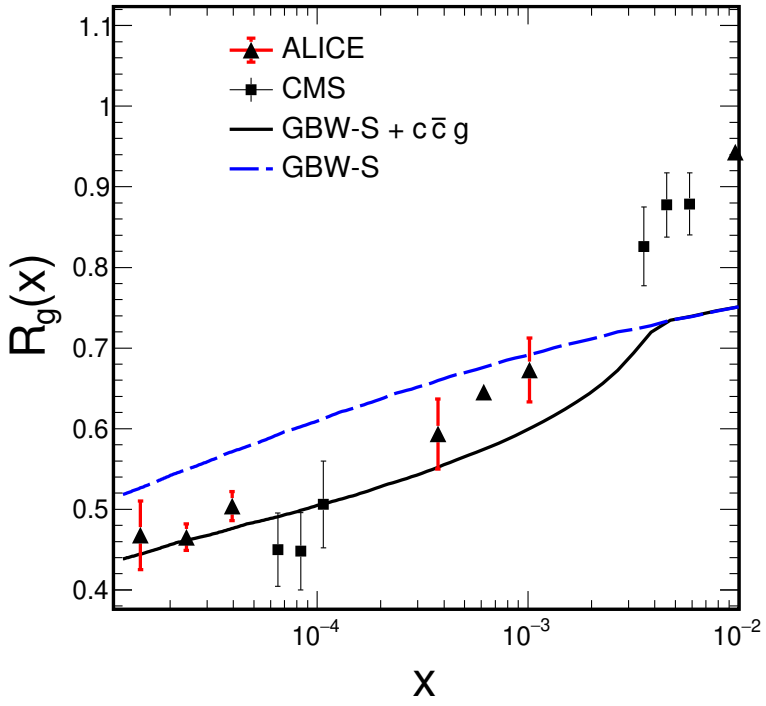

Figure 2: The "gluon shadowing ratio" $R_g(x)$ for ^{208}Pb obtained from the coherent cross section (9).

$x \sim 10^{-2}$, tensions may persist, pointing to the role of finite-coherence-length corrections and/or to ambiguities in the proton baseline and nuclear modeling (see also the discussion in [4, 12]).

6. Conclusions

Coherent J/ψ photoproduction on heavy nuclei exhibits strong suppression relative to the impulse approximation. In a dipole description, Glauber–Gribov rescattering of the $c\bar{c}$ dipole explains a large fraction of this effect, but at the smallest x values the data prefer additional shadowing. A minimal extension is to include the leading $c\bar{c}g$ Fock state, which represents inelastic (Gribov) shadowing and yields extra suppression at high energies. This mechanism improves the description of LHC data in the small-x region commonly associated with gluon shadowing.

The interpretation of the extracted ratio $R_g(x)$ in terms of a leading-twist nuclear gluon distribution is subtle: higher-twist rescattering corrections and saturation-related scales enter naturally in the dipole formulation. A more direct connection to collinear nuclear PDFs therefore requires a careful disentangling of these effects.

7. ACKNOWLEDGMENTS

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