Exclusive photoproduction of excited quarkonia in ultraperipheral collisions

In collaboration with Cheryl Henkels, Emmanuel G. de Oliveira and Roman Pasechnik

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December, 2023

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Ultraperipheral collision and final states

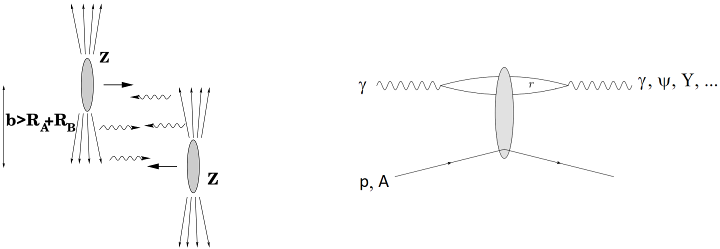
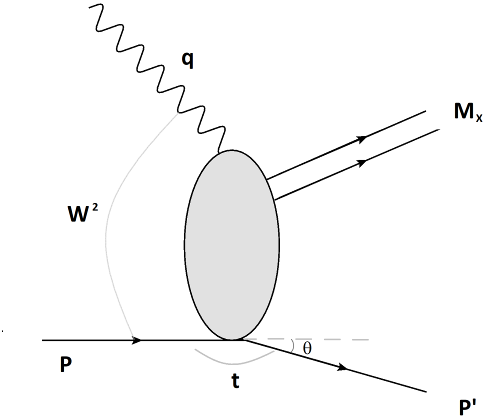


Figure 1: Condition for an ultraperipheral collision and possible final states.

In this work:

- Exclusive production of J/Ψ and Υ (vector mesons).
- Photoproduction limit, $Q^2 \to 0$.

Kinematics



Kinematics:

$$W^2 = (P+q)^2\,, \quad Q^2 = -q^2\,.$$

$$t = (P' - P)^2\,, \quad x = \frac{M_X^2 + Q^2}{W^2 + Q^2}\,.$$

High energies:

$$t \simeq -|\vec{\Delta}_T|^2\,.$$

Figure 2: Kinematics variables.

Cross Section

Differential in t cross section

$$\frac{d\sigma^{\gamma p \to Vp}}{dt}(W, t) = \frac{1}{16\pi} \left| \mathcal{A}^{\gamma p \to Vp}(W, t) \right|^2 . \tag{1}$$

Usually, with $t \approx 0$ (elastic collision) it is assumed:

$$\mathcal{A}^{\gamma p \to Vp}(W, t) \approx e^{-B|t|/2} \mathcal{A}^{\gamma p \to Vp}(W, t = 0) . \tag{2}$$

Integrating (1) over t, we have

$$\sigma^{\gamma p \to Vp}(W) = \frac{1}{16\pi B} \left| \mathcal{A}^{\gamma p \to Vp}(W, t = 0) \right|^2 . \tag{3}$$

where B can be fitted via Regge theory.

The dipole model

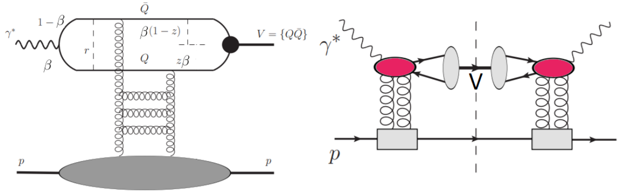


Figure 3: Interaction between the dipole and the proton.

The total amplitude is the product of the subprocesses:

$$\mathcal{A}_{T,L}^{\gamma p \to Vp}(x, t=0) = \int_0^1 d\beta \int d^2 r \Psi_V^{\dagger(\mu,\bar{\mu})}(r,\beta)\Psi_{\gamma T,L}^{(\mu,\bar{\mu})}(r,\beta;Q^2) \times \mathcal{A}_{q\bar{q}}(x, r, t \approx 0) \tag{4}$$

The photon wave function can be calculated perturbatively.

The dipole model

Two main considerations:

- Transparency: when $r \to 0$.
- Saturation: when $r \gg 0$.

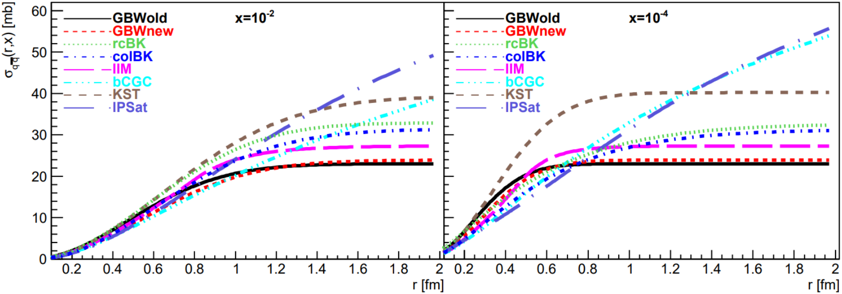


Figure 4: Dipole cross sections. Figure taken from Cepila, Nemchik, Krelina, Pasechnik, EPJ C 79, 495 (2019).

Vector meson wave function

The quarkonia wave function, in the $q\bar{q}$ rest frame, can be obtained via a Schrödinger type equation:

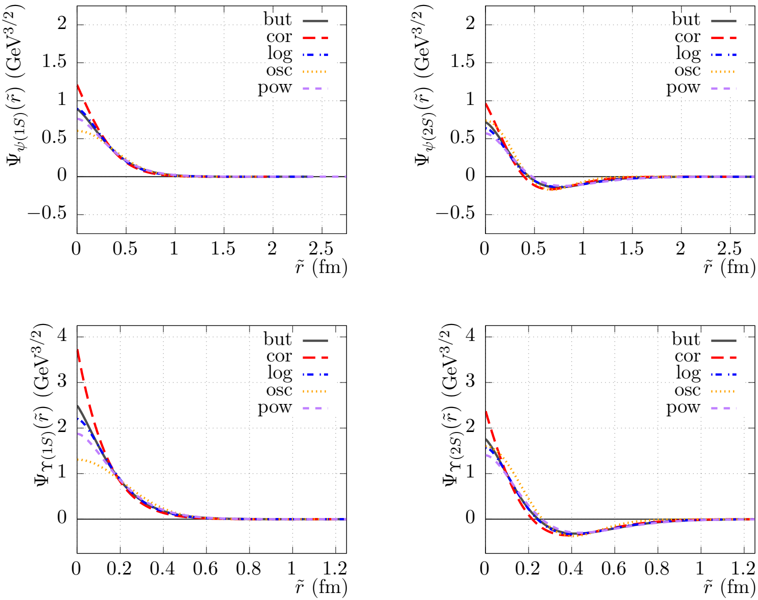
$$\left(-\frac{\nabla^2}{m_q} + V(r)\right)\Psi_{nl}(r) = E_{nl}\Psi_{nl}(r)\,. \tag{5}$$

For the quark-antiquark potential, we used five potentials:

- Cornell Potential
- Buchmüller-Tye Potential
- Logarithmic potential
- Harmonic Oscillator
- Power-law potential

Why to choose this procedure? Because we can calculate both the fundamental and the excited states of vector mesons.

Vector meson wave function (in $q\bar{q}$ rest frame)



Photoproduction cross section $\gamma p \to \Psi(nS)$

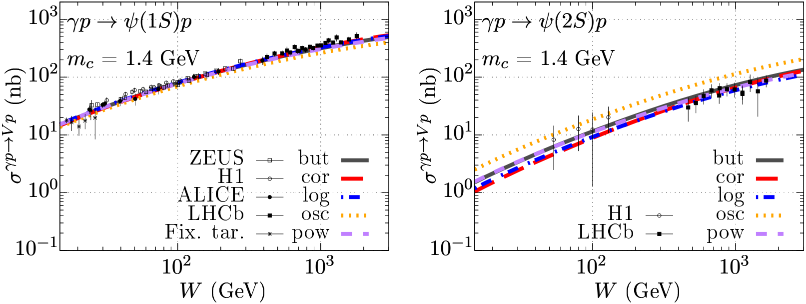


Figure 5: Plots were made using the GBW dipole parametrization.

Photoproduction cross section $\gamma p \to \Upsilon(nS)$

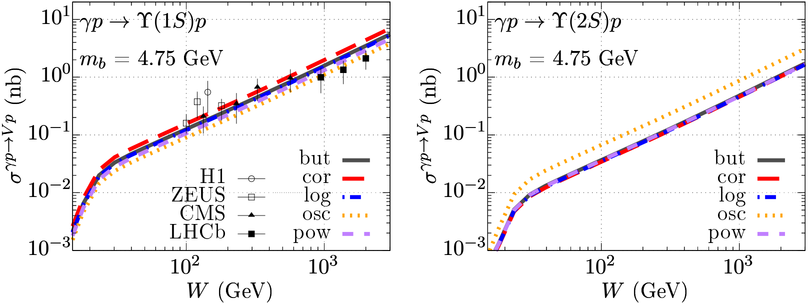


Figure 6: Plots were made using the KST dipole parametrization.

Differential in t cross section

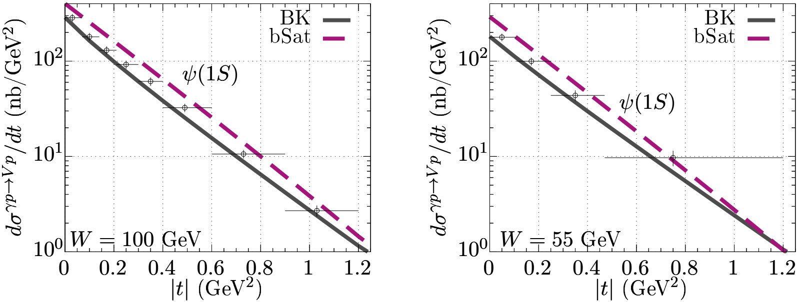


Figure 7: Differential cross section for $\psi(1S)$ photoproduction as a function of $|t|$ found using the Buchmüller-Tye potential as well as the BK and "bSat" models for $W = 100$ GeV (left) and $W = 55$ GeV (right). The $\psi(1S)$ results are compared to the corresponding data from H1 Collaboration.

[Henkels, Oliveira, Pasechnik, H. T., Phys. Rev. D 104, 054008 (2021)]

Nuclear photoproduction (coherent and incoherent cases)

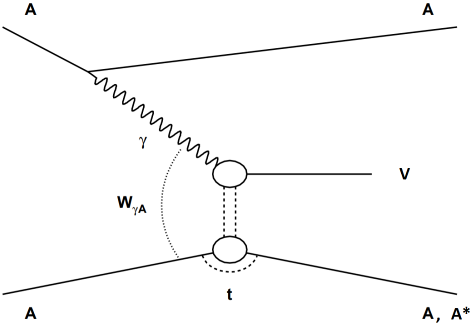


Figure 8: Photoproduction of vector mesons via ultraperipheral collisions of two nuclei.

$$\frac{d\sigma_{\gamma A \to VX}}{dy} = \omega \frac{dN_\gamma}{d\omega} \sigma_{\gamma A \to VX}(\omega) + (y \to -y) \tag{6}$$

Glauber-Gribov formalism

Considering the dipole model, via the Glauber-Gribov formalism we can obtain the photon-nucleus cross section.

Coherent:

$$\sigma^{\gamma A\to VA} = \int d^2b \Big| \int d\beta d^2r \Psi_V^\dagger \Psi_\gamma \left[1 - \exp\left(-\frac{1}{2}\sigma_{q\bar{q}}(x,r)\, T_A(b)\right)\right] \Big|^2 .$$

Incoherent:

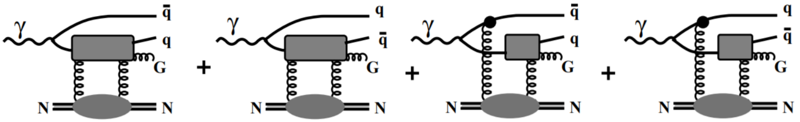
$$\sigma^{\gamma A\to VA^*} = \int d^2b \frac{T_A(b)}{16\pi B} \Big| \int d\beta d^2r \Psi_V^\dagger \Psi_\gamma \sigma_{q\bar{q}}(x,r) \\ \exp\Big(-\frac{1}{2}\sigma_{q\bar{q}}(x,r)\, T_A(b)\Big)\Big|^2 ,$$

Nuclear effects - Gluon Shadowing

The gluon density inside a nucleus at small x is expected to be suppressed compared to the one inside a free nucleon. It can be phenomenologically incorporated by "renormalising" the dipole cross section as

$$\sigma_{q\bar{q}}(x,r) \to \sigma_{q\bar{q}}(x,r) R_G(x,\mu^2)\,, \quad R_G(x,\mu^2) = \frac{x g_A(x,\mu^2)}{A\, x g_p(x,\mu^2)}\,.$$

Diagrams with the radiation of 1 gluon are:

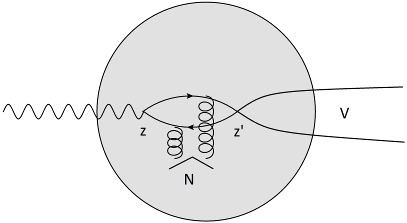


[Ref: Kopeliovich, Schafer and Tarasov, Phys. Rev. D 62 054022, 2000]

Nuclear effects - Finite Coherence lenght

The coherence length, in photoproduction, is given by the ration between the photon energy and the vector meson mass:

$$l_c = \frac{2\omega'}{M_V^2} \, . \tag{7}$$



This effect only appears for lower energies, being completely negligible for central rapidities.

Coherent photoproduction of $\psi(1S, 2S)$

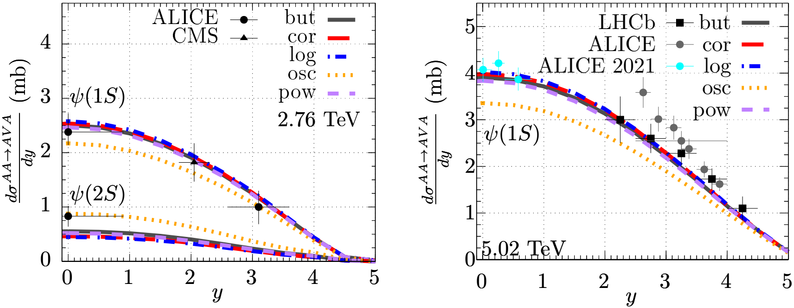


Figure 9: The results obtained with the GBW model are compared to the CMS and ALICE data

Incoherent photoproduction of ψ

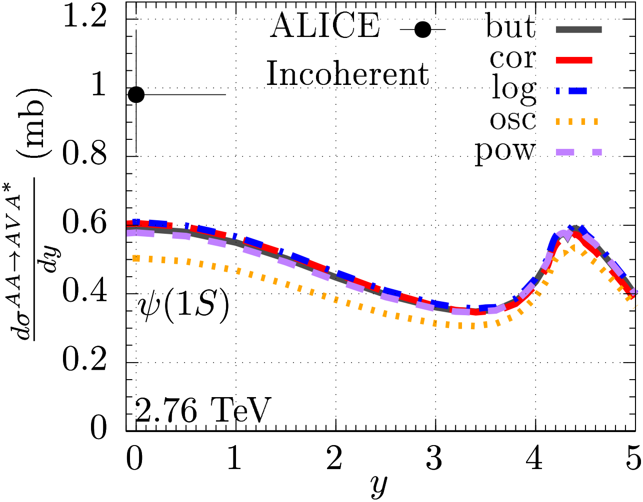


Figure 10: The result obtained using GBW model are compared to the ALICE data.

Importance of the gluon shadowing

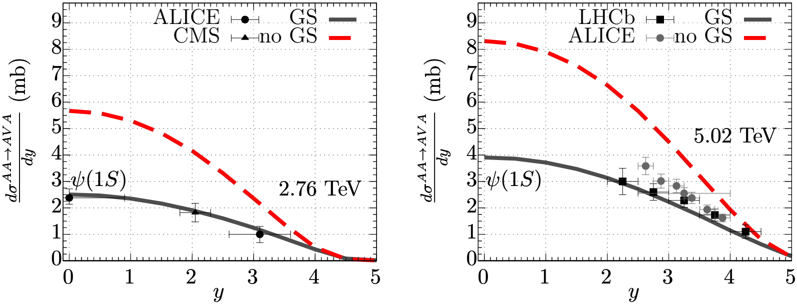


Figure 11: The results obtained, using BUT potential, are compared to the CMS and ALICE data.

[Henkels, Oliveira, Pasechnik, H. T., Phys. Rev. D 102, 014024 (2020)]

Conclusions

- The photoproduction can be a good channel to study the internal structure of hadrons.
- By using dipole model, we can describe the photoproduction of different types of mesons, considering the proton as the target.
- The extension to the nuclear case is natural (Glauber-Gribov). However, in order to describe the data, the inclusion of nuclear effects (such as the gluon shadowing) is needed.

Thank you!

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