Coherent photoproduction of J/Ψ and future perspectives for electron-ion collider

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- Predictions for J/ψ production on the proton target
- Results for photoproduction in ultraperipheral collisions
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Introduction

- Motivation: The recent measurements from LHC for coherent exclusive production of vector mesons in ultraperipheral heavy-ion collisions at the LHC
- The production takes place via the diffractive photoproduction process, where one of the ions serves as a source of quasireal photons, the second ion plays the role of the hadronic target on which the diffractive photoproduction proceeds
- The exclusive production of vector mesons composed of heavy quarks like J/ψ in ultraperipheral heavy-ion collisions has been investigated
- The heavy quark mass provides a hard scale which ensures a dominant contribution from short distances, so that a perturbative QCD approach becomes applicable
- The diffractive photoproduction then becomes a sensitive probe of the gluon structure of the target

Introduction

- We use the color-dipole approach, which allows us to take into account nuclear effects once the dipole cross section on a free nucleon has been fixed
- In view of the later application to ultraperipheral heavy-ion collisions the HERA energy range is the most relevant to us
- For the production of J/ψ vector mesons at high enough energies, the coherence length $l_c = 2\omega/M_V^2$ is much larger than the size of the proton $l_c \gg R_N$, where ω is the photon energy
- J/ψ photoproduction can be described as a elastic scattering of a $c\bar{c}$ of size r conserved during the interaction
- The $\gamma \to c\bar{c}$ transition and projection of the $c\bar{c}$ pair on the bound state are encoded in the relevant light-cone wave functions, which depend also on the fraction z of the photon's light-front momentum carried by the quark

Formalizm: Nucleon Target

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

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

Here $x = M_V^2/W^2$, where W is the γp -cms energy. Our 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:

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

Formalizm: 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:

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

Formalizm: 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:

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

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

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

Formalizm: Nuclear target

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

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

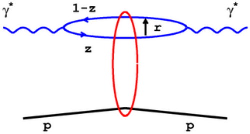
- The nuclear form factor $\mathcal{F}_A(q) = \exp[-R_{\rm ch}^2 q^2/6]$ depends on the finite longitudinal momentum transfer $q_z = x m_N$

- The total cross section for the $\gamma A \to VA$ reaction is finally 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: $f = u, d, s, c$

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

- 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

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

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

- BGK parametrization

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

- $\mu^2 = C/r^2 + \mu_0^2$ 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 :

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

- 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

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

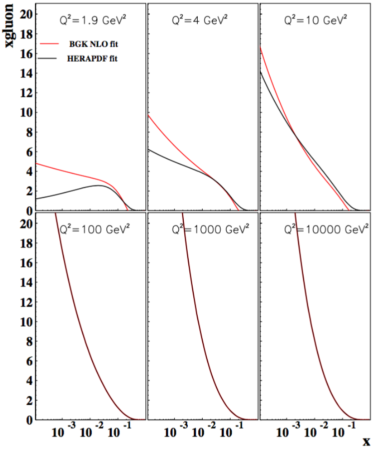
and

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

We take the numerical values found in the xFitter code:

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

Gluon density

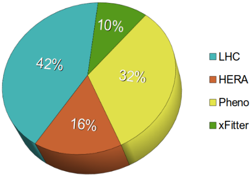


- The differences are disappearing at larger Q^2.

The xFitter Project

- The xFitter project (former HERAFitter) is an unique open-source QCD fit framework
- GitLab (CERN) is now the main repository of the project:
  https://gitlab.cern.ch/fitters/xfitter
  (open access to download for everyone - read only)

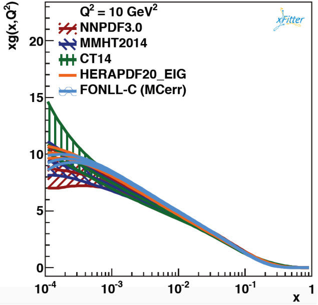
- This code allows users to:
  - extract PDFs from a large variety of experimental data,
  - assess the impact of new data on PDFs,
  - check the consistency of experimental data,
  - test different theoretical assumptions



- Around 30 active developers between experimentalists and theorists
- LHC experiments provide the main developments and usage of the xFitter platform

PDFs Fits in xFitter

- Parametrise PDFs at the initial scale:
  - several functional forms available (“standard”, Chebyshev, etc.)
  - define parameters to be fitted
- Evolve PDFs to the scales of the fitted data points:
  - DGLAP evolution up to NNLO in QCD and NLO QED (QCDNUM, APFEL, MELA)
  - non-DGLAP evolutions (dipole, CCFM)
- Compute predictions for DIS and hadron colliders:
  - several heavy quarks treatments are avaliable in DIS (ZM-VFNS, ACOT, FONLL, RT, FFNS)
  - predictions for hadron-collider data through fast interfaces (APPLgrid, FastNLO)
- Comparison data-predictions via χ^2 :
  - multiple definitions available
  - consistent treatment of the systematic uncertainties
- Minimise the χ^2 w.r.t. the fitted parameters
  - using MINUIT
- Useful drawing tools



Predictions for J/ψ production on the proton target

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

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

- The diffraction slope B is taken as $B = B_0 + 4\alpha' \log(W/W_0)$, 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:

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

- 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:

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

Predictions for J/ψ production on the proton target

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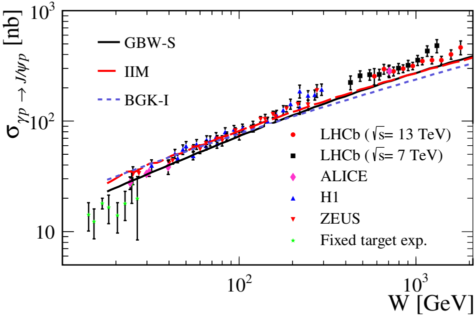
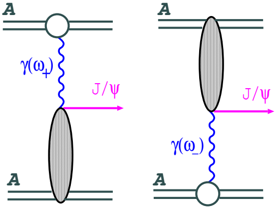


- Total cross section for the exclusive photoproduction $\gamma p \to J/\psi p$ as a function of γp-cms energy W
- We observe that the range of $30 \lesssim W \lesssim 300\text{GeV}$ is reasonably well described by all dipole cross sections. The very high-energy domain is covered by data extracted from the $pp \to ppJ/\psi$ reaction by the LHCb, none of the models does 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/ψ production from the Weizsäcker-Williams fluxes of quasi-real photons $n(\omega)$ as:

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

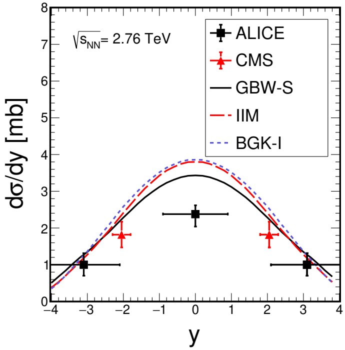
- We use the standard form of the Weizsäcker-Williams flux for the ion moving with boost γ:

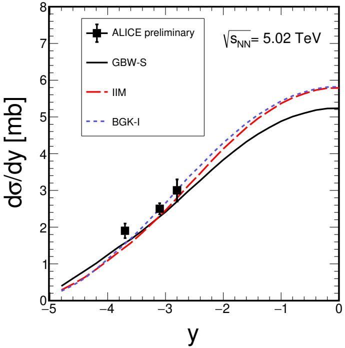
$$n(\omega) = \frac{2Z^2\alpha_{\rm em}}{\pi}\left[\xi K_0(\xi)K_1(\xi) - \frac{\xi^2}{2}(K_1^2(\xi) - K_0^2(\xi))\right]$$

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

Results for photoproduction in ultraperipheral collisions

Phys. Rev. C ***99****, no.4, 044905 (2019)*

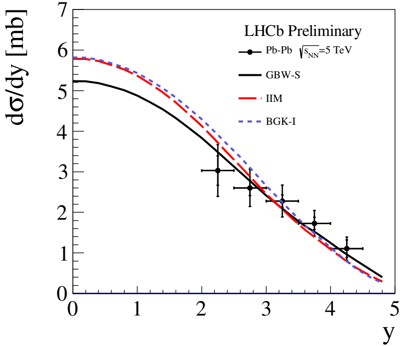




- Rapidity-dependent cross sections $d\sigma/dy$ for exclusive production of J/ψ in $^{208}\mathrm{Pb}^{208}\mathrm{Pb}$ collisions at per-nucleon c.m system energy $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ and $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$

Results for photoproduction in ultraperipheral collisions

*Phys. Rev. C **99**, no.4, 044905 (2019)*



- 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 $\sqrt{s_{NN}} = 5.02$

Dipole cross section vs. gluon distribution

- For small dipoles we can approximate the dipole-proton cross section as:

$$\sigma(x,r) = \frac{\pi^2}{3} r^2 \alpha_S(q^2) x g(x,q^2)\,,\; q^2 \approx \frac{10}{r^2}$$

from here we see, that if small dipoles dominate, the diffractive amplitude becomes proportional to the gluon distribution in the proton!

- Does this also work for the nucleus? We define the dipole cross section:

$$\sigma_A(x,r) = 2 \int d^2\boldsymbol{b}\, \Gamma_A(x,\boldsymbol{b},\boldsymbol{r})$$

Then the question is, when do we obtain

$$\sigma_A(x,r) = \frac{\pi^2}{3} r^2 \alpha_S(q^2) x g_A(x,q^2)\,,$$

with the DGLAP-evolving nuclear glue $g_A(x,q^2)$?

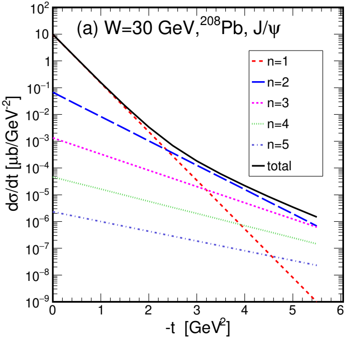
Future perspectives

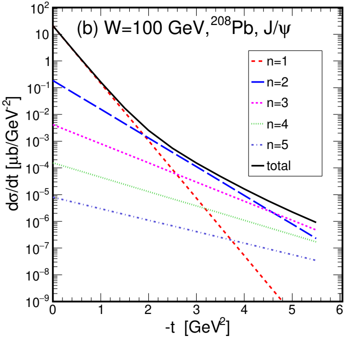
- Currently available data from photoproduction in ultraperipheral collisions are not sufficient in our opinion. We obtain a reasonable description of data with the Glauber-form of $\Gamma_A(x, \boldsymbol{b}, \boldsymbol{r})$, which explicitly contains higher-twist corrections
- An electron-ion collider EIC can shed much light on this question
- Large photon virtuality allows to investigate the small-dipole limit. Also light vector mesons at large Q^2 will be interesting

Future perspectives

Phys. Rev. **C 97**, *no. 2, 024903 (2018)*

- Diffractive incoherent photoproduction on the nuclear target: Typical energies as will be accessible at a future EIC





- $-t = \mathbf{\Delta}^2$, single scattering has the same diffractive slope as on the free nucleon, multiple scatterings have smaller slopes.

Summary

- We calculated the total elastic photoproduction of J/ψ on the free nucleon and compared to the data available from fixed-target epxeriments, 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/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 published and preliminary data can be regarded satisfactory
- It will be very interesting to investigate photoproduction in ultraperipheral collisions at the electron-ion collider where we will have a large Q^2