Coherent photoproduction of $J/\Psi$ and future perspectives for electron-ion collider

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xFitter
**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 $J/\psi$ 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.
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 $J/\psi$ 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 $\omega$ is the photon energy.

$J/\psi$ photoproduction can be described as an elastic scattering of a $c\bar{c}$ of size $r$ conserved during the interaction.

The $\gamma \rightarrow c\bar{c}$ 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:

\[
\mathcal{A}(\gamma N \to VN; W, q) = 2(i + \rho_N) \int d^2b \exp[i bq] \langle V \exp[i(1 - 2z)rq/2] \\
\times \Gamma_N(x, b, r)|\gamma\rangle \\
= (i + \rho_N) \int d^2r \rho_{V\gamma}(r, q)\sigma(x, r, q) \\
\approx (i + \rho_N) \int d^2r \rho_{V\gamma}(r, 0)\sigma(x, r) \exp[-Bq^2/2]
\]

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

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

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

\[
\rho_{V\gamma}(r, q) = \int_0^1 dz \Psi_V(z, r)\Psi_\gamma(z, r) \exp[i(1 - 2z)rq/2]
\]
For the dipole cross section we assume a factorized form:

$$\sigma(x, r, q) = \sigma(x, r) \exp[-Bq^2/2]$$

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:

$$\Psi^*_V(z, r) \Psi_\gamma(z, r) = \frac{e_Q \sqrt{4\pi \alpha_{em}} N_c}{4\pi^2 z(1 - z)} \left\{ m_Q^2 K_0(m_Q r) \psi(z, r) - [z^2 + (1 - z)^2] m_Q K_1(m_Q r) \frac{\partial \psi(z, r)}{\partial r} \right\}$$
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:
  \[
  \Gamma_A(x, b, r) = 1 - \exp\left[-\frac{1}{2} \sigma(x, r) T_A(b)\right]
  \]
- 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:
  \[
  \Gamma_A(x, b, r) = 1 - \exp\left[-\frac{1}{2} \sigma(x, r) (1 - i \rho_N) T_A(b)\right]
  \]
- The optical thickness \( T_A(b) \) is calculated from a Wood-Saxon distribution \( n_A(\vec{r}) \):
  \[
  T_A(b) = \int_{-\infty}^{\infty} dz \, n_A(\vec{r}) ; \quad \vec{r} = (b, z) , \quad \int d^2b \, T_A(b) = A
  \]
Formalizm: Nuclear target

- The diffractive amplitude in $b$-space is:

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

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

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

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

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

\[ \gamma^+ \quad \text{with} \quad r \quad - \quad \text{dipole size} \]

\[ z \quad - \quad \text{longitudinal momentum fraction of the quark/antiquark} \]

- Factorization: dipole formation + dipole interaction

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

- Dipole-proton interaction

\[ \hat{\sigma}(r, x) = \sigma_0 \left( 1 - \exp\{-\hat{r}^2\} \right) \quad \hat{r} = r/R_s(x) \]
Dipole cross section: GBW(Golec-Biernat-Wüsthoff)

- GBW parametrization with heavy quarks:
  \[ f = u, d, s, c \]
  \[ \hat{\sigma}(r, x) = \sigma_0 \left( 1 - \exp(-r^2/R_s^2) \right), \quad R_s^2 = Q_0^2 \cdot (x/x_0)^\lambda \text{ GeV}^2 \]

- The dipole scattering amplitude in such a case reads
  \[ \hat{N}(r, b, x) = \theta(b_0 - b) \left( 1 - \exp(-r^2/R_s^2) \right) \]
  where
  \[ \hat{\sigma}(r, x) = 2 \int d^2b \hat{N}(r, b, x) \]

- 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

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

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

\[ x g(x, \mu_0^2) = A_g x^{\lambda_g} (1 - x)^{C_g} \]

- soft + hard gluon:

\[ x g(x, \mu_0^2) = A_g x^{\lambda_g} (1 - x)^{C_g} (1 + D_g x + E_g x^2) \]

- A slightly different choice of the scale \( \mu \):

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

- 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

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

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:

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

- **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 available in DIS (ZM-VFNS, ACOT, FONLL, RT, FFNS)
  - predictions for hadron-collider data through fast interfaces (APPLgrid, FastNLO)

- **Comparison data-predictions via $\chi^2$:**
  - multiple definitions available
  - consistent treatment of the systematic uncertainties

- **Minimise the $\chi^2$ w.r.t. the fitted parameters**
  - using MINUIT

- **Useful drawing tools**
Predictions for $J/\psi$ production on the proton target

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

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

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

$$R_{\text{skewed}} = \frac{2^{2\Delta IP + 3}}{\sqrt{\pi}} \cdot \frac{\Gamma(\Delta IP + 5/2)}{\Gamma(\Delta IP + 4)}$$
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, 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

\[
\begin{align*}
A & \rightarrow A + J/\psi \\
A & \rightarrow A + J/\psi
\end{align*}
\]

- 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 \(\xi = 2R_A\omega/\gamma\)
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 and $\sqrt{s_{NN}} = 5.02$ TeV
Results for photoproduction in ultraperipheral collisions


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 $\sqrt{s_{NN}} = 5.02$
Dipole cross section vs. gluon distribution

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

\[
\sigma(x, r) = \frac{\pi^2}{3} r^2 \alpha_s(q^2) x g(x, q^2), \quad q^2 \approx \frac{10}{r^2}
\]

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:

\[
\sigma_A(x, r) = 2 \int d^2 b \Gamma_A(x, b, r)
\]

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 $\Gamma_A(x, b, r)$, 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.
Diffractive incoherent photoproduction on the nuclear target: Typical energies as will be accessible at a future EIC

\[ -t = \Delta^2 \], single scattering has the same diffractive slope as on the free nucleon, multiple scatterings have smaller slopes.
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 $\sqrt{s_{NN}} = 2.76$ GeV and $\sqrt{s_{NN}} = 5.02$ 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 $Q^2$. 