Coherent production

In the coherent vector meson photoproduction, the nucleus target remains intact.

![Diagram](image-url)

The rapidity differential cross section for the $AA \rightarrow AVA$ process can be factorized:

$$
\frac{d\sigma_{AA\rightarrow AVA}}{dy} = \int d^2b \frac{\omega dN_\gamma(\omega, b)}{d\omega} \frac{d\sigma_{\gamma A\rightarrow VA}(\omega, b)}{d^2b} + (y \rightarrow -y).
$$
Photon flux and ultraperipheral collisions

Photon flux at $b$ emitted by the projectile nucleus excluding strong interactions is [Glauber, Matthiae, Nucl. Phys. B 21, 135 (1970)]

$$\omega \frac{dN_\gamma(\omega, b)}{d\omega} = \int d^2 b\gamma \frac{\omega N_\gamma(\omega, b_\gamma)}{d\omega d^2 b_\gamma} \exp \left( -\sigma_{NN}^{\text{tot}} \int d^2 b' T_A(b') T_A(|b_\gamma - b'|) \right).$$  
(1)

The Weizsäcker-Williams method calculated for a punctual charge is used to calculate the $b$-dependent photon flux:

$$\omega d^3 N_\gamma(\omega, b_\gamma) = Z^2 \alpha_{em} \omega^2 \frac{K_1^2}{\pi^2 \gamma^2} \left( \frac{b_\gamma \omega}{\gamma} \right),$$  
(2)

The Woods-Saxon distribution for the lead nuclear density was used in the thickness function

$$T_A(b) = \int_{-\infty}^{+\infty} dz \, \rho_A(b, z) \quad \text{with} \quad \rho_A(b, z) = \frac{N_A}{1 + \exp \left[ \left( \sqrt{b^2 + z^2} - R_C \right) / \delta \right]},$$  
(3)

where $N_A$ is the normalization and the parameters for lead (Pb) nucleus are $R_C = 6.62$ fm and $\delta = 0.546$ fm.
Color dipole approach
Wave functions

The wave function overlap is:

$$[\Psi^* \Psi](\beta, r) = \frac{e_f e \sqrt{N_c}}{(2\pi)^{3/2} 2\beta(1 - \beta)} \left[ m_f^2 K_0(\epsilon r)\psi_{n,L}(\zeta) - (\beta^2 + (1 - \beta)^2) e K_1(\epsilon r) \partial_r \psi_{n,L}(\zeta) \right],$$

(4)

with $\zeta^2 = \beta(1 - \beta)r^2$. The QED photon wave function is used. The vector meson wave function is calculated from AdS/QCD holographic model in the light cone. The scalar part is factorized to:

$$\psi(\beta, \zeta, \varphi) = e^{iL\varphi} \sqrt{\beta(1 - \beta)} \frac{\phi(\zeta)}{\sqrt{2\pi\zeta}} e \frac{m_q^2}{\beta} + \frac{m_q^2}{1 - \beta},$$

The $\phi(\zeta)$ wave function is found by solving the relativistic equation

$$\left( -\frac{d^2}{d\zeta^2} - \frac{1 - 4L^2}{4\zeta^2} + U(\zeta) \right) \phi(\zeta) = M^2 \phi(\zeta)$$

with effective confining potential:

$$U(\zeta, J) = \kappa^4 \zeta^2 + 2\kappa^2 (J - 1)$$

The solutions are HO wave functions, with eigenvalues

$$M^2 = 4\kappa^2 \left( n + \frac{J}{2} + \frac{L}{2} \right).$$
The left panel shows the mass spectroscopy of $\rho$ and $\omega$ vector mesons.

The right panel presents the LF wave functions for the $\rho$ vector meson at ground and excited states.
The total cross sections for the $\gamma A \rightarrow VA$ process is

$$
\frac{d\sigma_{\gamma A \rightarrow VA}(\omega, b)}{d^2b} = \left| \int d\beta d^2r \Psi^*_V \Psi_\gamma (\beta, r) \left( 1 - e^{-\sigma_{q\bar{q}}(x,r)T_A(b)/2} \right) \right|^2
$$

\[7\] Dipole-nucleus cross section
The 2017 fit of the GBW model was used to describe the dipole cross section $\sigma_{q\bar{q}}$.

$$\sigma_{q\bar{q}}(x, r) = \sigma_0 \left(1 - e^{-r^2 Q_s^2(x)/4}\right),$$  \hspace{1cm} (5)

where parameters were taken from the Golec-Biernat & Sapeta 2017 fit to HERA DIS data: $\sigma_0 = 27.32 \text{ mb}$, $Q_s^2(x) = Q_0^2 \left(x_0/x\right)^\lambda$, with $Q_0^2 = 1 \text{ GeV}^2$, $x_0 = 0.42 \times 10^{-4}$ and $\lambda = 0.248$.

1. **Real part**

$$\sigma_{q\bar{q}}(x, r) \Rightarrow \sigma_{q\bar{q}}(x, r) \left(1 - i \frac{\pi}{2\lambda}\right)$$

2. **Skewness**

$$R_g(\lambda) = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + 5/2)}{\Gamma(\lambda + 4)}$$

$$\lambda = \frac{\partial \ln \sigma_{q\bar{q}}(x, r)}{\partial \ln (1/x)}$$
At high energies, the $q\bar{q}$ pair lifetime, called coherence length, is defined as

$$l_c = \frac{2\omega'}{M_V^2}. \quad (6)$$

The dipole model considers it to be much bigger than the nucleus radius.

At high energies, we need to consider that the photon can split into higher states with gluons $|q\bar{q}g\rangle$, $|q\bar{q}gg\rangle$, ..., with smaller coherence lengths.

• Higher states fully considered when the proton is the target. Effectively, they are included in the GBW fit.
• When the nucleus is the target, higher states contribute less since they do not survive long enough.
• This reduction of the $\gamma A$ cross section is called *gluon shadowing*.
• As a first approximation, it is just a rescaling of the dipole cross section by the factor $R_G$
  \[
  \sigma_{q\bar{q}}(r, x) \rightarrow \sigma_{q\bar{q}}(r, x) R_G(x, \mu^2) .
  \]
In the heavy vector meson case it is calculated with EPPS16 and a factorization scale $\mu = \frac{M_V}{2}$.

[Henkels, E.G.O., Pasechnik, Trebien, Phys. Rev. D 102, 014024 (2020)].

The evolution does not reach the light vector meson scale.

We do not have gluon shadowing for smaller scales $\Rightarrow$ This is a **PROBLEM**.
Gluon shadowing extraction from data

The available data led to an optimal value for the gluon shadowing

\[ R_G = 0.85 \]
Coherent photoproduction predictions

We used the same $R_G = 0.85$ factor to make predictions for other light vector mesons.

Measurements can bring information about the $R_G$ scale dependence.
$\rho$, $\omega$, and $\phi$ vector mesons

Predictions for the ratio between the excited state cross section and its corresponding ground state cross section.

This can be a tool for finding the best dipole cross section model.
• **Light vector meson** photoproduction: small hard scales $Q^2$.

• The **Glauber-Gribov** approach is used for nuclear targets.

• The inclusion of **gluon shadowing** $R_g$ is necessary.

• Fitting to ALICE $\rho(1S) \text{ UPC}$ and E665 $F_2$ data gives $R_g = 0.85$.

• We make **predictions**: $\rho(2S)$, $\omega(1S, 2S)$, and $\phi(1S, 2S)$.

• The **ratio** between excited and ground state cross sections depend on **vector meson wavefunctions** and probe the **dipole cross section**.

**See more:**
Haimon Trebien & Bruna Stahlhöfer talks
EXTRA SLIDES
The slope parameter for heavy vector mesons takes the form:

\[ B \left( W, Q^2 \right) \approx B_0 + 4\alpha'(0) \ln \left( \frac{W}{W_0} \right) - B_1 \ln \left( \frac{Q^2 + M_V^2}{M_{J/\Psi}^2} \right), \quad (7) \]

while the one for light vector mesons is given by:

\[ B = N \left[ 14.0 \left( \frac{1\text{GeV}^2}{Q^2 + M_V^2} \right)^{0.2} + 1 \right], \quad (8) \]
Slope parameter

\[ b \text{ [GeV}^2] \]

\[ \mu^2 \text{ [GeV}^2] \]

\( e p \rightarrow \rho p \)

\( e p \rightarrow \phi p \)

\( ep \rightarrow J/\psi p \)

DVCS

H1

ZEUS
GBW

It has the form:

\[ \sigma_{q\bar{q}}(x, r) = \sigma_0 \left( 1 - e^{-\frac{r^2 Q_s^2(x)}{4}} \right), \]  

with saturation scale defined as \( Q_s^2(x) = Q_0^2 \left( \frac{x_0}{x} \right)^{\lambda} \).

KST

It includes corrections for small \( \hat{s} \equiv W^2 \).

\[ \sigma_{q\bar{q}}(r, \hat{s}) = \sigma_0(\hat{s}) \left[ 1 - e^{-r^2/R_0^2(\hat{s})} \right]. \]

In this case, the \( \hat{s} \)-dependence appears in \( \sigma_0(\hat{s}) \) and \( R_0(\hat{s}) \), which are given by

\[ R_0(\hat{s}) = 0.88\text{fm} \left( s_0/\hat{s} \right)^{0.14}, \quad \sigma_0(\hat{s}) = \sigma_{\text{tot}}(\hat{s}) \left( 1 + \frac{3R_0^2(\hat{s})}{8 \langle r_{ch}^2 \rangle_\pi} \right). \]
bSat

The partial dipole amplitude is

\[ N(x, r, b) = 1 - \exp \left( -\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b) \right) \]  

(12)

with the following scale dependence \( \mu^2 = 4/r^2 + \mu_0^2 \).

BK

The BK evolution equation is given by

\[
\frac{\partial N(r, b, Y)}{\partial Y} = \int dr_1 K(r, r_1, r_2) \left( N(r_1, b_1, Y) + N(r_2, b_2 Y) - N(r, b, Y) \right. \\
\left. - N(r_1, b_1, Y) N(r_2, b_2, Y) \right) .
\]  

(13)

Gluon recombination effects are taken into account in the non-linear term.
bCGC

It is the interpolation of solutions for the BFKL and the BK:

\[
N(x, r, b) = \begin{cases} 
N_0 \left( \frac{r Q_s}{2} \right)^2 \left[ \gamma_s + \frac{1}{\eta \Lambda Y} \right] \ln \left( \frac{2}{r Q_s} \right) & \text{if } r Q_s \leq 2 \\
1 - e^{-A \ln^2 (B r Q_s)} & \text{if } r Q_s > 2
\end{cases}
\]

(14)

The \(b\)-dependence is introduced in the saturation scale

\[
Q_s \equiv Q_s(x, b) = \left( \frac{x_0}{x} \right)^{\Lambda/2} \left[ \exp \left( -\frac{b^2}{2B_{CGC}} \right) \right]^{1/(2 \gamma_s)}
\]

(15)