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Coherent photoproduction of light vector mesons off nuclear targets in the dipole picture.

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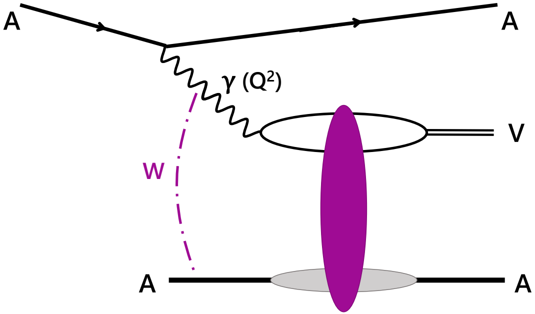
Coherent production

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



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

$$\frac{d\sigma^{AA\to AVA}}{dy} = \int d^2b \, \frac{\omega dN_\gamma(\omega,b)}{d\omega} \frac{d\sigma^{\gamma A\to VA}(\omega,b)}{d^2b} + (y \to -y)\,.$$

Photon flux and ultraperipheral collisons

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

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

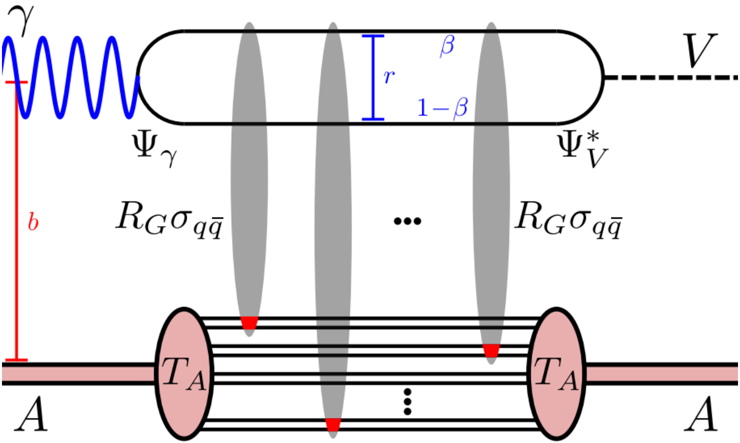
The Weizsäcker-Williams method calculated for a punctual charge is used to calculate the b-dependent photon flux:

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

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

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

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


γ
V
r
β
$1-\beta$
Ψ_γ
Ψ_V^*
b
$R_G\sigma_{q\bar{q}}$
$R_G\sigma_{q\bar{q}}$
T_A
T_A
A
A

Wave functions

The wave function overlap is:

$$[\Psi_V^*\Psi_\gamma](\beta, r) = \frac{e_f e\sqrt{N_c}}{(2\pi)^{3/2}2\beta(1-\beta)}\left[m_f^2 K_0(\epsilon r)\psi_{n,L}(\zeta) - \left(\beta^2 + (1-\beta)^2\right)\epsilon K_1(\epsilon r)\partial_r\psi_{n,L}(\zeta)\right], \quad (4)$$

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

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

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

$$M^2 = 4\kappa^2\left(n + \frac{J}{2} + \frac{L}{2}\right).$$

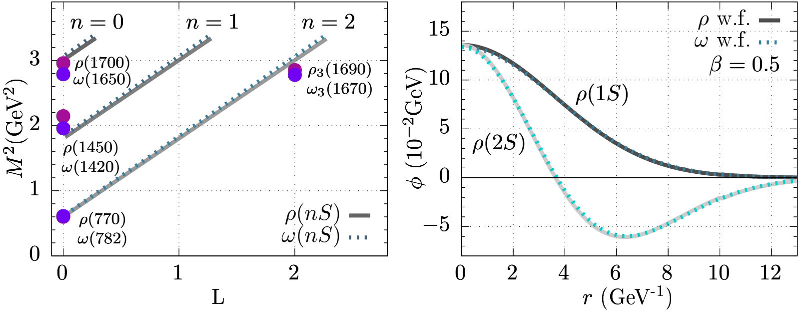
Vector meson wave function

AdS/QCD holographic model

Mass dependent κ

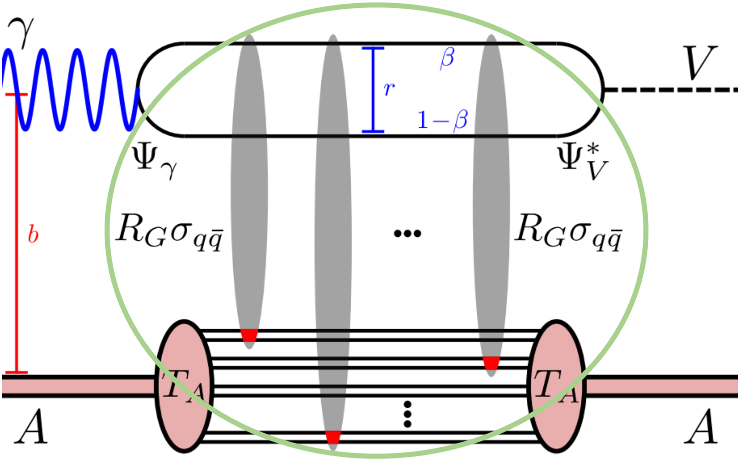
$$\kappa = M_{V\,(n=0)}/\sqrt{2}$$

The left panel shows the mass spectroscopy of ρ and ω vector mesons.



The right panel presents the LF wave functions for the ρ vector meson at ground and excited states.

Dipole-nucleus cross section



The total cross sections for the $\gamma A \to VA$ process is

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

Corrections

The 2017 fit of the GBW model was used to describe the dipole cross section $\sigma_{q\bar{q}}$.

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

where parameters were taken from the Golec-Biernat & Sapeta 2017 fit to HERA DIS data: $\sigma_0 = 27.32$ mb, $Q_s^2(x) = Q_0^2\,(x_0/x)^{\lambda}$, with $Q_0^2 = 1$ 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

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

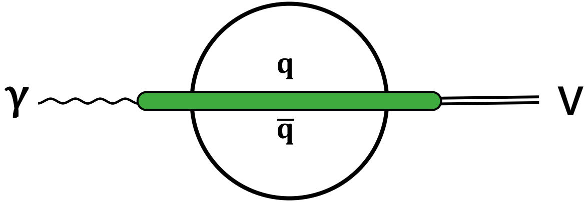
$$\lambda = \frac{\partial \ln \sigma_{q\bar{q}}(x, r)}{\partial \ln (1/x)}$$

Coherence length

At high energies, the $q\bar{q}$ pair lifetime, called coherence length, is defined as

$$l_c = \frac{2\omega'}{M_V^2} \, . \tag{6}$$

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.

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

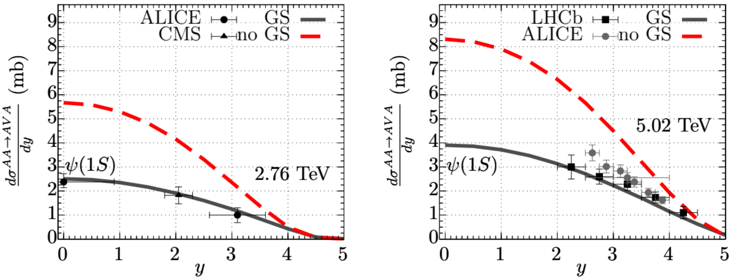
Gluon shadowing

- 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 γA 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

$$\sigma_{q\bar{q}}(r,x) \rightarrow \sigma_{q\bar{q}}(r,x) R_G(x,\mu^2)\,.$$

Gluon shadowing for heavy vector mesons

In the heavy vector meson case it is calculated with EPPS16 and a factorization scale $\mu = M_V/2$.
[Henkels, E.G.O., Pasechnik, Trebien, Phys. Rev. D 102, 014024 (2020)].

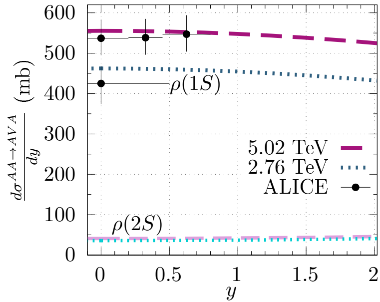


The evolution does not reach the light vector meson scale.

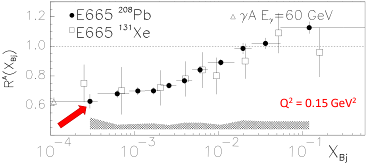
We do not have gluon shadowing for smaller scales
$\hookrightarrow$ This is a **PROBLEM**.

Gluon shadowing extraction from data

ρ vector meson



F_2 data



[Data taken from the Fermilab E665 Collaboration,

Z.Phys.C 67 (1995) 403-410]

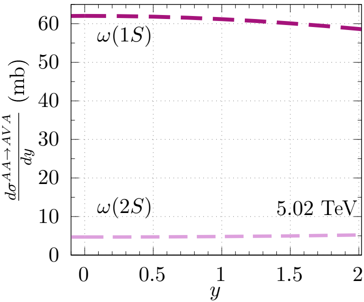
$$\frac{F_2^A}{AF_2^p} = 0.537$$

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

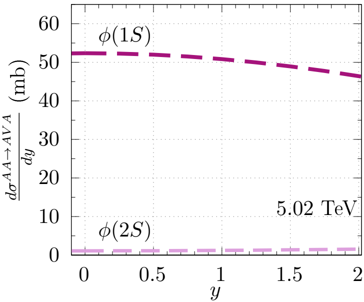
$$R_G = 0.85$$

Coherent photoproduction predictions

ω vector meson



ϕ vector meson

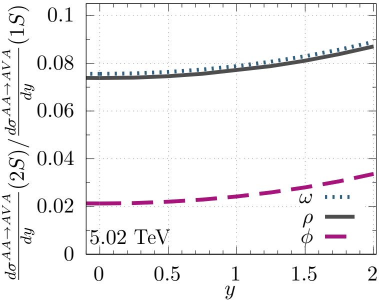


We used the same $R_G = 0.85$ factor to make predictions for other light vector mesons.

Measurements can bring information about the R_G scale dependence.

$2S$ to $1S$ ratio predictions

ρ, ω, and ϕ 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.

Conclusion

- **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 $\rho(1S)$ UPC** and E665 F_2 data gives $\boldsymbol{R_g = 0.85}$.
- 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

Thank you

EXTRA SLIDES

Slope parameter

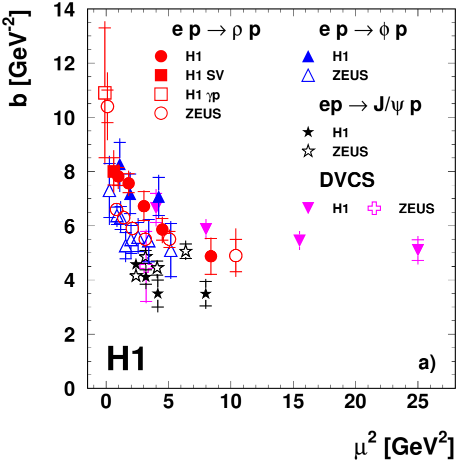
The slope parameter for heavy vector mesons takes the form:

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

while the one for light vector mesons is given by:

$$B = N\left[14.0\left(\frac{1\mathrm{GeV}^2}{Q^2+M_V^2}\right)^{0.2}+1\right], \tag{8}$$

Slope parameter



Color dipole parametrizations
without impact parameter dependence

1. GBW

It has the form:

$$\sigma_{q\bar{q}}(x,r) = \sigma_0 \left(1 - e^{-\frac{r^2 Q_s^2(x)}{4}}\right), \tag{9}$$

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

2. KST

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

$$\sigma_{\bar{q}q}(r,\hat{s}) = \sigma_0(\hat{s}) \left[1 - e^{-r^2/R_0^2(\hat{s})}\right]. \tag{10}$$

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

$$R_0(\hat{s}) = 0.88\text{fm}\,(s_0/\hat{s})^{0.14}, \quad \sigma_0(\hat{s}) = \sigma_{\text{tot}}^{\pi p}(\hat{s}) \left(1 + \frac{3R_0^2(\hat{s})}{8\left\langle r_{\text{ch}}^2 \right\rangle_\pi}\right). \tag{11}$$

Color dipole parametrizations
with impact parameter dependence

3. bSat

The partial dipole amplitude is

$$N(x, \boldsymbol{r}, \boldsymbol{b}) = 1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b)\right) \tag{12}$$

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

4. BK

The BK evolution equation is given by

$$\frac{\partial N(r, b, Y)}{\partial Y} = \int d\boldsymbol{r_1} K\left(r, r_1, r_2\right) \left(N\left(r_1, b_1, Y\right) + N\left(r_2, b_2 Y\right) - N(r, b, Y)\right.$$
$$\left. - N\left(r_1, b_1, Y\right) N\left(r_2, b_2, Y\right)\right) \; . \tag{13}$$

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

Color dipole parametrizations

5. bCGC

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

$$N(x,\mathbf{r},\mathbf{b}) = \begin{cases} N_0 \left(\frac{r\,Q_s}{2}\right)^{2[\gamma_s + (1/(\eta\Lambda Y))\ln(2/rQ_s)]} & rQ_s \le 2 \\ 1 - e^{-\mathcal{A}\ln^2(\mathcal{B}\,r\,Q_s)} & rQ_s > 2 \end{cases} . \quad (14)$$

The b-dependence is introduced in the saturation scale

$$Q_s \equiv Q_s(x,b) = \left(\frac{x_0}{x}\right)^{\Lambda/2}\left[\exp\left(-\frac{b^2}{2B_{\text{CGC}}}\right)\right]^{1/(2\gamma_s)} . \quad (15)$$