Predictions for exclusive vector meson production in the electron-ion collider.

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Outline

- Motivation
- Dipole approach
- Saturation models
- Results: V. M. production
  1. Coherent
  2. Incoherent
- Conclusions
Motivation

- Looking for Color Glass Condensate (CGC).
- At small $x$ the pQCD predicts that gluons should form the CGC.
- Diffractive processes played a central role in identifying the first signatures of the gluon saturation in DIS at HERA.
- They are of great interest as a tool for studying the low-$x$ dynamics in DIS at the proposed Electron Ion Collider (EIC).
- Vector meson production is an important part of the physics program at an eA collider.
Kinematical variables

\[ s = (l + P)^2 ; \quad W^2 = (P + q)^2 \]
\[ q^2 \equiv -Q^2 = (l - l')^2 = -4EE' \sin^2(\theta/2) \]
\[ x = \frac{Q^2}{2m_N \nu} = \frac{Q^2}{2P.q} = \frac{Q^2}{Q^2 + W^2 - m_N^2} \]

- \( x \) is the Bjorken variable
- \( Q^2 \) is the photon virtuality
- \( W \) is the energy of the \( \gamma^* \)-nucleon system.
At high energies, the lifetime of the $q\bar{q}$ pair is bigger than the interaction time.

The photon fluctuates in a color dipole which interacts with the target.

This fluctuation is given by the photon wave function $\Psi^{\gamma^*}(z, r)$ and the interaction by the cross section $\sigma_{dip}(x, r)$. 
In the CGC formalism $\sigma_{dip}$ can be calculated in the eikonal approximation:

$$\sigma_{dip}(x, r) = 2 \int d^2 b N(x = e^{-Y}, r, b)$$

$N(x = e^{-Y}, r, b)$ is the forward dipole-target scattering amplitude

encodes all the information about the hadronic scattering, and thus about the non-linear and quantum effects in the hadron wave function.

Can be obtained by solving the BK (JIMWLK) evolution equation in the rapidity $Y \equiv \ln(1/x)$.

Many groups have studied the numerical solution of the BK equation. It is a program in progress [Albacete (2007), Armesto et al. (2009)].

In the meantime it is necessary to use phenomenological models.
Saturation models


\[
N(x, r) = \left[ 1 - \exp \left( -\frac{(Q_s(\bar{x}) r)^2}{4} \right) \right]
\]

\[
Q_s^2(\bar{x}) = Q_0^2 \left( \frac{x_0}{\bar{x}} \right)^\lambda \text{ GeV}^2
\]

\[
\bar{x} = \frac{Q^2 + 4 m_f^2}{Q^2 + W^2_{\gamma N}}
\]

Parameters: \( \sigma_0 = 23 \text{ mb}, \lambda = 0.288 \text{ and } x_0 = 3.04 \times 10^{-4}. \)
Saturation models


\[
\mathcal{N}(x, r) = N_0 \left( \frac{r Q_s}{2} \right)^2 \left( \gamma_s + \frac{\ln(2/r Q_s)}{\kappa \lambda y} \right) \quad r Q_s \leq 2
\]

\[
\mathcal{N}(x, r) = 1 - e^{-a \ln^2(b r Q_s)} \quad r Q_s > 2
\]

where \(y \equiv \ln \frac{1}{x}\) and \(Q_s \equiv Q_s(x) = Q_0(x_0/x)^{\lambda/2}\)

Parameters: \(N_0 = 0.7\), \(Q_0 = 1\)GeV, \(\sigma_0 = 2\pi R^2\) with \(R = 0.641\) fm, \(\lambda = 0.253\), \(x_0 = 0.267 \times 10^{-4}\), \(\gamma_s = 0.63\) and \(\kappa = 9.9\).
Saturation models

- Saturation scale with \( b \) dependence.

\[
Q_{s,p} \equiv Q_{s,p}(x, \bar{b}) = \left( \frac{x_0}{x} \right)^{\lambda/2} \left[ \exp \left( - \frac{\bar{b}^2}{2B_{CGC}} \right) \right]^{\frac{1}{2\gamma_s}}.
\]

Parameters: \( \mathcal{N}_0 = 0.558, \gamma_s = 0.46, \lambda = 0.119, x_0 = 1.84 \times 10^{-6} \) and \( B_{CGC} = 7.5\text{GeV}^{-2} \).
Nuclear case

N. Armesto [EPJC26 (2002)]

- Based on the Glauber-Gribov idea ...

- dipole-nucleon scattering amplitude $\rightarrow$ dipole-nucleus scattering amplitude

$$N^A(x, r, b) = 1 - \exp \left[-\frac{1}{2} T_A(b) \sigma_{dip}^{\text{nucleon}}(x, r^2) \right],$$

- $b$ is the impact parameter and $T_A(b)$ is the nuclear profile function.

- $N^A$ considers multiple scattering of the $q\bar{q}$ with a nucleus made of nucleons. $q\bar{q}$ keeps a fixed size during the scattering process, the so-called dipole model.
For vector meson production: \( \gamma^* A \rightarrow VY \)

\[
x = \frac{Q^2 + M_V^2}{Q^2 + W^2}
\]

The scattering is mediated by a color singlet exchange, leaving a rapidity gap in the final state.

The nucleus can be scattered:

1. Elastically \( \rightarrow Y = A \), coherent diffraction
2. Inelastically \( \rightarrow \) the nucleus breaks up, incoherent diffraction.
Results

Predictions for vector meson production
- Make predictions for exclusive vector meson production off nuclei at energies for the future EIC
- Make an estimate of the non-linear physics
- We are taking the linear version of the phenomenological models

\[ r \to 0 \quad \Rightarrow \quad \sigma_{dp}^{GBW} \to \sigma_0 \frac{Q_s(\tilde{x})r^2}{4} \]

\[ rQ_s \leq 2 \quad \Rightarrow \quad \sigma_{dp}^{bCGC} \to \mathcal{N}_0 \left( \frac{rQ_s}{2} \right)^2 \left( \gamma_s + \frac{\ln(2/rQ_s)}{\kappa \lambda y} \right) \]
Coherent process

\[ \gamma^* A \rightarrow V A \]
Coherent production

Kopeliovich et al. [PRC76 (2007)]

If the target is left intact during the scattering, $\gamma^* A \rightarrow V A$, the process is called coherent. In this case the integrated cross section has the form (at $l_c \gg R_A$):

$$
\sigma^{coh} (\gamma^* A \rightarrow V A) = \int d^2 b \left\{ \int d^2 r \int dz |\Psi_V(r, z)|^2 \right\} 
\times \left[ 2 \left( 1 - \exp\left[ -\frac{1}{2} \sigma_{dp} T_A(b) \right] \right) \right] |\Psi_{\gamma^*}(r, z, Q^2)|^2
$$

- $\Psi_{\gamma^*}(r, z, Q^2) \Rightarrow$ QED.
- $\Psi_V(r, z, M^2_V) \Rightarrow$ is determined in a phenomenological way. We are going to consider the boosted Gaussian wave function (BG). (Nemchik et al. [PLB341 (1994); ZPC75 (1997)])
### Parameters

<table>
<thead>
<tr>
<th>$V(m_V)$ (MeV)</th>
<th>$m_f$ (GeV)</th>
<th>$R^2$ (GeV$^{-2}$)</th>
<th>$N_L$</th>
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<th>$\hat{e}_f$</th>
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<tbody>
<tr>
<td>$\rho$ (776)</td>
<td>0.14</td>
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<td>1/\sqrt{2}</td>
</tr>
<tr>
<td>$J/\Psi$ (3097)</td>
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Table 1: Parameters and normalization of the boosted-Gaussian overlap function.
Predictions for the energy dependence of the coherent photoproduction: the cross section grows with the energy and with the atomic number.
Predictions for the energy dependence of the coherent cross section: the cross section grows with the energy and with the atomic number.
The $Q^2$ behavior predicted by the GBW and bCGC models are similar. The difference is associated to the strong dependence on the saturation effects in the proton observed in GBW model. $Q^2$ dependence of the $J/\Psi$ cross section is smaller than the $\rho$ one, this is associated to the hard scale in the $J/\Psi$. 

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Incoherent process

\[ \gamma^* A \rightarrow VX \]
Incoherent production

Kopeliovich et al. [PRC65(2002)]

The incoherent diffractive production cross section of vector meson, $\gamma^* A \rightarrow V X$, is given by:

$$
\sigma^{inc} (\gamma^* A \rightarrow V X) = \frac{|I m A(s, t = 0)|^2}{16\pi B_V}
$$

where for large coherence length ($l_c \gg R_A$):

$$
|I m A(s, t = 0)|^2 = \int d^2b T_A(b)
$$

$$
\times \left[ | \int d^2r \int dz \Psi_V^*(r, z) \sigma_{dp} \exp[-\frac{1}{2}\sigma_{dp} T_A(b)] \Psi \gamma^*(r, z, Q^2)|^2 \right]
$$

and $B_V$ is the slope for vector meson production.
Caldwell and Soares [NPA696(2001)]

For the $B_V$ slope we use a parametrization to experimental data,

\[ B_V = 0.6 \times \left( \frac{14}{(Q^2 + M_V^2)^{0.26}} + 1 \right). \]
Predictions for the energy dependence of the incoherent photoproduction cross section: the cross section grows with the energy and with the atomic number.
Predictions for the energy dependence of the incoherent total cross section.
The $\rho$ production for GBW model, shows an inversion between the solid and long-dot-dashed lines. This inversion has no special meaning. We see that the Pb cross sections are always larger than the corresponding Ca cross sections. This is the expected physical behavior.
Predictions for the ratio
Incoherent to Coherent total cross section production
Predictions for the energy $W$ dependence of the ratio between the incoherent and coherent cross sections. The incoherent contribution is a small fraction of the coherent one and the ratio decreases with the energy. The ratio is larger for small values of the atomic number. These conclusions are weakly dependent model.
The ratio decreases at large $Q^2$, with a strong dependence in the case of the $\rho$ meson. At large $Q^2$ the ratio is larger for $J/\Psi$ than for $\rho$ production.
Some remarks ...

1. one motivation for our work is the search for a new signature of saturation in $eA$ collisions,

2. we can see in all results for bCGC model that there is almost no difference between “linear” and “full” results,

3. in the calculation of the “linear” results we have switched off only the non-linear part of the dipole-nucleon scattering amplitude,

4. there are other non-linear effects involving recombination of gluons from different nucleons, which, in our formalism, we were not able to properly disentangle and switch off.

5. the challenging task here is to disentangle properly the linear effects in the nucleus.
Conclusions

- In this work we have estimated the coherent and incoherent cross sections for the exclusive vector meson production considering color dipole approach and phenomenological saturation models.

- Our results demonstrate that the coherent production of vector mesons is dominant, with a small contribution coming from incoherent processes.

- Probably in the future $eA$ colliders the separation between coherent and incoherent processes will be difficult. However, in view of our results it might be worth trying.
The imaginary forward scattering amplitude is given by

\[ \text{Im} A(\gamma p \to V p) = \sum \int dz \, d^2 r \, \Psi^\gamma(z, r; Q^2) \, \sigma_{\text{dip}}^{\text{target}}(\tilde{x}, r) \, \Psi^*_{V}(z, r; M^2_V), \]

where

- \( \Psi^\gamma(z, r; Q^2) \) and \( \Psi^V(z, r; M^2_V) \) are the photon and vector meson wave functions, in the light cone.
- \( r \) defines the dipole transversal size.
- \( z(1-z) \) is the quark (antiquark) longitudinal momentum fraction.
Nemchik et al. [PLB341 (1994); ZPC75 (1997)]; Marquet et al. [PRD76(2007)]

The overlap function between the photon and vector meson wave function is given by

$$\Phi_{\lambda}^{\gamma*V}(z, r; Q^2, M^2_V) \rightarrow \left[\Psi^{V,\lambda}(z, r; M^2_V)\right]^* \Psi^{\gamma*,\lambda}(z, r; Q^2).$$

So,

$$\Phi_{L}^{\gamma*V} = \hat{e}_f \sqrt{\frac{\alpha_e}{4\pi}} N_c 2QK_0(\varepsilon r) \left[M_V z(1 - z)\phi_L(r, z) + \frac{m_f^2 - \nabla^2 r}{M_V}\phi_L(r, z)\right],$$

$$\Phi_{T}^{\gamma*V} = \hat{e}_f \sqrt{\frac{\alpha_e}{4\pi}} N_c \frac{\alpha_e N_c}{2\pi^2} \left\{m_f^2 K_0(\varepsilon r)\phi_T(r, z) - [z^2 + (1 - z)^2]\varepsilon K_1(\varepsilon r)\partial_r\phi_T(r, z)\right\},$$

where

$$\phi_{L,T} = N_{L,T} \exp \left[-\frac{m_f^2 R^2}{8z(1 - z)} + \frac{m_f^2 R^2}{2} - \frac{2z(1 - z)r^2}{R^2}\right].$$
The overlap function between the photon and vector meson wave function is given by

\[ \Phi_{\gamma}^* (z, r; Q^2, M_V^2) \rightarrow [\Psi^V,\lambda (z, r; M_V^2)]^* \Psi^{\gamma*,\lambda} (z, r; Q^2) . \]

So,

\[
\Phi_{\gamma}^* \quad = \quad \hat{e}_f \sqrt{ \frac{\alpha_e}{4\pi} N_c 2Q K_0(\varepsilon r) } \left[ M_V z(1 - z) \phi_L (r, z) + \frac{m_f^2 - \nabla^2_r}{M_V} \phi_L (r, z) \right] ,
\]

\[
\Phi_{T}^* \quad = \quad \hat{e}_f \sqrt{ \frac{\alpha_e}{4\pi} N_c \frac{\alpha_e N_c}{2\pi^2} } \left\{ m_f^2 K_0(\varepsilon r) \phi_T (r, z) - [z^2 + (1 - z)^2] \varepsilon K_1(\varepsilon r) \partial_r \phi_T (r, z) \right\} ,
\]

where

\[
\phi_{L,T} = N_{L,T} \exp \left[ -\frac{m_f^2 R^2}{8z(1 - z)} + \frac{m_f^2 R^2}{2} - \frac{2z(1 - z)r^2}{R^2} \right] .
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