Exclusive Vector Meson Photoproduction at Run 2 LHC energies: Color dipole predictions

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Outline

- Photon – induced interactions in hadronic collisions
- Exclusive vector meson photoproduction at the LHC – The color dipole model
- Comparison with the LHC data and predictions for the Run 2 energies
LHC = Photon collider
Motivation

Photon – Induced Interactions:

Center of mass energies

1. $\gamma h$ Processes: $\sigma(h_1 h_2 \rightarrow X) = n_h(\omega) \otimes \sigma^{\gamma h \rightarrow X}(W_{\gamma h})$

2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \rightarrow X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \rightarrow X}(W_{\gamma\gamma})$

<table>
<thead>
<tr>
<th>LHC</th>
<th>Interaction</th>
<th>$W_{\gamma p} \lesssim 8390$ GeV</th>
<th>$W_{\gamma\gamma} \lesssim 4504$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td></td>
<td>$W_{\gamma A} \lesssim 1500$ (2130) GeV</td>
<td>$W_{\gamma\gamma} \lesssim 260$ (480) GeV</td>
</tr>
<tr>
<td>$pPb$ (Ar)</td>
<td></td>
<td>$W_{\gamma A} \lesssim 950$ GeV</td>
<td>$W_{\gamma\gamma} \lesssim 160$ GeV</td>
</tr>
<tr>
<td>Pb Pb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HERA</td>
<td>$ep$</td>
<td>$W_{\gamma p} \lesssim 200$ GeV</td>
<td></td>
</tr>
</tbody>
</table>

Photoproduction in pp collisions at LHC probes photon – hadron center – of – mass energies one order of magnitude larger than HERA.
Exclusive vector meson photoproduction at the LHC
Exclusive vector meson photoproduction at the LHC
Exclusive vector meson photoproduction at the LHC

At leading order in LL(1/x) approx.:

\[
\left. \frac{d\sigma^{\gamma h \rightarrow V h}}{dt} \right|_{t=0} = N \frac{\pi^3 \Gamma_{e^+e^-} M_V^3}{48 \alpha_{em}} \left[ \frac{\alpha_s(Q^2)}{Q^4} x g_h(x, Q^2) \right]^2
\]

Cross section is proportional to the square of the hadron gluon distribution at \( x = 4Q^2/W^2 \)

\(^a\)VPG, Bertulani, PRC65, 054905 (2002)
Exclusive vector meson photoproduction at the LHC

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\frac{d\sigma^{\gamma p \rightarrow VH}}{dt} \bigg|_{t=0} = N \pi^3 \Gamma_{ee} \frac{M_V^3}{48 \alpha_{em}} \left[ \frac{\alpha_s(\bar{Q}^2)}{Q^4} x g_h(x, \bar{Q}^2) \right]^2
\]

Cross section is proportional to the square of the hadron gluon distribution at \( x = 4\bar{Q}^2/W^2 \)

Important probe of the QCD dynamics at high energies!

\textsuperscript{a}VPG, Bertulani, PRC65, 054905 (2002)
Linear QCD Evolution equations predict a power growth of gluon distribution at small $-x$;
Linear QCD Evolution equations predict a power growth of gluon distribution at small $-x$;

Number of gluons in the hadron becomes so large that gluon recombine. Nonlinear effects should be taken into account.
Exclusive vector meson photoproduction in UPHIC: Color Dipole Formalism

\[ \frac{d\sigma}{d^2b\,dy} \left[ h_1 + h_2 \rightarrow h_1 \otimes V \otimes h_2 \right] = [\omega N_{h_1}(\omega, b) \sigma_{\gamma h_2 \rightarrow V \otimes h_2} (\omega)]_{\omega_L} + [\omega N_{h_2}(\omega, b) \sigma_{\gamma h_1 \rightarrow V \otimes h_1} (\omega)]_{\omega_R} \]

\[ \sigma(\gamma h \rightarrow V h) = \int_{-\infty}^{0} \frac{d\sigma}{dt} dt = \frac{1}{16\pi} \int_{-\infty}^{0} |A_T^{\gamma h \rightarrow V h}(x, \Delta)|^2 dt \]

\[ A_T^{\gamma h \rightarrow V h}(x, \Delta) = i \int dz \, d^2r \, d^2b_h e^{-i[b_h-(1-z)r] \cdot \Delta} (\Psi^V \Psi)_T^{*} 2N_h(x, r, b_h) \]

\(^aVPG, \text{Machado, EPJC 40, 519 (2005)}\)
Exclusive vector meson photoproduction in UPHIC: Color Dipole Formalism

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\frac{d\sigma}{d^2bdy} \left[ h_1 + h_2 \rightarrow h_1 \otimes V \otimes h_2 \right] = \left[ \omega N_{h_1}(\omega, b) \sigma_{\gamma h_2 \rightarrow V \otimes h_2}(\omega) \right]_{\omega_L} + \left[ \omega N_{h_2}(\omega, b) \sigma_{\gamma h_1 \rightarrow V \otimes h_1}(\omega) \right]_{\omega_R}
\]

Overlap function for Vector Mesons

\[
\sigma(\gamma h \rightarrow V h) = \int_{-\infty}^{0} \frac{d\sigma}{dt} dt = \frac{1}{16\pi} \int_{-\infty}^{0} |A_T^{\gamma h \rightarrow V h}(x, \Delta)|^2 dt
\]

\[
A_T^{\gamma h \rightarrow V h}(x, \Delta) = i \int dz d^2r d^2b_h e^{-i[b_h-(1-z)r] \cdot \Delta} (\Psi^V \star \Psi)_T 2N_h(x, r, b_h)
\]
Exclusive vector meson photoproduction in UPHIC: Color Dipole Formalism

\[ W(r) = 2\pi r \int_0^1 dz \left[ \Psi^V(r, z) \Psi^*(r, z) \right] \]
Exclusive vector meson photoproduction in UPHIC: Color Dipole Formalism

\[
\frac{d\sigma}{d^2bdy} [h_1 + h_2 \rightarrow h_1 \otimes V \otimes h_2] = [\omega N_{h_1}(\omega, b) \sigma_{\gamma h_2 \rightarrow V \otimes h_2}(\omega)]_{\omega_L} + [\omega N_{h_2}(\omega, b) \sigma_{\gamma h_1 \rightarrow V \otimes h_1}(\omega)]_{\omega_R}
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\sigma(\gamma h \rightarrow V h) = \int_{-\infty}^{0} \frac{d\sigma}{dt} \, dt = \frac{1}{16\pi} \int_{-\infty}^{0} |A_{\gamma h \rightarrow V h}^T(x, \Delta)|^2 \, dt
\]

\[
A_{\gamma h \rightarrow V h}^T(x, \Delta) = i \int dz \, d^2r \, d^2b_h e^{-i[b_h-(1-z)r] \cdot \Delta} (\Psi^V*\Psi)_T \, 2N_h(x, r, b_h)
\]

Forward dipole - hadron scattering amplitude: Determined by the QCD dynamics
Diffractive vector meson photoproduction in UPHIC: Color Dipole Formalism

* IP – SAT model:

* bCGC model:

"Classical" CGC model.

"Quantum" CGC model.

Important: Both models describe quite well the HERA ep data.
A unified description of combined inclusive HERA data & diffractive data in CGC


The dipole scattering amplitude is the main ingredient with 3 or 4 free parameters fixed via a fit to the reduced cross-section.
Diffractive vector meson photoproduction in UPHIC: Color Dipole Formalism

The transition between the linear (small $- r$) and nonlinear (large $- r$) is distinct in the different models.
Diffractive vector meson photoproduction in UPHIC: Color Dipole Formalism

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\[A_T^{\gamma h \rightarrow V h}(x, \Delta) = i \int dz \, d^2r \, d^2b_h e^{-i[b_h - (1-z)\Delta] \cdot \vec{r}} \left( \Psi^V \Psi^* \right)_T 2N_h(x, r, b_h)\]

• Nucleus: \[N_A(x, r, b_A) = 1 - \exp \left[ -\frac{1}{2} \sigma_{dp}(x, r^2) T_A(b_A) \right] \]

\[\sigma_{dp}(x, r^2) = 2 \int d^2b_p \, N_p(x, r, b_p)\]

Sums all multiple elastic rescatterings of the dipole.
Diffractive vector meson photoproduction in UPHIC: Color Dipole Formalism

Dipole – nucleus scattering amplitude:

\[ N_A(x, r, b_A) = 1 - \exp \left( -\frac{1}{2} \sigma_{dp}(x, r^2) T_A(b_A) \right) \]
Exclusive vector meson photoproduction in UPHIC: Color Dipole Formalism

\[
\frac{d\sigma}{d^2b\,dy} \left[ h_1 + h_2 \rightarrow h_1 \otimes V \otimes h_2 \right] = \left[ \omega N_{h_1}(\omega, b) \sigma_{\gamma h_2 \rightarrow V \otimes h_2}(\omega) \right]_{\omega_L} + \left[ \omega N_{h_2}(\omega, b) \sigma_{\gamma h_1 \rightarrow V \otimes h_1}(\omega) \right]_{\omega_R}
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\[
\sigma(\gamma h \rightarrow V h) = \int_{-\infty}^{0} \frac{d\sigma}{dt} \, dt = \frac{1}{16\pi} \int_{-\infty}^{0} |A_{T}^{\gamma h \rightarrow V h}(x, \Delta)|^2 \, dt
\]

\[
A_{T}^{\gamma h \rightarrow V h}(x, \Delta) = i \int dz \, d^2r \, d^2b_h e^{-i[b_h - (1-z)r].\Delta} \left( \Psi V^* \Psi \right)_T \, 2N_h(x, r, b_h)
\]

In the dipole picture, all free parameters have been constrained by HERA data. Predictions for UPHIC are parameter free!
Exclusive vector meson photoproduction at the LHC: Comparison to the data and predictions for the Run 2
Predictions for pp collisions
Predictions for pPb collisions
Predictions for PbPb collisions
Open questions:

✓ Validity of the dipole picture for the light meson photoproduction;
✓ Modelling of the gap survival probability for the exclusive vector meson photoproduction;
✓ Treatment of the skeweness in the nucleon and nuclear case;
✓ Inclusion of QCD evolution in the nuclear scattering amplitude;
✓ Inclusion of the next-to-leading order corrections for the vector meson wave functions and nonlinear evolution;
Summary
The diffractive vector meson photoproduction in photon – induced interactions at the LHC is an important probe of the QCD dynamics at high energies.

The Run I data can be sucessfully described by the color dipole formalism taking into account the nonlinear effects in the QCD dynamics.

The Run II data can be used to constrain the description of the dipole – hadron scattering amplitude and the vector meson wave function.

Complementary studies can be performed by analysis of the double vector meson production and the vector meson production associated to a leading neutron.
The diffractive vector meson photoproduction in photon–induced interactions at the LHC is an important probe of the QCD dynamics at high energies.

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Thank you for your attention!
Extras
Comparison with the Run I data

Diffractive $J/\Psi$ photoproduction in hadronic collisions

(a) VPG, Moreira, Navarra, PRC 90, 015203 (2014)
Comparison with the Run I data
Comparison with the Run I data

Diffractive $\rho$ photoproduction in hadronic collisions

(c) VPG, Machado, EPJC 40, 519 (2005); PRC80, 054901 (2009); PRC84, 011902 (2011); Machado, dos Santos, PRC91, 025203 (2015)
Comparison with the Run I data

(a) Diffractive $\gamma$ photoproduction in hadronic collisions

Boosted Gaussian
$s^{1/2} = 7$ TeV

(b) Gaus-LC
$s^{1/2} = 7$ TeV

\cite{VPG, Moreira, Navarra, PLB 472, 172 (2015)}
Diffractive vector meson photoproduction in UPHIC: Impact of the gluon saturation effects

VPG, Spiering, Navarra, PLB 768, 299 (2017)
Diffractive vector meson photoproduction in UPHIC: Impact of the gluon saturation effects

\[ s^{1/2} = 13 \text{ TeV} \quad p + p \rightarrow \rho + p + p \]

\[ s^{1/2} = 13 \text{ TeV} \quad p + p \rightarrow J/\psi + p + p \]

\[ t_{\text{min}} = -m_N^2 M_V^4 / W^4 \]

VPG, Spiering, Navarra, PLB 768, 299 (2017)
Diffractive vector meson photoproduction in UPHIC: Impact of the gluon saturation effects

**pp Collisions:**

**PbPb Collisions:**

\[ t_{\text{min}} = -\frac{m_N^2 M_V^4}{W^4} \]

VPG, Spiering, Navarra, PLB 768, 299 (2017)
Diffractive vector meson photoproduction in UPHIC: Impact of the gluon saturation effects

$pp$ Collisions:

Linear model:

$$N^p(x, r, b_p) = N_0 \left( \frac{r Q_s(b_p)}{2} \right)^{2\left(\gamma_s + \frac{\ln(2/r Q_s(b_p))}{\alpha_s F}\right)}$$

VPG, Spiering, Navarra, PLB 768, 299 (2017)
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PbPb Collisions:

Coherent production:

Incoherent production:

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Diffractive vector meson photoproduction in UPHIC: Impact of the gluon saturation effects

PbPb Collisions:

Linear model: \[ N^A(x, r, b_A) = \frac{1}{2} \sigma_{dp}(x, r) A T_A(b_A) \]

VPG, Spiering, Navarra, PLB 768, 299 (2017)