Elastic vector meson production

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Diffractive vector meson production as a probe of small $x$

Exclusive production of a vector meson

\[ \gamma p \rightarrow Vp \]

\[ \gamma A \rightarrow VA \]

Pocket formula for diffraction (2-gluon exchange, LO)

\[
\left. \frac{d\sigma}{dt} \right|_{t=0} = \frac{16\pi^3\alpha_s^2\Gamma_{ee}}{3\alpha_{em}M_V^5} \bigg[ xg(x, Q^2) \bigg]^2
\]

- Diffraction is very sensitive to (small-$x$) gluons $\Rightarrow$ saturation effects
- In exclusive process we also have $t = \text{Fourier conjugate to } b_T$
  - Access to impact parameter dependence

Ryskin, 1993
Vector meson production in the dipole picture

High energy factorization:

1. $\gamma^* \to q\bar{q}: \Psi_{\gamma}(r, Q^2, z)$
2. $q\bar{q}$ dipole scatters elastically
   Amplitude $N$
3. $q\bar{q} \to J/\Psi: \Psi^V(r, Q^2, z)$

Diffractive scattering amplitude

$$\mathcal{A}_{\gamma^*p \to Vp} \sim \int d^2 b \, dz \, d^2 r \, \Psi_{\gamma} \Psi^V(r, z, Q^2) e^{-ib \cdot \Delta} N(r, x, b)$$

- Access to the spatial structure: Fourier transform to momentum space
- $N(r, x, b)$ satisfies perturbative evolution equation, known from CGC, Non-perturbative input from $F_2$ data fits
Two components – two target averages

Coherent diffraction:
Target remains in the same quantum state
Probes average density

\[
\frac{d\sigma^{\gamma^*p\rightarrow Vp}}{dt} \sim |\langle A^{\gamma^*p\rightarrow Vp} \rangle|^2
\]

\[\langle \rangle: \text{average over target configurations } [N(r, b)]\]

Incoherent/target dissociation:
Total diffractive − coherent cross section
Target breaks up

\[
d\sigma^{\gamma^*p\rightarrow Vp} \sim |\langle A^{\gamma^*p\rightarrow Vp} \rangle|^2 - |\langle A^{\gamma^*p\rightarrow Vp} \rangle|^2
\]

Variance, measures the amount of fluctuations!

Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001
Two components – two target averages

**Coherent diffraction:**
Target remains in the same quantum state
Probes average density

\[
\frac{d\sigma^{\gamma^*p\rightarrow Vp}}{dt} \sim |\langle A^{\gamma^*p\rightarrow Vp} \rangle|^2
\]

**Incoherent/target dissociation:**
Total diffractive – coherent cross section
Target breaks up

\[
\frac{d\sigma^{\gamma^*p\rightarrow Vp^*}}{dt} \sim \langle |A^{\gamma^*p\rightarrow Vp}|^2 \rangle - |\langle A^{\gamma^*p\rightarrow Vp} \rangle|^2
\]

Variance, measures the amount of fluctuations!
\langle \rangle: average over target configurations \([N(r, b)]\)
1. Proton targets
Accessing proton structure in $\gamma + p \rightarrow J/\Psi + p$

Proton structure (IP-Glasma)
- $\langle \text{Color charge density} \rangle \sim \sum \text{three hot spots} \Rightarrow \text{compute } N(r, x, b)$
- Free parameters: hot spot size and separation

![Graph showing elastic VM production graph with different lines for coherent and incoherent cases.](image)
Bjorken-$x$ evolution by solving perturbative JIMWLK equation

Initial state geometry is lost in the evolution

Note: parameters fixed at $W = 75$ GeV, the rest is prediction

$W = 75$ GeV:

$W = 680$ GeV

H.M, B. Schenke, arXiv:1806.06783
Hints of shape evolution from UPC

Ultraperipheral $p + A$ at the LHC:
Photon flux $\sim Z^2 \Rightarrow \gamma + p$ dominates

Forward/backward rapidity $J/\Psi$
High/low $W$

- **Low $W$:** significant coherent and incoherent contributions
- **High $W$:** no incoherent

Black disk limit expectation
LHC disadvantage: $Q^2 = 0$
So far can not see target breakup
Implications on heavy ion phenomenology: p+A

Hydro simulations with nucleon structure fluctuations from $J/\Psi$ data:
- Compatible with the LHC p+A data

Also pure initial state models describe $v_n$, e.g. Dusling, Mace, Venugopalan, 1705.00745
Implications on heavy ion phenomenology: \( p+A \)

\[ \text{Hydro + fluctuations from HERA } J/\psi \text{ data: success} \]

\[ \begin{align*}
  v_2(2) & \text{ IP-Glasm+fluc. proton+MUSIC+UrQMD } \tau_0=0.4 \text{ fm} \\
  v_3(2) & \text{ IP-Glasm+fluc. proton+MUSIC+UrQMD } \tau_0=0.4 \text{ fm} \\
  v_2(2) & \text{ CMS peripheral subtracted} \\
  v_3(2) & \text{ CMS peripheral subtracted}
\end{align*} \]

\[ \begin{align*}
  \text{ALICE } p^+ + \pi^- & \rightarrow \Xi^- + \pi^+ (\eta/s)(T) \\
  \text{ALICE } K^+ + K^- & \rightarrow \Delta^- (\eta/s)(T) \\
  \text{ALICE } p + \bar{p} & \rightarrow \eta (\eta/s)(T) \\
  \text{ALICE } \Lambda + \bar{\Lambda} & \rightarrow \Lambda (\eta/s)(T) \\
  \Lambda \eta/s=0.2
\end{align*} \]

\[ \begin{align*}
  R_{\text{K/Ch}}(\text{fm}) & \text{ decays only} \\
  R_{\text{K/Ch}}(\text{fm}) & \text{ full UrQMD}
\end{align*} \]

H.M, Schenke, Shen, Tribedy, 1705.03177

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2. Nuclear targets

\[ Q_{s,A}^2 \sim A^{1/3} Q_{s,p}^2 \]
Enhanced saturation effects in nuclei

Large nuclear suppression already seen in \( A + A \rightarrow J/\Psi + A + A \)

Calculations with nuclear PDF (EPS09) or saturation (IPsat) compatible
Dense ↔ dilute transition and the need for high energy

\[ \sigma_{\gamma + A \rightarrow J/\Psi + A} \sim Q^\gamma \]
\[ \gamma^* + Au \rightarrow V + Au, x_P = 0.01 \]

Large \( Q^2 \) lever arm needed to see the transition, and to probe the \( x \) dependence!
Extract nuclear geometry

Full EIC simulation with expected uncertainties in $\gamma + A \rightarrow J/\Psi + A$

Extract transverse density profile of small-$x$ gluons
Also: fluctuations at different length scales

T. Toll, T. Ullrich, 1211.3048
H. M, B. Schenke, 1703.09256
Centrality in exclusive scattering: probe highest $Q_s^2$

Incoherent diffraction: largish $p_T$ kick, localized to $\sim$ nucleon size

- A nucleon receives kick and scatters off other nucleons on its way out
- More “ballistic nucleons” in central events
- 2nd component: thermal emission in the rest frame
  - Different $p_T$ spectra in the LAB frame

T. Lappi, H. M, R. Venugopalan, PRL 114 (2015) 082301
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Centrality estimator

Centrality $\sim$ number of “ballistic protons” in the roman pot

EIC simulation:
Romat pot acceptance is good in $|t| \sim 0.5 \ldots 1$ GeV$^2$

T. Lappi, H. M, R. Venugopalan, PRL 114 (2015) 082301
Centrality dependence of incoherent cross section

Double ratio \[ \frac{\sigma(V_1)/\sigma(V_2)}{\sigma(V_1)/\sigma(V_2)} \]

\[ \gamma + A \rightarrow V_1/V_2 + A^*, x_p = 0.005 \]

Larger \( Q_s^2 \) in central events

- Light mesons are more suppressed in central events
  \( \Rightarrow \) enhancement at low \( Q^2 \)

T. Lappi, H. M, R. Venugopalan, PRL 114 (2015) 082301
Conclusions & outlook

Exclusive vector meson production is a powerful tool to study
- Geometric structure
- Structure fluctuations
- Saturation effects
- Initial condition for heavy ion collisions

LHeC/FCC-eh provides large $x$, $Q^2$ with precision

Additionally (not discussed here)
- Small-$x$ nuclear DIS data: much tighter model constraints
- Large $Q^2$ range: study mostly unknown vector meson wave function
- Event-by-event fluctuations of the small-$x$ nuclear structure
- And much more