Diffractive vector meson production in ultraperipheral heavy ion collisions from the Color Glass Condensate

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The Color Glass Condensate framework describes many small-\(x\) processes accurately.

Necessary input: gluon density at \(x = x_0\) (from DIS).

There is very little small-\(x\) nuclear DIS data.

eA collisions would be ideal, but before eRHIC/LHeC have to use something else.

\(\Rightarrow\) ultraperipheral AA
Diffractive deep inelastic scattering (DDIS) = DIS with no exchange of quantum numbers (color).

- $e + p \rightarrow e + p + X$, proton interacts via "pomeron exchange"
- $x_P$: fraction of proton momentum carried by the pomeron.
- $Q^2 = -q^2$: virtuality of the photon.
Ultraperipheral AA collision

\[ b \gtrsim 2R_A: \text{strong interactions suppressed, nucleus creates photon flux } n(\omega) \]
\[ \sigma \sim n(\omega)\gamma^A(\omega) \]

Probes gluons with \( x = M_V e^y / \sqrt{s} \)

- Forward LHC: \( x \sim 0.02 \) and \( x \sim 10^{-5} \).
- Midrapidity LHC: \( x \sim 10^{-3} \)

Dipole model is valid only at \( x \lesssim 10^{-2} \Rightarrow \text{at LHC limit } y \lesssim 2 \ldots 3. \)
Coherent and incoherent diffraction

Diffraction off the nucleus:

- Coherent diffraction: nucleus remains intact

\[
\frac{d\sigma}{dt} \gamma^* A \rightarrow VA \sim \langle |A(x, Q^2, t)|^2 \rangle
\]

- Quasielastic = coherent + incoherent

\[
\frac{d\sigma}{dt} \gamma^* A \rightarrow V(A^* + A) \sim \left| \langle A(x, Q^2, t) \rangle \right|^2
\]

- Incoherent, nucleus is allowed to break up

\[
\frac{d\sigma}{dt} \gamma^* A \rightarrow VA^* \sim \left| \langle A(x, Q^2, t) \rangle \right|^2 - \langle |A(x, Q^2, t)|^2 \rangle
\]

\langle \rangle = \text{Average over nucleon positions.}
Dipole cross section

CGC: Dipole-proton cross section
\[ \sigma_{\text{dip}}(x, r, \Delta) = 2 \int d^2 b e^{i b \cdot \Delta} N(r, x, b) \]

Universal dipole amplitude \( N \)

- Total \( \gamma^* p \):
  \[ \int d^2 r d z |\psi( Q^2, r, z)|^2 \sigma_{\text{dip}}(x, r, \Delta = 0) \]

- Total diffraction:
  \[ \frac{1}{16\pi} \int d^2 r d z |\psi( Q^2, r, z)\sigma_{\text{dip}}(x, r, \Delta)|^2 \]

- Exclusive diffraction:
  \[ \frac{1}{16\pi} \left| \int d^2 r d z \psi^* \psi^V( Q^2, r, z)\sigma_{\text{dip}}(x, r, \Delta) \right|^2 \]

- Inclusive particle production (pp, pA):
  \[ \sim x g(x, Q^2) \int d^2 r e^{i r \cdot p_T} [1 - N(r, x)] \]

  + Correlations, ...
Impact parameter dependent BK evolution is problematic (work in progress), use IPsat model (Kowalski, Teaney 2003; Rezaeian et al, 2013):

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

- Fit to HERA data: initial condition for DGLAP evolution of \(xg(x, \mu^2)\)
- Proton profile \(T_p\) gaussian

Generalize for nuclei:
- \(T_p(b) \rightarrow \sum_{i=1}^{A} T_p(b - b_i)\)
- Average over different nucleon configurations from Woods-Saxon
  \(\Rightarrow\) coherent/incoherent diffraction
Factorized IPsat

Quasielastic cross section can be computed using a factorized approximation (T. Lappi, H.M, 1011.1988)

\[ N(r, x, b) \approx T(b)N(r, x) \]

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

- Also large corrections from real part and skewness
- Compare “fIPsat” to IIM (lancu, Itacura, Munier) model: study dependence on dipole model
Comparison with the HERA data

Compare with HERA $\gamma^* p \rightarrow J/\Psi p$ data:

$$\gamma^* p \rightarrow J/\Psi p, \ W=90 \ \text{GeV}$$

$\sigma_p^{J/\Psi}$ [nb]

$M_{J/\Psi}^2 + Q^2$ [GeV$^2$]

T. Lappi, H. Mäntysaari, 1011.1988

Also a good description of the $F_2$ data.
Comparison with the ALICE data: coherent diffraction

\[ \text{Pb + Pb} \rightarrow \text{J/Ψ + Pb + Pb}, \quad \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

Different dipole and vector meson wavef models: change overall normalization, but shape is very similar.

RHIC midrapidity: \( d\sigma/dy = 109 \mu b \), experimental \( 76 \pm 34 \mu b \).
Pb+Pb → Pb+Pb+J/ψ  $\sqrt{s_{NN}} = 2.76$ TeV  a)

- ● ALICE Coherent J/ψ
- ○ Reflected

Unshadowed model (AB-MSTW08) clearly fails ⇒ saturation effects seen
Comparison of predictions (incoherent diffraction)

\[ \text{Pb}+\text{Pb} \rightarrow \text{Pb}+\text{Pb}+J/\psi \quad \sqrt{s_{NN}} = 2.76 \text{ TeV} \quad b) \]

- ALICE Incoherent \( J/\psi \)

Normalization dependence on the \( J/\Psi \) wave function model: \( \sim 25\% \)

ALICE, 1305.1467
\( \Psi(2S) \) production

\( \Psi(2S) \) wave function has a node \( \Rightarrow \) large suppression compared to \( J/\Psi \)

- Meson-photon wave function overlap, \( z = 0.5 \):

![Graph showing wave functions](image-url)
\(\Psi(2S)\) wave function has a node \(\Rightarrow\) large suppression compared to \(J/\Psi\)

- 2S/1S Ratio depends on event type:
  \(\gamma p <\) coherent \(\gamma A <\) incoherent \(\gamma A\)

\[
Pb+Pb \rightarrow J/\Psi+Pb+Pb, \sqrt{s_{NN}} = 2.76 \text{ TeV}
\]

- Data: ALICE, 1310.7732, 1305.1467
Conclusions

- Ultraperipheral heavy ion collisions make it possible to study $\gamma A$ diffraction at high energy
- Coherent and incoherent photoproduction measurements provide independent model constraints
- Dipole model description of incoherent and coherent diffraction in $\gamma^* A$
  - Here used IPsat parametrization fit to HERA
  - Absolute normalization has largish model dependence
  - Rapidity evolution of $d\sigma/dy$ is more precise prediction
- Prediction for $\Psi(2S)$ production and $\Psi(2S)/J/\Psi$ ratio
- Work in progress: use BK-evolved dipole amplitude consistently with the HERA $F_2$ and $F_{2c}$ data
Wave function overlap in \( J/\Psi \) production:

Transversely polarized \( J/\Psi \) meson

\[
\left\langle \frac{\langle \mathbf{r} \rangle}{2} \right\rangle \int dz (\Psi^* V \Psi) \quad \text{[GeV]} \quad Q^2 = 0.05 \text{ GeV}^2, Q^2 = 3.2 \text{ GeV}^2, Q^2 = 22.4 \text{ GeV}^2
\]

Longitudinally polarized \( J/\Psi \) meson

\[
\left\langle \frac{\langle \mathbf{r} \rangle}{2} \right\rangle \int dz (\Psi^* V \Psi) \quad \text{[GeV]} \quad Q^2 = 0.05 \text{ GeV}^2, Q^2 = 3.2 \text{ GeV}^2, Q^2 = 22.4 \text{ GeV}^2
\]
Assuming proton profile function $T_p(b) \sim e^{b^2/(2B_p)} \Rightarrow$ incoherent cross section $\sim e^{-B_p t}$: probes spatial distribution of gluons in proton!
As the photon flux $\sim Z^2$, dominant process is the one where the nucleus emits the photon \Rightarrow probes mostly proton structure.
Prediction for incoherent diffraction

Again overall normalization uncertainty, but \( \sigma(y = 0)/\sigma(y = 2) = 1.4 \) more precise prediction.
Fit HERA $\sigma_r$: get automatically good description of $\sigma_r^{\text{charm}}$. Assume factorized impact parameter profile and $\sigma = \frac{1}{B_p} \frac{d\sigma}{dt}|_{t=0}$

Problem: large $\sigma_0 \sim 50 \text{ mb}$