Coherent vector meson production at an EIC

Overview

• Motivation

• Photo-nuclear interaction in eSTARlight:
  • $\gamma p \rightarrow V.M. + p$ vector meson production
  • Comparison to data
  • Extension to $\gamma A$

• Vector meson production at an EIC:
  • Estimating rates
  • Final state particle distributions

• Summary
Why we need MC and what’s been done?

A Monte Carlo for ep and eA collisions is essential for EIC success:

• Study physics program and drive detector design

Some ep Monte Carlos developed for HERA

• M.C.'s don't cover more exotic processes, parametrizations missing

Lack of both experimental and simulations for eA:

• Fixed target experiments at low energy, SARTRE M.C.

eSTARlight motivated to study e+X \rightarrow e+X+V.M. cross sections for:

• Different center of mass energies (accelerator facilities)
• Different V.M. species
• Different collision systems (X = p, Au, etc.)
• Arbitrary virtuality Q^2
Diffraction at an EIC

- How are the quarks and gluons distributed within the nucleon? What about nucleus?
- Initial state geometry is necessary to understand heavy ion collisions:
  - Initial state (IS) geometry → final state collectivity
  - Collective phenomena has been observed in p-p and p-A collisions

- Diffractive processes (no color exchange) can probe gluon density and their spatial distribution
Some important kinematic quantities to consider in electron-ion collisions:

- Resolving power
  \[ Q^2 = -q^2 = -(k'_\mu - k'_{\mu})^2 = 2E_eE'_e(1 - \cos \theta_e) \]

- Momentum of struck quark
  \[ x = \frac{Q^2}{2pq} = \frac{Q^2}{sy} \]

- Measure of inelasticity
  \[ y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2 \left( \frac{\theta_e}{2} \right) \]
  \[ s = 4E_pE_e \]

**Inclusive:** Detect scattered lepton.
\[ e+p/A \rightarrow e' + X \]

**Semi-inclusive:** Detect scattered lepton in coincidence with identified hadrons/jets.
\[ e+p/A \rightarrow e' + h + X \]

**Exclusive:** Detect scattered lepton, id'd hadrons/jets and target fragments.

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Electro-nuclear interactions

\[ \sigma(e + X \rightarrow e + X + V.M.) = \int dQ^2 \int dE_\gamma \frac{dN_\gamma(E_\gamma, Q^2)}{dE_\gamma dQ^2} \sigma_\gamma X(W, Q^2) \]

- Using equivalent photon approach (EPA), boosted electron surrounded by photon cloud

- Include the corrections for finite virtuality\(^1\):
  \[
  \frac{d^2N}{d(Q^2)dE_\gamma} = \frac{\alpha}{\pi E_\gamma |Q^2|} \left[ 1 - \frac{E_\gamma}{E_e} + \frac{1}{2} \left( \frac{E_\gamma}{E_e} \right)^2 - \left( 1 - \frac{E_\gamma}{E_e} \right) \left| \frac{Q^2_{\text{min}}}{Q^2} \right| \right]
  \]

Photon flux

Photonuclear cross section

- Interactions are done, mostly, with parameterization from HERA\(^1\) for γp→Vp in terms of the γp center of mass energy \(W_{\gamma p}\).

\[ \sigma_{\gamma p} = \left( \frac{1}{1 + Q^2/M^2} \right)^n \sigma_{\gamma p}(W) \]

- The power \(n\) is also obtained from fits to data\(^2\)

\(1\): Phys.Rept. 15 181-281 (1975)
Vector meson decays

- Vector mesons retain photon spin → the angular distributions are determined by Clebsch-Gordon coefficients.

In the limit $Q^2 \to 0$, the photons are linearly polarized transverse ($T$) to the beam:
- 50% right-handed and 50% left-handed photons.

Virtual photons ($Q^2 > 0$) can also be longitudinally ($L$) polarized:
- $Q^2$ dependence of the longitudinal-to-transverse ratio $R_v$ is not well known.
- Parametrize $R_v$ to data (HERA) and extract spin matrix elements

$$R_v = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

- Only available for a subset of vector mesons

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HERA comparison to data: $\sigma(\gamma^* + p \to V.M. + p)$

- Gamma-proton cross-sections obtained following same procedure in experiment:

$$\sigma_{\gamma p} = \frac{\int dE_\gamma \int dQ^2 \frac{d^2N}{dE_\gamma d(Q^2)} \sigma_{\gamma p}(E_\gamma, Q^2)}{\int dE_\gamma \int dQ^2 \frac{d^2N}{dE_\gamma d(Q^2)}}$$

- $\sigma_{\gamma p}$ measured at HERA is well described by eSTARlight over a broad $Q^2$ range

$\rho$: JHEP 1005:032(2010)  
Photonuclear Cross Section $\sigma(\gamma A \rightarrow VA)$ and event generation

- Extrapolate photonuclear cross section from $\gamma p$ to $\gamma A$ using Quantum Glauber

$$\sigma_{\text{tot}}(VA) = \int d^2b \left[ 2 \cdot \left( 1 - e^{-\sigma_{\text{tot}}(Vp)T_{AA}(b)/2} \right) \right]$$

- Generalized vector dominance model and optical theorem used to obtain the photo-nuclear cross section

$$\sigma(\gamma A \rightarrow VA) = \left. \frac{d\sigma(\gamma A \rightarrow VA)}{dt} \right|_{t=0} \int_{t_{\text{min}}}^{\infty} dt |F(t)|^2$$

- eSTARlight can handle both narrow and wide resonances to model the generated vector mesons
- Coherent final states
- Track outgoing electron and target for semi-inclusive and exclusive measurements
### Estimating rates for an EIC

<table>
<thead>
<tr>
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<th>Photo-production ($Q^2 &lt; 1 \text{ GeV}^2$)</th>
<th>Electro-production ($Q^2 &gt; 1 \text{ GeV}^2$)</th>
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- $Q^2 > 1 \text{ GeV/c}^2$ affects V.M. species to different degree
- Rates are encouraging for meaningful $\psi'$ and possibly Y measurements


**: Likely overestimated: Doesn’t account for loss of longitudinal coherence

Don’t account for branching ratios
**Note: Generated distributions are not scaled in order to compare the different colliders**

- Vector meson ($\rho^0$ and $J/\psi$) production occurs over a large rapidity window.
- $\rho$ peak negative rapidity due to photon-meson exchange (mostly near threshold). Not present in heavier V.M.
- Peak at forward rapidity (higher $k$) due to Pomeron exchange.
- Detecting scattered electron requires far forward instrumentation.
**Event generation**

- Plots show $J/\psi$ production in energy ($k$) and Bjorken-$x$ bands
- Vector meson production roughly matches photon energy:
  - High energy photons to the right, low energy to the left
- Studying wide range in $k$ or $x$ requires large coverage. Could be done by running EIC at different energies $s$.
Predictions for eA at potential EIC’s

• Reduced C.M. energy per nucleon $\rightarrow$ lower Pomeron $p_z$. Production in a narrower rapidity range:
  • Good news for barrel detectors
• Middle: Scaled $(A^{-4/3})$ ratio of V.M. production on lead vs. iron:
  • Signs of nuclear shadowing at low $Q^2$
• Right plot shows predictions of diffractive minima for three nuclear targets. Fourier transform provides information on gluon distributions $g(b_T)$.
• Generated V.M. are then decayed to obtain daughter distributions (left):
  • Decay angular distributions match vector meson spin
  • Middle and right: Color curves show sampled V.M.'s for different detector acceptances.
  • Mid-rapidity detectors sample between ~60% ($|\eta|<3$) and <10% ($|\eta|<1$) of production for different V.M.:
    • eSTARlight kinematics can help drive detector design
Summary

• eSTARlight can simulate a wide variety of final states:
  • Evaluate feasibility (cross sections, rates, ...) of different physics topics to be studied
  • Inform on accelerator and detector design
• High enough $Y(1S)$ production at an EIC to allow limited studies ($Q^2 > 1 \text{ GeV}^2$ rates are somewhat low)
• Vector mesons are produced over a wide rapidity range
  • Photon energy roughly maps to rapidity
  • Overlap with CEBAF could be desirable: need coverage at large negative rapidity OR run EIC at lower energies
• Forward instrumentation is necessary to detect scattered electrons: essential for EIC physics
  • $Q^2$ dependence on saturation and nuclear structure
• eSTARlight will be available on HEPFORGE shortly