# Investigation of Vector Meson Backward-Production Capabilities at the EIC

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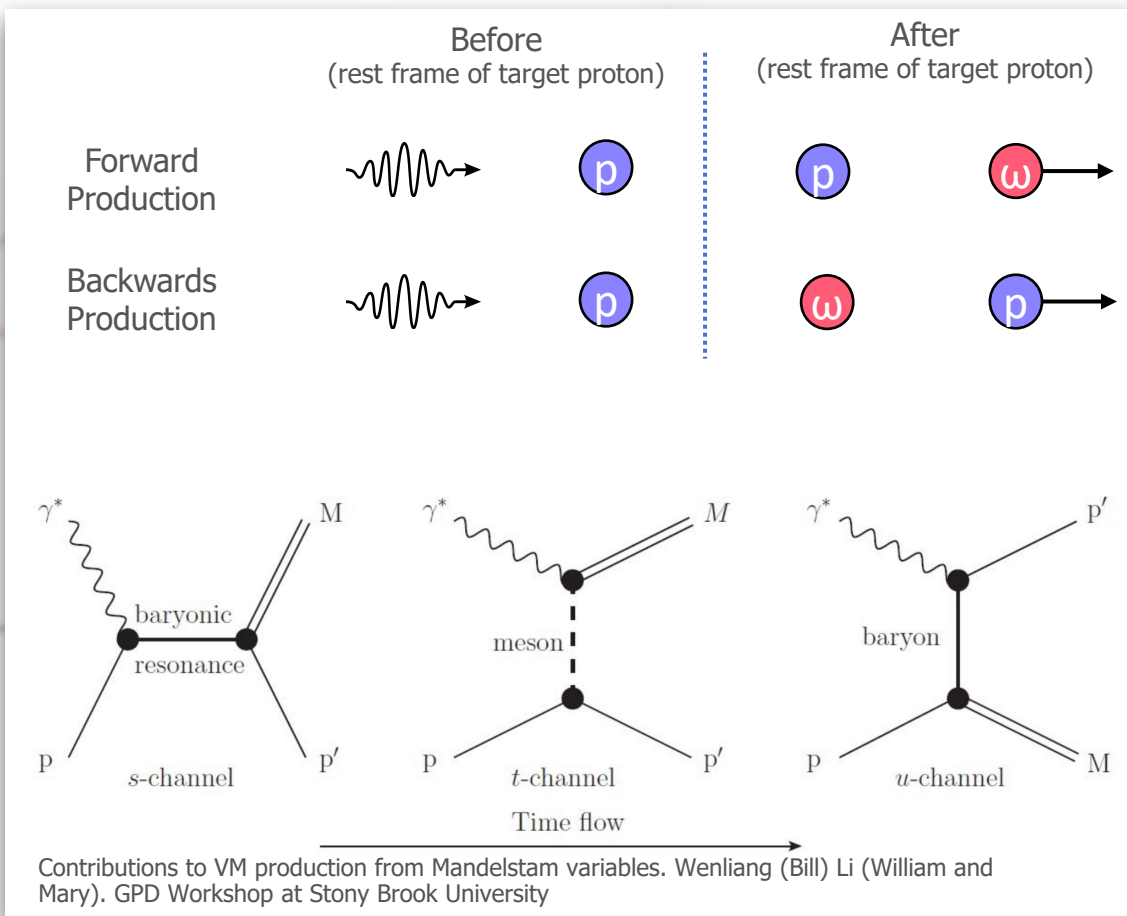Contributions to VM production from Mandelstam variables. Wenliang (Bill) Li (William and Mary). GPD Workshop at Stony Brook University

electron beam → ← p/A beam

Forward region          Backward region

# Forward vs Backwards Production

- Forward Production
  - $t$-channel: low Mandelstam $t$, high $u$
  - Momentum transfer from target is small
  - VM is produced in backwards (e⁻-going) direction
  - Proton in forward direction
    - Proton rapidity only slightly modified
- Backwards Production
  - $u$-channel: low Mandelstam $u$, high $t$
  - Momentum transfer from target is large
  - VM produced in forwards (p-going) direction
  - Proton in backwards direction
    - Proton shifted many units in rapidity
- Similarities with stopping in heavy ion collisions

protons in Au+Au at AGS energies, b = 2 fm
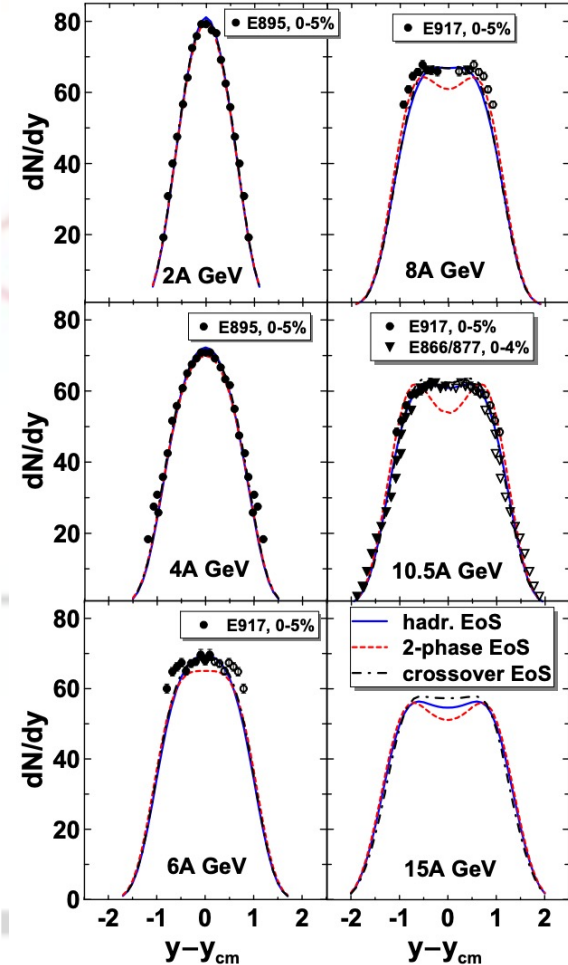
Net-proton rapidity distributions at AGS compared with three distinct models of EoS

## Stopping in Heavy-Ion Collisions

- Baryons participating in a collision can be shifted many units in rapidity
- Generally more collisions → more stopping
- Models of stopping using various equations of state indicate sensitivity to EoS
  - Onset of deconfinement may be probed by baryon stopping
  - **Understanding behavior of midrapidity baryons as a function of energy is critical** (see left)

Yu.B. Ivanov. Phys Lett B, Vol 721, Issues 1–3, 2013, 123-130, ISSN 0370-2693

## Stopping in ep collisions

- Single collision causes large momentum transfer
- $u$-channel mechanism is not well-understood as a function of energy
- ep collision is simple system for studying midrapidity proton behavior in absence of deconfinement and hot QCD effects
- **This gives us a better understanding of mechanisms contributing to baryon stopping in larger systems**



$u$-channel proton stopping in ep collision
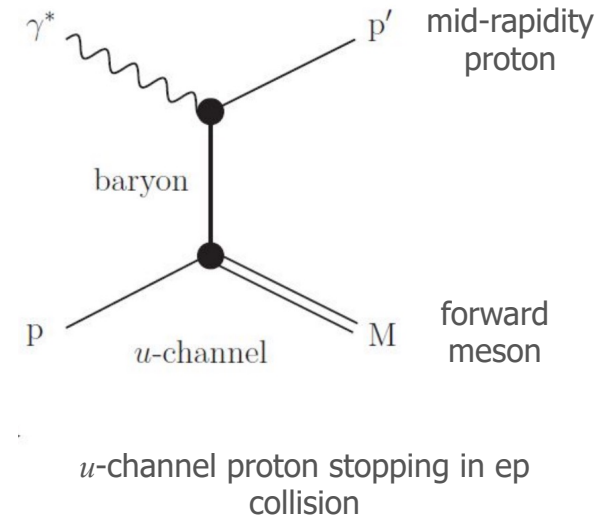
## How can a 275 GeV proton undergo this large momentum transfer and remain intact?

- Is there enough time available in a collision for all the quarks to "know" that a collision has occurred?

  Kharzeev, Phys.Lett. B378 (1996) 238-246, arXiv:nucl-th/9602027

- Is there a connection to the baryon-junction model (BJM)?
- The BJM posits that baryon number is not just carried by valence quarks
- In BJM, baryon number is also carried by a non-perturbative configuration of gluons. These gluons can be easily stopped in a collision



Baryon-junction model
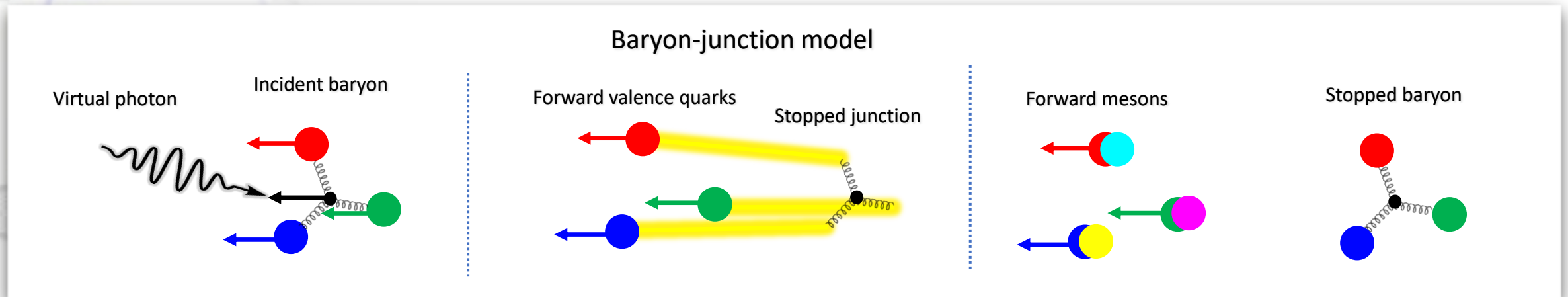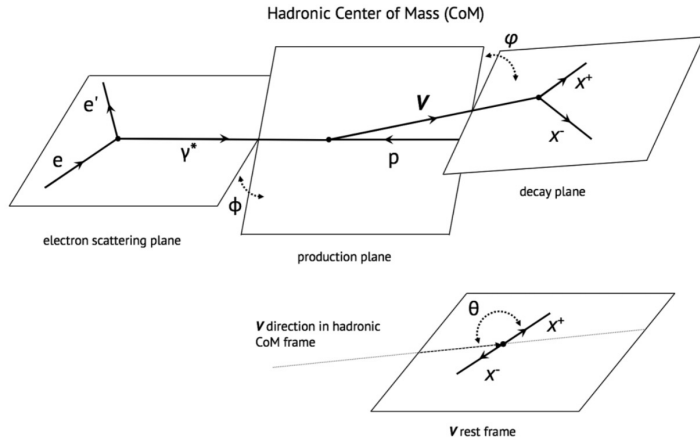
Kinematics of VM production and decay in eSTARlight
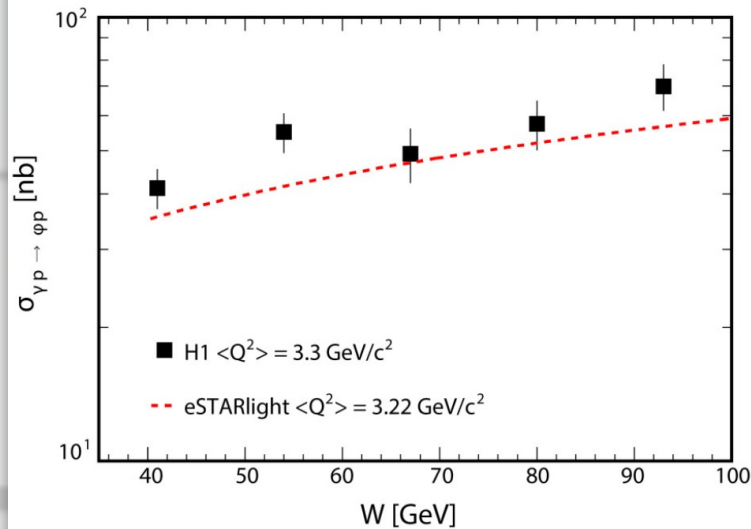


Benchmarking eSTARlight against HERA data. Michael Lomnitz and Spencer Klein. Phys. Rev. C **99**, 015203 – Published 11 January 2019

# Background on eSTARlight
- Models VM production in electron-ion collisions at finite photon virtuality
  - ➢ Includes a variety of vector mesons ($\rho$, $\rho'$, $\omega$, J/$\psi$, $\psi$(2S), $\Upsilon$)
  - ➢ Wide range of COM energies
  - ➢ Simulates final-state particle kinematics

- Complete kinematics simulations at variable energies make this a useful tool for informing detector design for EIC

- Variable photon virtuality ($Q^2$) allows predictions of production cross section scaling with $Q^2$

$$\sigma(eA \to eAV) = \int \frac{dW}{W} \int dk \int dQ^2 \frac{d^2 N_\gamma}{dk\, dQ^2} \sigma_{\gamma^* A \to VA}(W, Q^2)$$

## Modeling $u$-channel Production

C. Ayerbe Gayoso et al. Progress and Opportunities in Backward angle (u-channel) Physics. Eur. Phys. J. A (2021). arXiv:2107.06748

- eSTARlight has been modified include backward production!
- **The strategy: exploit similarities to $t$-channel**

$$\frac{d\sigma}{dt} \sim e^{-Bt} \qquad \longrightarrow \qquad \frac{d\sigma}{du} \sim e^{-Cu}$$

- Scaling depends on the meson produced
- $B$ and $C$ relate to size of production region which differs in $t$ and $u$ channels due to role of meson vs baryon exchange trajectories
- Effect of photon virtuality estimated with similar behavior to $t$-channel

$$\sigma_{\gamma^* p \to \omega p}(W, Q^2) = \sigma_{\gamma^* p \to \omega p}(W, Q^2 = 0)\left(\frac{M_\omega^2}{M_\omega^2 + Q^2}\right)^n$$

- Assumption based on data from HERA forward-production (a source of uncertainty)

F.D. Aaron et al. (H1), JHEP 05, 032 (2010)

- Rates: Forward production:   predicted rate $\sim$(billion events)/$10^7$s

  Backward production: predicted rate $\sim$(10 million events)/$10^7$s

- This model was developed by Aaron Stanek (LBNL) and implemented by Samuel Heppelmann (UC Davis)

- The cross section for backward production as a function of the center-of-mass energy of the photon+proton system is lower, effecting our expected statistics
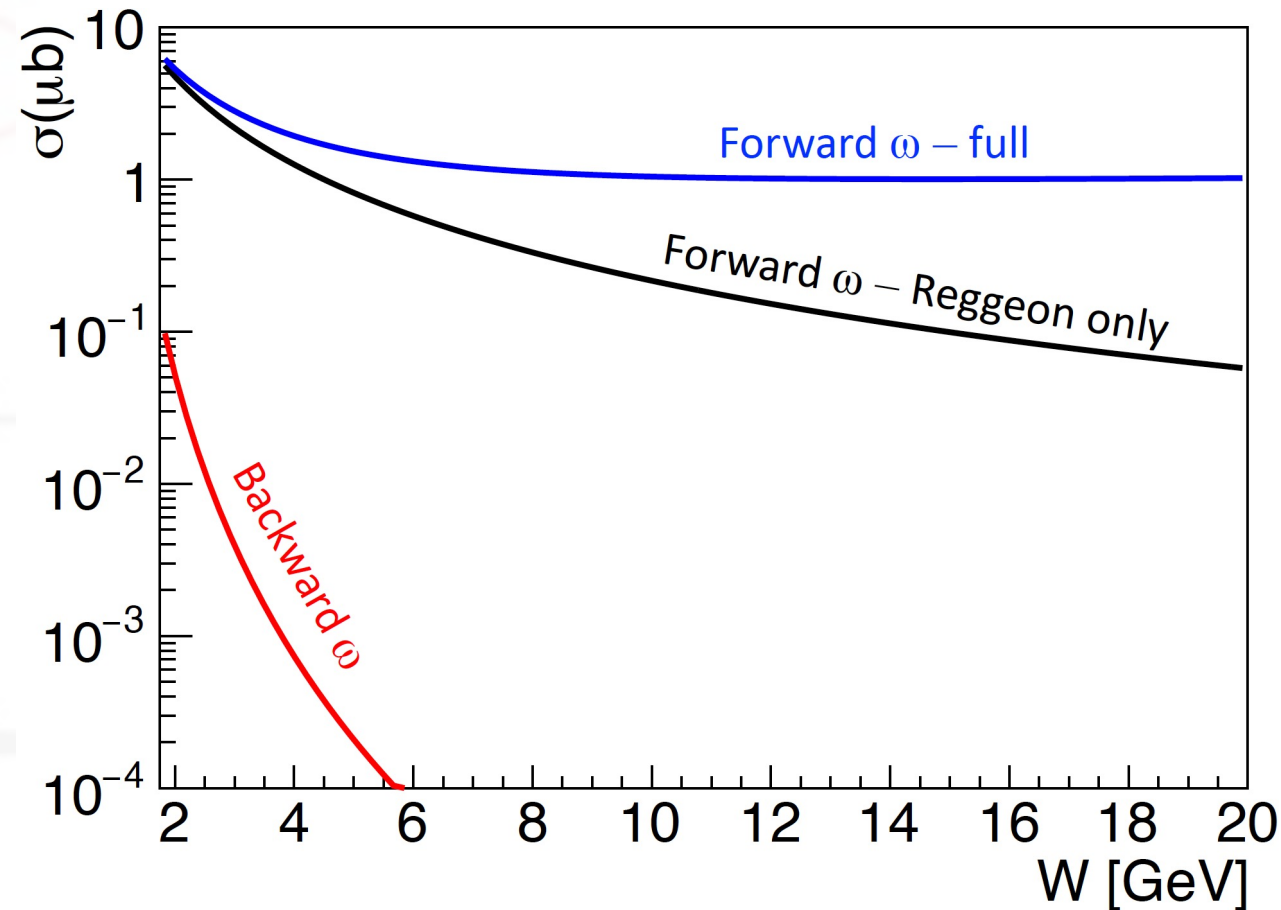


Cebra et al. Backward-Angle (u-channel) Production at an Electron-Ion Collider arXiv:2204.07915

# Vector Mesons Channels of Interest at EIC

## ω Neutral Decay Channel

- $\omega \rightarrow \pi^0 \gamma_{primary} \rightarrow \gamma\gamma\gamma_{primary}$ (8.3%) is fully calorimetric
- Data exists from JLab for benchmarking eSTARlight
- Spin of backward-produced ω still under discussion. In forward-production, ω has same polarization as photon. This polarization is being compared against unpolarized ω in u-channel
- We need far-forward electromagnetic calorimetry

## $\rho^0$ 2-Pion Decay Channel

- $\rho^0 \rightarrow \pi^+ \pi^-$ (100%)
- Expected to have similar behavior to ω
- Spin of backward-produced ρ still under discussion. Taken to be unpolarized for now
- We need far-forward charged-particle tracking

# There are three detector regions of interest for backwards production

- **Central Region (endcap & barrel): |η| < 3.5**
  - ✓ **Charged-particle tracking (ρ)**
  - ✓ **Electromagnetic calorimetry (ω)**
- **B0 Magnets: 4.6 < η < 6.0**
  - ✓ **Charged-particle tracking (ρ)**
  - ? **Electromagnetic calorimetry (ω)**
- **ZDC: η > 6.215–5.991**
  - ✓ **Electromagnetic calorimetry (ω)**
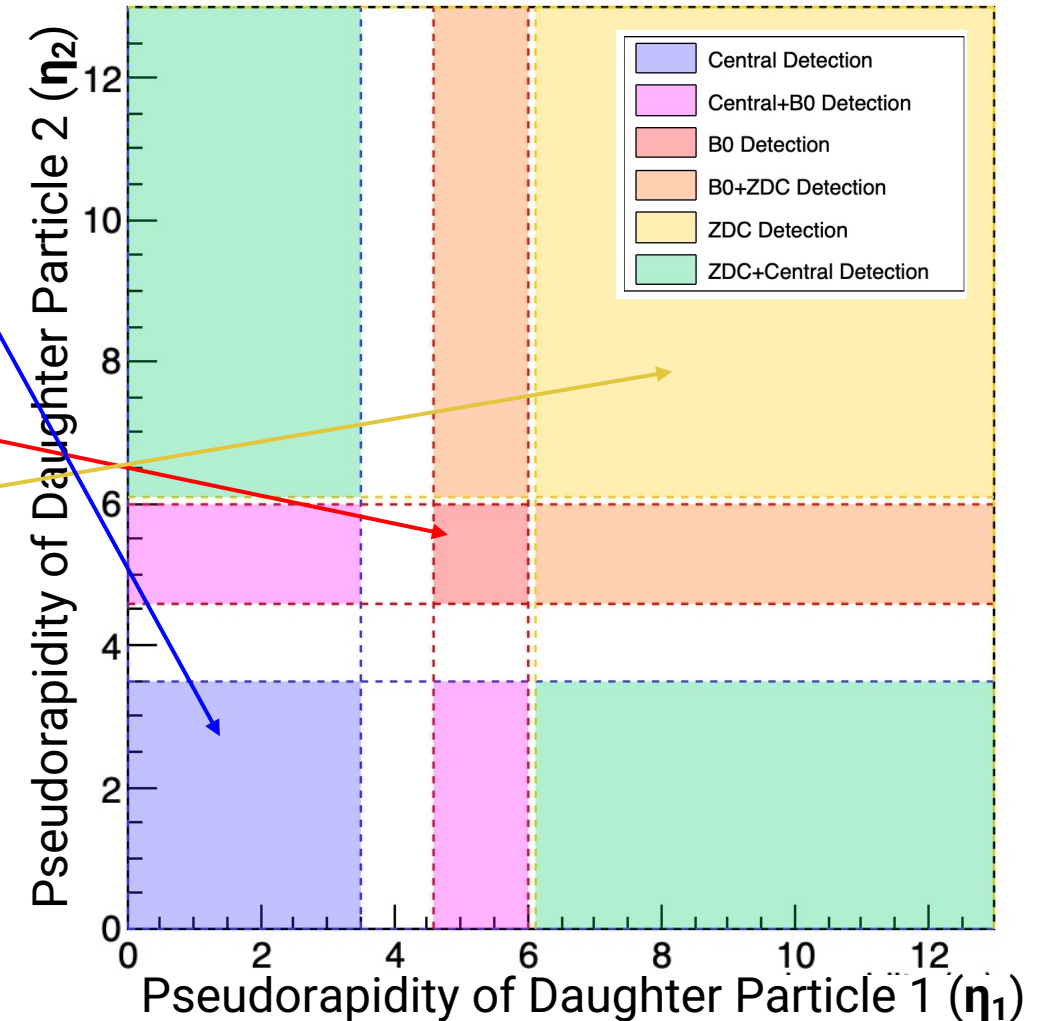
# Backwards ω Detection

$$\omega \rightarrow \pi^0\gamma_{\mathrm{primary}} \rightarrow \gamma\gamma\gamma_{\mathrm{primary}} \quad (8.3\%)$$

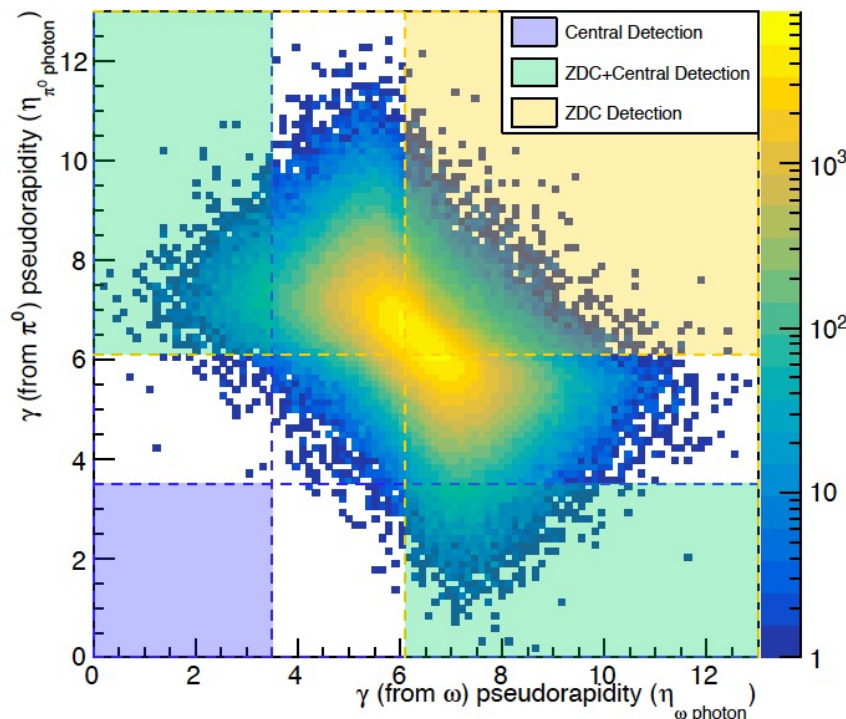| Proton beam energy | ω eff. cent.+ZDC | ω eff. cent.+B0+ZDC |
|---|---|---|
| 41 GeV | 1.4% | 18% |
| 100 GeV | 1.3% | 41% |
| 275 GeV | 6% | 63% |
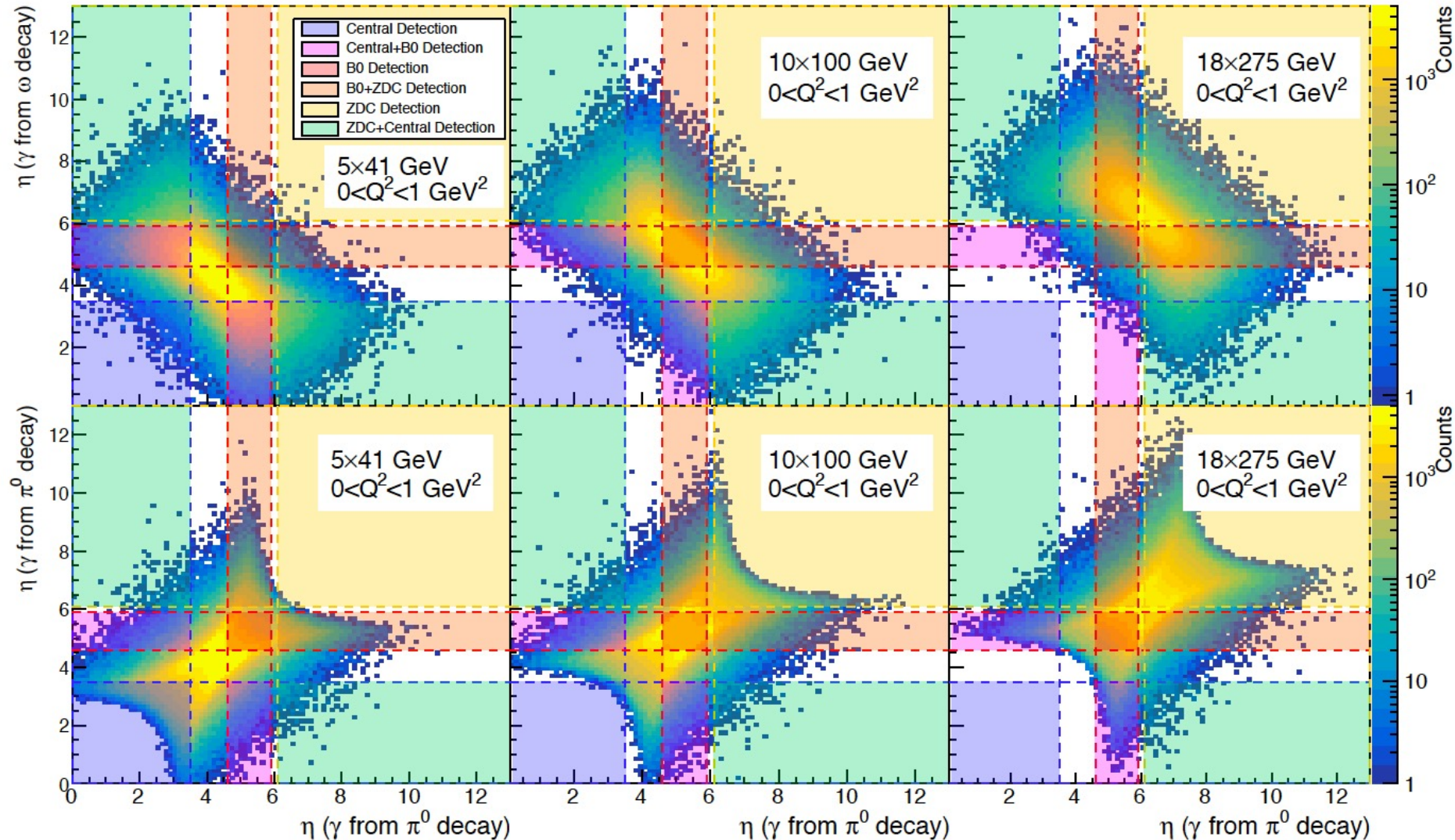


Cebra et al. Backward-Angle (u-channel) Production at an Electron-Ion Collider arXiv:2204.07915
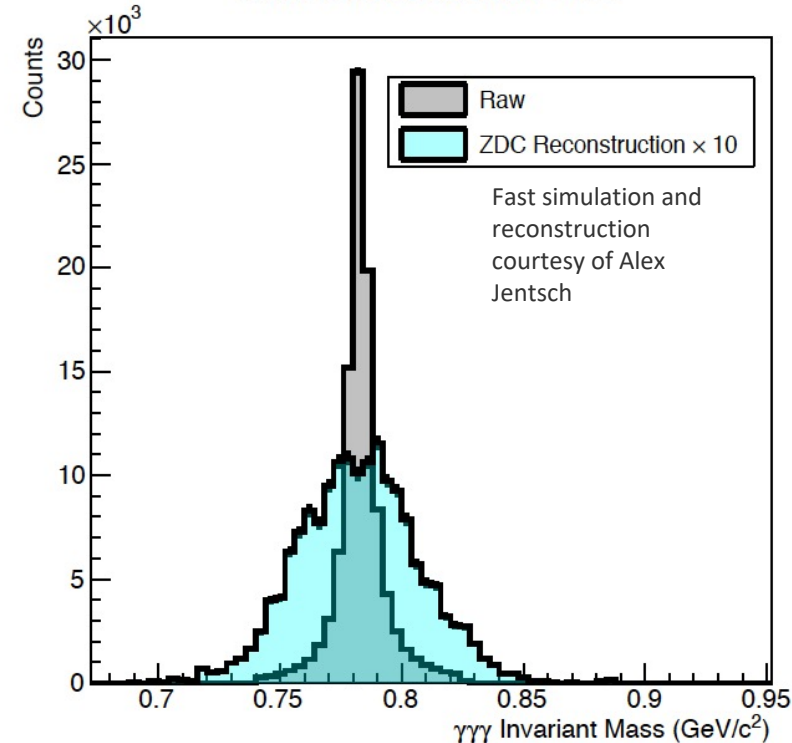
# Backwards ω Detection

- Backward ω events at 18╳275 GeV were simulated for the ATHENA proposal assuming no B0 calorimetry
- Simulated using a parameterization of the ZDC's acceptance and resolution
- Demonstrated that ωs could be faithfully reconstructed, but at a low (~6%) efficiency without B0 calorimeter



Fast simulation and reconstruction courtesy of Alex Jentsch

$\rho^0 \rightarrow \pi^+ \pi^-$ (100%)



| Proton beam energy | $\rho$ eff. cent.+B0 |
|---|---|
| 41 GeV | 13% |
| 100 GeV | 49% |
| 275 GeV | 0.7% |

Cebra et al. Backward-Angle (u-channel)
Production at an Electron-Ion Collider
arXiv:2204.07915

# Backwards ρ Detection

- Backward ρ events at 5×41 GeV were simulated for the ATHENA proposal
- B0 tracking should be the priorityfor this channel
- These too were able to be reconstructed in simulations of the B0 response



Pseudorapidity Distribution of Pions from $\rho^0$

ρ Reconstruction in B0 Tracker

Fast simulation and reconstruction courtesy of Alex Jentsch
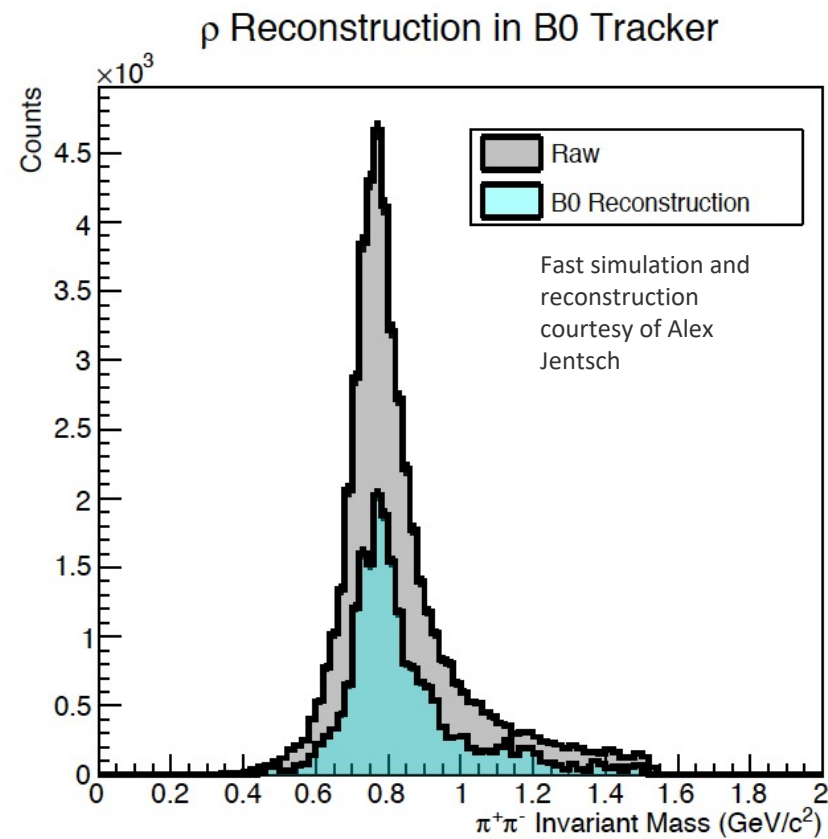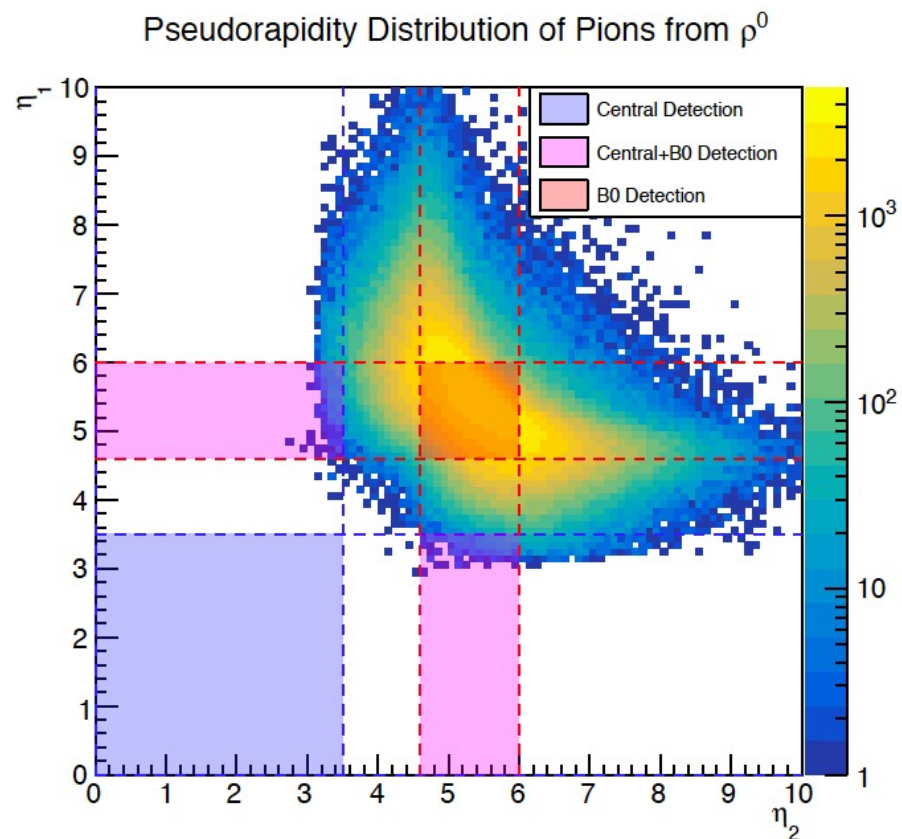
Check out our recent paper on backward-production at the EIC:
arXiv:2204.07915

## Backward-Angle ($u$-channel) Production at an Electron-Ion Collider

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*University of California, Davis*

Xin Dong, Yuanjing Ji, and Spencer R. Klein
*Lawrence Berkeley National Laboratory Berkeley CA*
(Dated: June 27, 2022)

In backward photoproduction of mesons, the produced vector meson takes most of the struck nucleon momentum. The nucleon loses most of its momentum, and so is shifted several units of rapidity. Thus the Mandelstam $u$ is small, while the squared momentum transfer $t$ is typically large, near the kinematic limit. In a collider geometry, backward production transfers the struck baryon by many units of rapidity, in a striking similarity to baryon stopping. We explore this similarity, and point out the similarities between the Regge theories used to model baryon stopping with those that are used for backward production.

We then explore how backward production can be explored at higher energies than are available at fixed target experiments, by studying production at an electron-ion collider. We calculate the expected $ep$ cross sections and rates, finding that the rate for backward $\omega$ production is about $1/300$ that of forward $\omega$s. We discuss the kinematics of backward production and consider the detector requirements for experimental study. We demonstrate that an experiment at the proposed U.S. Electron-Ion Collider will have the capability to detect backward-production events and may provide a test for models of stopping in high-energy $ep$ collisions including the baryon-junction model.

Zachary Sweger

# Conclusions and Outlook

- Vector meson production at the EIC will be an interesting reaction channel for probing nuclear structure including shedding light on the role of Reggeon and Pomeron exchange

- $u$-channel measurements at the EIC can improve our understanding of mechanisms involved in baryon stopping. This will be interesting as a control for large systems

- Backwards ω production requires far-forward electromagnetic calorimetry and will likely prioritize ZDC calorimetry at 18×275 GeV

- Backwards ρ production requires far-forward charged-particle tracking and will most likely prioritize B0 tracking system at 10×100 GeV

- We should now move towards simulating these events in ECCE framework

# Thank you for your attention!

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