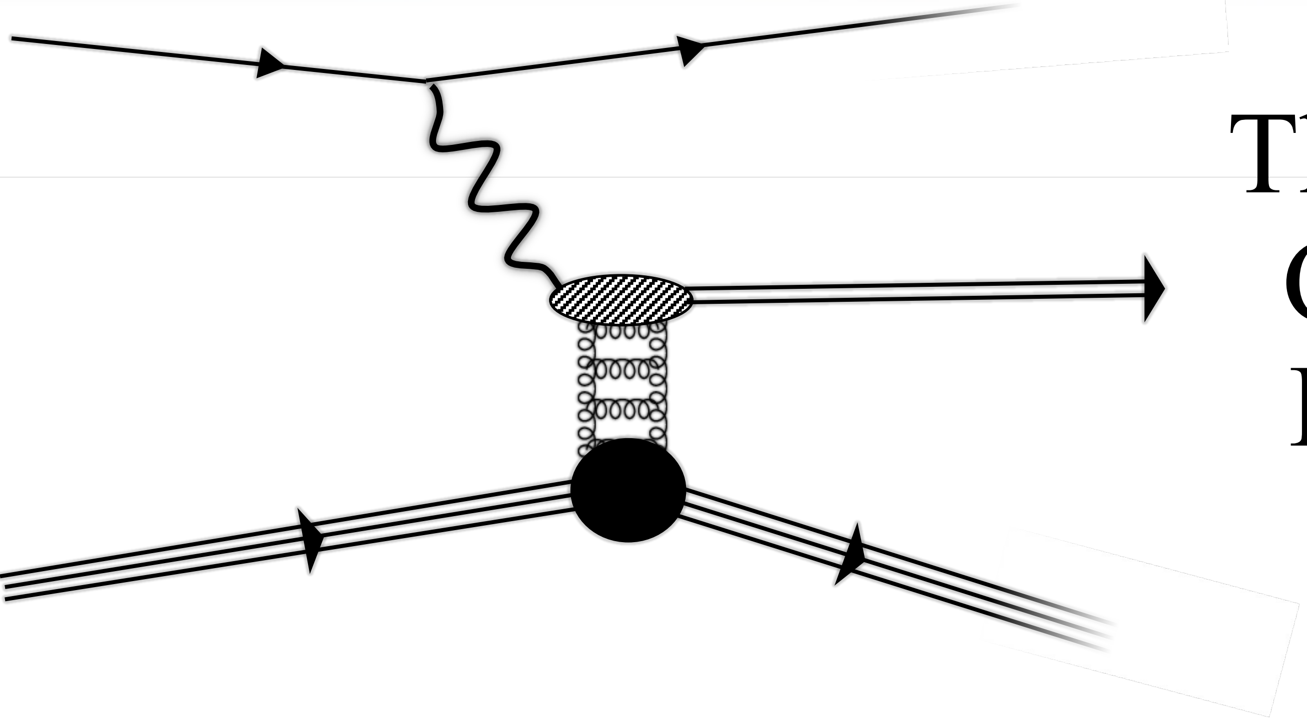


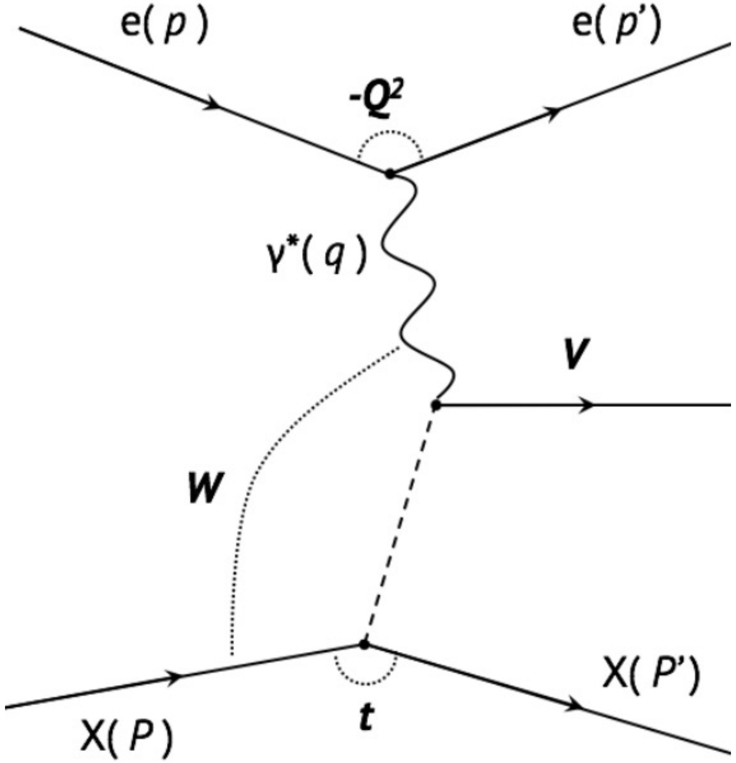
The eSTARlight Monte Carlo Package for the Electron-Ion Collider

Zachary Sweger
University of California, Davis
working with Spencer Klein,
Lawrence Berkeley National Laboratory

Supported in part by

What is eSTARlight?

- eSTARlight was created by Michael Lomnitz and Spencer Klein
- You can read more about the physics behind it at
  - ☐ *Exclusive Vector Meson Production at an Electron-Ion Collider*, M. Lomnitz & S. Klein, Phys Rev C 99, 015203 (2019) https://doi.org/10.1103/PhysRevC.99.015203



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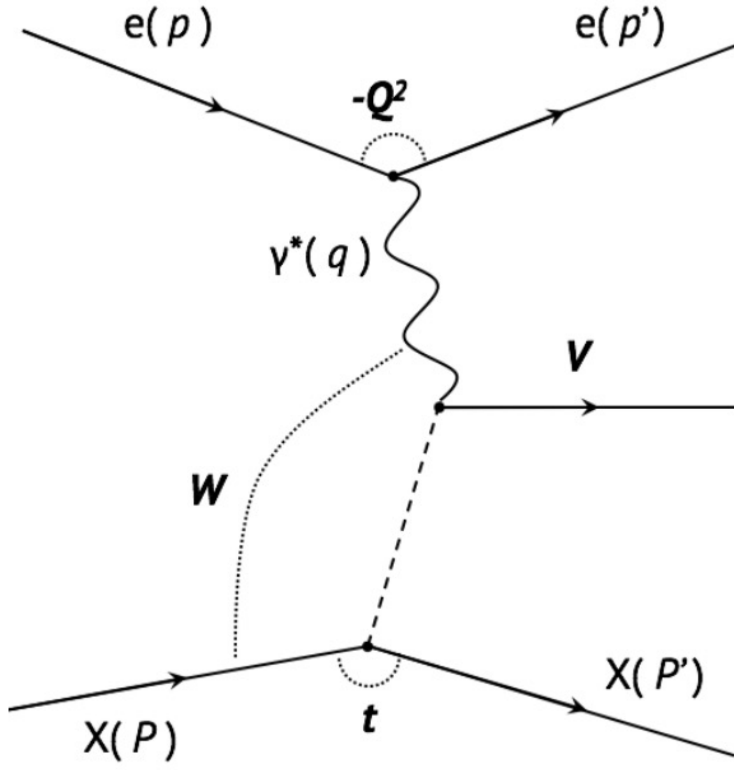
- It is available at https://github.com/eic/estarlight
- Evolved from STARlight Monte Carlo which models UPC cross-sections and final states



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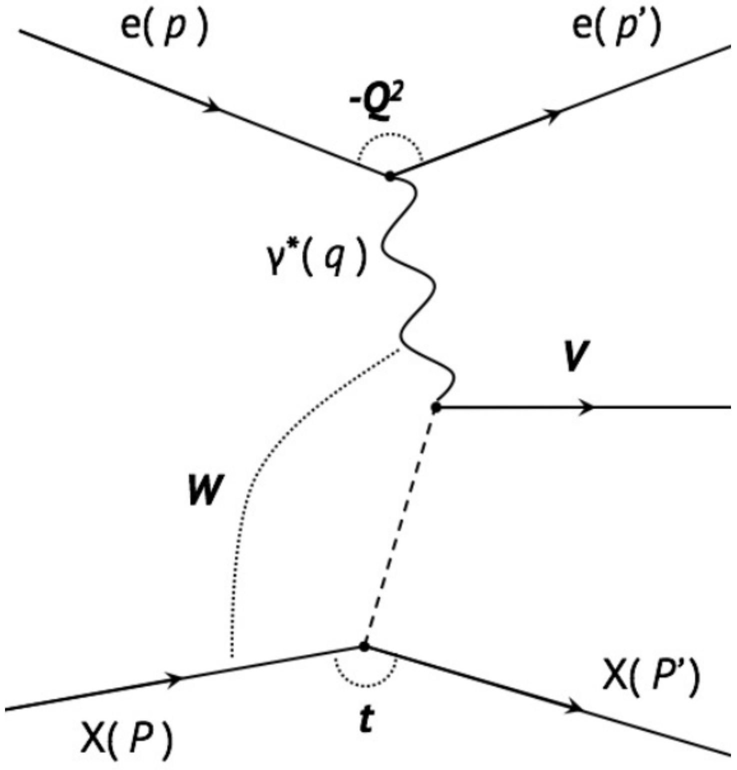
- Models exclusive photoproduction and electroproduction of vector mesons in ep and eA
- Generates final states and cross sections



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1. It's fast! I generated 100k exclusive ρ events in 25 seconds on my laptop

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3. Easy control of processes: easily set W, Q^2, final state, p_T range
4. It's flexible!
    - You can parameterize a production cross section yourself
    - It works for any target nucleus: think early science EIC, Ru/Cu
    - Wide range of final states
    - Can write to default (txt), Pythia, HepMC3, Lund formats

Why Use eSTARlight?

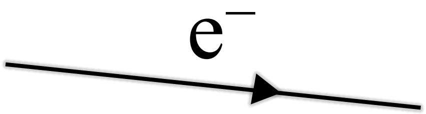
1. It’s fast! I generated 100k exclusive ρ events in 25 seconds on my laptop
2.
3. ge
4.

To summarize: in 10 minutes from *now* you could have downloaded and installed eSTARlight, generated 1M events with realistic J/ψ production, and be comparing the final-state e^+e^- to EPIC’s acceptance

- ➢ It works for any target nucleus: think early science EIC, Ru/Cu
- ➢ Wide range of final states
- ➢ Can write to default (txt), Pythia, HepMC3, Lund formats

eSTARlight Output

- Included in eSTARlight output are 4-vectors for:



eSTARlight Output

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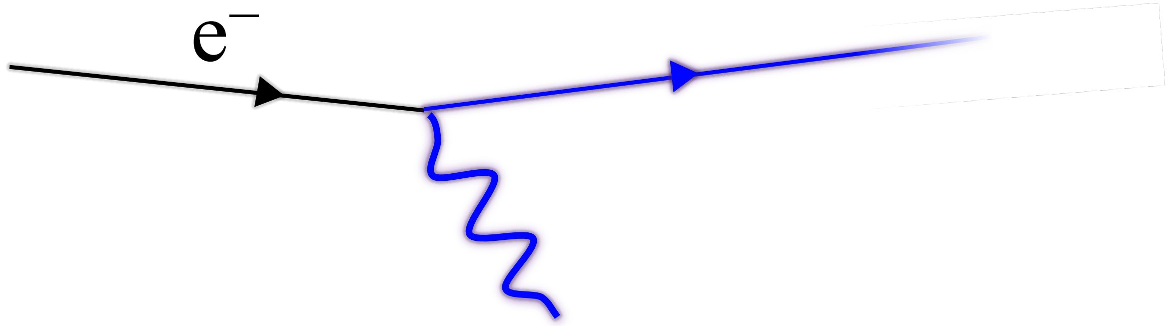
  - ✓ the scattered electron

eSTARlight Output

- Included in eSTARlight output are 4-vectors for:
  - ✓ the scattered electron
  - ✓ the virtual photon



states written to output

eSTARlight Output

- Included in eSTARlight output are 4-vectors for:
  - ✓ the scattered electron
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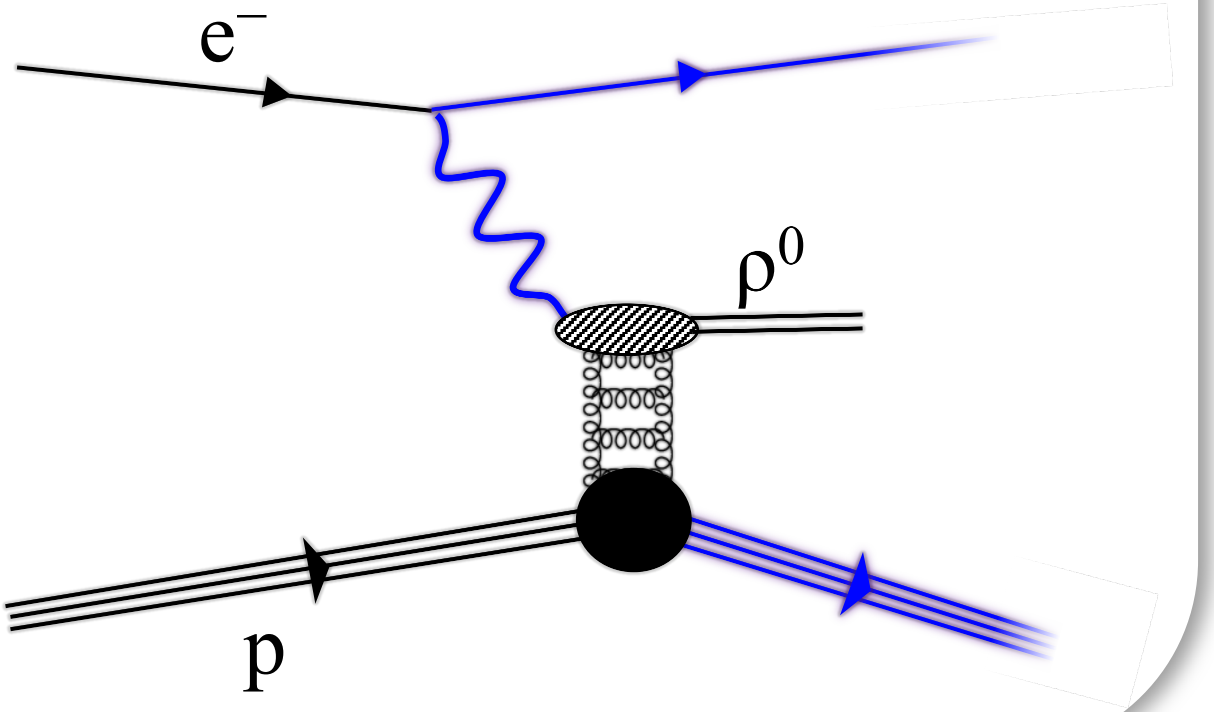
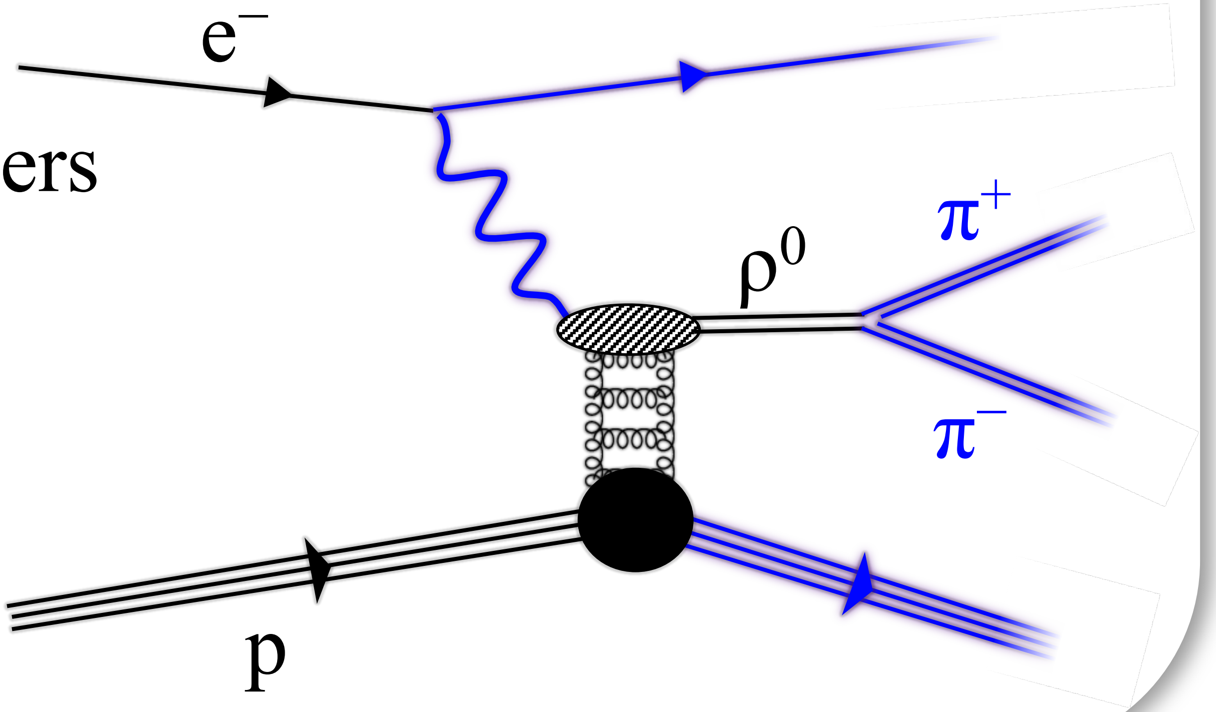
  - ✓ the scattered proton/ion

states written to output



eSTARlight Output

- Included in eSTARlight output are 4-vectors for:
  - ✓ the scattered electron
  - ✓ the virtual photon
  - ✓ the scattered proton/ion
  - ✓ meson final-state daughters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eSTARlight Mesons

- Meson-production channels are

eSTARlight Mesons

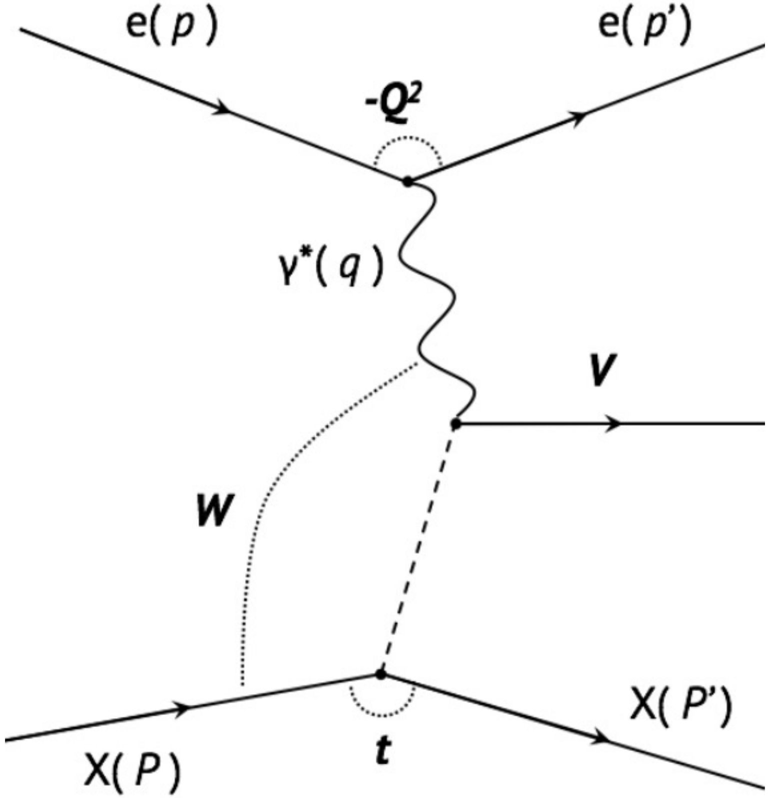
- Meson-production channels are
  - ρ, ω, φ
  - ρ’(1600)→4π, ψ’
  - ρ (interference from direct 2π)
  - J/ψ (1s, 2s), Υ (1s, 2s, 3s)

eSTARlight Mesons

- Meson-production channels are
  - ρ, ω, φ
  - ρ'(1600)→4π, ψ'
  - ρ (interference from direct 2π)
  - J/ψ (1s, 2s), Y (1s, 2s, 3s)
- Simple final states are decayed in eSTARlight with photon polarization informing angular distributions
- Complex decays handled via PYTHIA with loss of photon polarization info

Kinematic Selection

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



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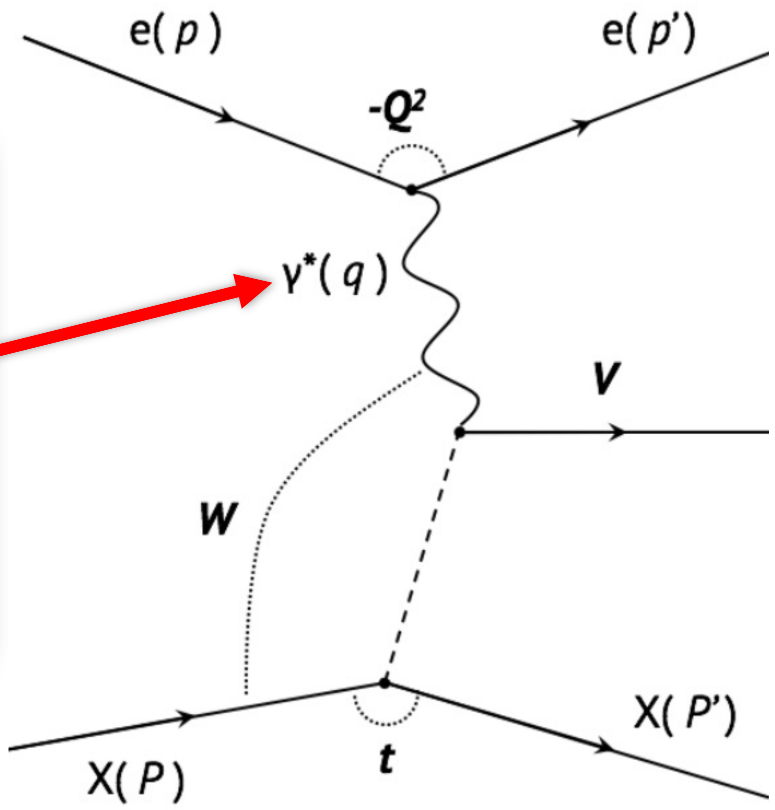
- First sample virtual photon from photon flux given by

$$\frac{d^2 N_\gamma}{dk\, dQ^2} = \frac{\alpha}{\pi k Q^2}\left[1 - \frac{k}{Ee} + \frac{k^2}{2E_e^2} - \left(1 - \frac{k}{Ee}\right)\left|\frac{Q^2_{\min}}{Q^2}\right|\right]$$

V. Budnev, *et al.*, Phys. Rep. **15**, 181 (1975)



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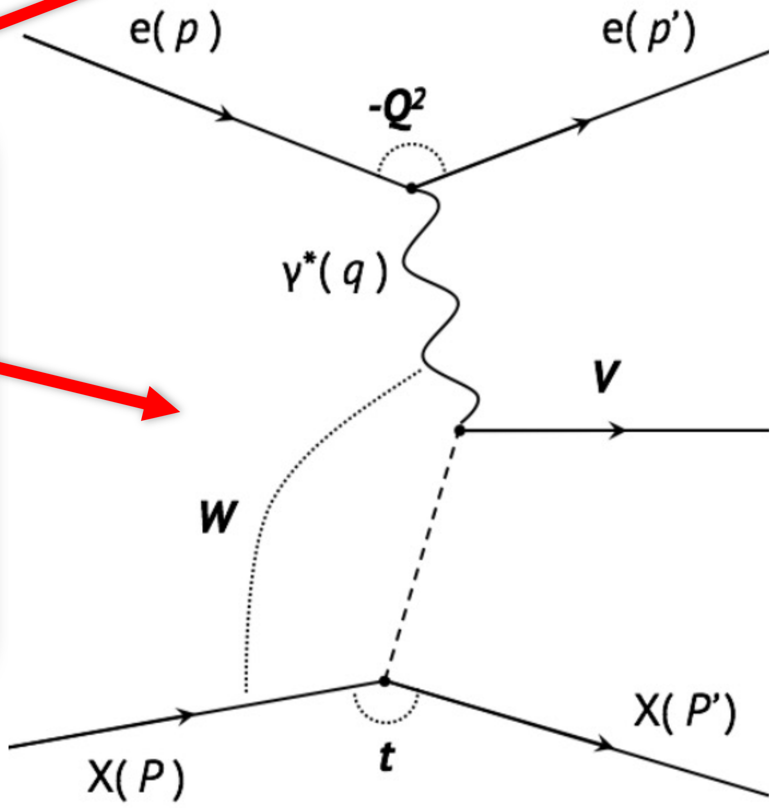
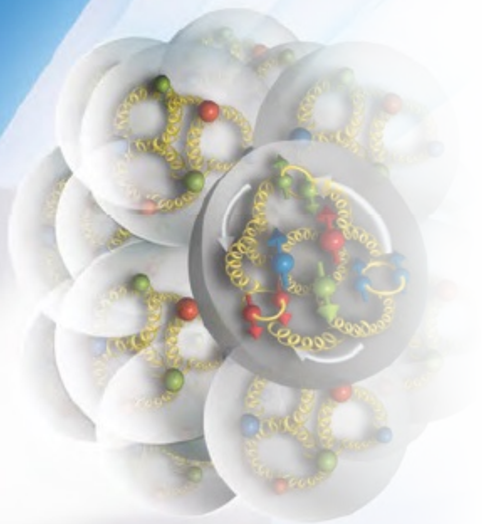
- Accept $A\gamma^*$ interaction according to cross section in W and Q^2

$$\sigma_{\gamma^* A \to VA}(W, Q^2) \sim \sigma(W, Q^2 = 0)\left(\frac{M_V^2}{M_V^2 + Q^2}\right)^n$$



eSTARlight Q^2 Scaling



$$\sigma_{\gamma^* A \to V A}(W, Q^2) \sim \sigma(W, Q^2 = 0) \boxed{\left(\frac{M_V^2}{M_V^2 + Q^2} \right)^n}$$

eSTARlight Q^2 Scaling

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$$\sigma_{\gamma^* A\to VA}(W, Q^2) \sim \sigma(W, Q^2 = 0)\boxed{\left(\frac{M_V^2}{M_V^2 + Q^2}\right)^n}$$

$$\downarrow$$

$$n = c_1 + c_2\left(Q^2 + M_V^2\right)$$

$$\downarrow$$

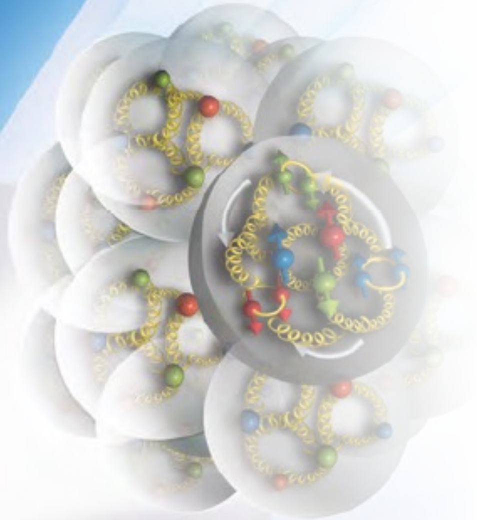
Meson	c_1	c_2 $(10^{-2}\mathrm{GeV}^{-2})$
ρ	2.09 ± 0.10	0.73 ± 0.18
ϕ	2.15 ± 0.17	0.74 ± 0.46
J/ψ	2.36 ± 0.20	0.29 ± 0.43

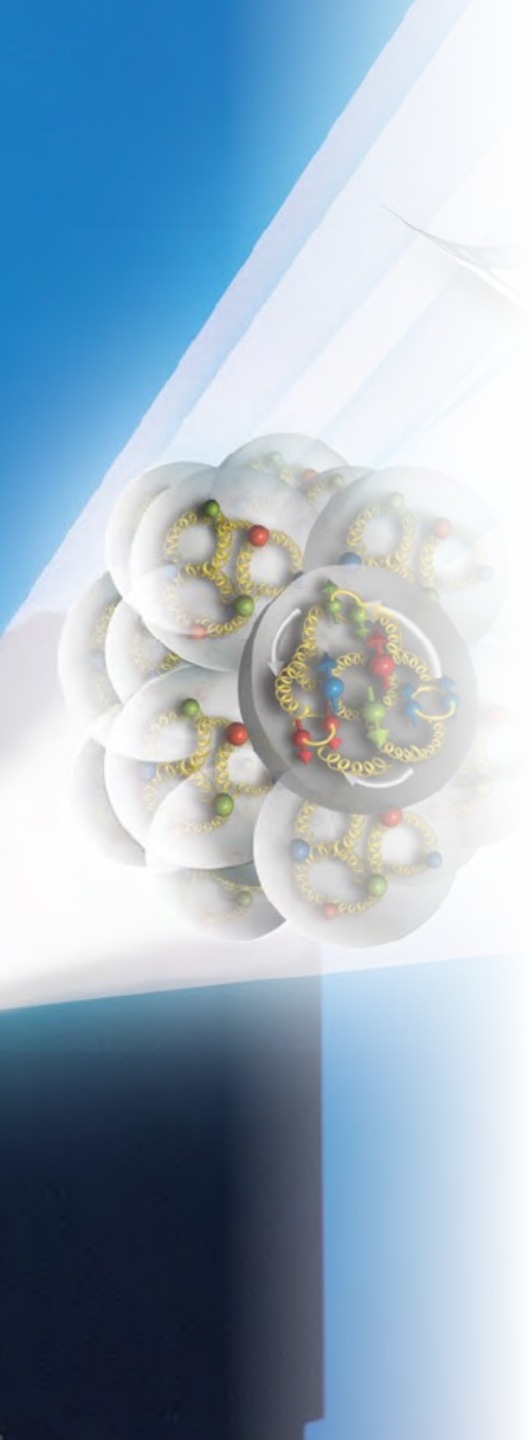
- Cross-section's Q^2-dependence follows exponential
- Scalings from HERA measurements

  F. D. Aaron et al., J. High Energy Phys. 05 (2010) 032
- Where scaling data isn't available, scaling for similar mesons is used

eSTARlight W Scaling

$$\sigma_{\gamma^* A \to V A}(W, Q^2) \sim \boxed{\sigma(W, Q^2 = 0)} \left(\frac{M_V^2}{M_V^2 + Q^2} \right)^n$$





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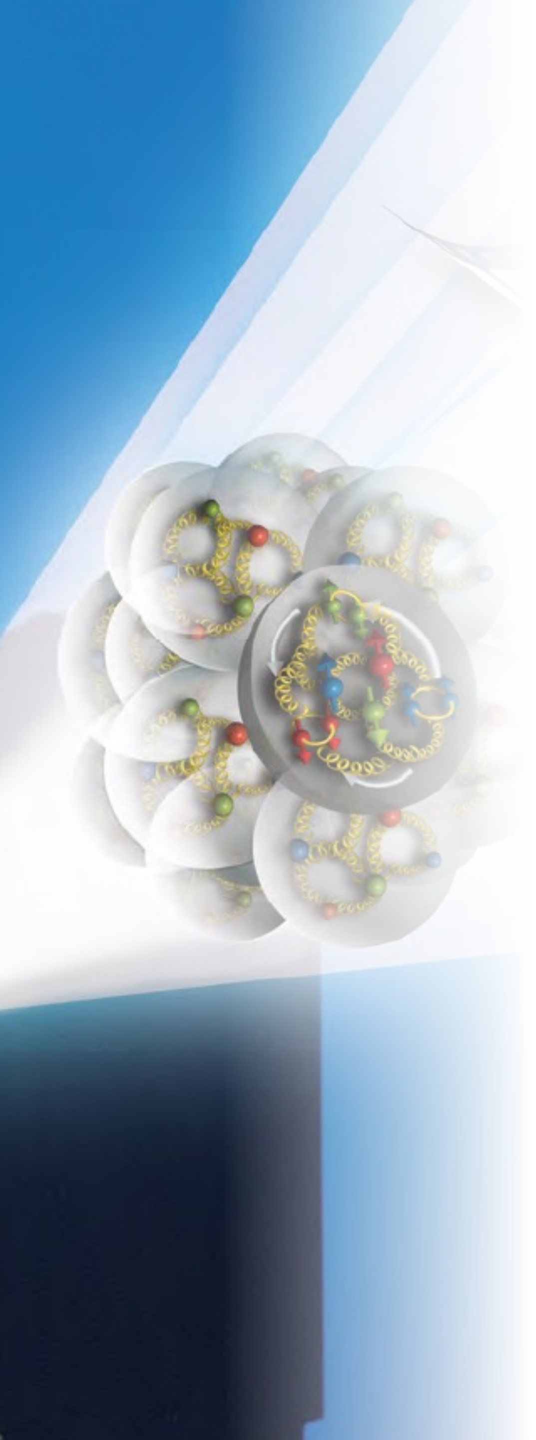
$$\sigma_{\gamma^* A \to VA}(W, Q^2) \sim \boxed{\sigma(W, Q^2 = 0)} \left(\frac{M_V^2}{M_V^2 + Q^2} \right)^n$$

$$\downarrow$$

$$\sigma(W, Q^2 = 0) = \sigma_P W^{\epsilon} + \sigma_M W^{\eta}$$

eSTARlight W Scaling



$$\sigma_{\gamma^* A\to VA}(W,Q^2) \sim \boxed{\sigma(W,Q^2=0)}\left(\frac{M_V^2}{M_V^2+Q^2}\right)^n$$

$$\sigma(W,Q^2=0) = \sigma_P W^\epsilon + \sigma_M W^\eta$$

Pomeron-exchange scaling ($\epsilon>0$)

Reggeon-exchange scaling ($\eta<0$)

S. R. Klein and J. Nystrand, Phys. Rev. C 60, 014903 (1999)

eSTARlight *W* Scaling

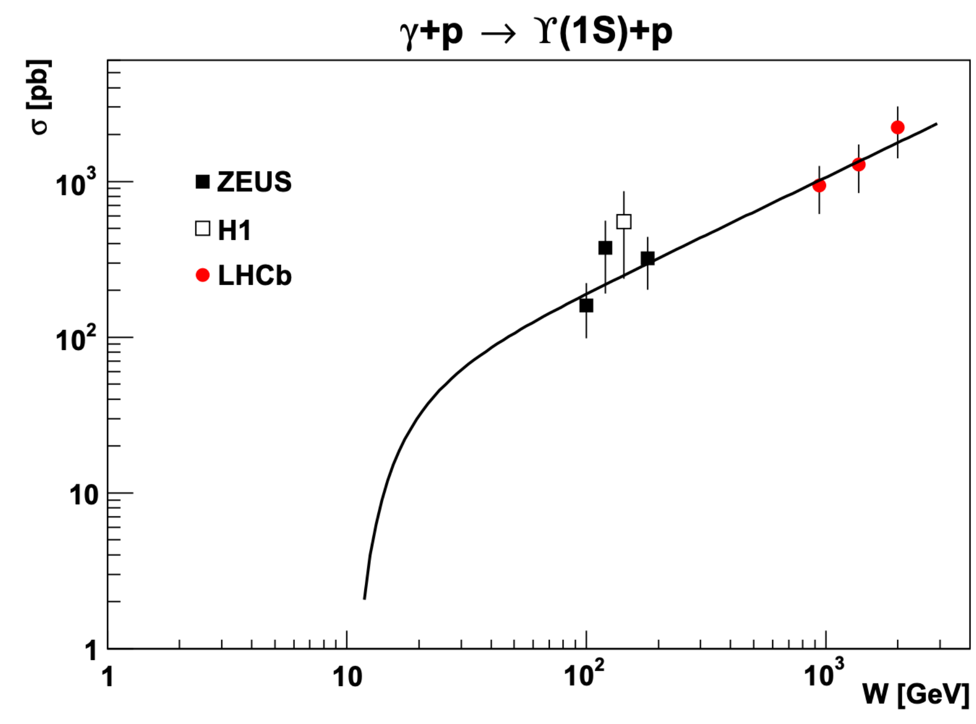
$$\sigma_{\gamma^* A\to VA}(W,\, Q^2) \sim \boxed{\sigma(W,\, Q^2=0)}\left(\frac{M_V^2}{M_V^2+Q^2}\right)^n$$

$$\Big\downarrow$$

$$\sigma(W,\, Q^2=0) = \sigma_P W^{\epsilon} + \sigma_M W^{\eta}$$

$$\Big\downarrow$$

$$\sigma_P \cdot \left[1-\frac{(m_p+m_V)^2}{W_{\gamma p}^2}\right]^2 \cdot W_{\gamma p}^{\epsilon}$$

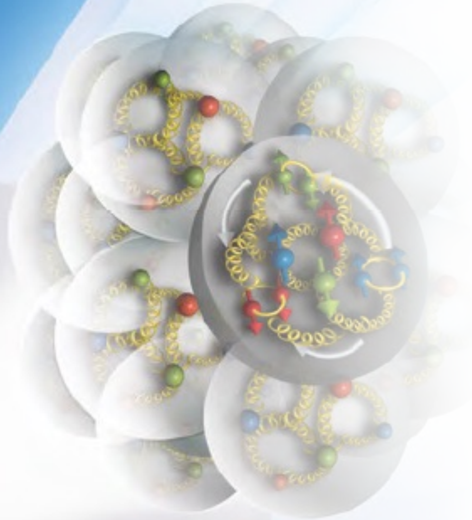


- J/ψ, ψ’, and *ϒ* have additional factor to suppress Xsec near threshold

S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, Comput.Phys.Commun. 212 (2017) 258-268

Momentum Transfer *t*

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



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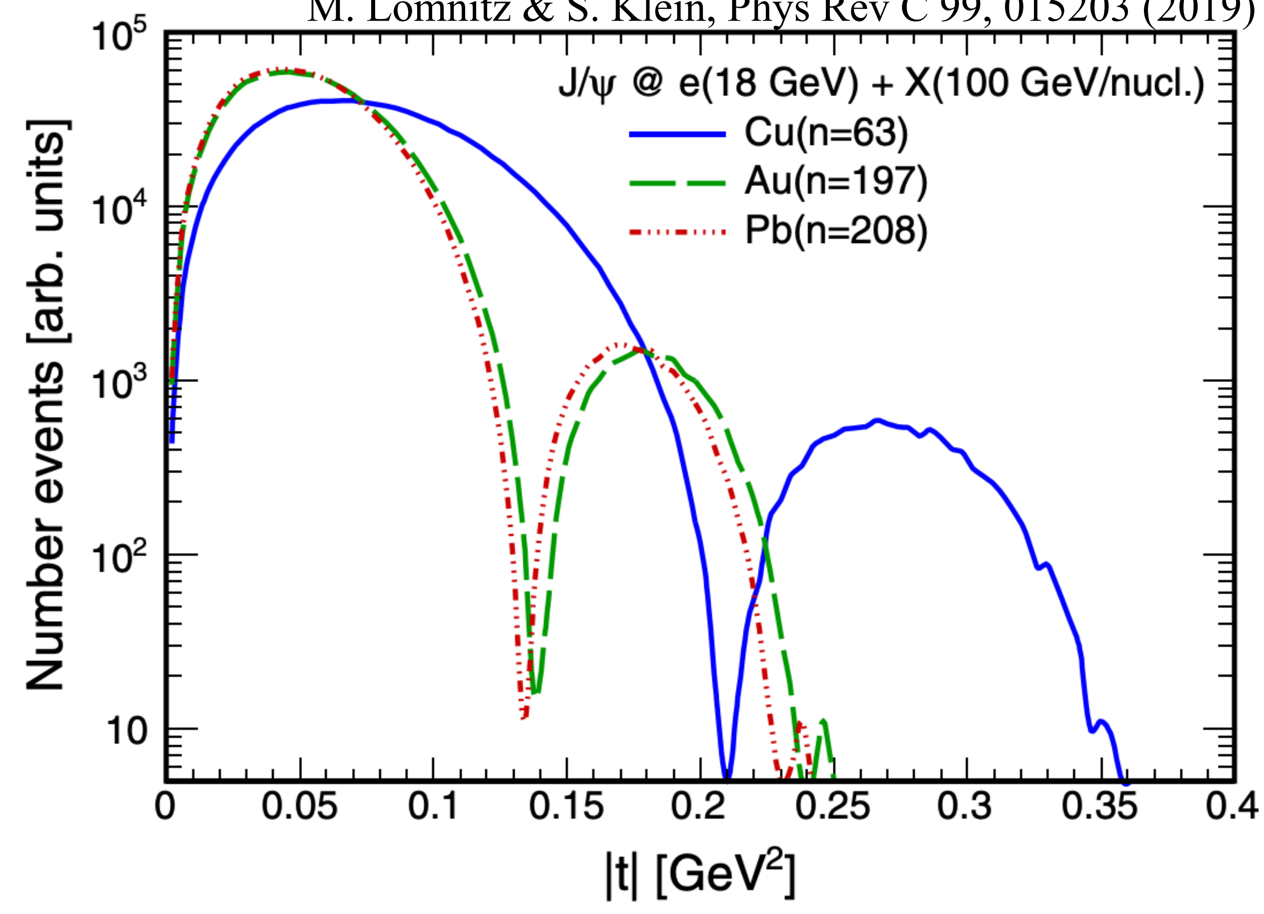
M. Lomnitz & S. Klein, Phys Rev C 99, 015203 (2019)



- Momentum transfer to the ion is determined by the form factor
- Heavy ions: convolution of hard sphere with Yukawa

$$F(t) = \frac{4\pi\rho_0}{Aq^3}[\sin(tR_A) - tR_A\cos(tR_A)]\left(\frac{1}{1+a^2t^2}\right)$$

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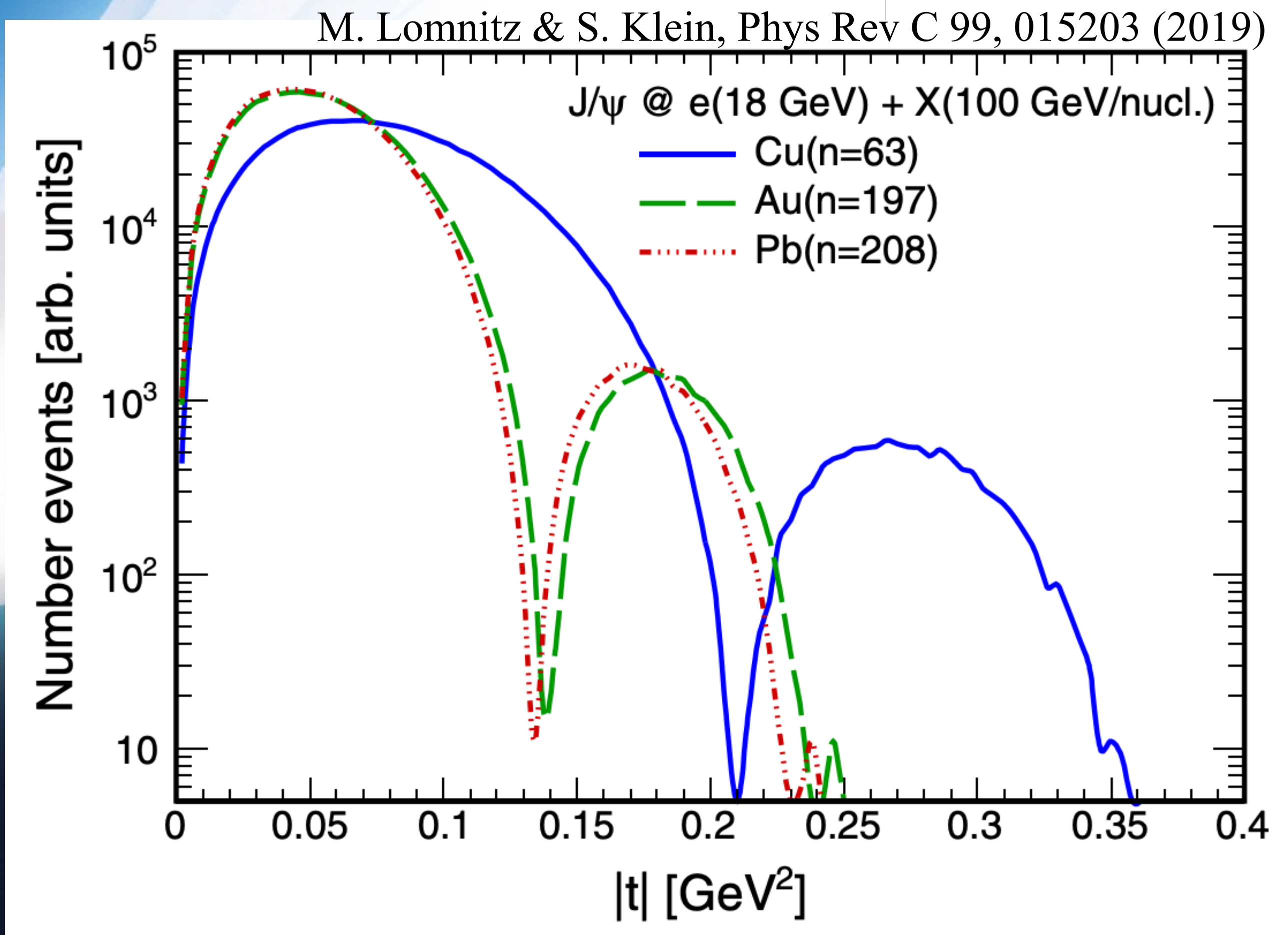

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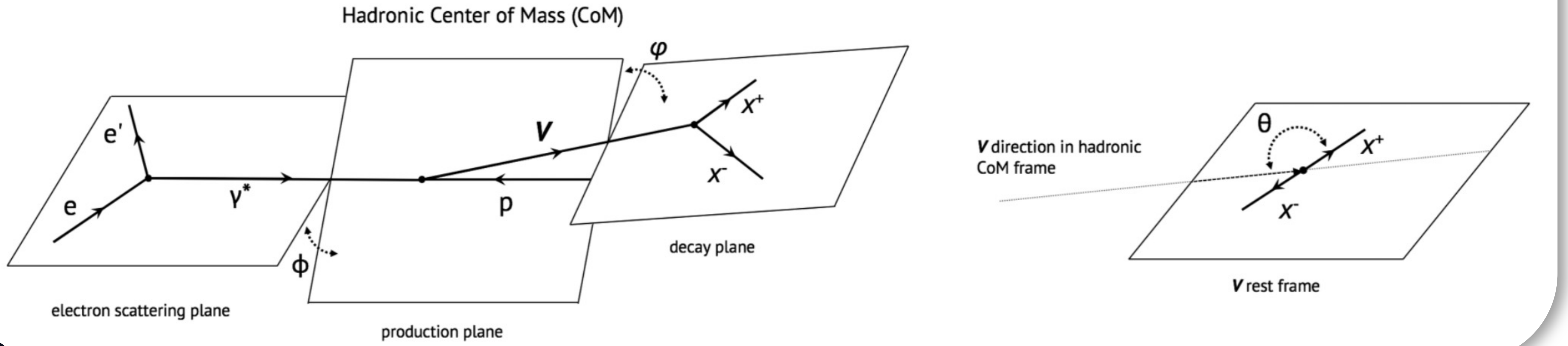
- Protons: dipole form factor

$$F(t) = \frac{1}{(1+q^2/0.71\ \mathrm{GeV}^2)^2}$$

eSTARlight Decay Distributions

- Vector mesons produced with polarization from virtual photon
- *s*-channel helicity conservation (SCHC) approximation

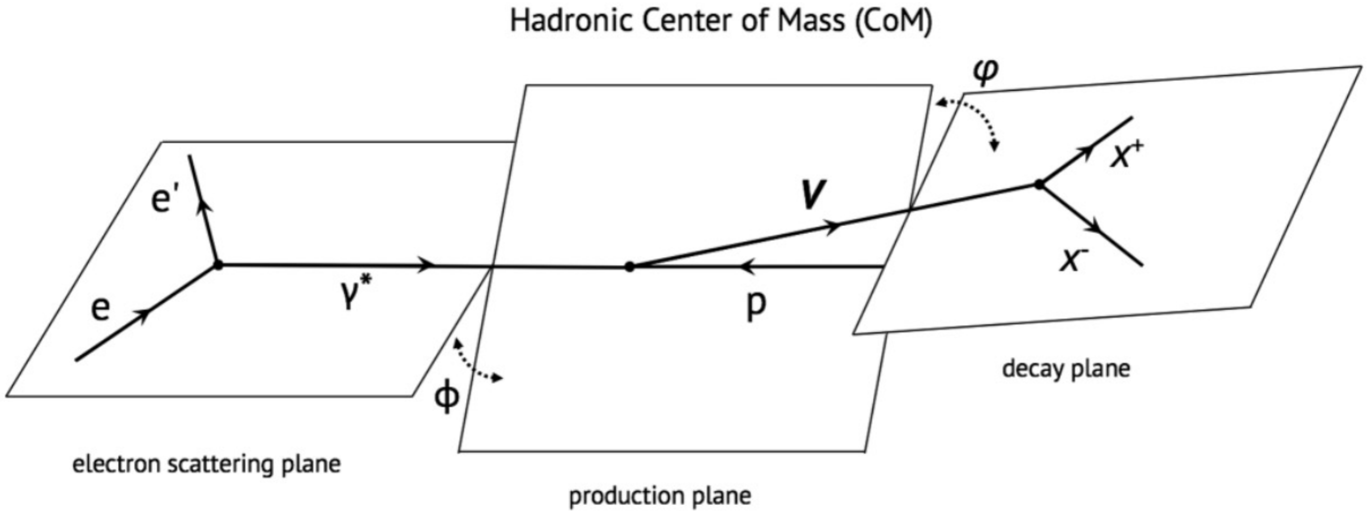


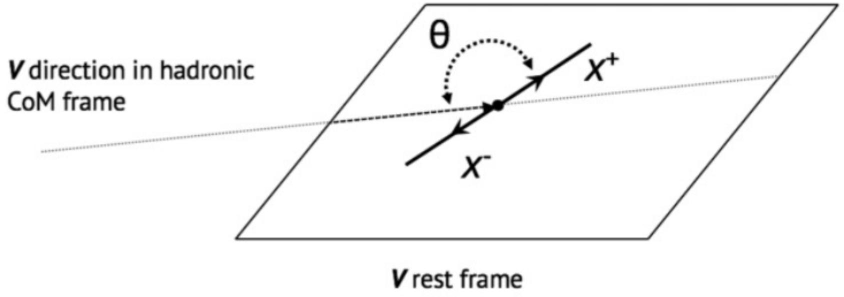
eSTARlight Decay Distributions

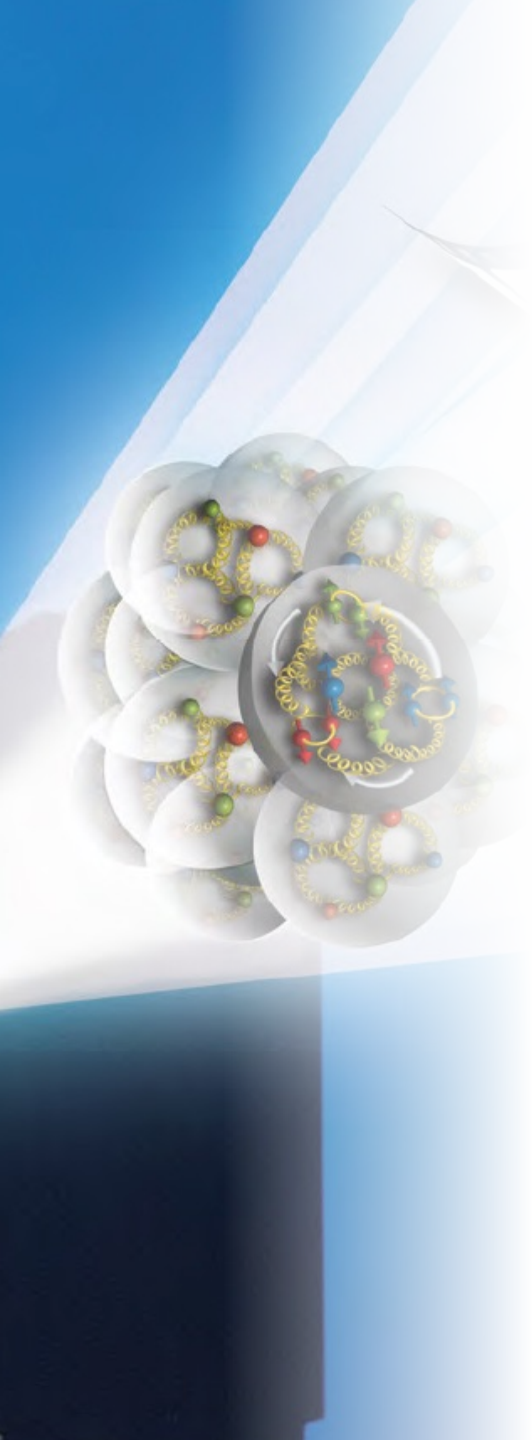
- Vector mesons produced with polarization from virtual photon
- *s*-channel helicity conservation (SCHC) approximation
- Decay anisotropically according to:

$$\text{spin-0 daughters:}\quad \Omega(\cos\theta) \propto 1 - r^{04}_{00} + \left(3r^{04}_{00} - 1\right)\cos^2(\theta)$$

$$\text{spin-1/2 daughters:}\quad \Omega(\cos\theta) \propto 1 + r^{04}_{00} + \left(1 - 3r^{04}_{00}\right)\cos^2(\theta)$$

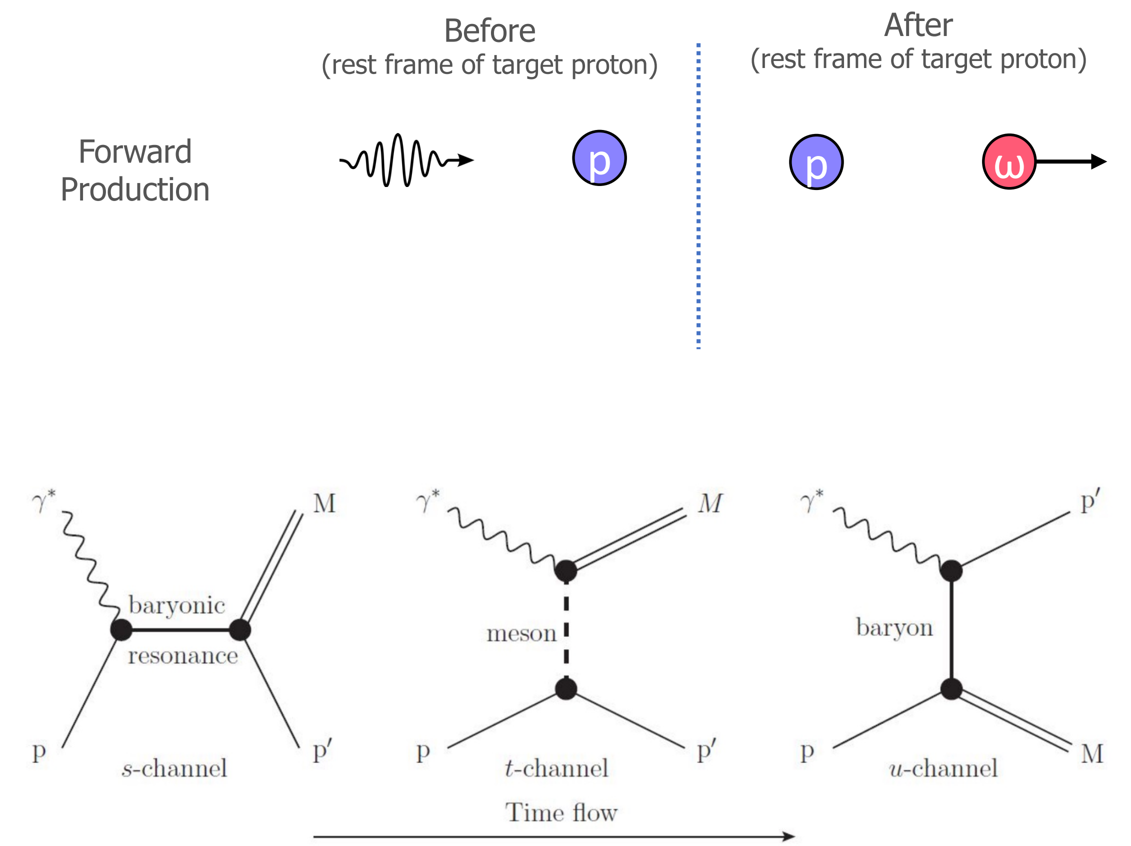




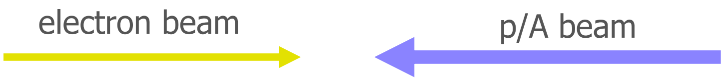


An Example Case:
Modifying eSTARlight to simulate *u*-channel production

Backwards (u-channel) Production



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

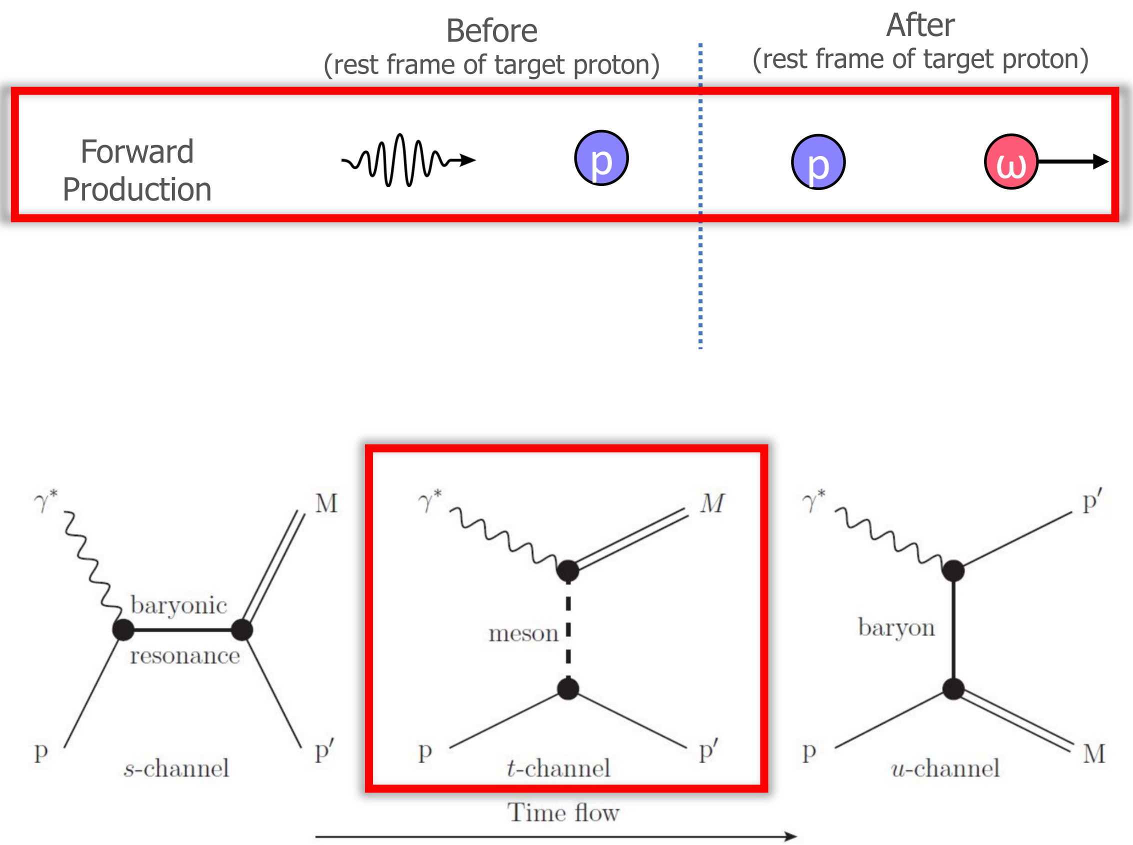


Forward region

Backward region

Forward vs Backwards Production

Backwards (u-channel) Production



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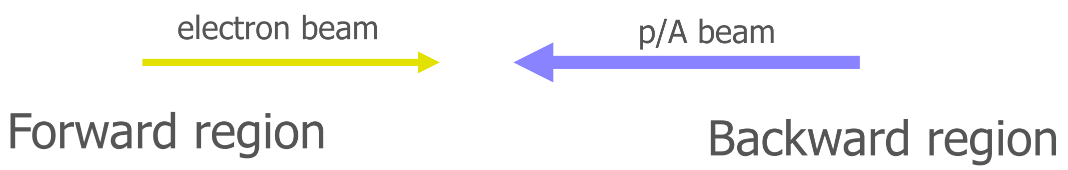

electron beam

p/A beam

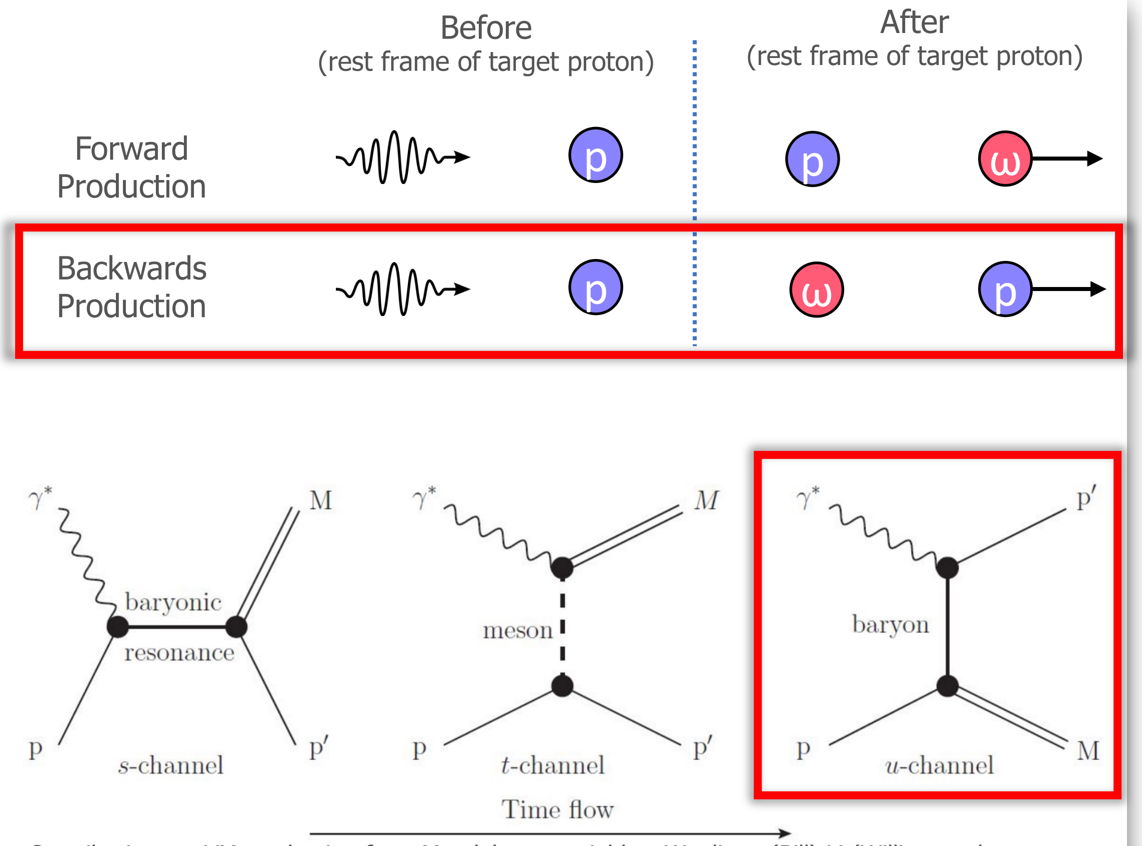
Forward region

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 (*u*-channel) Production



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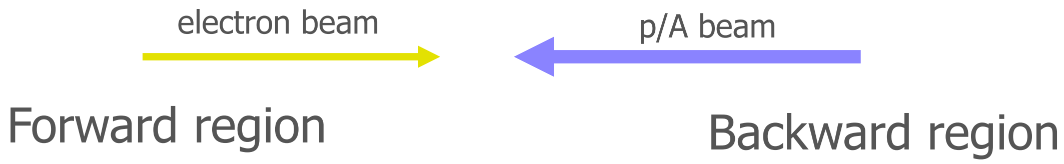

Forward vs Backwards Production

- 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

u-channel Processes We've Simulated

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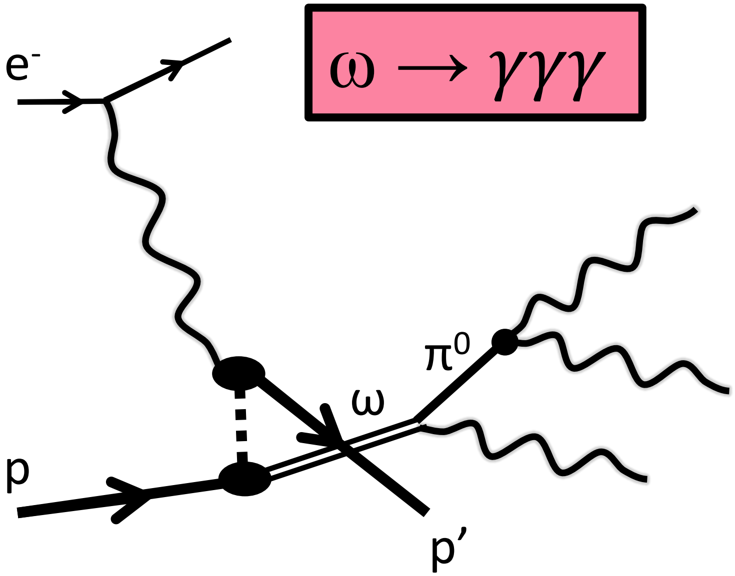
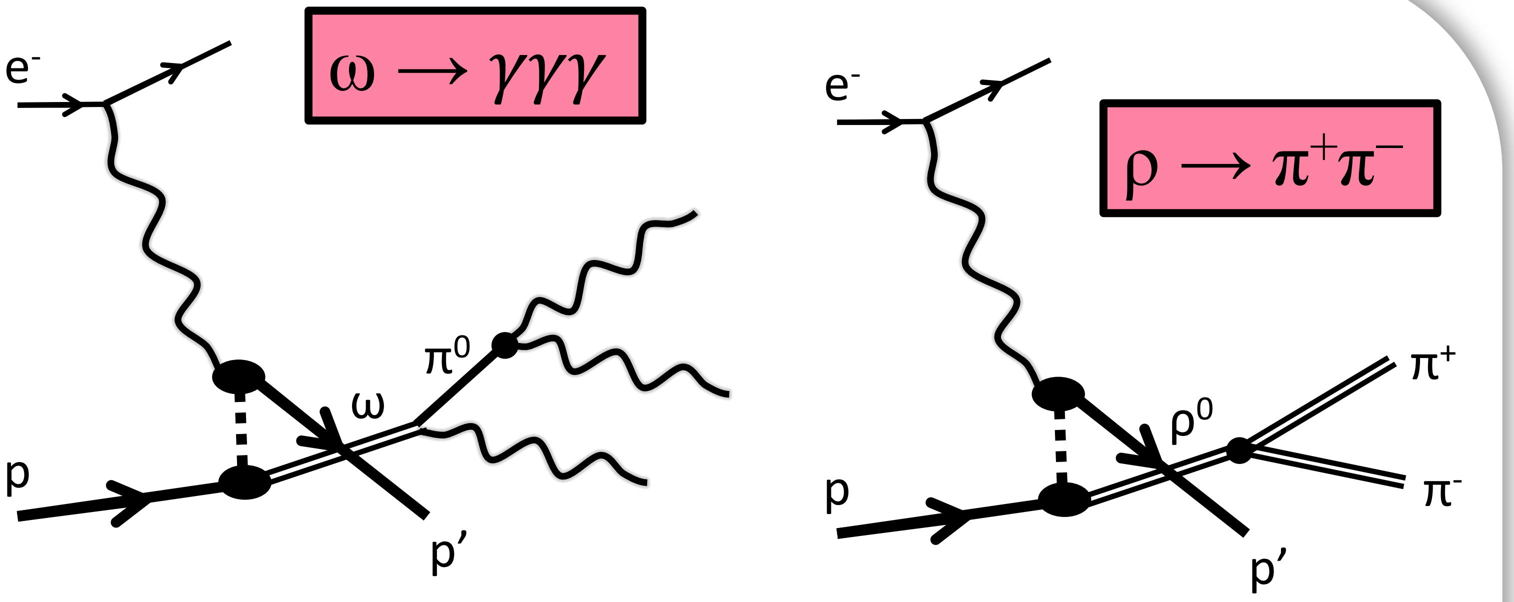


$\omega \rightarrow \gamma\gamma\gamma$

- *u*-channel vector meson production at the EIC

  Phys. Rev. C 106, 015204 (2022)

u-channel Processes We've Simulated



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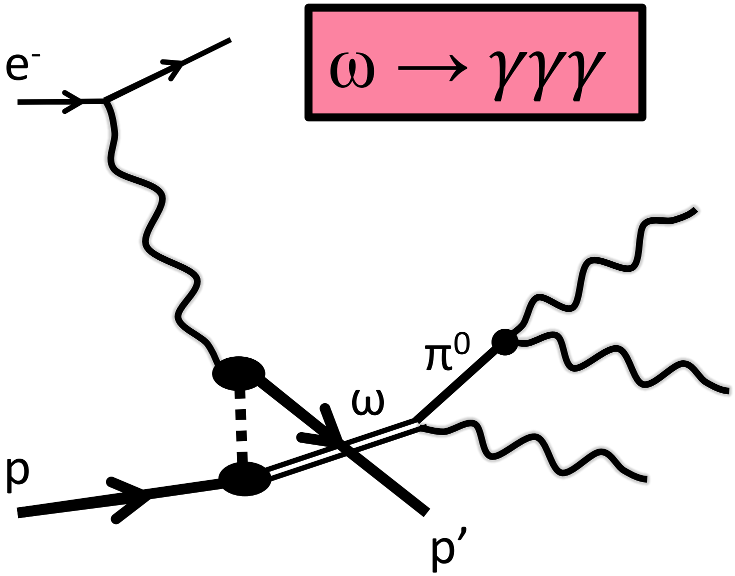
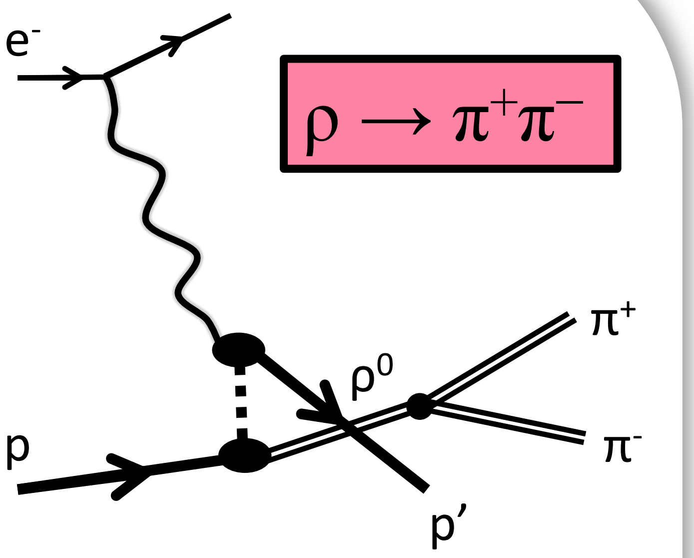
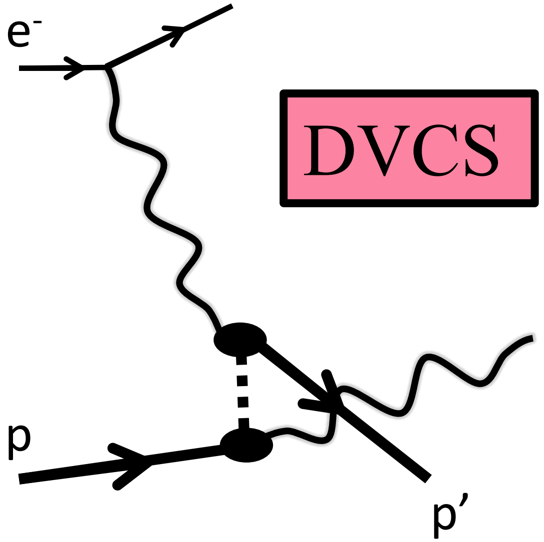






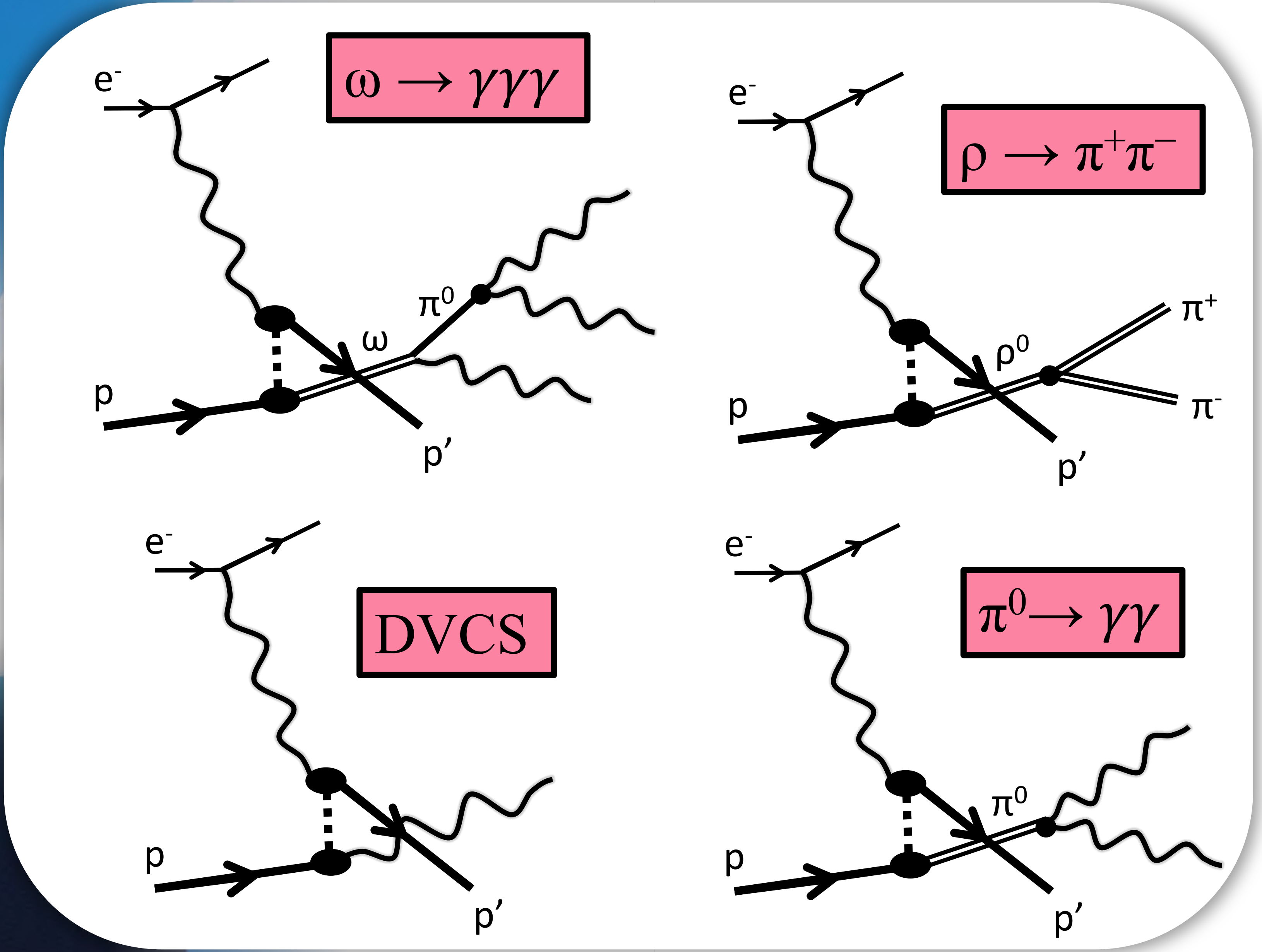
- u-channel vector meson production at the EIC

  Phys. Rev. C 106, 015204 (2022)

- u-channel virtual Compton scattering and π^0 production at the EIC

  Phys. Rev. C 108, 055205 (2023)

u-channel Processes We’ve Simulated



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  Phys. Rev. C 106, 015204 (2022)

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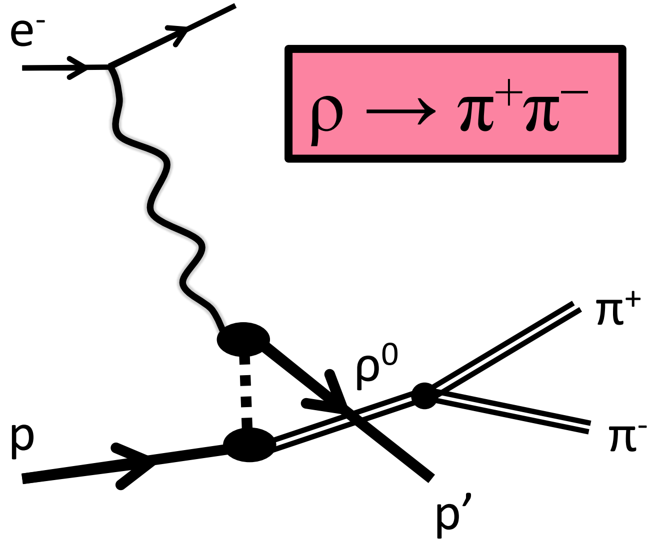
  Phys. Rev. C 108, 055205 (2023)

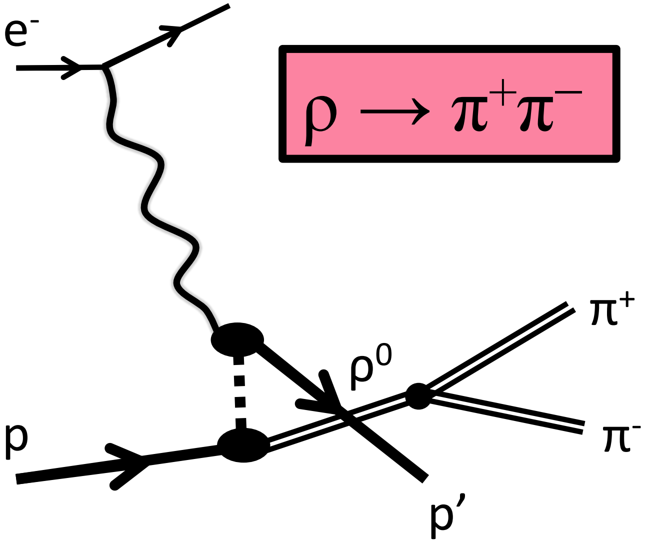
Modifying eSTARlight for u-channel $\rho \rightarrow \pi^+\pi^-$



Phys. Rev. C 106, 015204 (2022)

Modeling u-channel Production

Modifying eSTARlight for u-channel $\rho\to\pi^+\pi^-$



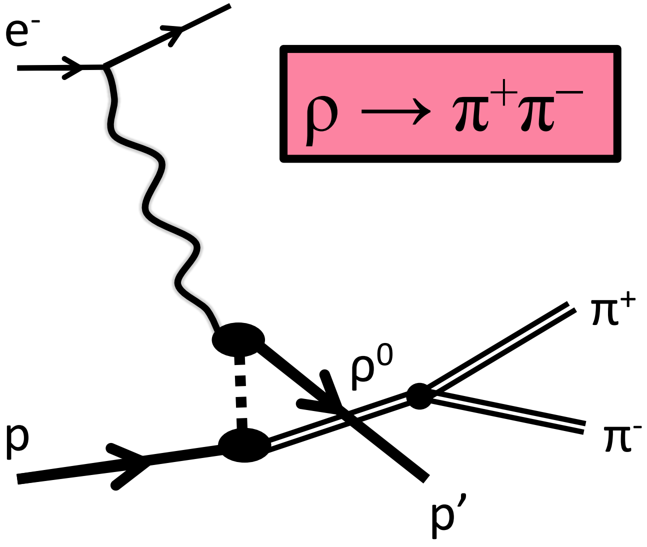
Phys. Rev. C 106, 015204 (2022)

Modeling u-channel Production

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

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

Modifying eSTARlight for *u*-channel $\rho \rightarrow \pi^+\pi^-$



Phys. Rev. C 106, 015204 (2022)

Modeling *u*-channel Production

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

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

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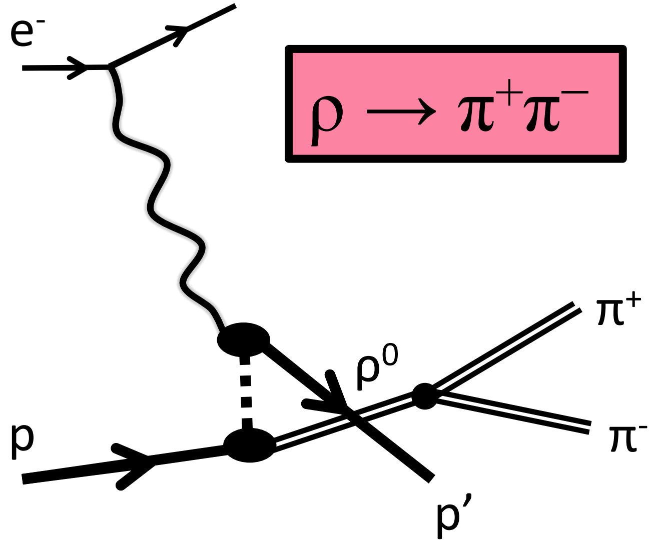
- B and C relate to size of production region which differs in t and u channels due to role of meson vs baryon exchange trajectories

Modifying eSTARlight for u-channel $\rho \rightarrow \pi^+\pi^-$



Phys. Rev. C 106, 015204 (2022)

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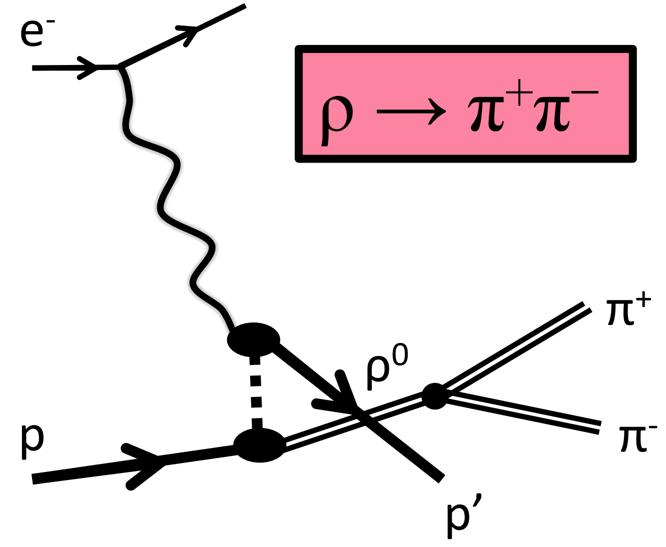
- Scaling depends on the meson produced
- B and C relate to size of production region which differs in t and u channels due to role of meson vs baryon exchange trajectories
- Effect of photon virtuality estimated with similar behavior to t-channel

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

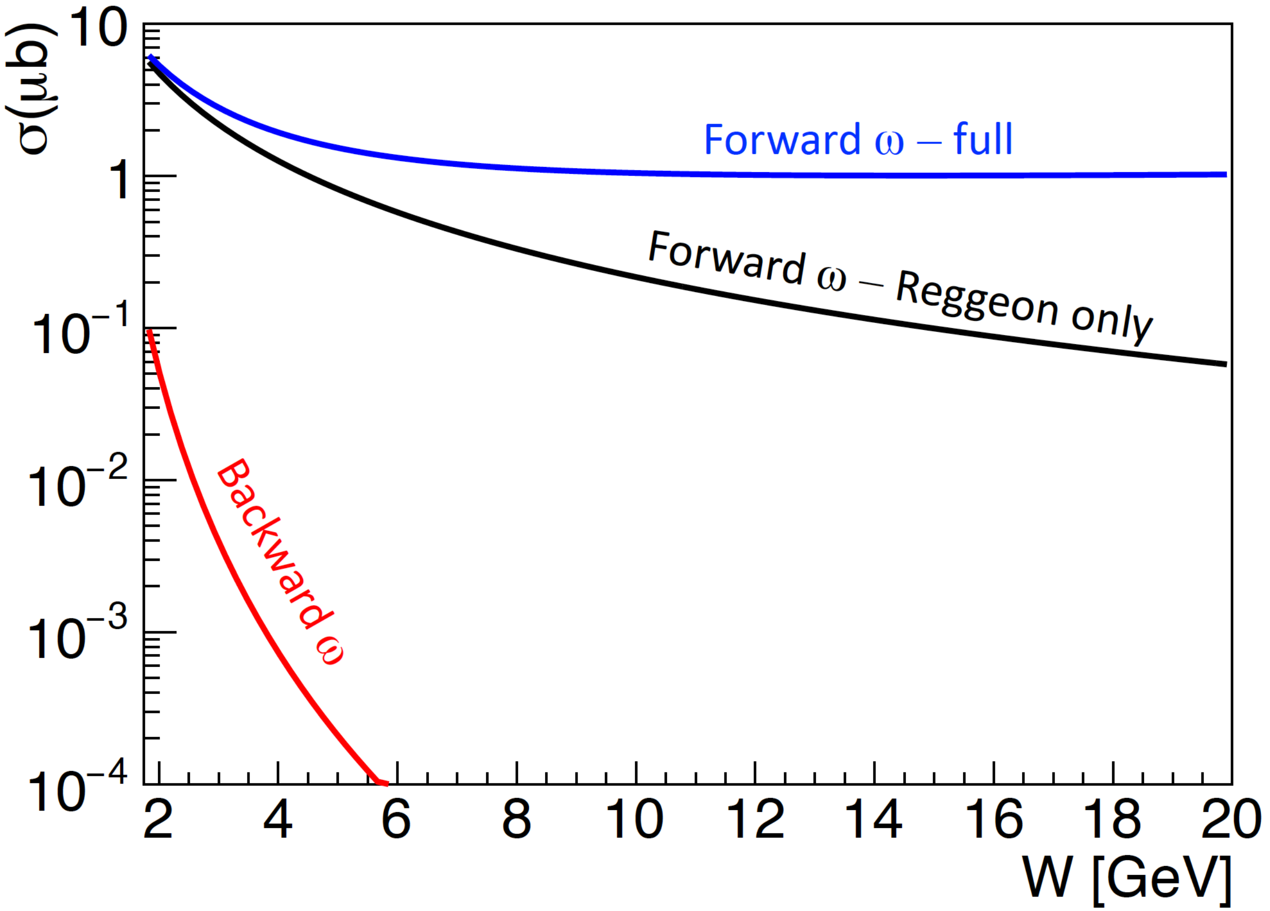
F.D. Aaron et al. (H1), JHEP 05, 032 (2010)

Modifying eSTARlight for *u*-channel $\rho\rightarrow\pi^+\pi^-$



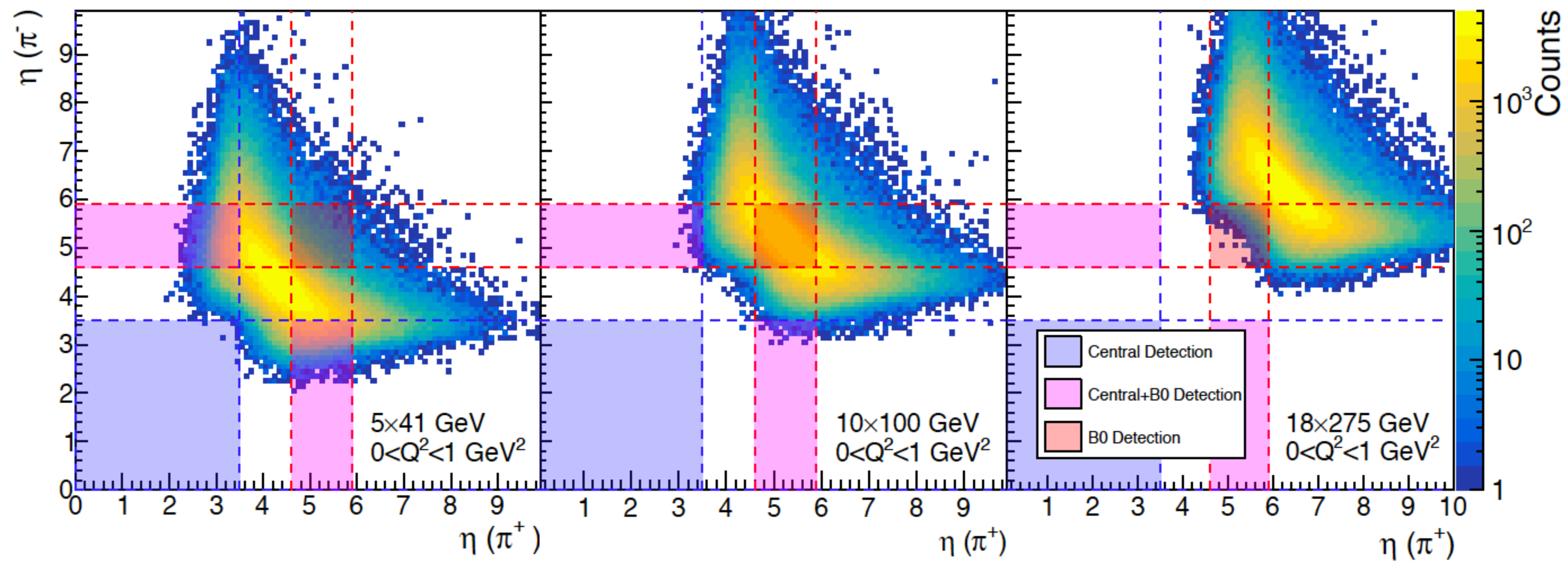
Phys. Rev. C 106, 015204 (2022)

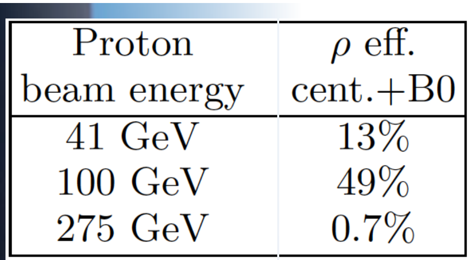
- Backward cross sections fall faster with increasing center-of-mass energy due to Reggeon exchange trajectories



u-channel $\rho \to \pi^+\pi^-$ at the EIC

- We can use this to start evaluating whether this channel will be observable





Proton beam energy	ρ eff. cent.+B0
41 GeV	13%
100 GeV	49%
275 GeV	0.7%

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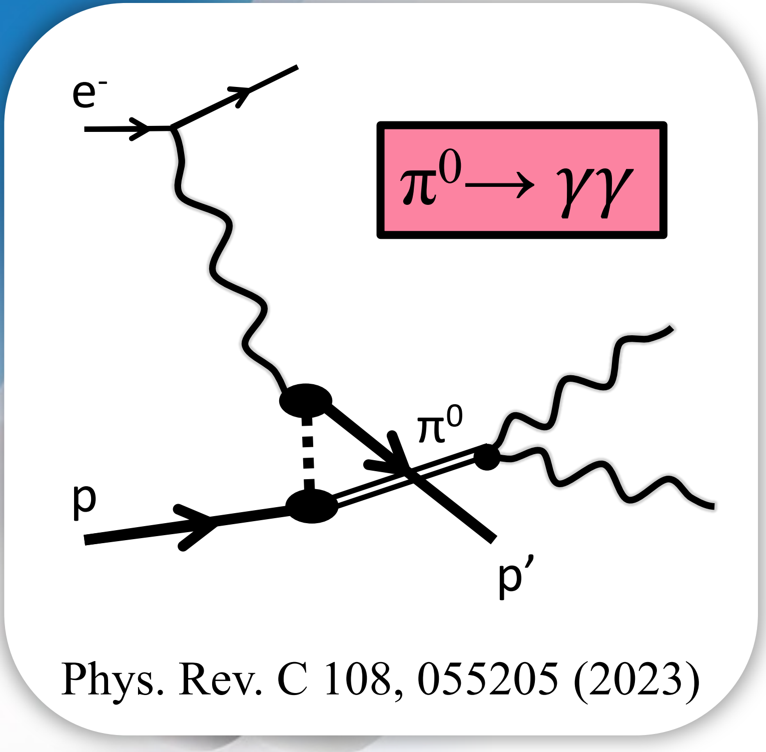
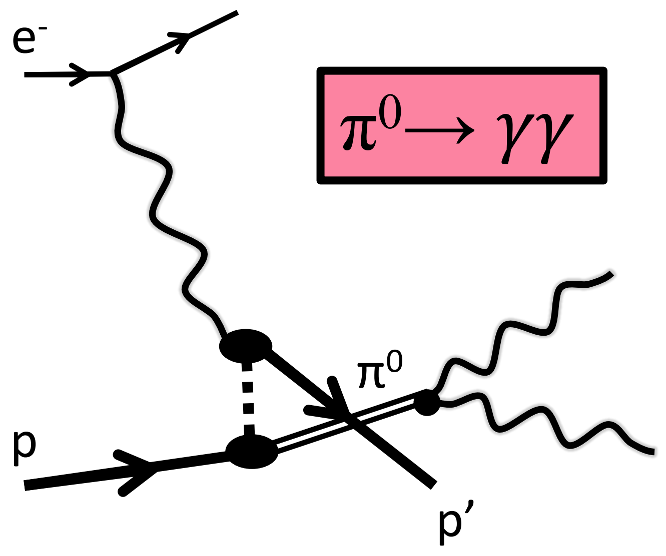
u-channel $\pi^0 \rightarrow \gamma\gamma$ at the EIC



Phys. Rev. C 108, 055205 (2023)

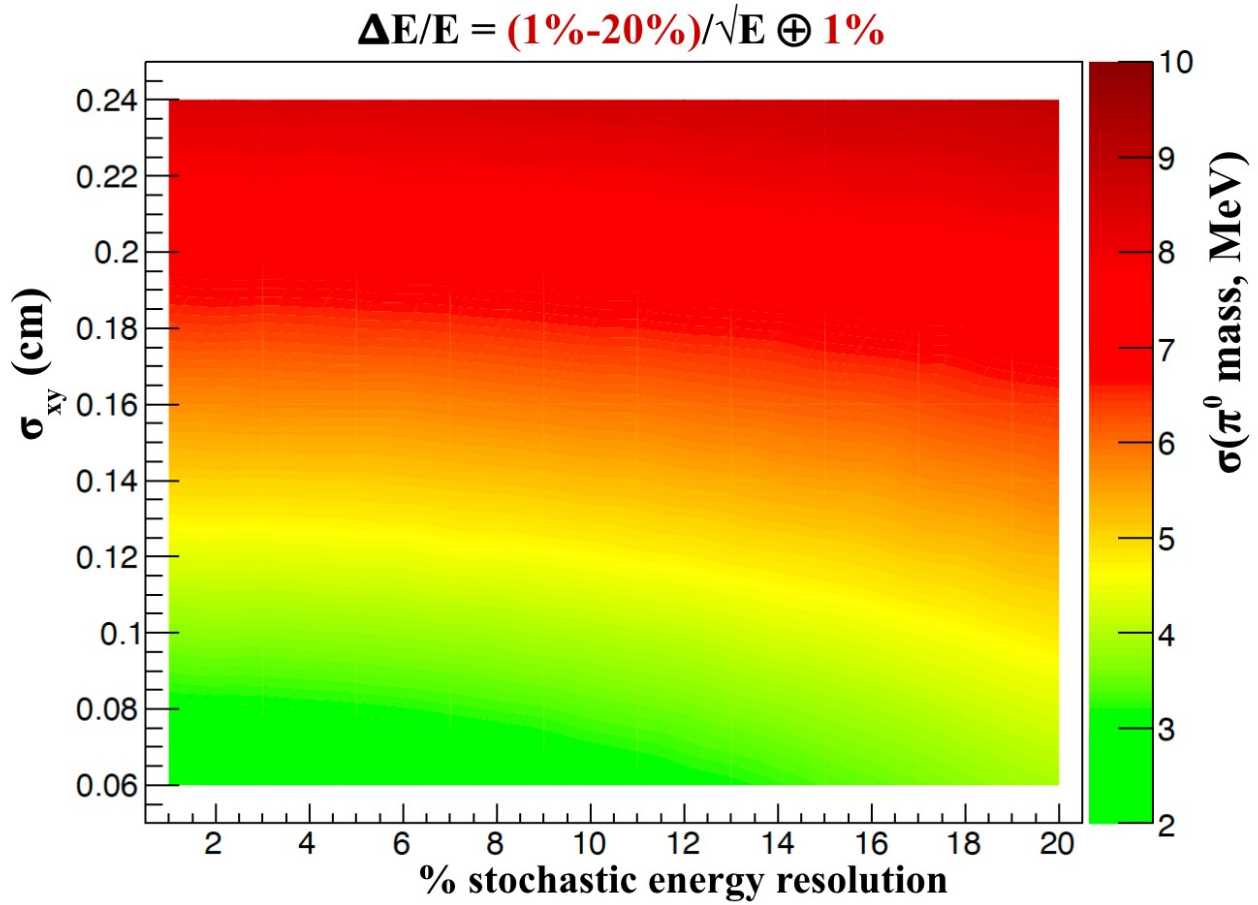
- Use similar method to simulate backward $\pi^0 \rightarrow \gamma\gamma$ in the ZDC
- Apply realistic energy and spatial resolutions to smear photons

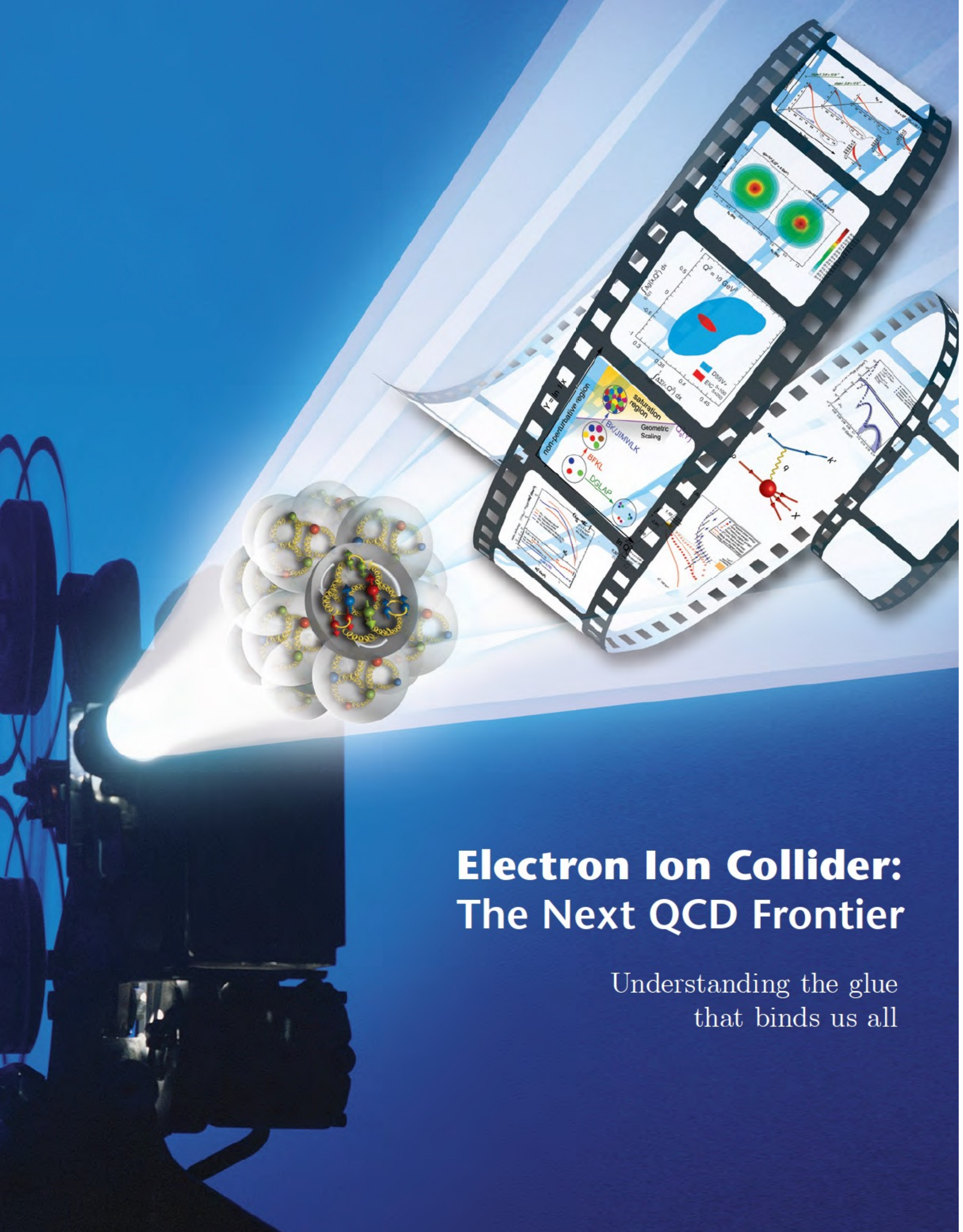
u-channel $\pi^0 \rightarrow \gamma\gamma$ at the EIC



Phys. Rev. C 108, 055205 (2023)

- Use similar method to simulate backward $\pi^0 \rightarrow \gamma\gamma$ in the ZDC
- Apply realistic energy and spatial resolutions to smear photons
- Use changes to π^0 reconstruction to inform detector design



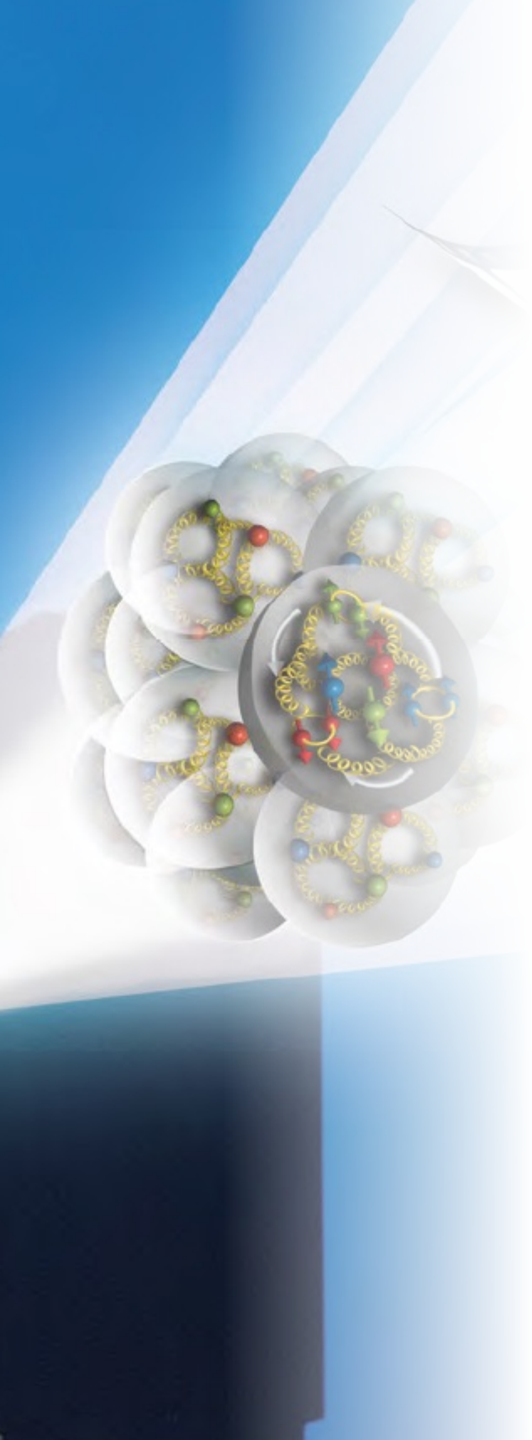


Electron Ion Collider: The Next QCD Frontier

Understanding the glue
that binds us all

Conclusions

- eSTARlight is a fast and flexible Monte Carlo for simulating vector-meson production in *ep* and *eA*
- More details about the physics behind the code available at https://doi.org/10.1103/PhysRevC.99.015203
- Code is available on GitHub: https://github.com/eic/estarlight
- eSTARlight is easy to modify to simulate novel processes



Thank you for your attention!

zwsweger@ucdavis.edu