Coherent vector meson production at an EIC

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Overview

- Motivation
- Photo-nuclear interaction in eSTARlight:
  - $\gamma p \rightarrow$ V.M. +p vector meson production
  - Comparison to data
  - Extension to γA
- Vector meson production at an EIC:
  - Estimating rates
  - Final state particle distributions
- Summary

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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

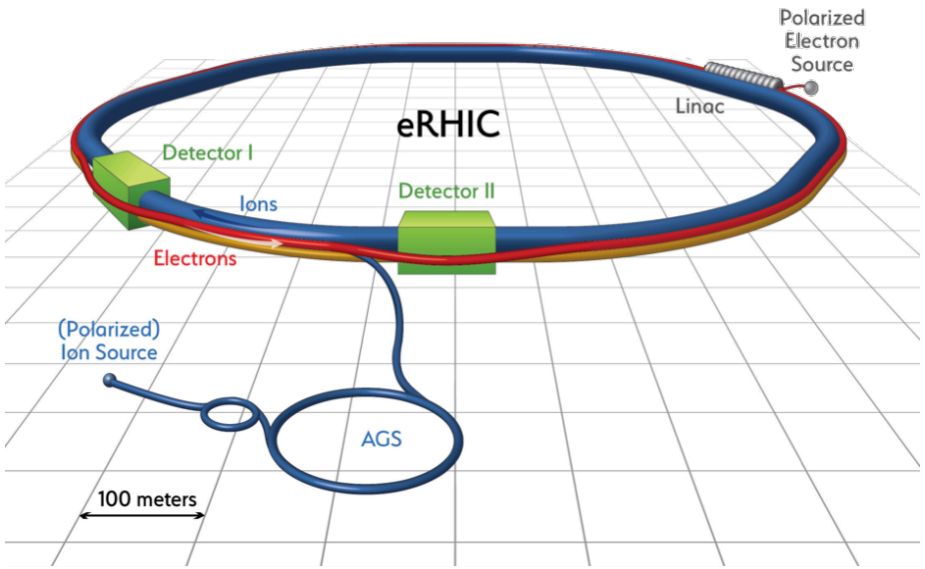
- M.C.'s don't cover more exotic processes, parametrizations missing

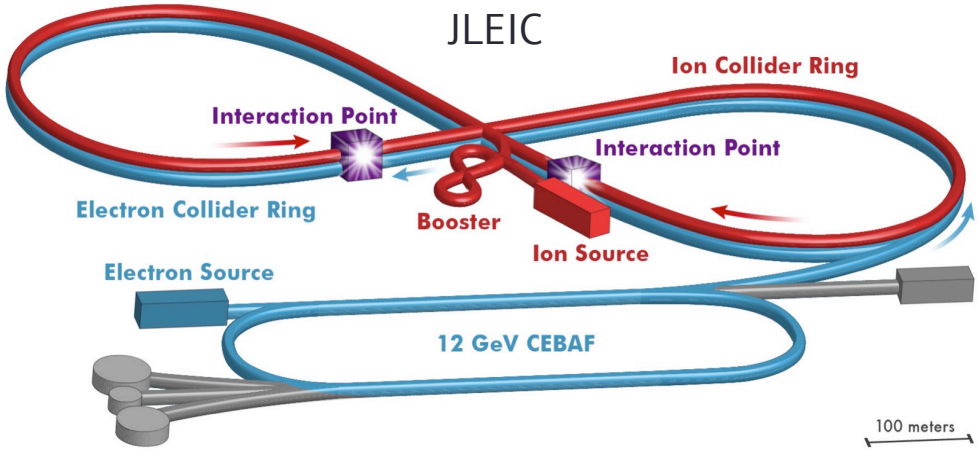
Lack of both experimental and simulations for eA:

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

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

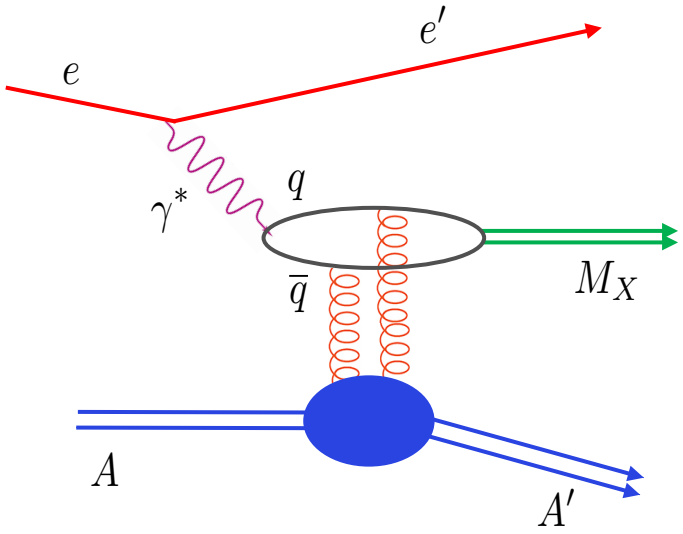
- Different center of mass energies (accelerator facilities)
- Different V.M. species
- Different collision systems (X = p, Au, etc.)
- Arbitrary virtuality Q^2





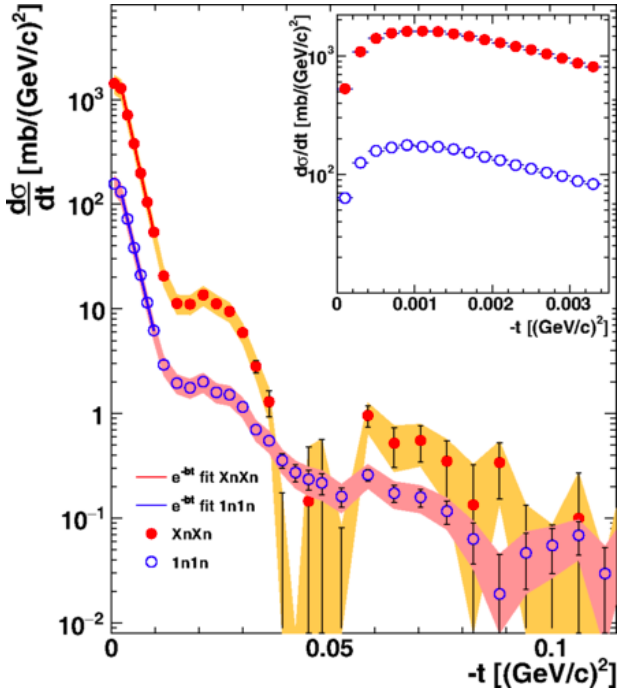
Diffraction at an EIC

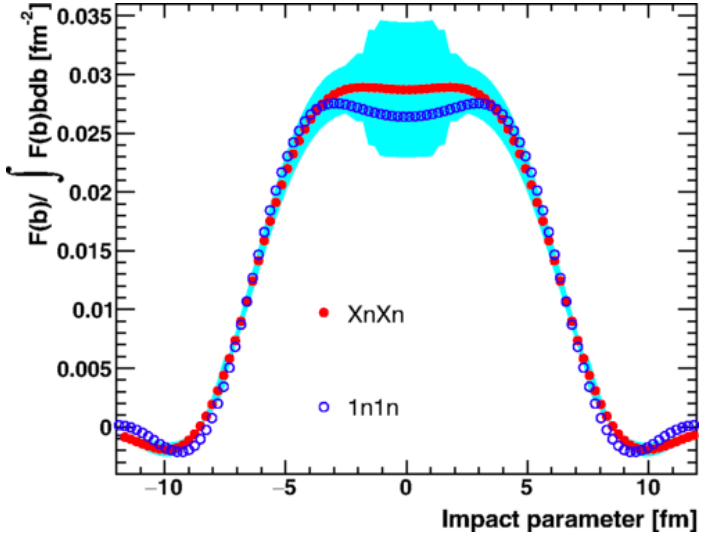
- How are the quarks and gluons distributed within the nucleon? What about nucleus?
- Initial state geometry is necessary to understand heavy ion collisions :
  - Initial state (IS) geometry → final state collectivity
  - Collective phenomena has been observed in p-p and p-A collisions



- Diffractive processes (no color exchange) can probe gluon density and their spatial distribution

STAR: PRC **96** 054904 (2017)





Electron-ion collisions

Some important kinematic quantities to consider in electron-ion collisions:

- Resolving power

$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$
$$= 2E_e E'_e (1 - \cos\theta_e)$$

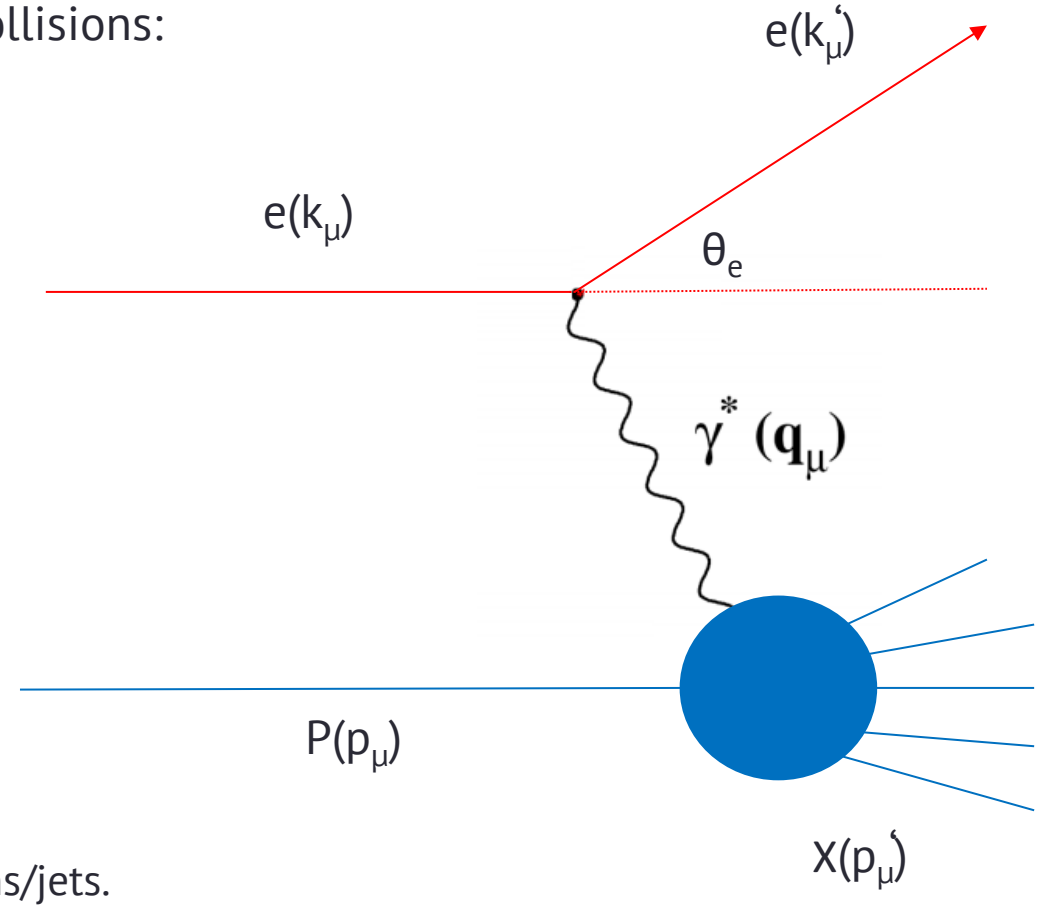
- Momentum of struck quark

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

- Measure of inelasticity

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta_e}{2}\right)$$

$$s = 4E_p E_e$$



Inclusive: Detect scattered lepton. e+p/A →e' + X

Semi-inclusive: Detect scattered lepton in coincidence with identified hadrons/jets.

e+p/A → e' + h + X

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

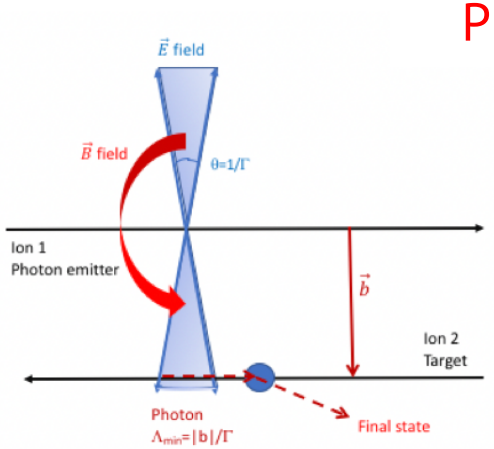
Electro-nuclear interactions

$$\sigma(e+X\rightarrow e+X+V.M.)=\int dQ^2\int dE_\gamma \frac{dN_\gamma(E_\gamma,Q^2)}{dE_\gamma dQ2}\sigma_{\gamma X}(W,Q^2)$$

Photon flux

Photonuclear cross section

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



- Include the corrections for finite virtuality[1]:

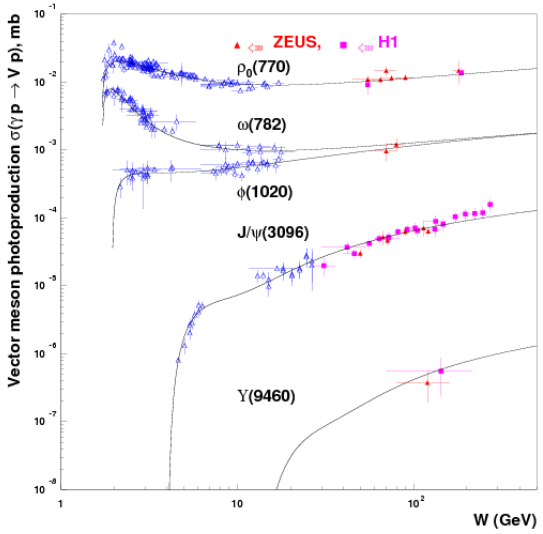
$$\frac{d^2N}{d(Q^2)dE_\gamma}=\frac{\alpha}{\pi}\frac{1}{E_\gamma|Q^2|}\left[1-\frac{E_\gamma}{E_e}+\frac{1}{2}\left(\frac{E_\gamma}{E_e}\right)^2-\left(1-\frac{E_\gamma}{E_e}\right)\left|\frac{Q^2_{min}}{Q^2}\right|\right]$$

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

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

$$\sigma_{\gamma p}(W)=\sigma_P\cdot W^\epsilon+\sigma_M\cdot W^\eta$$

- The power n is also obtained from fits to data[2]



[1]: Phys.Rept. 15 181-281 (1975)
[2]: Phys.Lett.B377:259-272(1996), JHEP 1005:032(2010), Nucl.Phys.B695:3-37(2004)

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:

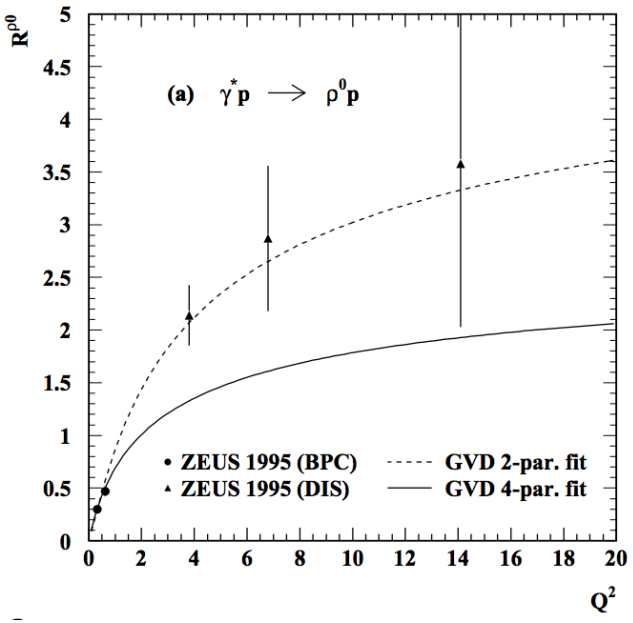
- 50% right-handed and 50% left-handed photons.

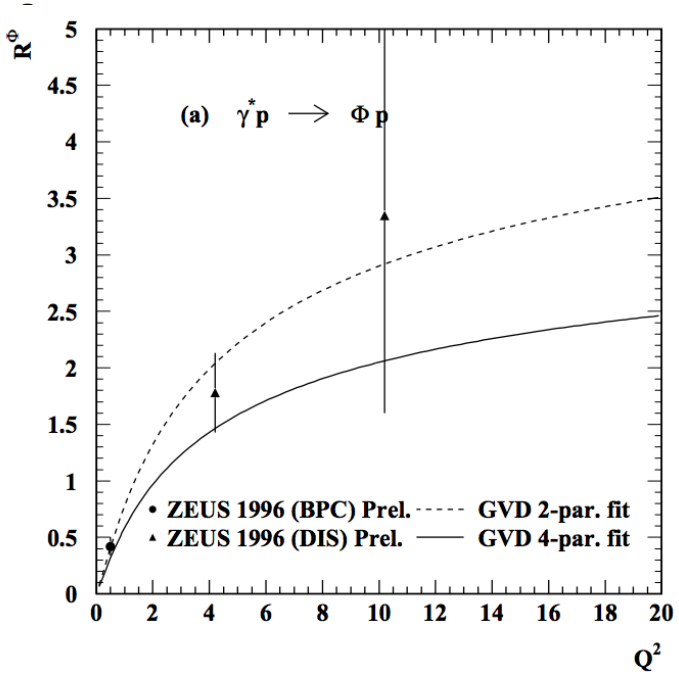
Virtual photons ($Q^2 > 0$) can also be longitudinally (*L*) polarized:

- 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

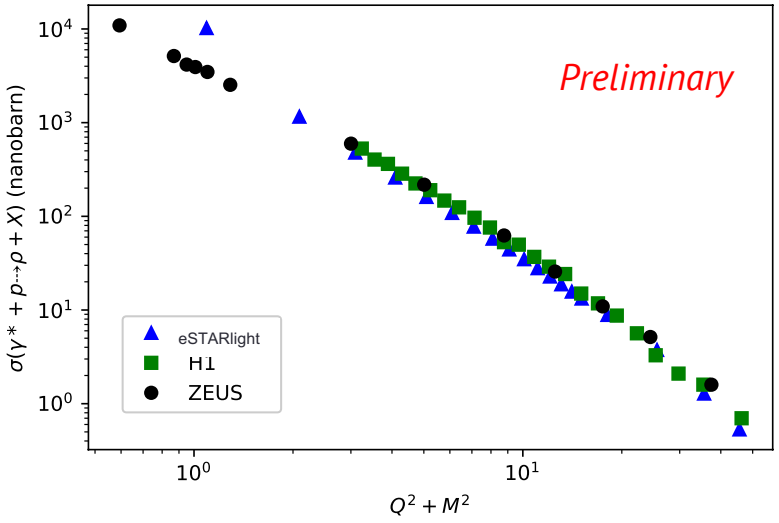




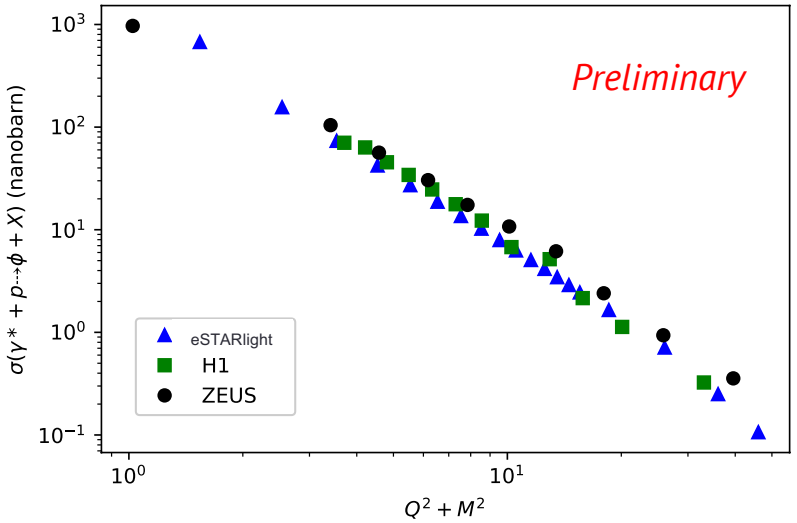
[1]: Phys.Lett. B449 (1999) 328-338

HERA comparison to data: σ(γ* + p → V.M. + p)

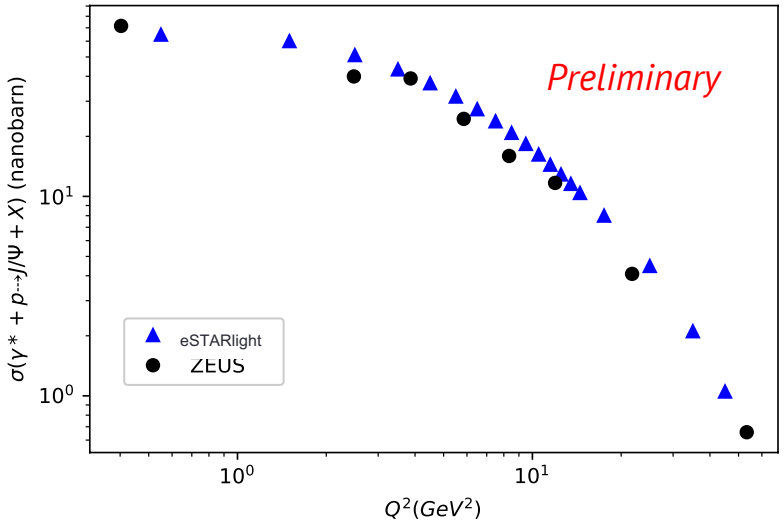
ρ



ϕ



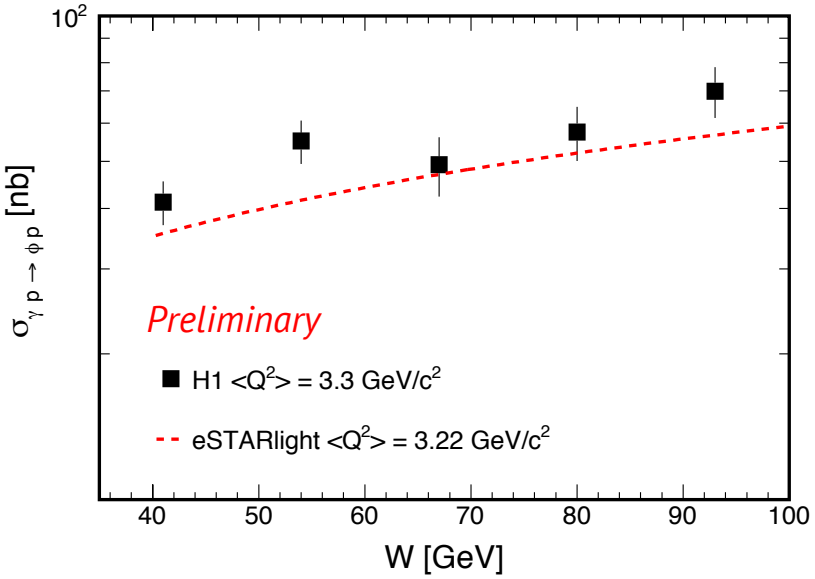
J/ψ



- 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



ϕ: Phys.Lett.B377:259-272(1996)
ρ: JHEP 1005:032(2010)
J/ψ: Nucl.Phys.B695:3-37(2004)

Photonuclear Cross Section σ(γA → VA) and event generation

- Extrapolate photonuclear cross section from γp to γA using Quantum Glauber

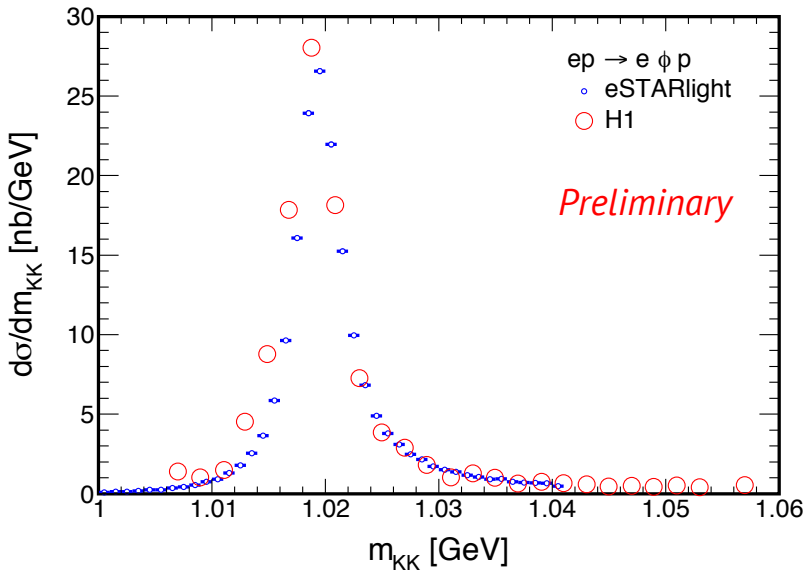
$$\sigma_{tot}(VA) = \int d^2b \left[2 \cdot \left(1 - e^{-\sigma_{tot}(Vp)T_{AA}(b)/2}\right)\right]$$

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

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

- 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

H1 data corrected for exp. resolution and background subtraction JHEP05(2010)032



Estimating rates for an EIC

		Photo-production ($Q^2 < 1$ GeV^2)					Electro-production ($Q^2 > 1$ GeV^2)				
		ρ	ϕ	J/ψ	ψ'	Υ	ρ	ϕ	J/ψ	ψ'	Υ
eRHIC	ep	50 G	2.3 G	85 M	14 M	140 K	140 M	17 M	5.7 M	1.2 M	24 K
	eAu	44 G	2.8 G	100 M	16 M	60 K	37 M	5.6 M	3.9 M	960 K	10 K
JLEIC	ep	37 G	1.6 G	39 M	6.0 M	43 K	100 M	12 M	2.7 M	550 K	7.9 K
	ePb	28 G	1.6 G	28 M	3.9 M	-	22 M	3.2 M	1.2 M	250 K	-
LHeC	ep	100 G	5.6 G	470 M	78 M	1.2 M	260 M	37 M	29 M	6.3 M	180 K
	ePb	110 G	8.2 G	720 M	140 M	2.0 M	100 M	16 M	27 M	7.2 M	250 K

- $Q^2 > 1$ GeV/c^2 affects V.M. species to different degree
- Rates are encouraging for meaningful ψ' and possibly Υ measurements

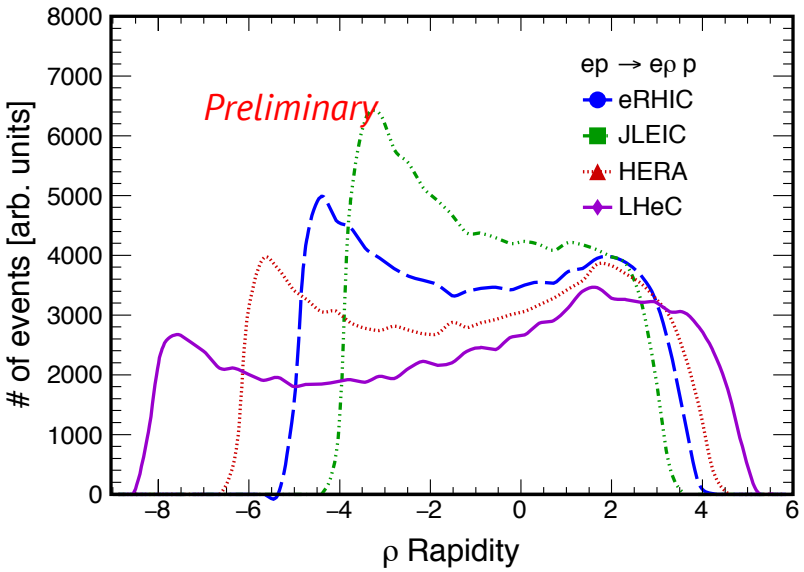
Accelerator	Collision System	Electron Energy	Heavy Ion Energy
eRHIC [21]	*ep*	18 GeV	275 GeV
-	*eA*	18 GeV	100 GeV/A
JLEIC [22]	*ep*	10 GeV	100 GeV
-	*eA*	10 GeV	40 GeV/A
LHeC [23]	*ep*	60 GeV	7 TeV
-	*eA*	60 GeV	2.8 TeV/A
HERA	*ep*	27.5 GeV	920 GeV

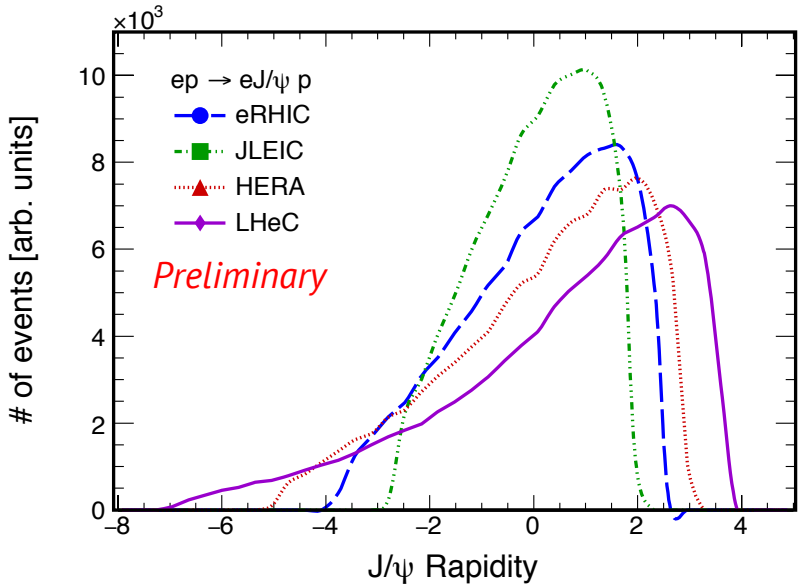
Don't account for branching ratios

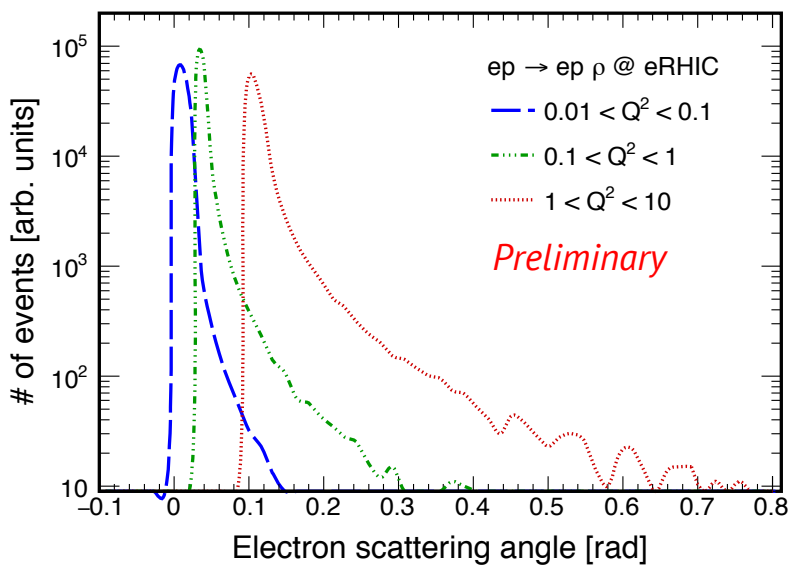
[1]: EIC whitepaper: A. Accardi et. al., Eur. Phys. J. A, 52 9(2016)
**: Likely overestimated: Doesn't account for loss of longitudinal coherence

** Note: Generated distributions are not scaled in order to compare the different colliders

Event generation

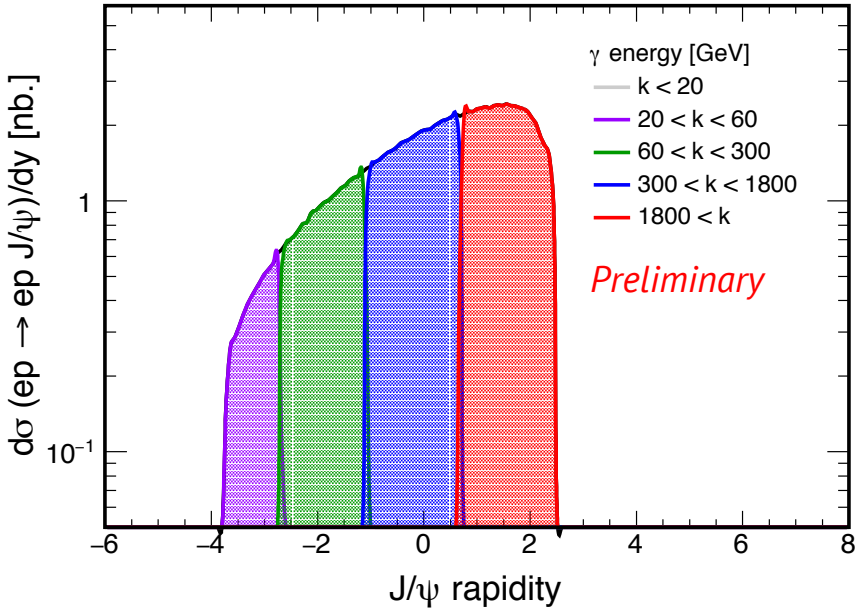


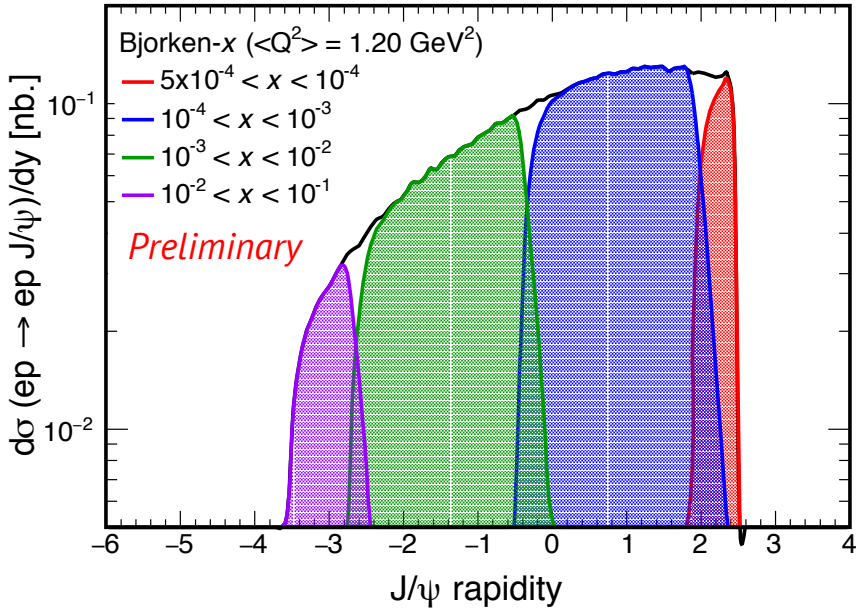




- Vector meson (ρ^0 and J/ψ) production occurs over a large rapidity window
- ρ peak negative rapidity due to photon-meson exchange (mostly near threshold). Not present in heavier V.M.
- Peak at forward rapidity (higher *k*) due to Pommeron exchange
- Detecting scattered electron requires far forward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

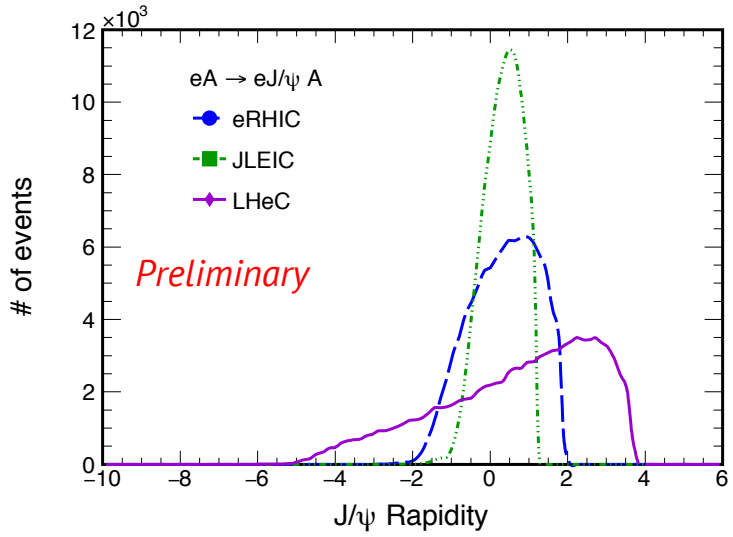
Event generation

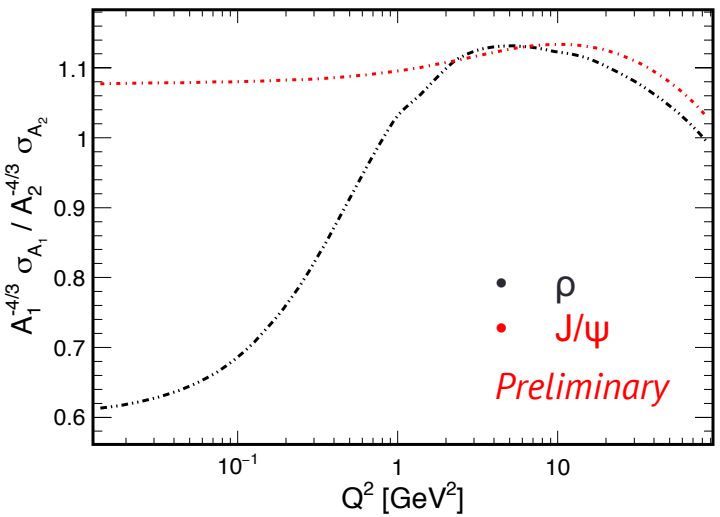


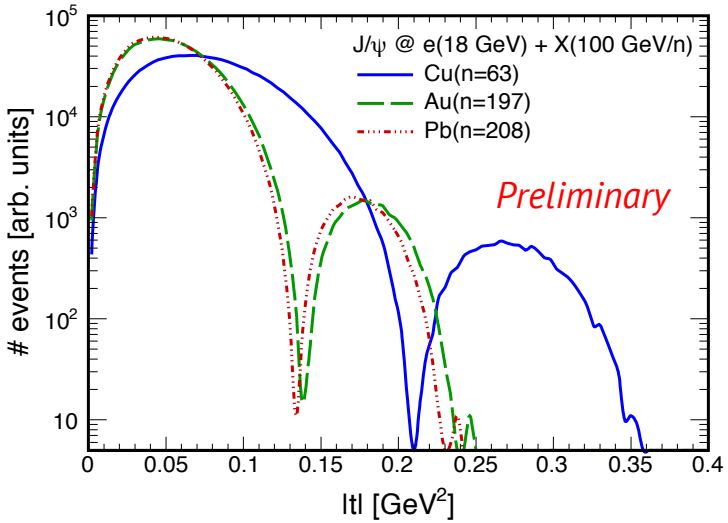


- Plots show J/ψ production in energy (*k*) and Bjorken-*x* bands
- Vector meson production roughly matches photon energy:
  - High energy photons to the right, low energy to the left
- Studying wide range in k or *x* requires large coverage. Could be done by running EIC at different energies *s*.

Predictions for eA at potential EIC's

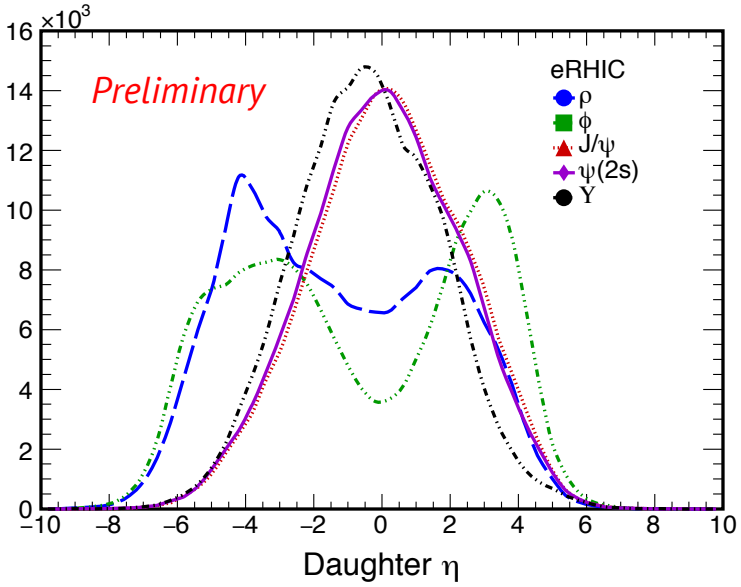




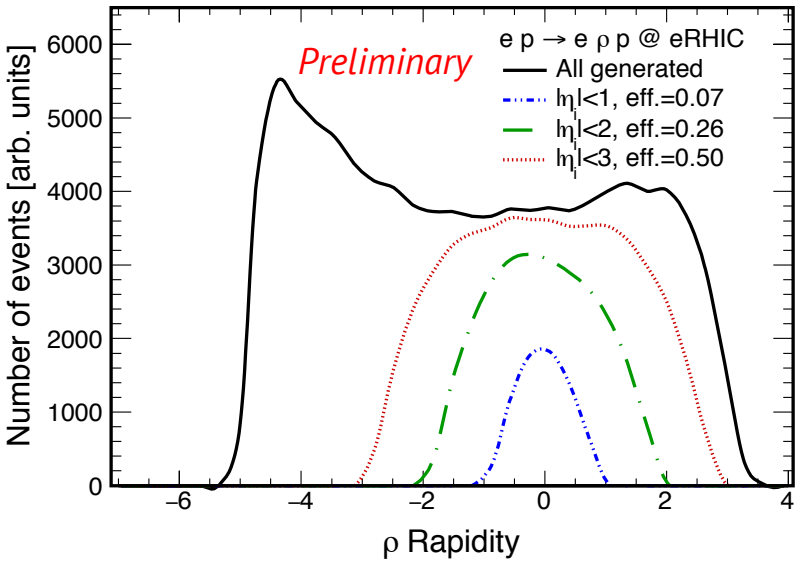


- Reduced C.M. energy per nucleon → lower Pomeron p_z. Production in a narrower rapidity range:
  - Good news for barrel detectors
- Middle: Scaled ($A^{-4/3}$) ratio of V.M. production on lead vs. iron:
  - Signs of nuclear shadowing at low Q^2
- Right plot shows predictions of diffractive minima for three nuclear targets. Fourier transform provides information on gluon distributions $g(b_T)$.

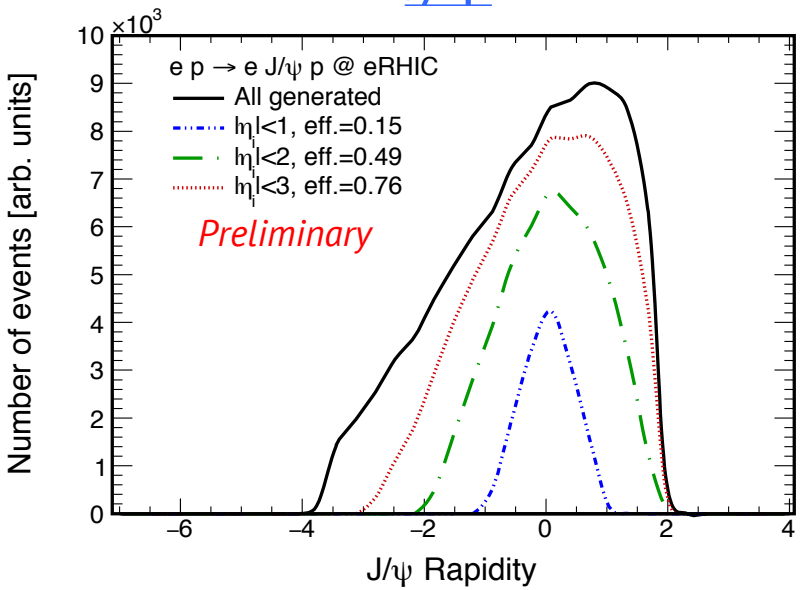
Final state distributions



ρ



J/ψ



- 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% (|η|<3) and <10% (|η|<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 Υ(1S) production at an EIC to allow limited studies ($Q^2 > 1$ 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