Separating coherent and incoherent vector meson production at an EIC

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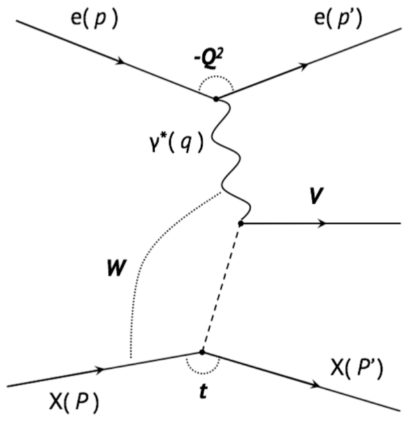
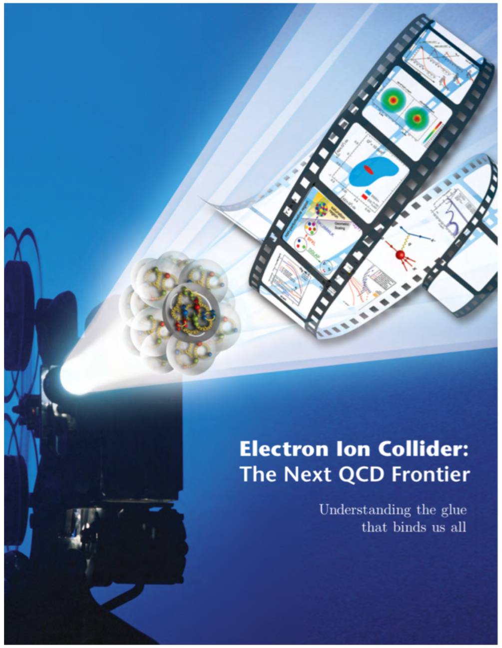


- Coherent and incoherent production
- Vector meson kinematics*
  - Detectability for different mesons
  - Differences between coherent and incoherent
- Nuclear Breakup
- Overlapping events
- Nuclear breakup without neutrons



*Work done in collaboration with Sam Heppelman

Coherent and incoherent vector meson production

- Coherent photoproduction probes the average nuclear distribution
- Incoherent photoproduction is sensitive to event-by-event changes in the nuclear configuration Ω (positions of nucleons, gluon hot spots, etc).
- In the Good-Walker formalism:

$$\frac{\mathrm{d}\sigma_{\mathrm{tot}}}{\mathrm{d}t} = \frac{1}{16\pi} \left\langle \left| A(K,\Omega) \right|^2 \right\rangle$$

Average cross-sections (Ω)

$$\frac{\mathrm{d}\sigma_{\mathrm{coh}}}{\mathrm{d}t} = \frac{1}{16\pi} \left| \langle A(K,\Omega) \rangle \right|^2$$

Average amplitudes (Ω)

$$\frac{\mathrm{d}\sigma_{\mathrm{inc}}}{\mathrm{d}t} = \frac{1}{16\pi} \left(\left\langle \left| A(K,\Omega) \right|^2 \right\rangle - \left| \langle A(K,\Omega) \rangle \right|^2 \right)$$

Incoherent is difference

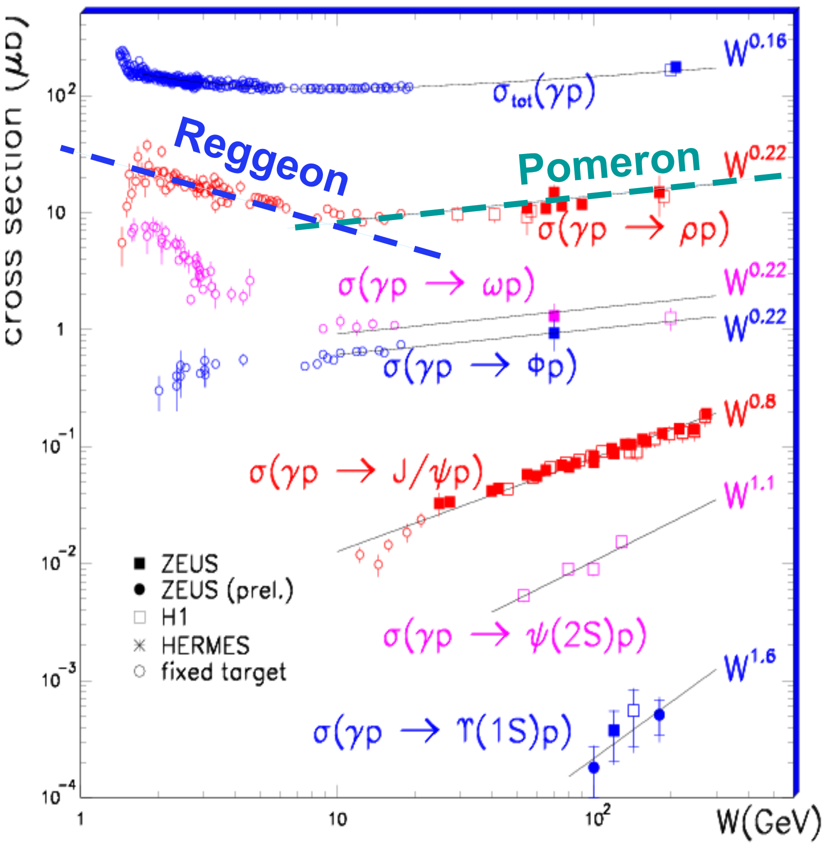
- So, highly desirable to analyze coherent & incoherent in parallel

SK & H. Mantysaari, Nature Phys. Reviews **1**, 662 (2019)

Vector meson production on proton targets

- HERA cross-sections fit by
- $\sigma(W) = XW^{\epsilon} + YW^{-\eta}$
  - W=γp CM energy
- XW^{ϵ}: Pomeron (gluons)
  - ε ~ > 0.2 – meson dependent
  - $J^{PC}=0^{++}$
  - Important for low-x
- $YW^{-\eta}$: 'Reggeon' (~~qqbar)
  - η~~1.5
  - Summed light-quark meson trajectories
    - ~valence quarks
    - Important for large x
  - *Zero* for ϕ, J/ψ, etc.
- Q^2 dependence – power law

Photoproduction data



Photoproduction & electroproduction model

- Convolution of photon flux from electron with $\sigma(\gamma p \to Vp)$
  - Both depend on Q^2
- Weizsacker-Williams photon flux (with non-zero Q^2)
- VM cross-sections parameterized from HERA data/theory….
  - Reggeon and Pomeron exchange
    - Q^2 dependence via a power law from HERA data
- Vector mesons retain the photon spin
  - For $Q^2 \sim 0$, transversely polarized
  - As Q^2 rises, longitudinal polarization enters
  - Spin-matrix elements quantified with HERA data
- Embodied in eSTARlight code, available at: http://starlight.hepforge.org

SK & M. Lomnitz, Phys. Rev. **C99**, 015203 (2019)

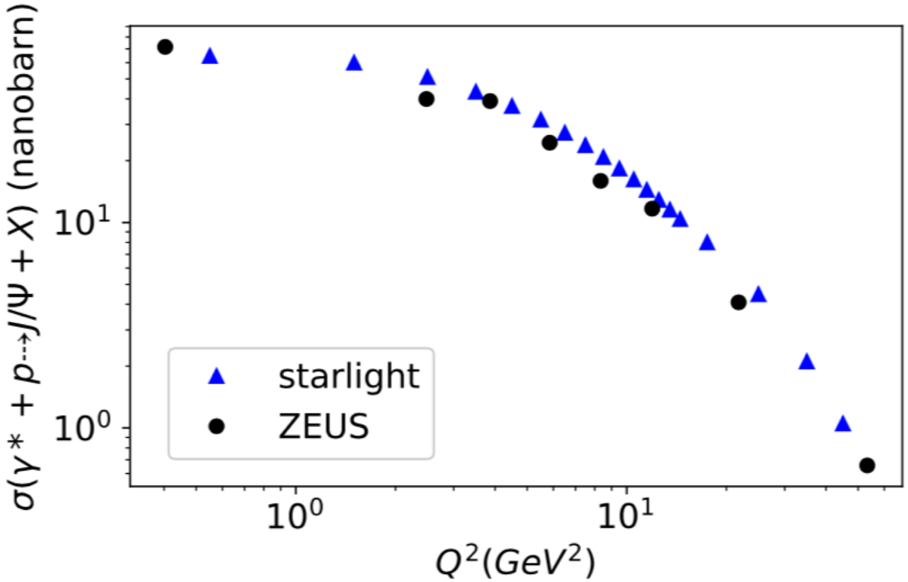
Q^2 dependence of cross-section

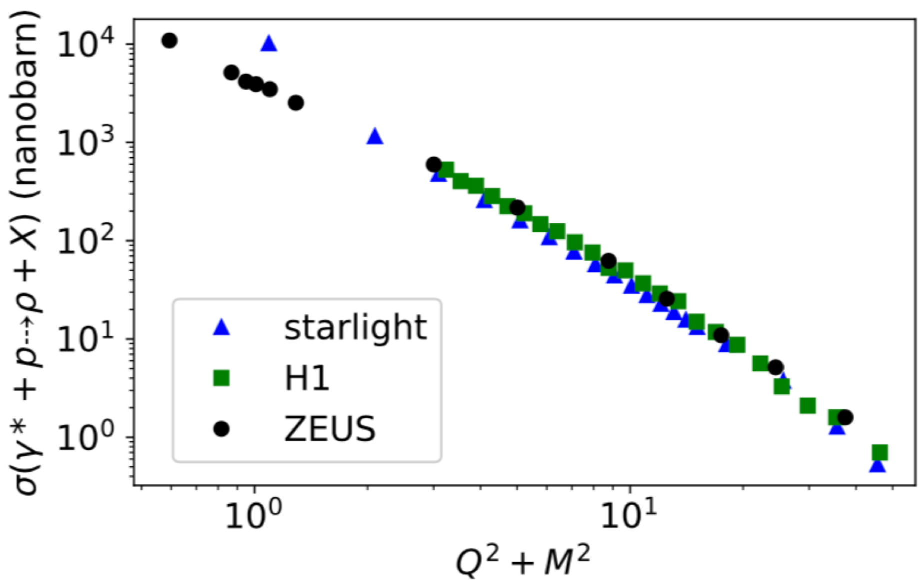
- Power law based on HERA data

$$\sigma_{\gamma^* A\to VA}(W,Q^2) = f(M_V)\sigma(W,Q^2=0)\left(\frac{M_V^2}{M_V^2+Q^2}\right)$$
$$n = c_1 + c_2(Q^2+M_V^2)$$

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

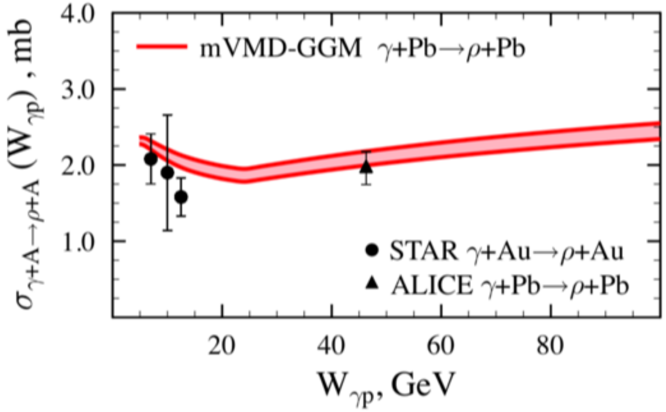
- Only measured for a smallish number of mesons
  - Source of uncertainty for others
- This determine how high in Q^2 the EIC can probe

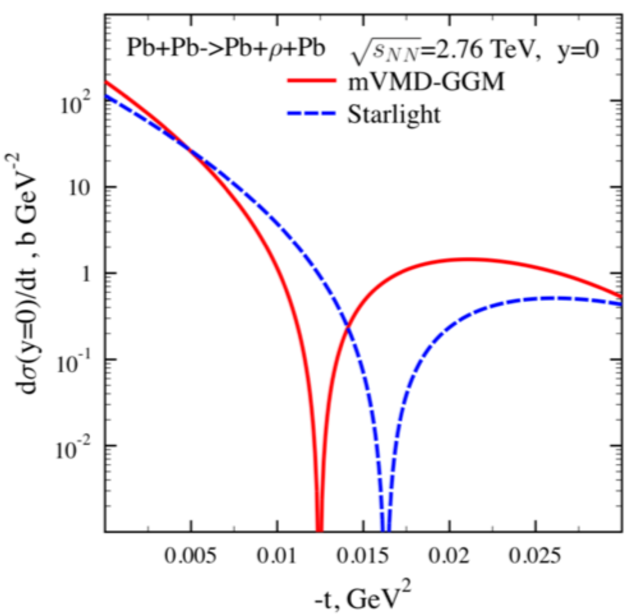




Light VM on nuclear targets

- (Too) Naïve approach: add amplitudes, with phase factor
  - $d\sigma/dt|_{t=0} = |\Sigma_i Ai \exp(ikr_i)|^2$
- A dipole traversing a nucleus may interact with multiple nucleons
- Standard approach: Glauber calculation
  - Accounts for multiple interactions
  - In RHIC & LHC ultra-peripheral collisions, Glauber over estimates ρ photoproduction
- Including high-mass photon inelastic diffraction in a Gribov-Glauber calculation leads to good agreement with the data

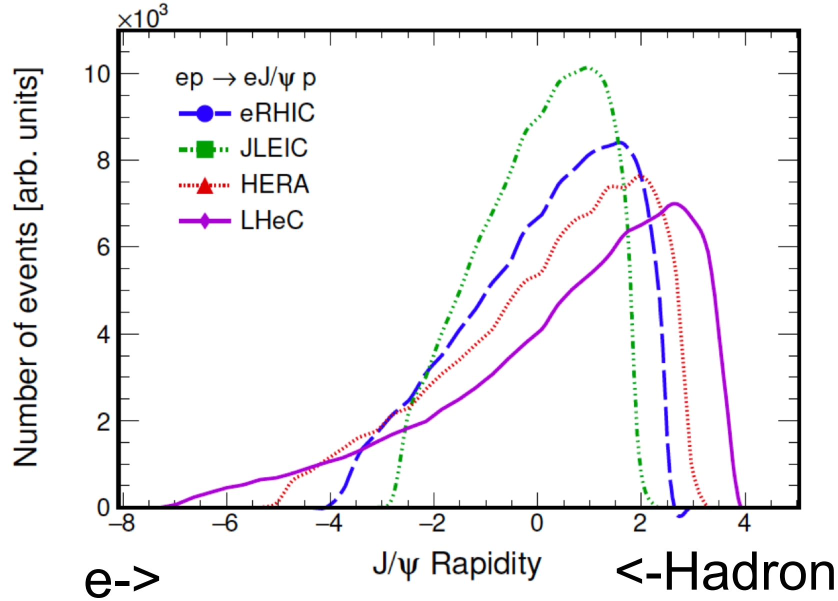


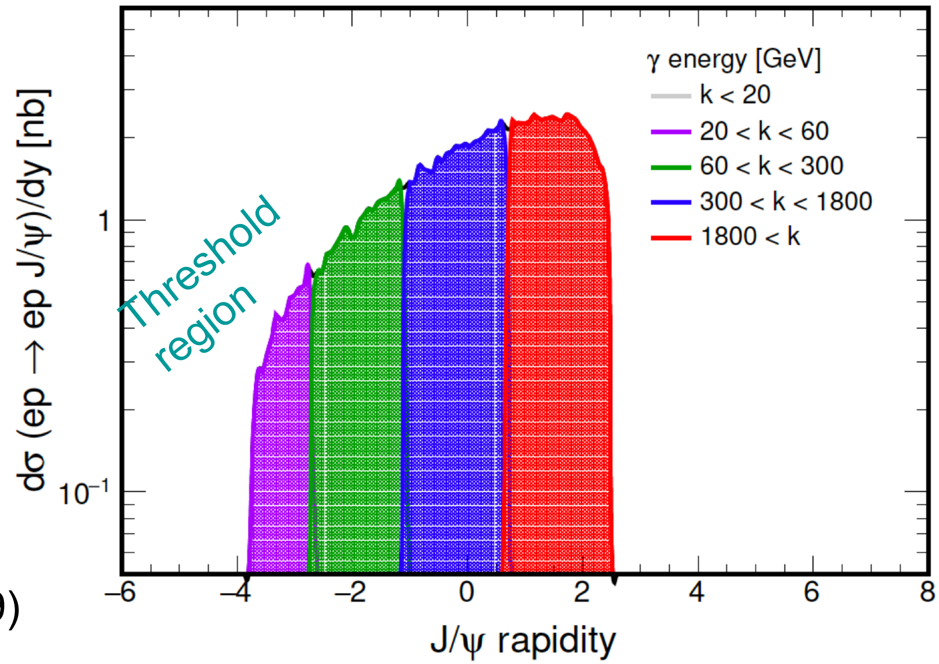


L. Frankfurt *et al.,* Phys.Lett. **B752**, 51 (2016)

EIC photoproduction kinematics

- Maps photon energy onto rapidity
- $k = \frac{M}{2}\exp(y)$
- y=ln(2k/M)
- Reggeon activity strongest at low photon energies
  - Hadron-going direction

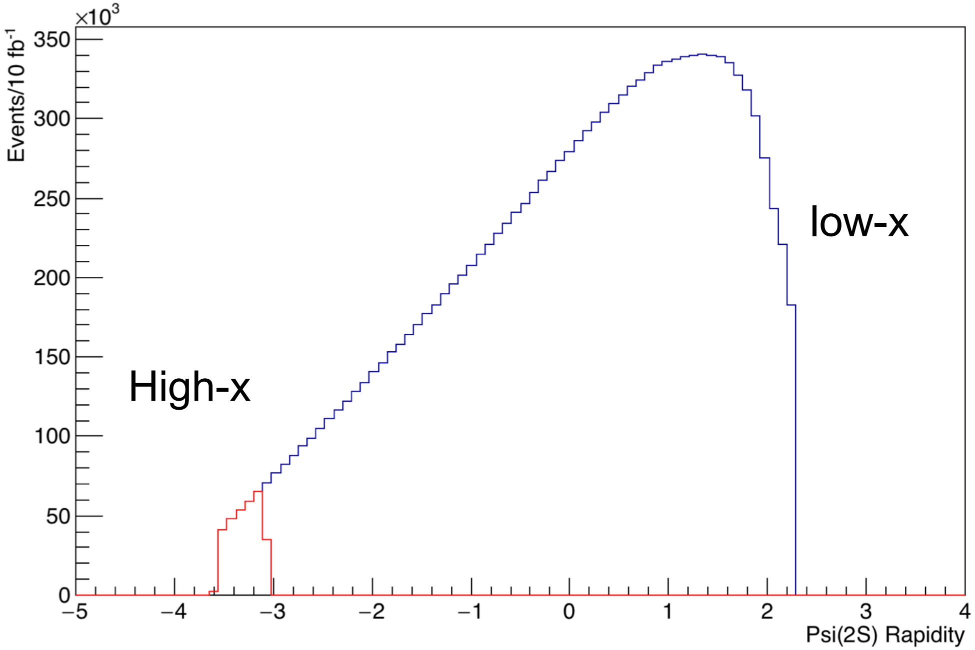




SK & M. Lomnitz, Phys. Rev. **C99**, 015203 (2019)

$\Psi(2S)$ & Υ photoproduction at eRHIC

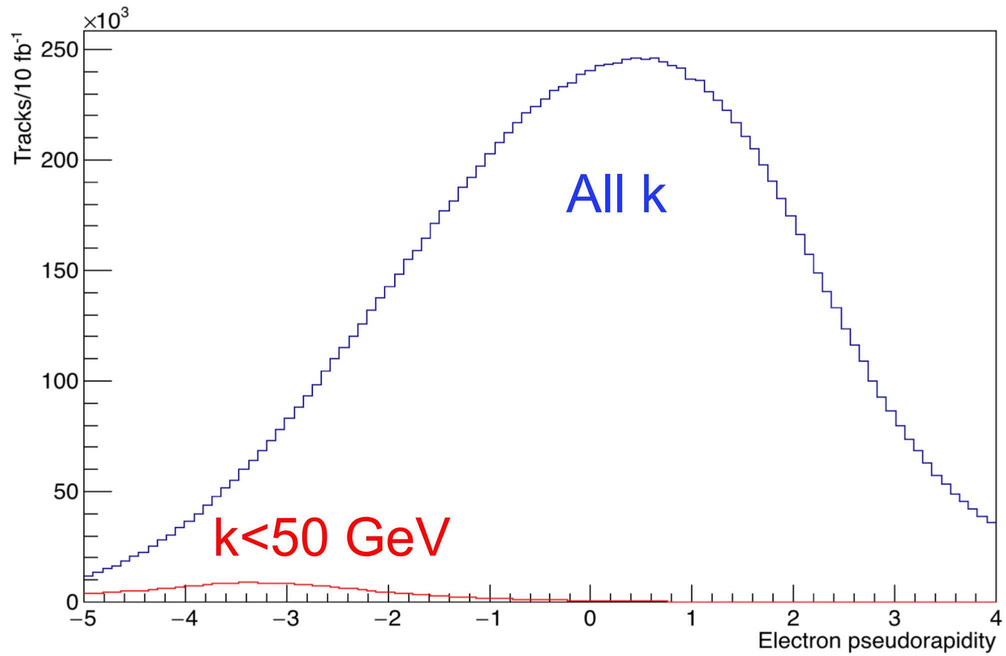
- 18 GeV e^- on 275 GeV protons
- σ=1.4 nb (1/6 of $\sigma(J/\psi)$)
  - 14 million events in 10 fb^{-1}
- $\sigma(\Upsilon(1S))=0.01\sigma(\psi')$
  - 140,000 events/10fb^{-1}
    - ~3,000 each to ee, $\mu\mu$
  - ~3,000 near-threshold events
    - ~75 each to ee, $\mu\mu$
    - More central than ψ'



e-> <-Hadron

Ψ(2S)->ee lepton pseudorapidities

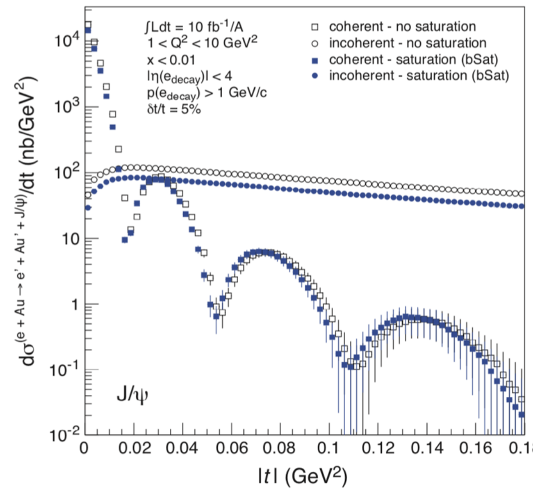
- Lepton pseudorapidity depends on Y(2S) rapidity, p_T and polarization (which depends on Q^2)
- Leptons from most near-threshold (k<50 GeV target frame) ψ(2S)->ll decays have -5<y<-2
  - Good acceptance required in hadron-going direction
  - N.b. Br(ψ(s)->ee or μμ is 0.7%. Plus $J/\psi\pi^+\pi^-$
- Rates for Υ(1S) usable.
- Higher ψ states

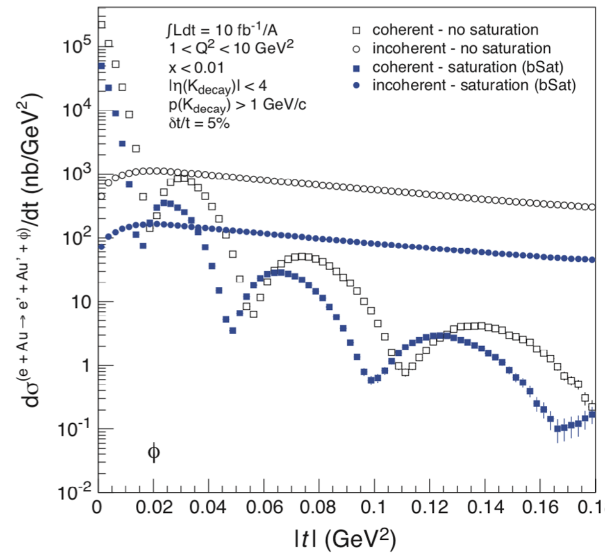


e-> <-Hadron

Choosing mesons: the 2012 White Paper

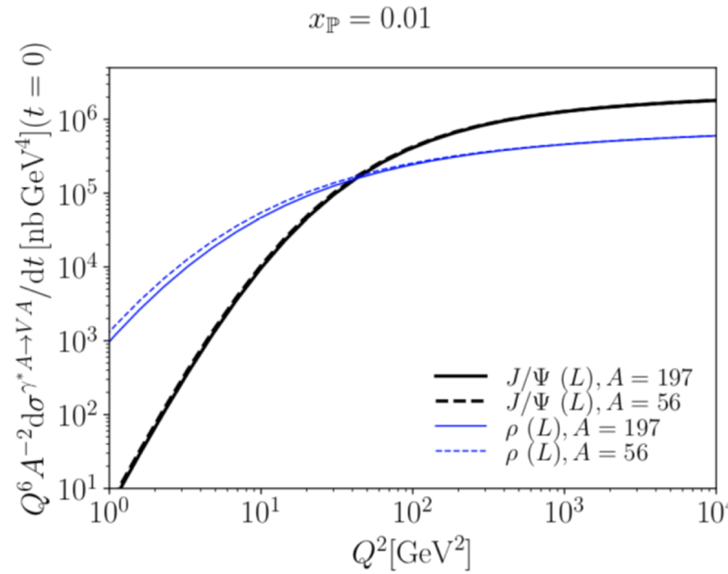
- Focused on the J/ψ and ϕ
- $J/\psi \to l^+ l^-$ is easy
- $\phi \to K^+K^-$ is not
  - the $K^\pm$ have p=135 MeV/c in the ϕ frame
  - OK at higher Q^2, where the ϕ has a kick in p_T,
  - Not OK at $Q^2=0$
    - How important is $Q^2=0$?
- An alternate approach: $\phi \to e^+e^-$, $\mu^+\mu^-$
  - Branching ratio is only $3*10^{-4}$ each, but, rates are useful
    - 70,000 (80,000) per 10 fb^{-1}/A for ep(eA)
  - Requires good PID

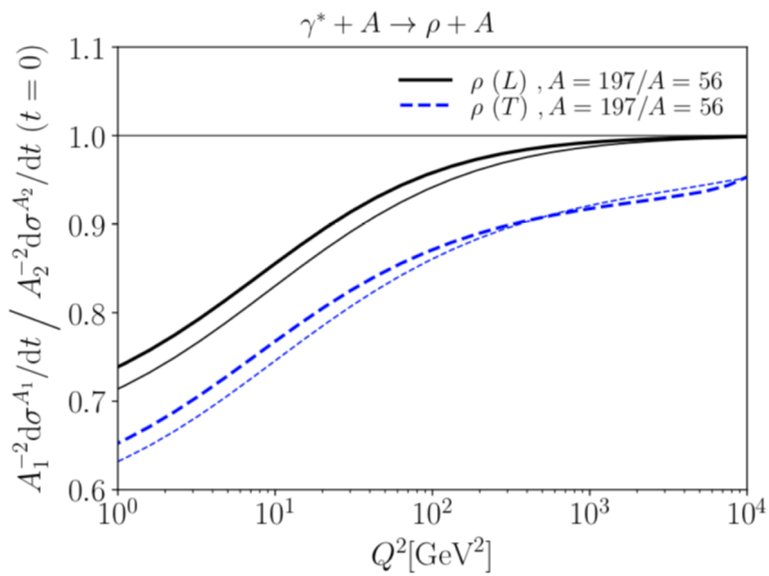




More mesons

- Lighter mesons correspond to larger dipoles which display more shadowing
  - Reach lower $Q_{tot}^2=Q_\gamma^2+M_V^2$
- Want a systematic study
  - ρ, ω, ϕ, J/ψ,y',Υ(1S),Υ(2S),Υ(3S)
- Detector requirements
  - Separate Υ(1S),Υ(2S),Υ(3S)
  - Reconstruct low p_T kaons from ϕ





Mantysaari and Venugopalan, Phys. Lett. **B781**, 664 (2018)

σ and rates for vector mesons,

- Coherent rates are for 10 fb^{-1}/A integrated luminosity
- Coherent ep and eA rates/integrated luminosity are similar
  - But ep interactions have much larger |t|
- Incoherent rates ~~< σ(ep->Vp)*A * $\mathcal{L}_{eA}$
  - A factor of ~ a couple over-estimate in UPCs
  - ~~ 1/A times coherent rates
- ϒ rates are moderate – enough to be useful for a wide Q^2 range

Photoproduction: Q^2<1 GeV^2

Accelerator	σ					Number of events				
	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$
eRHIC - *ep*	14.0 nb	1.7 nb	570.0 pb	120.0 pb	2.4 pb	140 mega	17 mega	5.7 mega	1.2 mega	24 kilo
eRHIC - *eA*	730.0 nb	110.0 nb	77.0 nb	19.0 nb	200.0 pb	37 mega	5.6 mega	3.9 mega	960 kilo	10 kilo

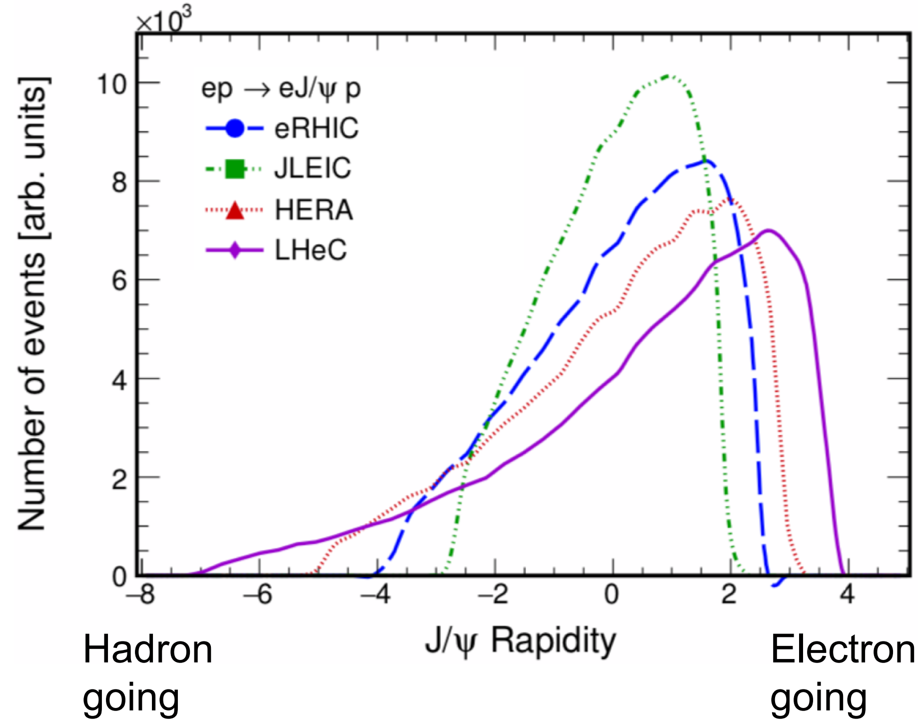
Electroproduction: Q^2>1 GeV^2

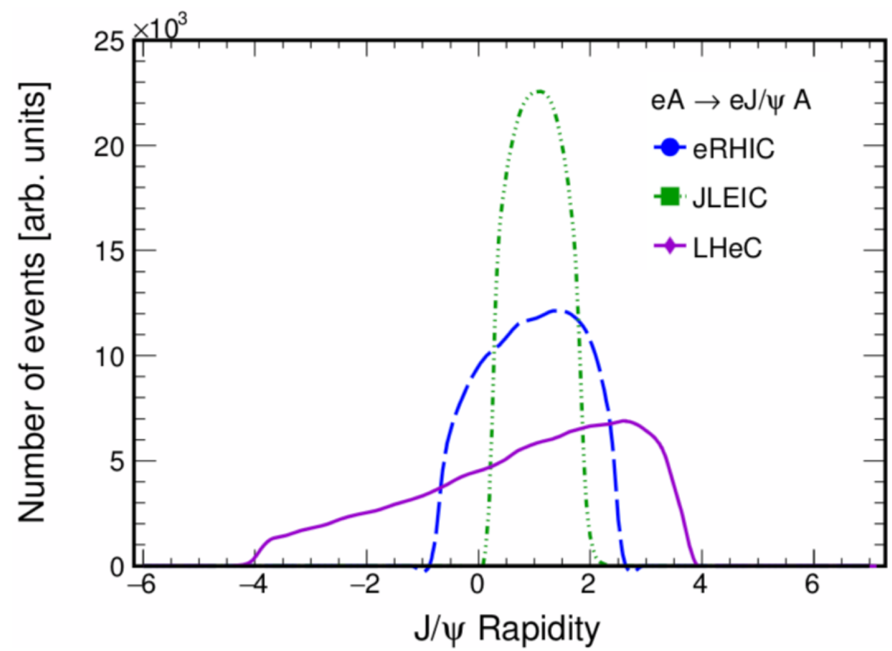
Accelerator	σ					Number of events				
	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$	ρ^0	ϕ	J/ψ	ψ'	$\Upsilon(1S)$
eRHIC - *ep*	5.0 μb	230.0 nb	8.5 nb	1.4 nb	14.0 pb	50 giga	2.3 giga	85 mega	14 mega	140 kilo
eRHIC - *eA*	870.0 μb	55.0 μb	1.9 μb	320.0 nb	1.2 nb	44 giga	2.8 giga	100 mega	16 mega	60 kilo

SK & M. Lomnitz, Phys. Rev. **C99**, 015203 (2019)

ep and eA rapidities

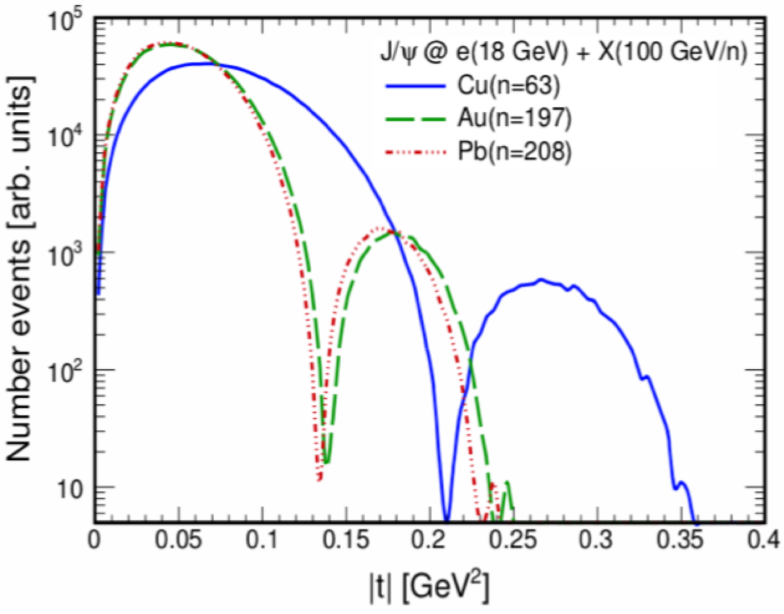
- Differences due to…
- Lower per-ion beam energy shifts VM in electron-going direction
- Coherent requirement limits p_z from nucleus
  - $p_z = M_V^2/2k < \text{hbar}/R_A$
  - Cuts off production in hadron going direction
    - Can only probe x> 0.03
- ep collisions at the eA beam energy are a good proxy for incoherent photoproduction

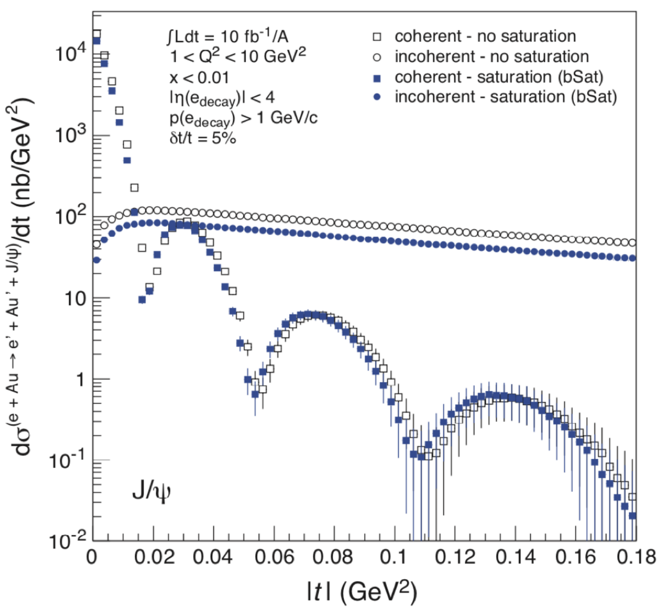




Kinematics of coherent & incoherent production

- dσ/dt - depends on nuclear size
  - Naively t_{max} ~ hbar/R_A
  - For incoherent production
    - r_p ~ 0.7 fm
  - Proton dissociation also possible
    - Effective r even smaller
- Otherwise, indistinguishable, except for nuclear breakup
- How well can we use nuclear breakup to classify events?
  - Why do we get this wrong
    - From physics
    - From detector inadequacies

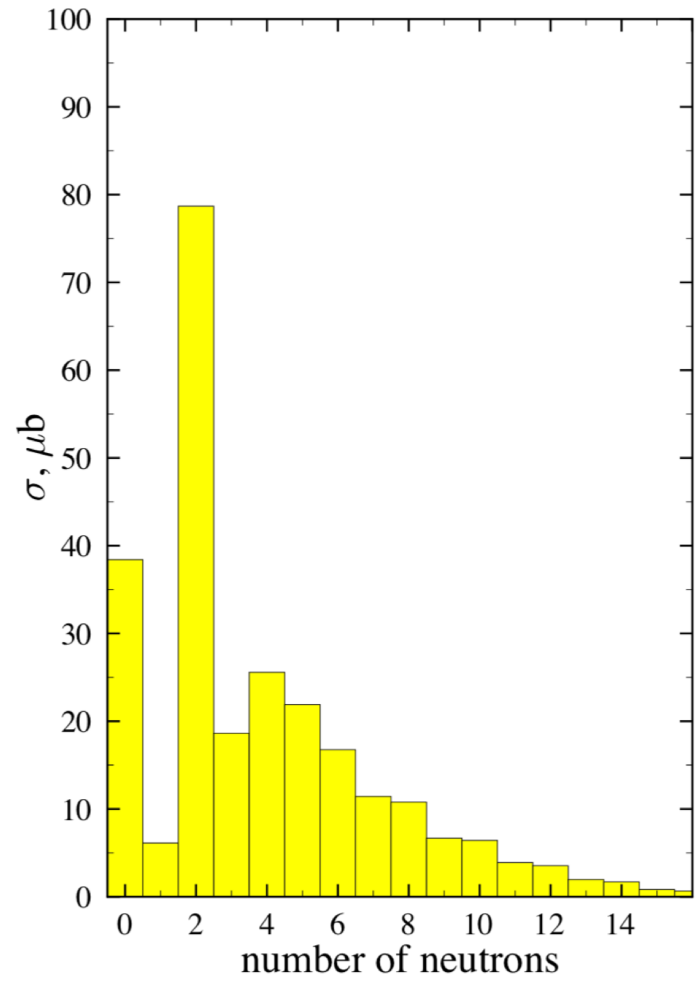




SK & M. Lomnitz, Phys. Rev. **C99**, 015203 (2019) & White Paper

Zero neutrons from nuclear breakup

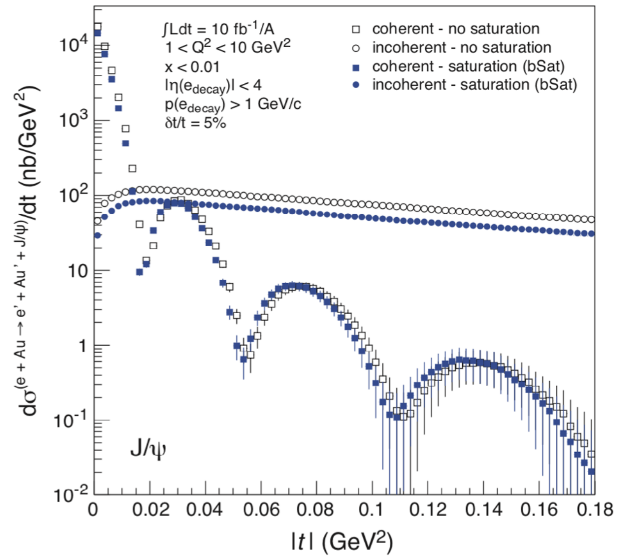
- $\gamma^{(*)}A \rightarrow J/\psi X$ @ RHIC(EIC) energies
- Neutron emission caused by recoiling struck nucleon
- No neutrons in ~~ 15% of cases
  - γ emission
- RELDIS code predicts that 3% of electromagnetic dissociation events (of Pb at the LHC) do not result in neutron emission
- These events are important in kinematic (t) regions where incoherent interactions dominate.
  - i. e. diffractive dips, large t
- More specific/detailed calculations are needed



Strikman, Tverskoy and Zhalov, Phys. Lett. **B626**, 72 (2005);
ALICE Phys. Rev. Lett. **109 (2012)** 252302

Pileup backgrounds

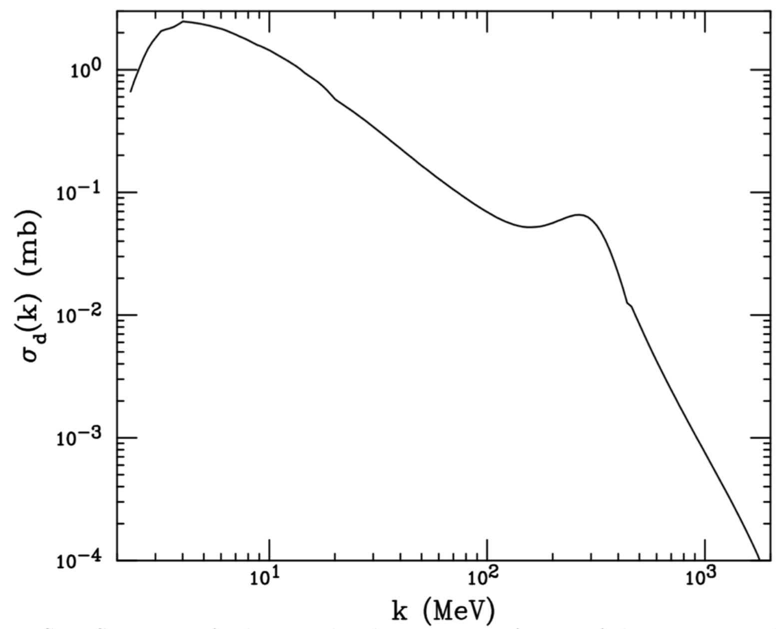
- σ(eAu -> eAu*) at eRHIC is 31 mb
  - For giant dipole resonance excitation, the photon energy is ~< 20 MeV in nuclear frame, <~ 100 keV in accelerator frame, so the electron remains in the beam.
- Rate = $\sigma * \mathcal{L} = 3.1*10^{-26}\ \mathrm{cm}^2 * (10^{34}/\mathrm{cm}^2\mathrm{s}/197)$ = 1.5 M breakup/s
- Collision rate = 25 MHz
  - 1 breakup/16 crossings
  - False incoherent VM prod = coherent VM rate/16
- A lesser issue at top energy/lower luminosity
- Difficult to measure incoherent J/ψ at small t (t<~0,005 GeV^2)



SK, Phys. Rev. ST Accel. Beams **17**, 121003 (2014)

Deuteron breakup pileup rate

- Deuteron is easy to photodissociate
  - k_{min}=2.2 MeV in target frame
- σ(ed->eX) = 0.113 mb at eRHIC
- For $\mathcal{L}$=5*10^{33} /cm^{2}s rate=560,000/s
  - 1 per 50 beam crossings
- A lesser problem, but maybe not negligible



Preliminary!

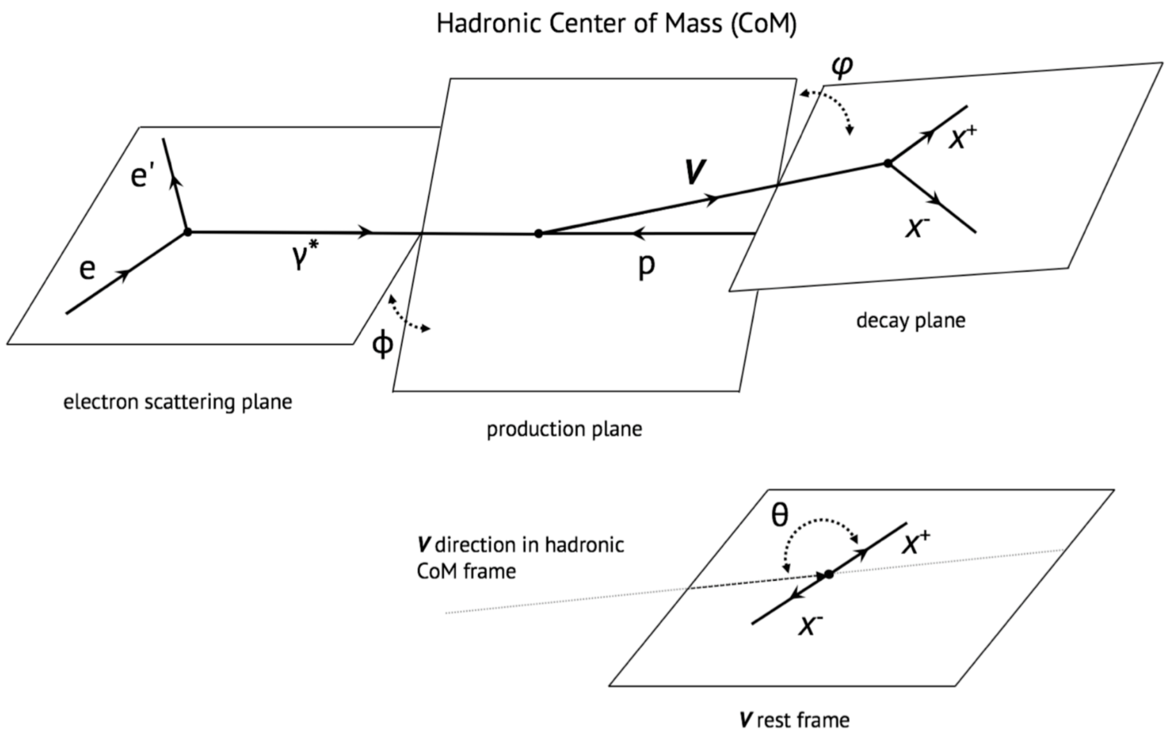
UPC calc: SK & Ramona Vogt, Phys. Rev. **C68**, 017902 (2003)

Conclusions

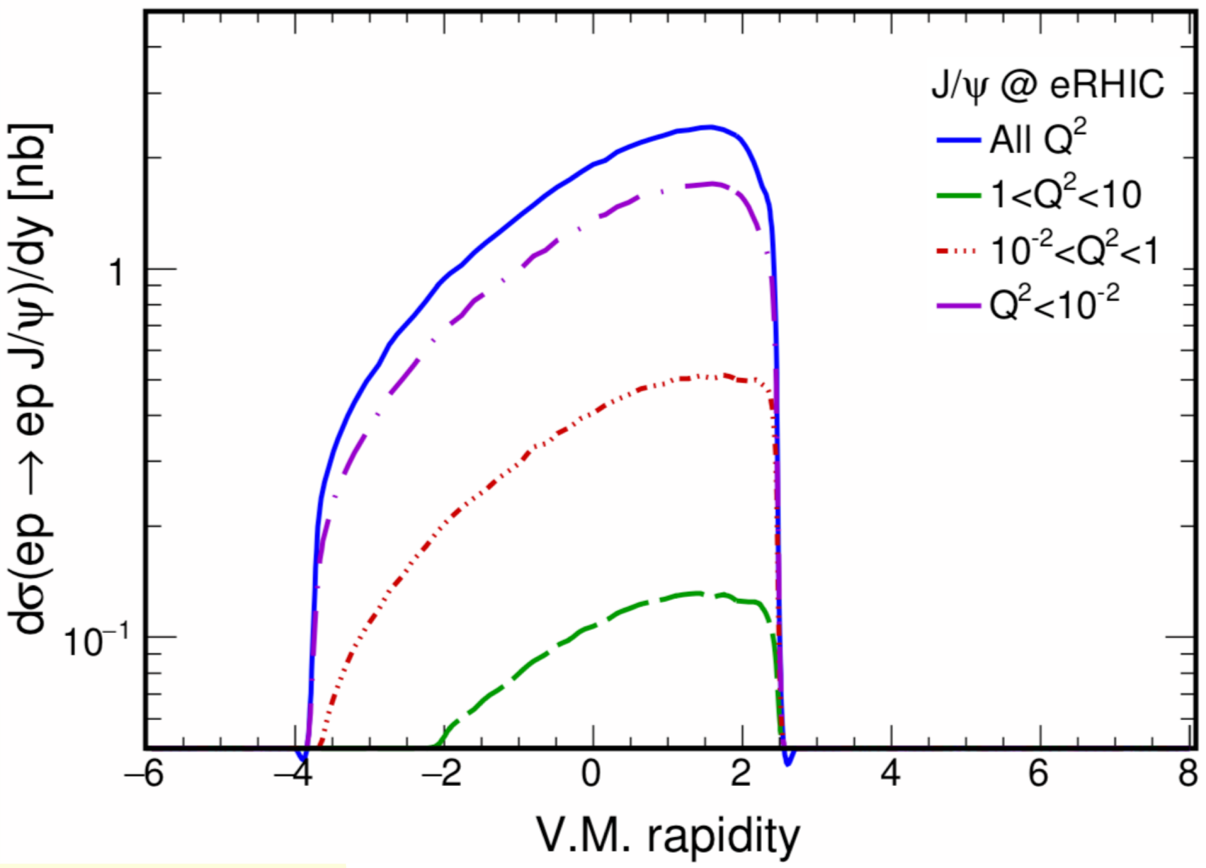
- Coherent and incoherent photoproduction are deeply linked.
  - Theoretically, the Good-Walker formalism links them.
  - Experimentally, they look very similar, differentiated only by nuclear breakup.
- The EIC will be able to study a wide variety of vector mesons, probing states containing different quarks and wave functions.
  - Studying the full range of VM is desirable to fully map out saturation as a function of x,Q^2
- Bjorken-x maps into final state rapidity. To cover a wide range of x requires a wide-acceptance detector.
- Some incoherent photoproduction does not lead to neutron emission. We urgently need to quantify this fraction.
- Pileup events can make coherent photoproduction look incoherent.

Backup

Angular definitions



Rapidity vs. Q^2



The dipole approach for heavier VM

- Needed to incorporate transverse size into calculation
- Start with basics: $\sigma = |\langle\Psi_\gamma|M|\Psi_V\rangle|^2$
- Treat the $q\bar{q}$ pair as a dipole with size r
  - Need VM and photon wave functions, matrix element as f(r)
  - $\sigma \sim r^2$
  - r scales with 1/Q, but relationship is not simple
  - Different matrix elements for different nuclear models
    - pQCD, colored glass condensate, etc.

$$A(K,\Omega) = 2\mathrm{i}\int \mathrm{d}^2\mathbf{r}_T \frac{\mathrm{d}z}{4\pi}\mathrm{d}^2\mathbf{b}_T e^{-i\mathbf{b}_T\cdot\mathbf{k}_T/\hbar} \times \Psi^*(\mathbf{r}_T,z,Q^2)\Psi_V(\mathbf{r}_T,z,Q^2)N_\Omega(\mathbf{r}_T,\mathbf{b}_T)$$

- Impact-parameter dependent formalism allows for calculations of $d\sigma/dt$, and, with it, changes in the effective shape of the nucleus at different x,Q^2