Vector mesons and more at an EIC

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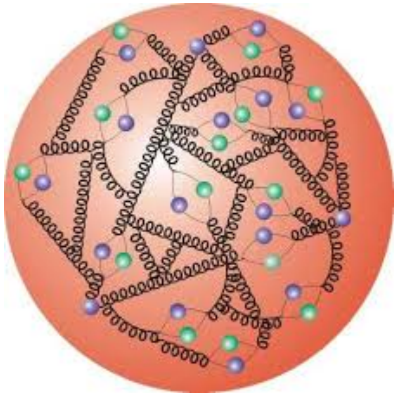
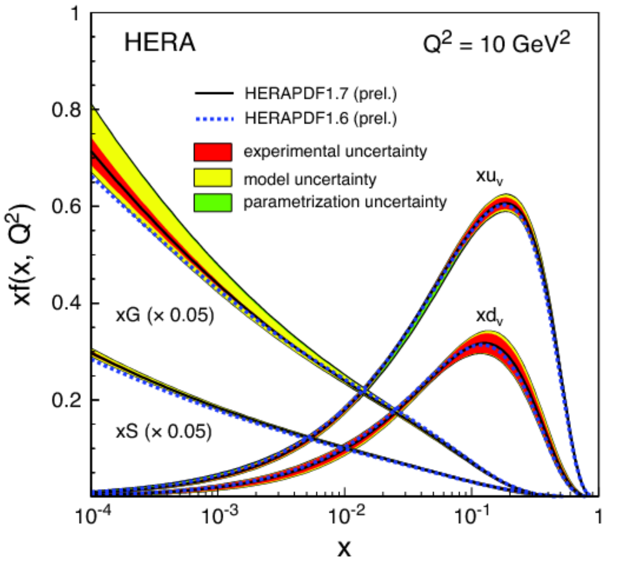
NSD Tuesday Meeting, Jan. 8, 2019

- Motivation:
  - Partons and nuclear shadowing
  - Nuclear imaging with vector mesons
- Vector mesons at an EIC
- The eSTARlight Monte Carlo
- Vector meson rates and kinematics
- Beyond vector mesons: the $a_2^+(1320)$ and Z_c^+

Parton distributions

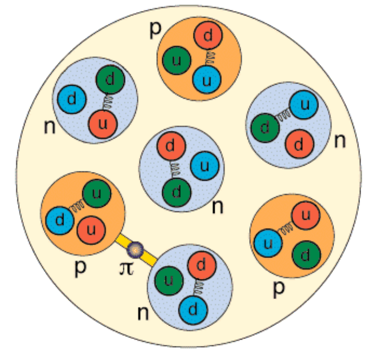


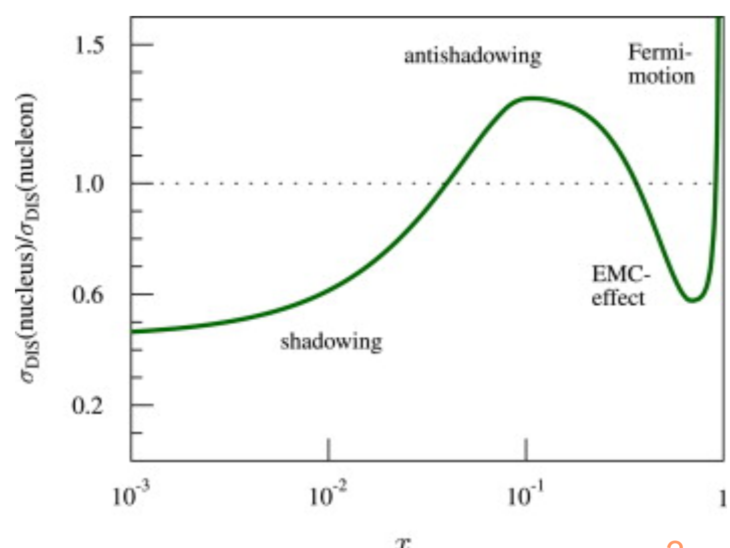
- The quarks and gluons abundances in a nucleon at a given momentum fraction are the parton distributions
  - $u(x,Q^2)$, $d(x,Q^2)$, $g(x,Q^2)$, etc.
  - x is momentum fraction in infinite momentum frame
  - Q^2 is photon virtuality (effective mass)
    - 1/photon (dipole) size
- 3 valence quarks + gluons + sea quarks
  - Gluons split into quarks, etc.
- Mostly measured in deep inelastic scattering
- $g(x,Q^2)$ increases with decreasing x
  - Valence quarks follow
  - $xg(x,Q^2) \sim x^{-\lambda}$ ~~~ power law
- At sufficiently small x, the gluon density should reach a limit-> 'saturation'



Nuclear shadowing

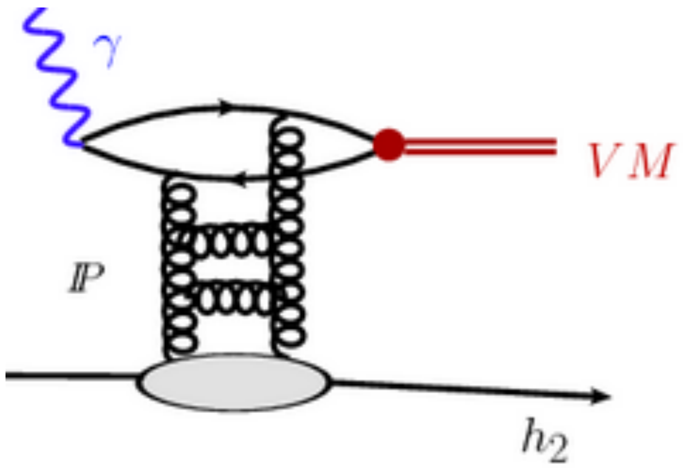
- When a proton or neutron is inserted into a nucleus, the parton distributions may change
  - Quark/gluon exchange
  - Multiple scattering
  - Higher parton densities –> gluon fusion, etc.
    - expected at higher x values than in isolated protons
      - Scaling arguments give $x_s \sim A^{1/3}$
- Data shows complex behavior, with multiple regions
- Current nuclear-target data (mostly) at large x
  - An EIC can map out parton densities in a wide range of x, Q^2 in diverse nuclei





Vector meson photoproduction

- Vector Meson photoproduction occurs via Pomeron (two-gluon) exchange
- To lowest order, $\sigma(VM) \sim |xg(x)|^2$
  - Square of gluon density
  - But, gluons are not 'bare'
    - Corrections for skewing, NLO, etc.
      - Ongoing work….
  - If $xg(x,Q^2) \sim x^{-\lambda}$ -> $\sigma(k) \sim W^{4\lambda} \sim W^{0.7}$
    - Lowest order only!
    - Pure power law, exponent ~ good for J/ψ

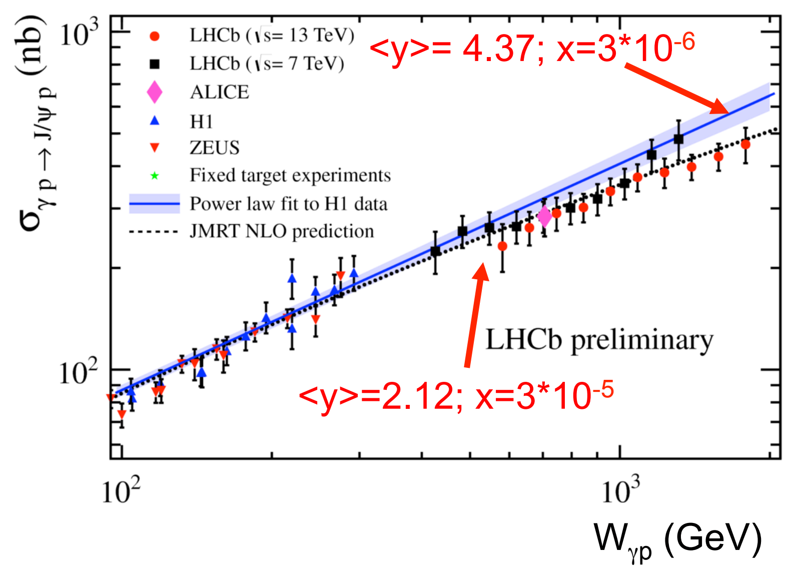


- By comparing γp->Vp and γA->VA, we can measure shadowing
  - J/ψ & heavier probe pQCD
  - $Q^2 = M_V^2 + Q_\gamma^2$
    - Need an EIC to scan over Q^2
    - High photon energy -> low x

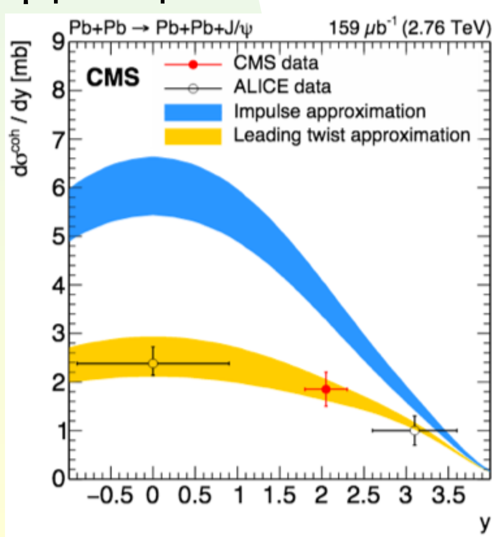
LHC data shows moderate shadowing

- x ~few 10^{-6} with proton targets (LHCb)
  - Evidence for NLO terms?
- x ~ 10^{-3} to 10^{-1} for lead targets
- Moderate shadowing
  - Consistent with 'leading twist' approach
    - Shadowing from multiple scattering
    - At some x, expect 'saturation'

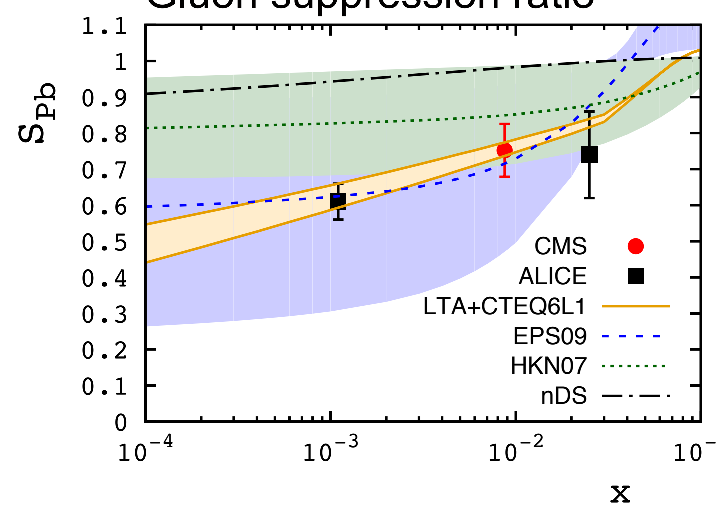
J/ψ photoproduction on protons



J/ψ photoproduction on lead

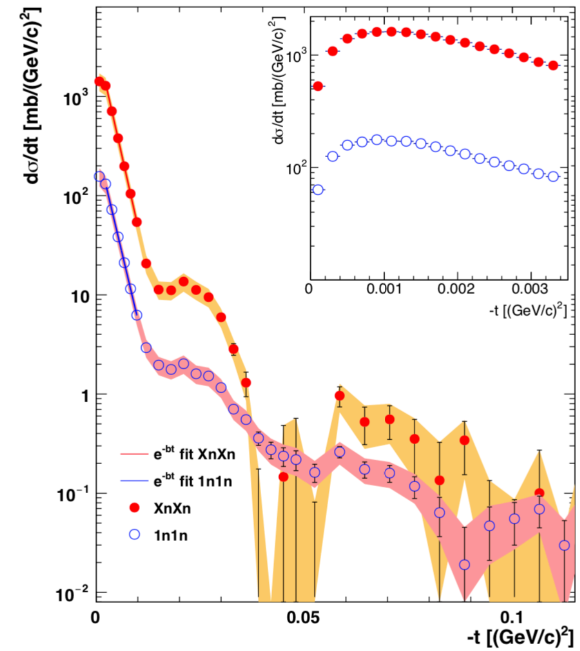


Gluon suppression ratio

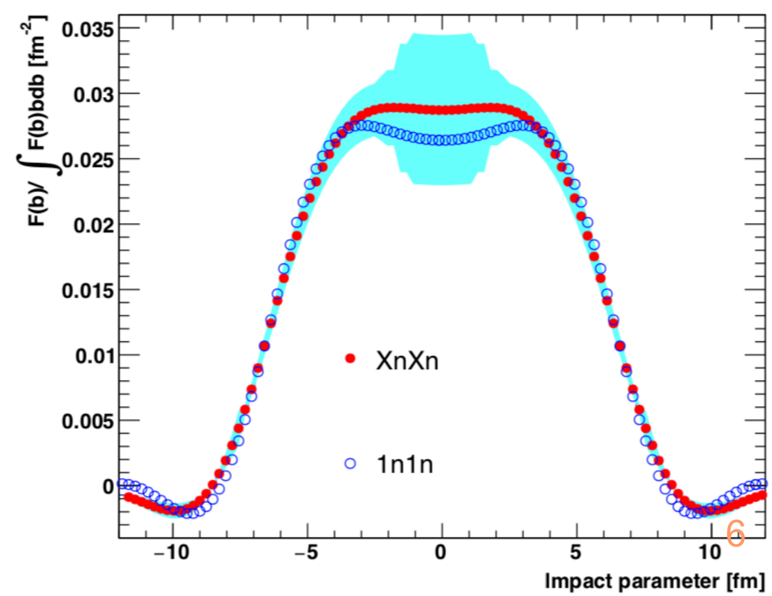


Imaging with vector mesons

- Photoproduction carries information about the actual positions of the interaction sites in the target
- $\sigma = |\Sigma_i A_i e(^{ikx})|^2$
  - A_i is interactions strength
  - x_i is interaction position
  - k is momentum transfer from target
- Coherence for k<hbar/R_A
- $d\sigma_{coherent}/dt$ encodes position of interaction sites in target
  - $t = p_T^2$
- Expect most shadowing in nuclear interior, less at edges



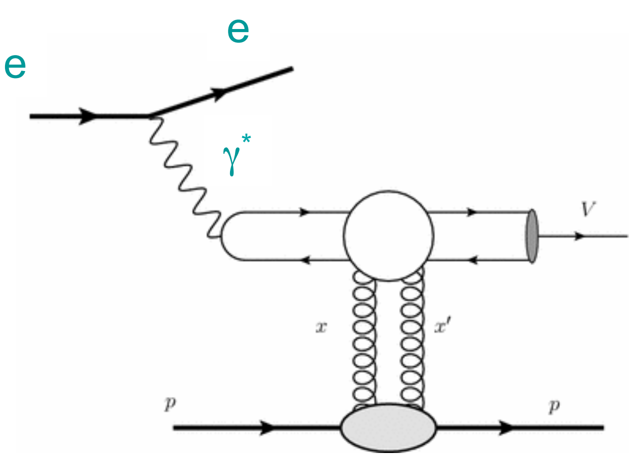
Fourier Transform



STAR, Phys. Rev. C96, 054904 (2017)

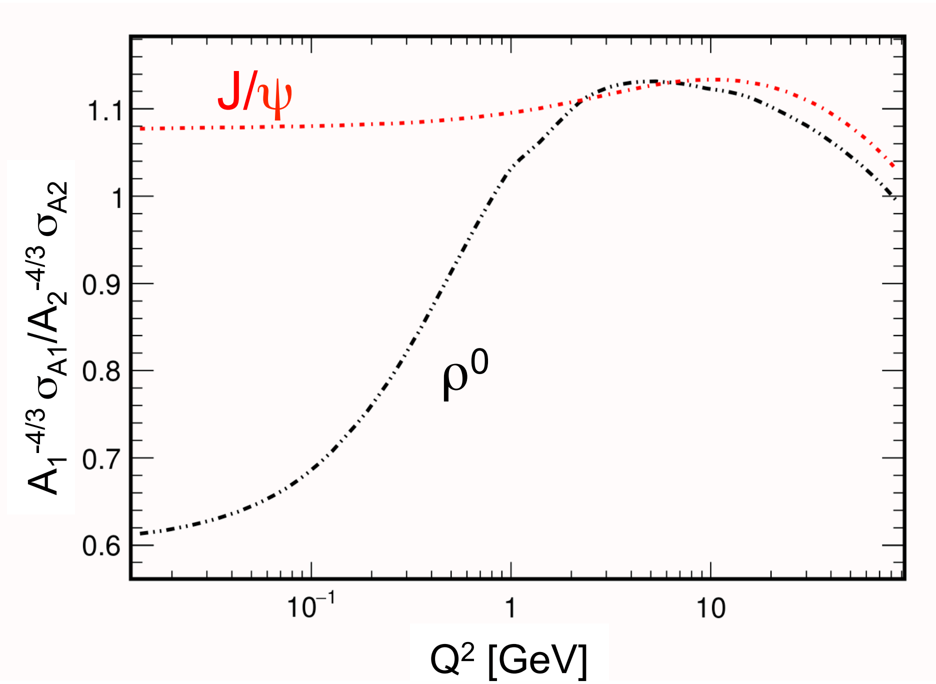
Vector mesons at an EIC

- UPC mostly probe fixed $Q^2=M_V^2$
  - Exception: Vary $M_{\pi\pi}$ in UPCs, but only $M_{\pi\pi} < 1$ GeV
- An Electron-Ion Collider can vary Q^2 independently
  - Outgoing electron tags Q^2 independent of rest of reaction
    - Photon virtuality $Q^2=(p_e - p_e')^2$
    - Independent of:
      - k = Photon energy
      - W = gamma Pomeron center of mass energy
        - Vector meson mass
- An EIC can also vary A, collide polarized electrons and light ions



Q^2 evolution of shadowing

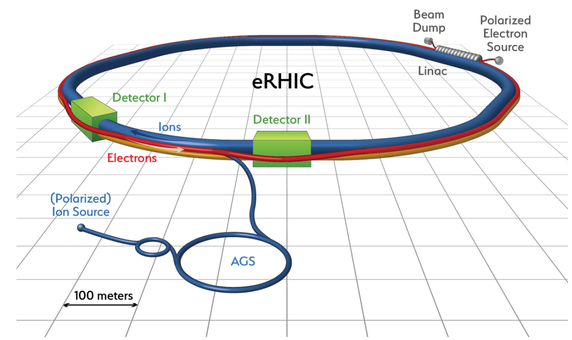
- <Dipole size> scales with $1/Q^2$
- Shadowing disappears with increasing Q^2 /smaller dipoles
- Probe ratio of lead:iron cross-section ratio, scaled by $A^{-4/3}$
- Large dipole (ρ^0, black) shows very large shadowing
  - Breakdown of 'independent nucleon' picture
- Small dipole (J/ψ, red) shows less shadowing



eSTARlight, qualitatively similar to Mantysaari & Venugopalan, Phys. Lett. B781, 664 (2018).

Proposed EICs

- eRHIC at Brookhaven
  - Adds an electron ring to RHIC
- MEIC at Jefferson Lab
  - Uses existing accelerator as injector
- LHeC at CERN
  - Adds an electron linac/ring to the LHC
- EICC, in China
  - Focus on valence quarks



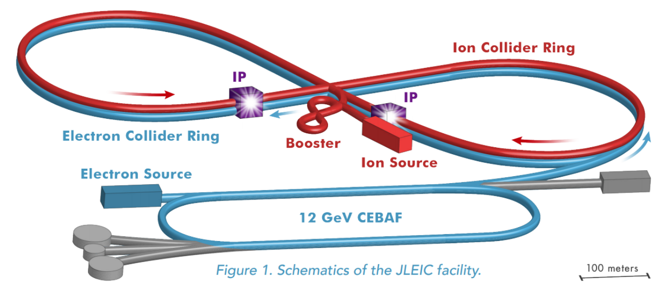
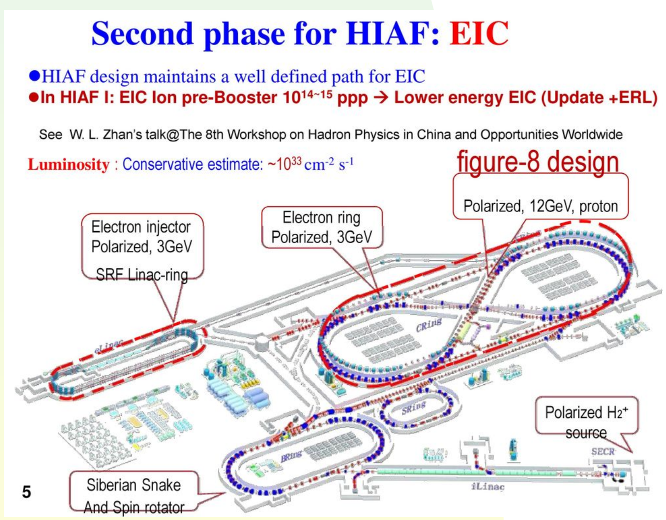
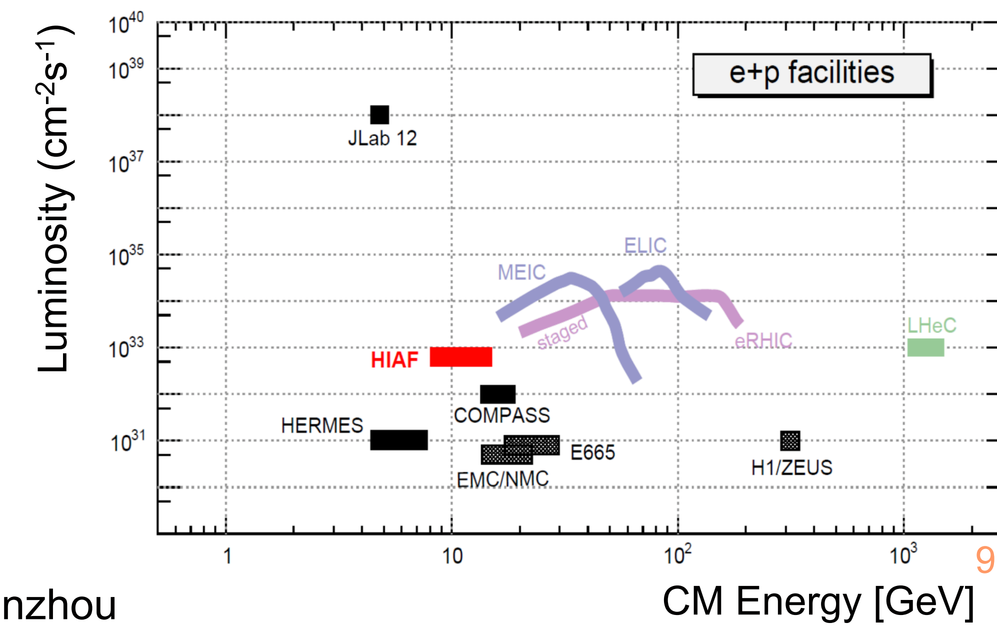


Figure 1. Schematics of the JLEIC facility.





Plot & graphic from Xurong Chen, IMP, Lanzhou

The eSTARlight Monte Carlo

- Collides electrons with ions (of any A,Z) at arbitrary energy
- Diverse final states: ρ, ω, ϕ, ρ', J/ψ, ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$
  - Simple (two-prong) decays correctly account for photon polarization
    - Real photons are transversely polarized
    - Virtual photons can be longitudinally polarized
      - Fraction scales with increasing Q^2
  - Complex decays via Pythia 8
- Based on parameterized HERA data
  - Judicious extrapolations/analogies needed.

Accelerator	AB	e/p Energy	p Energy	integrated luminosity
eRHIC [22]	ep	18 GeV	275 GeV	10 fb^{-1}
JLEIC[23]	ep	10 GeV	100 GeV	10 fb^{-1}
LHeC[5]	ep	60 GeV	7000 GeV	10 fb^{-1}
EicC [25]	ep	3.5 GeV	20 GeV	10 fb^{-1}
RHIC[26]	pAu	100 GeV	100 GeV	4.5 pb^{-1}
LHC	pPb	7000 GeV	2778 GeV	2 pb^{-1}

Michael Lomnitz and SK, arXiv:1803.06420, to appear in Phys. Rev. C

Framework for production of vector mesons in ep scattering

- In ep scattering, we calculate the vector meson cross section:

$$\sigma(ep \to epV) = \int \frac{dk}{k} \int dQ^2 \frac{dN_\gamma}{dkdQ^2}(k, Q^2)\sigma_{\gamma^* p \to Vp}(W, Q^2).$$

Photon flux

γp Cross-section

- The cross section of photon-proton interaction is

$$\sigma_{\gamma^* p \to Vp}(W, Q^2) = \left(\frac{M_V^2}{M_V^2 + Q^2}\right)^n \sigma_{\gamma p \to Vp}(W, Q^2 = 0) f(M_V).$$

Q^2 dependence

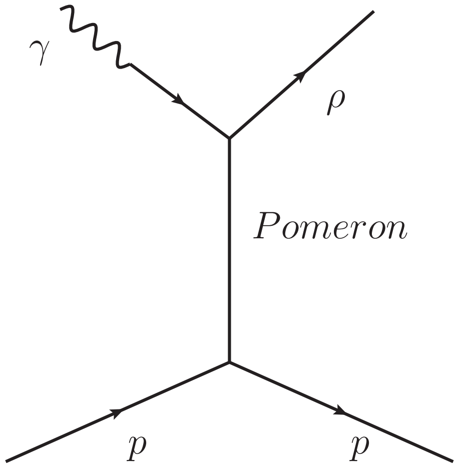
$\sigma(Q^2=0)$

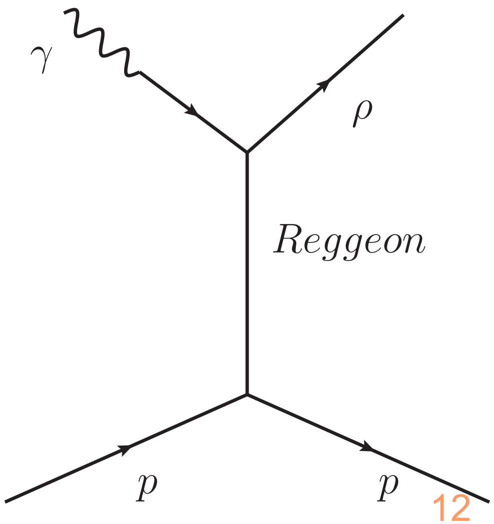
Meson width (Breit-Wigner)

- eSTARlight refactorizes this, and uses lookup tables and rejection sampling to generate events from these distributions

Mechanisms for photoproduction of vector mesons

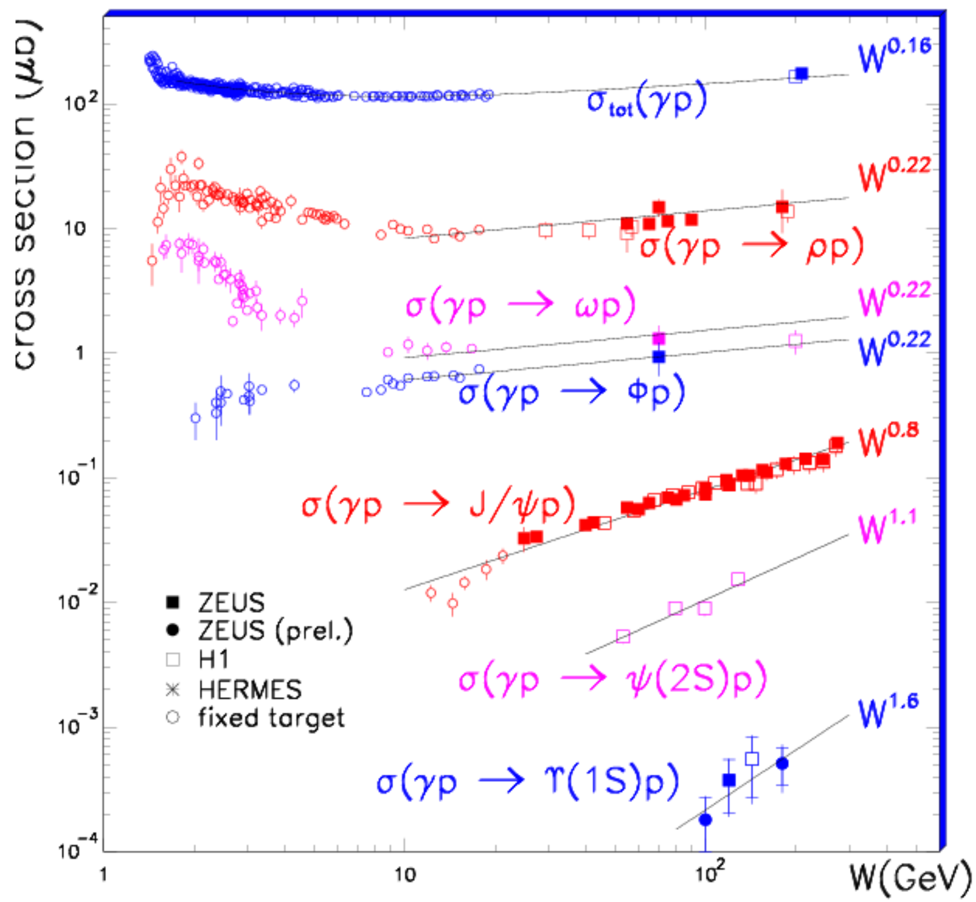
- In light vector meson photoproduction, Pomeron exchange and Reggeon exchange both contribute to the total cross section.
  - In pQCD, Pomeron is a gluon ladder
  - Reggeon represents meson exchange
    - Summed over multiple mesons
    - High quark content
  - Near threshold, the Reggeon exchange contributions are dominant.
- For heavy quarkonium (including the ϕ), only the Pomeron contributes to the total cross section
  - No c, few s quarks in nucleon





Cross sections for vector meson photoproduction

- The cross-section for γp->Vp has a simple form:
  - Light vector mesons:
    $\sigma(W)=XW^{\epsilon}+YW^{-\eta}$
  - Heavy vector mesons:
    $\sigma(W)=XW^{\epsilon}$
  - X term is from Pomeron exchange
  - Y term is from Reggeon exchange
    - Only for light mesons
  - ε increases with increasing meson mass

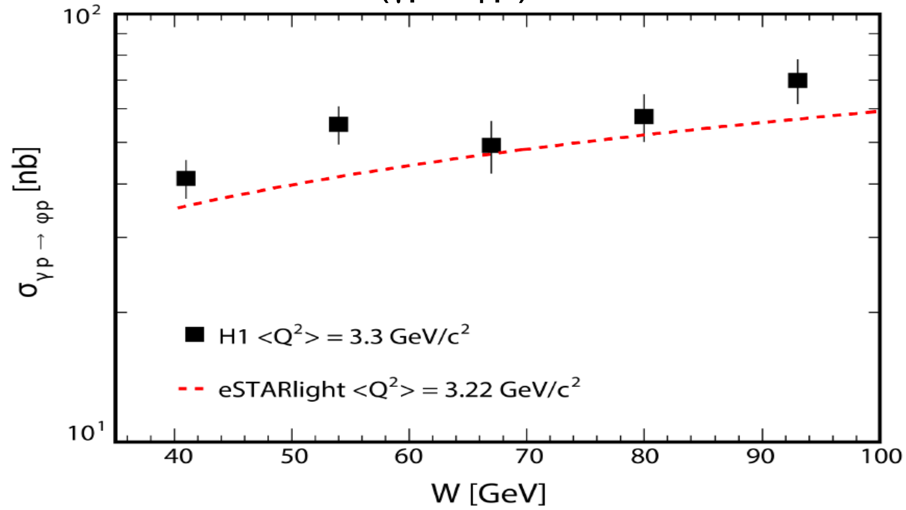


arXiv:0709.2178

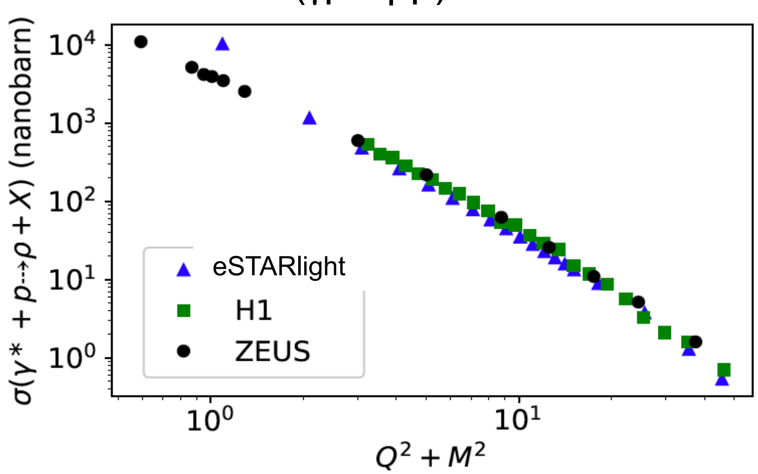
eSTARlight compared with HERA data

- We use eSTARlight to calculate the total cross section as a function of Q^2 and W.
- It shows good agreement with HERA data

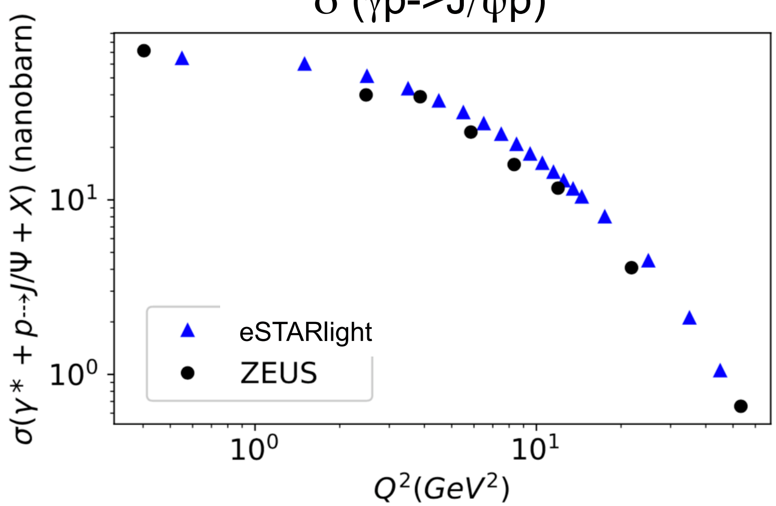
σ (γp->φp)



σ (γp->ρp)



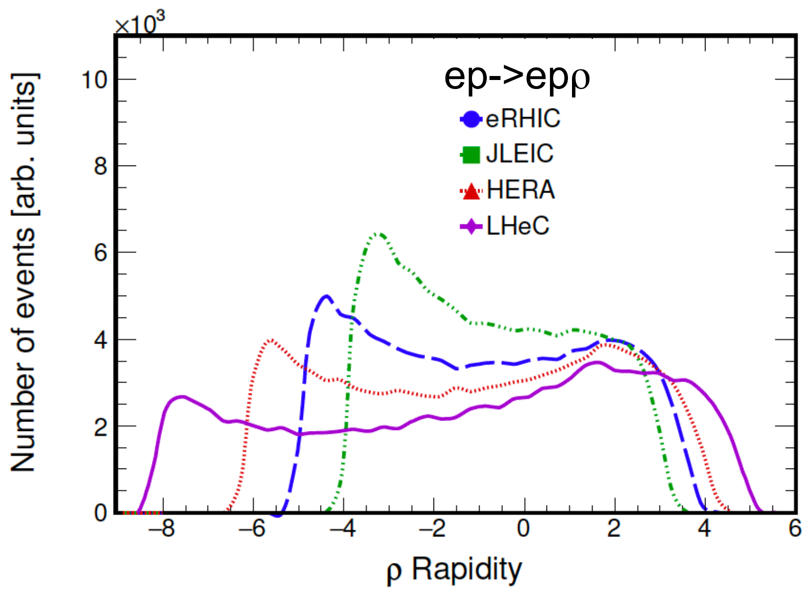
σ (γp->J/ψp)

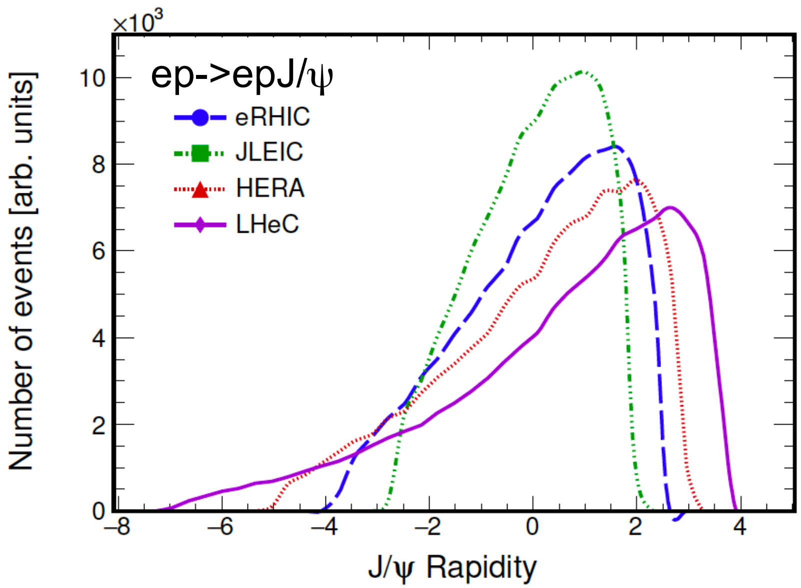


Michael Lomnitz and SK, arXiv:1803.06420, to appear in Phys. Rev. C

ρ and J/ψ cross section in ep scattering

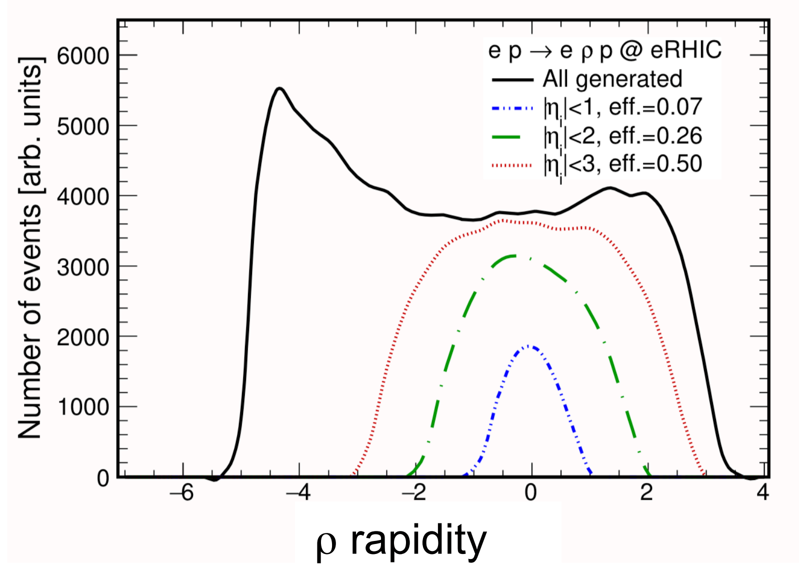
- We use eSTARlight to find dσ/dy at proposed EICs
  - dσ/dy distribution is very broad
  - ρ^0 - two peaks correspond to Reggeon exchange (near threshold) and Pomeron exchange
  - J/ψ single peak due to Pomeron exchange
- Need a wide acceptance detector to study full energy range

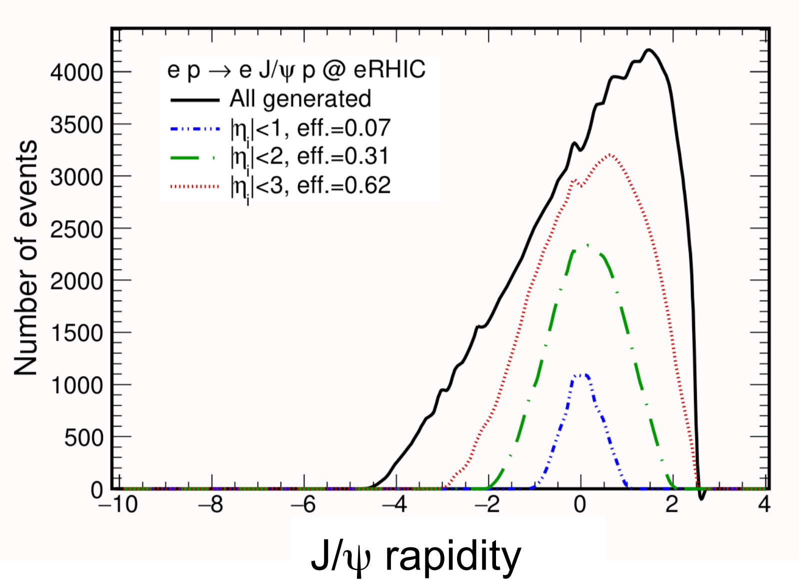




Detector acceptance

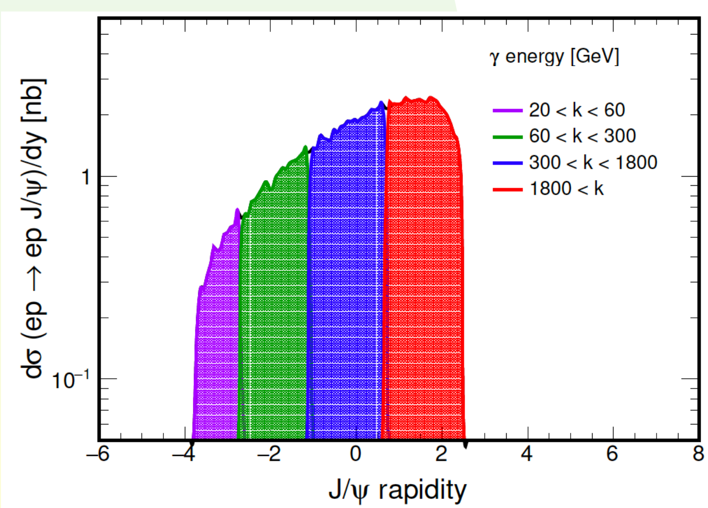
- Vector meson acceptance depends on the chargedparticle pseudorapidity coverage of the detector.
  - In $\rho \to \pi^+\pi^-$, $J/\psi \to e^+e^-$, the final state π/e particle pseudorapidity (η) is correlated with the vector meson rapidity (y)
  - The plots show vector meson efficiency for 3 toy detectors, with charged particles detection over $|\eta|<1$, $|\eta|<2$ and $|\eta|<3$
- A wide-acceptance detector is needed

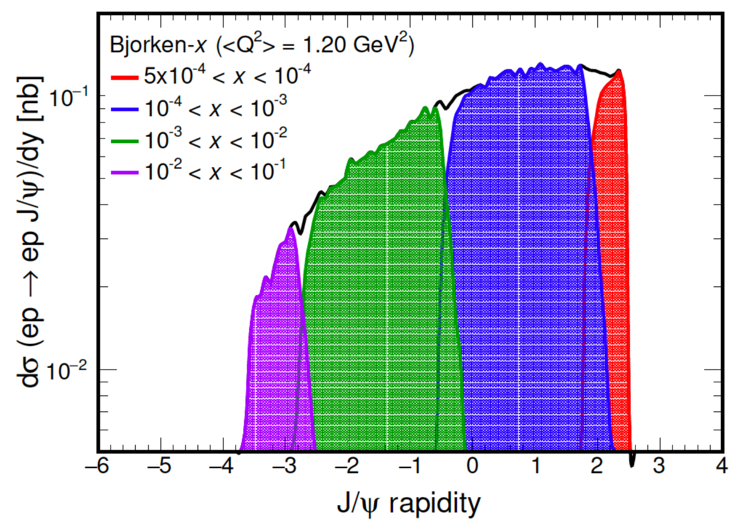




dσ/dy vs. photon energy and Bjorken-x

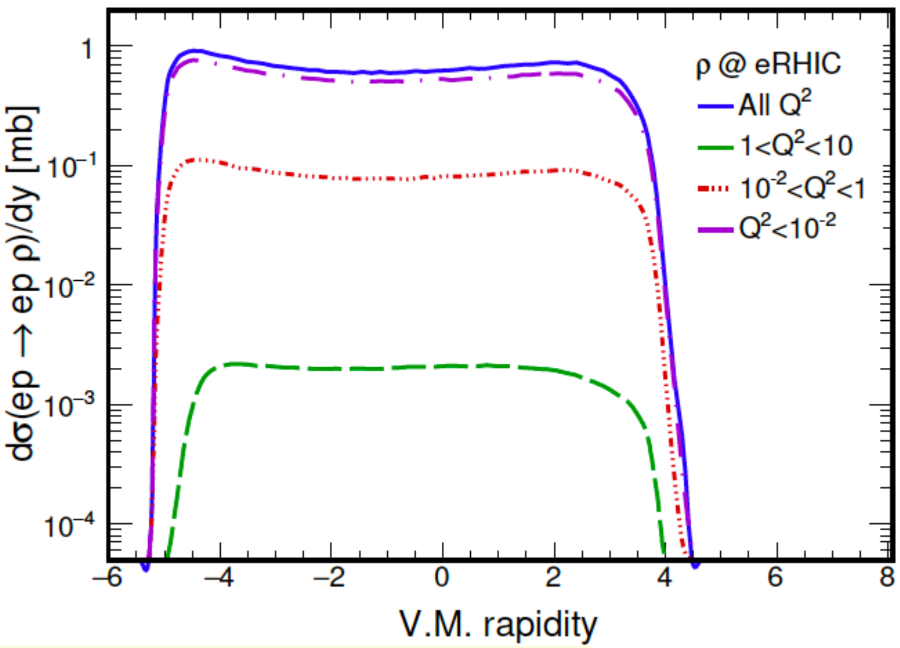
- Photon energy increases, and Bjorken-x values decrease with increasing rapidity. $k = M/2 \exp(y)$ and $x = M/\sqrt{s} \exp(-y)$
- The most 'interesting' collisions are those with the highest photon energy/lowest Bjorken-x. These occur at large rapidity.
- Low photon energies occur at negative rapidity.
  - Key to understanding threshold effects and Reggeon exchange
  - J/ψ production via 3-gluon exchange may occur near threshold
- Detector should have good forward and backward acceptance, including particle identification

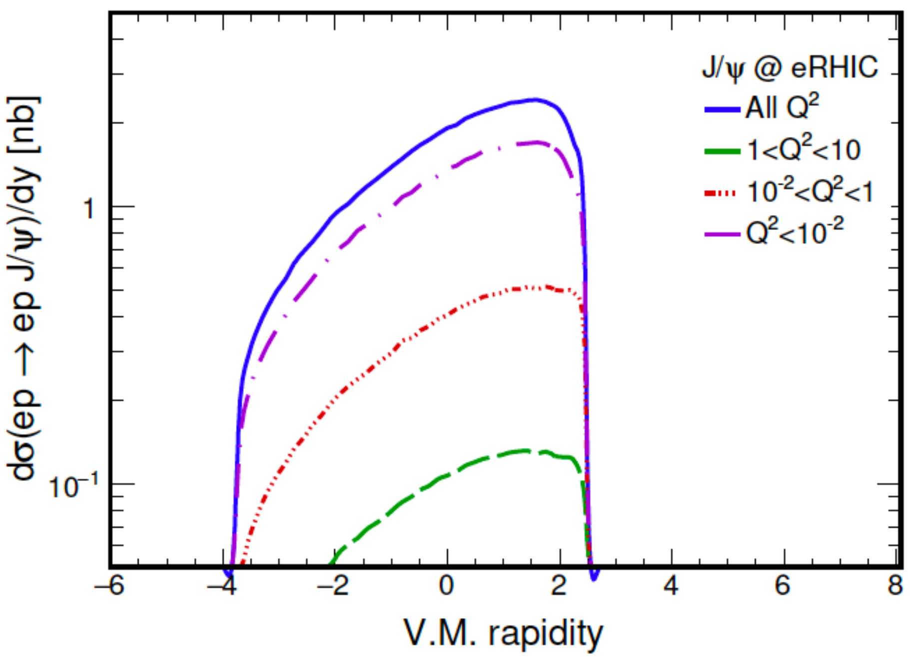




Q^2 -dependent cross section of vector mesons in ep scattering

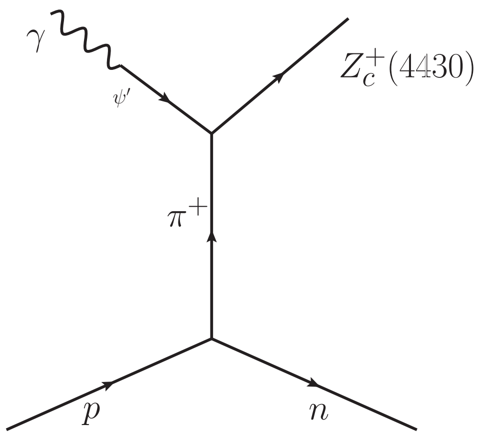
- We also investigate the contribution of Q^2 of photon to the production of vector mesons in ep scattering
  - As Q^2 increases, threshold shifts slightly toward larger rapidity





Mechanics for photoproduction of charged particles

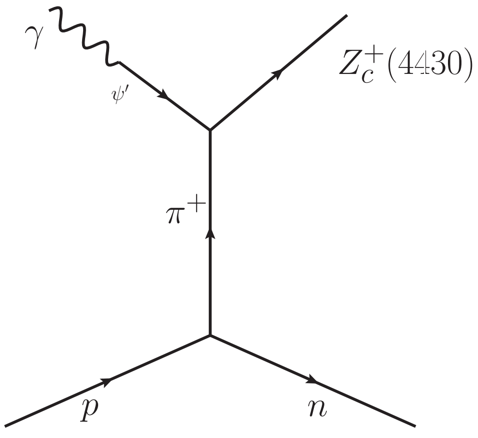
- Reggeons can be charged or neutral
  - Trajectories of charged mesons, like π^+
  - Wider range of spin/parity states than the Pomeron
- Greatly extends the range of particles that can be studied with photoproduction
  - Both standard $q\bar{q}$ mesons and exotica
- Example: The a_2^+ is a 'standard candle' $u\bar{d}$ meson: $\gamma p \rightarrow a_2(1320)^+ n$
  - Large branching ratio to $\pi^+\pi^-\pi^+$
    - Easy to reconstruct
  - Limited $Q^2=0$ data from fixed-target experiments
- Then look at more exotic objects
  - Photoproduction cross-section depends on their nature: tetraquark, mesonic molecule or ???

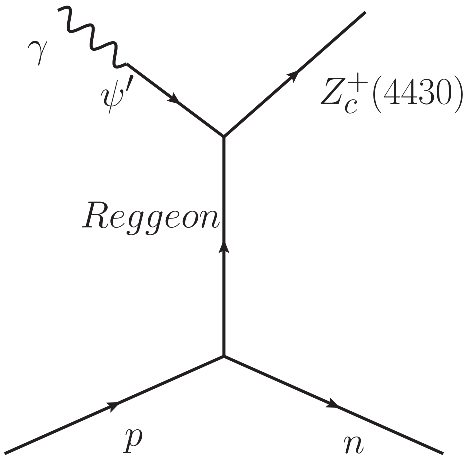


IJMPA(30)1530002, PRD(77)094005

The $Z_c^+(4430)$

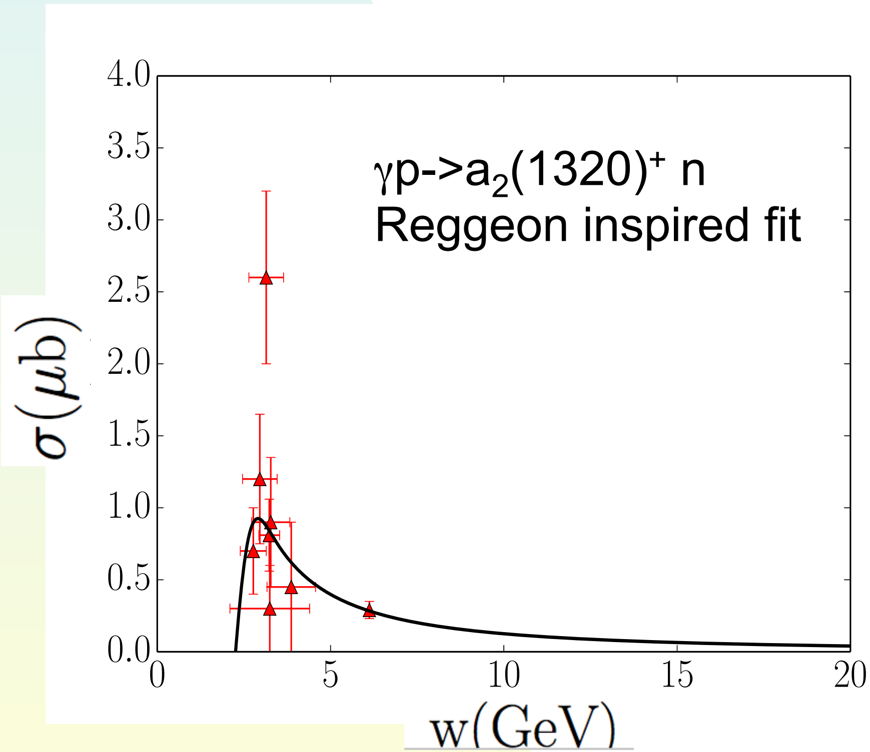
- Observed in Belle in $B \to K \psi' \pi$
- Decays to $J/\psi\pi^+$, $\psi' \pi^+$
- Contains $c\bar{c}$ and is charged, so cannot be a quark-antiquark meson. Nature is unknown
  - tetraquark ($c\bar{c}u\bar{d}$ or $c\bar{c}\bar{u}d$)?
  - Mesonic molecule (2 loosely bound mesons)?
  - Hadro-charmonium?
- These three hypotheses should lead to different photoproduction cross-sections
  - Today: focus on published tetraquark model cross-section
- Similar arguments apply for the $Z_c^+(3900)$
  - Lighter -> higher photoproduction rates

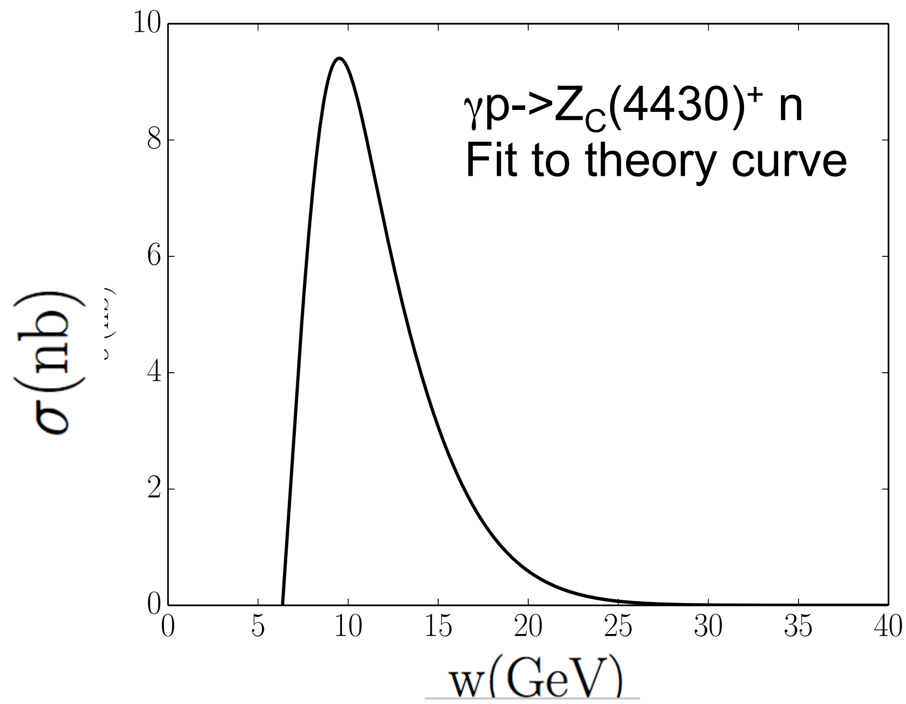




Cross section of charged particles in photoproduction process

- Use data or calculations of σ(γp->X+n) as input to eSTARlight to predict dσ/dy for the same process in EIC collisions.
  - Assume the same Q^2 scaling as similar vector mesons.



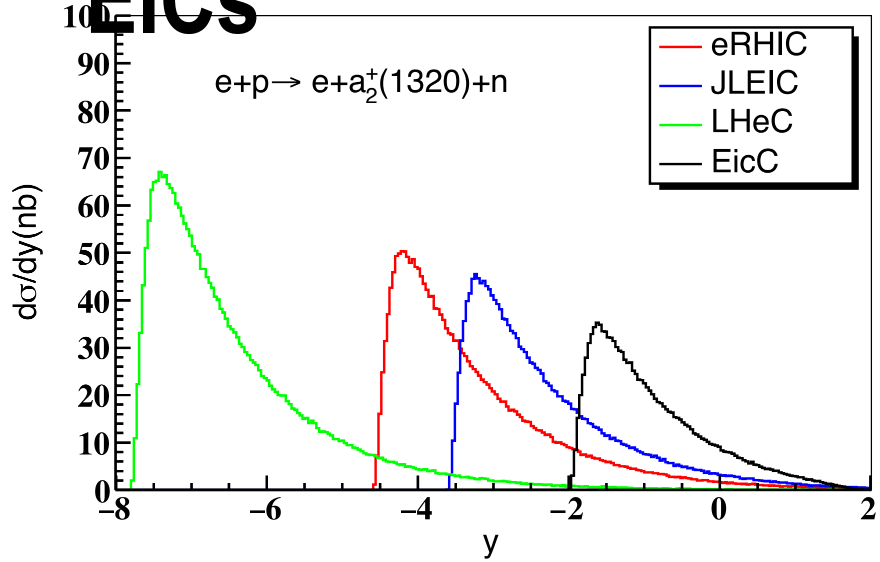


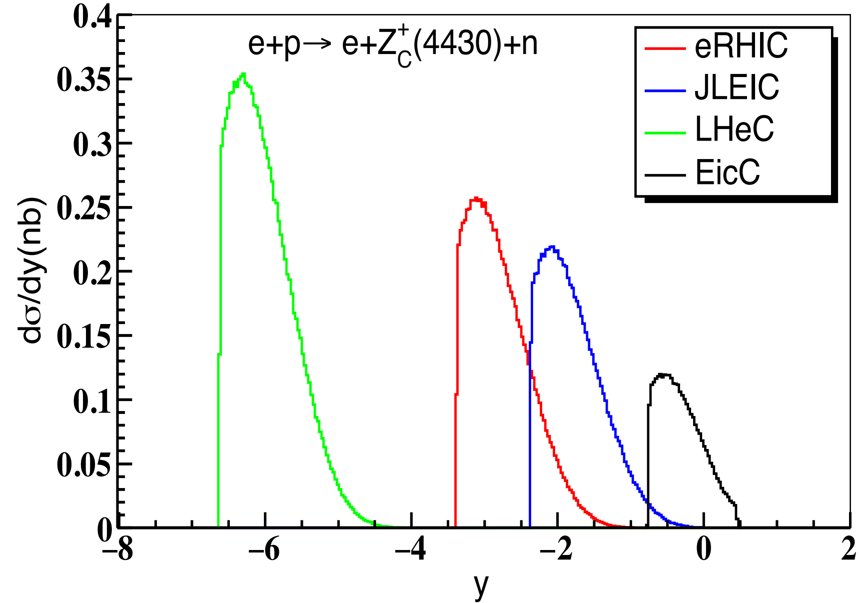
PRD(93)074016 & PRC(83)065203

$a_2^+(1320)$ and $Z_c^+(4430)$ production in ep scattering for proposed EICs

- We compute rapidity distributions of $a_2^+(1320)$ in ep scattering in proposed EICs. The electron is moving in the positive y direction.

- The $a_2^+(1320)$ is mainly in the negative rapidity region, and there is a large rate in EICs. It is easy to measure $a_2^+(1320)$ in EicC at small rapidity regions



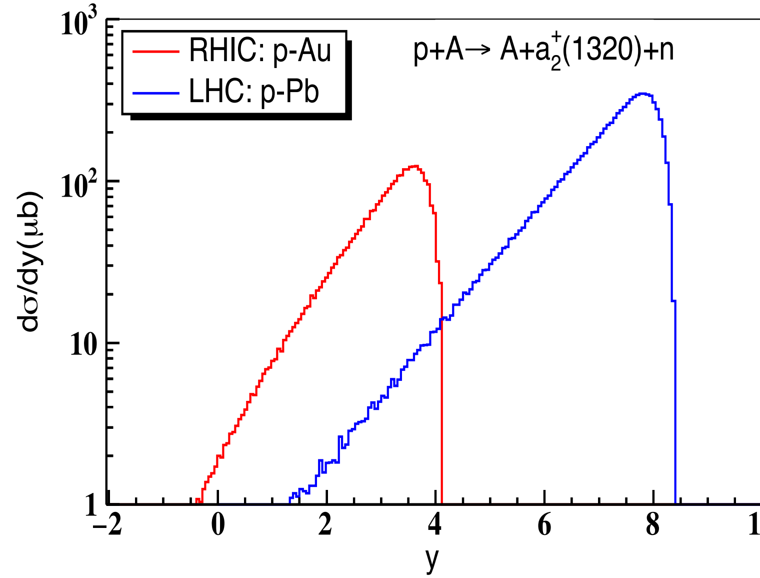


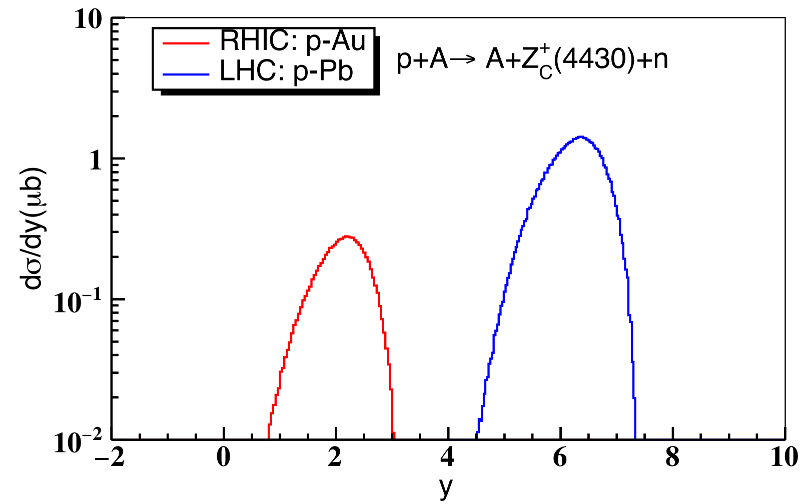
$Z_c^+(4430)$ and $a_2^+(1320)$ production in pA UPCs at RHIC and LHC

- Ultra-peripheral collisions means that two nuclear collide with each other in a large impact parameter.
  - Strong interaction is suppressed
  - Electromagnetic interactions.
- We also compute the two charged particles production in pA UPCs. The cross-section is:

$$\sigma(pA \to nAM) = \int dk \frac{dN_\gamma(k)}{dk} \sigma_{\gamma p \to nM}(W)$$

- The photon flux from protons is much smaller that photon flux from heavy ions. The **γ**-p cross-section is dominant in p-A UPCs.





Expected event rate for vector mesons, a2+(1320) and ZC+

- Total cross sections and expected events for vector mesons and two charged particles on EICs, RHIC and LHC
  - For ~ 1 year (for HLLHC – all of Run period 3 & 4)

	Events ($0 < Q^2 < 1.0 GeV^2$)				Events ($Q^2 > 1.0 GeV^2$)			
	ρ	ϕ	J/ψ	ψ'	ρ	ϕ	J/ψ	ψ'
eRHIC -ep	50 giga	2.3 giga	85 mega	14 mega	140 mega	17 mega	5.7 mega	1.2 mega
eRHIC -eA	44 giga	2.8 mega	100 mega	16 mega	37 mega	5.6 mega	3.9 mega	960 kilo
JLEIC -ep	37 giga	1.6 giga	39 mega	6.0 mega	100.0 mega	12.0 mega	2.7 mega	550 kilo
JLEIC -eA	28 giga	1.6 giga	28 mega	3.9 mega	22 mega	3.2 mega	1.2 mega	250 kilo
LheC -ep	100 giga	5.6 giga	470 mega	78 mega	260 mega	37 mega	29 mega	6.3 mega
LHeC -eA	110 giga	8.2 giga	720 mega	140 mega	100 mega	16 mega	27 mega	7.2 mega

	Events ($0 < Q^2 < 1.0 GeV^2$)				Events ($1.0 GeV^2 < Q^2 < 5.0 GeV^2$)				Events ($Q^2 = 0.0$)	
	eRHIC	JLEIC	LHeC	EicC	eRHIC	JLEIC	LHeC	EicC	RHIC	LHC
$a_2^+(1320)$	0.79 giga	0.69 giga	1.06 giga	0.47 giga	5.1 mega	5.0 mega	5.2 mega	4.0 mega	0.78 giga	1.12 giga
$Z_c^+(4430)$	2.6 mega	2.2 mega	3.6 mega	0.94 mega	0.12 mega	0.12 mega	0.12 mega	68.0 kilo	1.4 mega	3.52 mega

Conclusions

- Vector meson photoproduction is an attractive way to image the partons in the nucleus.
  - Data from ultra-peripheral collisions points to moderate shadowing in heavy ions for $10^{-3} < x < 10^{-2}$ & moderate Q^2
- An electron-ion collider will allow precise measurements of shadowing as a function of Q^2
  - High rates for ρ,ρ', J/ψ, ψ'; moderate rates for the Υ(1S)
- The eSTARlight Monte Carlo can simulate the production of different vector mesons in ep and eA collisions.
- To reach the lowest possible Bjorken-x requires a forward detector.
- ep and pA UPCs also produce charged mesons, via charged Reggeon exchange. The a_2^+(1320) is a 'standard candle'.
  - This is a way to determine the nature of exotic mesons like the Z_c^+