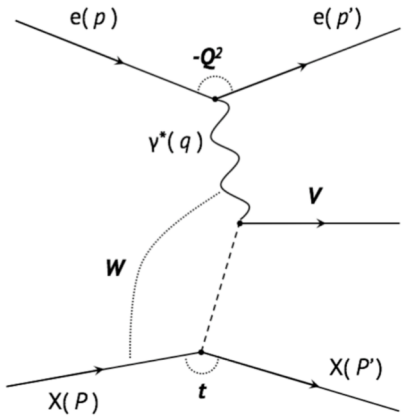
EIC diffractive/exclusive physics requirements with some thoughts on a second detector

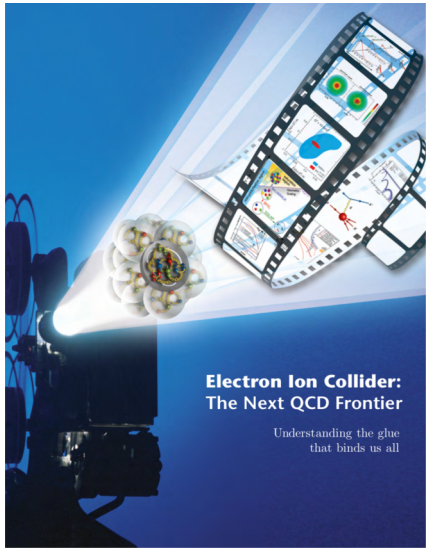
Spencer Klein, LBNL

Presented to the EICUG 2nd detector meeti

December 6-8, 2022

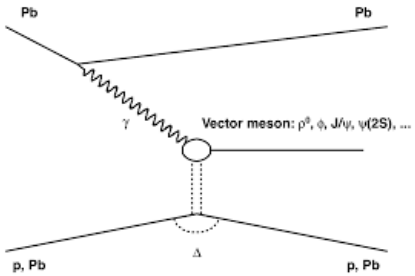


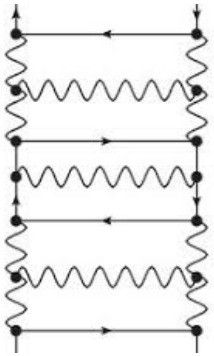
- Photo & electroproduction at an EIC
- Bjorken-x and rapidity
  - Near threshold photoproduction
  - Low-x production
- Charged photoproduction & the structure of exotics
- Backward photoproduction via baryon exchange & baryon stopping*
- Conclusions



Photoproduction and Electroproduction

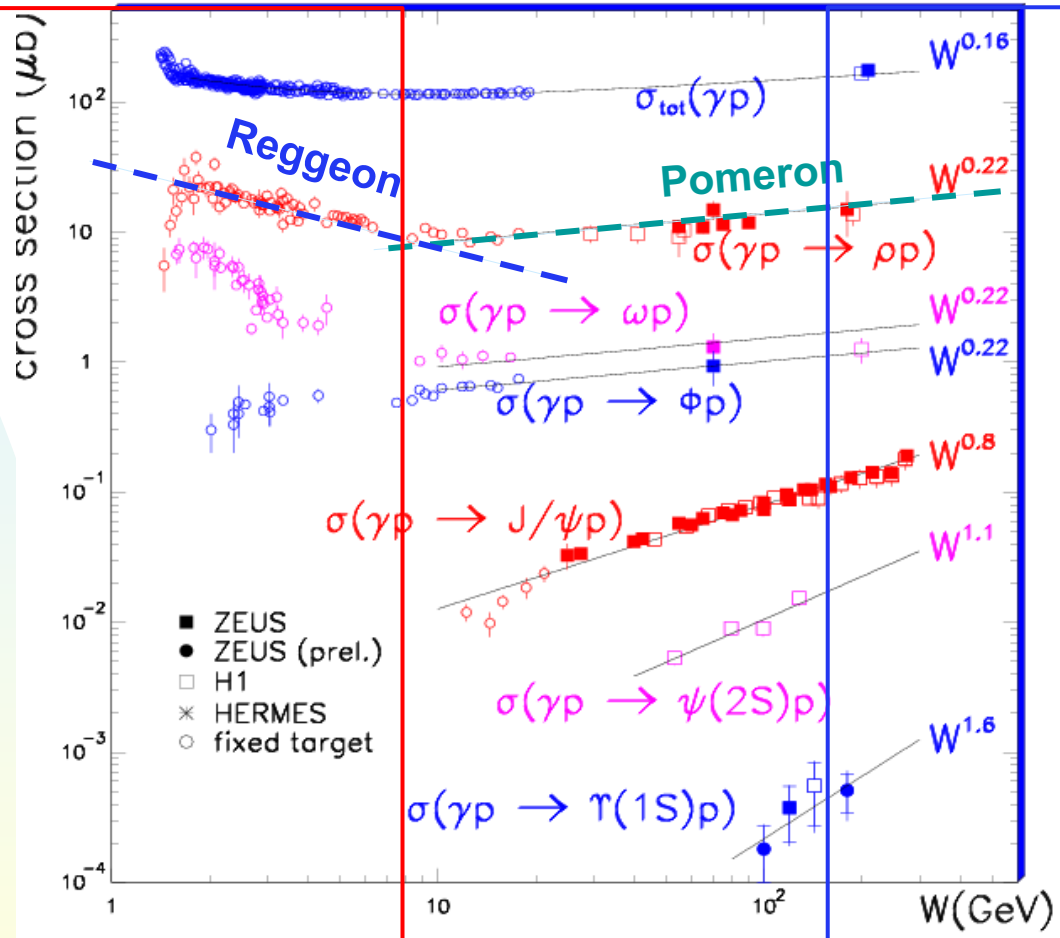
- Two models
- Gluon exchange
  - Lowest order is 2-gluon exchange
  - Higher orders is gluon ladder
- Pomeron + Reggeon exchange
  - Pomeron is gluon ladder
    - $J^{PC}=0^{++}$ explains vector meson dominance
      - Absorptive part of the potential
  - Reggeon involves quark exchange
    - meson trajectories (q-qbar)
    - Wide range of spin, parity and charge
    - Allows production of pentaquarks, other exotica etc.





Pomerons, Reggeons and kinematics

HERA + fixed target data



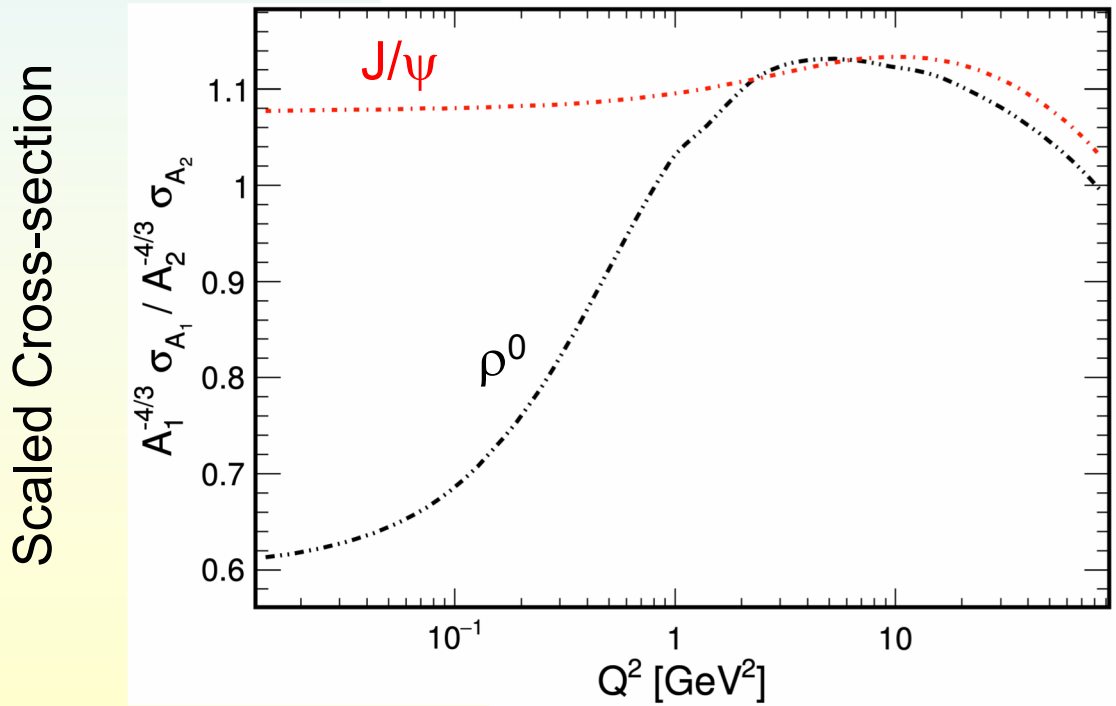
Ion-going direction
Reggeon dominated
Near threshold production
Pentaquarks, other exotica

Rapidity:
$y=\ln(W^2/m_p m_V)$

Electron-going direction
Pomeron- dominated
Low-x gluons
saturation

Photoproduction vs. electroprodution

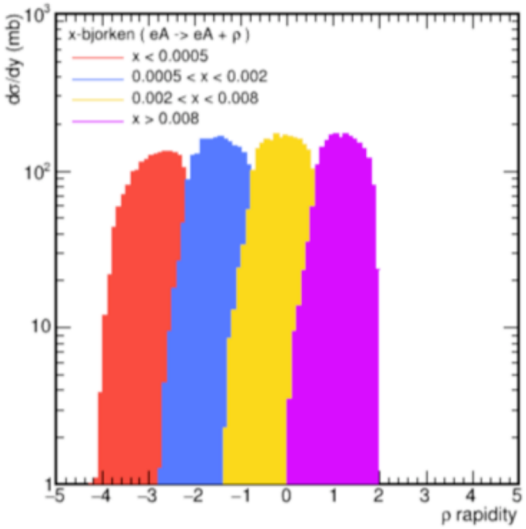
- Most EIC attention is on electroproduction ($Q^2 > 1$ GeV^2)
- Photoproduction ($Q^2 < 1$ GeV^2) is critical for studying shadowing, which should disappear at large Q^2
  - Good acceptance is needed for vector mesons at low p_T
- Shadowing is larger for lighter mesons
  - ρ/ϕ are experimentally important

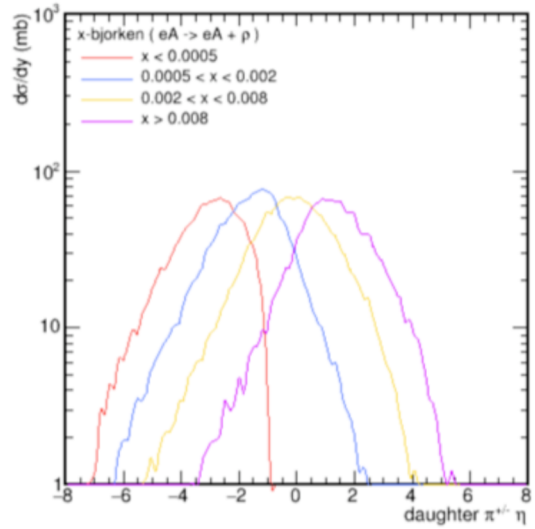


From eSTARlight. Similar plot by Mantyssari and Venugopalan, Phys. Lett. B **781**, 664 (2018)

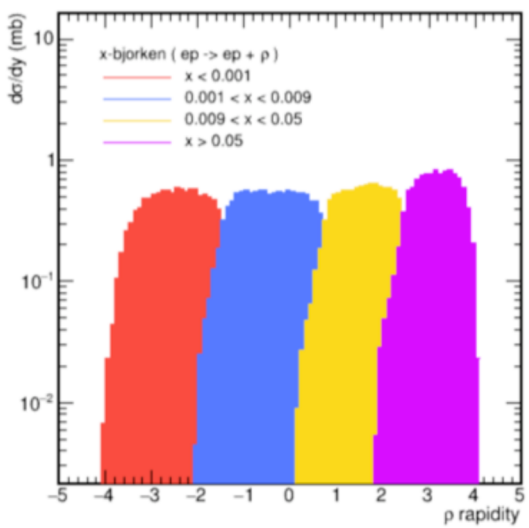
The ρ^0

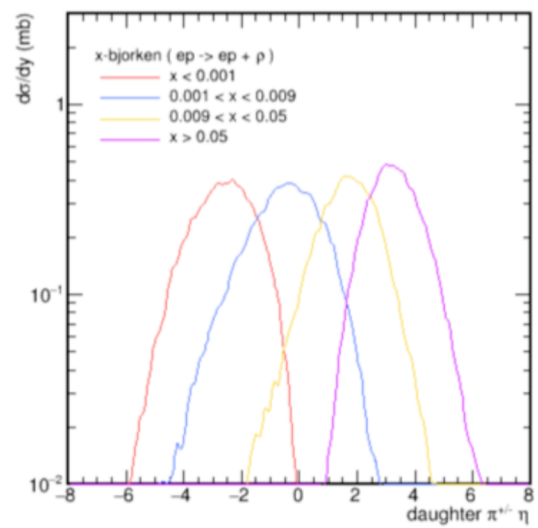
- $10^{-4} < x < 1$ corresponds to $-4 < y < 4$
- Coverage up to rapidity $|y|$ requires coverage to $|\eta| > |y|+1$





eAu
18 GeV * 100 GeV



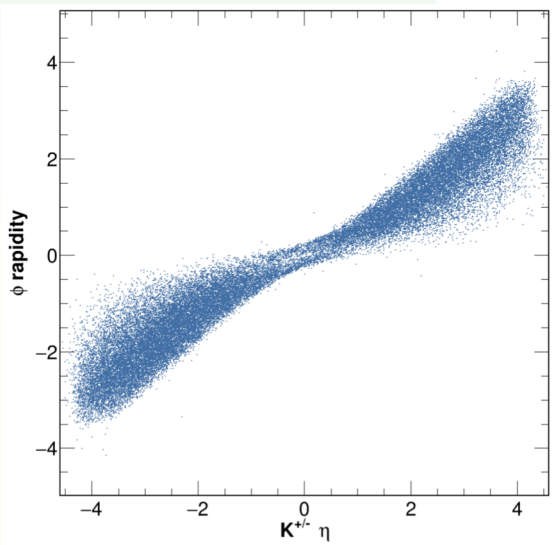


ep
18 GeV * 275 GeV

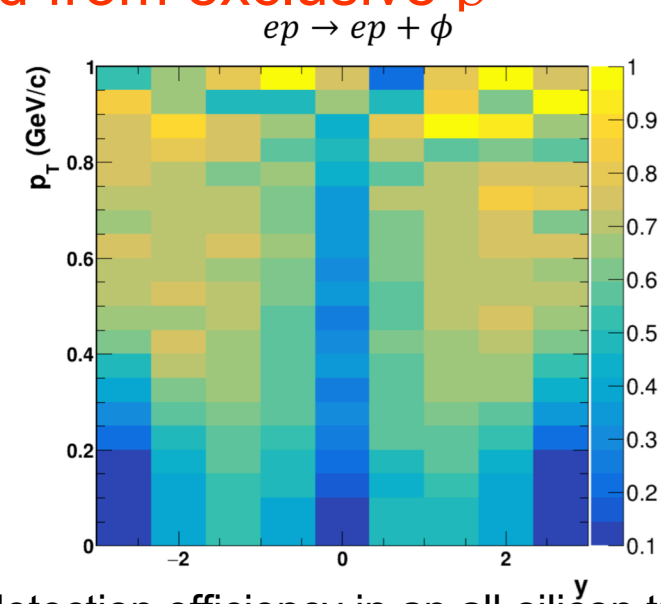
J. Arrington *et al.*, arXiv:2102.08337

The ϕ

- $\Phi \to K^+K^-$ is the only viable decay mode
  - Kaon momentum is 135 MeV/c in ϕ frame
    - Relationship between kaon $\langle\eta\rangle$ and ϕ $\langle y\rangle$ is nonlinear
      - Reduces detection efficiency at large $|y|$
- For photoproduction near y=0, kaons have p=135 MeV/c
  - Highly ionizing
  - Requires low B field and very low material to detect
- Need PID to reject background from exclusive ρ



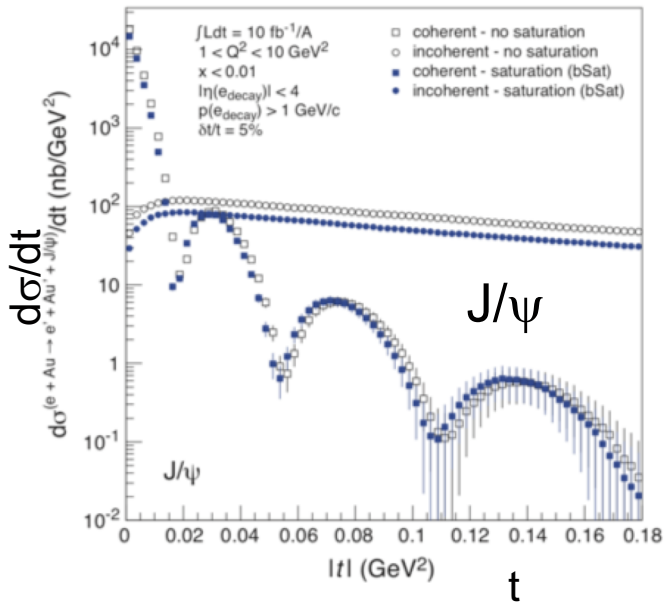
ϕ Rapidity vs. kaon pseudorapidity



ϕ detection efficiency in an all-silicon tracker

Separating Coherent and Incoherent production

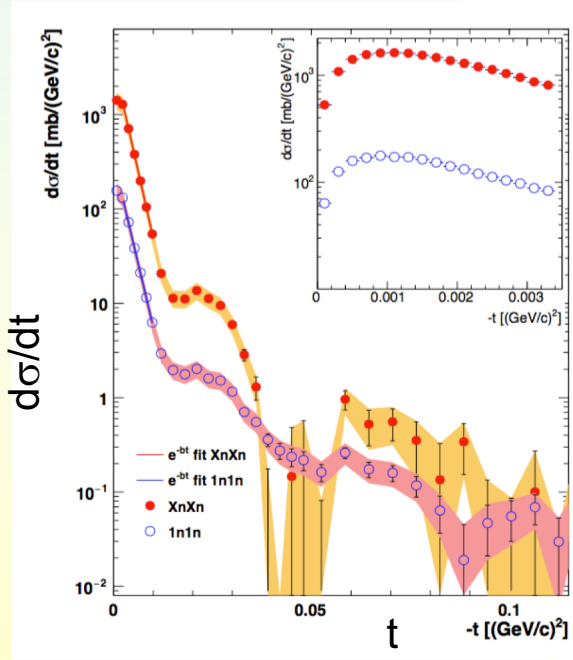
- In the Good-Walker paradigm, coherent photoproduction is sensitive to the average nuclear shape, while the incoherent production is sensitive to event-by-event fluctuations
  - Need 500:1 coherent:incoherent separation at 2nd minimum
    - Neutron or proton emission is easy, but there are excitations that decay by emitting MeV (in the target frame) photons
    - Situation murky; requires good acceptance for far-forward E< 100 MeV
- Lead preferred over gold. It has no low-lying, long-lived states



EIC White Paper

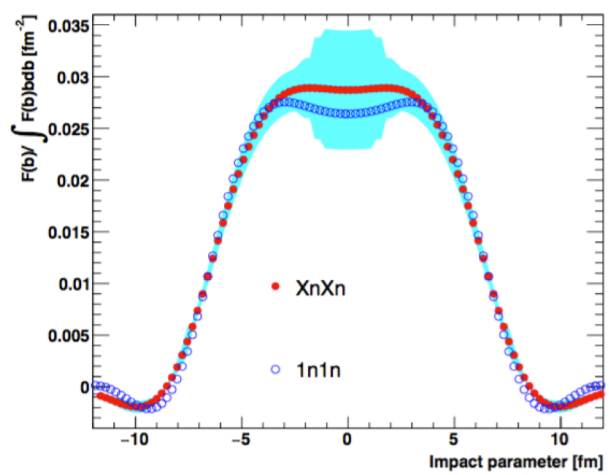
Observing diffractive dips

- $d\sigma/dt$ for coherent photoproduction probes the transverse gluon distribution in nuclei – like GPDs, but for nuclei.
- Requires good measurement of $t \sim p_{T,Pomeron}^2$
- $P_{T,VM} = P_{T,Pomeron} \oplus P_{T,photon} \oplus$ Resolution
  - Need photon p_T to accurately determine Pomeron p_T
    - Observe scattered electron down to low Q^2
      - Limited by beam emittance; easier at higher k/E_e



STAR ρ^0

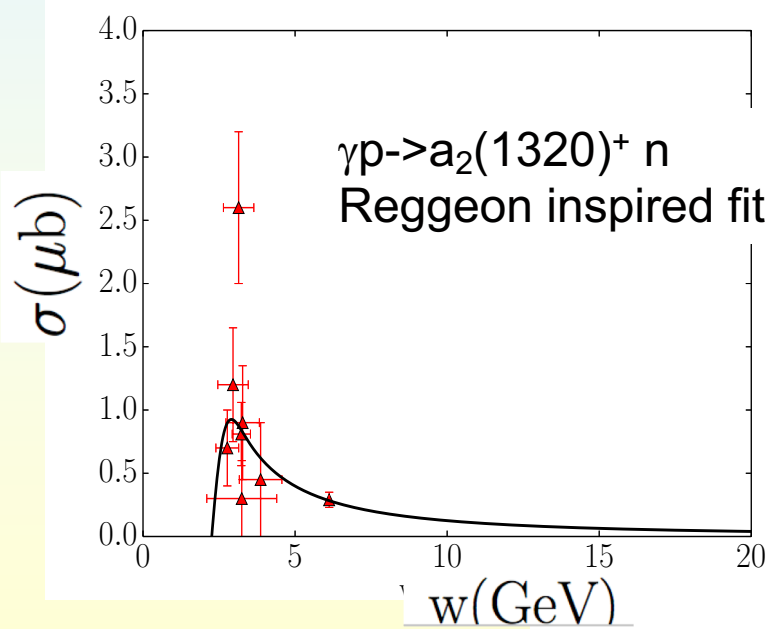
$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T p_T J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$

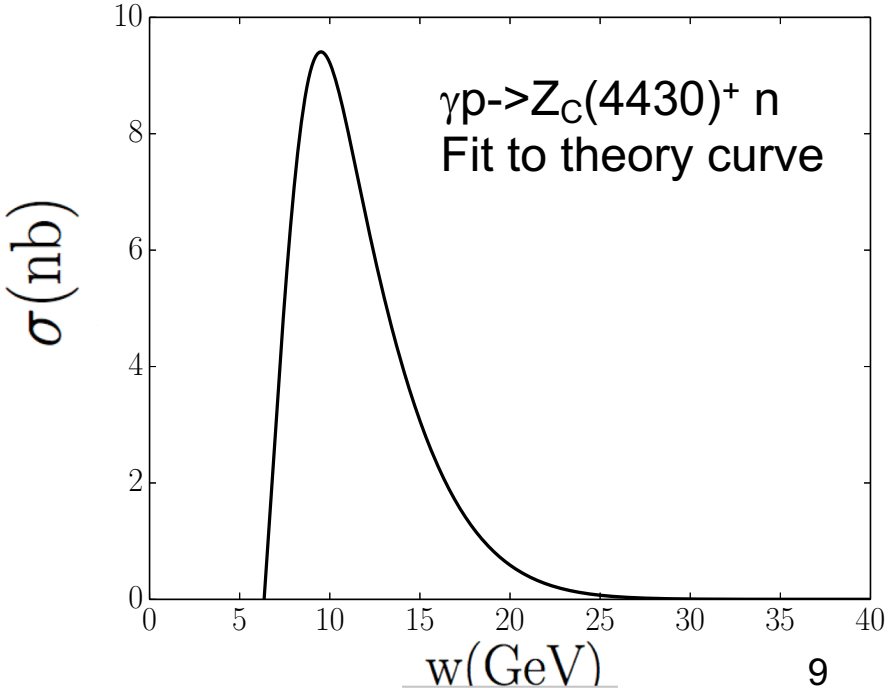


STAR, Phys. Rev. **C96**, 054904 (2017)

Reggeon exchange and forward production

- Examples: the $a_2^+(1320)$ standard candle and the exotic $Z_c^+(4430)$
- Use data/calculations of $\sigma(\gamma p \to X+n)$ as input to eSTARlight to predict $d\sigma/dy$ for the same process in EIC collisions/
  - Use the same Q^2 scaling as the ρ (for the a_2) and $J/_y$ (for the Z_c)

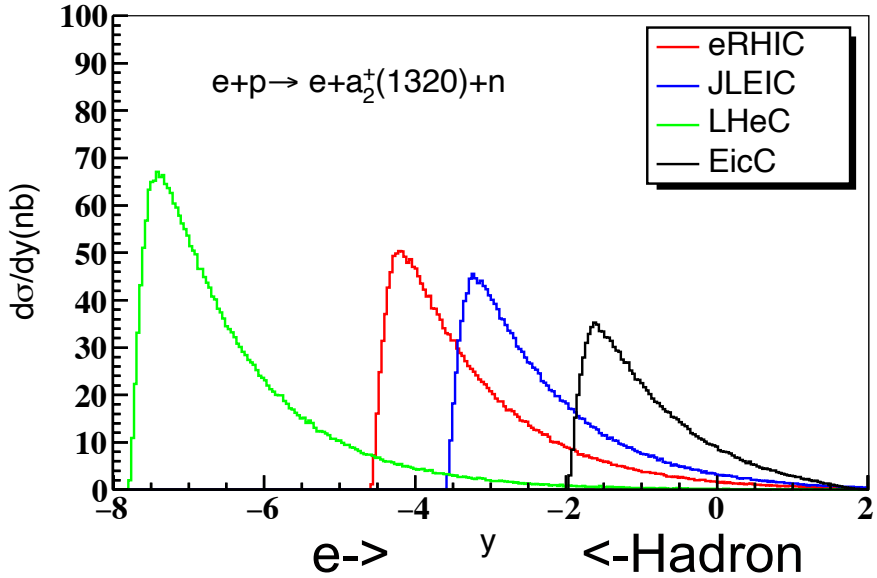


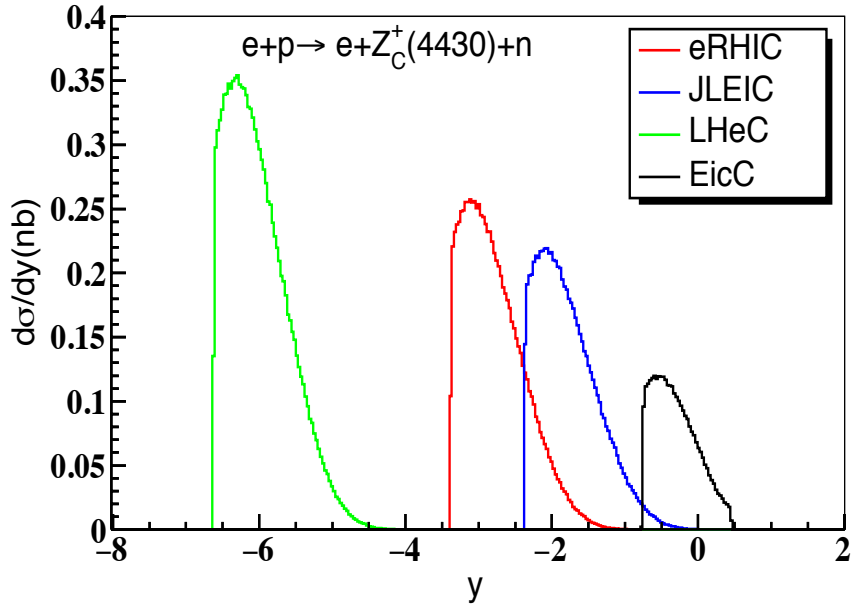


PRD(93)074016 & PRC(83)065203

$a_2^+(1320)$ and $Z_c^+(4430)$ production in ep collisions at the EICs

- The $a_2^+(1320)$ is mainly at negative rapidity
  - σ ~80 nb at eRHIC
    - Copiously produced
- The $Z_c^+(4430)$ is heavier, and so somewhat more centrally produced.
  - σ is 0.26 nb at eRHIC
- Both require good ion-going acceptance to be observable
- Both might be easier to observe at lower beam energies

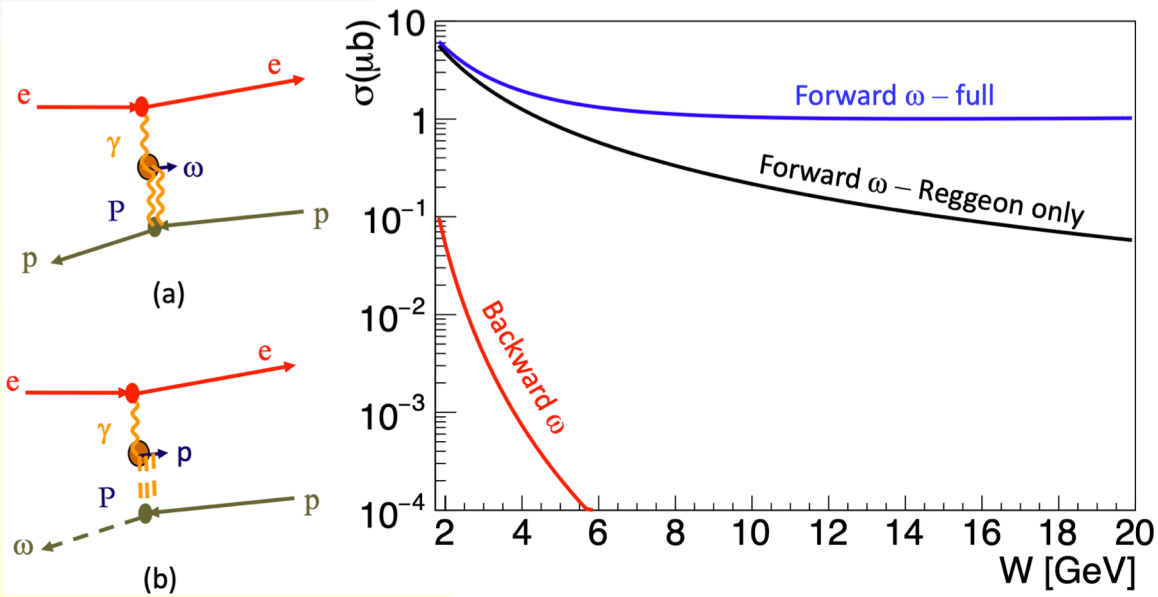




SK and Ya-Ping Xie, PRC **100**, 024620 (2019)

Backward meson production

- In backward production, |t| is large, but |u| is small
- Transports baryon number over several units of rapidity
  - Baryon transport
  - Vector meson takes most of baryon momentum
- Studied extensively at fixed-target facilities (including JLab)
- Describable with Regge theory or transition distribution amplitudes (kind of like GPDs)



D. Cebra *et al.*, Phys. Rev. C **106**, 015204 (2022)

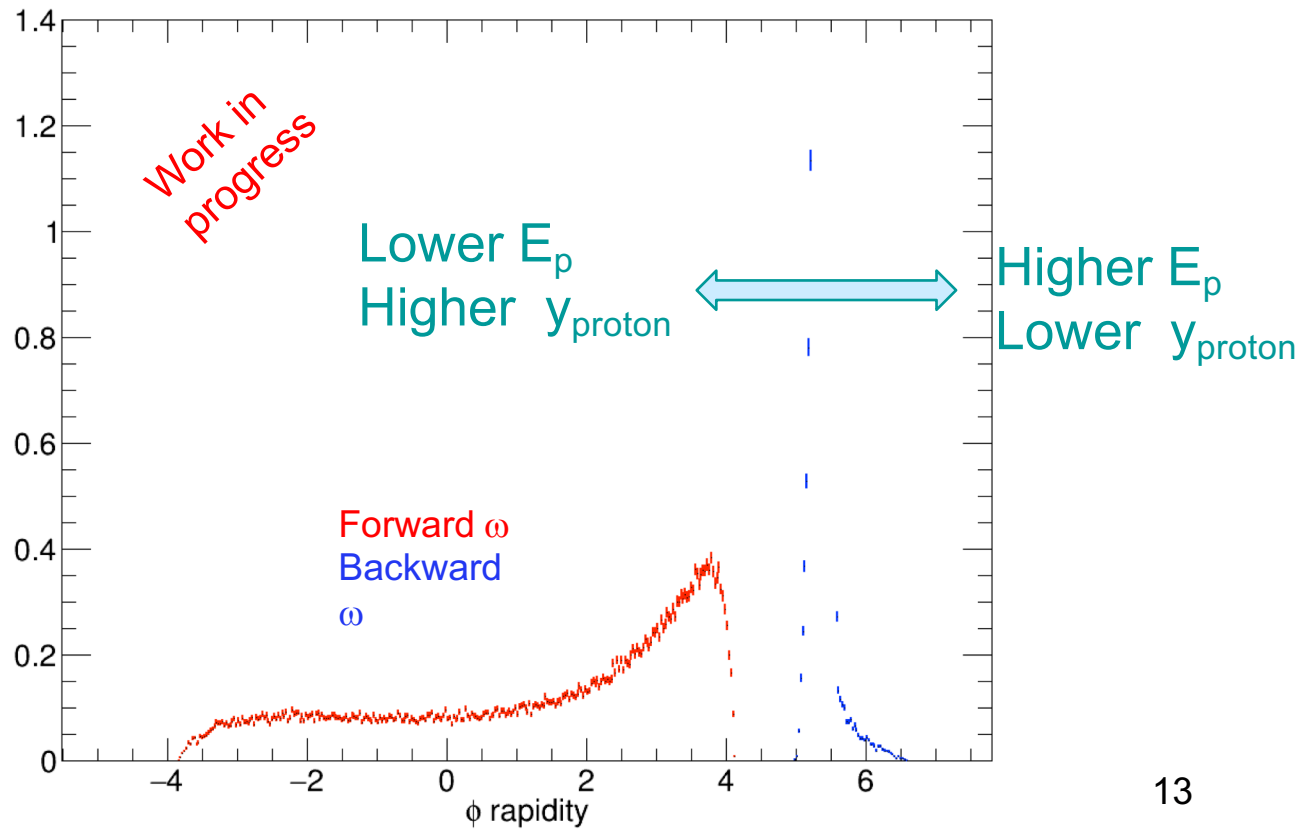
Backward production at an EIC

- Use parameterizations based on fixed-target data
  - Focus on ω, since the best data is available
- Extrapolate to EIC energies, etc.
- Consider $\omega \to \pi^0\gamma$ and $\rho \to \pi^+\pi^-$
  - One all-neutral and one all-charged final state
- Rates are ample – probably enough to study heavier mesons, like the ϕ and maybe J/ψ
  - Cross-sections are guestimates, since these mesons share no valence quarks with the proton
- Fixed-target backward ω data parametrized with a Regge model
  - Usual $d\sigma/dt \sim \exp(-bt)$ swapped for $d\sigma/du \sim \exp(-ct)$

Beam energy dependence of ω peak

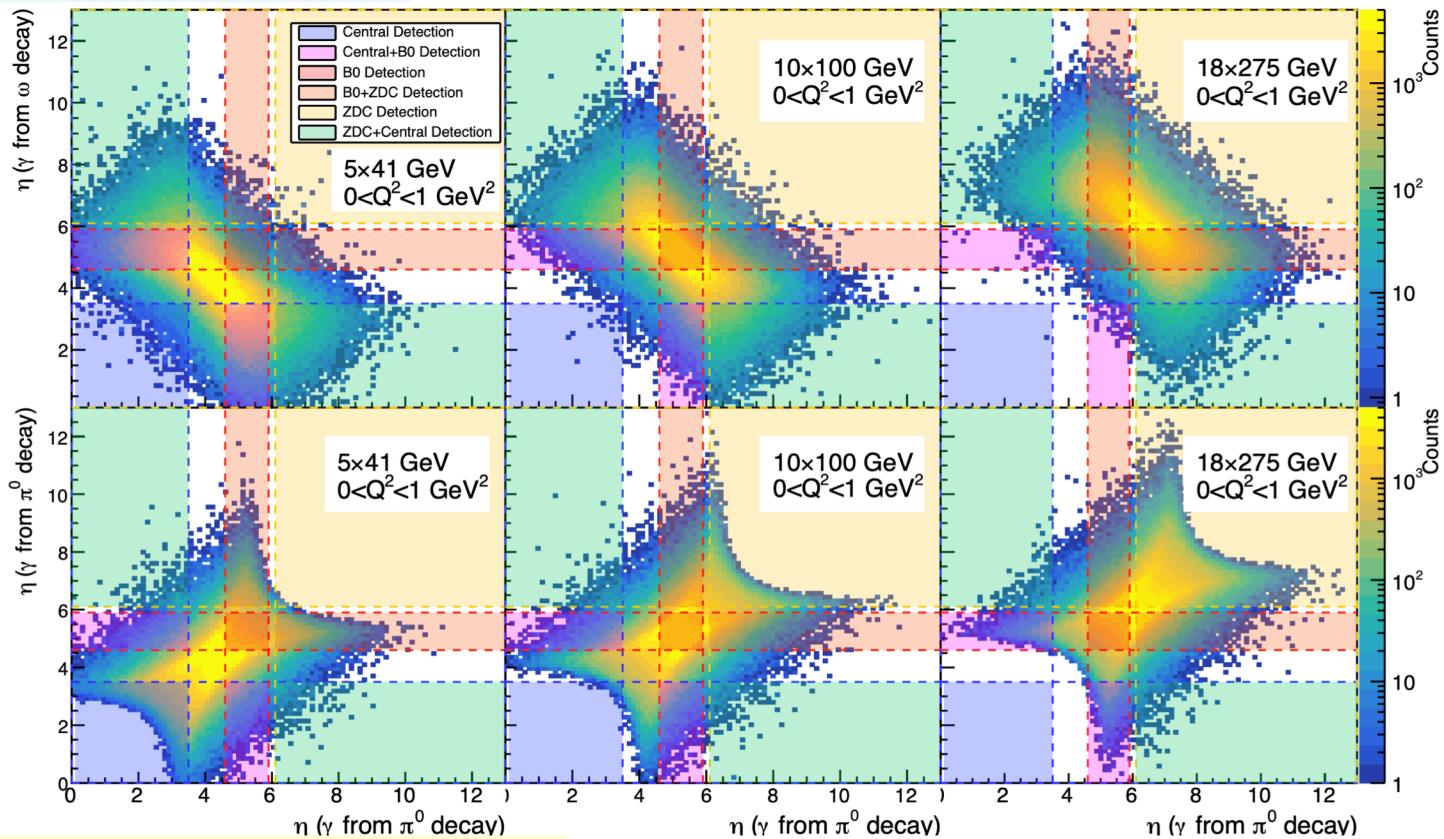
- For 275 GeV proton beams, y_ω rapidity ~ 6.5
- For 41 GeV protons beams
  - Proton rapidity = 0.0 -> typical ω rapidity is 4.6
  - Proton rapidity = 4.0 -> typical ω rapidity is 3.7
- Need to explore full phase space, but lower proton beam energies seem better

ep->e p ω
18 GeV e on 100 GeV
eSTARlight simulation



Backward ω production at the EIC

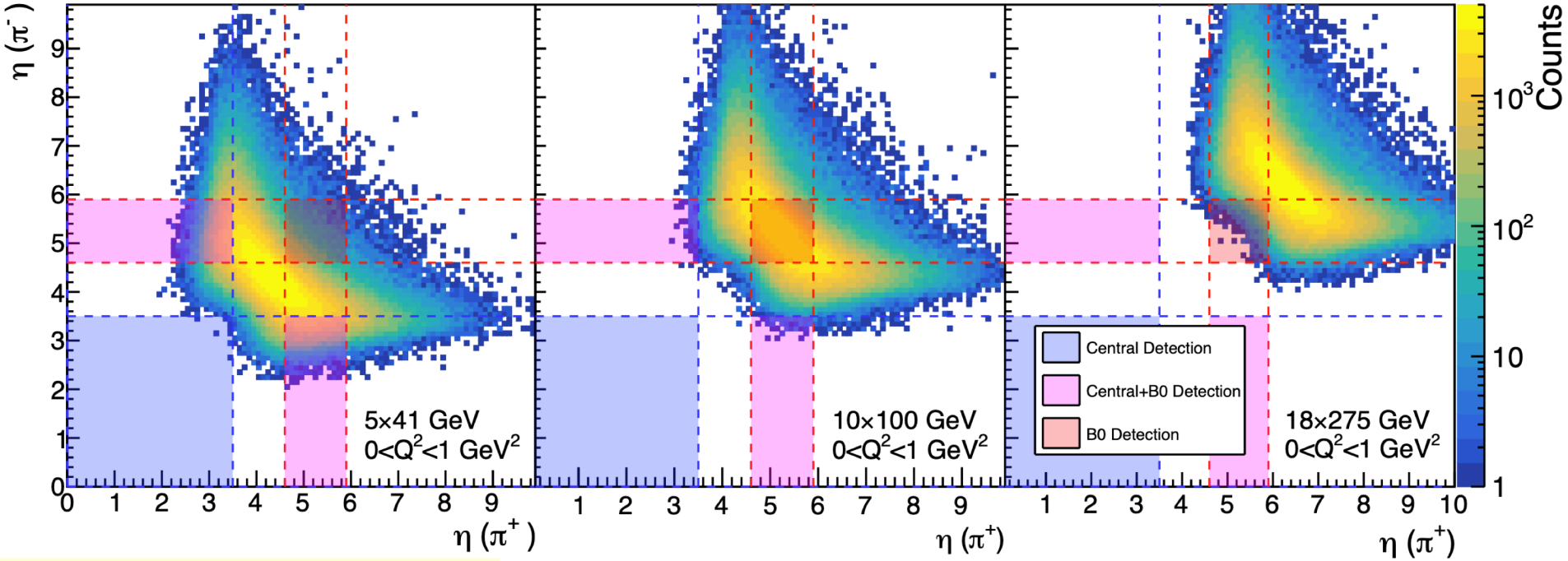
- Forward detectors are critical
  - B0 detector is key in existing designs
  - Gaps around B0 detector are painful
  - ZDC needs to detect multiple photons
- Detection best at less than full beam energies



$\omega \to \pi^0\gamma$

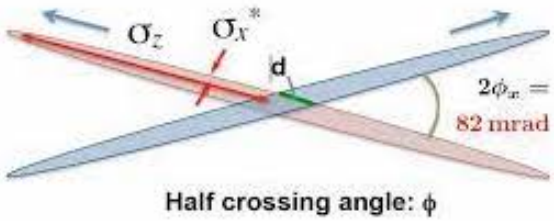
Backward ρ at the EIC

- Requires charged particle momentum measurement in B0 magnet detector
- ZDC not useful



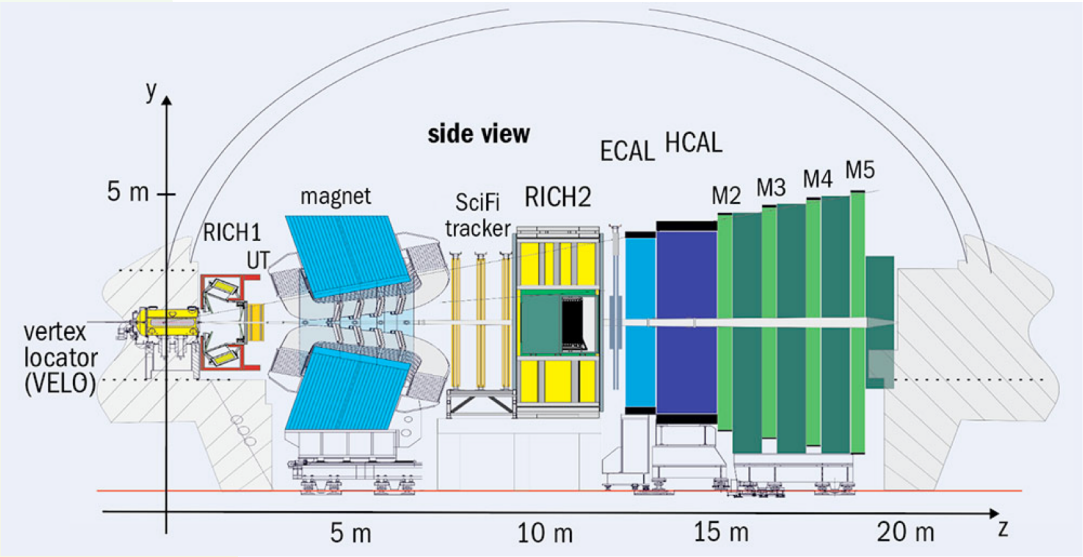
How would a 2nd detector/low energy improve the rapidity/energy coverage?

- Low-energy running shifts the forward region toward mid-rapidity.
  - Near-threshold production, pentaquarks etc. become more central
- This does not work on the low-x side
  - Good rapidity coverage is needed to exploit the full EIC energy
- Another partial solution: instrument the IR above & below the plane where the beams diverge



A radical suggestion (for discussion)

- Much interesting diffractive/exclusive physics requires excellent forward instrumentation
  - Some topics can live with lesser central-barrel coverage
- Consider a forward-spectrometer-like approach, ala LHCb
  - Likely with wider rapidity coverage
  - With a dipole magnet
  - Necessary detector ‘holes’ could be at mid-rapidity



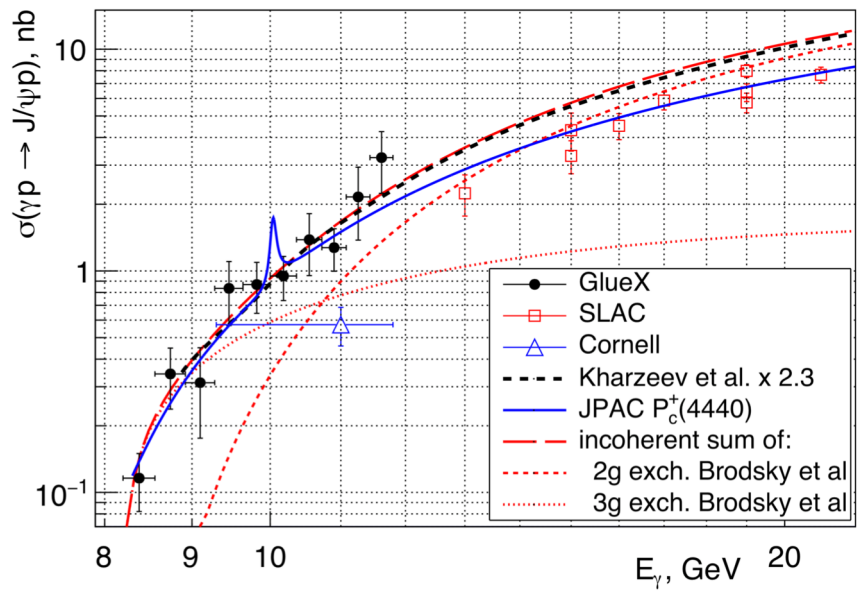
Conclusions

- Very wide pseudorapidity coverage is required to study vector meson production over the full range of Bjorken-x.
- Near-threshold production & Reggeon-exchange production, including exotica requires good forward acceptance
  - Running at a reduced ion beam energy will shift this production toward mid-rapidity.
- These requirements challenge EPIC in some places.
- Excellent far-forward ion-going detectors are required to separate coherent and incoherent photoproduction.
- Backward production reactions lead to mid-rapidity baryons and far-forward mesons. The later are a detector challenge, requiring more study.
- A second detector could emphasize forward coverage, at the expense of the central barrel.

Backup

Near threshold quarkonium production

- Near-threshold quarkonium production is sensitive to new mechanisms (i. e. 3-gluon exchange)
  - GlueX data favors a mix gluon exchange for J/ψ
- Sensitive to near-threshold
  - $P_C^+(4440)$ == J/ψ p
    - Pentaquark candidate



- EIC will study ψ', Υ states and probe the Q^2 dependence of multiple resonances
- For nuclei, near-threshold or sub-threshold production is sensitive to short-range nuclear correlations.
- Requires good acceptance in the ion-going direction

GlueX Collaboration, PRL **123**, 072001 (2019)

Photoproduction & electroproduction in eSTARlight

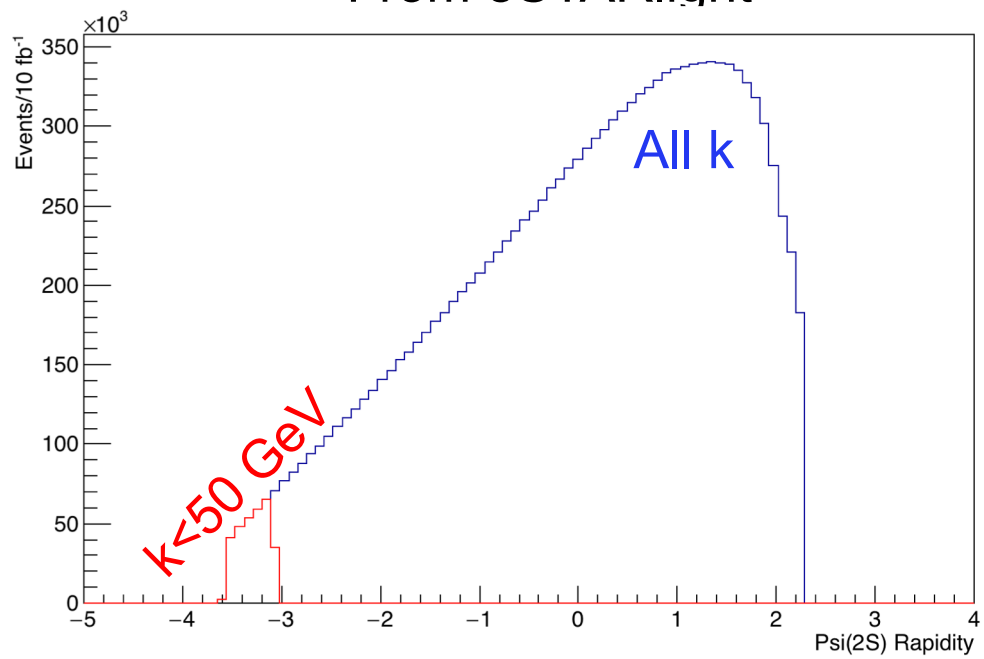
- Convolution of photon flux from electron with $\sigma(\gamma p \to Vp)$
  - Both depend on Q^2
- Weizsacker-Williams photon flux (with non-zero Q^2)
- VM cross-sections parameterized from HERA data/theory….
  - Reggeon and Pomeron exchange
    - Q^2 dependence via a power law from HERA data
- Other cross-sections from theory predictions
- Nuclear targets included with a Glauber calculation
- 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: https://github.com/eic/estarlight/

n.b. new location

Ψ(2S) & Υ photoproduction at eRHIC

- 18 GeV e^- on 275 GeV protons
- Ψ(2S): σ=1.4 nb (1/6 of σ(J/ψ))
  - 14 million events in 10 fb^{-1}
- 300,000 events with photon energy <50 GeV (target frame)
  - Ψ(2s) threshold region is 3.5 < y < 3.0 for this configuration
  - ~ 2,800 each Ψ(2S)->ee, μμ
- σ(Υ(1S))=0.01σ(ψ')
  - 140,000 events/10fb^{-1}
    - ~3,000 each to ee, μμ
  - ~3,000 near-threshold events
    - ~75 each to ee, μμ
    - More central than ψ'

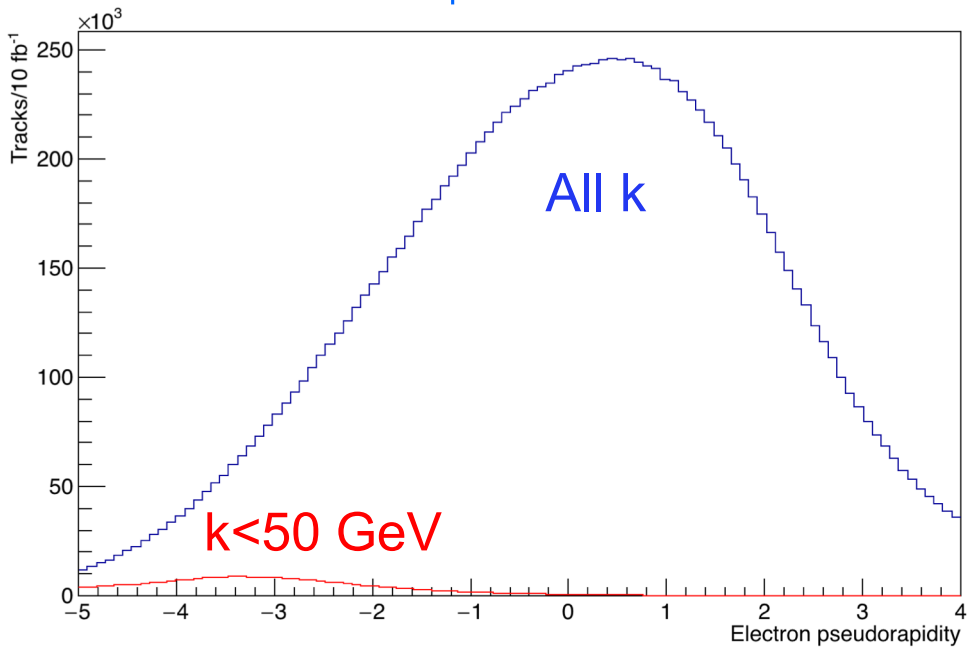
From eSTARlight



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 $\mu\mu$ is 0.7%. Plus J/$\psi\pi^+\pi^-$
- Rates for Υ(1S) smaller - usable.
- Higher ψ states accessible



e-> <-Hadron

Expected event rate for vector mesons, $a_2^+(1320)$ and Z_C^+

- Total cross sections and expected events for vector mesons and two charged particles in ep collisions
  - 10 fb^{-1} integrated luminosity

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

Theoretical approach - I

- GPD-like model, with Transition Distribution Amplitude quantifying baryon trajectories.

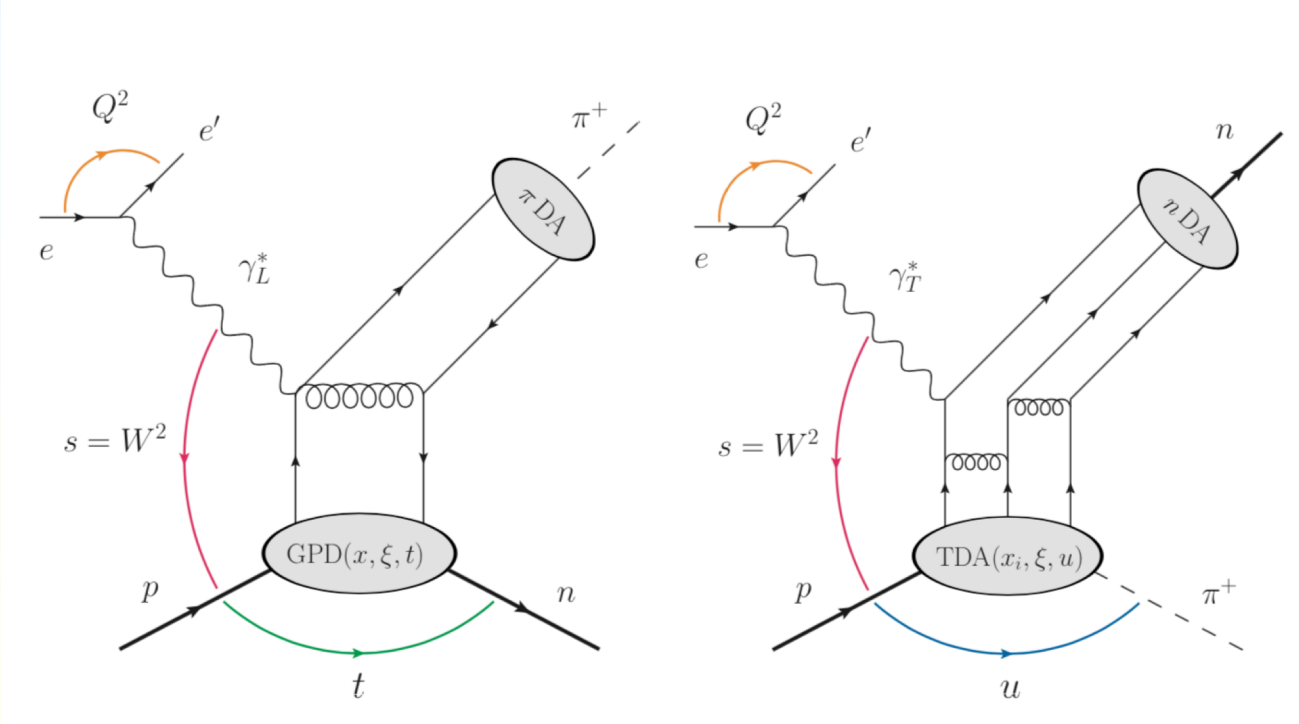
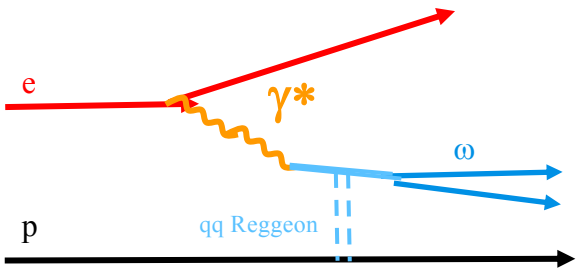
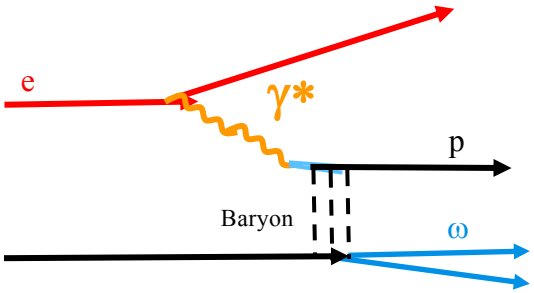


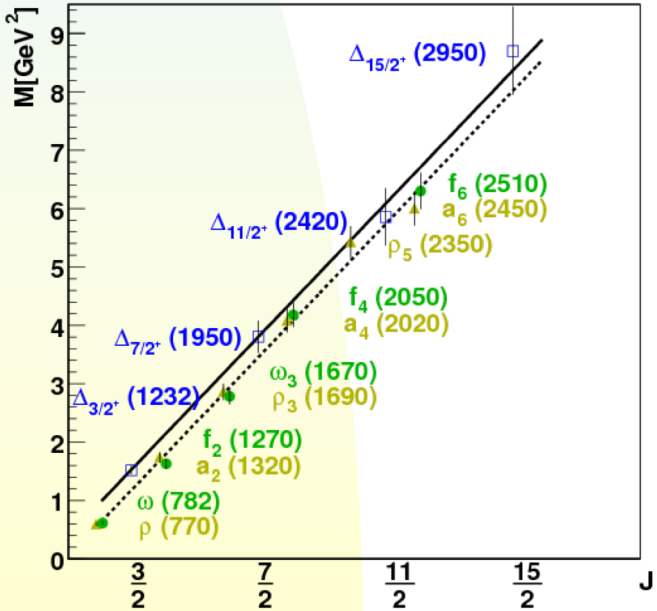
Diagram from K. Park et al., Phys. Lett. B780, 340 (2018)

Theoretical approach II – Baryon trajectories

- For baryonic Regge trajectory
  - $\sigma(W) = XW^{\epsilon} + YW^{-\eta}$
  - Replace t with u, and much familiar behavior is restored.
    - Similar to meson trajectories
- Key trajectories: N, Δ,
  - Λ/Σ for strangeness (not today)





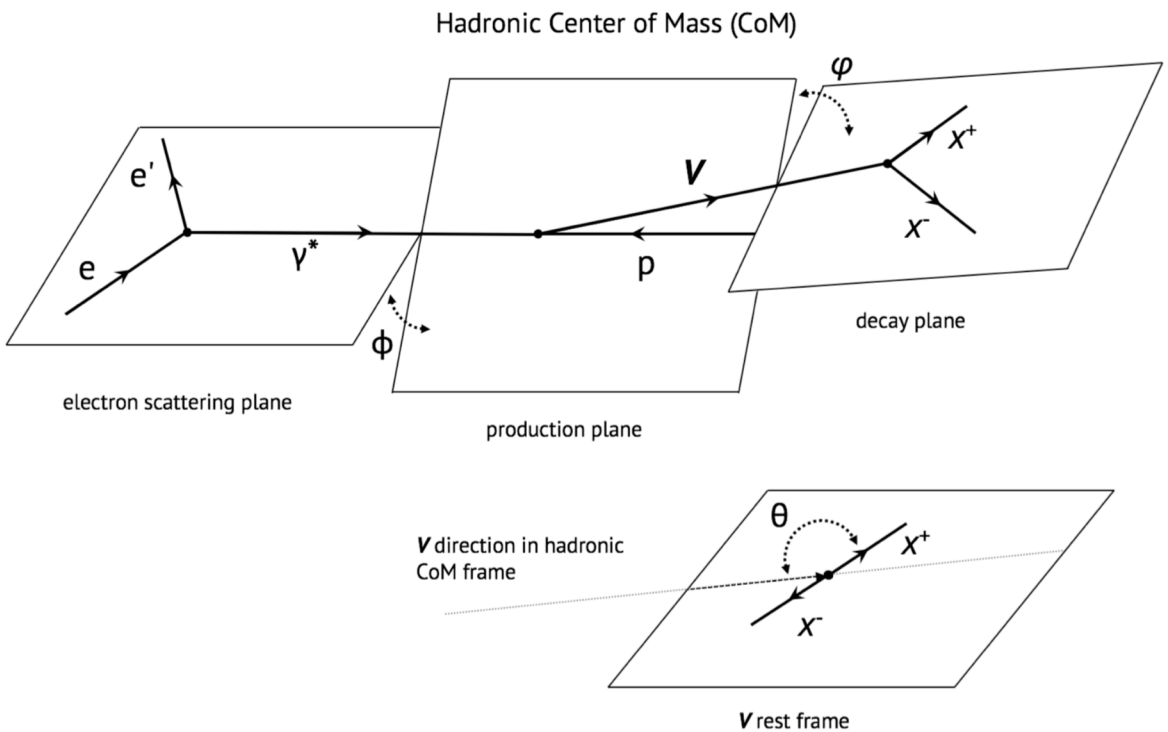


Implications for baryon stopping

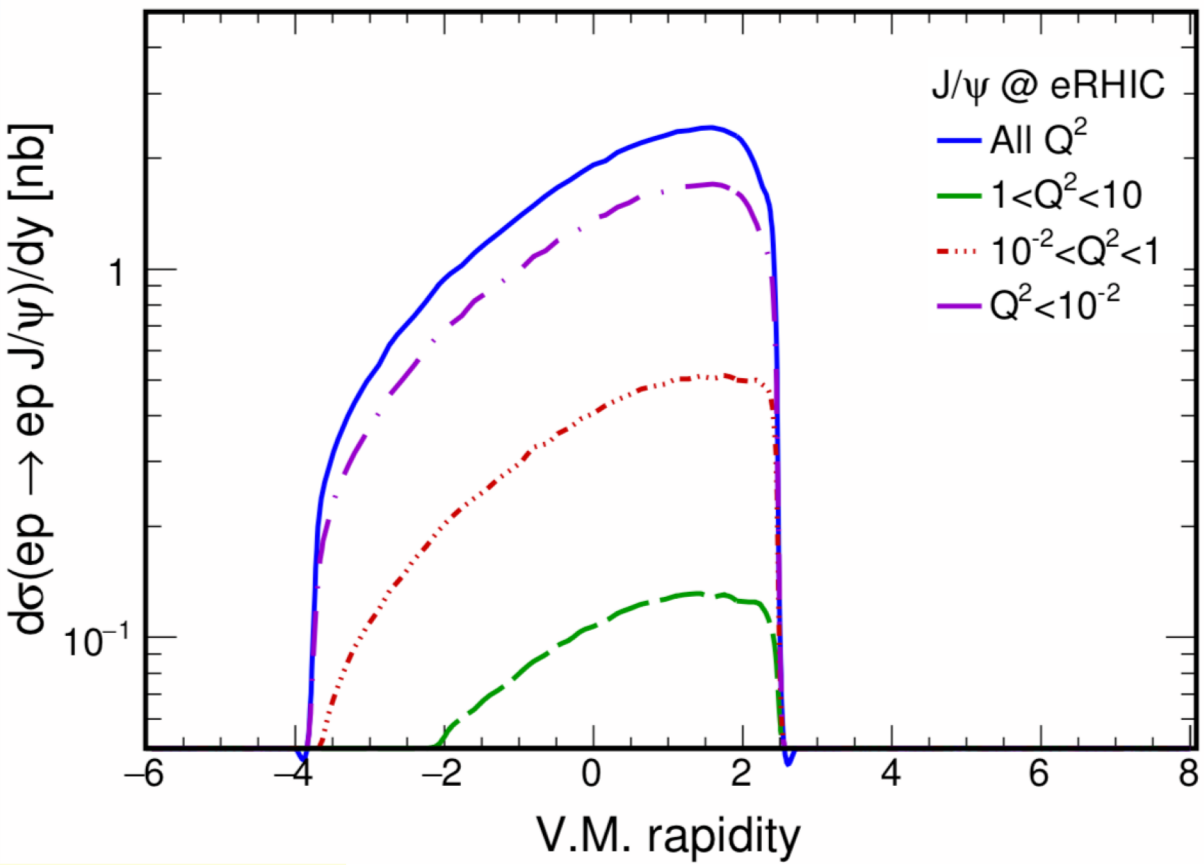
- Conventional wisdom: Regge phenomenology only matters at low energy
  - But… the relevant energy is the dipole-baryon CM energy.
  - soft dipole -> small CM energy.
    - Low-energy UPC photon
    - A soft virtual π
    - A low-x q-qbar dipole
    - Other configuration within an incident nucleus
- The baryon recoils but remains intact
  - Transport over multiple units in rapidity.
    - Like baryon stopping.
  - Phenomenology is very reminiscent of the baryon junction model.
    - Are there connections?

Vance, Gyulassy and Wang, Phys. Lett. B443, 45 (1998)

Angular definitions



Rapidity vs. Q^2



Parameterization of backward $\gamma p \to \omega p$

- ω is best studied backward photoproduction case
  - Fit to data from two experiments
- Assume same Reggeon-like form as forward production:
  - $d\sigma/dt|_{t=0} \sim A\,(s/1\text{GeV})^B$ embodies physics of reaction
  - $d\sigma/dt \sim \exp(-Ct)$ accounts for form factor (size) of target
  - Swap u for t, to match behavior of backward kinematics
- $d\sigma/du|_{u\sim 0} = A\,(s/1\text{GeV})^B$
  - $A = 4.4\ \mu b/\text{GeV}^2$
    - $A=180\ \mu b/\text{GeV}^2$ for forward ω photoproduction
  - $B = -2.7$
    - $B=-1.92$ for forward ω photoproduction
- $d\sigma/du \sim \exp(-Cu)$, with $C=-21\ \text{GeV}^{-2}$
  - Similar slope as C in e^{Ct} term for forward $\gamma p \to \rho p$
- Rate is few % of the forward rate for k~ GeV
  - Falls off a bit faster with increasing energy.
  - Cross-sections are large enough to be easily accessible.