Diffraction at the EIC, with topics that would benefit from a 2nd detector or lower energy running

Spencer Klein, LBNL

Presented at the CORE Workshop

March 29-30, 2021

- 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

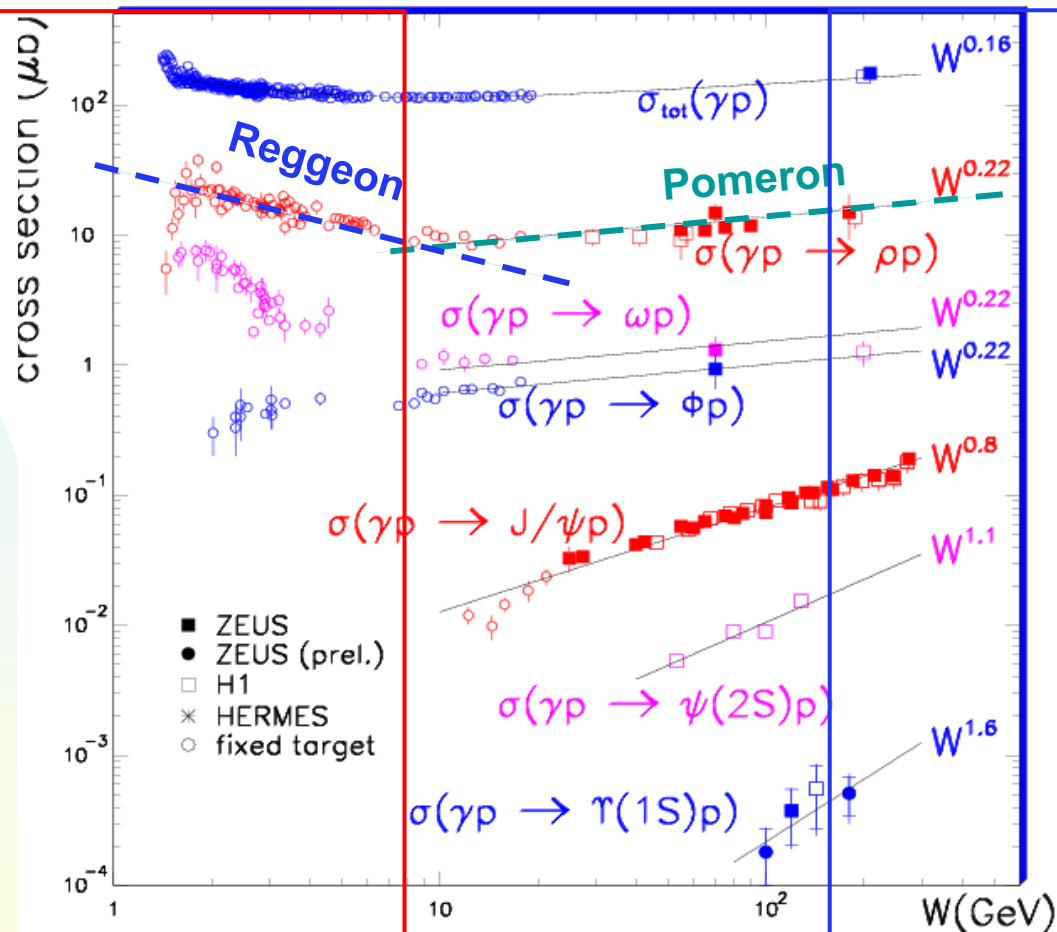*Work done in collaboration with Aaron Stanek & Sam Heppelman

**Electron Ion Collider:
The Next QCD Frontier**

Understanding the glue
that binds us all
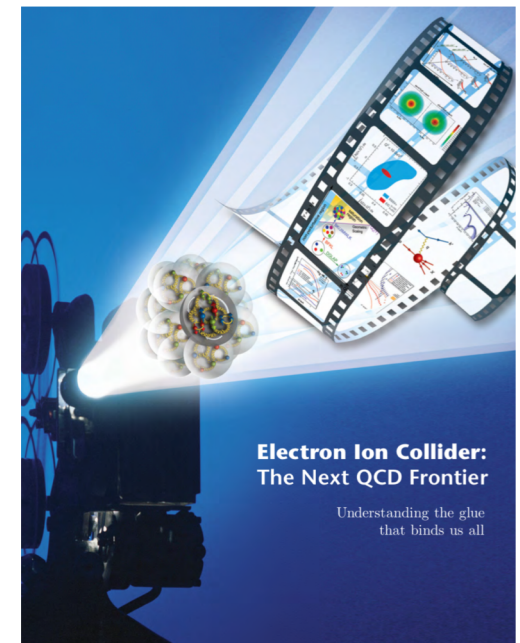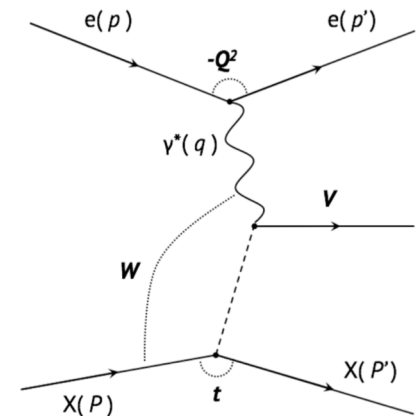
Photoproduction and Electroproduction

- 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.
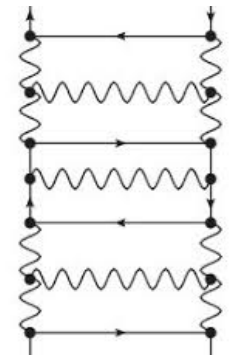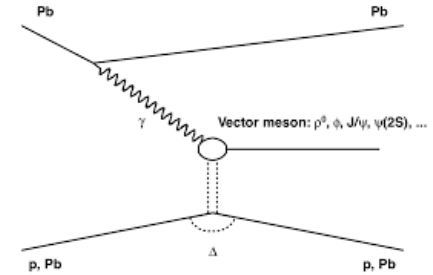
Pomerons, Reggeons and kinematics

HERA + fixed target data

Reggeon

Pomeron

$\sigma_{tot}(\gamma p)$ — $W^{0.16}$

$\sigma(\gamma p \rightarrow \rho p)$ — $W^{0.22}$

$\sigma(\gamma p \rightarrow \omega p)$ — $W^{0.22}$

$\sigma(\gamma p \rightarrow \phi p)$ — $W^{0.22}$

$\sigma(\gamma p \rightarrow J/\psi p)$ — $W^{0.8}$

$\sigma(\gamma p \rightarrow \psi(2S)p)$ — $W^{1.1}$

$\sigma(\gamma p \rightarrow \Upsilon(1S)p)$ — $W^{1.6}$

cross section (μb)

W(GeV)

- ■ ZEUS
- ● ZEUS (prel.)
- □ H1
- ✳ HERMES
- ○ fixed target

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

3

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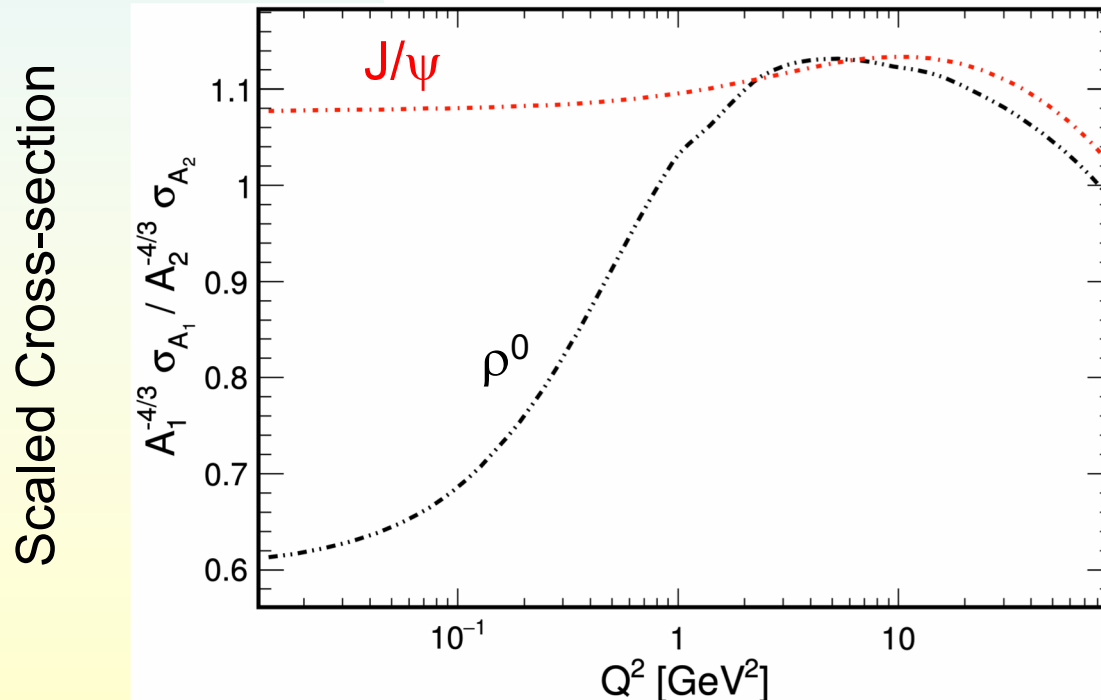
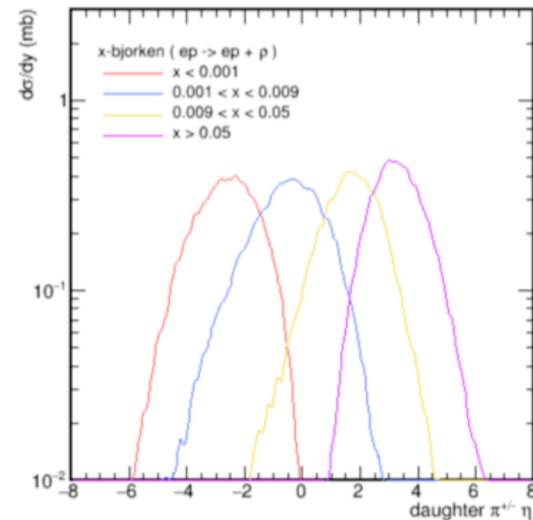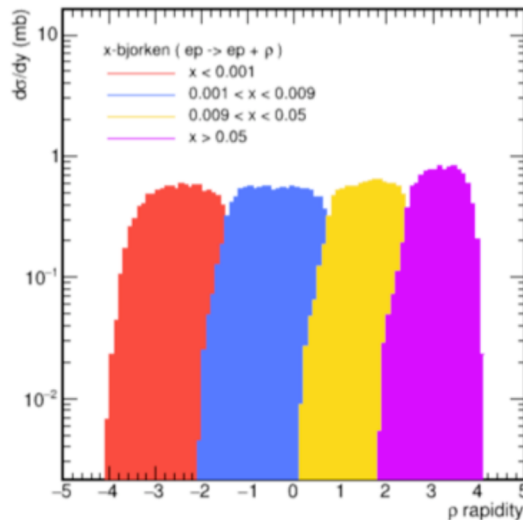From eSTARlight. Similar plot by Mantyssari and Venugopalan, Phys. Lett. B **781**, 664 (2018)

The ρ^0

- $10^{-4} < x < 1$ corresponds to $-4 < y < 4$
- Coverage up to rapidity $|y|$ requires coverage to $|\eta| > |y|+1$
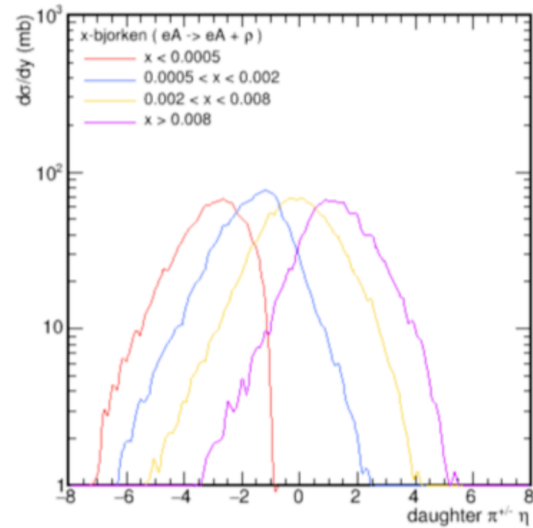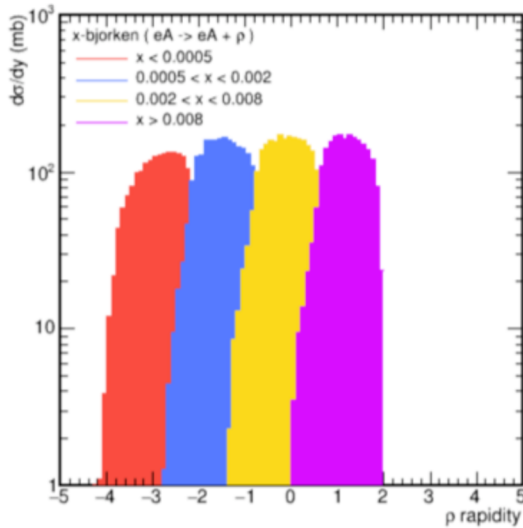
eAu
18 GeV * 100 GeV

ep
18 GeV * 275 GeV

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

5

The ϕ

- Φ->K⁺K⁻ is the only viable decay mode
  - Kaon momentum is 135 MeV/c in ϕ frame
    - Relationship between kaon $<\eta>$ and ϕ $<y>$ 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
- J/ψ & heavier mesons well handled by reference detector
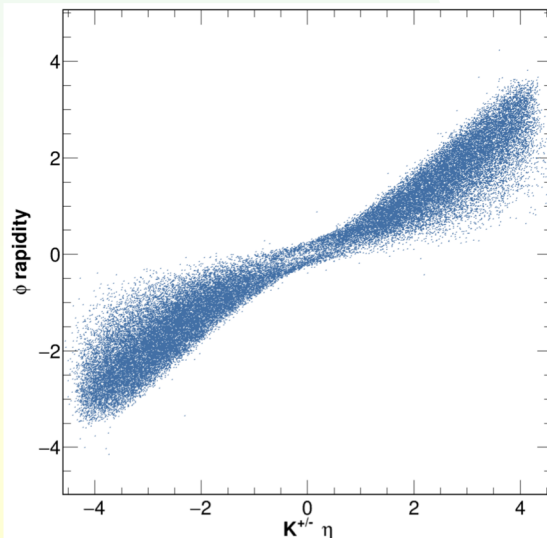
ϕ Rapidity vs. kaon pseudorapidity

$ep \rightarrow ep + \phi$
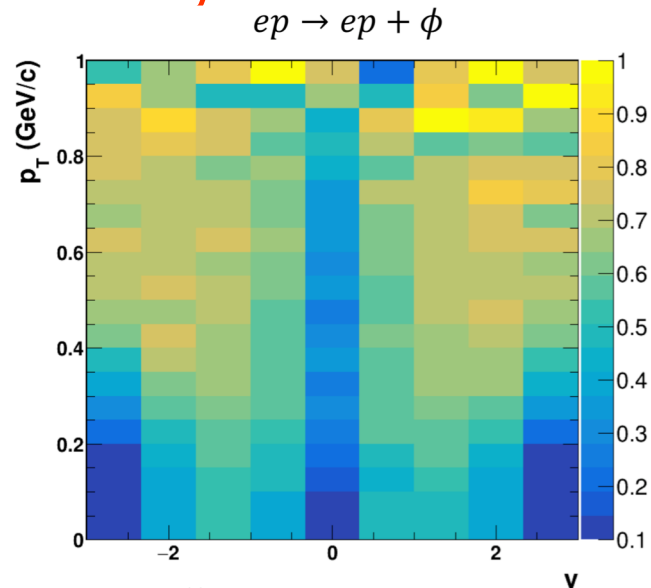
ϕ detection efficiency in an all-silicon tracker

6

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 some excitations 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
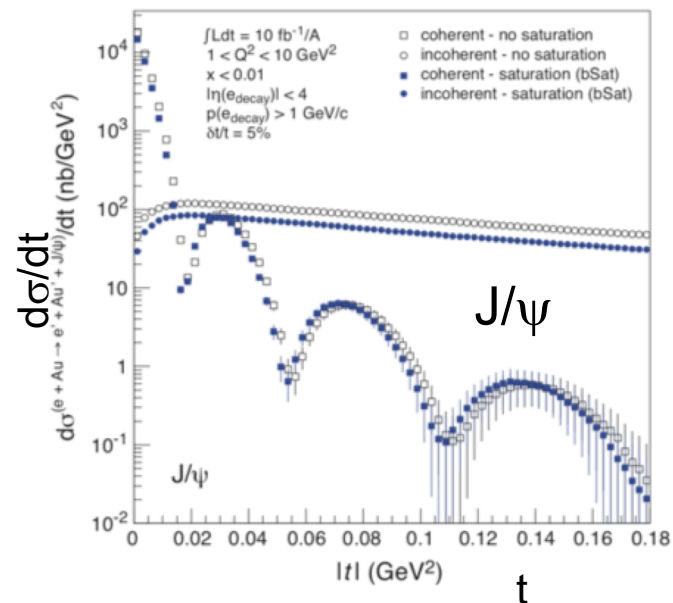
Observing diffractive dips

- dσ/dt for coherent photoproduction probes the transverse gluon distribution in nuclei – like GPDs, but for nuclei.

- Requires good measurement of t ~ $p_{T,Pomeron}^2$

- $P_{T,VM} = P_{T,Pomeron} \oplus P_{T,photon} \oplus$ 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

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

STAR, Phys. Rev. **C96**, 054904 (2017) [8]
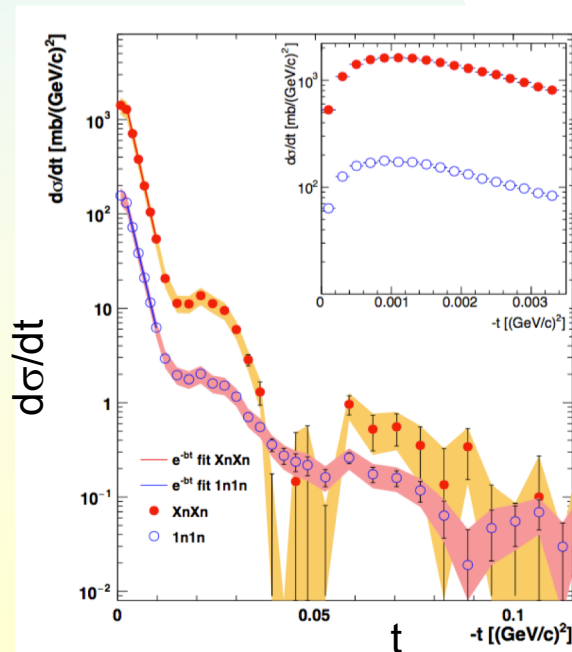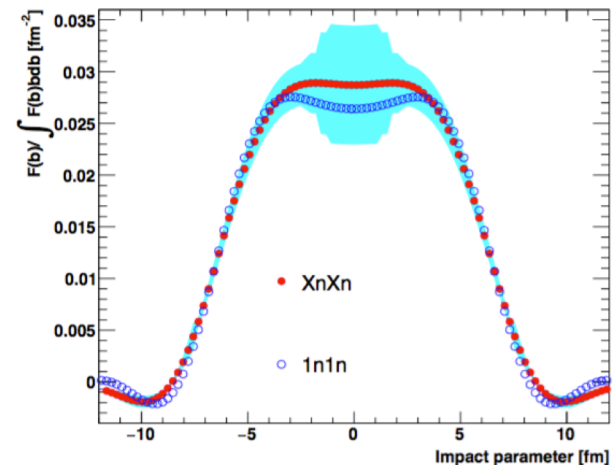
Reggeon exchange and forward production

➢ Examples: the a_2^+(1320) standard candle and the exotic Z_c^+(4430)

➢ Use data/calculations of $\sigma(\gamma p \rightarrow X+n)$ 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)

$\gamma p \rightarrow a_2(1320)^+ n$
Reggeon inspired fit

$\gamma p \rightarrow Z_C(4430)^+ n$
Fit to theory curve
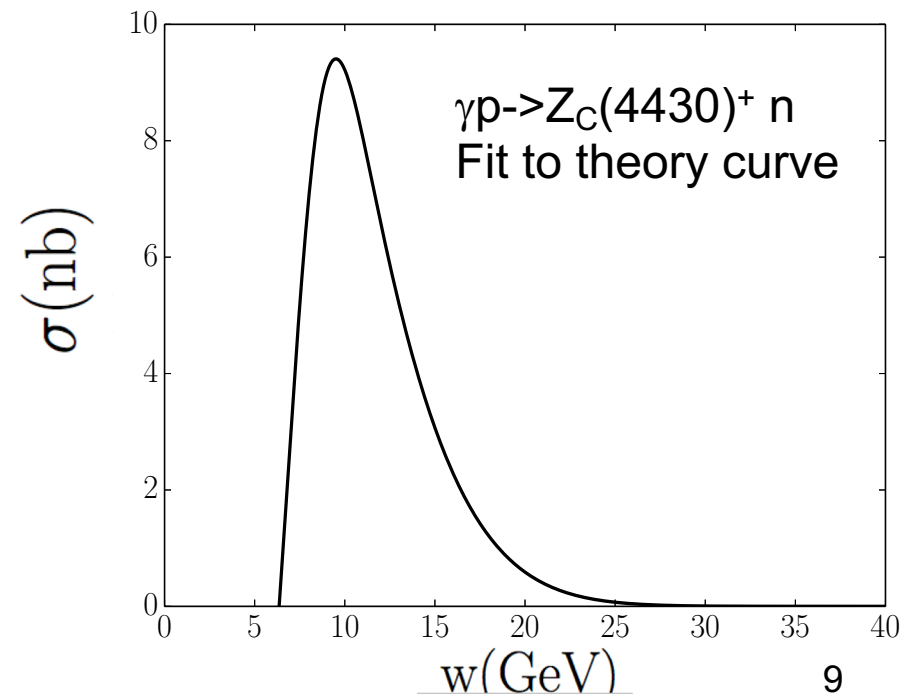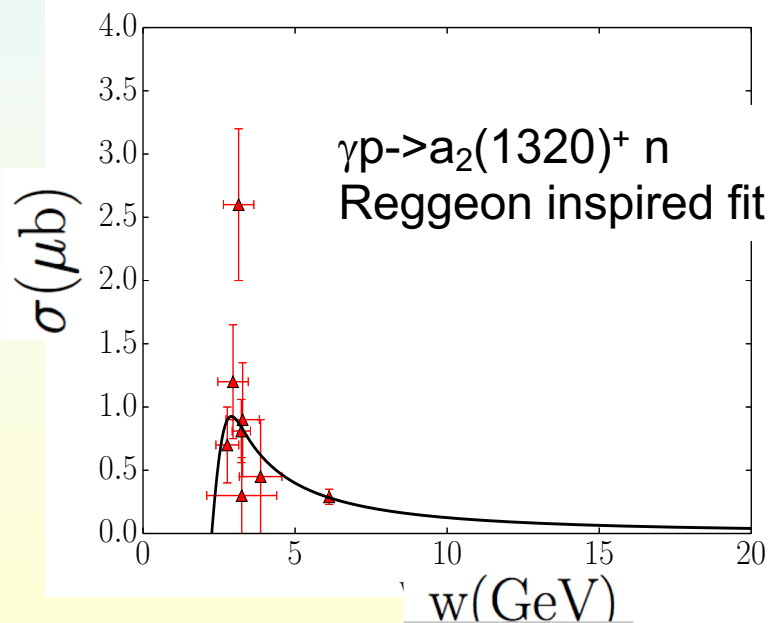
$a_2^+(1320)$ and $Z_c^+(4430)$ production in ep collisions at the EICs

- 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)
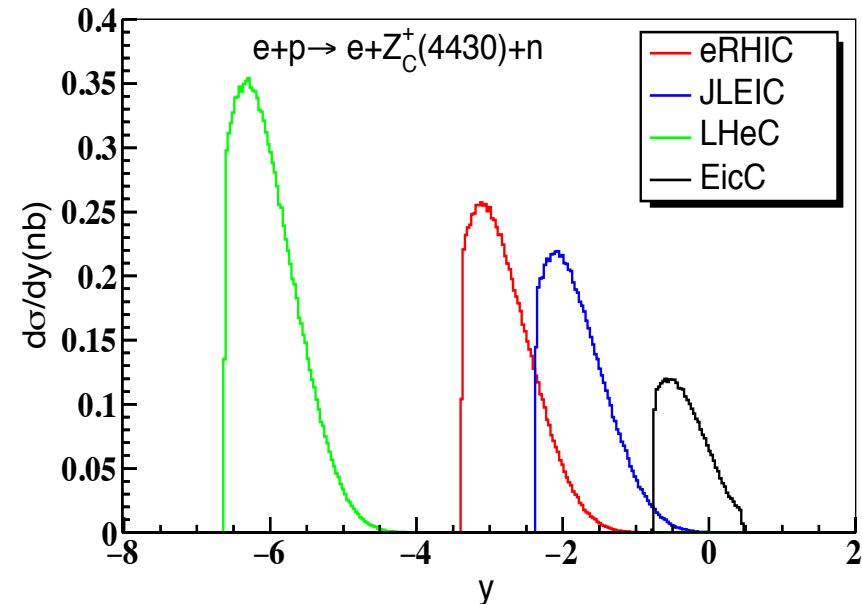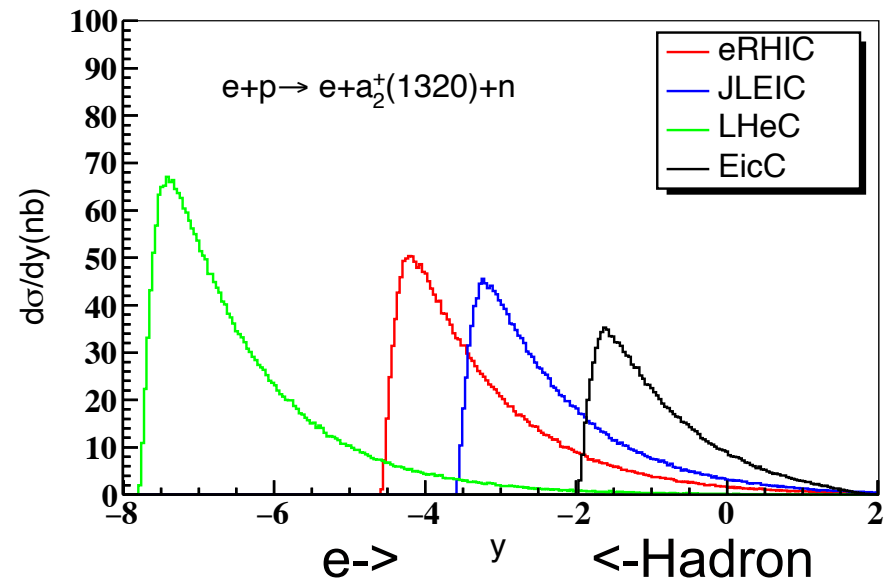
Backward meson production

- Data from fixed-target experiments (including JLab), show that photoproduction can also occur in the backward production
  - Model via a baryon exchange trajectory
- Normally, photoproduction is maximal when t (momentum transfer from target) is small
  - $d\sigma/dt \sim \exp(-Bt)$
    - B~ hbar/target size
- In baryon exchange, in the CM frame, the meson scatters backward 180 degrees causing the baryon to recoil
  - In CM frame, baryon and photon/meson trade momentum
  - Mandelstam u is small, but t is large ($t>Q^2$)
- How does an intact baryon recoil at high energies? Similar to baryon stopping in RHI collisions
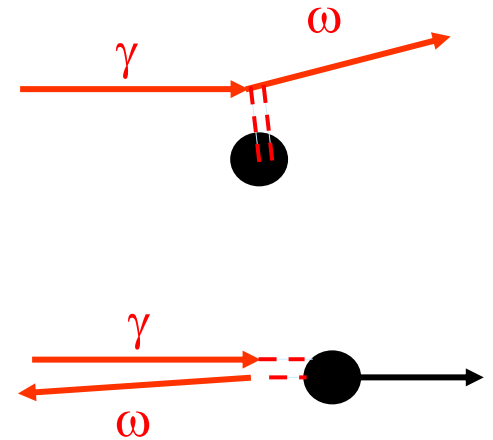
γp -> ωp+ ρp

■ Electroproduction data from Clas 6 at Jlab

■ Forward & backward interactions are soft; intermediate is hard

$\gamma^* + p \rightarrow p + \omega$, W=2.47 GeV, Q^2 = 2.35 GeV^2

σ_u vs -u

CLAS 6 data

Large Angle Emission

Forward Angle Physics (low -t)

Backward Angle Physics (low -u)

- - JML Model
● Morand Data
× Fpi-2 Data (Scaled)

Soft structure -> Hard -> Soft transition

First time in electroproduction
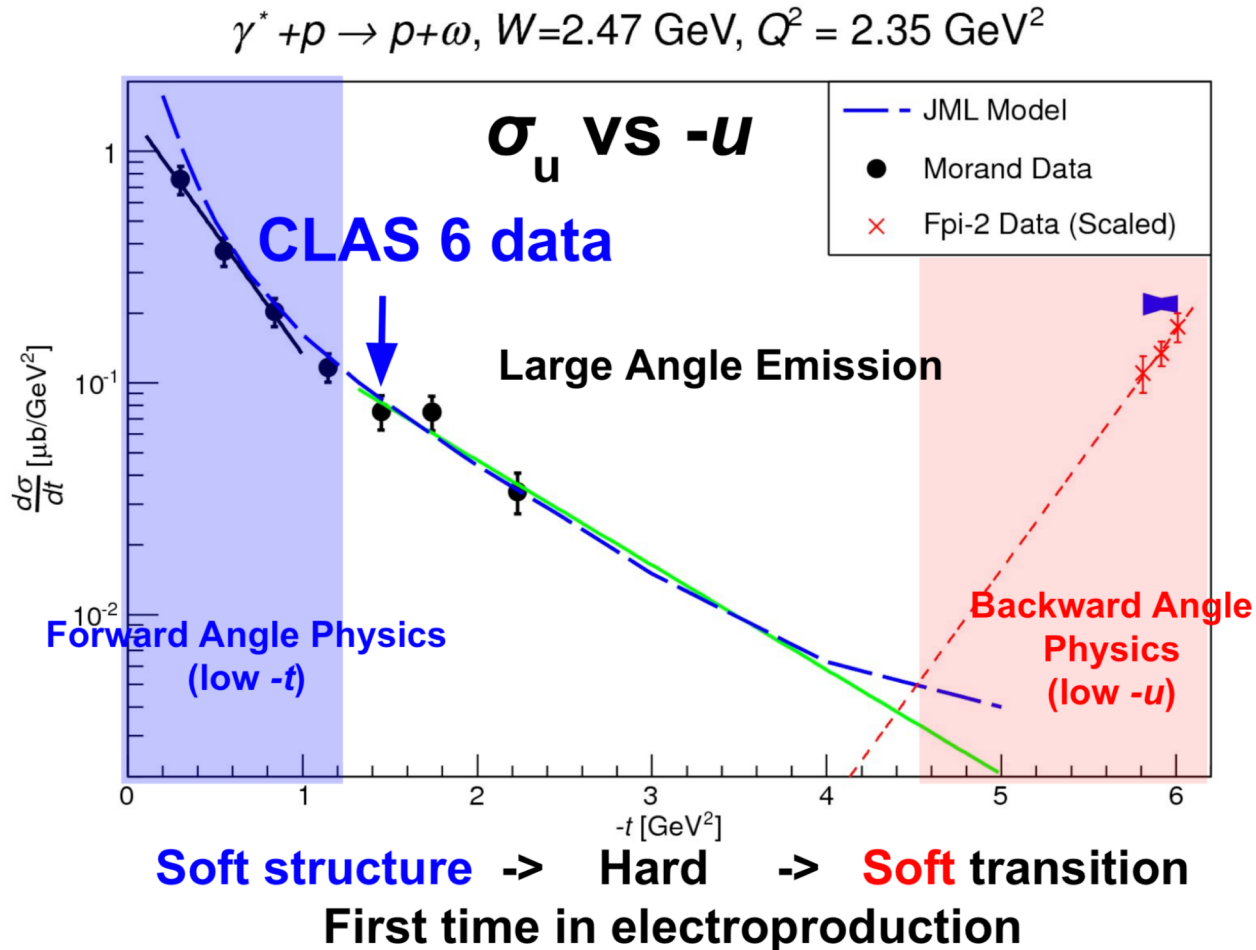
Plot from Bill Li (William & Mary).

12

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

- 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
- $d\sigma/du|_{u\sim0} = A\,(s/1\text{GeV})^B$
  - $A = 4.4\ \mu\text{b/GeV}^2$
    - $A=180\ \mu\text{b/GeV}^2$ 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 $\gamma p \rightarrow \rho p$
- 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.

EIC backward production kinematics

■ An ω at near-beam rapidity, and a mid-rapidity proton

- ◆ The proton is easily detectable
- ◆ The forward vector meson looks tough.
  - ✦ Charged particle tracking problematic (?)
  - ✦ $\omega \to \pi^0 \gamma$ is a promising channel, since it is fully calorimetric

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

Work in progress

Forward ω
Backward ω
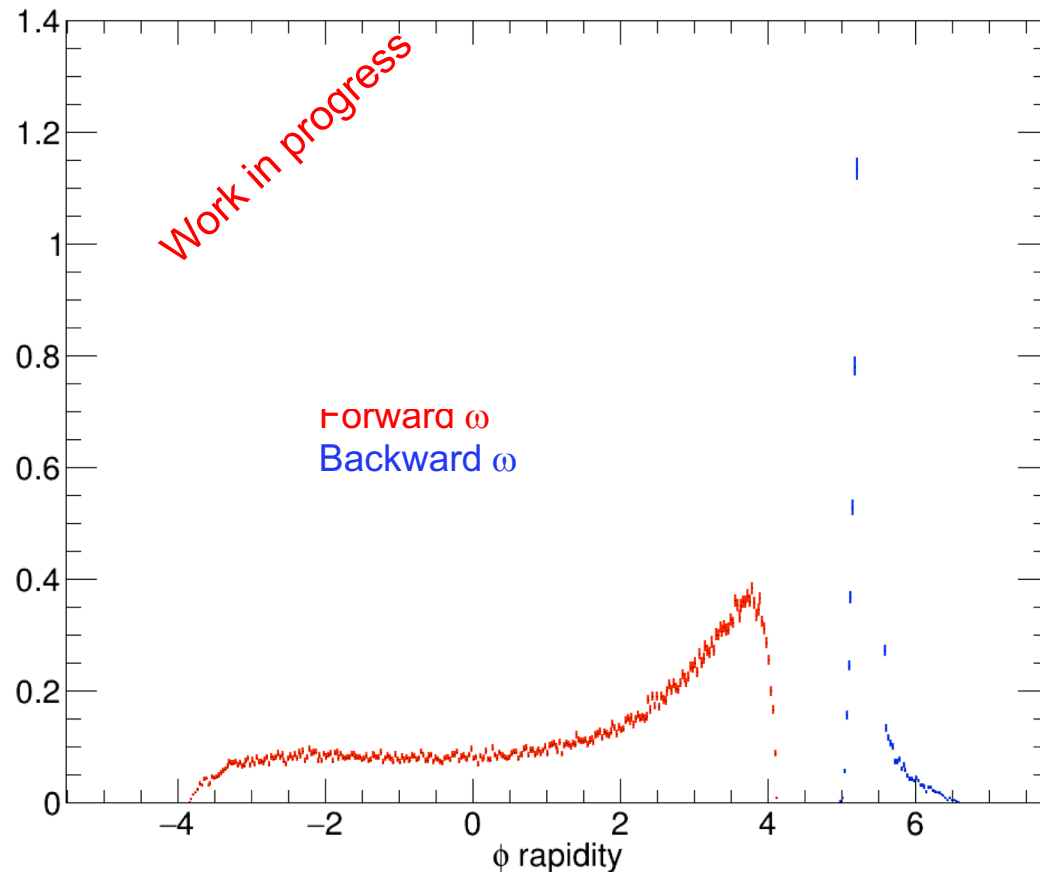
ϕ rapidity

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

Work in progress

Lower E_p
Higher y_{proton}

Higher E_p
Lower y_{proton}
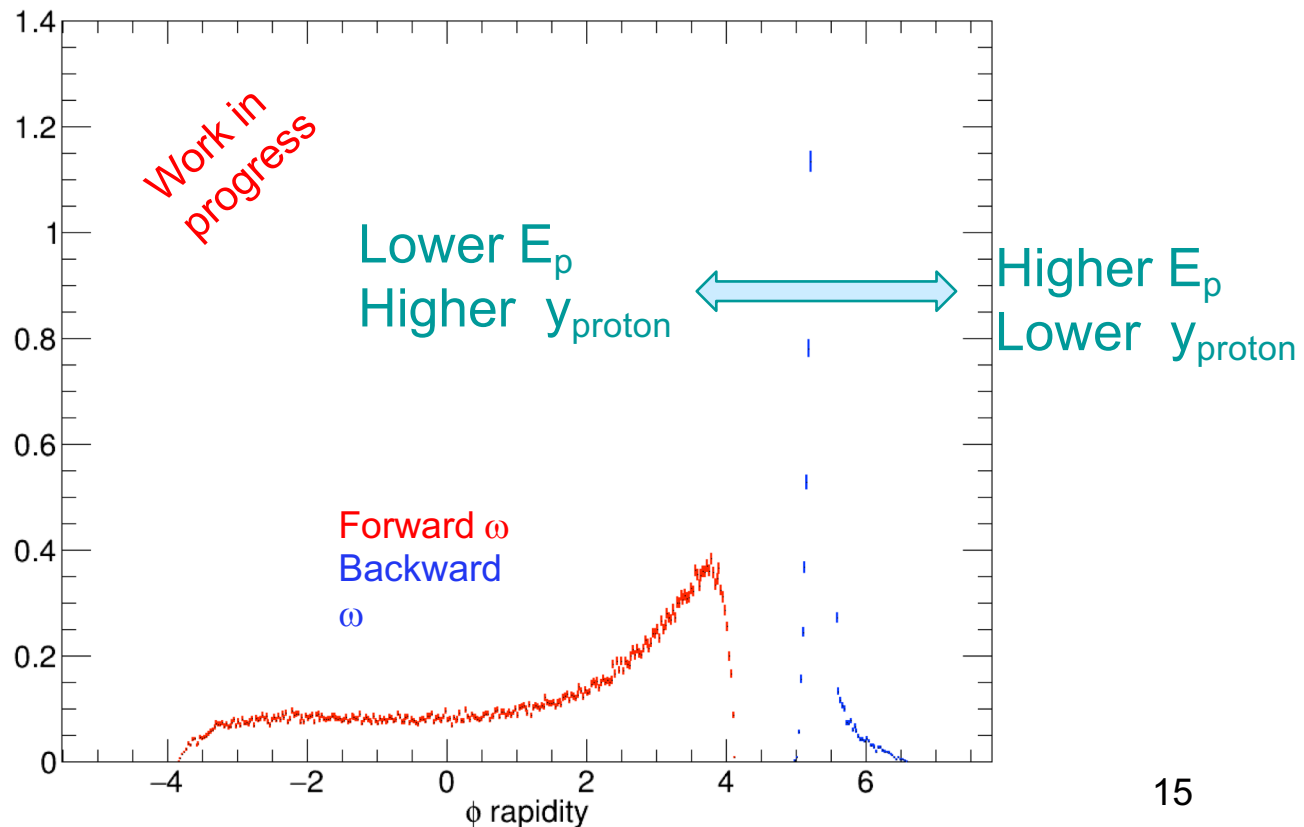
Forward ω
Backward
ω

φ rapidity

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
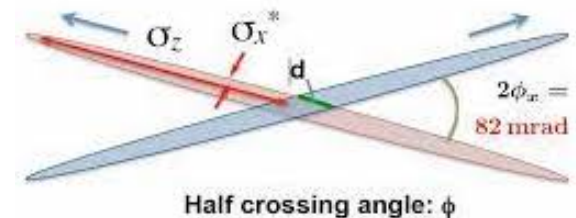
Conclusions

- Vector meson and other exclusive/semi-exclusive production reactions can challenge proposed EIC detector designs.

- Very wide pseudorapidity coverage is required to study vector meson production over the full range of Bjorken-x.

- Near-threshold production and Reggeon-exchange production, (including exotica) requires good acceptance in the ion-going direction.
    - Running at a reduced ion beam energy will shift this production toward mid-rapidity.

- Excellent far-forward ion-going side 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.

Backup

$\pi^+p \rightarrow \pi^+p$ elastic scattering

- 5.9 GeV < E_π < 13.7 GeV
  - ◆ Above the resonance region
- Clear peak near u=0
  - ◆ Elastic scattering in the backward direction
- Diffractive minima visible in u-spectrum
  - ◆ Looks a lot like a form factor

V. Barger and D. Cline, Phys. Rev. Lett. 21, 392 (1968).

19
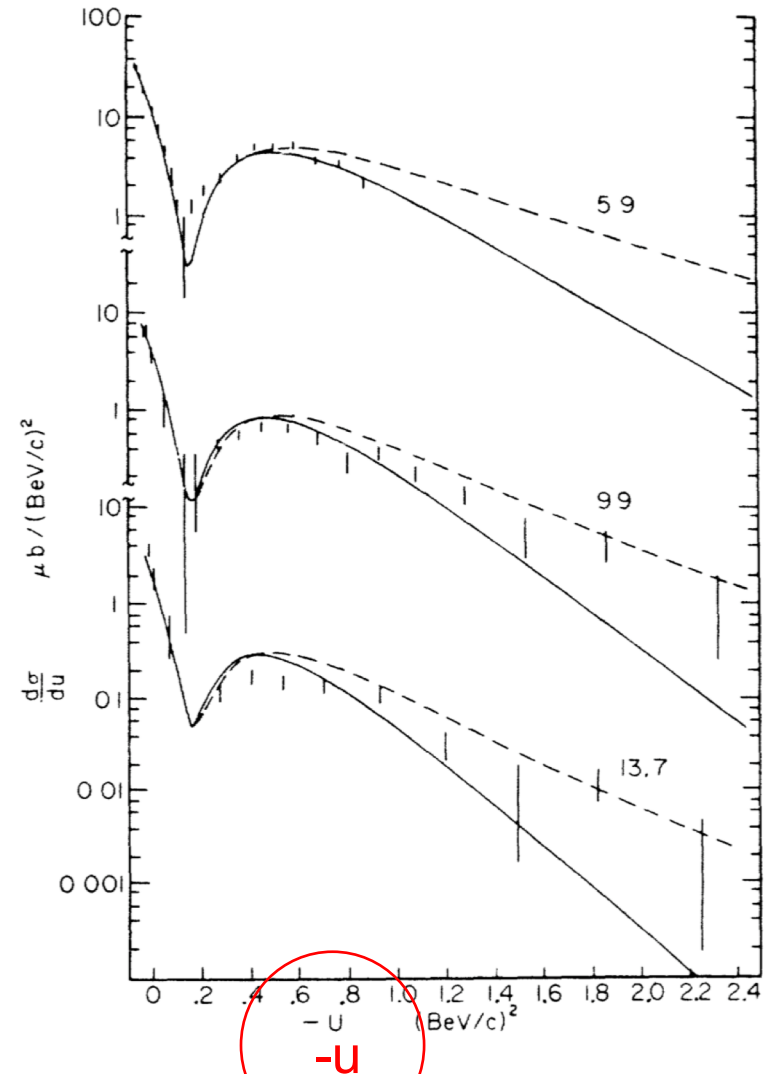
$\gamma p \rightarrow \pi^+ n$

- **Data from multiple experiments**
- **Data exists for 4 GeV < E_γ < 16 GeV**
  - ◆ Again, above the resonance region

M. Guidal et al., Phys. Lett. B400, 6 (1997).
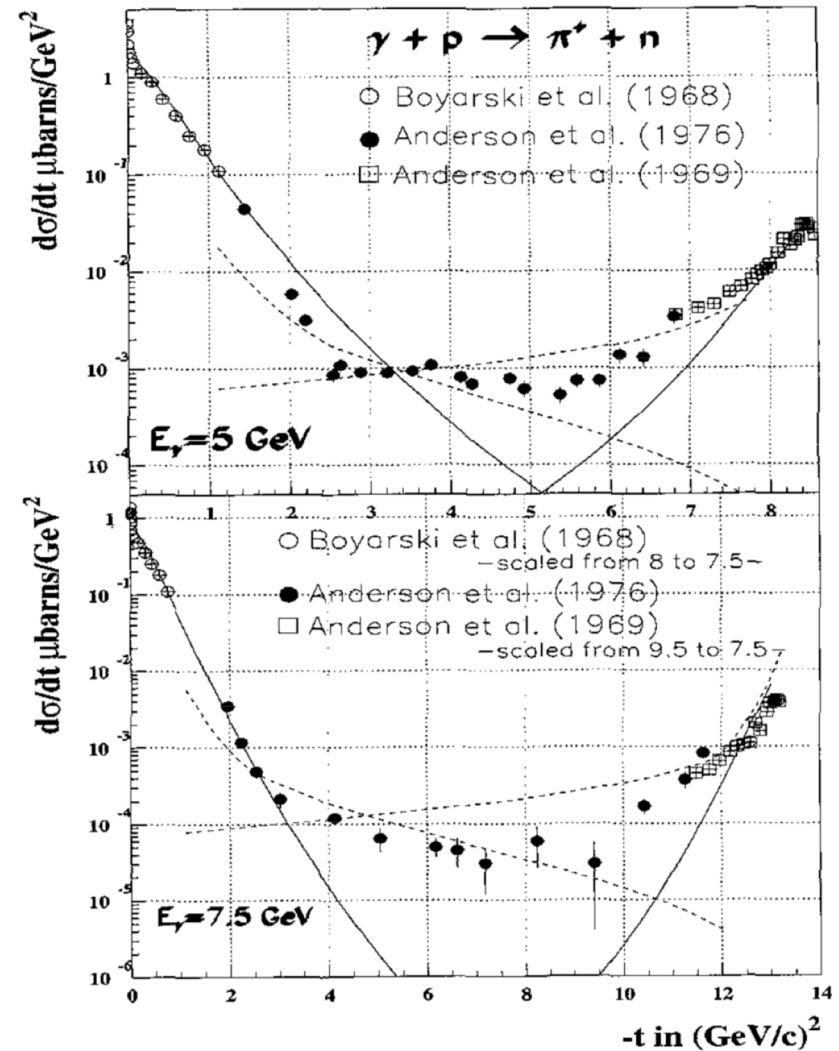
Backward ω data for fit

■ The ω is one of the better studied mesons for backward production. There is more data available than for the ρ.

   ◆ Reasonable lever arm for photon energy.

TABLE I. The compiled data. Errors on original data were around 25% of the listed value. Error due to transcription from figure is estimated to be less than 5%.

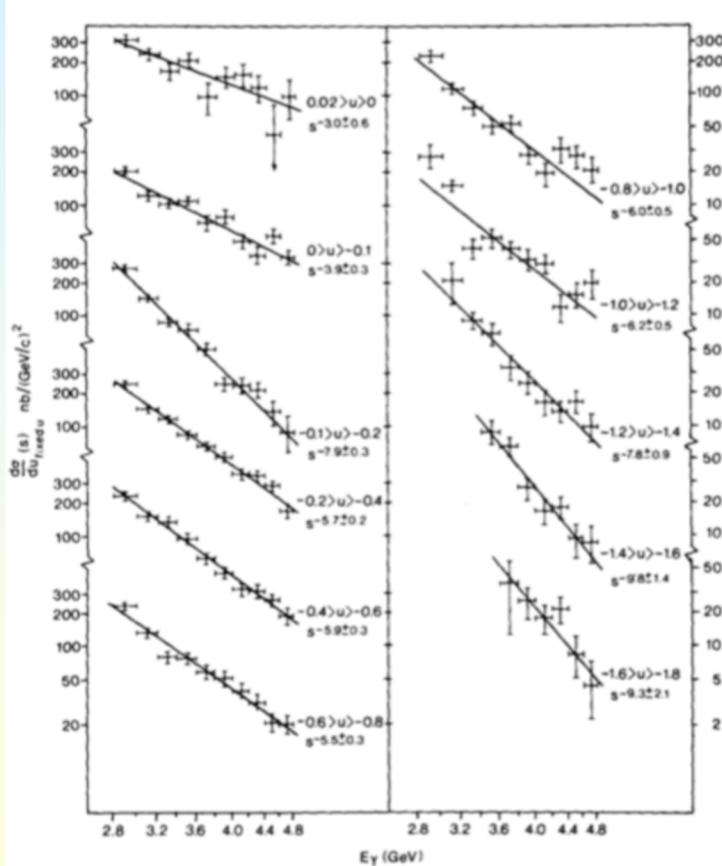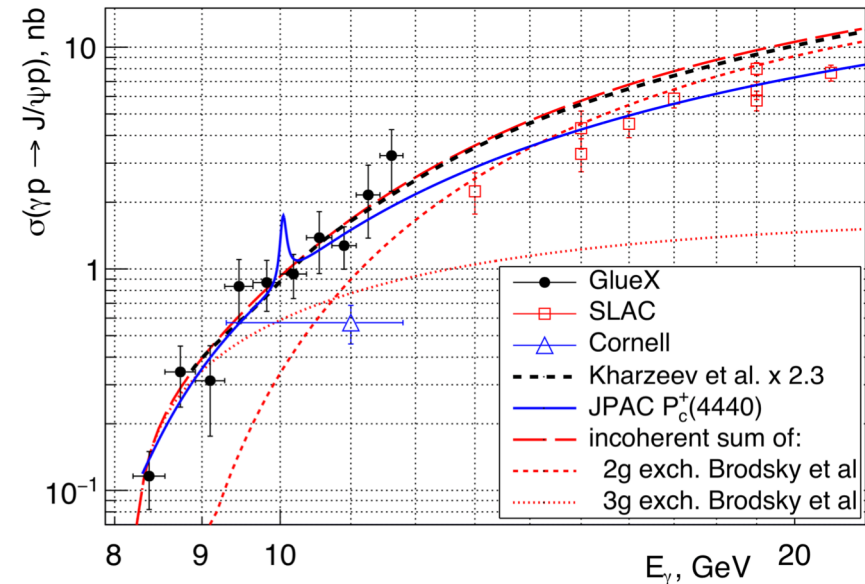| E_γ GeV	$d\sigma/du(u \approx 0)$ nb/GeV^2	Source
2.9	200	Sibirtsev et al.[6] Figure 1
3.0	300	Clifft et al.[4] Figure 3
3.0	200	Sibirtsev et al.[6] Figure 7
3.2	240	Clifft et al.[4] Figure 3
3.3	110	Sibirtsev et al.[6] Figure 7
3.5	170	Clifft et al.[4] Figure 2
3.5	170	Sibirtsev et al.[6] Figure 1
3.5	100	Sibirtsev et al.[6] Figure 7
3.6	210	Clifft et al.[4] Figure 3
3.6	100	Sibirtsev et al.[6] Figure 7
3.8	90	Clifft et al.[4] Figure 3
3.9	60	Sibirtsev et al.[6] Figure 7
4.0	150	Clifft et al.[4] Figure 3
4.1	70	Sibirtsev et al.[6] Figure 7
4.2	160	Clifft et al.[4] Figure 3
4.3	40	Sibirtsev et al.[6] Figure 7
4.4	120	Clifft et al.[4] Figure 3
4.4	30	Sibirtsev et al.[6] Figure 7
4.5	50	Sibirtsev et al.[6] Figure 7
4.6	30	Sibirtsev et al.[6] Figure 7
4.7	75	Clifft et al.[4] Figure 2
4.7	80	Sibirtsev et al.[6] Figure 1
4.8	100	Clifft et al.[4] Figure 3

[4] R. Clifft *et al.*, Physics Letters **72B**, 144 (1977).
[5] B.-G. Yu and K.-J. Kong, Physical Review D **99** (2019).
[6] R. Sibirtsev *et al.*, arXiv:nucl-th/0202083v1 (2002).

21

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
  - $P_C^+(4440) == J/\psi\ p$
    - 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
SLAC
Cornell
Kharzeev et al. x 2.3
JPAC $P_c^+(4440)$
incoherent sum of:
2g exch. Brodsky et al
3g exch. Brodsky et al

$\sigma(\gamma p \rightarrow J/\psi p)$, nb

E_γ, GeV

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

22

Photoproduction & electroproduction in eSTARlight

- Convolution of photon flux from electron with $\sigma(\gamma p \text{->} Vp)$
  - 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

23

Pomerons and Reggeons in photoproduction

- HERA photoproduction cross-sections well fit by
- $\sigma(W) = X W^{\epsilon} + Y W^{-\eta}$
  - ◆ W=γp CM energy
- $X W^{\epsilon}$: Pomeron (gluons)
  - ◆ ϵ ~ > 0.2 – meson dependent
  - ◆ $J^{PC}=0^{++}$
- $Y W^{-\eta}$: 'Reggeon' (~~qqbar)
  - ◆ η~~1.5
  - ◆ Summed light-quark meson trajectories
    - ✦ ~valence quarks
  - ◆ *Zero* for ϕ, J/ψ, etc.
  - ◆ Range of spin/parity
- Q^2 dependence – power law

Photoproduction data

24
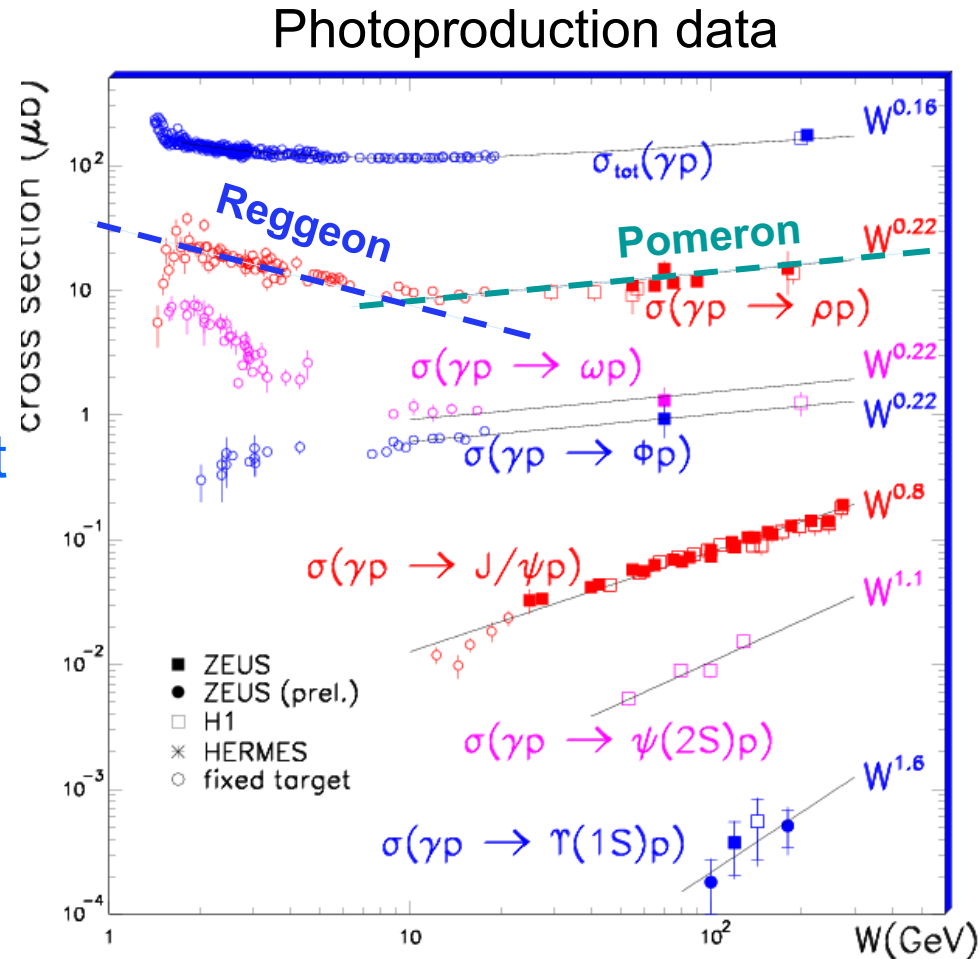
EIC photoproduction kinematics

- Maps photon energy onto rapidity

- $k = \dfrac{M}{2}\exp(y)$

- y=ln(2k/M)

- Reggeon activity strongest at low photon energies

  - ◆ Requires good acceptance in the hadron-going direction

- Highest photon energies correspond to electron-going direction

  - ◆ Need good e-going acceptance

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

e->   <-Hadron
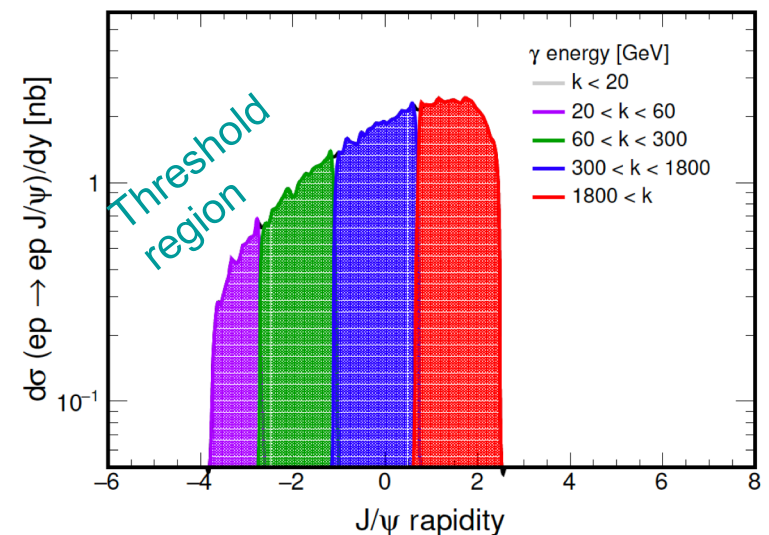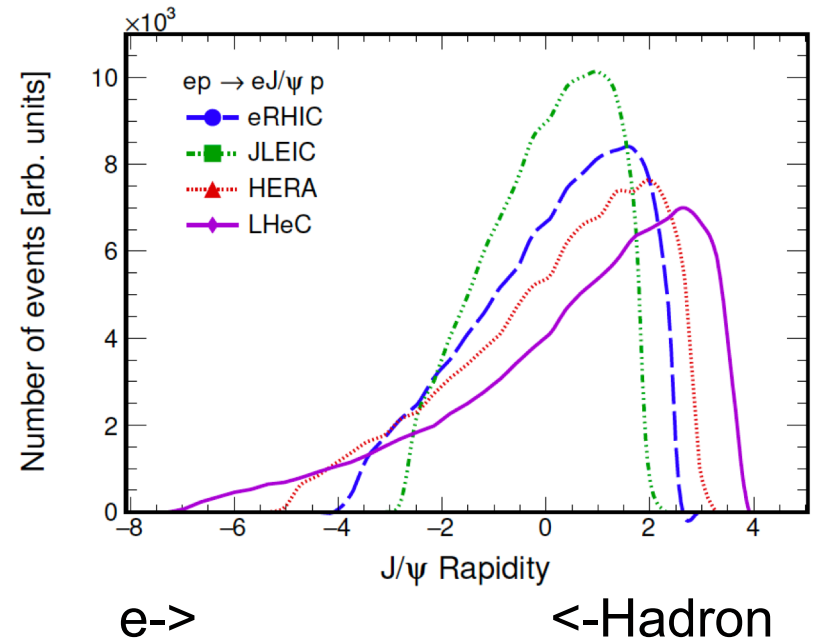
# Ψ(2S) & Υ photoproduction at eRHIC

- **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, $\mu\mu$

- **σ(Υ(1S))=0.01σ(ψ')**
  - ◆ 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'

From eSTARlight

All k

k<50 GeV

e->   <-Hadron

26
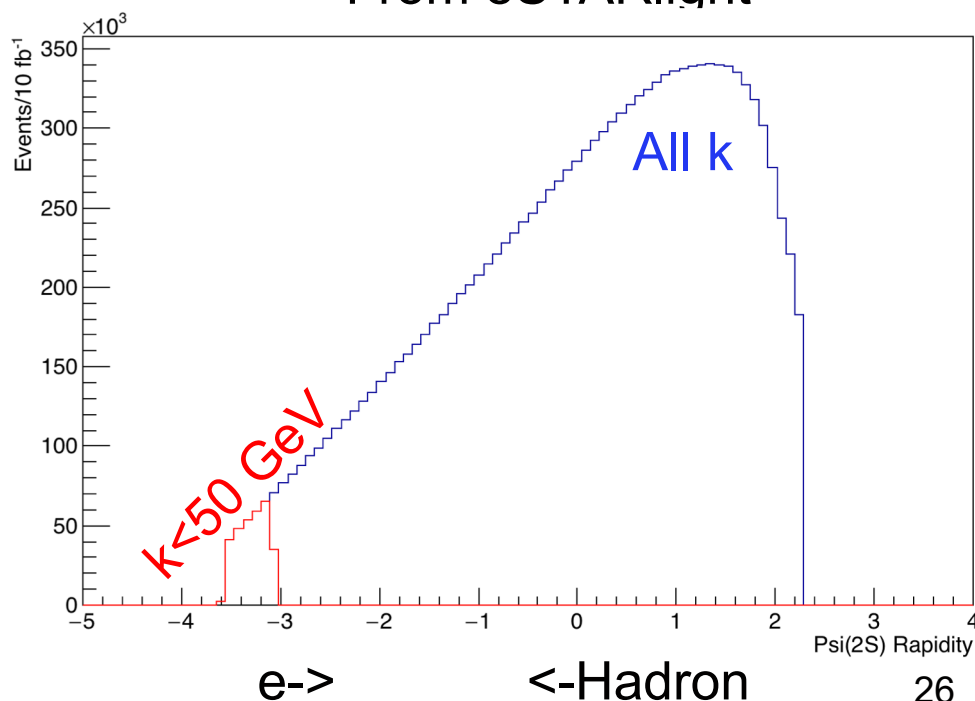
$\Psi(2S)$->ee lepton pseudorapidities

- Lepton pseudorapidity depends on $\Upsilon(2S)$ rapidity, p_T and polarization (which depends on Q^2)

- Leptons from most near-threshold (k<50 GeV target frame) $\psi(2S)$->ll decays have -5<y<-2
  - ◆ Good acceptance required in hadron-going direction
  - ◆ N.b. Br($\psi(s)$->ee or $\mu\mu$ is 0.7%. Plus J/$\psi\pi^+\pi^-$

- Rates for $\Upsilon(1S)$ smaller - usable.

- Higher ψ states accessible

e->   <-Hadron
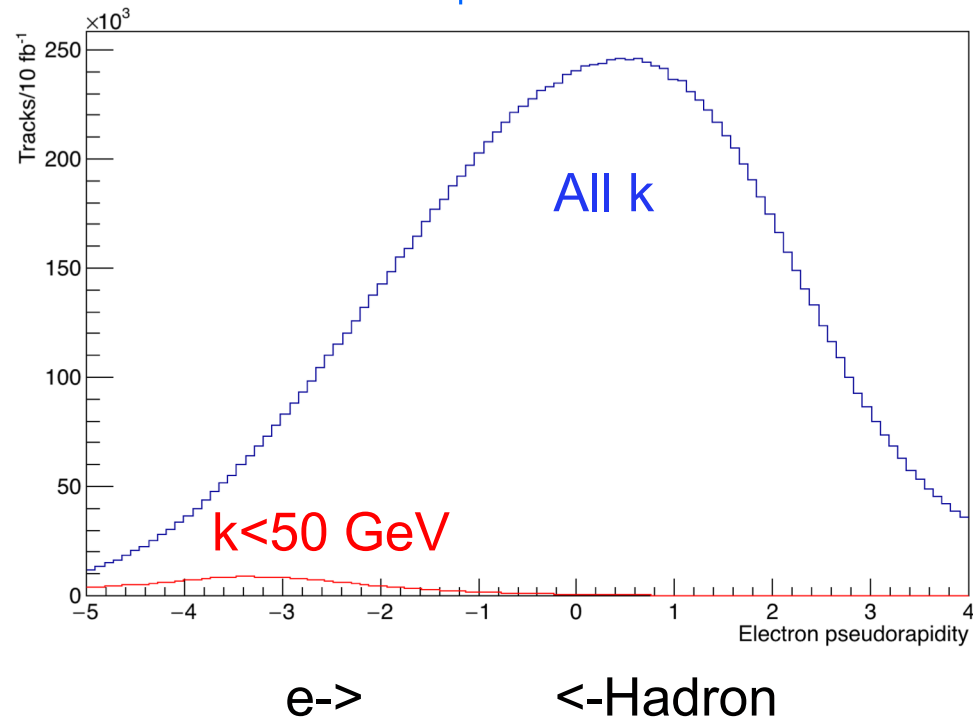
Expected event rate for vector mesons, $a_2^+(1320)$ and Z_C^+

■ Total cross sections and expected events for vector mesons and two charged particles in ep collisions

◆ 10 fb^{-1} integrated luminosity

	Events ($0 < Q^2 < 1.0 \text{GeV}^2$)				Events ($Q^2 > 1.0 \text{GeV}^2$)			
	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 ($0 < Q^2 < 1.0 \text{GeV}^2$)				Events ($1.0 \text{GeV}^2 < Q^2 < 5.0 \text{GeV}^2$)			
	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)
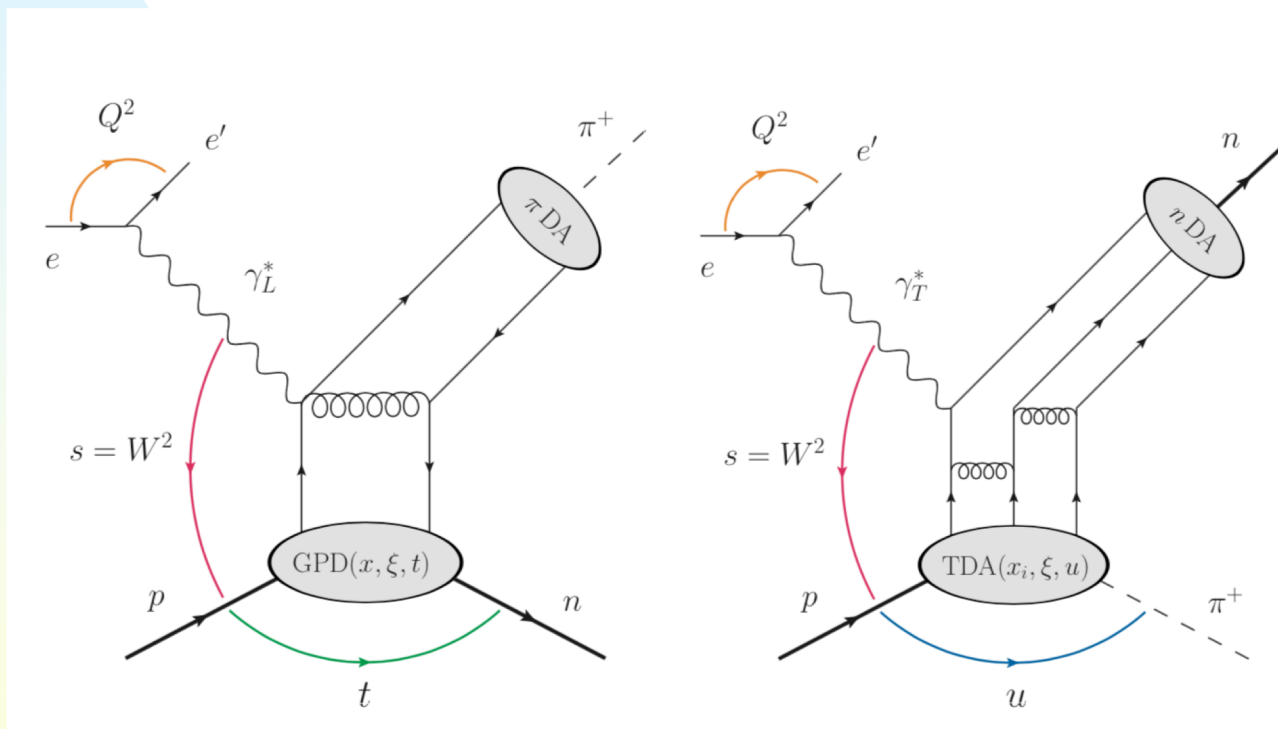
Theoretical approach II – Baryon trajectories

- 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,
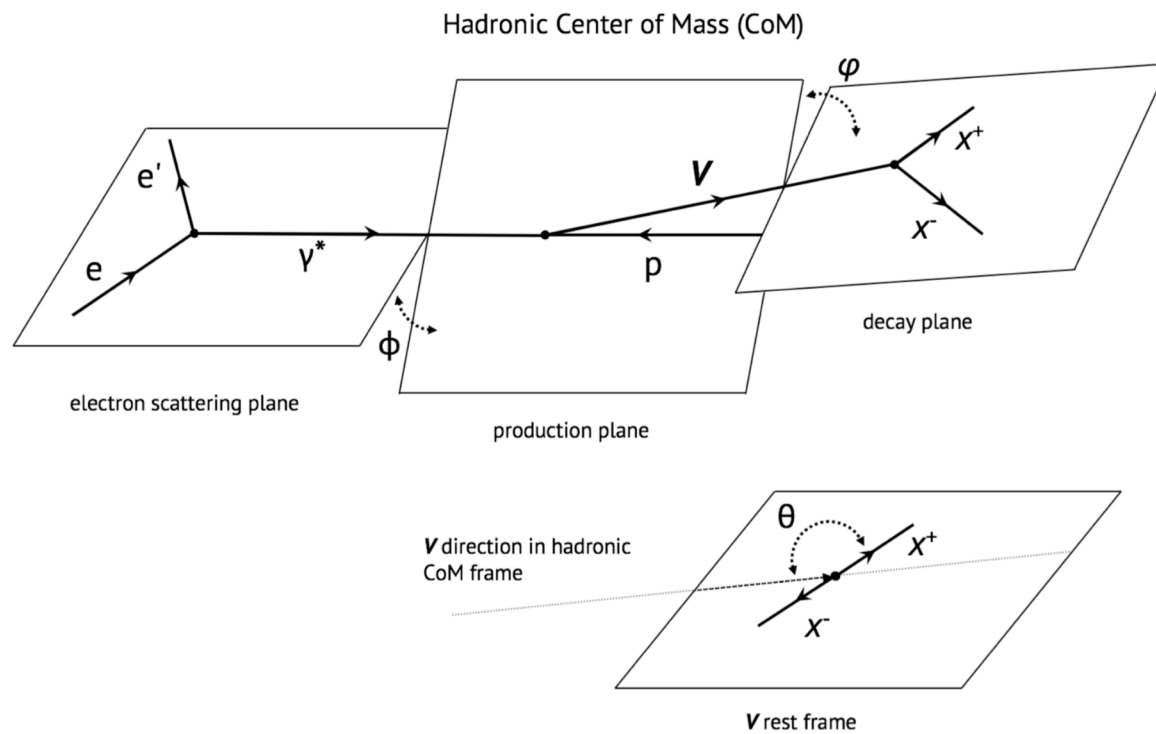 - ◆ Λ/Σ for strangeness (not today)
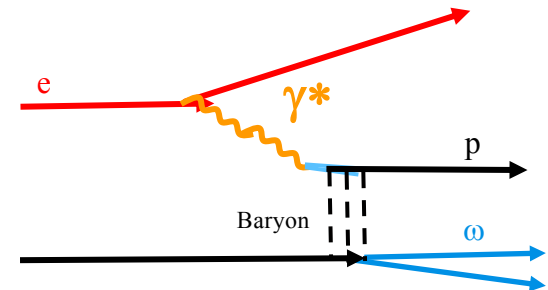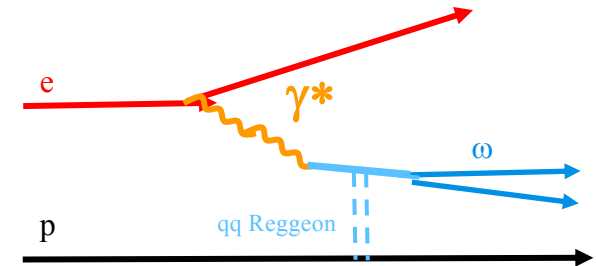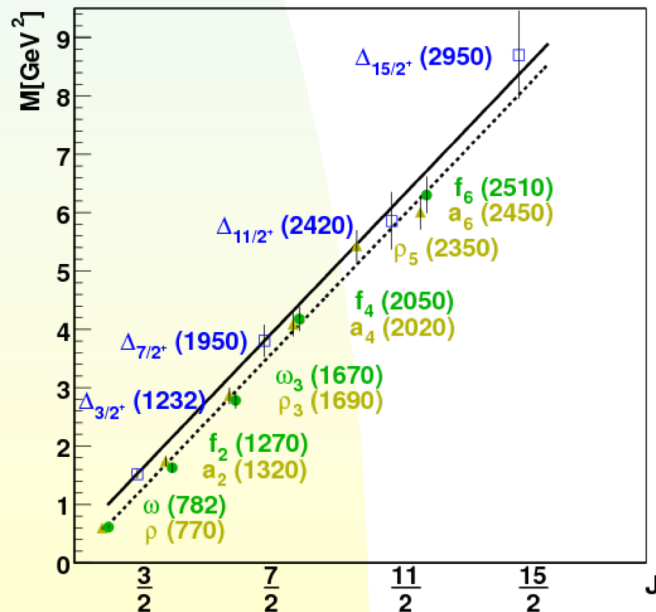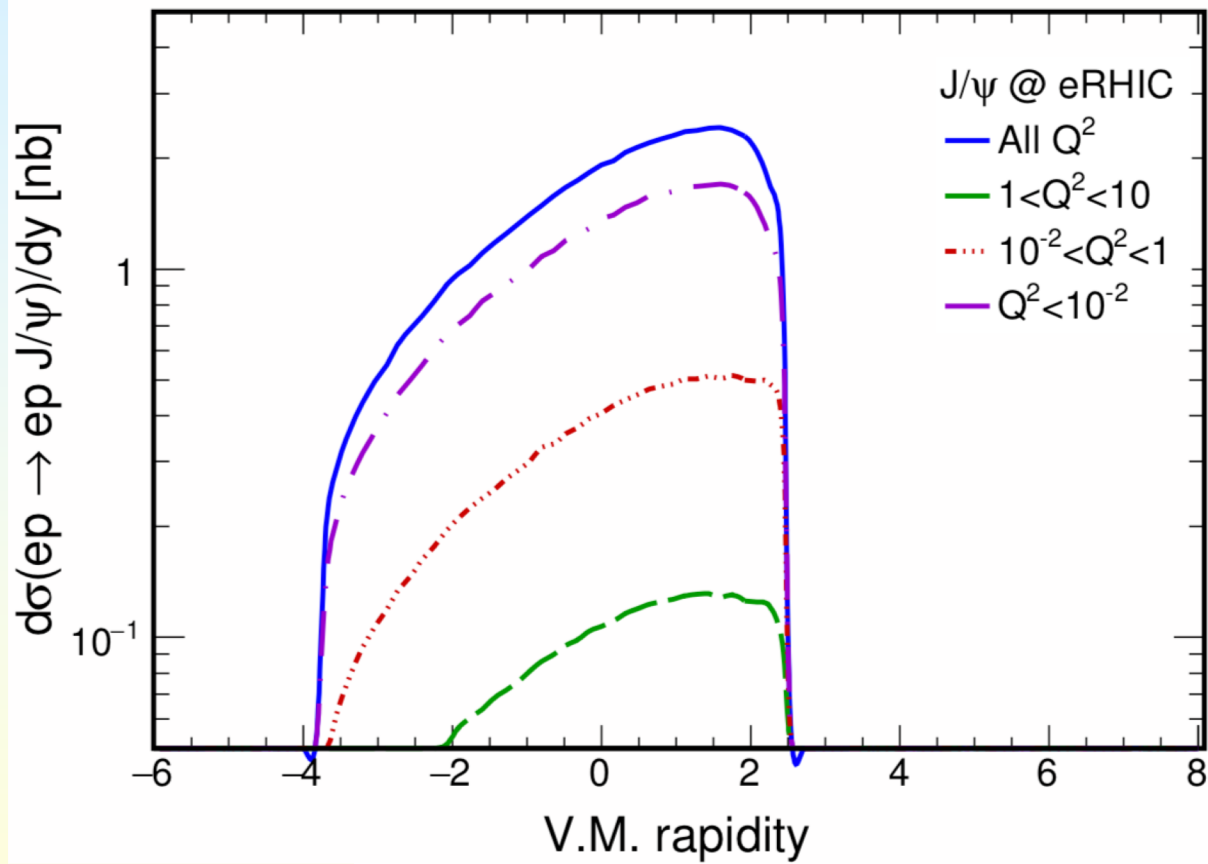
Implications for baryon stopping

- 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)

Backup

Angular definitions

Rapidity vs. Q^2

γp->ωp data

TABLE I. The compiled data. Errors on original data were around 25% of the listed value. Error due to transcription from figure is estimated to be less than 5%.

E_γ GeV	$d\sigma/du(u \approx 0)$ nb/GeV^2	Source
2.9	200	Sibirtsev et al.[6] Figure 1
3.0	300	Clifft et al.[4] Figure 3
3.0	200	Sibirtsev et al.[6] Figure 7
3.2	240	Clifft et al.[4] Figure 3
3.3	110	Sibirtsev et al.[6] Figure 7
3.5	170	Clifft et al.[4] Figure 2
3.5	170	Sibirtsev et al.[6] Figure 1
3.5	100	Sibirtsev et al.[6] Figure 7
3.6	210	Clifft et al.[4] Figure 3
3.6	100	Sibirtsev et al.[6] Figure 7
3.8	90	Clifft et al.[4] Figure 3
3.9	60	Sibirtsev et al.[6] Figure 7
4.0	150	Clifft et al.[4] Figure 3
4.1	70	Sibirtsev et al.[6] Figure 7
4.2	160	Clifft et al.[4] Figure 3
4.3	40	Sibirtsev et al.[6] Figure 7
4.4	120	Clifft et al.[4] Figure 3
4.4	30	Sibirtsev et al.[6] Figure 7
4.5	50	Sibirtsev et al.[6] Figure 7
4.6	30	Sibirtsev et al.[6] Figure 7
4.7	75	Clifft et al.[4] Figure 2
4.7	80	Sibirtsev et al.[6] Figure 1
4.8	100	Clifft et al.[4] Figure 3

[4]R. Clifft et al., Physics Letters 72B, 144 (1977).
[5]B.-G. Yu and K.-J. Kong, Physical Review D 99 (2019).
[6]R. Sibirtsev et al., arXiv:nucl-th/0202083v1 (2002).