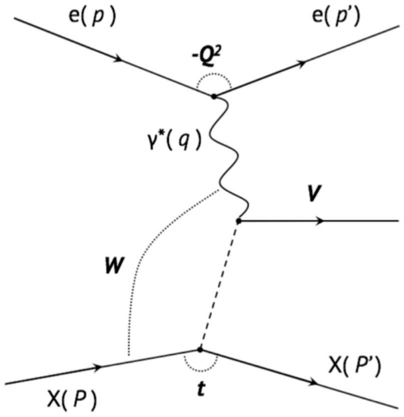
# EIC Physics (mostly eA) that would benefit from lower energies and/or a second detector

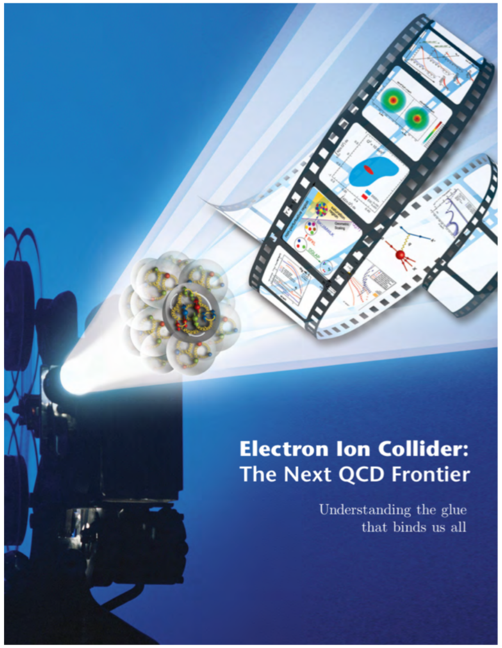
## Spencer Klein, LBNL

**Presented at the IR2@EIC Workshop**
**March 17-19, 2020**



- 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

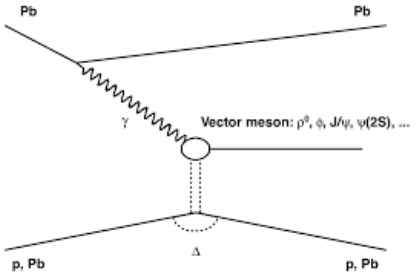
*Work done in collaboration with Aaron Stanek & Sam Heppelman

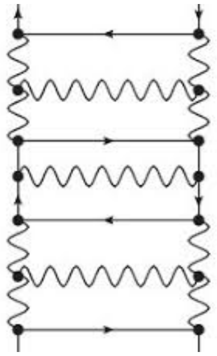

**Electron Ion Collider:**
**The Next QCD Frontier**

Understanding the glue
that binds us all

# Photoproduction and Electroproduction

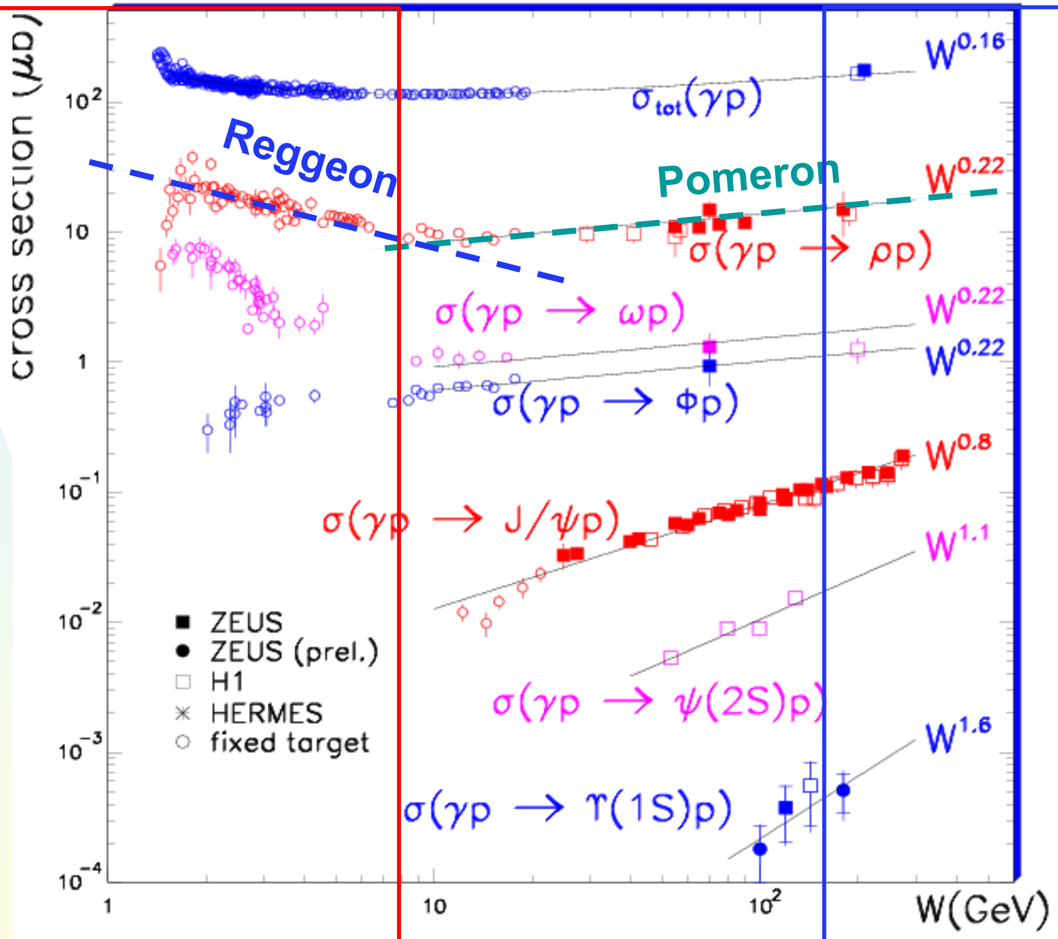
- Two models
- Gluon exchange
  - Lowest order is 2-gluon exchange
  - Higher orders is gluon ladder
- Pomeron + Reggeon exchange
  - Pomeron is gluon ladder
    - $J^{PC}=0^{++}$ explains vector meson dominance
      - Absorptive part of the potential
  - Reggeon involves quark exchange
    - meson 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



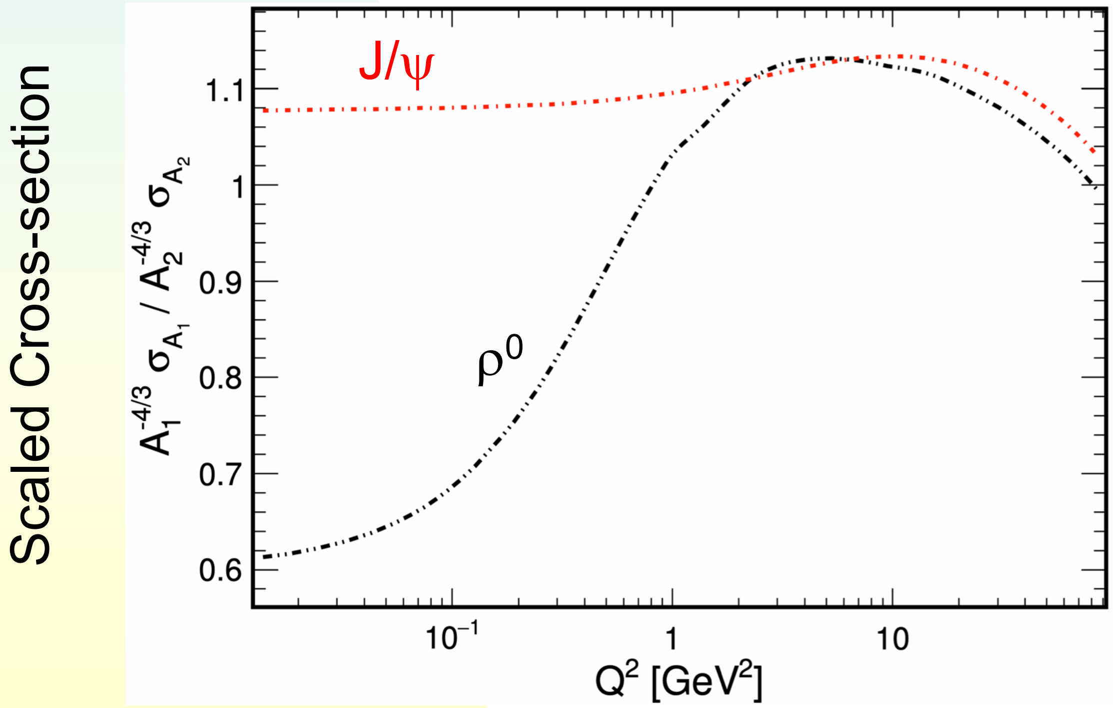
Ion-going direction
Reggeon dominated
Near threshold production
Pentaquarks, other exotica

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

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

# Photoproduction vs. electroprodution

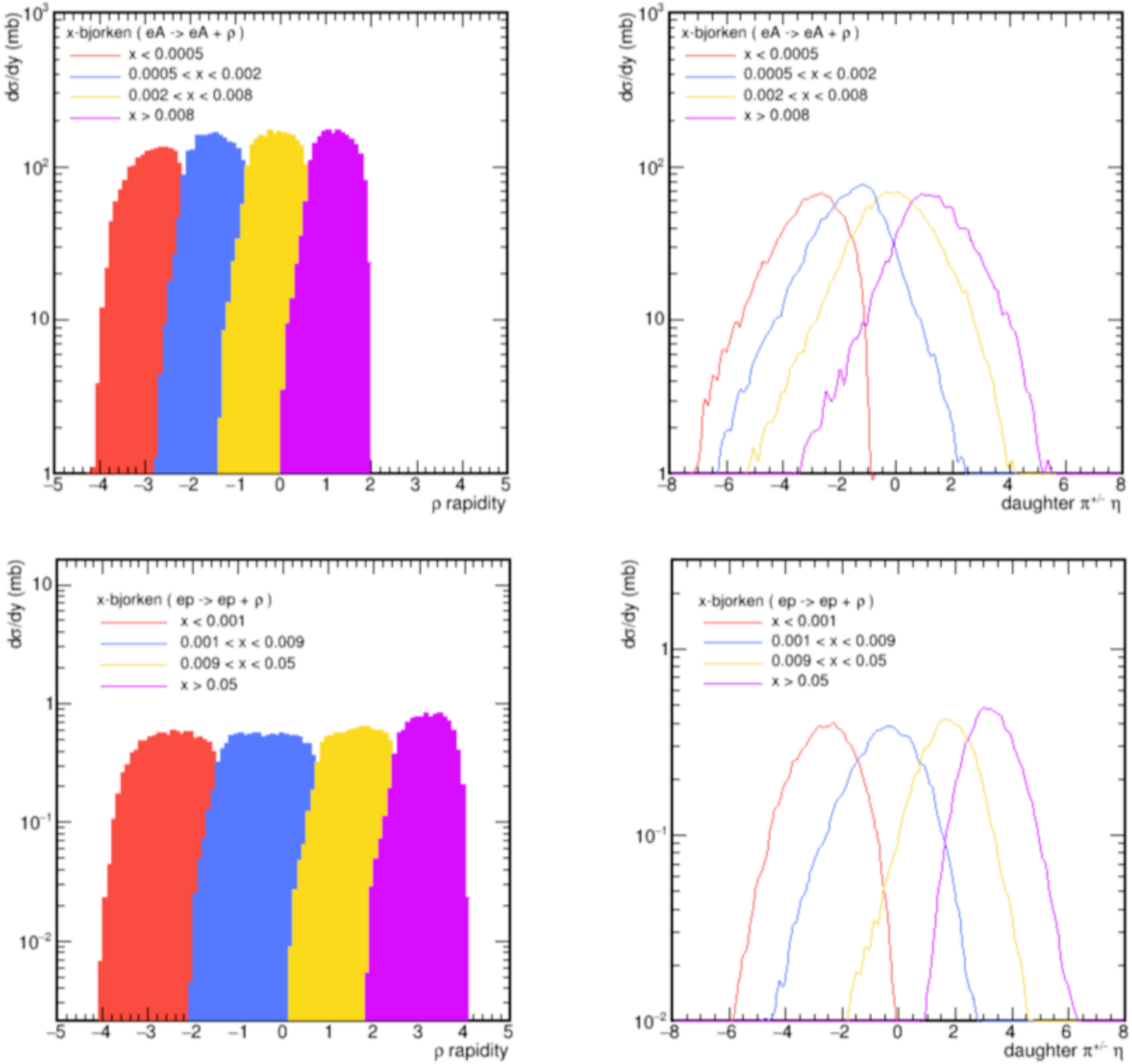
- Most EIC attention is on electroproduction ($Q^2 > 1$ GeV$^2$)
- Photoproduction ($Q^2 < 1$ GeV$^2$) is critical for studying shadowing, which should disappear at large $Q^2$
  - Good acceptance is needed for vector mesons at low $p_T$
- Shadowing is larger for lighter mesons
  - $\rho/\phi$ are experimentally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



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

# The $\rho^0$

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



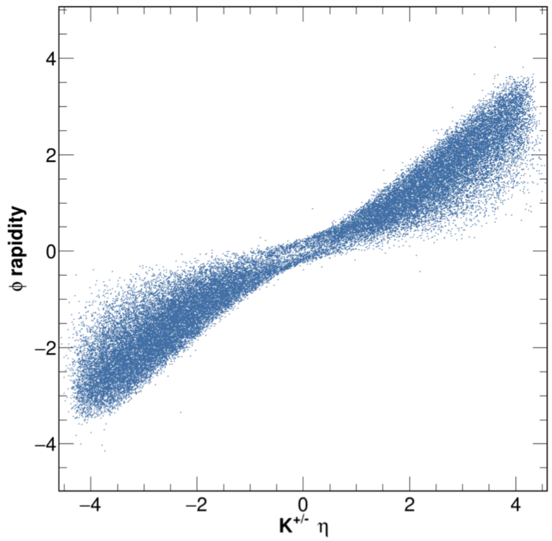
eAu
18 GeV * 100 GeV

ep
18 GeV * 275 GeV

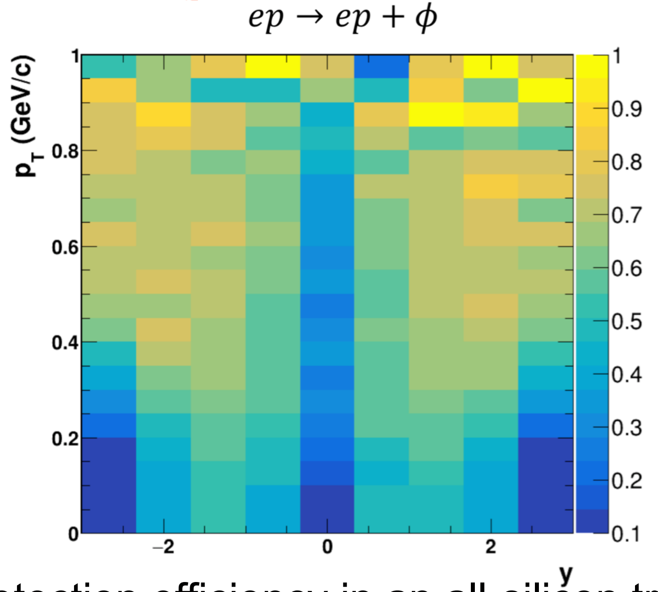
J. Arrington *et al.*,
arXiv:2102.08337

# The $\phi$

- $\Phi \to K^+K^-$ is the only viable decay mode
    - Kaon momentum is 135 MeV/c in $\phi$ frame
        - Relationship between kaon $<\eta>$ and $\phi$ $<y>$ 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/$\psi$ & heavier mesons well handled by reference detector



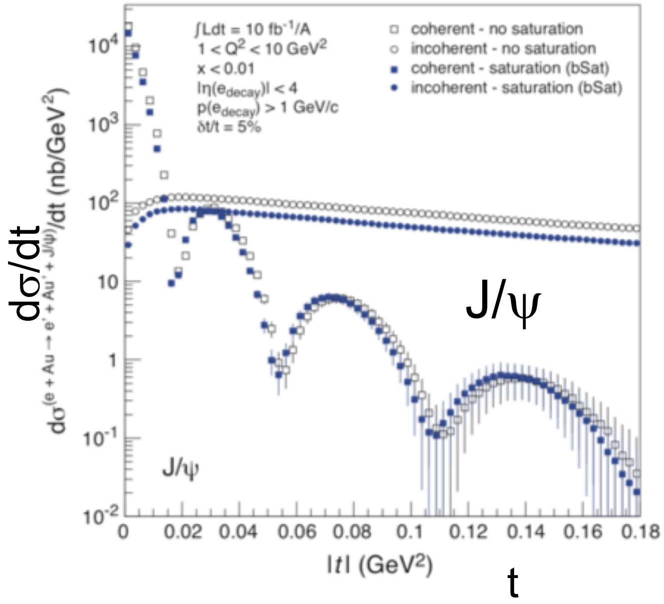
$\phi$ Rapidity vs. kaon pseudorapidity



$\phi$ detection efficiency in an all-silicon tracker

# Separating Coherent and Incoherent production

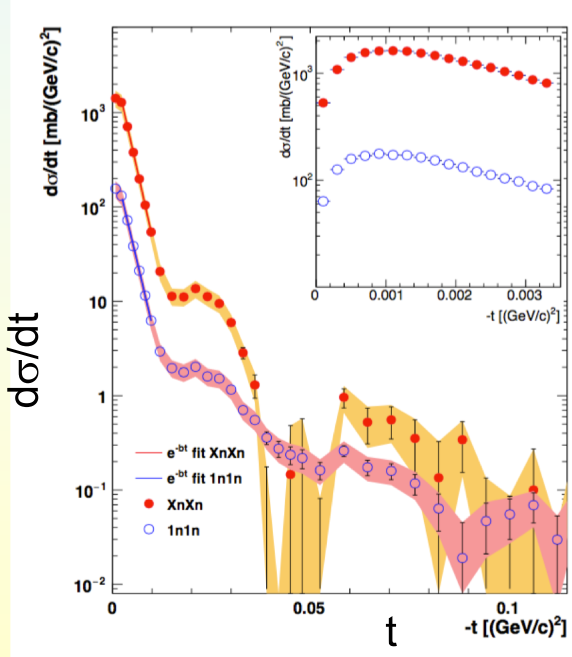
- In the Good-Walker paradigm, coherent photoproduction is sensitive to the average nuclear shape, while the incoherent production is sensitive to event-by-event fluctuations
  - Need 500:1 coherent:incoherent separation at 2nd minimum
    - Neutron or proton emission is easy, but there are excitations 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

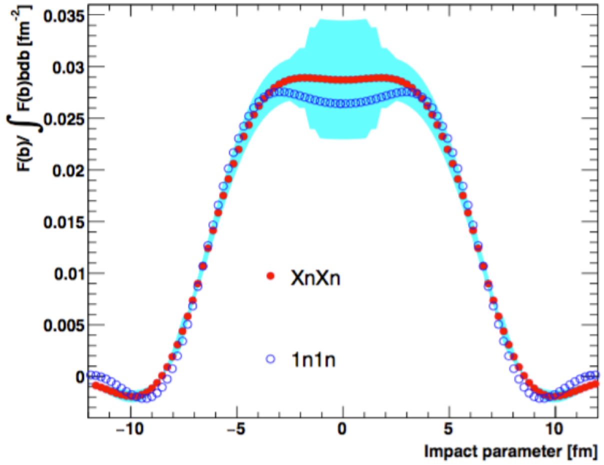
# Observing diffractive dips

- $d\sigma/dt$ for coherent photoproduction probes the transverse gluon distribution in nuclei – like GPDs, but for nuclei.
- Requires good measurement of $t \sim p_{T,\mathrm{Pomeron}}^2$
- $P_{T,VM} = P_{T,\mathrm{Pomeron}} \oplus P_{T,\mathrm{photon}} \oplus \mathrm{Resolution}$
    - 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 $\rho^0$

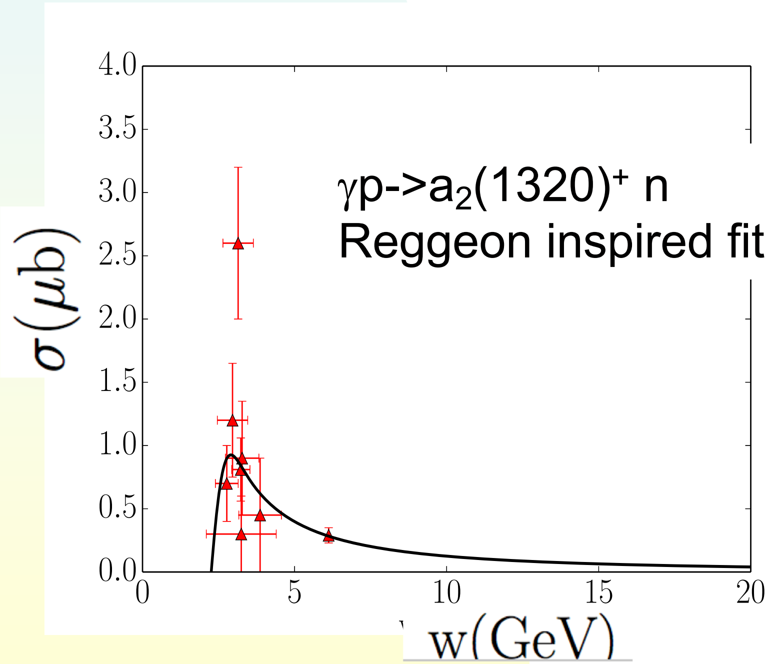
$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T\, p_T J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$

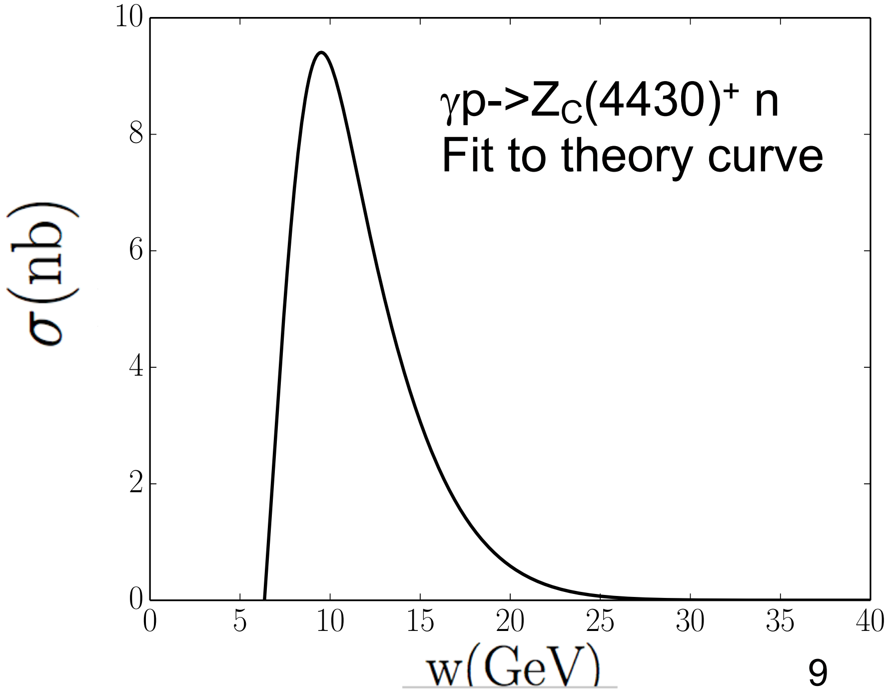


STAR, Phys. Rev. **C96**, 054904 (2017)

# Reggeon exchange and forward production

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

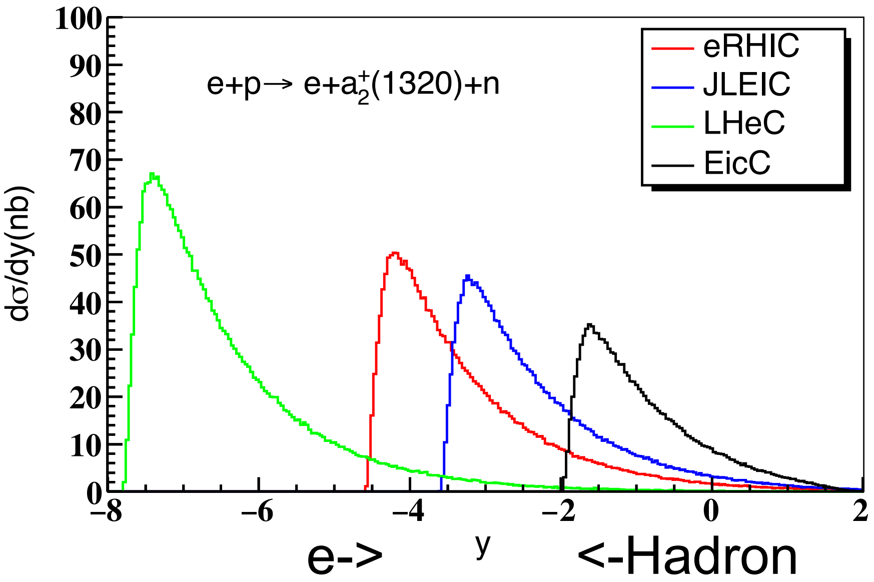


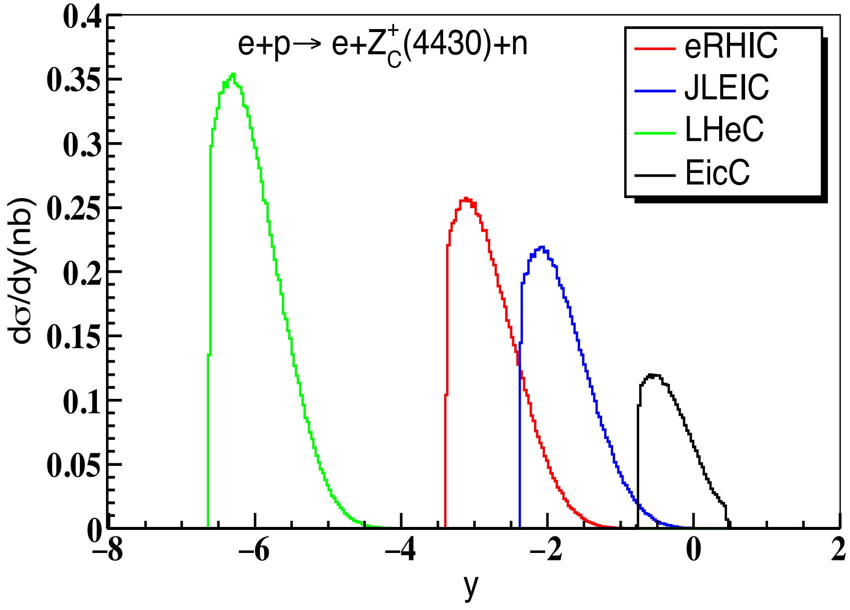


PRD(93)074016 & PRC(83)065203

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

- The $a_2^+(1320)$ is mainly at negative rapidity
  - $\sigma$ ~80 nb at eRHIC
    - Copiously produced
- The $Z_c^+(4430)$ is heavier, and so somewhat more centrally produced.
  - $\sigma$ 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

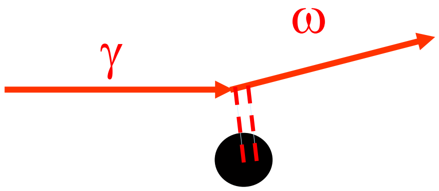




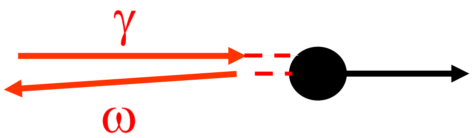
SK and Ya-Ping Xie, PRC **100**, 024620 (2019)

# 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



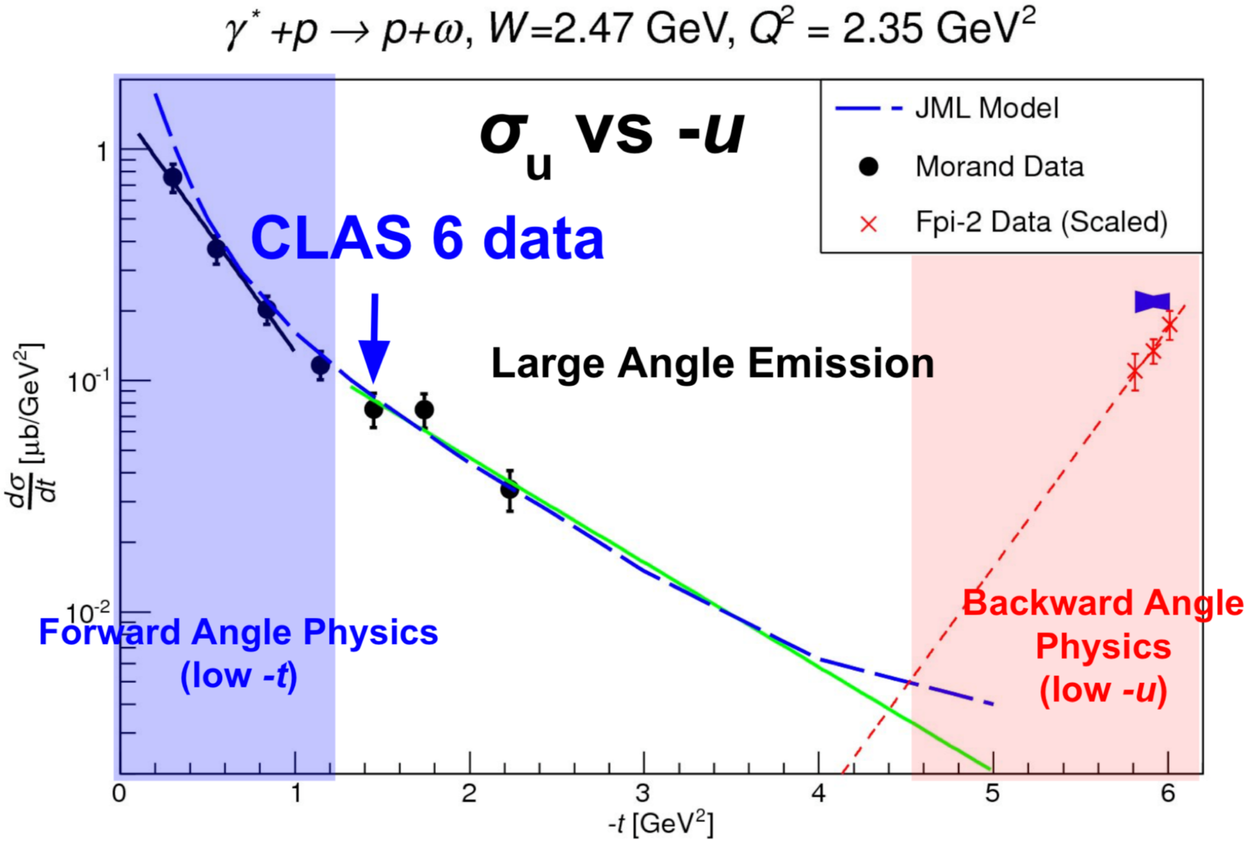
- Normally, photoproduction is maximal when t (momentum transfer from target) is small
  - dσ/dt ~ exp(-Bt)
    - B~ hbar/target size



- 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

# $\gamma p \to \omega p + \rho p$

- Electroproduction data from Clas 6 at Jlab
- Forward & backward interactions are soft; intermediate is hard



**Soft structure -> Hard -> Soft transition**

**First time in electroproduction**

Plot from Bill Li (William & Mary).

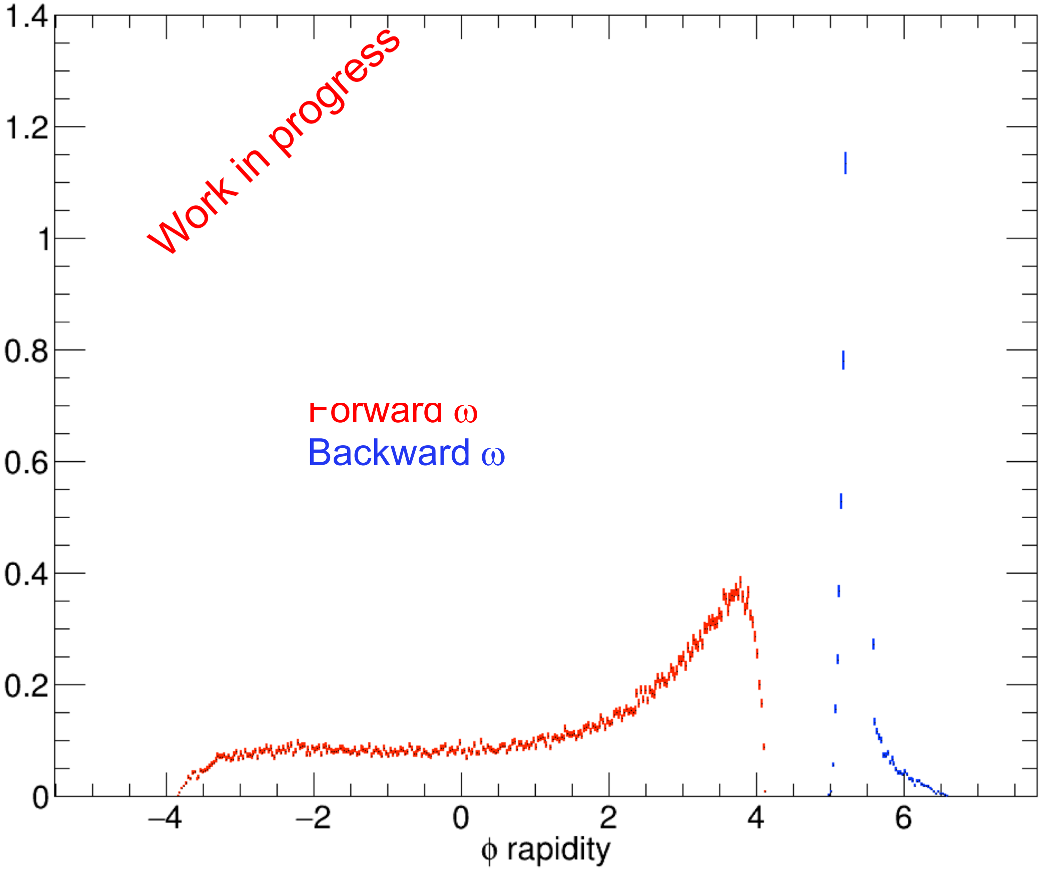
# Parameterization of backward $\gamma p \to \omega p$

- $\omega$ 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 $\omega$ photoproduction
  - $B = -2.7$
    - $B=-1.92$ for forward $\omega$ 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.

# EIC backward production kinematics

- An $\omega$ 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

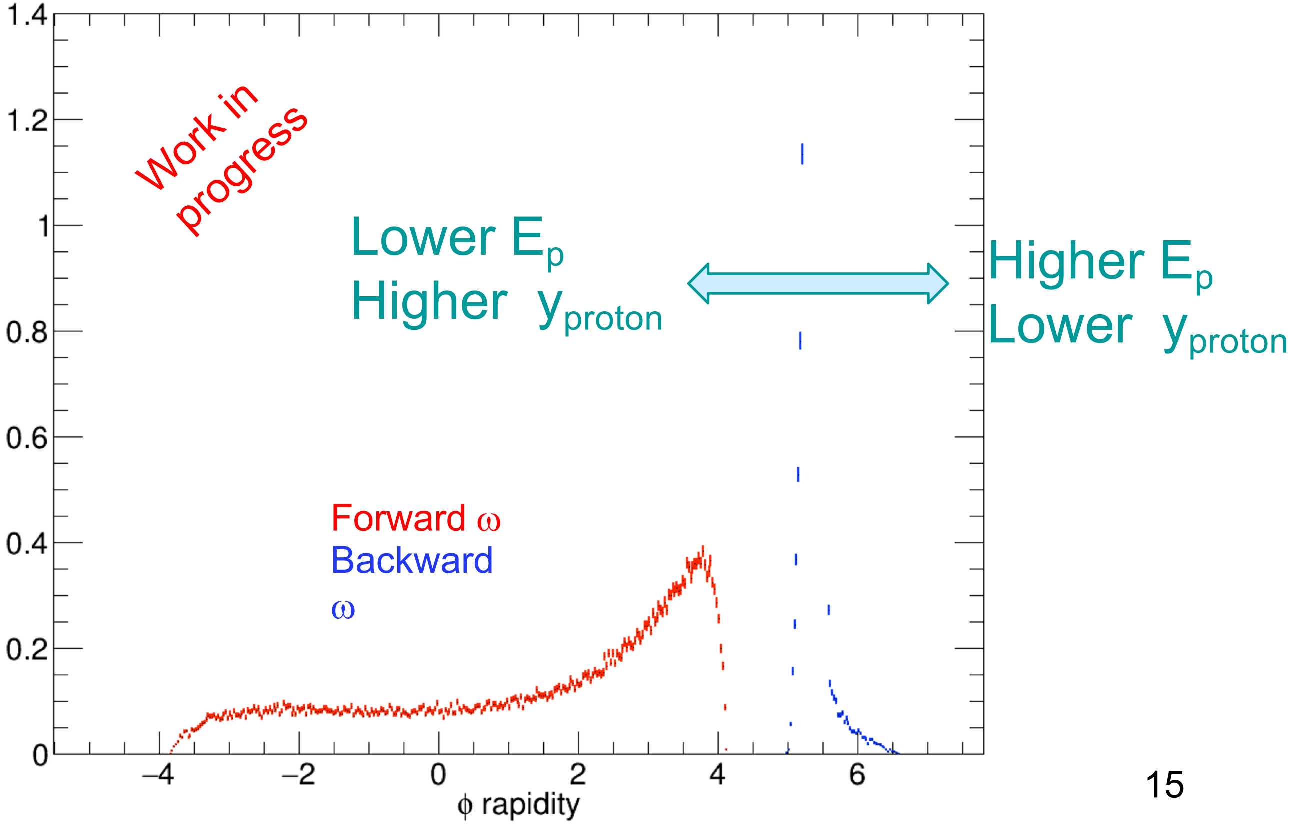
ep->e p $\omega$
18 GeV e on 100 GeV
eSTARlight simulation



# Beam energy dependence of ω peak

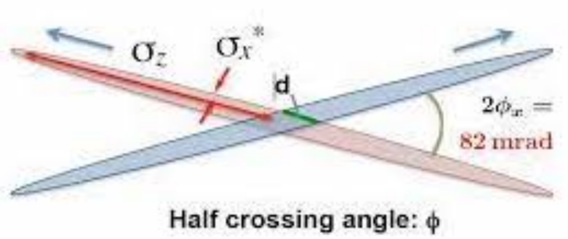
- For 275 GeV proton beams, $y_\omega$ rapidity ~ 6.5
- For 41 GeV protons beams
  - Proton rapidity = 0.0 -> typical ω rapidity is 4.6
  - Proton rapidity = 4.0 -> typical ω rapidity is 3.7
- Need to explore full phase space, but lower proton beam energies seem better

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



# 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



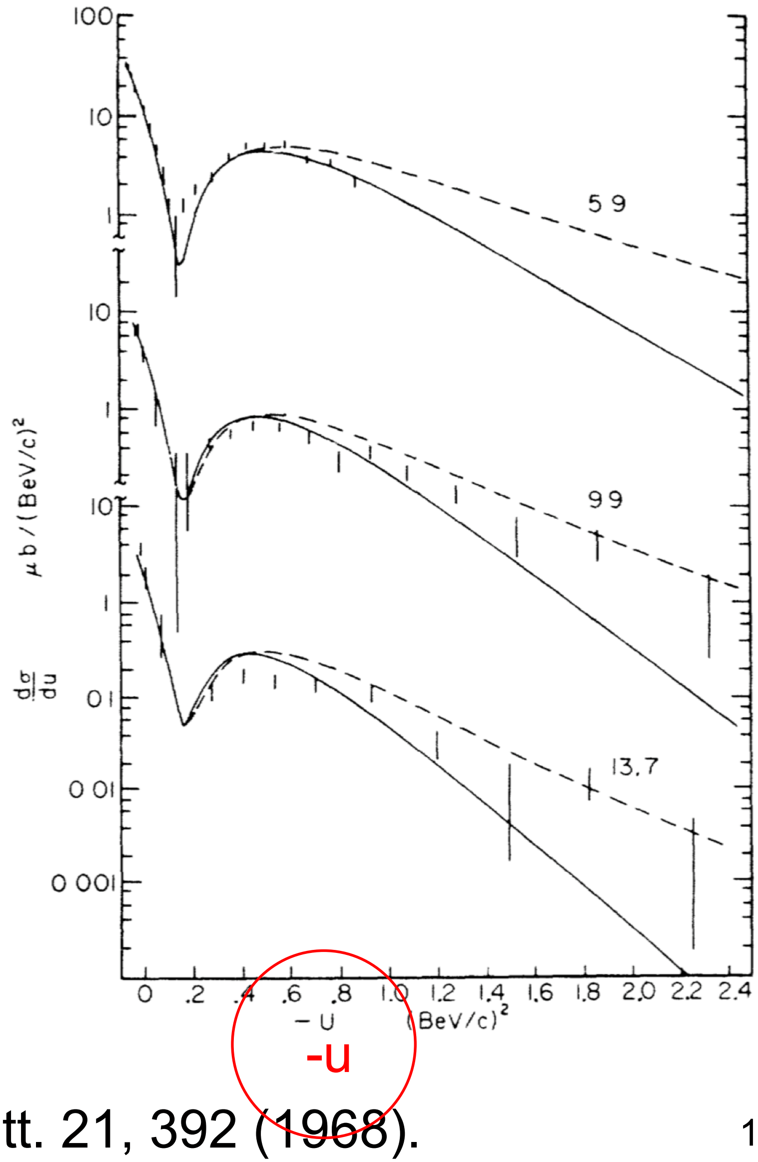
# Conclusions

- Vector meson and other exclusive/semi-exclusive production reactions can challenge proposed EIC 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 detectors are required to separate coherent and incoherent photoproduction, and to study.
- Backward production reactions lead to mid-rapidity baryons and far-forward mesons. The later are a detector challenge, requiring more study.

# Backup

# $\pi^+p \to \pi^+p$ elastic scattering

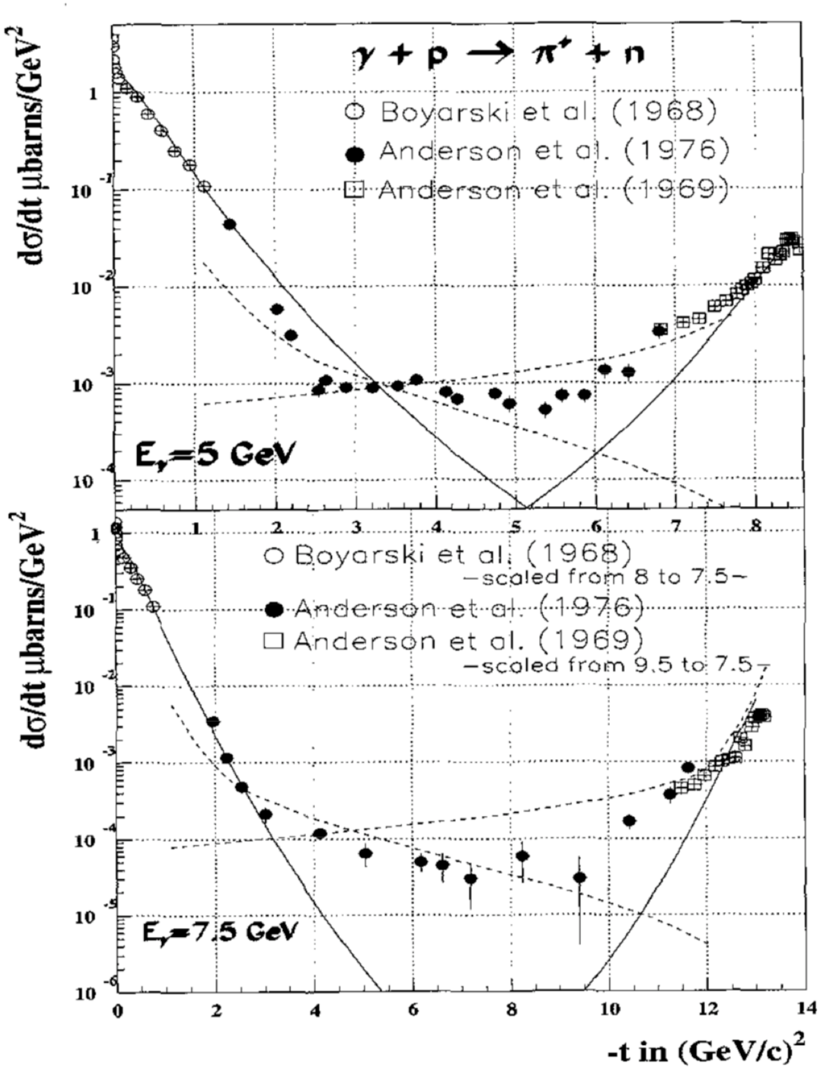
- 5.9 GeV < $E_\pi$ < 13.7 GeV
  - Above the resonance region
- Clear peak near u=0
  - Elastic scattering in the backward direction
- Diffractive minima visible in u-spectrum
  - Looks a lot like a form factor



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

# $\gamma p\text{->}\pi^+ n$

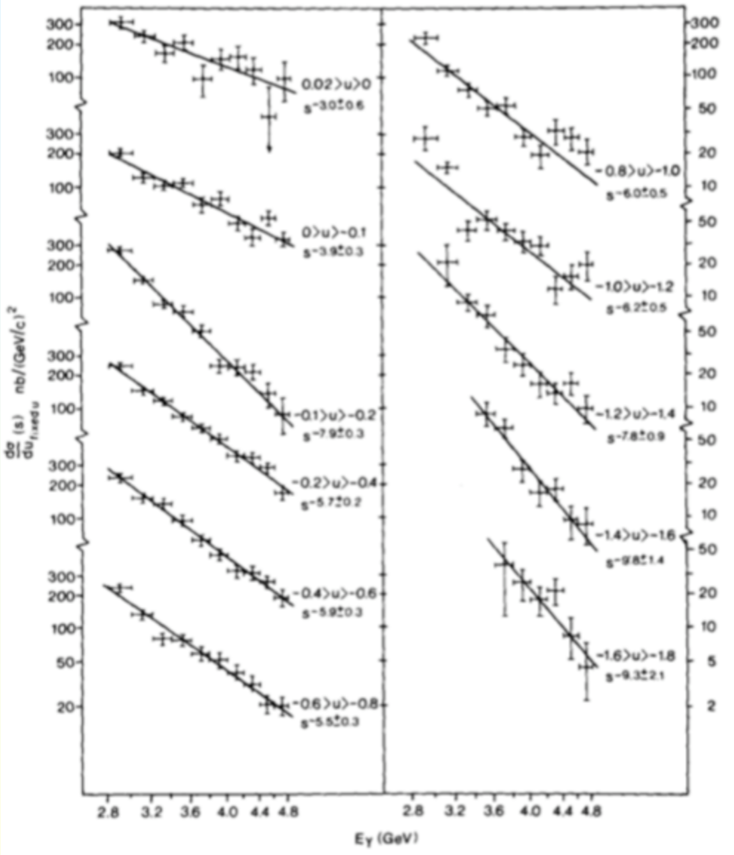
- Data from multiple experiments
- Data exists for 4 GeV < $E_\gamma$ < 16 GeV
  - Again, above the resonance region



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.



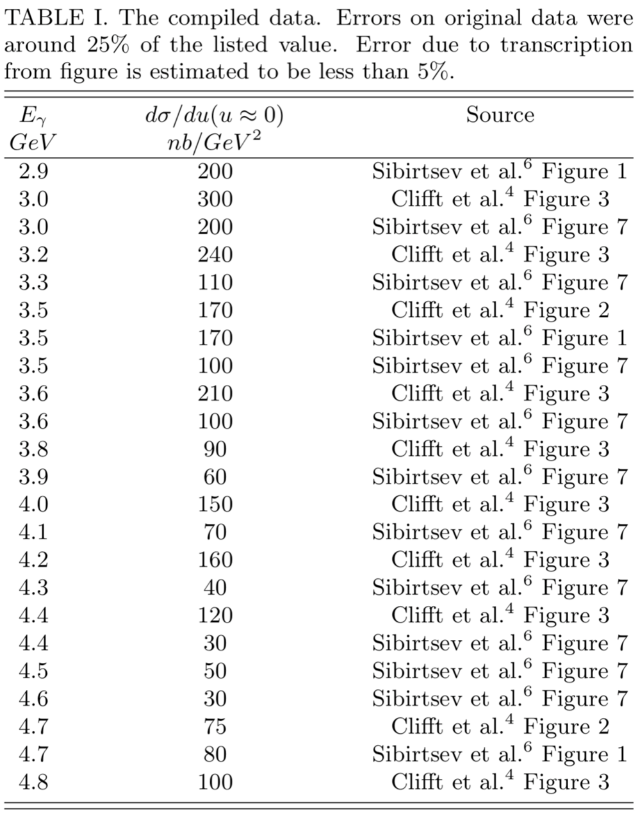


TABLE I. The compiled data. Errors on original data were around 25% of the listed value. Error due to transcription from figure is estimated to be less than 5%.

| $E_\gamma$<br>$GeV$ | $d\sigma/du(u \approx 0)$<br>$nb/GeV^2$ | 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 |

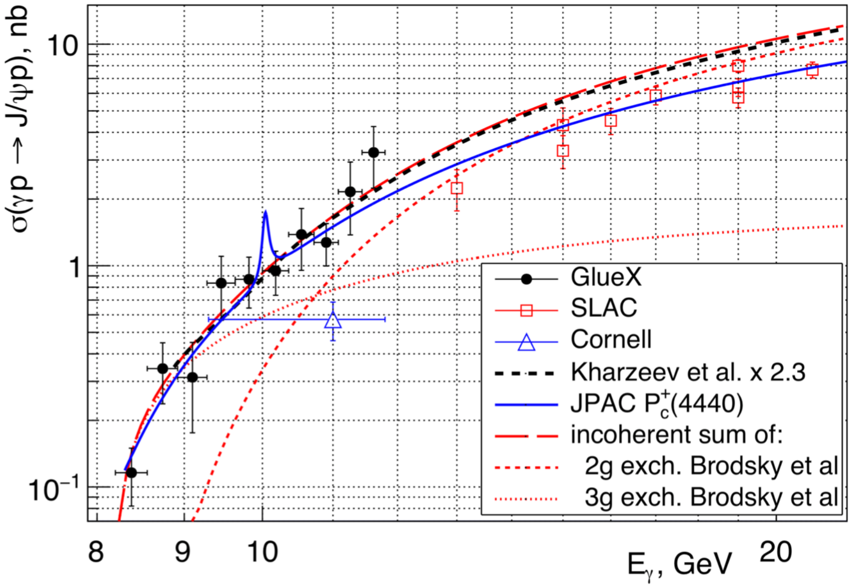
[4] R. Clifft *et al.*, Physics Letters **72B**, 144 (1977).

[5] B.-G. Yu and K.-J. Kong, Physical Review D **99** (2019).

[6] R. Sibirtsev *et al.*, arXiv:nucl-th/0202083v1 (2002).

# 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

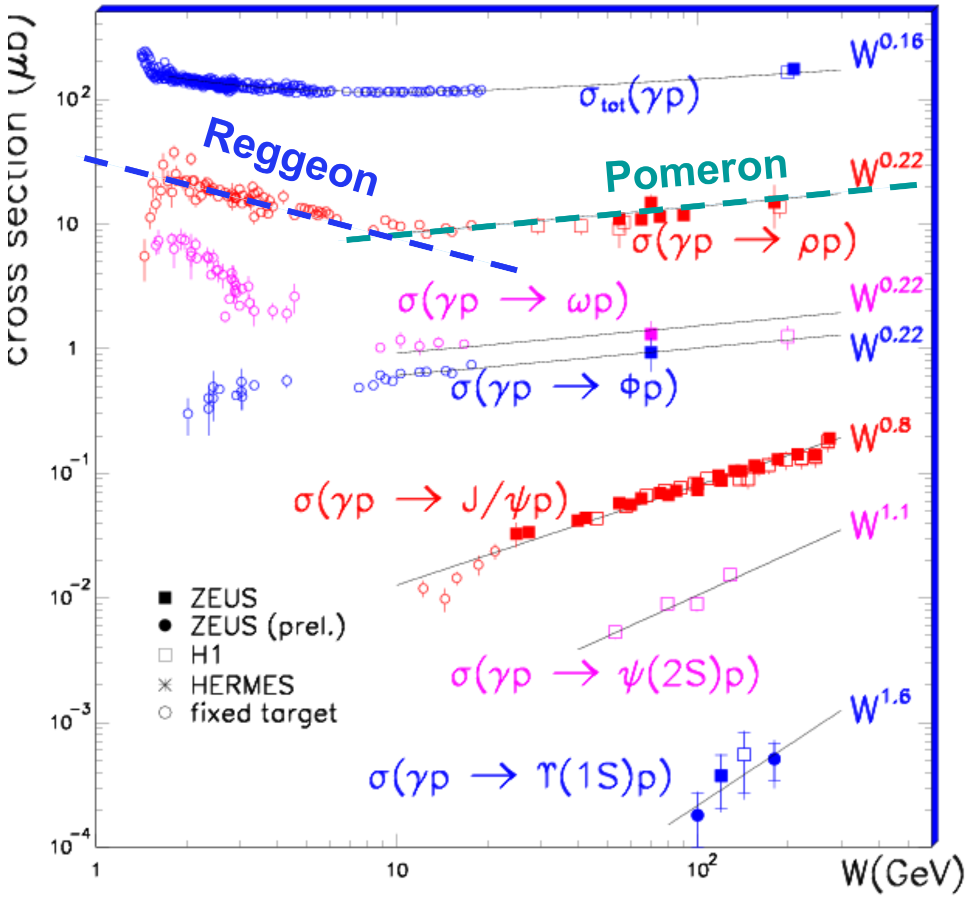
- Convolution of photon flux from electron with $\sigma(\gamma p\text{->}Vp)$
  - Both depend on $Q^2$
- Weizsacker-Williams photon flux (with non-zero $Q^2$)
- VM cross-sections parameterized from HERA data/theory….
  - Reggeon and Pomeron exchange
    - $Q^2$ dependence via a power law from HERA data
- 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

# Pomerons and Reggeons in photoproduction

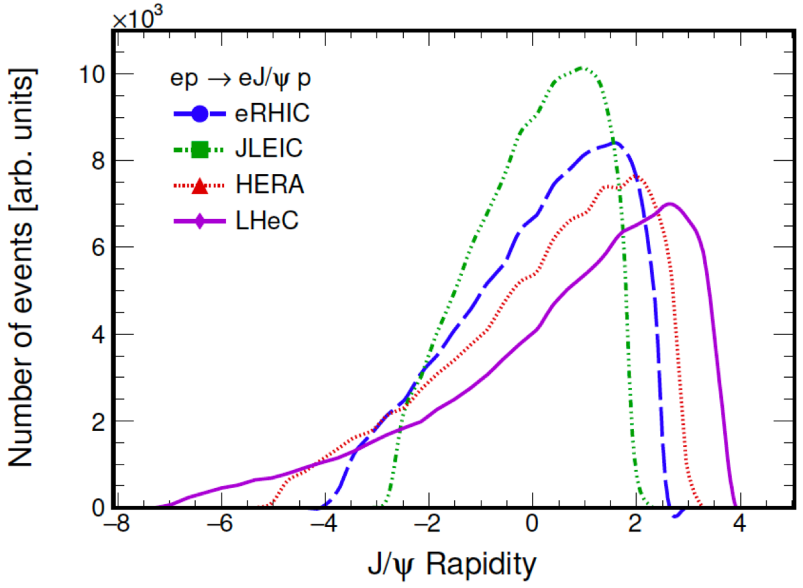
- HERA photoproduction cross-sections well fit by
- $\sigma(W) = XW^{\epsilon} + YW^{-\eta}$
  - W=γp CM energy
- $XW^{\epsilon}$: Pomeron (gluons)
  - ε ~ > 0.2 – meson dependent
  - $J^{PC}=0^{++}$
- $YW^{-\eta}$: 'Reggeon' (~~qqbar)
  - η~~1.5
  - Summed light-quark meson trajectories
    - ~valence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

Photoproduction data

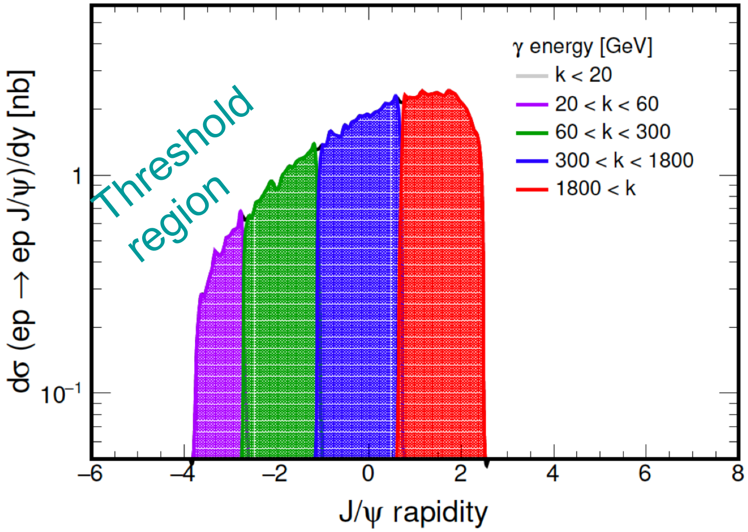


# EIC photoproduction kinematics

- Maps photon energy onto rapidity
- $k = \frac{M}{2}\exp(y)$
- y=ln(2k/M)
- Reggeon activity strongest at low photon energies
  - Requires good acceptance in the hadron-going direction
- Highest photon energies correspond to electron-going direction
  - Need good e-going acceptance



e-> <-Hadron



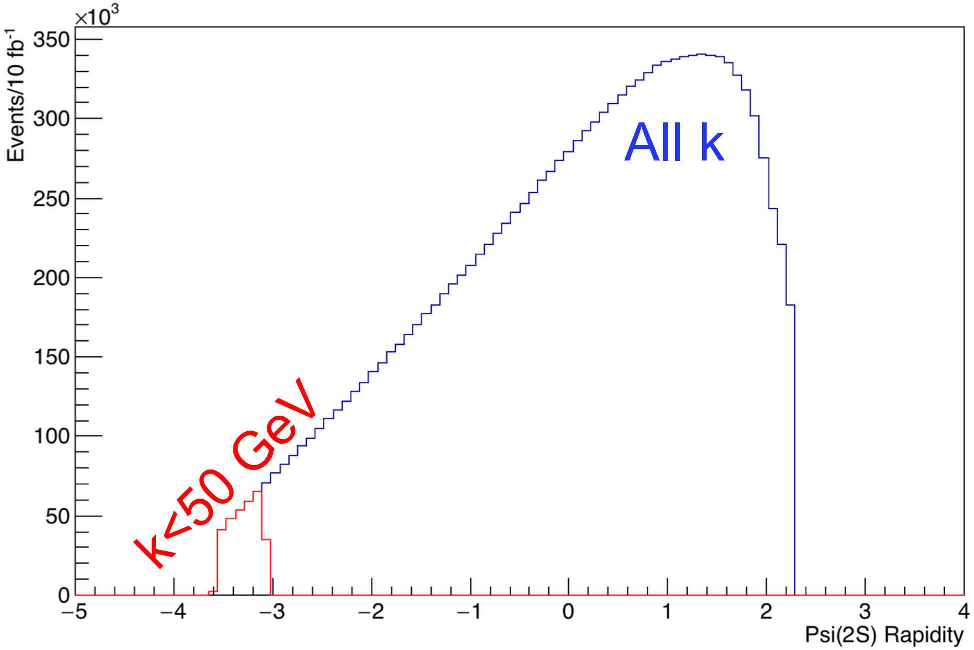
Threshold region

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

# $\Psi(2S)$ & $\Upsilon$ photoproduction at eRHIC

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

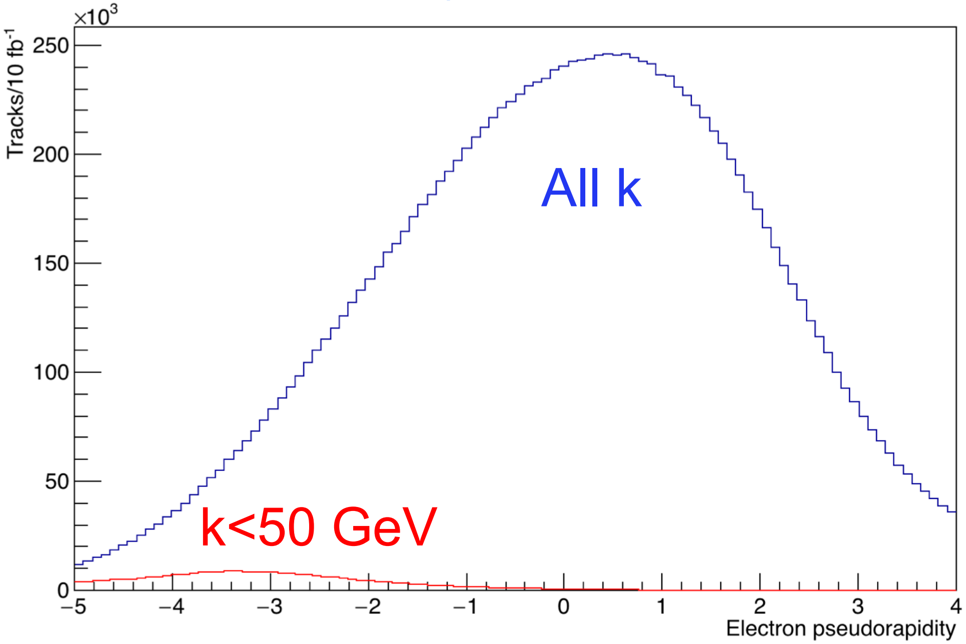
From eSTARlight



e->   <-Hadron

# Ψ(2S)->ee lepton pseudorapidities

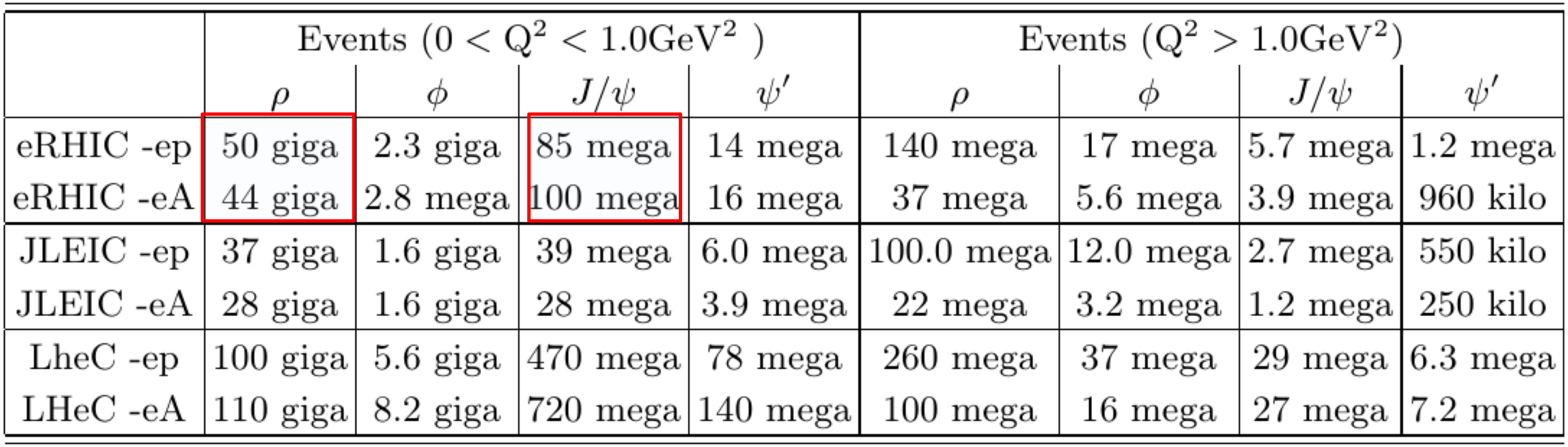
- Lepton pseudorapidity depends on Υ(2S) rapidity, $p_T$ and polarization (which depends on $Q^2$)
- Leptons from most near-threshold (k<50 GeV target frame ) ψ(2S)->ll decays have -5<y<-2
  - Good acceptance required in hadron-going direction
  - N.b. Br(ψ(s)->ee or μμ is 0.7%. Plus $J/\psi\pi^+\pi^-$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



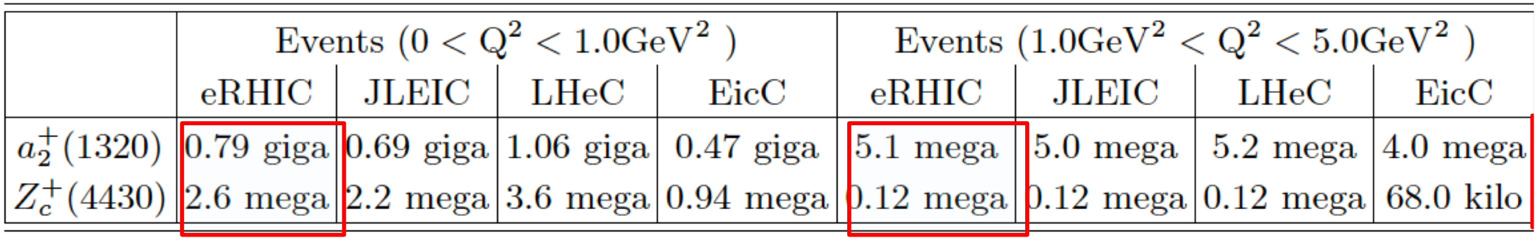
e-> <-Hadron

# 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 ($0 < Q^2 < 1.0 GeV^2$) | | | | Events ($Q^2 > 1.0 GeV^2$) | | | |
|---|---|---|---|---|---|---|---|---|
| | $\rho$ | $\phi$ | $J/\psi$ | $\psi'$ | $\rho$ | $\phi$ | $J/\psi$ | $\psi'$ |
| 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 ($1.0 GeV^2 < Q^2 < 5.0 GeV^2$) | | | |
|---|---|---|---|---|---|---|---|---|
| | 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.

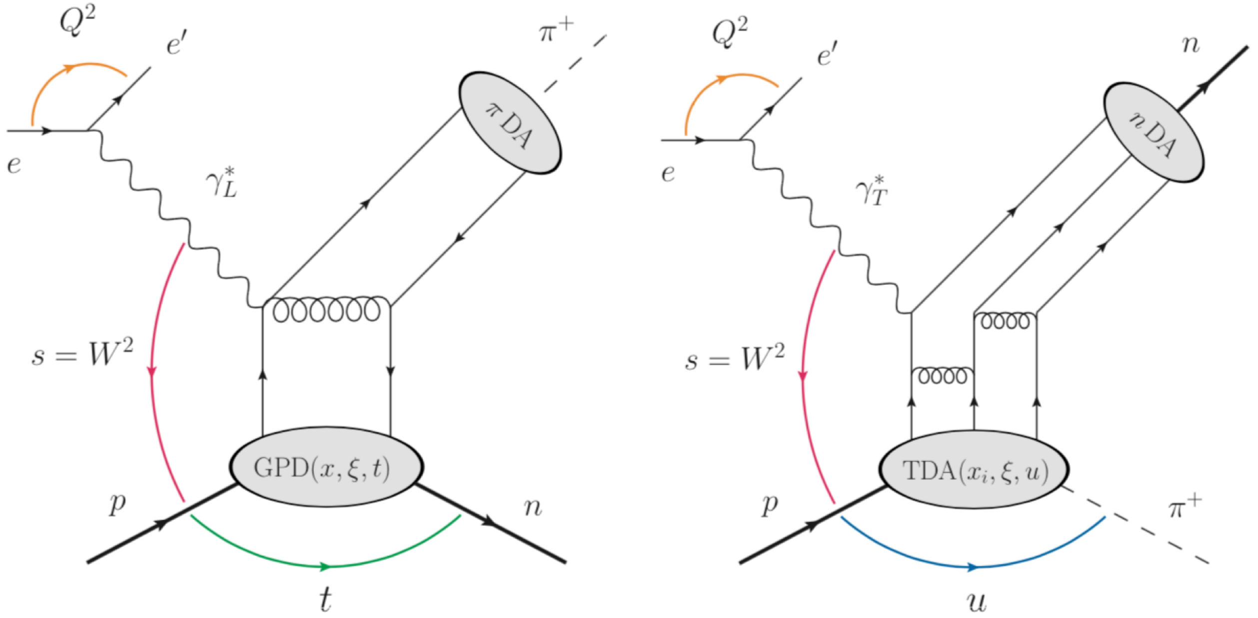
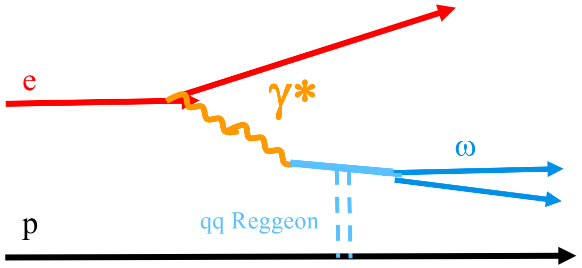
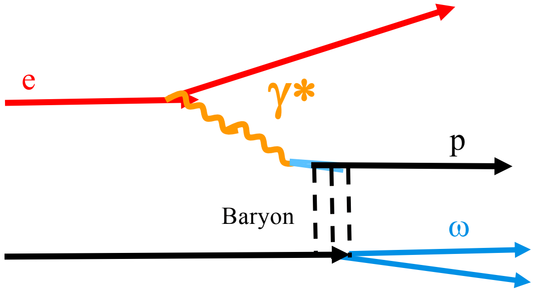


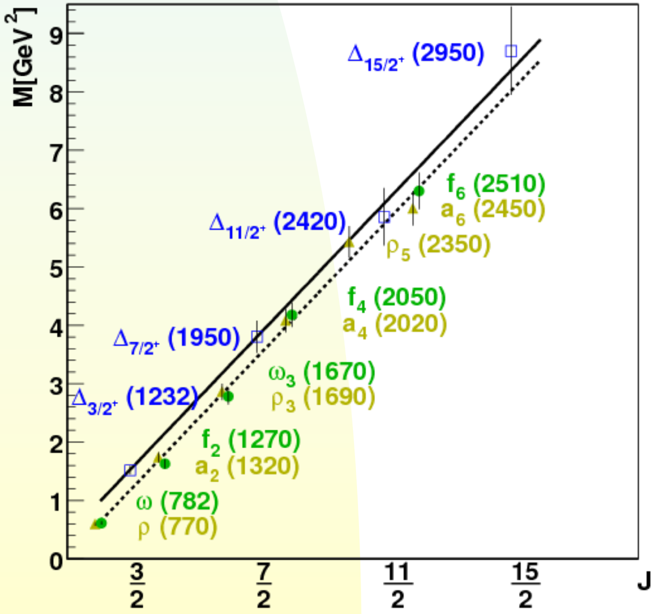
Diagram from K. Park et al., Phys. Lett. B780, 340 (2018)

# 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)







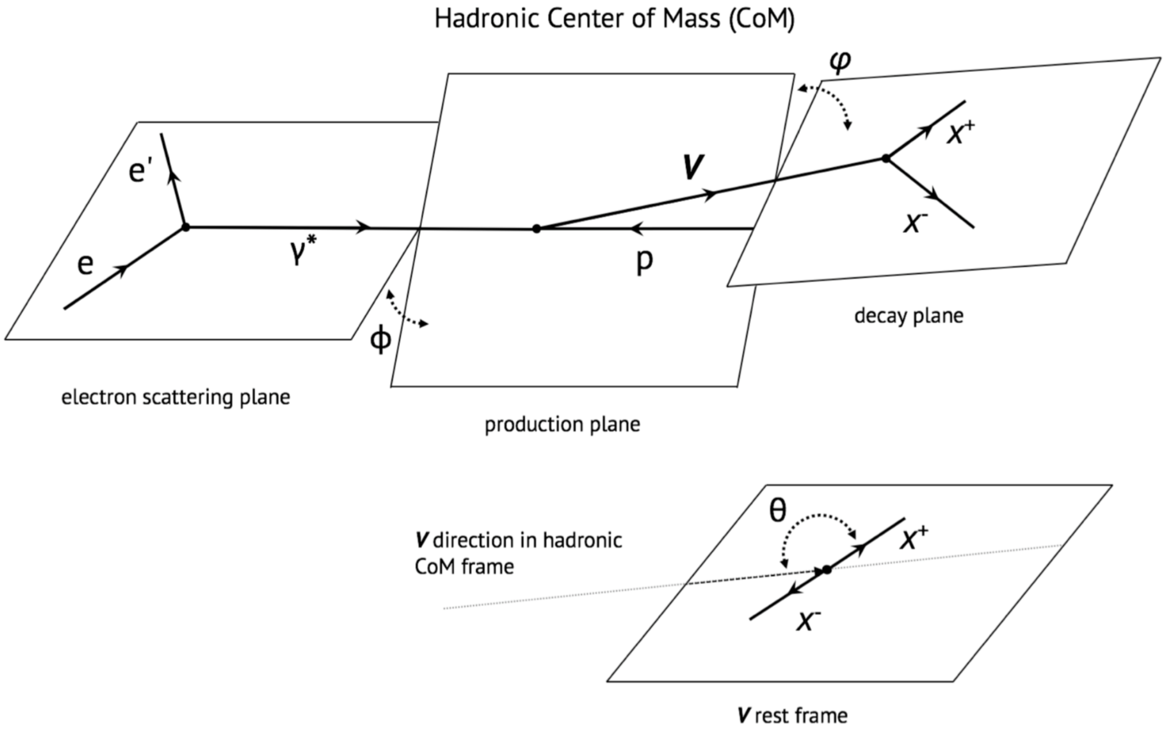
# Implications for baryon stopping

- 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 $\pi$
    - 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?

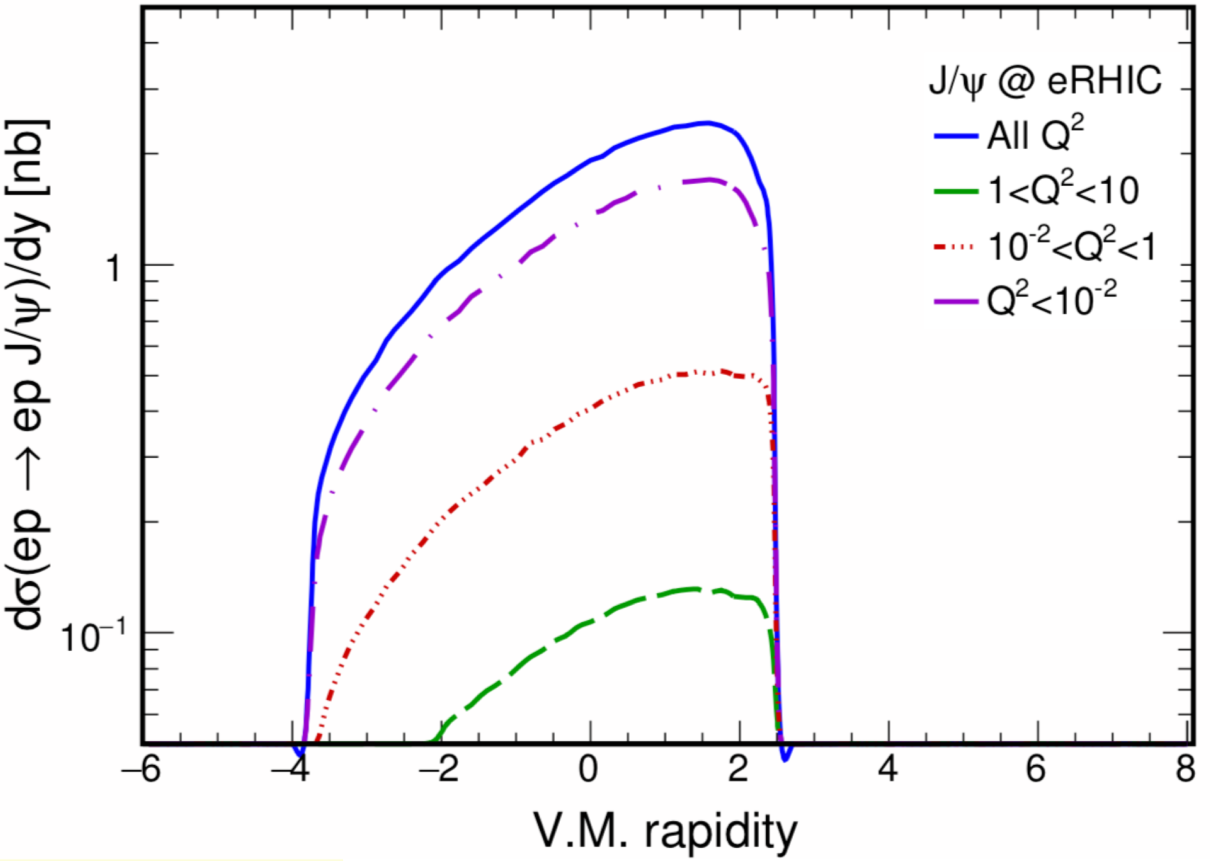
Vance, Gyulassy and Wang, Phys. Lett. B443, 45 (1998)

# Backup

# Angular definitions



# Rapidity vs. $Q^2$



# γp->ωp data

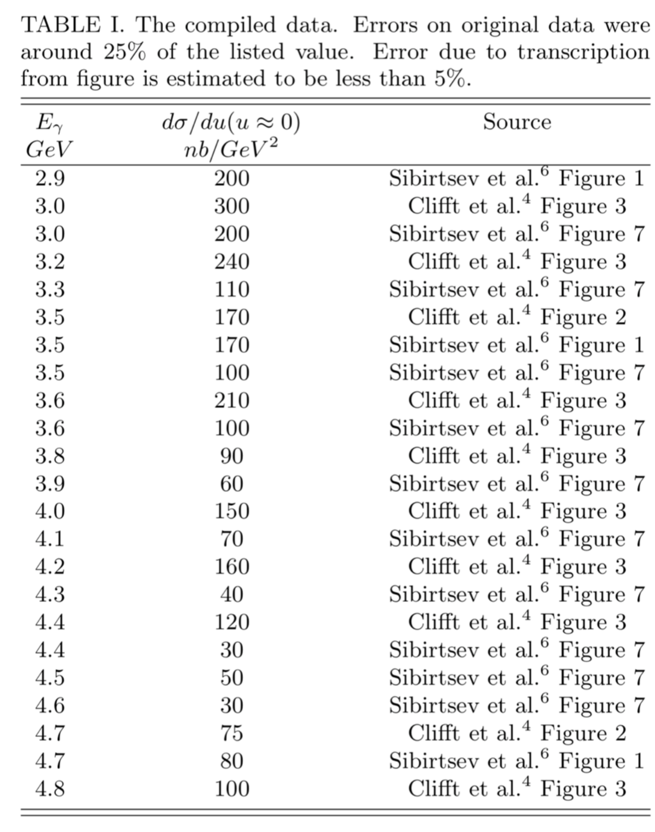
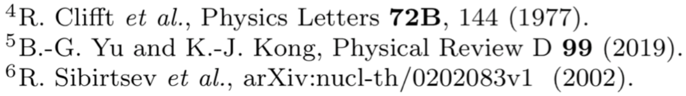


TABLE I. The compiled data. Errors on original data were around 25% of the listed value. Error due to transcription from figure is estimated to be less than 5%.

| $E_\gamma$ $GeV$ | $d\sigma/du(u \approx 0)$ $nb/GeV^2$ | 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).