Near threshold photoproduction: the $a_2(1320)$, Z_c^+ and other topics

Presented at the 1st EIC Yellow Report Workshop
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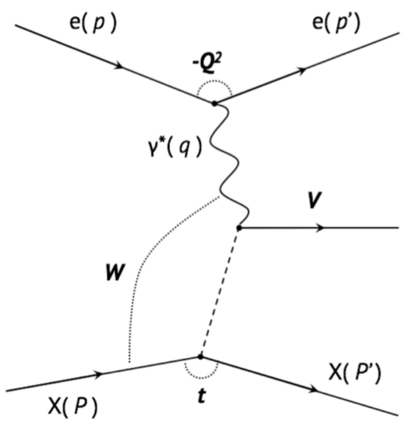
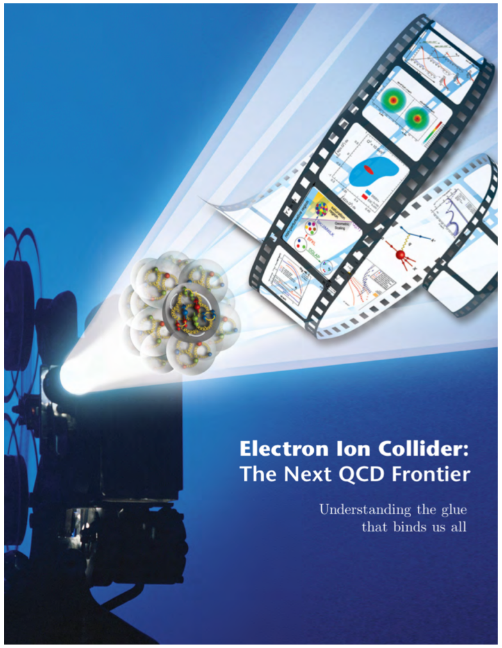


Spencer Klein, LBNL

- Reggeon exchange
- Near threshold photoproduction
- Charged photoproduction & the structure of exotics*
- Backward photoproduction via baryon exchange & baryon stopping**
- Conclusions

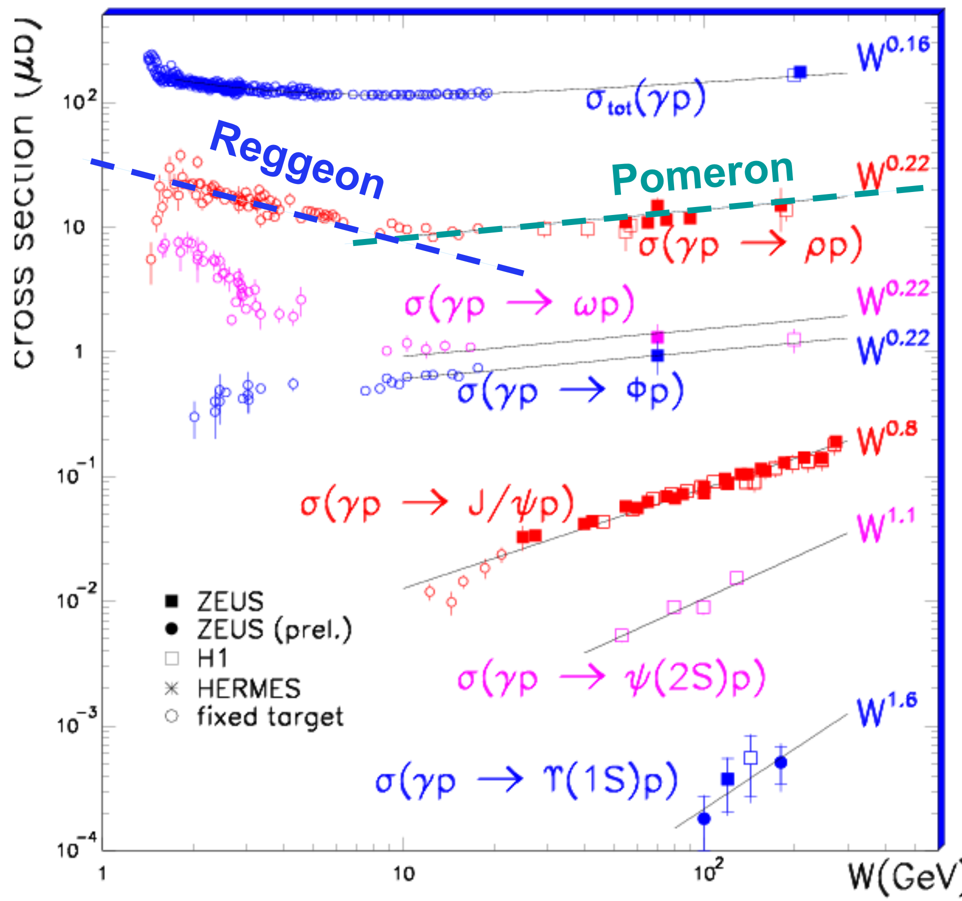
*Work done in collaboration with Ya-Ping Xie
**Work done in collaboration with Aaron Stanek



Reggeons in photoproduction

- HERA photoproduction cross-sections well fit by
- $\sigma(W) = XW^{\epsilon} + YW^{-\eta}$
  - W=γp CM energy
- XW^{ϵ}: 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

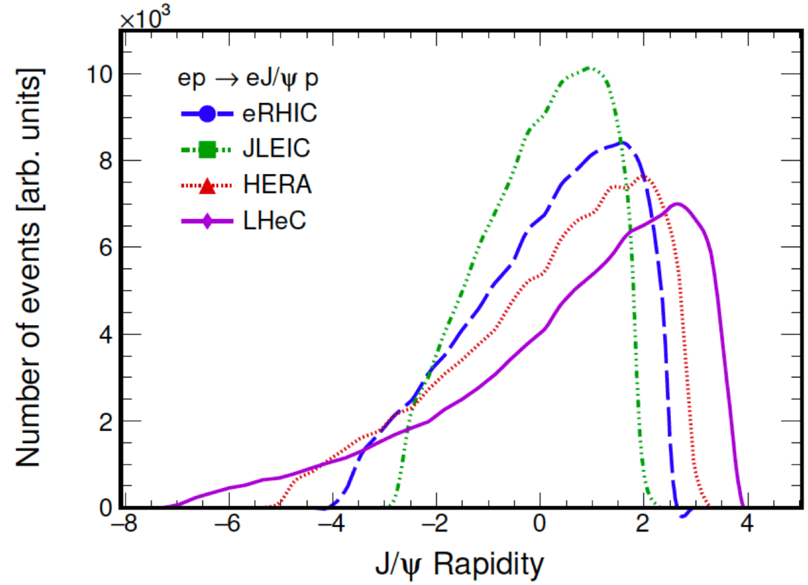


Photoproduction & electroproduction model

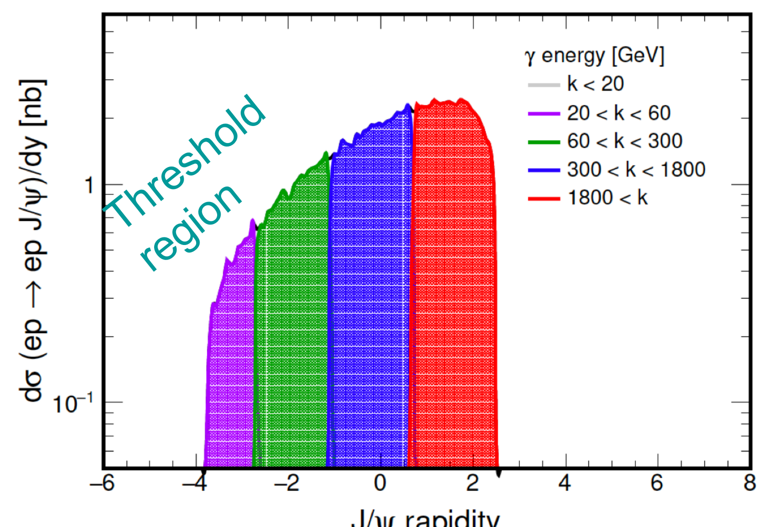
- Convolution of photon flux from electron with $\sigma(\gamma p \to Vp)$
  - Both depend on Q^2
- Weizsacker-Williams photon flux (with non-zero Q^2)
- VM cross-sections parameterized from HERA data/theory….
  - Reggeon and Pomeron exchange
    - Q^2 dependence via a power law from HERA data
- Other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

EIC photoproduction kinematics

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



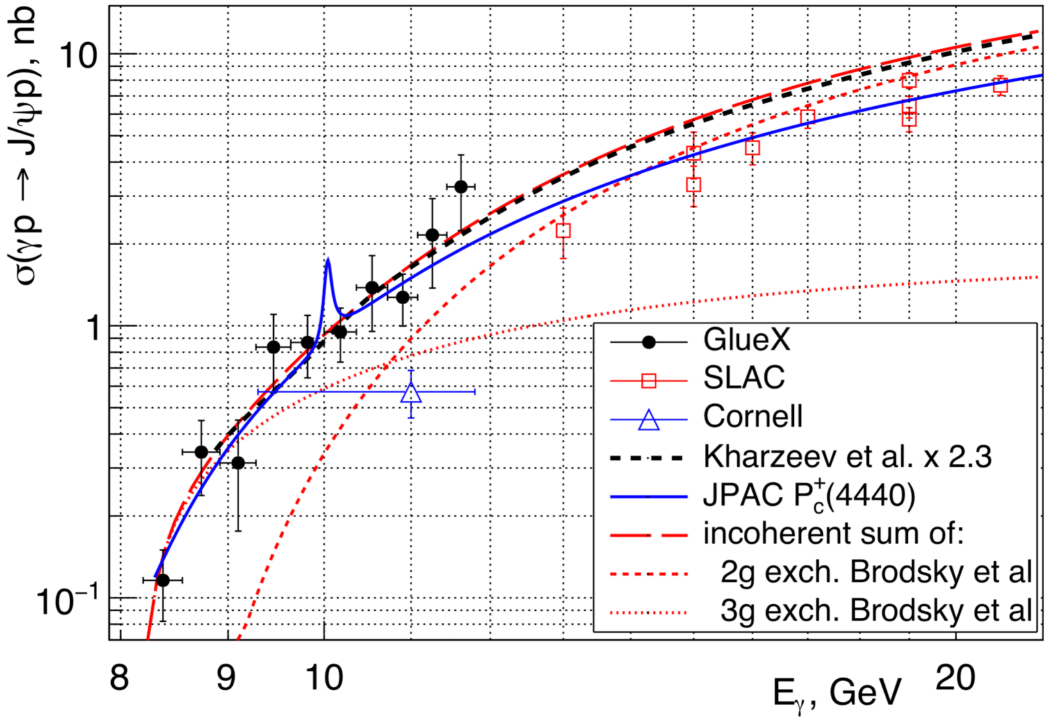
e->   <-Hadron



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

Near threshold quarkonium production

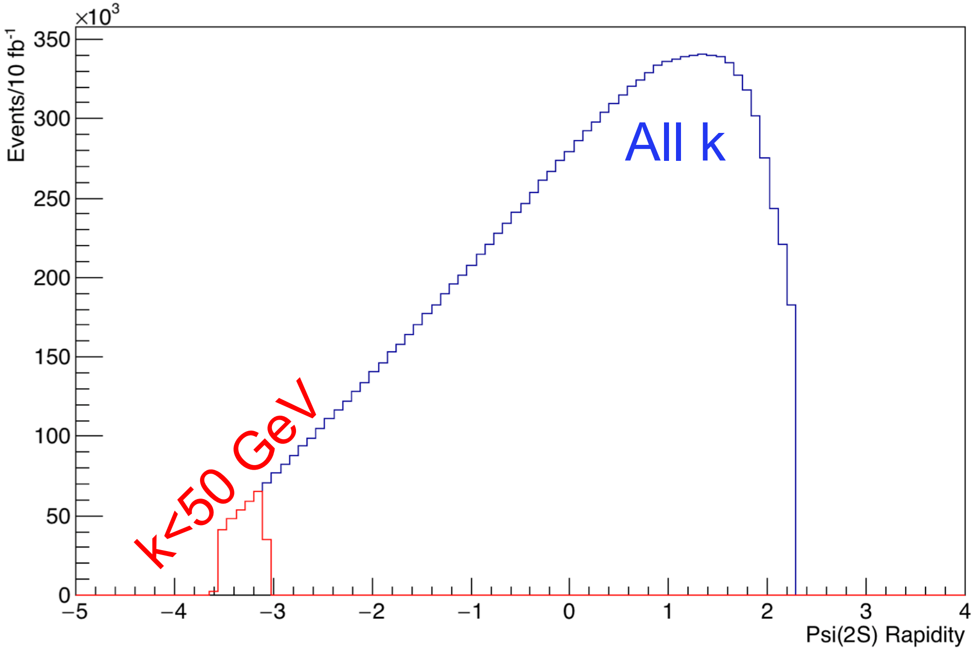
- Near-threshold quarkonium production is sensitive to new mechanisms (i. e. 3-gluon exchange)
  - GlueX data favors a mixture of 2 & 3 gluon exchange for J/ψ
- Sensitive to near-threshold resonances
  - $P_C^+(4440)$ == J/ψ p
    - Pentaquark candidate
- Q^2 dependence?



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

Ψ(2S) & Υ photoproduction at eRHIC

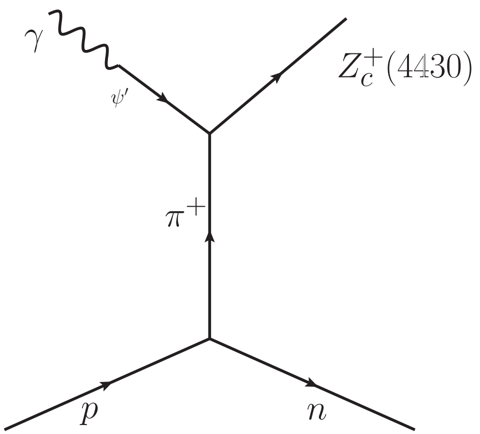
- 18 GeV e^- on 275 GeV protons
- σ=1.4 nb (1/6 of $\sigma(J/\psi)$)
  - 14 million events in 10 fb^{-1}
- 300,000 events with photon energy <50 GeV (target frame)
  - Ψ(2s) threshold region is 3.5 < y < 3.0 for this configuration
  - ~ 2,800 each Ψ(2S)->ee, $\mu\mu$
- $\sigma(\Upsilon(1S))=0.01\sigma(\psi')$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



e-> <-Hadron

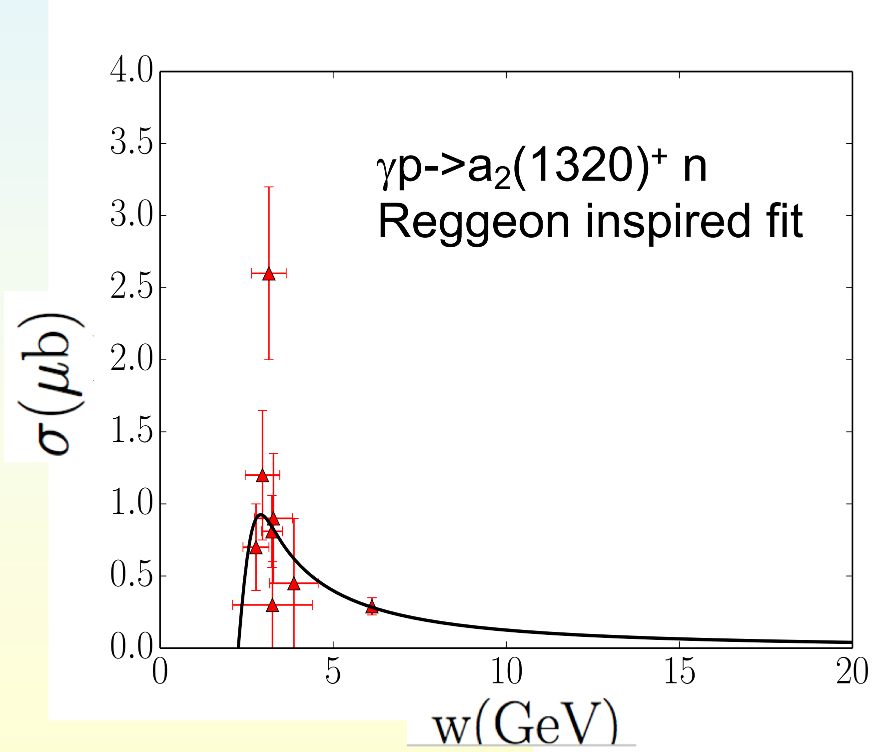
Charged photoproduction and exotics

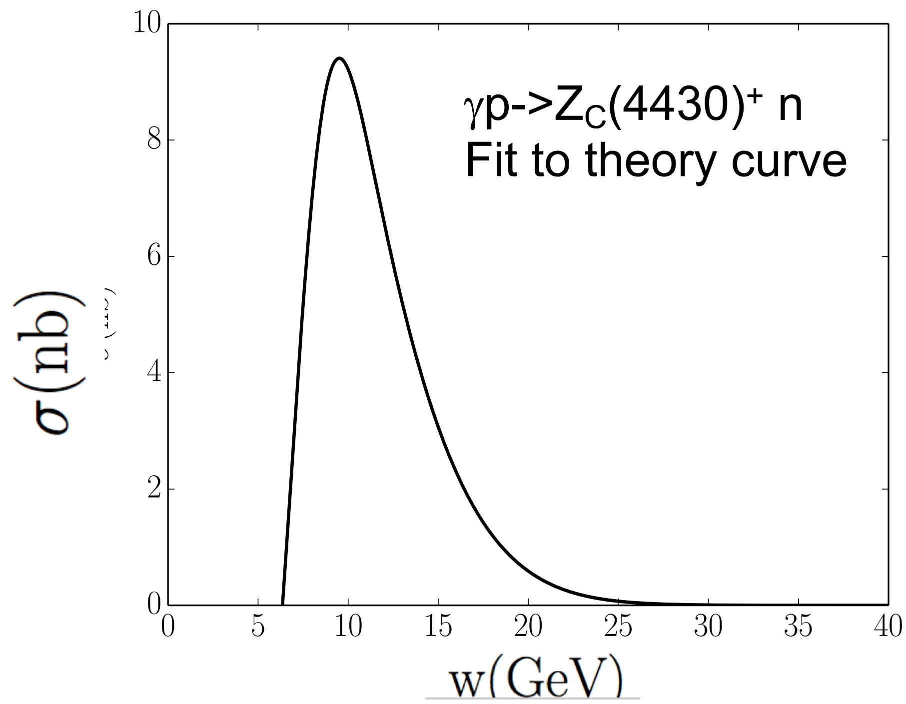
- Meson trajectories cover a wider range of spin/parity/charge than Pomerons
  - Good for meson spectroscopy, including exotics.
- 2 examples
  - $a_2^+(1320)$ standard qqbar meson. Illustrates Reggeon phenomenology & kinematics.
    - Large branching ratio to $\pi^+\pi^-\pi^+$
      - Easy to reconstruct
  - $Z_c^+(4430)$ exotic
    - Well established at Belle & LHCb
    - likely a tetraquark, molecular molecule or ???
    - Easy to reconstruct via $J/\psi\pi^+$, $\psi(2S)\pi^+$
    - Photoproduction probes structure, quantum numbers
- p->n, so little/no coherent nuclear enhancement, and target breaks up
- These examples are also relevant for neutral final states



Cross section of charged particles in photoproduction process

- Use data or 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)

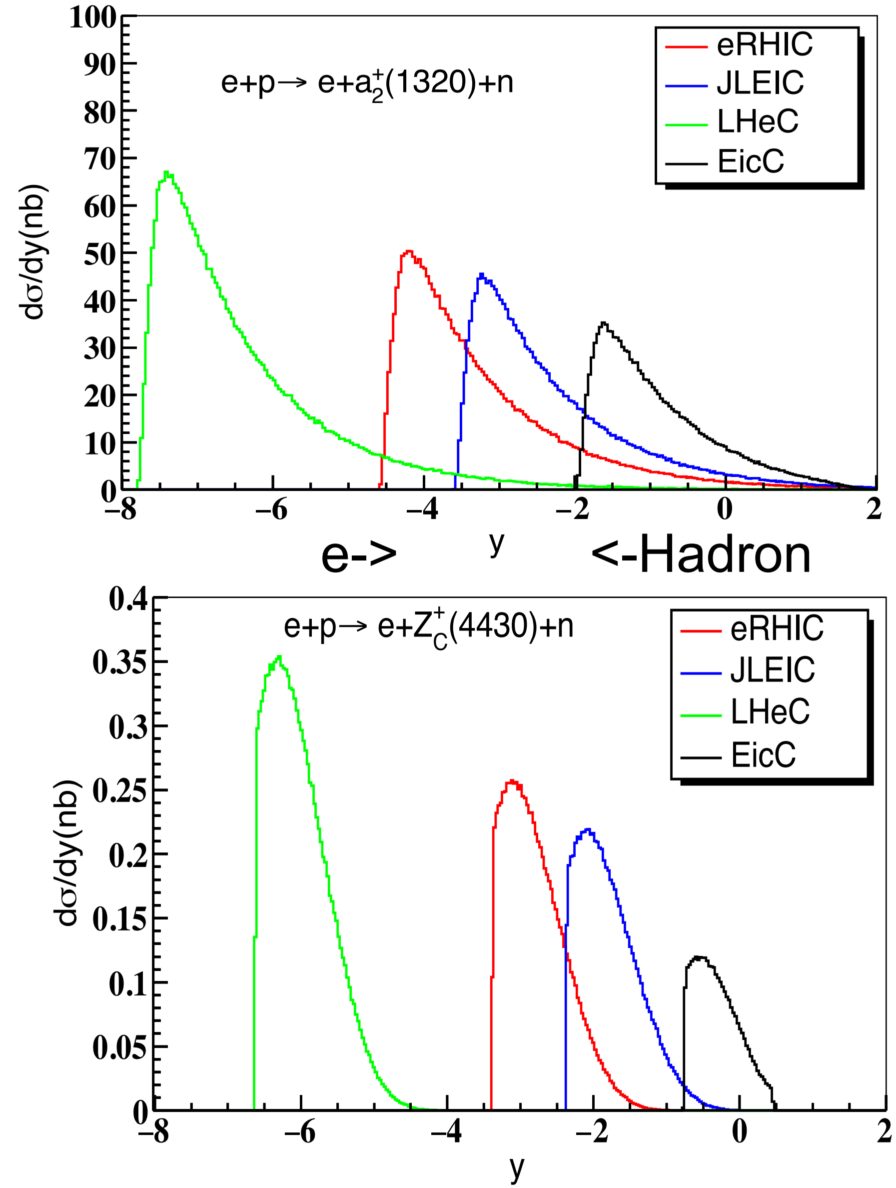




PRD(93)074016 & PRC(83)065203

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

- The $a_2^+(1320)$ is mainly at negative rapidity
  - σ is large
    - ~80 nb at eRHIC
- The $Z_c^+(4430)$ is also at negative rapidity, but, because of its mass, is somewhat more centrally produced.
  - σ is moderate
    - 0.26 nb at eRHIC



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 ($Q^2 > 1.0 GeV^2$)			
	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

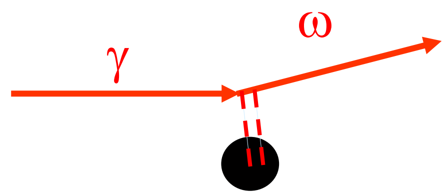
	Events ($0 < Q^2 < 1.0 GeV^2$)				Events ($1.0 GeV^2 < Q^2 < 5.0 GeV^2$)			
	eRHIC	JLEIC	LHeC	EicC	eRHIC	JLEIC	LHeC	EicC
$a_2^+(1320)$	0.79 giga	0.69 giga	1.06 giga	0.47 giga	5.1 mega	5.0 mega	5.2 mega	4.0 mega
$Z_c^+(4430)$	2.6 mega	2.2 mega	3.6 mega	0.94 mega	0.12 mega	0.12 mega	0.12 mega	68.0 kilo

Reggeon exchange conclusions

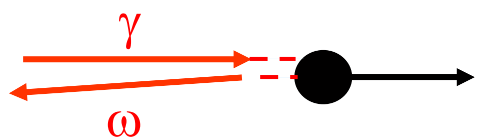
- Reggeon exchange can probe a wide variety of final states with different spins and parities, including charged final states.
- Rates are high for light-quark mesons. The outgoing electron tags the photon, so missing-mass techniques can be used, allowing the study of wide range of final states, for meson classification and spectroscopy.
- Rates are also attractive for c cbar mesons, including exotics. An EIC can study the XYZ states, including charged states. Photoproduction cross-sections are an important clue to their structure and spin.
- b-bbar quarkonium is also accessible.
- These studies require good instrumentation in the hadron-going direction.

Baryon exchange trajectories

- There is clear evidence, from both old fixed-target experiments, and from Jefferson Lab, that photoproduction can also occur via baryon exchange.



- Normally, photoproduction is maximal when t (momentum transfer from target) is small
  - $d\sigma/dt \sim \exp(-Bt)$
    - B~ hbar/target size

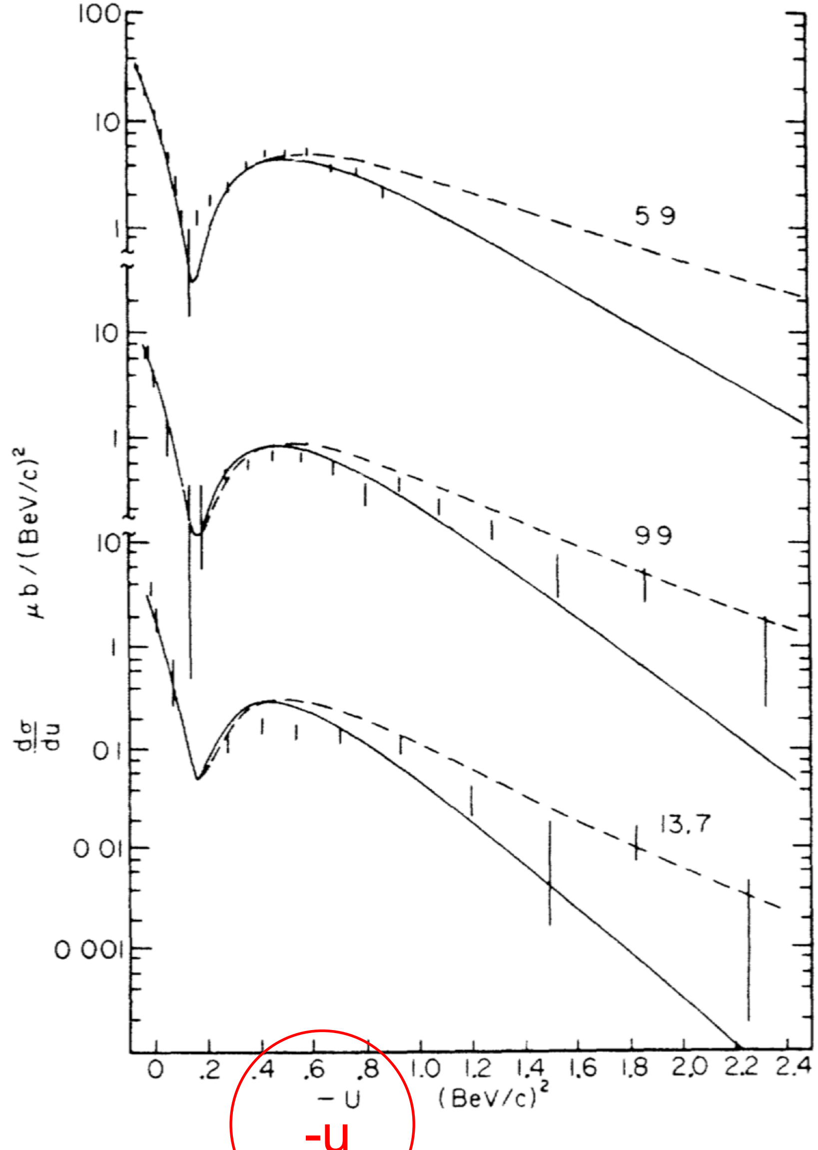


- In baryon exchange, in the CM frame, the meson scatters backward 180 degrees causing the baryon to recoil
  - In CM frame, baryon and photon/meson trade momentum
  - Mandelstam u is small, but t is large ($t>Q^2$)
- How does an intact baryon recoil at high energies?

Thanks to Bill Li (William & Mary) for inspiration and discussion.

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

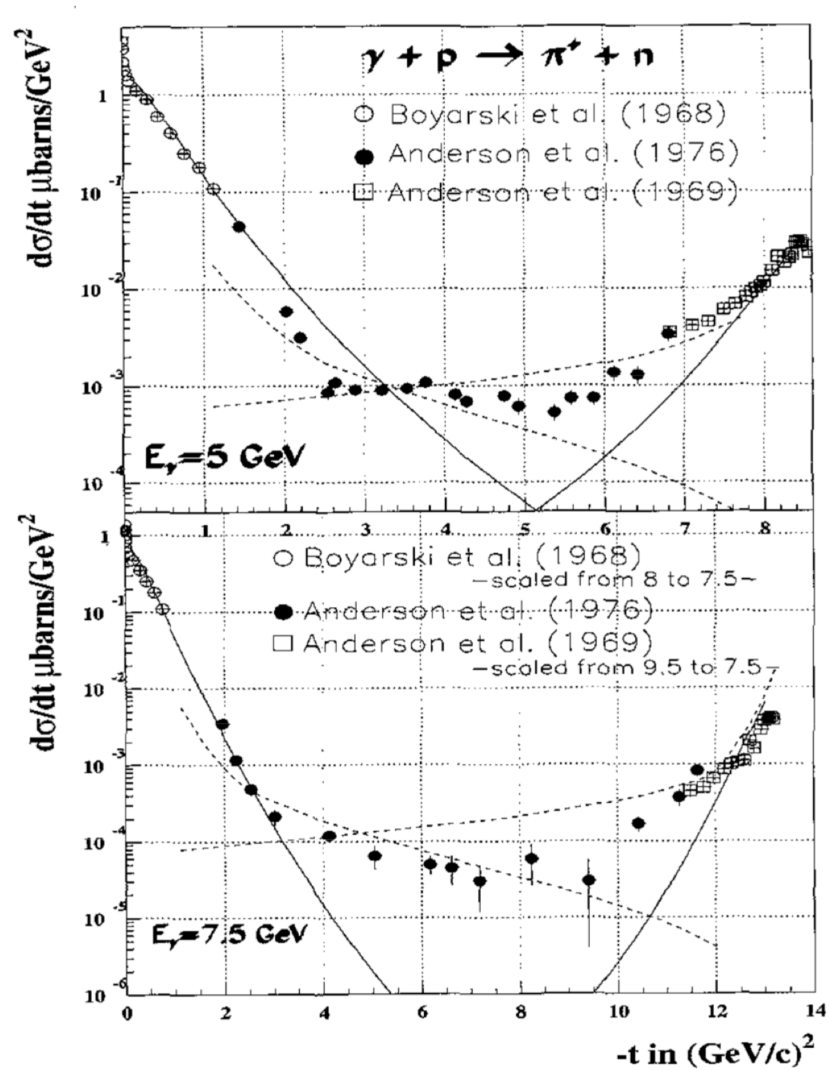
- 5.9 GeV < E_π < 13.7 GeV
  - Above the resonance region
- Clear peak near u=0
  - Elastic scattering in the backward direction
- Diffractive minima visible in u-spectrum
  - Looks a lot like a form factor



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

$\gamma p \to \pi^+ n$

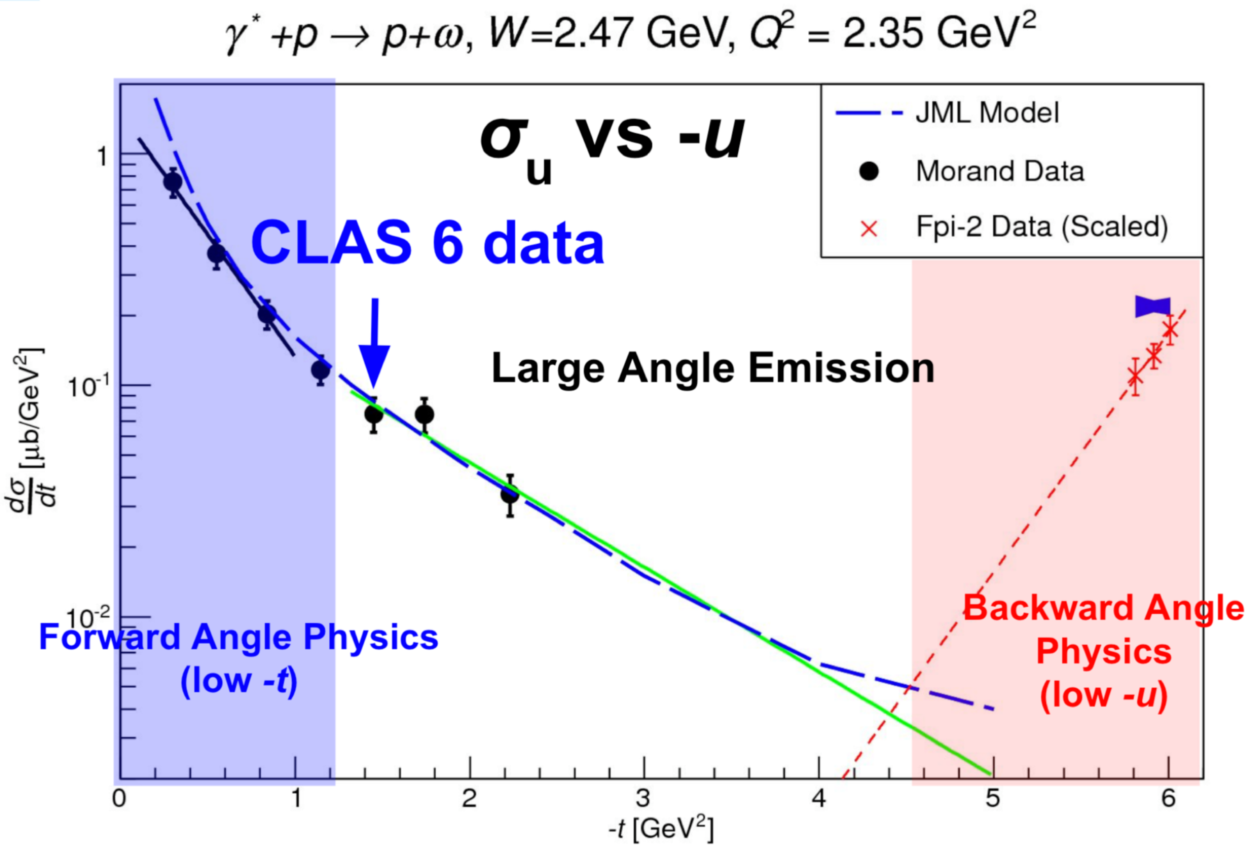
- Data from multiple experiments
- Data exists for 4 GeV < E_γ < 16 GeV
  - Again, above the resonance region



M. Guidal et al., Phys. Lett. B400, 6 (1997).

$\gamma p \rightarrow \omega p + \rho p$

- 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).

Theoretical approach - I

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

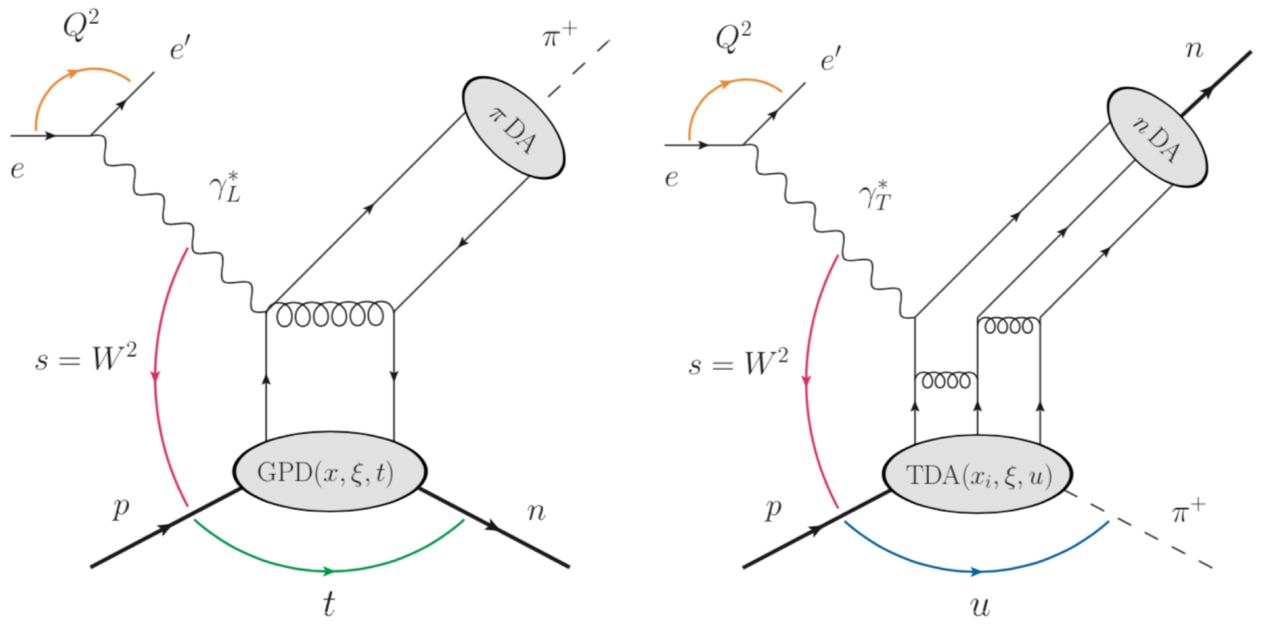
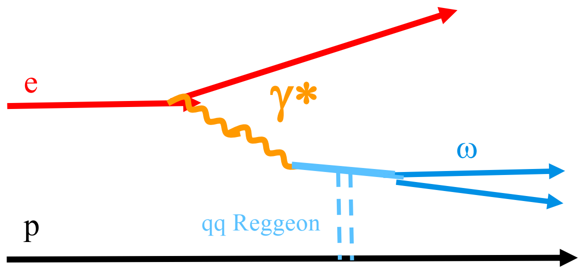
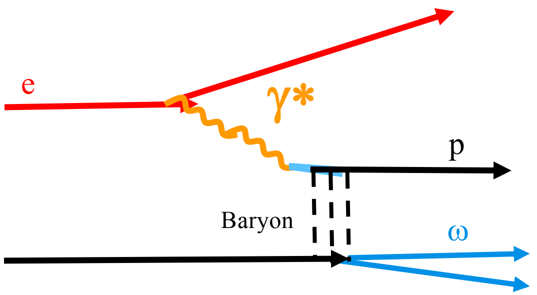


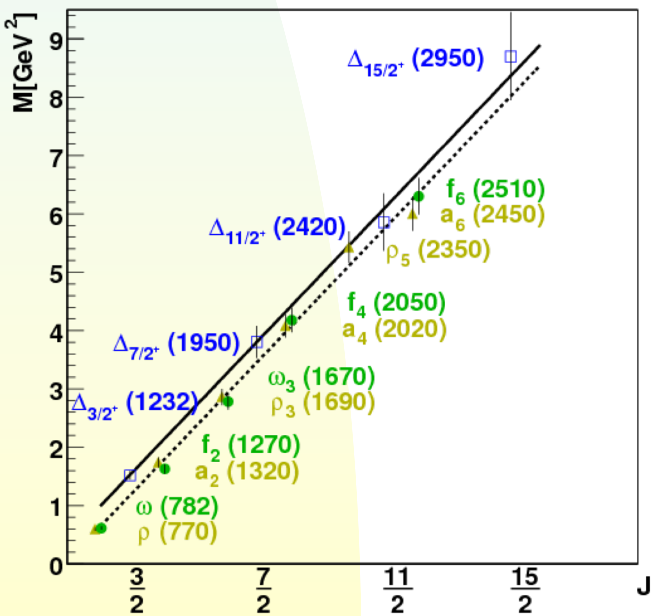
Diagram from K. Park et al., Phys. Lett. B780, 340 (2018)

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)







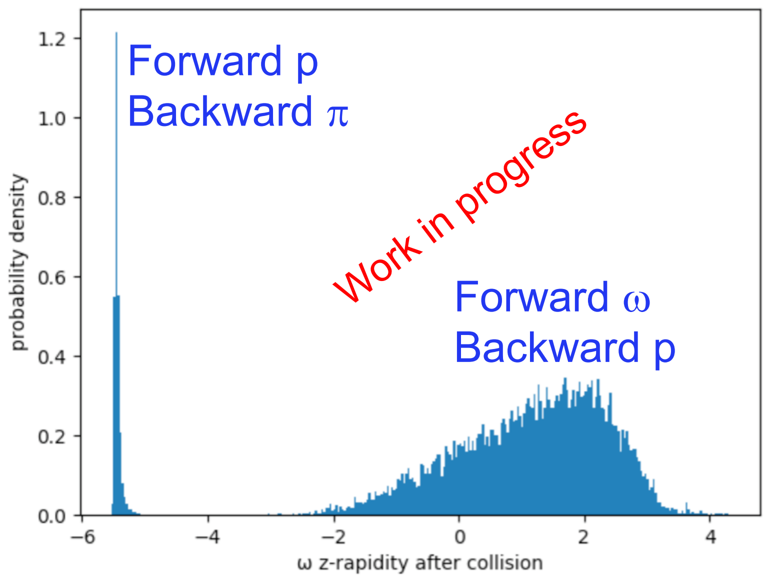
Parameterization of backward $\gamma p \to \omega p$

- ω is best studied backward photoproduction case
  - Fit to data from two experiments (see backup), after selection
- Follow approach used for vector meson dominance production:
  - $d\sigma/dt|_{t=0} \sim A\,(s/1\mathrm{GeV})^B$ 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
- $d\sigma/du|_{u\sim 0} = A\,(s/1\mathrm{GeV})^B$
  - $A = 4.4\ \mu b/\mathrm{GeV}^2$
    - $A=180\ \mu b/\mathrm{GeV}^2$ for forward ω photoproduction
  - $B = -2.7$
    - $B=-1.92$ for forward ω photoproduction
- $d\sigma/du \sim \exp(-Cu)$, with $C=-21\ \mathrm{GeV}^{-2}$
  - 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.

Implications for EICs

- First simulations done for ultra-peripheral collisions. UPC reactions create ω at near-beam rapidity, and a mid-rapidity proton
- Similar expectations at an EIC. Need to detect vector mesons with rapidity <~ beam rapidity.
  - Need to instrument far-forward hadron going direction

UPC Au p->Au p ω at RHIC



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)

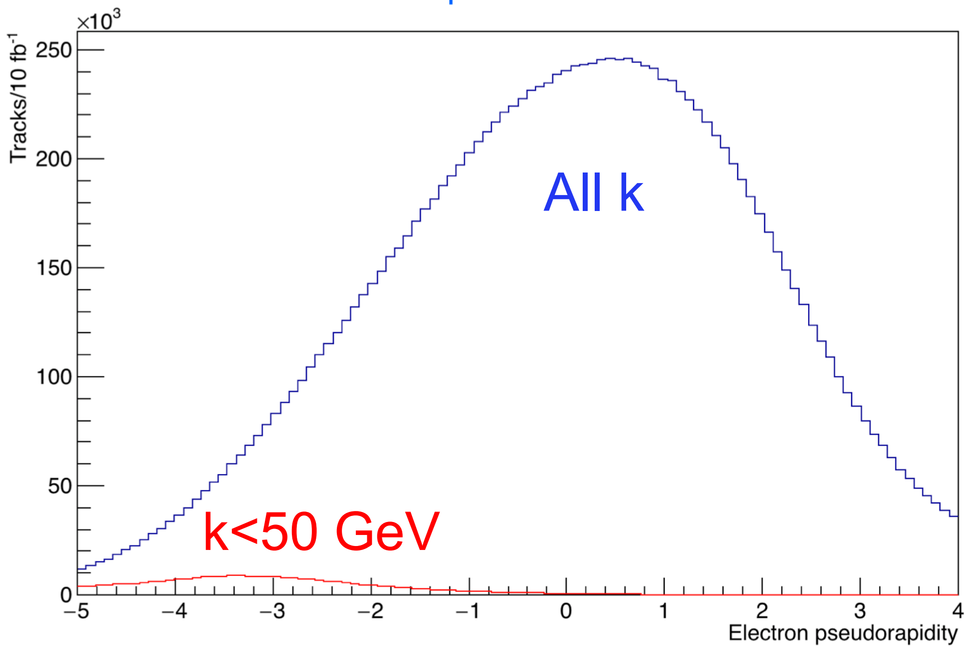
Conclusions

- Many interesting QCD phenomena appear in photoproduction relatively near the kinematic threshold.
  - 3-gluon exchange & exotic production mechanisms for heavy quarkonium
  - Photon-Reggeon fusion, to conventional and exotic mesons.
  - Baryon exchange channels, with large shifts in baryon rapidity.
    - The phenomenology is similar to baryon stopping in heavy-ion collisions.
      - Ala the baryon junction model.
- The signature of these phenomena are predominantly in the hadron-going direction at an ep/eA collider.
  - The forward region is particularly important.

Backup

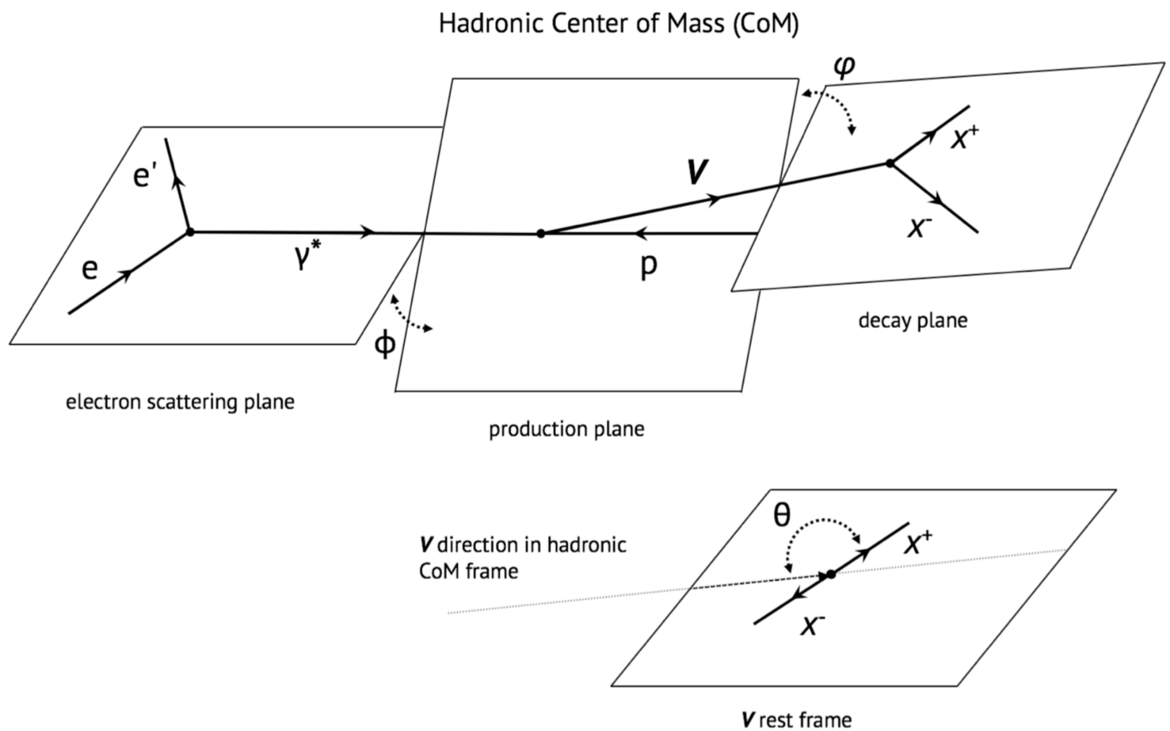
Ψ(2S)->ee lepton pseudorapidities

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

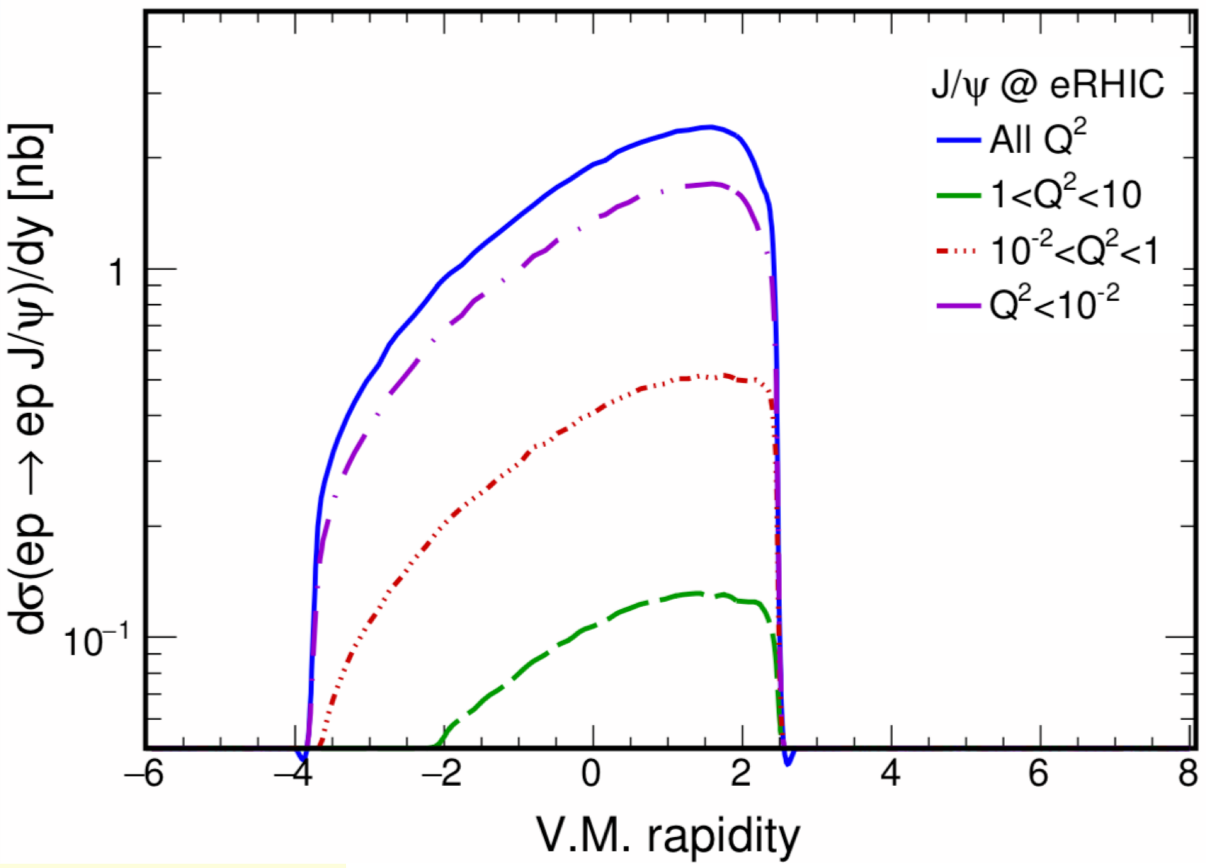


e->   <-Hadron

Angular definitions



Rapidity vs. Q^2



$\gamma p \to \omega p$ 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).