Backward meson production at high energies: Connection with baryon stopping, and experimental prospects

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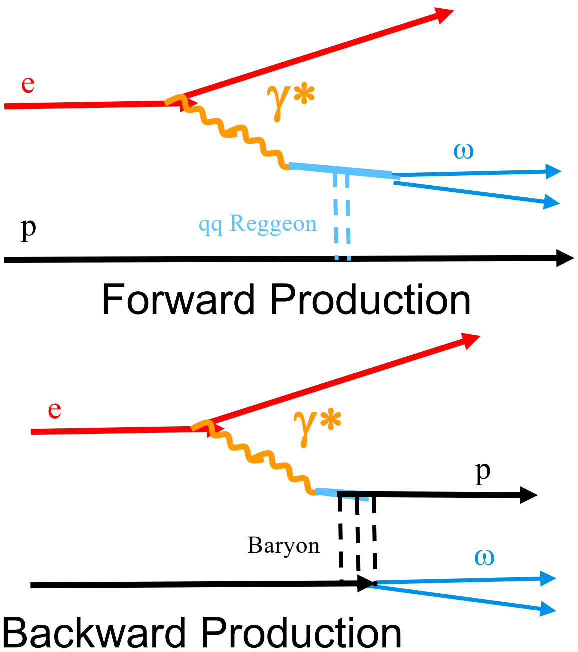
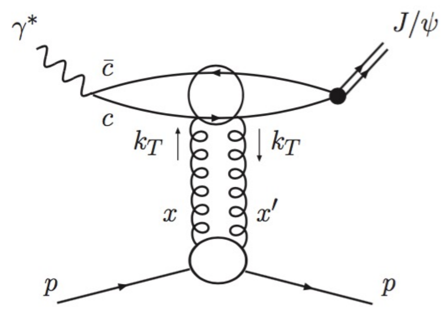
- Backward meson production
- Connection with baryon stopping
- Observability in ultra-peripheral collisions
- Observability at the EIC
- Conclusions



*Work done in collaboration with Zach Sweger

Conventional (forward) production

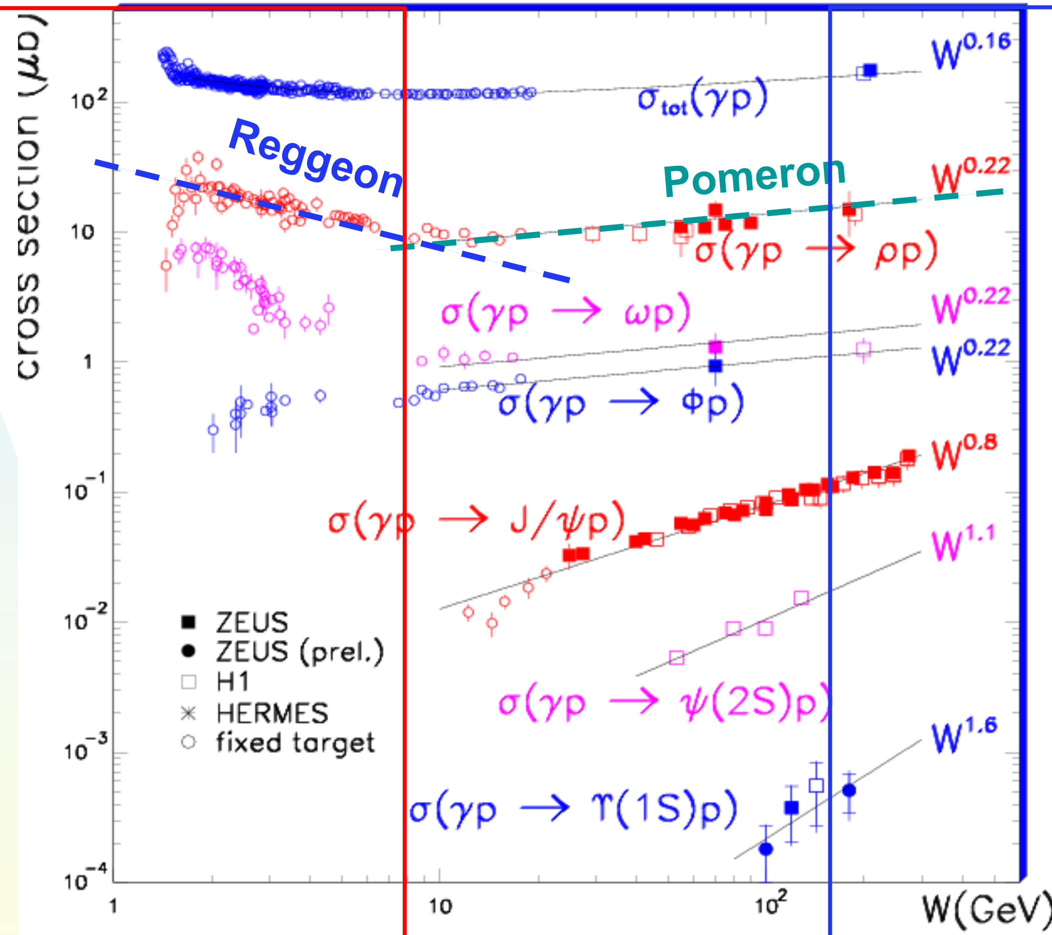
- In conventional (forward) meson a photon fluctuates to a q-qbar dipole (virtual vector meson), which scatters from a target, emerging as a real meson
  - Strong force, without color exchange
  - Pomeron or Reggeon exchange
- The Pomeron dominates at high energies
  - To lowest order, 2 gluons
    - LO may be inadequate here



- Reggeon (mesonic) trajectories dominate at low energies
- Describes light meson production well:
  - $\sigma(W) = XW^{\epsilon} + YW^{-\eta}$
    - $\varepsilon \sim 0.22$ for the Pomeron trajectory
    - $\eta \sim 1.5$ for Reggeon (summed meson)trajectories
  - $d\sigma/dt \sim \exp(-bt)$, where b depends on the size of the target
    - t is generally small (p_T<hbar/R_A)

Pomerons, Reggeons and kinematics

HERA + fixed target data



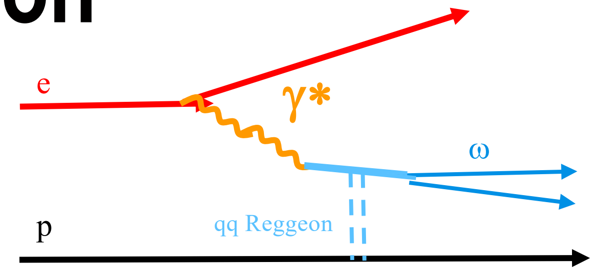
Ion-going direction
Reggeon dominated
Near threshold production

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

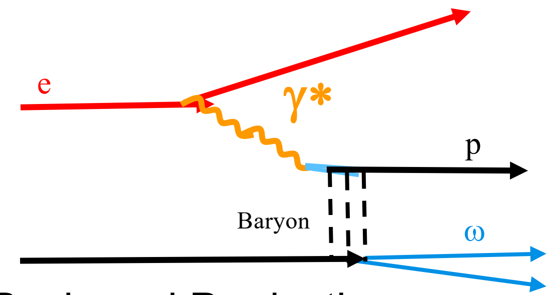
Electron-going direction
Pomeron- dominated
Low-x gluons
saturation

Backward (u-channel) production

- t is large and u is small
  - In γp center-of-mass frame, meson and proton switch places
  - The meson is far-forward, while the proton is at mid-rapidity
  - u replaces t: $d\sigma/du \sim \exp(-Cu)$
- Studied at fixed target accelerators
  - Generally only light mesons*
    - Proton and meson share quark flavors
- Baryon is shifted by multiple units in rapidity
  - In one picture, the baryon and meson both recoil backwards after the collision (ala Rutherford)
  - Alternately, the baryon number is transferred to the photon
- Two models:
  - Transition Distribution Amplitudes (TDA, like GPDs)
  - Regge trajectories involving baryons



Forward Production



Backward Production

C. Ayerbe Gayoso et al., arXiv:2107.06748; D. Cebra et al. Phys. Rev. C **106**, 015204 (2022)

Backward π^+ production

- $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$
  - Charged & neutral baryon trajectories

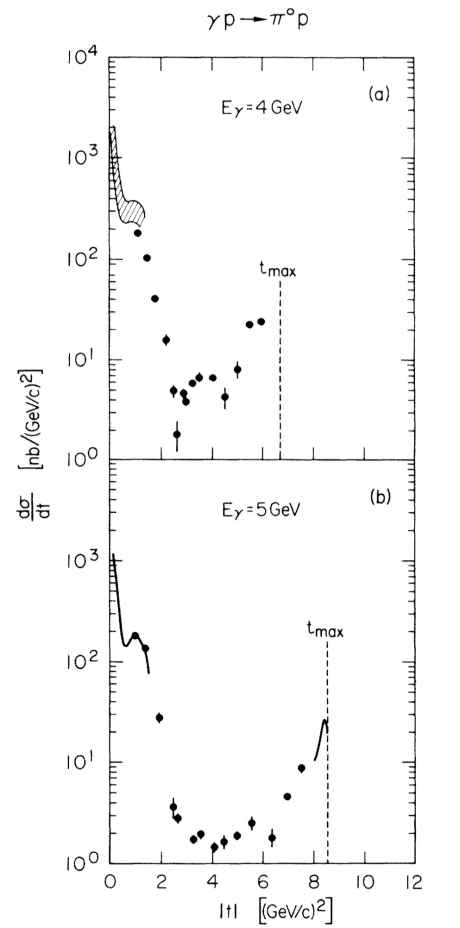
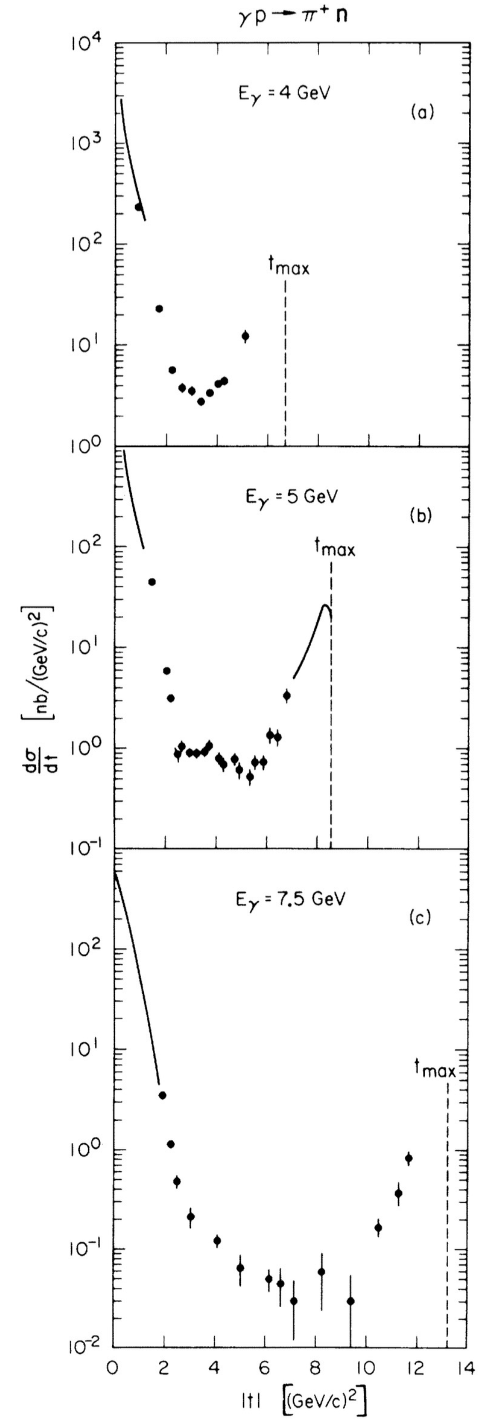


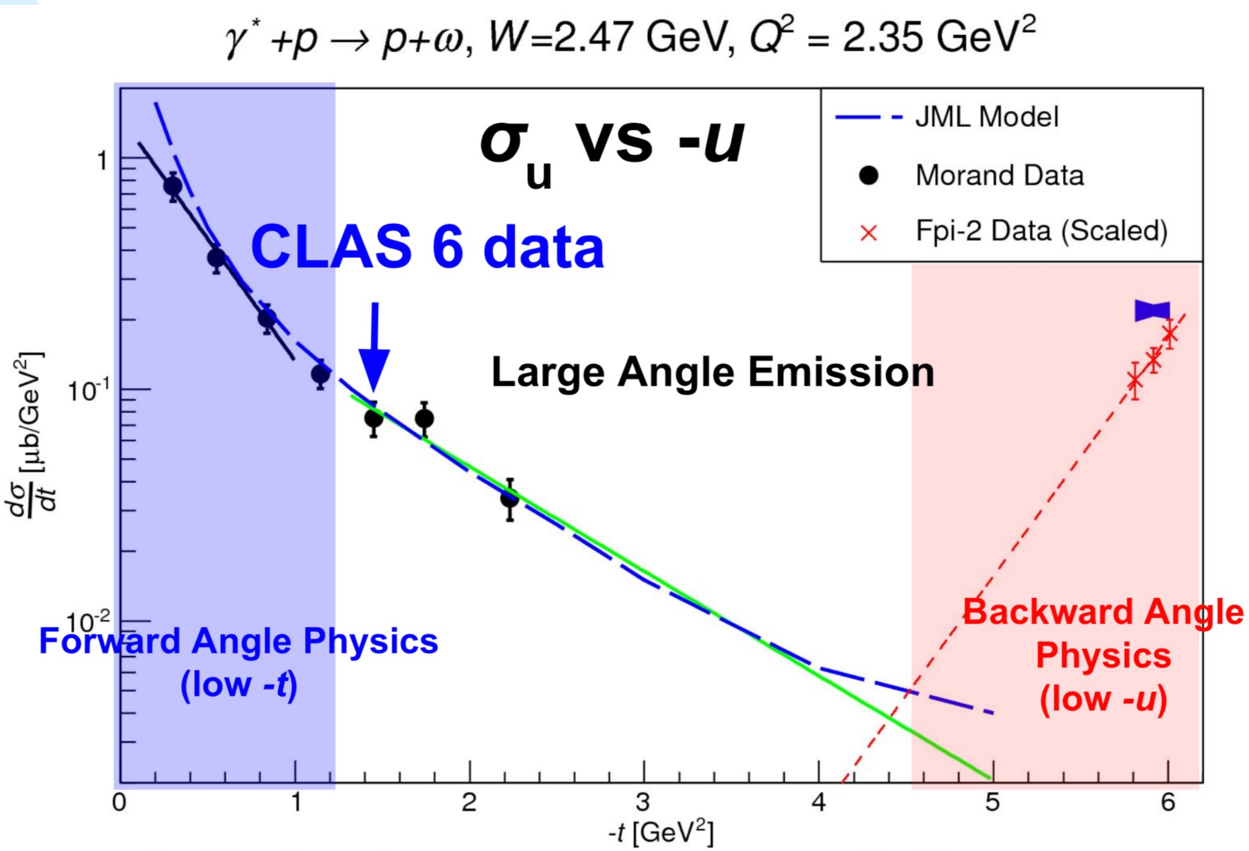
FIG. 7. $d\sigma/dt$ versus t for the reaction $\gamma p \to \pi^0 p$ at (a) $E_\gamma = 4.0$ GeV and (b) $E_\gamma = 5.0$ GeV.



R. L. Anderson et al.,
Phys. Rev. D **14**, 679 (1976)

$\gamma^*p \to \omega p$

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



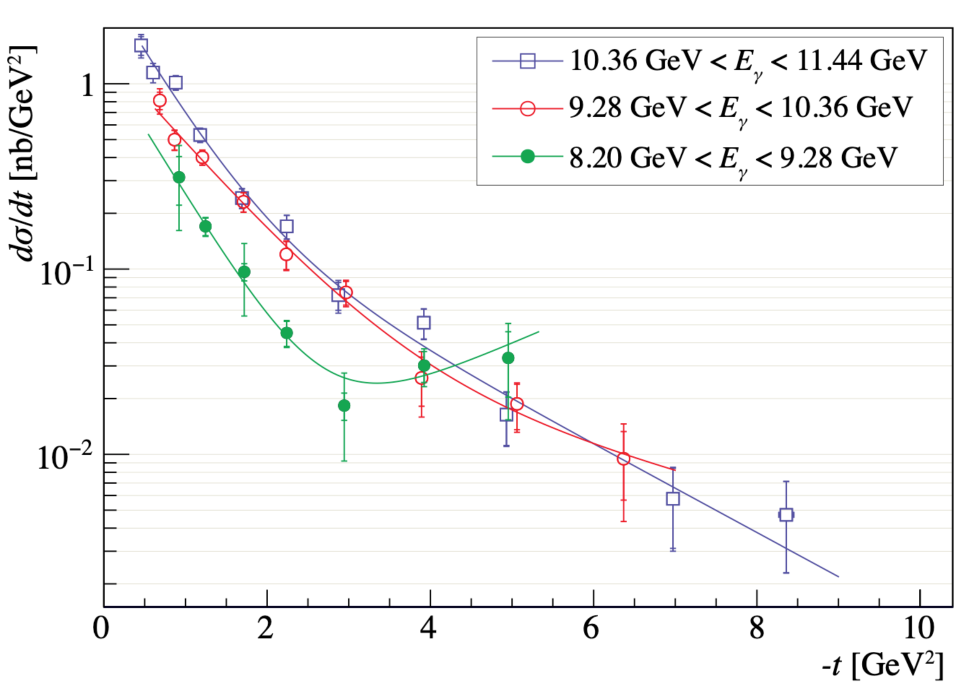
Soft structure -> Hard -> Soft transition

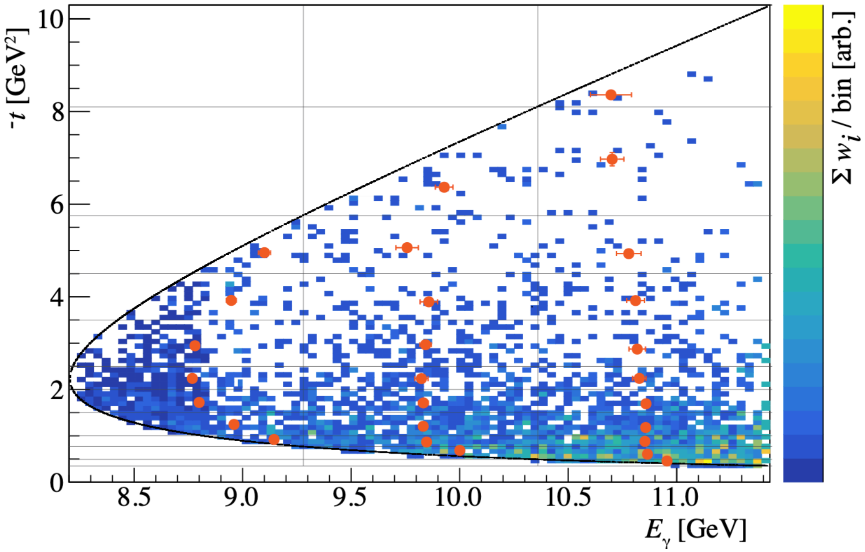
First time in electroproduction

Plot from Bill Li (Stony Brook); data from W. B. Li et al. (Jlab Fπ) PRL **123**, 182501 (2019).

Backward J/ψ production?

- Intriguing near-threshold J/ψ data from Glue-X @ Jlab
- At the lowest photon energy, dσ/dt turns upward at large t
  - Small-u region
- As the photon energy rises, u->0 corresponds to larger t
- The J/ψ shares no quarks with the incident baryon





Glue-X,
arXiv:2304.03845

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.

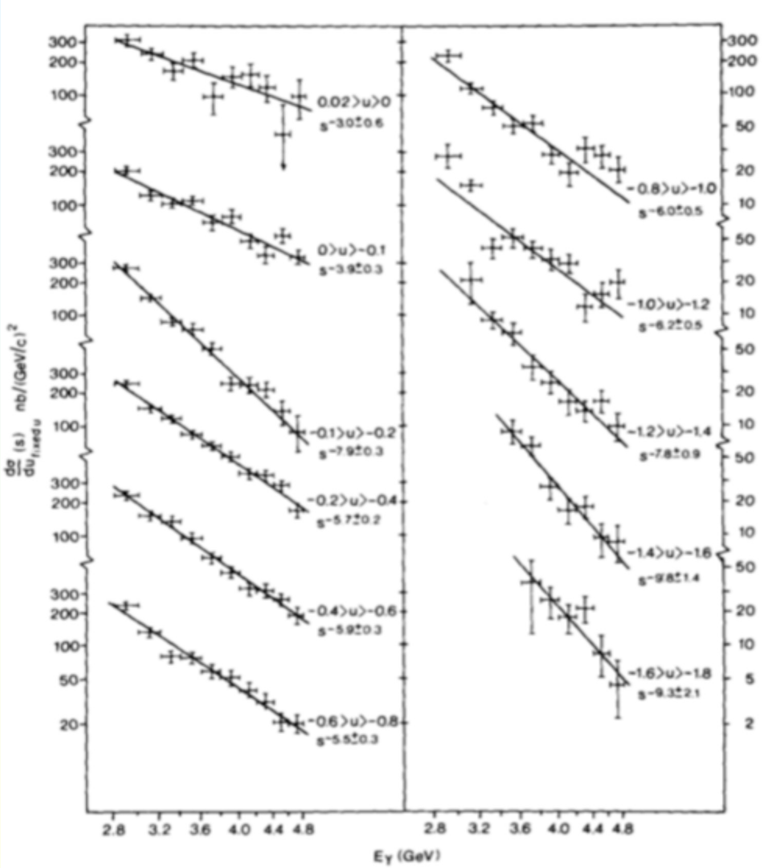


TABLE I. The compiled data. Errors on original data were around 25% of the listed value. Error due to transcription from figure is estimated to be less than 5%.

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[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).

Transition Distribution Amplitude Approach

- GPD-like model
  - Functions - Transition Distribution Amplitudes quantify baryon trajectories.

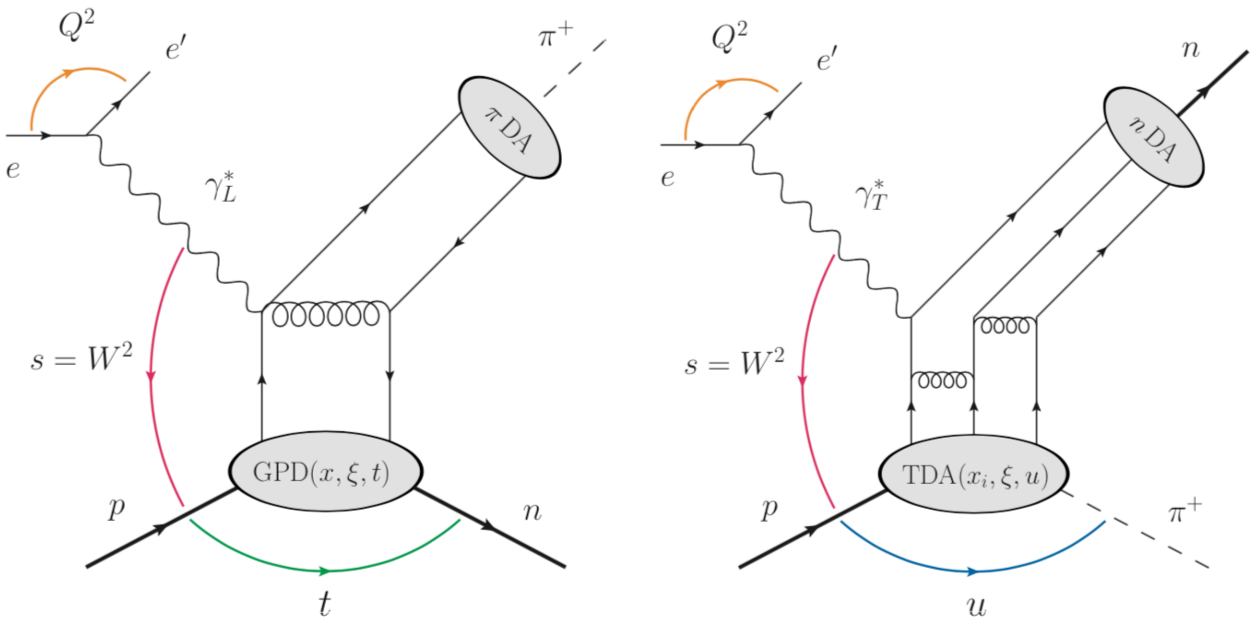


Diagram from K. Park et al., Phys. Lett. B780, 340 (2018)

Regge parameterization of backward $\gamma p \to \omega p$

- Fit to data from two experiments after selection
- Follow approach used for vector meson dominance 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
- $d\sigma/du|_{u\sim0} = A\,(s/1\text{GeV})^B$
  - $A = 4.4\ \mu b/\text{GeV}^2$
    - $A=180\ \mu b/\text{GeV}^2$ for forward ω photoproduction
  - $B = -2.7$
    - $B=-1.92$ for forward ω photoproduction
      - Falls off faster with increasing energy.
- $d\sigma/du \sim \exp(-Cu)$, with $C= 21\ \text{GeV}^{-2}$
  - Compared with $b \sim\sim 10\ \text{GeV}^{-2}$ for forward $\gamma p \to \omega p$
    - Object larger than a baryon???

  } Zach's Talk
- Rate is few ‰ of the forward rate for k~ GeV
  - Cross-sections are large enough to be easily accessible.

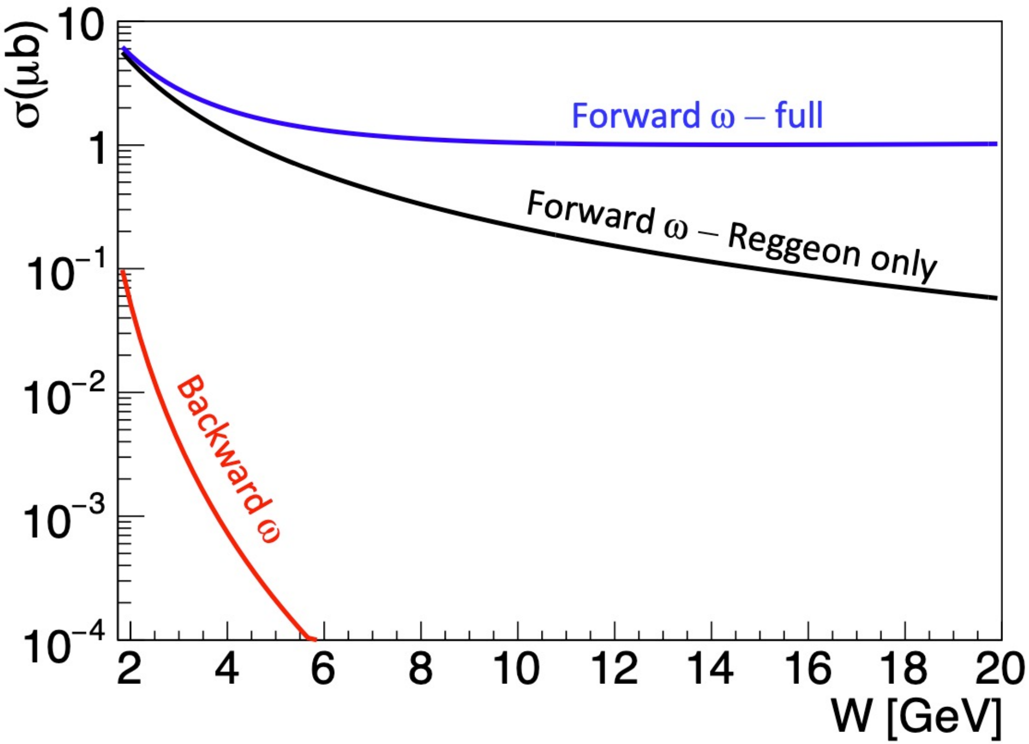
D. Cebra *et al.*, Phys. Rev. C **106**, 015204 (2022)

Energy dependence: a more detailed view

- Need to account for threshold region
  - Linear cutoff below W_{max}
    - W_{max} for forward production

$$T(W) = \mathrm{Min}\left(\frac{W - W_T}{W_{\max} - W_T}, 1.0\right)$$

$$\left.\frac{d\sigma}{du}\right|_{u=0} = A\left(\frac{k}{1\ \mathrm{GeV}}\right)^{-\eta} = A\left(\frac{W^2 - m_p^2}{2m_p(1\ \mathrm{GeV})}\right)^{-\eta}$$



Faster falloff than for forward Regge trajectories

Electroproduction

- Data from Jefferson lab at $Q^2=2.21$ GeV^2 and 2.45 GeV^2
  - $\sigma_{\text{Longitudinal}} \sim 1/Q^{10.22}$
    - Small lever arm
    - Transition Distribution Amplitude (GPD-like) predicts $1/Q^8$
    - Divergent as Q^2->0
  - $\sigma_{\text{Transverse}} \sim 1/Q^{1.08}$
    - Very slow Q dependence
- Probably not a single power law
  - For now, assume same Q^2 dependence as forward production

$$\sigma(Q^2,W) = \sigma(0,W)\left(\frac{M_\omega^2}{M_\omega^2+Q^2}\right)^{2.09+0.73(M_\omega^2+Q^2)/\text{GeV}^2}$$

  - From fits to ρ^0 data done for eSTARlight

W. B. Li et al. (Jlab Fπ) PRL **123**, 182501 (2019);
M. Lomnitz and SK, Phys. Rev. C **99**, 015203)2019)

Backward production and baryon stopping

- Baryon stopping can be explained in baryon-junction models using Regge trajectories that can shift baryon number by many units of rapidity.
- This is very similar to backward production
  - Regge trajectories seem comparable
  - Baryon stopping in ion collisions is via hadron-hadron (or parton-parton) interactions, while backward production involves dipole-hadron interactions
  - In hadron-hadron collisions, usually only one baryon is stopped
    - Small difference – factor of 2/3 in coupling to dipole vs. hadron?
- Both seem to be non-perturbative processes
  - Backward production is very simple, and can be a useful test laboratory for these phenomena.

D. Cebra *et al.*, Phys. Rev. C **106**, 015204 (2022);
D. Kharzeev, Phys. Lett. B **378**, 238 (1996)

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.

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

Tests for backward production models

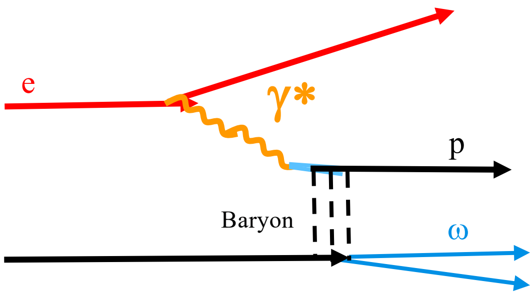
- New kinematic regimes
  - High energies
  - Wide range of Q^2 (preferably in a single experiment)
- Differences between mesons that share a quark with the baryon (ρ, ω) and those that do not (ϕ, J/ψ)
- Systematic measurements of a variety of charged and uncharged vector and non-vector mesons
  - π^0, η, η', ϕ, $a_2(1320)^+$ J/ψ and γ (Virtual Compton Scattering)
  - Can we fit all of the data into a neat Regge model with a small-ish number of parmeters?
    - N. b. Here, I am thinking only of data above the resonance region
      - $W_{\gamma p} > \sim 2$ GeV
- Nuclear targets (to measure neutron cross-sections and look at nuclear modifications)
- Final state meson polarization, if any

High energies with UPCs and the EIC

- UPCs: ultra-peripheral collisions in relativistic heavy ion collisions
  - Heavy ions carry strong EM fields which act as fields of nearly-real photons
    - Flux ~ Z^2
    - Maximum photon energy ~ γ hbar c/R_A in lab frame
      - Maximum $W_{\gamma p}$ ~ 2 TeV at the LHC
- Rates/cross-sections are high
  - $\sigma(PbPb \rightarrow PbPb\rho^0)$ ~ 7 barns at the LHC
- Poorly exploited due to problems triggering
  - LHC Run 3 detectors have generally moved to continuous readout DAQ systems
    - Increases UPC event collection by orders of magnitude
    - Sensitivity to processes with relatively small cross sections

Rapidity distributions for UPCs and an EIC

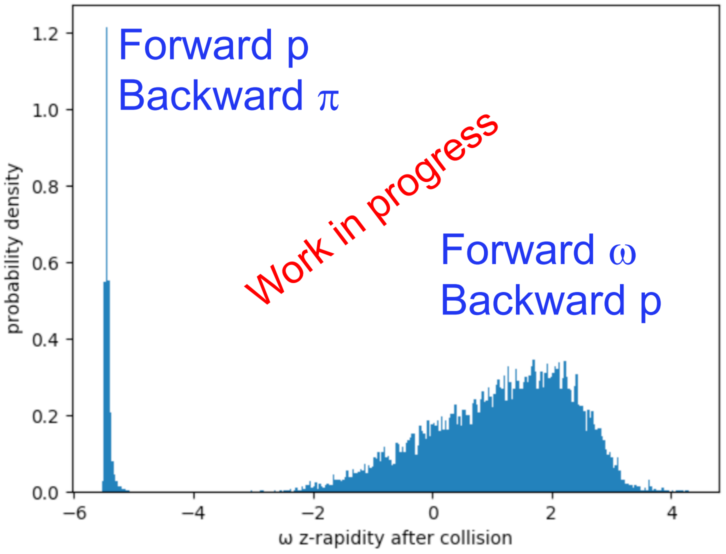
- Model as forward production, except:
  - In γp CM frame, swap ω and p rapidity
    - Photon is soft
    - ω is in far-forward region (near beam rapidity)
    - Proton is at mid-rapidity
  - Use backward Regge trajectories, discussed earlier
    - Different $W_{\gamma p}$ dependence
    - $d\sigma/du \sim \exp(-Cu)$



Production with UPCs

- UPCs create ω near-beam rapidity, with a mid-rapidity proton
- ω is outside the range of existing/planned future detectors
  - Lower beam energies would shift it to smaller rapidity, but this will not lead to practical detection
- π^0 and photons (virtual Compton scattering) should be produced at higher rapidity, and could be visible in zero degree calorimeters
  - Some ZDCs are segmented, so can separate γ/π^0 from neutrons
    - At the LHC, γ and π^0 should hit ZDC
  - More investigation needed!

UPC Au p->Au p ω at RHIC



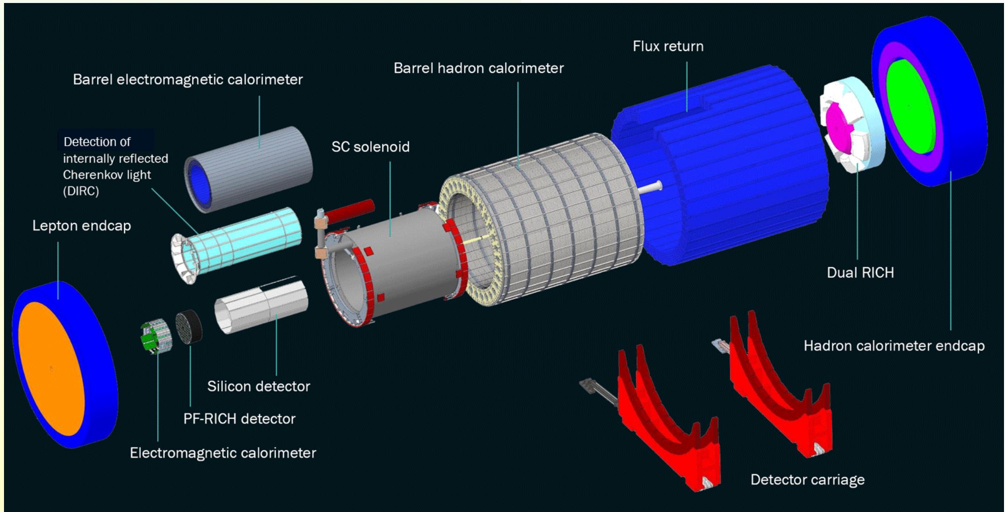
C. Ayerbe Gayoso, Eur. Phys. J. A**57**, 342 (2021)

EIC studies

- The backward Regge model was implemented in eSTARlight
  - ρ^0, ω, π^0 and Compton scattering
  - Mesons are assumed unpolarized
- Acceptance was studied in ePIC-like detector
  - 5X41 GeV^2, 10X100 GeV^2 and 18X275 GeV^2

I will discuss ρ^0, ω; Zach will cover the π^0 and γ

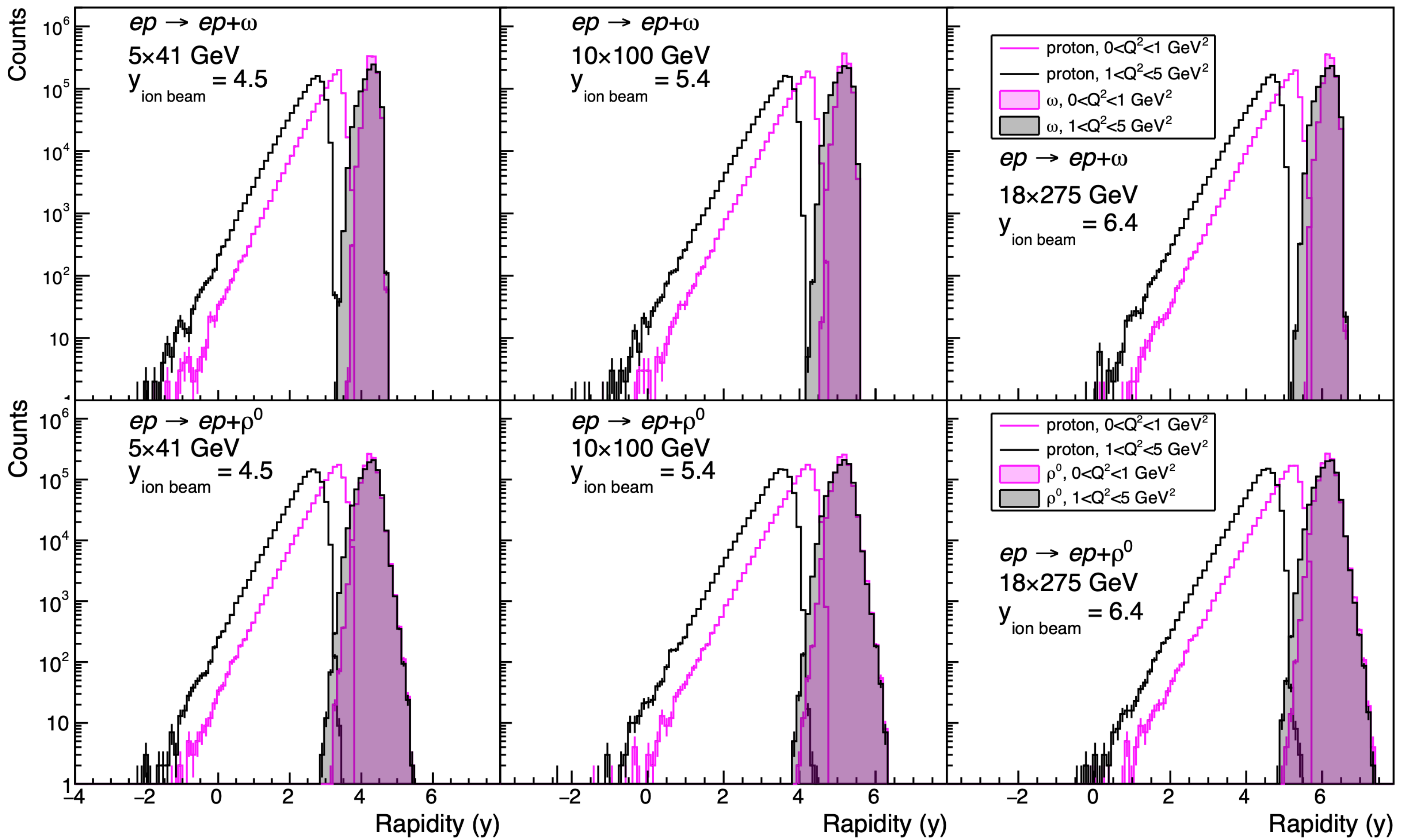
Detector	Capabilities	Pseudorapidity Coverage
Central	charged-particle tracking	$-3.5 < \eta < 3.5$
	electromagnetic calorimetry	
B0	charged-particle tracking	$4.6 < \eta < 5.9$
	potential electromagnetic calorimetry	
ZDC	electromagnetic calorimetry	$\eta >\sim 6.1$



D. Cebra et al.,
Phys. Rev. C **106**, 015204 (2022);
Z. Sweger et al.,
Phys. Rev. C **108**, 055205 (2023)

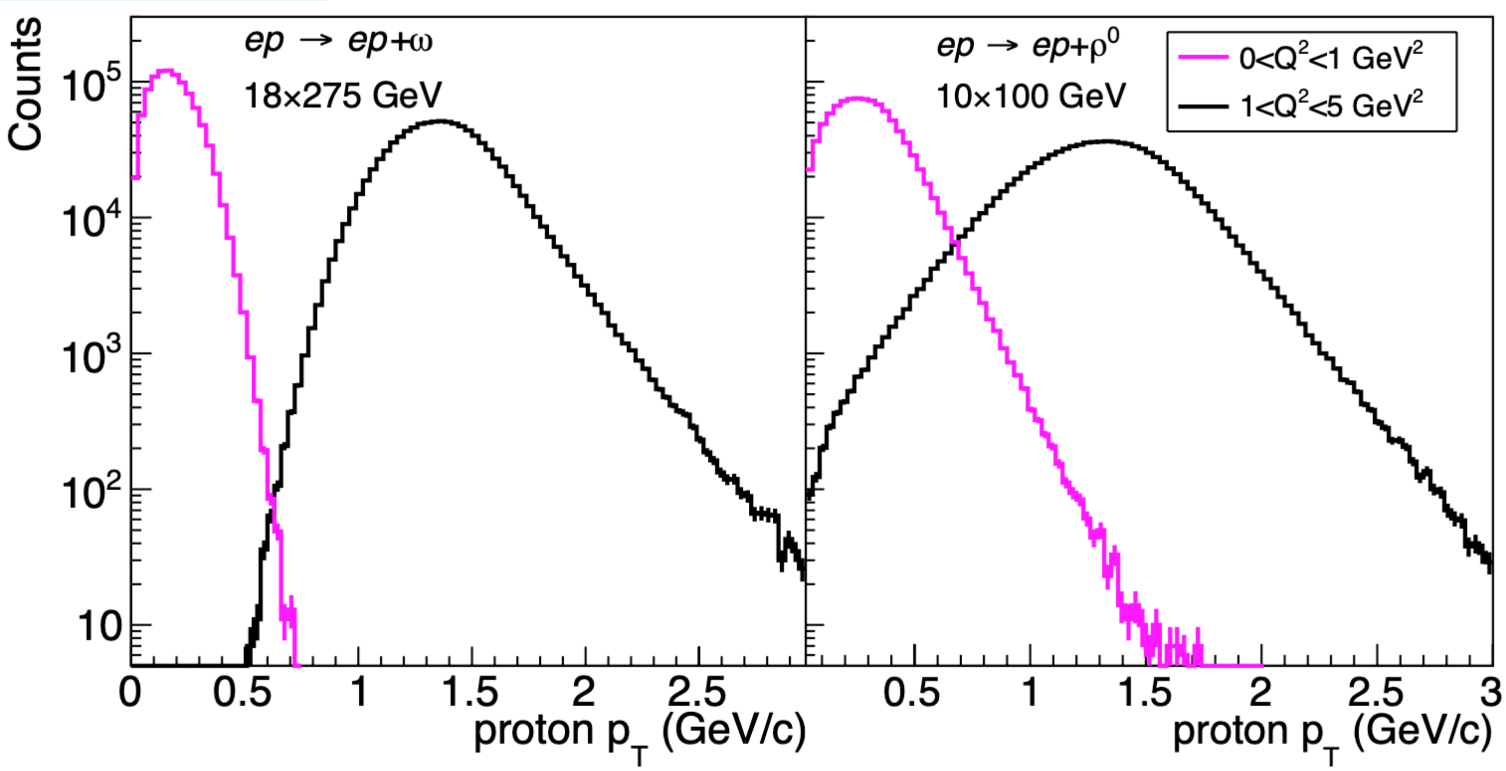
Proton and meson rapidities

- Proton is mostly visible in central detector
- Meson is mostly at rapidity 4-7, increasing with beam energy



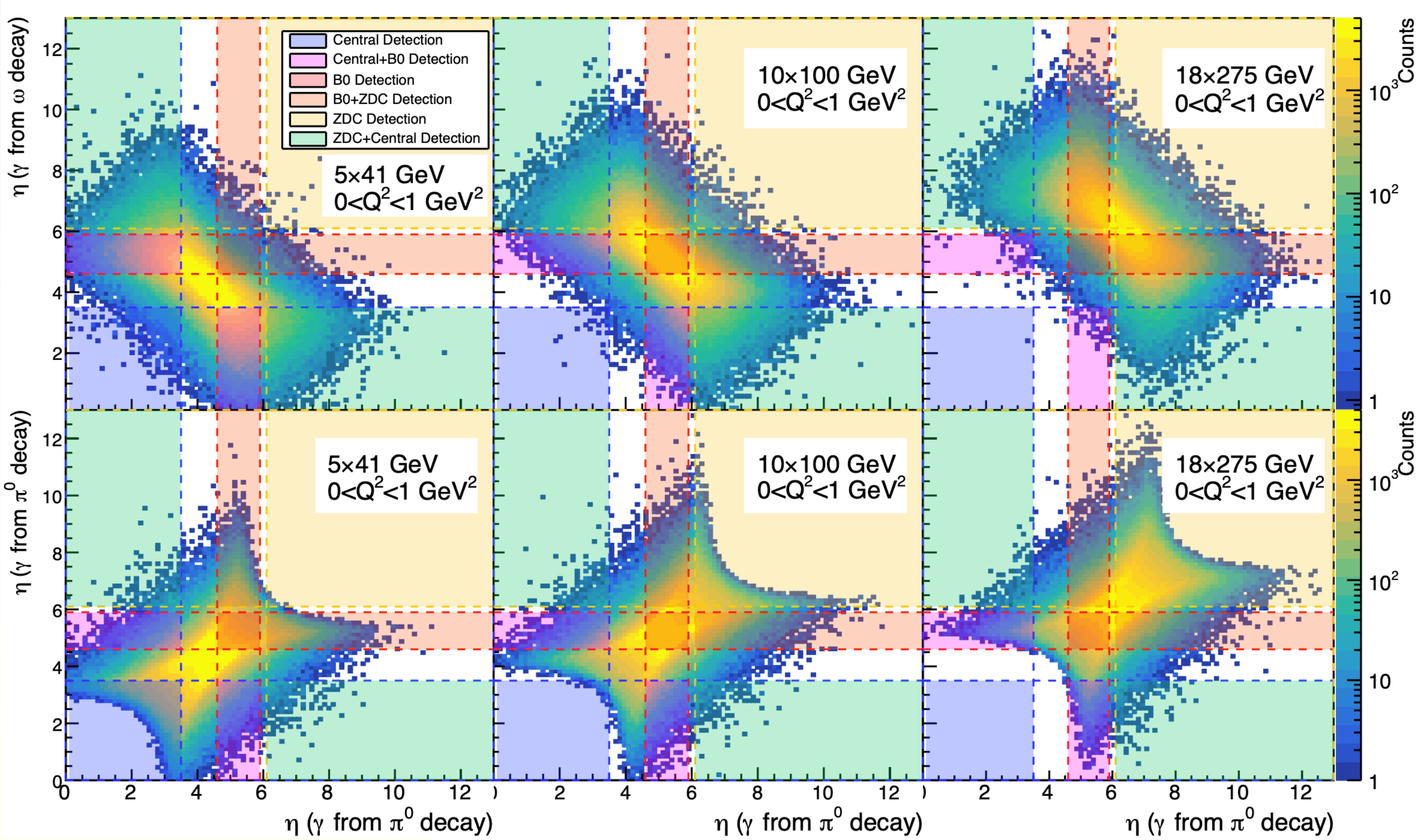
Proton p_T

- Proton p_T is moderate, well within detection and particle identification limits
- Proton p_T increases with photon Q^2



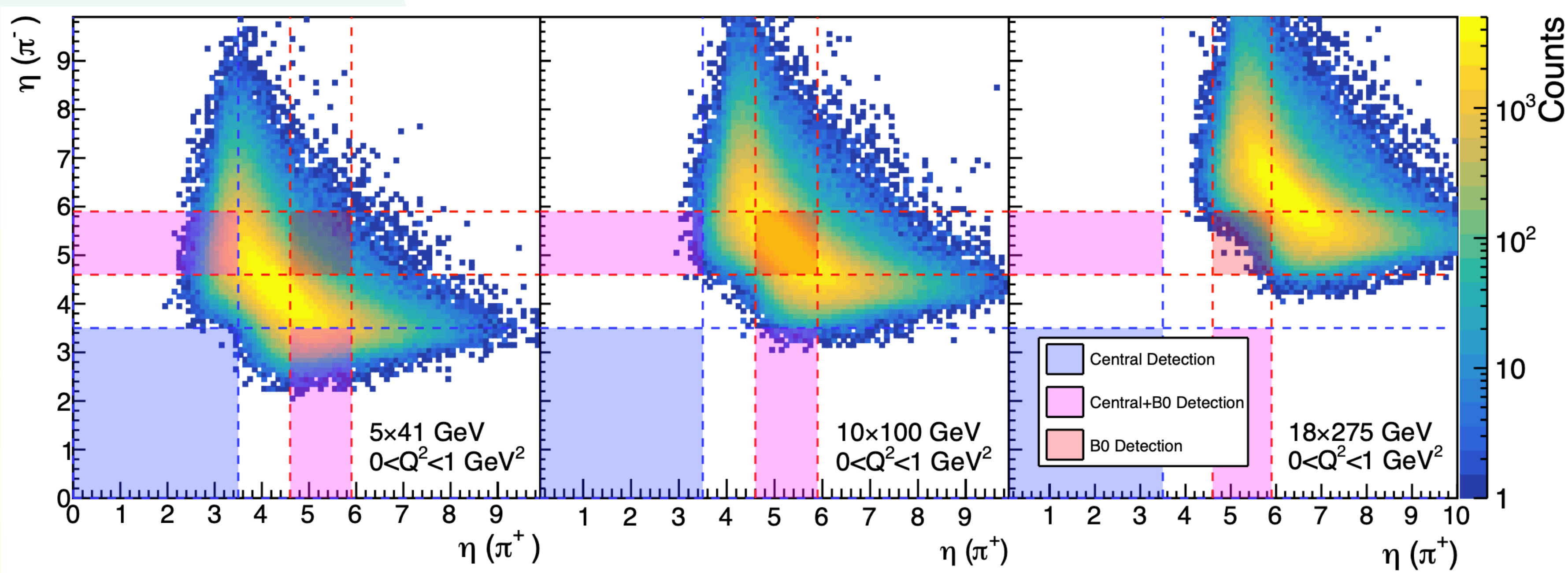
ω acceptance in $\gamma p \to \omega p \to \pi^0\gamma \to (\gamma\gamma)\gamma$

- Photons from π^0 are equivalent.
- A good fraction of the photons end up in the B0 detector or ZDC
- B0 is critical at medium energies, ZDC for 18X275 GeV^2



ρ acceptance in $\gamma p \to \rho p \to p\, \pi^+\pi^-$

- ZDC cannot measure charged particle momentum
- Pions miss the central detector
- Only visible in B0 detector
  - Efficiency good for 10X100 GeV^2 beams



Rates and efficiencies

- ω rates are high ~ 10M events/10 fb $^{-1}$
  - Little dependence on beam energy
  - Q^2 lever arm depends on Q^2 distribution
  - ρ rates are likely similar to or higher than ω

Collider energy	t-channel σ_{Tot} (nb)	u-channel σ_{Tot} (nb)	u-channel events per 10 fb^{-1}
5×41 GeV	501	1.8	1.8×10^7
5×100 GeV	583	1.9	1.9×10^7
10×100 GeV	651	2.0	2.0×10^7
10×275 GeV	758	2.2	2.2×10^7
18×275 GeV	825	3.2	3.2×10^7

- Efficiency for ω good with B0 magnet
- Efficiency for ρ is only good with B0 detector
  - B0 tracking is difficult, due to tough geometry

Proton beam energy	ω eff. cent.+ZDC	ω eff. cent.+B0+ZDC	ρ eff. cent.+B0
41 GeV	1.4%	18%	13%
100 GeV	1.3%	41%	49%
275 GeV	6%	63%	0.7%

Extension to other mesons

- Meson mass and proton energy are the key variables

$$y_V \approx 0.7 - \ln\left(\frac{m_V}{E_p}\right)$$

- Should work for UPCs also
- At the EIC:

Meson	5x41 GeV^2	10X100 GeV^2	18X275 GeV^2
ϕ	6.3	5.3	4.4
J/ψ	5.2	4.2	3.3

- $\phi \to K^+K^-$ may be tough because of the soft kaons
- J/ψ-> ee, $\mu\mu$ should be geometrically accessible in a combination of the central tracker + B0 detector.
    - PID requirements do not seem stringent.
- For UPC π^0 at the LHC (7 TeV protons), y=11.5, which should be within the ZDC acceptance

Conclusions

- Backward (u channel) production can produce mesons with large t exchange, but small u
- The struck baryons are shifted by many units in rapidity. This shift is very similar to baryon stopping.
  - Backward production and baryon stopping can be described by similar Regge models. It would be interesting to explore if a single set of parameters can explain both.
- Systematic measurements are needed of backward production of a large number of mesons, under varied kinematic conditions.
- It may be possible to explore backward π^0 and γ production at high energies using ultra-peripheral collisions.
- Looking further ahead, the EIC and ePIC detector are quite well suited to making systematic measurements of backward production at high energies, over a range of Q^2.

Backup

- Thank you

$\gamma p \to \omega p$ data

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