Backward–Angle Exclusive ω Production from JLab 6 GeV Hall C

University of Regina

Garth Huber

Backward–Angle (u–channel) Physics Workshop
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Jefferson Lab Fπ Collaboration

W.B. Li, et al., Phys. Rev. Lett. 123 (2019) 182501., arXiv: 1910.00464

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Mandelstam variables (*s,t,u*–channels)

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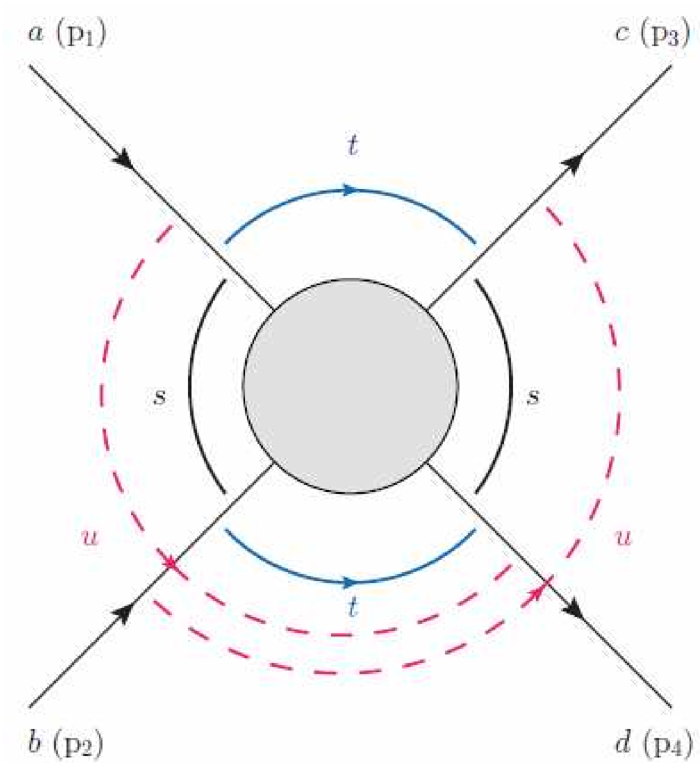

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

s: invariant mass of the system

t: Four–momentum–transfer squared between **target before and after interaction**

u: Four–momentum–transfer squared between **virtual photon before interaction and target after interaction**

***t*-channel: *–t ~ 0*, after interaction**
- **Target: stationary**
- **Meson: forward**
- **Measure of how forward could the meson go.**

***u*-channel: *–u~0*, after interaction**
- **Target: forward**
- **Meson: stationary**
- **Measure of how backward could the meson go**

Evolution of Proton Structure

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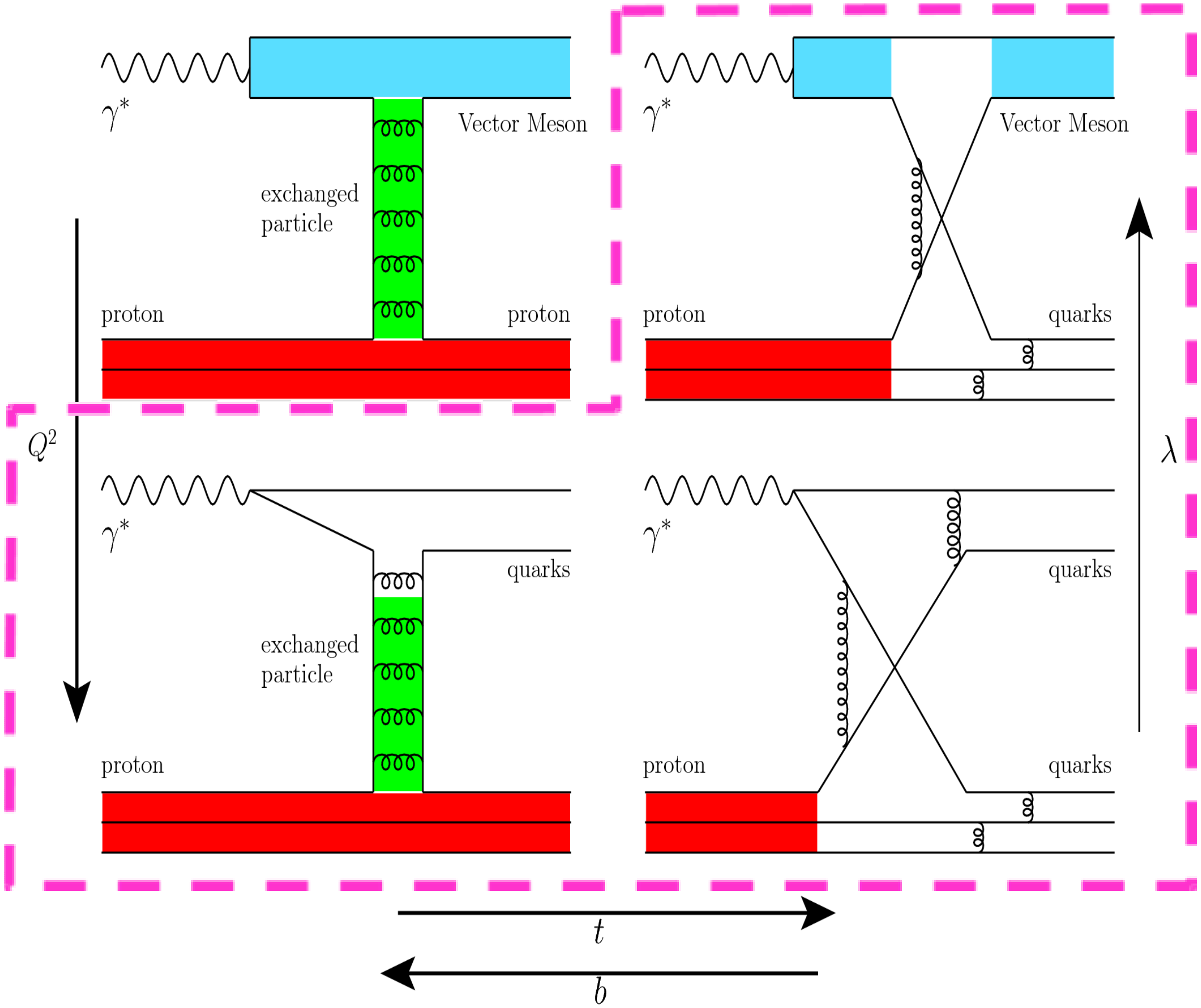

Evolution of the Proton Structure

- Physics observables
  - ***t*, *W* (*s*), *Q*², *x***
- *x* Evolution:
  - 0.2–0.3 valence quark distribution pronounced
- *W* Evolution:
  - Above resonance region
- ***Q*² Evolution**
  - **Wavelength of γ^* probe**
- ***t* Evolution**
  - **Impact parameter** $\left(b \sim 1/\sqrt{-t}\right)$
- What about ***u***?
  - **Baryon exchange processes**

t–Channel π^+ vs *u*–Channel ω Production

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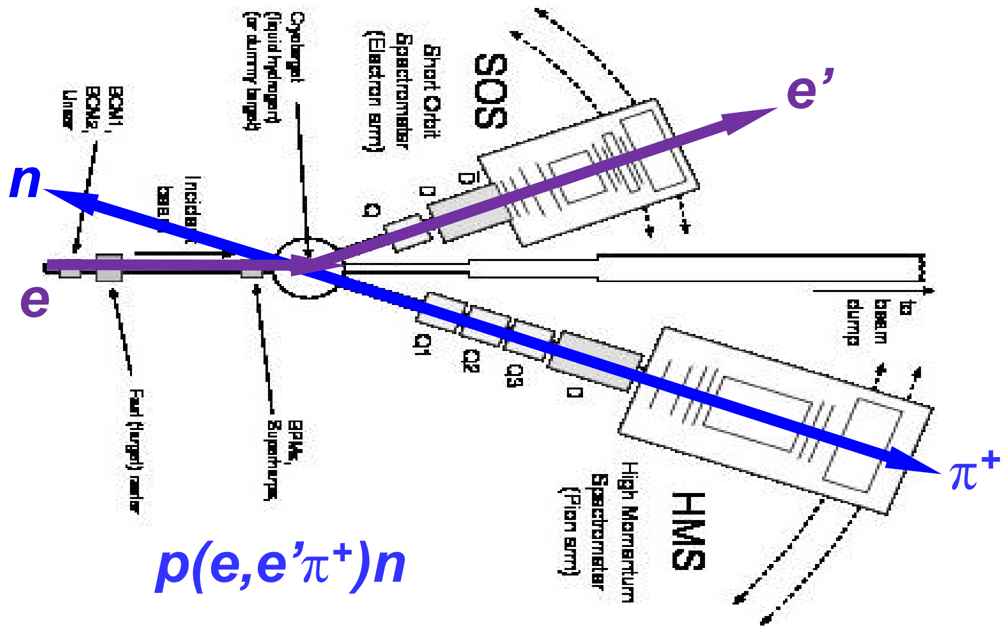
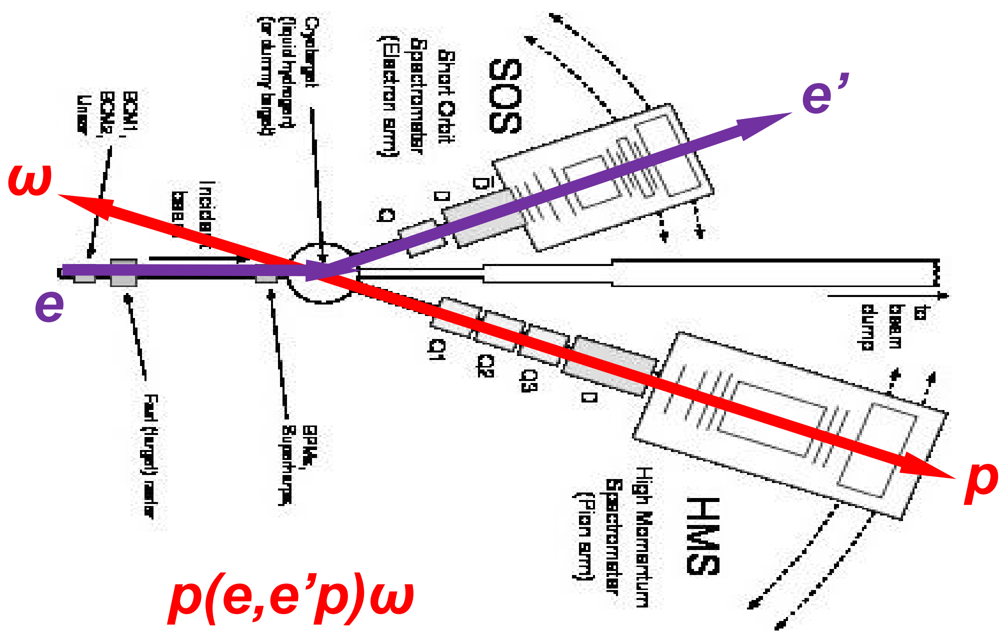


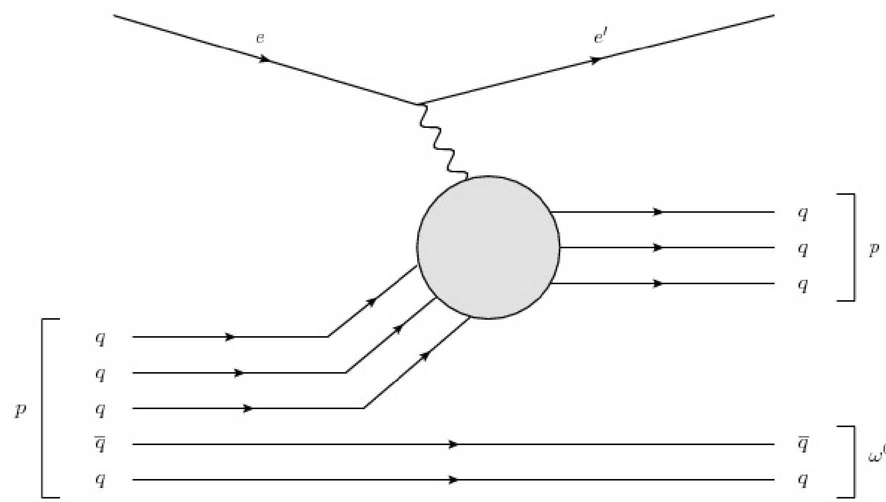


HMS is along *q*–vector (p_{γ^*})

- $p_{\pi+}$ is parallel to p_{γ^*} (forward)
- p_{ω} is anti–parallel to p_{γ^*} (backward)

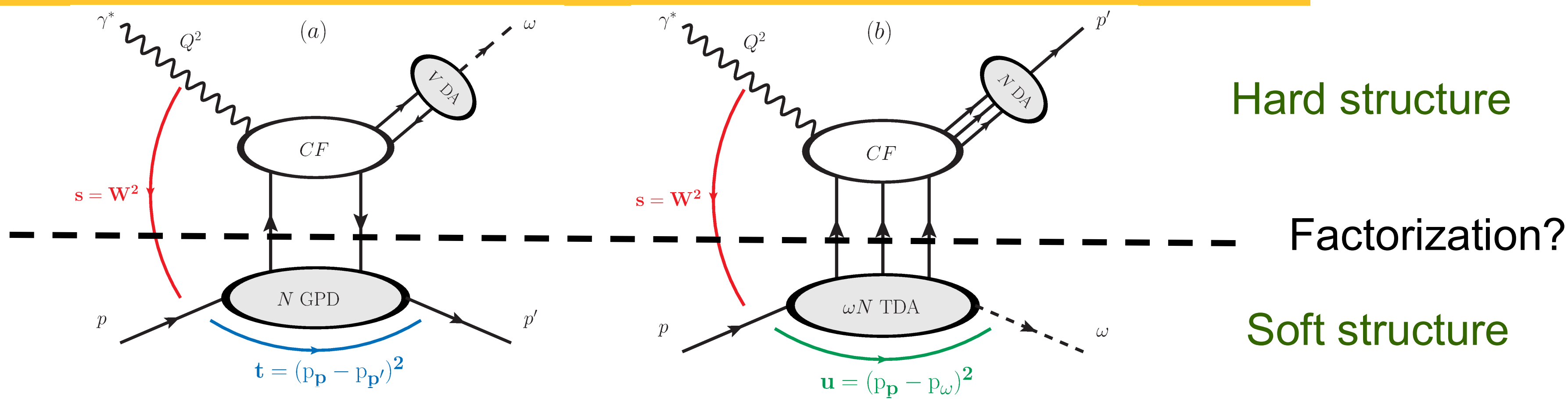
***p(e,e'p)ω* Exclusive channel**

- Full kinematic reconstruction of final state
- Do not detect any part of decayed ω



Mark Strikman: Knocking the proton out of the proton process.

GPD–Like Model: TDA and Factorization



***t*–channel (Forward)** ***u*–channel (Backward)**

Baryon to Meson Transition Distribution Amplitude (TDA)

- Extension of collinear factorization to backward angle regime. Further generalization of the concept of GPDs.
- Backward angle factorization first suggested by Frankfurt, Polykaov, Strikman, Zhalov, Zhalov at JLab 2002 Exclusive Reactions Workshop.
- TDAs describe the transition of nucleon to 3–quark state and final state meson. *[gray oval of plot b]*
- A fundamental difference between GPDs and TDAs is that TDAs are defined as hadronic matrix elements of 3–quark operator, while GPDs involve quark–antiquark operator.
- **Can be accessed experimentally in backward angle meson electroproduction reactions.**

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Backward Angle Collinear Factorization

- **Kinematical regime for collinear factorization involving TDAs is similar to that involving GPDs:**
  - x_B fixed
  - $|u|$–momentum transfer small compared to Q^2 and s
  - Q^2 and s sufficiently large

- Early scaling for GPD physics occurs $2<Q^2<5$ GeV^2
  - Maybe something similar occurs for TDA physics…

Two Key Predictions in Factorization Regime:

- **Dominance of transverse polarization** of virtual photon, resulting in suppression of longitudinal cross section by at least $1/Q^2$: $\sigma_T \gg \sigma_L$
- Characteristic $1/Q^8$–scaling behavior of σ_T for fixed x_B

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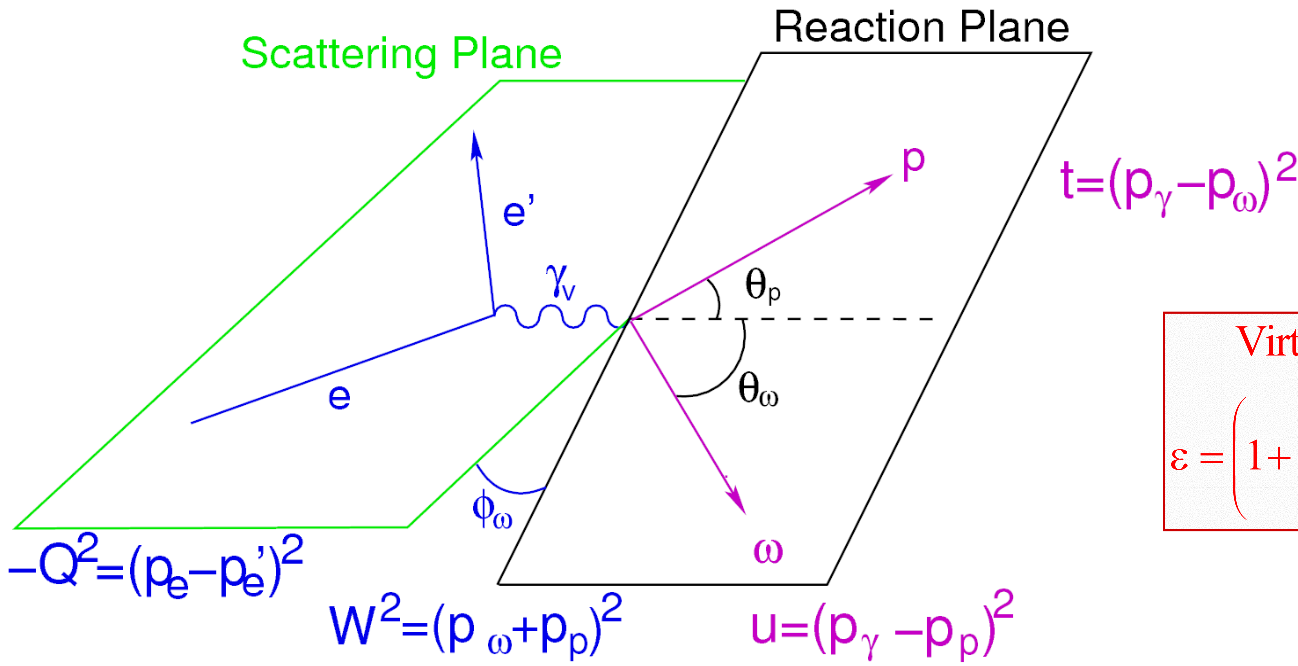
Rosenbluth (L/T/LT/TT) Separation



Virtual-photon polarization:

$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Rosenbluth Separation requires:

- Separate measurements at different ε (virtual photon polarization)
- All Lorentz invariant physics quantities: *Q^2, W, t, u,* remain constant
- Beam energy, scattered e' angle and virtual photon angle will change as a result, event rates are dramatically different at high, low ε

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Jefferson Lab Hall C Experimental Setup

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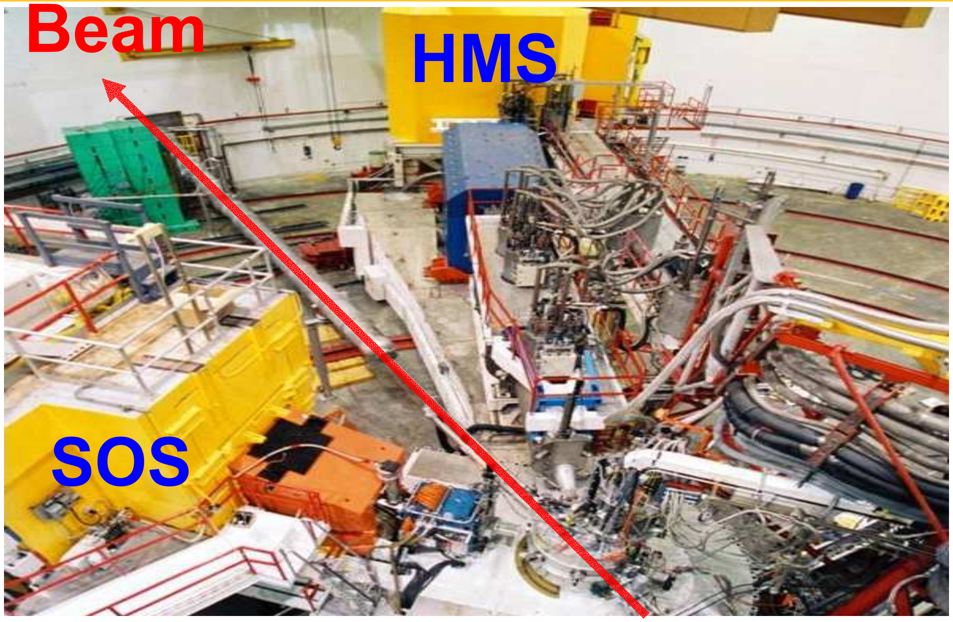
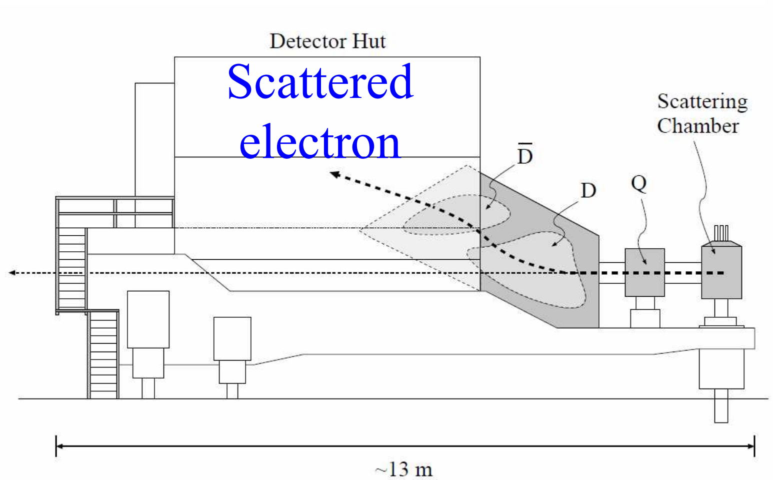
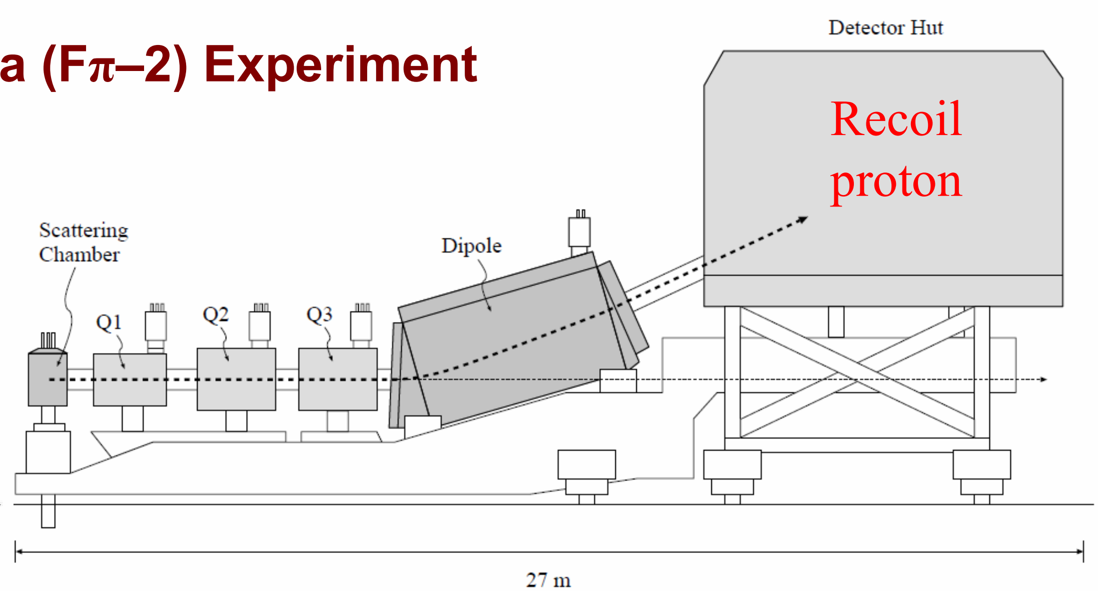


E_e (GeV)	ε	$-u$ (GeV²)	$-t$ (GeV²)	ξ_u	ξ_t
$\langle Q^2\rangle$=1.60 GeV² $\langle W\rangle$=2.21 GeV					
3.772	0.328	0.058 – 0.245	3.85 – 4.15	0.075 – 0.177	0.722 – 0.735
4.702	0.593				
$\langle Q^2\rangle$=2.45 GeV² $\langle W\rangle$=2.21 GeV					
4.210	0.270	0.117 – 0.400	4.48 – 4.94	0.126 – 0.256	0.748 – 0.764
5.248	0.554				

One of last analyses of 6 GeV era (Fπ–2) Experiment



Short Orbit Spectrometer (SOS)



High Momentum Spectrometer (HMS)

Experimental Setup and Acceptance

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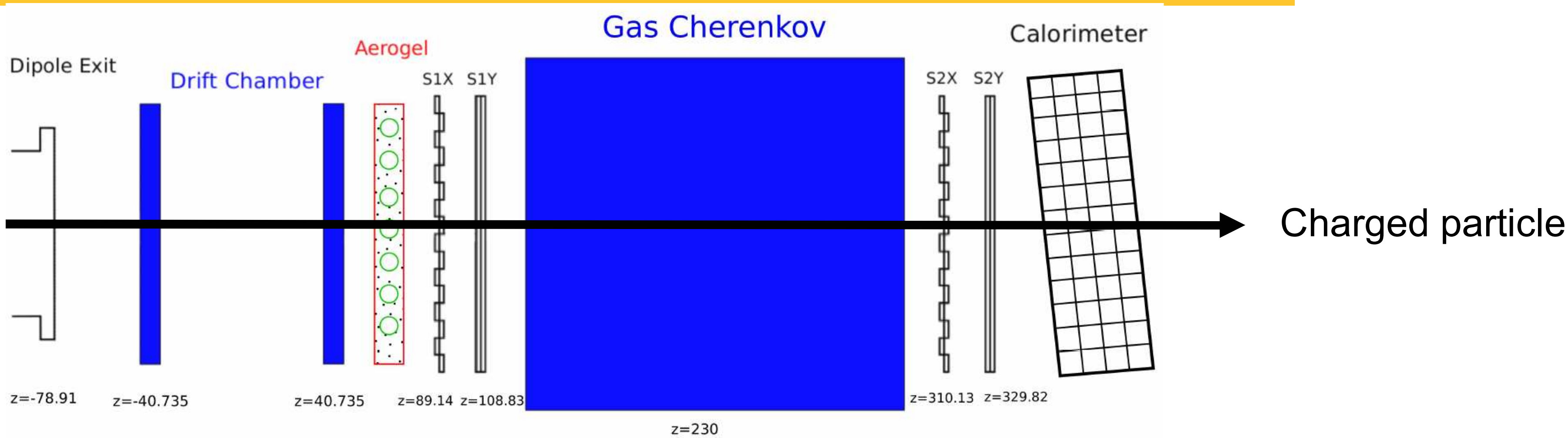
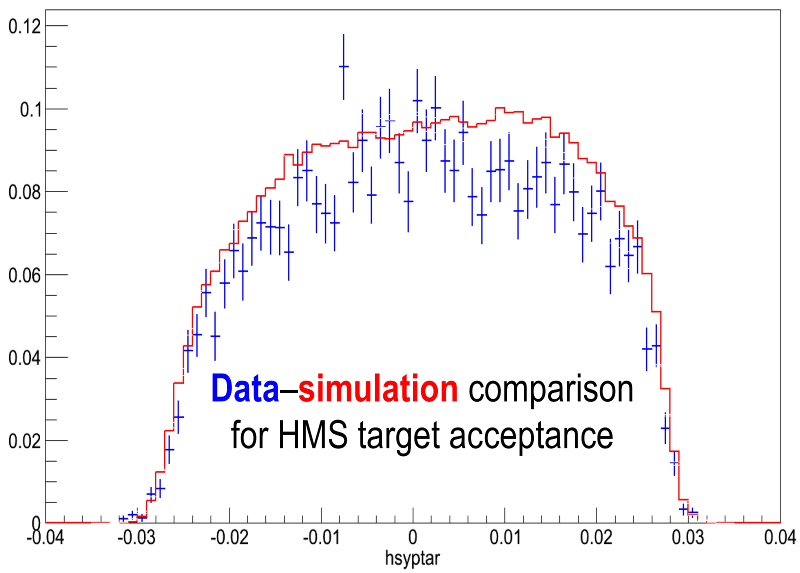
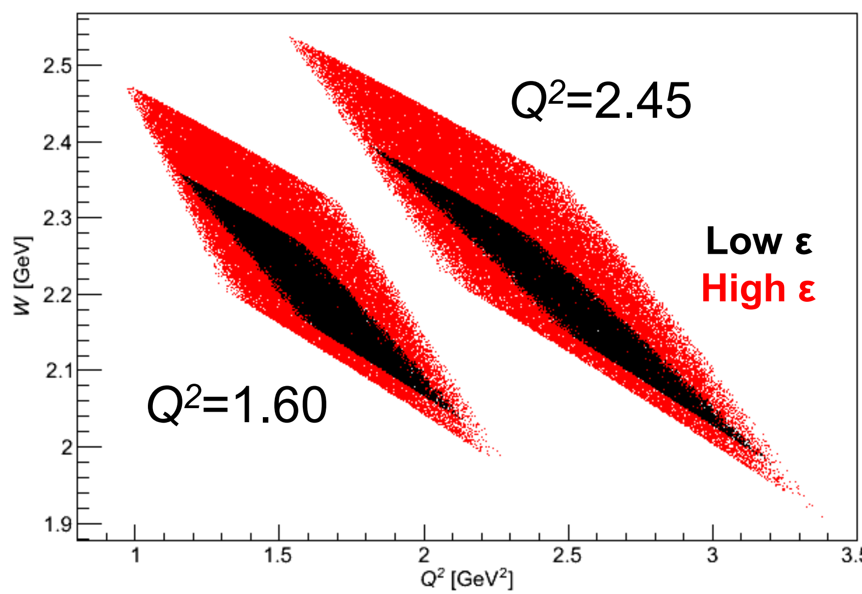
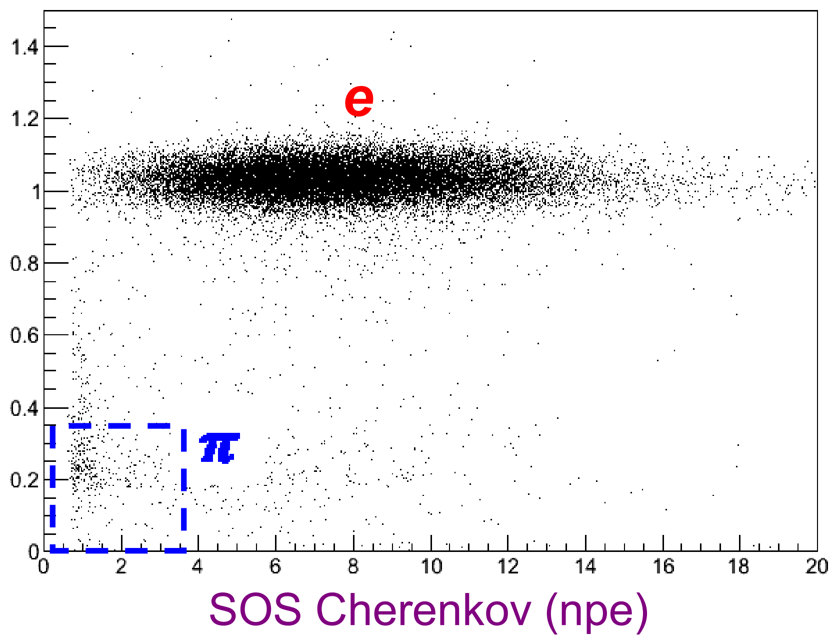


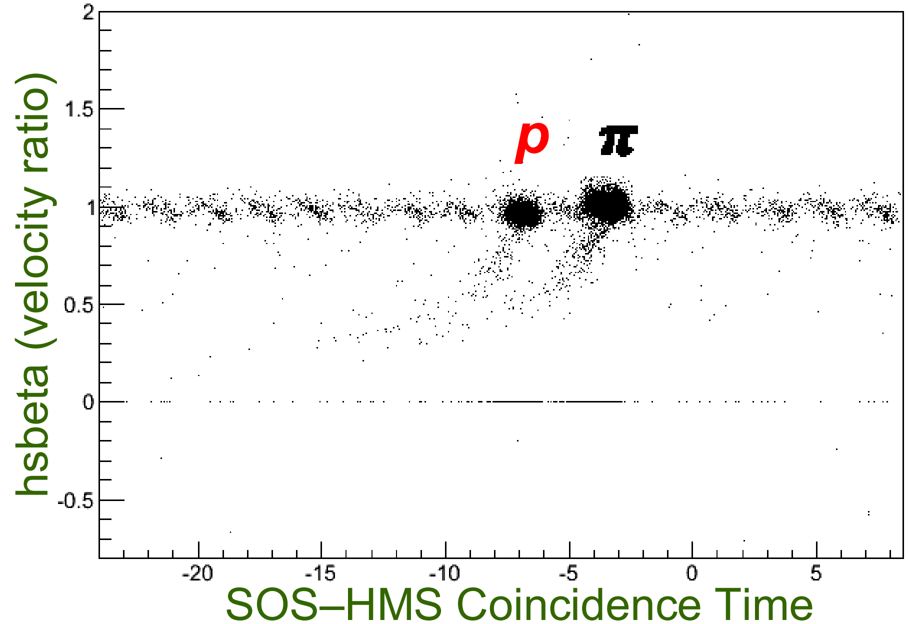
HMS focal plane detector layout, SOS is very similar
Trigger: ¾ planes of Hodoscopes





Particle Identification

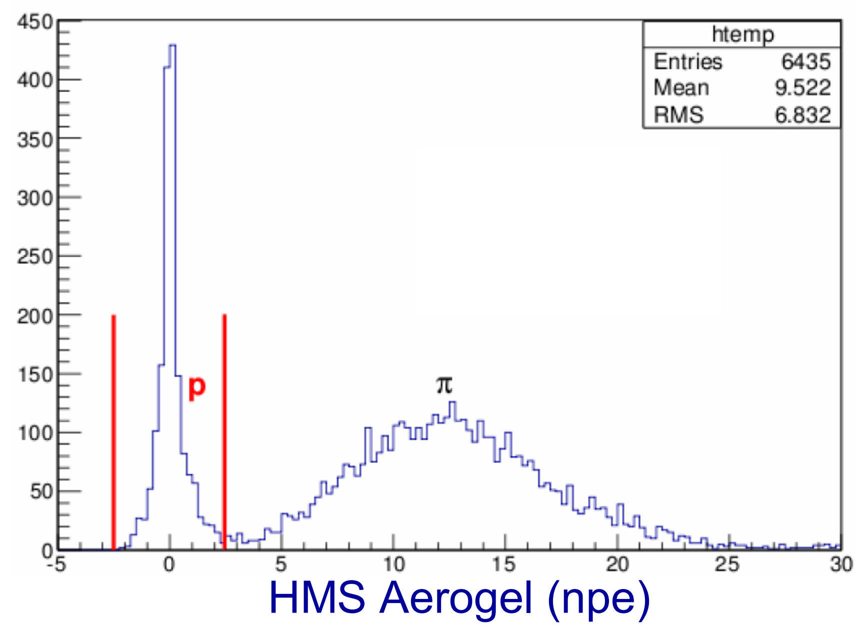




SOS: select electron
- Calorimeter cut
- Cherenkov cut

~99% efficiency

HMS: select proton
- Coincidence timing cut
- hsbeta (particle velocity)
- Aerogel Cut
- Cherenkov cut: veto e^+



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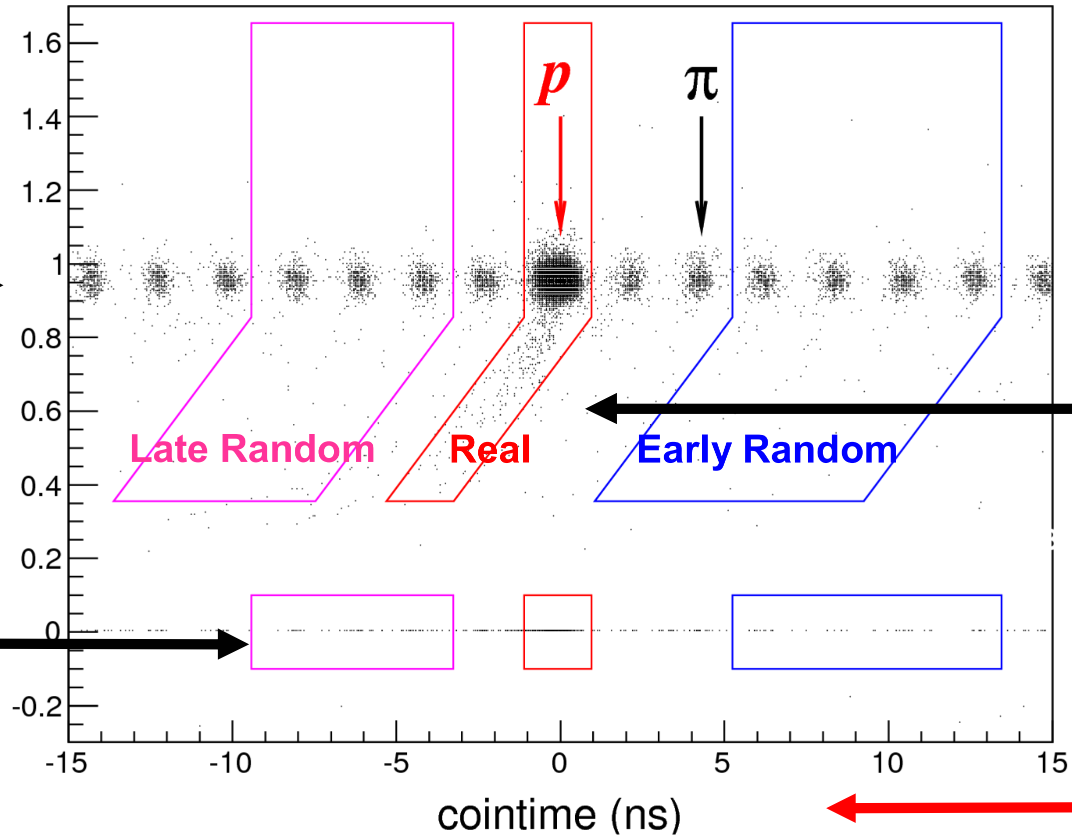
Coincidence Time Selection

Blob: Good events

β=0: Events missing fiducial cut during reconstruction



Tail: Multiple scattering contribution

- **Random subtraction:**

$$\text{Coincidence proton} = \text{Real Events} - \left(\frac{\text{Late Random Events} + \text{Early Random Events}}{7}\right)$$

- **Missing proton due to scattering, absorption: ~7%**

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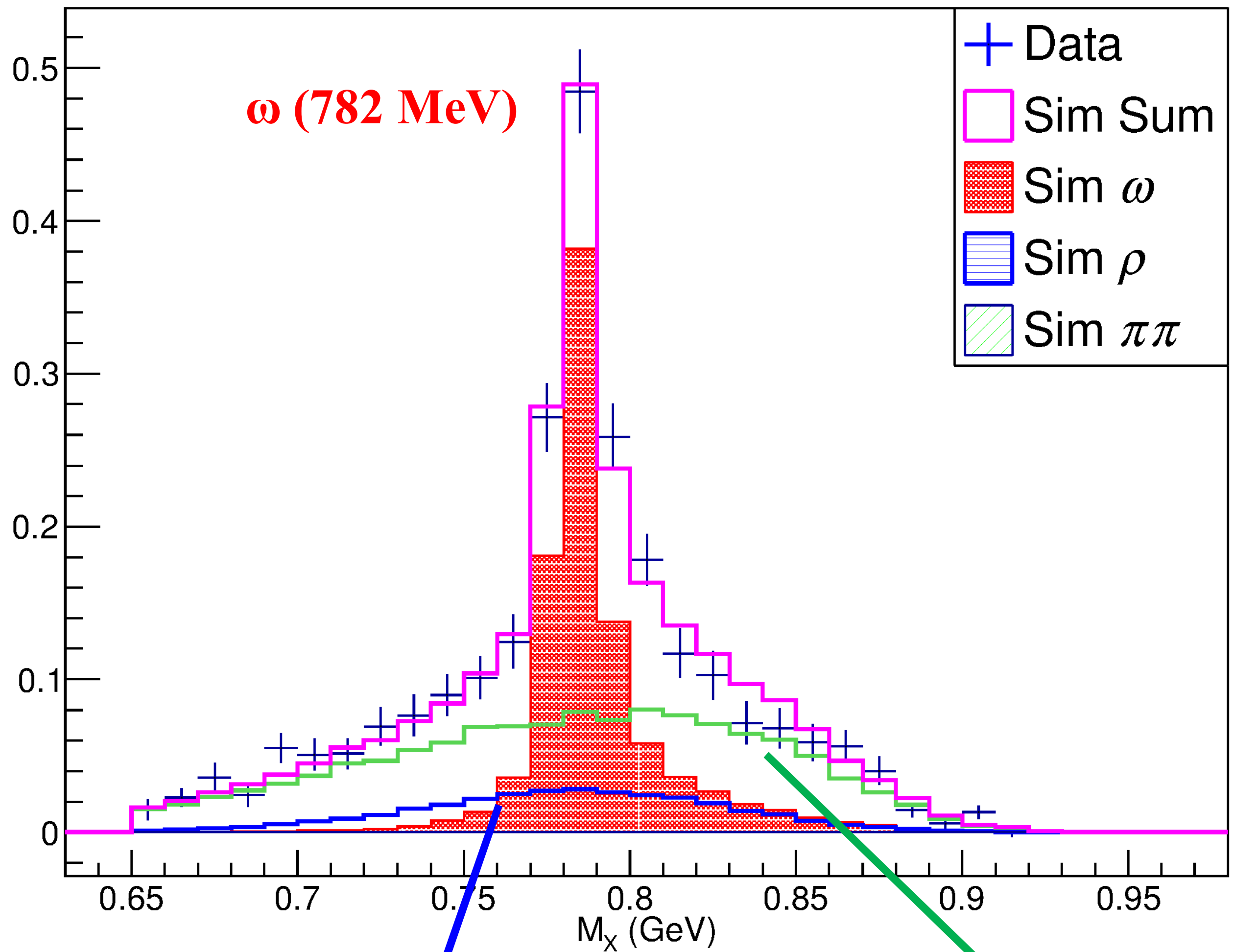
Physics Background Subtraction

$$M_x = \sqrt{(E_e + m_p - E_{e'} - E_{p'})^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_{p'})^2}$$



W.B. Li, GMH, et al., Phys.Rev.Lett. **123**(2019)182501

ρ (770 MeV)
HERMES Empirical parameterization with Soding skewness factor

2π production phase-space

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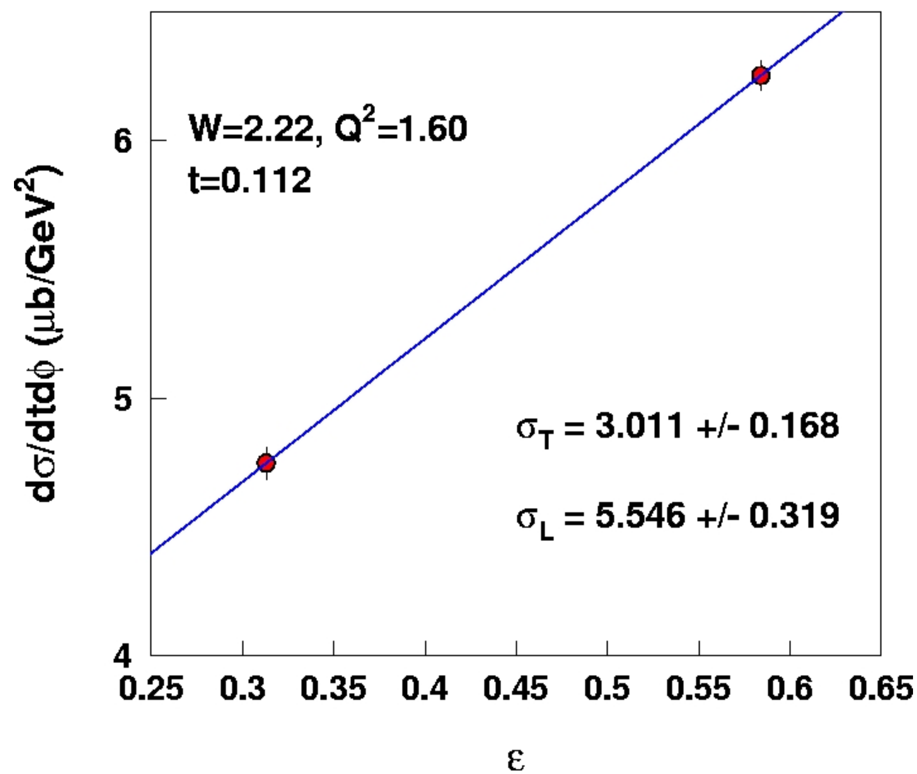
“Simple” Longitudinal–Transverse Separation

- For uniform φ–acceptance, σ_{TT}, $\sigma_{LT} \to 0$ when integrated over φ
- Determine $\sigma_T + \varepsilon\,\sigma_L$ for high and low ε in each *u*–bin for each Q^2
- Isolate σ_L, by varying photon polarization, ε



$$\varepsilon = [1+2(1+\tau)\tan^2(\theta/2)]^{-1}$$

$$2\pi \frac{d\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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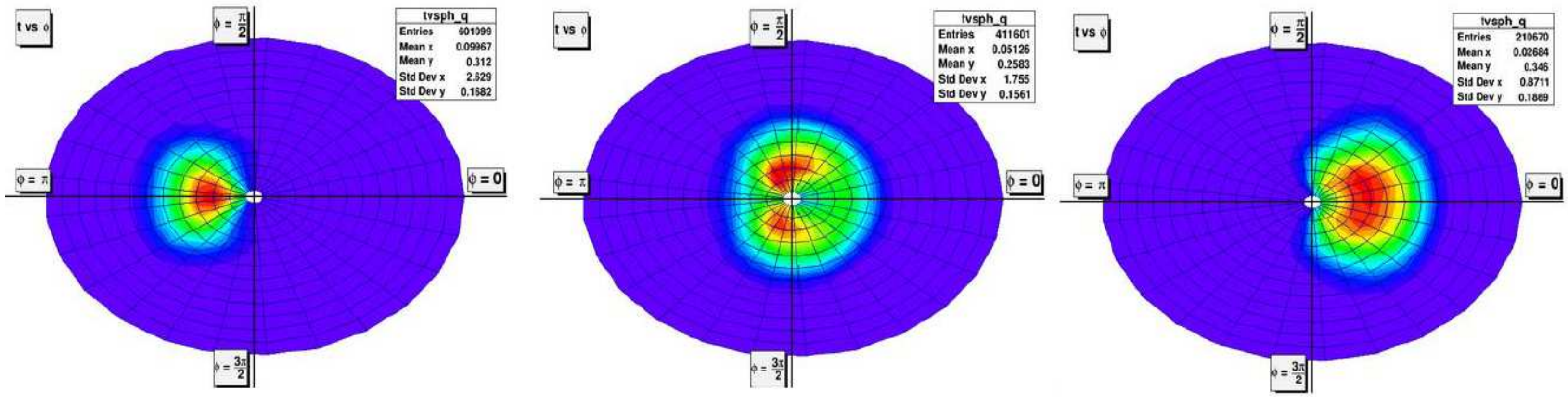
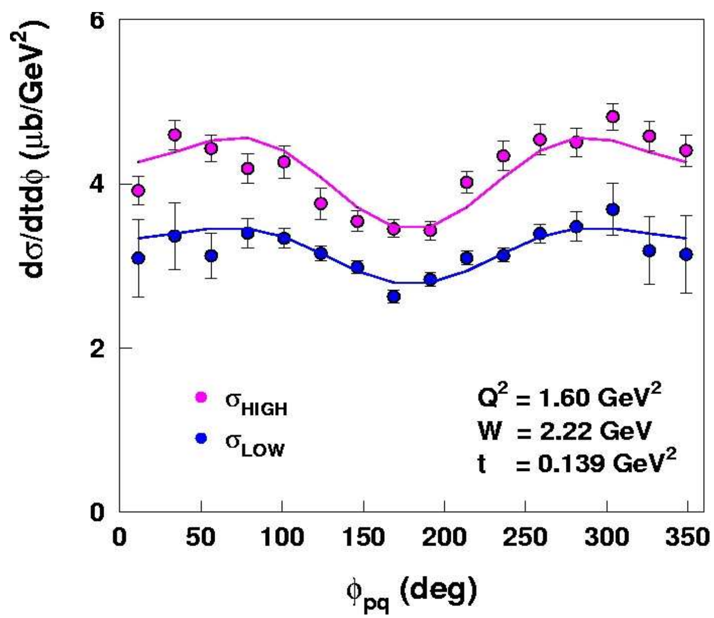
“More Realistic” L/T Separation

$$2\pi \frac{d^2\sigma}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$



- **Cross-Section Determination:**
  - In reality, φ acceptance not uniform
  - Must measure σ_{LT} and σ_{TT}
  - Three hadron spectrometer angles needed for full azimuthal (φ_p) coverage to determine the interference terms

- Extract σ_L by simultaneous fit using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε)



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Iterative Procedure for L/T Separation

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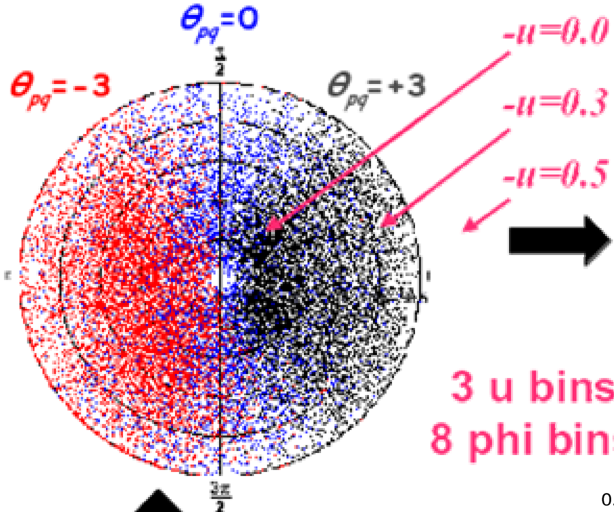
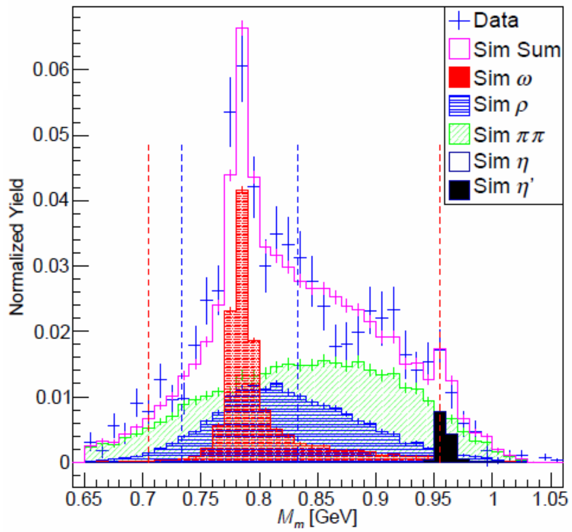
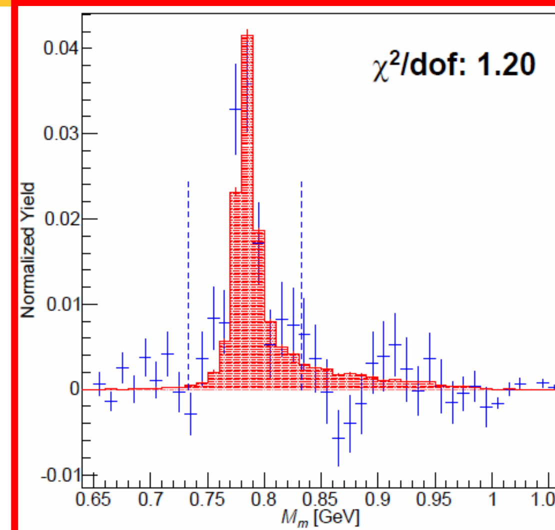
Improve φ coverage by taking data at multiple HMS angles, $-3^\circ < \theta_{pq} < +3^\circ$.



3 u bins
8 phi bins



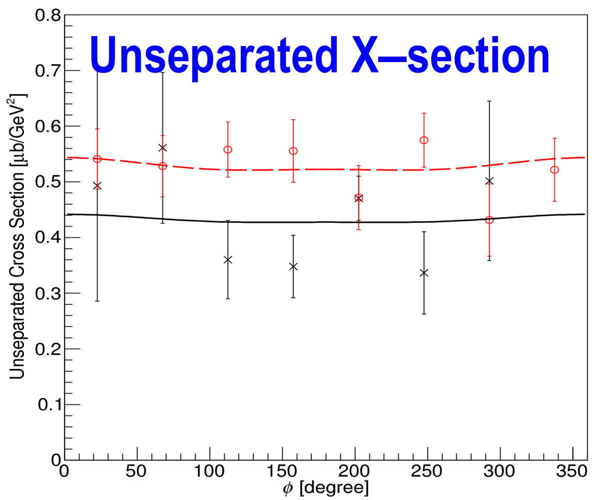


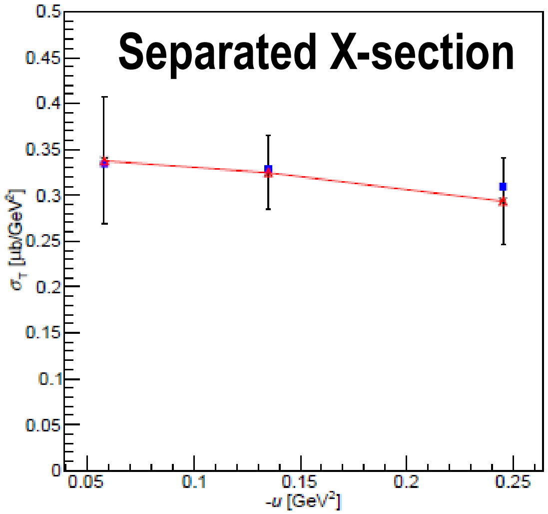
$$R = \frac{Y_{Exp} - Y_{\rho\ sim} - Y_{Xspace\ sim}}{Y_{\omega\ sim}}$$

Combine ratios for settings together, propagating errors accordingly.

$$\frac{d^2\sigma}{dt d\varphi}_{EXP} = R \frac{d^2\sigma}{dt d\varphi}_{SIMC}$$

Empirical Model





Extract L,T,LT,TT via simultaneous fit

$$2\pi \frac{d^2\sigma}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$

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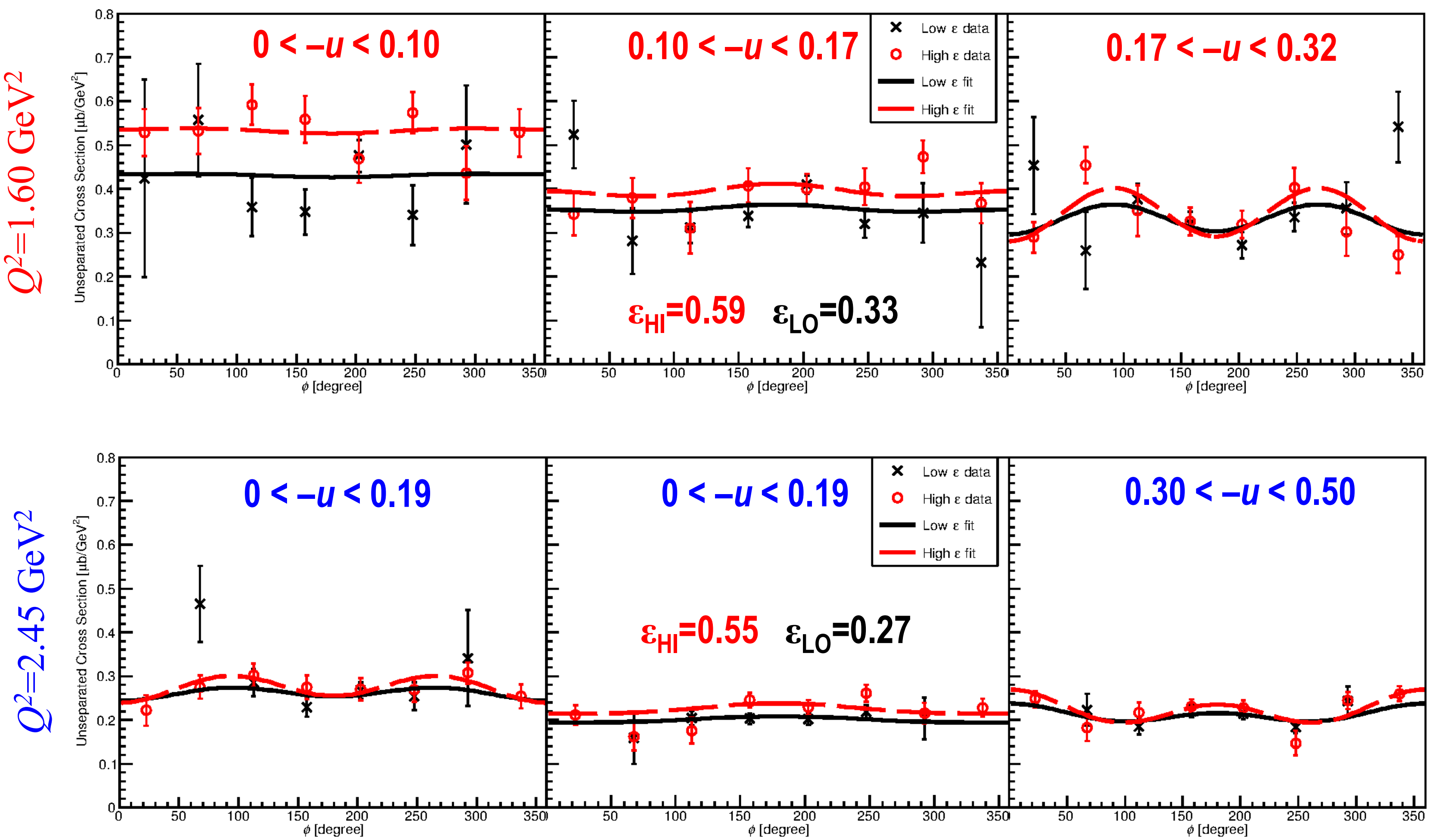
Unseparated Cross Sections

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$



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Separated Cross Sections $\frac{d\sigma}{dt}$ vs $-u$

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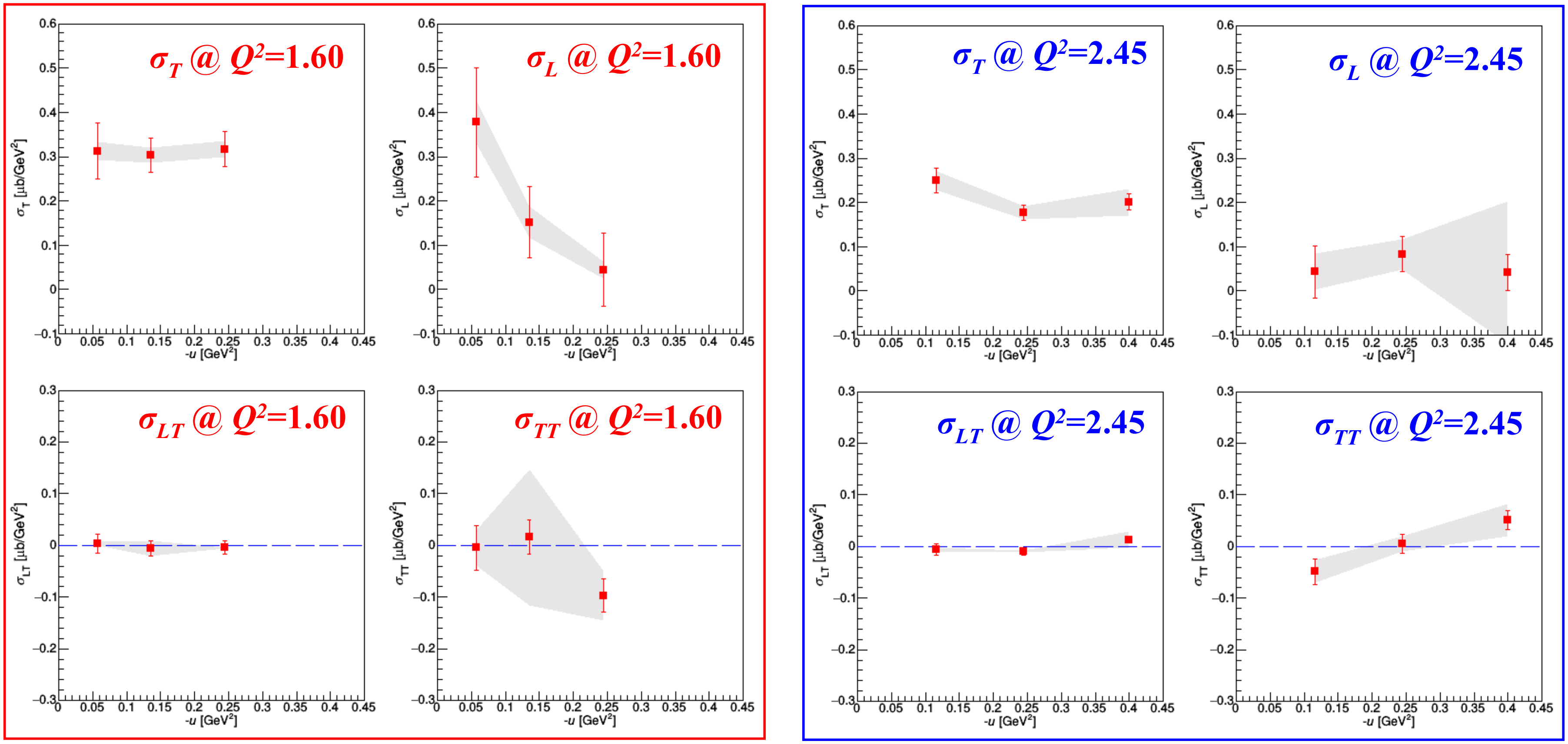

Observations:

- σ_T falls slowly with $-u$; σ_L falls faster.
- σ_{LT} is very small; σ_{TT} may sign flip for different Q^2 values.

Error bars = statistical and uncorrelated syst. unc; Error bands = correlated syst. unc.

Backward Angle Omega Electroproduction Peak

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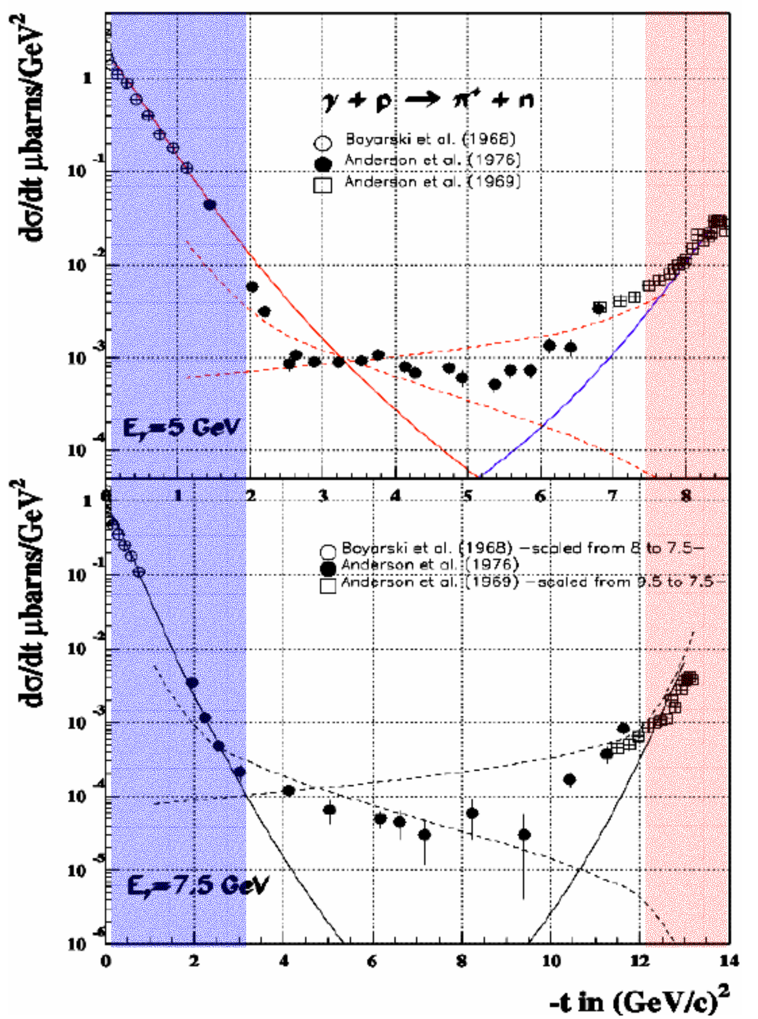
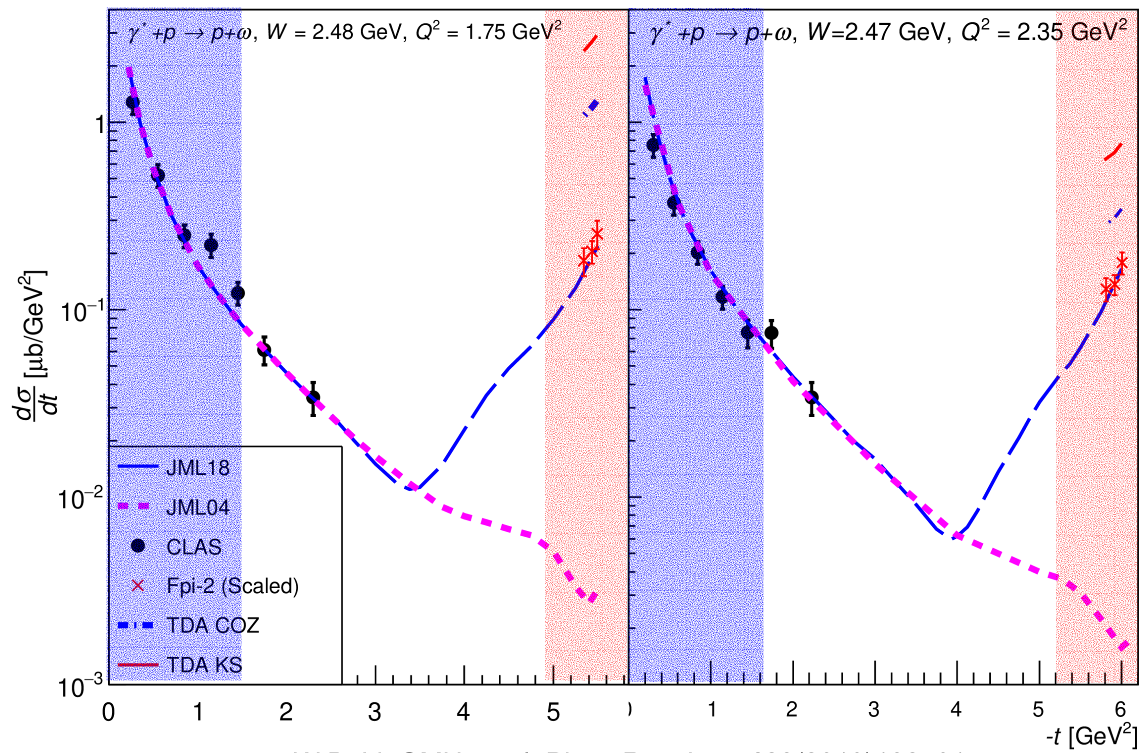
Photoproduction



M. Guidal, J.–M. Laget, M. Vanderhaeghen, PLB **400**(1997)6

First observation of backward angle peak in electroproduction!

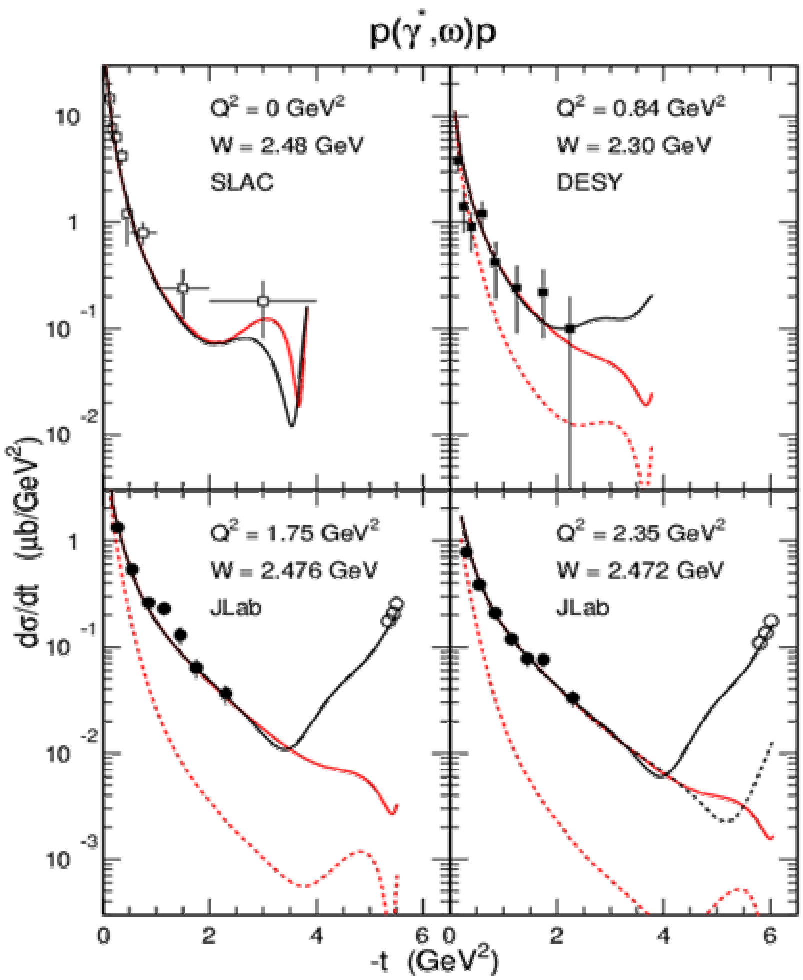


W.B. Li, GMH, et al, Phys. Rev. Lett. **123**(2019)182501

Hall C data are scaled to match kinematics of Hall B data

	W (GeV)	x_B	Q² (GeV²)	–*t* (GeV²)	–*u* (GeV²)
Hall B	1.8 – 2.8	0.16 – 0.64	1.6 –5.1	< 2.7	> 1.68
Fπ–2	2.21	0.29	1.6	4.014	0.08 – 0.13
		0.38	2.45	4.724	0.17 – 0.24

JML Regge Model description of *u*–Peak

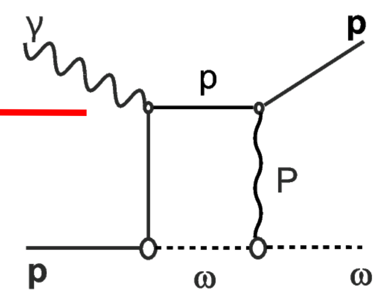


J–M Laget, Private Communication (2018)

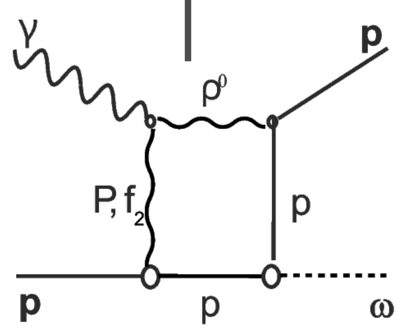
- Model provides natural description of JLab π electroproduction cross sections without destroying good agreement at Q^2=0.

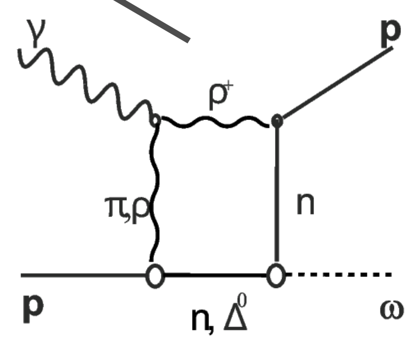
  [PLB **685**(2010)146; PLB **695**(2011)1999]
- Model also consistent with magnitude and slope of backward angle ω peak.
- Would be interesting to examine L/T ratio predicted by model when full calc available.

Red line: Non–degenerated Regge trajectory for *N*–exchange in *u*–channel w/ *t*–dependent cutoff mass



Black line: Include *ρN* and *ρΔ* rescattering inside nucleon (Regge cuts)





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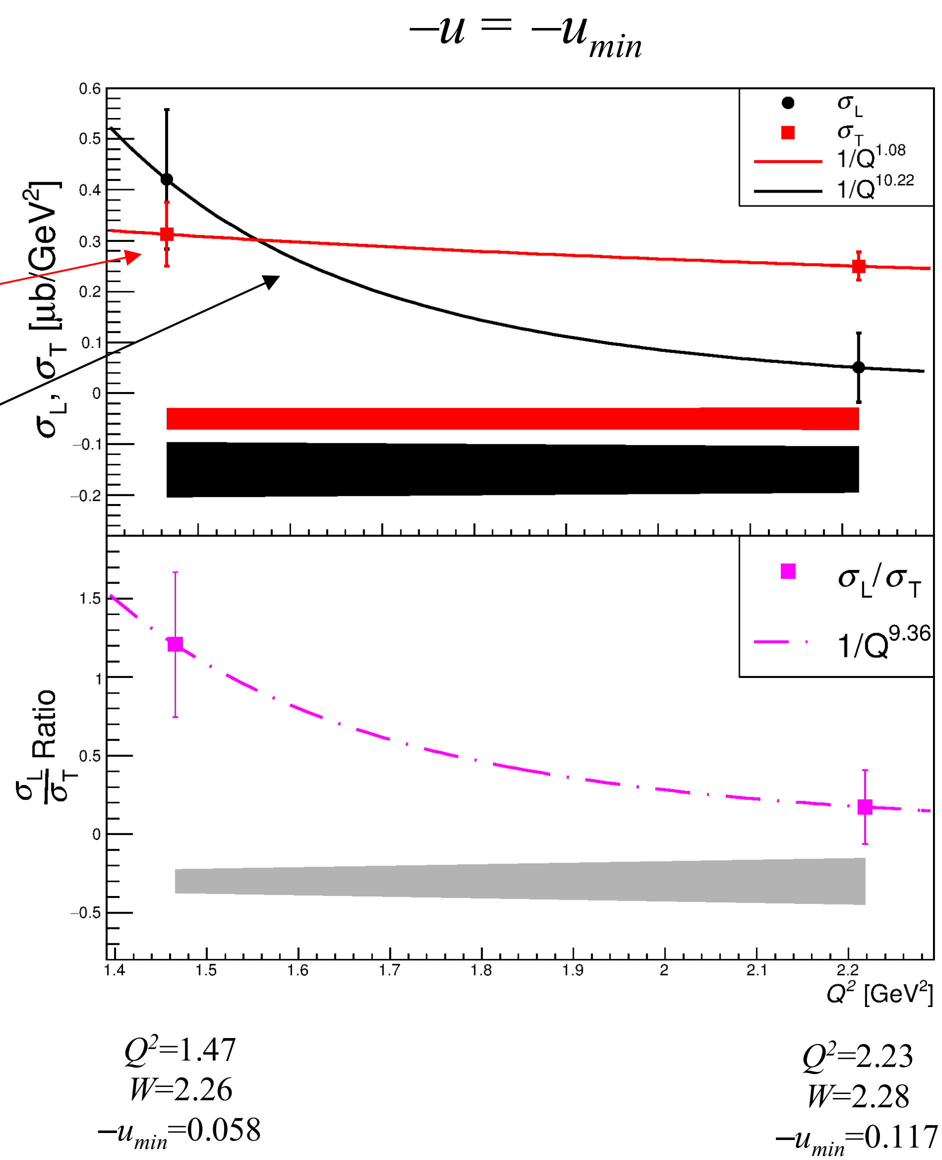
$p(e,e'p)\omega$ Q^2–Dependence

- To investigate Q^2–dependence, fit lowest $-u$ bin values of σ_T and σ_L to Q^{-n} function
  - σ_T appears to have a flat Q^2–dependence within measured range
  - σ_L shows much stronger decrease
- **Decreasing L/T ratio indicates the gradual dominance of σ_T as Q^2 increases.**
- Trend qualitatively consistent with prediction of TDA Collinear Factorization.



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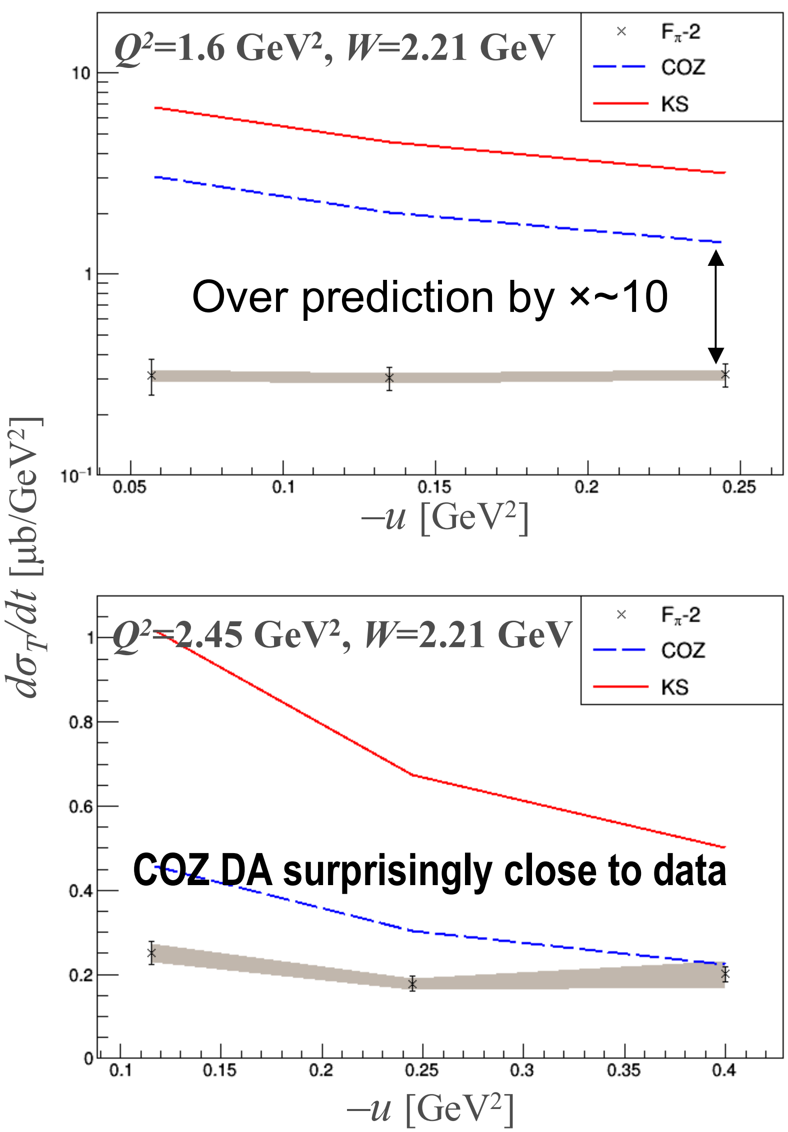
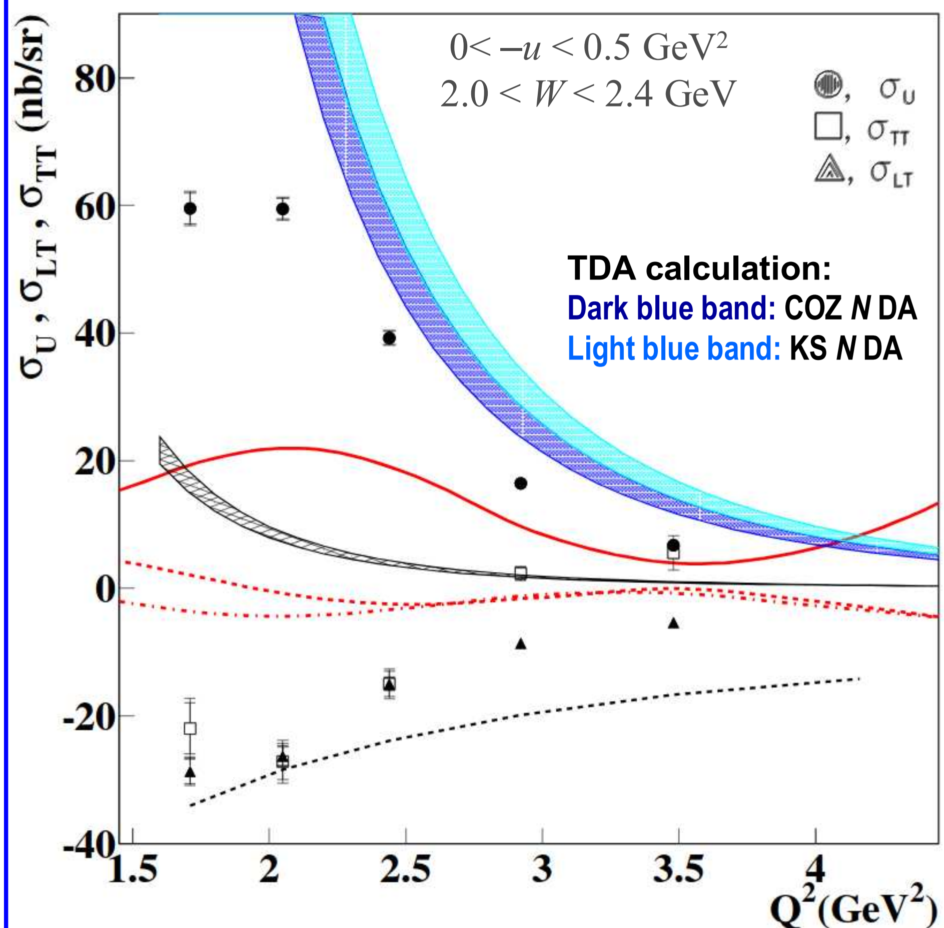
TDA model Comparison to Data

Hall C ω electroproduction



TDA calculation by B. Pire, K. Semenov, L. Szymanowski
Private Communication (2015)

Both data sets suggestive of early TDA scaling Q^2≈2.5 GeV² !?



Hall B π^+ Electroproduction

K. Park et al., PLB **780** (2017) 340

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Hall C *u*–channel Near–term Goals

1. Determine if the backward angle peak observed in exclusive ω electroproduction occurs also in other channels, over a broad kinematic range.
2. Measure the *u*–dependence of L/T–separated cross sections, to determine the relevance of Regge–rescattering and TDA mechanisms in JLab kinematics.
3. Assuming the backward angle peak is present, as expected, measure the σ_T/σ_L ratio over a wide Q^2 range for W>2 GeV.
   - Where does $\sigma_T \gg \sigma_L$, as predicted by TDA formalism?
4. Determine the Q^2–dependence of σ_T at fixed x_B.
   - Where does $\sigma_T \propto 1/Q^8$ as predicted by TDA formalism?

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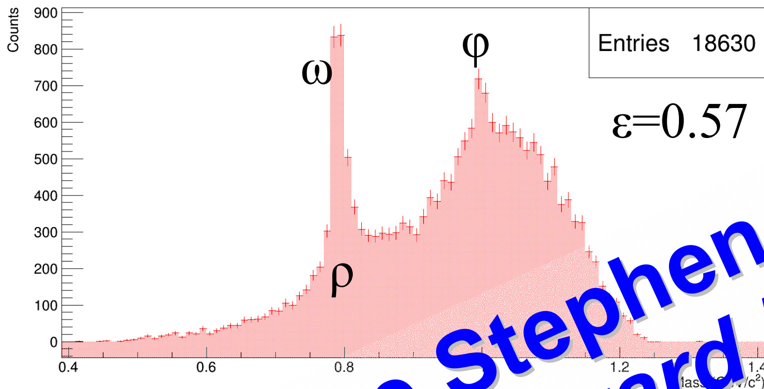
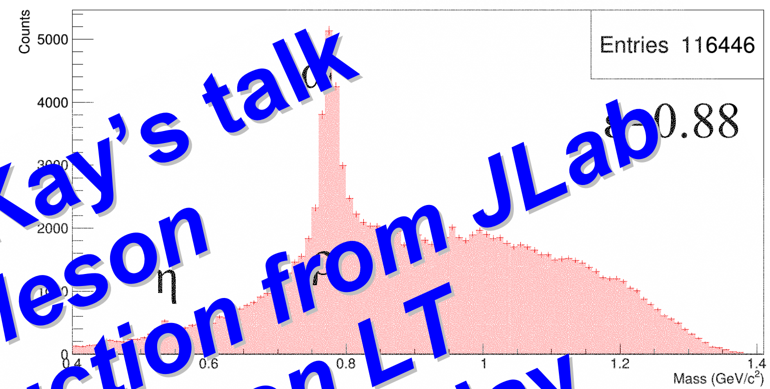
12 GeV Hall C u–Channel Data Acquired

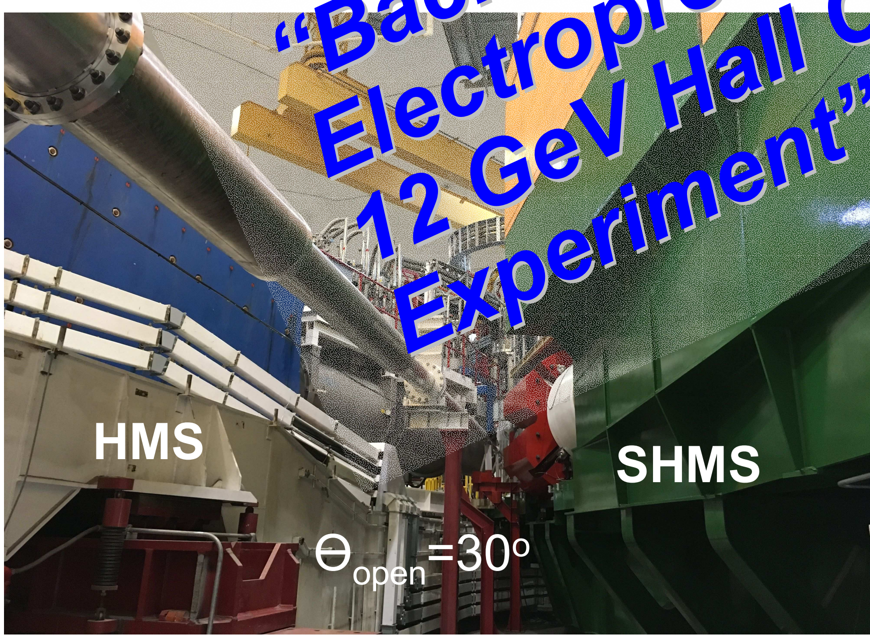
p(e,e'p)X   Online Data Analysis

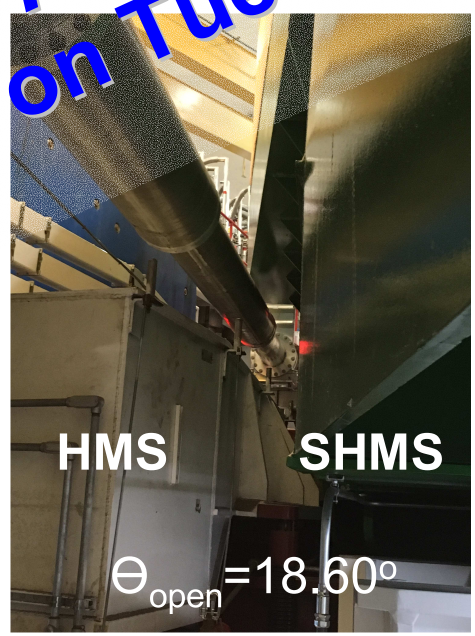
Q^2=3.00 W=2.32 θ_{pq}=+3.0° $-u$=0.15 ξ_u=0.15





See Stephen Kay's talk "Backward Meson Electroproduction from JLab 12 GeV Hall C Kaon LT Experiment" on Tuesday





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Summary

- **New experimental technique pioneered at JLab Hall C has opened up a unique kinematic regime for study:**
  - Extreme backward angle ($u \approx 0$) scattering
  - Detect forward–going proton in parallel kinematics
    - Leaves "recoil" meson nearly–at–rest in target
- Possible access to **Transition Distribution Amplitudes**
  - Universal perturbative objects in *u*–channel, analogous to GPDs
  - Access to 3–quark plus sea component $\Psi_{(3q+q\bar{q})}$ of nucleon
- **J.–M. Laget Regge Model** provides natural explanation of magnitude and *u*–slope of observed backward angle peak
- **σ_L/σ_T separations will be essential to distinguish between alternate theoretical descriptions**

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