Hall C Backward Angle Experimental Program:

Unique Access to *u*–channel Physics

Garth Huber

University of Regina

Supported by:

NSERC CRSNG

SAPIN-2016-00031

CLAS12 Mini–Workshop
July 14, 2020

Jefferson Lab Fπ Collaboration

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

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Jefferson Lab

Hall C

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

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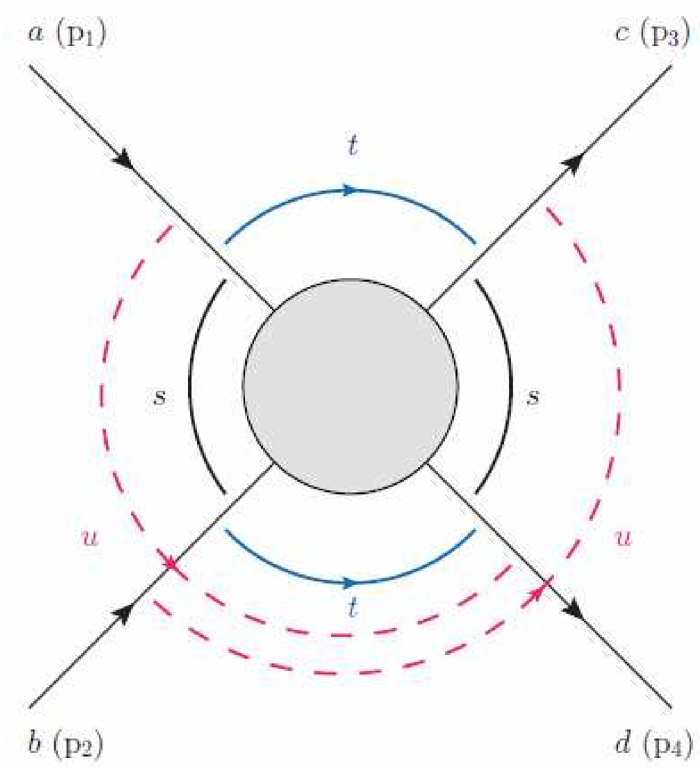


$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

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

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

s: invariant mass of the system

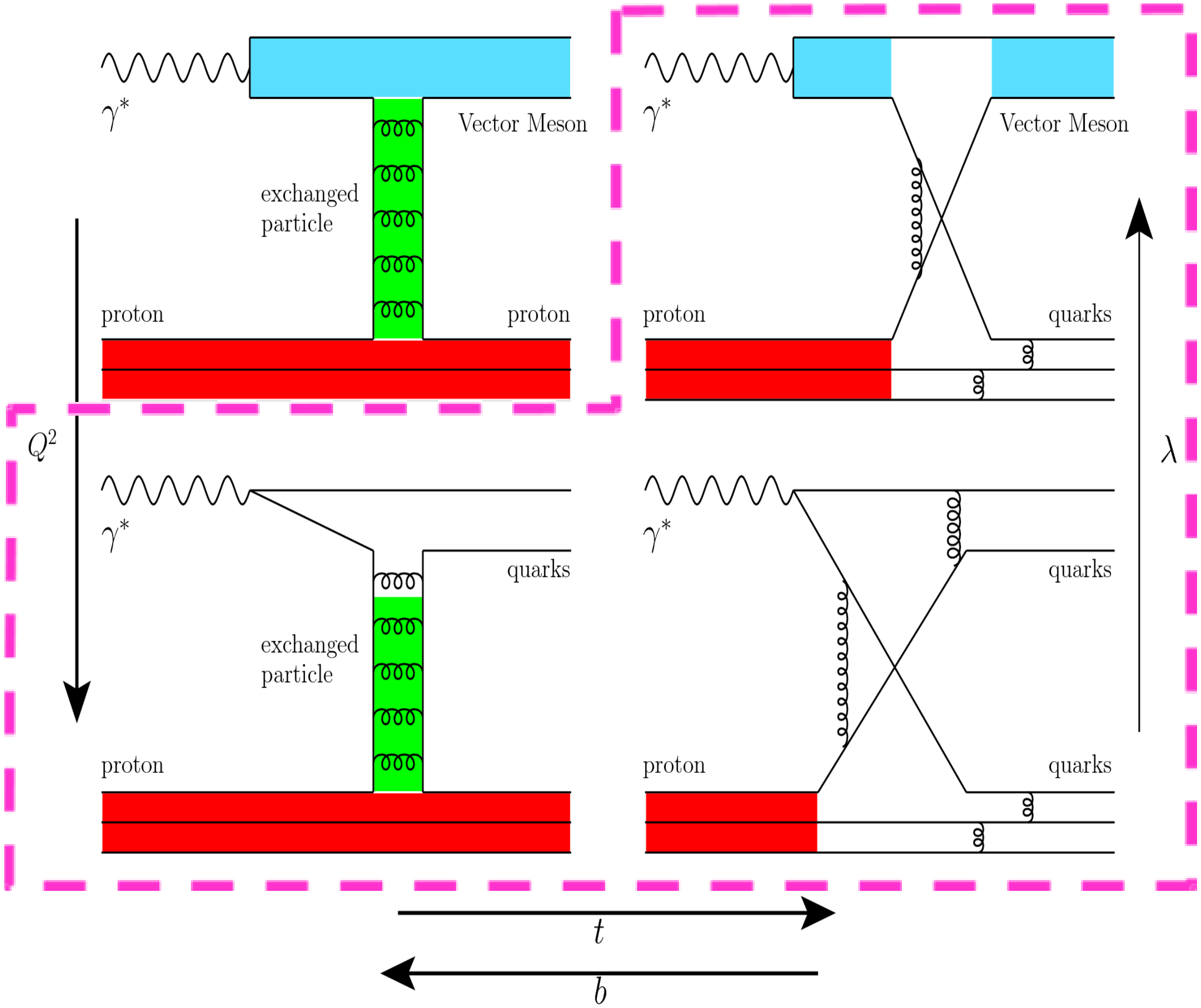
t: Four–momentum–transfer squared between **target before and after interaction**

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



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**

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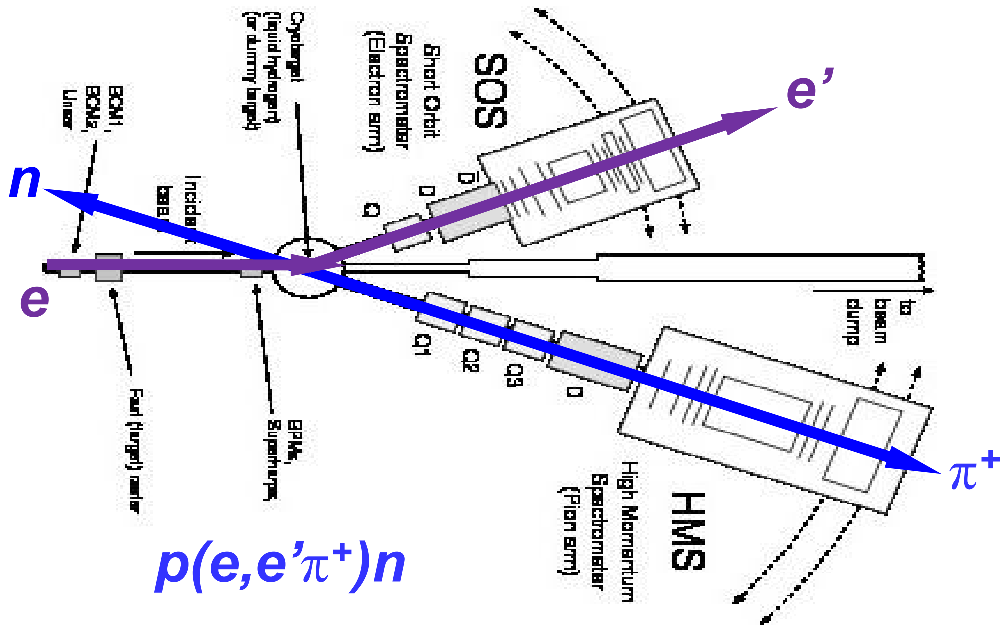
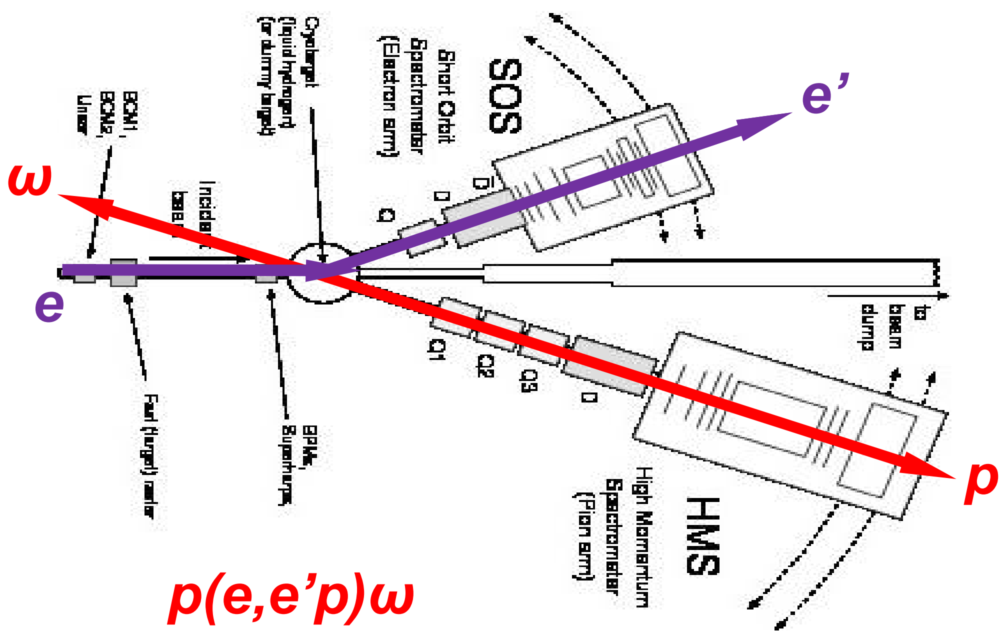
t–Channel π^+ vs u–Channel ω Production



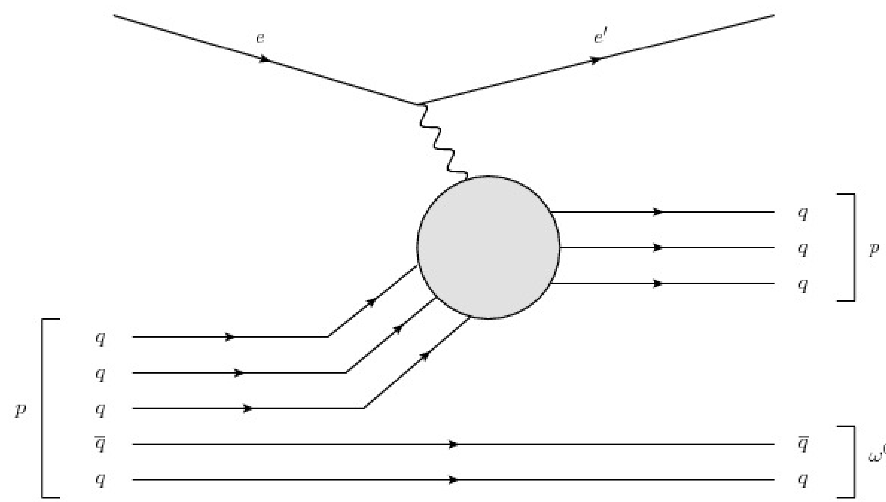


HMS is along q–vector ($p_{\gamma*}$)

- $p_{\pi+}$ is parallel to $p_{\gamma*}$ (forward)
- p_{ω} is anti–parallel to $p_{\gamma*}$ (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.

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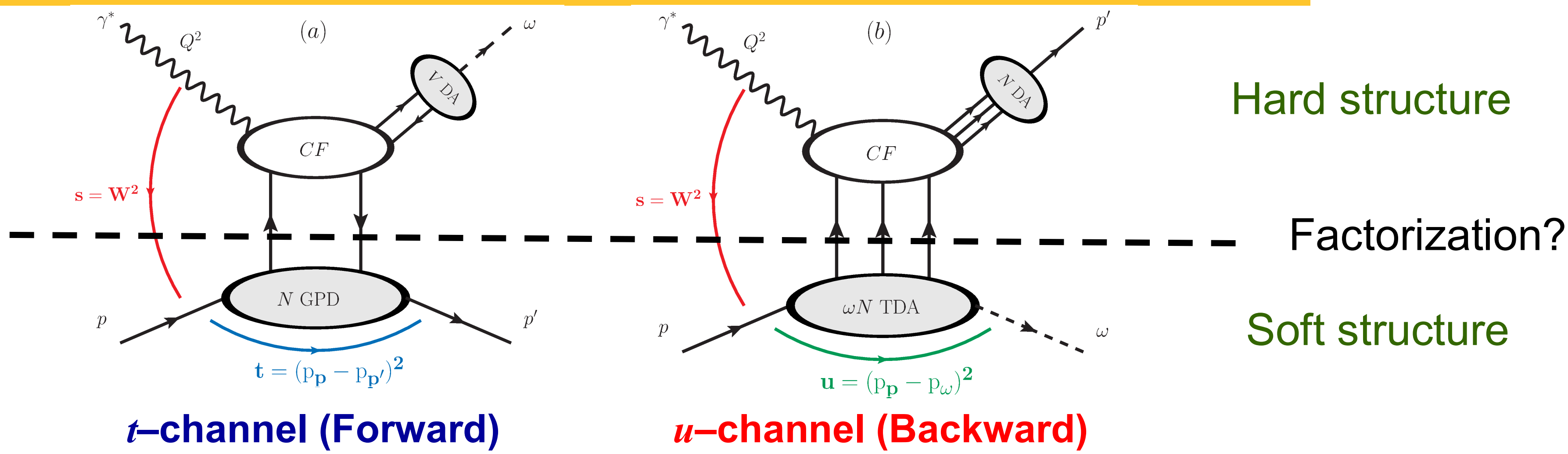
GPD–Like Model: TDA and Factorization



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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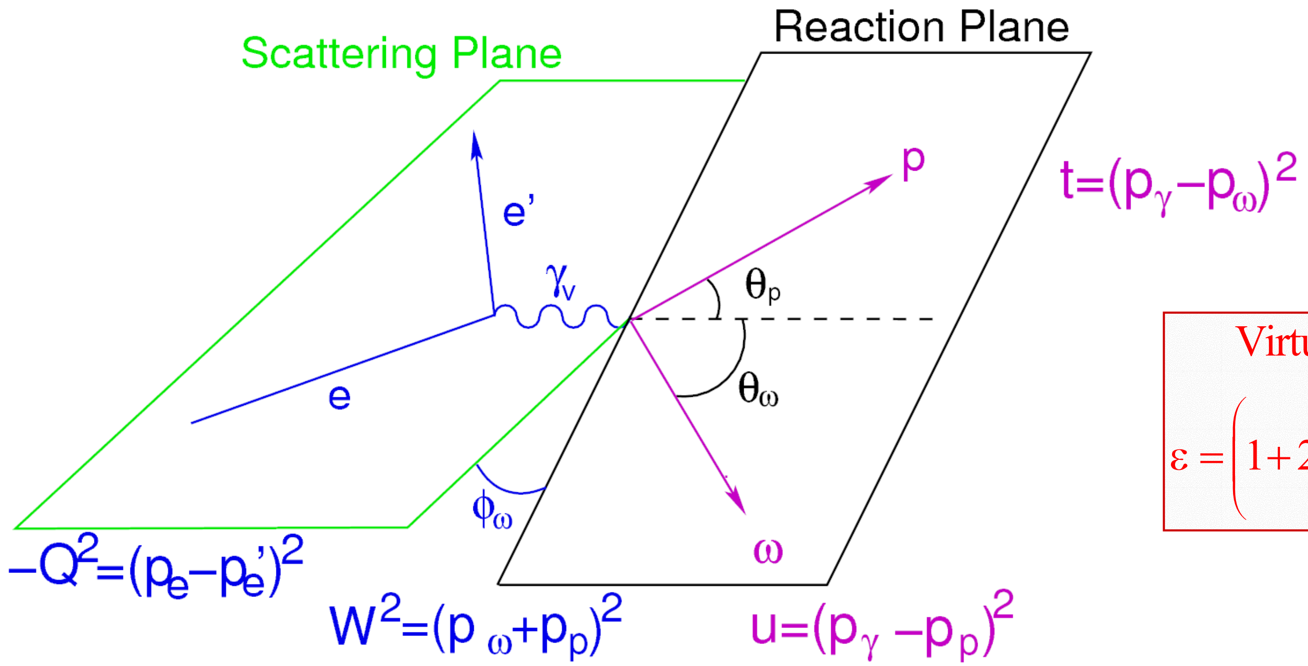
Rosenbluth (L/T/LT/TT) Separation



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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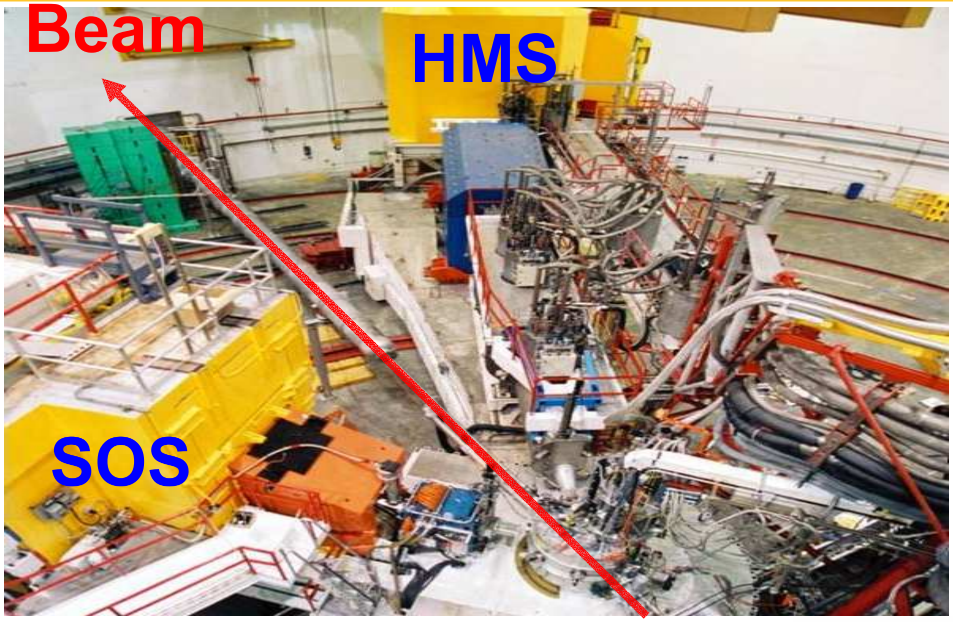
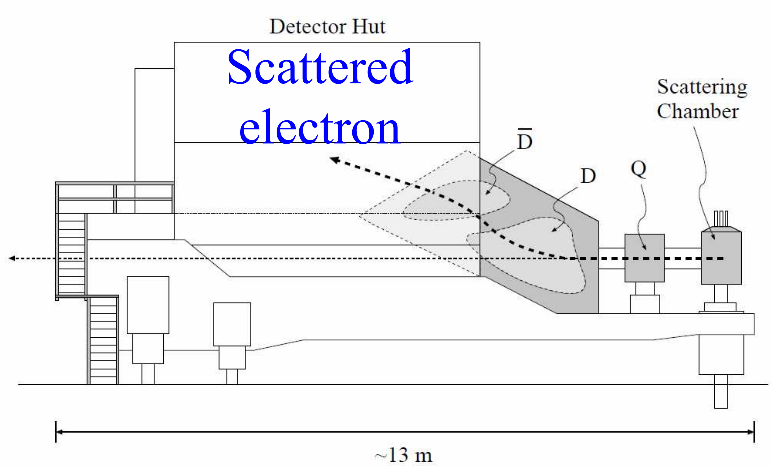
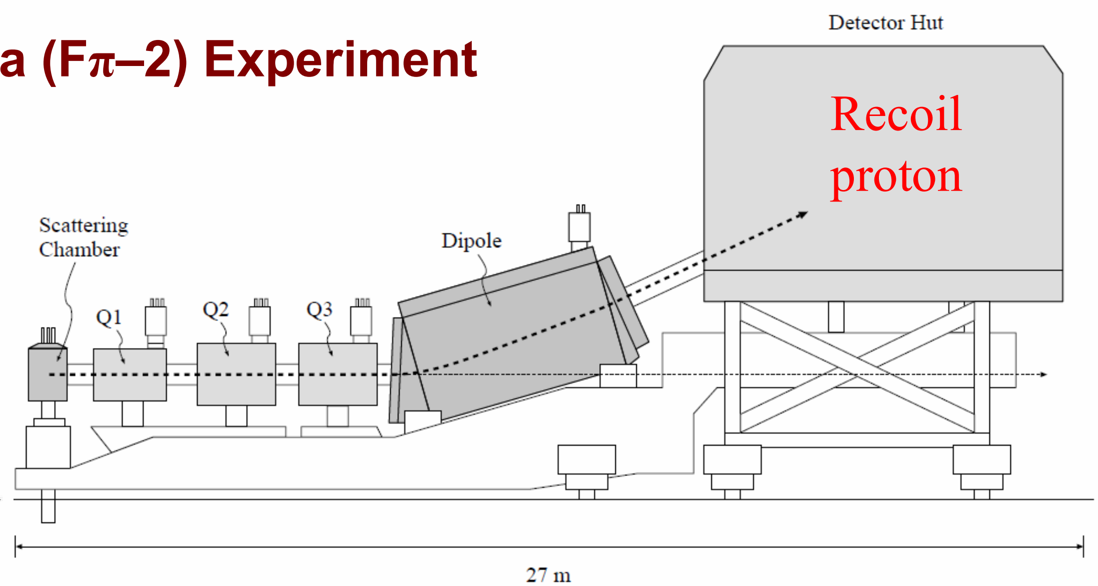


E_e (GeV)	ε	$-u$ (GeV^2)	$-t$ (GeV^2)	ξ_u	ξ_t
$\langle Q^2 \rangle$=1.60 GeV^2 $\langle W \rangle$=2.21 GeV					
3.772	0.328	0.058 – 0.245	3.85 – 4.15	0.075 – 0.177	0.722 – 0.735
4.702	0.593				
$\langle Q^2 \rangle$=2.45 GeV^2 $\langle W \rangle$=2.21 GeV					
4.210	0.270	0.117 – 0.400	4.48 – 4.94	0.126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

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



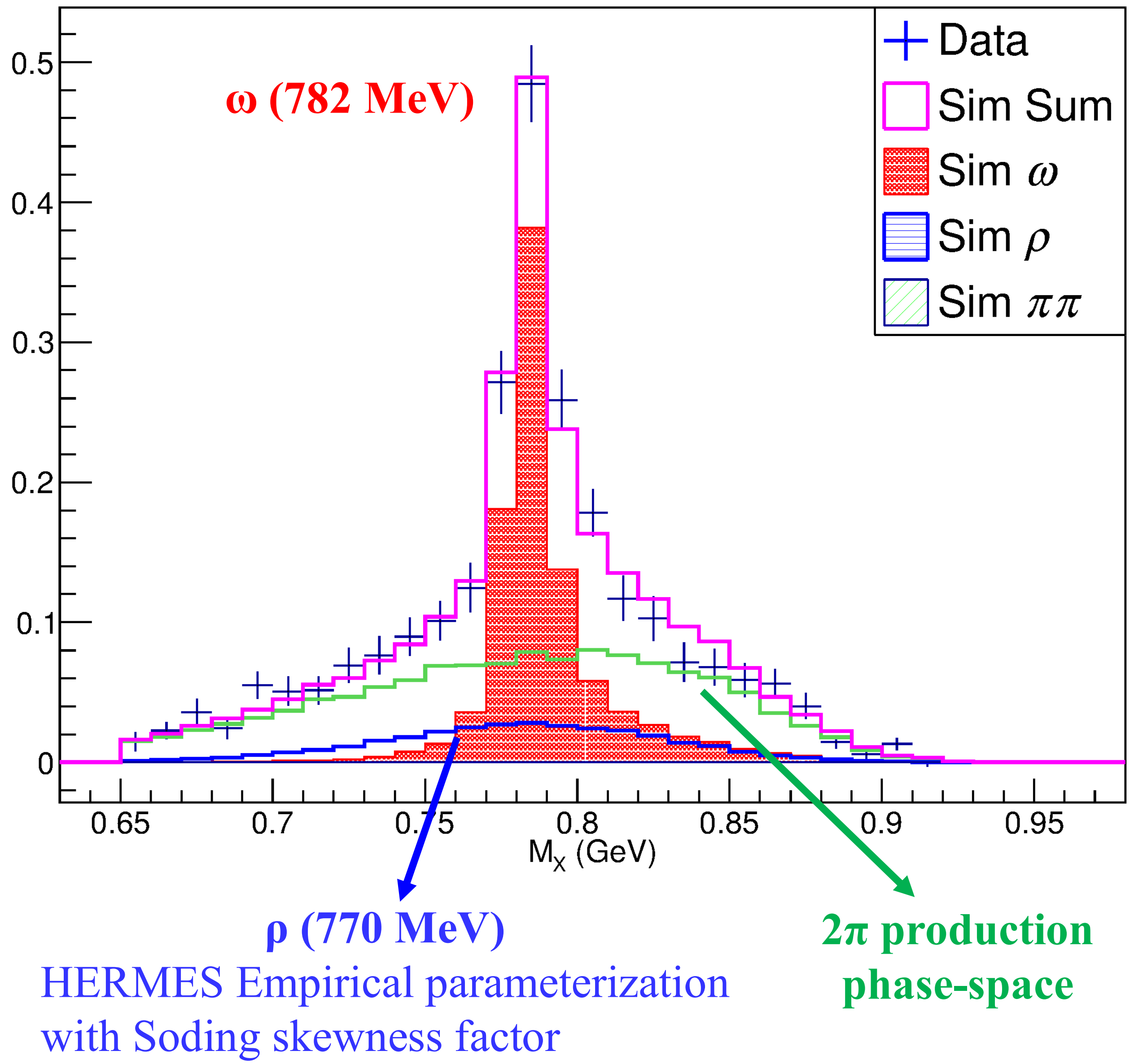
Short Orbit Spectrometer (SOS)



High Momentum Spectrometer (HMS)

Physics Background Subtraction

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



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

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L/T Separation Technique

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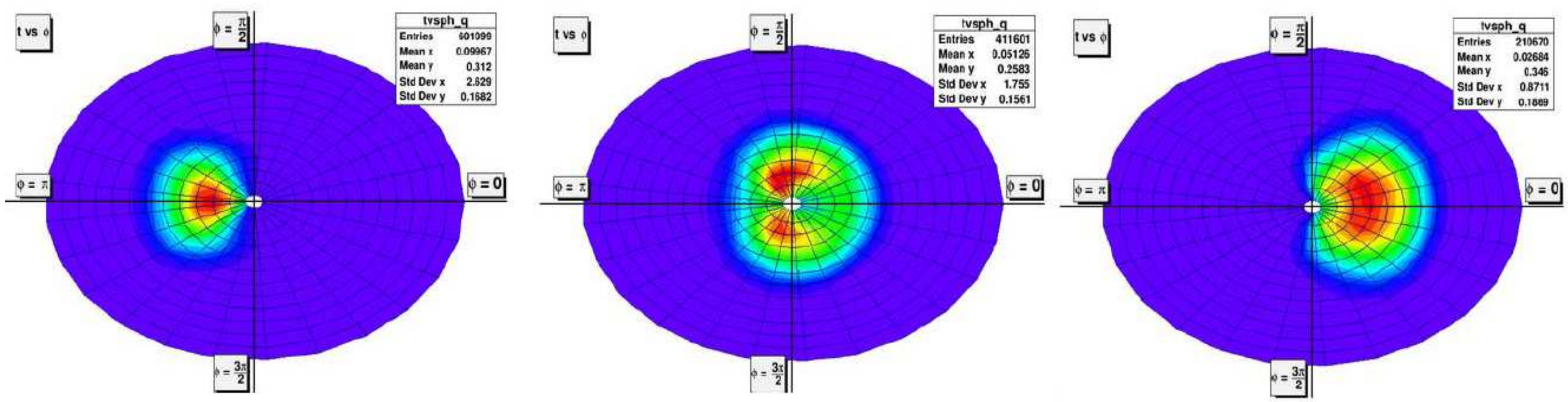
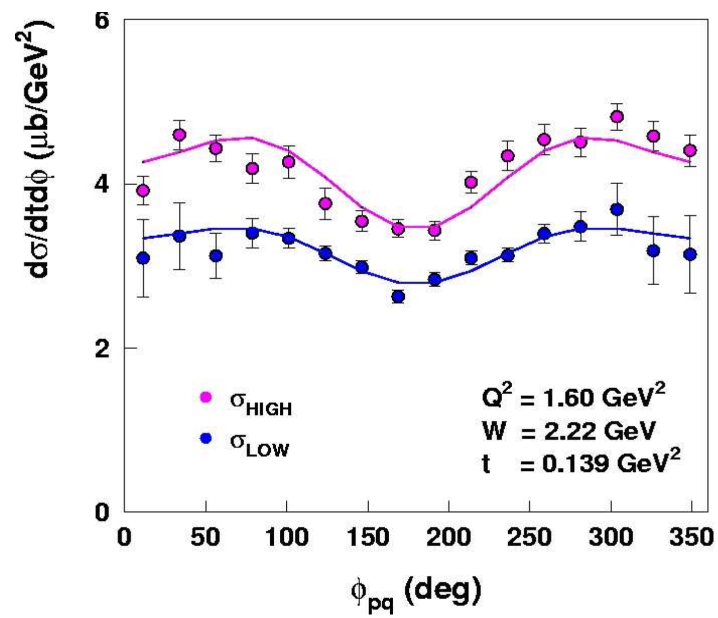
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$



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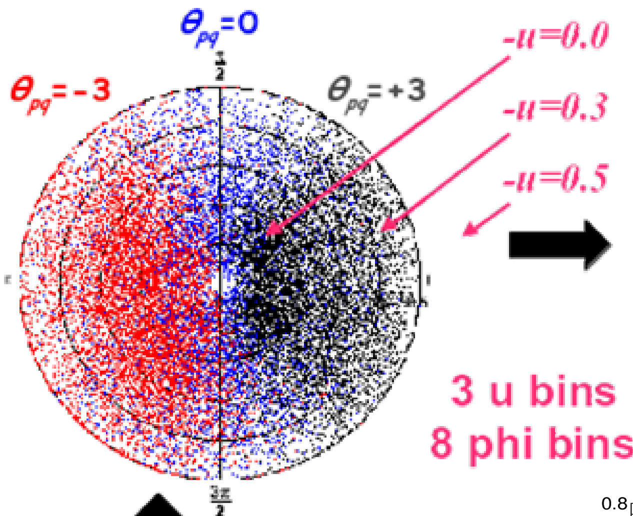
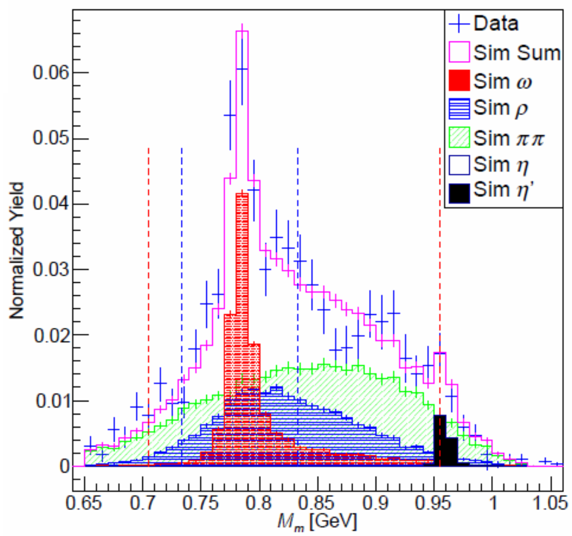
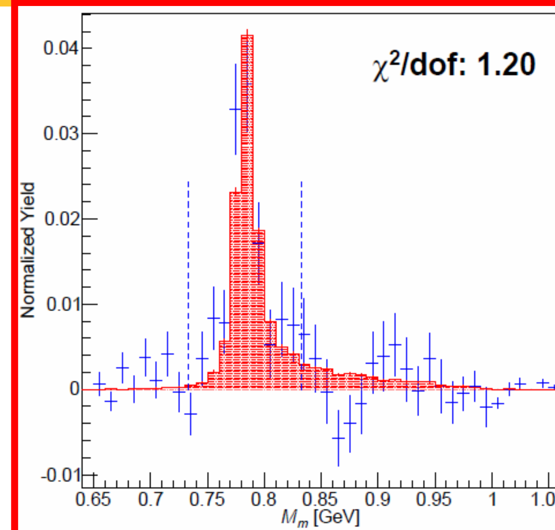
Improve φ coverage by taking data at multiple HMS angles, $-3^{o}<\theta_{pq}<+3^{o}$.





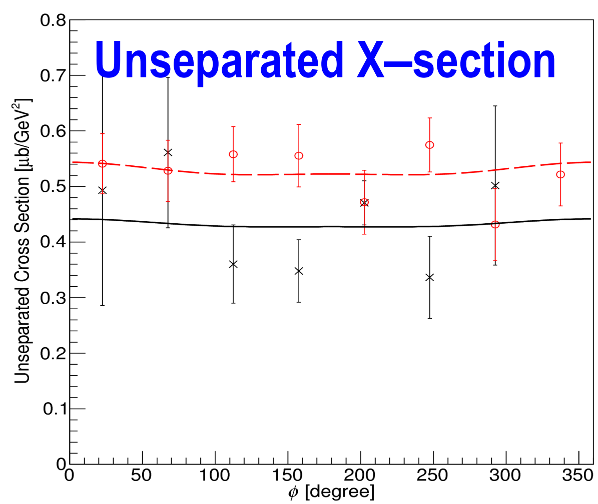


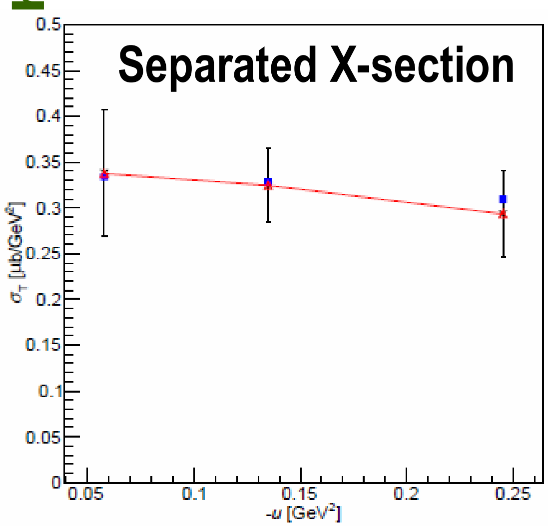
$$R=\frac{Y_{Exp}-Y_{\rho\ sim}-Y_{Xspace\ sim}}{Y_{\omega\ sim}}$$

Combine ratios for settings together, propagating errors accordingly.

$$\left.\frac{d^2\sigma}{dtd\varphi}\right|_{EXP}=R\left.\frac{d^2\sigma}{dtd\varphi}\right|_{SIMC}$$

Empirical Model





Extract L,T,LT,TT via simultaneous fit

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

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

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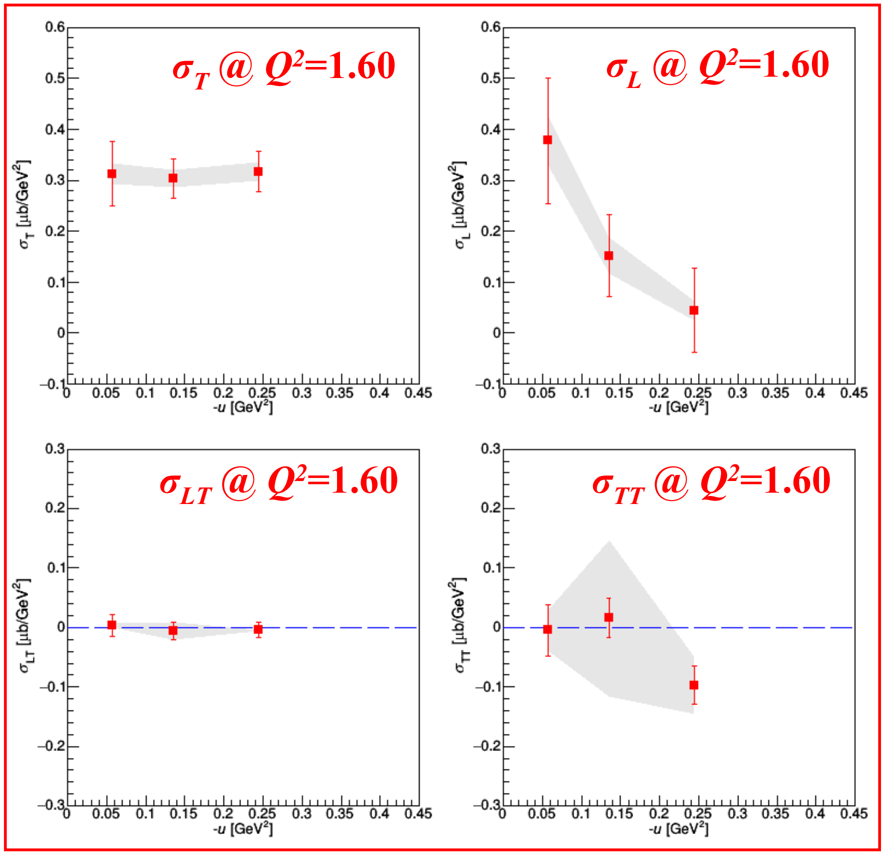

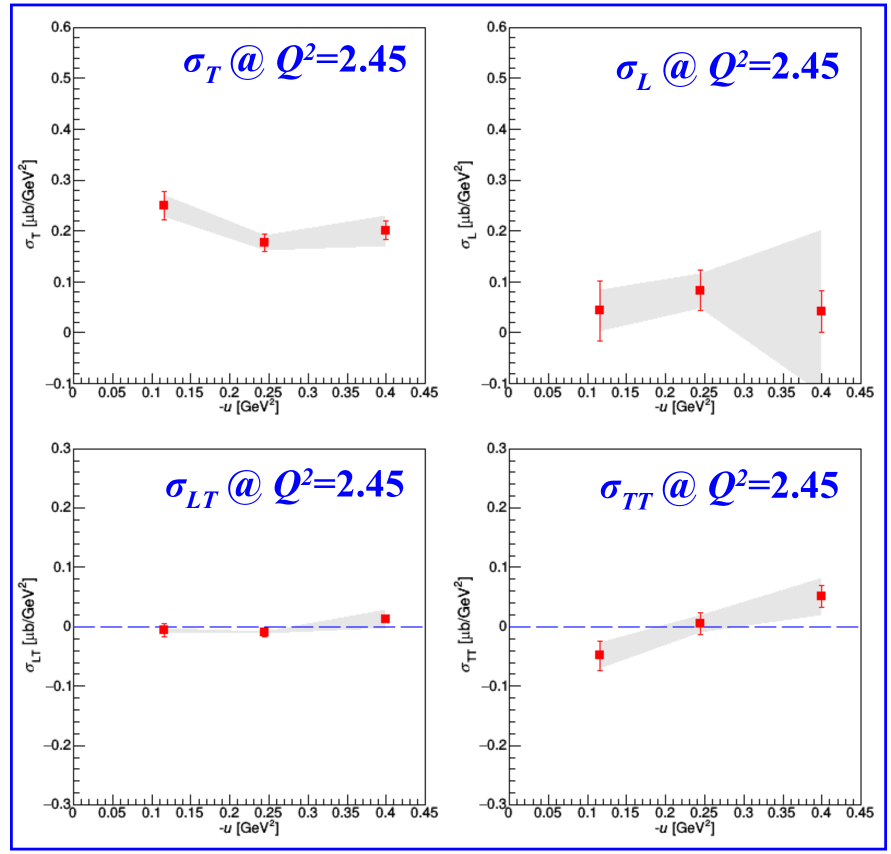

Observations:

- 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.

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Backward Angle Omega Electroproduction Peak

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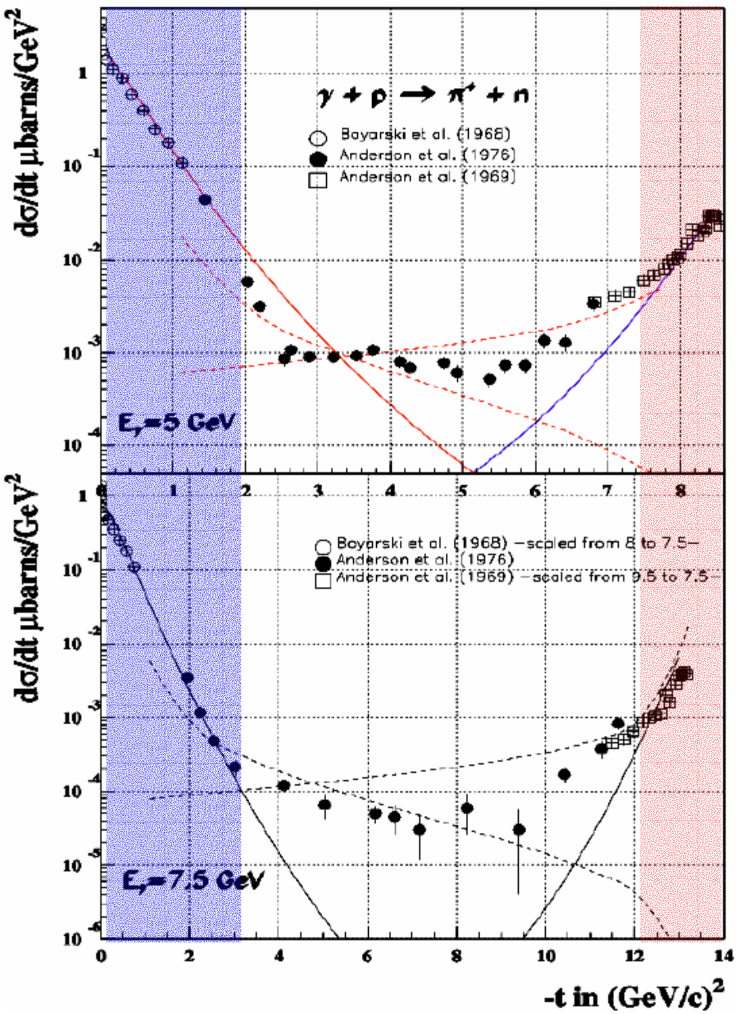
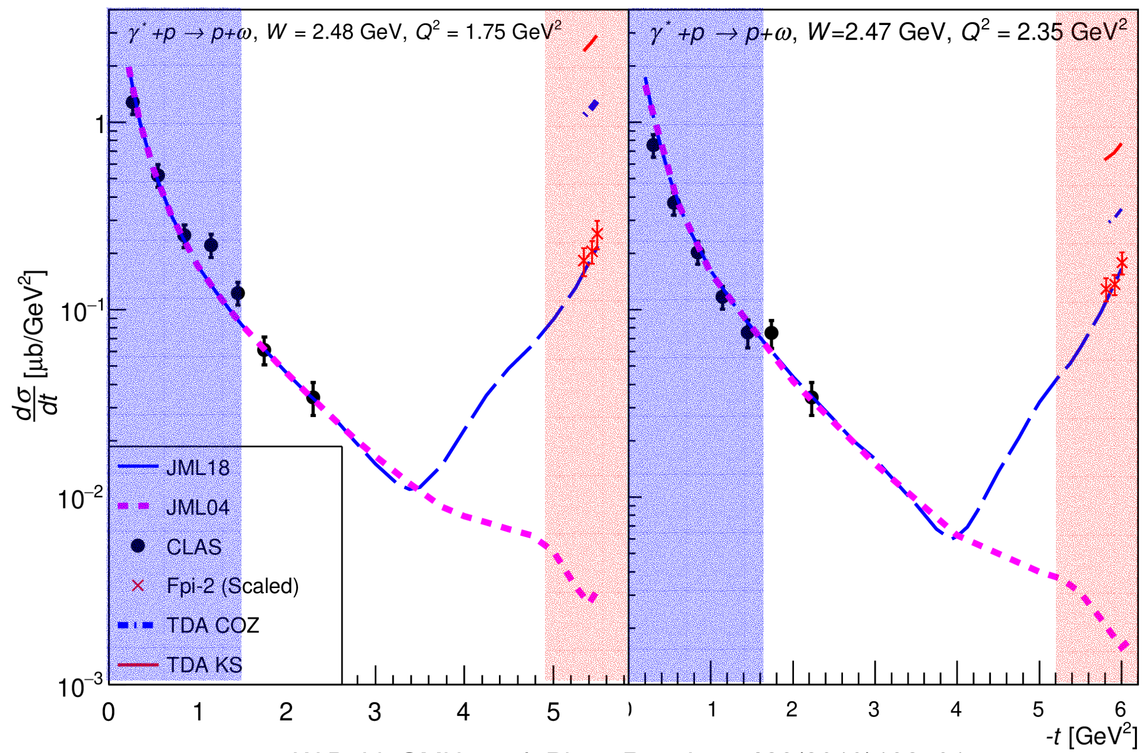
Photoproduction



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	Q^2 (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

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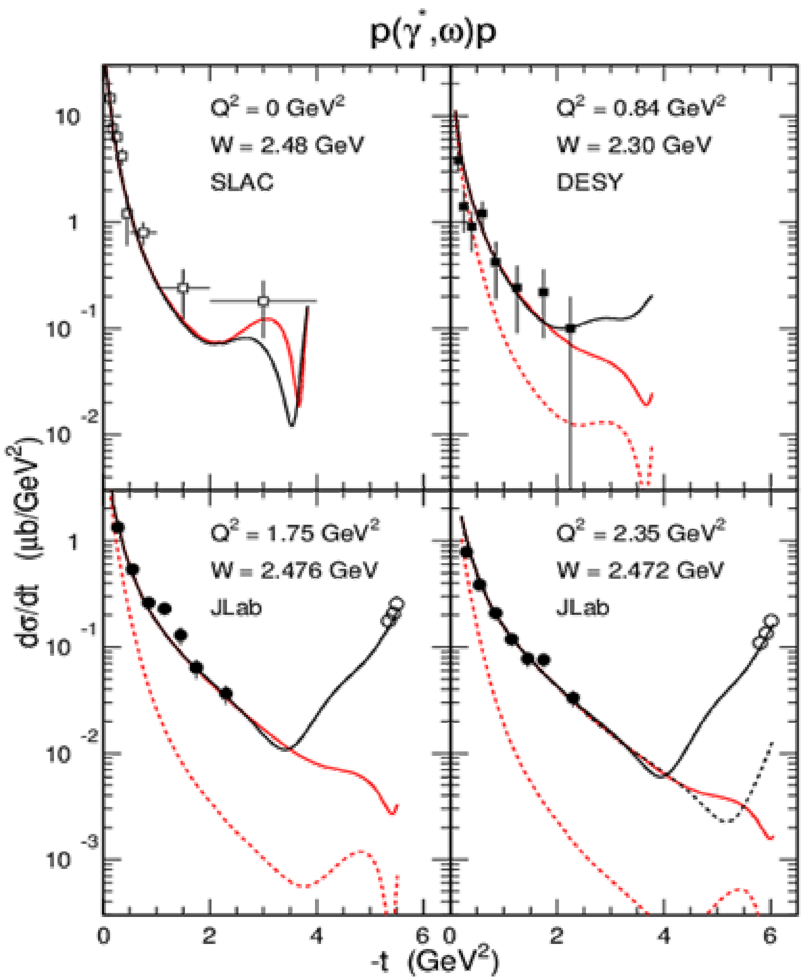
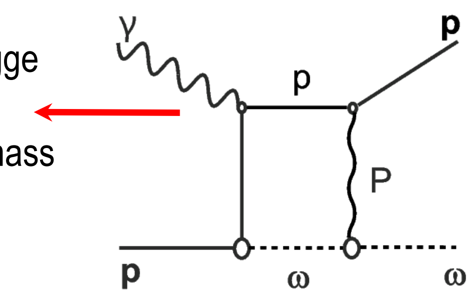


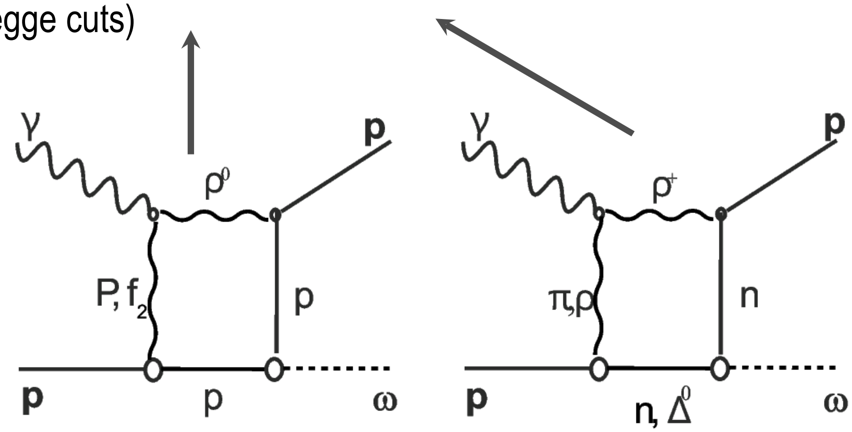
J–M Laget, Private Communication (2018)

- 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

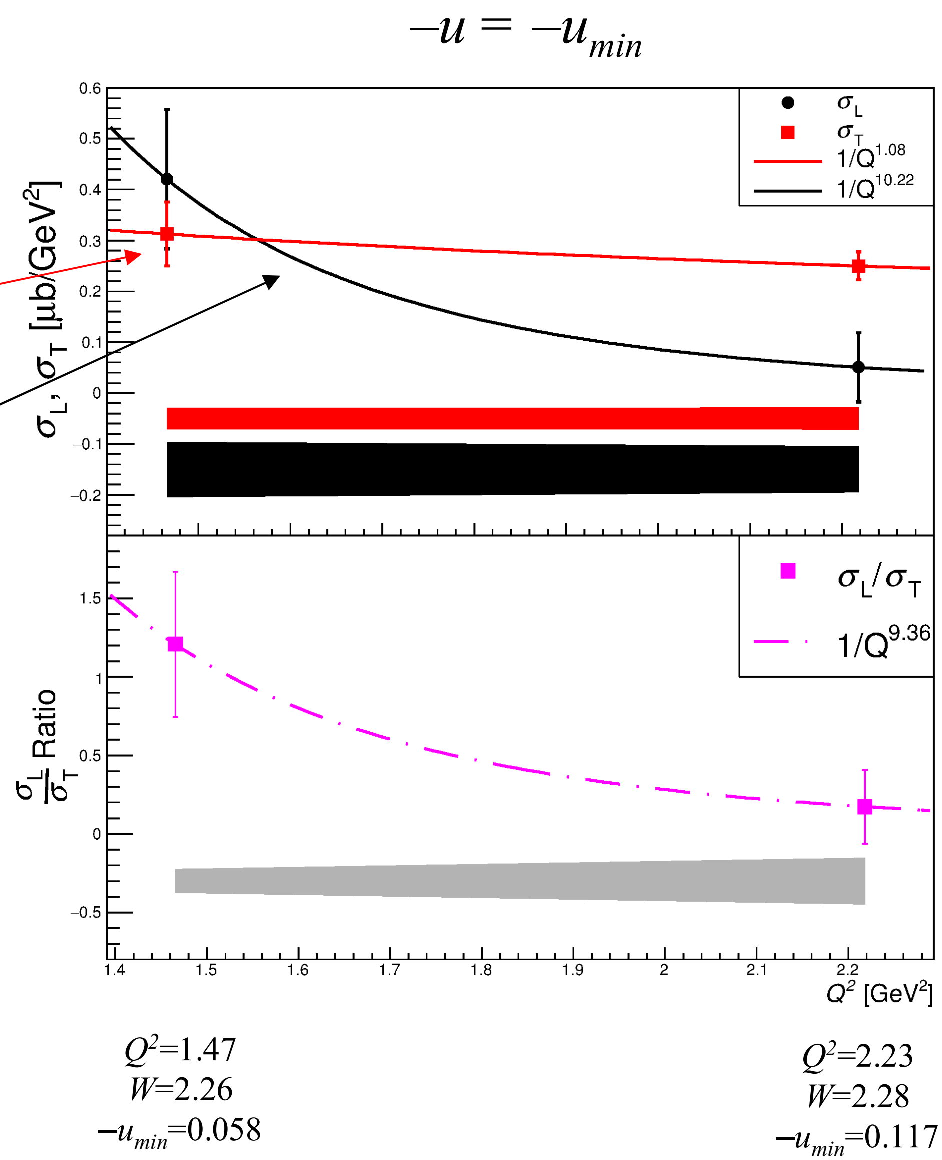


Black line: Include *ρN* and *ρΔ* rescattering inside nucleon (Regge cuts)



$p(e,e'p)\omega$ 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

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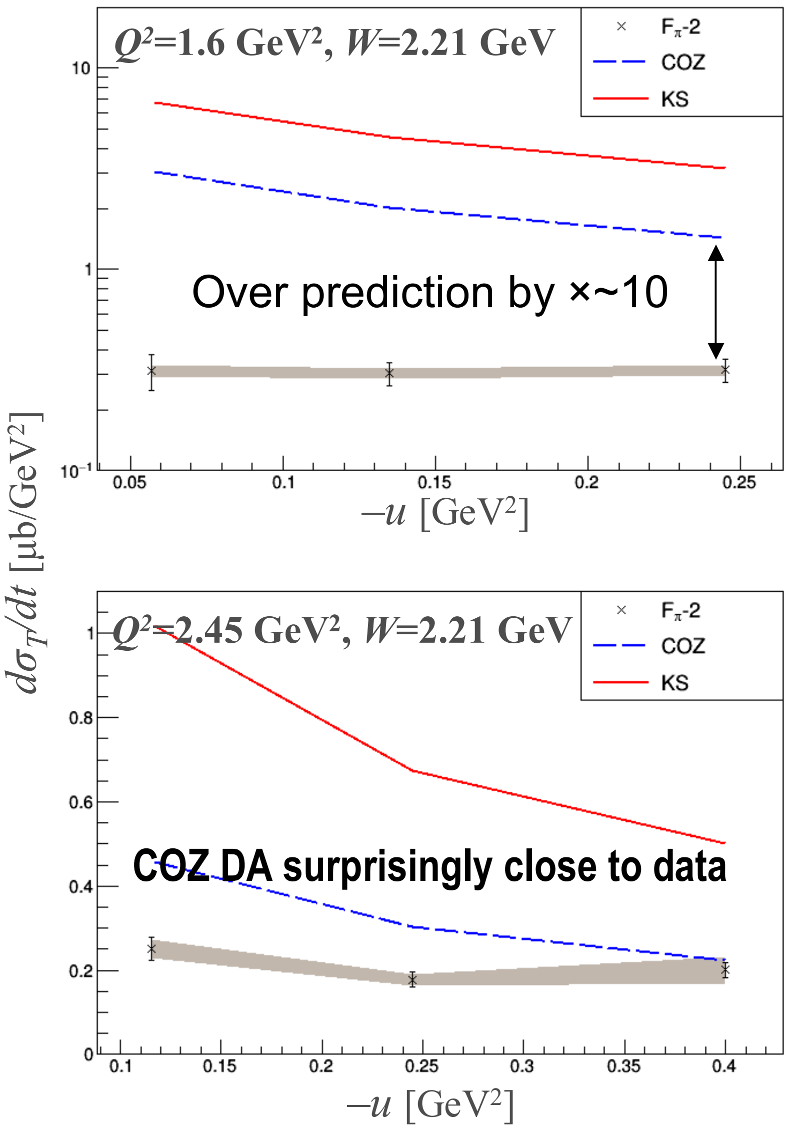
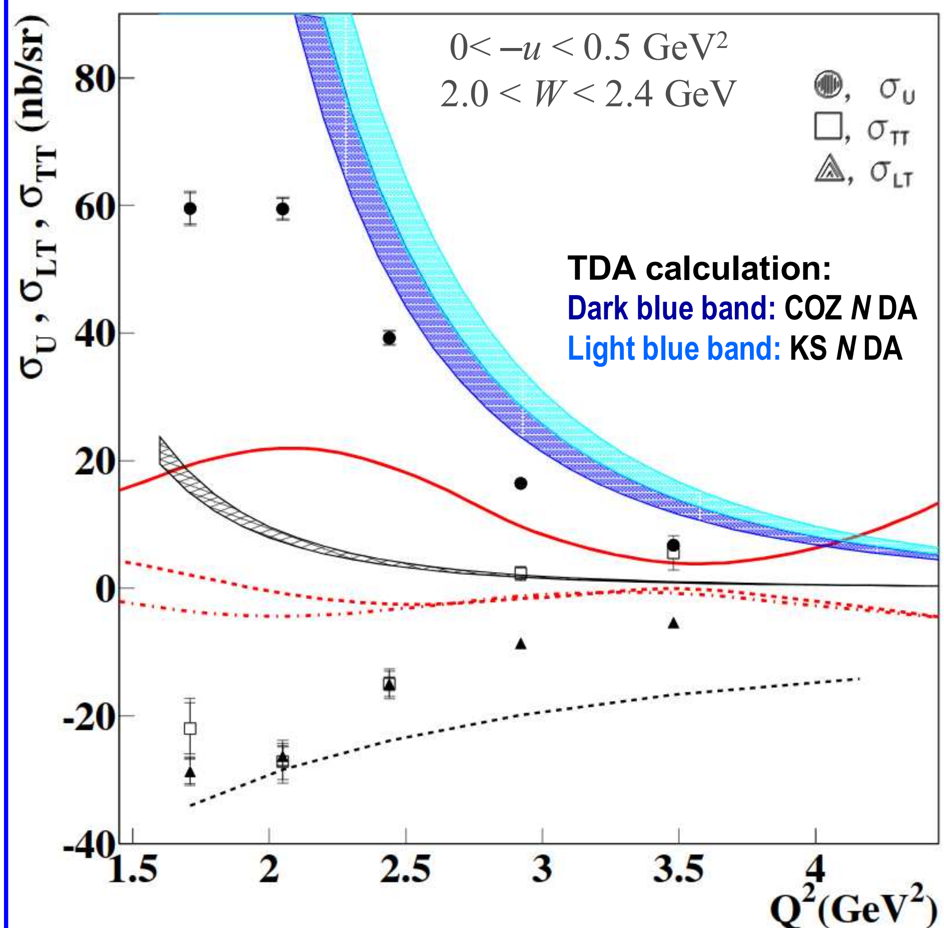


TDA calculation by B. Pire, K. Semenov, L. Szymanowski
Private Communication (2015)

Hall C ω electroproduction

Both data sets suggestive of early TDA scaling $Q^2 \approx 2.5$ GeV² !?



Hall B π^+ Electroproduction

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

Hall C *u*–channel Near–term Goals

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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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Example 12 GeV data already acquired

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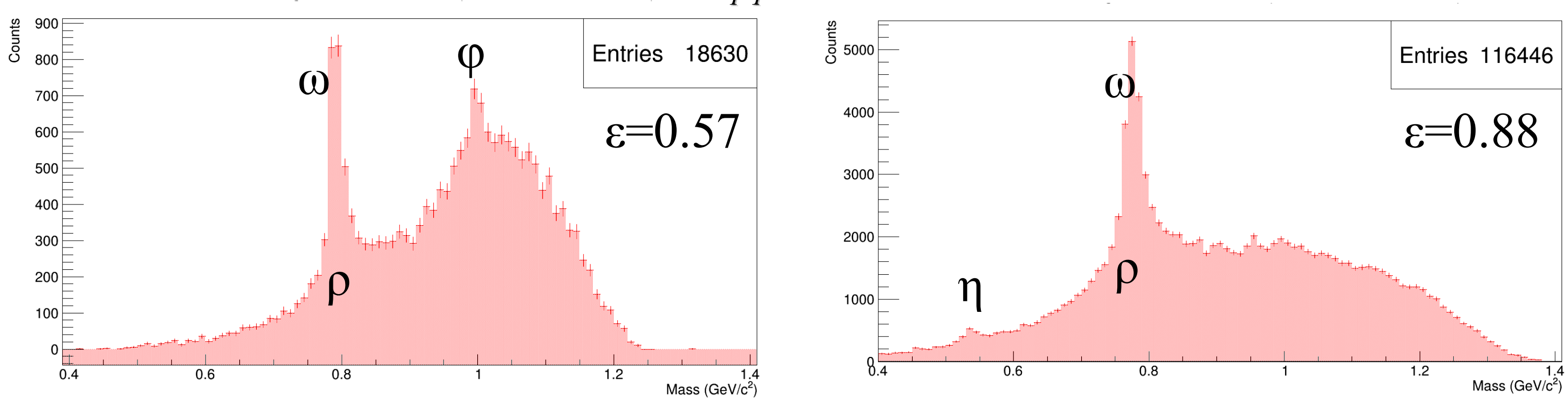
p(e,e'p)X Online Data Analysis

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



Plots by Stephen Kay

K^+ L/T–experiment (E12–09–011)

Spokespersons: T. Horn, G.M. Huber, P. Markowitz

- Data acquired fall 2018–spring 2019
- Main purpose of experiment is to acquire *t*-channel L/T–separated *p(e,e'K⁺)Λ* data for reaction mechanism and K^+ form factor studies
- Abundant *u*–channel *p(e,e'p)X* data acquired parasitically
  - Will allow backward angle studies for several meson states over a wide kinematic range

Setting	Low ε data	High ε data
Q^2=0.50 W=2.40	✓	✓
Q^2=2.1 W=2.95	✓	✓
Q^2=3.0 W=2.32	✓	✓
Q^2=3.0 W=3.14	✓	✓
Q^2=4.4 W=2.74	✓	✓
Q^2=5.5 W=3.02	✓	✓

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TDA Model Predictions for JLab E12–19–006

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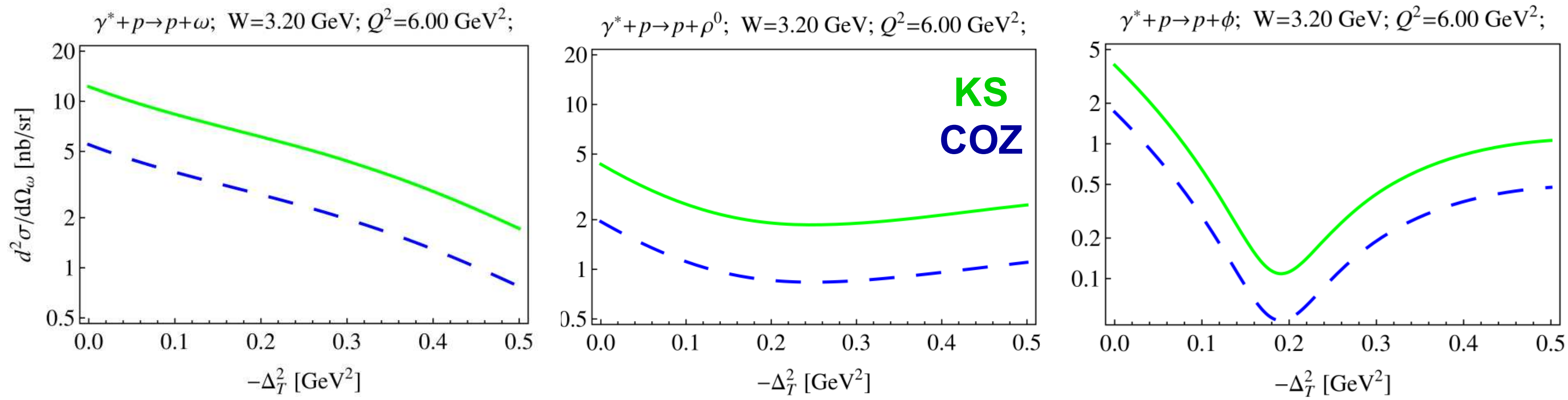
Fπ–12 experiment (E12–19–006) L/T separations up to Q^2=8.5 GeV^2

Spokespersons: D. Gaskell, G.M. Huber, T. Horn

- **L/T–Separations over wide kinematic range will allow σ_T » σ_L and $1/Q^8$ scaling predictions to be checked with greater authority**
- u–channel φ–electroproduction particularly interesting
  - Sensitive to Strangeness content of nucleon
- Combined analysis of ρ, ω production allows one to disentangle isotopic structure of VN TDAs in non–strange sector



B. Pire et al., PRD 91 (2015) 094006

At Q^2=6.0 GeV^2, ω predicted to remain dominant (unlike t-channel), φ to drop rapidly with $-u$.

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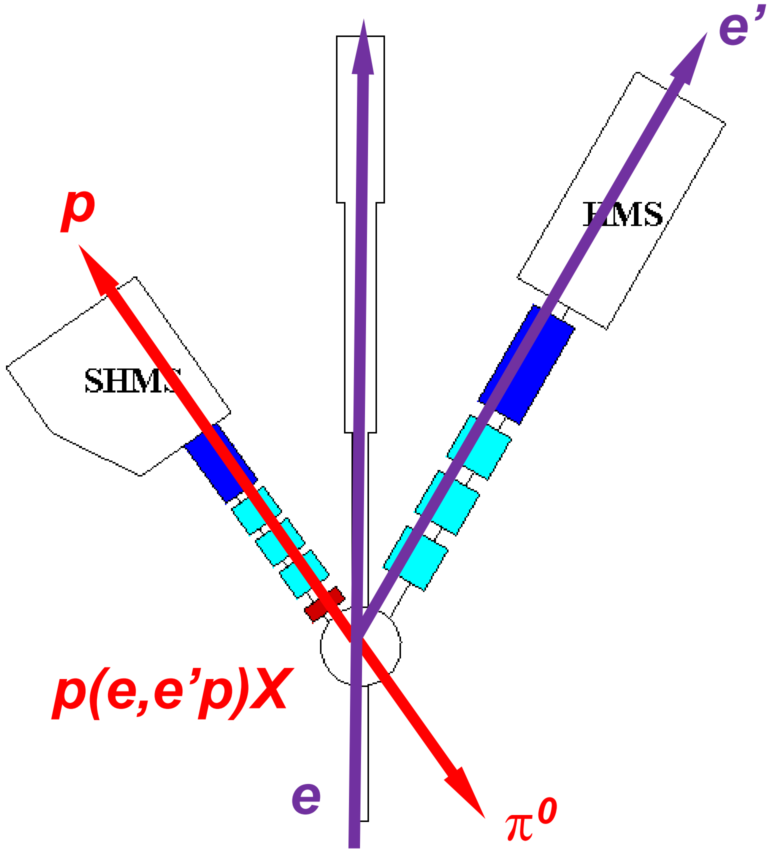
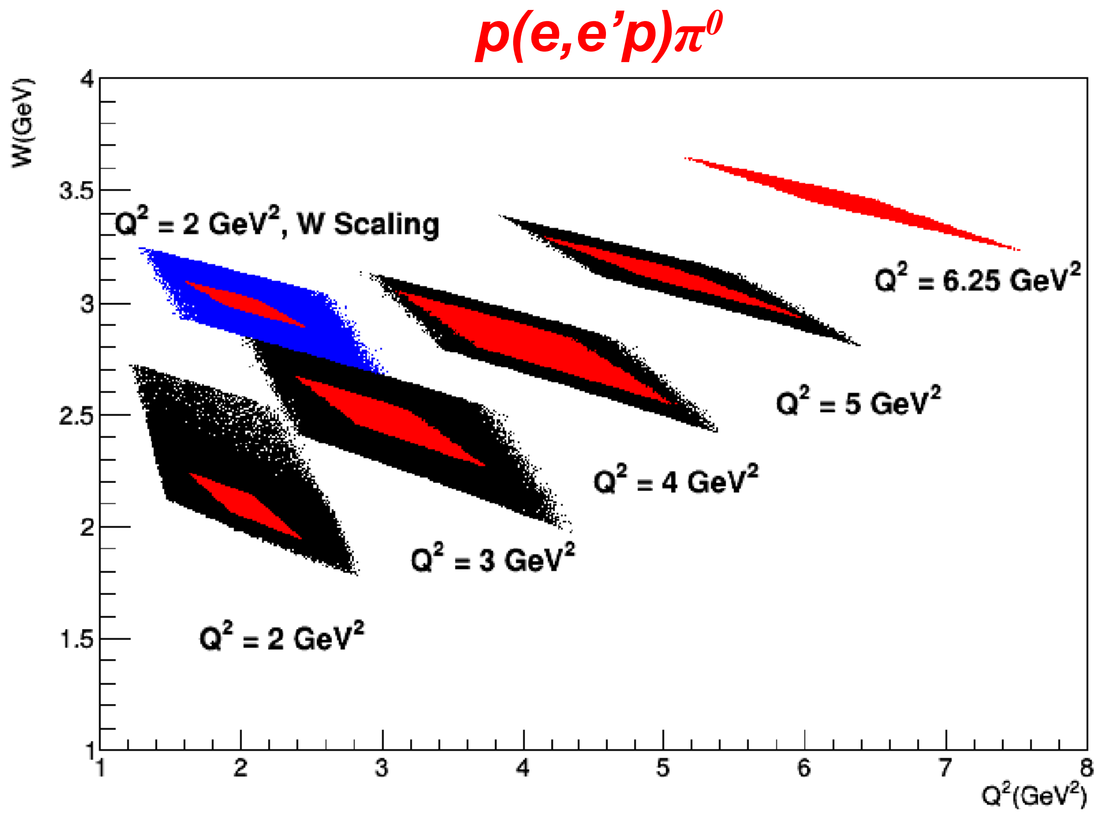
Backward Exclusive π^0 Production





PR 12–20–007: *u*≈0 π^0 production in Hall C

Spokespersons: W.B. Li, G.M. Huber, J. Stevens

Purpose: test applicability of TDA formalism for π^0 production

- Is σ_T dominant over σ_L?
- Does the σ_T cross section at constant x_B scale as $1/Q^8$?

- Kinematics overlap forward angle $p(e,e'\pi^0)p$ experiment with NPS+HMS

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π^0 Channel Expected to be Clean

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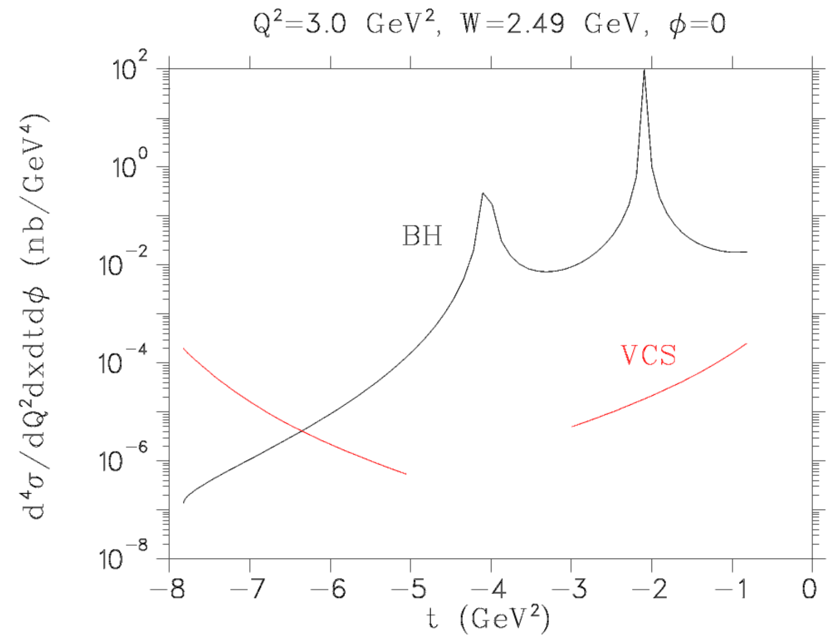
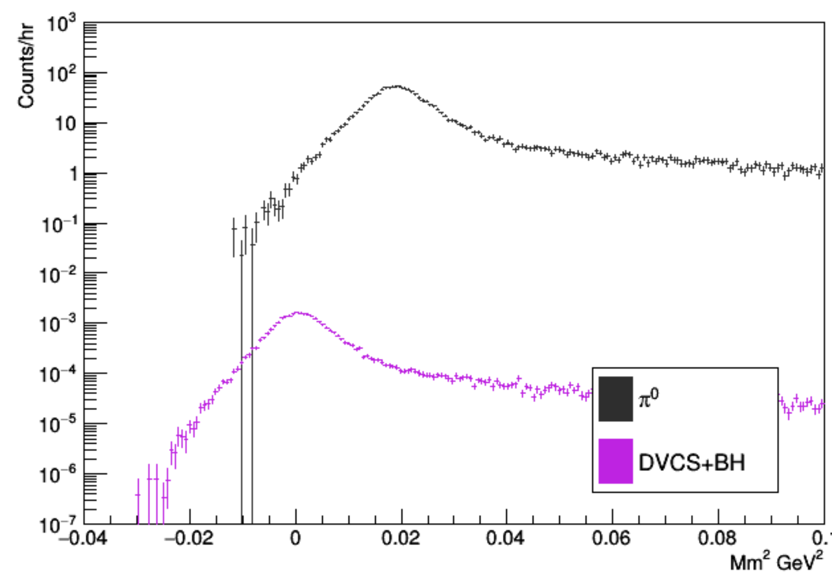
- In comparison to backward–angle ω electroproduction, there is little physics background in π^0 production.
- Bethe–Heitler process has no backward–angle peak, and will be negligible.
- VCS should dominate backward–angle γ production, but is expected to be much smaller than π^0 production.



SHMS+HMS Q^2=3.0 Simulation



BH+VCS simulations based on code by P. Guichon and M. Vanderhaeghen.
- BH calculation is exact.
- VCS calculation makes use of ad–hoc ansatz based on *u*–channel ω data.

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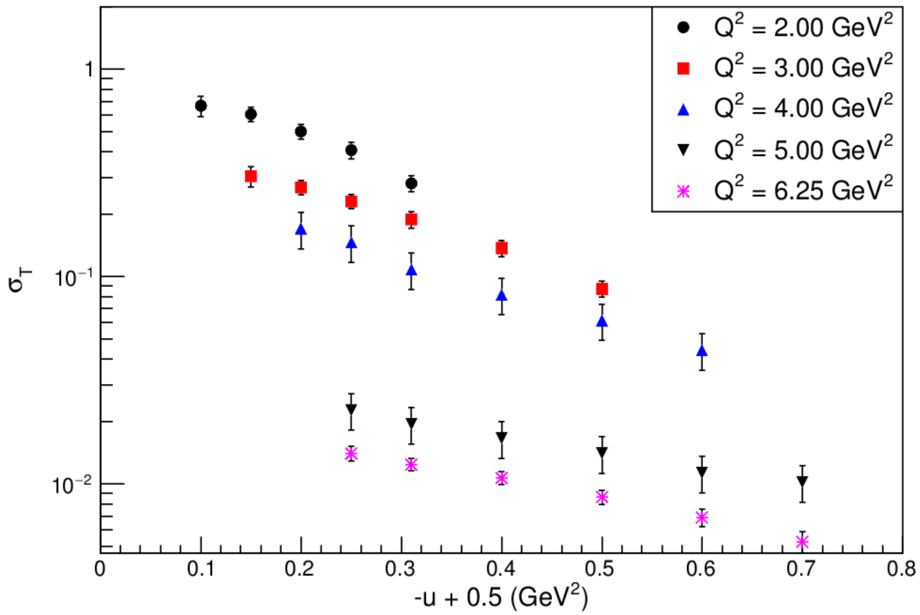
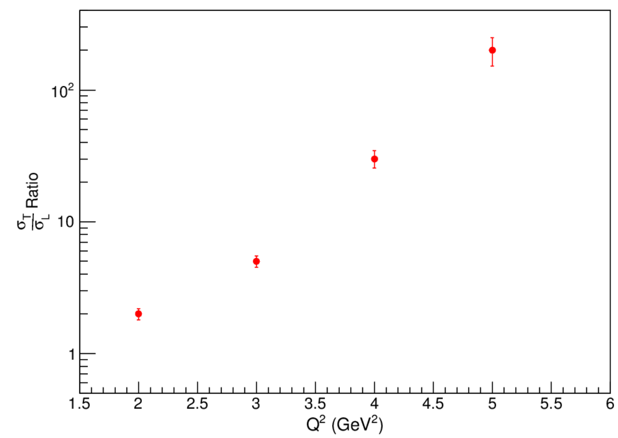
PR 12–20–007 Projected Data Quality

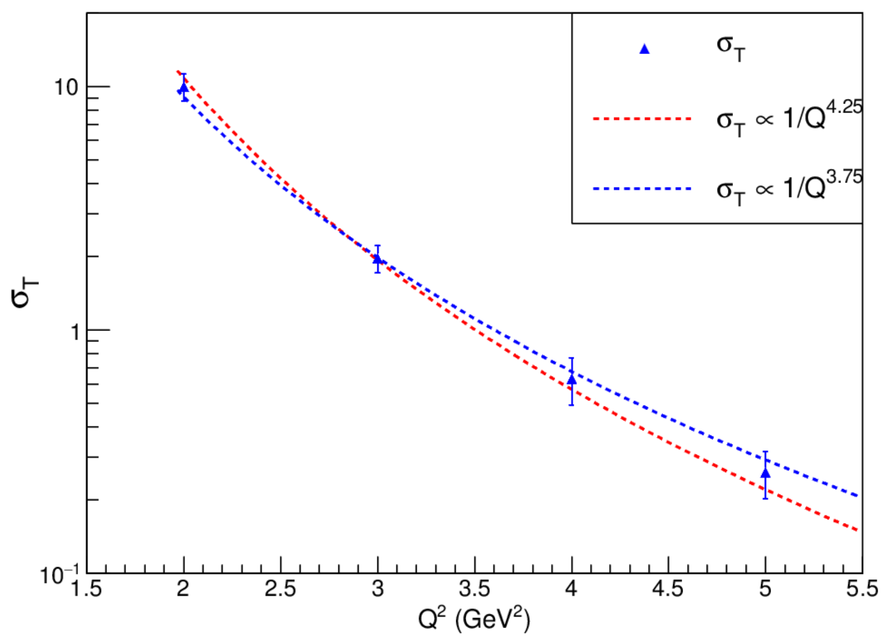


Projected SHMS+HMS *u*–coverage and uncertainties at each Q^2.

- L/T separations for comparison with Regge and TDA model calculations.
- σ_T units are arbitrary.

T/L ratio is expected to be large.





Projected uncertainty in Q^{-n}, which could be used to test TDA prediction: $\sigma_T \propto Q^{-8}$.

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u–Channel Workshop

The First Backward Angle Physics Workshop at Jefferson Lab
- **Exclusive to the *u*–channel or backward angle physics**

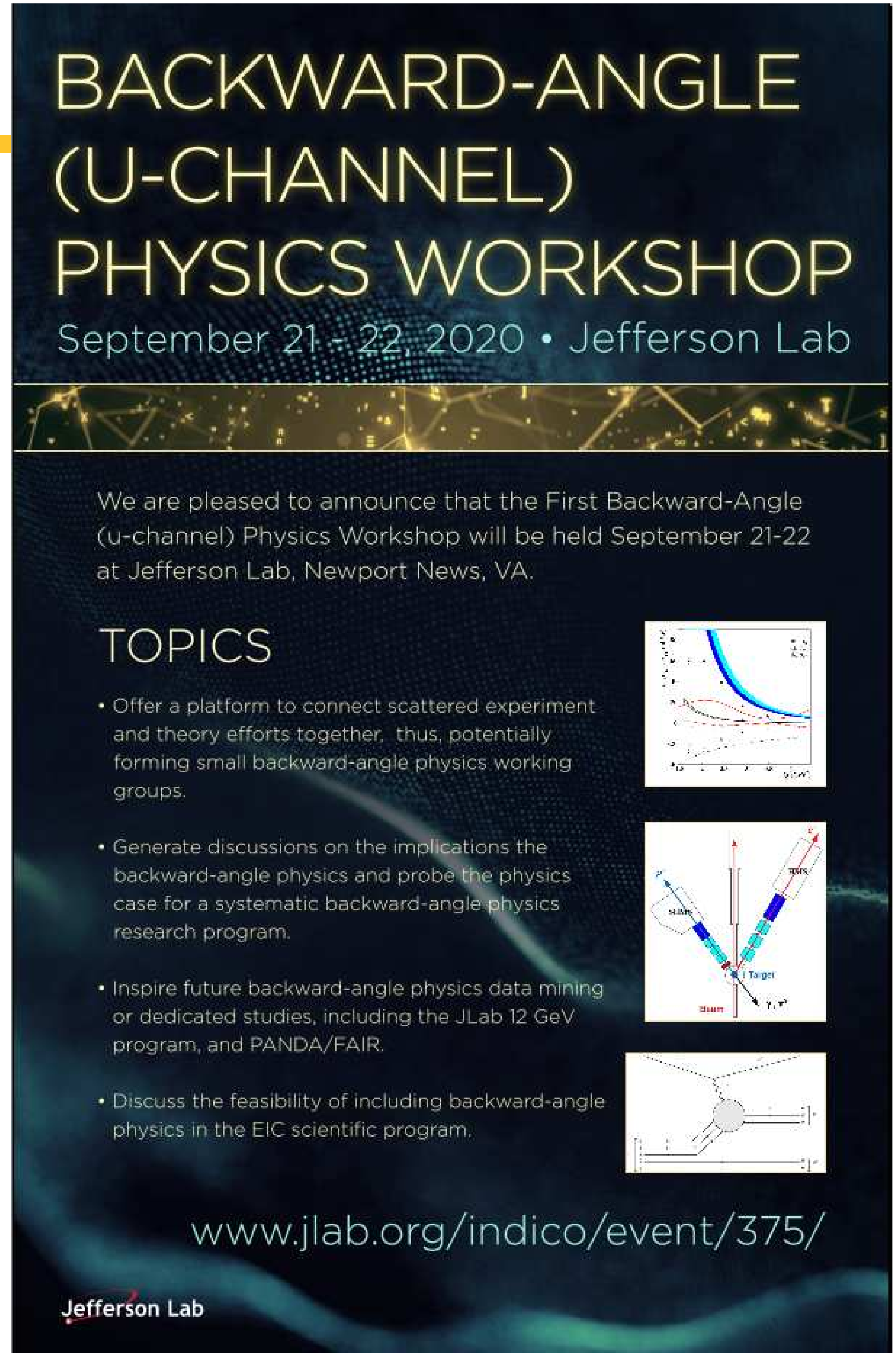
Topics:
- **Explore Backward Photoproduction experiments**
  - **Programs at JLab Hall D**
- **Explore Backward Electroproduction experiments**
  - **Programs at JLab A, B and C**
  - **PANDA TDA program will be invited**
- **TDA and Regge Approaches**

Organizers: Wenliang (Bill) Li, Justin Stevens, GH

Date: Sept 21–22, 2020

Register at:

https://www.jlab.org/conference/BACKANGLE



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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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