u–channel Exclusive Electroproduction at Jefferson Lab

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University of Regina

CFNS Workshop on Baryon Dynamics
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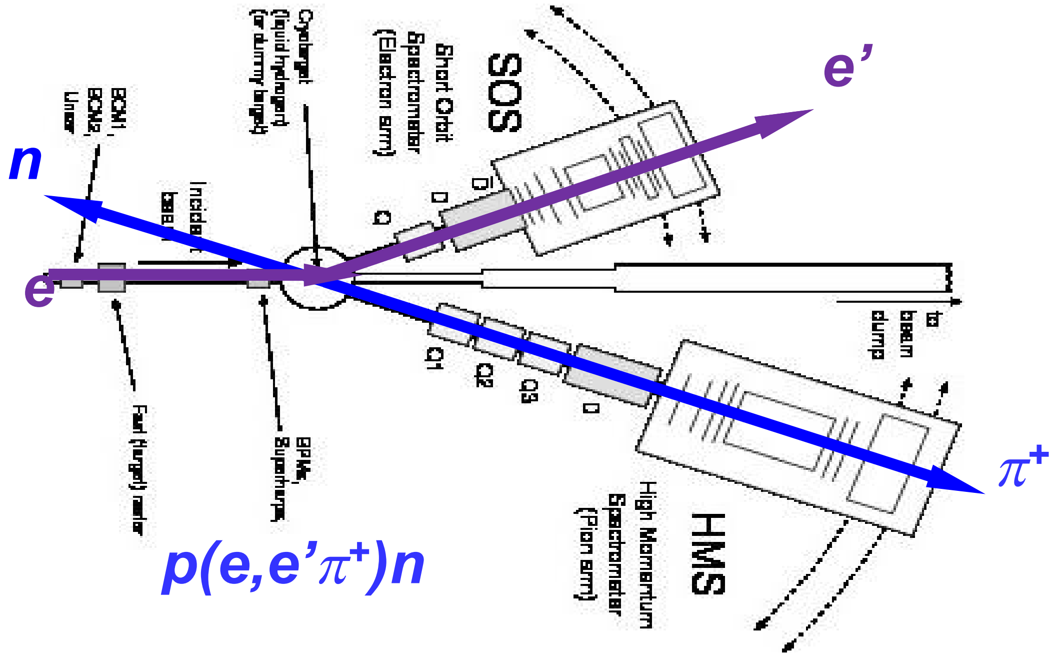
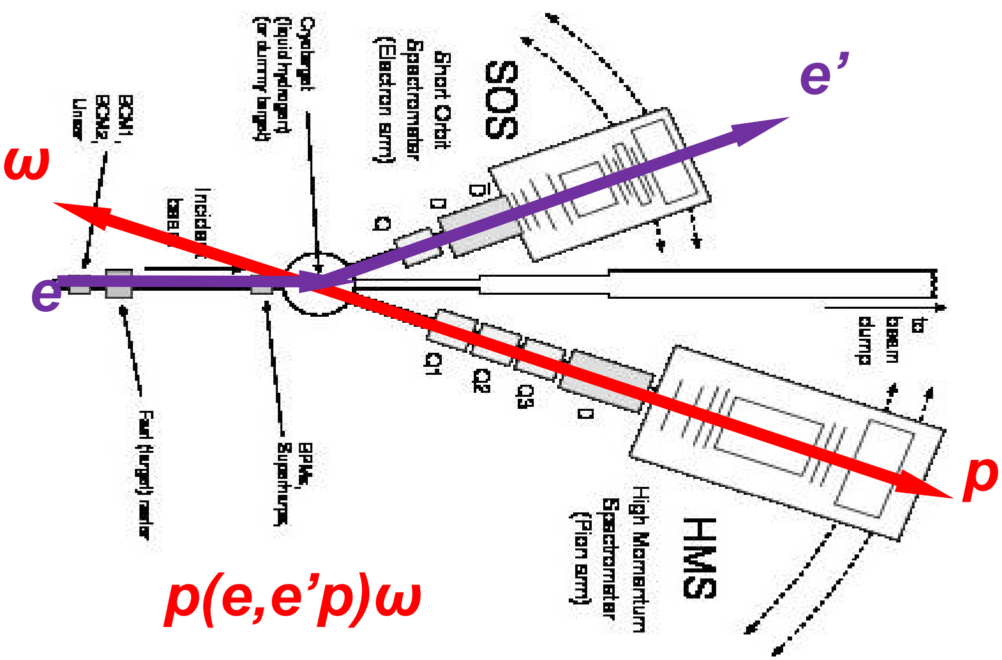
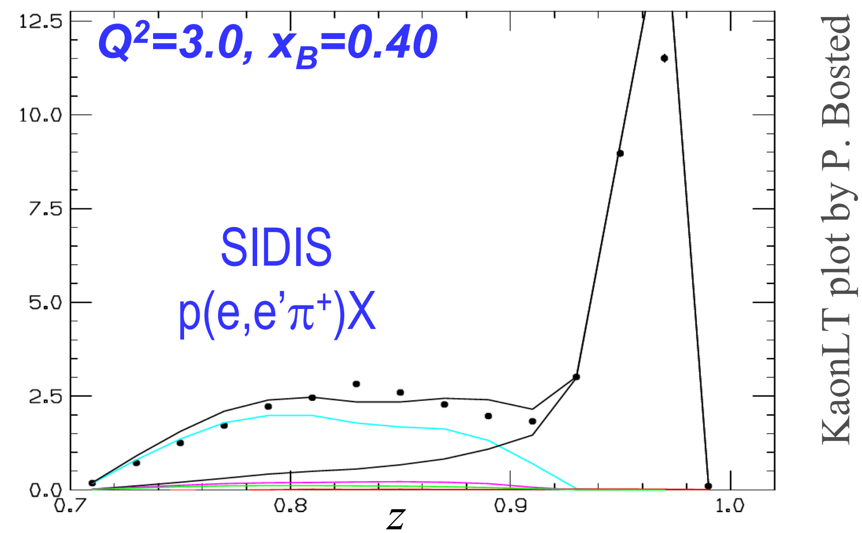
t–Channel π^+ vs u–Channel ω Production





Hadron detected along *q*–vector ($p_{\gamma*}$)

- $p_{\pi+}$ is parallel to $p_{\gamma*}$ (forward)
- p_{ω} is anti–parallel to $p_{\gamma*}$ (backward)
- Exclusive channel is kinematic endpoint at $z\rightarrow 1$



p(e,e'p)ω **Exclusive channel**

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

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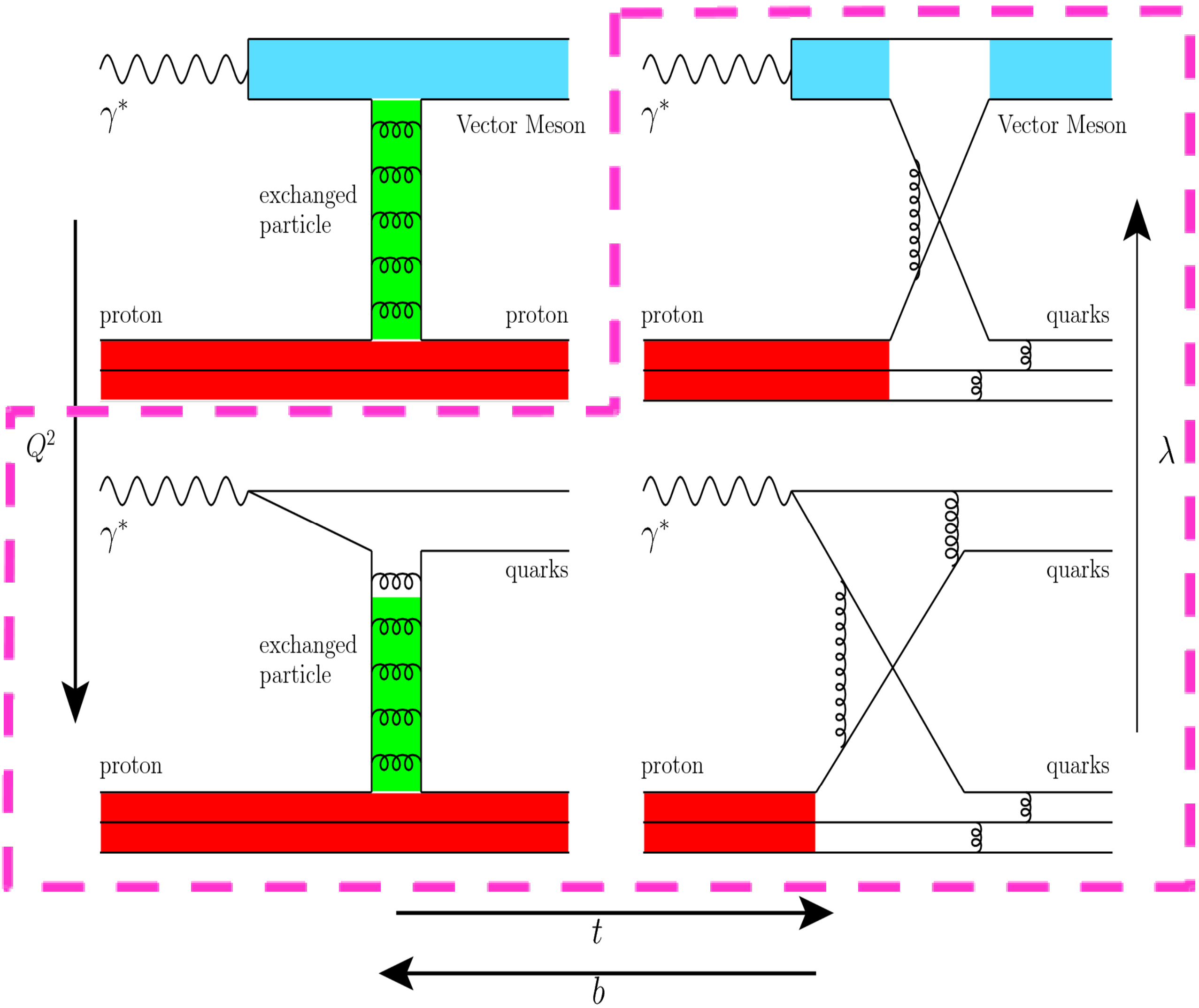
Hadronic Model: Evolution of Proton Structure



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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Hadronic Model: Regge Model by JM Laget

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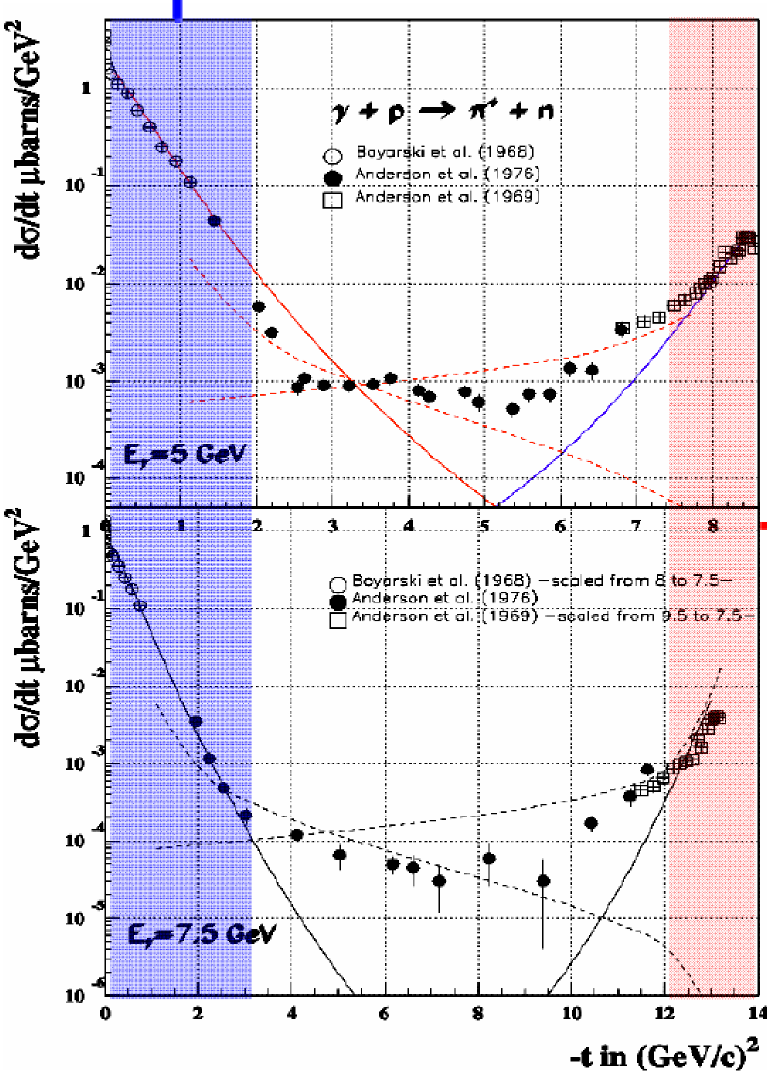
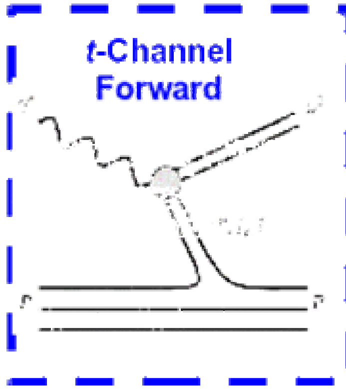
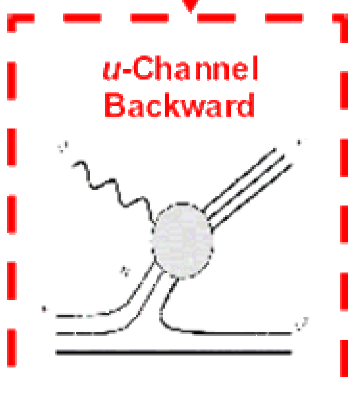
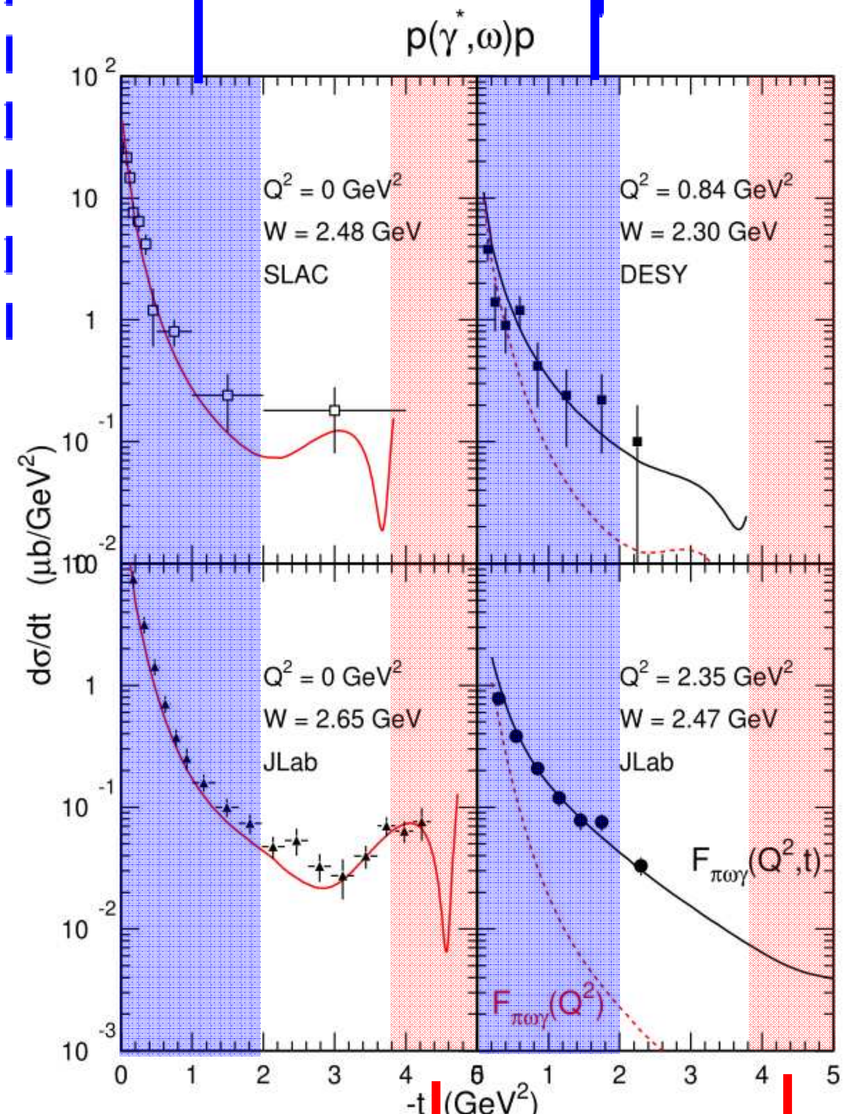
M. Guidal, J.-M. Laget, M. Vanderhaeghen, PLB **400**(1997)6

J.-M. Laget, Prog.Part.Nucl.Phys. **111**(2020)103737









Soft structure → Hard → Soft transition

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Partonic Model: TDA and Factorization

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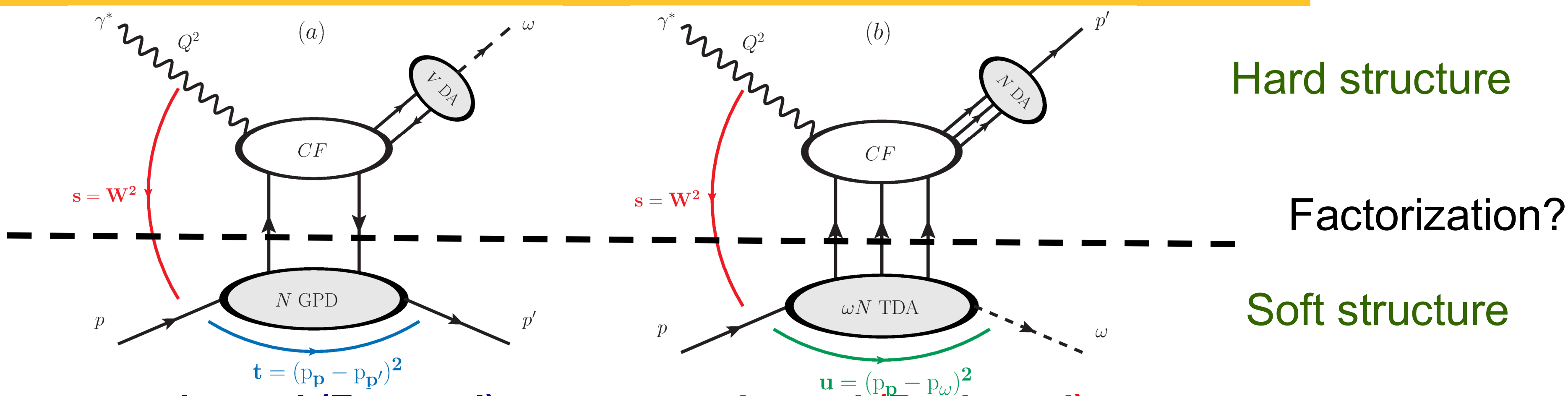

t–channel (Forward) *u*–channel (Backward)

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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Skewness in Backward Angle Regime

- **Forward angle kinematics,** $-t \sim -t_{min}$ and $-u \sim -u_{max}$, in the regime where handbag mechanism and GPD description may apply, Skewness is defined in usual manner:

$$\xi_t = \frac{p_1^+ - p_2^+}{p_1^+ + p_2^+} \quad \text{where } p_{1,2} \text{ refer to light cone + components}$$

$$\text{in } \gamma^*(q) + p(p_1) \to \omega(p_\omega) + p'(p_2)$$

- **Backward angle kinematics,** $-u \sim -u_{min}$ and $-t \sim -t_{max}$, Skewness is defined with respect to *u*–channel momentum transfer in TDA formalism

$$\xi_u = \frac{p_1^+ - p_\omega^+}{p_1^+ + p_\omega^+}$$

- GPDs depend on x, ξ_t and $t=(\Delta^t)^2=(p_2-p_1)^2$

  TDAs depend on x, ξ_u and $u=(\Delta^u)^2=(p_\omega-p_1)^2$

- Impact parameter space interpretation of TDAs is similar to GPDs, except one has to Fourier transform with respect to $\Delta^u_T \approx (p_\omega-p_1)_T$

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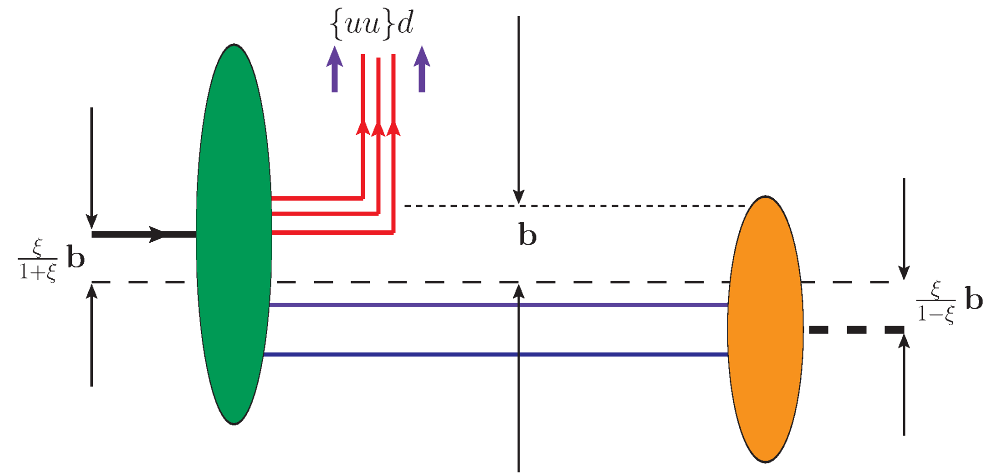
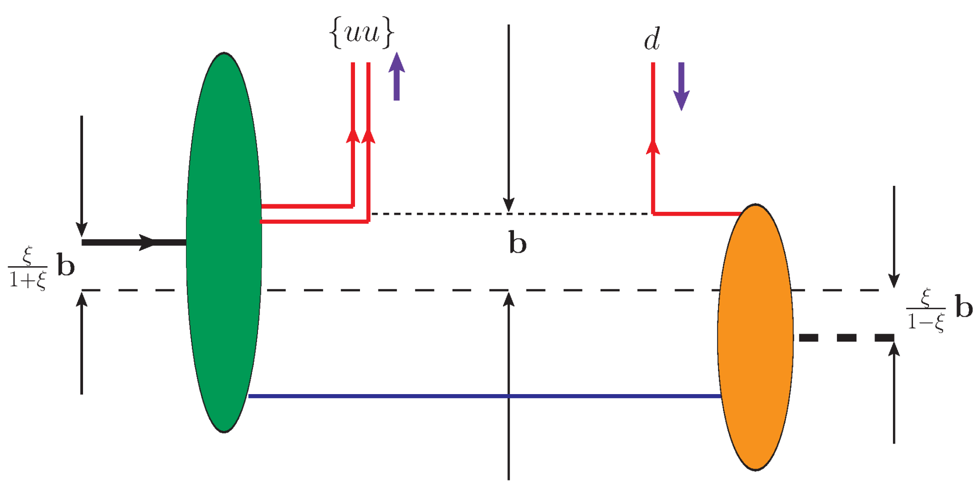
Impact parameter Interpretation of TDA

- After integrating over one momentum fraction x_i, the three exchanged quarks can be treated as an effective diquark+quark pair
- Impact picture then looks very much like that for GPDs



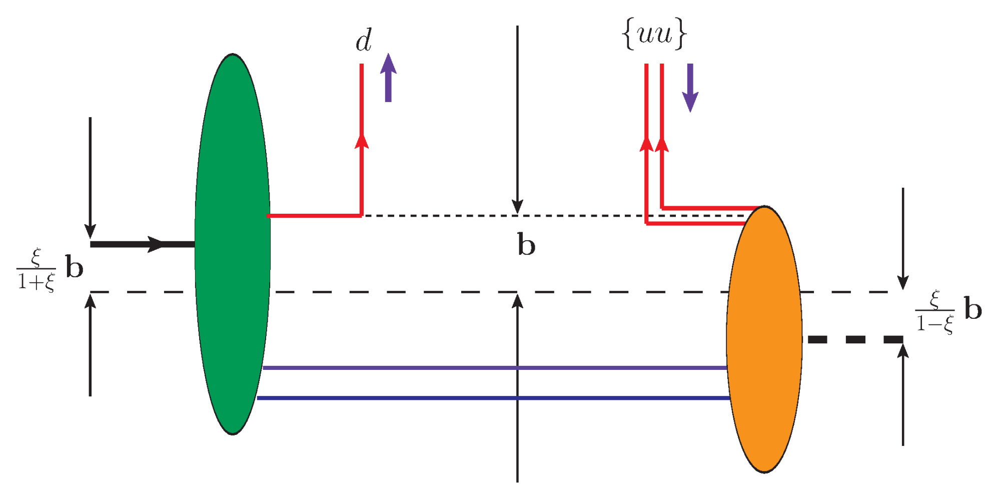
$$\text{ERBL}: \quad x_3 = w_3 + \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$$

$\longrightarrow$ All 3 quark momentum fractions x_i positive



$$\text{DGLAP I}: \quad x_3 = w_3 + \xi \leq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$$

$\longrightarrow$ One x_i negative



$$\text{DGLAP II}: \quad x_3 = w_3 + \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \leq 0;$$

$\longrightarrow$ Two x_i negative

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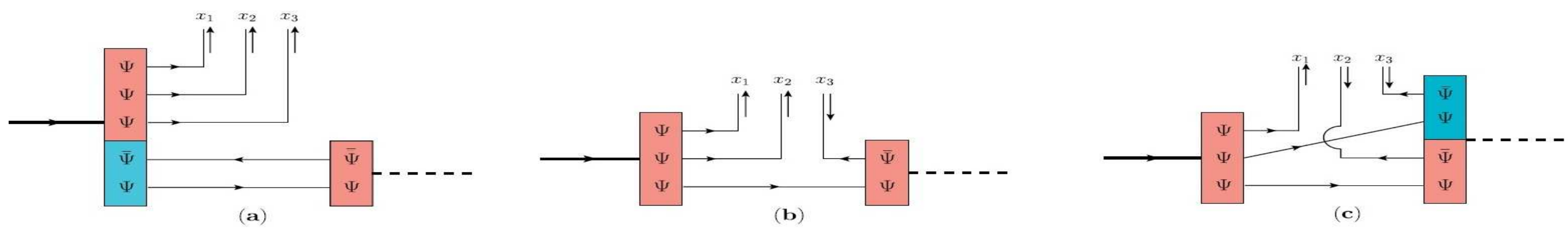
Partonic Interpretation of TDA

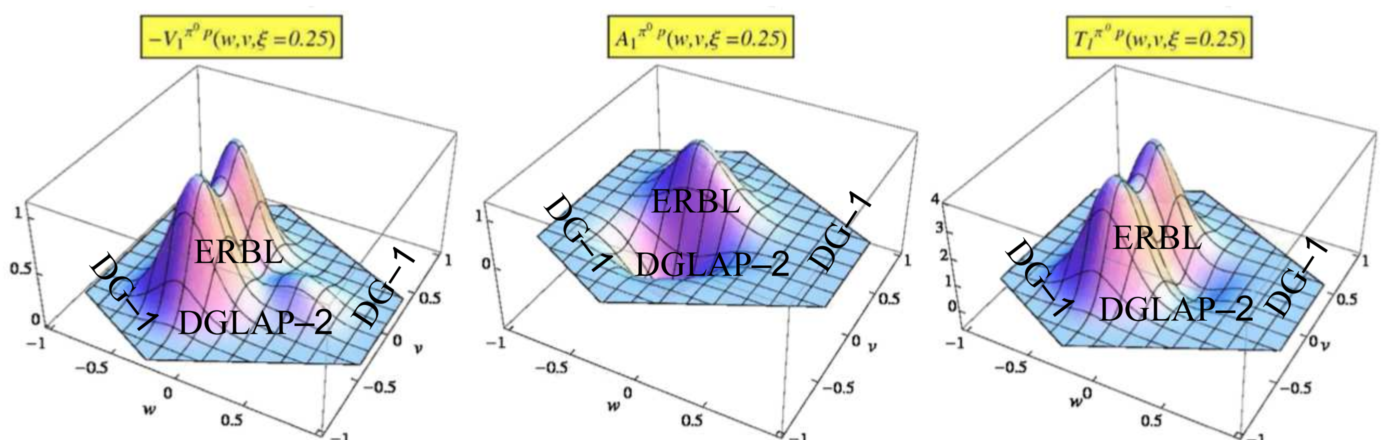
Main reactions of interest to date:

- Backward angle exclusive $\pi^0, \pi^+, \rho, \omega, \varphi$ production
- Backward angle DVCS



Interpretation of πN TDAs in light–cone quark model

a) Quark sea contrib to baryon wf (ERBL region)
b) Minimal Fock states of baryon & meson (DGLAP–1) region
c) Quark sea contribution to meson wf (DGLAP–2)



$v = (x_1 - x_2)/2$
$w = (x_3 - x_1 - x_2)/2$

$\pi^0 p$ TDAs (CZ): **Vector** **Axial–Vector** **Tensor**

J.P. Lansberg et al., PRD **85** (2012) 054201

Model based on spectral representation w/ CZ sol for DA as input (function of quark–diquark coord)

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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

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

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

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Limitations

- Exclusive ERBL and DGLAP1,2 regions are somewhat analogous to J/3q, J+2q, J+q exchange processes in SIDIS *u*–channel, could have different Junction contributions
- **Very difficult to selectively probe ERBL and DGLAP regions**. In an exclusive process, one has to exchange entire baryon in *u*–channel, and the problem is even more complicated than familiar deconvolution problem for GPDs
  - **Only exception appears to be at high ξ_u, where DGLAP regions disappear, so dominant picture (e.g. for impact parameter interpretation) is ERBL based one**
  - In general, JLab kinematics are expected to be more ERBL dominated, while EIC kinematics will be more DGLAP region
- Comparing exclusive *u*–channel processes for different final states (e.g. π^0, ρ^0, ω, φ) might help disentangle any Junction contributions from hadron form factor parts

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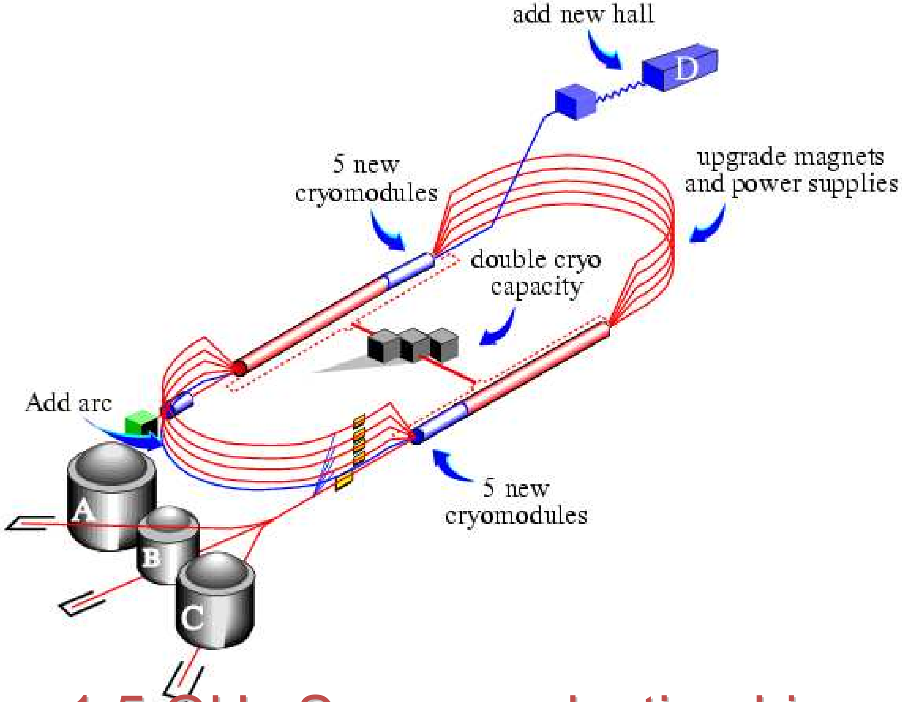

Two 1.5 GHz Superconducting Linear Accelerators provide electron beam for Nucleon & Nuclear structure studies.

- **Beam energy E → 12 GeV.**
- **Beam current >100 μA.**
- **Duty factor 100%, 85% polarization.**
- Experiments in all 4 Halls can receive beam simultaneously.

"6 GeV" JLab Hall C Experimental Setup

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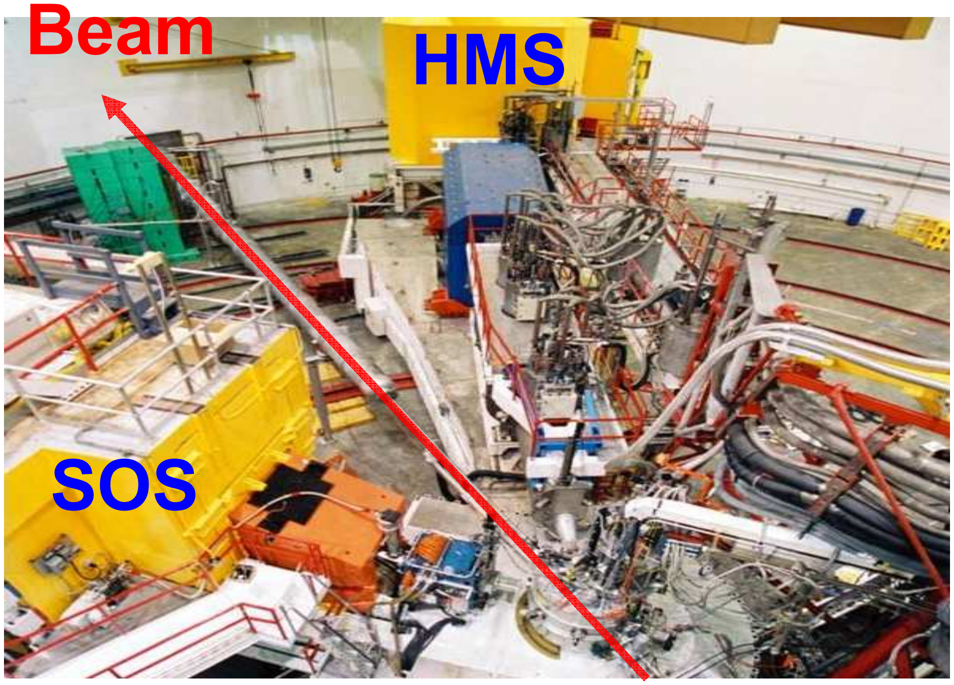
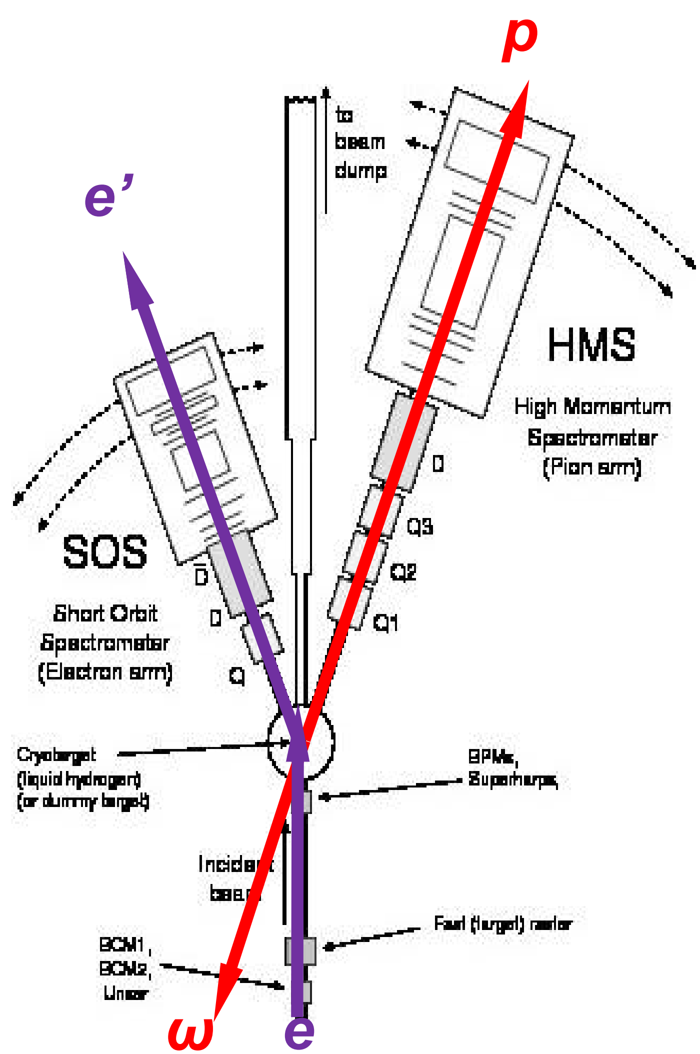


E_e (GeV)	ε	$-u$ (GeV^2)	$-t$ (GeV^2)	ξ_u	ξ_t
$<Q^2>$=1.60 GeV^2 $<W>$=2.21 GeV					
3.772	0.328	0.058 – 0.245	3.85 – 4.15	0.075 – 0.177	0.722 – 0.735
4.702	0.593				
$<Q^2>$=2.45 GeV^2 $<W>$=2.21 GeV					
4.210	0.270	0.117 – 0.400	4.48 – 4.94	0.126 – 0.256	0.748 – 0.764
5.248	0.554				

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



One of last analyses of Hall C 6 GeV era

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Physics Background Subtraction

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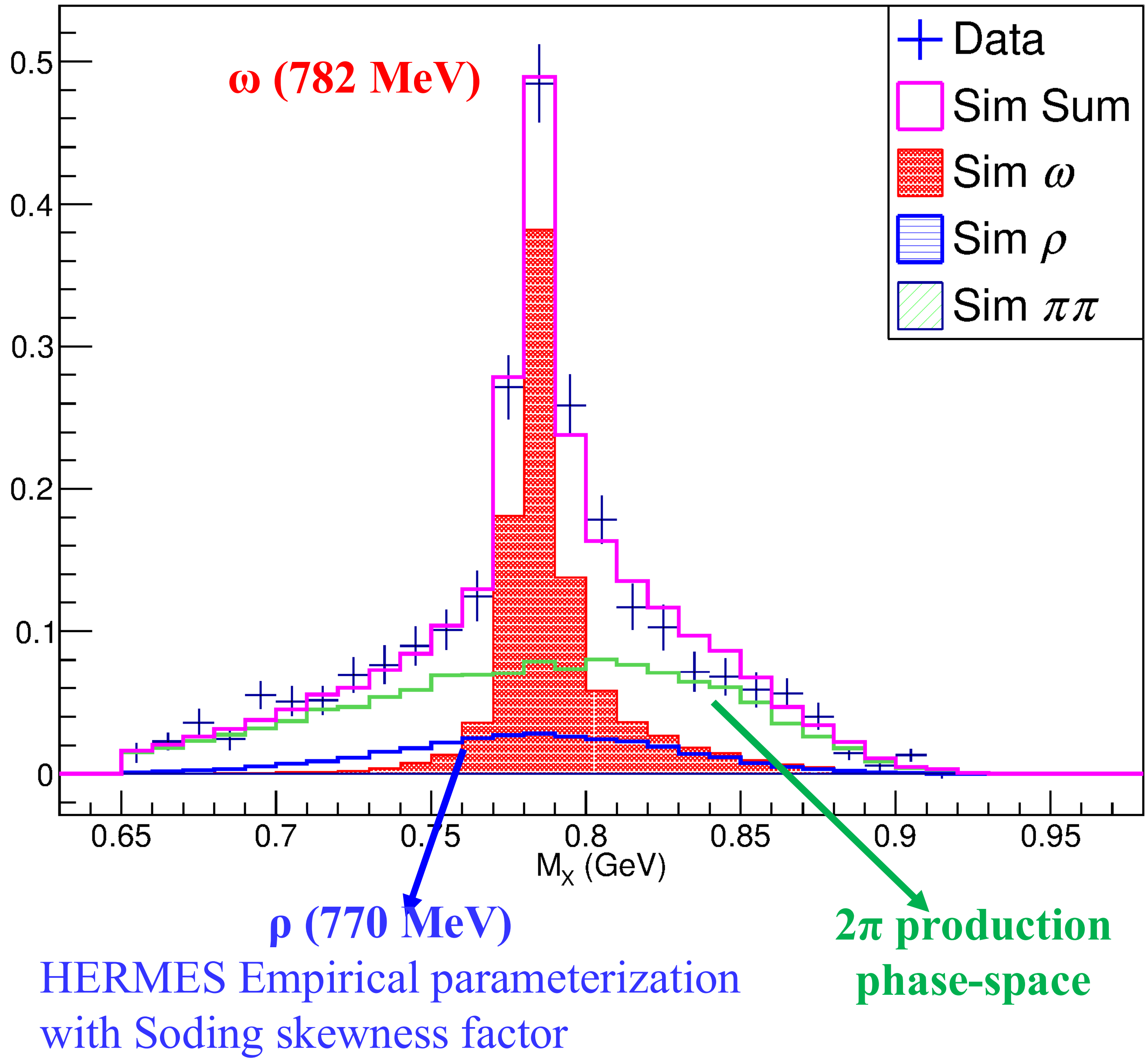
$$M_x = \sqrt{(E_e + m_p - m_{e'} - E_p)^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_p)^2}$$



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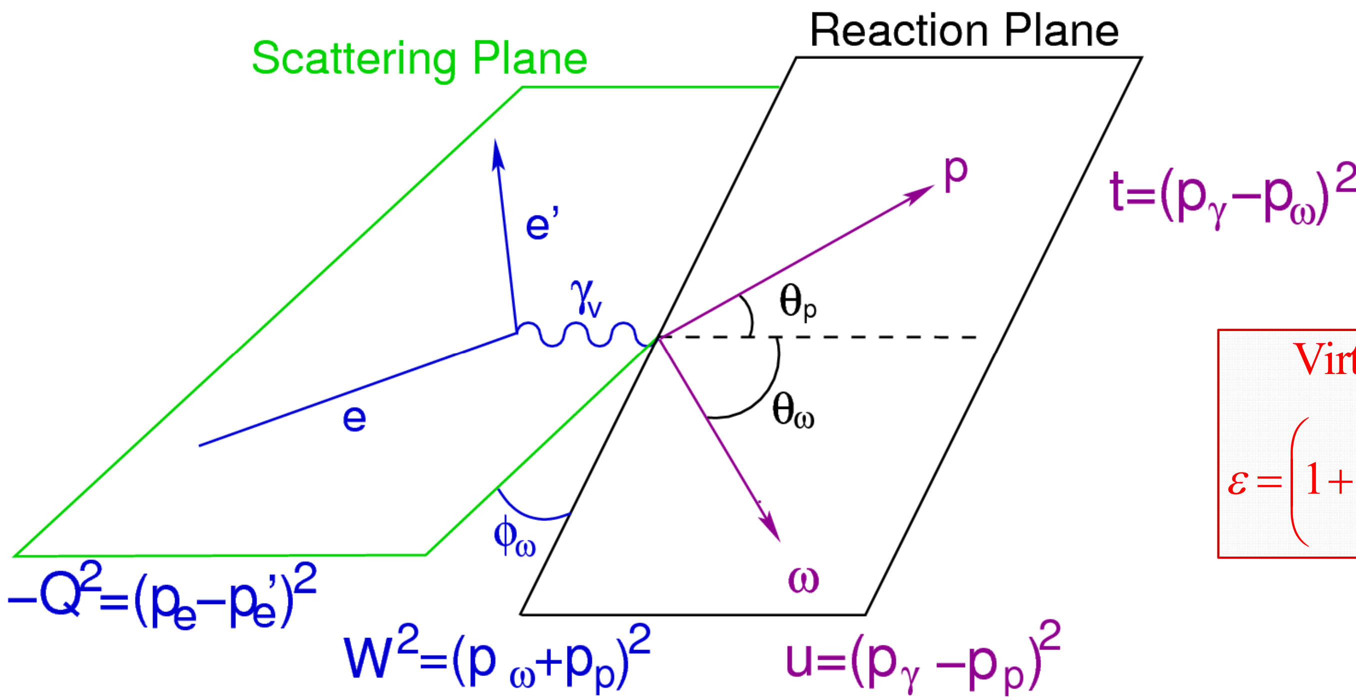
Rosenbluth (L/T/LT/TT) Separation



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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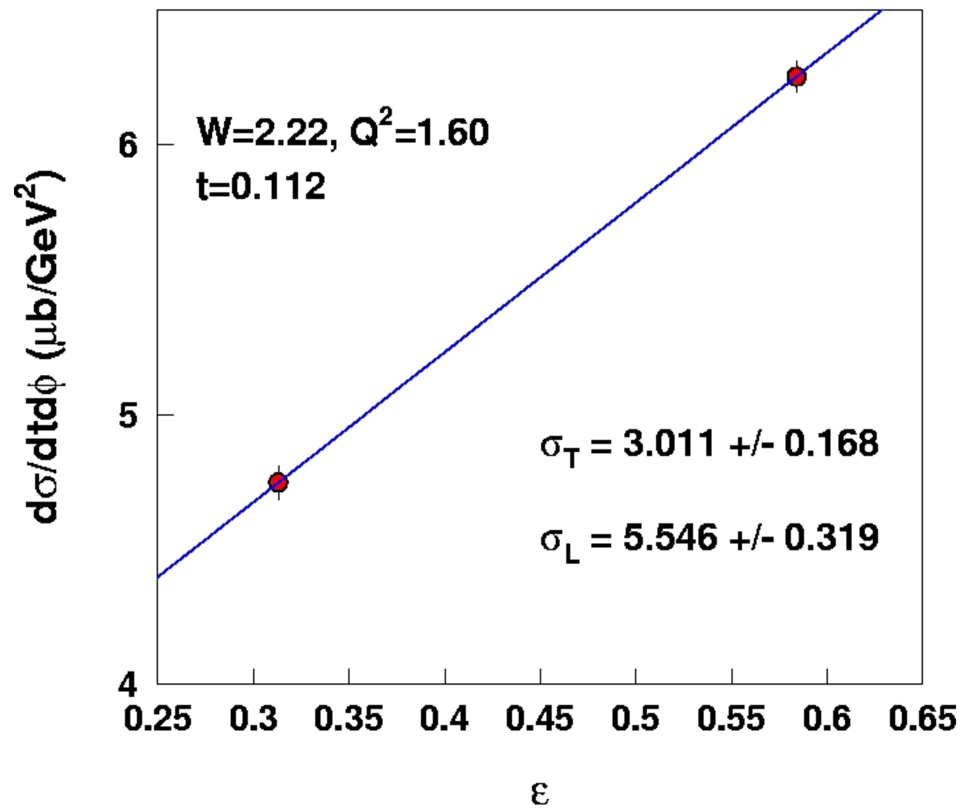
“Simple” Longitudinal–Transverse Separation

- For uniform φ–acceptance, σ_{TT}, $\sigma_{LT}\rightarrow 0$ 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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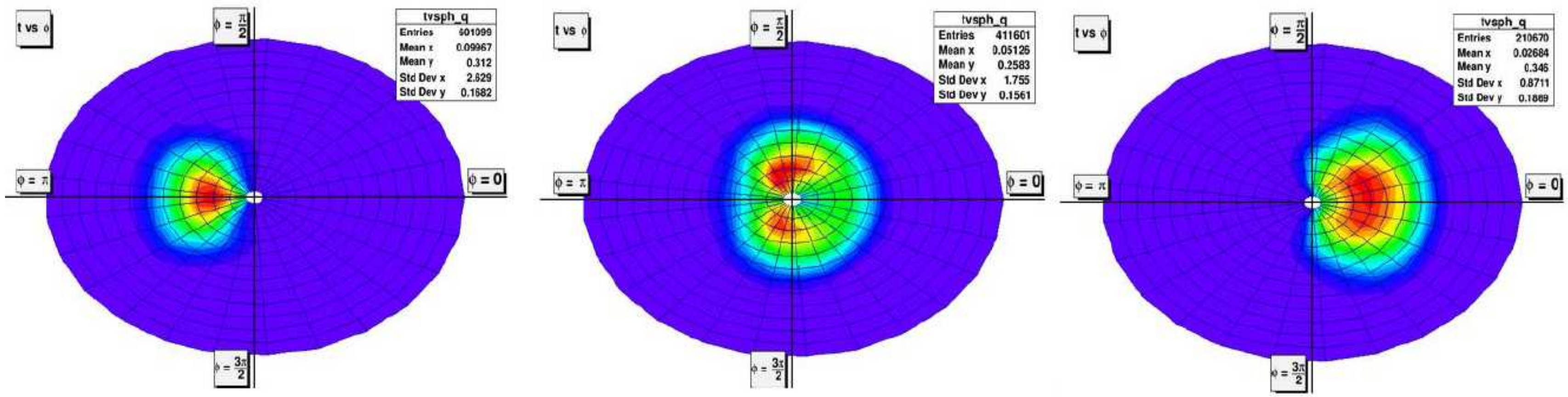
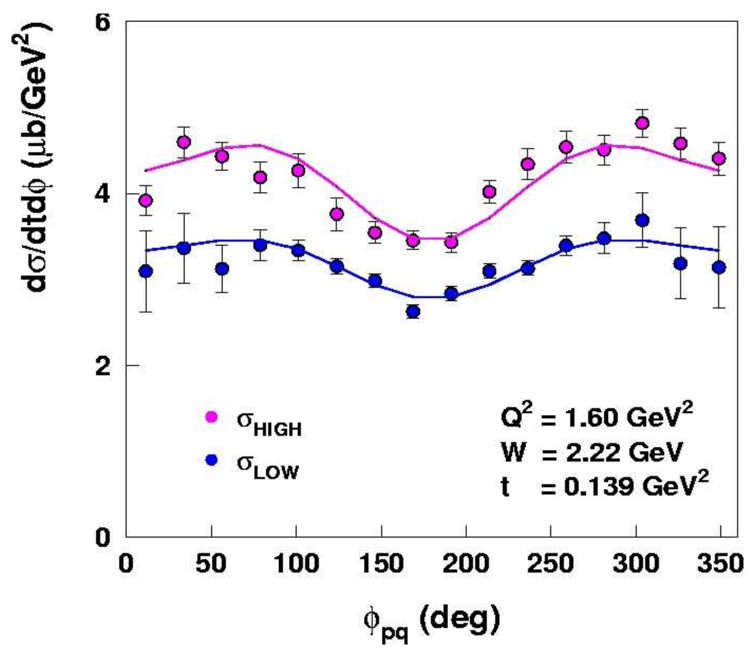
“More Realistic” L/T Separation

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



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_p) and knowledge of photon polarization (ε)



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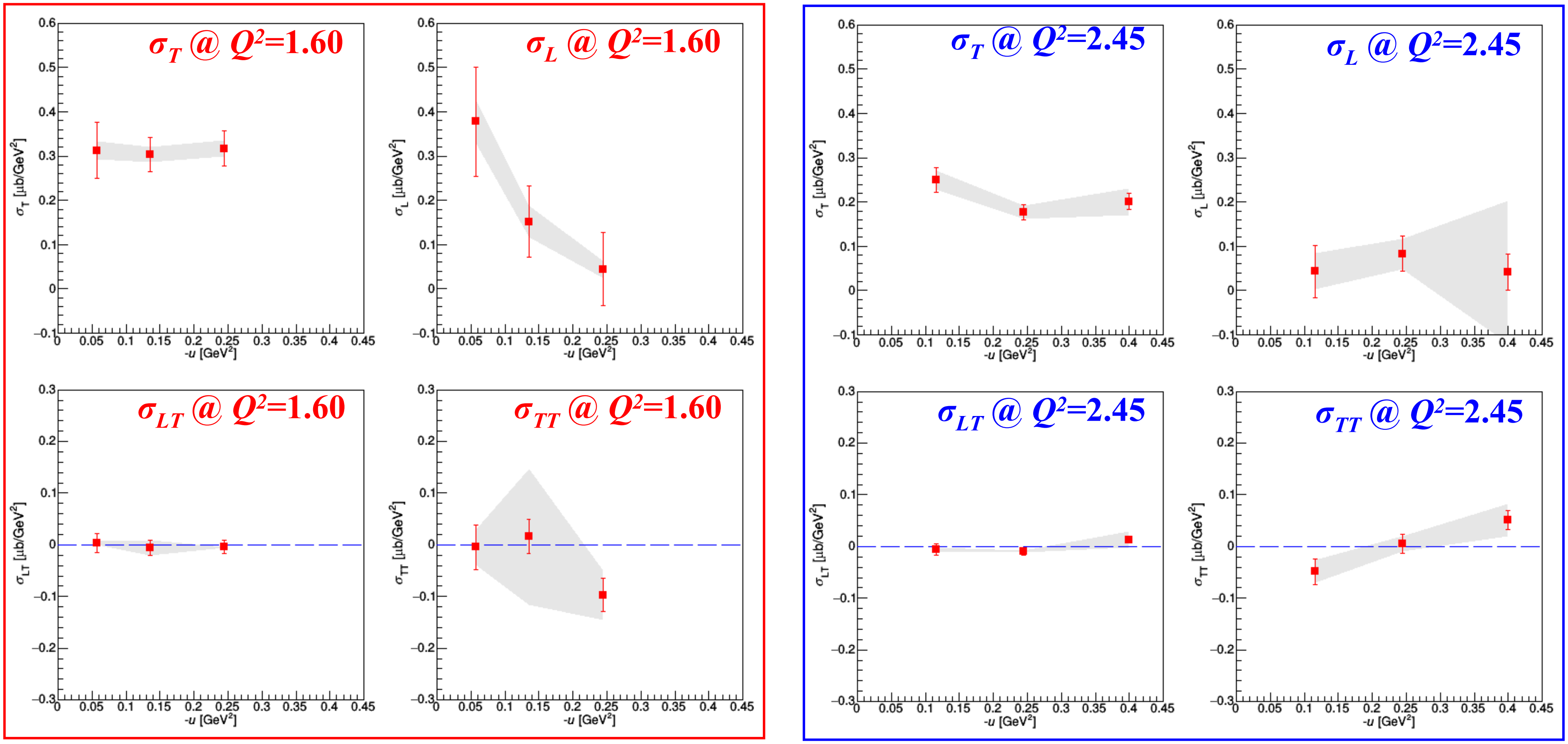
Separated Cross Sections $\frac{d\sigma}{dt}$ vs $-u$

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



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.

W.B. Li, arXiv: 1712.03214

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Backward Angle Omega Electroproduction Peak

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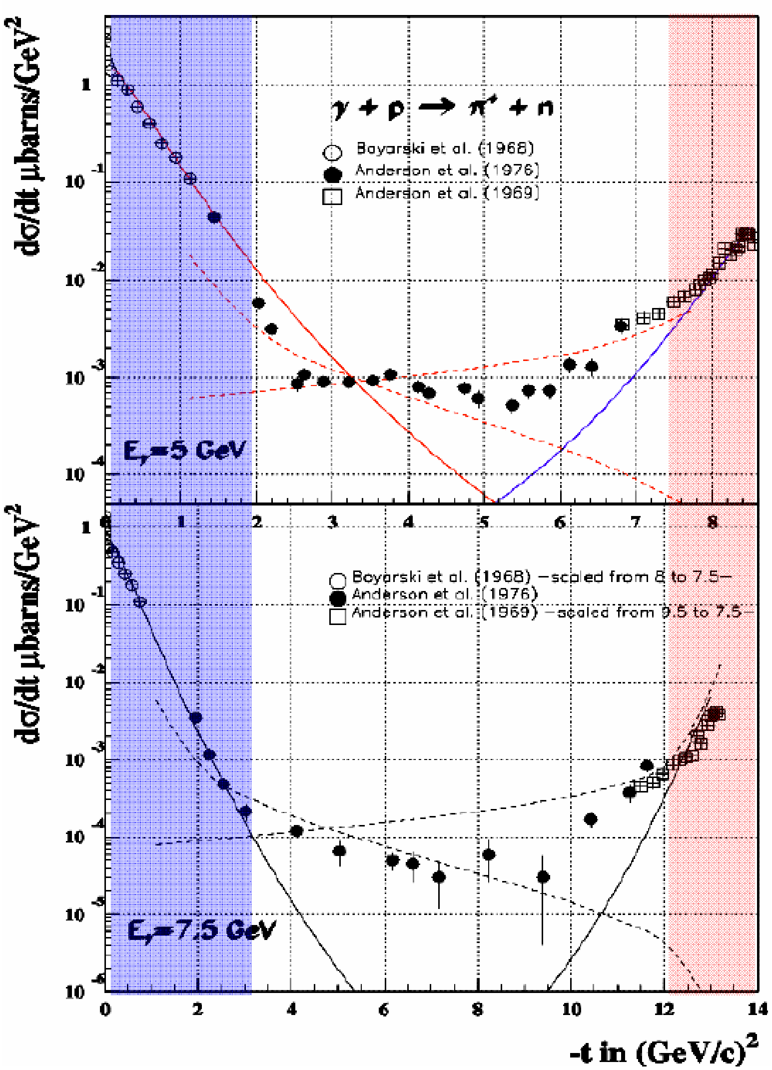
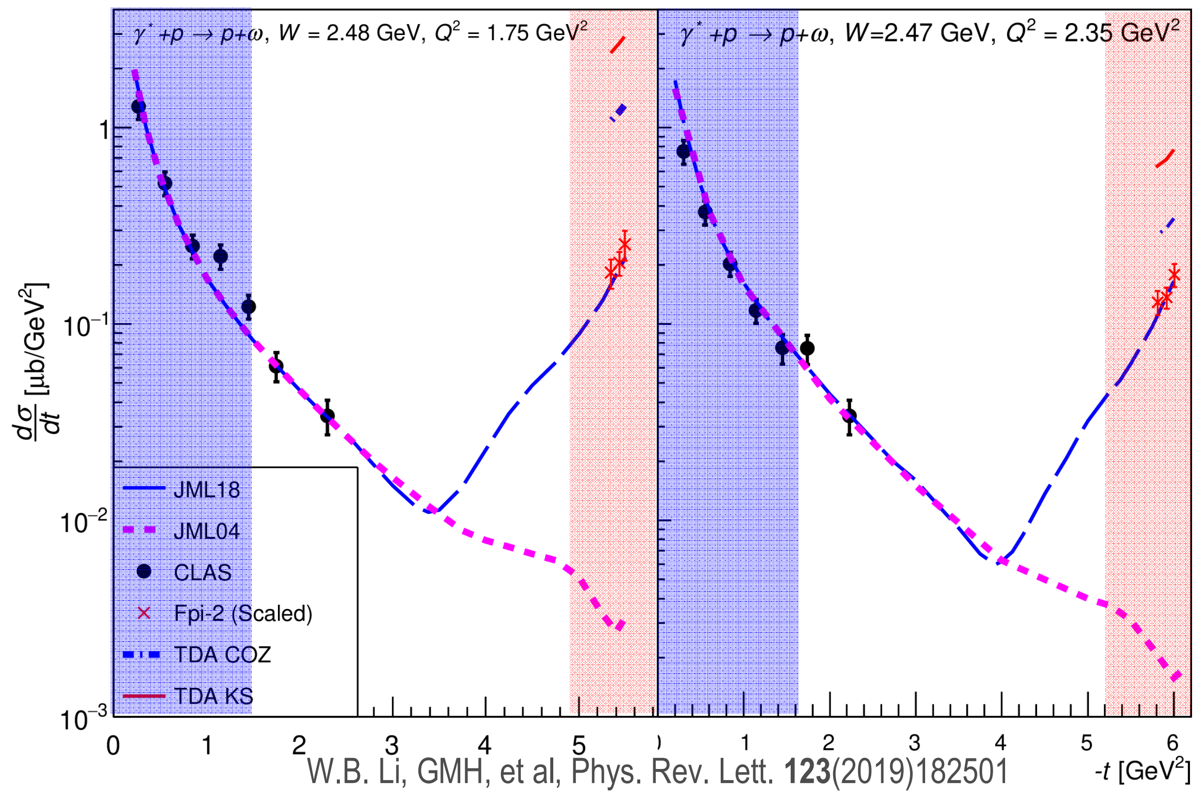
Photoproduction



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
Hall C	2.21	0.29	1.6	4.014	0.08 – 0.13
		0.38	2.45	4.724	0.17 – 0.24

Backward Peak is Larger than Expected

- In photoproduction, the ratio of the forward (t–channel) to backward (u–channel) peaks is ~100:1
- The same was expected for electroproduction
  - It was thus a surprise when we observed the ratio of forward/backward peaks to be ~10:1
- J.M. Laget (JML) has been able to provide a natural explanation for this surprisingly large ratio within the Regge model formalism
  - The L/T ratio for the backward peak can help distinguish various theoretical explanations, but JML model is not yet able to give such predictions
- Study of other exclusive channels over a broad kinematic range is needed to confirm whether strong backward peaks are ubiquitous or not

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JML Regge Model description of *u*–Peak

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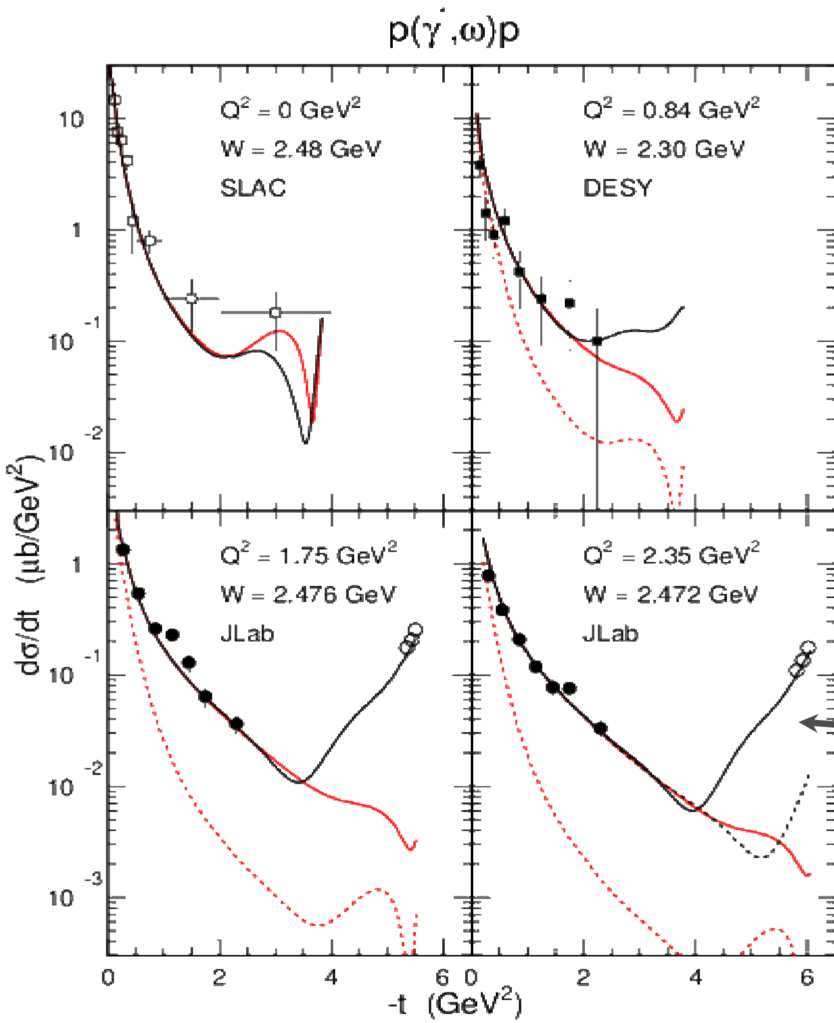
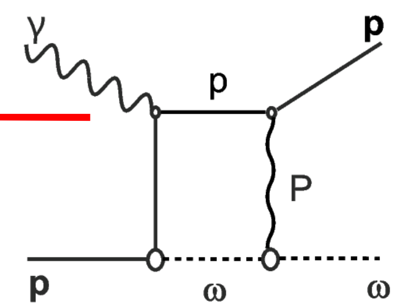


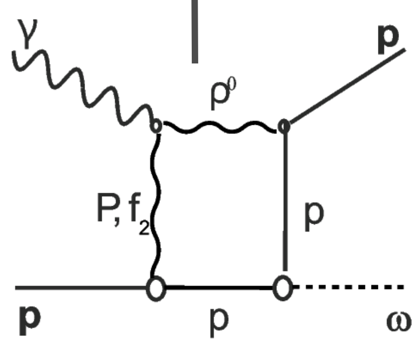
J–M Laget, Private Communication (2018) and W.B. Li, GMH, et al., PRL **123**(2019)182501

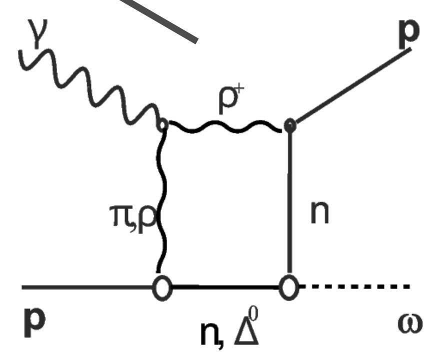
- **Model provides natural description of JLab π electroproduction cross sections without destroying good agreement at Q^2=0.**
  [PLB **685**(2010)146; PLB **695**(2011)1999]
- Model also consistent with magnitude and slope of backward angle ω peak.
- Would be interesting to examine L/T ratio predicted 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

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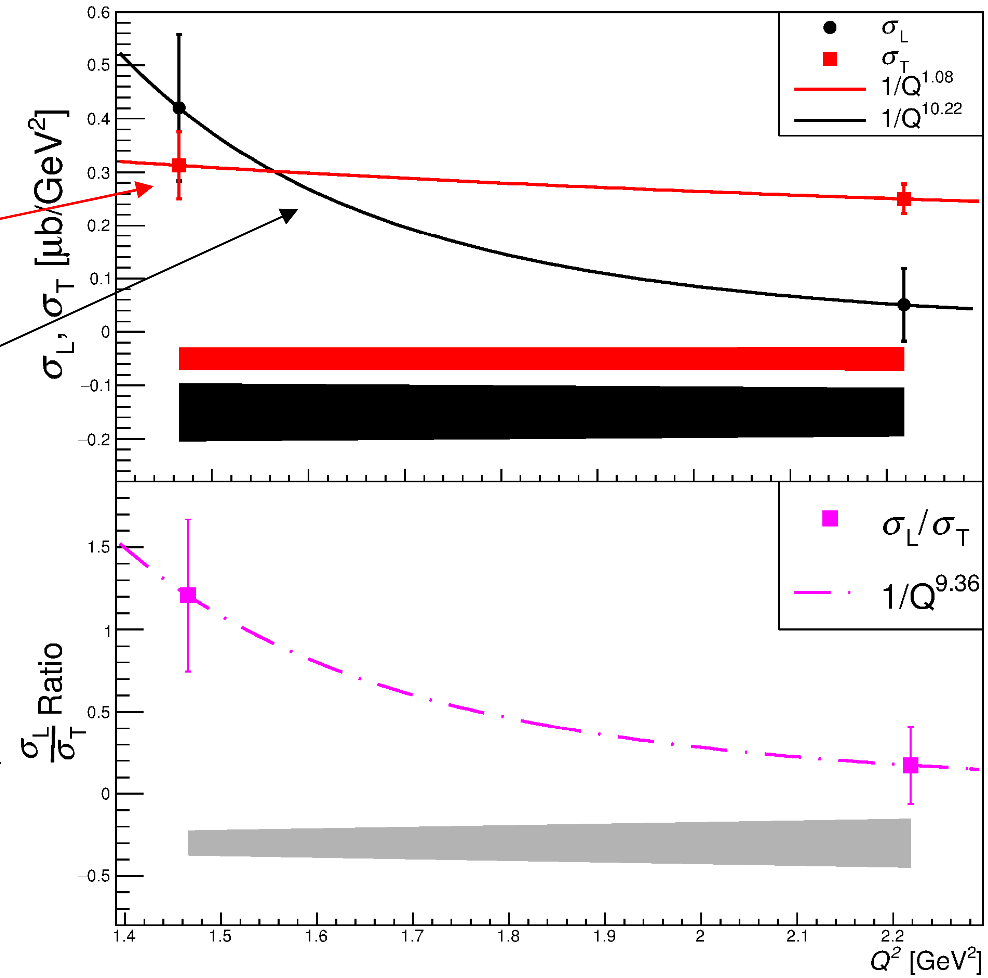
- To investigate Q^2–dependence, fit lowest $-u$ bin values of σ_T and σ_L to Q^{-n} function
  - σ_T appears to have a flat Q^2–dependence within measured range
  - σ_L shows much stronger decrease
- **Decreasing L/T ratio indicates the gradual dominance of σ_T as Q^2 increases.**
- Trend qualitatively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

$-u = -u_{min}$



Q^2=1.47
W=2.26
$-u_{min}$=0.058

Q^2=2.23
W=2.28
$-u_{min}$=0.117

W.B. Li, GMH, et al., PRL **123** (2019) 182501

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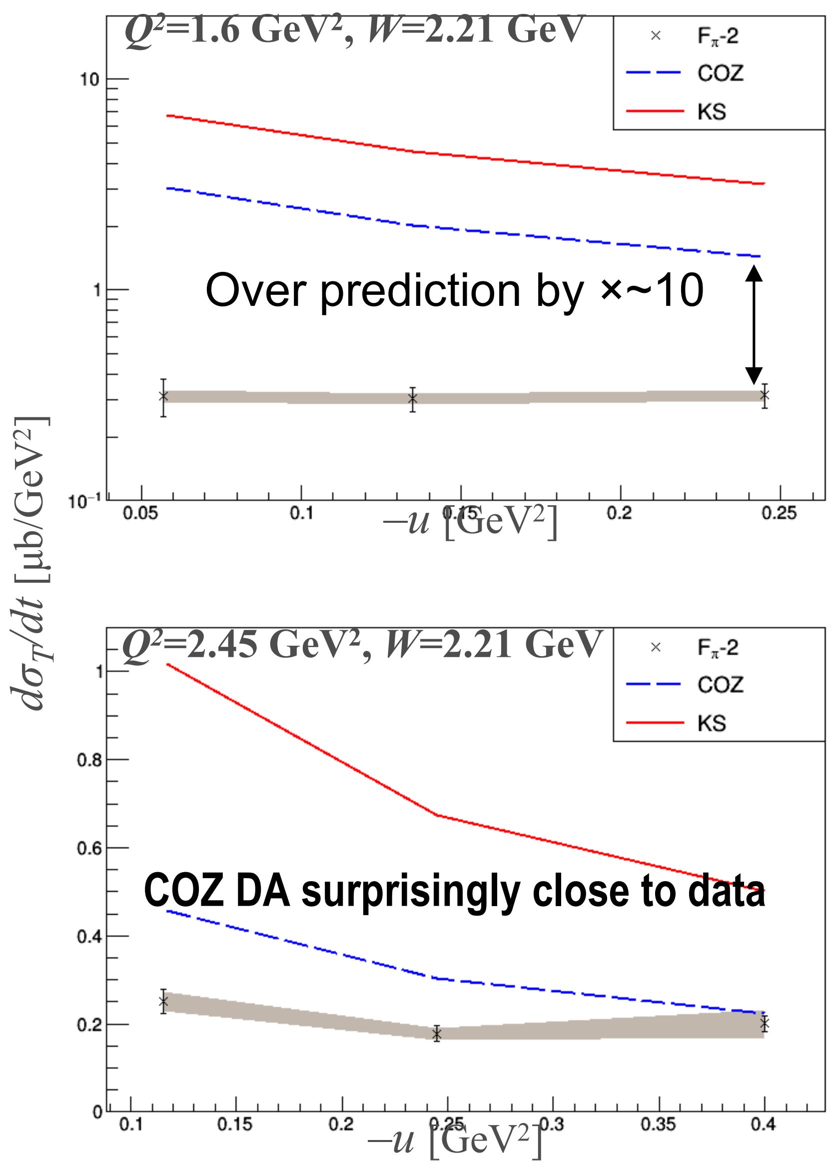
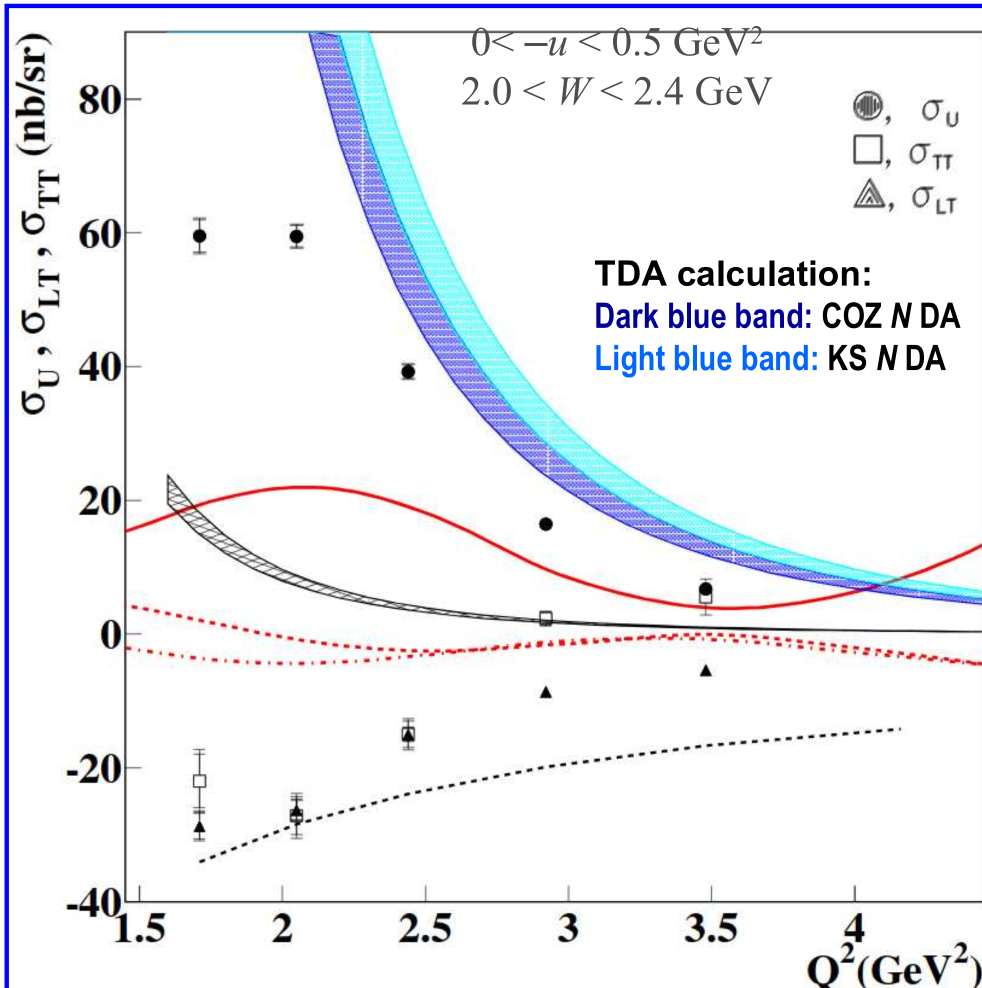
TDA model Comparison to Data



Hall C ω electroproduction

TDA calculation by B. Pire, K. Semenov, L. Szymanowski
W.B. Li, GMH, et al., PRL **123** (2019) 182501

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

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1. Determine if backward angle peak observed in exclusive ω electroproduction occurs also in other channels, over a broad kinematic range.
2. Measure *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 $\sigma_T \sim Q^{-8}$ as predicted by TDA formalism?

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JLab Hall C – 12 GeV Upgrade

SHMS:
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

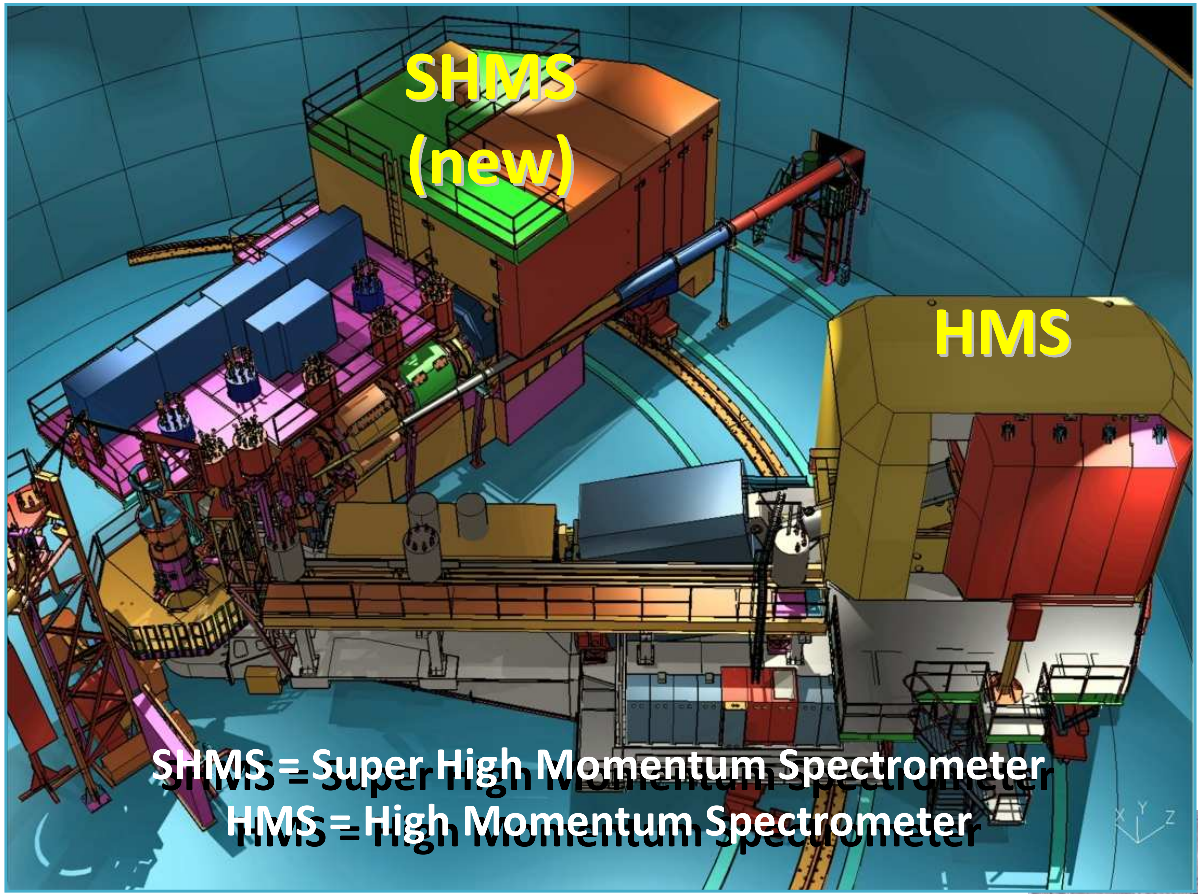
MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

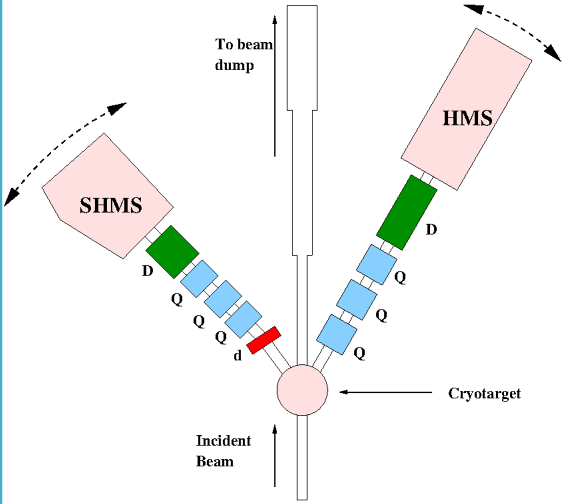
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter

Well-Shielded Detector Enclosure

Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

Luminosity
- ~4x10^{38} cm^{-2} s^{-1}





Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.

TDA Model Predictions for JLab E12–19–006

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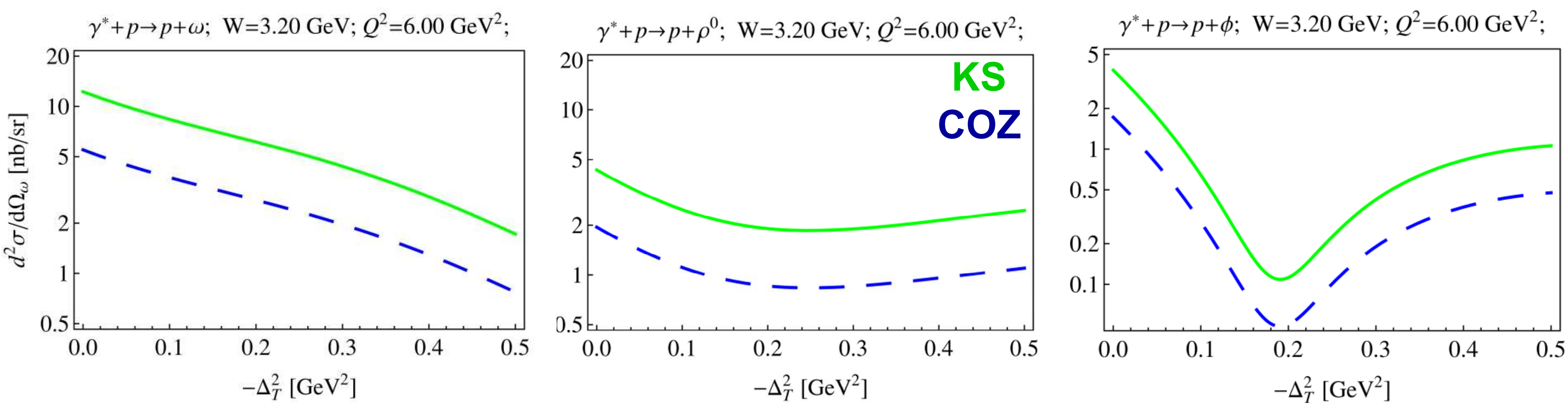
PionLT experiment (E12–19–006) L/T separations up to Q^2=8.5 GeV^2
Spokespersons: D. Gaskell, G.M. Huber, T. Horn

- **Data acquired 2021–22**
- **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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Example "12 GeV" data already acquired

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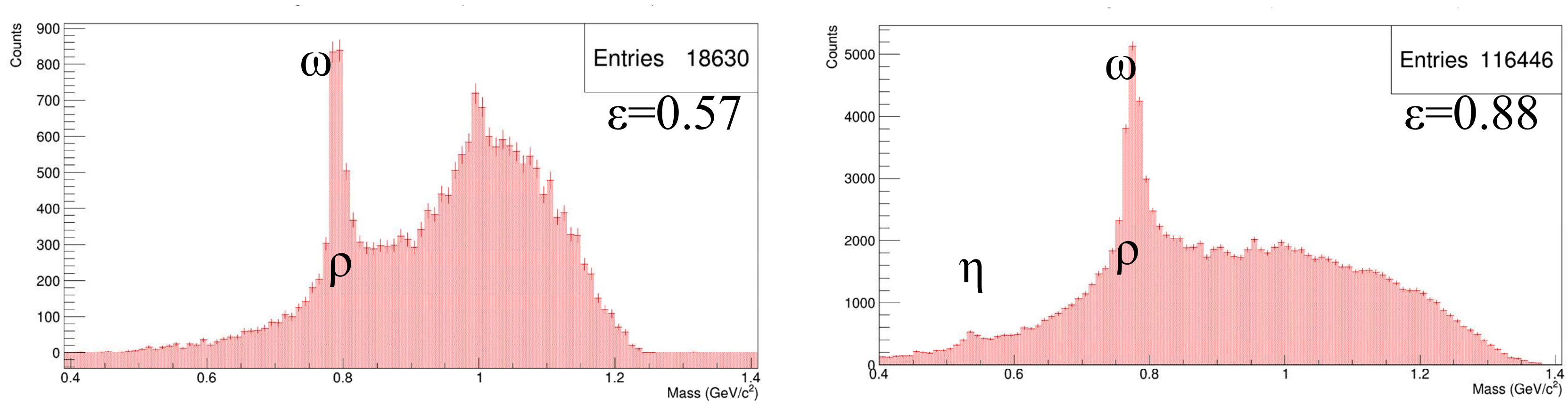
p(e,e'p)X Online Data Analysis

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 2018–19
- Abundant *u*–channel *p(e,e'p)X* data acquired will allow backward angle studies over a wide kinematic range
- Planned first extraction of Beam Spin Asymmetry for *u*–channel reactions (PhD student: Alicia Postuma)

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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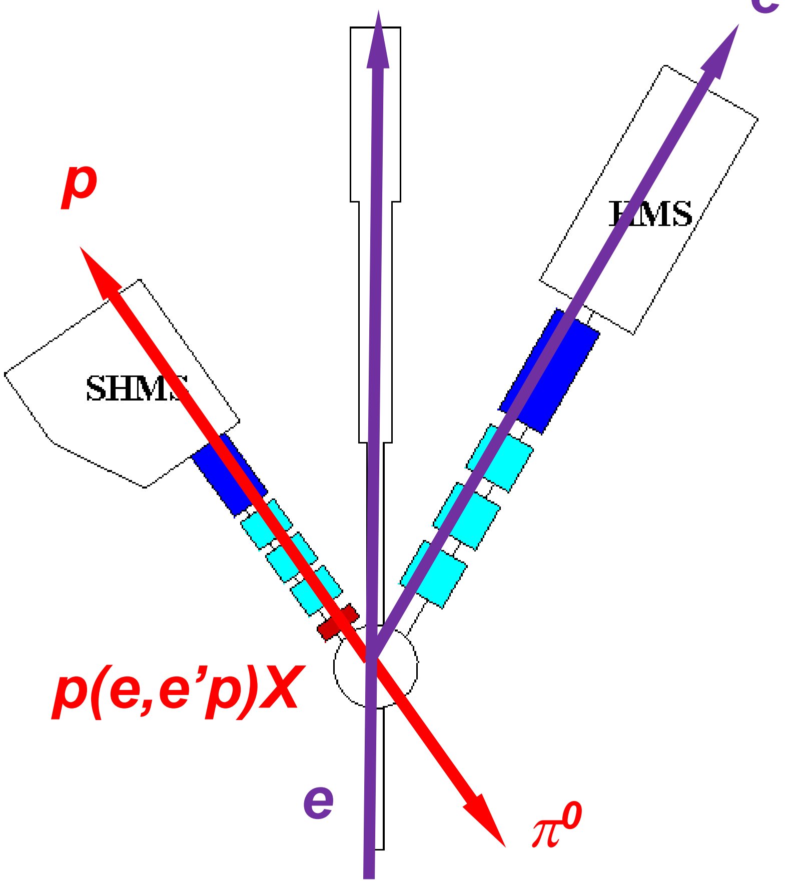
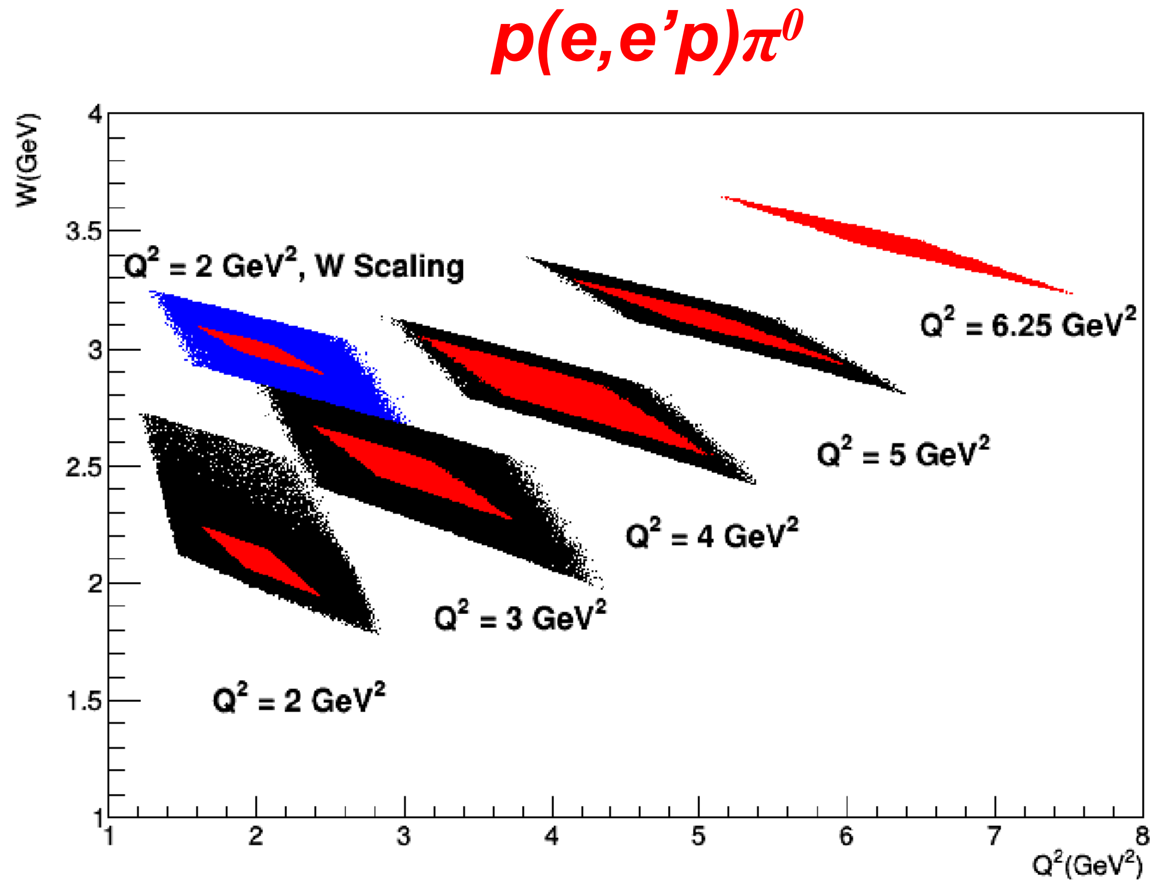
Backward Exclusive π^0 Production





E12–20–007: $u\approx0$ 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'π^0)p* experiment with NPS+HMS
- Beam time possible for 2025–26

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p(e,e'p)π^0 Kinematics

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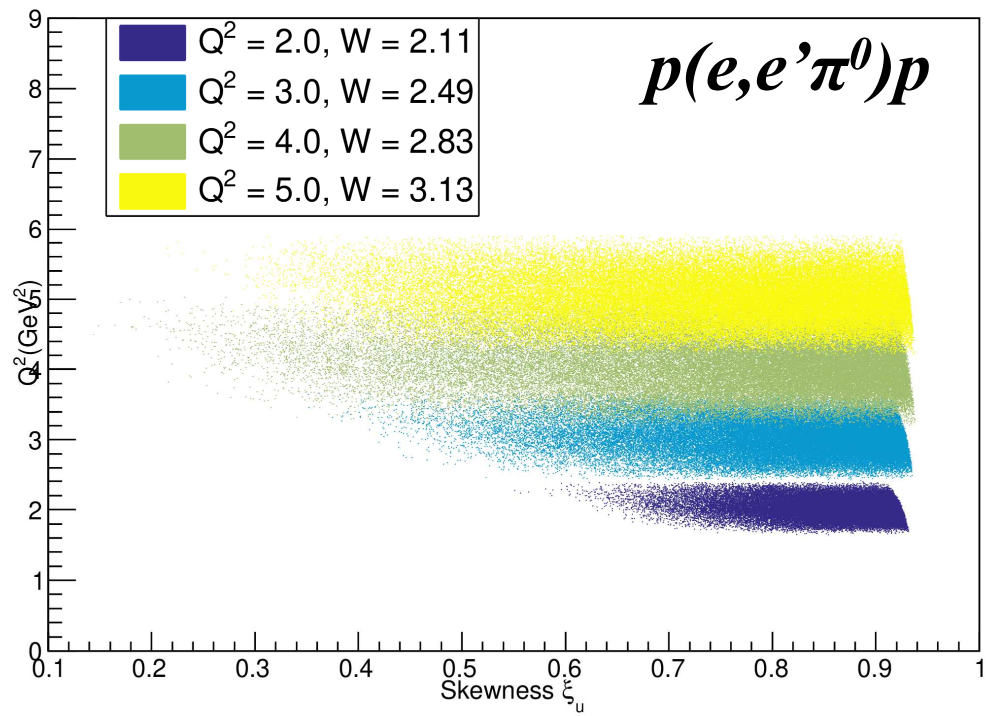
- Backward angle kinematics match forward angle experiment using NPS currently running in Hall C
  - **DVCS/π^0 E12-13-010** *(Spokespersons: T. Horn, C. Hyde, C. Munoz-Camacho, R. Paremuzyan, J. Roche)*
- Combination of both experiments will allow forward/backward peak ratio to be measured for π^0 electroproduction for first time

L/T–separations planned for fixed x_B=0.36 at:

Q^2	2.0	3.0	4.0	5.5*
W	2.11	2.49	2.83	3.26*

* Low ε only possible for θ_{pq}=+1.64°

E12–20–007 covers a broad range in skewness, approaching $\xi_u \rightarrow 1$, which is ERBL dominated



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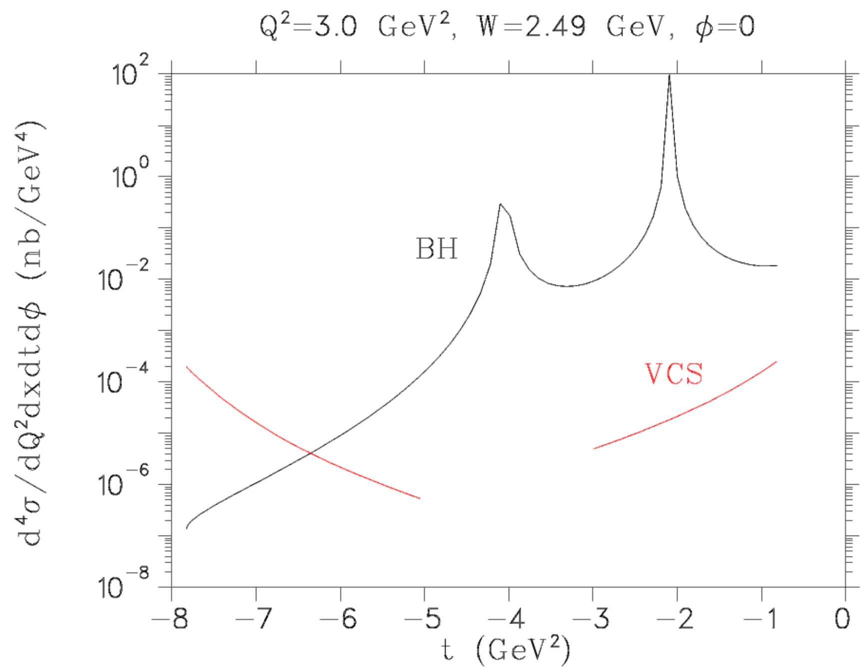
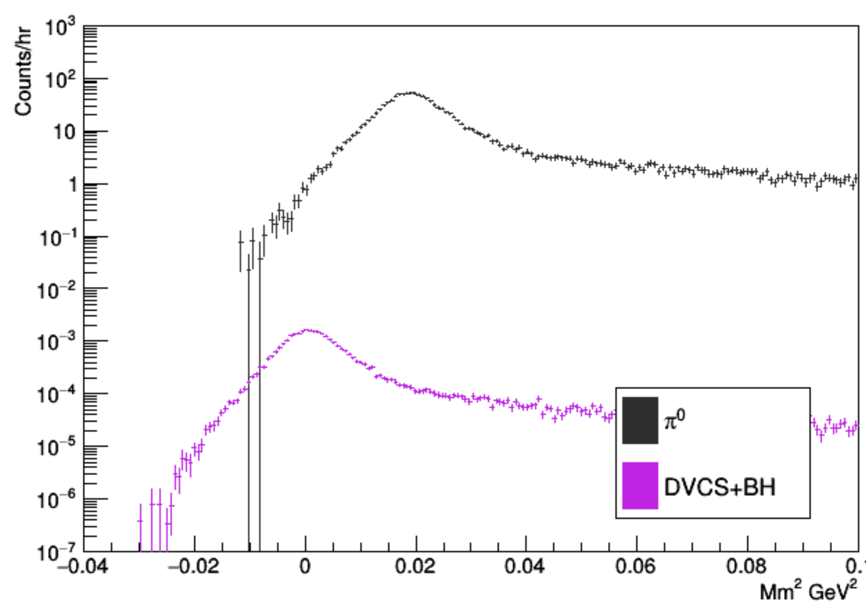
π^0 Channel Expected to be Clean

- 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.
- Virtual Compton Scattering (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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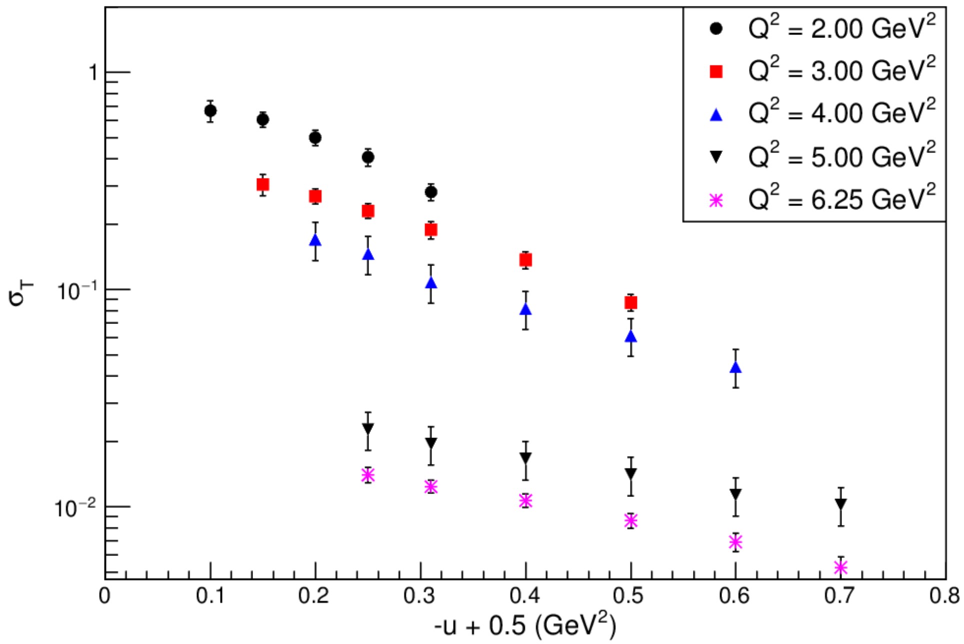
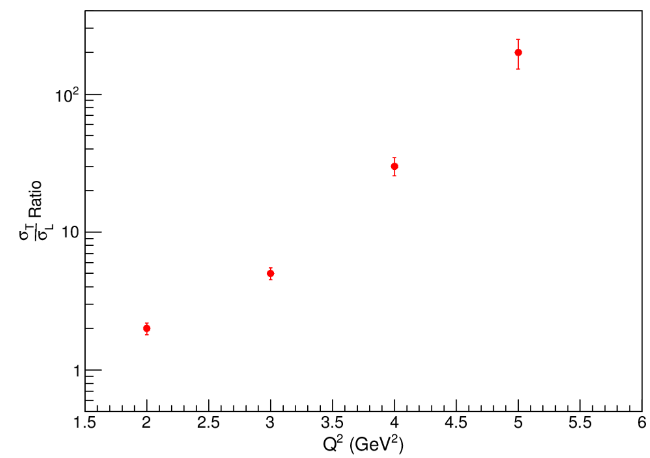
E12–20–007 Projected Data Quality

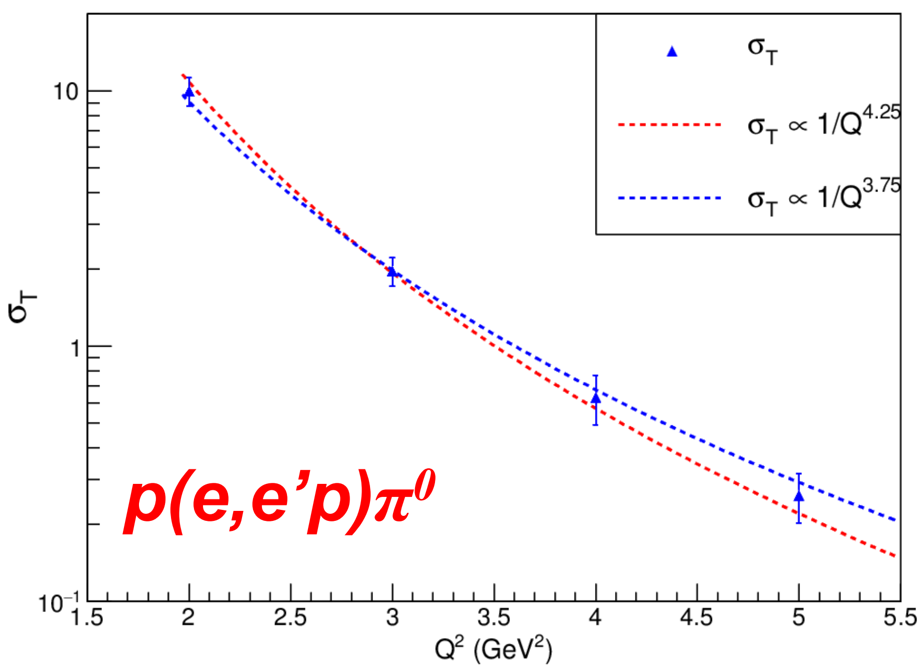


Projected SHMS+HMS *u*–coverage and uncertainties at each Q^2.

- 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: $\sigma_T \sim Q^{-8}$.

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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, leaving "recoil" meson nearly–at–rest in target
- Possible access to **Transition Distribution Amplitudes**
  - Universal perturbative objects in *u*–channel, analogous to Generalized Parton Distributions (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
- **Color Transparency (CT) also is a signal of factorization** and can be used to distinguish Regge and TDA explanations (see our LOI12-23-009)
  - Does Baryon Junction predict absence of *u*–channel CT? If so, the comparison would be interesting

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