

Deep Exclusive $p(e, e' \pi^+)n$ Studies at Jefferson Lab

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University
of Regina

Supported by:



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On behalf of the PionLT Collaboration

Towards Improved Hadron Femtography with Hard Exclusive Reactions

University of Virginia

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Collaboration Acknowledgement



■ PionLT Spokespersons:

- Dave Gaskell (JLab), Tanja Horn (CUA), GMH

■ PionLT Graduate Students:

- Nathan Heinrich (Regina), Sameer Jain (CUA),
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Kathleen Ramage (Glasgow),
Nermin Sadoun (Regina)

* PhD awarded 2024

■ PionLT/KaonLT Analysis Group:

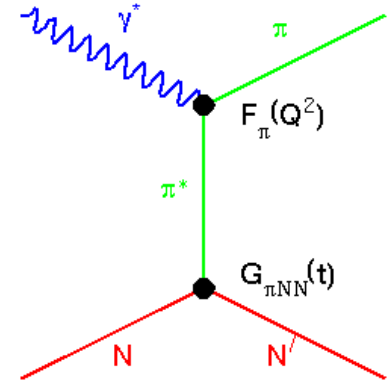
- Abdennacer Hamdi, Stephen Kay, Pete Markowitz,
Rachel Montgomery, Gabriel Niculescu,
Ioana Niculescu, Alicia Postuma, Julie Roche,
Chi Kin Tam, Richard Trotta, Ali Usman

Two Motivations for Studying DEMP

1) Determine the Pion Form Factor at $Q^2 > 0.3 \text{ GeV}^2$:

- Indirectly measure F_π using the “pion cloud” of the proton via $p(e, e' \pi^+) n$

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \dots$$
- Pion pole process dominates σ_L in forward kinematics.

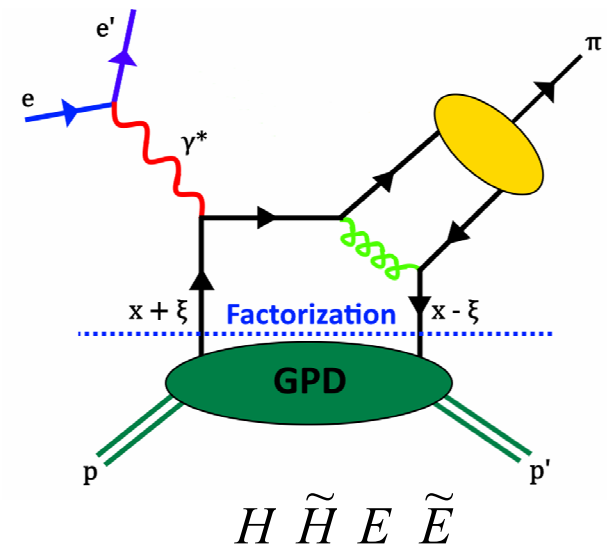


2) Study the Hard-Soft Factorization Regime:

Implications for GPD studies, as they can only be extracted from hard exclusive data where hard-soft factorization applies.

- Investigate if $p(e, e' \pi^+) n$ cross sections at fixed x behave according to the Q^{-n} scaling expectations of hard QCD

- Form $\frac{\sigma_T[n(e, e' \pi^-) p]}{\sigma_T[p(e, e' \pi^+) n]}$ ratios where soft contributions may cancel, yielding insight to factorization at modest Q^2 .

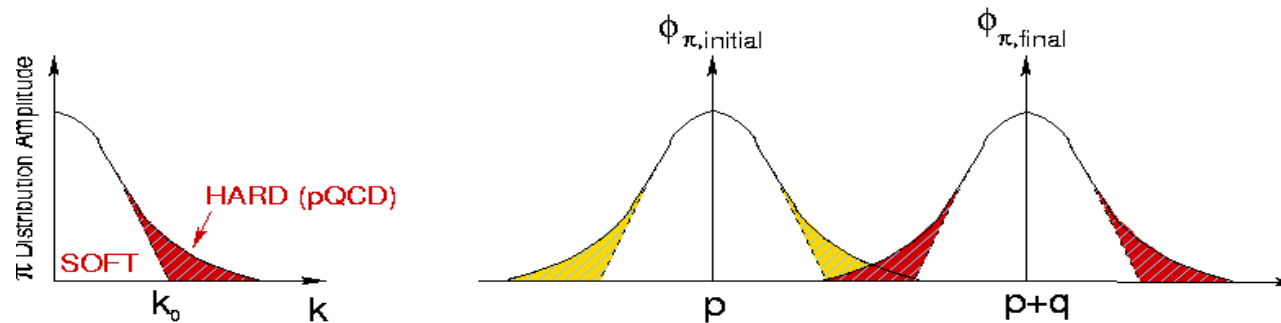


Charged Meson Form Factors

Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

In quantum field theory, the form factor is the overlap integral:

$$F_{\pi}(Q^2) = \int \phi_{\pi}^*(p) \phi_{\pi}(p+q) dp$$



The meson wave function can be separated into ϕ_{π}^{soft} with only low momentum contributions ($k < k_0$) and a hard tail ϕ_{π}^{hard} .

While ϕ_{π}^{hard} can be treated in pQCD, ϕ_{π}^{soft} cannot.

From a theoretical standpoint, the study of the Q^2 -dependence of the form factor focuses on finding a description for the hard and soft contributions of the meson wave-function.

The Pion in perturbative QCD

At very large Q^2 , pion form factor (F_π) can be calculated using pQCD

$$F_\pi(Q^2) = \frac{4\pi C_F \alpha_s(Q^2)}{Q^2} \left| \sum_{n=0}^{\infty} a_n \left(\log \left(\frac{Q^2}{\Lambda^2} \right) \right)^{-\gamma_n} \right|^2 \left[1 + O \left(\alpha_s(Q^2), \frac{m}{Q} \right) \right]$$

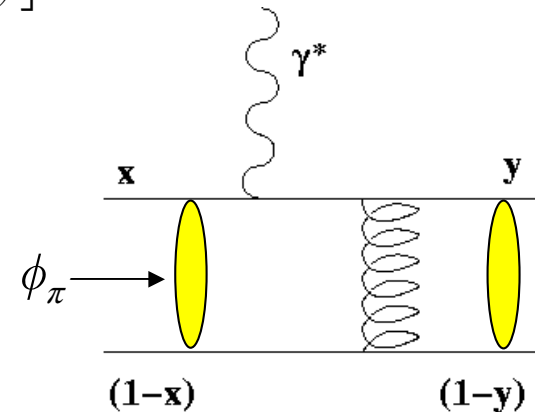
At asymptotically high Q^2 , only hardest portion of pion distribution amplitude contributes

$$\phi_\pi(x) \xrightarrow{Q^2 \rightarrow \infty} \frac{3f_\pi}{\sqrt{n_c}} x(1-x)$$

and F_π takes the very simple form

$$Q^2 F_\pi(Q^2) \xrightarrow{Q^2 \rightarrow \infty} 16\pi \alpha_s(Q^2) f_\pi^2$$

$f_\pi = 93$ MeV is the $\pi^+ \rightarrow \mu^+ \nu$ decay constant



G.P. Lepage, S.J. Brodsky, Phys.Lett. **87B**(1979)359.

This only relies on asymptotic freedom in QCD, *i.e.* $(\partial\alpha_s/\partial\mu) < 0$ as $\mu \rightarrow \infty$.

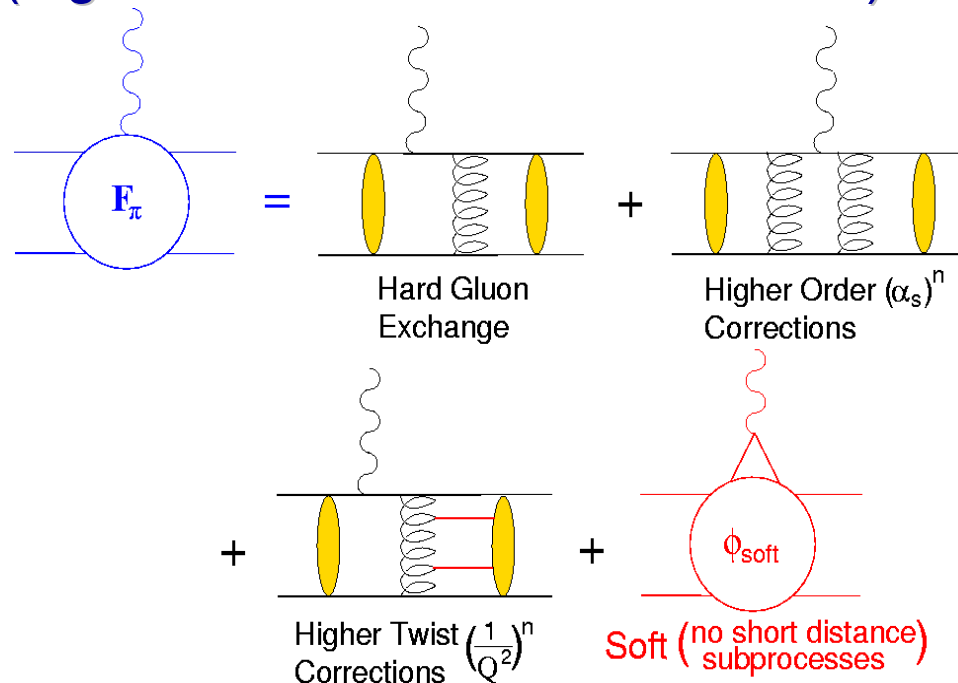
$Q^2 F_\pi$ should behave like $\alpha_s(Q^2)$ even for moderately large Q^2 .

→ Pion form factor seems to be best tool for experimental study of nature of the quark-gluon coupling constant renormalization.

[A.V. Radyushkin, JINR 1977, arXiv:hep-ph/0410276]

Pion Form Factor at Intermediate Q^2

At experimentally-accessible Q^2 , both the “hard” and “soft” components (e.g. transverse momentum effects) contribute.



- **The interplay of hard and soft contributions is poorly understood.**
 - Different theoretical viewpoints on whether higher-twist mechanisms dominate until very large momentum transfer or not.
- **The pion elastic and transition form factors experimentally accessible over a wide kinematic range.**
 - A laboratory to study the **transition** from the soft to hard regime.

Measurement of π^+ Form Factor – Low Q^2

At low Q^2 , F_π can be measured model-independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

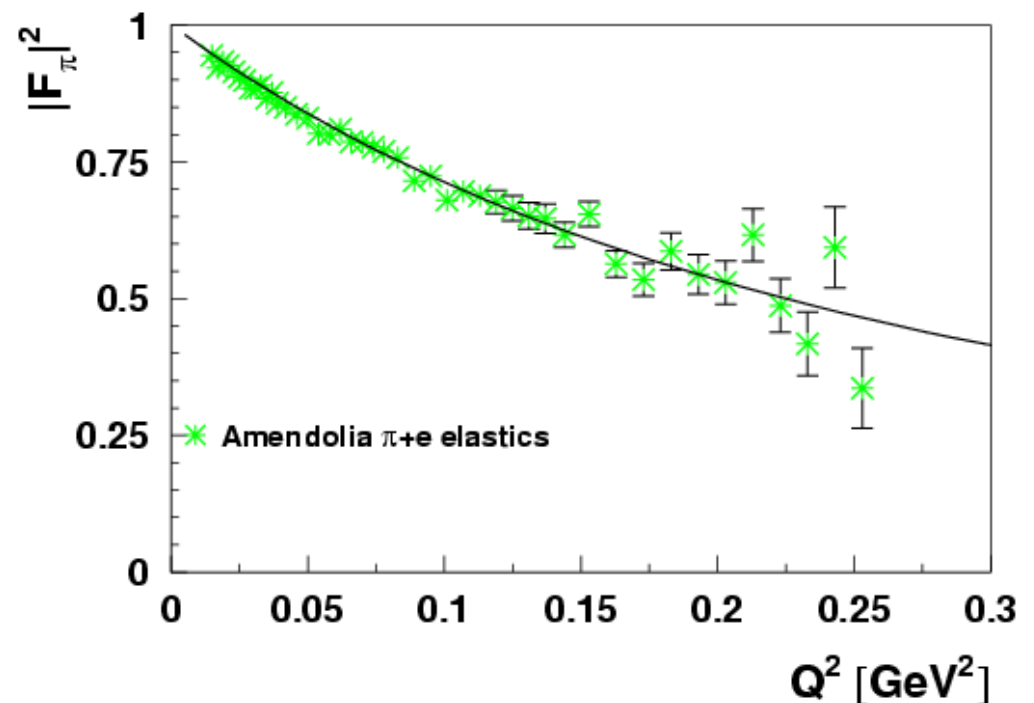
- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25 \text{ GeV}^2$ [*Amendolia, et al., NP B277 (1986) 168*]

- Data used to extract pion charge radius

$$r_\pi = 0.657 \pm 0.012 \text{ fm}$$

Maximum accessible Q^2
roughly proportional to pion
beam energy

*$Q^2 = 1 \text{ GeV}^2$ requires
1 TeV pion beam*



Measurement of π^+ Form Factor – Larger Q^2

At larger Q^2 , F_π must be measured indirectly using the “pion cloud” of the proton via pion electroproduction $p(e, e'\pi^+)n$ “Sullivan process”

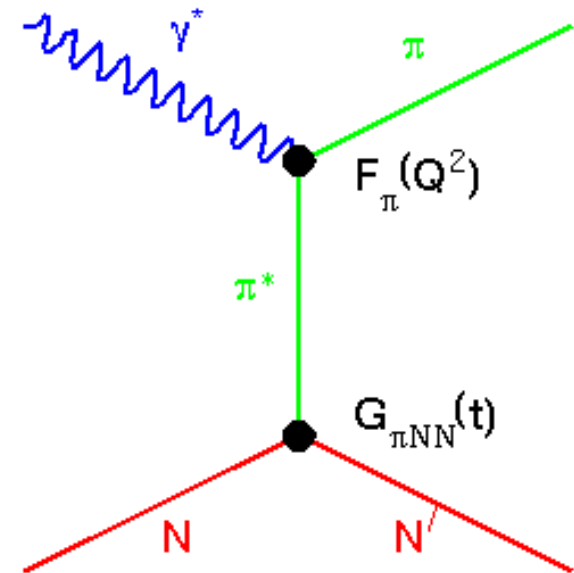
$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \dots$$

- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as,

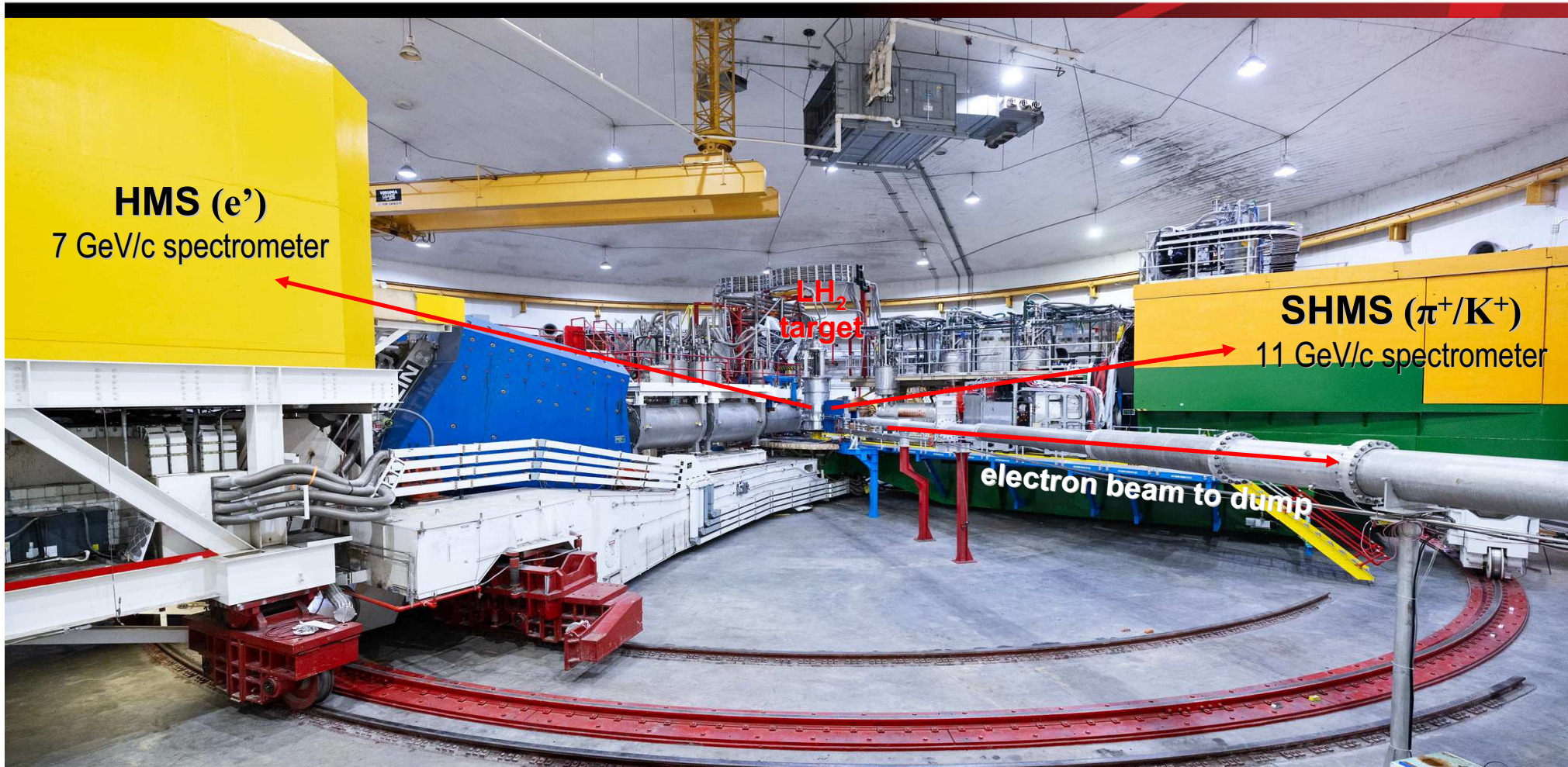
$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2, t)$$

Drawbacks of this technique

1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.



Jefferson Lab Hall C



- **HMS and SHMS MAGNETIC OPTICS:**

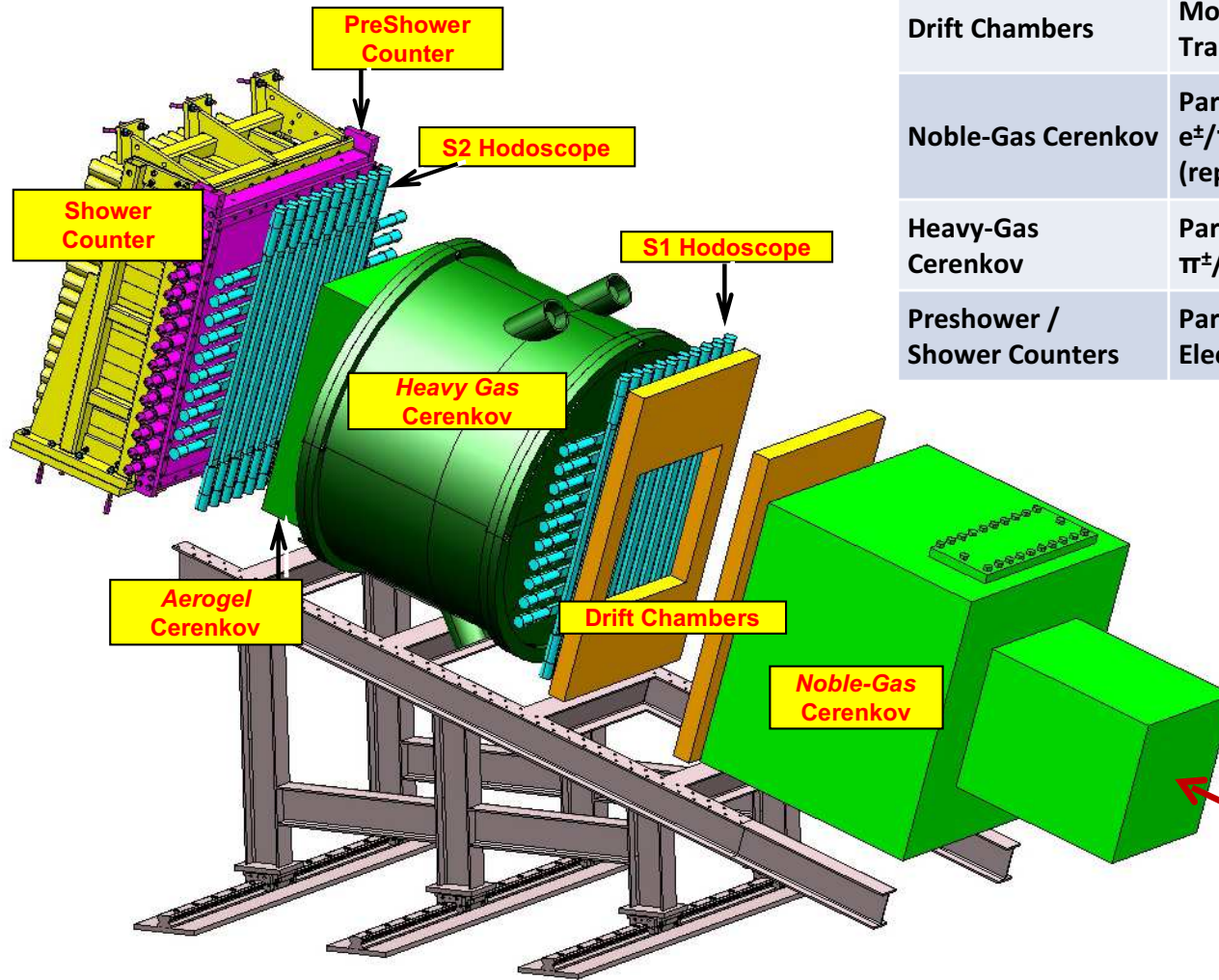
- Point-to Point QQD for easy calibration of magnetic optics acceptance and event reconstruction
- SHMS Horizontal bend magnet allows spectrometer rotation to forward angles (5.5°); the HMS can rotate to a minimum of 10.5°

- **Rigid Support Structure and Connection to Pivot:** Provide Rapid & Remote Rotation, Pointing Accuracy & Reproducibility

- **Spectrometer Detector Packages:** Drift Chambers, Hodoscopes, Cherenkovs, PbG Calorimeter

- **Well-Shielded Detector Enclosures permit measurements at Very High Luminosity:** $\sim 4 \times 10^{38} \text{ cm}^{-2} \text{ s}^{-1}$

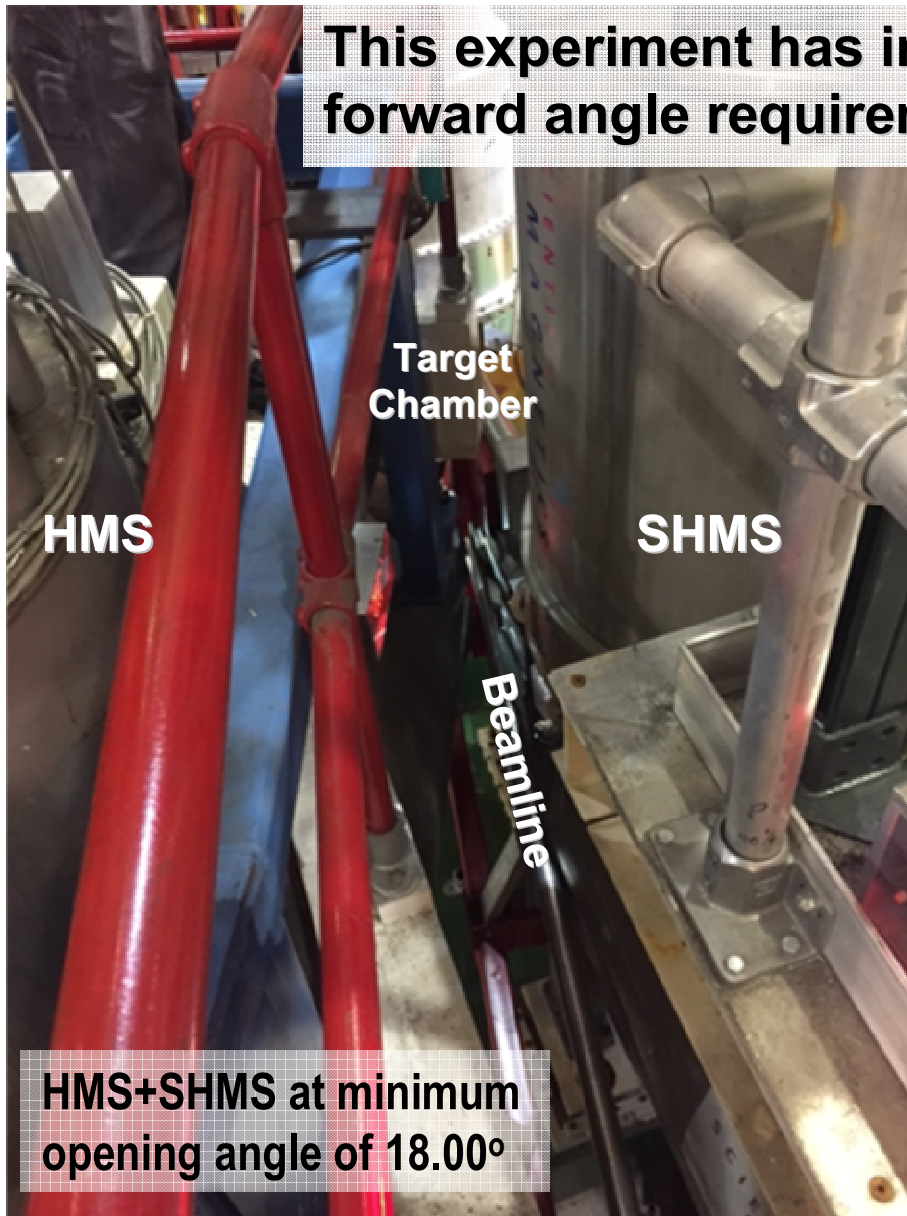
SHMS Focal Plane Detector System



DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Noble-Gas Cerenkov	Particle ID, Trigger. $e^\pm/\pi^\pm$ at high momentum (replace by vacuum at low p)	Vary Ar/Ne mixture to set index at $\pi^\pm$ threshold.
Heavy-Gas Cerenkov	Particle ID, Trigger. $\pi^\pm/K^\pm$ discrimination	C_4F_8O – Vary pressure to set index at $K^\pm$ threshold
Preshower / Shower Counters	Particle ID, Trigger. Electron tag	

HMS and SHMS during Data Taking

This experiment has in large part driven the forward angle requirements of the SHMS+HMS

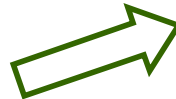


$p(e, e'\pi^+)n$ Event Selection

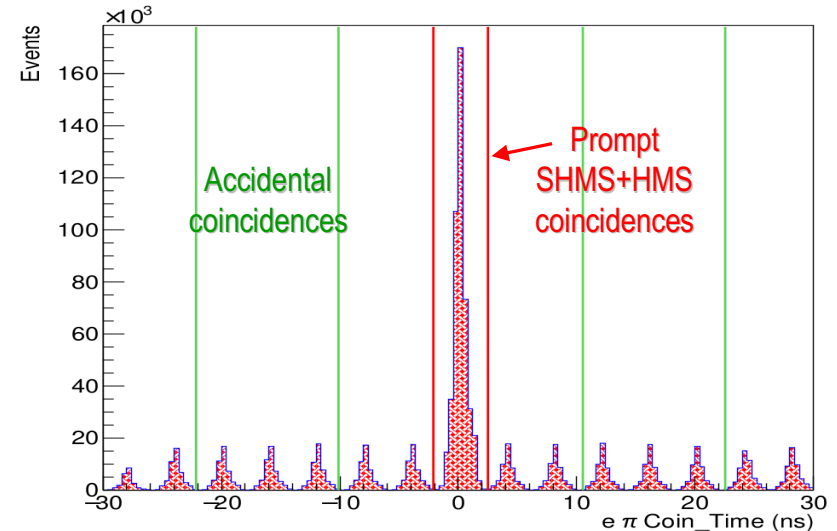
Coincidence measurement between charged pions in SHMS and electrons in HMS.

Easy to isolate
exclusive channel

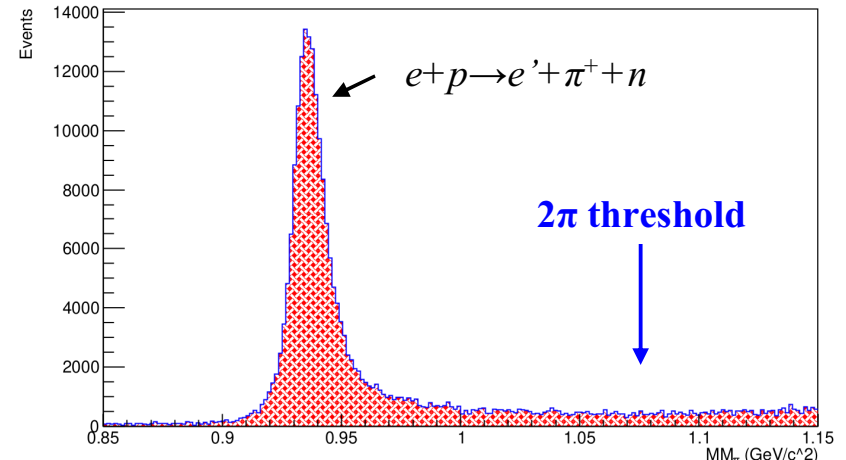
- Excellent particle identification
- CW beam minimizes “accidental” coincidences
- Missing mass resolution easily excludes 2-pion contributions



Electron-Pion CTime Distribution



Missing Mass Distribution



PionLT experiment E12-19-006 Data

$Q^2=1.60$, $W=3.08$, $x=0.157$, $\varepsilon=0.685$

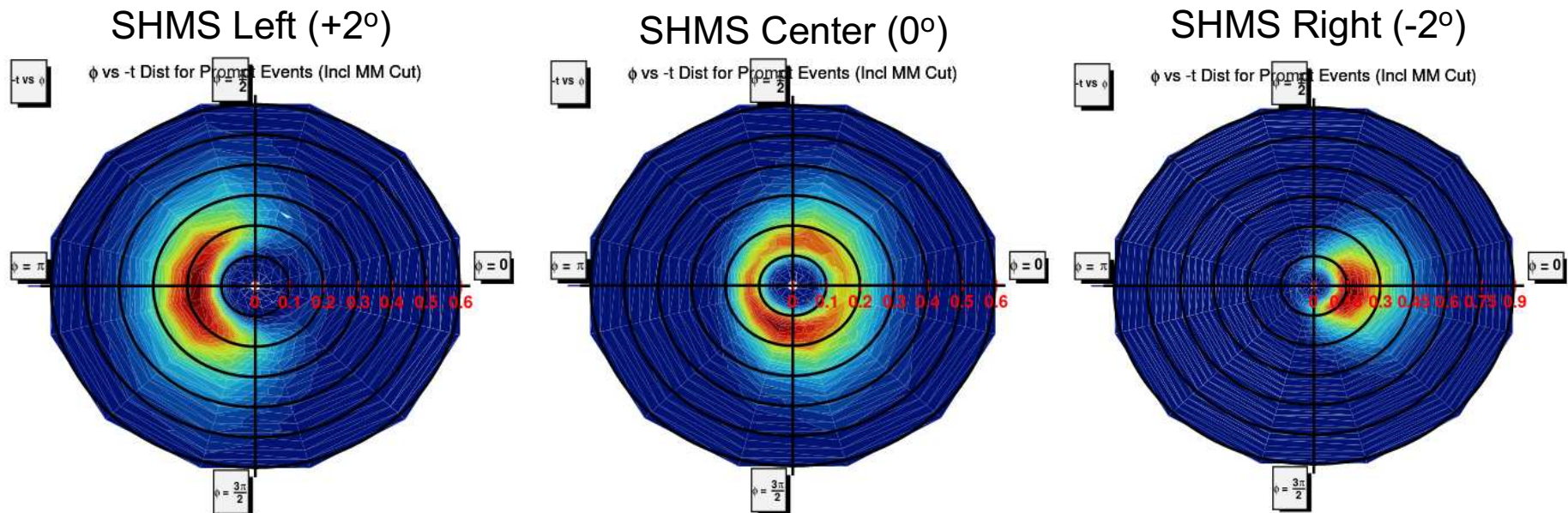
$E_{\text{beam}}=9.177$ GeV, $P_{\text{SHMS}}=+5.422$ GeV/c, $\theta_{\text{SHMS}}=10.26^\circ$ (left)

Plots by Muhammad Junaid (Regina PhD student)

PionLT t - ϕ Coverage

- Measure σ_{LT} , σ_{TT} by taking data at three pion spectrometer (SHMS) angles, $+2^\circ$, 0° , -2° , with respect to q -vector

Example t - ϕ plots from: $Q^2=3.85$, $W=3.07$, High ε



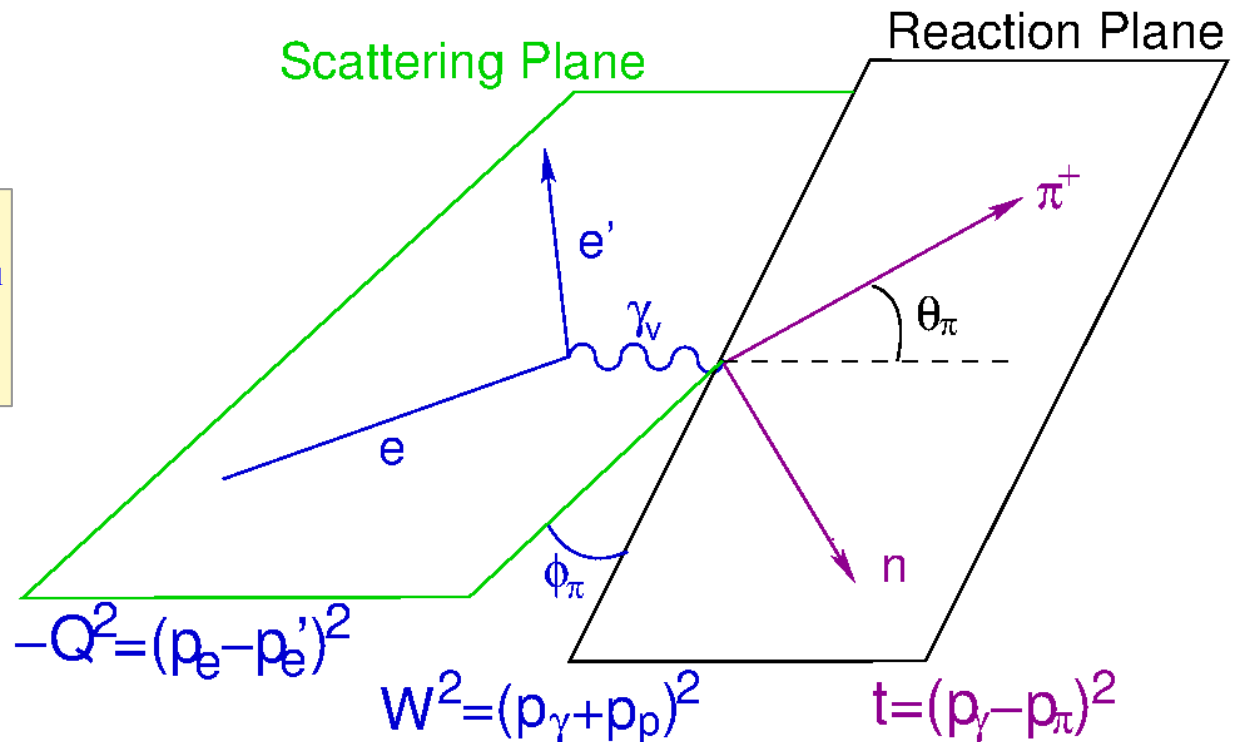
Plots by Nathan Heinrich (Regina PhD student)

- To control systematics, an excellent understanding of spectrometer acceptances is required
 - Over-constrained $p(e, e'p)$ reaction, and inelastic $e+^{12}\text{C}$, used to calibrated spectrometer acceptances, momenta, kinematic offsets, efficiencies.
 - Control of point-to-point systematic uncertainties crucial due to $1/\Delta\varepsilon$ error amplification in σ_L

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

Virtual-photon polarization:

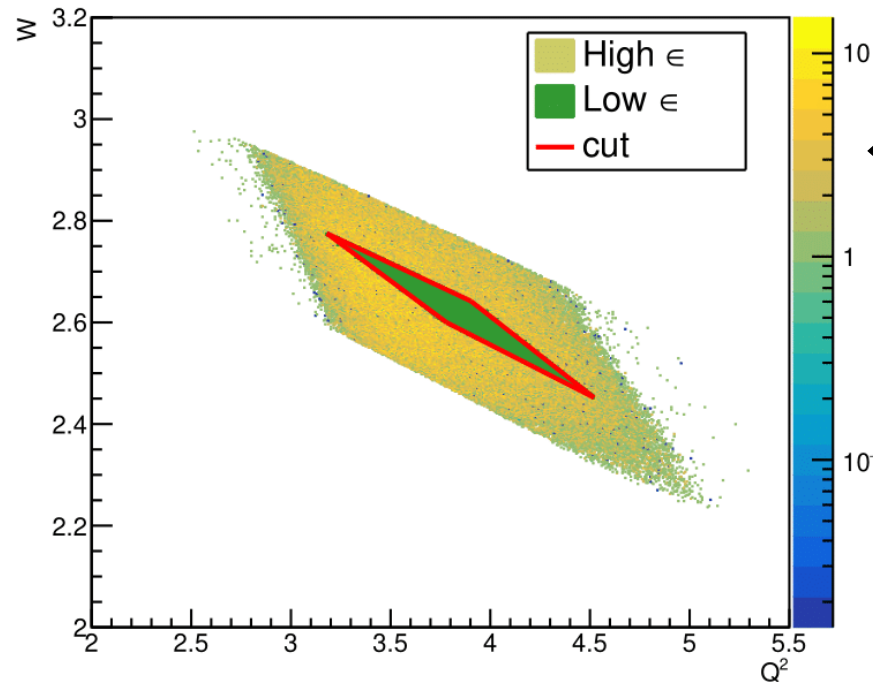
$$\varepsilon = \left(1 + 2 \frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \tan^2 \frac{\theta_{e'}}{2} \right)^{-1}$$



- L-T separation required to separate σ_L from σ_T
- Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole
- Need to measure t -dependence of σ_L at fixed Q^2, W

The different pion arm (SHMS) settings are combined to yield ϕ -distributions for each t -bin

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



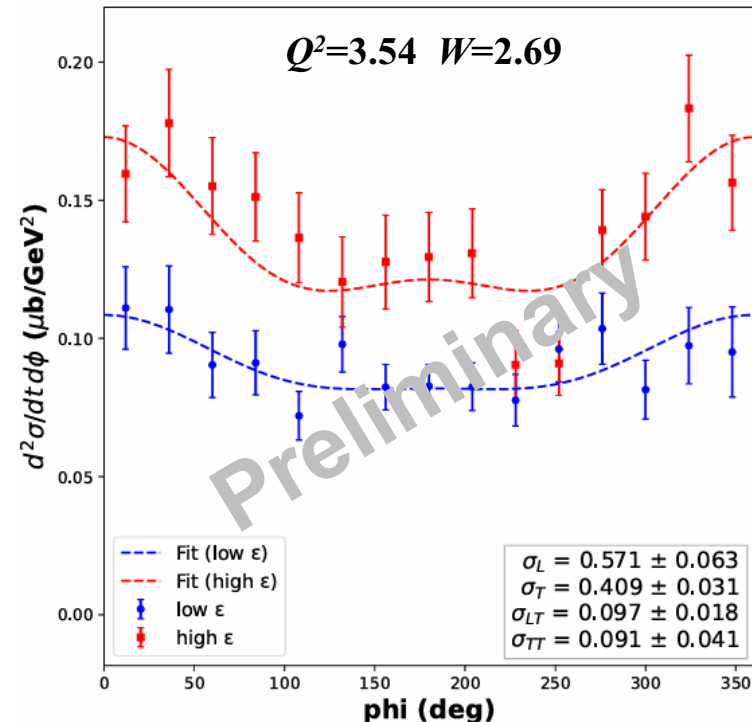
Diamond cuts define common (W, Q^2) acceptance at both ε

SHMS+HMS data at $Q^2=3.85, W=2.62$

■ High $\varepsilon=0.78$ ■ Low $\varepsilon=0.29$

t central = 0.184

$Q^2=3.54 \quad W=2.69$



- Extract σ_L by simultaneous fit of L,T,LT,TT using measured azimuthal angle (ϕ_π) and knowledge of photon polarization (ε)

Meson Form Factors require a Model

- Meson elastic form factors determined via the electroproduction technique are in principle model-dependent, although this dependence is reduced if σ_L data are taken at sufficiently low $-t$
- Our JLab 6 GeV studies indicate the method is reliable for low $-t < 0.4 \text{ GeV}^2$ $p(e, e' \pi^+)n$ data [GMH et al., PRC 78 (2008) 045203]
 - A recent theory paper [PRC 97 (2018) 015203] suggests the Sullivan process can provide a reliable pion target up to $-t=0.6 \text{ GeV}^2$
- It is important determine over what t -range the Sullivan process is reliable, as well as to verify the reliability of the models used to infer the pion form factor from $d\sigma_L/dt$ data
- The PionLT experiment has adopted a data-driven approach to address these to the greatest extent possible:
 - Check consistency of model with data
 - Extract form factor at several values of $-t_{min}$ for fixed Q^2
 - Test that the pole diagram is really the dominant contribution to the reaction mechanism
 - Verify that electroproduction technique yields results consistent with p-e elastic scattering at same Q^2

F_π Extraction from JLab data

- A model is required to extract F_π from $d\sigma_L/dt$
 - Fit of model to σ_L gives F_π at each Q^2

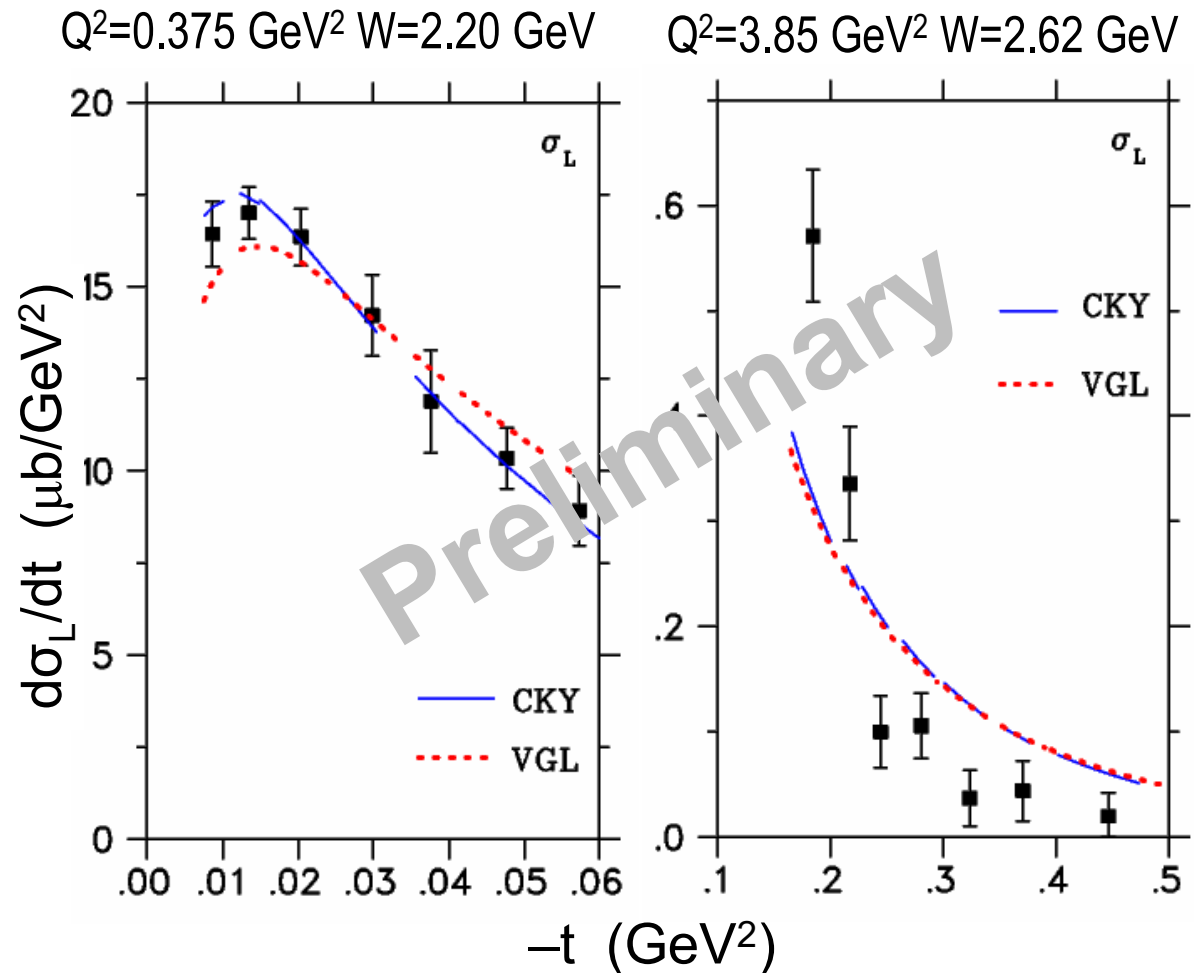
- JLab 6 GeV F_p expts used VGL Regge model

[Vanderhaeghen, Guidal, Laget, PRC 57(1998)1454]

- Most parameters fixed by photoproduction data
- At small $-t$, σ_L only sensitive to π Regge trajectory cutoff Λ_π

- Choi, Kong, Yu (CKY) Regge model allows 2nd way to extract F_π from σ_L data [JKorPhysSoc 67(2015)L1089, arXiv: 1508.00969]

- Perry, Kizilersu, Thomas model also now available [PLB 807(2020)135581]



V.Kumar et al, publication submitted

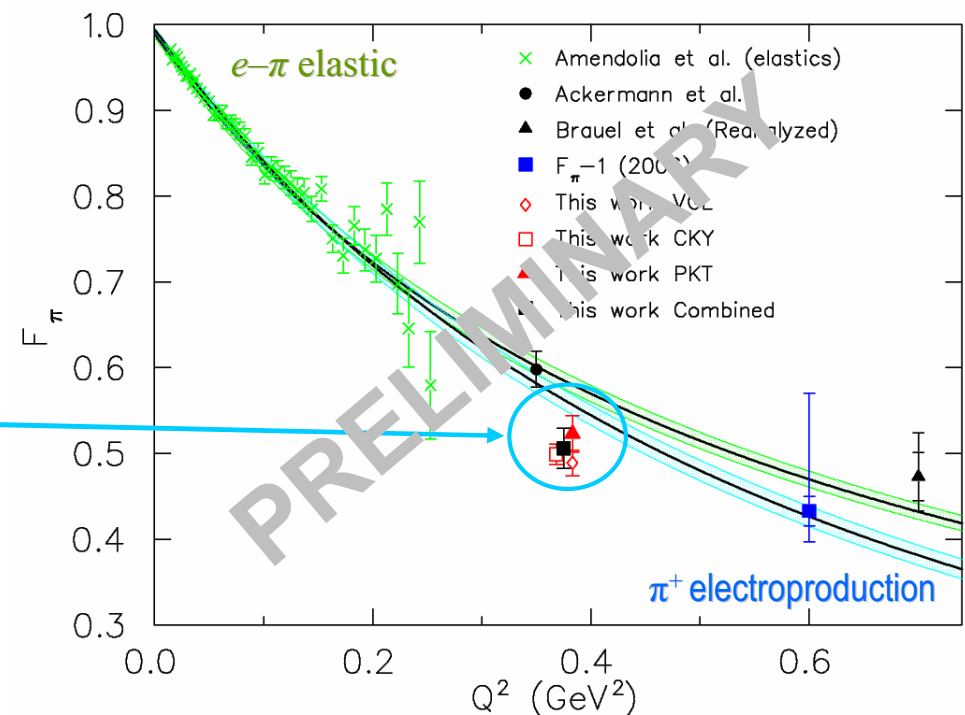
M. Junaid et al, publication in process

Directly compare $F_\pi(Q^2)$ values extracted from very low $-t$ electroproduction with values measured in elastic $e-\pi$ scattering

- $Q^2=0.35 \text{ GeV}^2$ data from DESY consistent with limit of elastic scattering data within uncertainties.

[H. Ackermann, et al., NP B137(1978)294]

- **PionLT acquired $p(e,e'\pi^+)n$ data for a low Q^2 test with much lower statistical and systematic uncertainties**



V.Kumar et al, publication submitted

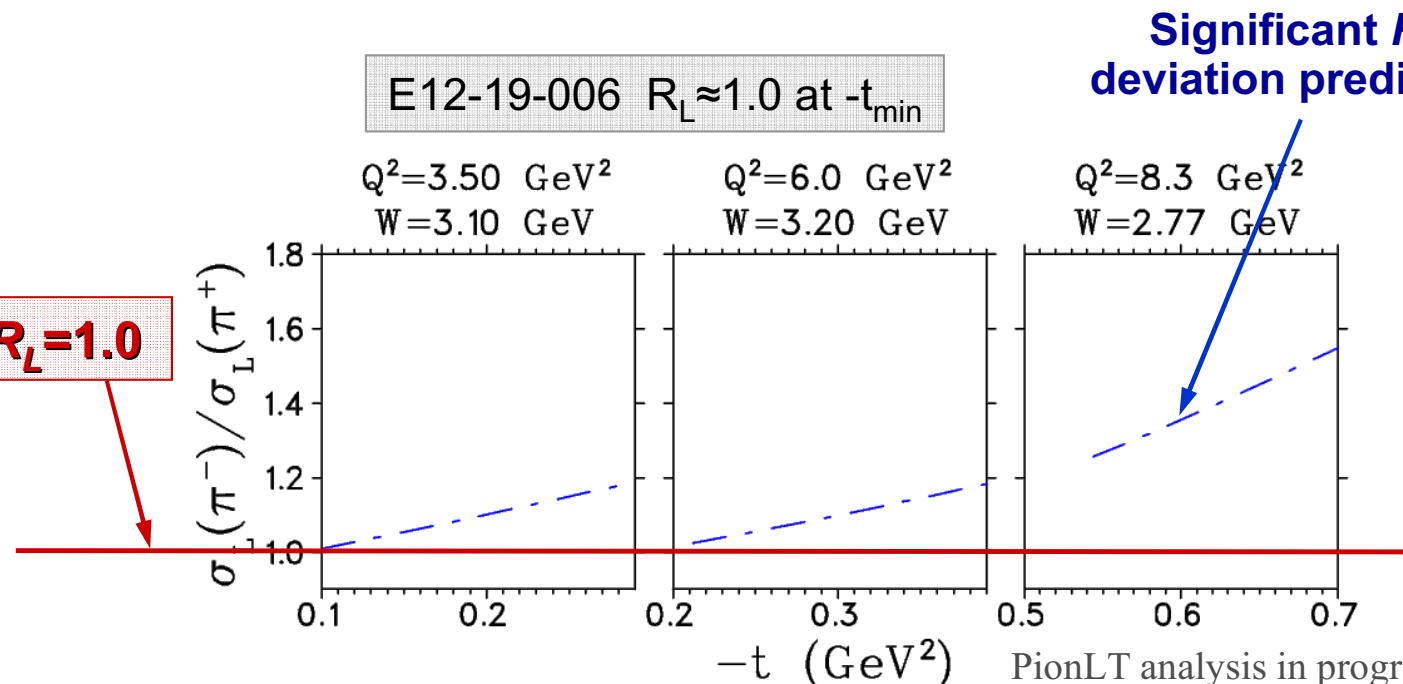
One way to understand non-pole to σ_L

Data-driven approach to better understand non-pole backgrounds at higher $-t$.

- Exclusive $^2\text{H}(e,e'\pi^+)nn$ and $^2\text{H}(e,e'\pi^-)pp$ L/T-separations.
- π^+ t -channel diagram is purely isovector (G-parity conservation).

$$R_L = \frac{\sigma_L[n(e,e'\pi^-)p]}{\sigma_L[p(e,e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

- Isoscalar backgrounds would distort ratio (e.g. $b_1(1235)$ in t -channel).



Another way to understand non-pole to σ_L

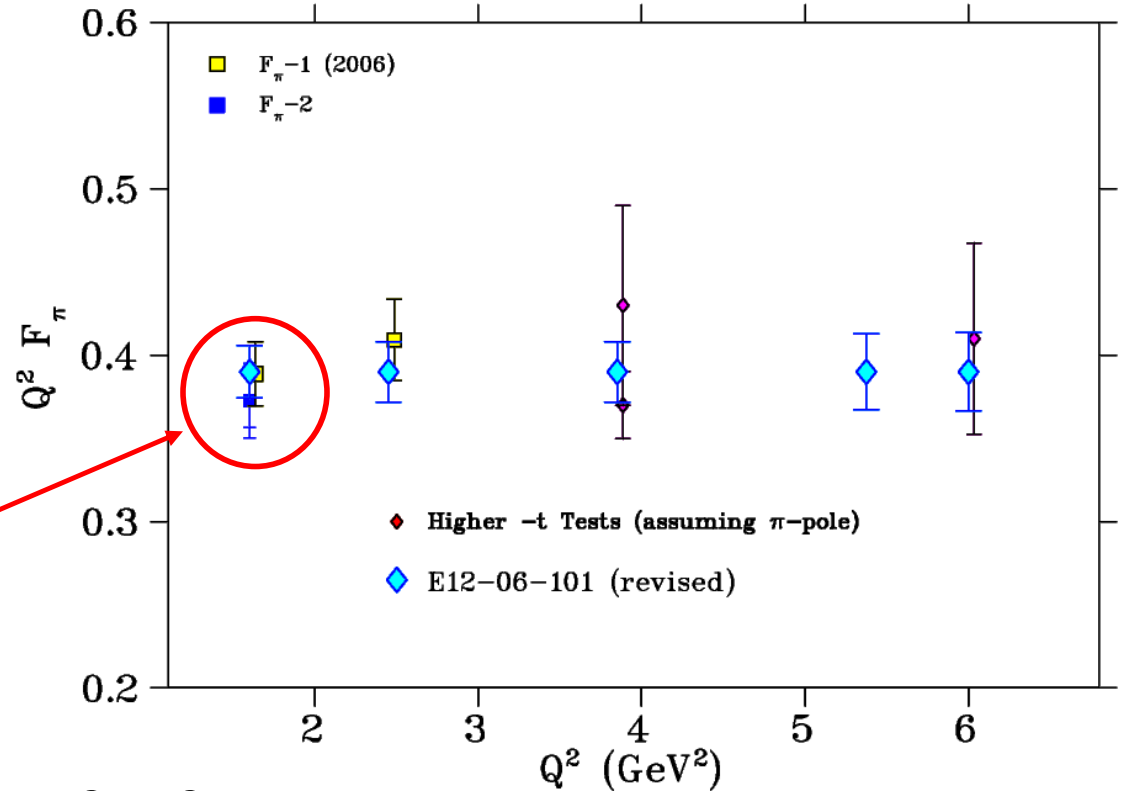
Test by extracting F_π at different distances from pole.

Expt: $F_{\pi-2}$, $-t_{min}=0.093 \text{ GeV}^2$
 $W=2.22 \text{ GeV}$.

$F_{\pi-1}$, $-t_{min}=0.15 \text{ GeV}^2$
 $W=1.95 \text{ GeV}$.

$W=2.22$ point 30% closer to pole.

→ Agreement $\sim 4\%$.



We have taken 12 GeV data for further tests:

$Q^2=1.6 \text{ GeV}^2$	$-t_{min}=0.029 \text{ GeV}^2$	$W=3.00 \text{ GeV}$
$Q^2=2.45 \text{ GeV}^2$	$-t_{min}=0.048 \text{ GeV}^2$	$W=3.20 \text{ GeV}$
$Q^2=3.85 \text{ GeV}^2$	$-t_{min}=0.12, 0.21, 0.49 \text{ GeV}^2$	$W=3.07, 2.62, 2.02 \text{ GeV}$
$Q^2=6.0 \text{ GeV}^2$	$-t_{min}=0.21, 0.53 \text{ GeV}^2$	$W=3.19, 2.40 \text{ GeV}$

Current and Projected F_π Data

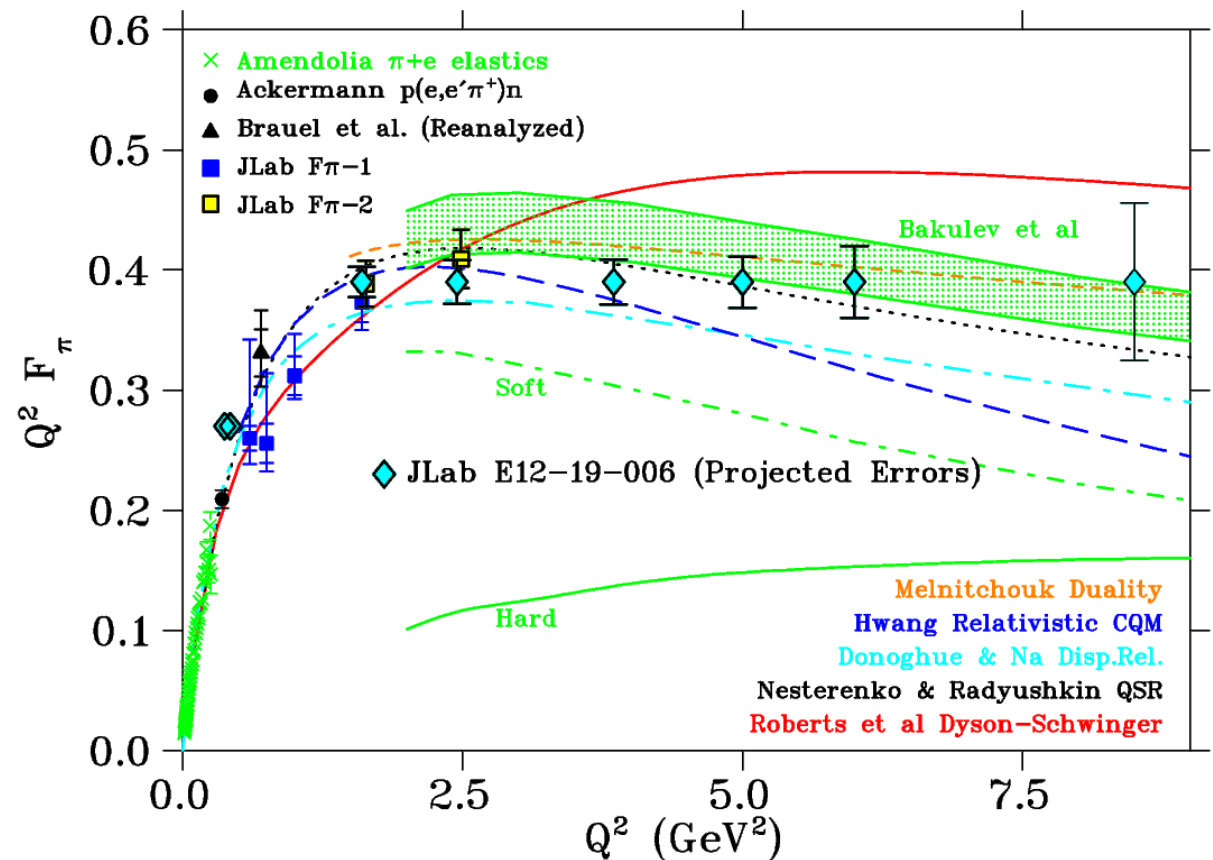
SHMS+HMS will allow measurement of F_π to much higher Q^2

No other facility worldwide can perform this measurement

Data taking completed September 2022
(E12-19-006: G. Huber, D. Gaskell and T. Horn, spokespersons)

y-positions of projected points are arbitrary

Error bars are calculated from obtained statistics and projected systematic uncertainties



The $\sim 10\%$ measurement of F_π at $Q^2 = 8.5 \text{ GeV}^2$ is at higher $-t_{min} = 0.45 \text{ GeV}^2$

The pion form factor is the clearest test case for studies of QCD's transition from non-perturbative to perturbative regions

-
- The diagram illustrates the factorization of the GPD cross section. It shows an incoming electron (e) and an outgoing electron (e') connected by a virtual photon (γ^*). The photon splits into a quark and an antiquark. The quark interacts with a GPD (green oval) and emits a pion (π). The antiquark interacts with the GPD and emits a pion (π). The GPD is labeled "GPD" and "Factorization". The momentum fractions are $x + \xi$ and $x - \xi$. The diagram is labeled with H , $\tilde{H}$, E , and $\tilde{E}$ at the bottom.

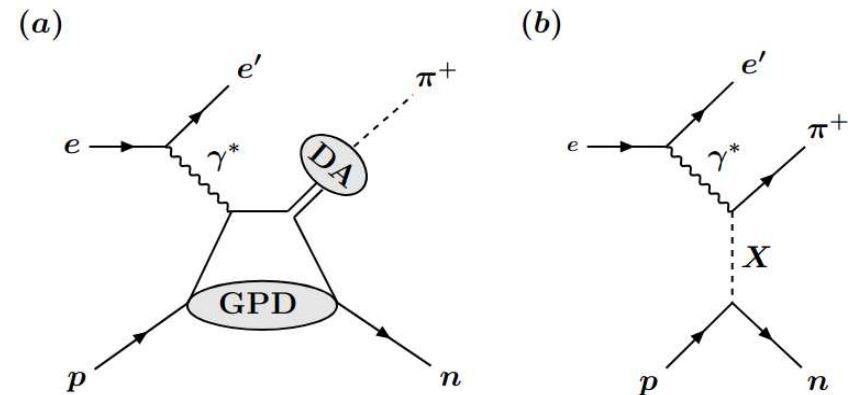
$$H \quad \tilde{H} \quad E \quad \tilde{E}$$

- Garth Huber, huberg@uregina.ca**

Beam Spin Asymmetry Test of Hard-Soft Factorization

First publication using 12 GeV $p(e,e'\pi^+)n$ data set

- Compare data to **GPD** (a) and **Regge** (b) models
- Data show better agreement with Regge models
- Implies **hard/soft factorization** not valid for $Q^2 \leq 5.5 \text{ GeV}^2$ in $p(e,e'\pi^+)n$
- New data are an **improvement on previous results**: new YCK models, finer kinematic binning
- First measurement of **Q^2 dependence** of $\sigma_{LT'}/\sigma_0$ at fixed (x_B, t) : mostly flat



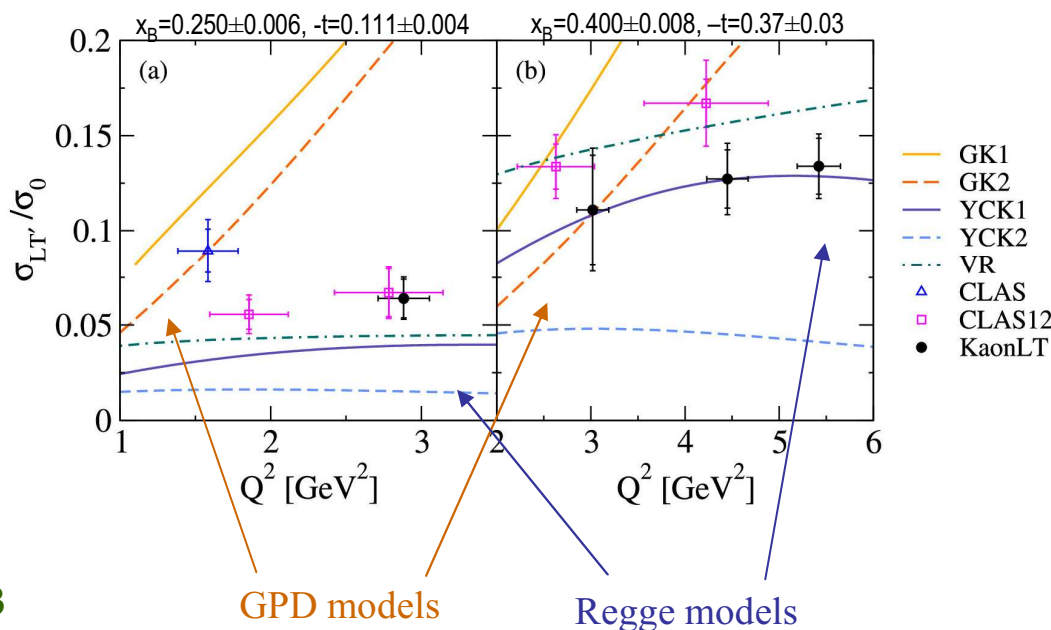
Physics Letters B
Volume 872, January 2026, 140094



Letter

Probing hard/soft factorization via beam-spin asymmetry in exclusive pion electroproduction from the proton

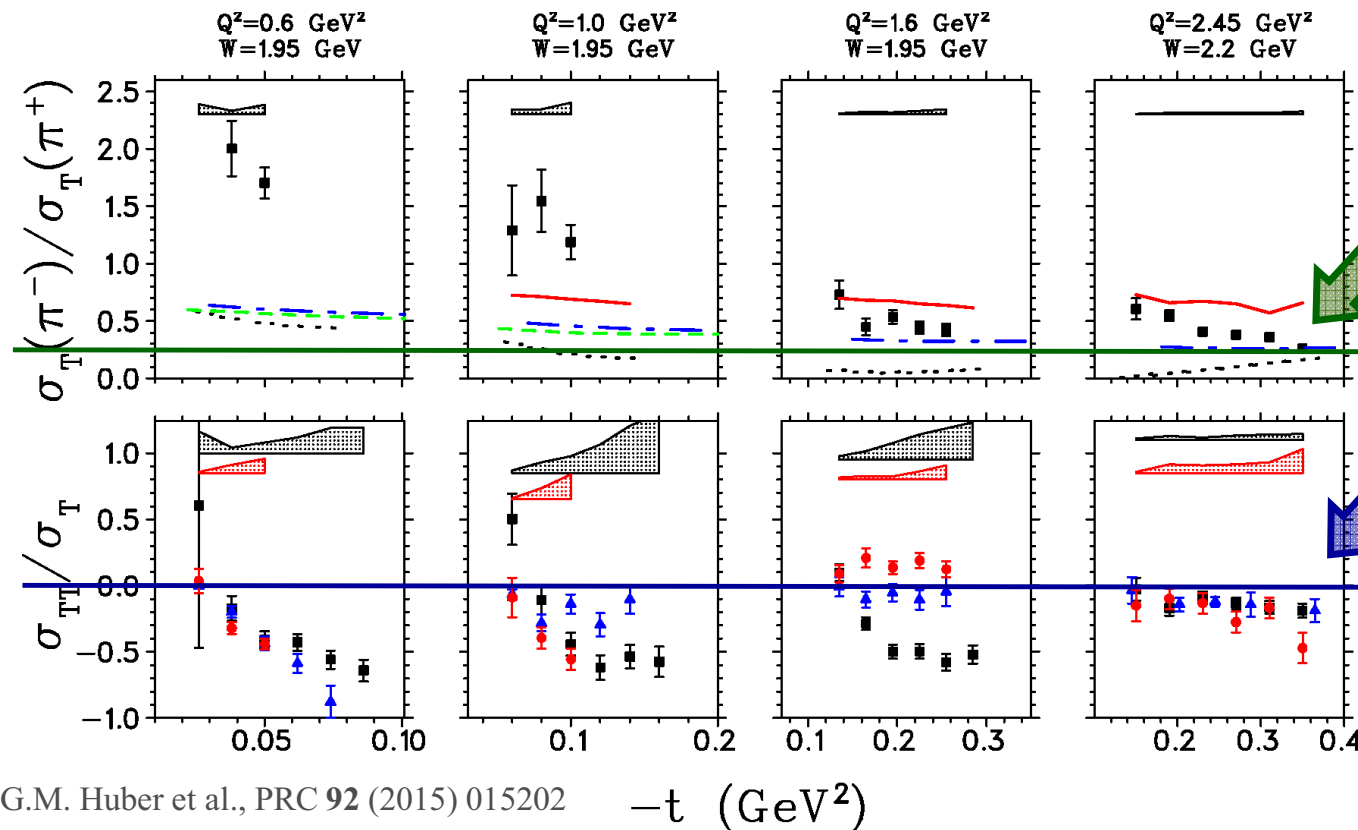
A.C. Postuma^a, G.M. Huber^a, D.J. Gaskell^b, N. Heinrich^a, T. Horn^{c,b}, M. Junaid^a, S.J.D. Kay^{a,d}, V. Kumar^a, P. Markowitz^e, J. Roche^f, R. Trotta^c, A. Usman^a, B.-G. Yu^g, T.K. Choi^h, K.-J. Kong^g, S. Ali^c, R. Ambrose^a, D. Androicⁱ, W. Armstrong^{j,k}, A. Bandari^l, V. Berdnikov^c, H. Bhatt^m, D. Bhetuwal^m, D. Biswasⁿ, M. Boer^j, P. Bosted^l, E. Brash^o, A. Camsonne^b, J.-P. Chen^b, J. Chen^l, M. Chen^p, M.E. Christyⁿ, S. Covrig^b, M.M. Dalton^b, W. Deconinck^q, M. Diefenthaler^b, B. Duran^j, D. Dutta^m, M. Elaasar^r, R. Ent^b, H. Fenker^b, E. Fuchey^s, D. Hamilton^t, J.-O. Hansen^b, F. Hauenstein^u, S. Jia^j, M.K. Jones^b, S. Joosten^k, M.L. Kabir^m, A. Karki^m, C. Keppel^b, E. Kinney^v, N. Lashley-Colthirstⁿ, W.B. Li^w, D. Mack^b, S. Malace^b, M. McCaughan^b, Z.E. Meziani^{k,j}, R. Michaels^b, R. Montgomery^t, M. Muhoza^c, C. Muñoz Camacho^x, G. Niculescu^y, I. Niculescu^y, Z. Papandreou^a, S. Park^w, E. Pooser^b, M. Rehfuß^j, B. Sawatzky^b, G.R. Smith^b, H. Szumila-Vance^b, A. Teymurazyan^a, H. Voskanyan^z, B. Wojtsekhowski^b, S.A. Wood^b, Z. Ye^k, C. Yero^e, J. Zhang^p, X. Zheng^p



π^-/π^+ Hard-Soft Factorization Test

- Transverse Ratios tend to $1/4$ as $-t$ increases:
 → Is this an indication of Nachtmann's quark charge scaling?
- $-t=0.3 \text{ GeV}^2$ seems too low for this to apply. Might indicate the partial cancellation of soft QCD contributions in the formation of the ratio.

Garth Huber, huberg@uregina.ca



A. Nachtmann,
Nucl.Phys. **B115** (1976) 61

$$R_T \rightarrow \frac{2Q_d^2}{2Q_u^2} = \frac{1}{4}$$

- Another prediction of quark-parton mechanism is the suppression of σ_{TT}/σ_T due to s -channel helicity conservation.
- Data qualitatively consistent with this, since σ_{TT} decreases more rapidly than σ_T with increasing Q^2 .

G.M. Huber et al., PRC **92** (2015) 015202

$^2\text{H}(e,e'\pi^+)nn$ $^2\text{H}(e,e'\pi^-)pp$ $^1\text{H}(e,e'\pi^+)n$

Testing Factorization: 6 GeV $p(e, e' \pi^+) n$

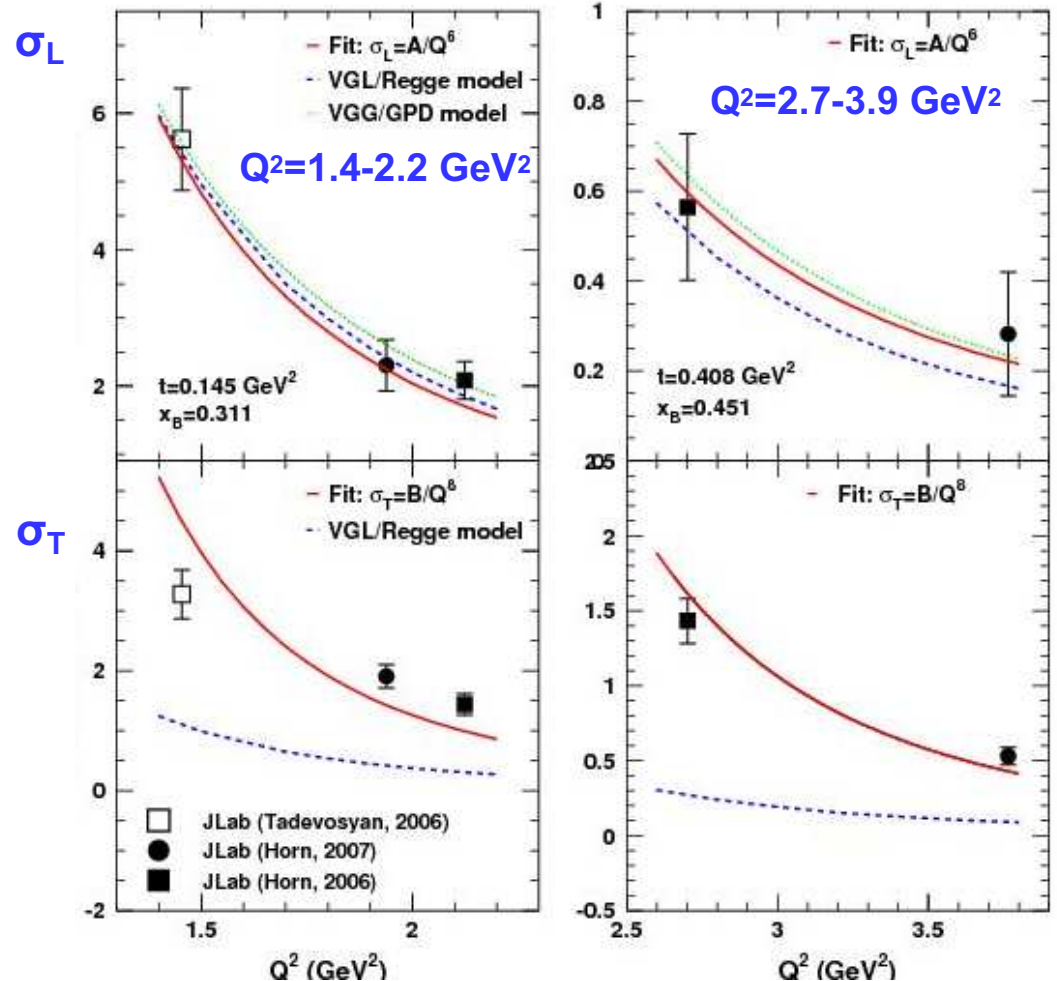
- One of most stringent tests of factorization is Q^2 dependence of π^+ electroproduction cross sections

- σ_L scales to leading order as Q^{-6}
- As Q^2 becomes large: $\sigma_L \gg \sigma_T$

- JLab 6 GeV σ_L data is consistent with Q^{-6} QCD scaling
 - Limited Q^2 coverage and large uncertainties make it difficult to draw a conclusion

- Two additional factorization predictions: $\sigma_L \gg \sigma_T$ and $\sigma_T \sim Q^{-8}$ are not consistent with 6 GeV data

Hall C data at 6 GeV: 3 different experiments

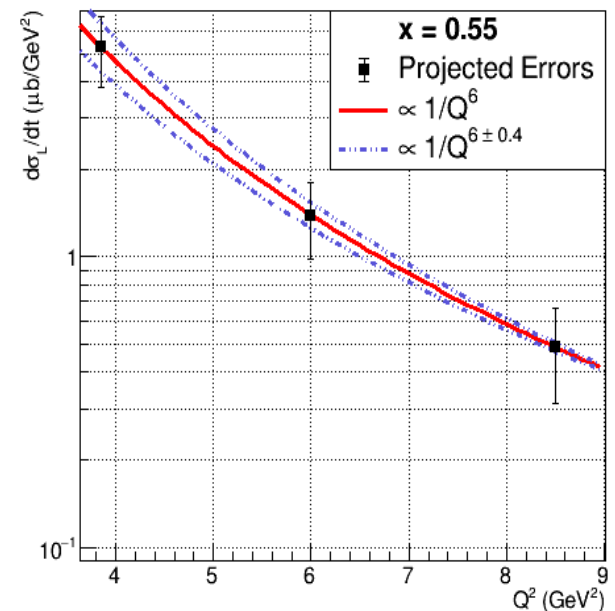
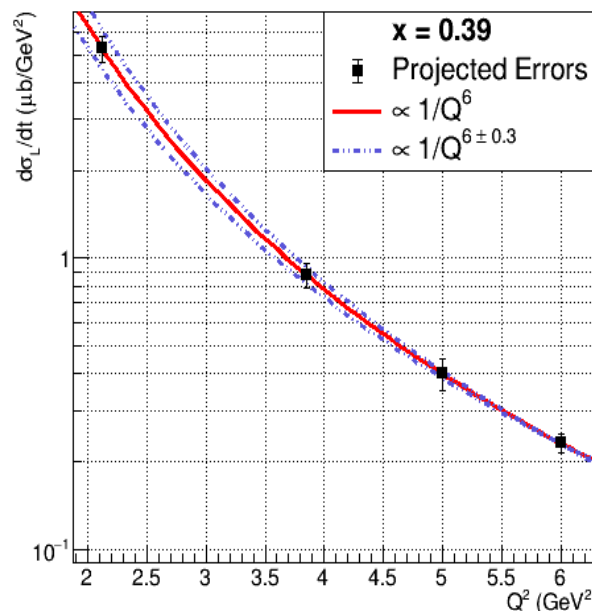
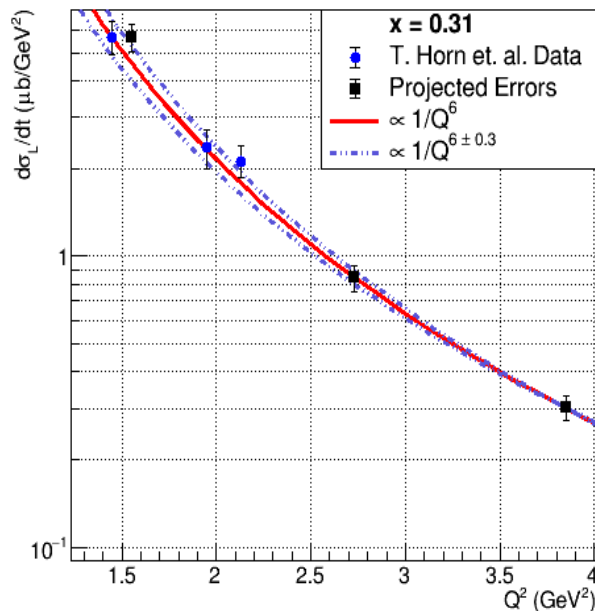


T. Horn et al, PRC 78 (2008) 058201

Testing Factorization: 12 GeV $p(e, e' \pi^+) n$

- Testing the applicability of factorization requires PionLT's larger kinematic coverage and improved precision
- If we show factorization regime is not reached, it will have major implications for meson production GPD experiments in this Q^2 regime
- Some of these experiments are already taking data!

$p(e, e' \pi^+) n$ Existing ■ and Projected ■ Data



PionLT analysis in progress: N. Heinrich

- Higher Q^2 data on π^+ form factor is vital to our better understanding of hadronic physics
 - PionLT (E12–19–006) has for the first time, since the pioneering measurements at Cornell in 1970's, acquired the high quality data needed to test these theoretical developments with authority
 - First $d\sigma/dt$ should be out later this year
- Factorization studies are crucial if the field is to fully utilize the information encoded in GPDs, as GPDs are only accessible experimentally in the hard–soft factorization regime
 - PionLT (E12–19–006) has acquired data for LT–separated $p(e, e'\pi^+)n$ Q^{-n} scans at $x_B=0.31, 0.39, 0.55$
- KaonLT will be presented by Chi Kin Tam on Friday afternoon