Deep Exclusive p(e,e'π^+)n Studies at Jefferson Lab

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On behalf of the PionLT Collaboration

Towards Improved Hadron Femtography with Hard Exclusive Reactions
University of Virginia
July 22, 2026

Collaboration Acknowledgement

- **PionLT Spokespersons:**
  - Dave Gaskell (JLab), Tanja Horn (CUA), GMH
- **PionLT Graduate Students:**
  - Nathan Heinrich (Regina), Sameer Jain (CUA), Muhammad Junaid (Regina), Vijay Kumar* (Regina), 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

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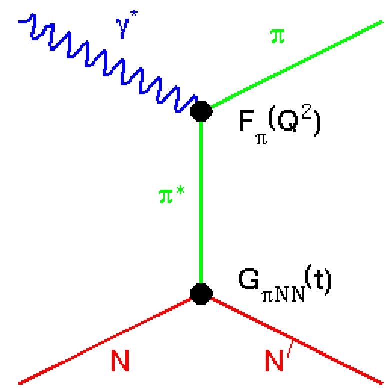
1) Determine the Pion Form Factor at Q^2>0.3 GeV^2:

- Indirectly measure F_π using the “pion cloud” of the proton via p(e,e’π^+)n

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

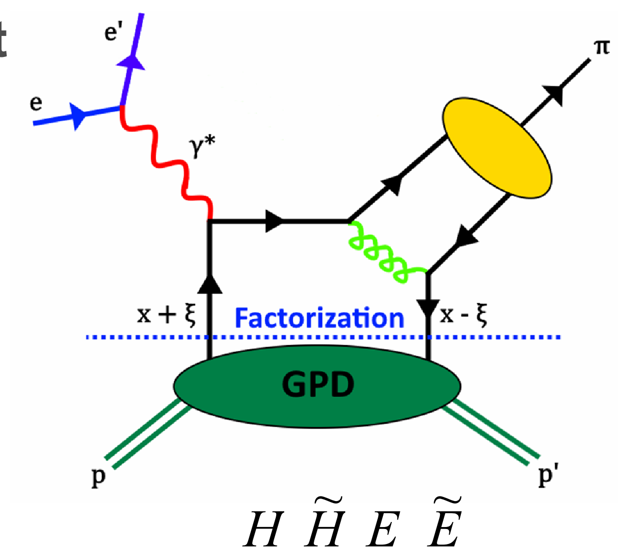
  - Pion pole process dominates σ_L in forward kinematics.



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’π^+)n cross sections at fixed x behave according to the Q^{-n} scaling expectations of hard QCD
- Form $\dfrac{\sigma_T[n(e,e'\pi^-)p]}{\sigma_T[p(e,e'\pi^+)n]}$ ratios where soft contributions may cancel, yielding insight to factorization at modest Q^2.

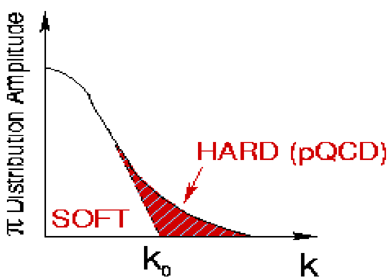


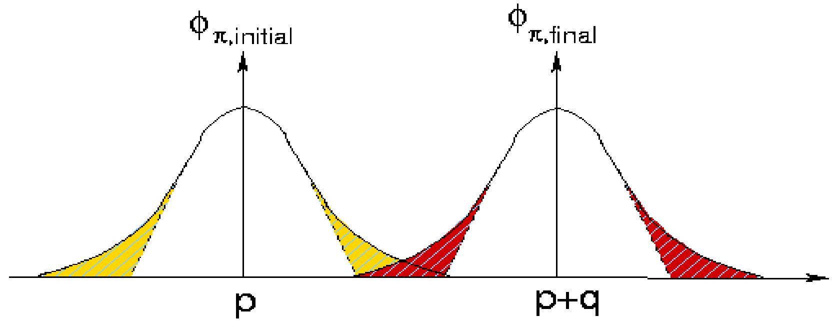
Charged Meson Form Factors

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.

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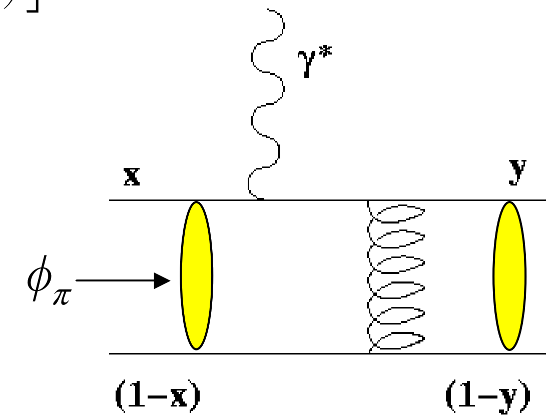
The Pion in perturbative QCD

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

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



and F_π takes the very simple form

$$Q^2 F_\pi(Q^2) \underset{Q^2\to\infty}{\longrightarrow} 16\pi\alpha_s(Q^2) f_\pi^2$$

f_π=93 MeV is the $\pi^+ \to \mu^+ \nu$ 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 $\mu\to\infty$.

Q^2F_π 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]

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Pion Form Factor at Intermediate Q^2

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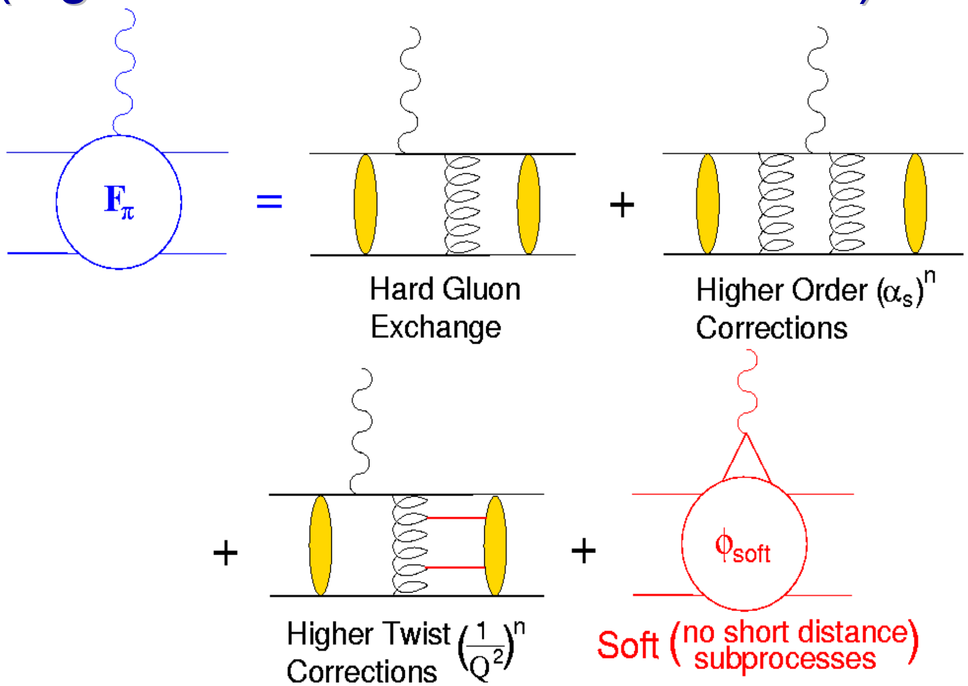
At experimentally–accessible Q^2, both the "hard" and "soft" components (e.g. transverse momentum effects) contribute.



- **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.

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

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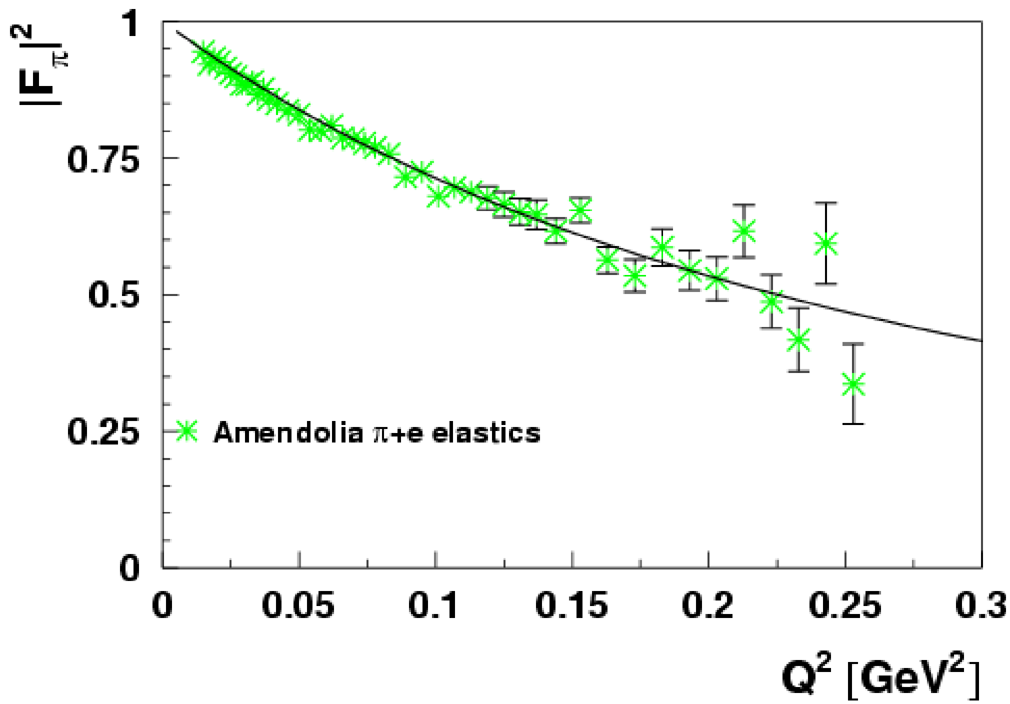
At low Q^2, F_π can be measured model-independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

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

- Data used to extract pion charge radius
  $r_\pi = 0.657 \pm 0.012$ fm

Maximum accessible Q^2 roughly proportional to pion beam energy

Q^2=1 GeV^2 requires 1 TeV pion beam



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

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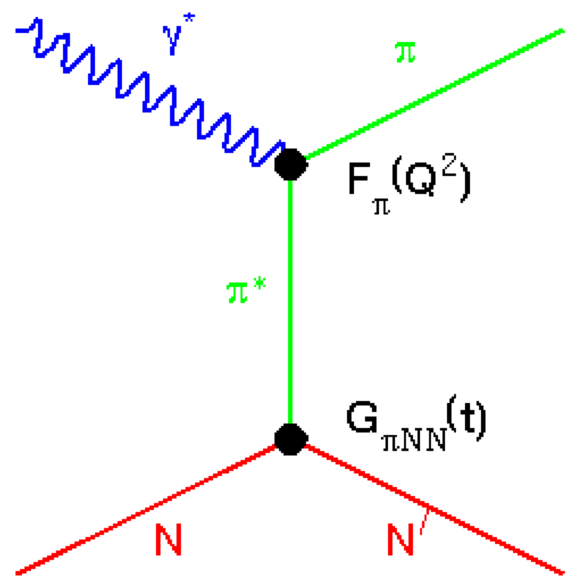
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction *p(e,e'π^+)n "Sullivan process"*

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

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

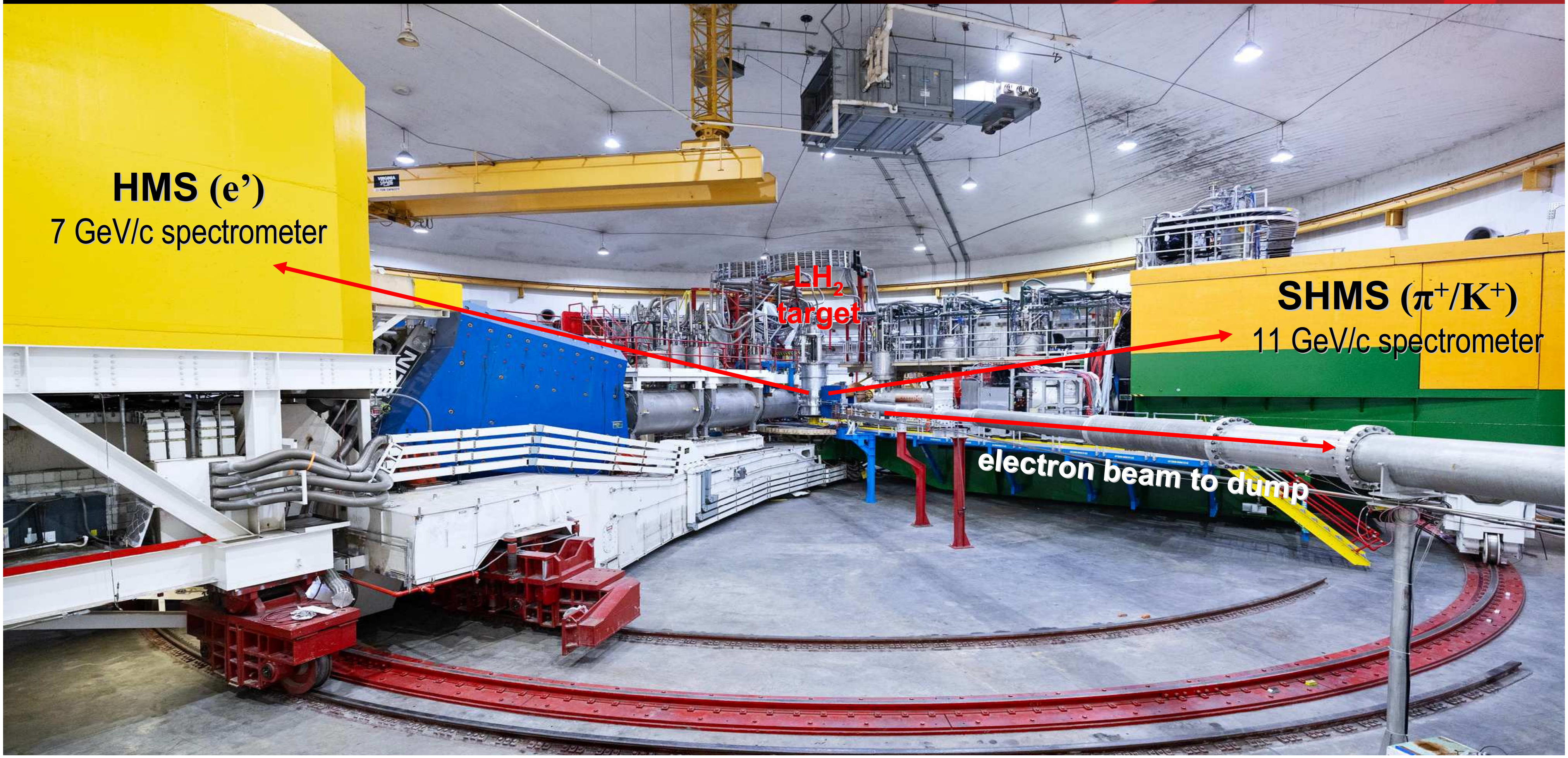
$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2,t)$$



Drawbacks of this technique

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

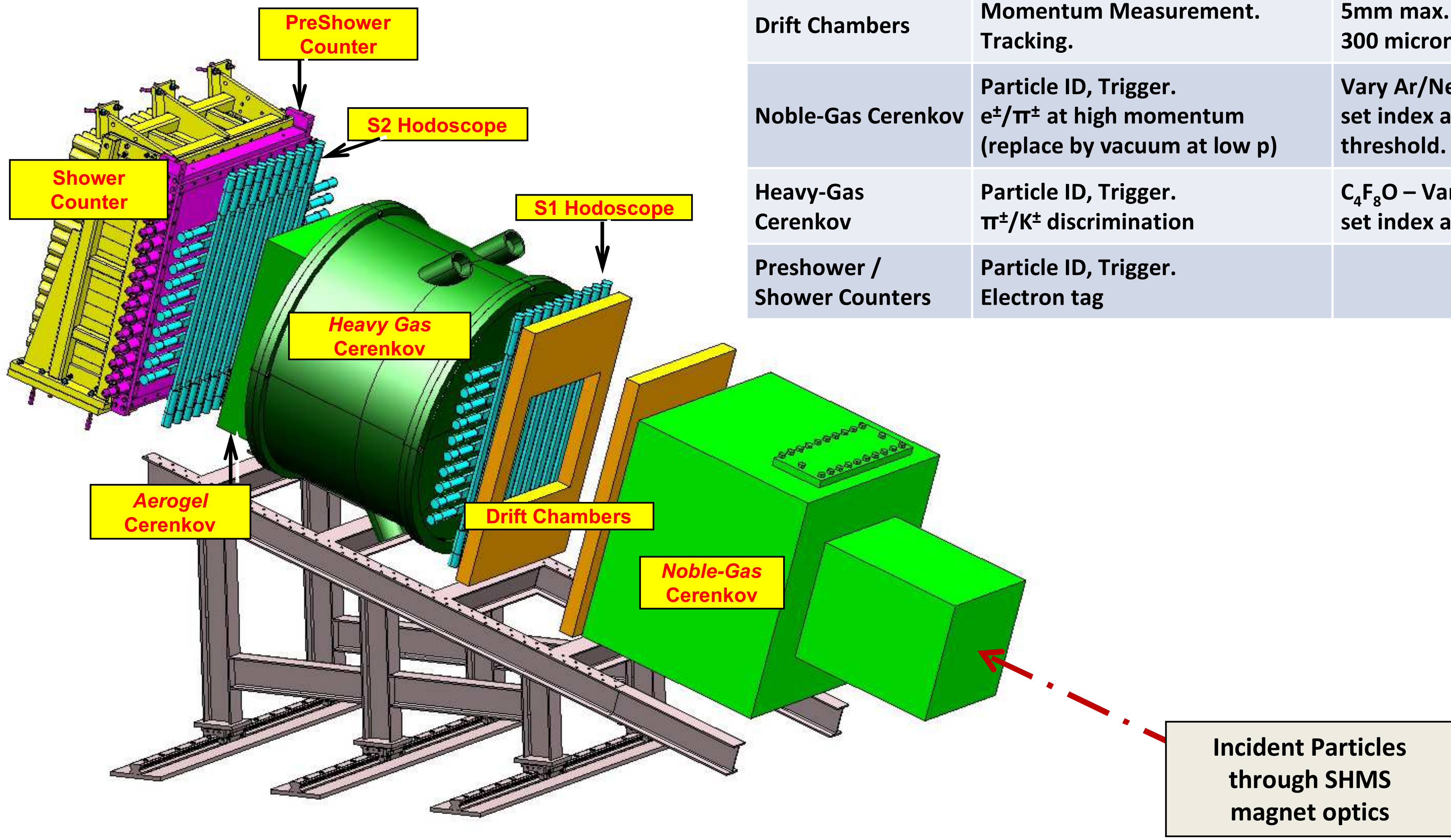
Jefferson Lab Hall C



- **HMS and SHMS MAGNETIC OPTICS:**
  - Point-to Point QQQD 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:** ~4×10^{38} cm^{-2} s^{-1}

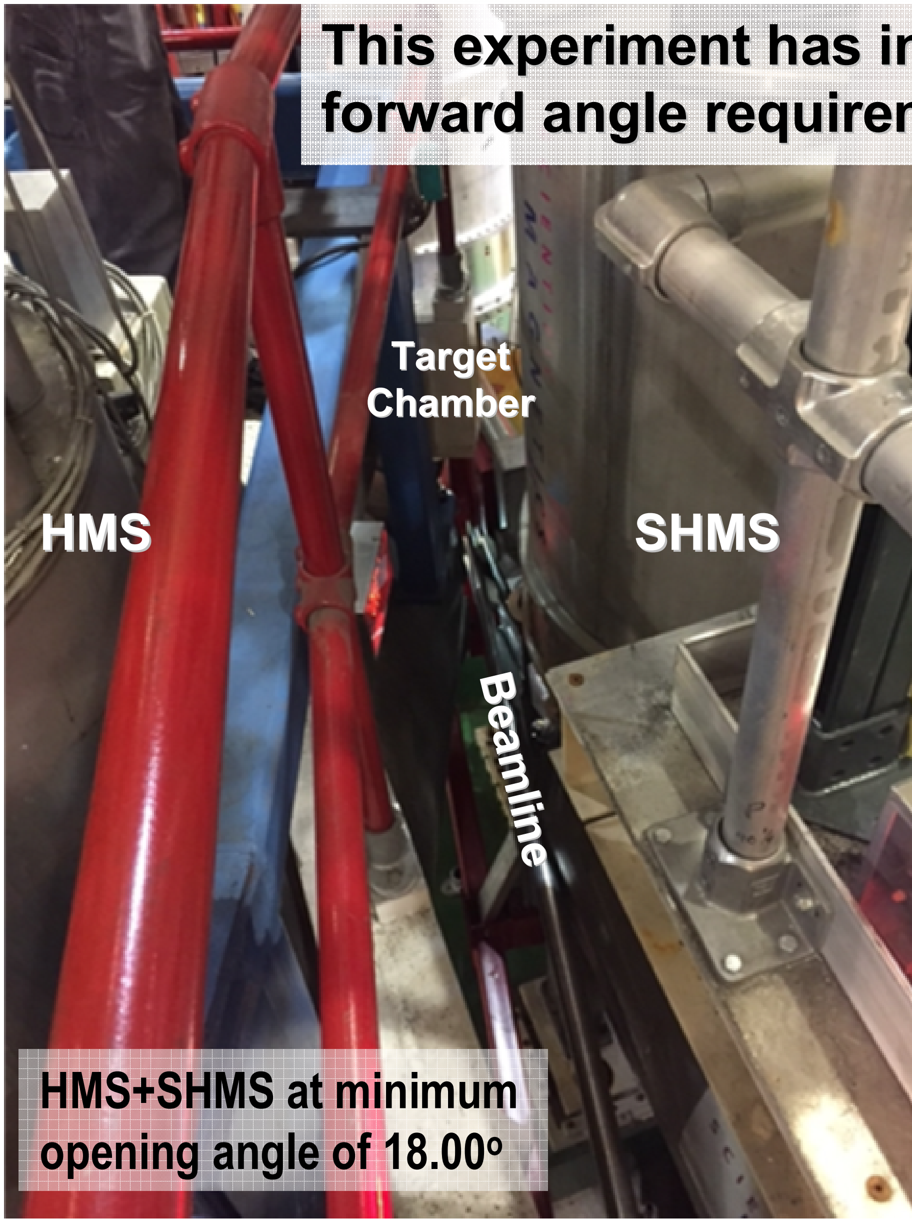
SHMS Focal Plane Detector System

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

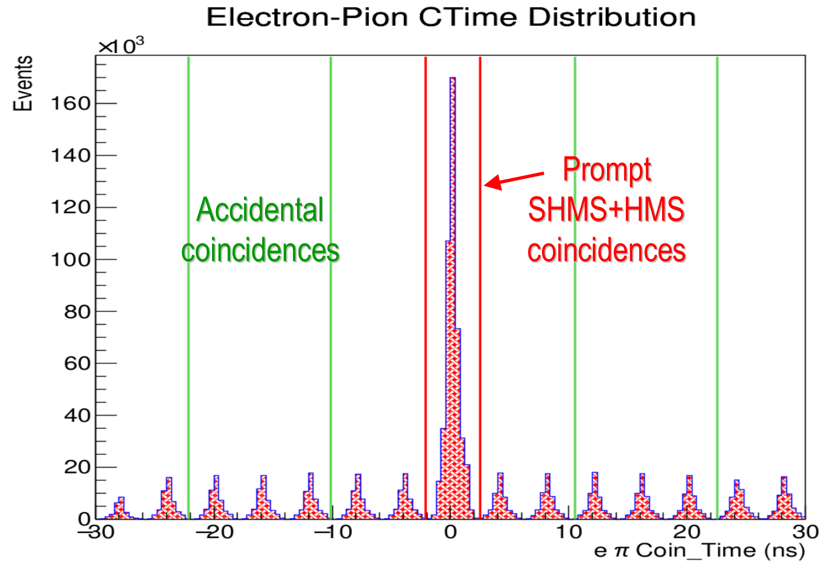


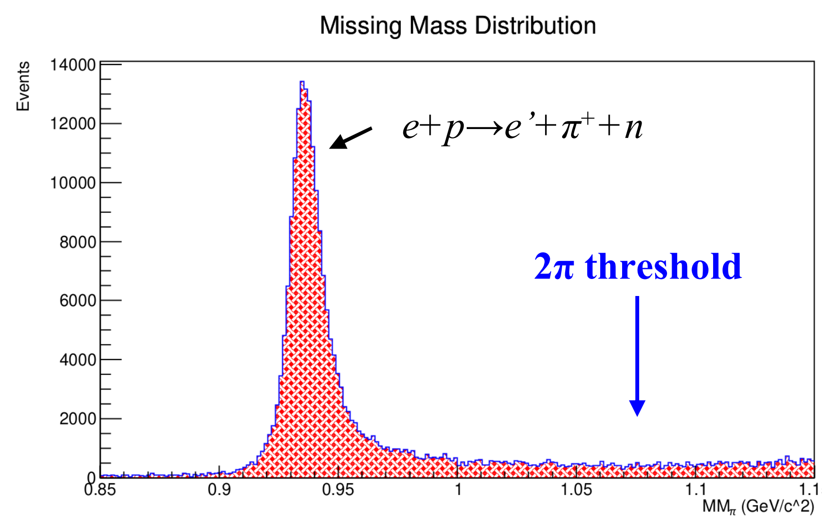
$p(e,e'\pi^+)n$ Event Selection

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





PionLT experiment E12–19–006 Data

Q^2=1.60, W=3.08, x= 0.157, ε=0.685

E_{beam}=9.177 GeV, P_{SHMS}=+5.422 GeV/c, θ_{SHMS}= 10.26° (left)

Plots by Muhammad Junaid (Regina PhD student)

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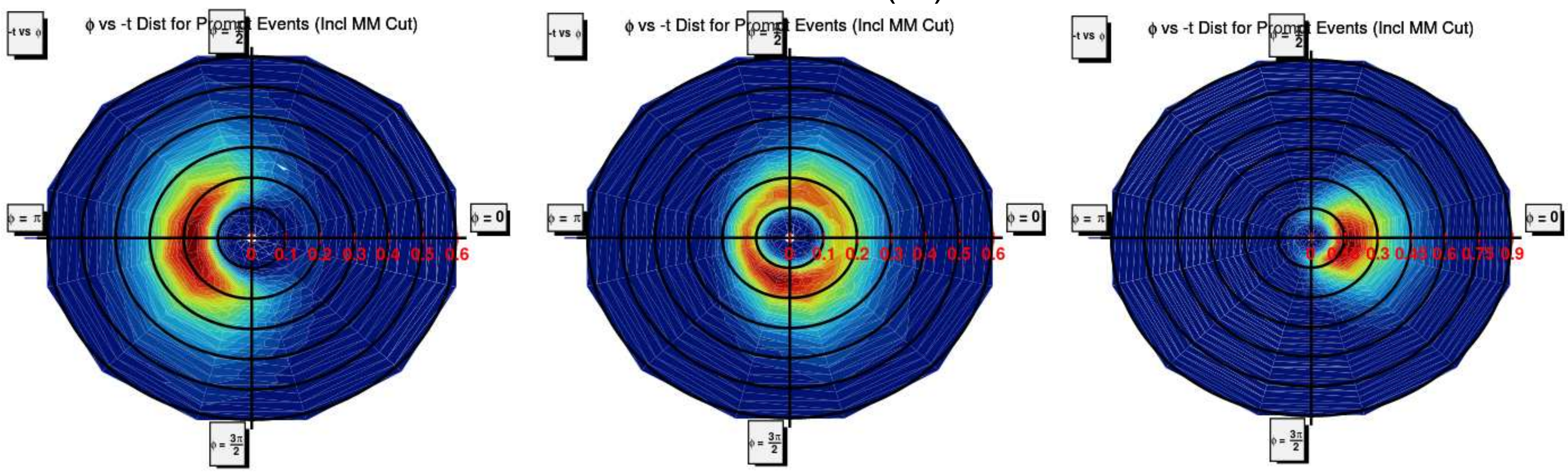
PionLT t–φ Coverage

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

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

SHMS Left (+2°) SHMS Center (0°) SHMS Right (-2°)



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}C, used to calibrated spectrometer acceptances, momenta, kinematic offsets, efficiencies.
  - Control of point–to–point systematic uncertainties crucial due to 1/Δε error amplification in σ_L

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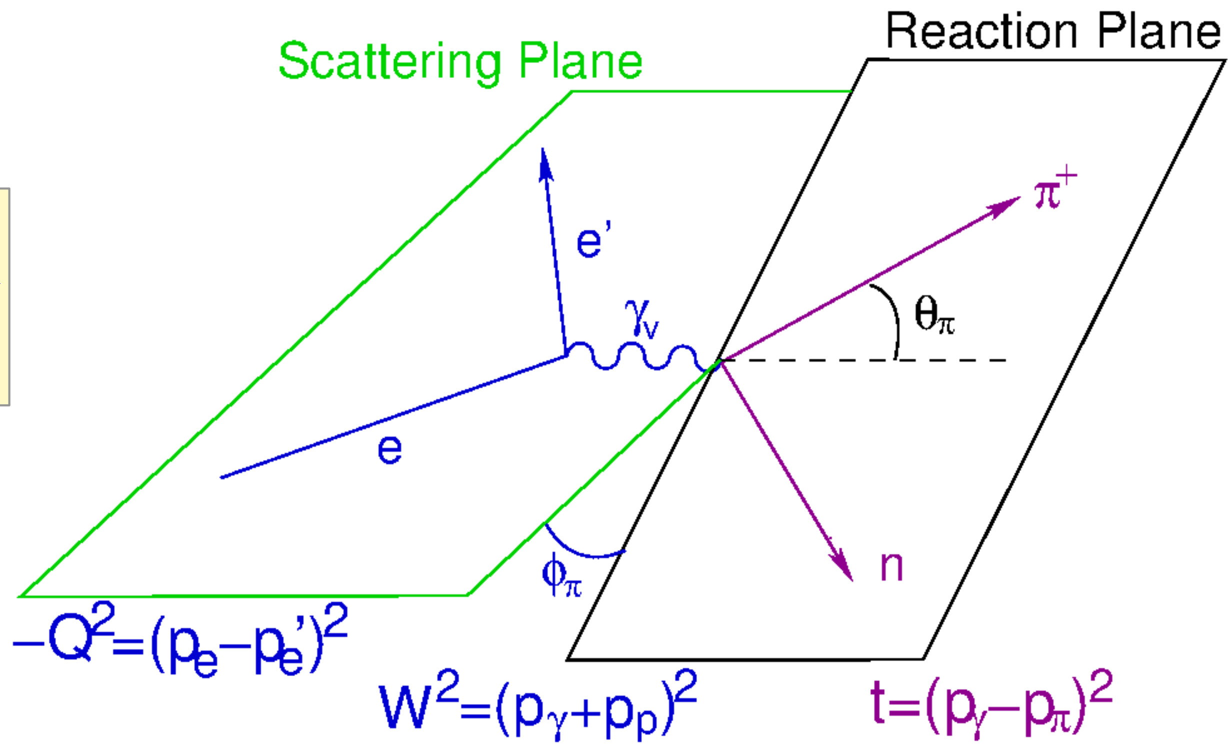
$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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**

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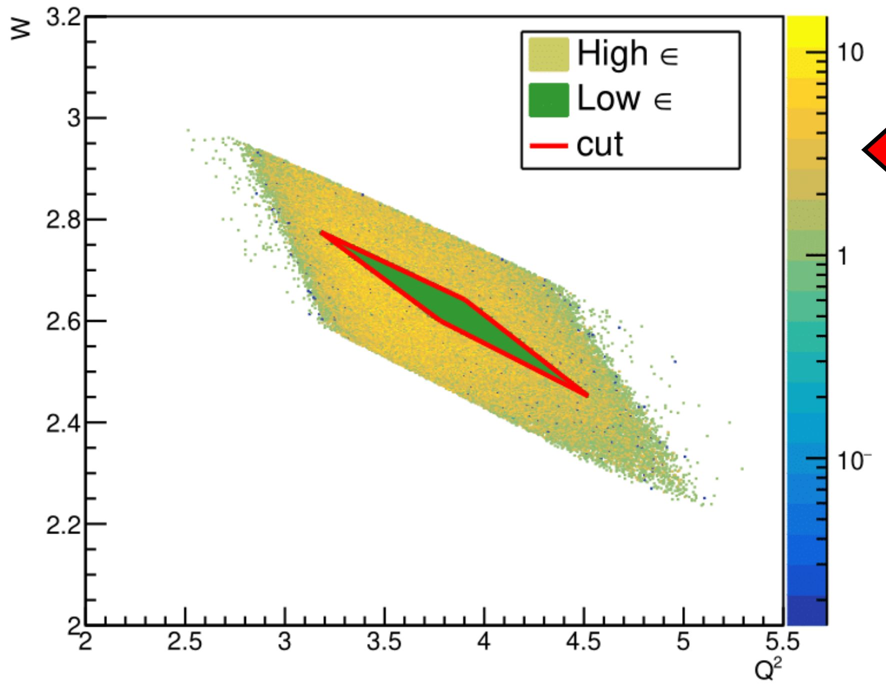
The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

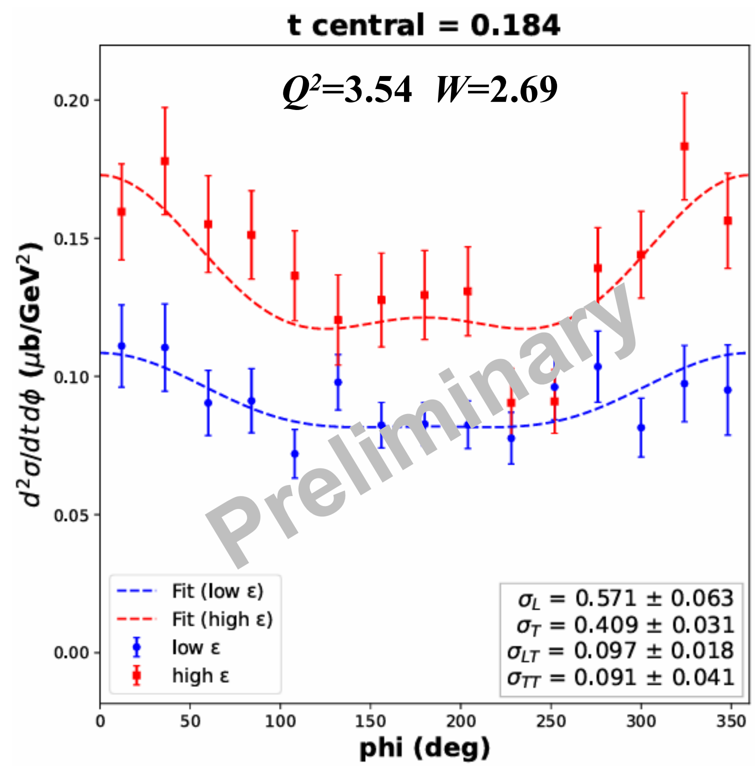
$$2\pi\frac{d^2\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$



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

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

High ε=0.78   Low ε=0.29



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

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Plots by Muhammad Junaid (Regina PhD student)

Meson Form Factors require a Model

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- **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 $-t < 0.4$ 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 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

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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

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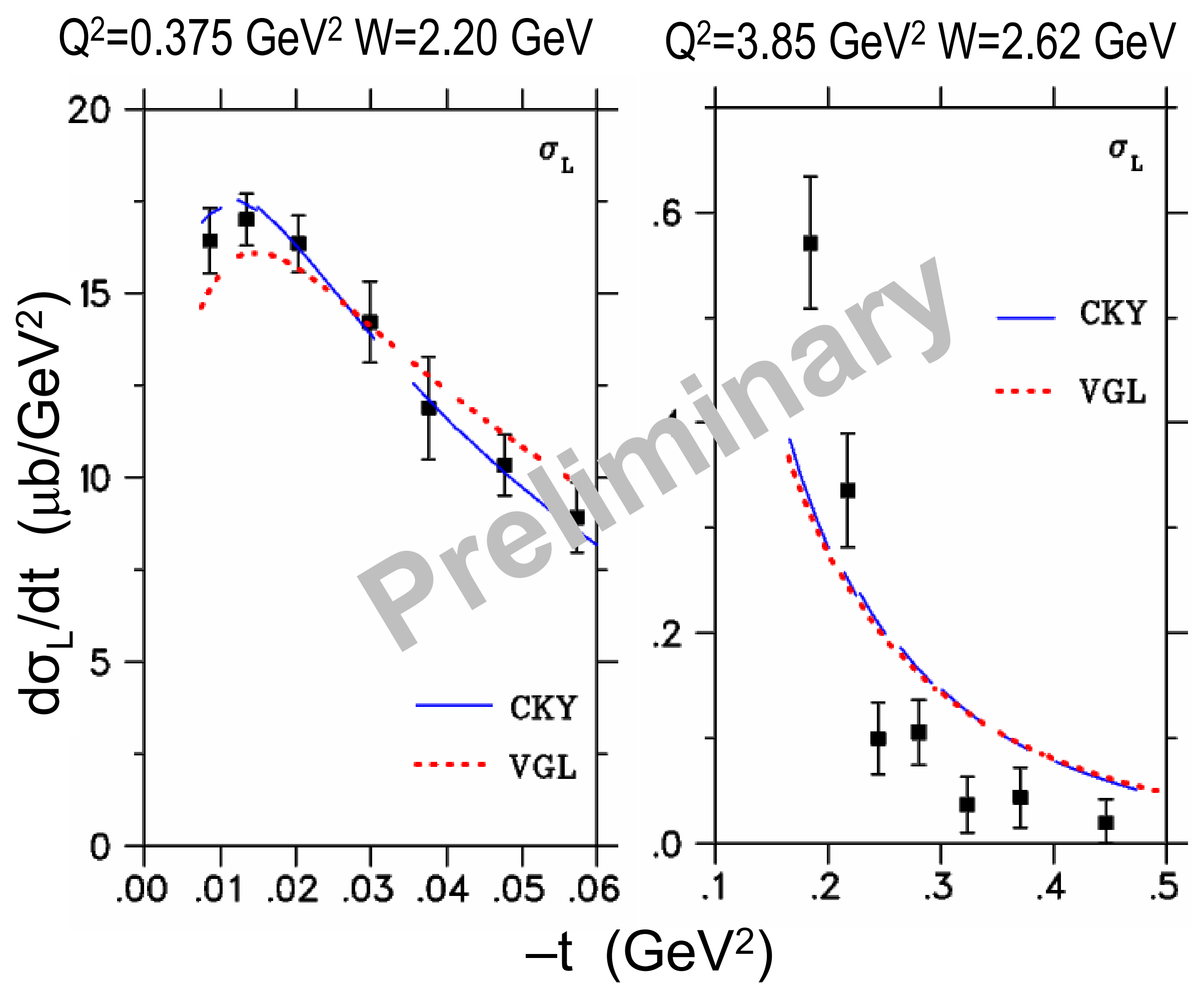
- **JLab 6 GeV F_p expts used VGL Regge model** [Vanderhaeghen, Guidal, Laget, PRC 57(1998)1454]
  - Most parameters fixed by photoproduction data
  - At small $-t$, σ_L only sensitive to π Regge trajectory cutoff Λ_π
- **Choi, Kong, Yu (CKY) Regge model allows 2nd way to extract F_π from σ_L data** [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

Low Q^2 Check of Electroproduction Technique

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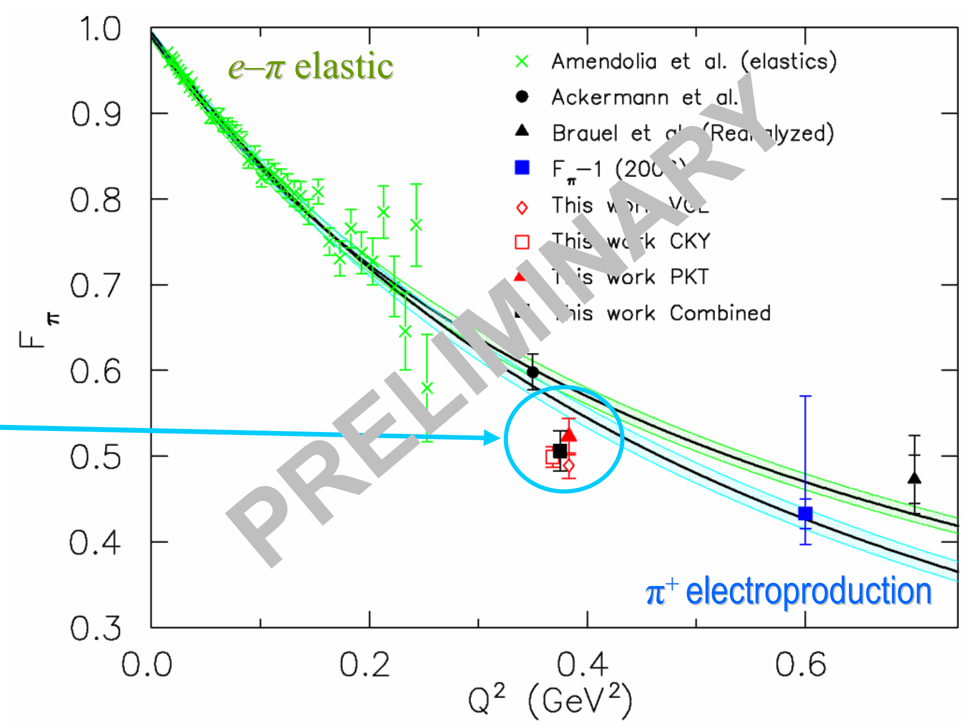
Directly compare $F_\pi(Q^2)$ values extracted from very low $-t$ electroproduction with values measured in elastic e-π scattering

- Q^2=0.35 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'π^+)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*.

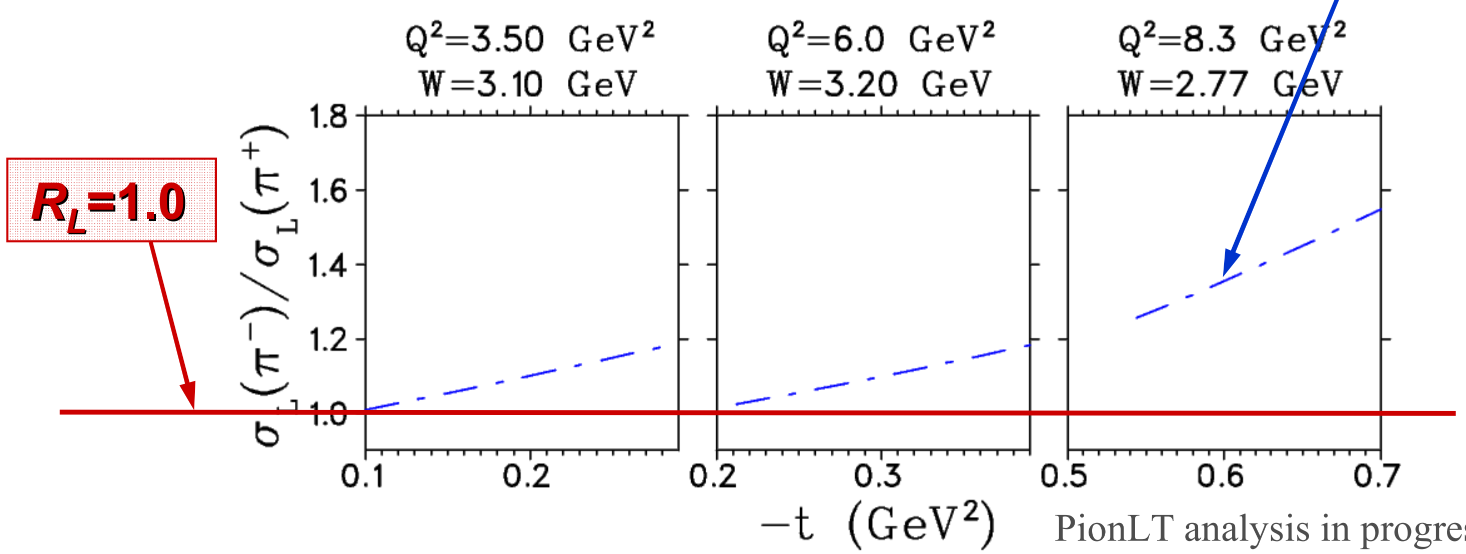
- Exclusive ^{2}H(e,e'π^+)nn and ^{2}H(e,e'π^-)pp L/T-separations.
- π^+ *t*–channel diagram is purely isovector (G-parity conservation).

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

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

E12-19-006 $R_L \approx 1.0$ at $-t_{min}$

Significant R_L deviation predicted



Deviation of data from R_L=1.0 could confirm large non-pole contributions estimated by model.

PionLT analysis in progress: K Ramage, N. Sadoun

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Another way to understand non-pole to σ_L

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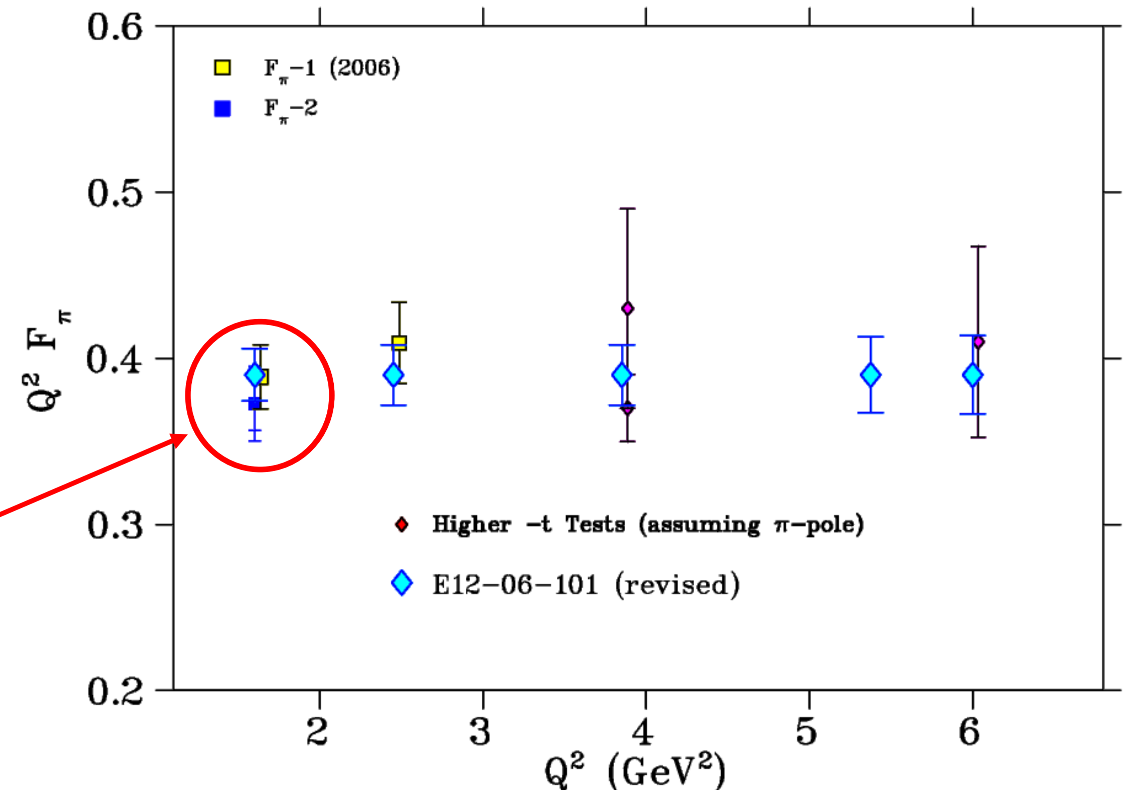
Test by extracting F_π at different distances from pole.

Expt: F_π-2, $-t_{min}=0.093$ GeV^2
$W=2.22$ GeV.
F_π-1, $-t_{min}=0.15$ GeV^2
$W=1.95$ GeV.

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

⟶ Agreement ~4%.



We have taken 12 GeV data for further tests:

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

PionLT analysis in progress: S. Jain, M. Junaid

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Current and Projected F_π Data

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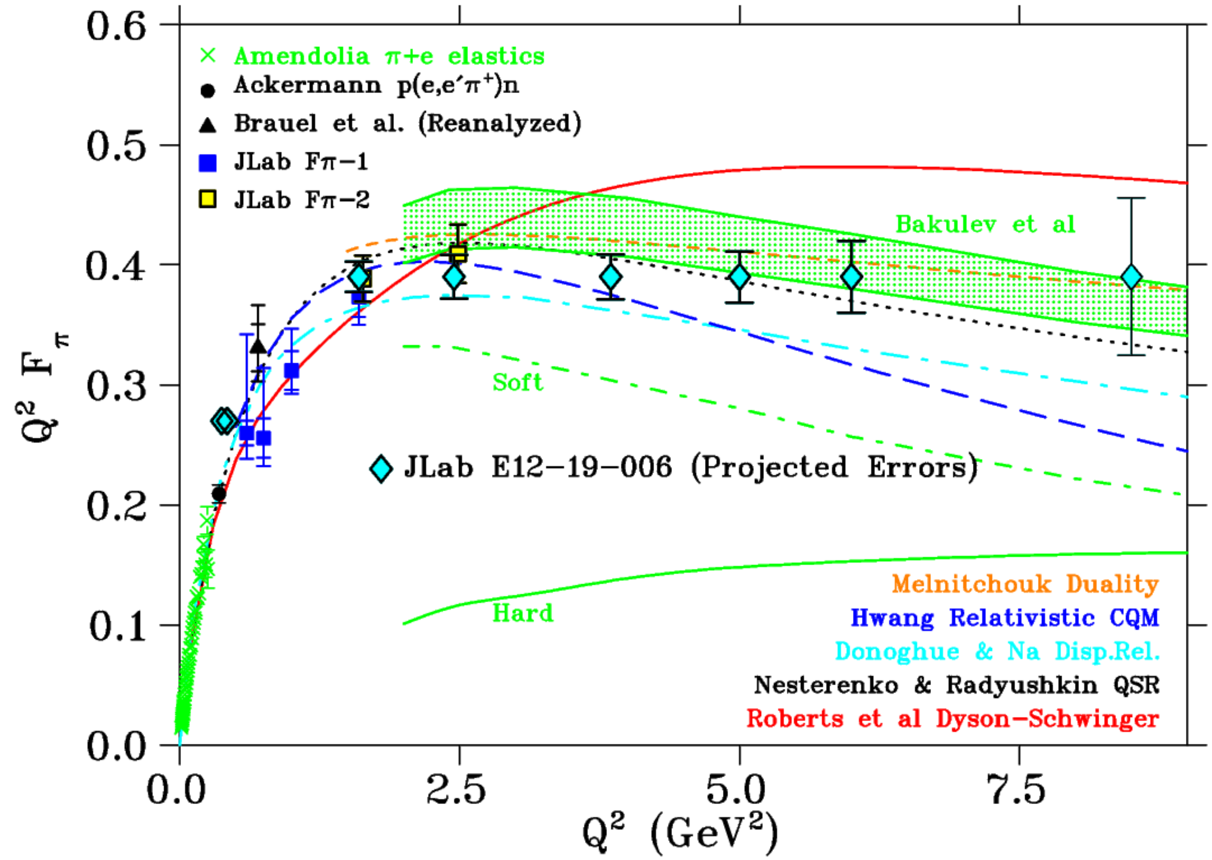
SHMS+HMS will allow measurement of F_π to much higher Q^2

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

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

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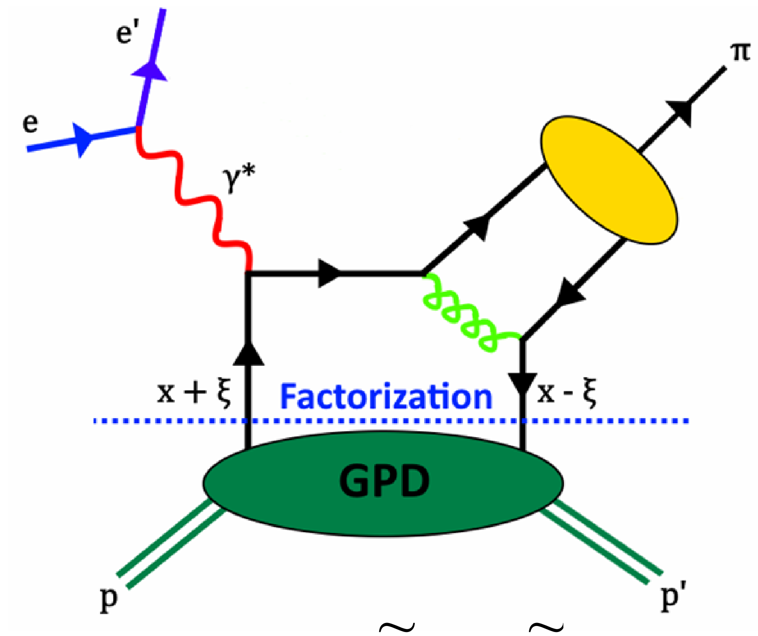
Verification of GPD Accessibility

- **At sufficiently high Q^2, the Hard–Soft Factorization Theorem separates the reaction amplitude into two parts:**
  - Hard scattering process, where perturbative QCD can be used
  - A non–perturbative (soft) part, where the response of the target nucleon to the virtual photon probe is encoded in GPDs

Collins, Frankfurt, Strikman PRD 56(1997)2982



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

- **To access physics contained in GPDs, one is limited to the kinematic regime where hard–soft factorization applies**
- No single criterion for applicability, but tests of necessary conditions can provide evidence that Q^2 scaling regime reached

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Beam Spin Asymmetry Test of Hard-Soft Factorization

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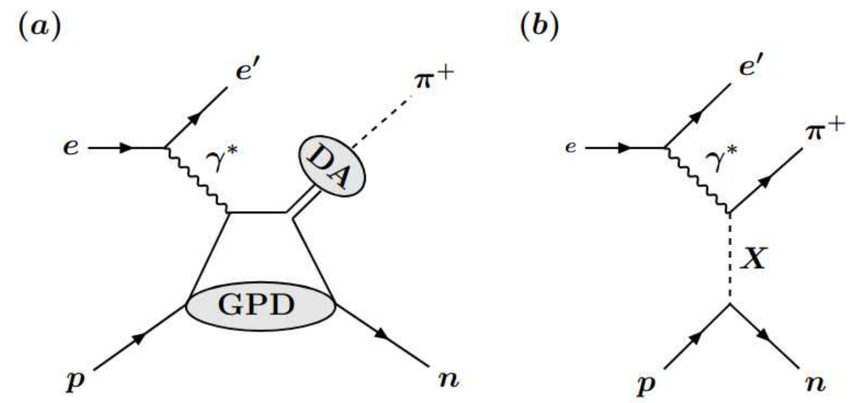
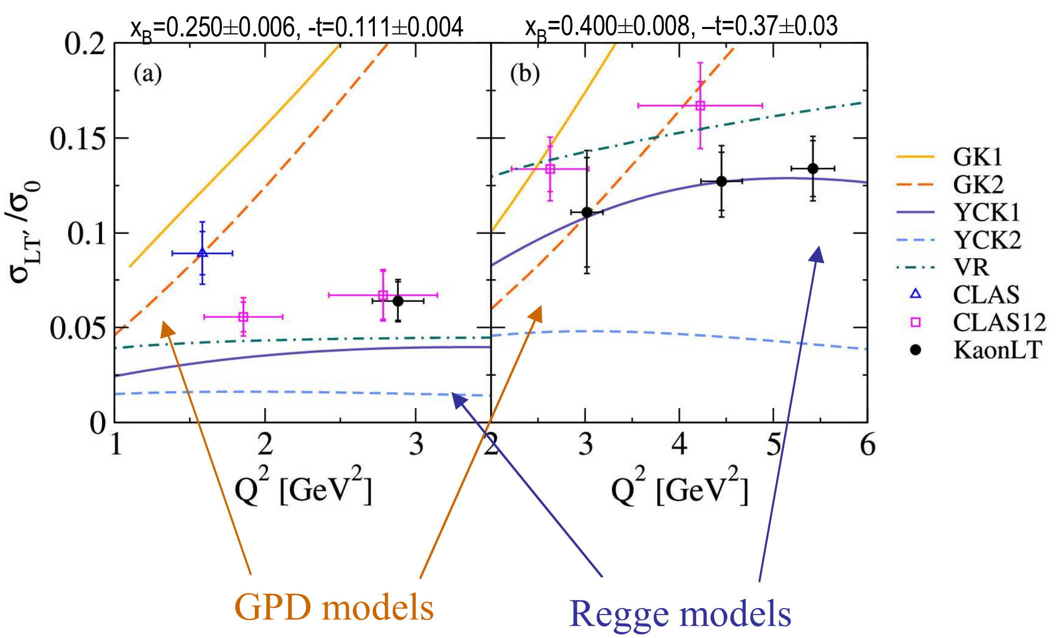
First publication using 12 GeV $p(e,e'\pi^+)n$ data set

- Compare data to **GPD** (a) and **Regge** (b) models
- Data show better agreement with Regge models
- Implies **hard/soft factorization** not valid for $Q^2 \leq 5.5$ 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





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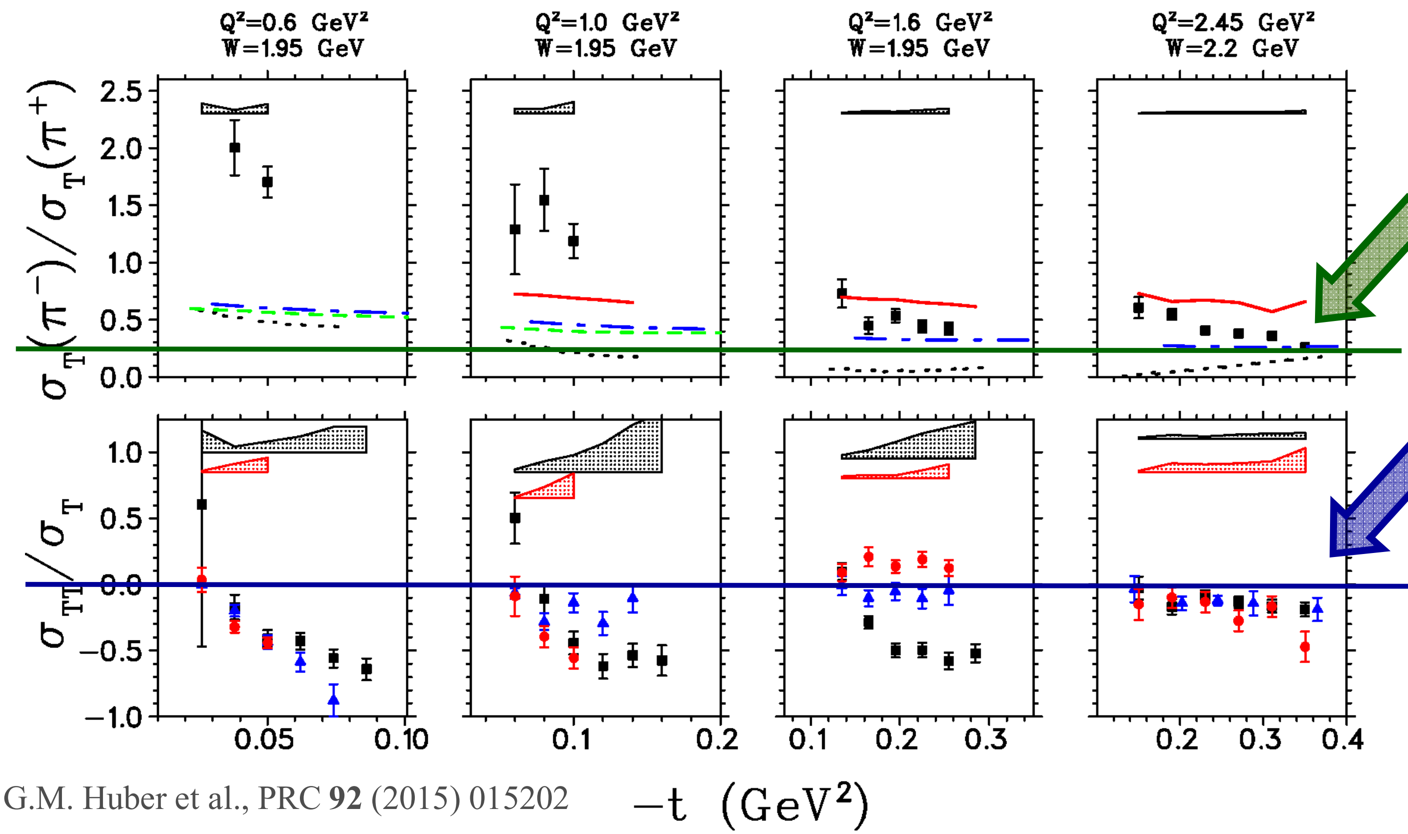
Letter

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. Androic [i], W. Armstrong [j k], A. Bandari [l], V. Berdnikov [c], H. Bhatt [m], D. Bhetuwal [m], D. Biswas [n], M. Boer [j], P. Bosted [l], E. Brash [o], A. Camsonne [b], J.-P. Chen [b], J. Chen [l], M. Chen [p], M.E. Christy [n], 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-Colthirst [n], W.B. Li [l 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 ¼ as –t increases:**
  → Is this an indication of Nachtmann's quark charge scaling?
- **-t=0.3 GeV^2 seems too low for this to apply. Might indicate the partial cancellation of soft QCD contributions in the formation of the ratio.**



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

^{2}H(e,e'π^+)nn ^{2}H(e,e'π^-)pp ^{1}H(e,e'π^+)n

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.

PionLT analysis in progress: K Ramage, N. Sadoun

Garth Huber, huberg@uregina.ca

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

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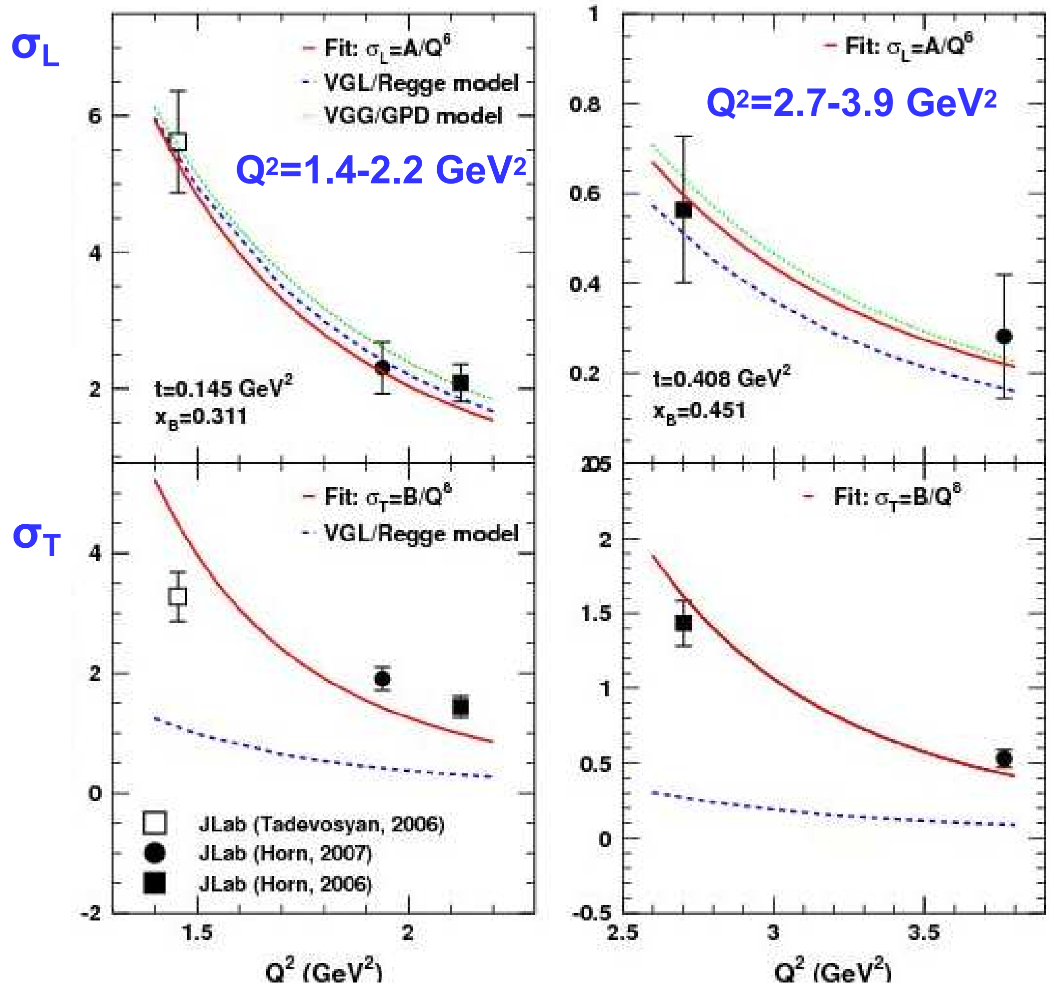
- One of most stringent tests of factorization is Q^2 dependence of π^+ electroproduction cross sections
  - σ_L scales to leading order as Q^{-6}
  - As Q^2 becomes large: $\sigma_L \gg \sigma_T$
- JLab 6 GeV σ_L data is consistent with Q^{-6} QCD scaling
  - Limited Q^2 coverage and large uncertainties 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

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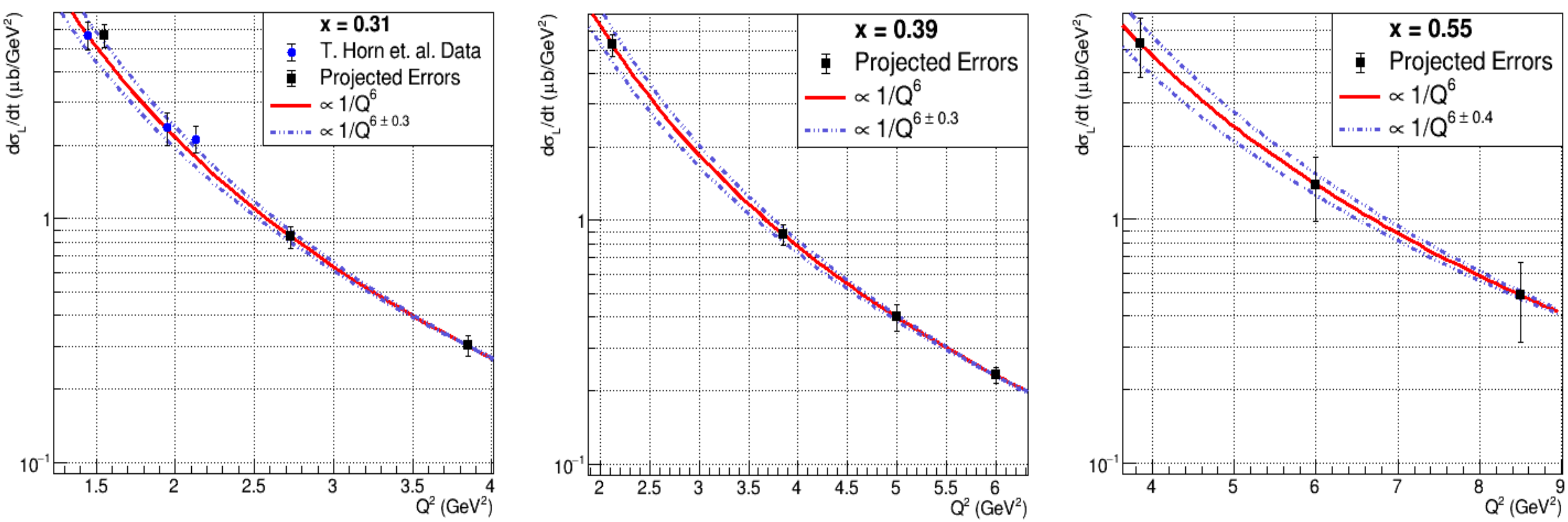
Testing Factorization: 12 GeV $p(e,e'\pi^+)n$

- 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

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Summary

- 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 dσ/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

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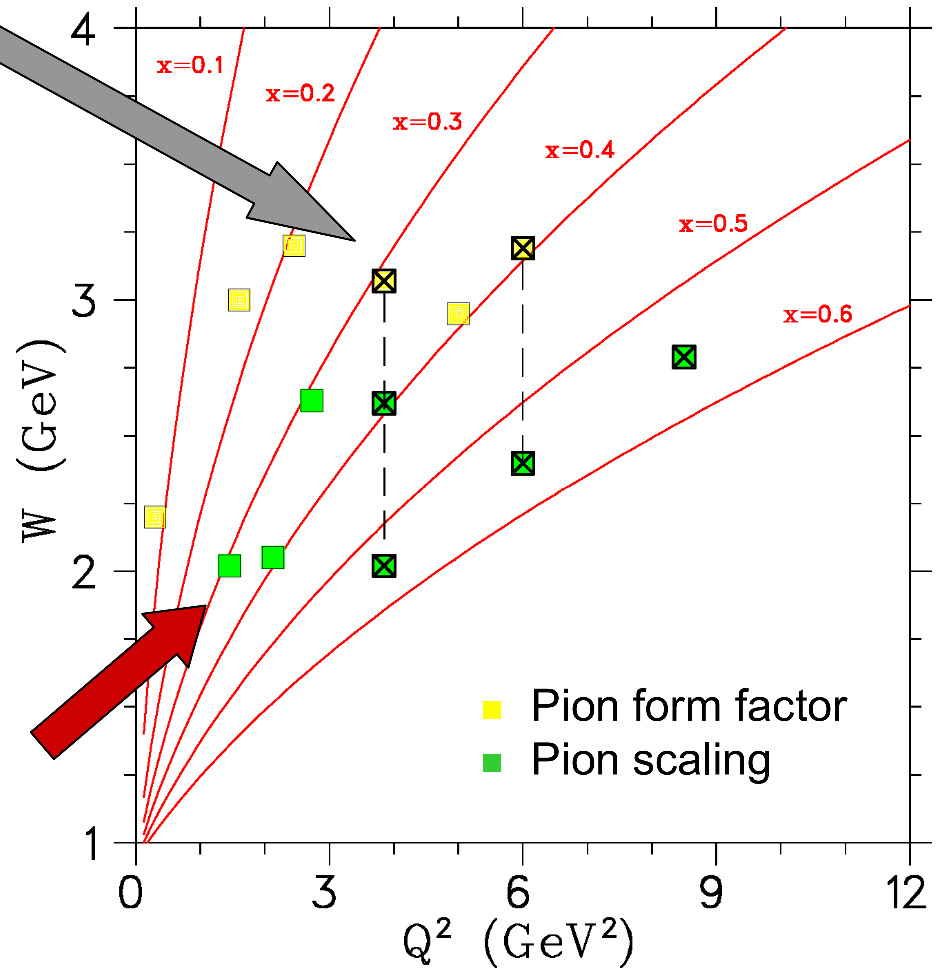
PionLT Optimized Run Plan

Points along vertical lines allow F_π values at different distances from pion pole, to check model properly accounts for:

- **π^+ production mechanism**
- **spectator nucleon**
- **off-shell (*t*–dependent) effects**

Points along red curves allow $1/Q^n$ scaling tests at fixed x_B



For more details, visit Pion-LT RedMine: https://redmine.jlab.org/projects/hall-c/wiki/

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L/T–separation error propagation

Error in $d\sigma_L/dt$ is magnified by $1/\Delta\varepsilon$, where $\Delta\varepsilon=(\varepsilon_{Hi}-\varepsilon_{Low})$

→ To keep magnification factor <5x, need $\Delta\varepsilon>0.2$, preferably more!

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

$$\frac{\Delta\sigma_L}{\sigma_L}=\frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{(R+\varepsilon_1)^2+(R+\varepsilon_2)^2}\qquad \text{where } R=\frac{\sigma_T}{\sigma_L}$$

$$\frac{\Delta\sigma_T}{\sigma_T}=\frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{\varepsilon_1^{\,2}\left(1+\frac{\varepsilon_2}{R}\right)^2+\varepsilon_2^{\,2}\left(1+\frac{\varepsilon_1}{R}\right)^2}$$

The relevant quantities for F_π extraction are R and $\Delta\varepsilon$

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

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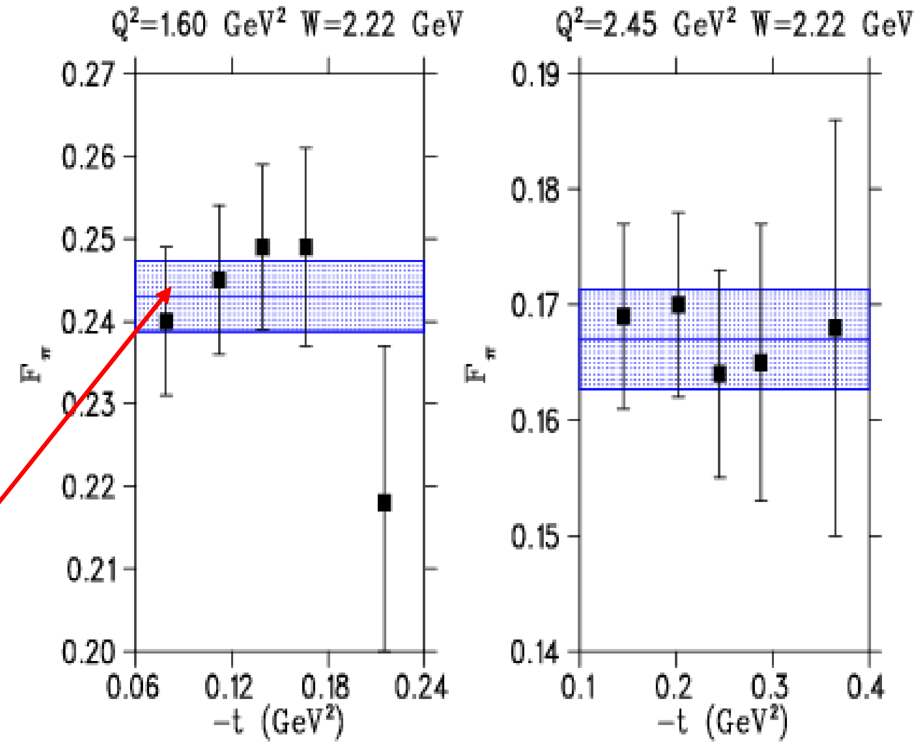
Fπ-2 VGL $p(e,e'\pi^+)n$ model check

- To check whether VGL Regge model properly accounts for:
  - π^+ production mechanism.
  - spectator nucleon.
  - other off-shell (*t*-dependent) effects.

  extract F_π values for each *t*-bin separately, instead of one value from fit to all *t*-bins.

Error band based on fit to all *t*-bins.



G.M. Huber, et al., PRC **78** (2008) 045203

Only statistical and t-uncorrelated systematic uncertainties shown.

- Deficiencies in model may show up as *t*-dependence in extracted $F_\pi(Q^2)$ values.
- Resulting F_π values are insensitive (<2%) to *t*-bin used.
- Lends confidence in applicability of VGL model to the kinematical regime of the JLab data, and the validity of the extracted $F_\pi(Q^2)$ values.

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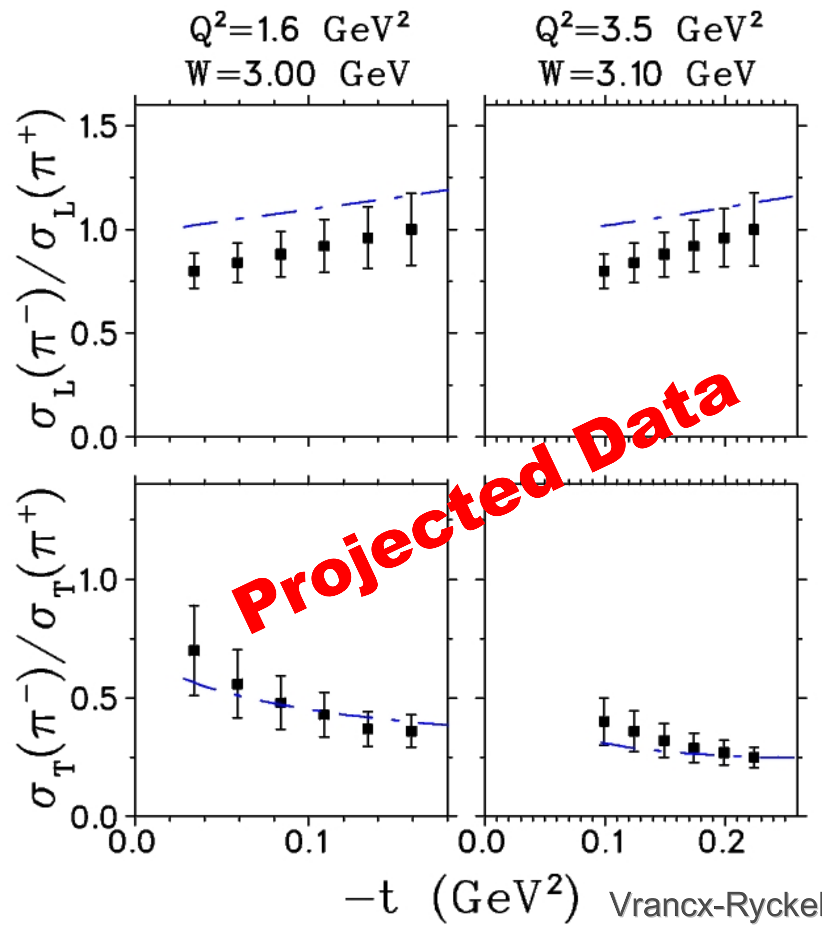
Verify that σ_L is dominated by *t*-channel process

- π^+ *t*-channel diagram is purely isovector.
- Measure

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

using a deuterium target.

- Isoscalar backgrounds (such as $b_1(1235)$ contributions to the *t*-channel) will dilute the ratio.
- We will do the same tests at Q^2=1.60, 3.85, 6.0 GeV².



Vrancx-Ryckebusch Regge+DIS Model [PRC **89**(2014)025203]

Because one of the many problems encountered by the historical data was isoscalar contamination, this test will increase the confidence in the extraction of $F_\pi(Q^2)$ from our σ_L data.

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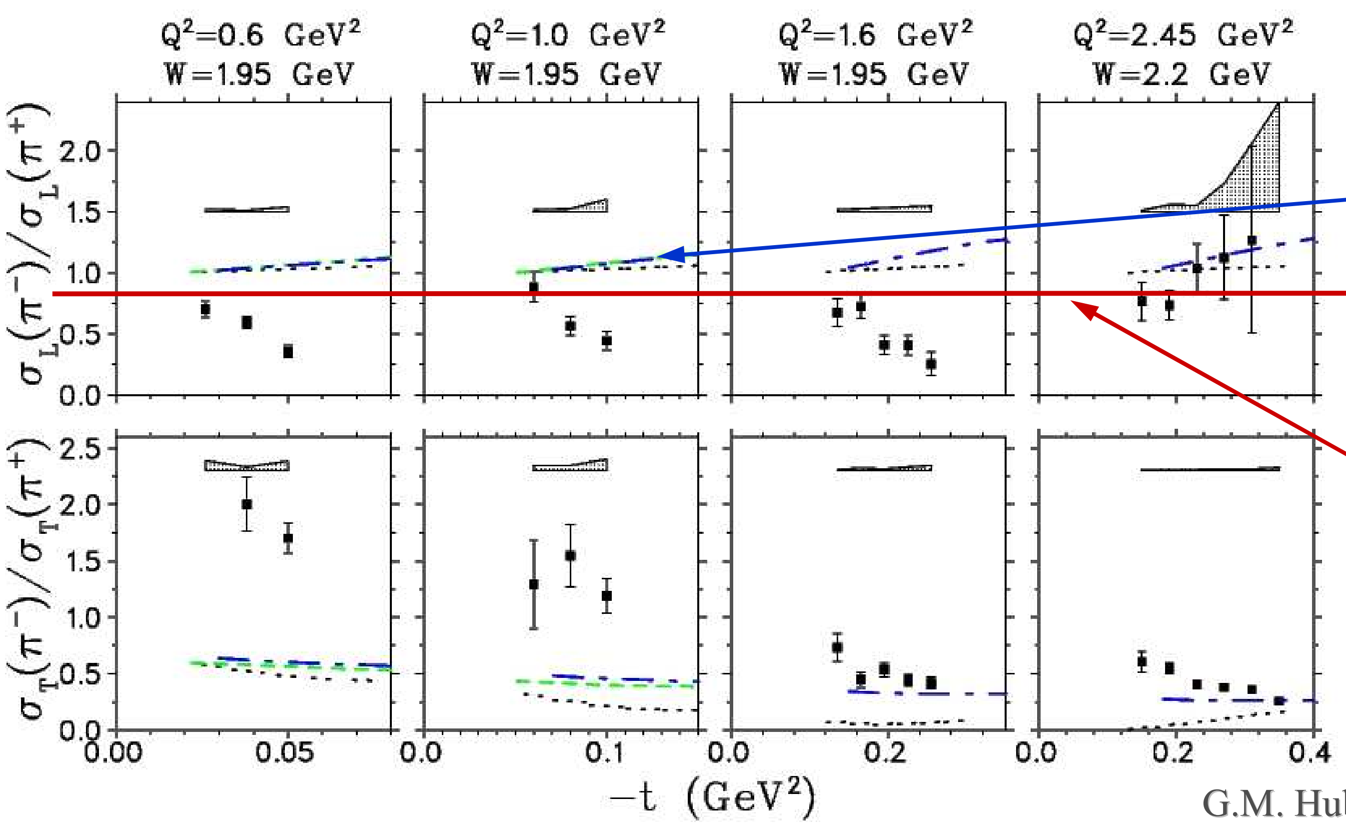
π^-/π^+ data to check *t*-channel dominance

- 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 (such as $b_1(1235)$ contributions to *t*-channel) will dilute ratio.

- **Qualitatively in agreement with our F_π-1 analysis:**
  - We found evidence for small additional contribution to σ_L at W=1.95 GeV not taken into account by the VGL model.
- We found no evidence for this contribution at W=2.2 GeV.



Vrancx-Ryckebusch Model:

- VR extend VGL with hard DIS process of virtual photons off nucleons.

[PRC **89**(2014)025203]

***R*$_L$=0.8 consistent with $|A_S/A_V|$<6%.**

G.M. Huber, et al., PRL **112** (2014) 182501

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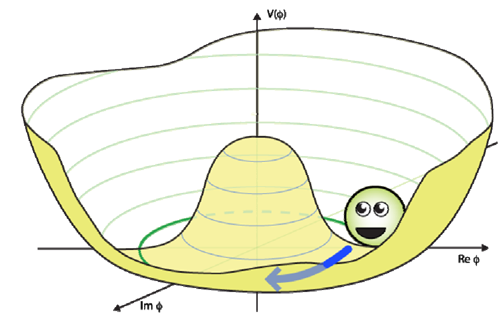
The Pion as a Goldstone Boson

- A remarkable feature of QCD is Dynamical Chiral Symmetry Breaking (DCSB) because it cannot be derived directly from the Lagrangian and is related to nontrivial nature of QCD vacuum.
  - Explicit symmetry breaking, which is put in "by hand" through finite quark masses, is quite different.
- DCSB is now understood to be one of the most important emergent phenomena in the Standard Model, responsible for generation of >98% baryonic mass.



- **Two important consequences of DCSB:**
  1. Valence quarks acquire a dynamical or constituent quark mass through their interactions with the QCD vacuum.
  2. The pion is the spin-0 boson that arises when Chiral Symmetry is broken, similar to how Higgs boson arises from Electroweak Symmetry Breaking.

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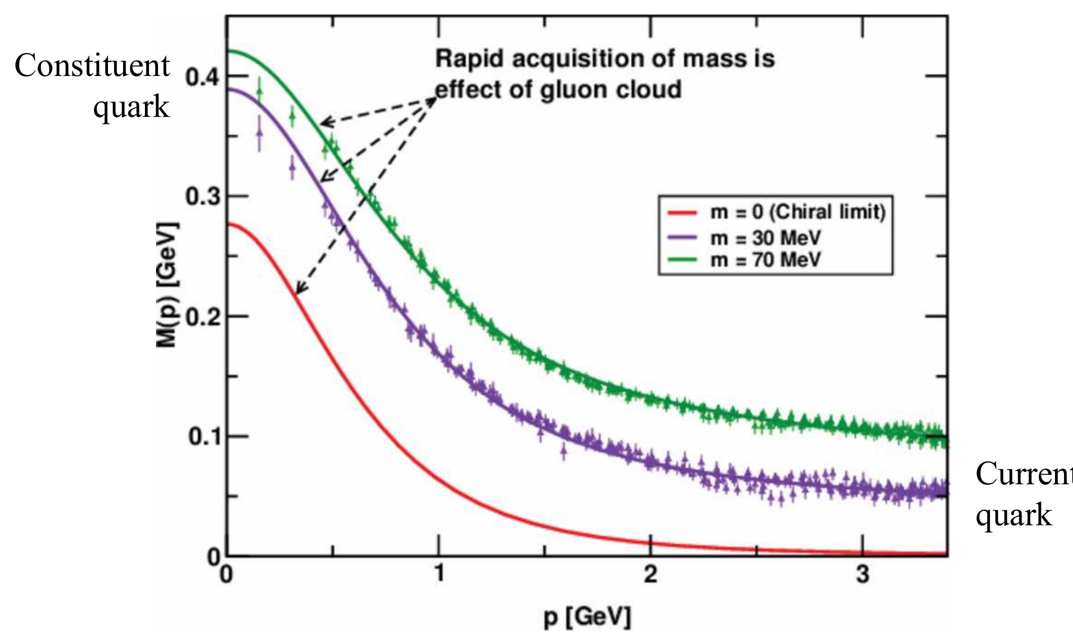
Recent Theoretical Advances

Amazing progress in the last few years.

- **We now have a much better understanding how Dynamical Chiral Symmetry Breaking (DCSB) generates hadron mass.**
- Quenched lattice–QCD data on the dressed–quark wave function were analyzed in a Bethe–Salpeter Equation framework by Bhagwat, et al.
- For the first time, the evolution of the current–quark of pQCD into constituent quark was observed as its momentum becomes smaller.

- The constituent–quark mass arises from a cloud of low–momentum gluons attaching themselves to the current quark.
- **This is DCSB:** an essentially non-perturbative effect that generates a quark *mass from nothing*: namely, it occurs even in the chiral (m=0) limit.



M.S. Bhagwat, et al., PRC **68** (2003) 015203.
L. Chang, et al., Chin.J.Phys. **49** (2011) 955.

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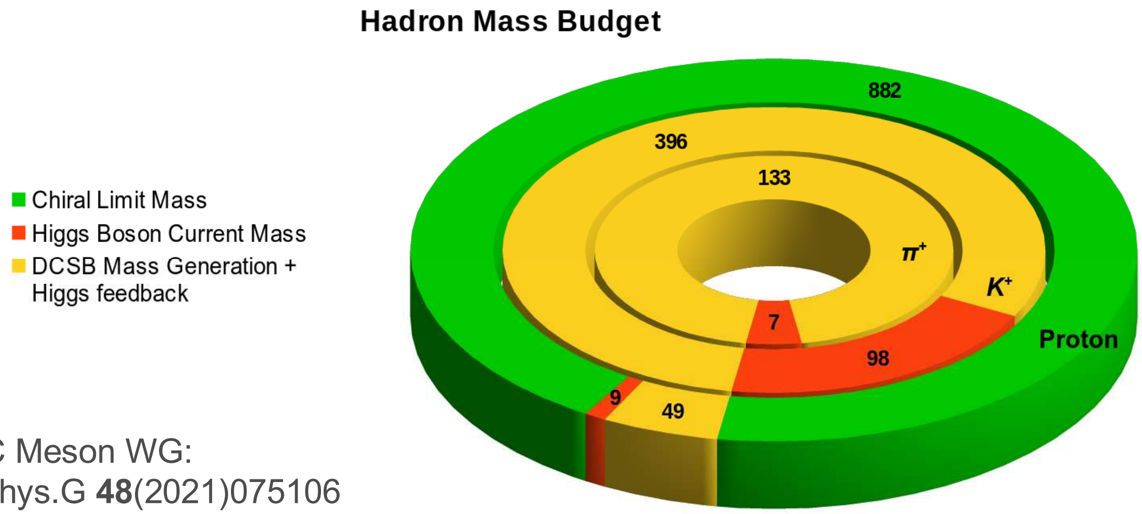
Contrasts in Hadron Mass Budgets



EIC Meson WG:
J.Phys.G **48**(2021)075106

Stark Differences between proton, K^+, π^+ mass budgets

- Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit).
- Conversely, and yet still due to EHM and DCSB, *K* and π are massless in chiral limit (i.e. they are Goldstone bosons).
- The mass budgets of these crucially important particles demand interpretation.
- Equations of QCD stress that any explanation of the proton's mass is incomplete, unless it simultaneously explains the light masses of QCD's Goldstone bosons, the π and *K*.

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Synergy: Emergent Mass and π^+ Form Factor

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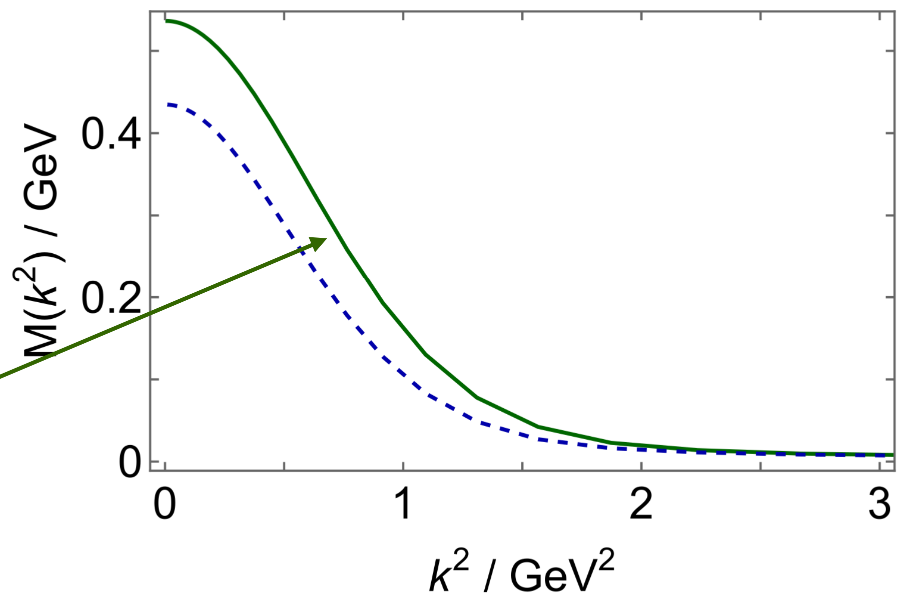
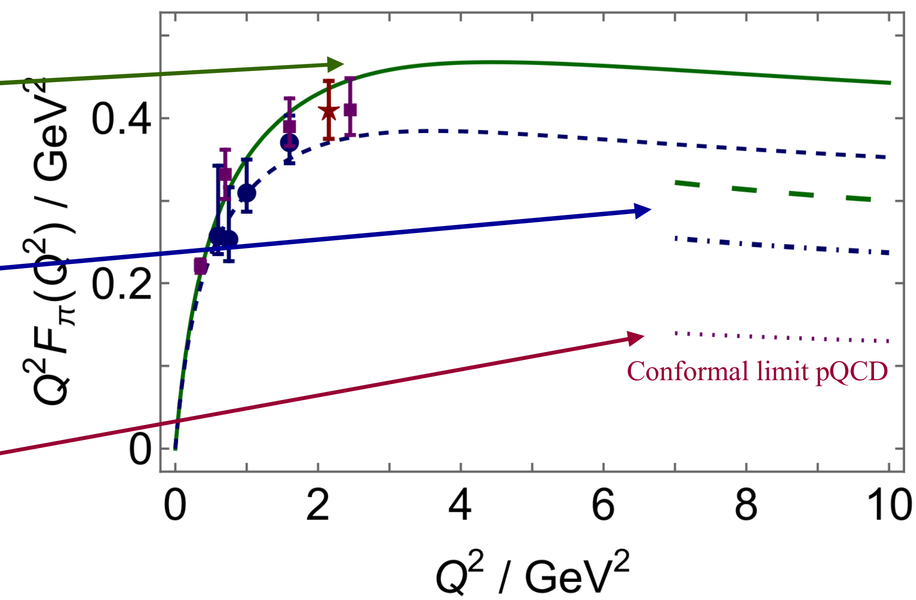
At empirically accessible energy scales, π^+ form factor is sensitive to emergent mass scale in QCD

- **Two dressed–quark mass functions distinguished by amount of DCSB**
  - DCSB emergent mass generation is 20% stronger in system characterized by solid green curve, which is more realistic case
- **$F_\pi(Q^2)$ obtained with these mass functions**
  - r_π=0.66 fm with solid green curve
  - r_π=0.73 fm with solid dashed blue curve
- **$F_\pi(Q^2)$ predictions from QCD hard scattering formula, obtained with related, computed pion PDAs**
- **QCD hard scattering formula, using conformal limit of pion's twist–2 PDA**

$$\phi_\pi^{cl}(x) = 6x(1-x)$$





Chen, et al., PRD **98**(2018)091505(R); Aguilar et al, EPJA **55**(2019)190

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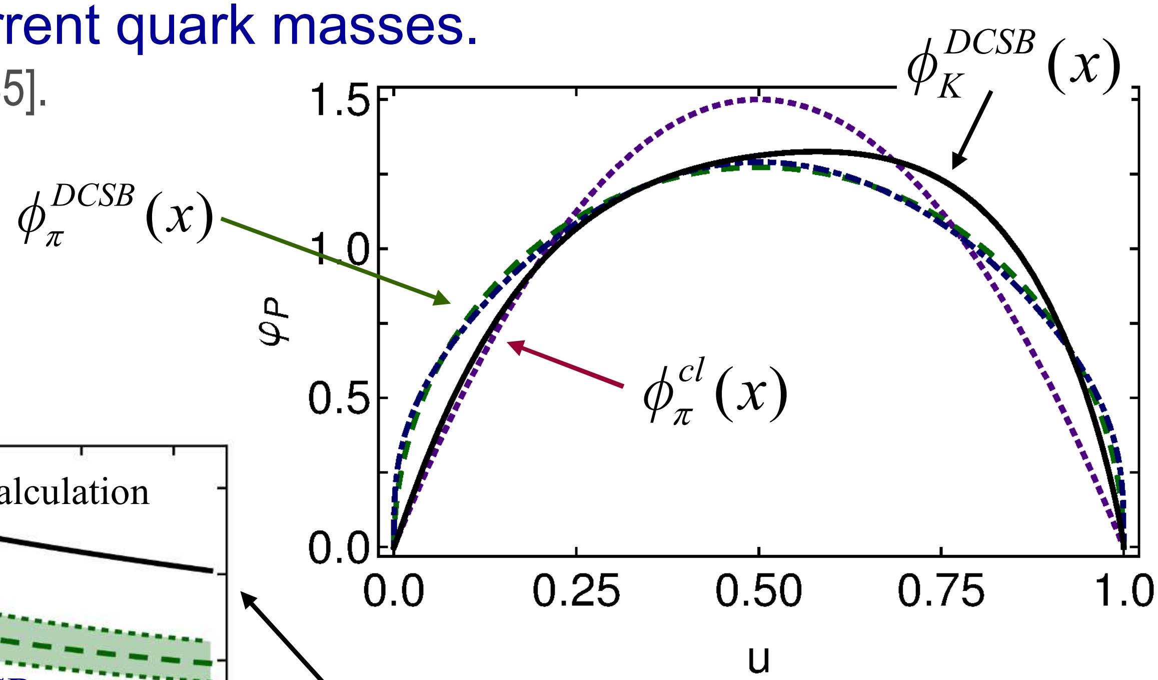
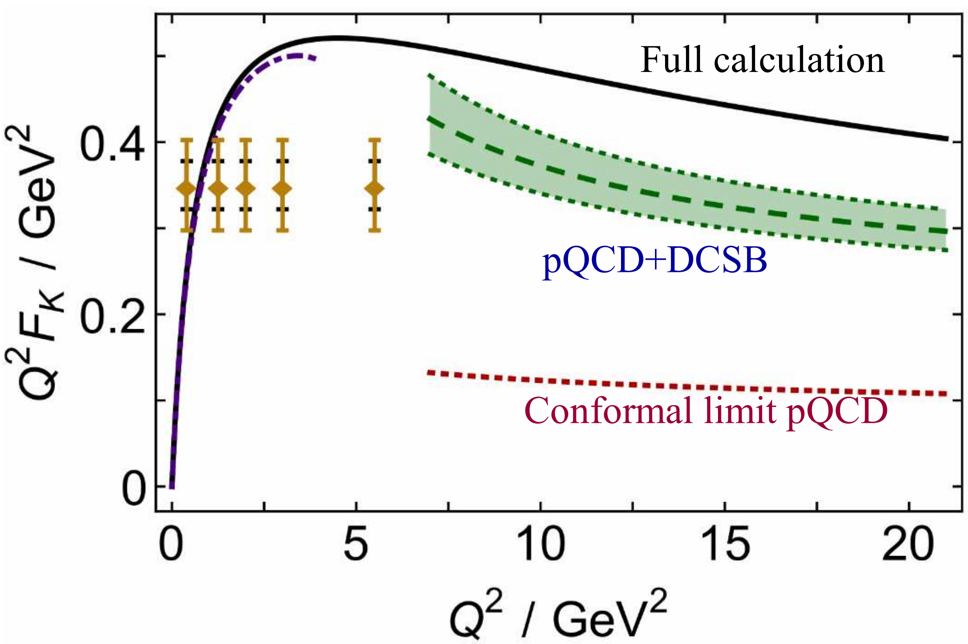
K^+ properties also strongly influenced by DCSB

- **K^+ PDA also is broad, concave and asymmetric.**
- While the heavier s quark carries more bound state momentum than the u quark, the shift is markedly less than one might naively expect based on the difference of u, s current quark masses.
  [C. Shi, et al., PRD **92** (2015) 014035].





- **F_K DCSB model prediction for JLab kinematics**
  [F. Guo, et al., arXiv: 1703.04875].

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The Charged Kaon – a 2nd QCD test case

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π^+ K^+

- In the hard scattering limit, pQCD predicts that the π^+ and K^+ form factors will behave similarly

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \underset{Q^2 \to \infty}{\longrightarrow} \frac{f_K^2}{f_\pi^{\,2}}$$

- It is important to compare the magnitudes and Q^2-dependences of both form factors.

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Kaon Form Factor Experiment Goals

- **Measure the –t dependence of the $p(e,e'K^+)\Lambda,\Sigma^{\circ}$ cross section at fixed Q^2 and W>2.5 GeV to search for evidence of K^+ pole dominance in σ_L**
  - Separate the cross section components: L, T, LT, TT
  - First L/T measurement above the resonance region in K^+ production
- **<u>If warranted by the data</u>, extract the Q^2 dependence of the kaon form factor to shed new light on QCD's transition to quark-gluon degrees of freedom.**

- **<u>Even if we cannot extract the kaon form factor</u>, the measurements are important.**
  - $K^+\Lambda$ and $K^+\Sigma^{\circ}$ reaction mechanisms provide valuable information in our study of hadron structure
  - – Flavor degrees of freedom provide important information for QCD model building and understanding of basic coupling constants

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$p(e,e'K^+)\Lambda(\Sigma^0)$ Experiment

Isolate Exclusive Final States via Missing Mass

$$M_X = \sqrt{(E_{det} - E_{init})^2 - (p_{det} - p_{init})^2}$$

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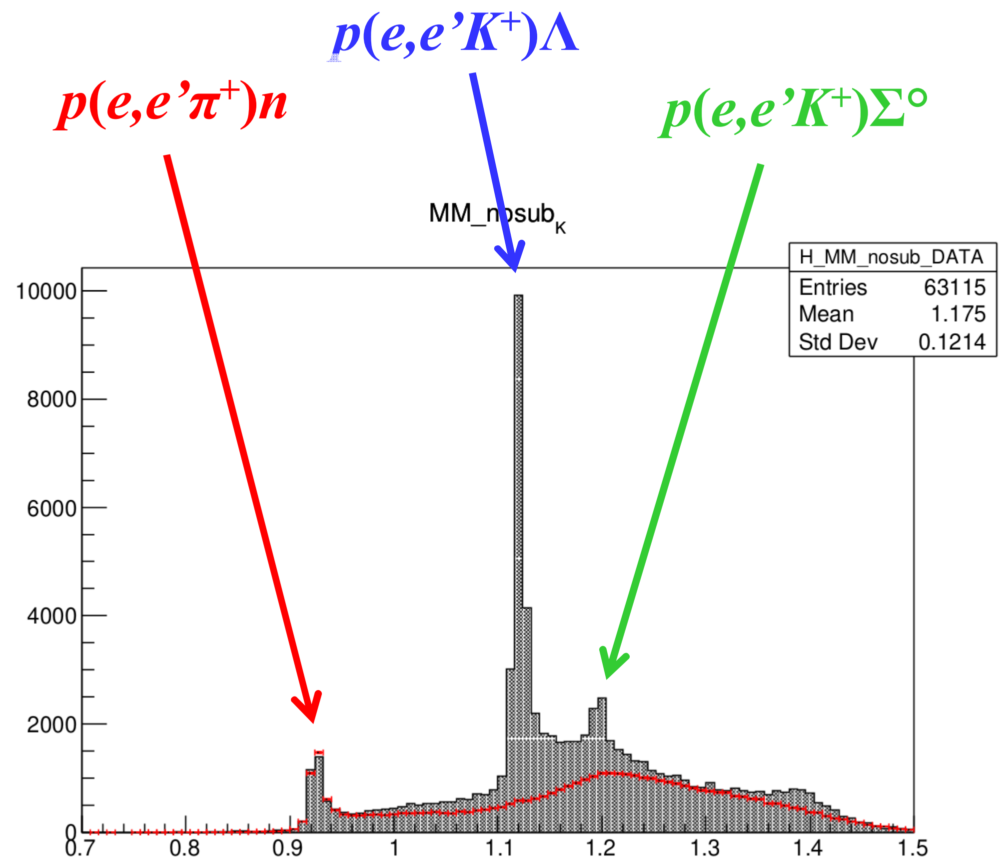
- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and Σ° channels.

- Kaon-pole dominance test through

$$\frac{\sigma_L(\gamma^* p \to K^+\Sigma^0)}{\sigma_L(\gamma^* p \to K^+\Lambda^0)}$$

- Should be similar to ratio of $g^2_{pK\Lambda}/g^2_{pK\Sigma}$ coupling constants if t-channel exchange dominates.



Q^2=3.0 GeV^2 , W=3.14, low ε, θ_{Kq}=+0.0

Plot by Richard Trotta (CUA/Virginia)

Measurement of K^+ Form Factor

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- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon form factor at low Q^2

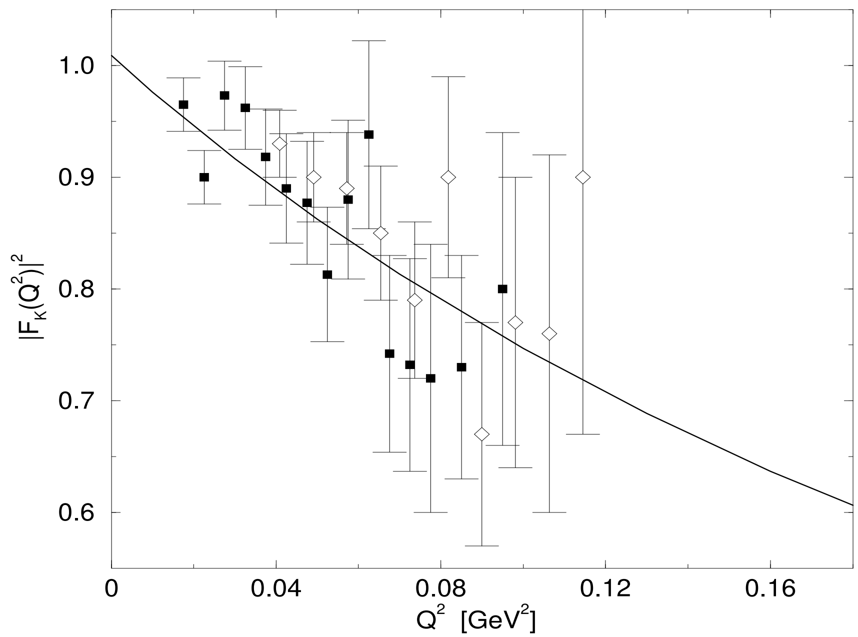
  [Amendolia, et al., PL **B178** (1986) 435]

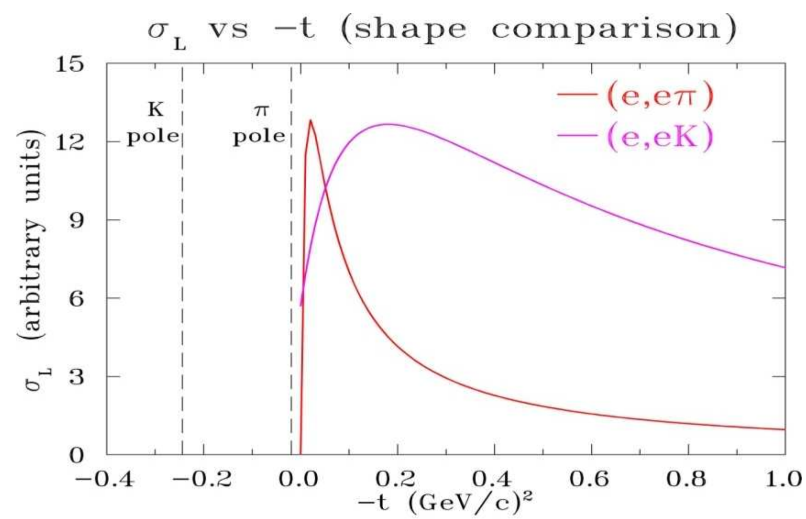
- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)***Λ ?

- Kaon pole further from kinematically allowed region.

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_K^2)} g^2_{K\Lambda N}(t) F_K^2(Q^2,t)$$

- Many of these issues will be explored in JLab E12-09-011.





$p(e,e'K^+)\Lambda(\Sigma^0)$ Experiment Overview

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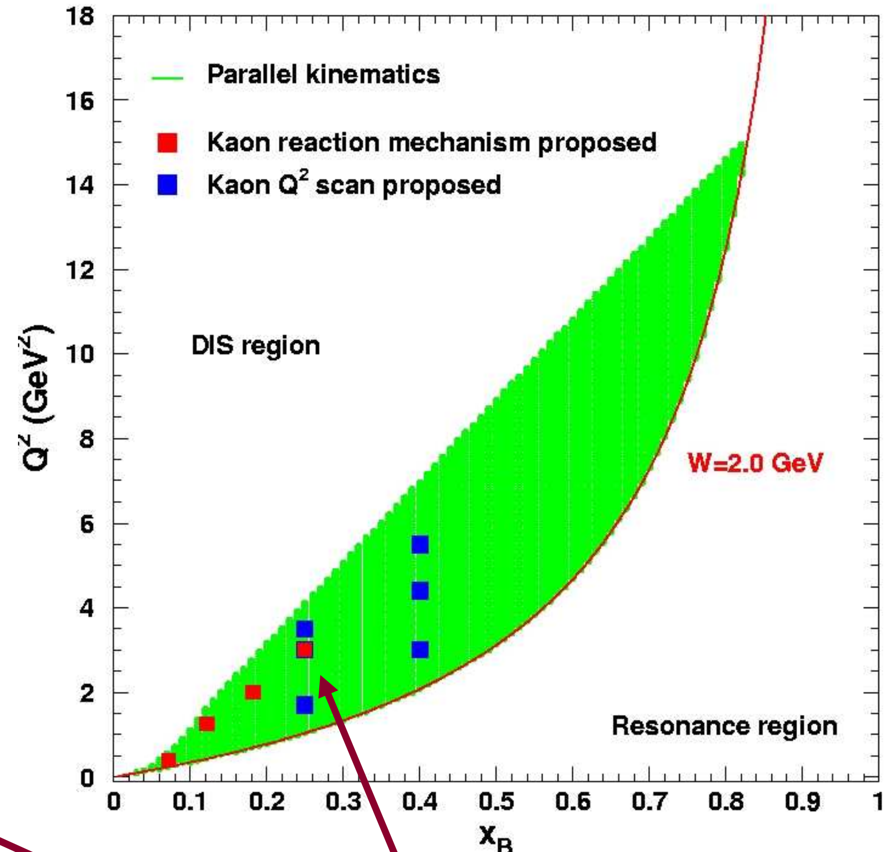
- Measure the separated cross sections at varying $-t$ and x_B
  - If K^+ pole dominates σ_L allows for extraction of the kaon ff (W>2.5 GeV)
- Measure separated cross sections for the $p(e,e'K^+)\Lambda(\Sigma^\circ)$ reaction at two fixed values of $-t$ and x_B
  - Q^2 coverage is a factor of 2-3 larger compared to 6 GeV at much smaller $-t$
  - Facilitates tests of Q^2 dependence even if L/T ratio less favorable than predicted



x	Q^2 (GeV^2)	W (GeV)	-t $(GeV/c)^2$
0.1-0.2	0.4-3.0	2.5-3.1	0.06-0.2
0.25	1.7-3.5	2.5-3.4	0.2
0.40	3.0-5.5	2.3-3.0	0.5

Q^2=3.0 GeV^2 was optimized to be used for both t-channel and Q^{-n} scaling tests

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Projected Uncertainties for K^+ Form Factor

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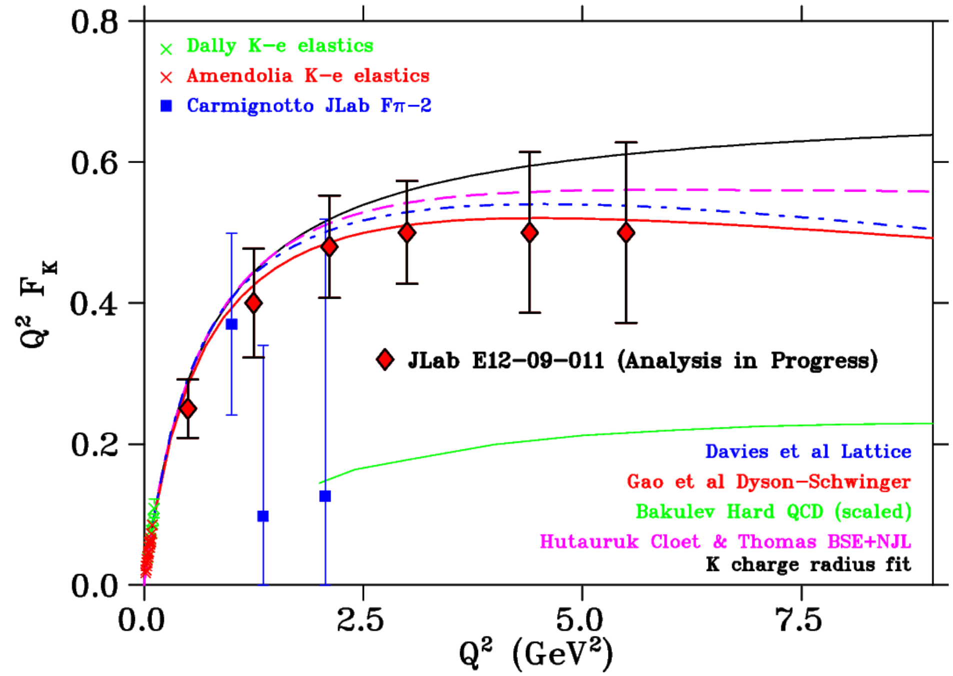
- First measurement of F_K well above the resonance region.
- Measure form factor to Q^2=3 GeV^2 with good overlap with elastic scattering data.
  - Limited by $-t$<0.2 GeV^2 requirement to minimize non–pole contributions.
- Data will provide an important second $q\bar{q}$ system for theoretical models, this time involving a strange quark.

p(e,e'K$^+$)Λ W>2.5 GeV



Extraction of F_K from Q^2>4 GeV^2 data is more uncertain, due to higher $-t_{min}$

- ***Partially completed as an early SHMS commissioning experiment: LT–separation (E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons)***
- ***Data under analysis, expecting final results next year***

— R. Trotta (CUA/Virginia)

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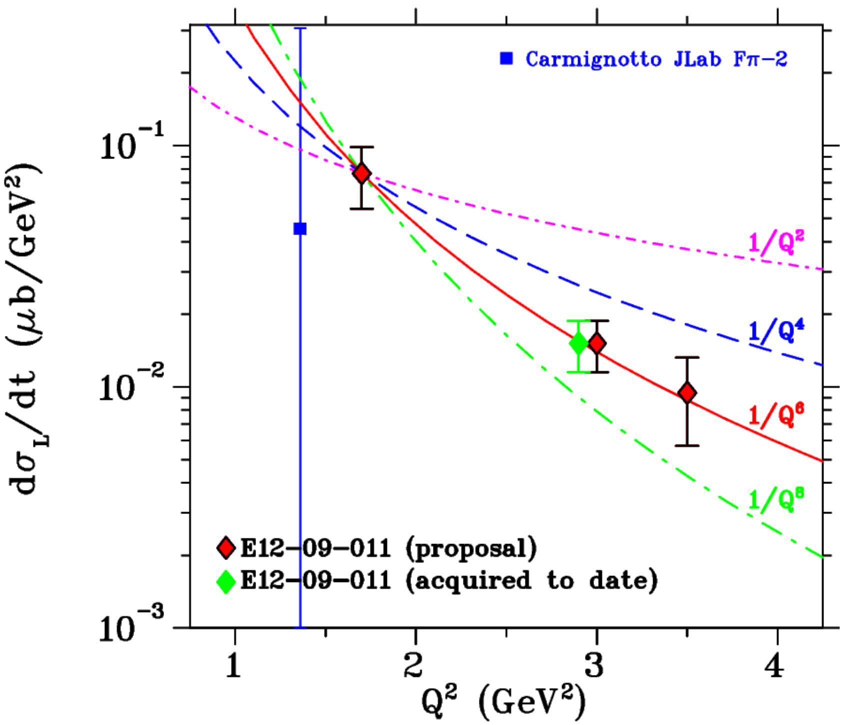
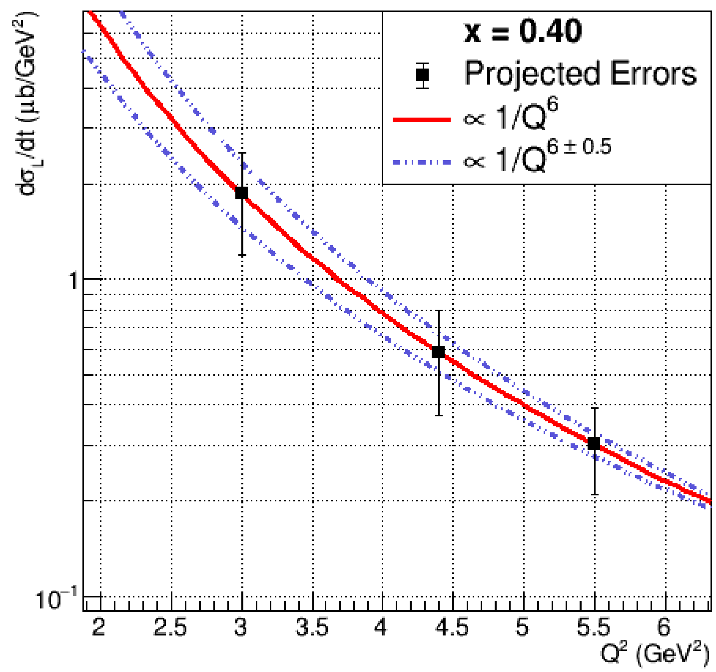
Important 2nd Test: $p(e,e'K^+)\Lambda$

- Experimental validation of onset of hard scattering regime is essential for reliable interpretation of JLab GPD program results
- Is onset of scaling different for kaons than pions?
- K^+ and π^+ together provide quasi model-independent study





$p(e,e'K^+)\Lambda$ Existing ■ and Projected ♦♦■ Data

- E12-09-011 data taking partially completed in 2019
- Data for x_B=0.40 scan in hand. Data for x_B=0.25 scan only partly acquired.
  - Spokespersons: T. Horn, P. Markowitz, GMH

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