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

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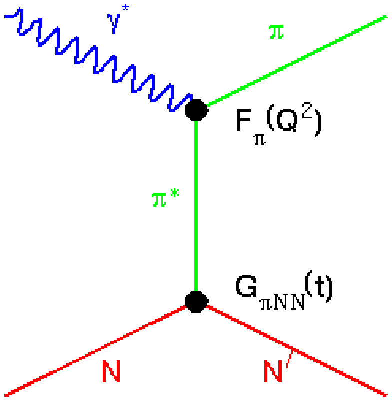
On behalf of the PionLT and KaonLT Collaborations

Towards Improved Hadron Femtography with Hard Exclusive Reactions
ECT* Workshop, Trento, Italy
August 9, 2024

Two Motivations for Studying DEMP

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



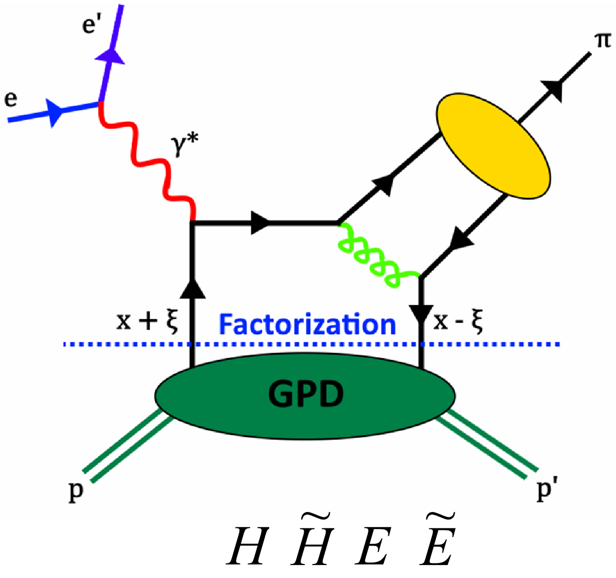
- Indirectly measure F_π using the "pion cloud" of the proton via p(e,e'π^+)n

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

  - Pion pole process dominates σ_L in forward kinematics.
  - Can a similar method be used to determine the kaon form factor?

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 and p(e,e'K$^+$)Λ 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.

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Charged Meson Form Factors

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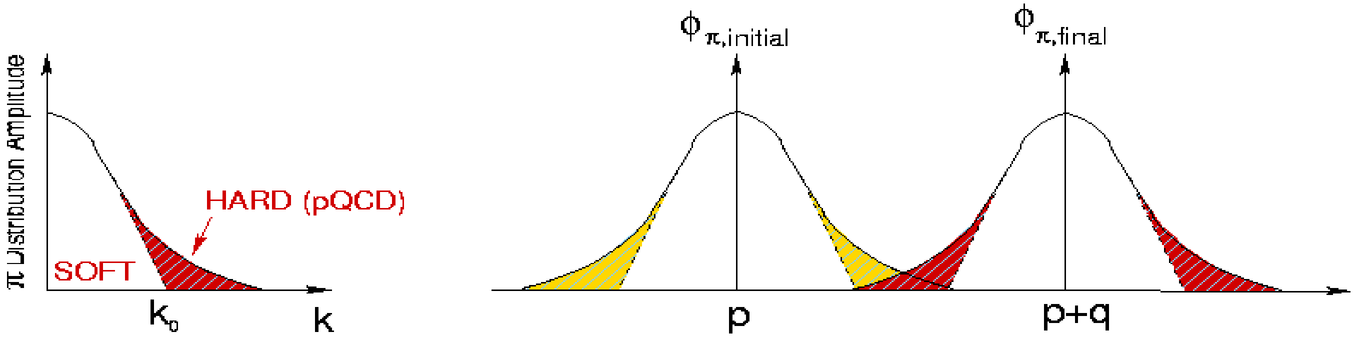
Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

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.

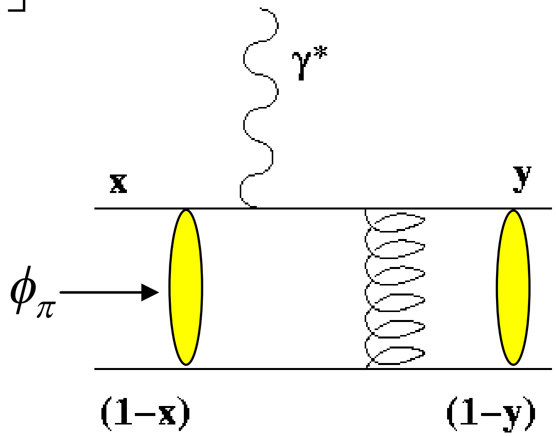
The Pion in perturbative QCD

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

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



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 $\mu\to\infty$.

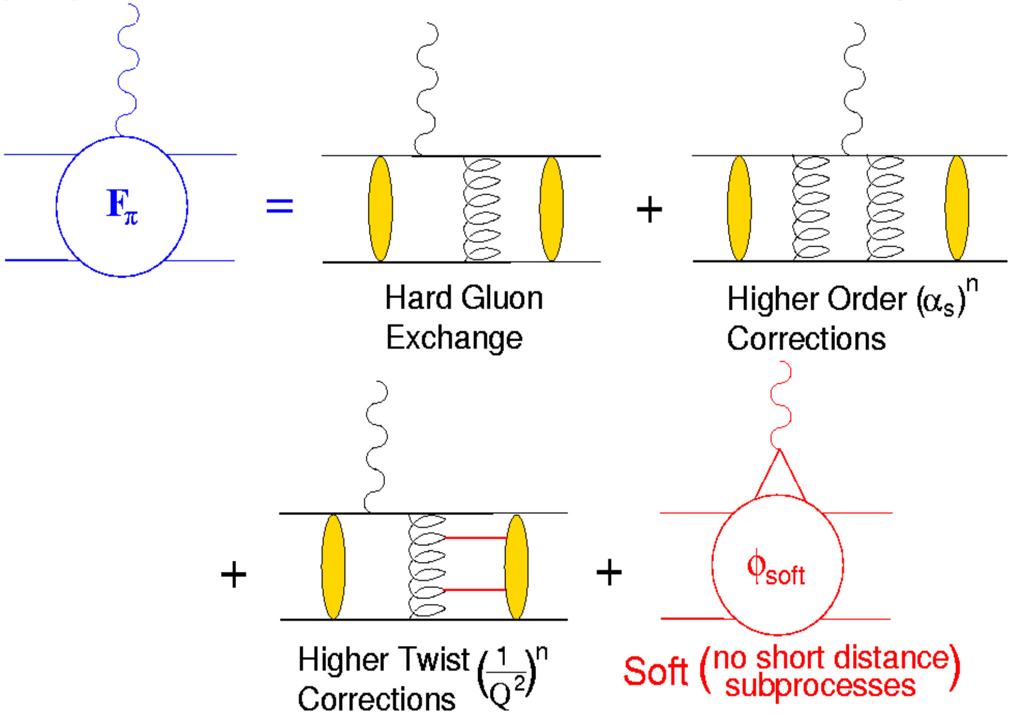
***$Q^2 F_\pi$* should behave like *$\alpha_s(Q^2)$* even for moderately large *Q^2*.**

→ 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.

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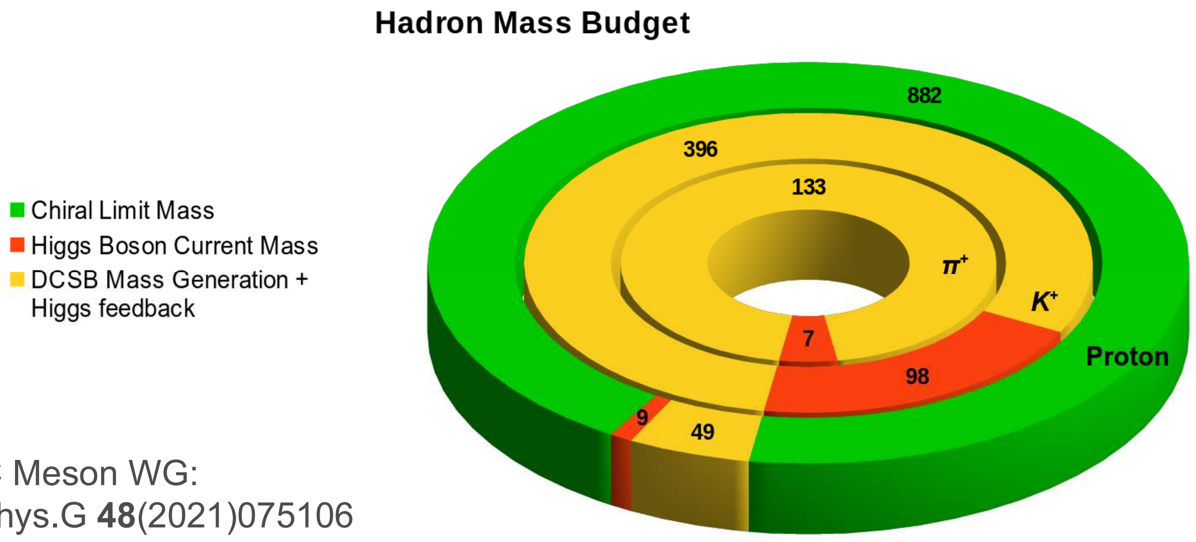
Contrasts in Hadron Mass Budgets



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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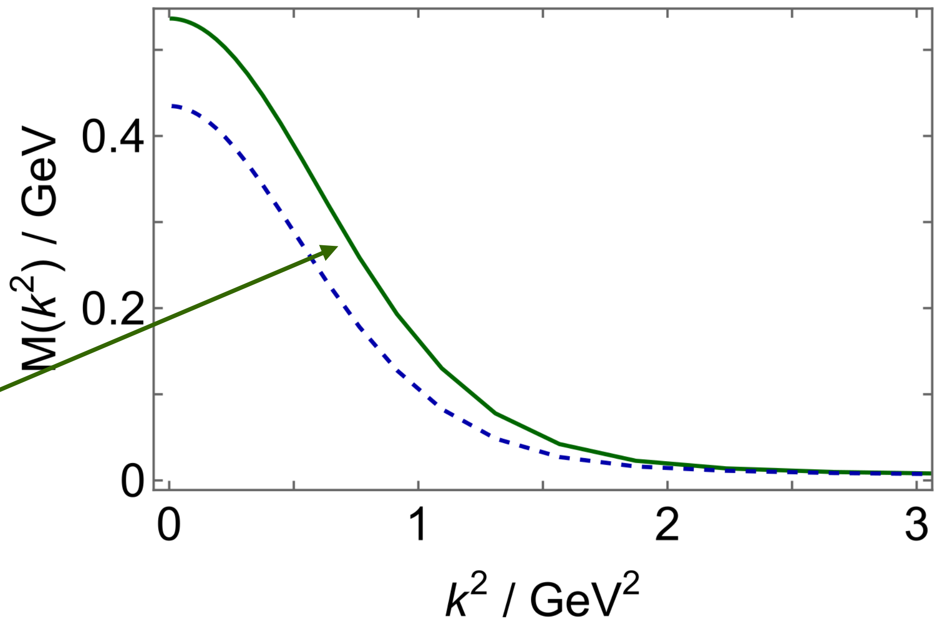
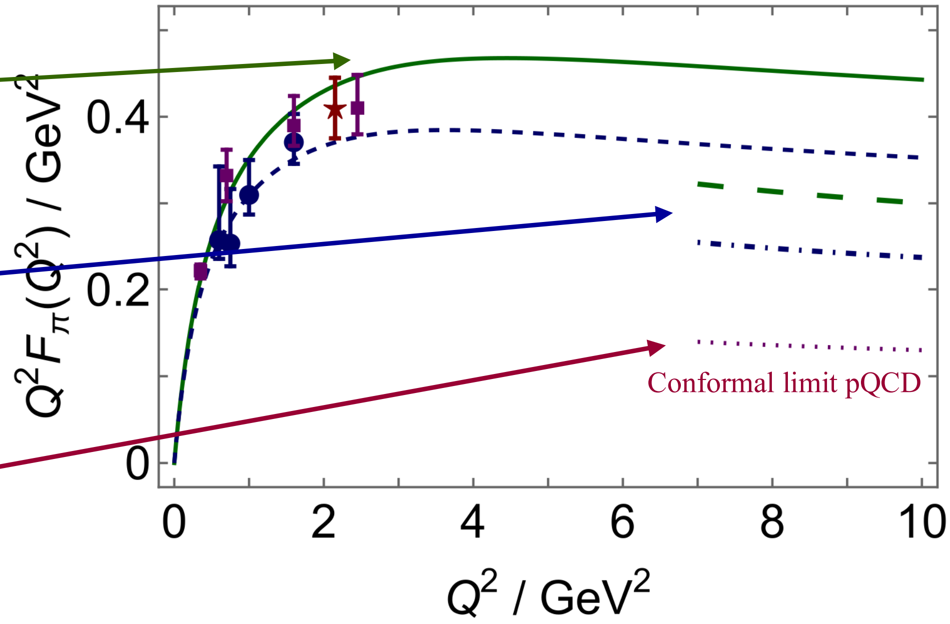
Synergy: Emergent Mass and π^+ Form Factor

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**

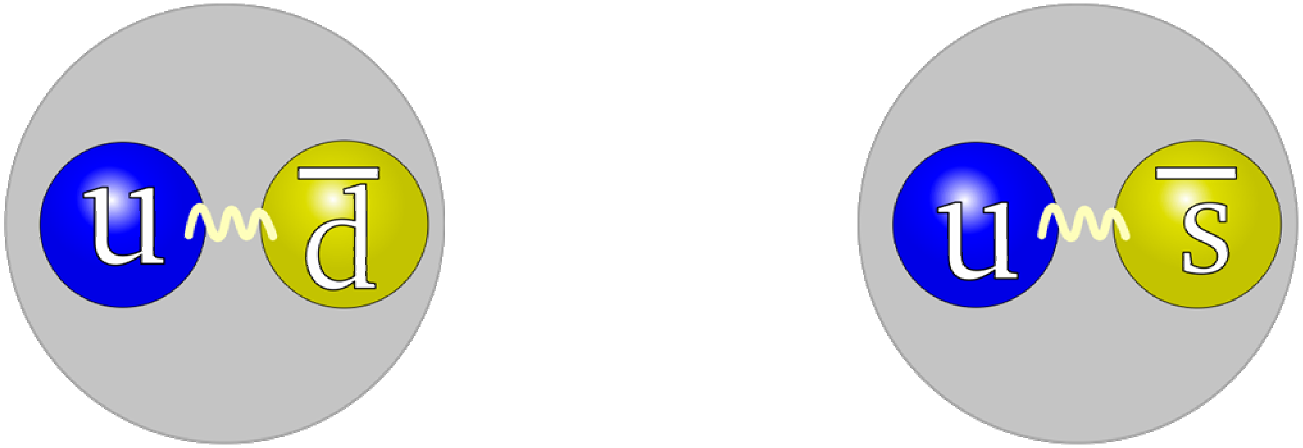
$$\phi_\pi^{cl}(x) = 6x(1-x)$$





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

The Charged Kaon – a 2nd QCD test case



π^+ K^+

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

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \xrightarrow[Q^2\to\infty]{} \frac{f_K^2}{f_\pi^{\,2}}$$

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

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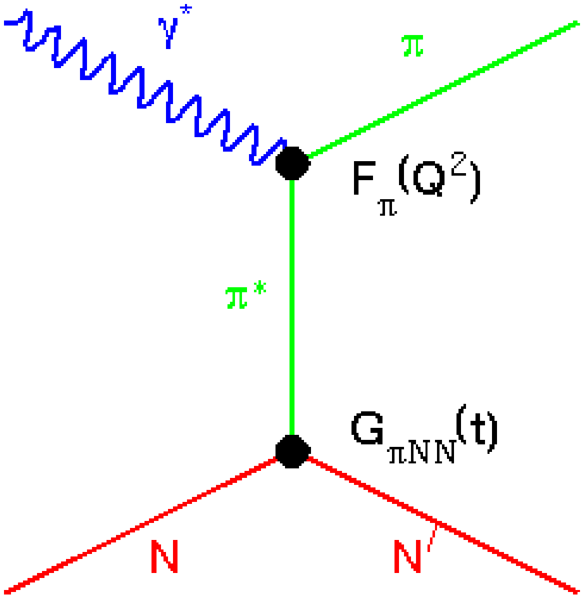
Measurement of π^+ Form Factor – Larger Q^2

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

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

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

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



Drawbacks of this technique
1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.

K^+ pole is further in the unphysical region, uncertainties will be larger

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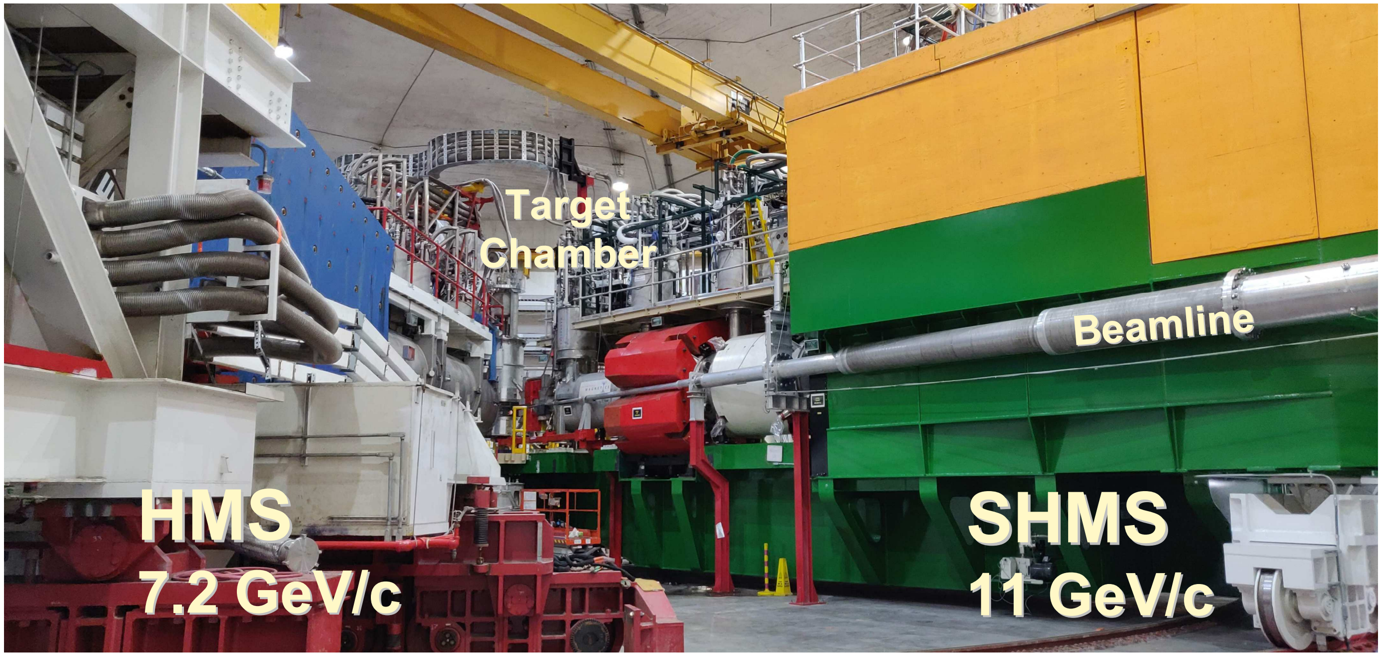
Experimental Issues

- Deep Exclusive Meson Production (DEMP) cross section is small, can exclusive $p(e,e'\pi^+)n$ and $p(e,e'K^+)\Lambda$ channels be cleanly identified?
  - High momentum, forward angle (5.5°) meson detection is required, with good Particle ID to separate π^+, K^+, p
  - Good momentum resolution required to reconstruct crucial kinematics, such as M_{miss}, Q^2, W, t
- Need to measure the longitudinal cross section $d\sigma_L/dt$ needed for form factor extraction



Hall C of Jefferson Lab has been optimized for specifically such studies

p(*e*,*e'*π^+)*n* Event Selection

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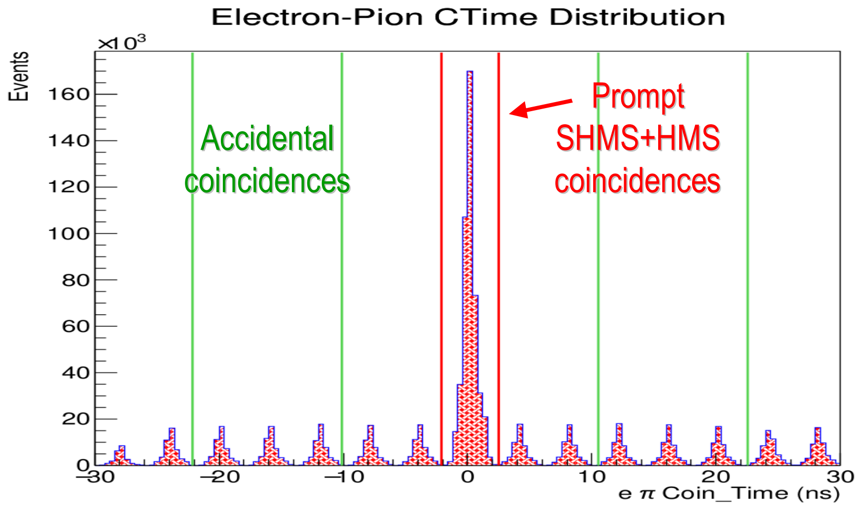
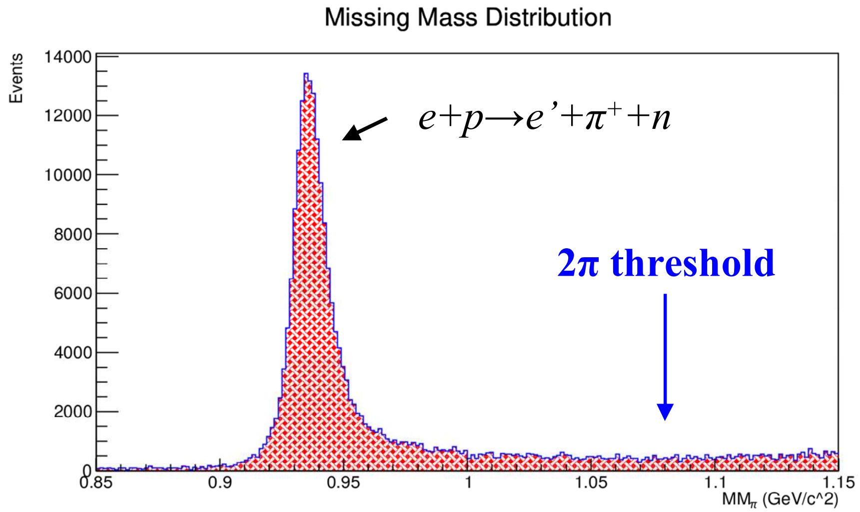
Coincidence measurement between charged pions in SHMS and electrons in HMS

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

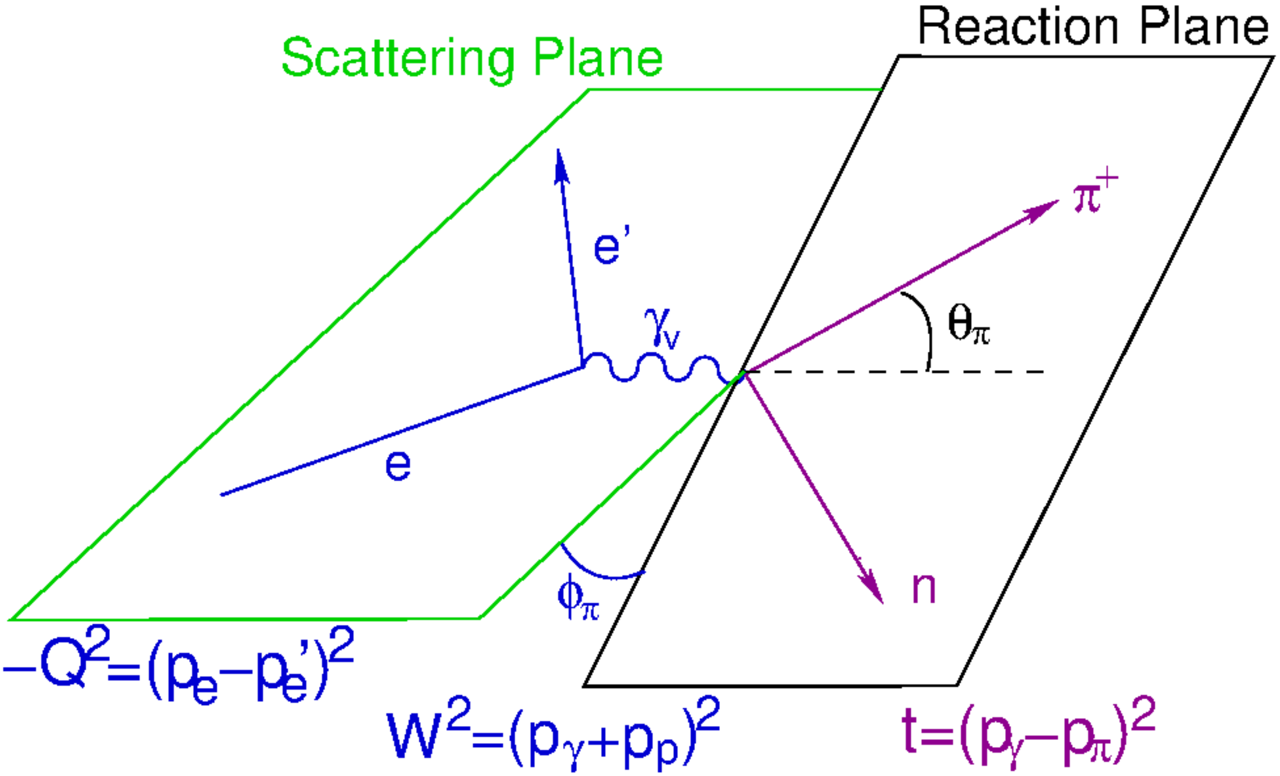
E_{beam}=9.177 GeV, P_{SHMS}=+5.422 GeV/c, θ_{SHMS}= 10.26° (left)

Plots by Muhammad Junaid

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

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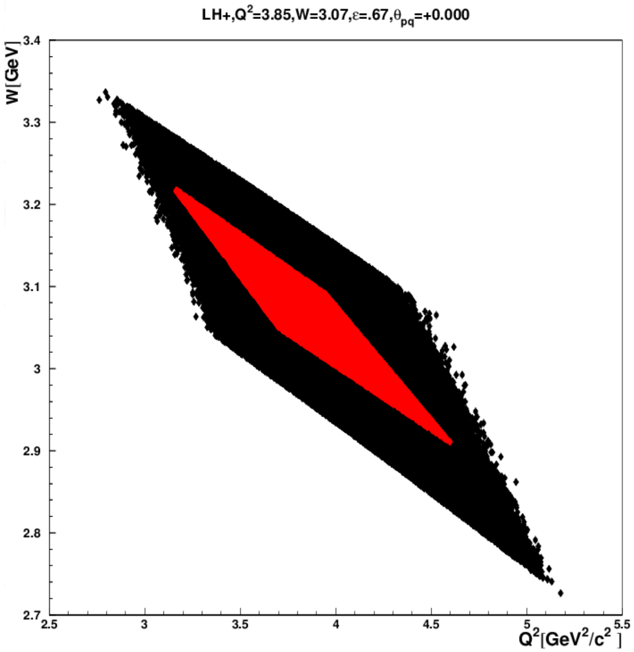
The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos2\phi$$

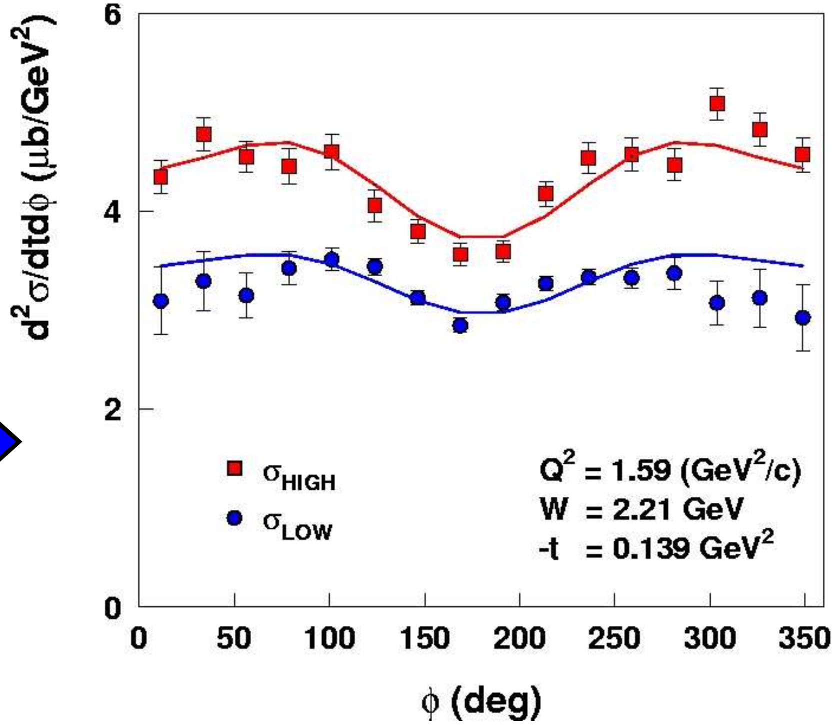


Diamond cuts define common (W,Q^2) coverage at both ε

Simulated SHMS+HMS acceptance at Q^2=3.85, W=3.07

■ High ε=0.67 🟥 Low ε=0.30

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



Fπ-2 data: T. Horn, *et al*, *PRL* **97** (2006)192001

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Extract $F_\pi(Q^2)$ from JLab σ_L data

Model incorporates π^+ production mechanism and spectator neutron effects:

VGL Regge Model:

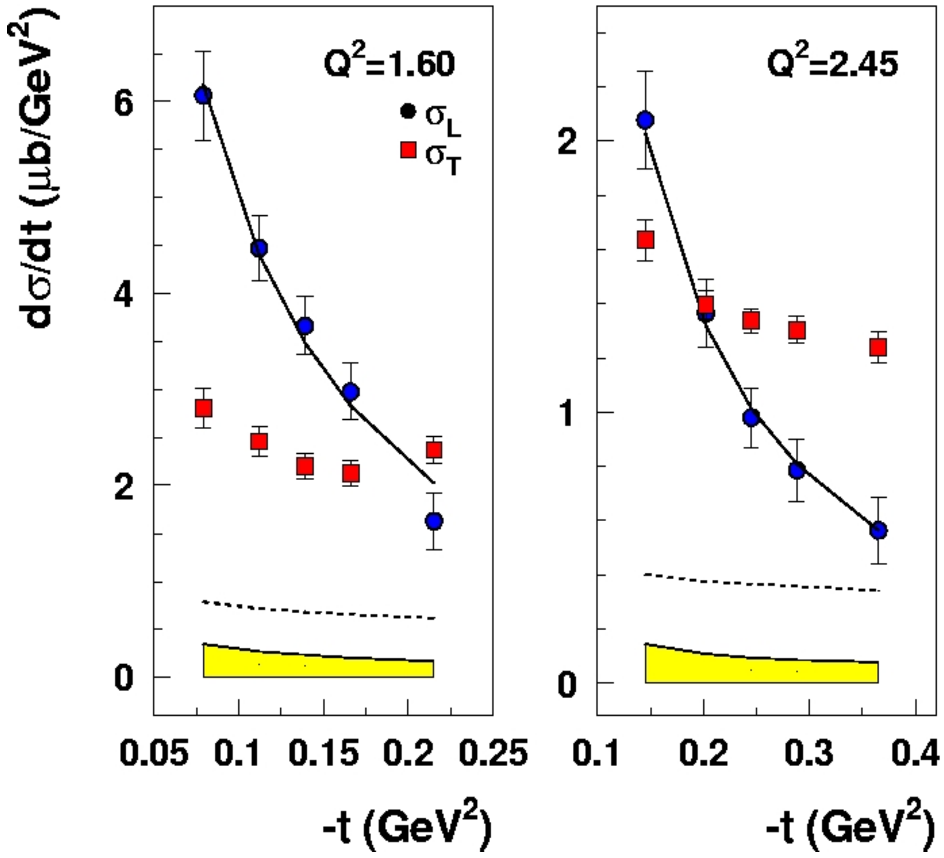
- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$

  replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).

  [Vanderhaeghen, Guidal, Laget, PRC **57**(1998)1454]
- At small –*t*, σ_L only sensitive to F_π

$$\boxed{F_\pi = \frac{1}{1 + Q^2/\Lambda_\pi^2}}$$

Fit to σ_L to model gives F_π at each Q^2



Fπ-2 data: T. Horn et al., PRL **97**(2006)192001.

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature.
Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.

Λ_π^2=0.513, 0.491 GeV², Λ_ρ^2=1.7 GeV².

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Current and Projected F_π Data

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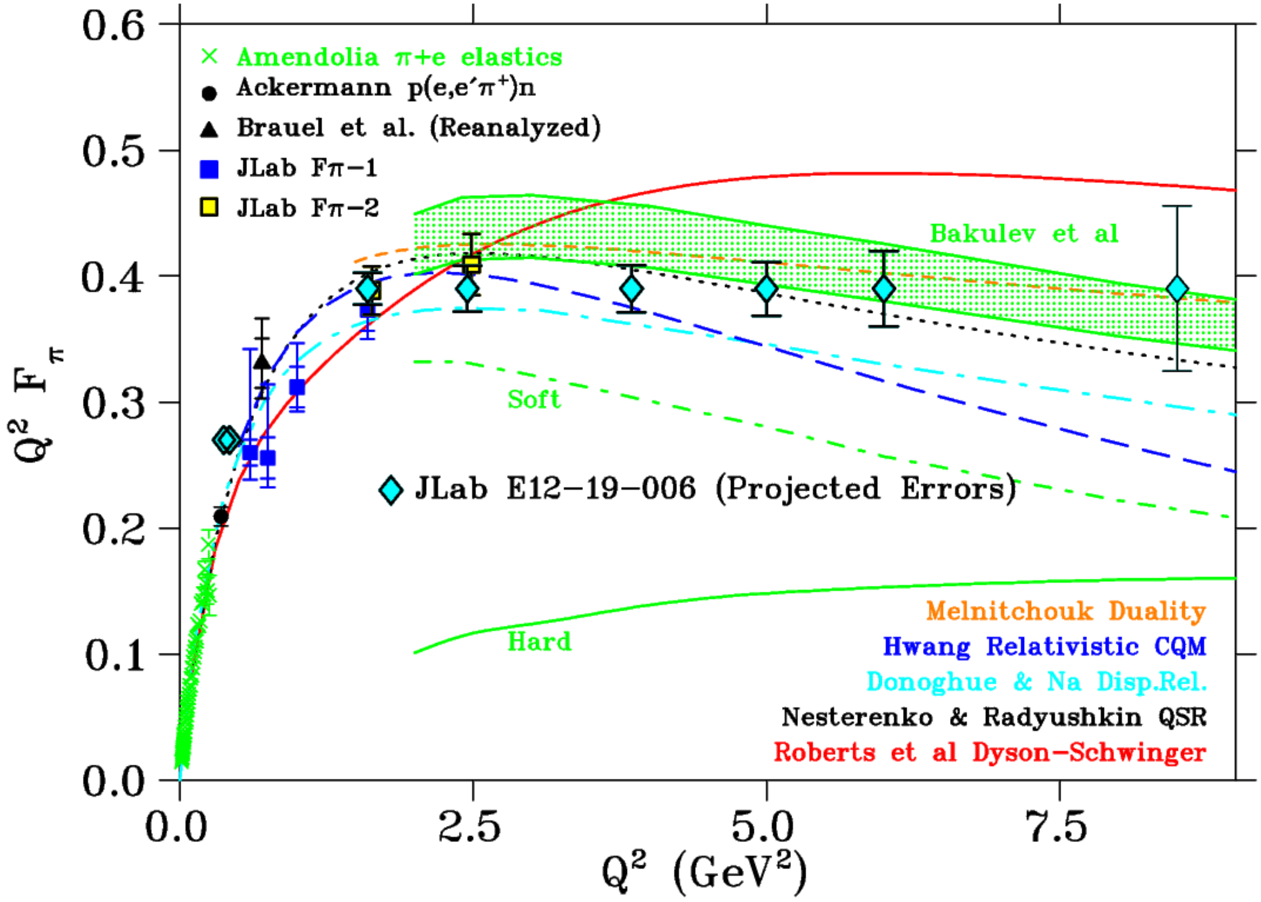
SHMS+HMS will allow measurement of F_π to much higher Q^2

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

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

Isolate Exclusive Final States via Missing Mass

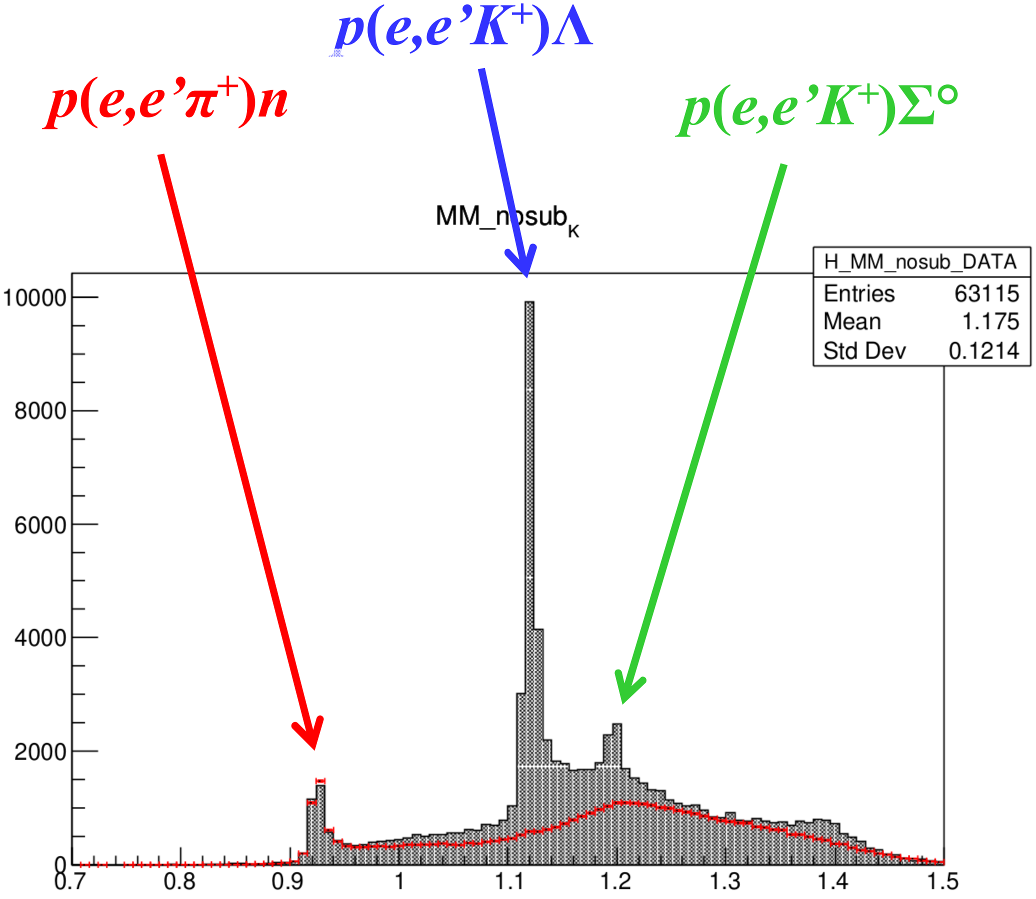
$$M_X = \sqrt{(E_{\det} - E_{init})^2 - (p_{\det} - p_{init})^2}$$

- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and $\Sigma°$ 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)

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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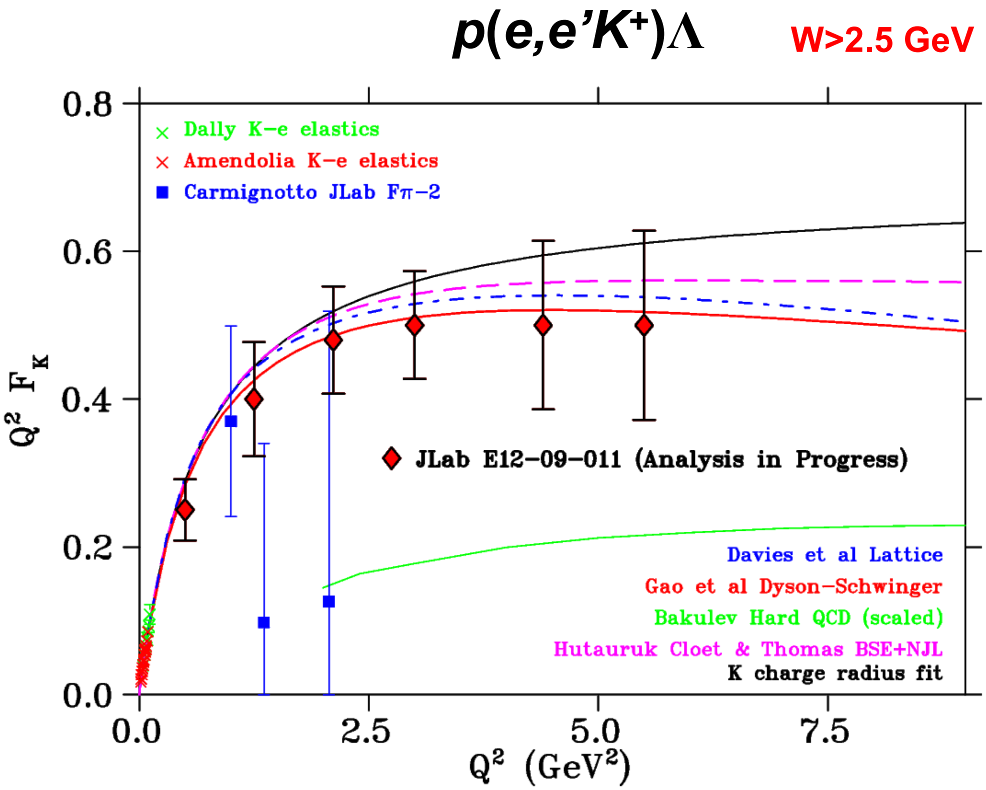
Projected Uncertainties for K^+ Form Factor

- 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.



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

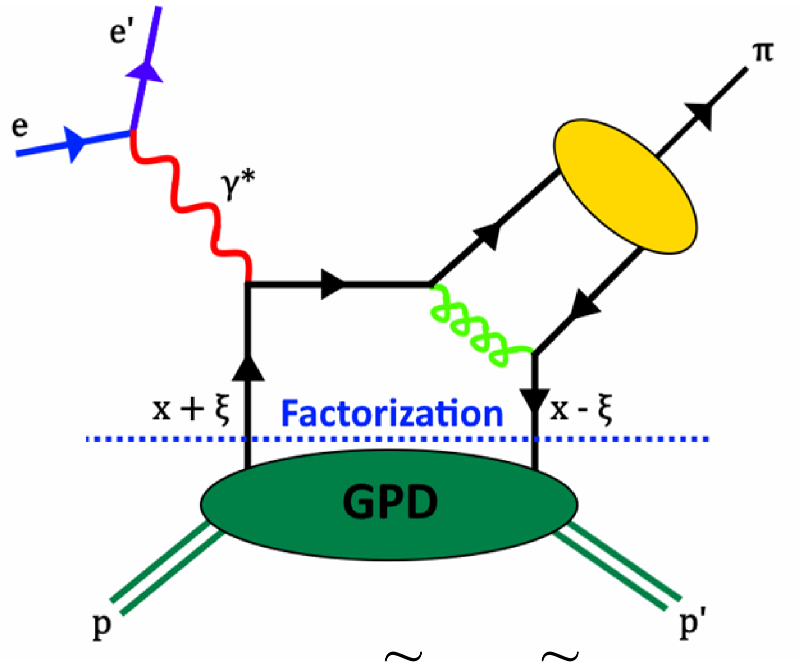
- ***Partially completed as an early SHMS commissioning experiment: LT–separation (E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons)***
- ***Data under analysis, expecting final results next year***

— R. Trotta (CUA/Virginia)

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

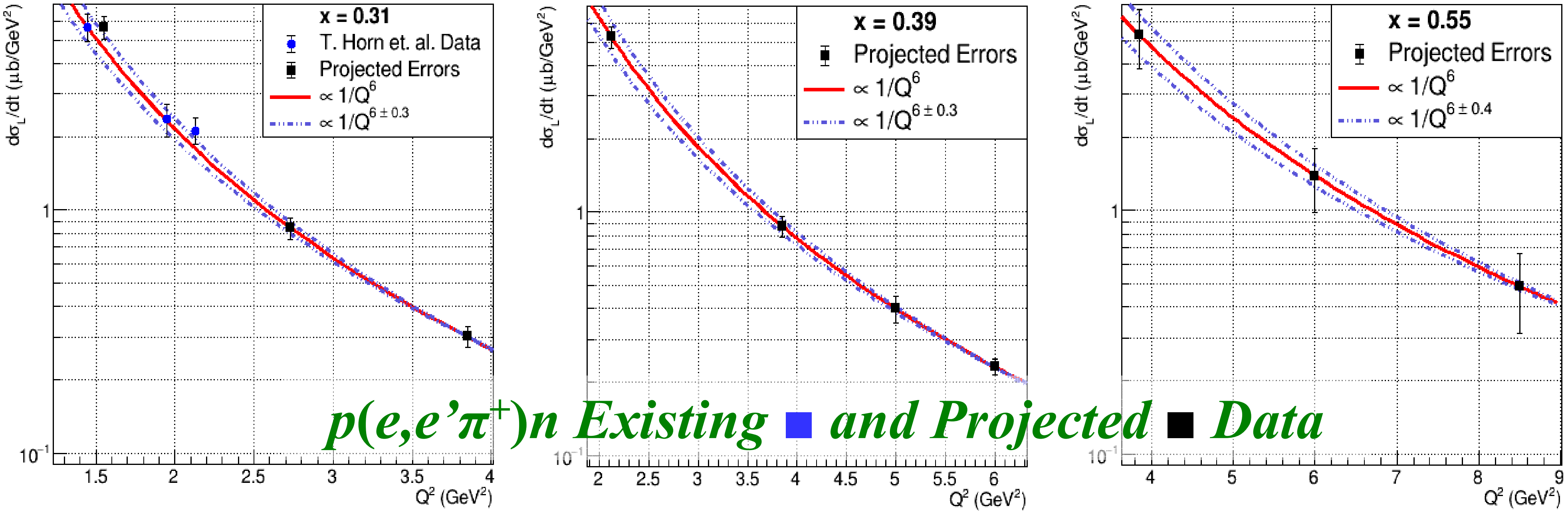


$H \quad \widetilde{H} \quad E \quad \widetilde{E}$

- **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

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

- **One of most stringent tests of factorization is Q^2 dependence of π/K electroproduction cross sections**
  - σ_L scales to leading order as Q^{-6}
  - As Q^2 becomes large: $\sigma_L \gg \sigma_T$
- **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*

- E12–19–006 data taking completed 2022
- PhD students: N. Heinrich, M. Junaid Spokespersons: D. Gaskell, T. Horn, GMH

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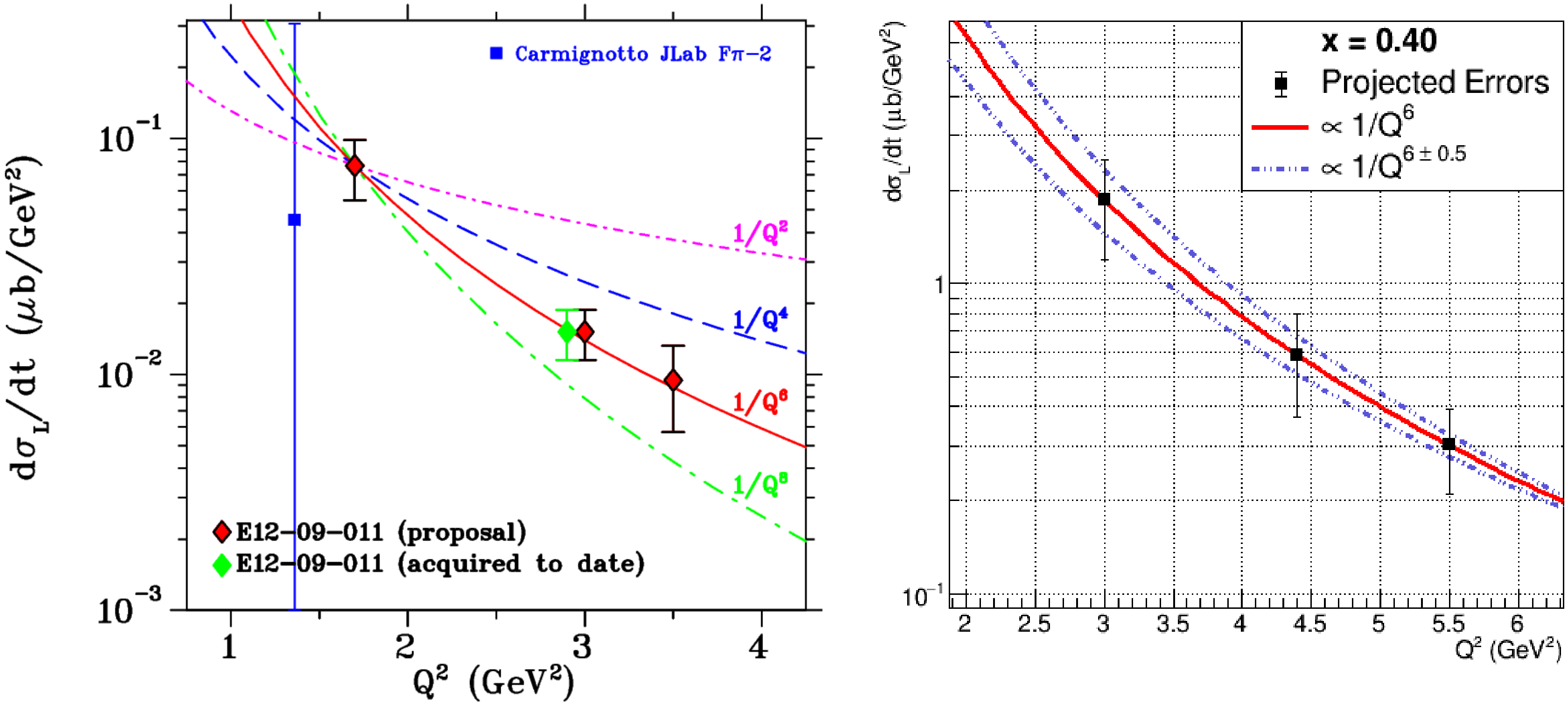
Important 2nd Test: $p(e,e'K^+)\Lambda$

- 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

Summary

- Higher Q^2 data on π^+ and K^+ form factors are 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
  - KaonLT (E12–09–011) partially completed. First results hopefully out next 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 (E12–09–011) has acquired $p(e,e'K^+)\Lambda$ data for Q^{-n} scan at x_B=0.40, eventual extension to x_B=0.25

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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 $\Delta\varepsilon$

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

JLab Hall C – 12 GeV Upgrade

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

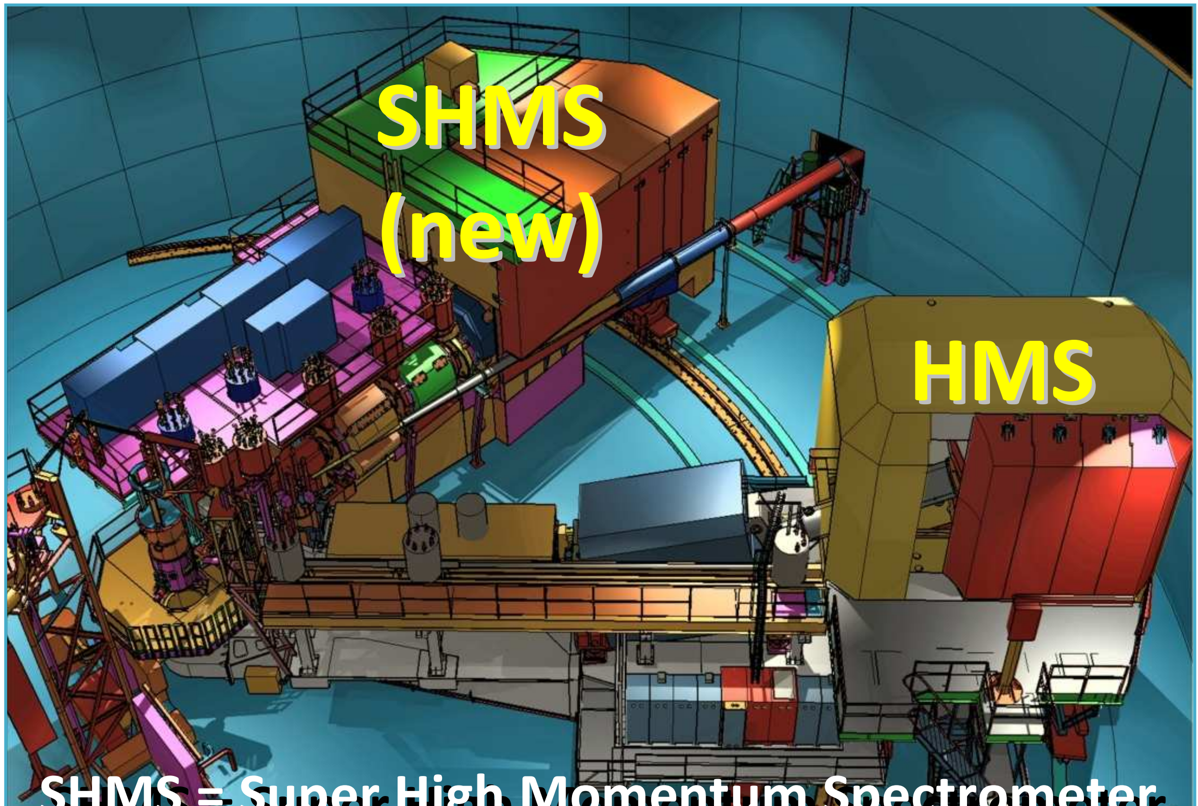
MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

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

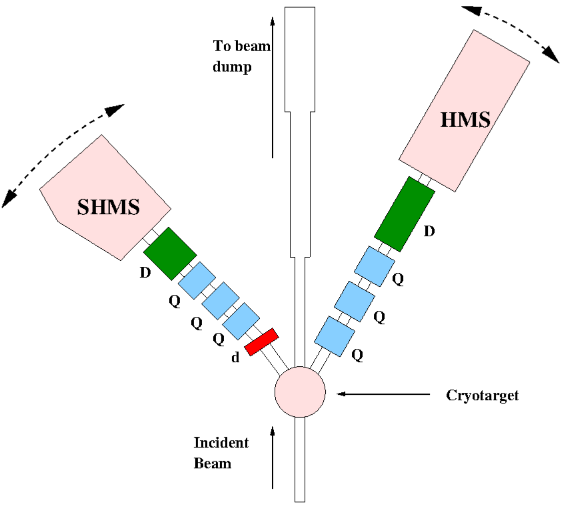
Well-Shielded Detector Enclosure

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

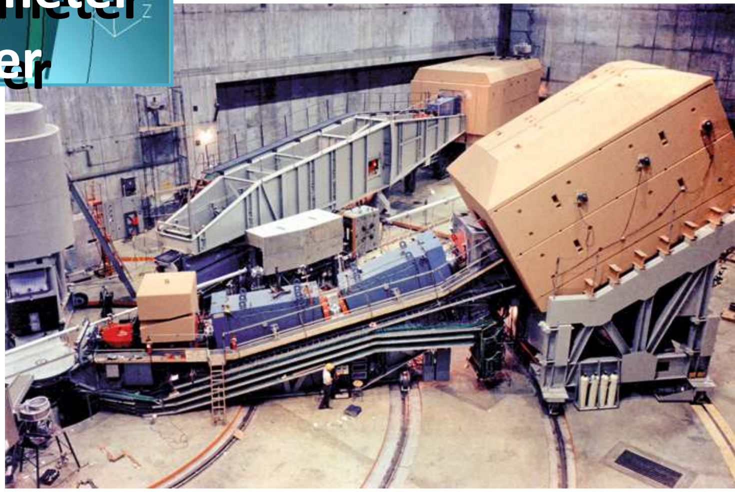
Luminosity
- ~4x10^{38} cm^{-2} s^{-1}



SHMS = Super High Momentum Spectrometer
HMS = High Momentum Spectrometer

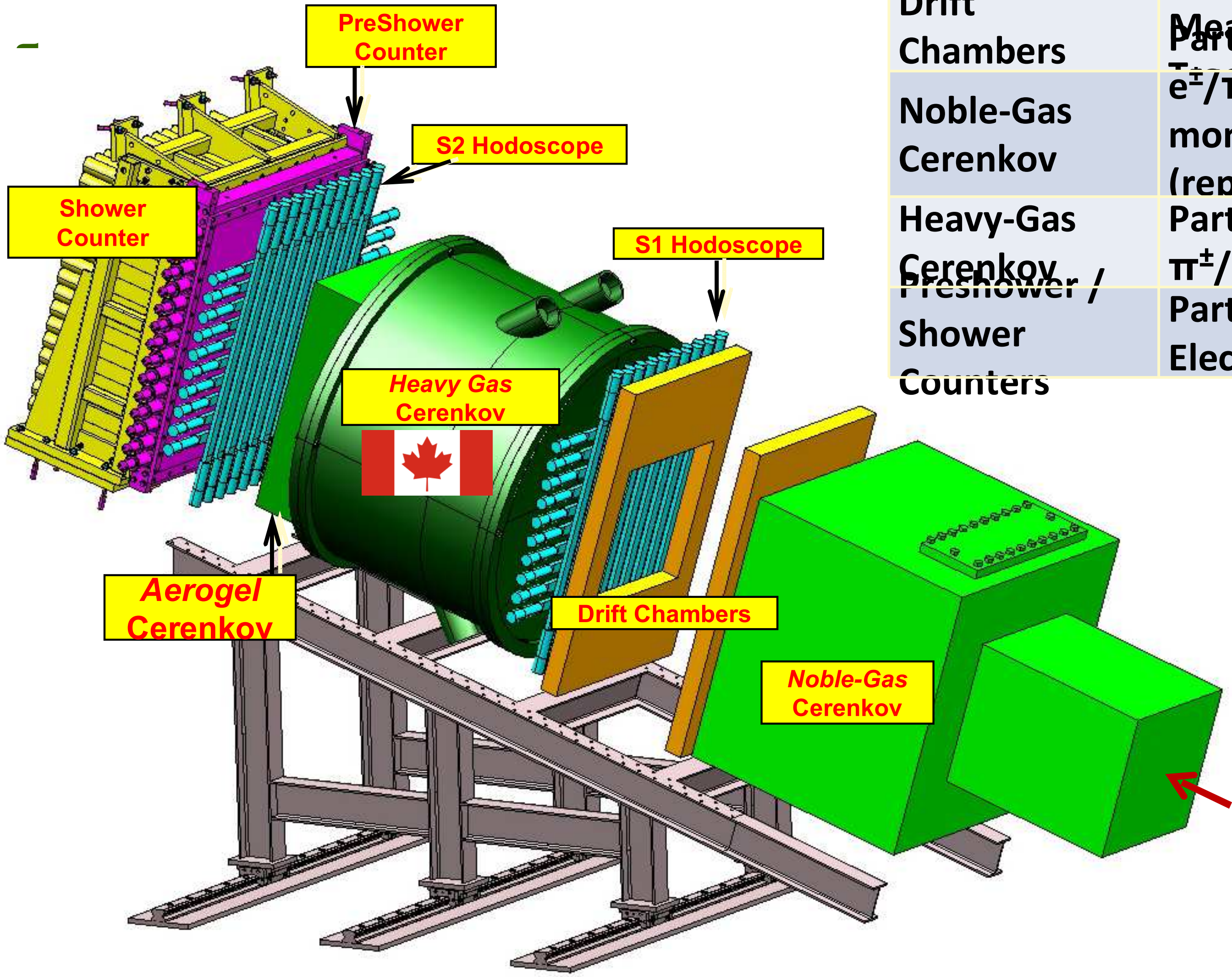


Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.



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
Noble-Gas Cerenkov	Particle ID, Trigger. $e^\pm/\pi^\pm$ at high momentum (replace by vacuum at	Vary Ar/Ne mixture to set index at $\pi^\pm$
Heavy-Gas Cerenkov	Particle ID, Trigger. $\pi^\pm/K^\pm$ discrimination	C_4F_8O – Vary pressure to set index at $K^\pm$
Preshower / Shower Counters	Particle ID, Trigger. Electron tag	



Incident Particles through SHMS magnet optics

Hall C during Data Taking

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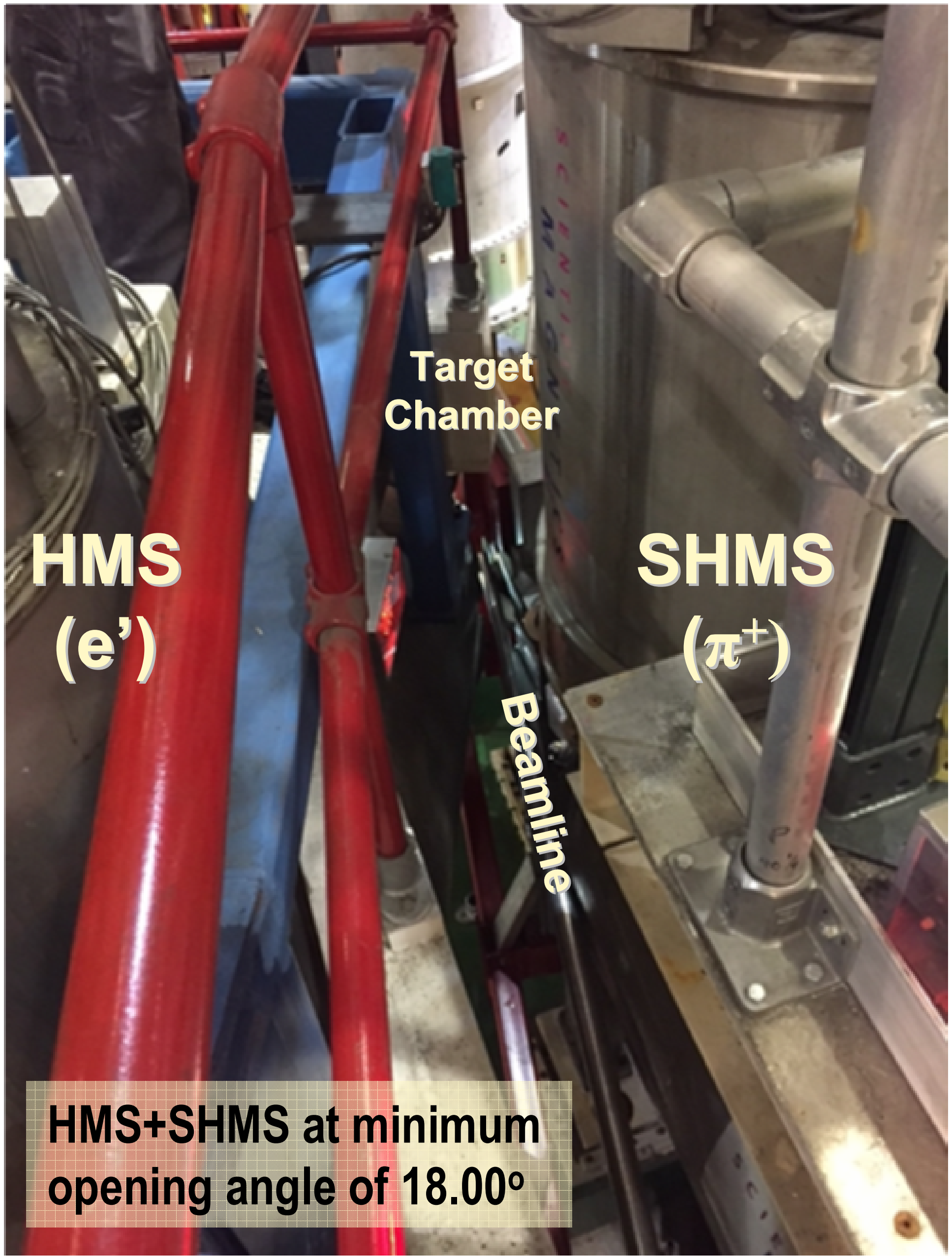
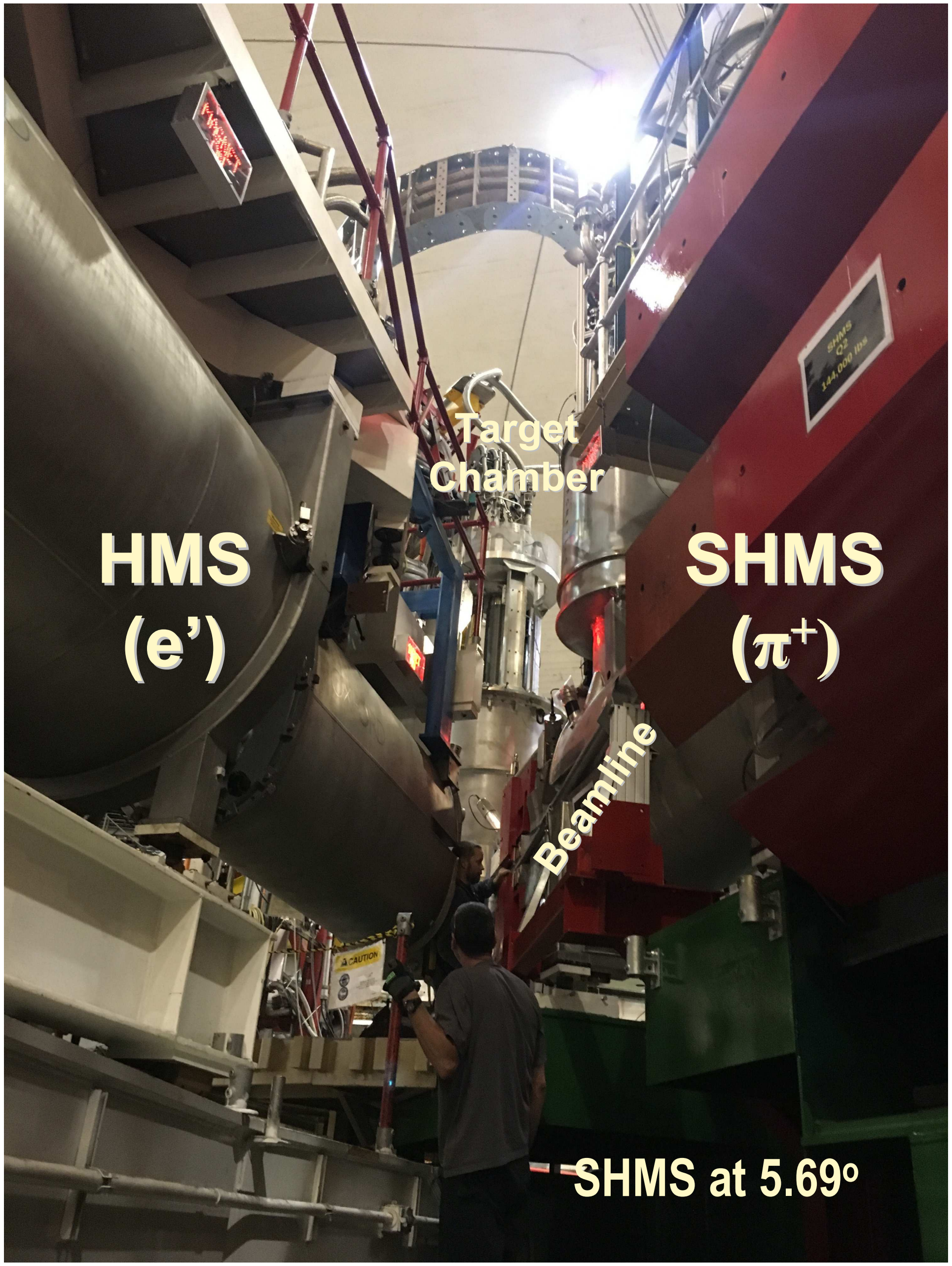
π^+/K^+ FF experiments have challenging forward angle requirements



HMS+SHMS at minimum opening angle of 18.00°

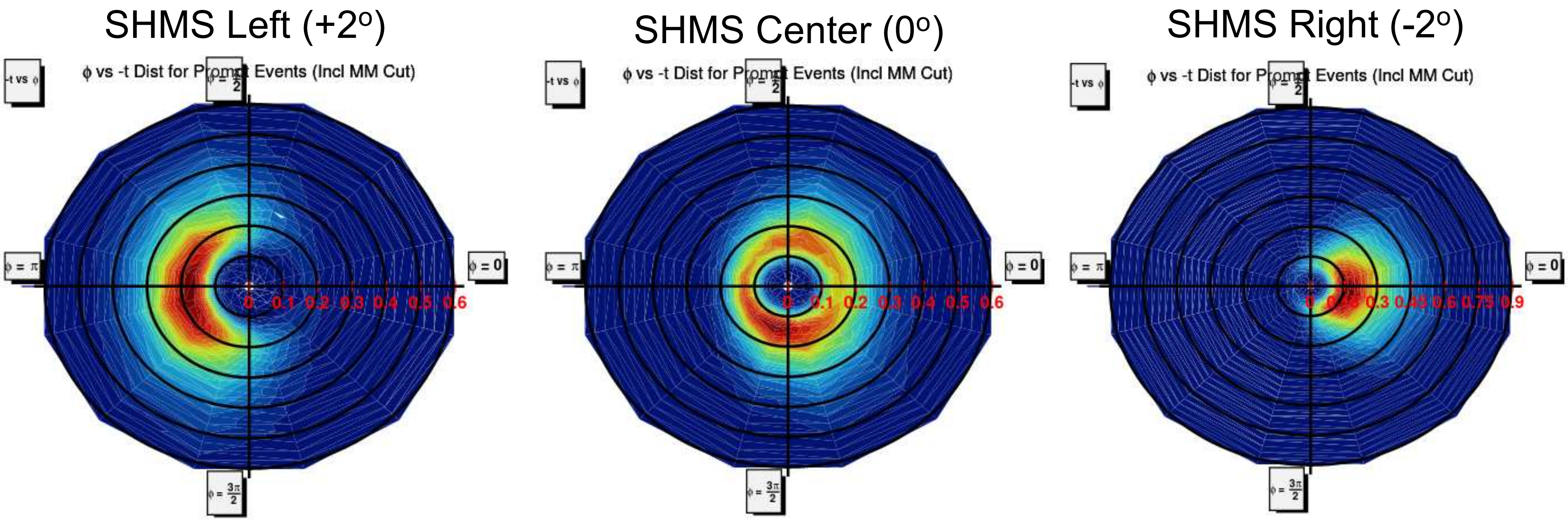


SHMS at 5.69°

PionLT (E12–19–006) 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

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

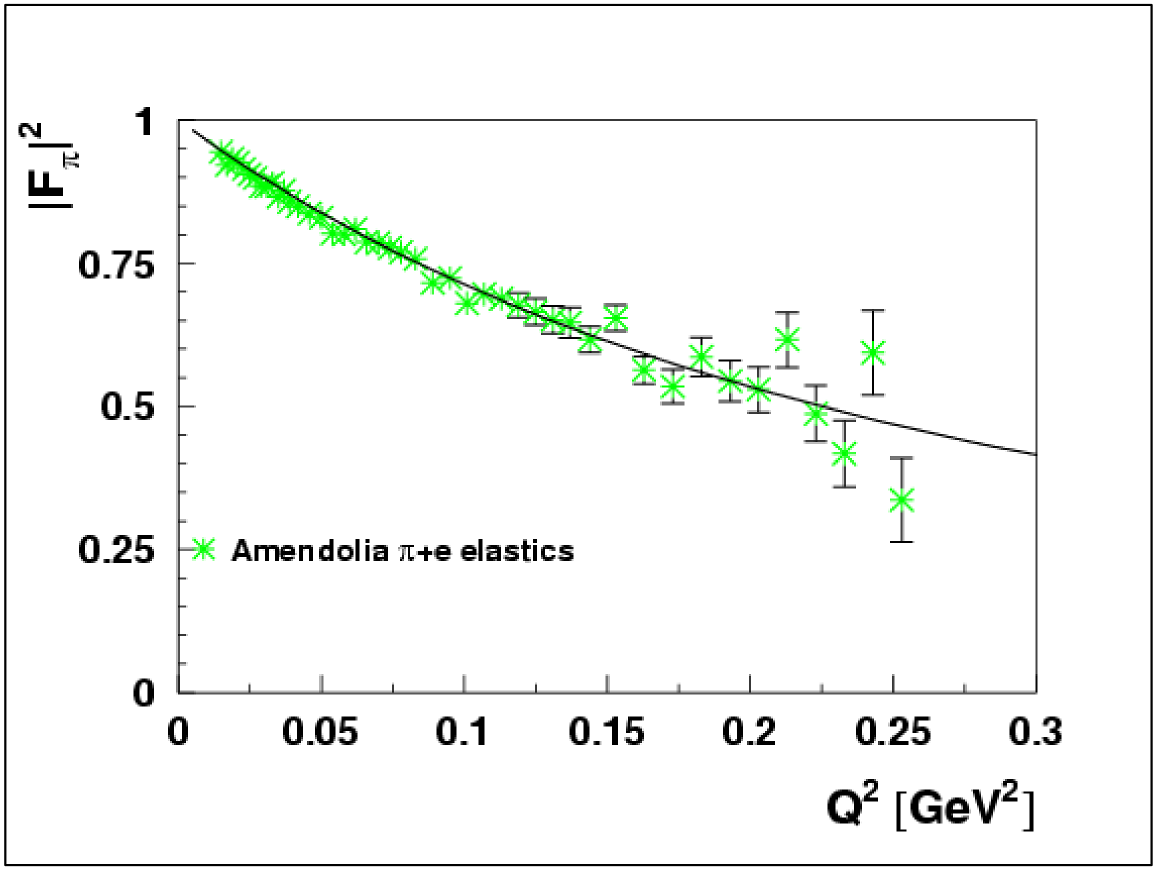
At low Q^2, F_π can be measured model-independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ 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

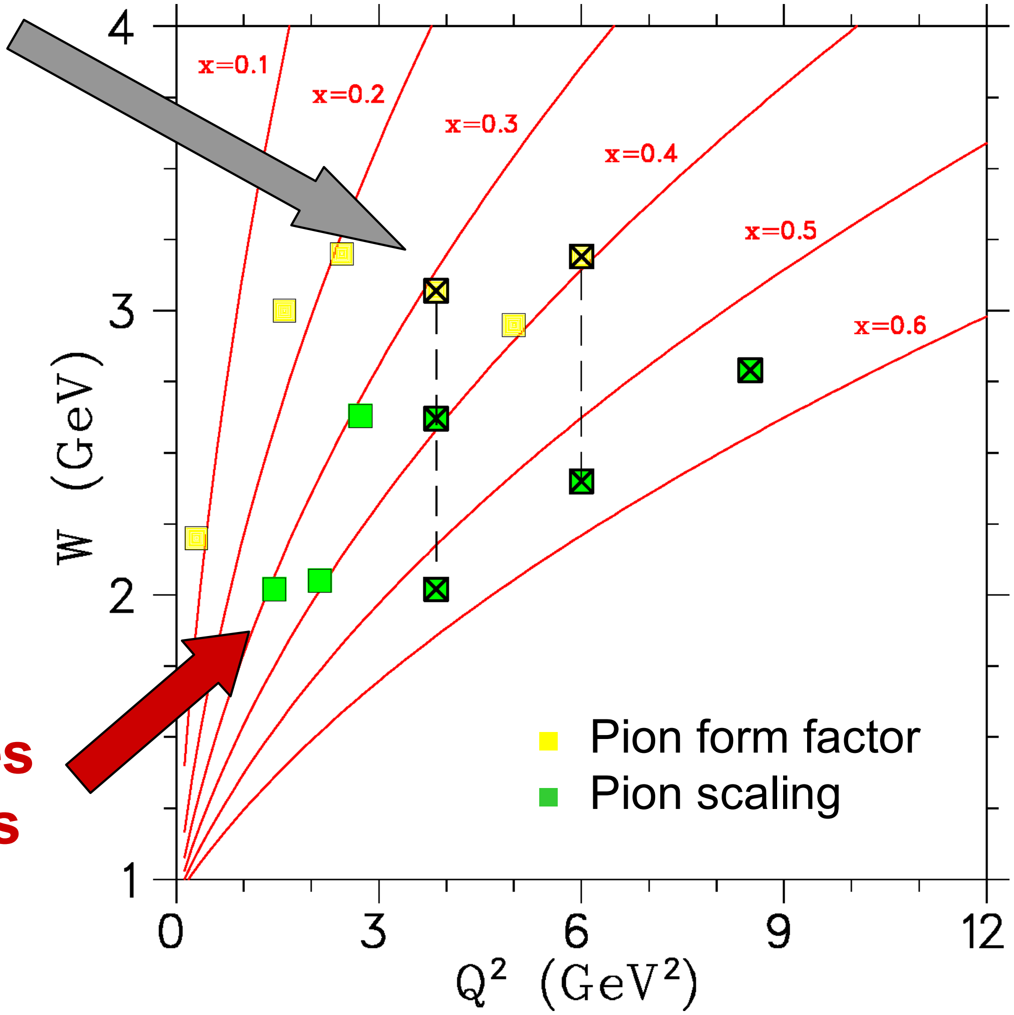
Q^2=1 GeV^2 requires 1 TeV pion beam



E12–19–006 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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Measurement of K^+ Form Factor

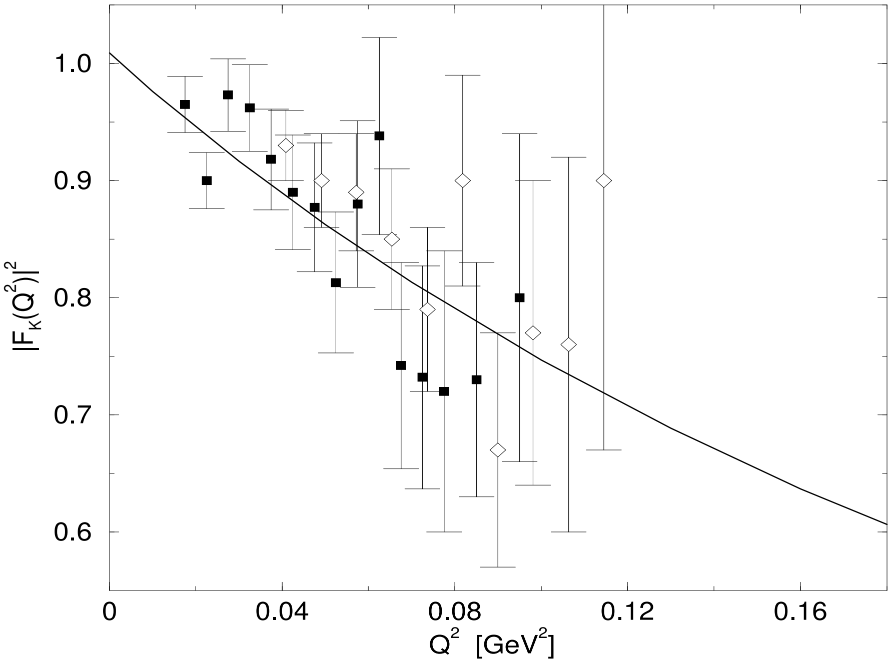
- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon form factor at low Q^2

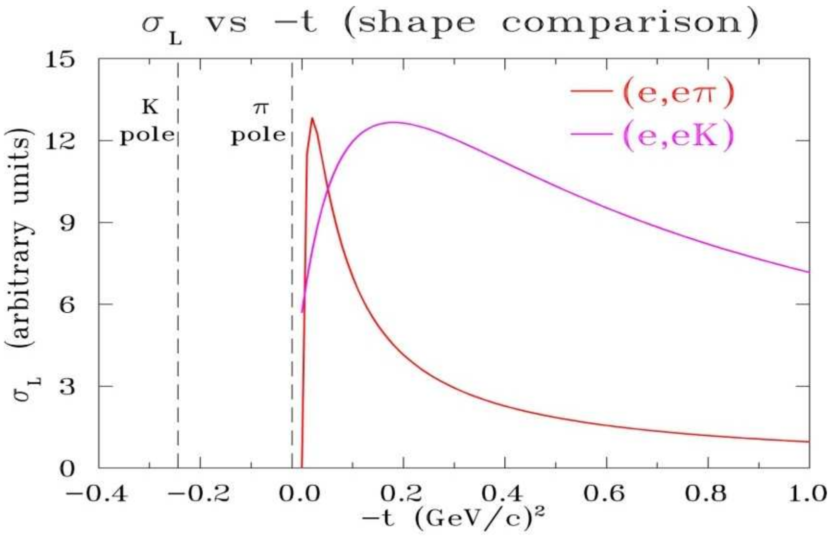
  [Amendolia, et al., PL **B178** (1986) 435]

- 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.

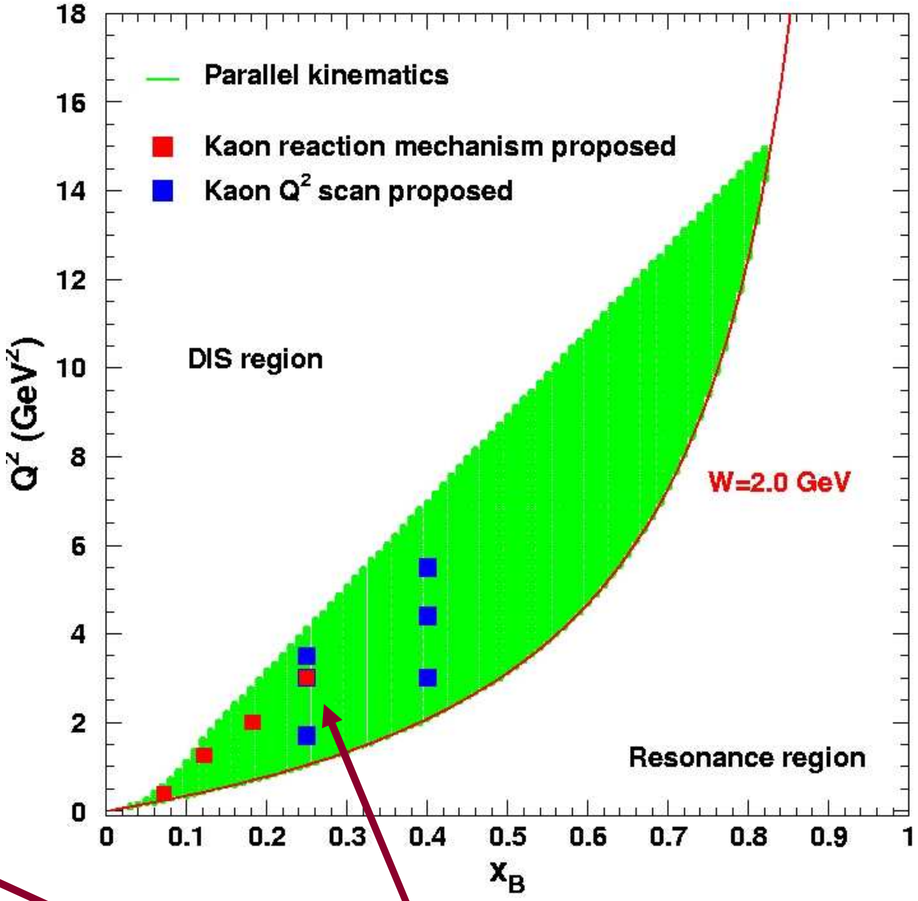




$p(e,e'K^+)\Lambda(\Sigma^0)$ Experiment Overview

- 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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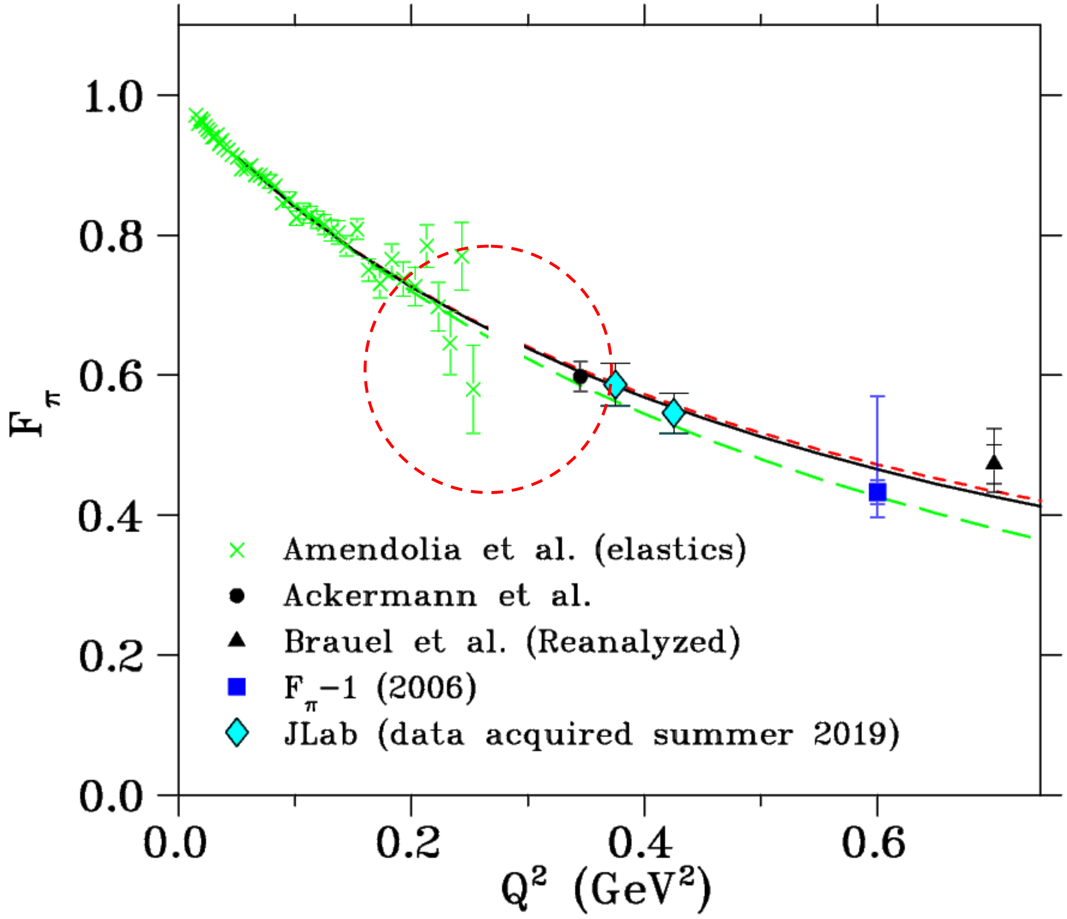
Check of Pion Electroproduction Technique

- Does electroproduction really measure the on–shell form–factor?
- Test by making *p(e,e'π^+)n* measurements at same kinematics as π^+e elastics.
- ***Can't quite reach the same Q^2, but electro–production appears consistent with extrapolated elastic data.***



Data for new test acquired in Summer 2019:

- small Q^2 (0.375, 0.425) competitive with DESY Q^2=0.35
- $-t$ closer to pole (=*0.008* GeV^2) vs. DESY 0.013

Expecting results to be finalized soon — V. Kumar (Regina)

- **A similar test for F_{K+} (KaonLT) is under analysis — A. Hamdi (Regina)**

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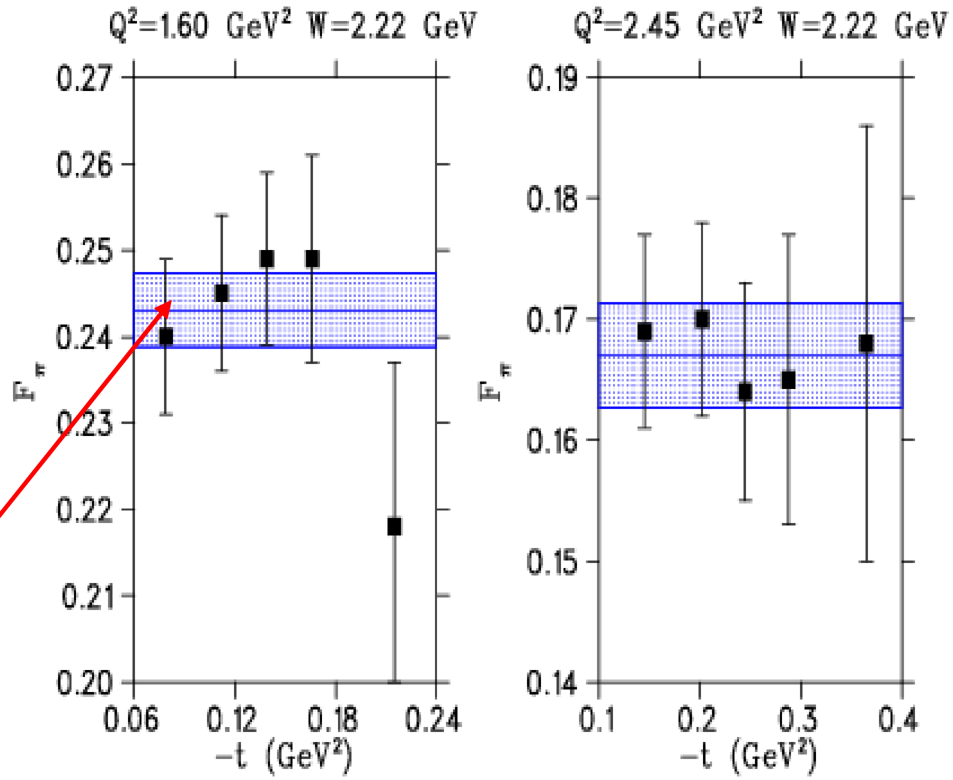
Fπ-2 VGL $p(e,e'\pi^+)n$ model check

- 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.

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

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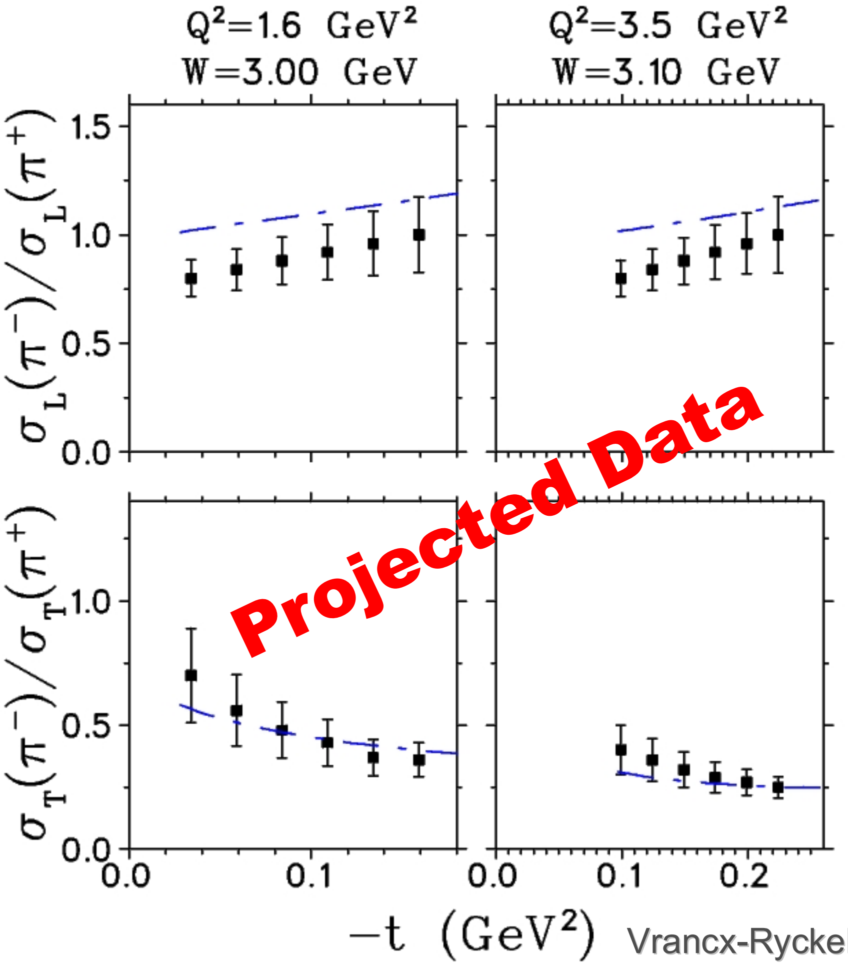
- π^+ *t*-channel diagram is purely isovector.
- Measure

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

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.

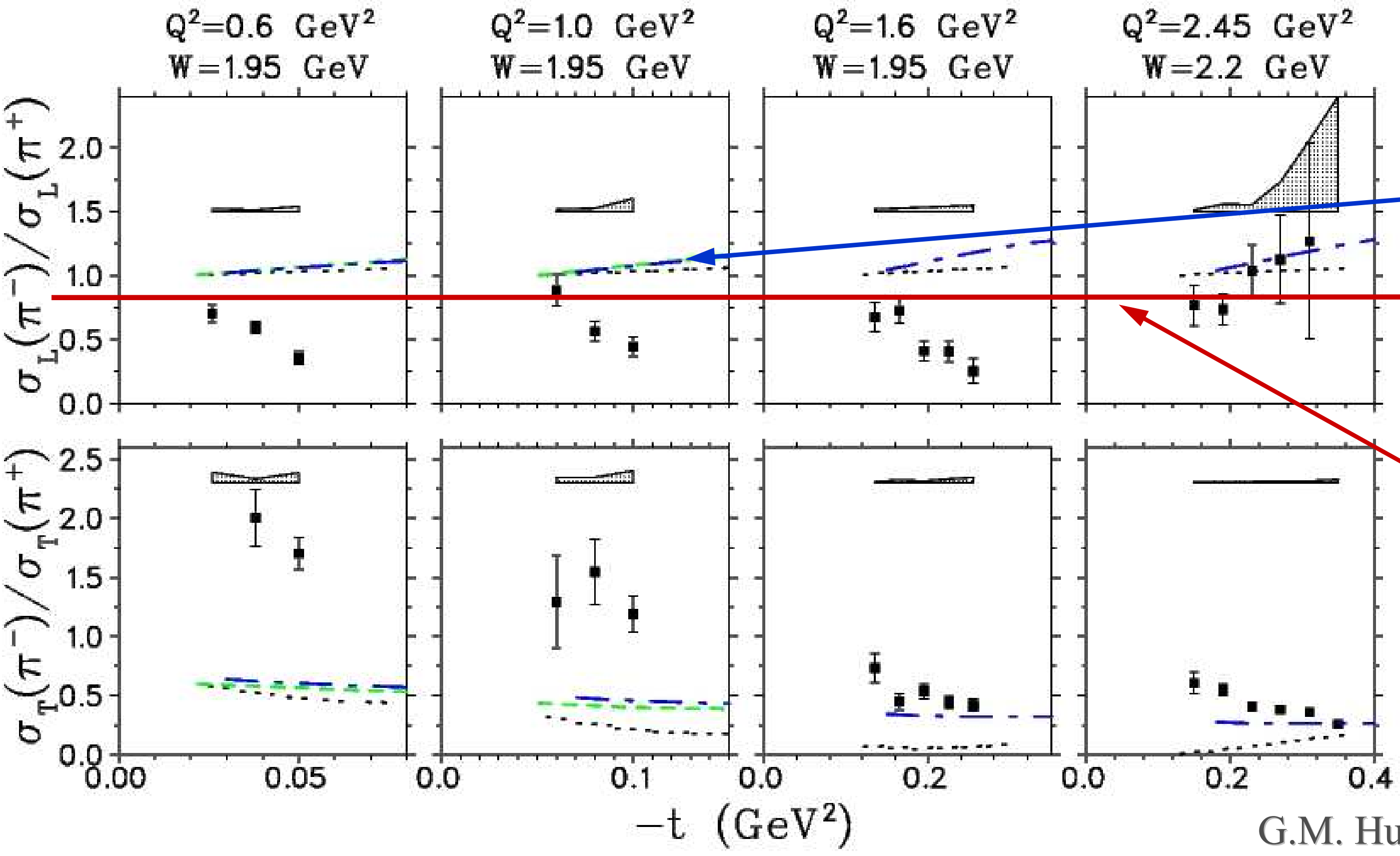
π^-/π^+ data to check *t*-channel dominance

- 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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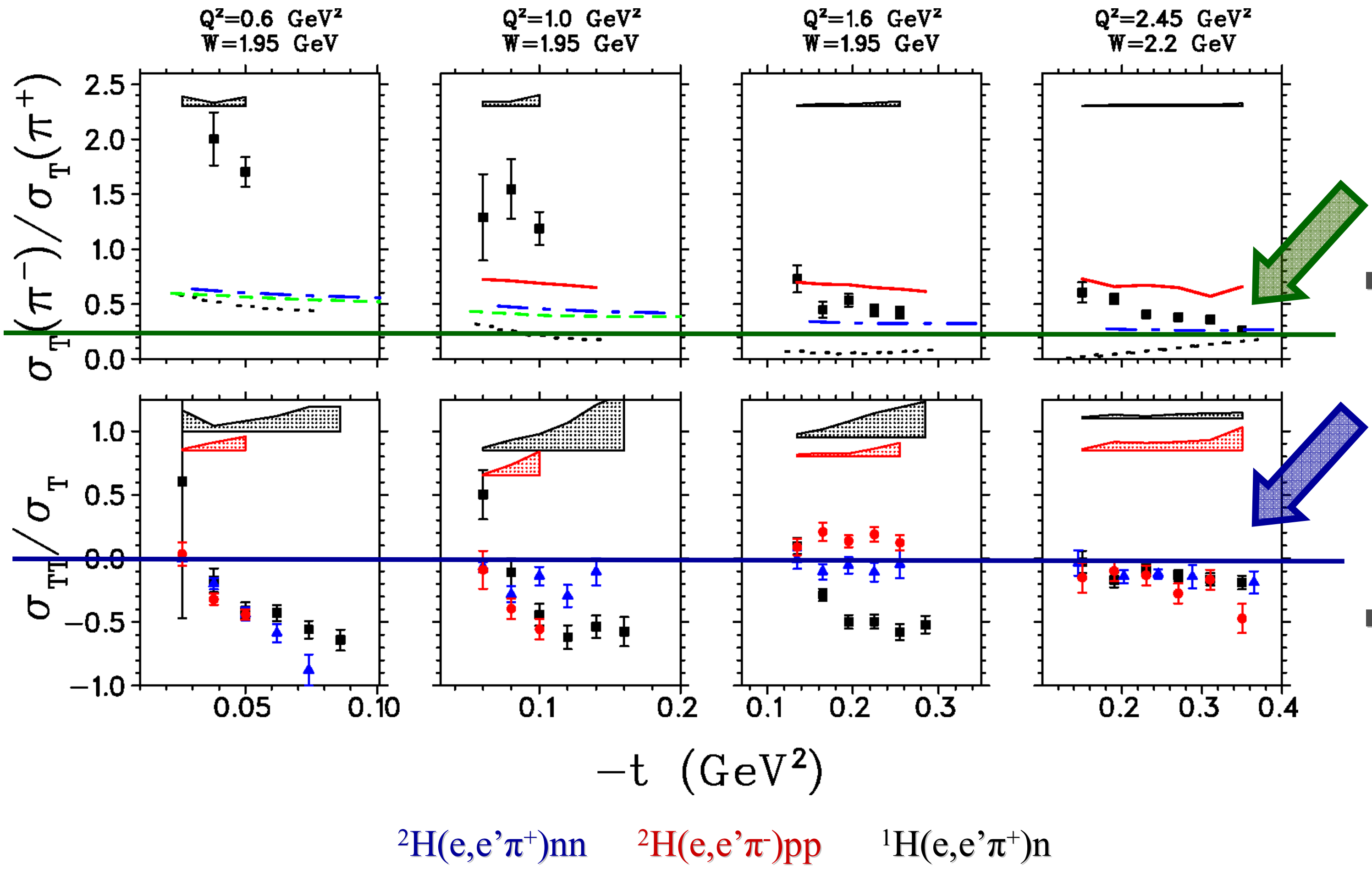
π^-/π^+ Hard–Soft Factorization Test

University of Regina

- **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.**

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

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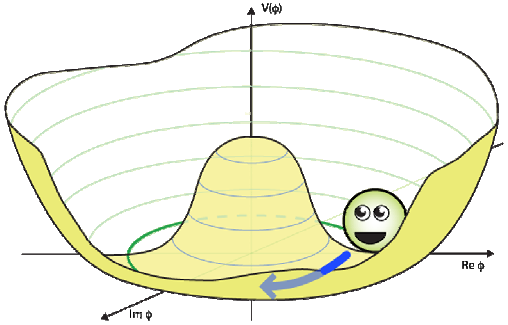
The Pion as a Goldstone Boson

- 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.

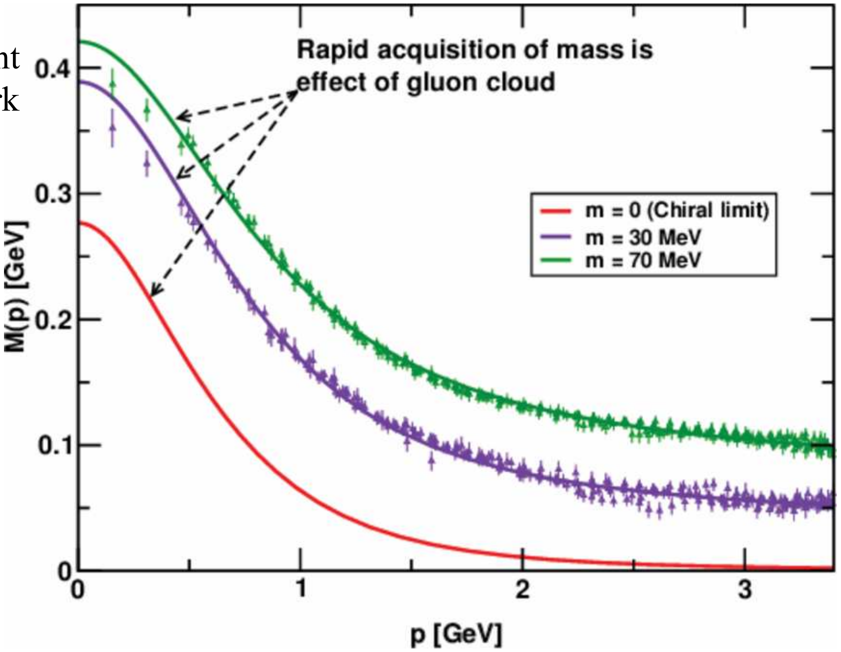
Recent Theoretical Advances

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.

Constituent quark



Current quark

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

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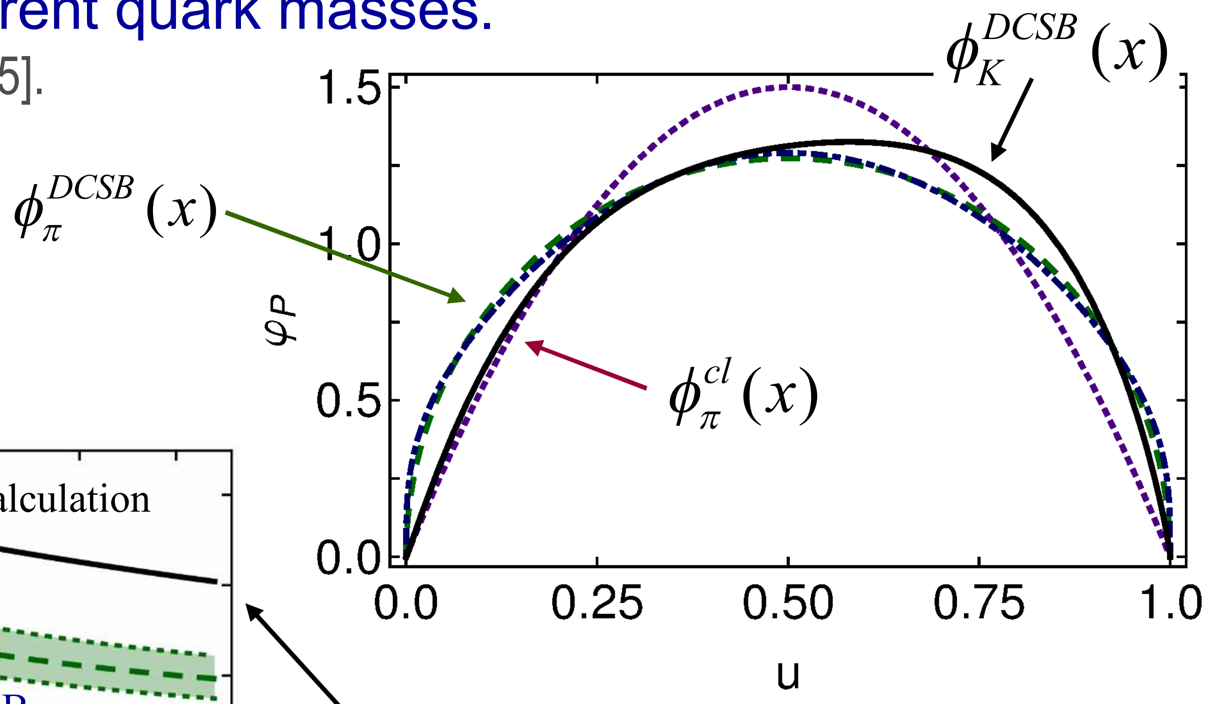
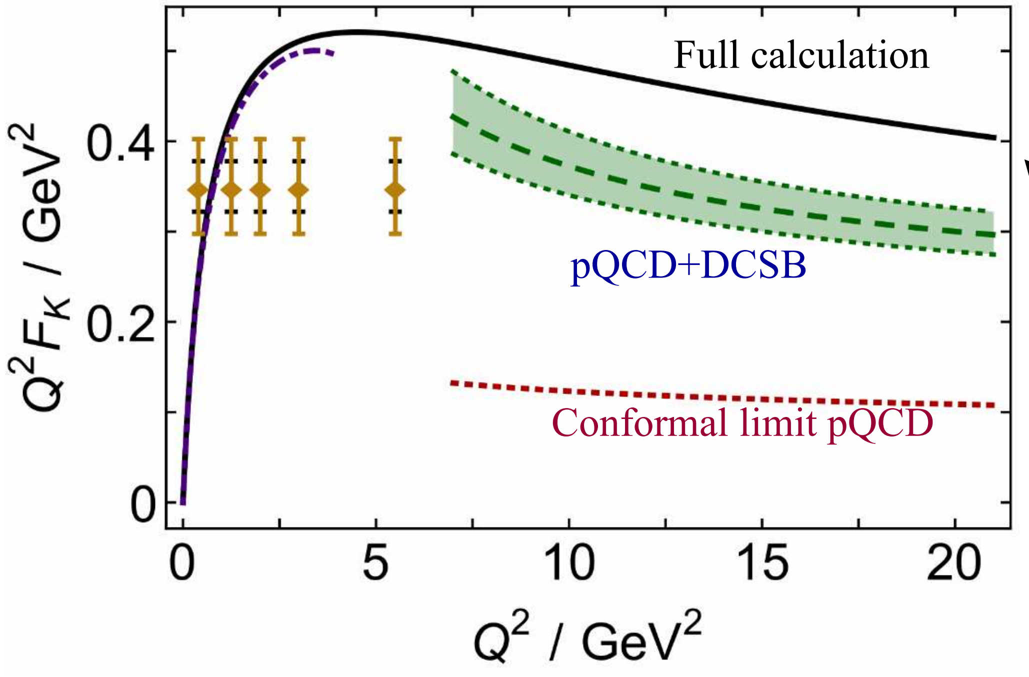
K^+ properties also strongly influenced by DCSB

- **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].