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

Garth Huber

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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

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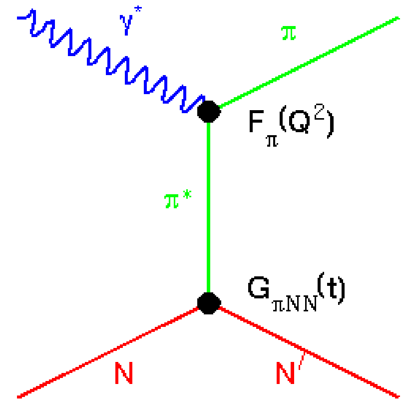
1) Determine the Pion Form Factor at Q^2>0.3 GeV^2:

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

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

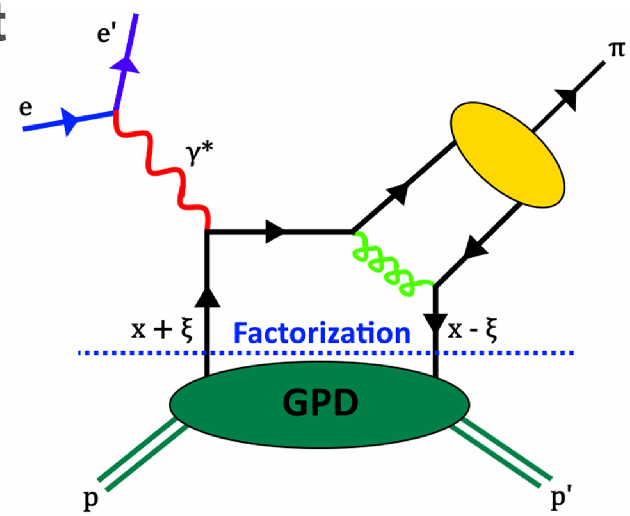
  - Pion pole process dominates σ_L in forward kinematics.
  - Can a similar method be used to determine the kaon form factor?



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



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

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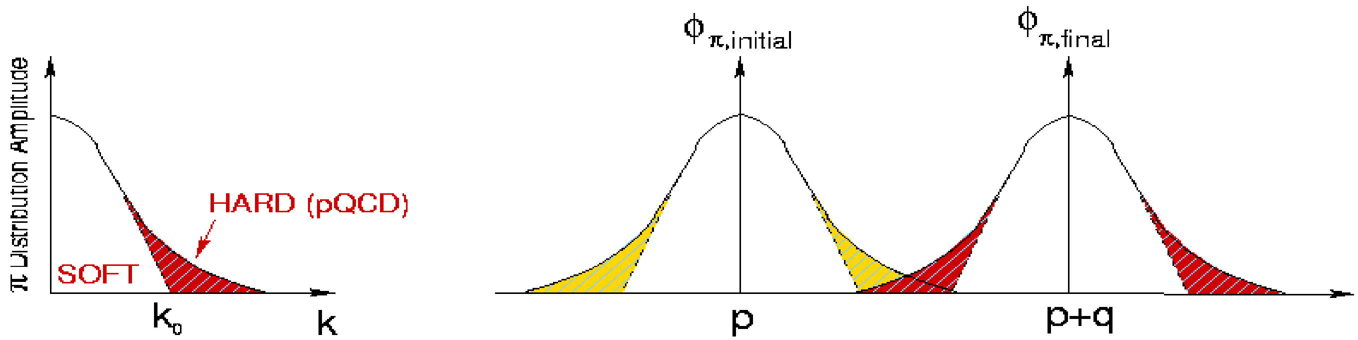
Charged Meson Form Factors

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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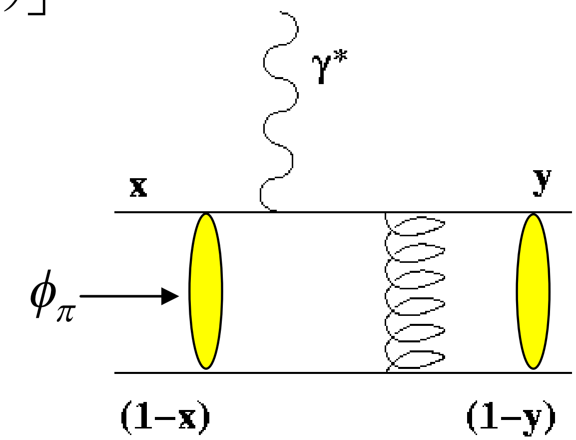
The Pion in perturbative QCD

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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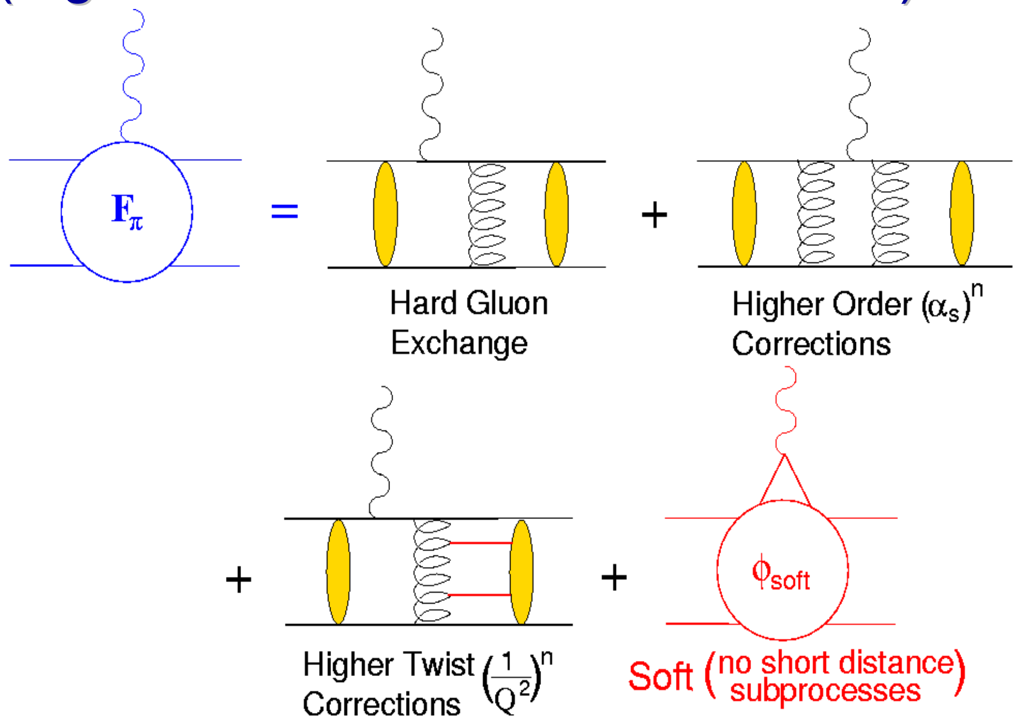
Pion Form Factor at Intermediate Q^2

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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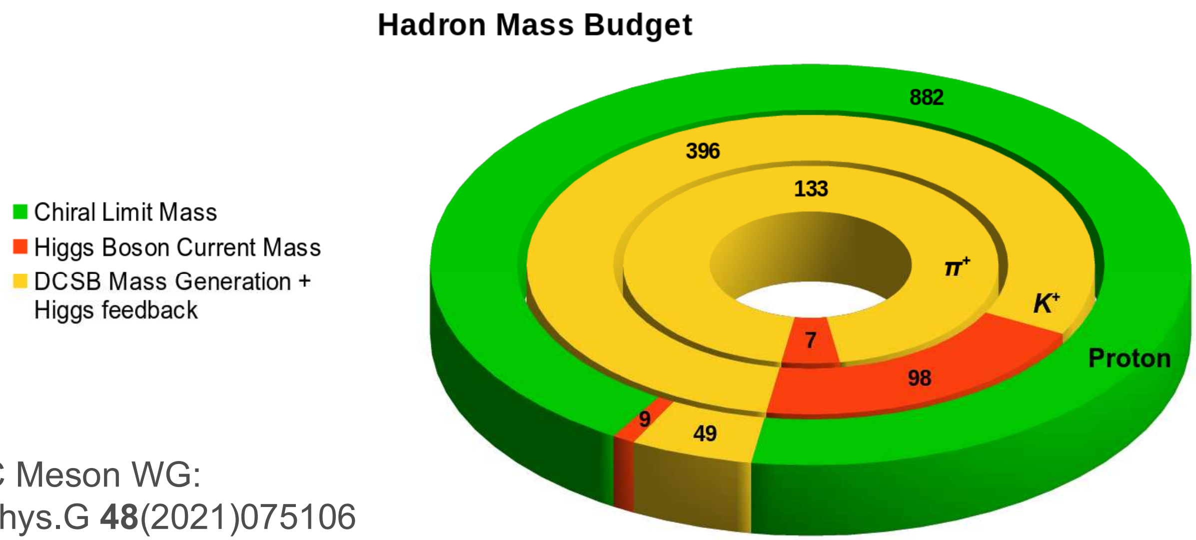
Contrasts in Hadron Mass Budgets



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

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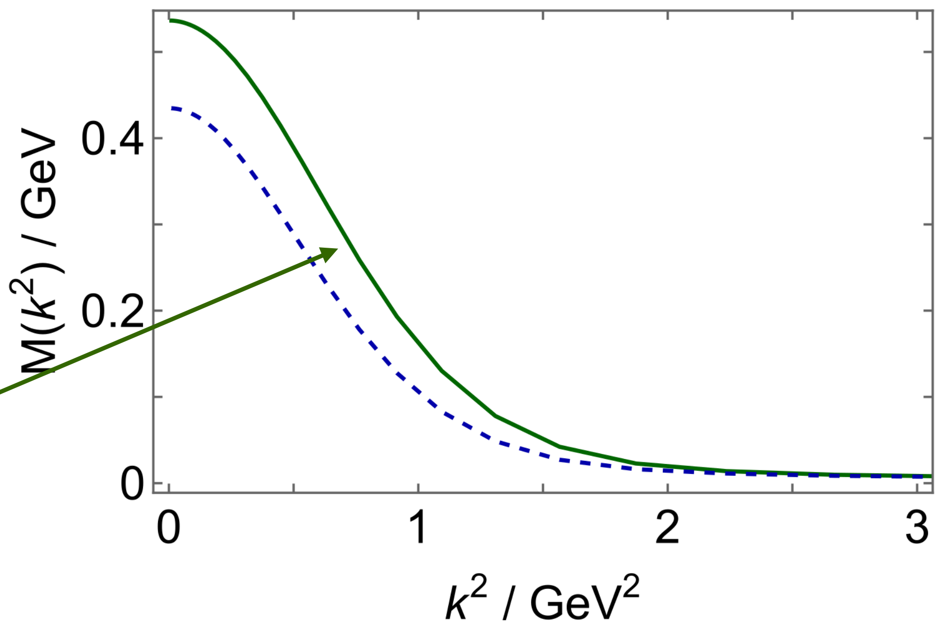
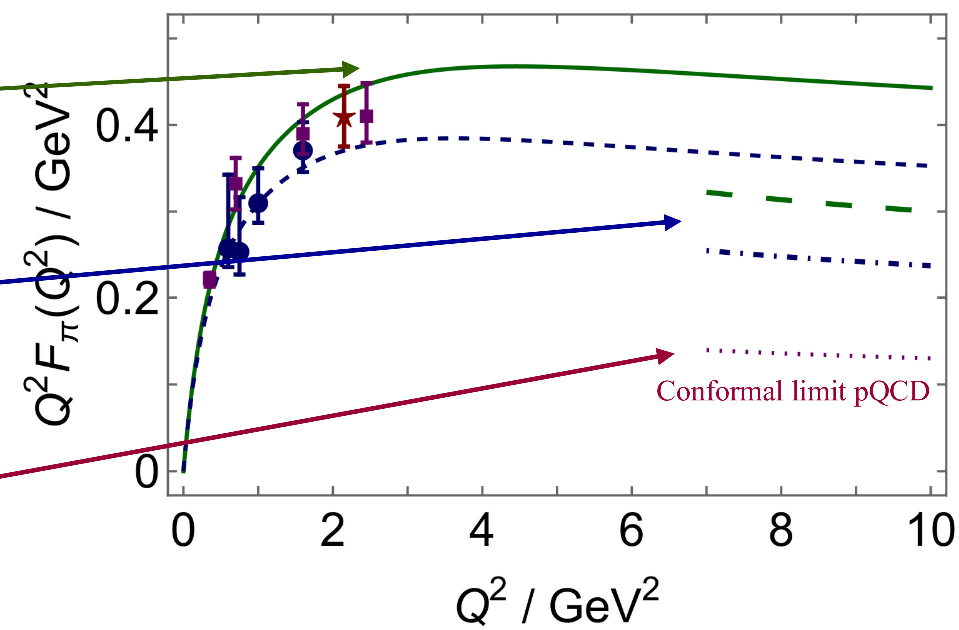
At empirically accessible energy scales, π^+ form factor is sensitive to emergent mass scale in QCD

- **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 (slide #3), 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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The Charged Kaon – a 2nd QCD test case

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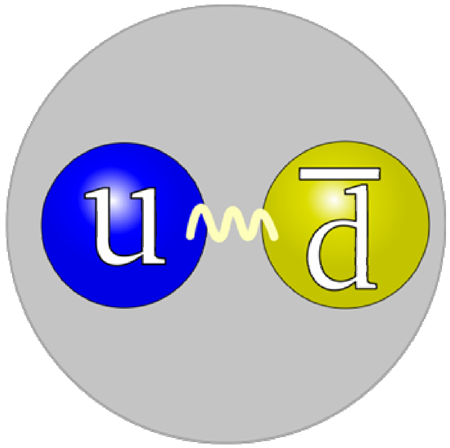
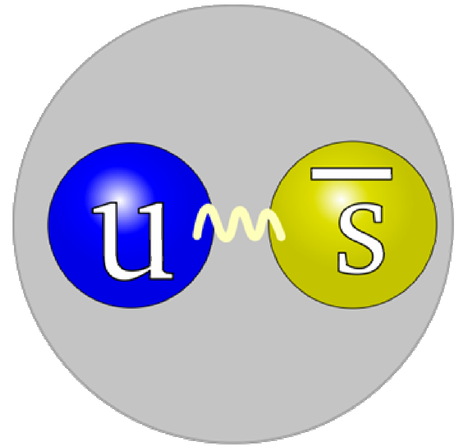


π^+



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

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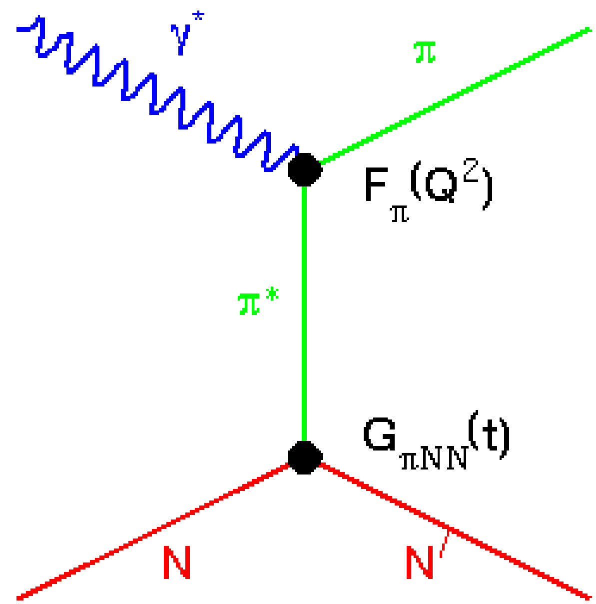
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

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

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



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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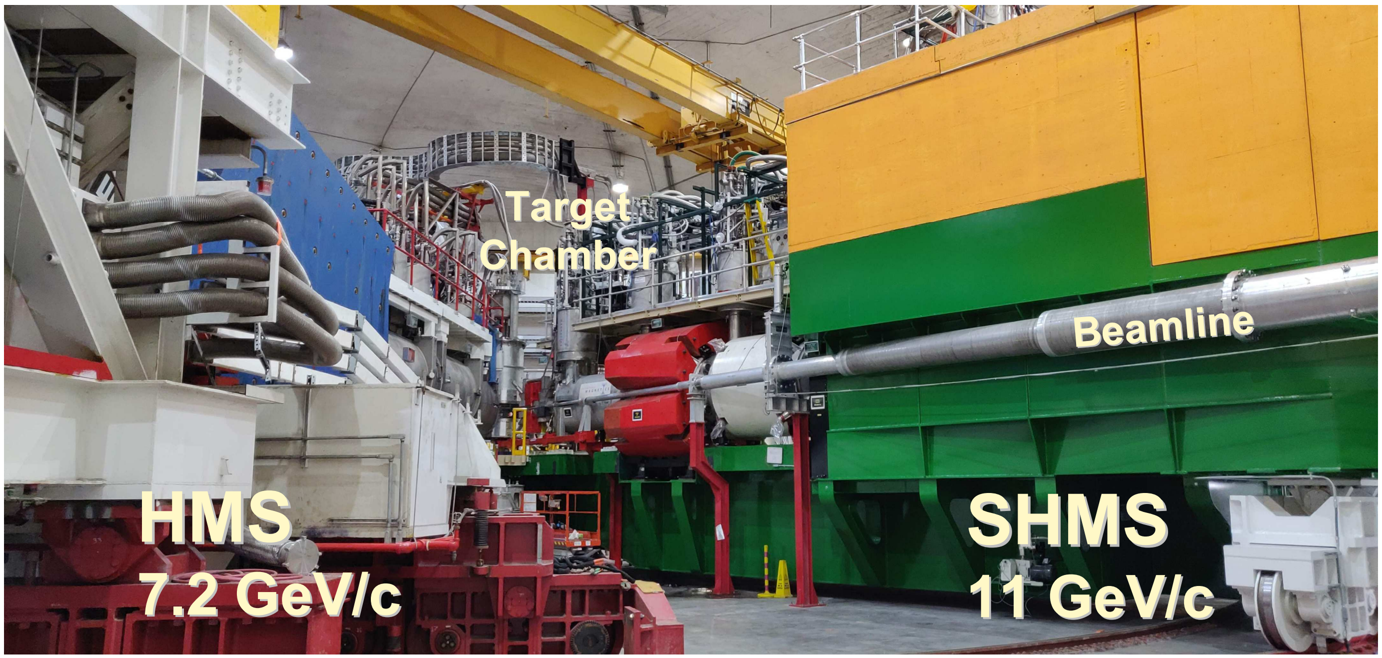
Experimental Issues

- Deep Exclusive Meson Production (DEMP) cross section is small, can exclusive *p(e,e'π^+)n* and *p(e,e'K^+)Λ* channels be cleanly identified?
  - High momentum, forward angle (5.5^o) 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

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

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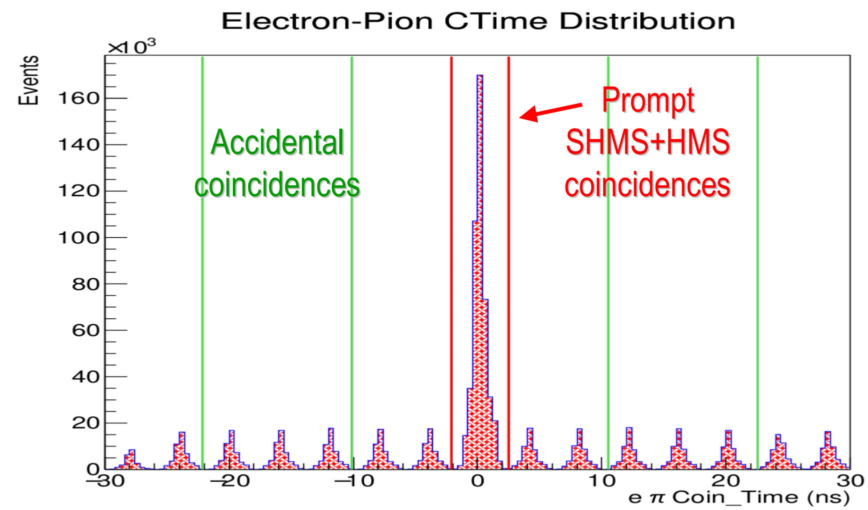
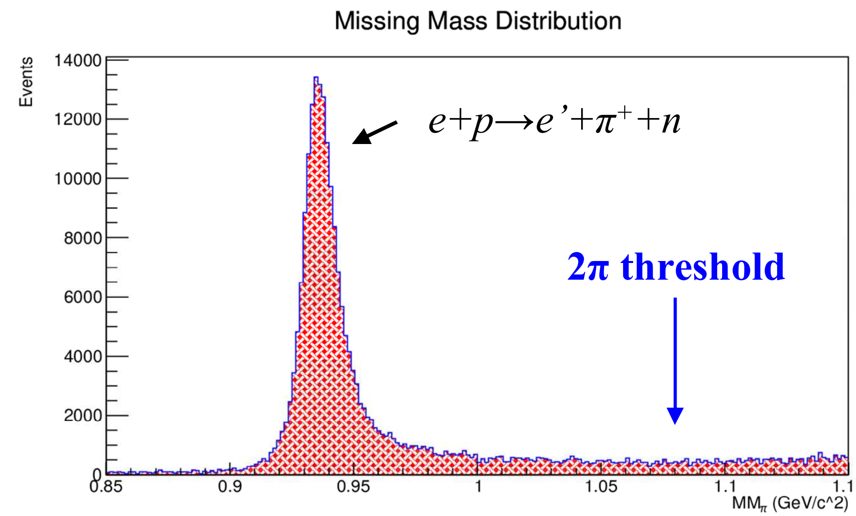
Coincidence measurement between charged pions in SHMS and electrons in HMS

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

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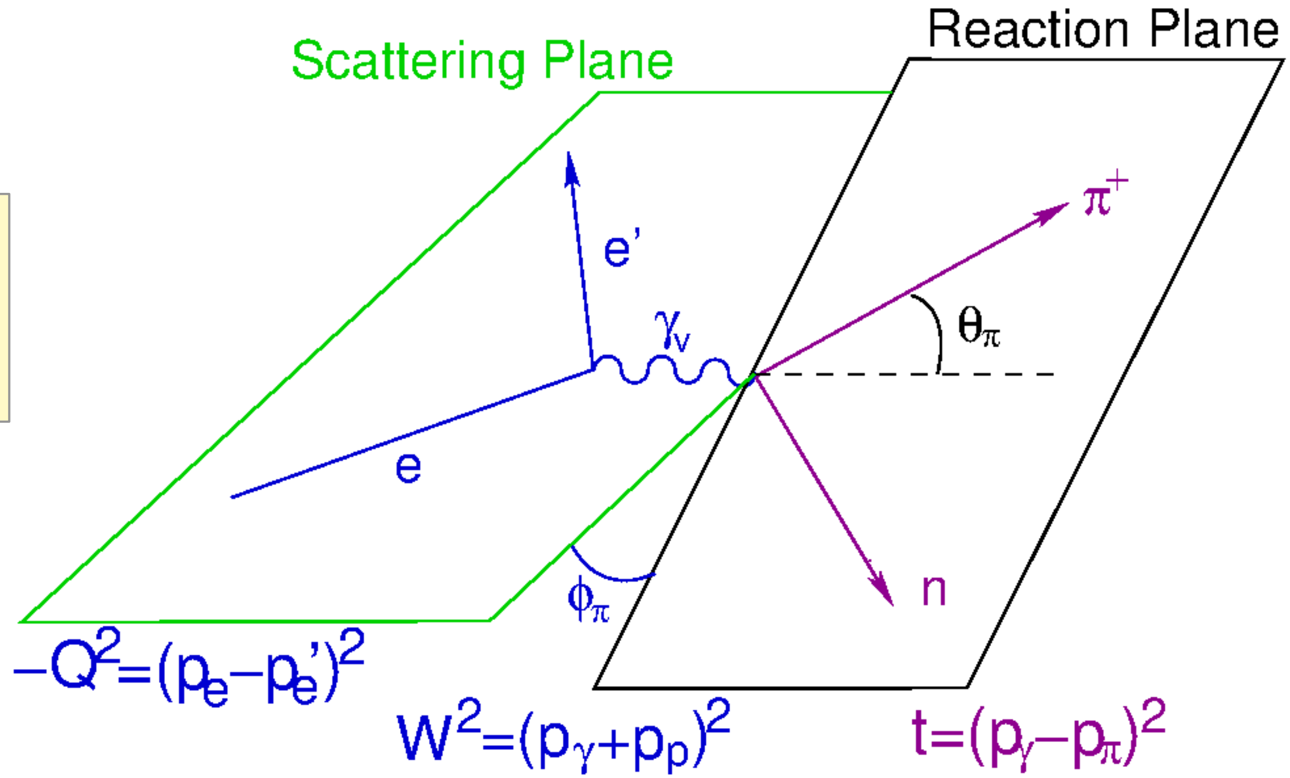
$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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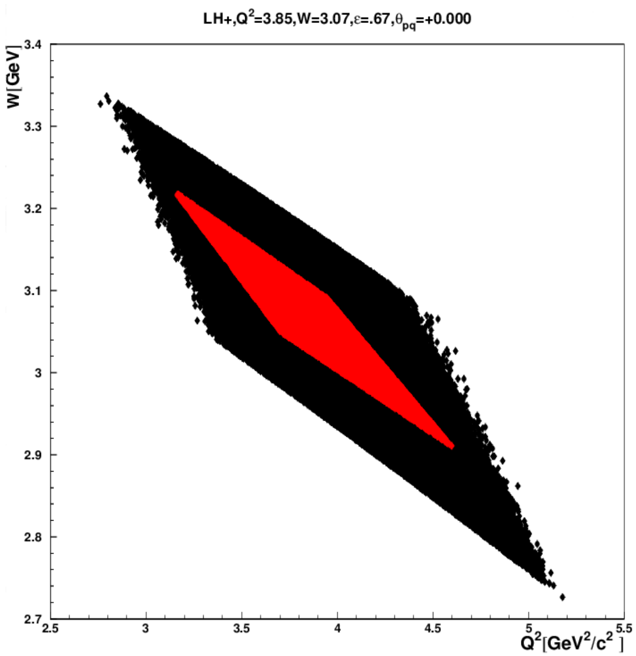
The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

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

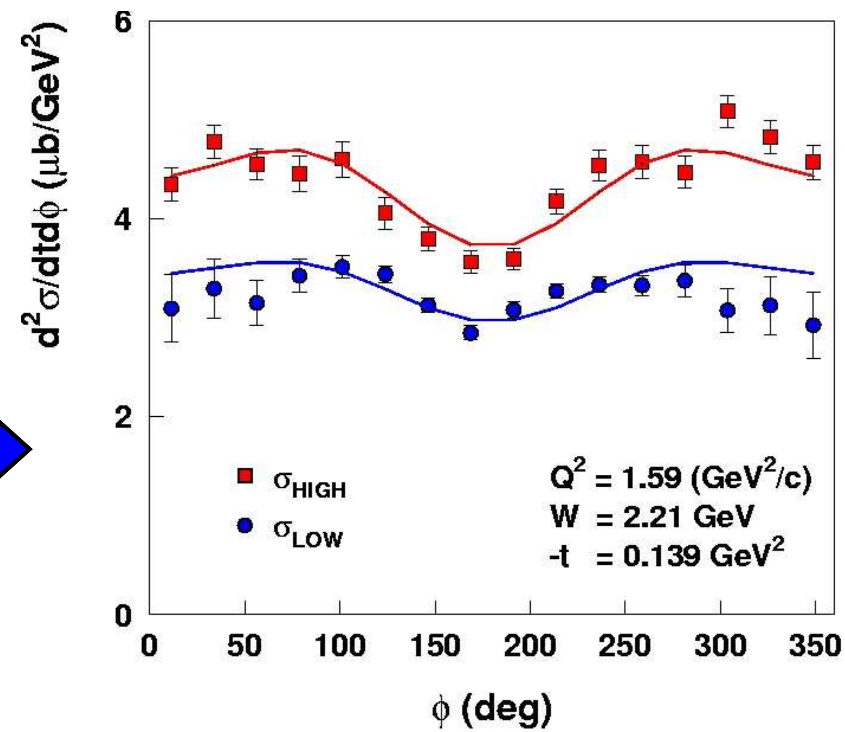


Diamond cuts define common (W,Q^2) coverage at both ε

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

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

VGL Regge Model:

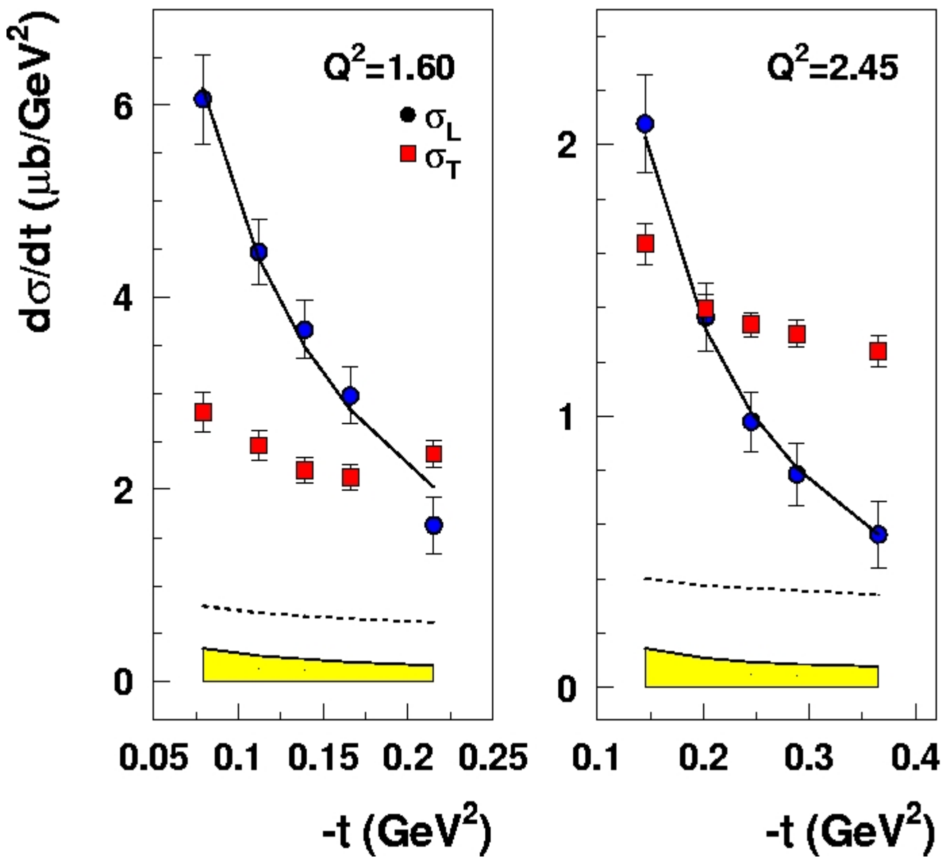
- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$

  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

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

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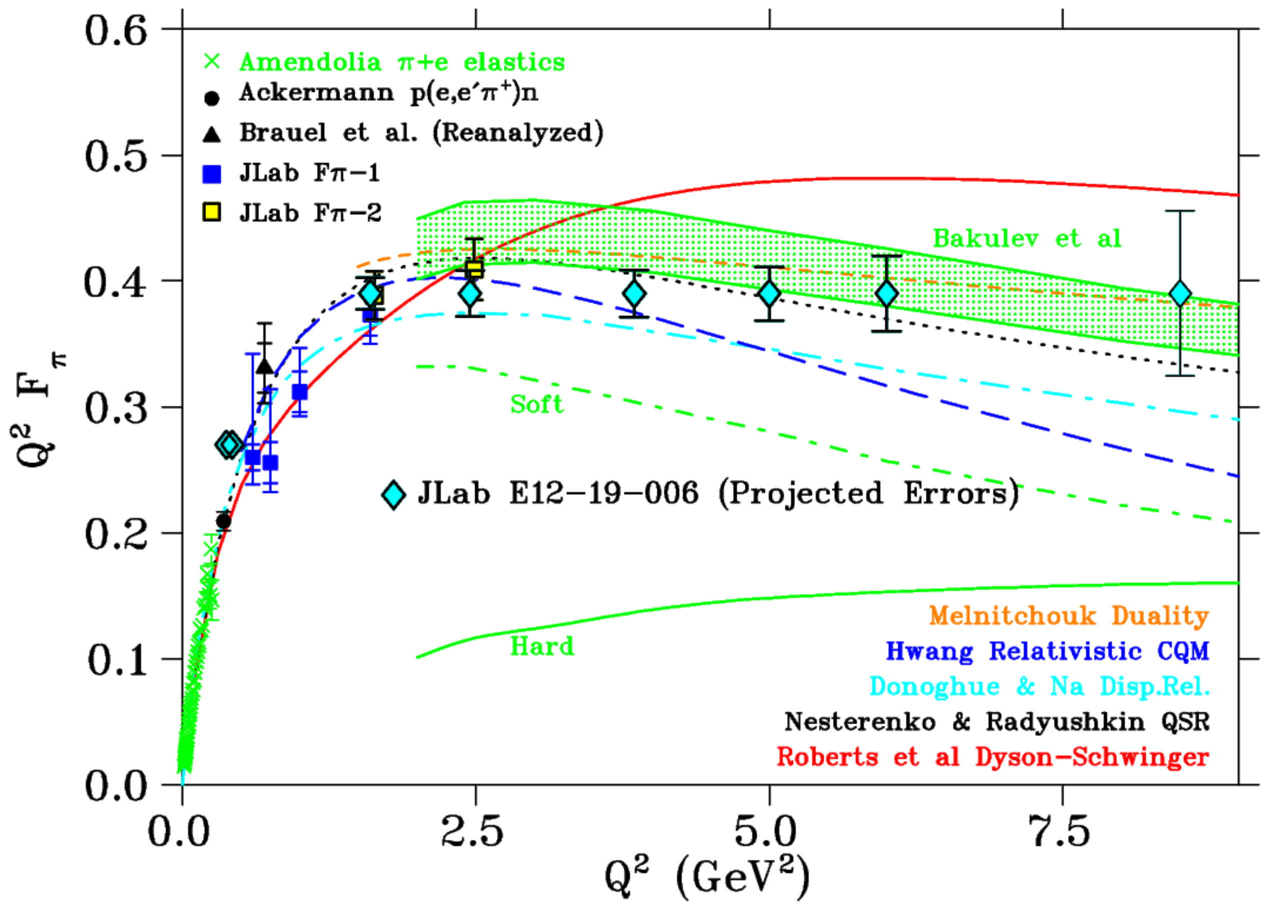
SHMS+HMS will allow measurement of F_π to much higher Q^2

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

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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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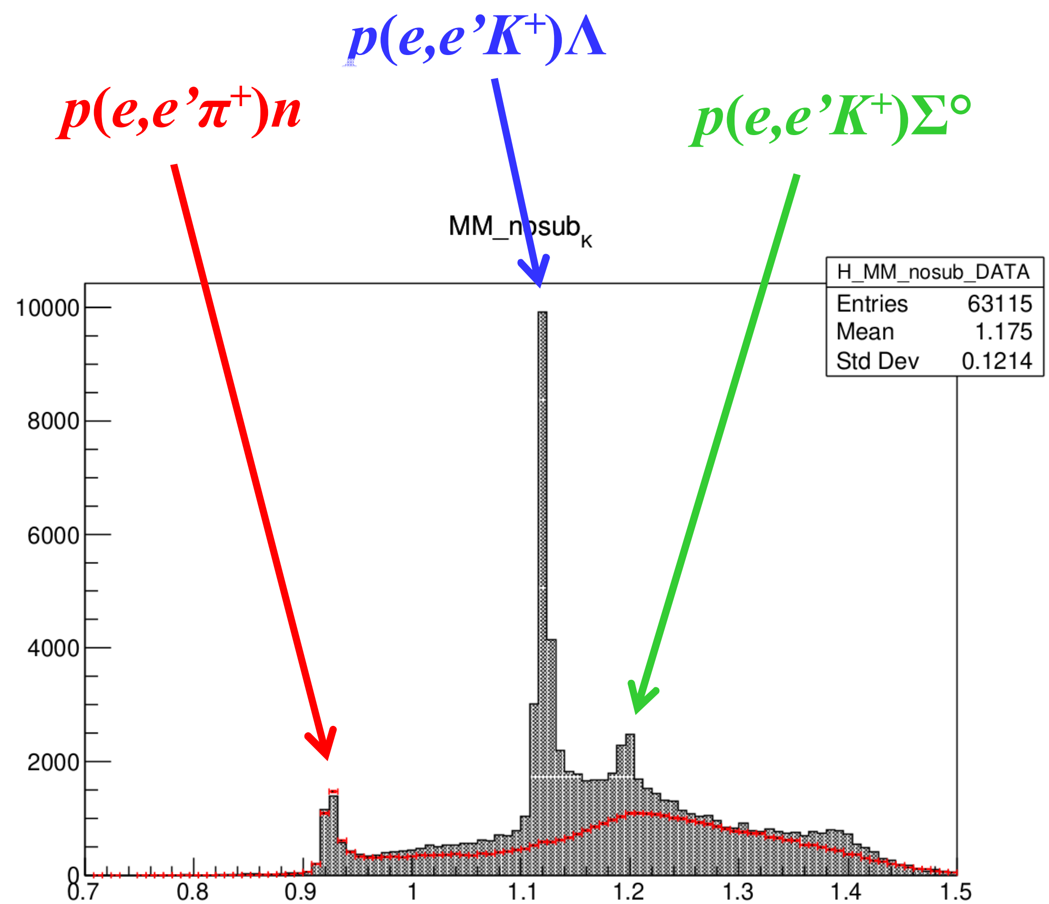
- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and Σ° channels.
- Kaon-pole dominance test through

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

- 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)

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

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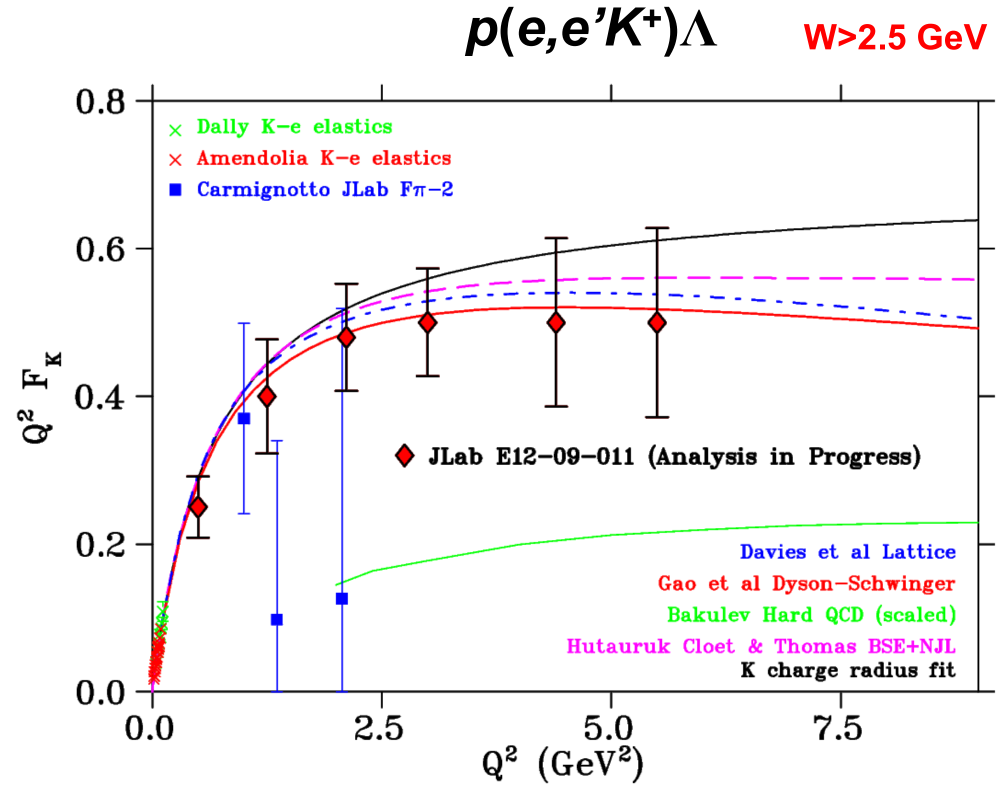
- First measurement of F_K well above the resonance region.
- Measure form factor to Q^2=3 GeV^2 with good overlap with elastic scattering data.
  - Limited by $-t$<0.2 GeV^2 requirement to minimize non–pole contributions.
- Data will provide an important second $q\bar{q}$ system for theoretical models,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



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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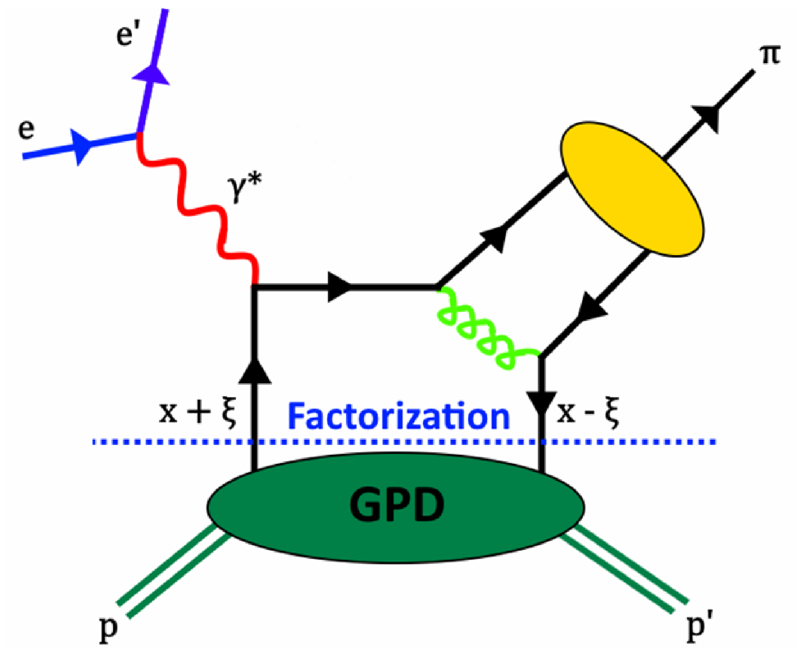
Verification of GPD Accessibility

- **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



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

- **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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Testing Factorization: *p(e,e'π⁺)n*

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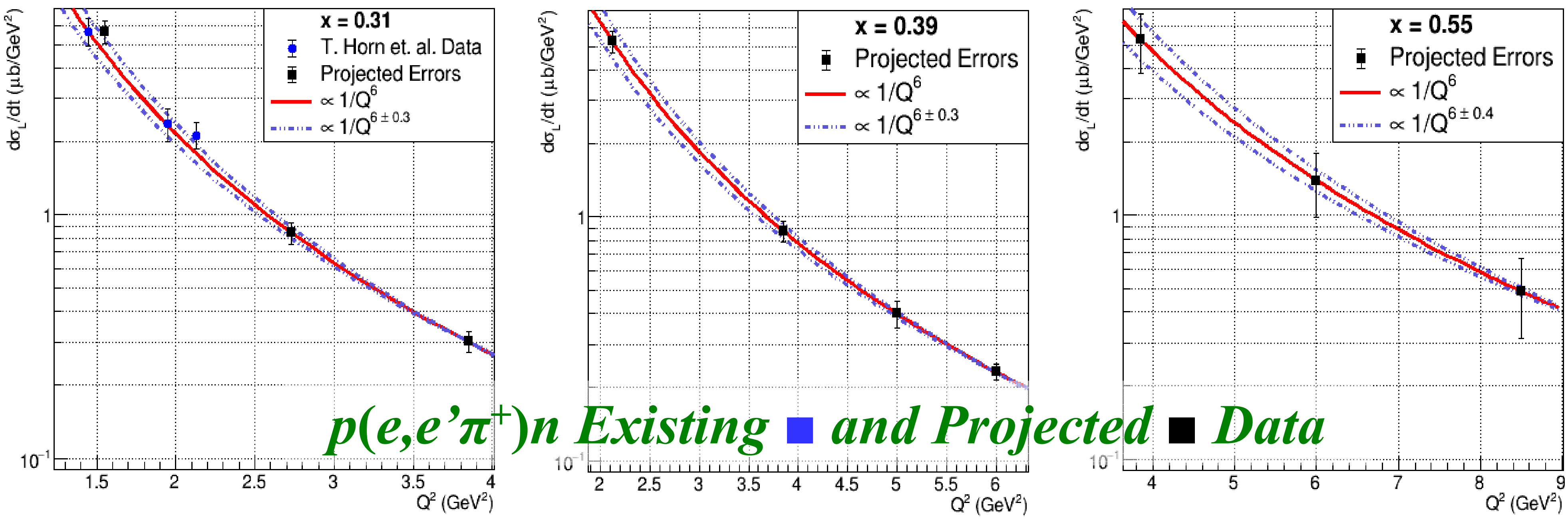
- **One of most stringent tests of factorization is Q^2 dependence of π/K electroproduction cross sections**
  - σ_L scales to leading order as Q^{-6}
  - As Q^2 becomes large: $\sigma_L \gg \sigma_T$
- **If we show factorization regime is not reached, it will have major implications for meson production GPD experiments in this Q^2 regime** (Some of these experiments are already taking data!)



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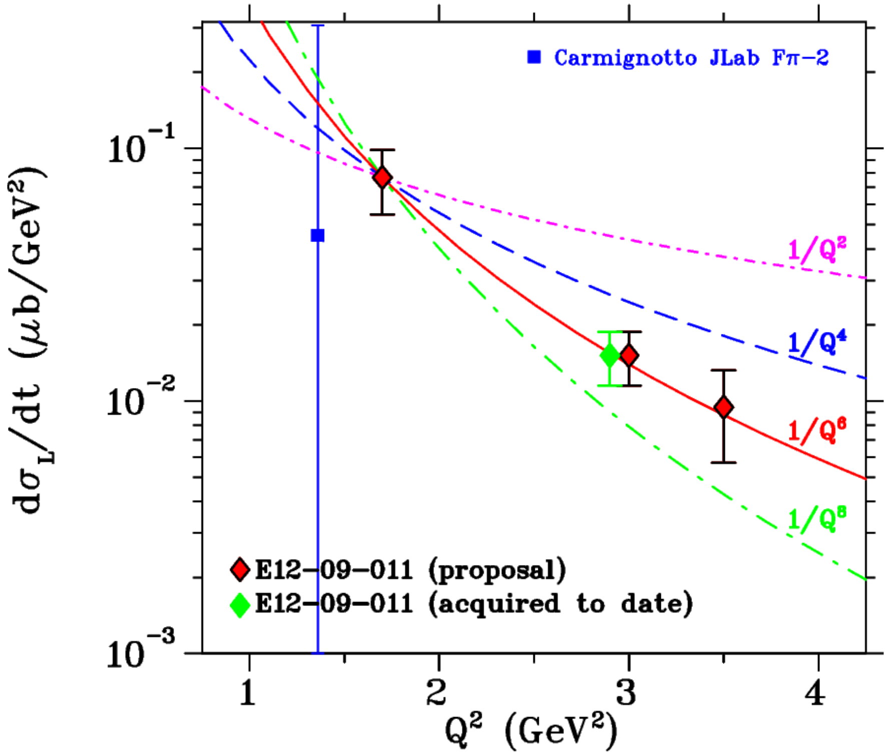
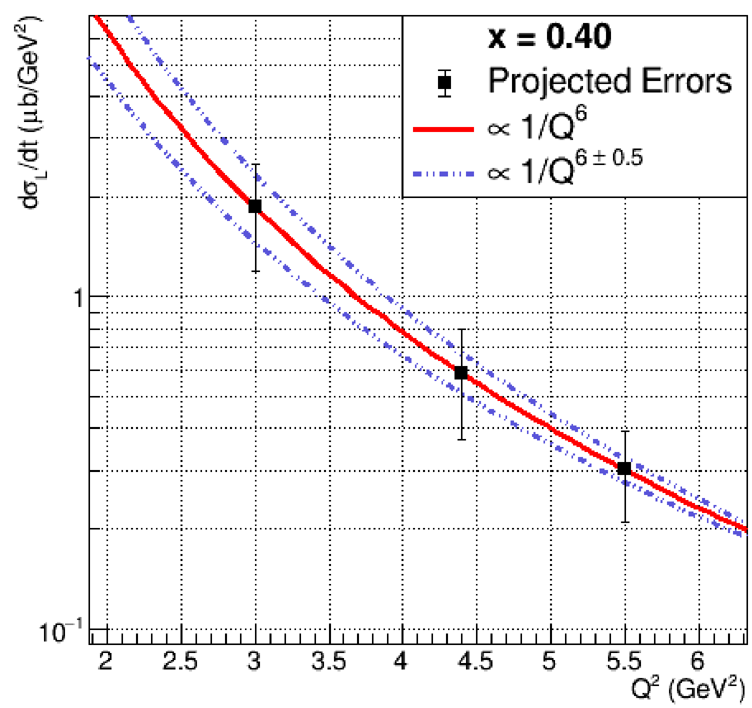
Important 2nd Test: $p(e,e'K^+)\Lambda$

- 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

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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