L–T Separations in Deep Exclusive Meson Production with JLab 22 GeV

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DEMP Opportunities in Hall C

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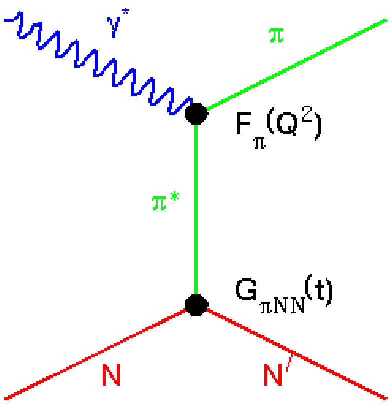
1) Determine the Pion Form Factor to high Q^2:

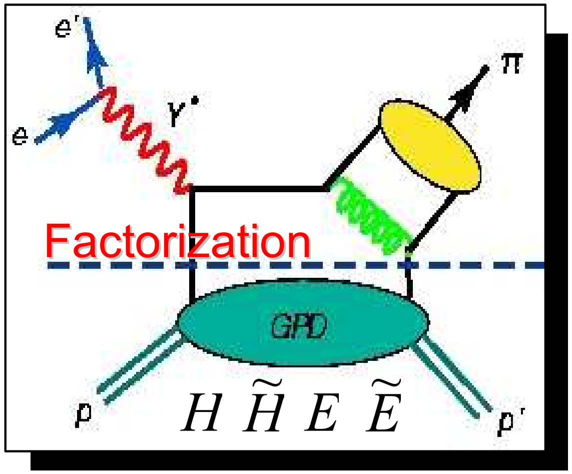


- Indirectly measure F_π using the "pion cloud" of the proton via $p(e,e'\pi^+)n$

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

- **The pion form factor is a key QCD observable**
- Extension of studies to Kaon Form Factor expected to reveal insights on hadronic mass generation via DCSB

2) Study the Hard-Soft Factorization Regime:



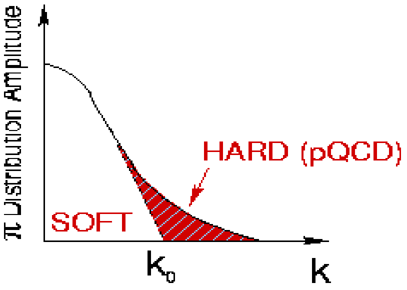
- **Need to determine region of validity of hard-exclusive reaction meachanism, as GPDs can only be extracted where factorization applies**
- Separated $p(e,e'\pi^+/K^+)$ cross sections vs. Q^2 at fixed x to investigate reaction mechanism towards 3D imaging studies
- Extension of studies to u–channel $p(e,e'p)\omega$ can reveal hard–soft factorization at backward angle

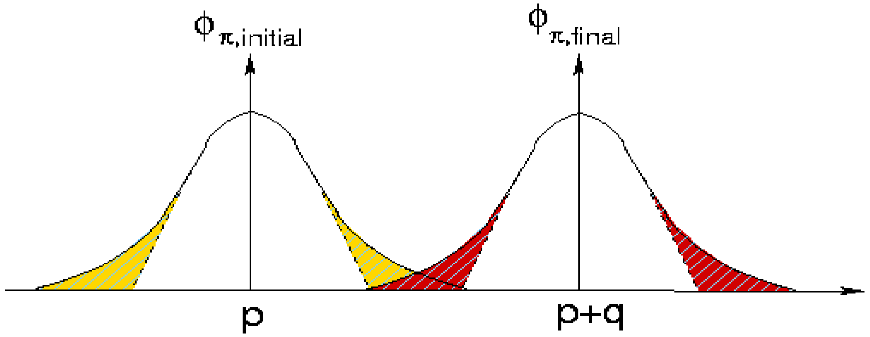
Meson Form Factors

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.

A program of study unique to Hall C (until completion of EIC)

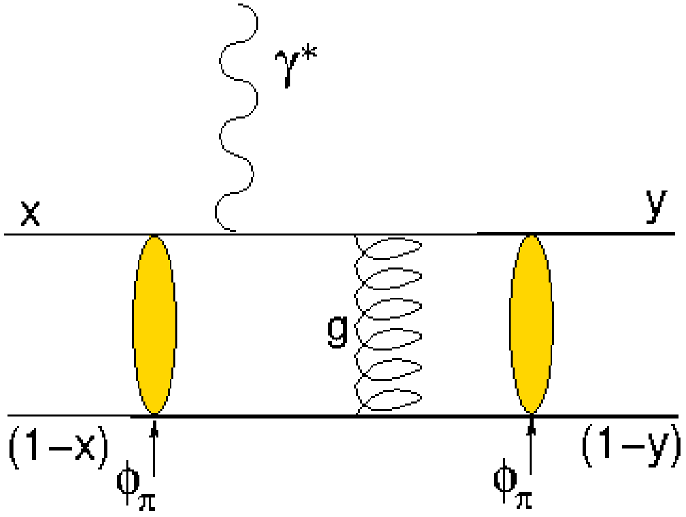
pQCD and the Charged Pion Form Factor

At large Q^2, perturbative QCD (pQCD) can be used

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

at asymptotically high Q^2, only the hardest portion of the wave function remains

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



and F_π takes the very simple form

$$F_\pi(Q^2) \xrightarrow[Q^2\to\infty]{} \frac{16\pi\alpha_s(Q^2) f_\pi^2}{Q^2}$$

where f_π=92.4 MeV is the $\pi^+ \to \mu^+ \nu$ decay constant.

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

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

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Pion Form Factor at Finite Q^2

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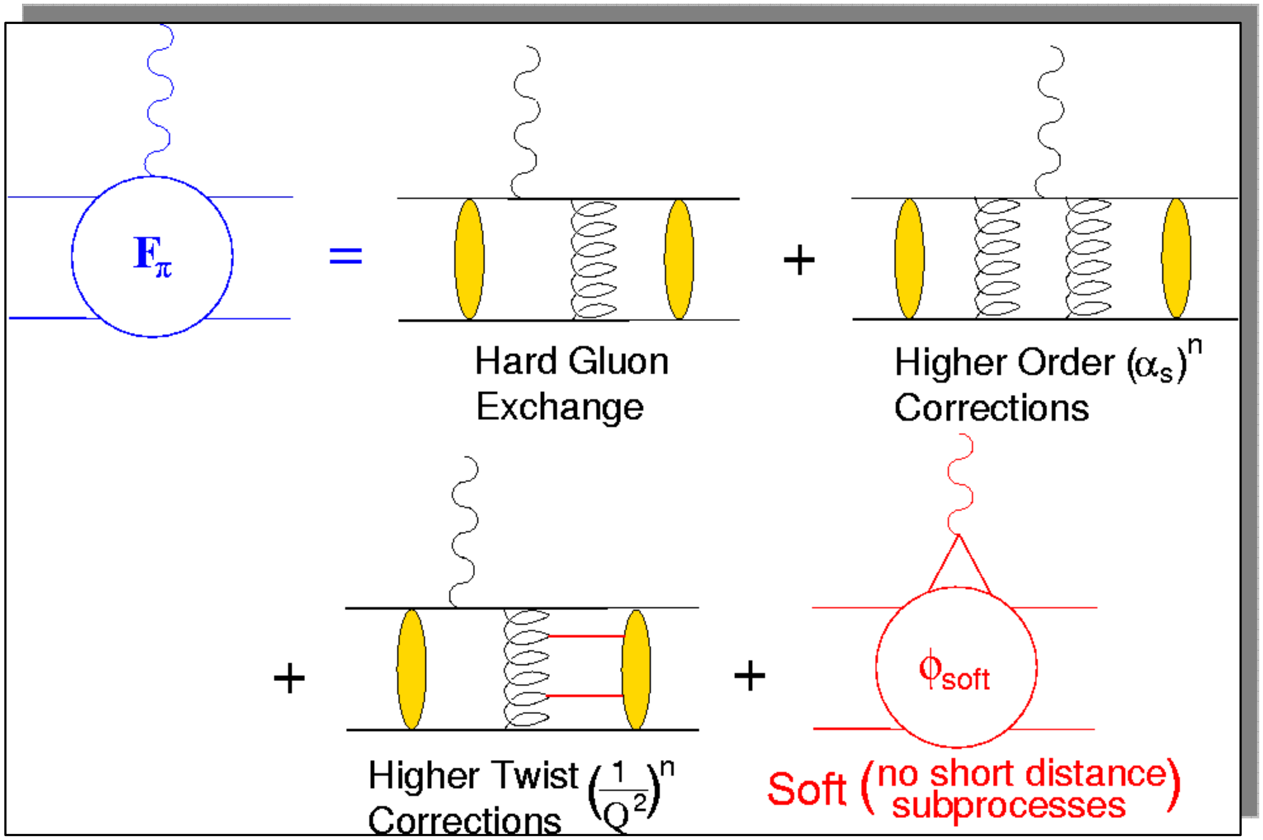
- At finite momentum transfer, higher order terms contribute.
- Calculation of higher order, “hard” (short distance) processes difficult, but tractable.



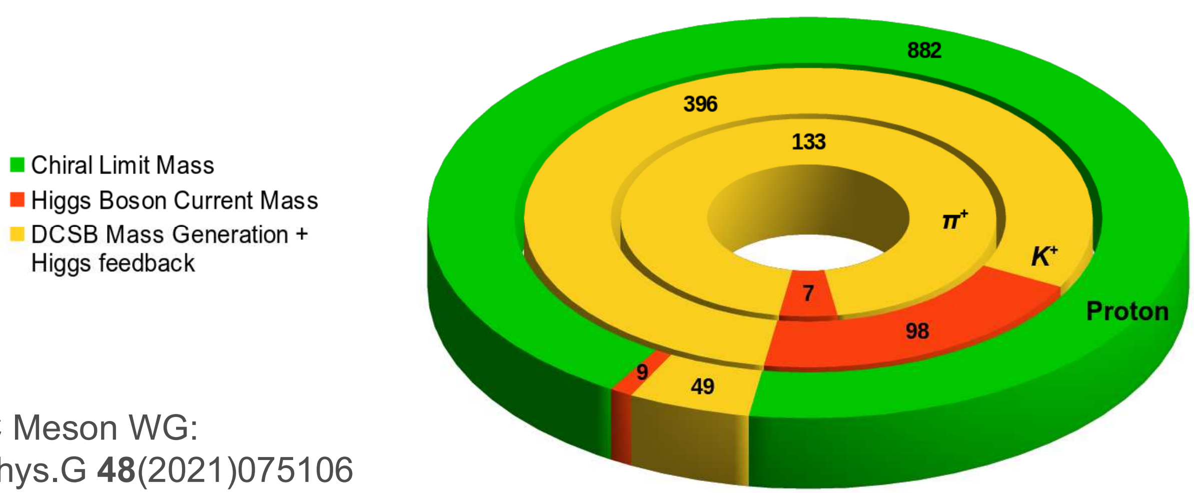
Q^2F_π should behave like $\alpha_s(Q^2)$ even for moderately large Q^2.

→ 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]

Contrasts in Hadron Mass Budgets

Hadron Mass Budget



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

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

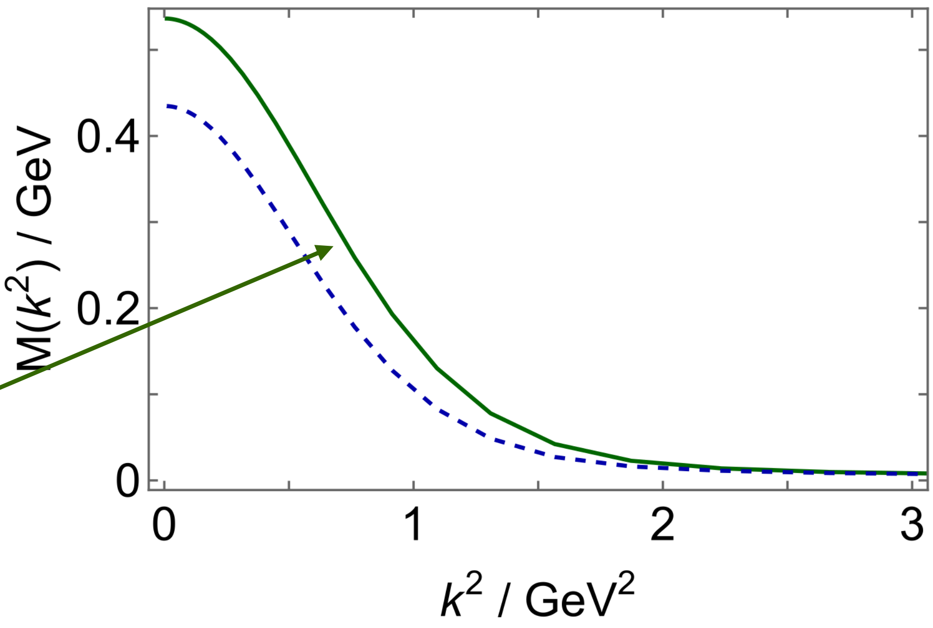
- Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit).
- Conversely, and yet still due to EHM and DCSB, *K* and π are massless in chiral limit (i.e. they are Goldstone bosons of QCD).
- The mass budgets of these crucially important particles 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*.

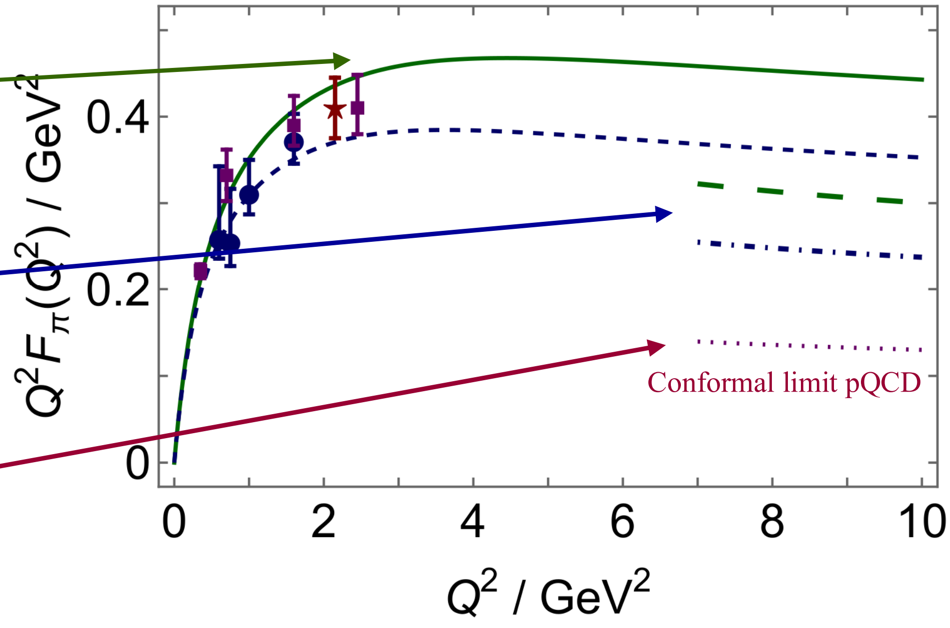
Synergy: Emergent Mass and π^+ Form Factor

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**

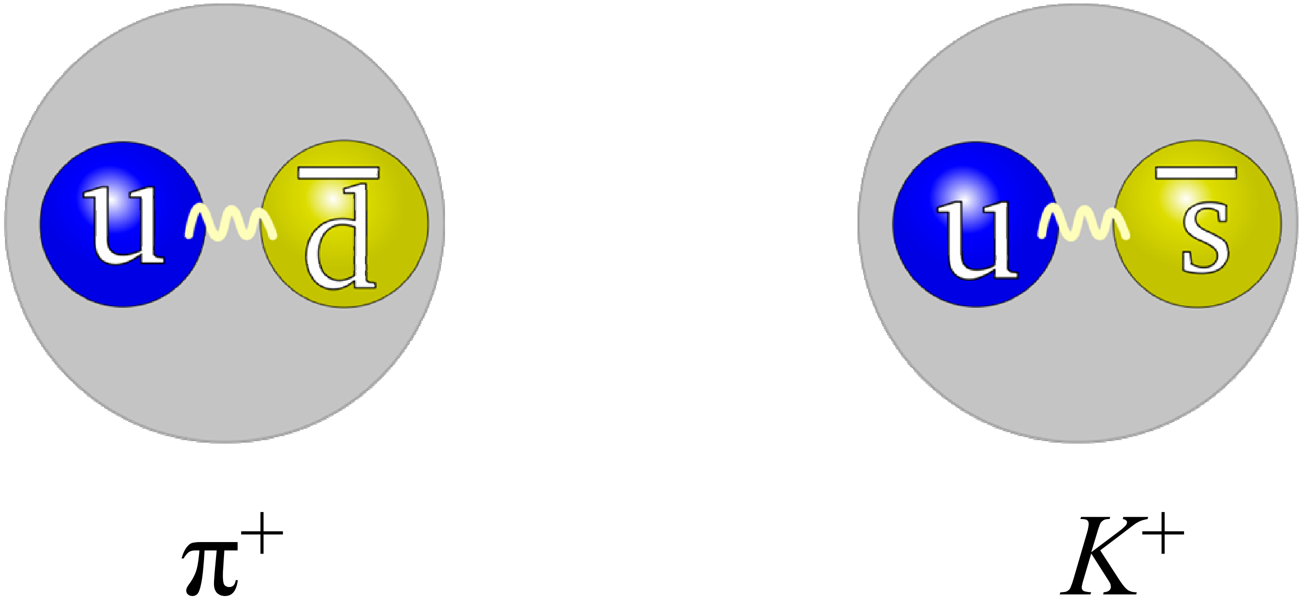
$$\phi_\pi^{cl}(x) = 6x(1-x)$$





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

The Charged Kaon – a 2nd QCD test case



- 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.

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

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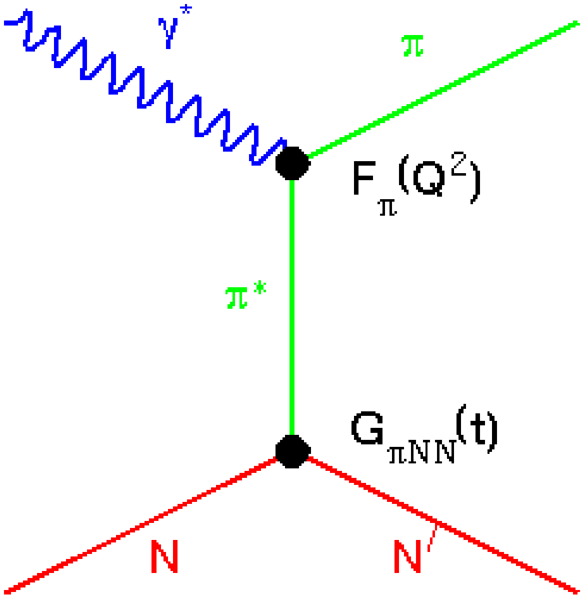
At larger Q^2, F_π must be measured indirectly using the “pion cloud” of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

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

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



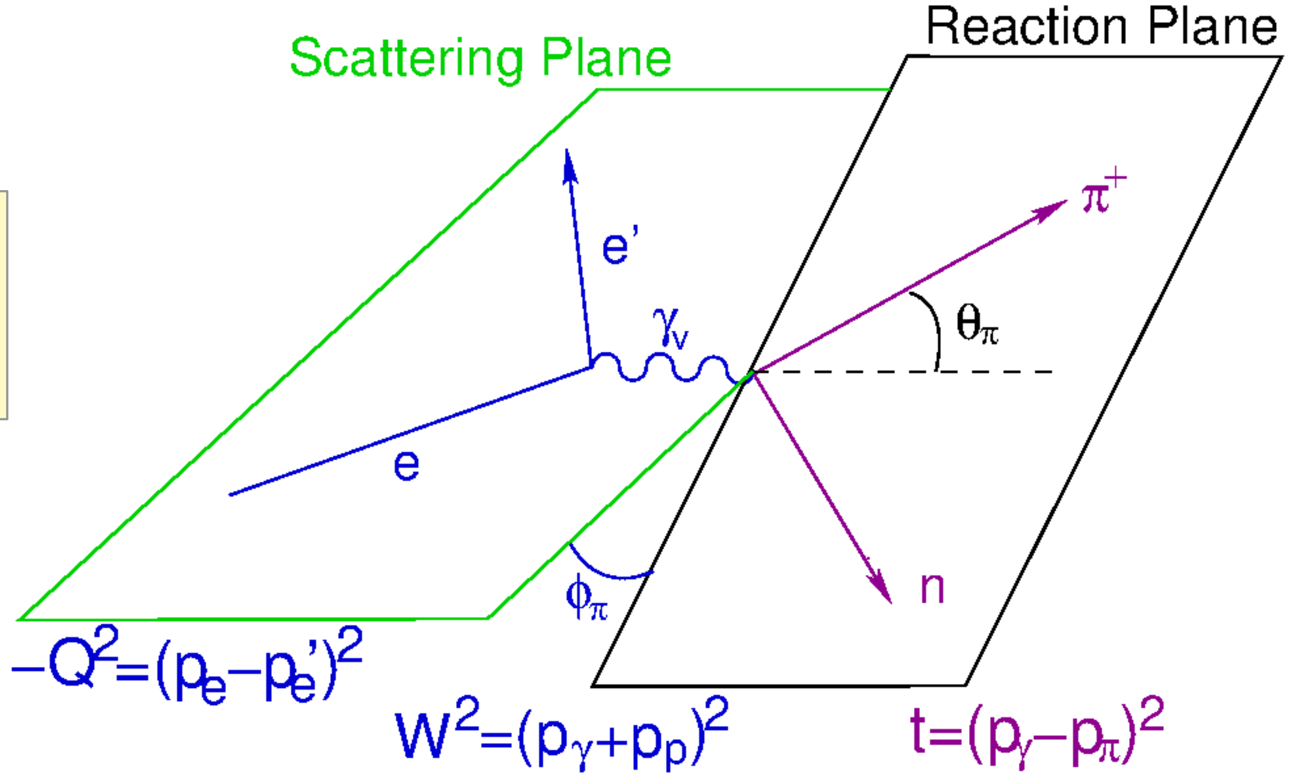
Drawbacks of this technique

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

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

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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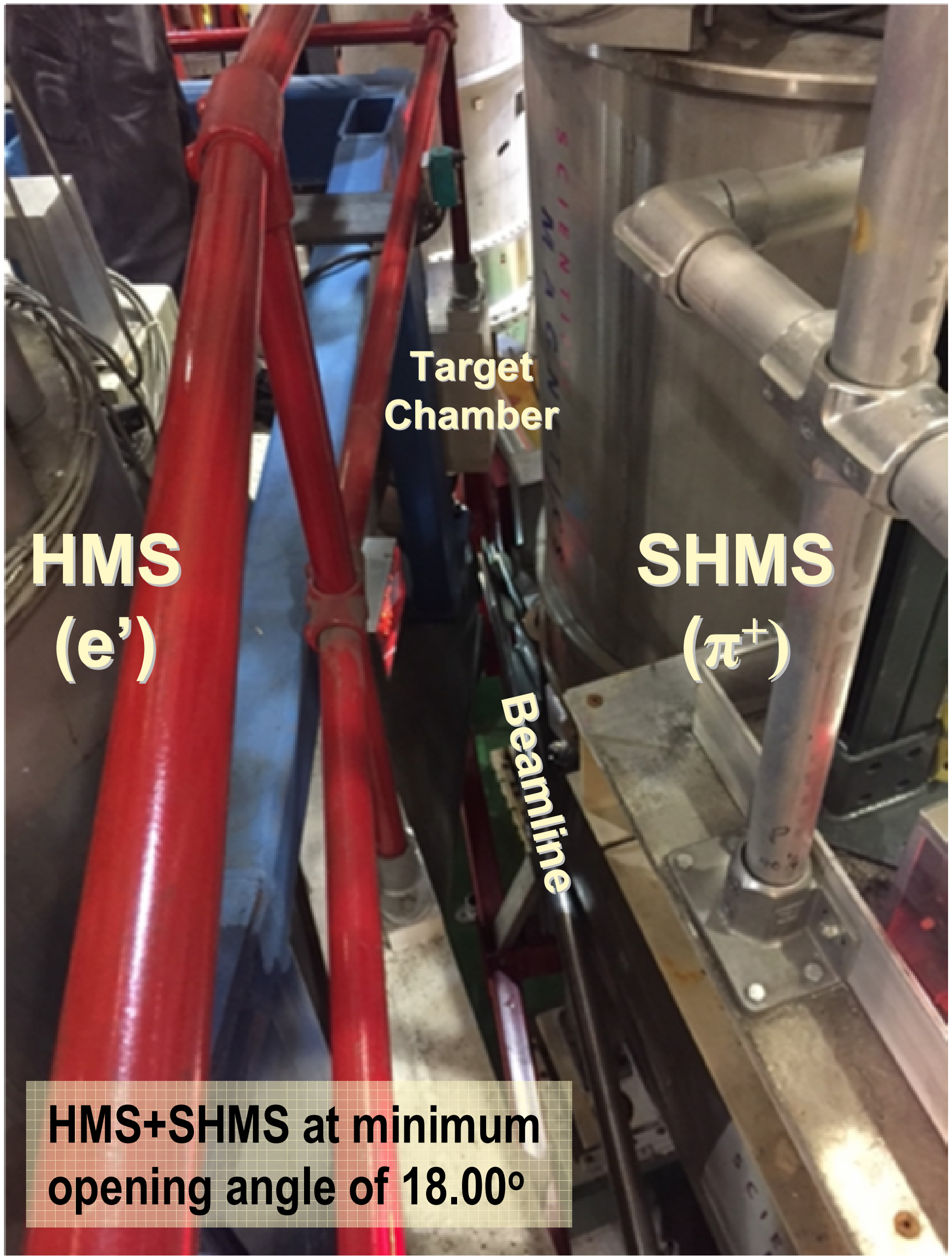
Experimental Issues

- 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

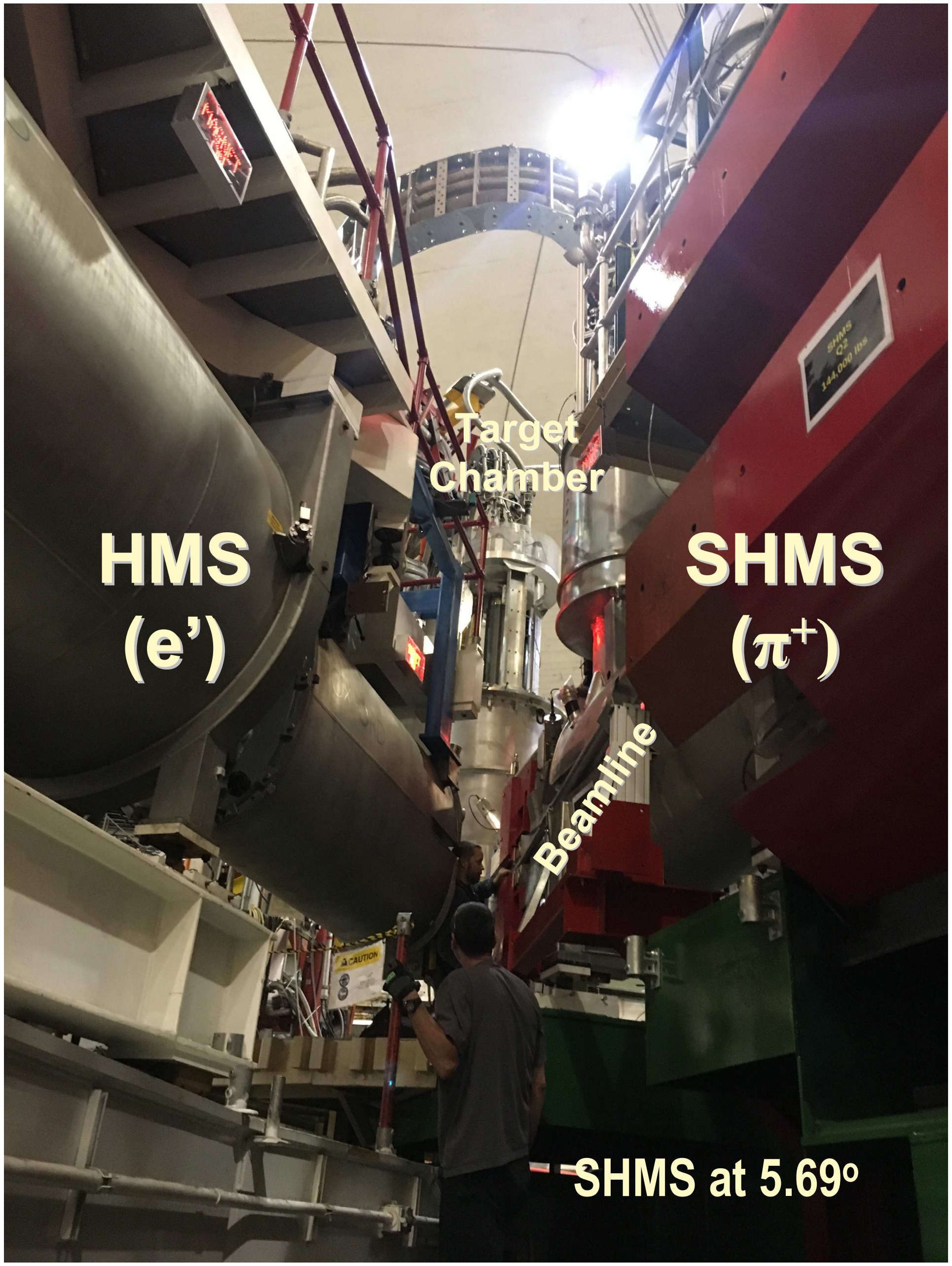
Hall C of Jefferson Lab has been optimized for specifically such studies

Hall C during Data Taking

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



HMS+SHMS at minimum opening angle of 18.00°



SHMS at 5.69°

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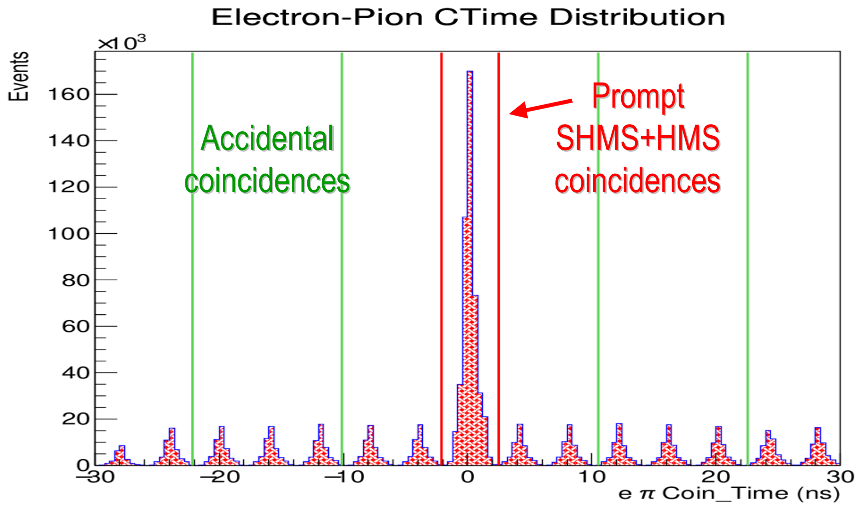
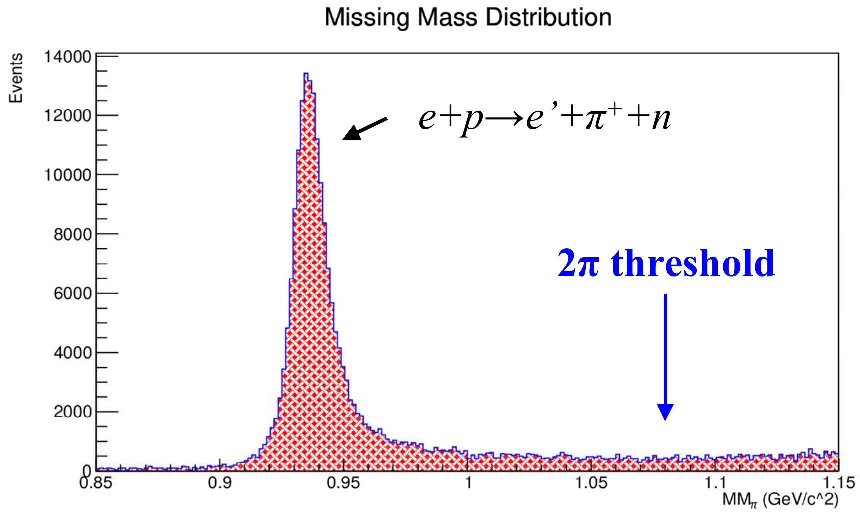
$p(e,e'\pi^+)n$ Event Selection

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

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

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

VGL Regge Model:

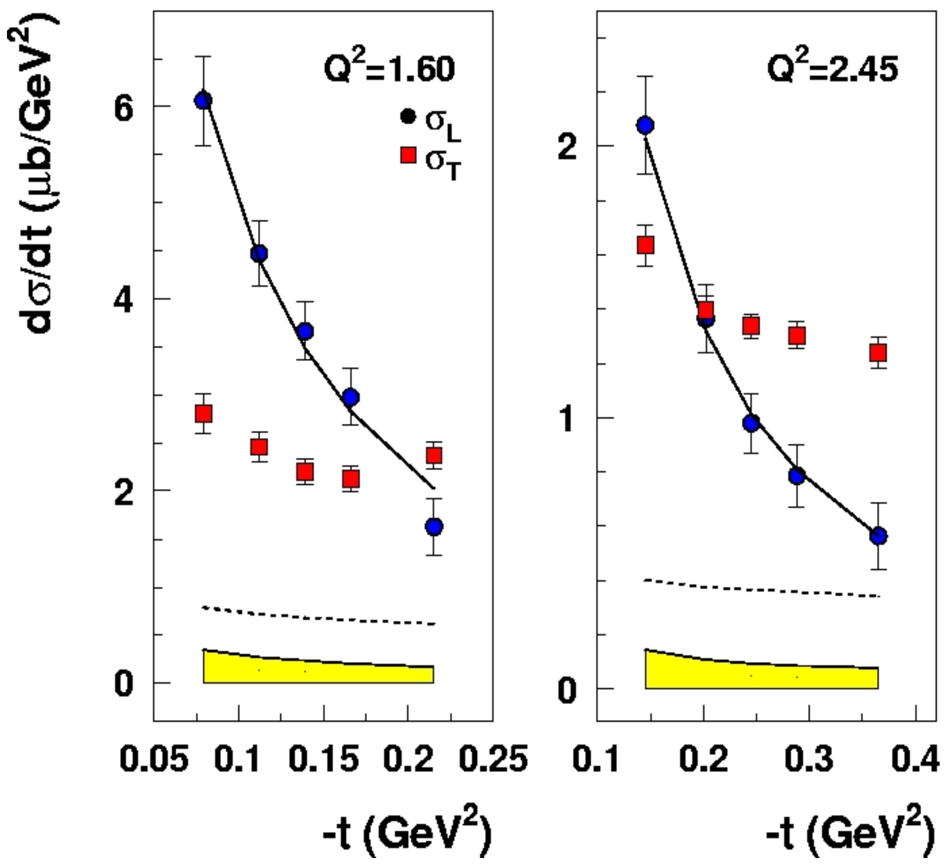
- Feynman propagator $\left(\frac{1}{t-m_\pi^{\;2}}\right)$

  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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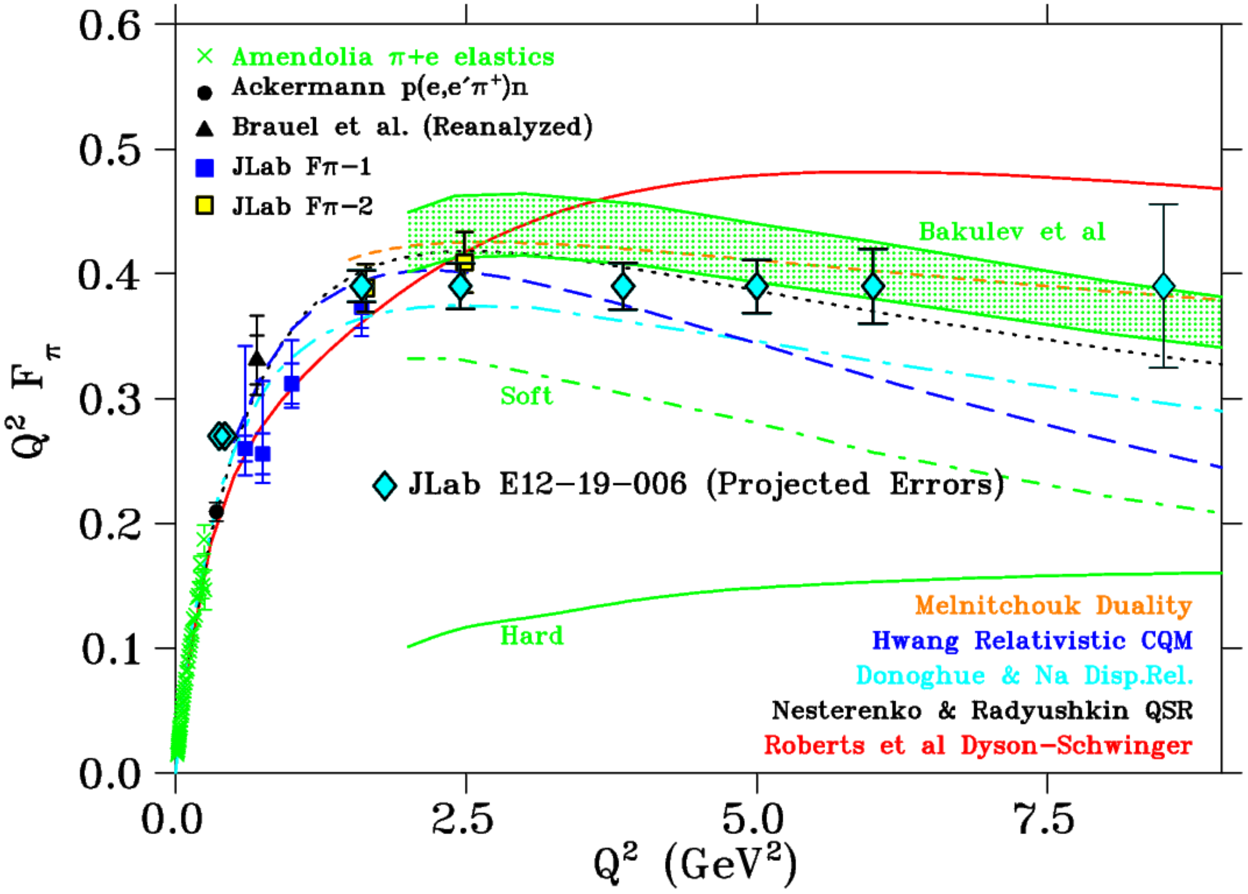
Current and Projected F_π Data

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

No other facility worldwide can perform this measurement.

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



The ~17% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2

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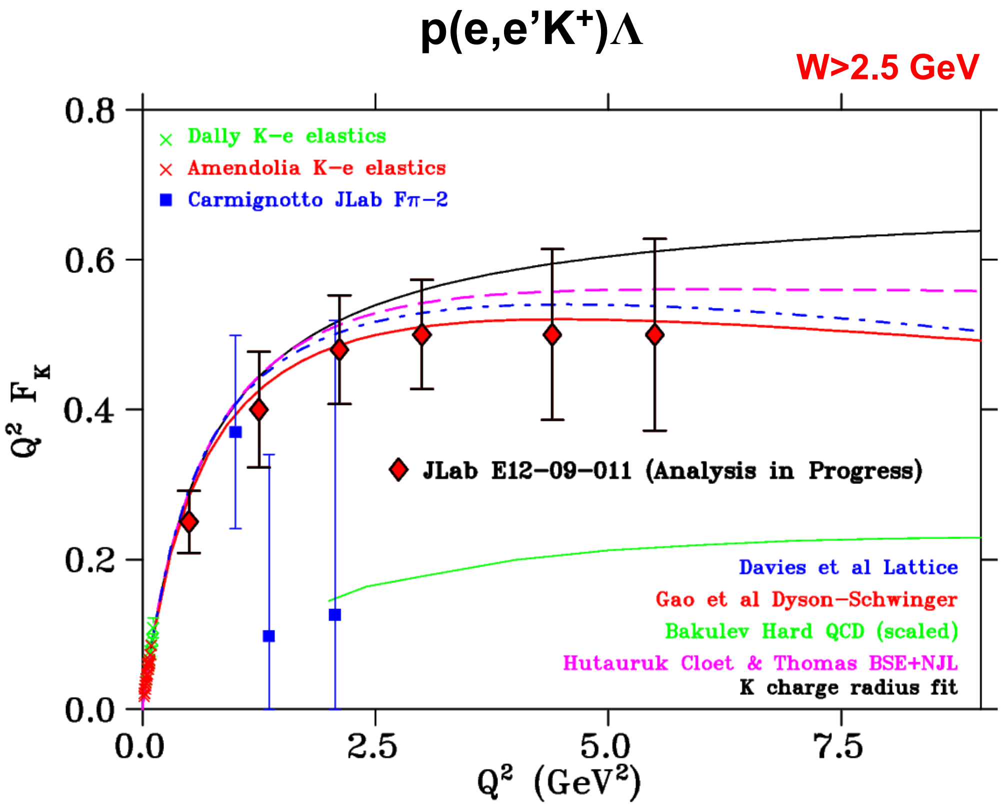
PionLT E12–19–006: D. Gaskell, T. Horn and G. Huber, spokespersons00

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 $q\overline{q}$ system for theoretical models, this time involving a strange quark.



KaonLT E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons

Upgrade Scenarios Considered

Phase 1: higher energy beam, keep HMS+SHMS largely as is, with relatively small DAQ and PID upgrades

- See what can be accomplished in "cost effective approach"
- Goal: to extend kinematic range of L/T–separated measurements beyond what is possible with JLab 11 GeV beam

Phase 2: Replace HMS with a new Very High Momentum Spectrometer (VHMS) to enable measurements utilizing full 22 GeV beam energy

- See what extra physics can be obtained for significantly larger investment

Phase 1 Scenario: π^+ Form Factor

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- 7.2 GeV/c HMS & 11.0 GeV/c SHMS allow a lot of kinematic flexibility, **with no major upgrades**
  - Experiment could be done as soon as beam energy is available!
  - Maximum beam energy and higher Q^2 reach constrained by sum of HMS+SHMS maximum momenta
  - Q^2=8.5 and 11.5 Time FOM similar to PionLT Q^2=6.0 and 8.5 points

	10.6 GeV	18.0 GeV	Improvement in $\delta F_\pi/F_\pi$
Q^2=8.5	$\Delta\varepsilon$=0.22	$\Delta\varepsilon$=0.40	16.8%→8.0%
Q^2=10.0	New high quality F_π data		
Q^2=11.5	Larger F_π extraction uncertainty due to higher $-t_{min}$		

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

E_{beam}	θ_{HMS} (e’)	P_{HMS} (e’)	$\theta_{q(SHMS)}$ (π^+)	P_{SHMS} (π^+)	Time FOM
Q^2=8.5 W=3.64 $-t_{min}$=0.24 $\Delta\varepsilon$=0.40					
13.0	34.30	1.88	5.29	10.99	64.7
18.0	15.05	6.88	8.94	10.99	2.2
Q^2=10.0 W=3.44 $-t_{min}$=0.37 $\Delta\varepsilon$=0.40					
13.0	37.78	1.83	5.56	10.97	122.7
18.0	16.39	6.83	9.57	10.97	4.5
Q^2=11.5 W=3.24 $-t_{min}$=0.54 $\Delta\varepsilon$=0.29					
14.0	31.73	2.75	7.06	10.96	82.4
18.0	17.70	6.75	10.05	10.96	8.8

- **Since quality L–T separations are impossible at EIC (can’t access ε<0.95) this extension of L–T separated data considerably increases F_π data set overlap between JLab and EIC**

Phase 1 Scenario: K^+ Form Factor

- 7.2 GeV/c HMS & 11.0 GeV/c SHMS allow a lot of kinematic flexibility
- Maximum beam energy and higher Q^2 reach constrained by sum of HMS+SHMS maximum momenta
- Success depends on good K^+/π^+ separation in SHMS at high momenta, likely requires a modest aerogel detector upgrade
- Counting rates are roughly 10x lower than pion form factor measurement

	10.6 GeV	16.0 GeV	Improvement in $\delta F_K/F_K$
Q^2=5.5	$\Delta\varepsilon$=0.33	$\Delta\varepsilon$=0.40	17.9%→10.7%
Q^2=7.0	New high quality F_K data		
Q^2=9.0	Larger F_K extraction uncertainty due to higher $-t_{min}$		

$p(e,e'K^+)\Lambda$ Kinematics

E_{beam}	θ_{HMS} (e')	P_{HMS} (e')	$\theta_{q(SHMS)}$ (π^+)	P_{SHMS} (π^+)	Time FOM
Q^2=5.5 W=3.56 $-t_{min}$=0.32 $\Delta\varepsilon$=0.40					
11.0	30.69	1.79	5.50	8.84	746
16.0	12.92	6.79	9.18	8.84	150
Q^2=7.0 W=3.90 $-t_{min}$=0.33 $\Delta\varepsilon$=0.29					
14.0	25.16	2.64	5.51	10.98	620
18.0	13.91	6.64	7.85	10.98	192
Q^2=9.0 W=3.66 $-t_{min}$=0.54 $\Delta\varepsilon$=0.30					
14.0	29.17	2.54	5.98	10.97	964
18.0	15.90	6.54	8.69	10.97	350

- **F_K feasibility studies at EIC are ongoing, but we already know that such measurements there are exceptionally complex.**
- **JLab measurements likely a complement to those at EicC.**

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Phase 1: Form Factor Projections

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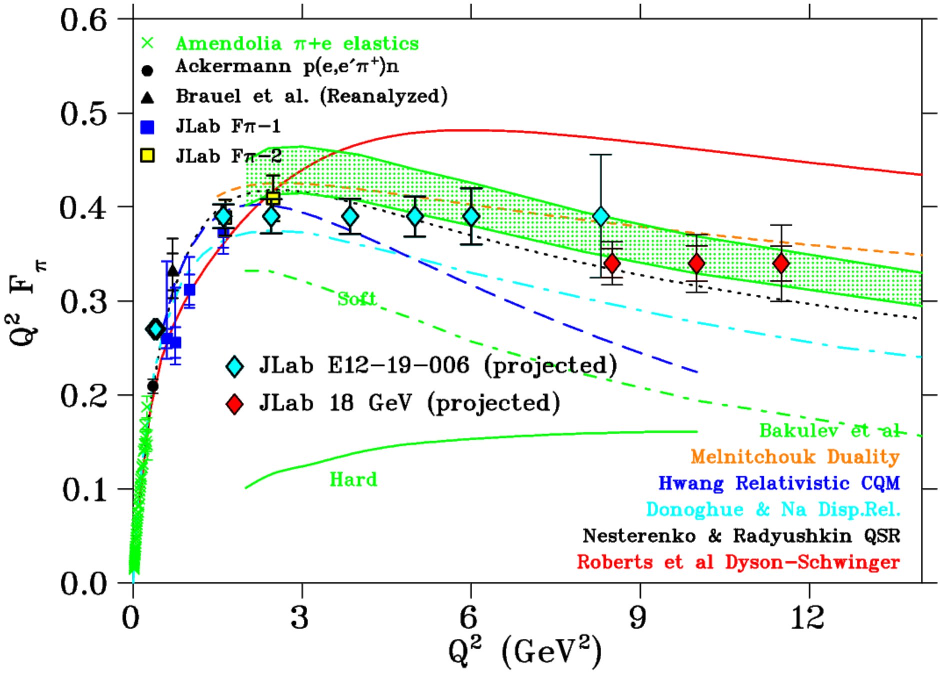
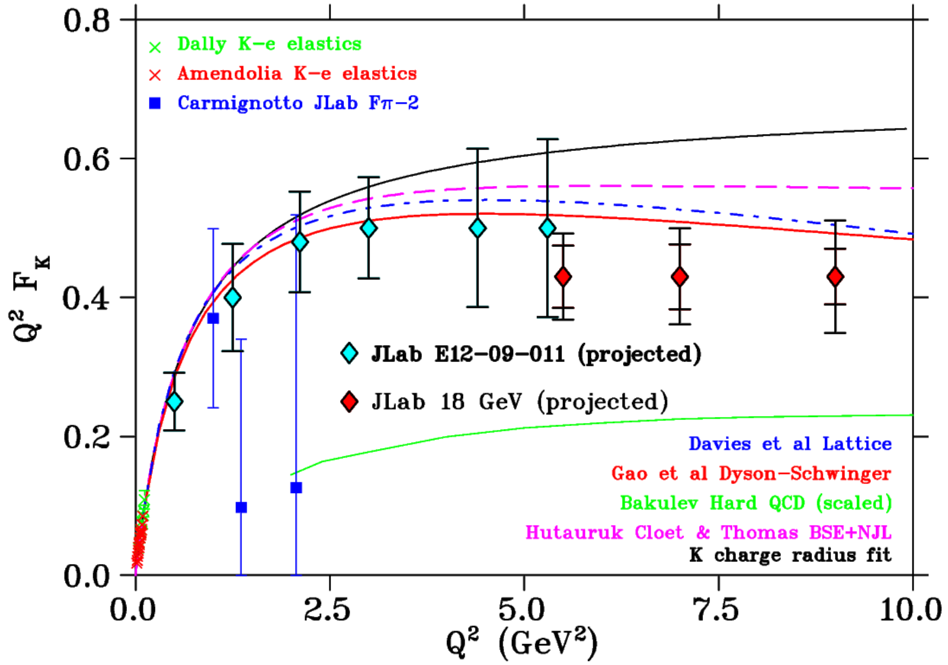
- Y-axis values of projected data are arbitrary
- The errors are projected, based on Δε from beam energies on earlier slides, and T/L ratio calculated with Vrancx Ryckebusch model
- Assumes same statistics as acquired in PionLT experiment
- Inner error bar is projected statistical and systematic error
- Outer error bar also includes a model uncertainty in the form factor extraction, added in quadrature
- F_π errors based on Fπ–2 and E12–19–006 experience
- F_K errors more uncertain, as E12–09–011 analysis not yet completed, projected running times extremely long





Phase 2 Scenario: π^+ Form Factor

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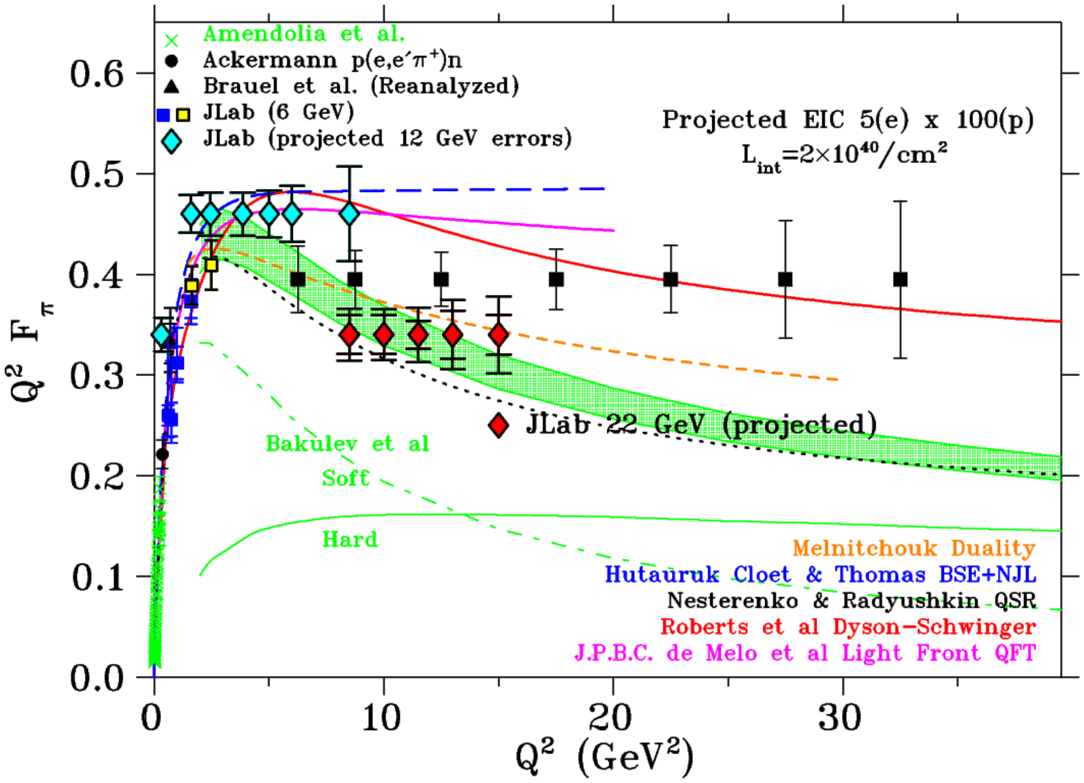
- **Replace HMS with VHMS for π^+, use SHMS for e'**
  - Assume θ_{min}=5.5°, θ_{open}=15.0°
  - VHMS: ΔΩ, ΔP/P similar SHMS
- P_{VHMS}=15.0 GeV/c is sufficient, constrained by max beam energy
- θ_{VHMS}~5.5° allows improved Δε, but does not affect maximum Q^2 reach
- θ_{SHMS}<12.0°, P_{SHMS}>9.0 not used
- Dramatic increase in upper Q^2 11.5 → 15.0 GeV^2
- Error bars for Q^2=8.5–11.5 GeV^2 substantially decrease due to smaller $-t_{min}$ (better $R=\sigma_T/\sigma_L$) and shorter running times
- Q^2=15.0 GeV^2 point would be very "expensive" in terms of running time, but it would likely have very high scientific priority
- **Feasible scenario for Phase 2 Upgrade**

<table>
<tr><th colspan="6">p(e,e'π^+)n Kinematics</th></tr>
<tr><th>E_{beam}</th><th>θ_{SHMS} (e')</th><th>P_{SHMS} (e')</th><th>$\theta_{q(VHMS)}$ (π^+)</th><th>P_{VHMS} (π^+)</th><th>Time FOM</th></tr>
<tr><td colspan="6">Q^2=8.5 W=4.18 $-t_{min}$=0.15 Δε=0.28</td></tr>
<tr><td>17.0</td><td>21.39</td><td>3.63</td><td>5.55</td><td>13.29</td><td>20.5</td></tr>
<tr><td>22.0</td><td>12.15</td><td>8.63</td><td>7.62</td><td>13.29</td><td>1.8</td></tr>
<tr><td colspan="6">Q^2=10.0 W=4.08 $-t_{min}$=0.21 Δε=0.30</td></tr>
<tr><td>17.0</td><td>24.49</td><td>3.27</td><td>5.52</td><td>13.62</td><td>53.3</td></tr>
<tr><td>22.0</td><td>13.46</td><td>8.27</td><td>7.85</td><td>13.62</td><td>4.3</td></tr>
<tr><td colspan="6">Q^2=11.5 W=3.95 $-t_{min}$=0.29 Δε=0.31</td></tr>
<tr><td>17.0</td><td>27.34</td><td>3.03</td><td>5.55</td><td>13.82</td><td>124.8</td></tr>
<tr><td>22.0</td><td>14.66</td><td>8.03</td><td>8.12</td><td>13.82</td><td>9.3</td></tr>
<tr><td colspan="6">Q^2=13.0 W=3.96 $-t_{min}$=0.35 Δε=0.25</td></tr>
<tr><td>18.0</td><td>27.55</td><td>3.18</td><td>5.54</td><td>14.63</td><td>209.5</td></tr>
<tr><td>22.0</td><td>16.49</td><td>7.18</td><td>7.69</td><td>14.63</td><td>24.4</td></tr>
<tr><td colspan="6">Q^2=15.0 W=3.73 $-t_{min}$=0.52 Δε=0.26</td></tr>
<tr><td>18.0</td><td>30.24</td><td>3.06</td><td>5.73</td><td>14.66</td><td>560</td></tr>
<tr><td>22.0</td><td>17.88</td><td>7.06</td><td>8.07</td><td>14.66</td><td>65.7</td></tr>
</table>

Importance of JLab F_π in EIC Era



- Quality L/T-separations impossible at EIC (can't access ε<0.95)
- JLab will remain ONLY source of quality L–T separated data!
- **Phase 2: 22 GeV beam with upgraded VHMS**
  - Extends region of high quality F_π values to $Q^2=13$ GeV^2
  - Somewhat larger errors to $Q^2=15$ GeV^2
- Provides MUCH improved overlap of F_π data set between JLab and EIC!

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Hard–Soft Factorization in DEMP

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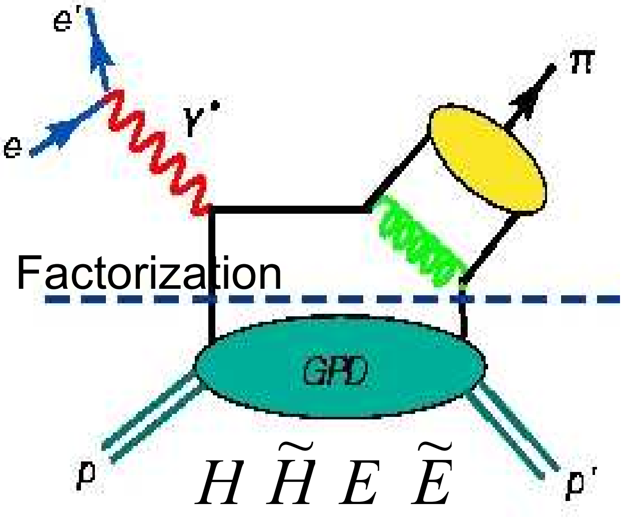
- **To access physics contained in GPDs, one is limited to the kinematic regime where hard-soft factorization applies**
  - No single criterion for the applicability, but tests of necessary conditions can provide evidence that the Q^2 scaling regime has been reached

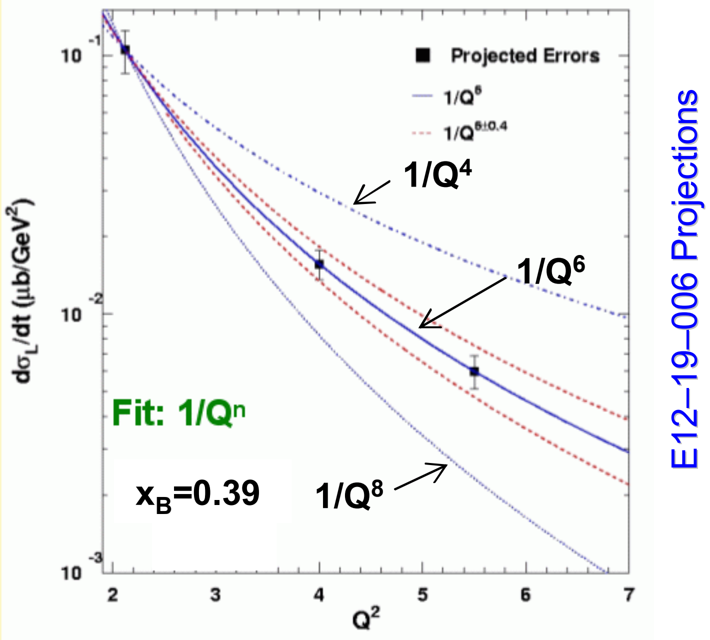
- **One of the most stringent tests of factorization is the Q^2 dependence of the π/K electroproduction cross sections**
  - σ_L scales to leading order as Q^{-6}
  - σ_T does not, expectation of Q^{-8}
  - As Q^2 becomes large: $\sigma_L >> \sigma_T$



- **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

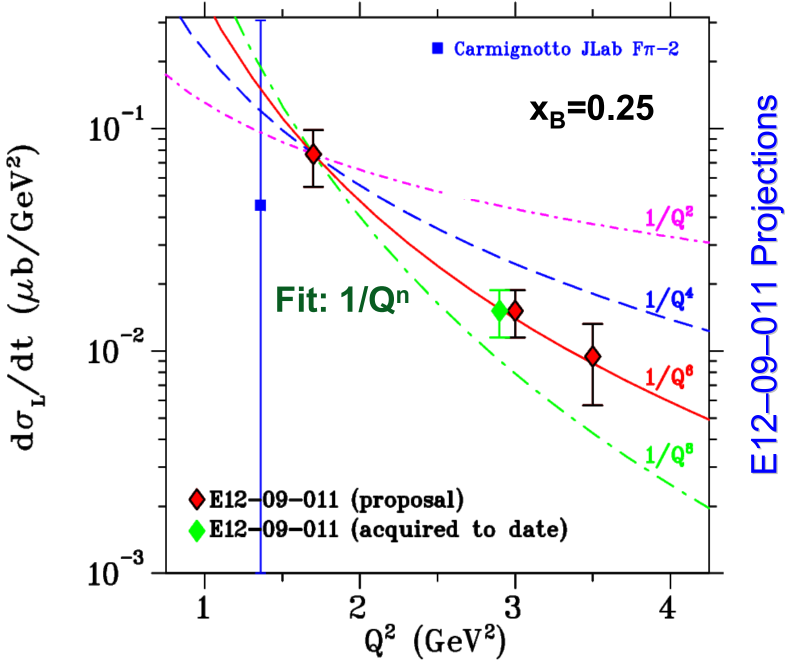
DEMP Q^{-n} Hard–Soft Factorization Tests

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



x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ (GeV^2)
0.31	1.45–3.65	2.02–3.07	0.12
	1.45–6.5	2.02–3.89	
0.39	2.12–6.0	2.05–3.19	0.21
	2.12–8.2	2.05–3.67	
0.55	3.85–8.5	2.02–2.79	0.55
	3.85–11.5	2.02–3.23	

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



x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ (GeV^2)
0.25	1.7–3.5	2.45-3.37	0.20
	1.7–5.5	2.45–4.05	
0.40	3.0–5.5	2.32–3.02	0.50
	3.0–8.7	2.32–3.70	

PHASE 1 SCENARIO

***Q^{-n}* scaling test range nearly doubles with 18 GeV beam and HMS+SHMS**

Hard–Soft Factorization in Backward Exclusive π^0

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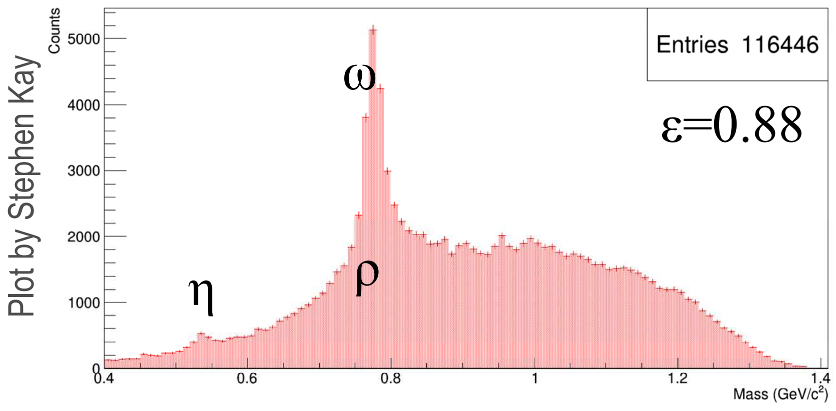
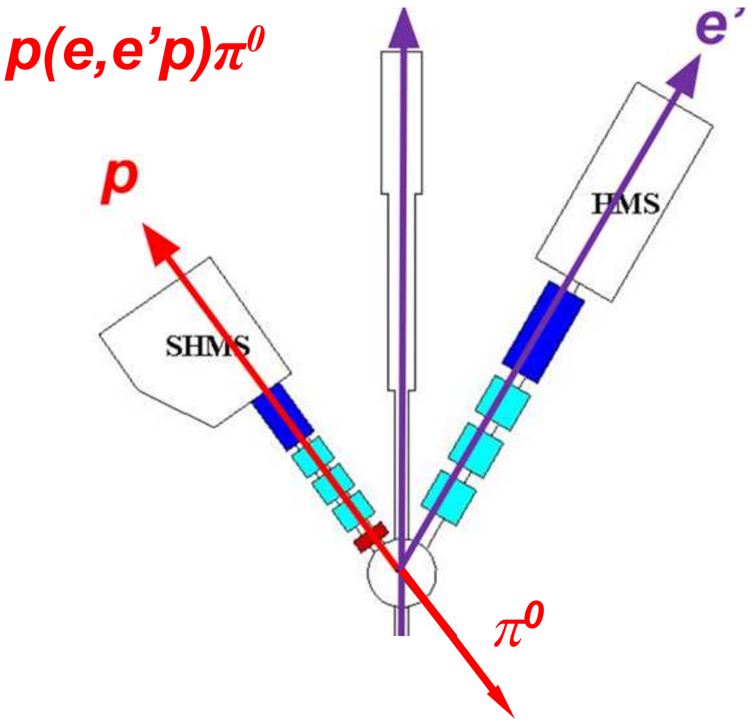
p(e ,e'p)X KaonLT Data Analysis

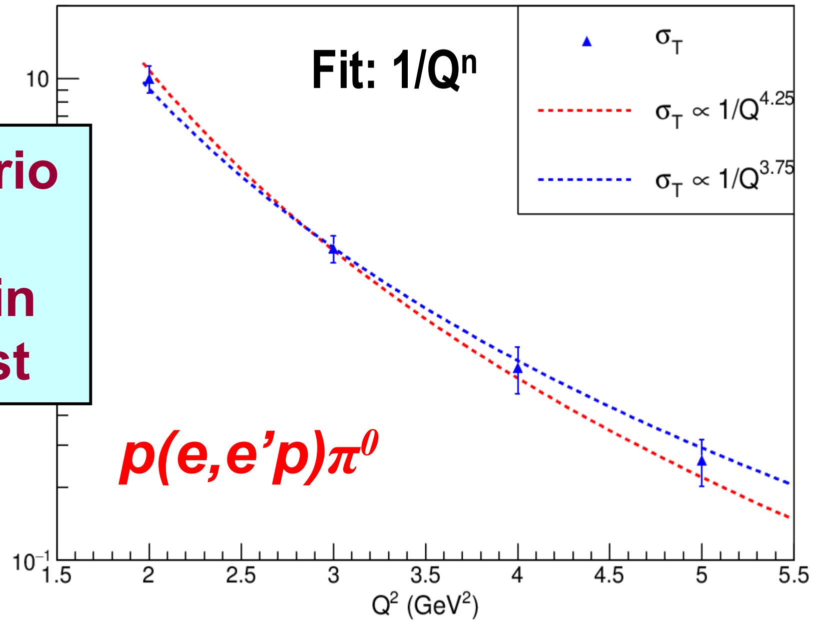
Q^2=3.00 W=2.32 θ_{pq}=+3.0° $-u$=0.15 ξ_u=0.15



- **Fortuitous discovery of substantial backward angle meson production during meson form factor experiments**
- Can be described by extension of collinear factorization to backward angle (u–channel)
- Backward angle factorization first suggested by Frankfurt, Polykaov, Strikman, Zhalov, Zhalov [arXiv:hep-ph/0211263]



Phase 1 Scenario will enable improvement in *Q⁻ⁿ* scaling test



E12–20–007: First dedicated u–channel experiment

Spokespersons: W.B. Li, G.M. Huber, J. Stevens

Purpose: test applicability of TDA formalism for π^0 production

Staged Upgrade Seems Logical

- **Phase 1:** Upgrade Beam to 18 GeV, minor upgrades of SHMS, HMS PID, tracking and DAQ
  - Example Measurements:
  - Pion form factor to Q^2=10 GeV^2 with small errors, and to 11.5 with larger uncertainties
  - Kaon form factor requires very long running times, but could allow Q^2=7.0 GeV^2 with small errors, and to 9.0 with larger uncertainties
  - Hard–Soft Q^{-n} factorization tests with $p(e,e'\pi^+)n$ and $p(e,e'K^+)\Lambda$
  - Studies of backward angle Q^{-n} factorization via u–channel $p(e,e'p)\pi^0$ and $p(e,e'p)\omega$
- **Phase 2:** Upgrade Beam to 22 GeV, upgrade VHMS to 15 GeV/c
  - Would enable a significant increase in Q^2 reach of quality L–T separations for Deep Exclusive Meson Production
    - e.g. Pion Form factor up to Q^2=15 GeV^2

The importance of L–T Separations

- **Hall C is world's only facility that can do L–T separations over a wide kinematic range**
- The error magnification in L–T separations depends crucially on the achievable difference in the virtual photon polarization parameter, ε.
  - Errors magnify as 1/Δε, where $\Delta\varepsilon=\varepsilon_{High}-\varepsilon_{Low}$
  - To keep the magnification <500%, one desires Δε>0.2
  - This is not feasible at the EIC, as the high ion ring energy constrains ε>0.98
- **As the interpretation of some EIC data (e.g. GPD extraction) will depend on extrapolation of Hall C L–T separated data, maximizing overlap between Hall C and EIC data sets should be a high priority**
  - An important motivation for extending reach of Hall C data using 22 GeV beam

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14 GeV/c HMS Scenario: π^+ Form Factor

- **Replace HMS with a higher momentum spectrometer**
  - For high *z* reactions, such as DEMP, usable beam energy constrained by sum of HMS+SHMS maximum momenta
  - i.e. 22 GeV beam energy is a larger constraint than the maximum HMS momentum
- **New HMS would not extend the Q^2 reach beyond Scenario 1.** However, it would result in smaller errors due to larger Δε and faster high ε data rates

$p(e,e'\pi^+)n$ **Kinematics**					
E_{beam}	θ_{HMS} (e')	P_{HMS} (e')	$\theta_{q(SHMS}$ (π^+)	P_{SHMS} (π^+)	Time FOM
Q^2=8.5 W=3.64 $-t_{min}$=0.24 Δε=0.53					
13.0	34.30	1.88	5.29	10.99	64.7
22.0	10.81	10.88	10.23	10.99	0.6
Q^2=10.0 W=3.44 $-t_{min}$=0.37 Δε=0.54					
13.0	37.78	1.83	5.56	10.97	122.7
22.0	11.76	10.83	10.97	10.97	1.3
Q^2=11.5 W=3.24 $-t_{min}$=0.54 Δε=0.29					
14.0	31.73	2.75	7.06	10.96	82.4
22.0	12.66	10.75	11.56	10.96	2.5

- **This scenario is judged to not be worth it, at least for this reaction channel**

Upgrade HMS Momentum and Angle: F_π

- **Upgrade both HMS momentum and forward angle capabilities**
  - 7 GeV/c → 11 GeV/c
  - $\theta_{min}=10.50^o \rightarrow 7.5^o$
  - $\theta_{open}=18.00^o \rightarrow 15.00^o$
- **This upgrade also does not extend the Q^2 reach beyond Scenario 1.**
- However, it would result in smaller errors due to larger $\Delta\varepsilon$ and faster high ε data rates

$p(e,e'\pi^+)n$ Kinematics					
E_{beam}	θ_{HMS} (e')	P_{HMS} (e')	$\theta_{q(SHMS)}$ (π^+)	P_{SHMS} (π^+)	Time FOM
$Q^2=8.5$ $W=3.64$ $-t_{min}=0.24$ $\Delta\varepsilon=0.53$					
13.0	34.30	1.88	5.29	10.99	64.7
22.0	10.81	10.88	10.23	10.99	0.6
$Q^2=10.0$ $W=3.44$ $-t_{min}=0.37$ $\Delta\varepsilon=0.54$					
13.0	37.78	1.83	5.56	10.97	122.7
22.0	11.76	10.83	10.97	10.97	1.3
$Q^2=11.5$ $W=3.24$ $-t_{min}=0.54$ $\Delta\varepsilon=0.29$					
14.0	31.73	2.75	7.06	10.96	82.4
22.0	12.66	10.75	11.56	10.96	2.5

- **Basically the same as Scenario 2. Not worth it, at least for this channel**

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15 GeV/c SHMS Scenario: π^+ Form Factor

- **Replace SHMS with higher momentum spectrometer, but keep HMS as is**
  - Dramatic increase in upper Q^2 11.5 → 15.0 GeV^2
  - Error bars for Q^2=8.5–11.5 GeV^2 would substantially decrease due to smaller $-t_{min}$ (better $R=\sigma_T/\sigma_L$) and shorter running times
  - The Q^2=15.0 GeV^2 point would be "expensive" in terms of running time, but its high scientific priority would make it worthwhile
  - **This seems a compelling scenario for a Phase 2 Upgrade**

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

E_{beam}	θ_{HMS} (e')	P_{HMS} (e')	$\theta_{q(SHMS)}$ (π^+)	P_{SHMS} (π^+)	Time FOM
Q^2=8.5 W=4.06 $-t_{min}$=0.17 $\Delta\varepsilon$=0.26					
16.0	23.68	3.15	5.52	12.75	17.7
20.0	14.00	7.15	7.55	12.75	1.9
Q^2=10.0 W=3.96 $-t_{min}$=0.23 $\Delta\varepsilon$=0.28					
16.0	27.41	2.78	5.41	13.09	47.7
20.0	15.60	6.78	7.72	13.09	4.5
Q^2=11.5 W=3.96 $-t_{min}$=0.29 $\Delta\varepsilon$=0.27					
17.0	27.54	2.98	5.49	13.86	76.3
21.0	16.10	6.98	7.72	13.86	8.1
Q^2=13.0 W=3.96 $-t_{min}$=0.35 $\Delta\varepsilon$=0.25					
18.0	27.55	3.18	5.54	14.63	123.6
22.0	16.49	7.18	7.69	14.63	14.4
Q^2=15.0 W=3.78 $-t_{min}$=0.50 $\Delta\varepsilon$=0.27					
18.0	31.30	2.86	5.46	14.87	391
22.0	18.14	6.86	7.86	14.87	41.4

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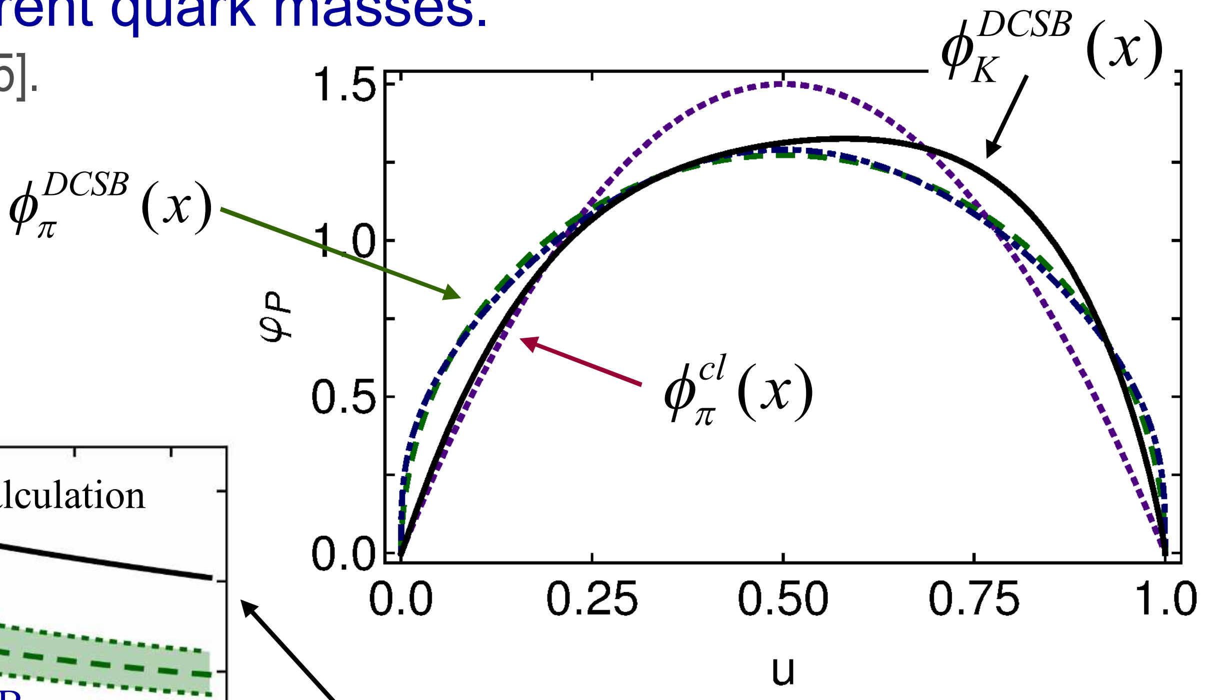
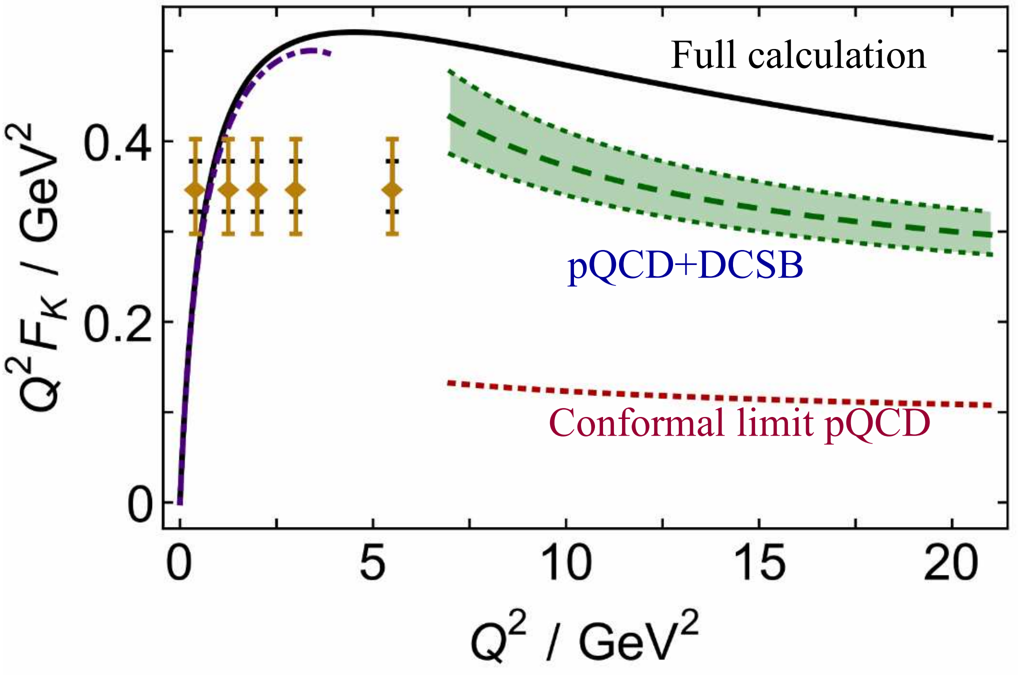
K^+ properties also strongly influenced by EHM

- **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].