Deep Exclusive Meson Production in Hall C with Upgraded JLab Beam

University of Regina

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The Next Generation of 3D Imaging Workshop
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DEMP Opportunities in Hall C

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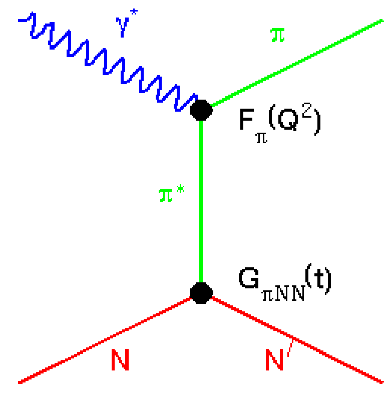
1) Determine the Pion Form Factor to high Q^2:

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

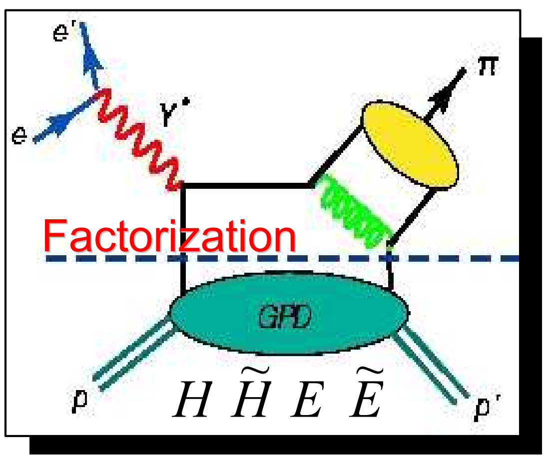
$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$



- **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'π^+/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)ω can reveal hard–soft factorization at backward angle



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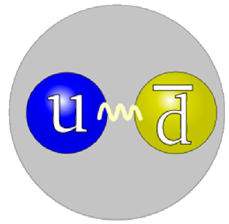
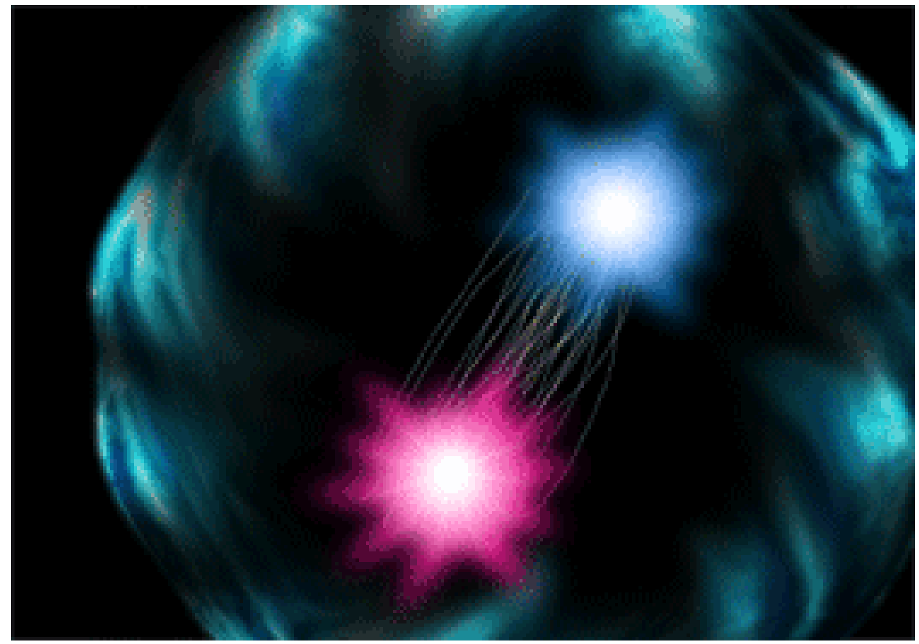
Charged Pion Form Factor

- **The pion is attractive as a QCD laboratory:**
  - Simple, 2 quark system



- **The pion is the "positronium atom" of QCD, its form factor is a test case for most model calculations**
- **The important question to answer is: What is the structure of the π^+ at all Q^2?**



Pion's structure is determined by two valence quarks, and the quark-gluon sea.

- **A program of study unique to Jefferson Lab Hall C** (until the completion of the EIC)

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

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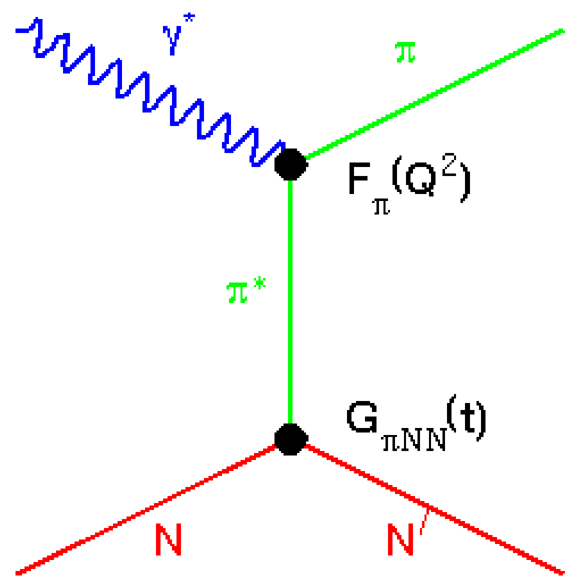
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

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

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



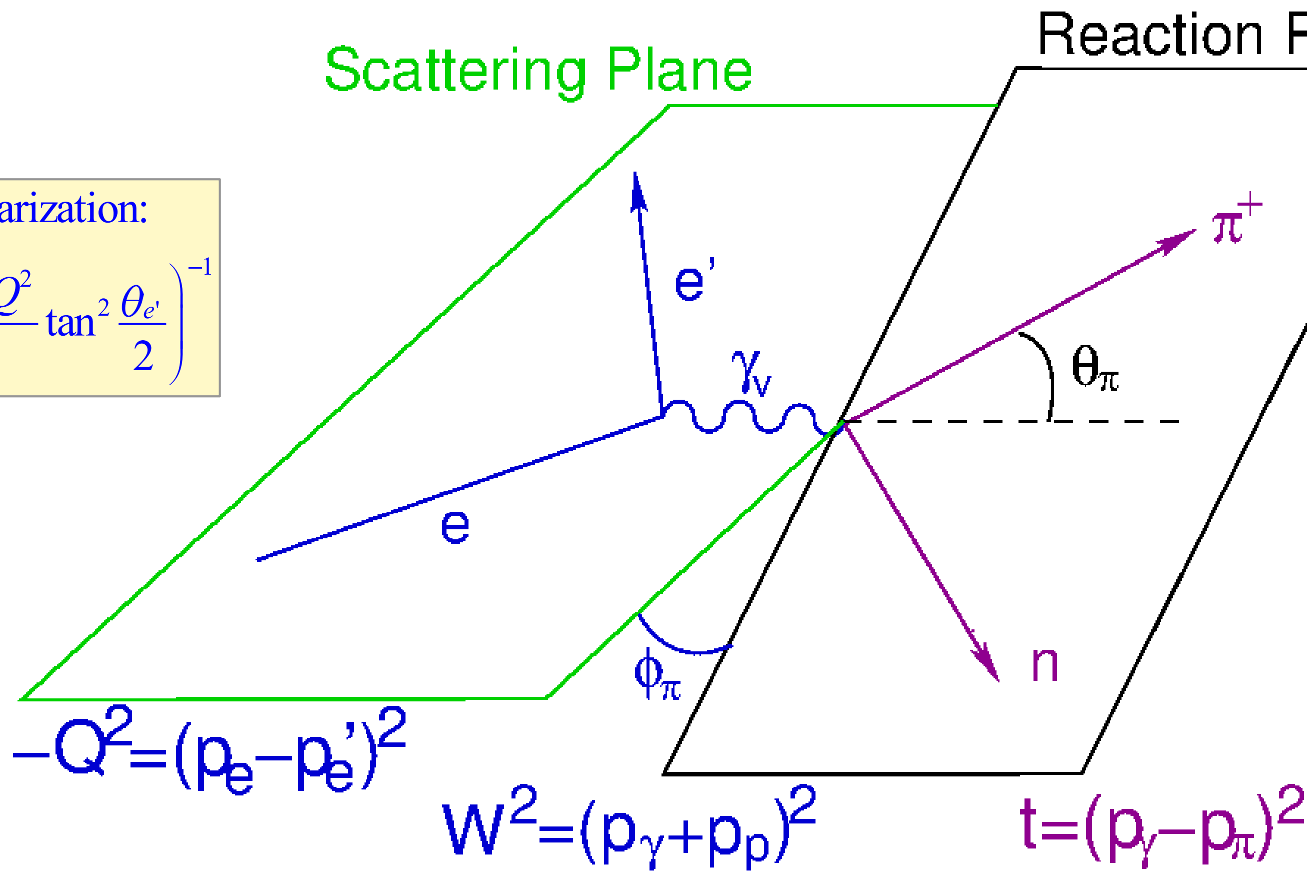
Drawbacks of this technique

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

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

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

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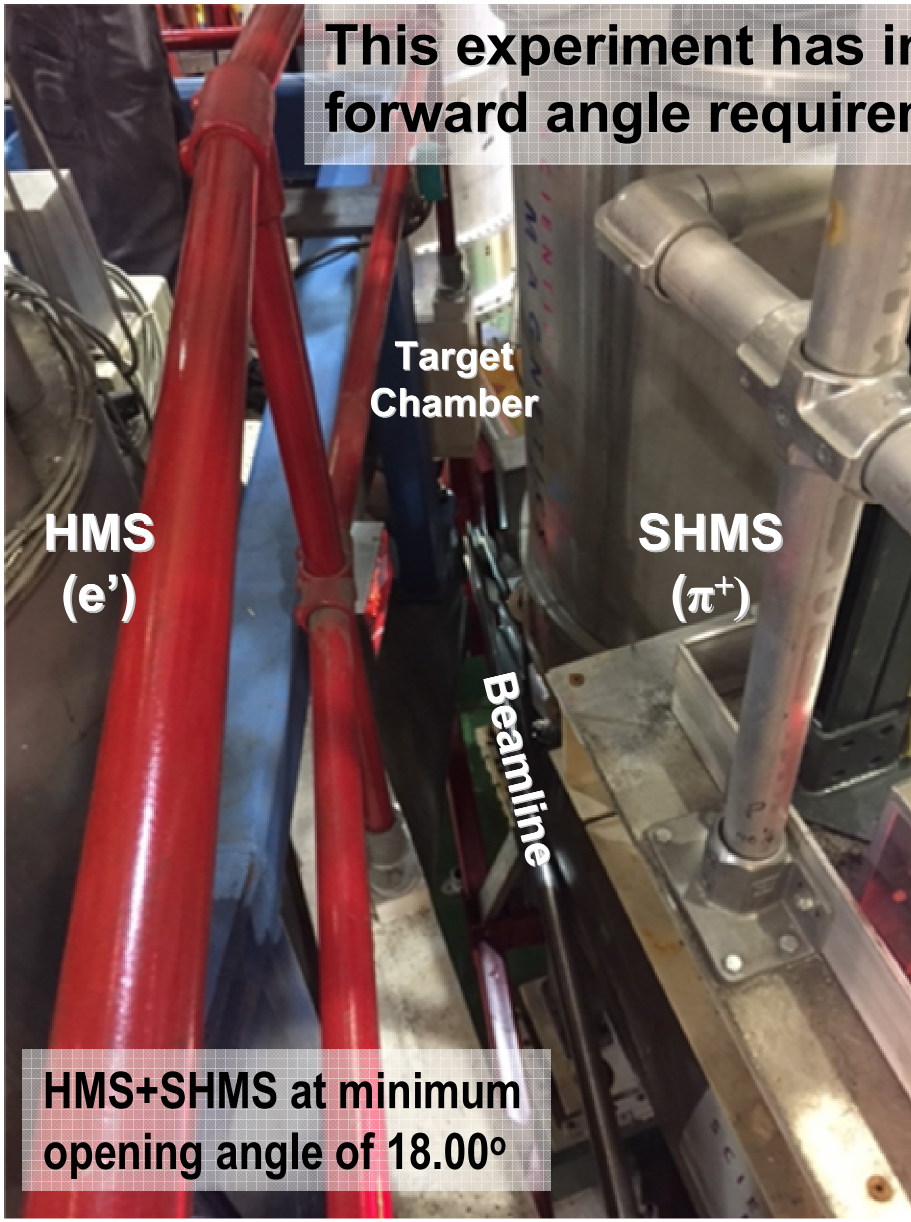
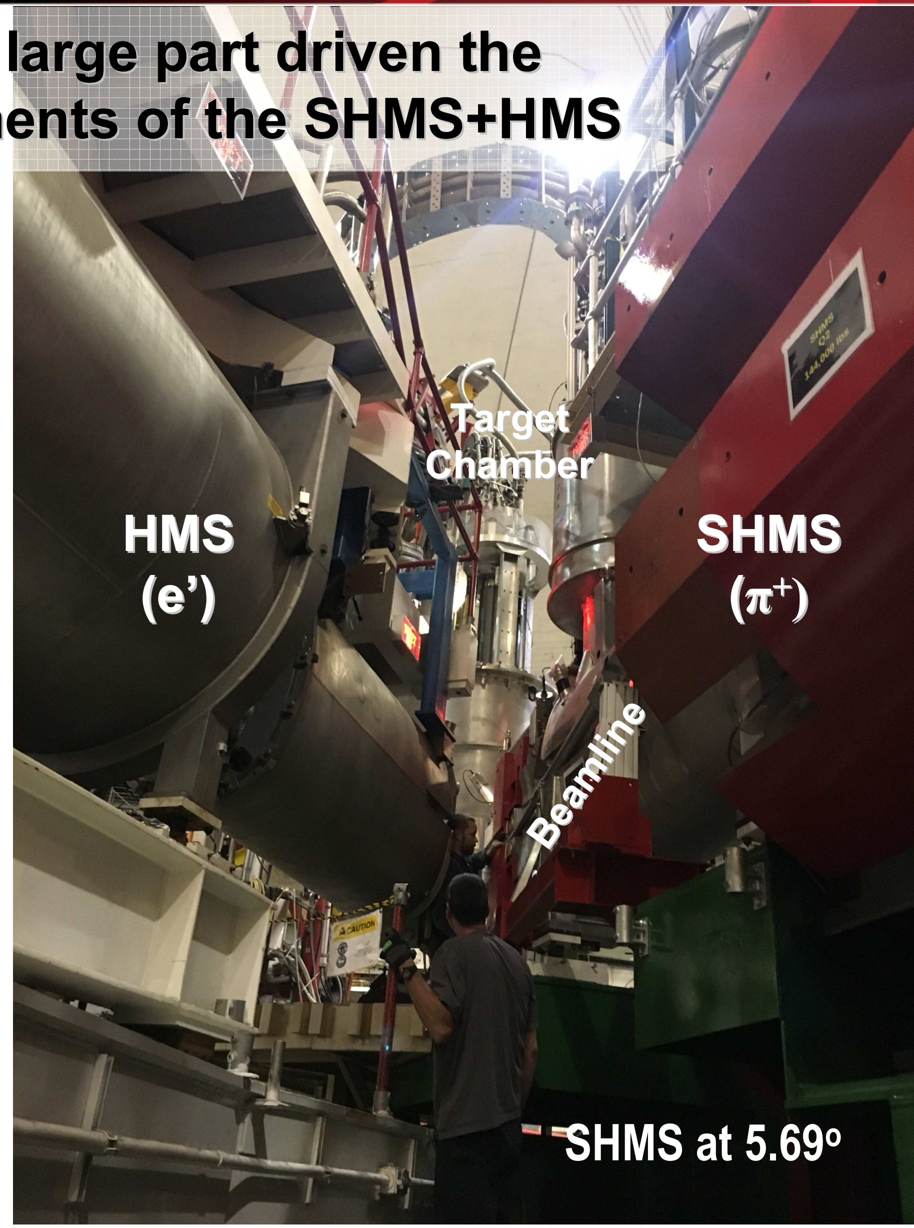
HMS and SHMS during Data Taking

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





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:

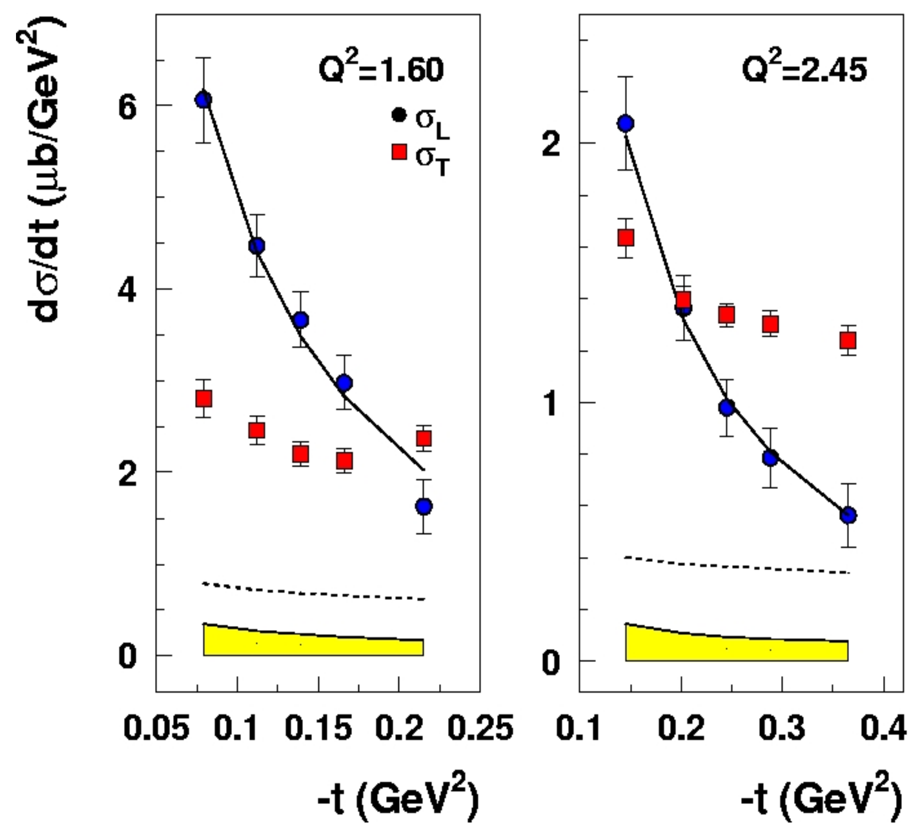
- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$ replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).

[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 GeV^2, Λ_ρ^2=1.7 GeV^2.

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Current and Projected F_π Data

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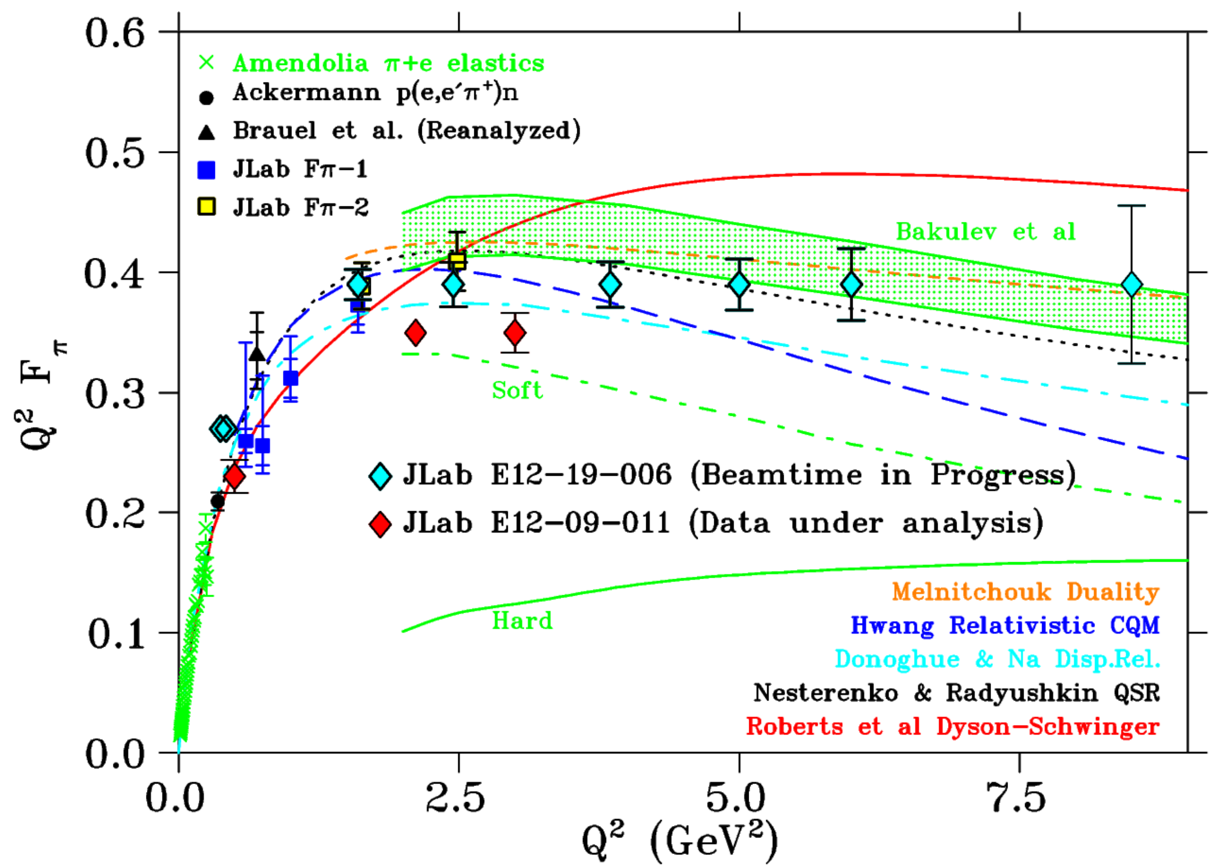
SHMS+HMS will allow measurement of F_π to much higher Q^2.

No other facility worldwide can perform this measurement.

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

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

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Strong Endorsement in many Reviews

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Report to PAC18, 12 GeV Session:

Measuring F_π at Higher Q^2

G.M. Huber, H.P. Blok, D.J. Mack

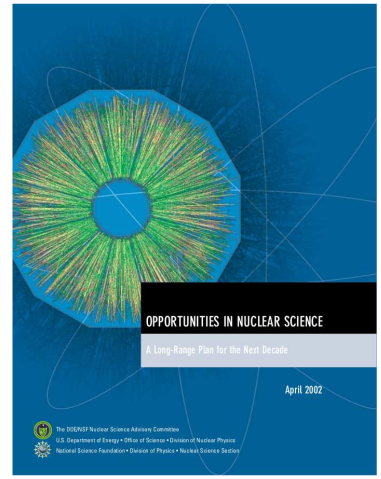
on behalf of the Exclusive Reactions Working Group

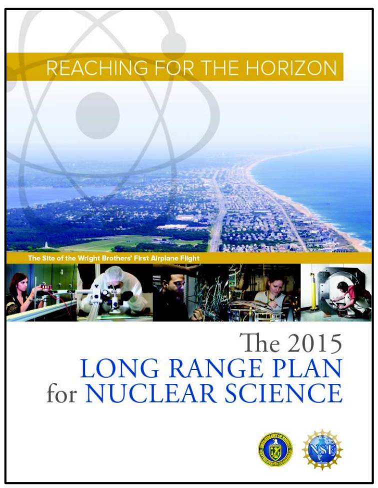
July 6, 2000

***F_π* first proposed to JLab PAC in 2000!**

***F_π* Rated "Early High Impact" by PAC35 in 2010**

***F_π* endorsed by NSAC in 2002, as one of the key motivations for the 12 GeV Upgrade**





F_π* endorsed again by NSAC in 2015,** ***"as one of the flagship goals of the JLab 12 GeV Upgrade"

PAC47 (2019) Theory Report:

> ***"Since the proposals were originally reviewed, the physics motivations for both studies have only increased."***

"A" rating reaffirmed by PAC47

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Opportunities with higher E_{beam} & Hall C

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- 7.2 GeV/c HMS & 11.0 GeV/c SHMS allow a lot of kinematic flexibility, **with no 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
  - Investigated possible septum magnet to improve forward angle capability of HMS+SHMS, but this did not help

	10.6 GeV	18.0 GeV	Improvement in $\delta F_\pi/F_\pi$
Q^2=8.5	Δε=0.22	Δε=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')	θ_{SHMS} (π^+)	P_{SHMS} (π^+)	Time FOM
Q^2=8.5 W=3.64 $-t_{min}$=0.24 Δε=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 Δε=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 Δε=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

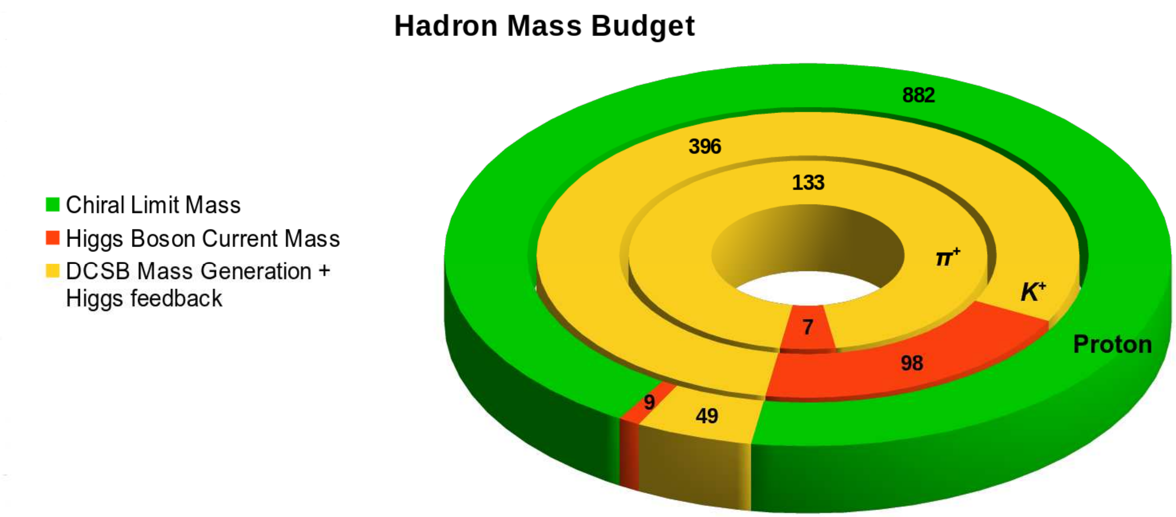
- **Since quality L/T-separations are impossible at EIC (can't access ε<0.95) this extension of L/T-separated data considerably increases F_π data set overlap between JLab and EIC**

The Charged Kaon – 2nd QCD test case

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

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

- Important to compare magnitudes and Q^2–dependences of both form factors



Ref: Craig Roberts (2021)

- Proton mass large in absence of quark couplings to Higgs boson (chiral limit). Conversely, 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.
- Understanding π^+ and K^+ form factors over broad Q^2 range is central to this puzzle.

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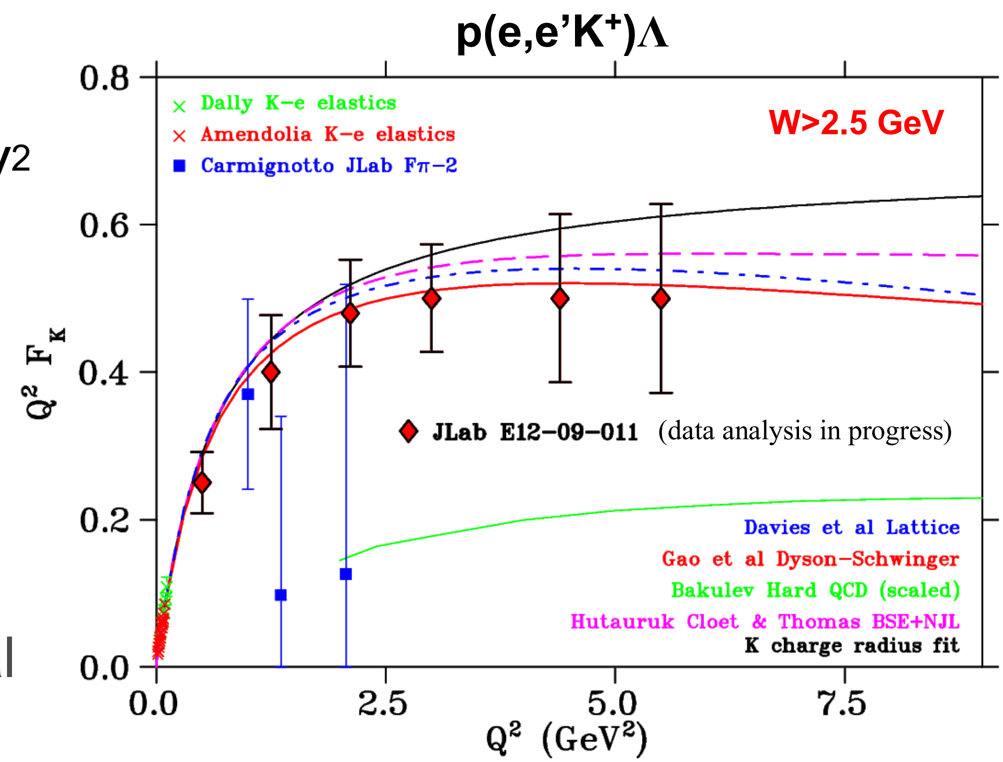
Projected Uncertainties for K^+ Form Factor

- 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.



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

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Opportunities with higher E_{beam} & Hall C

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- 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 $-t_{min}$		

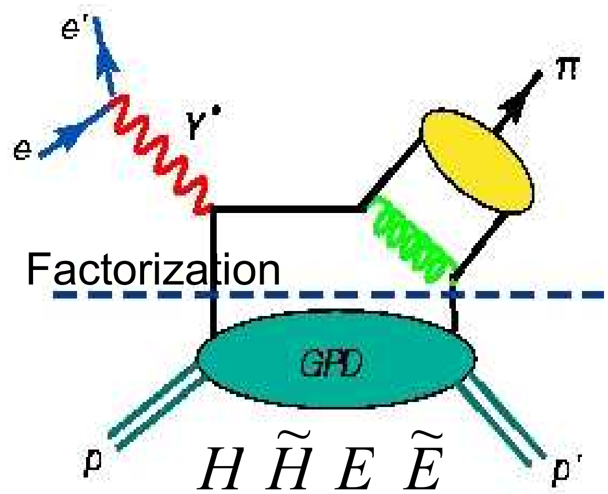
$p(e,e'K^+)\Lambda$ Kinematics					
E_{beam}	θ_{HMS} (e')	P_{HMS} (e')	θ_{SHMS} (π^+)	P_{SHMS} (π^+)	Time FOM
Q^2=5.5 W=3.56 $-t_{min}$=0.32 $\Delta\varepsilon$=0.40					
11.0	30.69	1.79	5.50	8.84	746
16.0	12.92	6.79	9.18	8.84	150
Q^2=7.0 W=3.90 $-t_{min}$=0.33 $\Delta\varepsilon$=0.29					
14.0	25.16	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.**

Hard–Soft Factorization in DEMP

- **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

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

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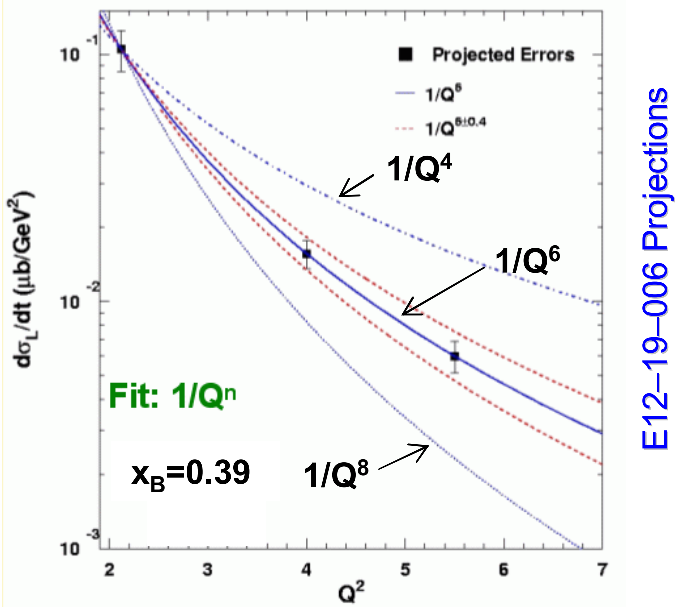
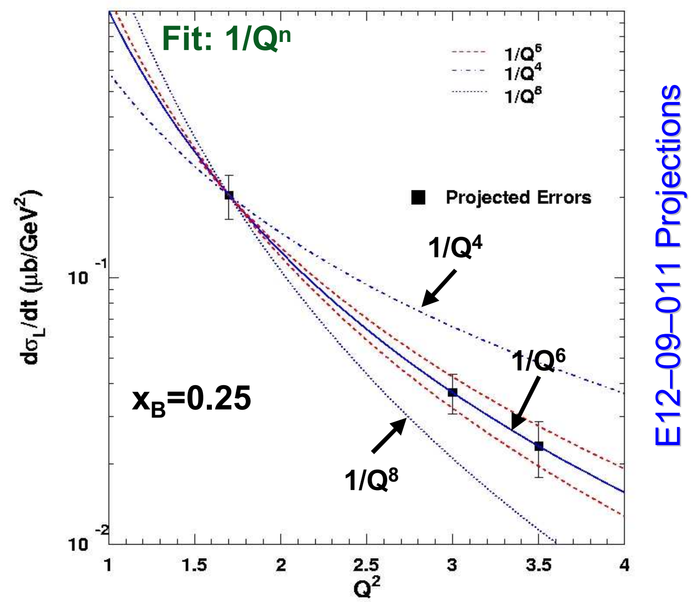
$p(e,e'\pi^+)n$



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	

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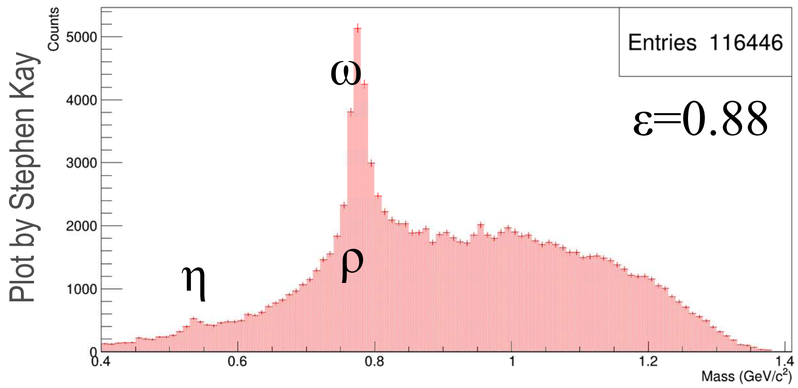
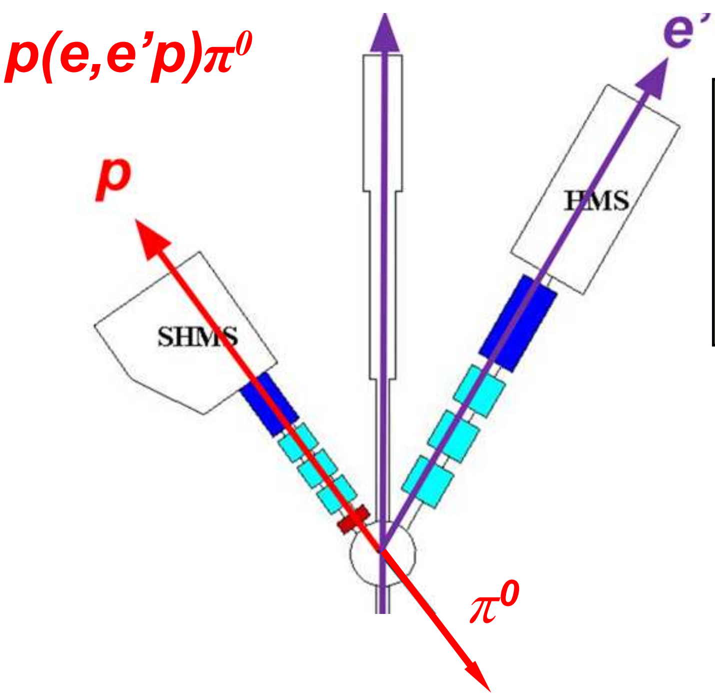
p(e ,e'p)X KaonLT Data Analysis

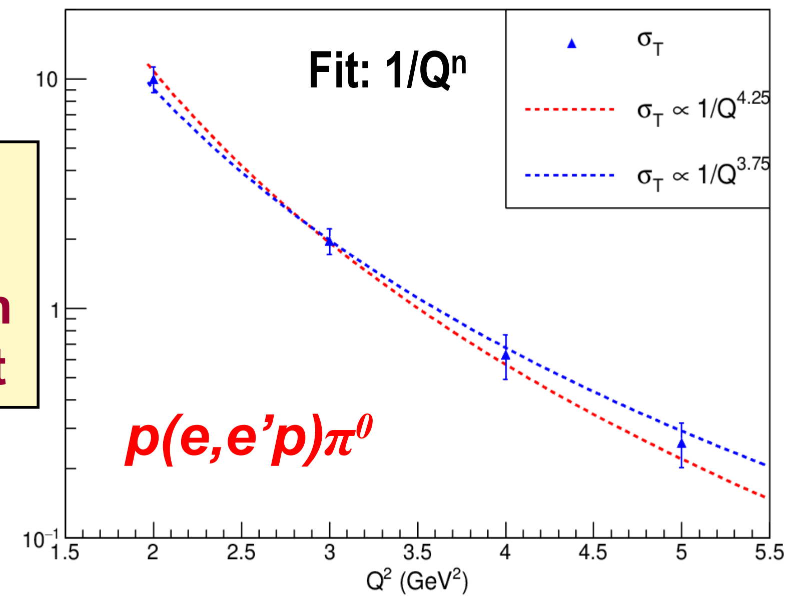
Q^2=3.00 W=2.32 θ_{pq}=+3.0° $-u$=0.15 ξ_u=0.15



- **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]



18 GeV beam 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

Summary

- The existing HMS+SHMS and 18 GeV beam enable important Deep Exclusive Meson Production (DEMP) measurements which build upon the 11 GeV measurements and set the bridge between JLab and EIC
- Hall C is optimized for quality L/T–separations, which are not possible at EIC due to difficulty to access $\varepsilon<0.9$
- **Discussed measurements:**
  - Pion form factor to Q^2=10 GeV^2 with small errors, and to 11.5 with larger uncertainties
  - Kaon form factor to 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'π^+)n and p(e,e'K^+)Λ
  - Studies of backward angle Q^{-n} factorization via u–channel p(e,e'p)π^0 and p(e,e'p)ω
- Higher Q^2 reach requires replacement of HMS with a new spectrometer. I wanted to concentrate on what science is possible with "cost-effective investment".

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