Opportunities for studies of Deep Exclusive Meson Production with JLab 20+

University of Regina

Garth Huber

ECT* Workshop: JLab Energy and Luminosity Upgrade
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DEMP Opportunities in Hall C

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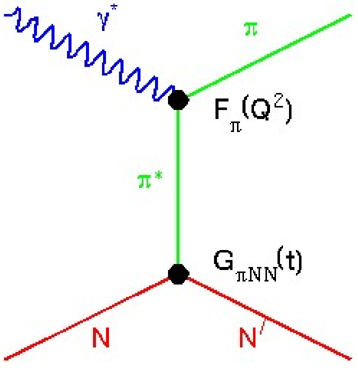
1) Determine the Pion Form Factor to high Q^2:

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

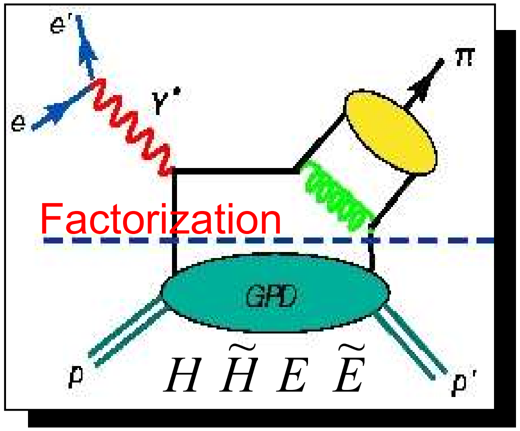
$$\left| p \right\rangle = \left| p \right\rangle_0 + \left| n\pi^+ \right\rangle + \ldots$$



- **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



Meson Form Factors

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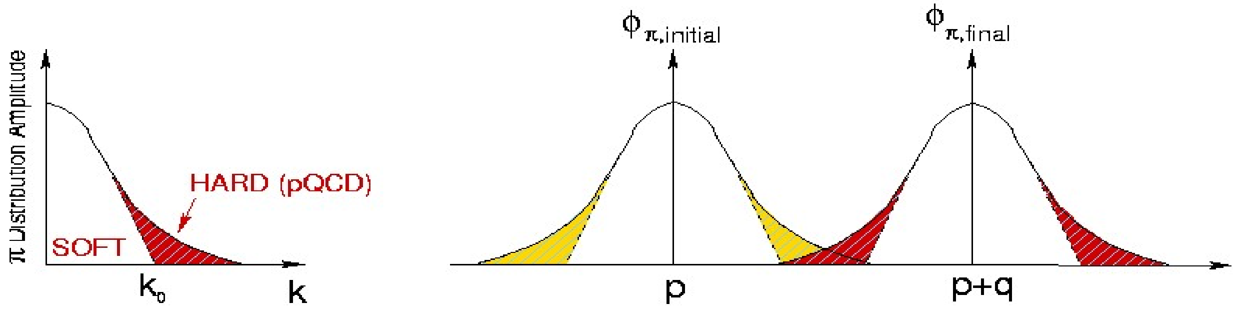
Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

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.

pQCD and the Charged Pion Form Factor

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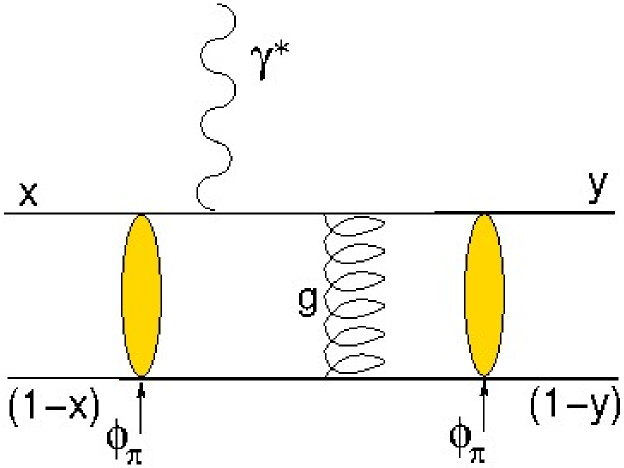
At large Q^2, perturbative QCD (pQCD) can be used

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

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

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



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.

Pion Form Factor at Finite Q^2

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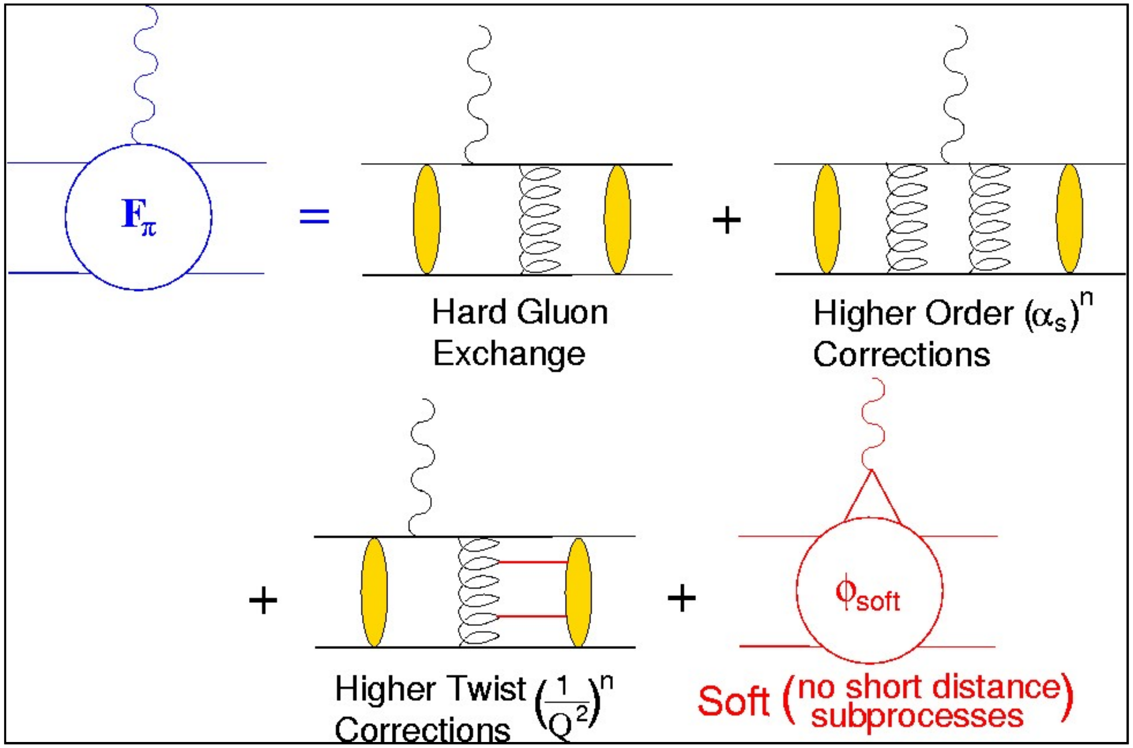
- At finite momentum transfer, higher order terms contribute.
- Calculation of higher order, “hard” (short distance) processes difficult, but tractable.



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.

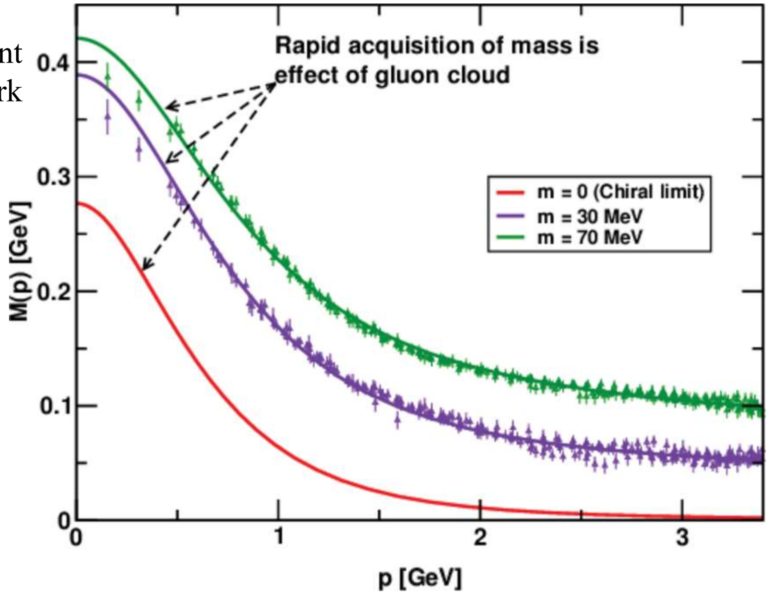
[A.V. Radyushkin, JINR 1977, arXiv:hep–ph/0410276]

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 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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Implications for Pion Structure

Craig Roberts (2016): ***"No understanding of confinement within the Standard Model is practically relevant unless it also explains the connection between confinement and DCSB, and therefore the existence and role of pions."***

- For the pQCD derivation on slide #4, the normalization for F_π has been based on the conformal limit of the pion's twist–2 PDA.

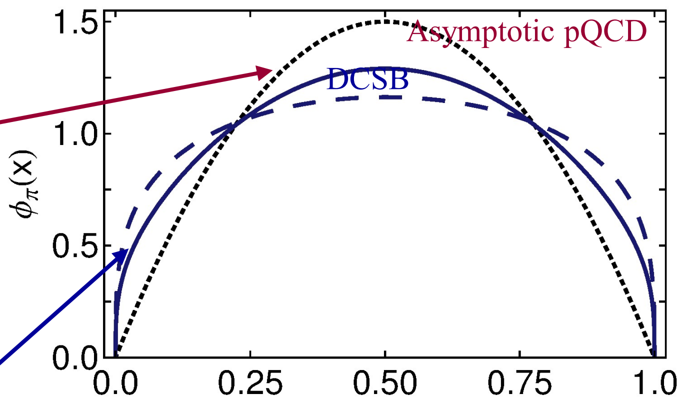
$$\phi_\pi^{cl}(x) = 6x(1-x)$$

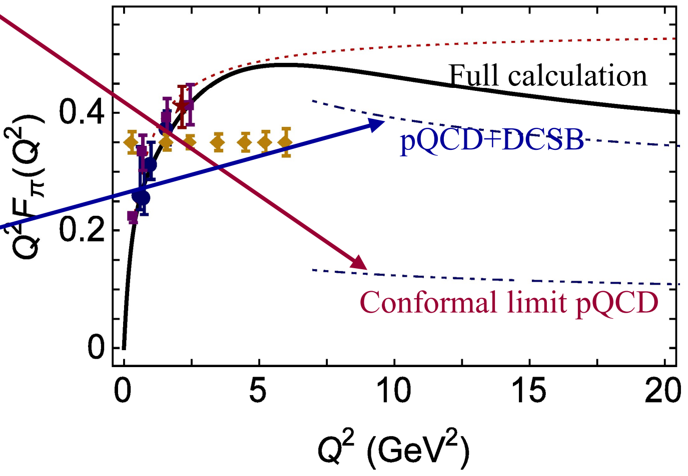
- This leads to "too small" F_π values in comparison with present & projected JLab data.

- Recent works incorporating DCSB effects indicate that at experimentally accessible energy scales the actual pion PDA is broader, concave function, close to

$$\phi_\pi(x) = (8/\pi)\sqrt{x(1-x)}$$

- Simply inputting this $\varphi_\pi(x)$ into the pQCD expression for F_π brings the calculation much closer to the data.
- **Underestimates full computation by ~15% for $Q^2 \geq 8$ GeV^2. Addresses issue raised in 1977.**





L. Chang, et al., PRL **110** (2013) 132001; **111** (2013) 141802.

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

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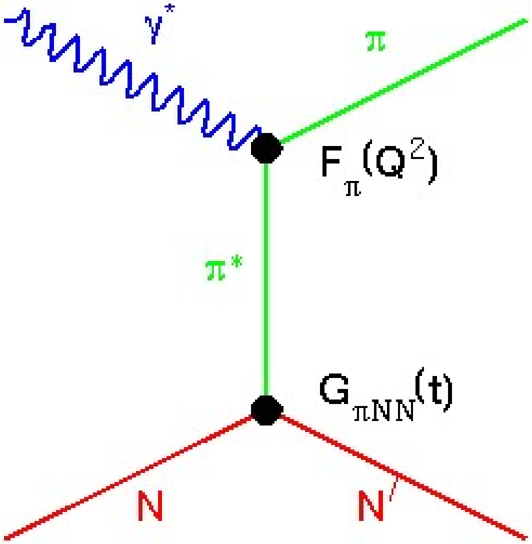
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

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

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



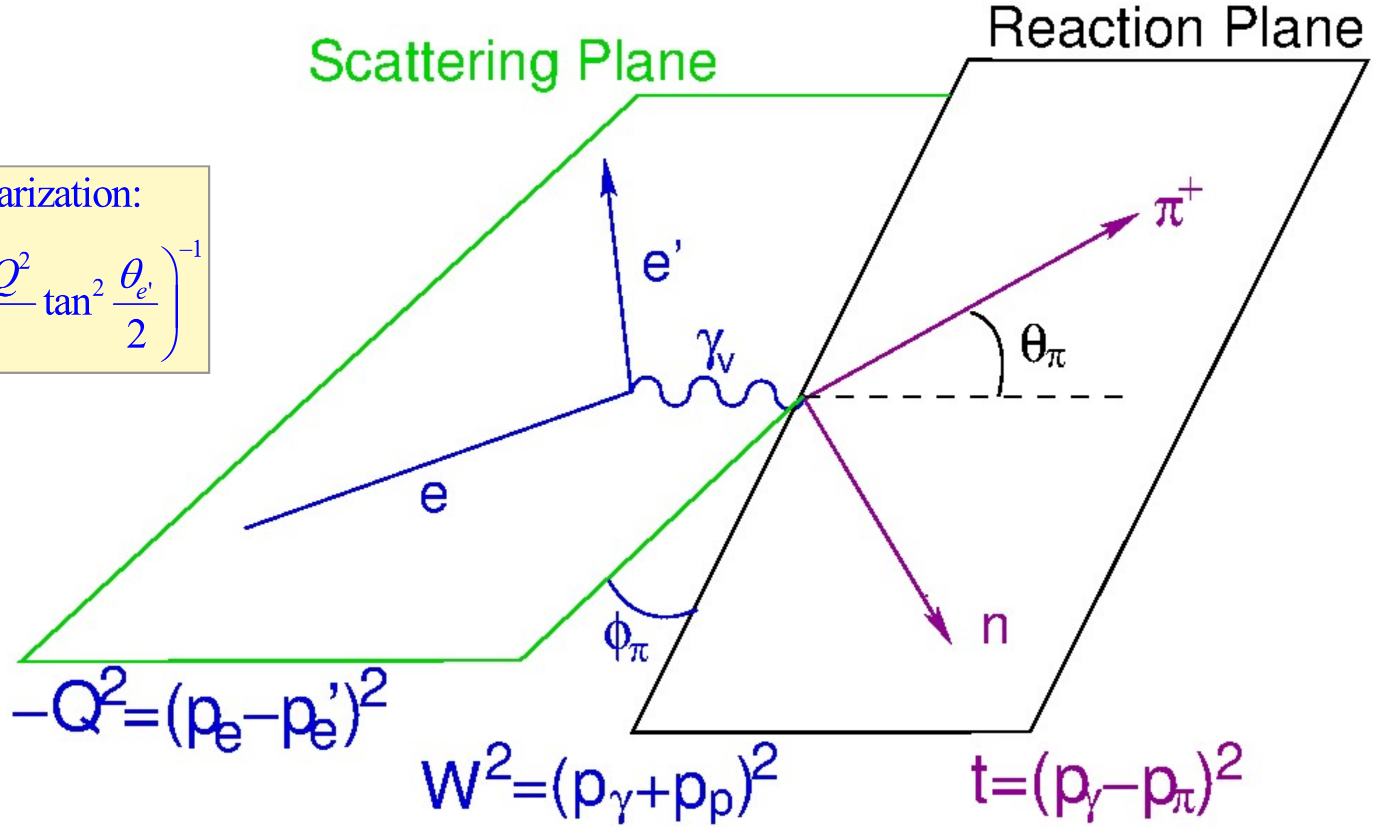
Drawbacks of this technique

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

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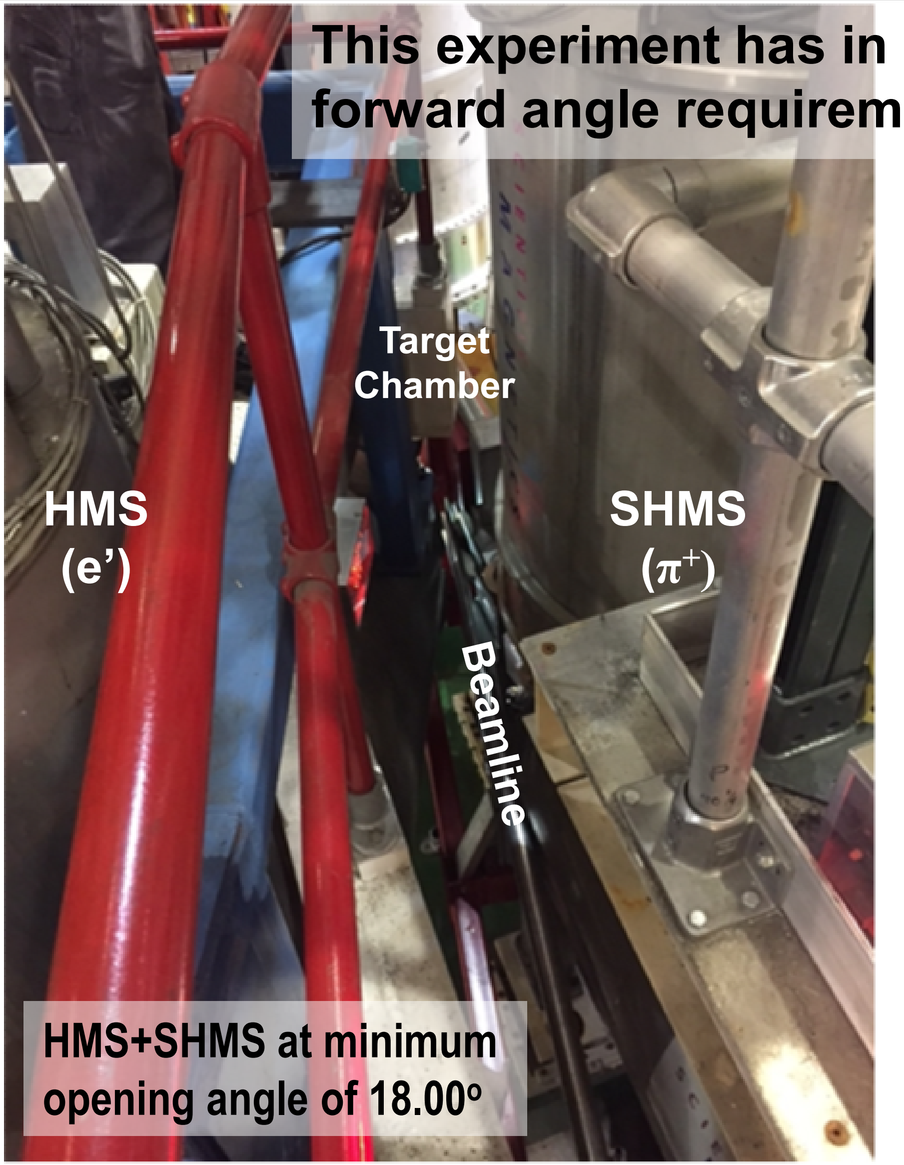
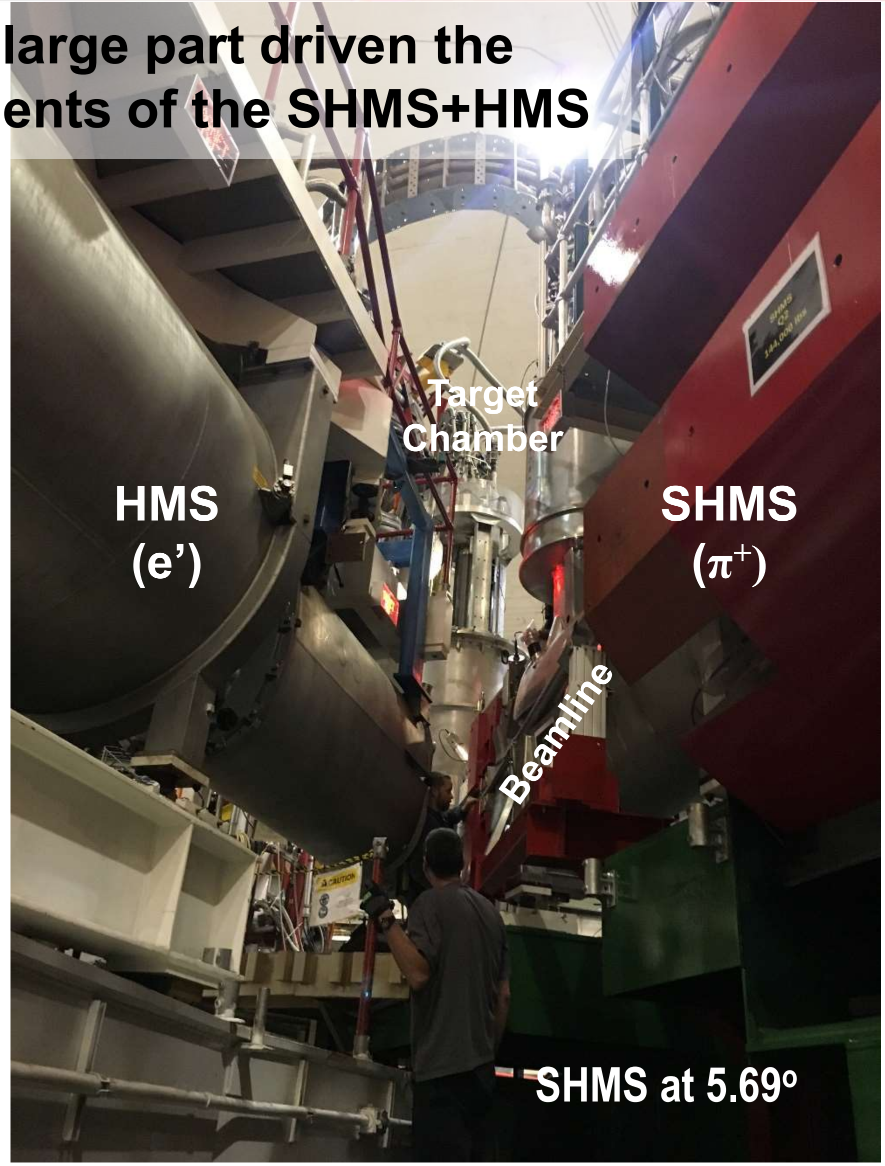
HMS and SHMS during Data Taking

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



HMS+SHMS at minimum opening angle of 18.00°



SHMS at 5.69°

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

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

VGL Regge Model:

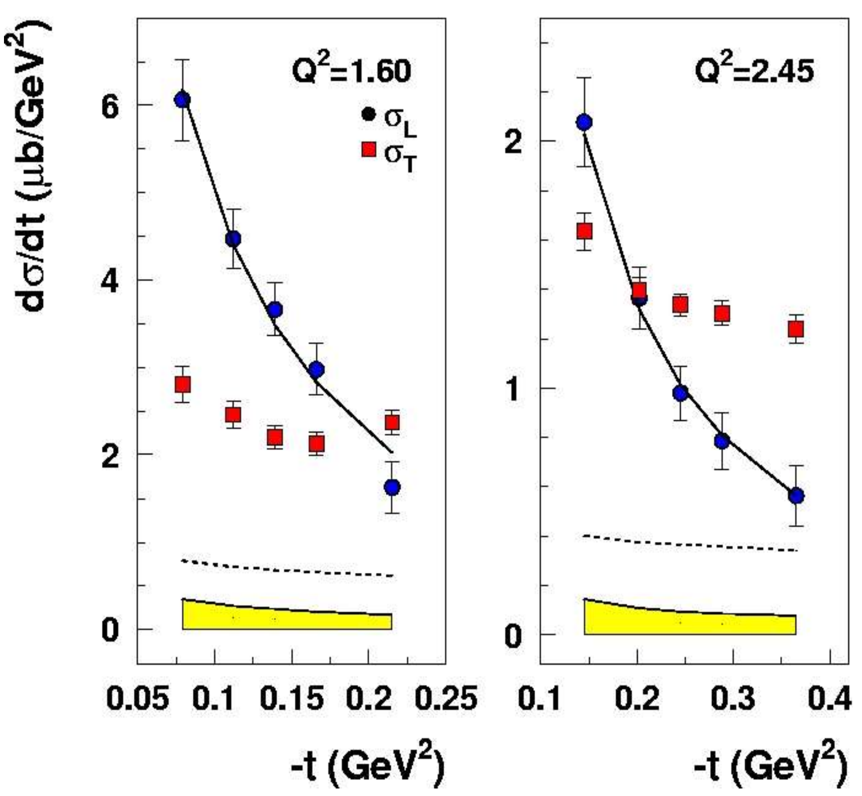
- Feynman propagator $\left(\frac{1}{t-m_\pi^2}\right)$

  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

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

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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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	$\Delta\varepsilon$=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')	θ_{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

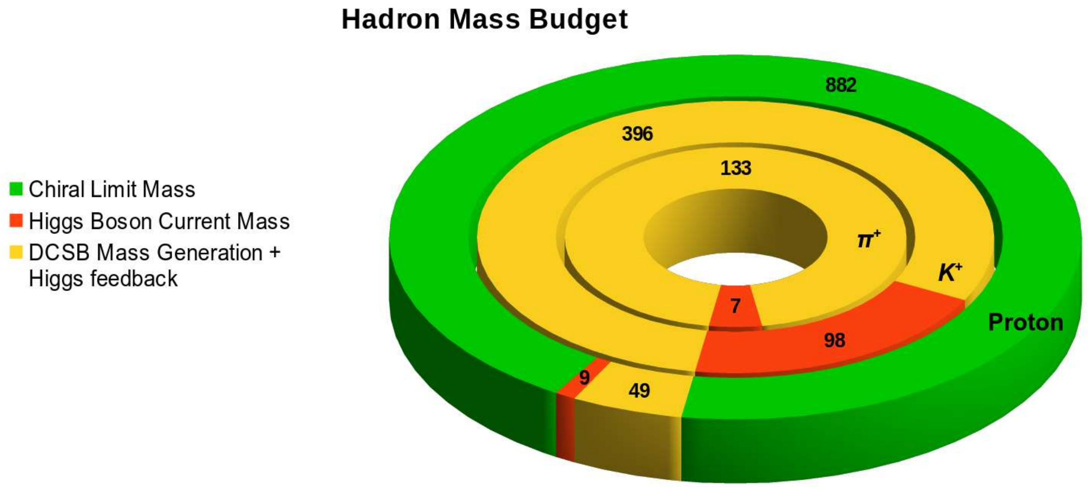
- **F_π feasibility studies at EIC are advanced**
- **JLab measurements will be an important source of quality L/T–separated data in EIC era**

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.

Opportunities with higher E_{beam} & Hall C

- 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

	Improvement in $\delta F_K/F_K$
Q^2=5.5	17.9%→10.4% (statistical)
Q^2=7.0	New high quality F_K data
Q^2=9.0	Larger F_K extraction uncertainty due to higher $-t_{min}$

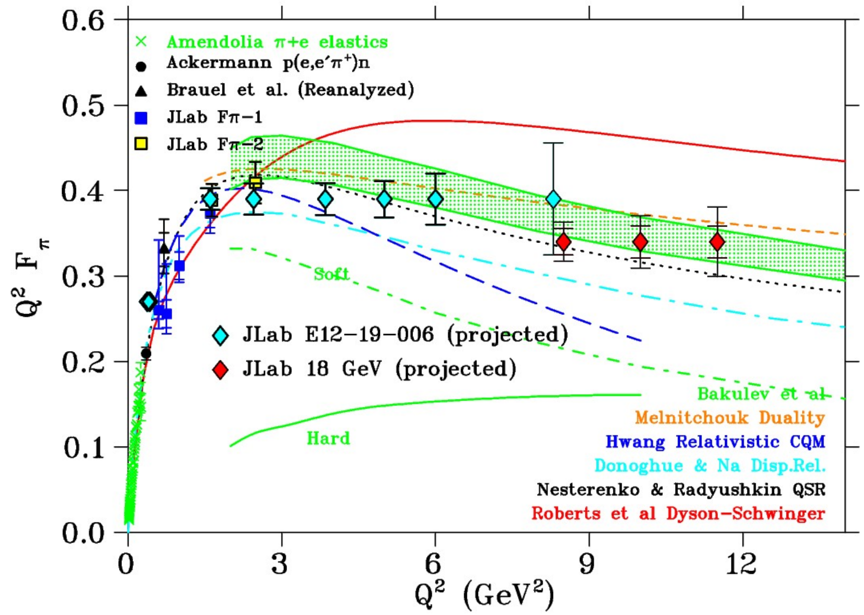
$p(e,e'K^+)\Lambda$ Kinematics

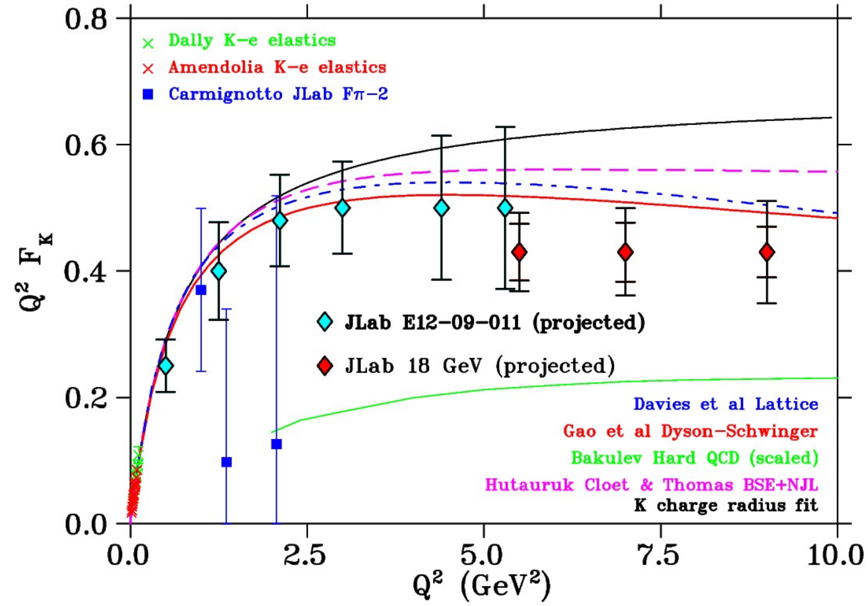
E_{beam}	θ_{HMS} (e')	P_{HMS} (e')	θ_{SHMS} (π^+)	P_{SHMS} (π^+)	Time FOM
Q^2=5.5 W=4.07 $-t_{min}$=0.22 $\Delta\varepsilon$=0.29					
14.0	21.94	2.71	5.50	10.97	684
18.0	12.25	6.71	7.09	10.97	35
Q^2=7.0 W=3.90 $-t_{min}$=0.33 $\Delta\varepsilon$=0.29					
14.0	25.16	2.64	5.51	10.98	620
18.0	13.91	6.64	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.**

Form Factor Projections

- *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
- 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





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Importance of JLab F_π in EIC Era

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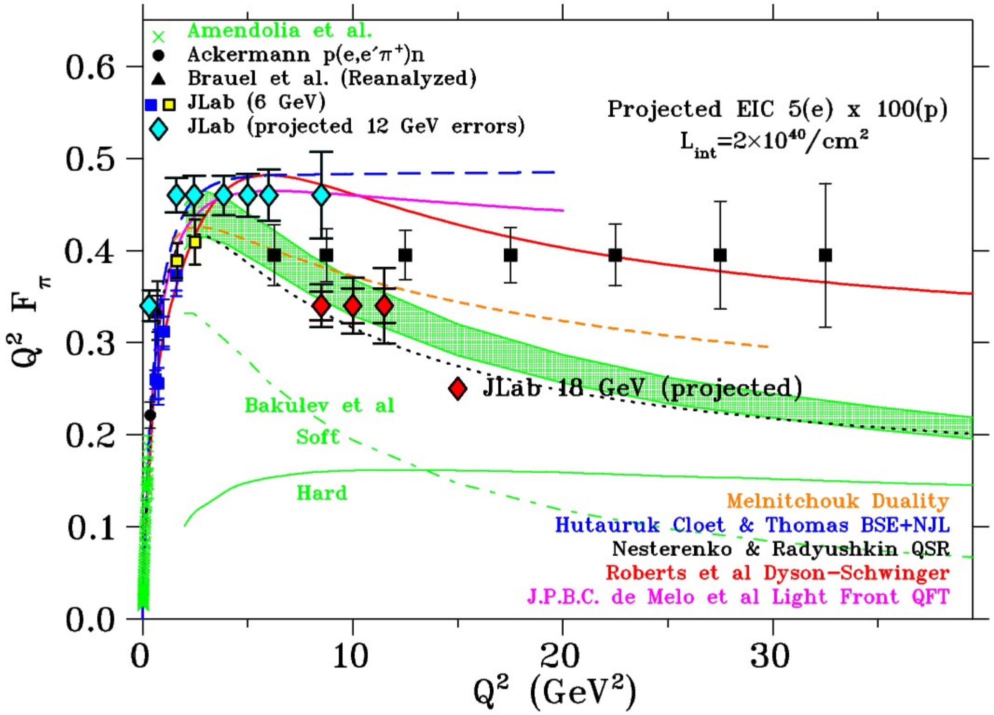

- **Quality L/T-separations impossible at EIC (can't access ε<0.95)**
- **JLab will remain ONLY source of quality L/T-separated data!**
- Extrapolation of EIC data to JLab L/T-separated region will be necessary for theoretical interpretation of many data sets in EIC era
- **18 GeV beam with HMS+SHMS provides MUCH improved overlap of F_π data set between JLab and EIC!**

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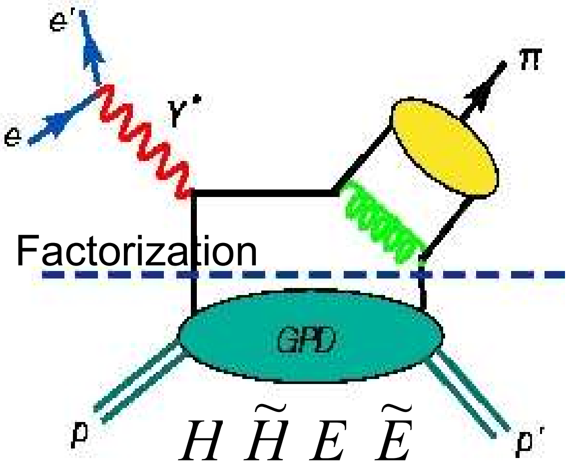
Hard–Soft Factorization in DEMP

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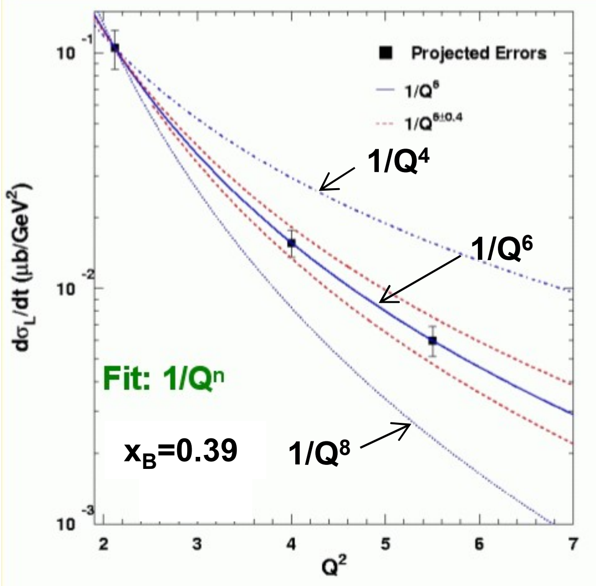
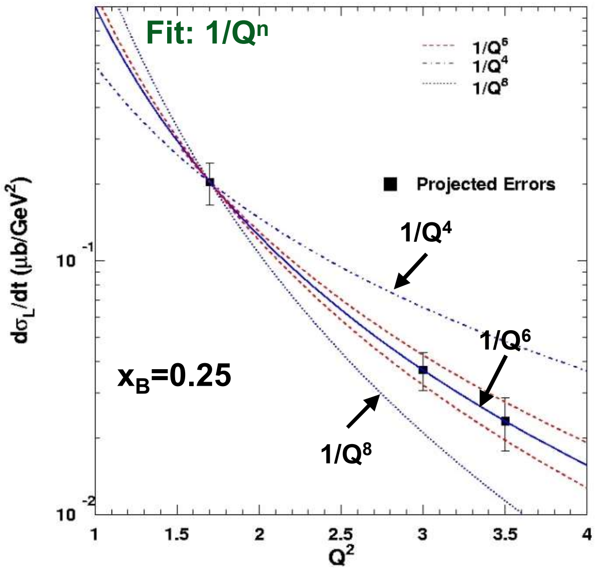
$p(e,e'\pi^+)n$



E12–19–006 Projections

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	

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



E12–09–011 Projections

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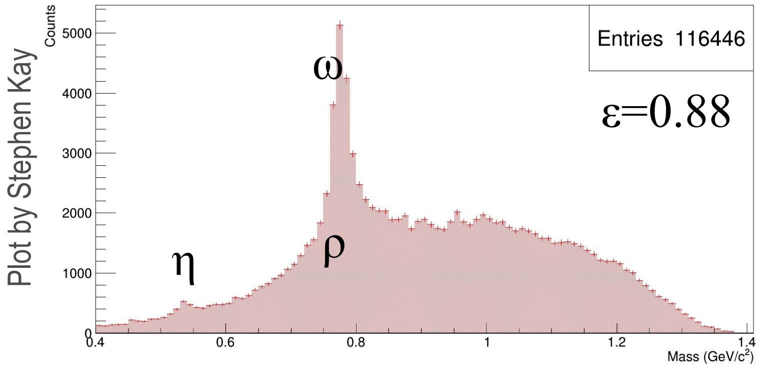
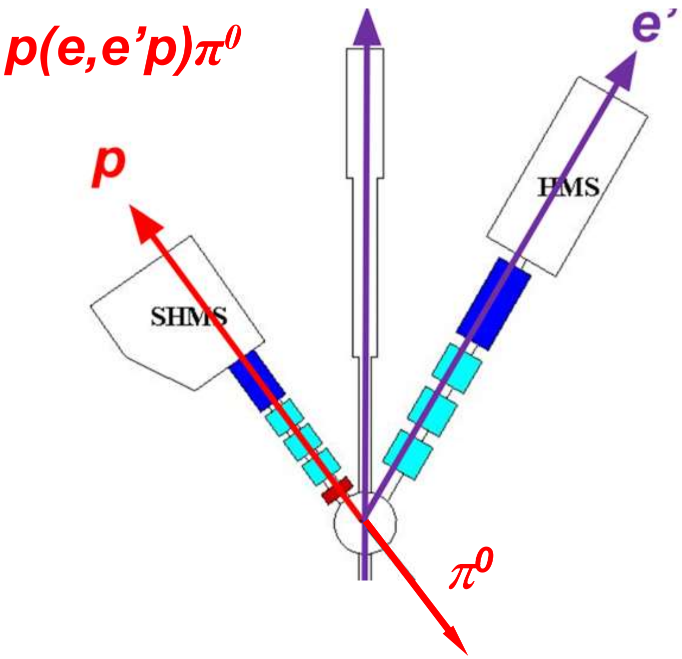
p(e ,e'p)X KaonLT Data Analysis

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

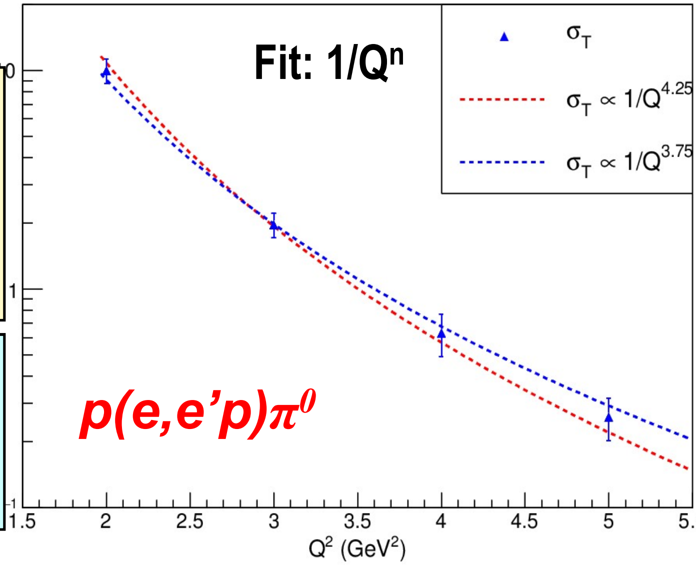


- **Fortuitous discovery of substantial backward angle meson production during meson form factor experiments**
- Can be described by extension of collinear factorization to backward angle (*u*–channel)
- Backward angle factorization first suggested by Frankfurt, Polykaov, Strikman, Zhalov, Zhalov [arXiv:hep-ph/0211263]



18 GeV beam will enable improvement in Q^{-n} scaling test

See Wenliang Li's talk tomorrow!



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

- 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 $\varepsilon<0.95$
- **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 $p(e,e'\pi^+)n$ and $p(e,e'K^+)\Lambda$
  - Studies of backward angle Q^{-n} factorization via u–channel $p(e,e'p)\pi^0$ and $p(e,e'p)\omega$