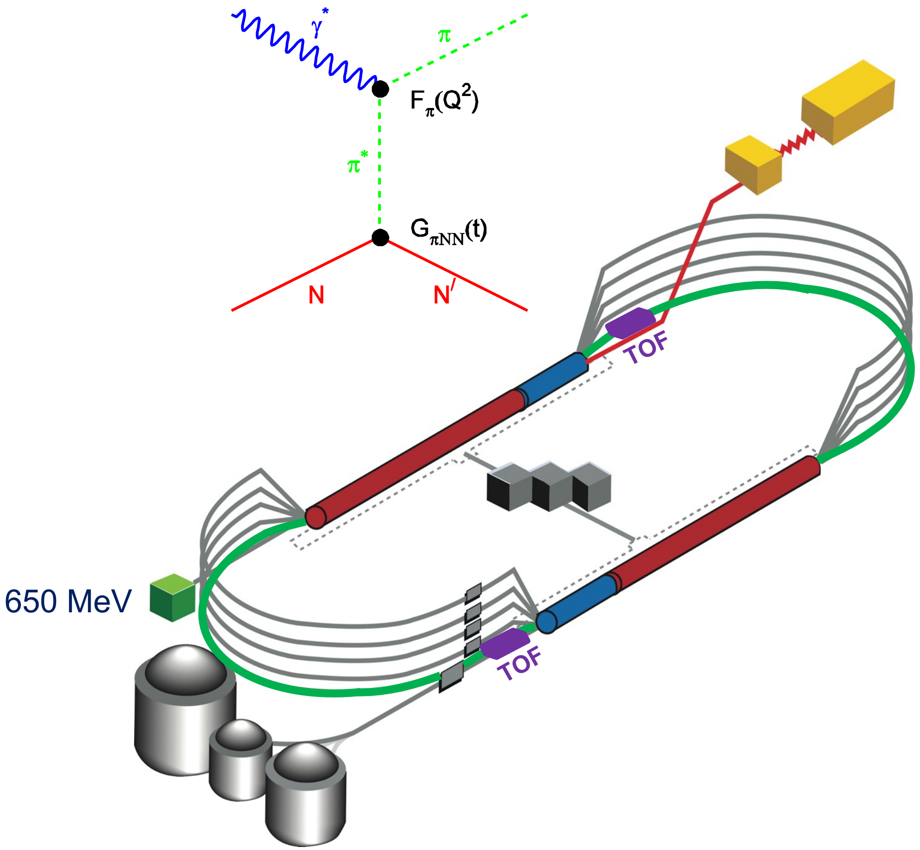
Studies of Meson Structure at Jefferson Lab at Higher Energies



Dave Gaskell (JLab)

Towards Improved Hadron Femtography with Exclusive Reactions

August 7-11, 2023

Outline

- Motivation – elastic pion and kaon form factors
- Extraction of pion and kaon form factors from electroproduction
- Kinematic constraints
- Q^2 reach at 12 GeV
- Possible measurements with 22 GeV and complementarity with EIC

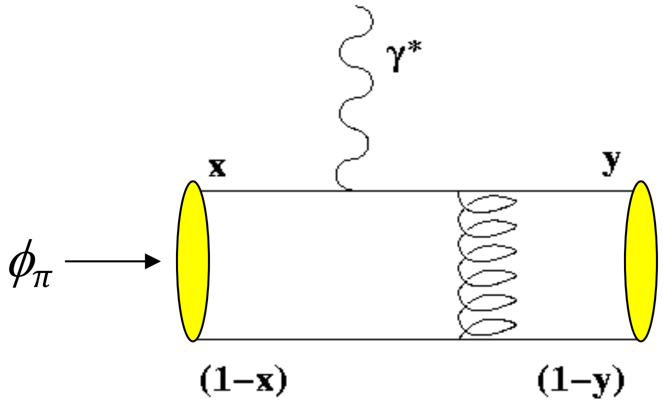
The Pion Form Factor and the Interplay of Soft and Hard Physics

The pion form factor is unique in that its asymptotic form can be calculated exactly in pQCD

However, it is unclear at what Q^2 the pQCD expression is relevant – soft processes play an important role at moderate Q^2

Recent calculations suggest that the most significant soft physics is found in the pion distribution amplitude

→ Calculations of pion DA from lattice give pion DA similar to that from state of the art DSE calculations

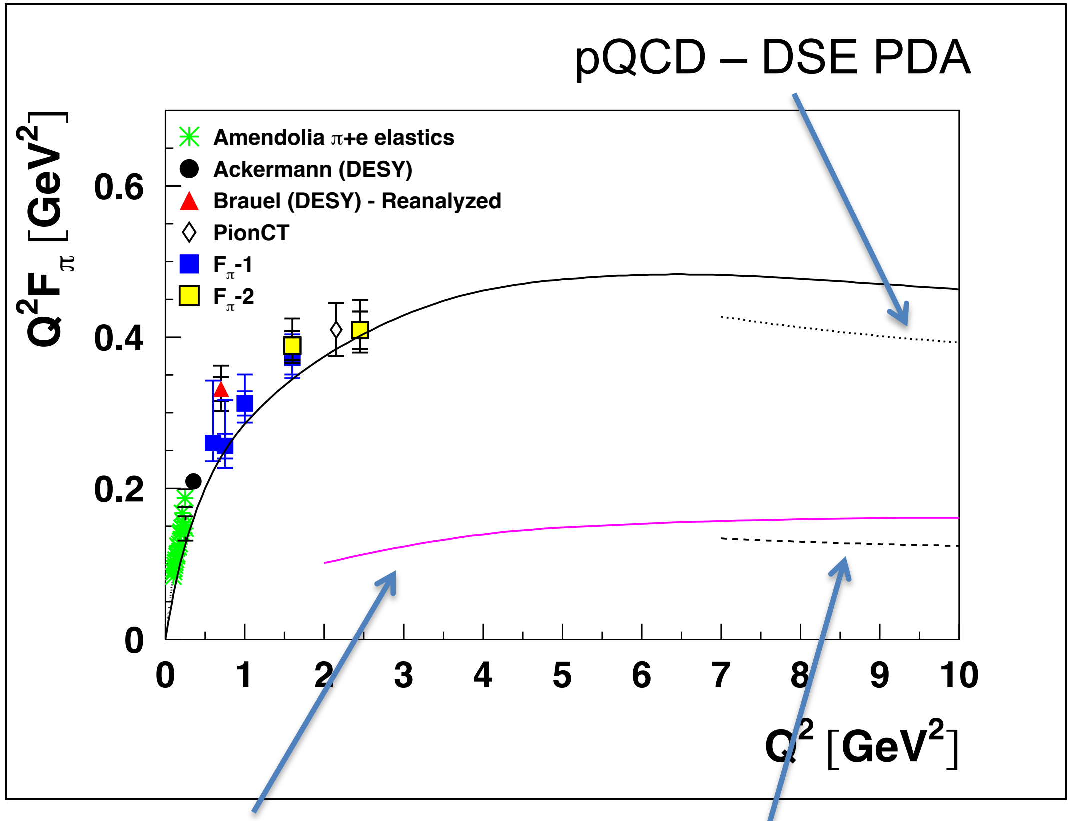


f_π=93 MeV is the $\pi^+ \rightarrow \mu^+ \nu$ decay constant.

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

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

pQCD and the Pion Form Factor



pQCD – DSE PDA

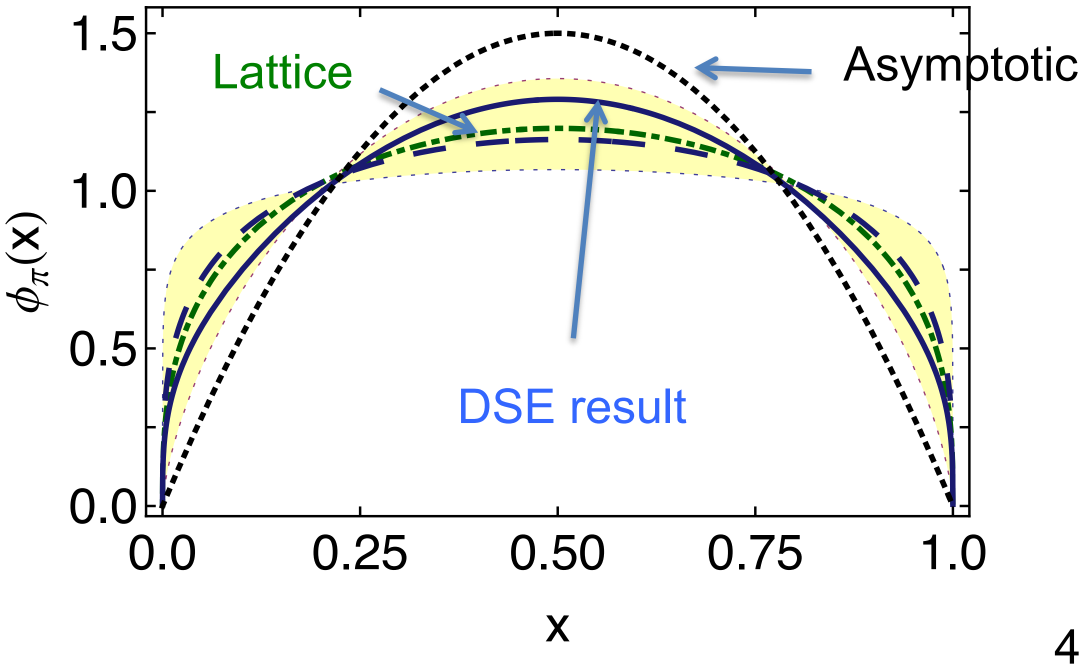
Bakulev – hard QCD

pQCD – asymptotic PDA

Is it possible to apply pQCD at experimentally accessible Q^2?

→ Use pion DA derived using DSE formalism

→ DSE-based result consistent with DA derived using constraints from lattice

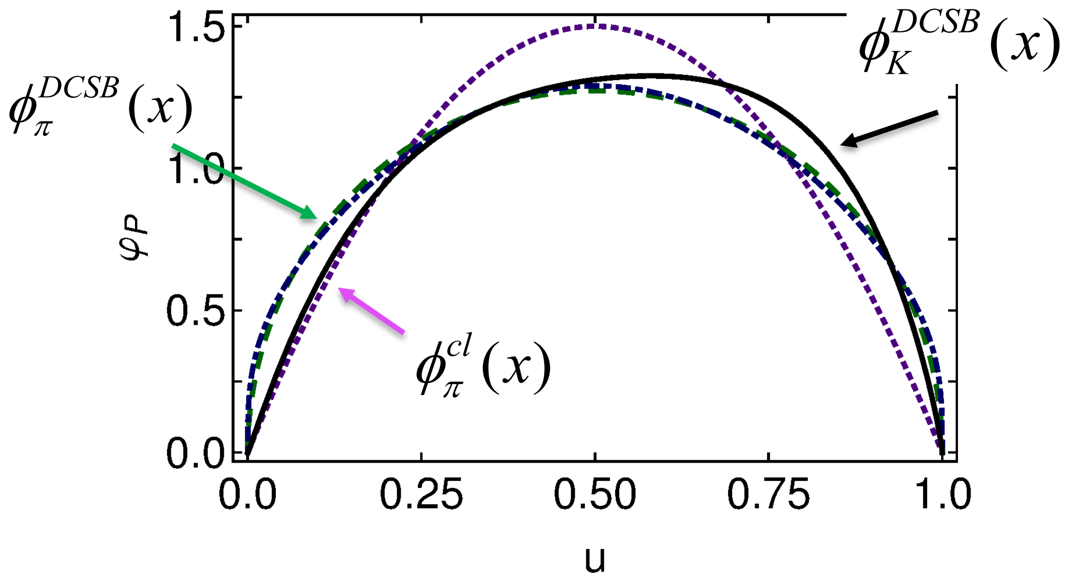


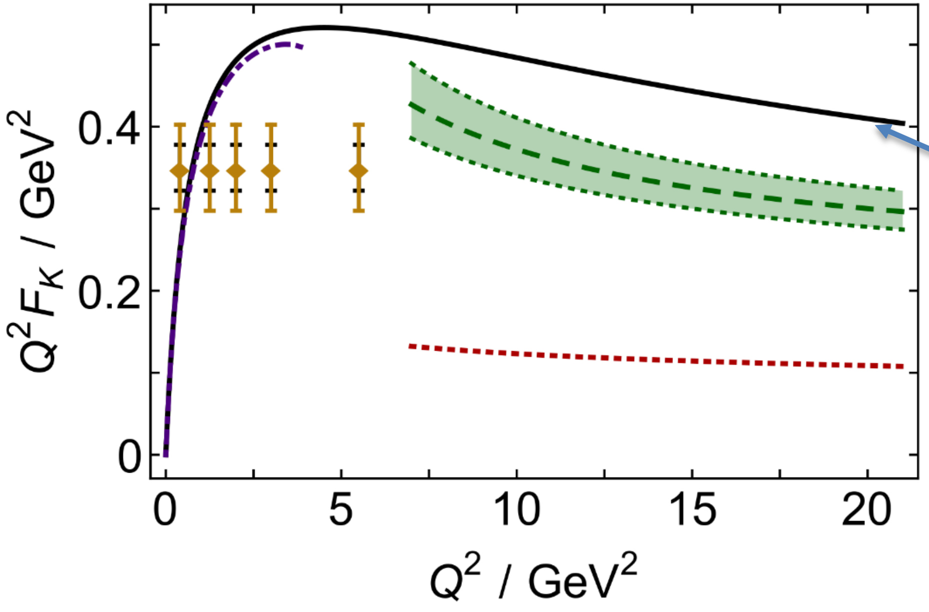
L. Chang et al, Phys.Rev.Lett. 111 (2013) 14, 141802
I. Cloet et al, Phys.Rev.Lett. 111 (2013) 092001
L. Chang et al, Phys.Rev.Lett. 110 (2013) 13, 132001

Kaon Form Factor

Kaon similar to pion, but with heavier *s* quark
→ Similar behavior in asymptotic limit
→ Distribution amplitudes similar although not identical

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \rightarrow \frac{f_K^2}{f_\pi^2} \qquad Q^2 \rightarrow \text{infinity}$$





F_K DCSB model prediction for JLab kinematics [F. Guo, et al., arXiv: 1703.04875].

Does Kaon FF approach asymptotic limit in same was as pion?

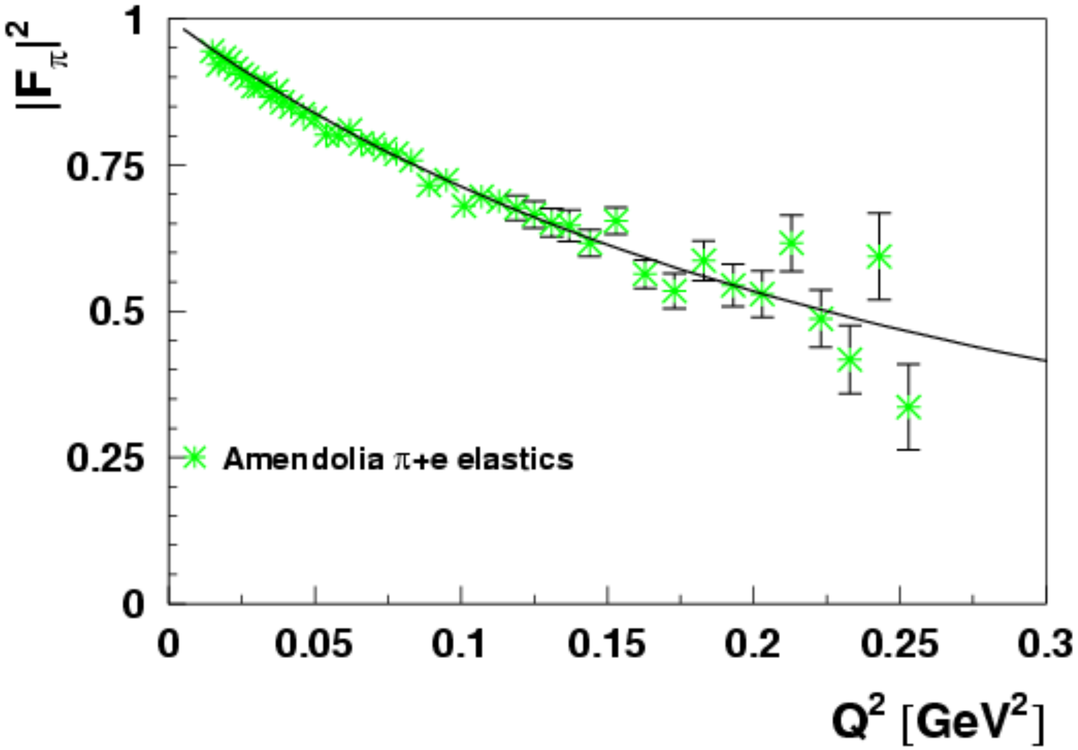
Understanding Q^2 dependence of both pion and kaon provides important test of our understanding of QCD

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

- At low Q^2, F_π can be measured ***directly*** via high energy elastic π^- scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2

    [Amendolia et al, NPB277, 168 (1986)]
  - These data used to extract the 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 1000 GeV pion beam

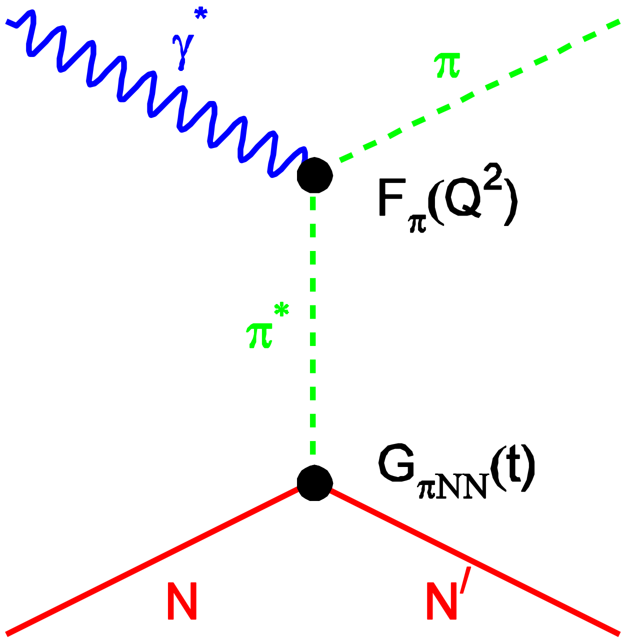


Measurement of π⁺ Form Factor – Larger Q^2

- At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via $p(e,e'\pi^+)n$
  - At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
  - In Born term model, F_π^2 appears as,

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

(In practice more sophisticated model is used)



- Requirements for this technique
  - Isolate σ_L (L-T separation)
  - Model to extract form factor from data – model dependence should be small at small $-t$

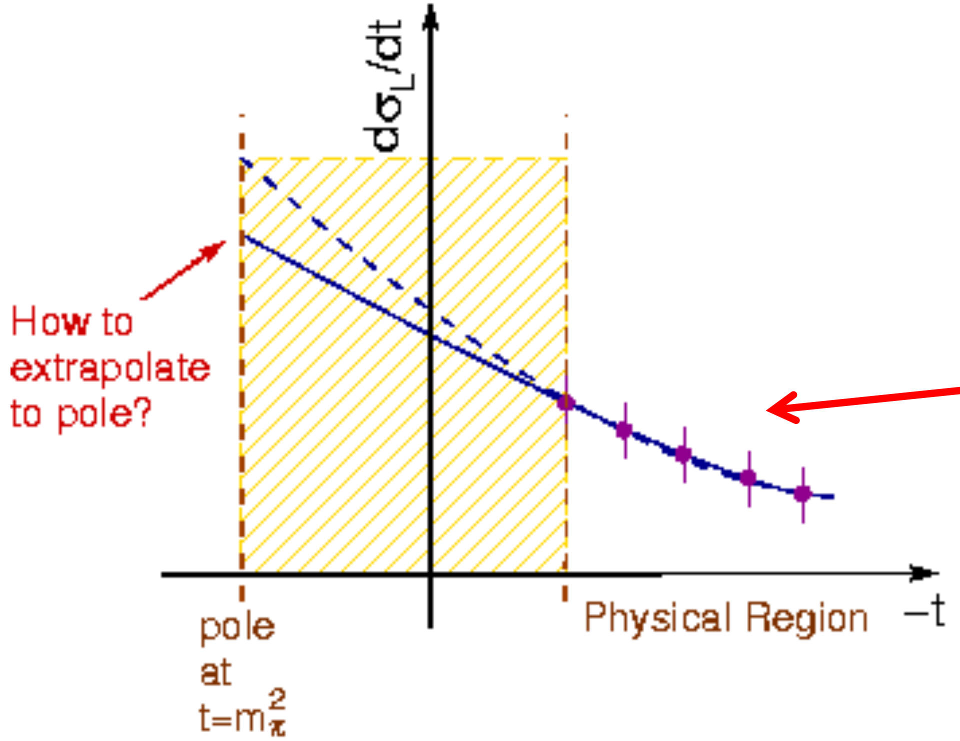
$t=(\gamma^*-\pi)^2$

= (mass)^2 of struck virtual pion

Jefferson Lab

Extraction of π^+ Form Factor in $p(e,e'\pi^+)n$

π^+ electroproduction can only access $t<0$ (away from pole)



Early experiments used "Chew-Low" technique

1. Measured –*t* dependence
2. Extrapolated to physical pole

Chew-Low extrapolation unreliable – FF depends on fit form

Fitting/constraining a ***model*** incorporating FF is a more robust technique

→ *t-pole* "extrapolation" is implicit, but one is only fitting data in physical region

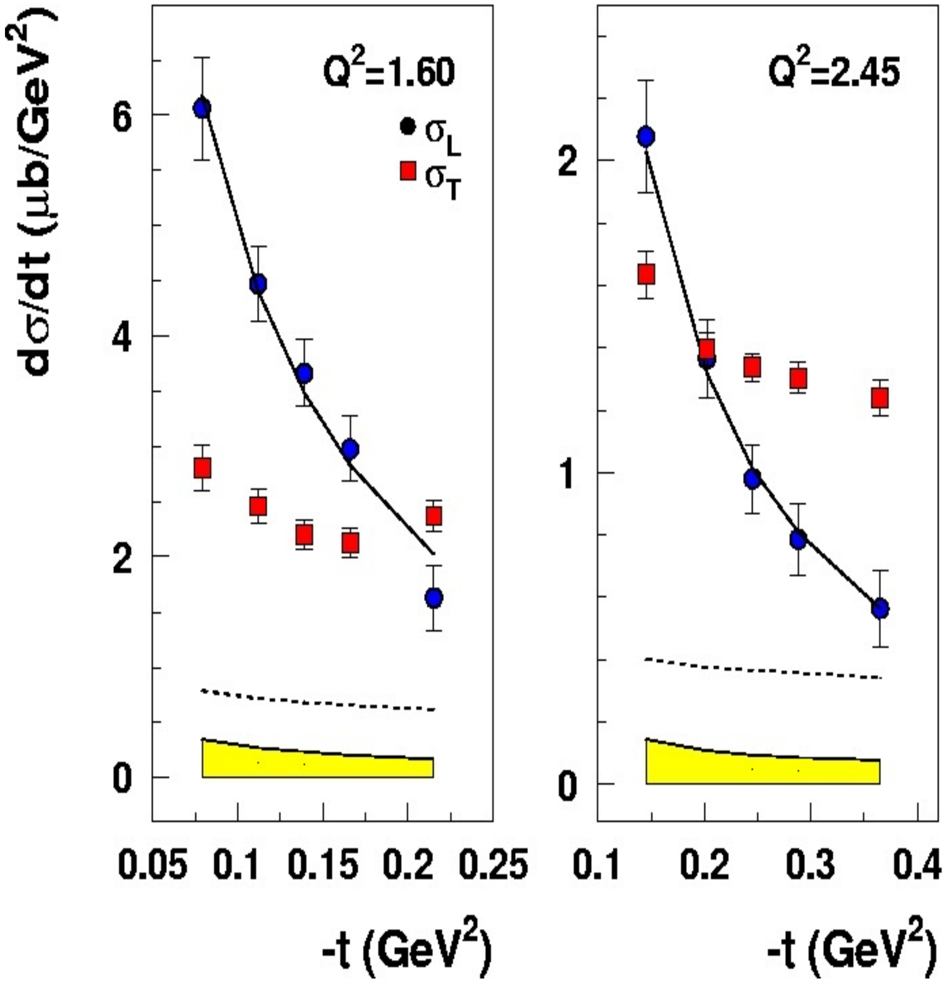
F_π Extraction from σ_L

VGL Regge Model

- Feynman propagator
  replaced by π and ρ Regge propagators
  - Represents the exchange of a <u>series</u> of particles, compared to a <u>single</u> particle
- Model parameters fixed from pion photoproduction.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff)

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

Horn et al, PRL97, 192001,2006

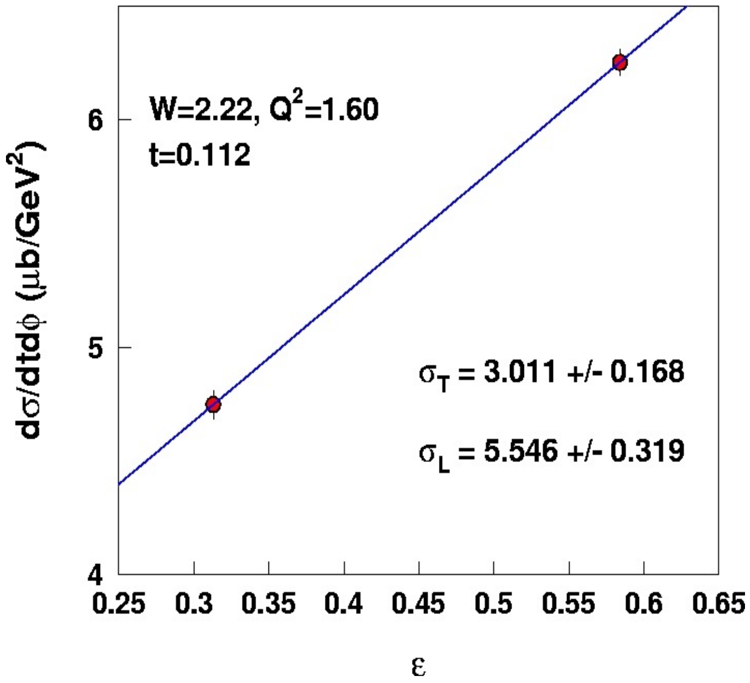


Λ_π^2=0.513, 0.491 GeV², Λ_ρ^2=1.7 GeV²

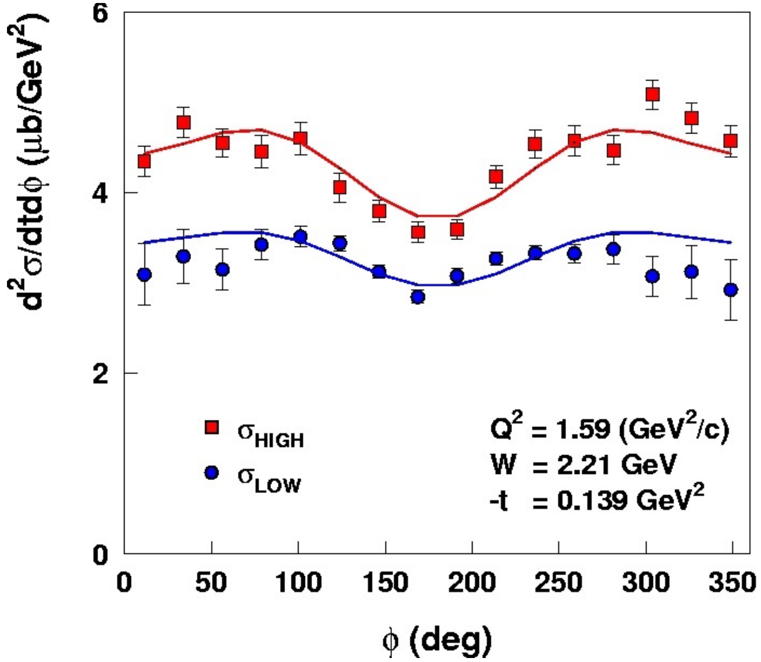
Measurement of σ_L

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

Rosenbluth separation required to extract σ_L → measurements of cross section at multiple beam energies, same (*W*, *Q*^{2},-*t*)



Simple extraction – no ***LT/TT*** terms



4-parameter fit: ***L/T/TT/LT***

Experimental Considerations for F_π Measurements

- Several constraints involved in making measurements of pion form factor
- Spectrometer capabilities:
  - Spectrometers must be able to detect electron and pion in coincidence (at same (W,Q^2,$-t$) at multiple beam energies
- $\Delta\varepsilon$: want largest possible range in ε to minimize uncertainty in σ_L
  - L/T cross section ratio also plays an important role, but beyond control of the experimentalist
- $-t_{min}$: want –t as small as possible to be close to pion pole → how close is close enough?

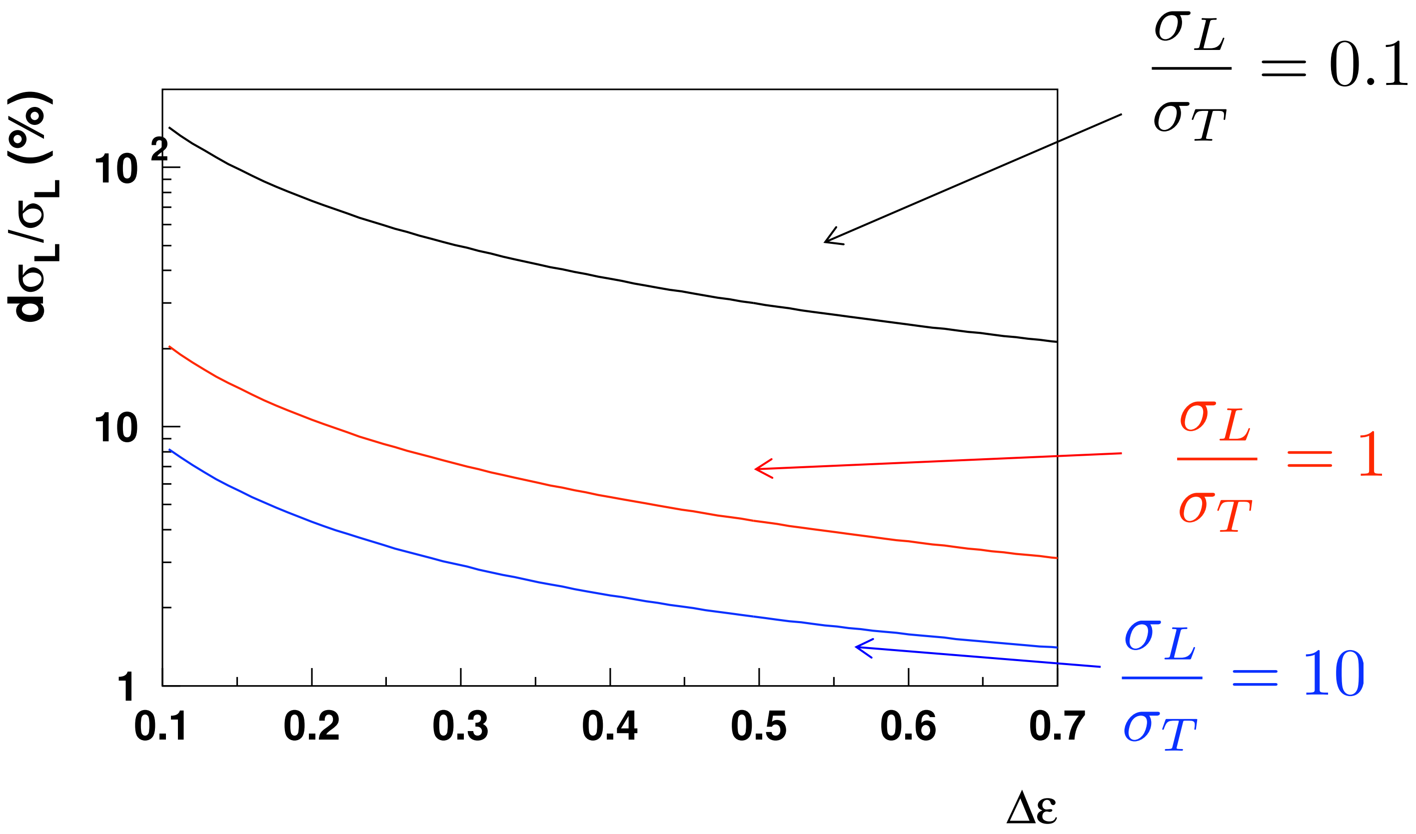
σ_L Uncertainties

$$\frac{d\sigma_L}{\sigma_L} = \frac{d\sigma}{\sigma}\frac{1}{\epsilon_1 - \epsilon_2}\sqrt{(1/R+\epsilon_1)^2 + (1/R+\epsilon_2)^2}$$

Uncertainty on σ_L for 1% uncertainty on unseparated cross section

→ Small $\Delta\varepsilon$ and unfavorable L/T ratio can lead to significant uncertainty penalty in σ_L

→ Example: $\sigma_L/\sigma_T=1$, $\Delta\varepsilon=0.3$, $d\sigma_L/\sigma_L$ ~ 10%



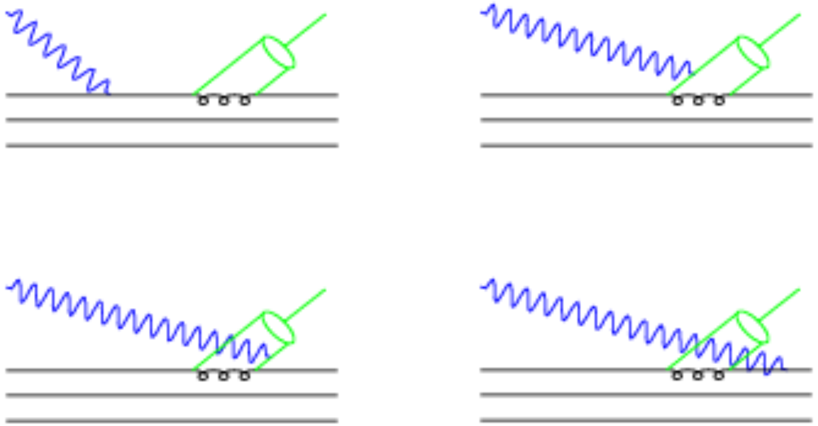
$-t_{min}$ and F_{π} Extraction

In addition to Born terms, pQCD processes can also contribute to π^+ production
→ How small must $-t$ be for Born term to dominate?

Before JLab program, only concrete guidance from Carlson and Milana ***[PRL 65, 1717 (1990)]***

For $-t>0.2$ GeV^2, pQCD contributions grow rapidly

JLab 6 GeV and 12 GeV programs planned with this constraint in mind, ***however***:
→ π^+ reaction mechanism better understood
→ Additional measurements planned for 12 GeV measurements to extend this range



Q^2 (GeV^2)	W(GeV)	**$-t$ (GeV^2)**	**M_{pQCD}/M_{pole}**
1.94	2.67	**0.07**	**0.12**
3.33	2.63	**0.17**	**0.18**
6.30	2.66	**0.43**	**0.81**
9.77	2.63	**0.87**	**2.82**

Kinematics of older Cornell measurements

Hall C π^+ Program at 12 GeV

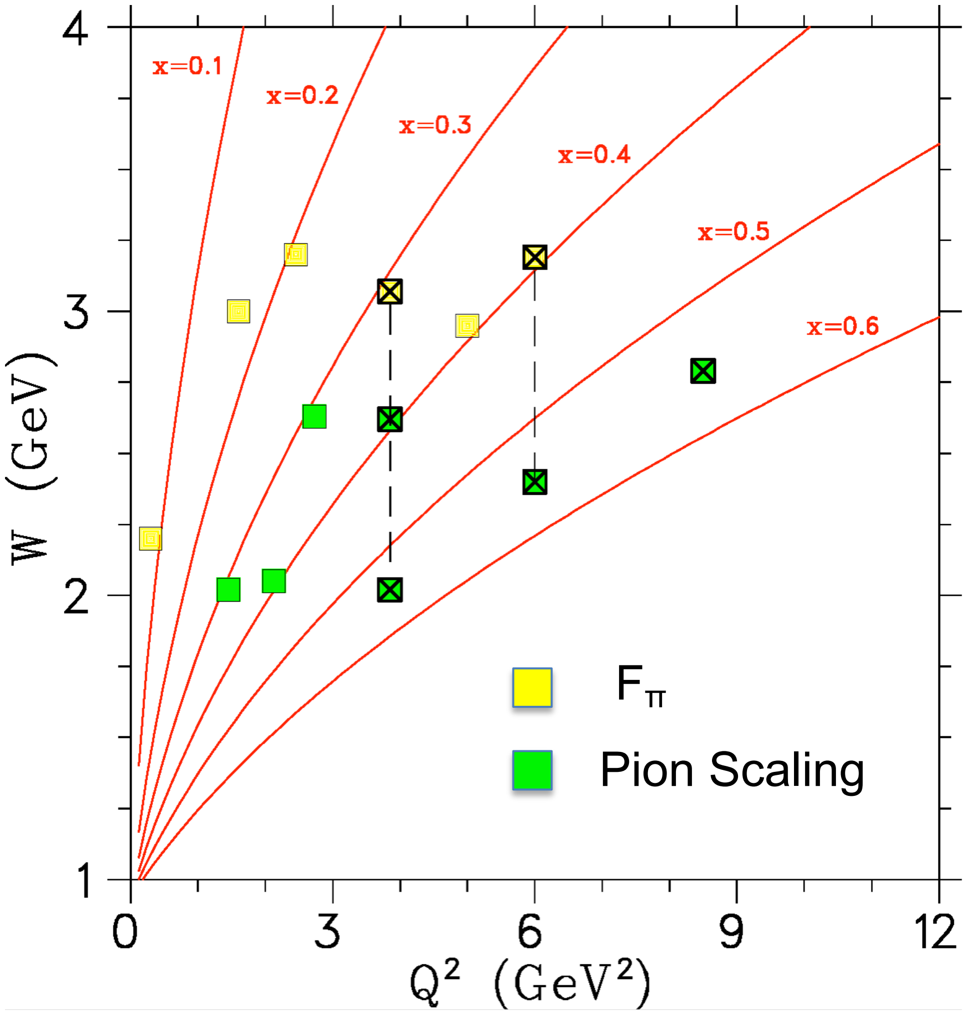
E12-19-006: Study of the L–T Separated Pion Electroproduction Cross Section at 11 GeV and Measurement of the Charged Pion Form Factor to High Q^2

Ran in 2019 (low Q^2) and 2021-2022

Program of L-T separated π^+ cross sections to measure:

1. Pion form factor at low $-t$ up to Q^2=6 GeV^2
2. Q^2 dependence of σ_L at fixed x and $-t$
3. Pion form factor up to Q^2=8.5 GeV^2

Additional data were taken to verify dominance of pole contribution and explore larger $-t_{min}$ for F_π extraction

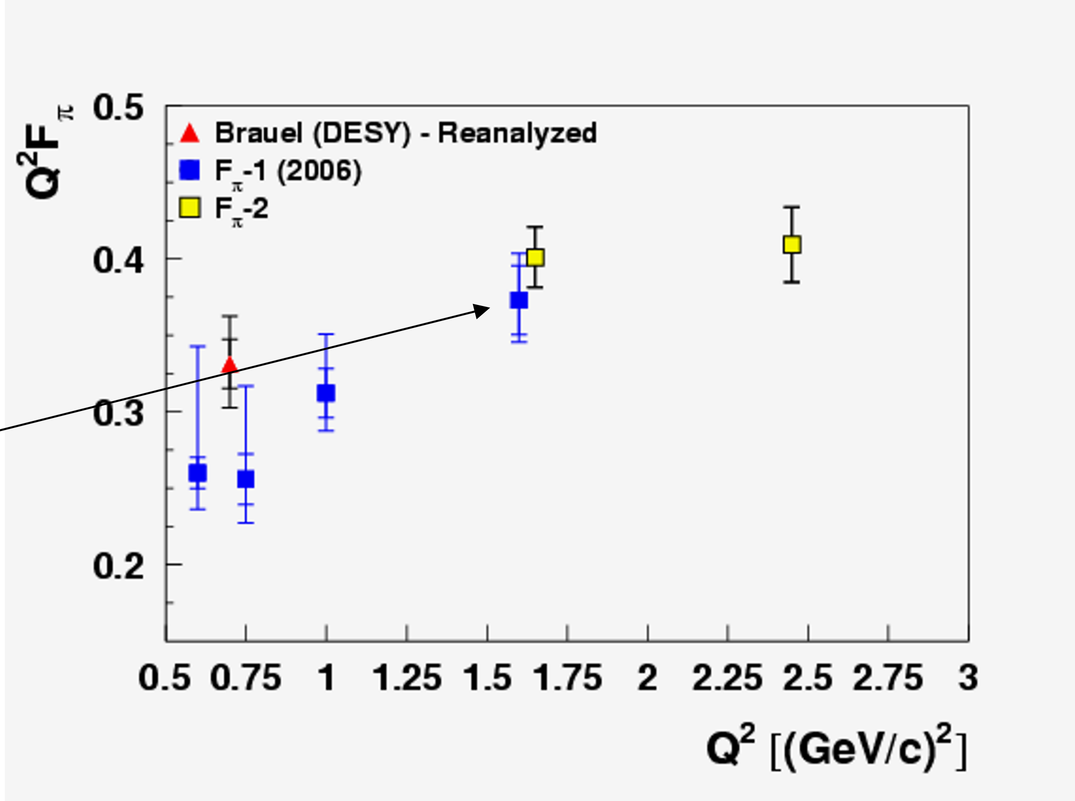


Form Factor Extraction at different $-t_{min}$

Is the model used to extract the form factor sensitive to the distance from the pion pole?

→Can be tested by extracting FF at different distances from –t pole

→Ex: F_π-2, $-t_{min}=0.093$ GeV^2
F_π-1, $-t_{min}=0.15$ GeV^2



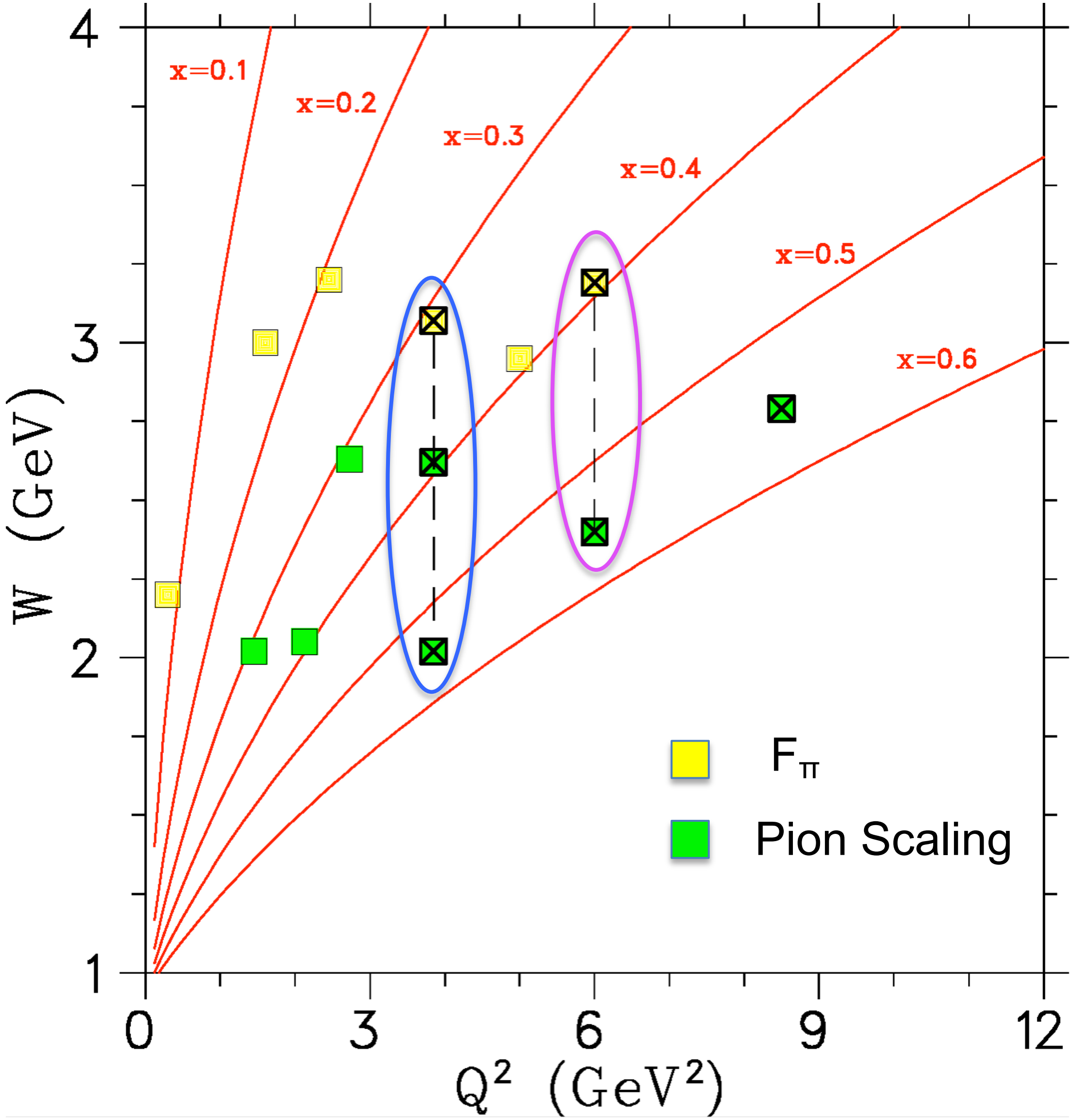
Additional data were taken as part of the Hall C π+ program to extend these studies to higher Q^2 and $-t_{min}$

Hall C π^+ Program Kinematics

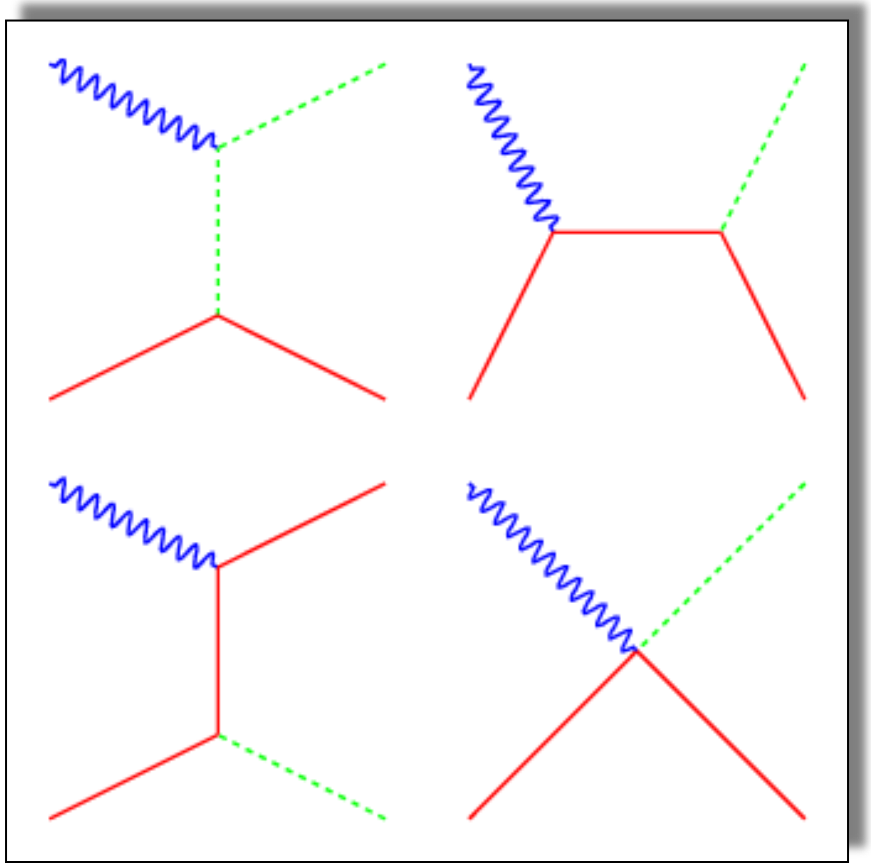
-t_{min} scans at fixed Q^2

→ Q^2=3.85 GeV^2
-t_{min}=0.12, 0.21, **0.49** GeV^2

→ Q^2=6.0 GeV^2
-t_{min}=0.21, **0.53** GeV^2



Pole Dominance Tests via π^-/π^+



Extraction of F_π relies on dominance of pole diagram

→t-channel diagram pure isovector

→Other Born diagrams both isovector and isoscalar

Measure (separated) π^-/π^+ ratios to test pole dominance

$$\frac{\sigma_L(\pi^-)}{\sigma_L(\pi^+)} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

Ratio = 1 suggests no isoscalar backgrounds

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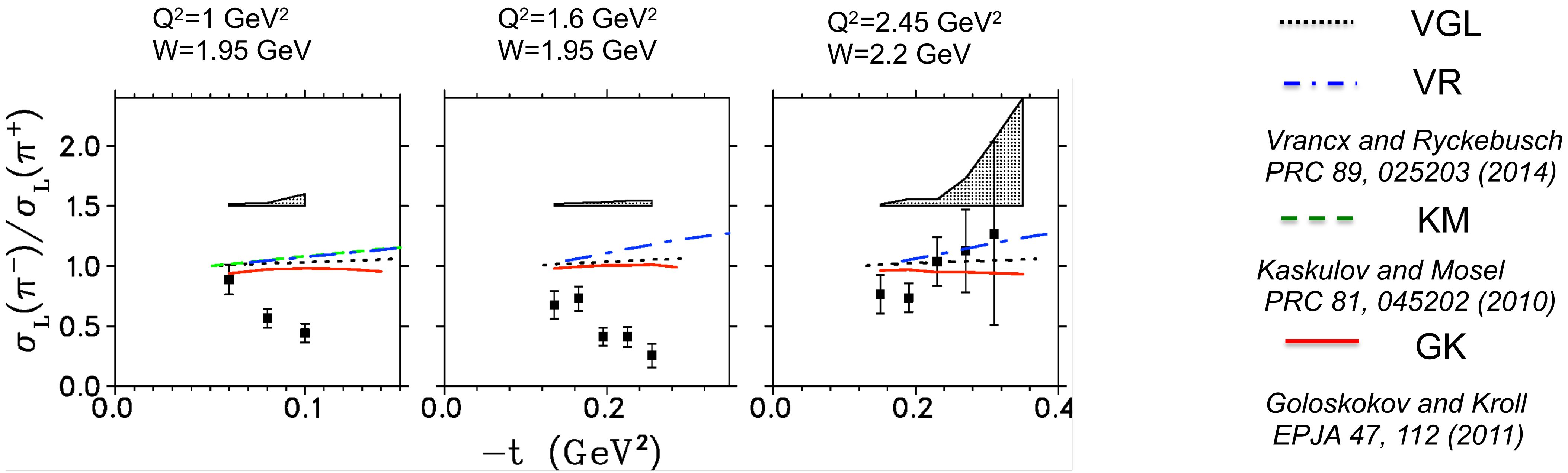
π^-/π^+ Ratios from F_π-1 and F_π-2



Vrancx and Ryckebusch PRC 89, 025203 (2014)

Kaskulov and Mosel PRC 81, 045202 (2010)

Goloskokov and Kroll EPJA 47, 112 (2011)

Huber et al, Phys.Rev.Lett. 112 (2014) 18, 182501

Longitudinal ratios in general < 1: approach 0.8 at $-t_{min}$

Consistent with VGL prediction for all $-t$ at Q^2=2.45 GeV^2

Assuming A_V and A_S are real: R_L=0.8 implies A_S/A_V = 0.06

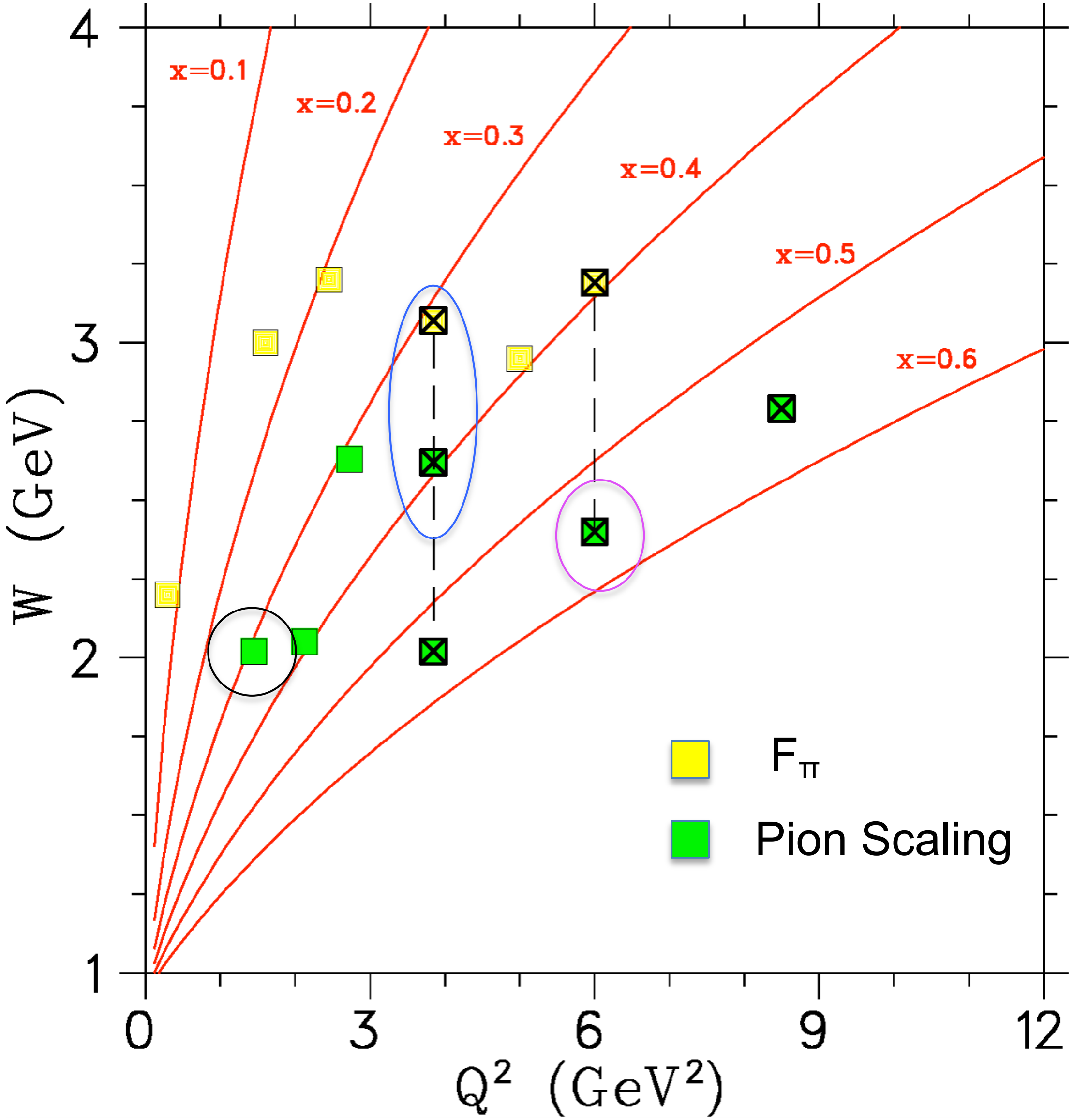
Hall C π^+ Program Kinematics

Separated π-/π+ Ratios

→ Q^2=1.6 GeV^2
$-t_{min}$=0.03 GeV^2

→ Q^2=3.85 GeV^2
$-t_{min}$=0.12, 0.21 GeV^2

→ Q^2=6.0 GeV^2
$-t_{min}$=**0.53** GeV^2



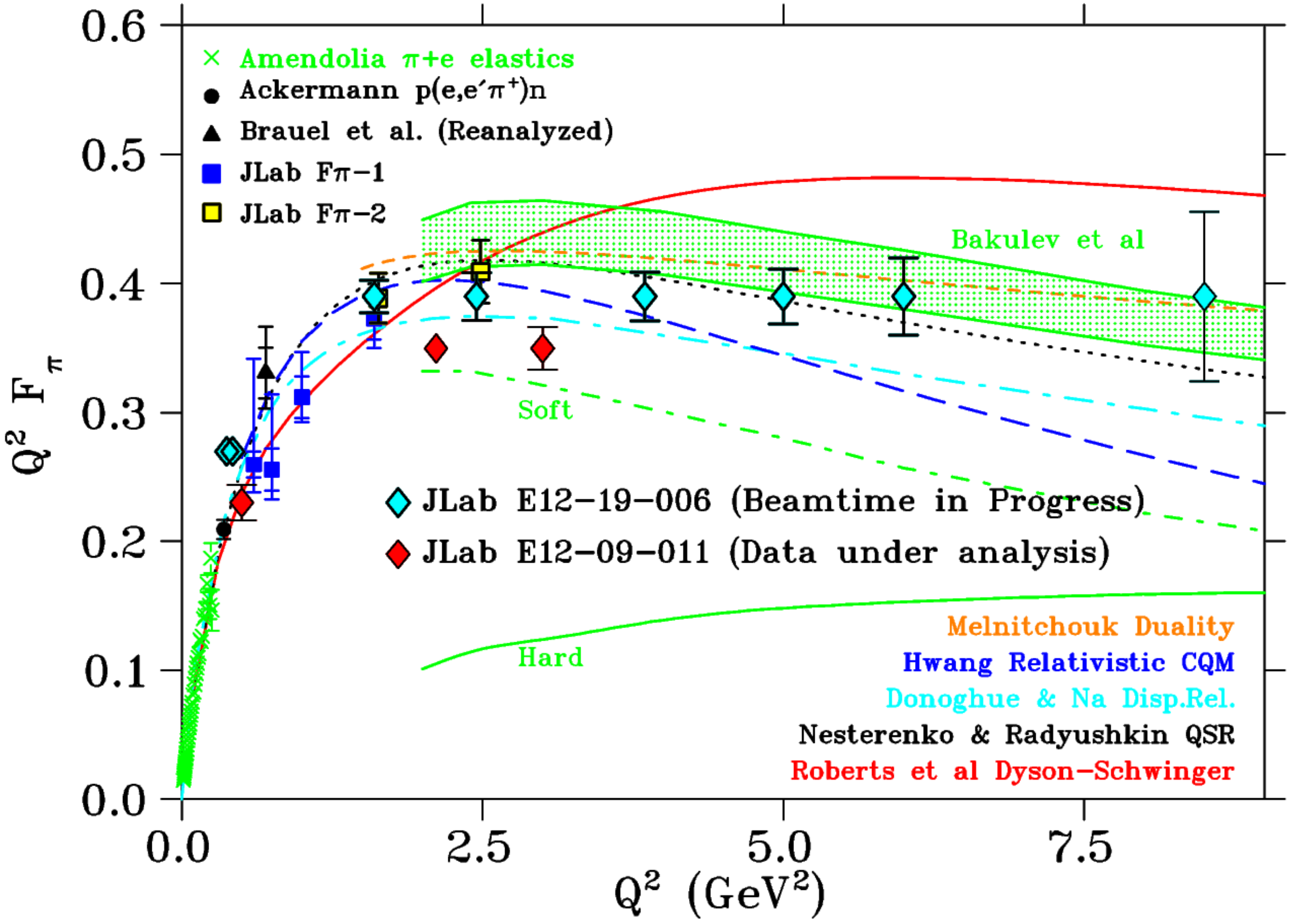
Jefferson Lab

F_π Kinematic Reach at 12 GeV

JLab 12 GeV program will allow measurements up to Q^2=8.5 GeV^2

→ Largest Q^2 data at $-t_{min}$=0.55 so ultimate precision will in part depend on supplemental data

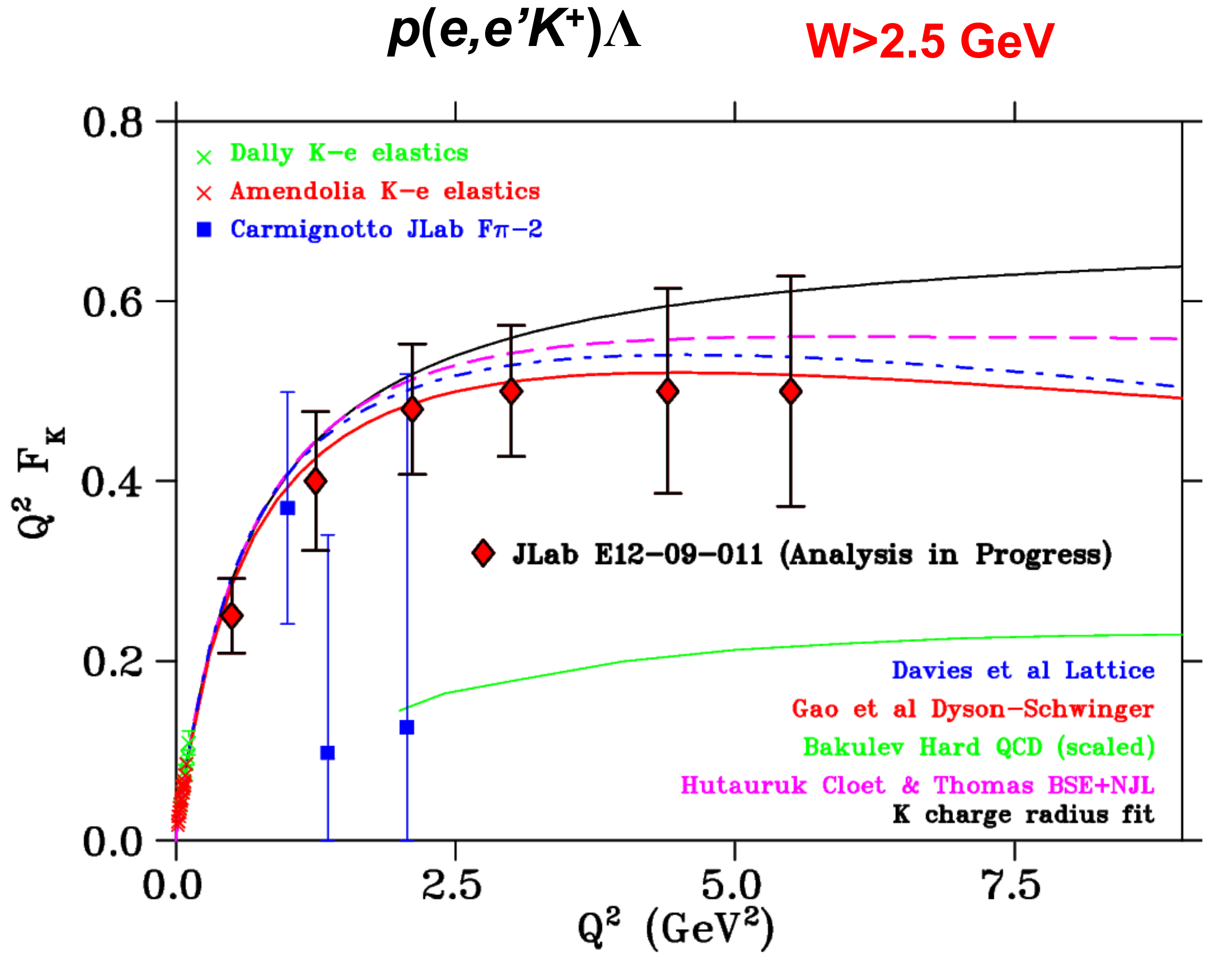
Require $\Delta\varepsilon$>0.2 to minimize error amplification in L-T separation



E12–19–006: G. Huber, D. Gaskell and T. Horn, spokespersons (data taking complete 2022)

F_K Measurements at 12 GeV

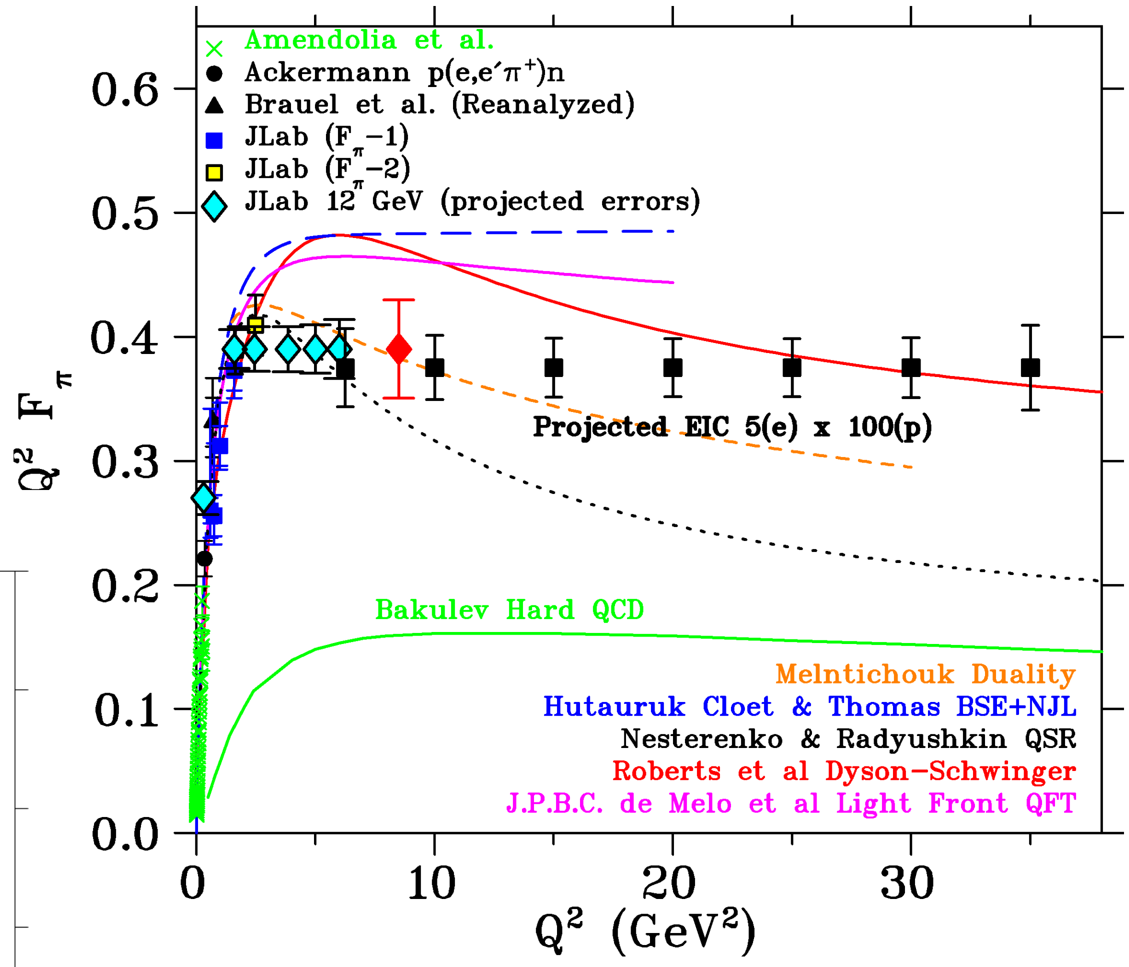
- Kaon form factor can also be extracted in manner analogous to pion
- *E12-09-011 (T. Horn, G. Huber, P. Markowitz)*
  - Partially completed in 2019
  - Data at low Q^2 to check overlap with elastic scattering data
  - Extraction of form factor up to Q^2=3 → larger uncertainties at larger Q^2 due to larger $-t_{min}$



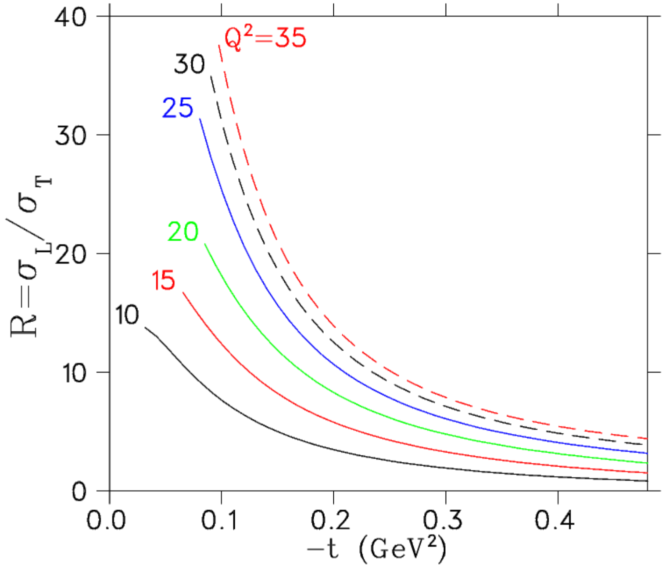
F_π at EIC

Pion form factor measurements also planned at EIC
→ L-T separations not possible at EIC – requires lower center of mass energy to access low e

Form factor extraction at EIC will rely on dominance of σ_L at large W and Q2
→ Extraction will be model dependent, although σ_T is expected to be small
→ Crucial to verify validity of FF extractions without L-T separation



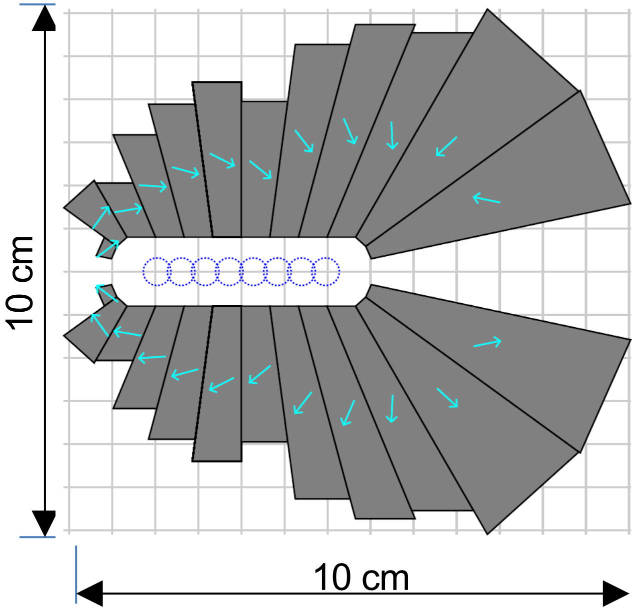
Predictions using model from:
T. Vrancx, J. Ryckebusch,
PRC 89, 025203 (2014)



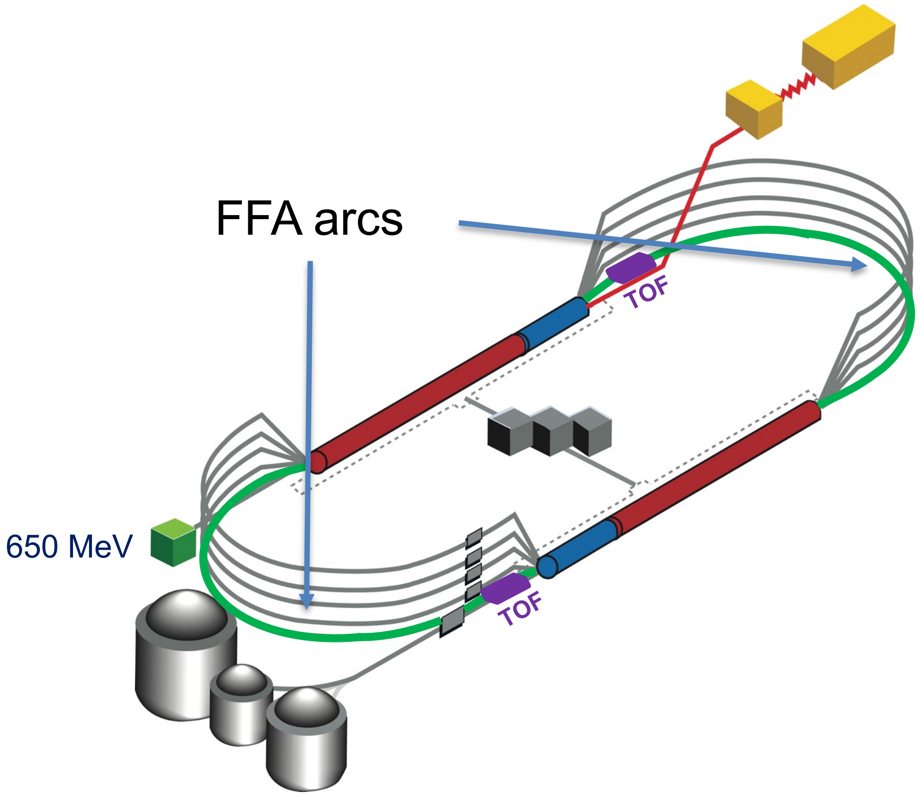
JLab 22 GeV Upgrade

JLab investigating energy upgrade making use of fixed-field alternating gradient (FFA) arcs

- → Replace Arcs 9 and A with FFA arcs
- → Recirculate beam 4 times through conventional arcs + 6.5 times through FFA → 10.5 passes
- → Assuming nominal 1.1 GeV per linac + (new) 650 injector, maximum beam energy = 22 GeV



Focusing Magnet BF
G_F= -41.13 T/m
L_{QF}= 1.67 m
B_F= -0.812 T



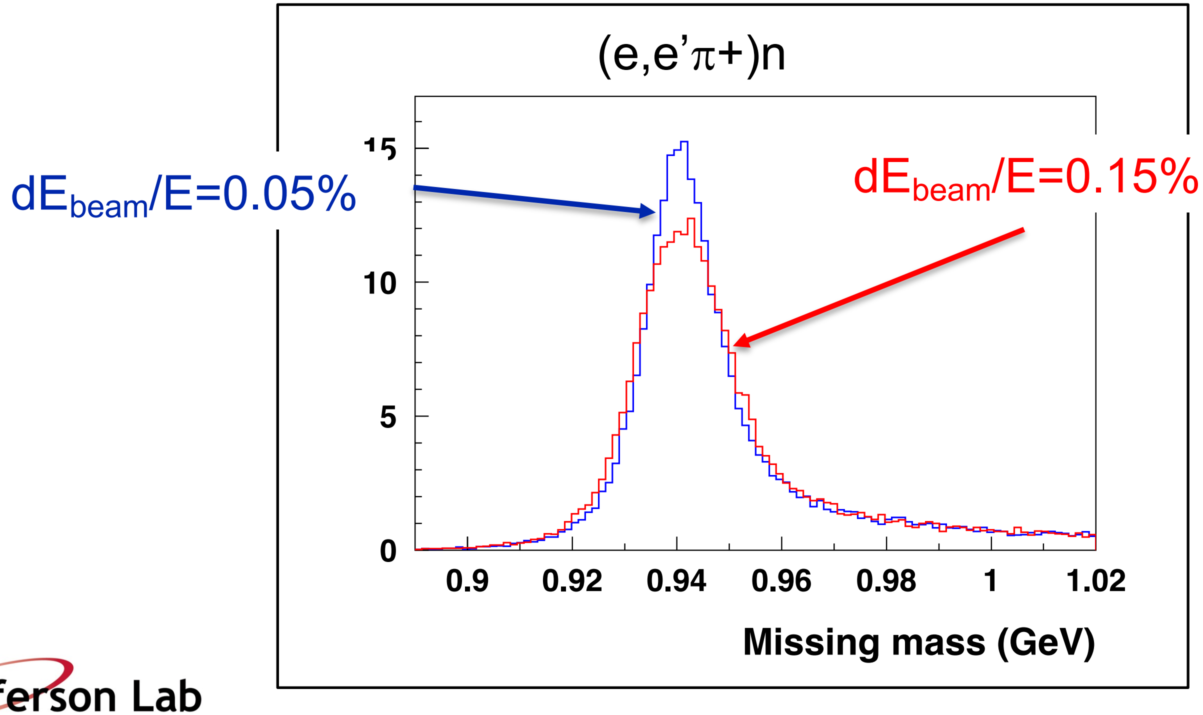
JLab 22 GeV Beam Properties and Exclusive Meson Production

Beam properties at higher energies will be somewhat worse than at 6 and 12 GeV

→ At 22 GeV, energy width ~ 0.15%

→ Still ok for exclusive meson production – just need enough resolution to cleanly identify exclusive final state

Beamlines	**$\Delta\epsilon_N$ [m rad]**		**$\Delta\sigma_{\Delta E/E}$**
	horizontal	vertical	
Arcs	6.0E-05		9.0E-4
Spr/Rec		2.0E-5	3.0E-4
Splitters*	2.0E-05		3.0E-4
Total	8.0E-05	2.0E-5	**1.5E-3**



★Projected value from the Spr/Rec contribution

Todd Satogata, JLUO meeting, 2023

Phase 1: Higher Energy + HMS/SHMS

Assume no upgrades to experimental equipment → just higher beam energy

→ HMS: P=1-7.2 GeV, θ=10.5-80 deg.
→ SHMS: P=1-11 GeV, θ=5.5-40 deg.
→ Opening angle = 18 deg.

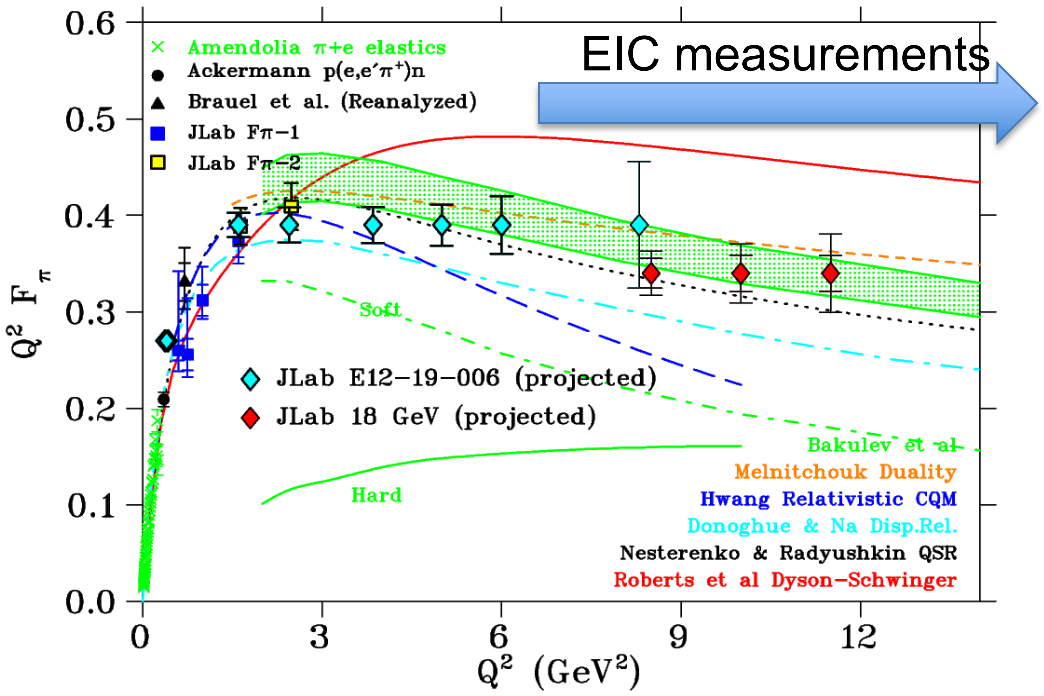
Total useful beam energy limited by sum of HMS and SHMS max. momentum → 18 GeV

Q^2=8.5: Improved F_π measurement
dF_π/F_π = 16.8%→8.0%
Q^2=10: New, high quality F_π data
Q^2=11: Highest accessible Q^2, but larger extraction uncertainty

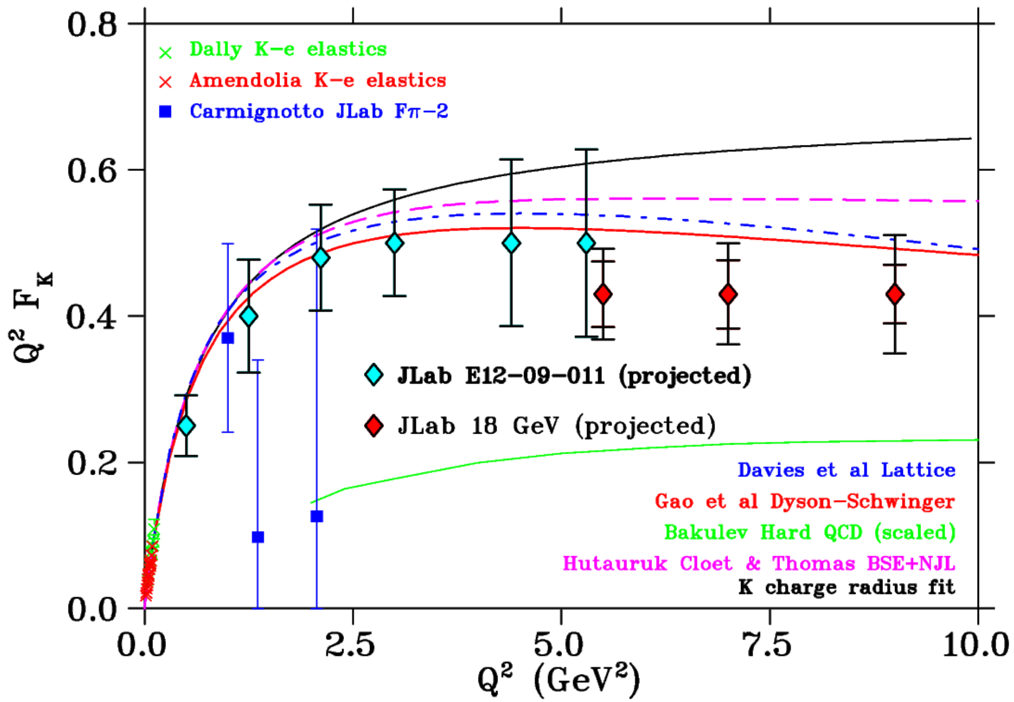
E_{Beam}	θ_{HMS} (e')	P_{HMS} (e')	θ_{SHMS} (π+)	P_{SHMS} (π+)	Time
Q^2=8.5 W=3.64 $-t_{min}$=0.24 $\Delta\varepsilon$=0.40					
13.0	34.30	1.88	5.29	10.99	64.7
18.0	15.05	6.88	8.94	10.99	2.2
Q^2=10.0 W=3.44 $-t_{min}$=0.37 $\Delta\varepsilon$=0.40					
13.0	37.78	1.83	5.56	10.97	122.7
18.0	16.39	6.83	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

Phase 1: Higher Energy + HMS/SHMS

F_π



F_K



Inner error bars = statistical + systematic
Outer error bars → includes uncertainty from model used in FF extraction

Since uncertainty on σ_L depends on L/T ratio, projections also rely on model (Vrancx Ryckebusch)

Phase 2: Higher Energy + SHMS/new VHMS

New spectrometer with higher momentum and small angle capability

HMS → VHMS "very high momentum spectrometer"

VHMS: θ_{min}=5.5 deg., P_{max}=15 GeV

Opening angle between VHMS-SHMS ~ 20 degrees

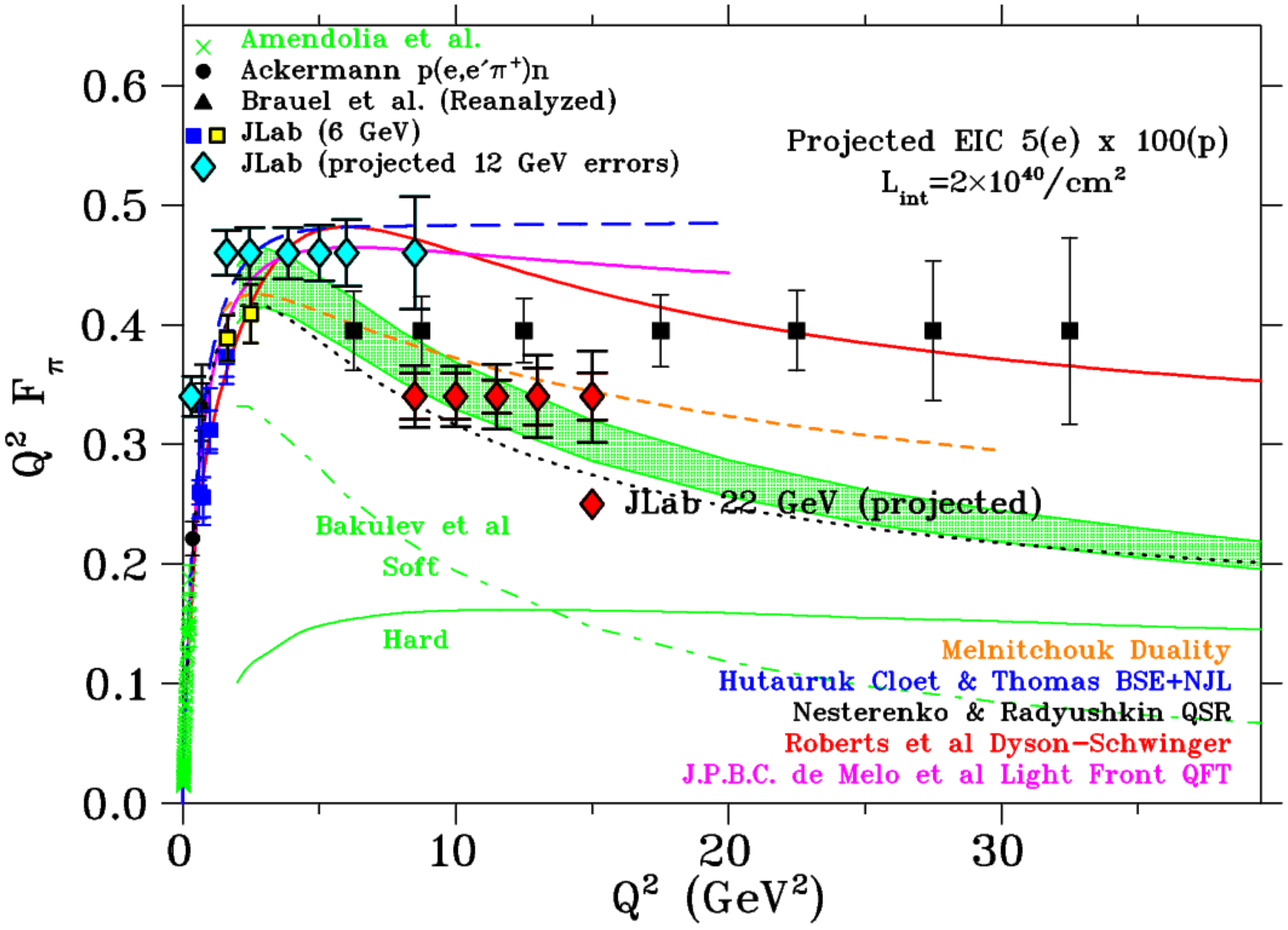
Increase Q^2 reach to 15 GeV^2
→ Higher precision at Q^2=10, 11.5

E_{Beam}	θ_{SHMS} (e')	P_{SHMS} (e')	θ_{VHMS} (π+)	P_{VHMS} (π+)	Time
Q^2=8.5 W=4.18 $-t_{min}$=0.15 $\Delta\varepsilon$=0.28					
17.0	21.39	3.63	5.55	13.29	20.5
22.0	12.15	8.63	7.62	13.29	1.8
Q^2=10.0 W=4.08 $-t_{min}$=0.21 $\Delta\varepsilon$=0.30					
17.0	24.49	3.27	5.52	13.62	53.3
22.0	13.46	8.27	7.85	13.62	4.3
Q^2=11.5 W=3.95 $-t_{min}$=0.29 $\Delta\varepsilon$=0.31					
17.0	27.34	3.03	5.55	13.82	124.8
22.0	14.66	8.03	8.12	13.82	9.3
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	209.5
22.0	16.49	7.18	7.69	14.63	24.4
Q^2=15.0 W=3.73 $-t_{min}$=0.52 $\Delta\varepsilon$=0.26					
18.0	30.24	3.06	5.73	14.66	560
22.0	17.88	7.06	8.07	14.66	65.7

F_π at 22 GeV with SHMS/new VHMS

JLab is the ***only*** facility for the foreseeable future that will be able to make precise measurements of L-T separated cross sections
→ These measurements can't be made at EIC

JLab at 22 GeV will allow F_π measurements up to Q^2=15 GeV^2
→ Will provide substantial overlap with EIC measurements from unseparated cross sections
→ Crucial cross-check of model-dependent EIC results



Summary

- Measurements of pion and kaon form factors important for testing our understanding of QCD
- Form factor extraction at large Q^2 requires measurement of longitudinal cross section (σ_L)
- JLab has extensive program of F_π at 6 and and 12 GeV
  - Measurements of kaon FF accessible from 12 GeV data
- JLab energy upgrade will allow measurements of pion FF up to 11.5 GeV^2 with existing spectrometers
  - New "VHMS" would allow measurements up to Q^2=15 GeV^2
  - Measurements at EIC will extend to very large Q^2, but L-T separation not possible, will rely on models to estimate transverse contribution

EXTRA

DEMP Scaling Tests

At large Q^2, in region where soft-hard factorization valid, separated cross section Q2 dependence expected to be:

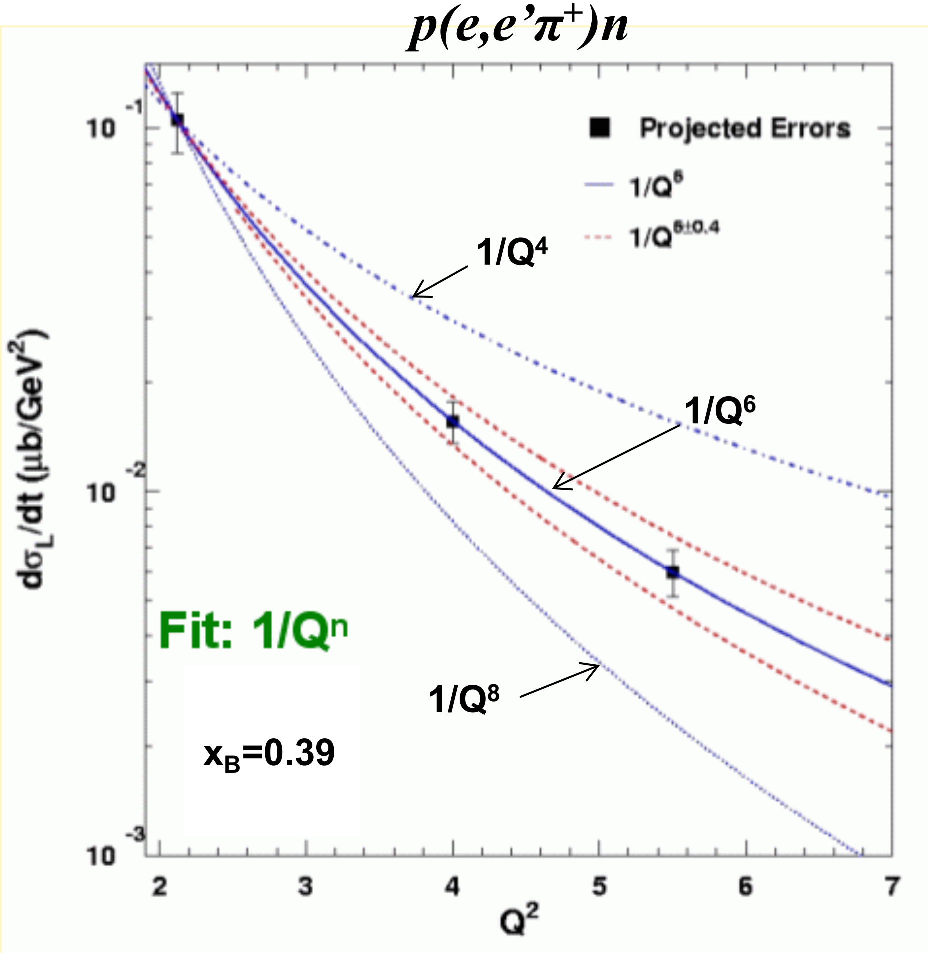
$\rightarrow \sigma_L \sim 1/Q^6$

$\rightarrow \sigma_T \sim 1/Q^8$

Tests of this prediction will carried out as part of E12-19-006

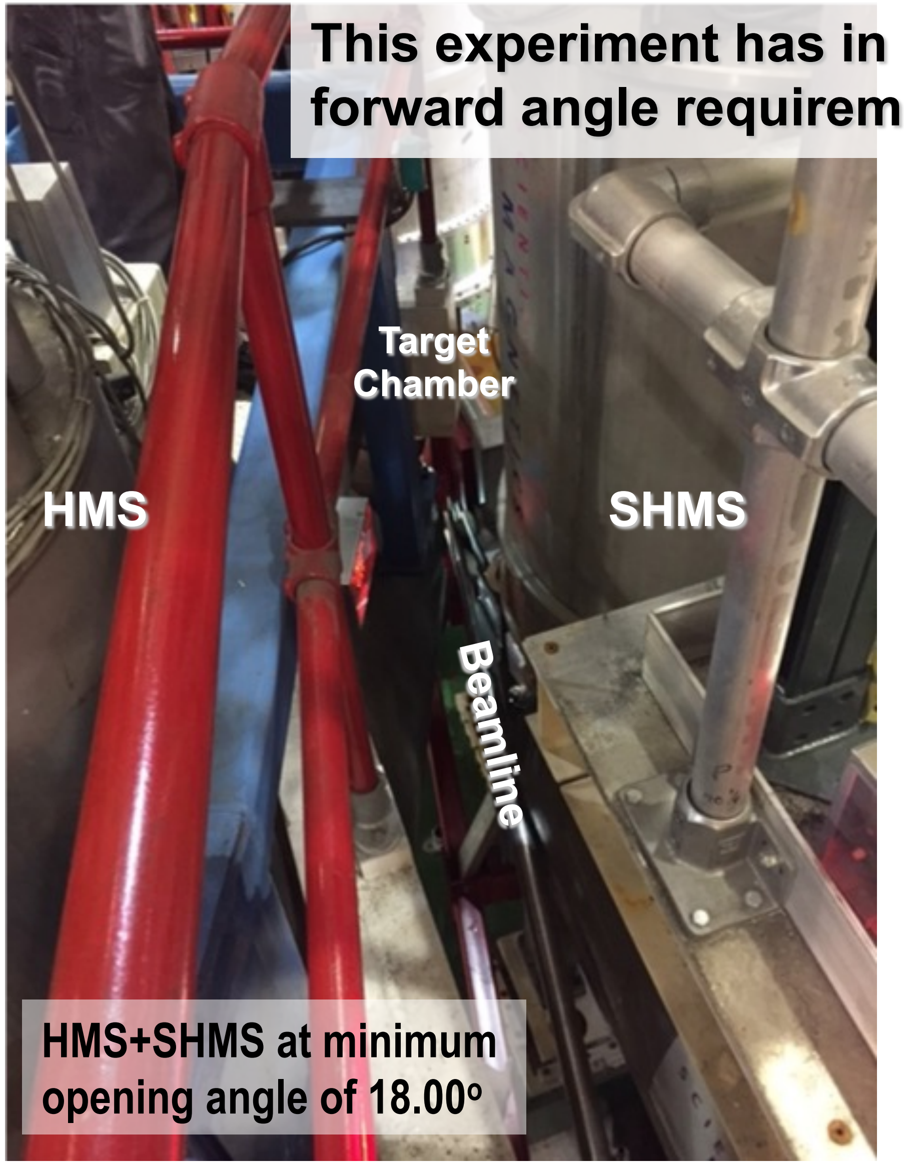
Q^2 range of these tests can be nearly doubled with 22 GeV upgrade and HMS+SHMS

x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ $(\mathrm{GeV/c})^2$
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	



HMS and SHMS during pionLT

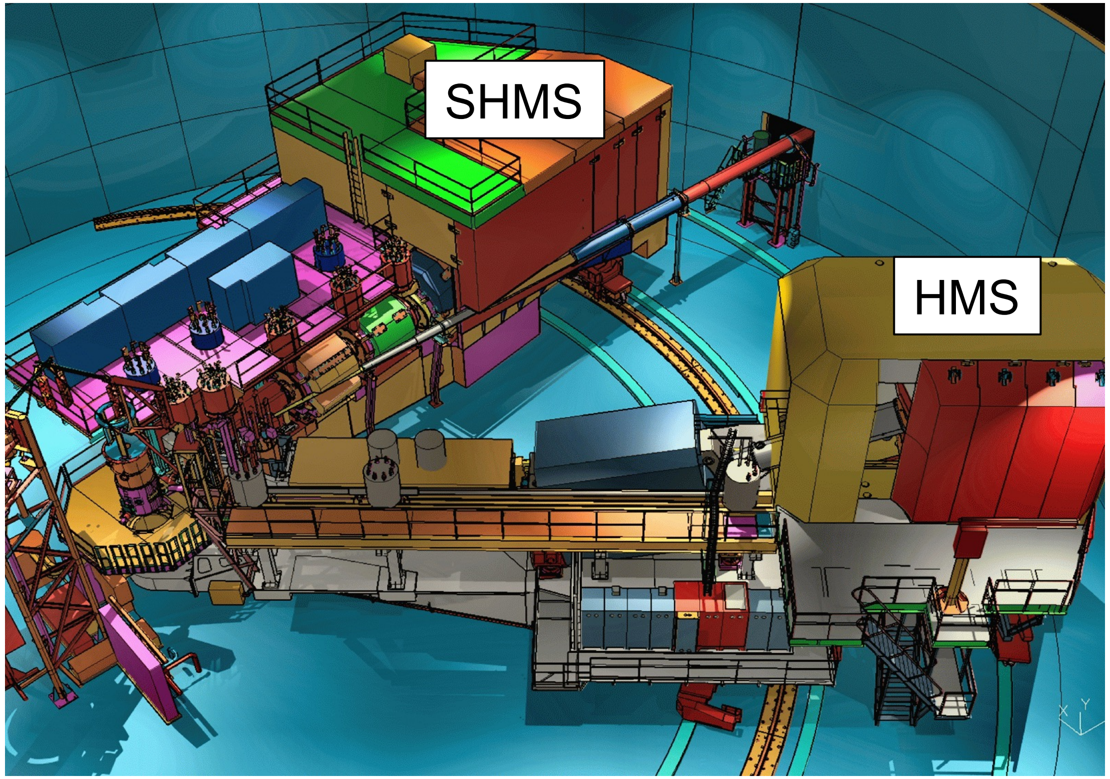
This experiment has in large part driven the forward angle requirements of the SHMS+HMS



HMS+SHMS at minimum opening angle of 18.00°

SHMS at 5.69°

π^+ Production in Experimental Hall C



Excellent control of point-to-point systematic uncertainties required for precise L-T separations
→ Ideally suited for focusing spectrometers
→ One of the drivers for SHMS design

Spectrometer properties

HMS: Electron arm
Nominal capabilities:
$d\Omega \sim 6$ msr, $P_0 = 0.5 - 7$ GeV/c
$\theta_0 = 10.5$ to 80 degrees
e ID via calorimeter and gas Cerenkov

SHMS: Pion arm
Nominal capabilities:
$d\Omega \sim 4$ msr, $P_0 = 1 - 11$ GeV/c
$\theta_0 = 5.5$ to 40 degrees
π:K:p separation via heavy gas Cerenkov and aerogel detectors