Measurement of the Charged Pion Form Factor in Hall C

Dave Gaskell
Jefferson Lab

Towards Improved Hadron Femtography with Hard Exclusive Reactions
July 18-20

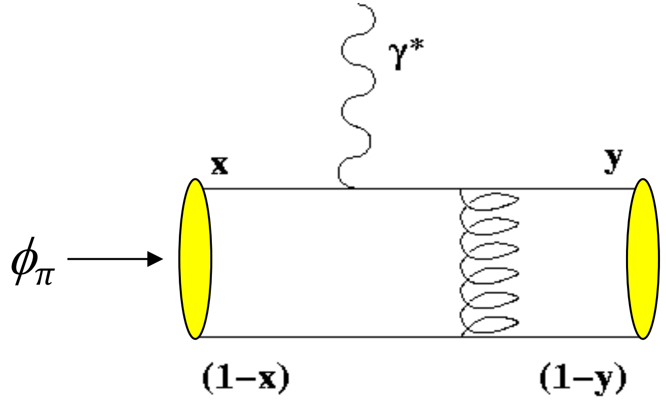
The Pion Form Factor and the Interplay of Soft and Hard Physics

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



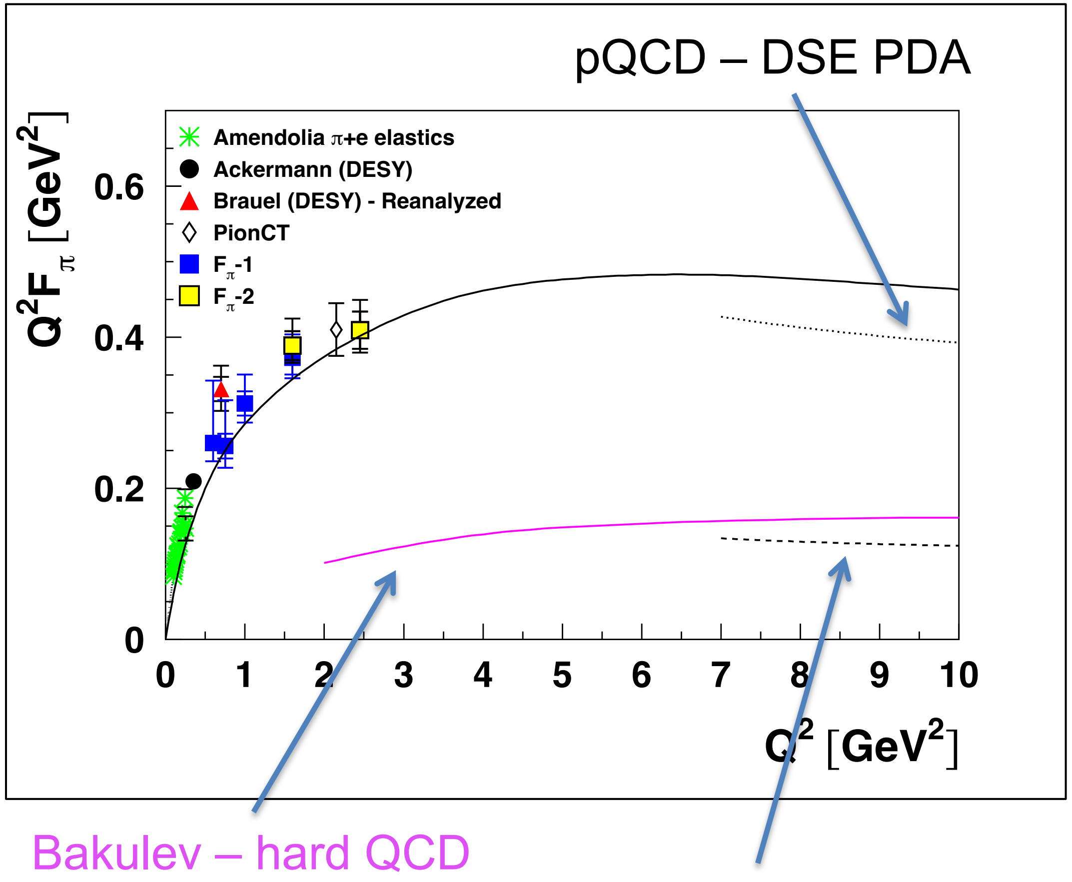
f_π=93 MeV is the $\pi^+ \rightarrow \mu^+ \nu$ decay constant.

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

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

Jefferson Lab

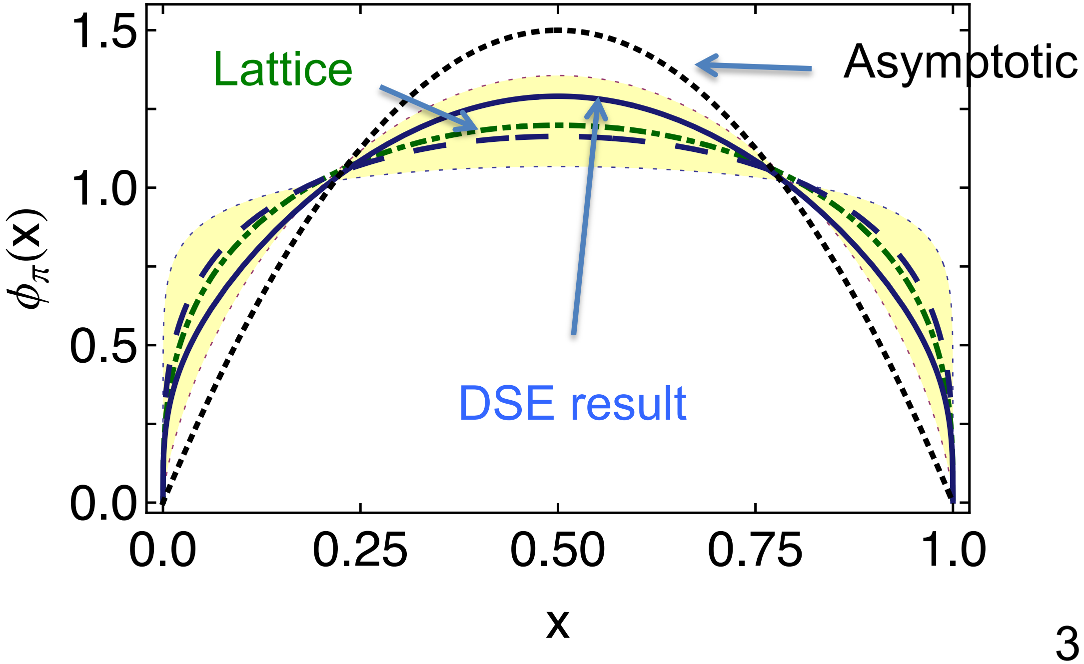
pQCD and the Pion Form Factor



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

F_π at Large Q^2

There is great interest in extending measurements of the pion form factor up to Q^2=8-9 GeV^2

- A measurement near Q^2=8-9 GeV^2 would access the region where lattice-based pion DA calculations are valid → explore shape of pion DA relative to asymptotic form

- Access regime where F_π begins to deviate from monopole form

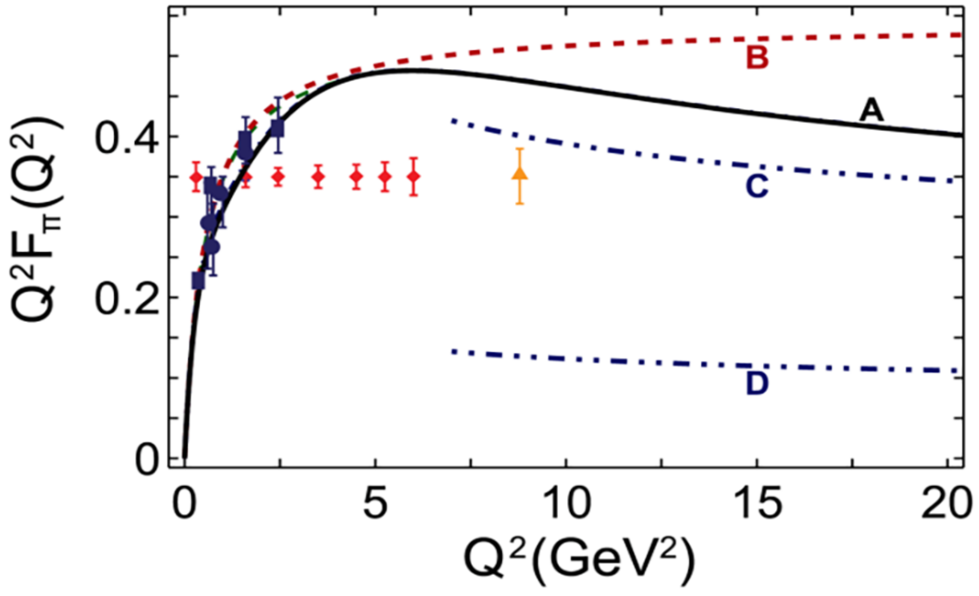


Figure 2.2: *Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate calculations based on a short-distance quark-gluon view.*

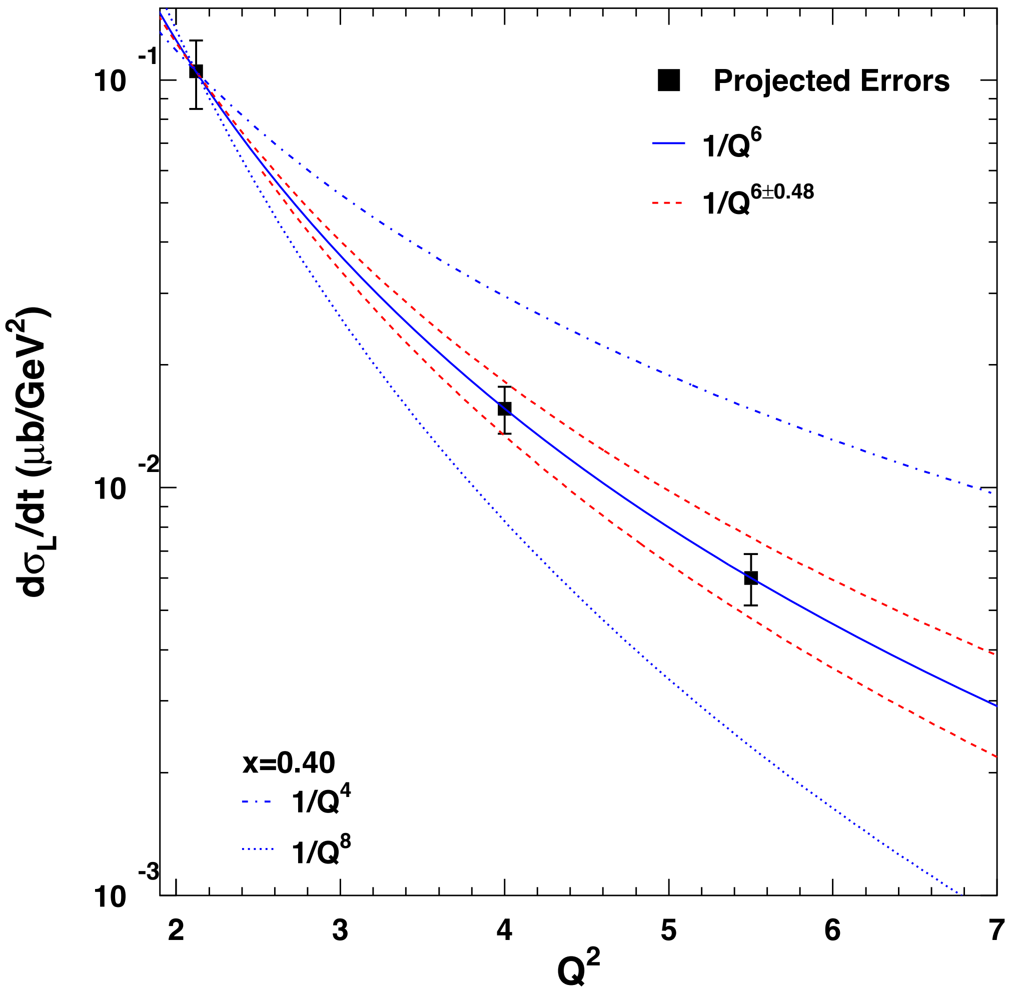
NSAC Long Range Plan (2015)
"Reaching for the Horizon"

F_π and Factorization

Measurement of pion form factor also related to GPD program

Factorization proof* for longitudinal photons assumes pion wave function at endpoint has shape similar to *z(1-z)*
→ Deviation of pionFF from asymptotic form suggests this may not apply

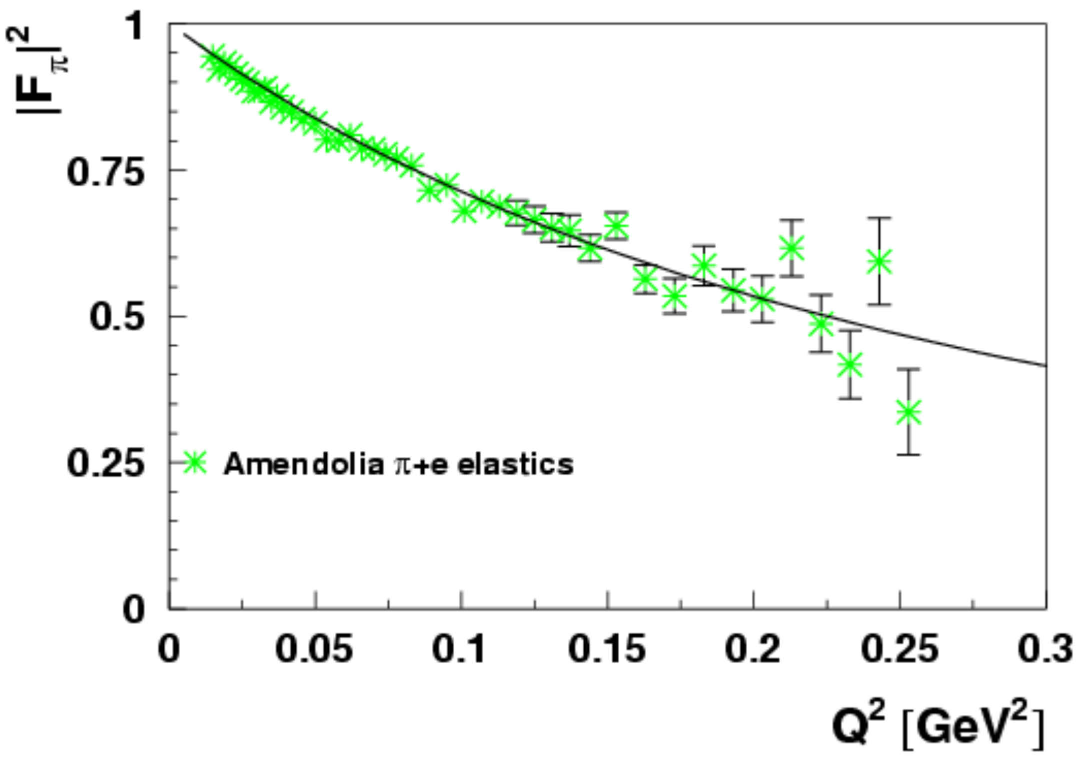
Note: in addition to FF measurements, JLab Hall C will make L-T separated measurements at fixed *x,-t* to test for expected $1/Q^6$ scaling



*Collins, Frankfurt, and Strikman PRD 56 (1997) 2982-3006

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



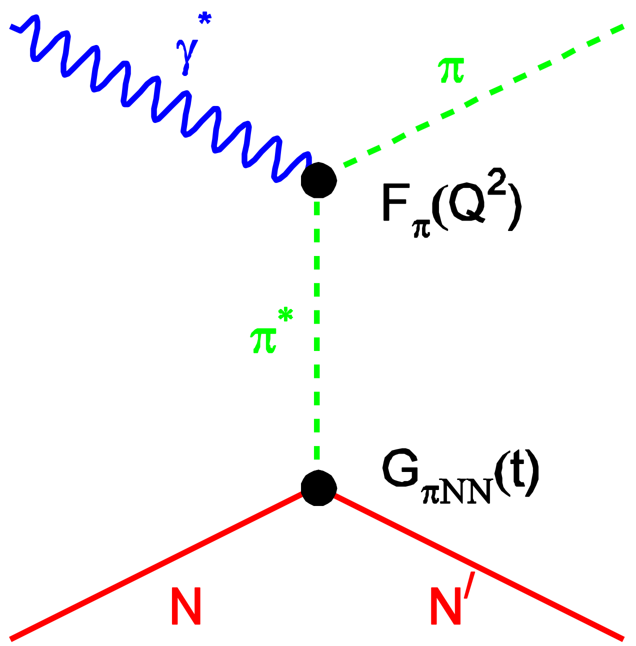
Measurement of π^+ Form Factor – Larger Q^2

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

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

(In practice more sophisticated model is used)

- Requirements for this technique
  - Isolate σ_L (L-T separation)
  - Theory to extract form factor from data

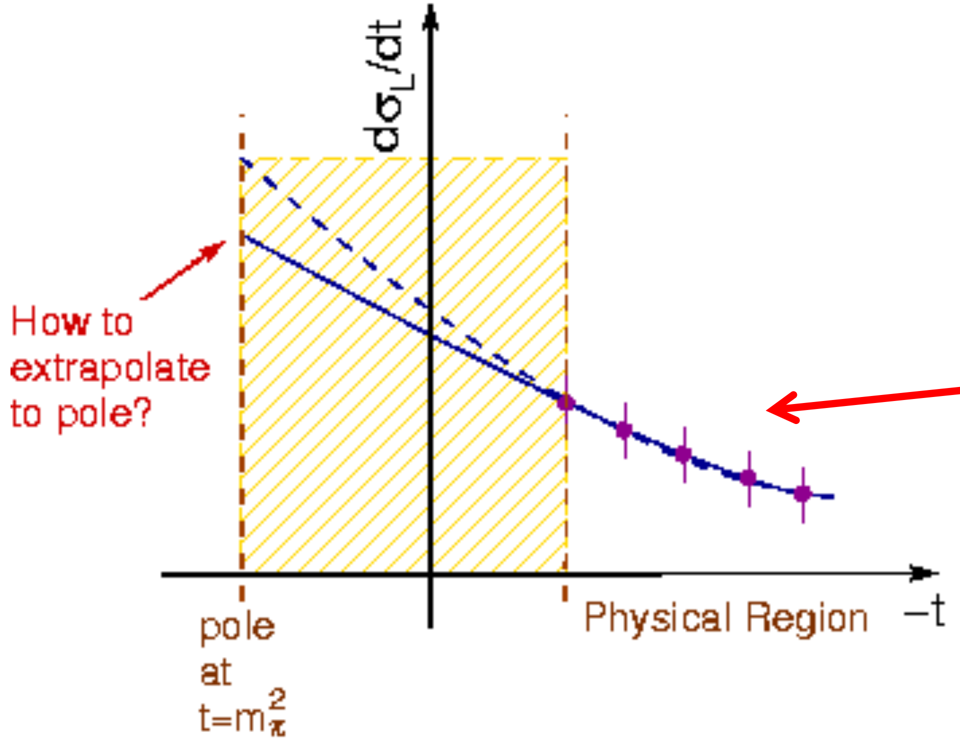


$t=(\gamma^*-\pi)^2$

= (mass)^2 of struck virtual pion

Extraction of π⁺ Form Factor in *p(e,e'π⁺)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 Program at Jefferson Lab at 6 GeV

Two F_π experiments were carried out in Hall C in 6 GeV era

F_π-1: Q^2=0.6-1.6 GeV^2
F_π-2: Q^2=1.6, 2.45 GeV^2

Expt	Q^2 (GeV^2)	W (GeV)	$\|t_{min}\|$ (Gev^2)	E_e (GeV)
F_π-1	0.6-1.6	1.95	0.03-0.150	2.45-4.05
F_π-2	1.6,2.45	2.22	0.093,0.189	3.78-5.25

→ Second experiment took advantage of higher beam energy to access larger *W*, smaller –*t*

→ Full deconvolution of ***L/T/TT/LT*** terms in cross section

→ Ancillary measurement of π-/π+ (separated) ratios to test reaction mechanism

→ F_π-1 ran in 1997 and F_π-2 in 2003

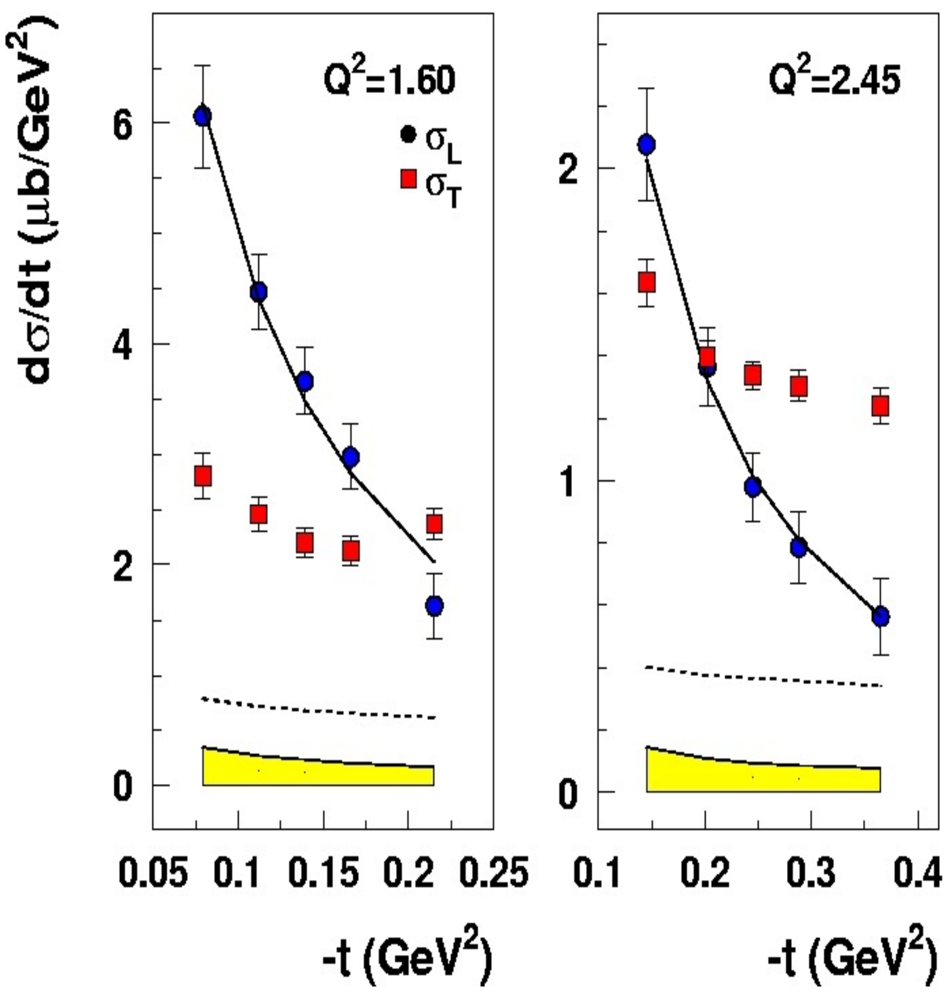
F_π Extraction from σ_L

VGL Regge Model

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

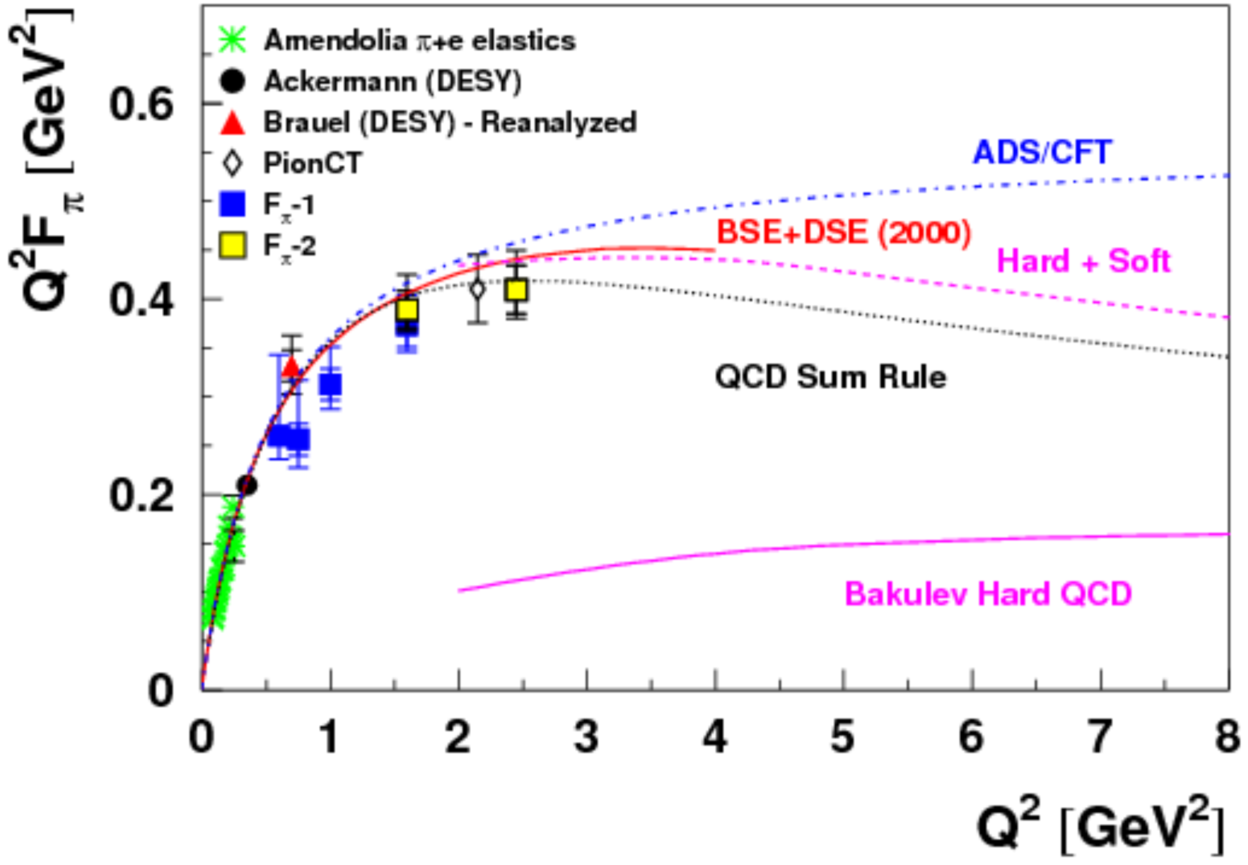
$$F_\pi(Q^2) = \frac{1}{1 + Q^2/\Lambda_\pi^2}$$

Horn et al, PRL97, 192001,2006



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

$F_\pi(Q^2)$ Results and Models



Maris and Tandy, Phys. Rev. ***C62****, 055204 (2000)*
→ relativistic treatment of bound quarks (Bethe-Salpether equation + Dyson-Schwinger expansion)

Nesterenko and Radyushkin, Phys. Lett. ***B115****, 410(1982)*
→ Green's function analyticity used to extract form factor

Brodsky and de Teramond Phys.Rev.D77, 056007 (2008)
→ Anti-de Sitter/Conformal Field Theory approach

A.P. Bakulev et al, Phys. Rev. ***D70****, 033014 (2004)*

Pole Dominance Tests

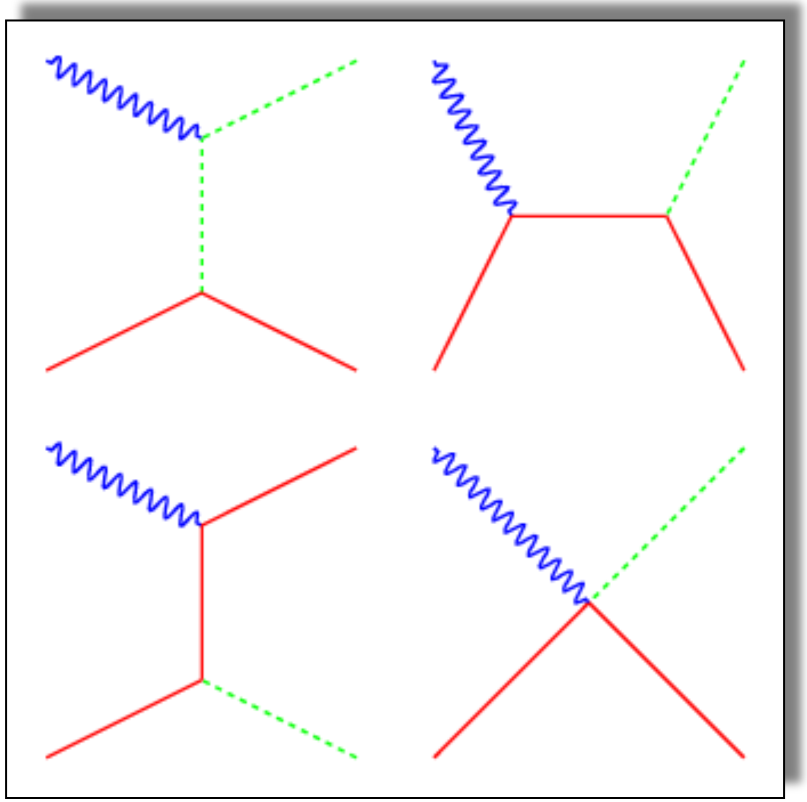
Extraction of F_π relies on dominance of pole diagram

→t-channel diagram pure isovector

→Other Born diagrams both isovector and isoscalar

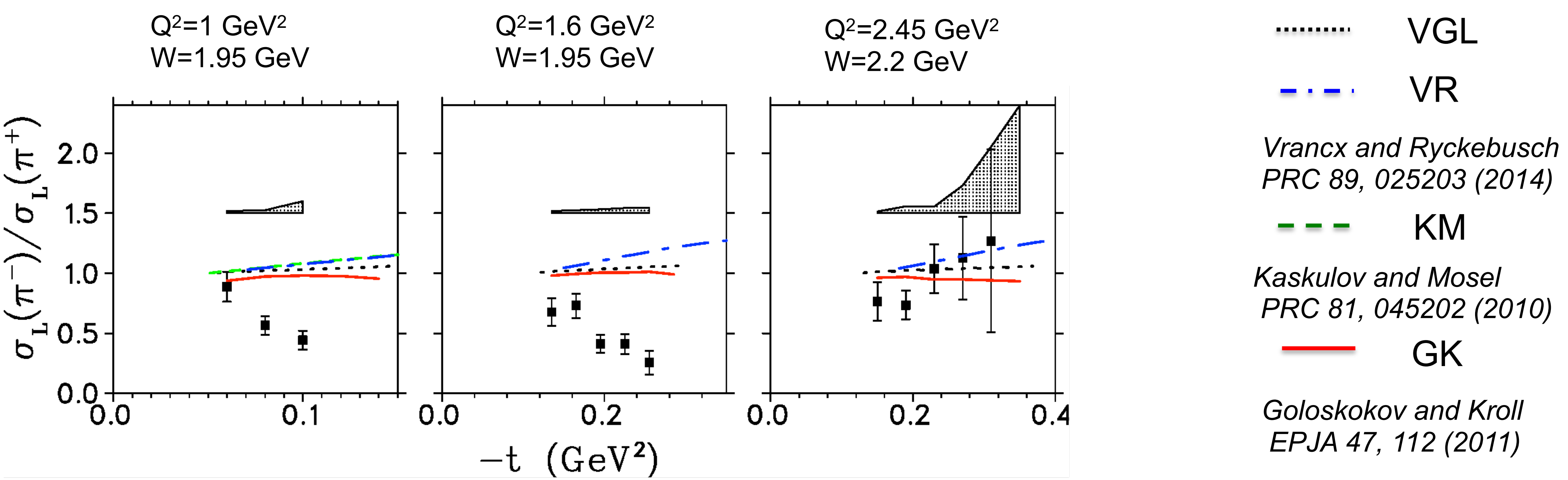
Measure (separated) π^-/π^+ ratios to test pole dominance

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



Ratio = 1 suggests no isoscalar backgrounds

π^-/π^+ Ratios from F_π-1 and F_π-2



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

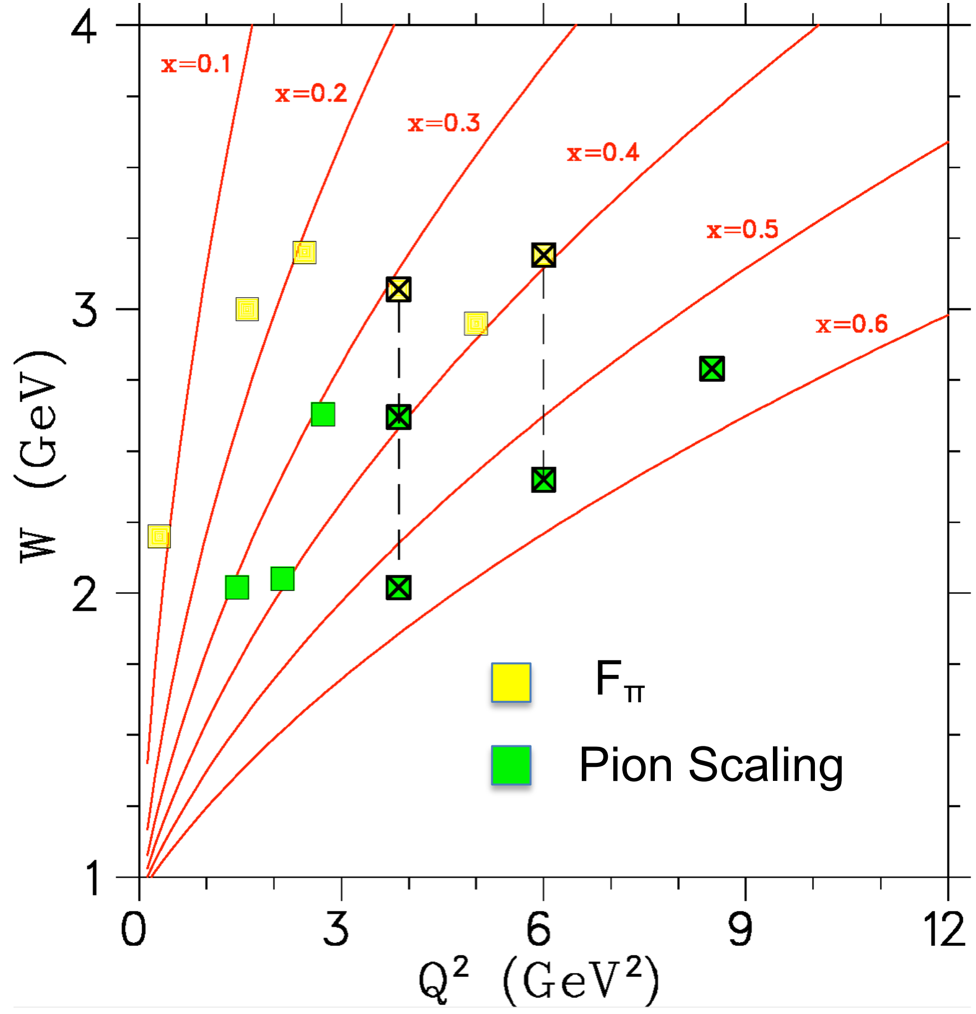
Assuming A_V and A_S are real: R_L=0.8 implies A_S/A_V = 0.06

Hall C π^+ Program at 12 GeV

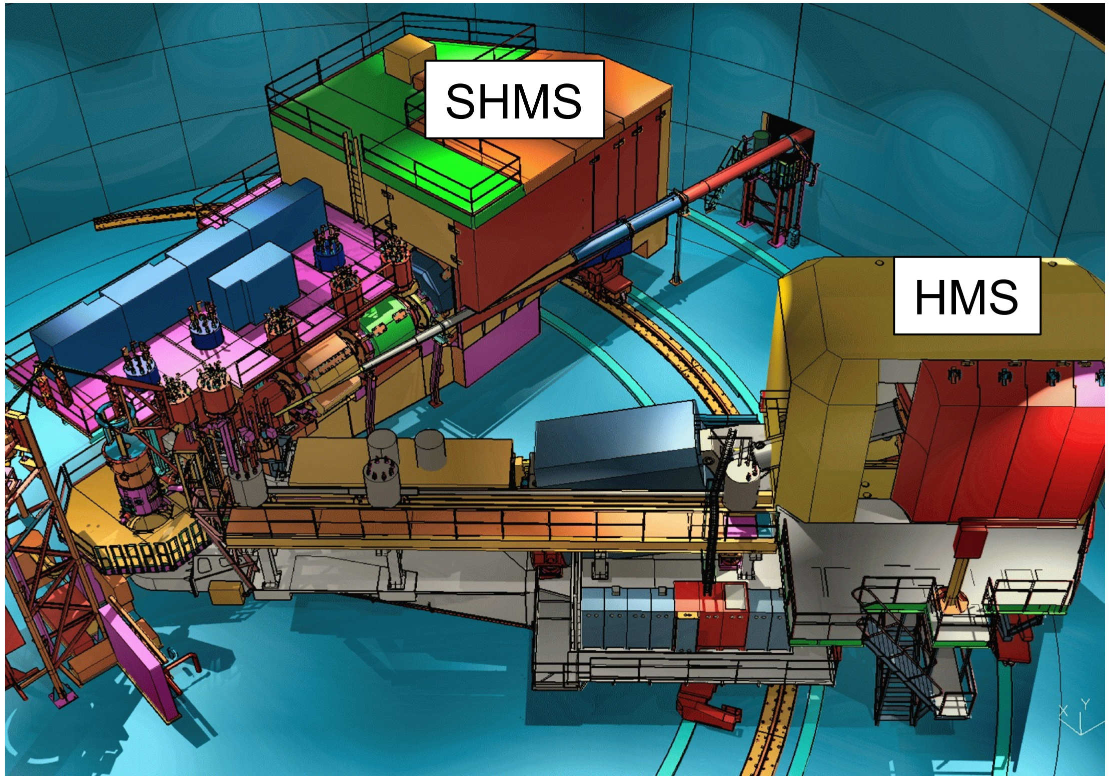
E12-19-006: Study of the L–T Separated Pion Electroproduction Cross Section at 11 GeV and Measurement of the Charged Pion Form Factor to High Q^2

<u>Program of L-T separated π^+ cross sections to measure:</u>

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



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:
dΩ ~ *6* msr, P_0= *0.5 – 7 GeV/c*
θ_0=*10.5 to 80 degrees*
e ID via calorimeter and gas Cerenkov

SHMS: Pion arm
Nominal capabilities:
dΩ ~ *4* msr, P_0= *1 – 11 GeV/c*
θ_0=*5.5 to 40 degrees*
π:K:p separation via heavy gas Cerenkov and aerogel detectors

F_π at the Largest Q^2

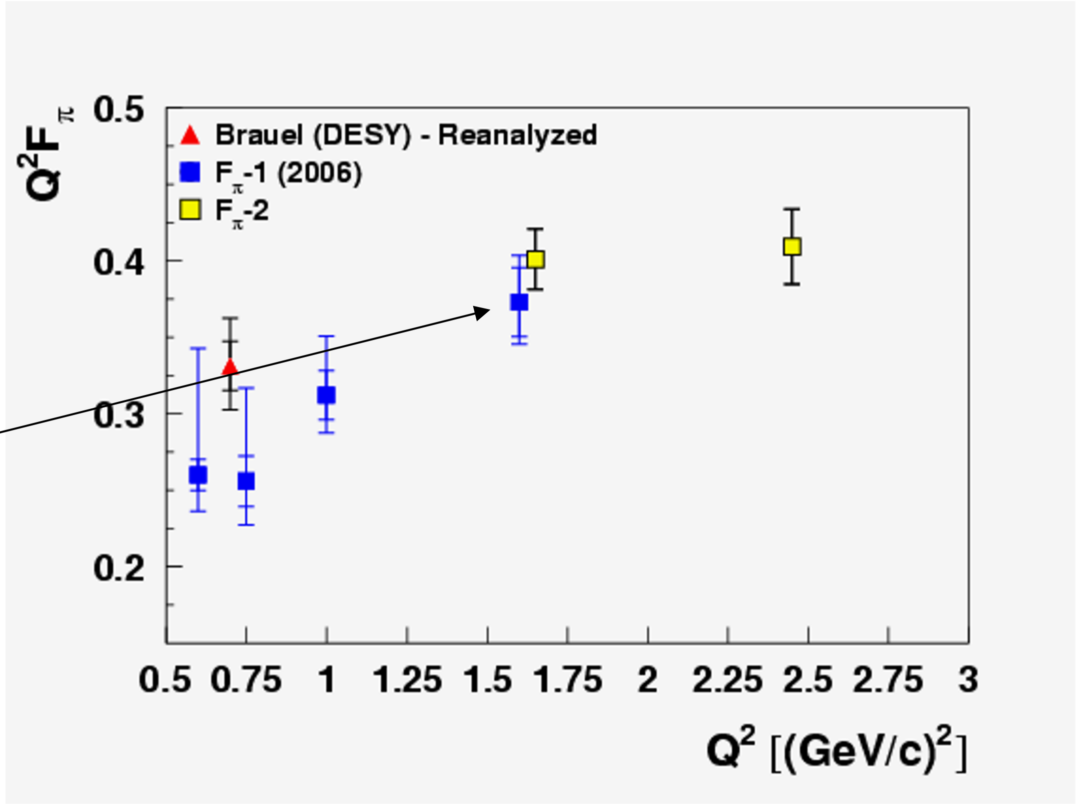
- Original F_π-12 proposal aimed to measure $F_\pi(Q^2)$ up to Q^2=6 GeV^2
  - Maximum Q^2 limited by requirement to keep $-t_{min} \leq 0.2$ GeV^2 (pole dominance, non-pole backgrounds)
- Since 2006, significant progress has been made in our understanding of pion electroproduction
- Optimization of runplan allows measurements of F_π up to Q^2=8.5 GeV^2
  - Extends form factor measurements to largest Q^2 accessible at 12 GeV JLab
- Some additional measurements needed to validate form factor extraction at larger Q^2
  - At Q^2= 8.5 GeV^2, $-t_{min}$=0.55 GeV^2

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



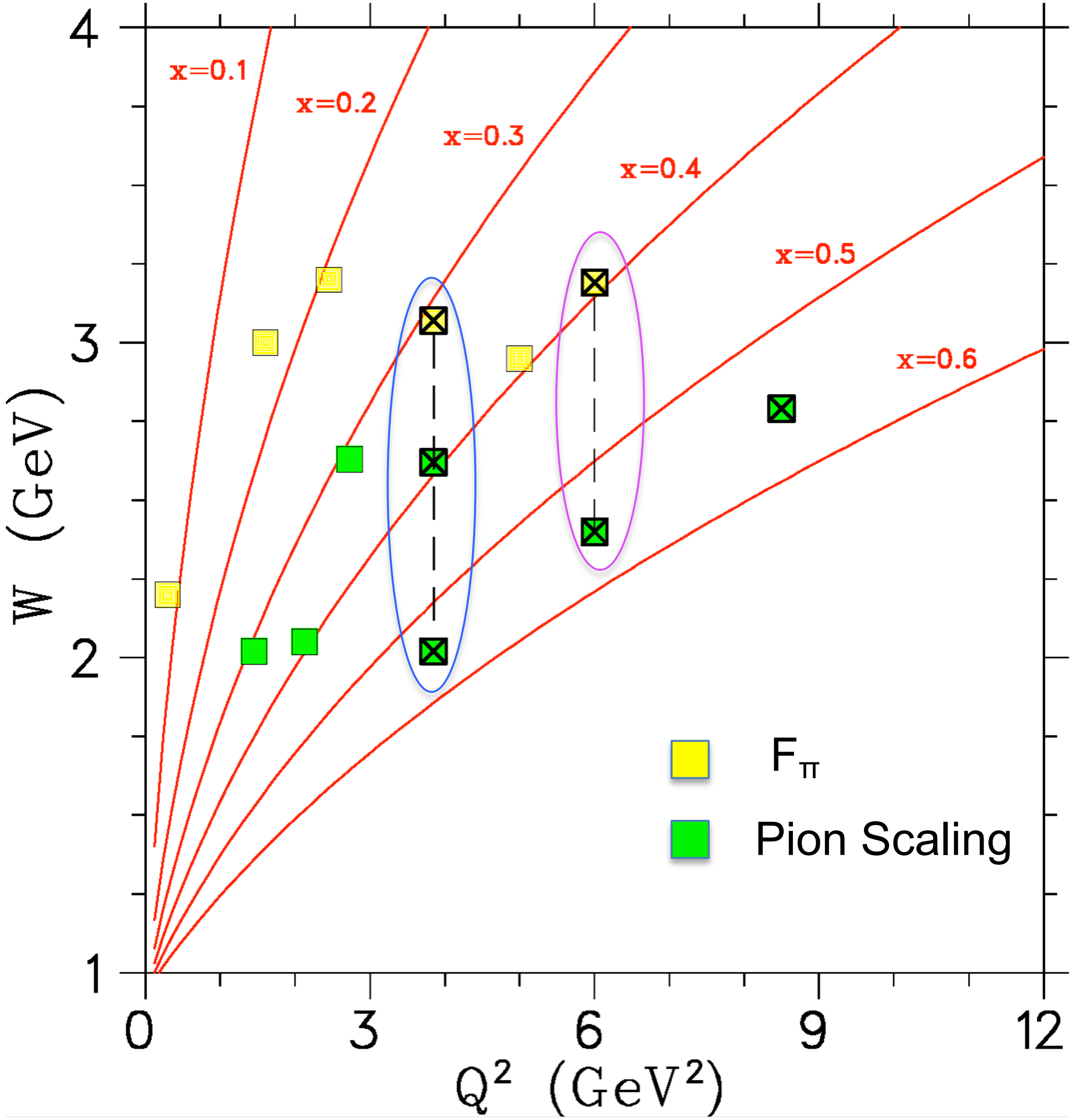
Additional data will be taken as part of the Hall C π+ program to extend these studies to higher Q^2 and $-t_{min}$

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



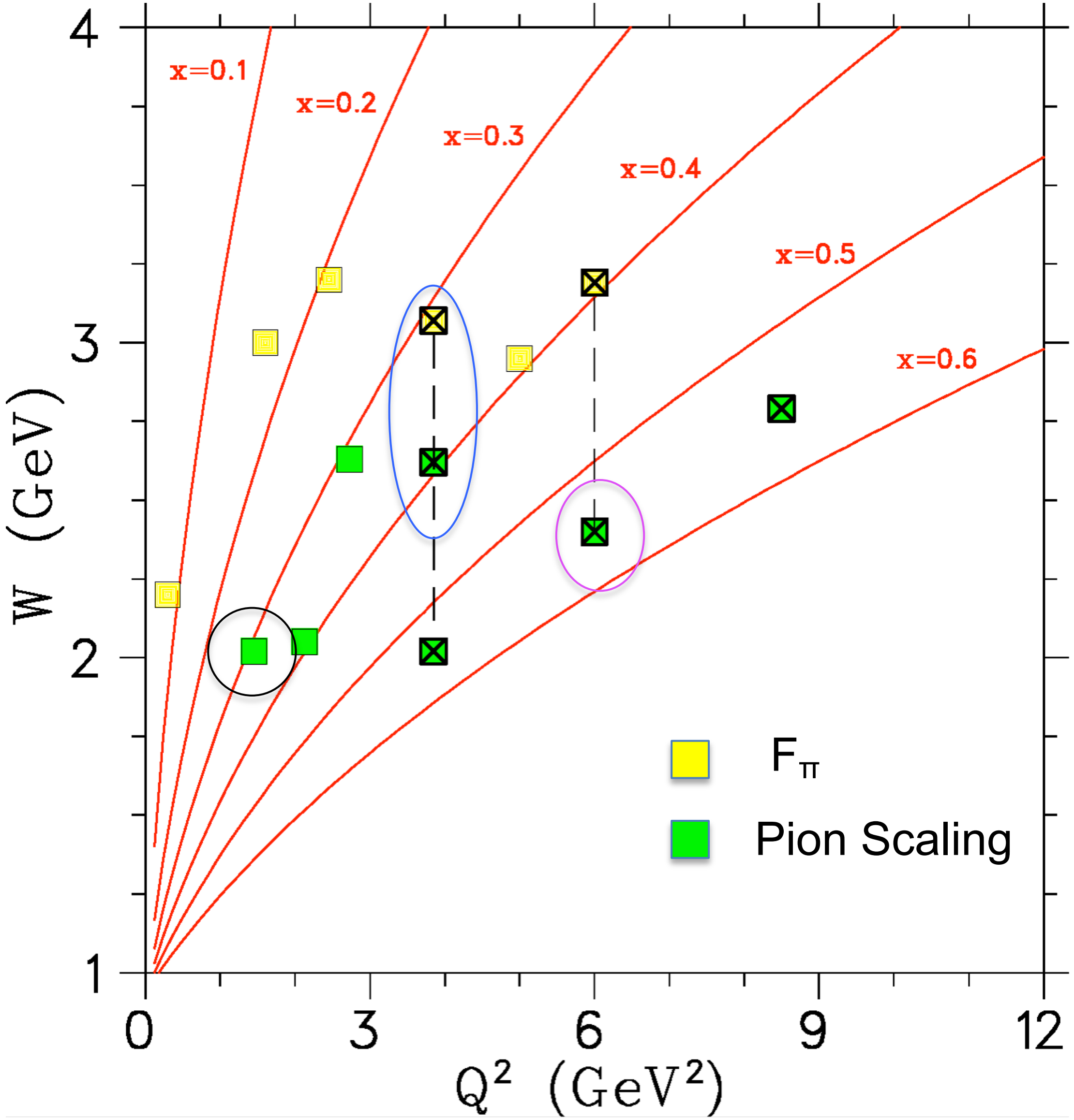
Hall C π^+ Program Kinematics

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

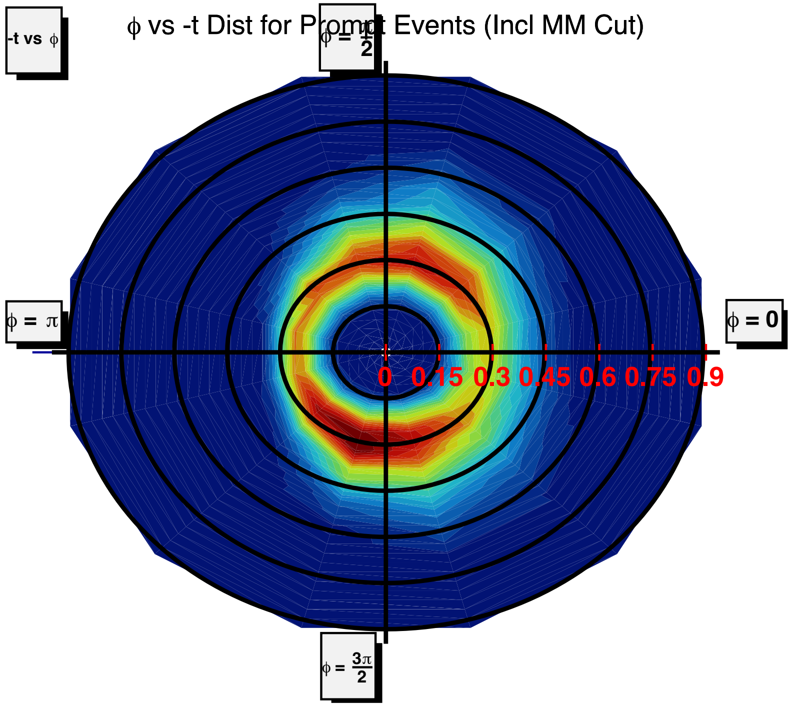


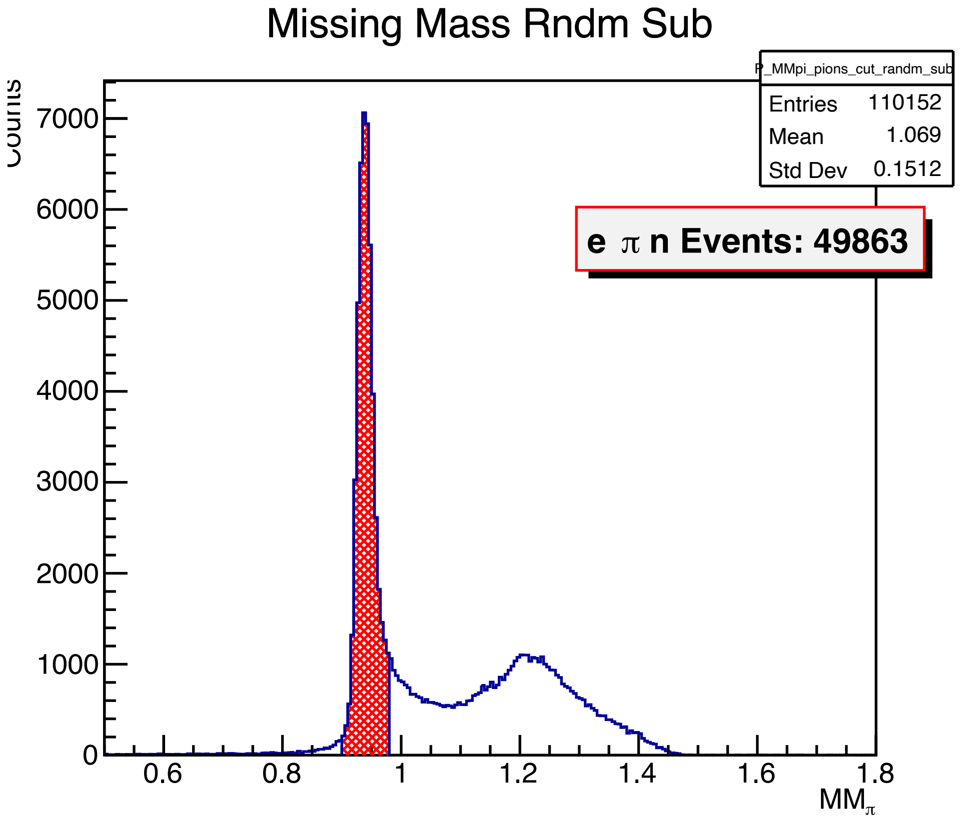
E12-19-006: Study of the L–T Separated Pion Electroproduction Cross Section at 11 GeV and Measurement of the Charged Pion Form Factor to High Q^2

Experiment is running now in Hall C!

→ Took bulk of low epsilon data from August, 2021 to February, 2022

→ Now taking high epsilon data (started early June) with expected completion early September



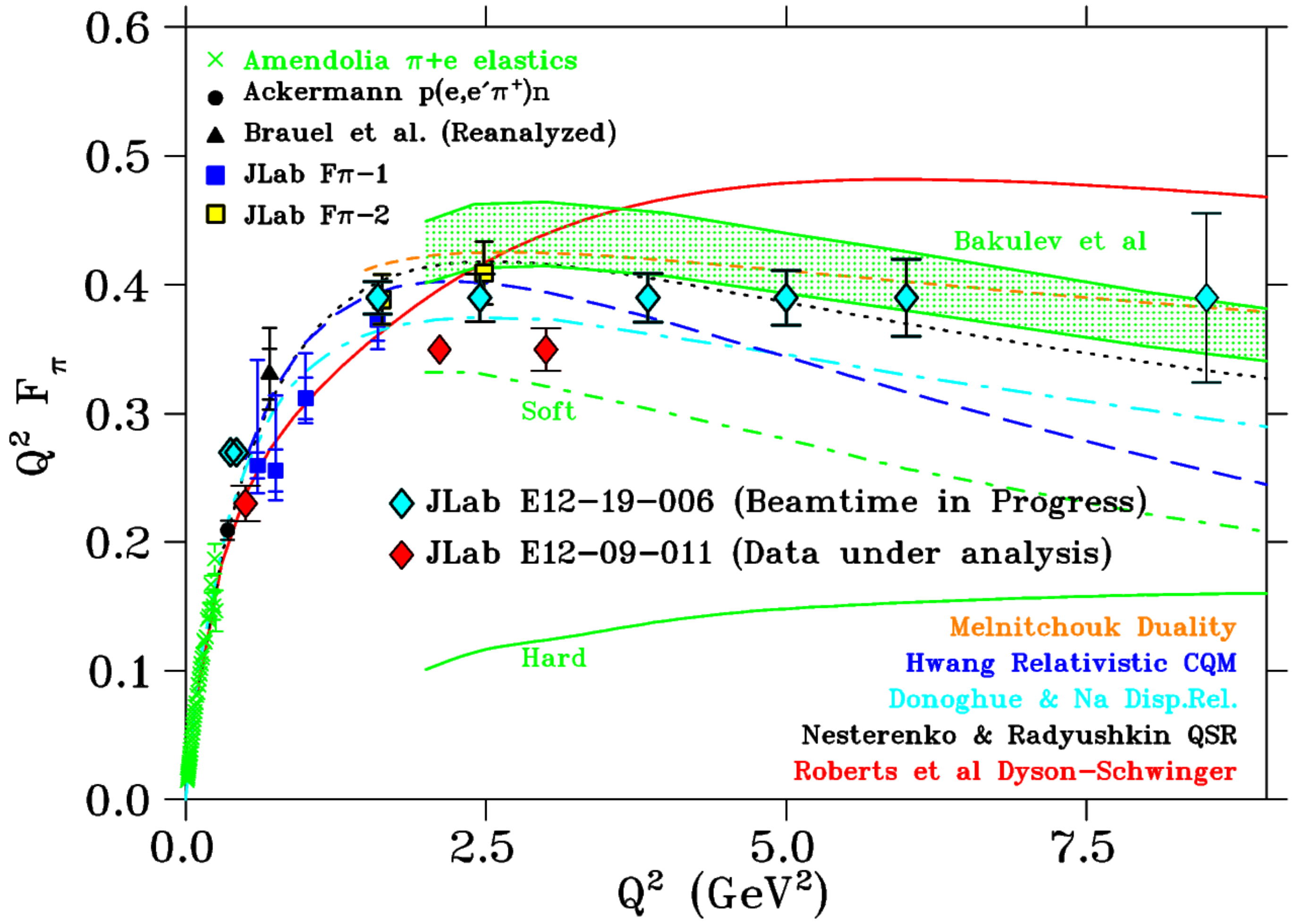


Q^2=6 GeV^2, W=3.19 GeV

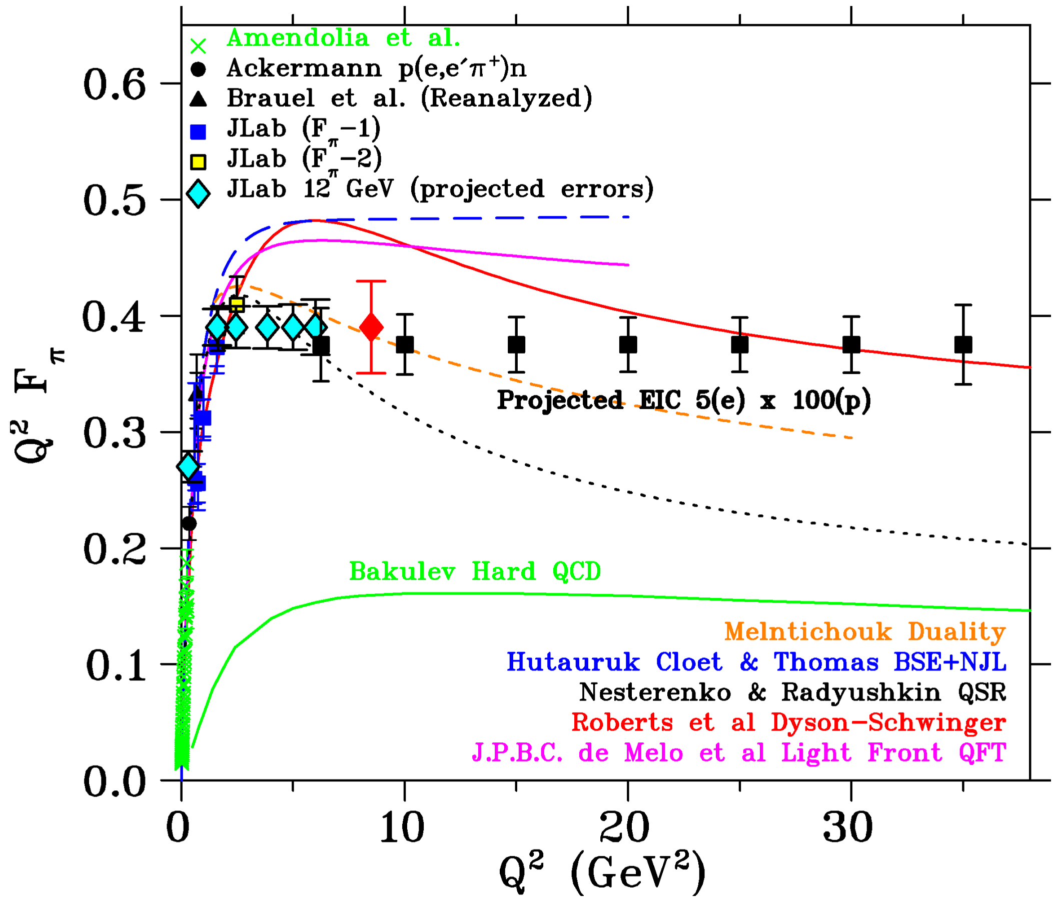
F_π Kinematic Reach at 12 GeV

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

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



F_π at EIC and JLab 24 GeV



Pion FF will be measured at EIC – LT separation not possible, must use model for L/T ratio

With JLab energy upgrade, pionFF from LT separations can be extended up to Q^2=11.5 GeV^2
→ Increase overlap with EIC, test/verify model dependent extraction

	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 $-t_{min}$		

Summary

- Pion form factor an excellent observable for exploring the transition to pQCD
- Requires measurement of L-T separated cross sections and model to extract pion factor at large Q^2
- Extensive experimental program carried out in Hall C at Jefferson Lab in 6 GeV era → continuing in 12 GeV era
  - Will provide high precision form factor measurement up to Q^2=6 GeV^2, and a measurement at the ultimate kinematic reach of JLab12, Q^2=8.5 GeV^2
  - Several measurements to validate technique (p+/p- ratios, measurements at same Q^2, different $-t$)
- Measurements planned at EIC – JLab energy upgrade would help bridge the gap between JLab12 and EIC