Measurement of the Charged Pion Form Factor to High Q^2

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JLab Users Group Meeting

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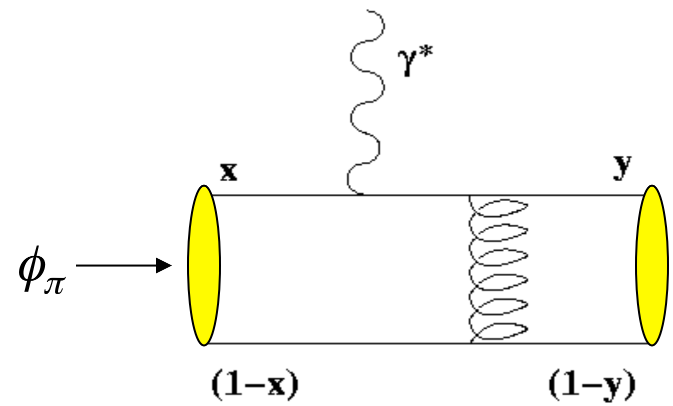
Outline

1. Motivation and techniques for measuring $F_\pi(Q^2)$
2. Data
   →Elastic π-e scattering
   →H($e,e'\pi^+$): JLab F_π program at 6 GeV
3. Hall C Pion Electroproduction Program at 12 GeV
   – Pion Form Factor Measurements: Precision and accessing the largest possible Q^2
   – Probing conditions for factorization
4. Experimental considerations for measuring F_π at the largest values of Q^2
5. Summary

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

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

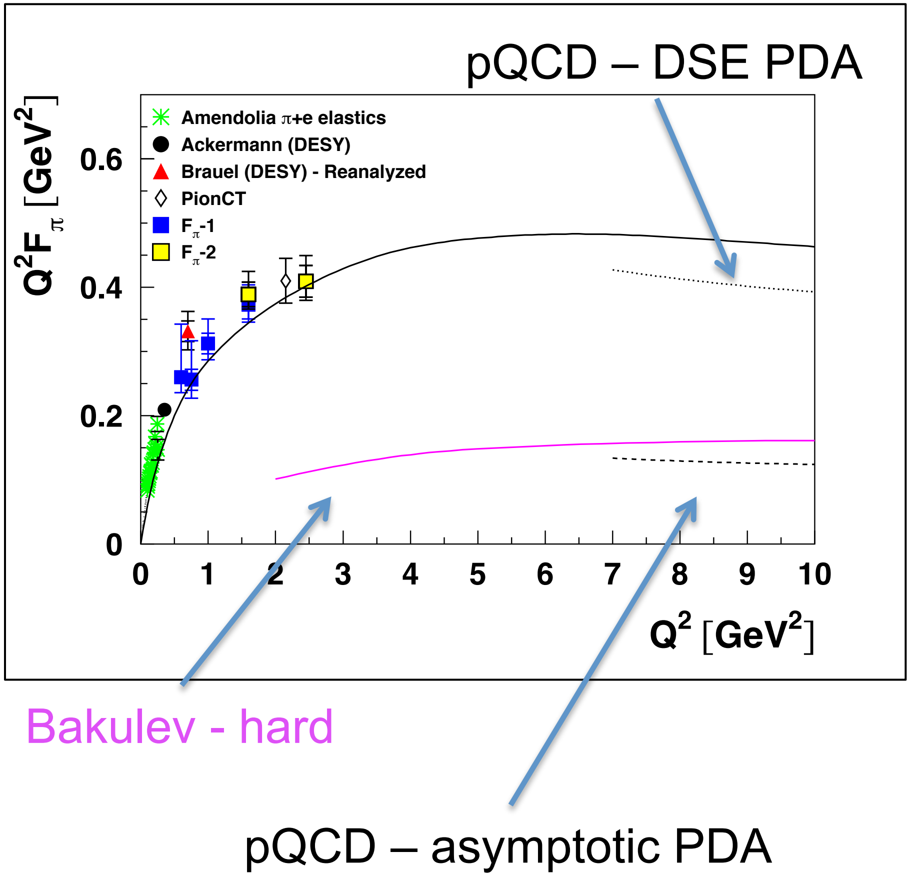
Recent calculations suggest that the most significant soft physics is found in the pion distribution amplitude

→ Calculations using pion DA consistent with lattice give form factors similar to those from state of the art DSE calculations

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

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

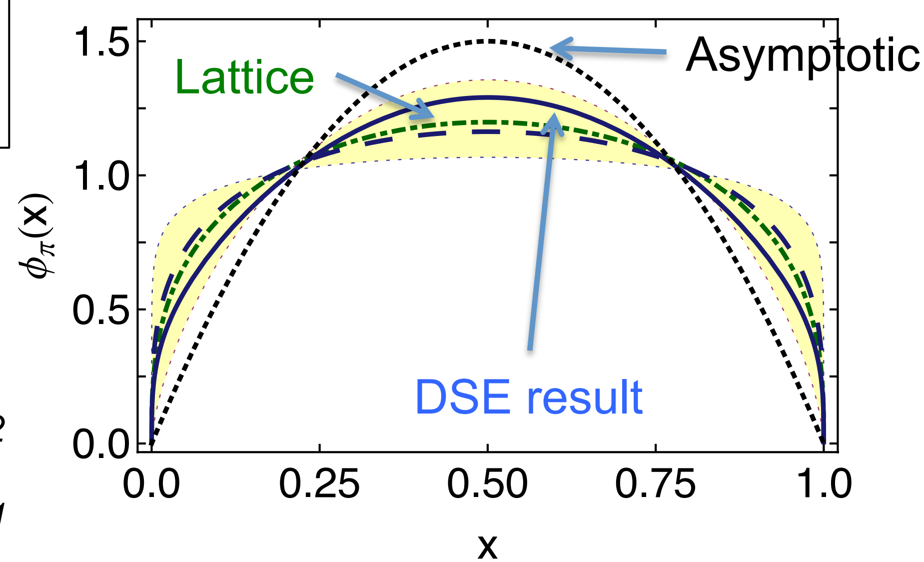
pQCD and the Pion Form Factor



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

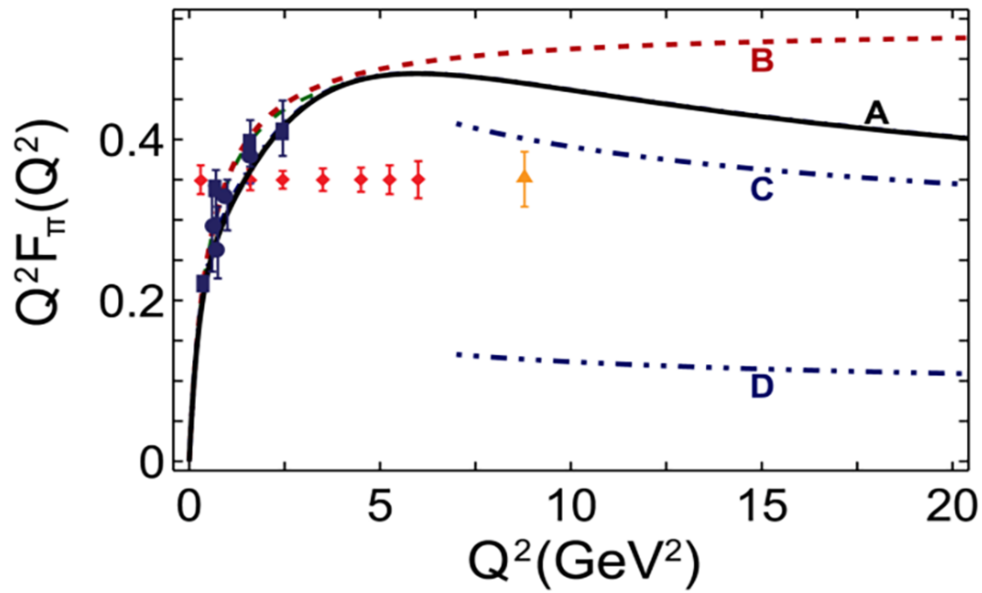


Figure 2.2: *Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate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

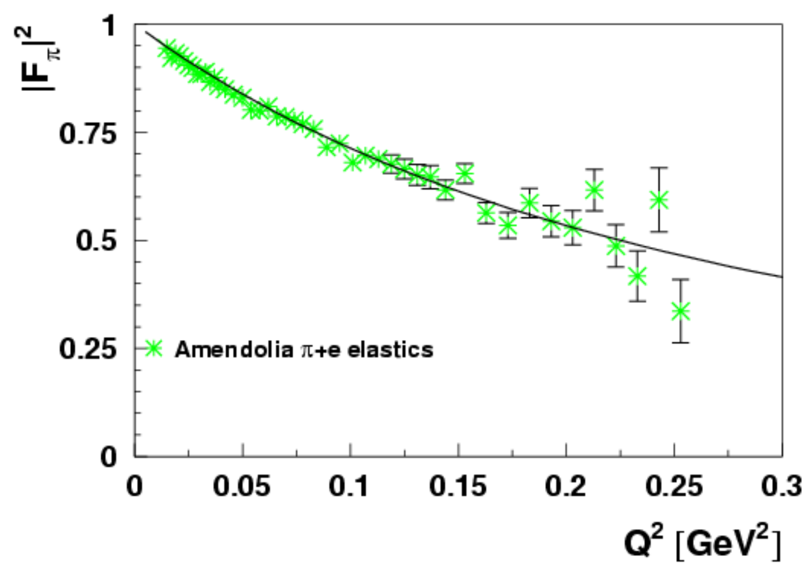
NSAC Long Range Plan (2015)
"Reaching for the Horizon"

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_π = *0.657 ± 0.012* fm
- Maximum accessible Q^2 roughly proportional to pion beam energy
  - Q^2=1 GeV^2 requires 1000 GeV pion beam

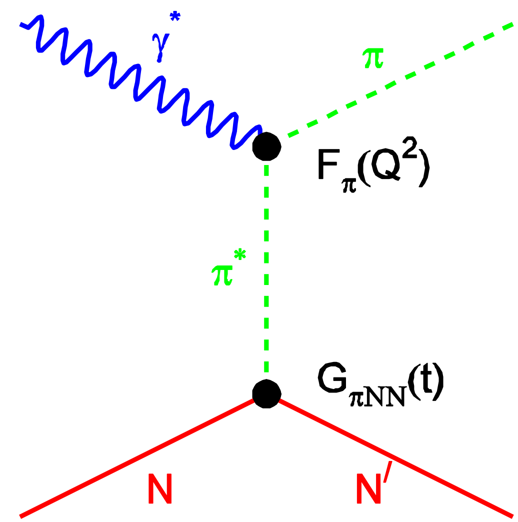


Measurement of π^+ Form Factor – Larger Q^2

- 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)
  - Theory to extract form factor from data

$t=(\gamma^*-\pi)^2$
= (mass)^2 of struck virtual pion

F_π Program at Jefferson Lab at 6 GeV

Two F_π experiments have been carried out in Hall C

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)	$\lvert t_{min}\rvert$ (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

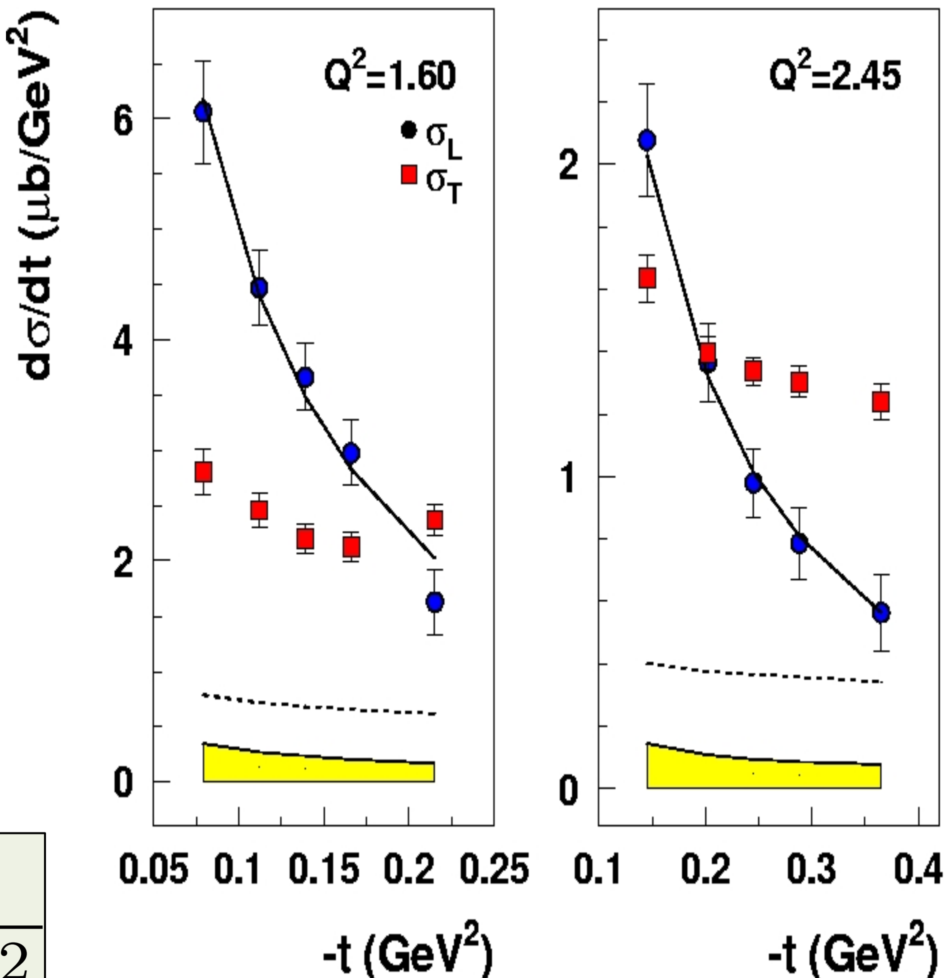
F_π Extraction from JLab data

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)

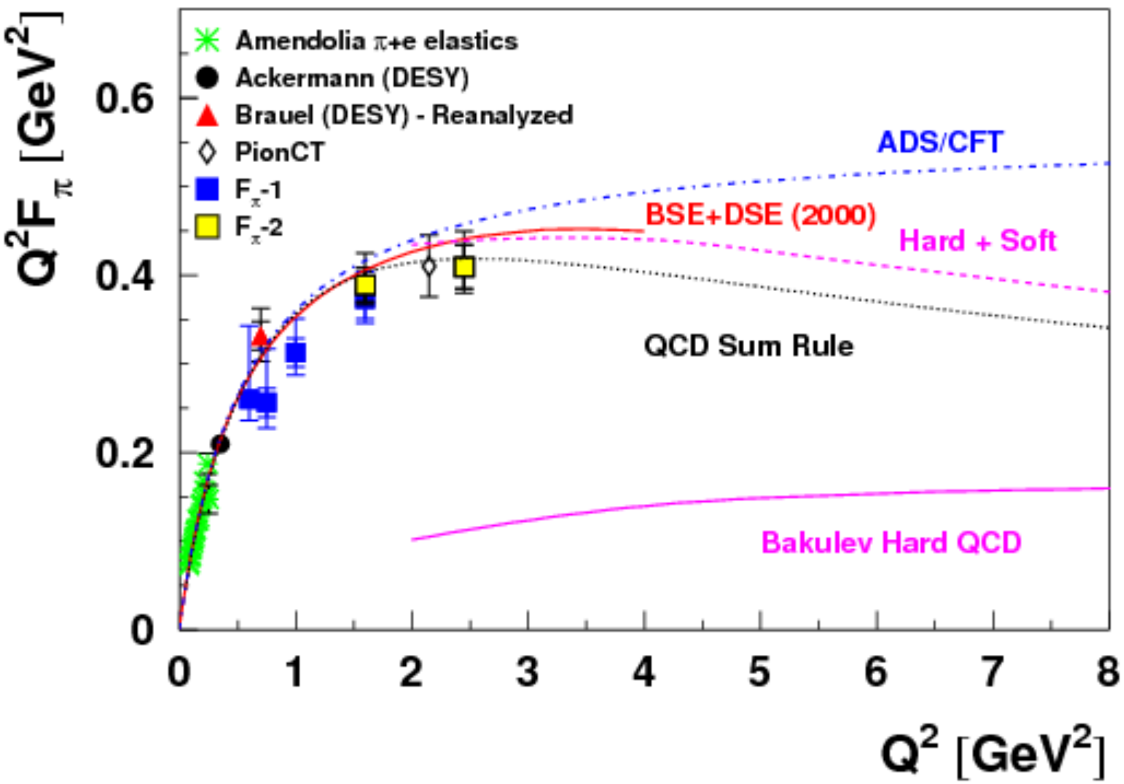
$$F_\pi(Q^2) = \frac{1}{1 + Q^2/\Lambda_\pi^2}$$

Horn et al, PRL97, 192001,2006



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

$F_\pi(Q^2)$ 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

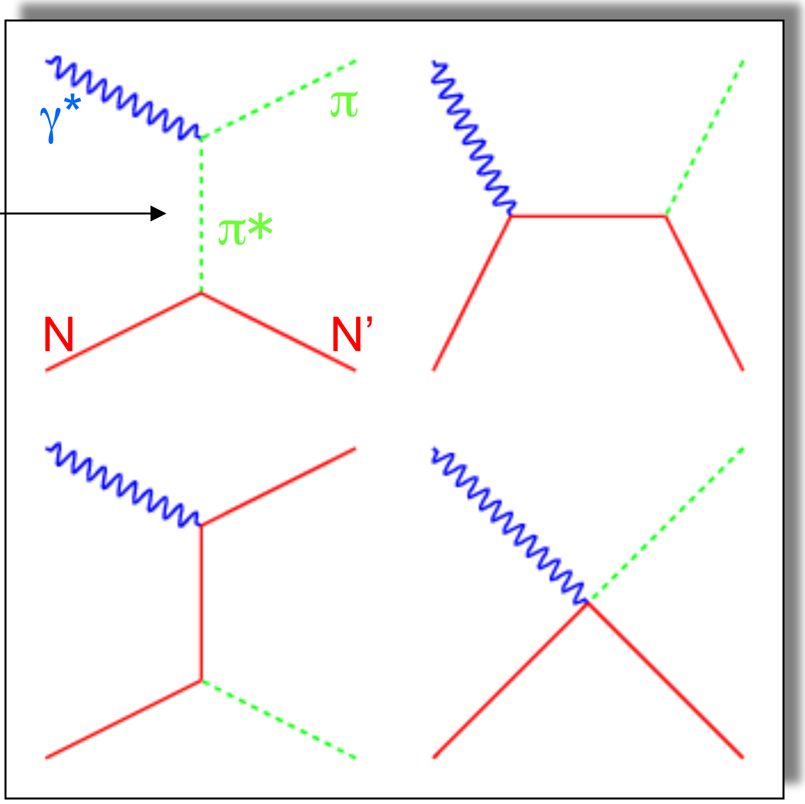
A.P. Bakulev et al, Phys. Rev. ***D70****, 033014 (2004)*

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

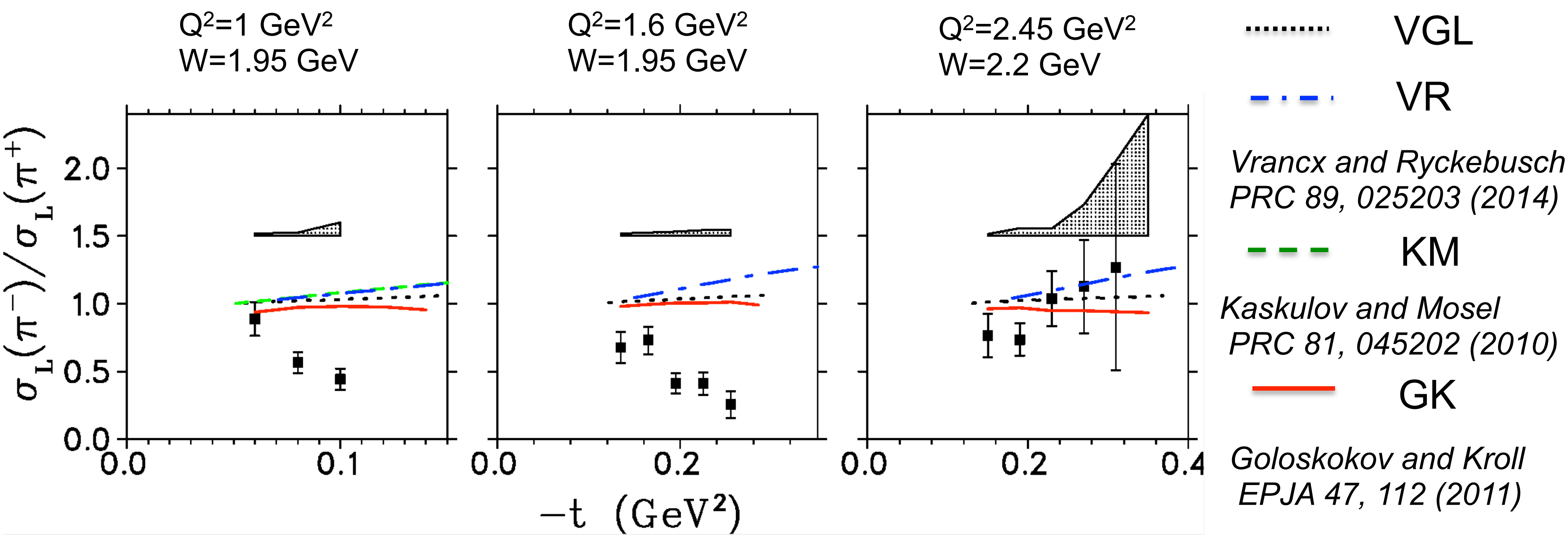


Measure (separated) π^-/π^+ ratios to test pole dominance

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

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

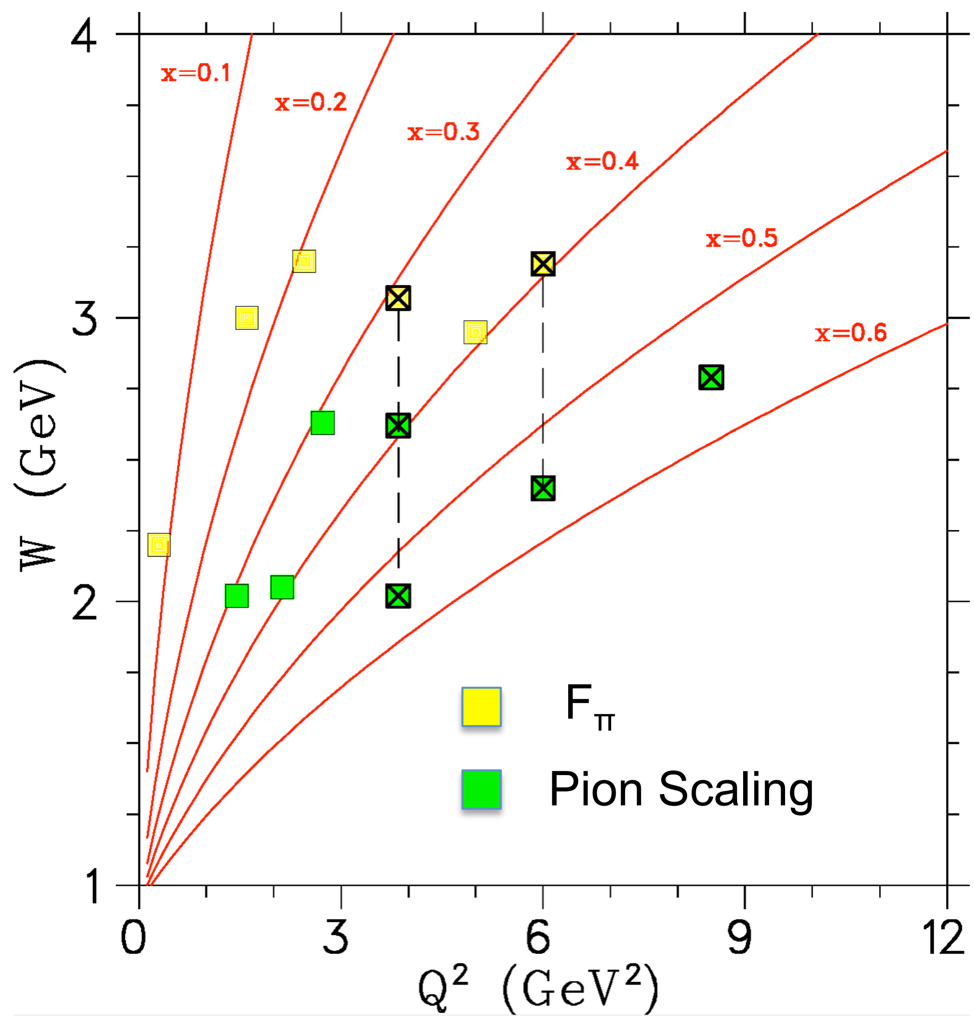
E12-06-101 (F_π), E12-07-105 (Pion Scaling), PR12-16-003

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

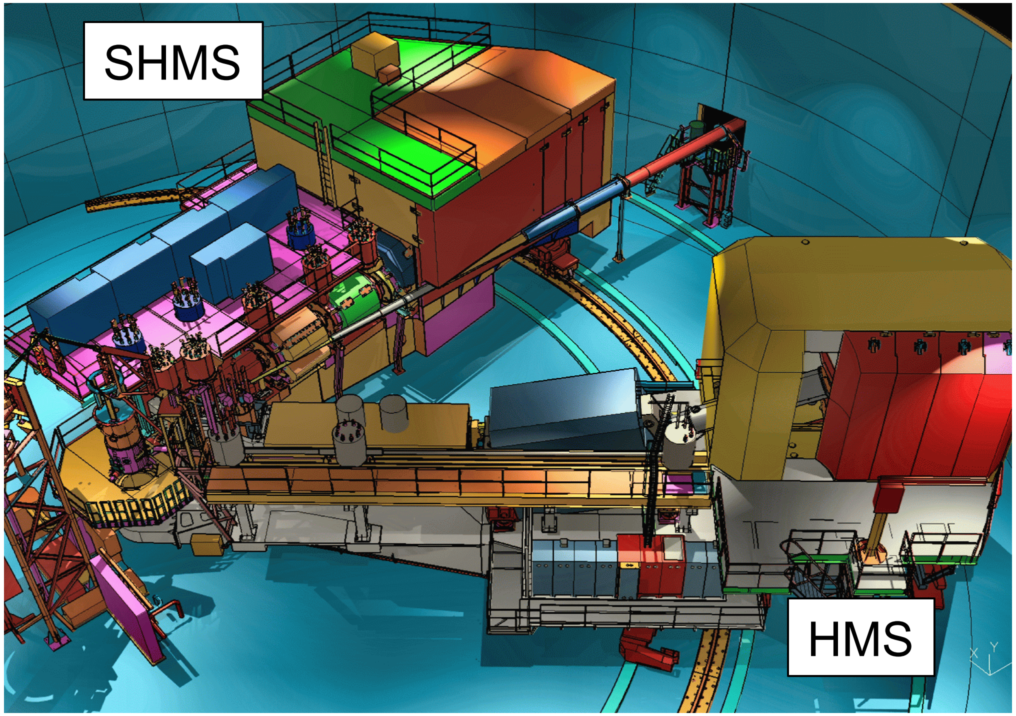
1. Pion form factor at low $-t$ up to Q^2=6 GeV^2
→ *E12-06-101 (G. Huber and D.G.), 52 PAC days, "High impact" @ PAC 42*

2. Q^2 dependence of σ_L at fixed *x and -t*
→ *E12-07-105 (T. Horn and G. Huber), 36 PAC days*

3. Pion form factor up to Q^2=8.5 GeV^2
→ *PR12-16-003 (G. Huber, T. Horn, D.G.), 5 PAC days*



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 requirements

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

PR12-16-003: F_π at Largest Q^2

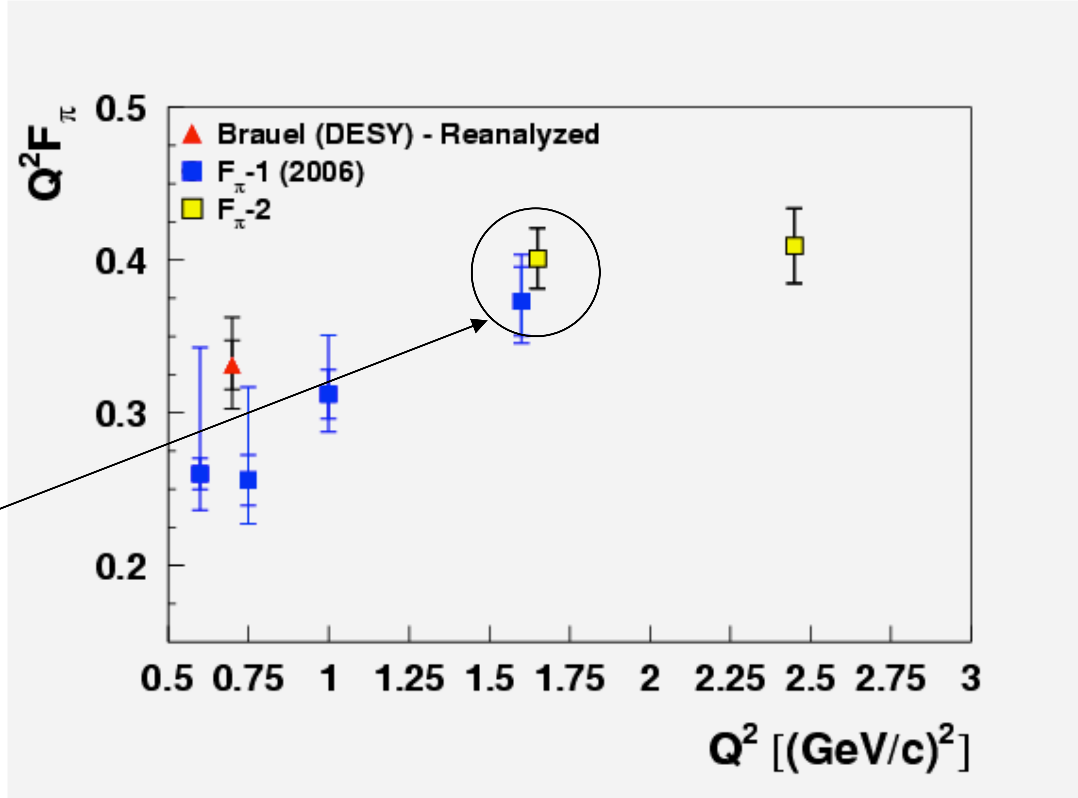
- F_π-12 Experiment (E12-06-101) proposed to measure $F_\pi(Q^2)$ up to Q^2=6 GeV^2
  - Maximum Q^2 limited by requirement to keep $-t_{min} \leq 0.2$ GeV^2 (pole dominance, non-pole backgrounds)
- Since 2006, significant progress has been made in our understanding of pion electroproduction
- Optimization of combined E12-06-101 and E12-07-105 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
  - Address PAC suggestions with regards to statistics for highest Q^2 point, runplan coordination, expt. scheduling
- Some additional time requested 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 $-t_{min}$

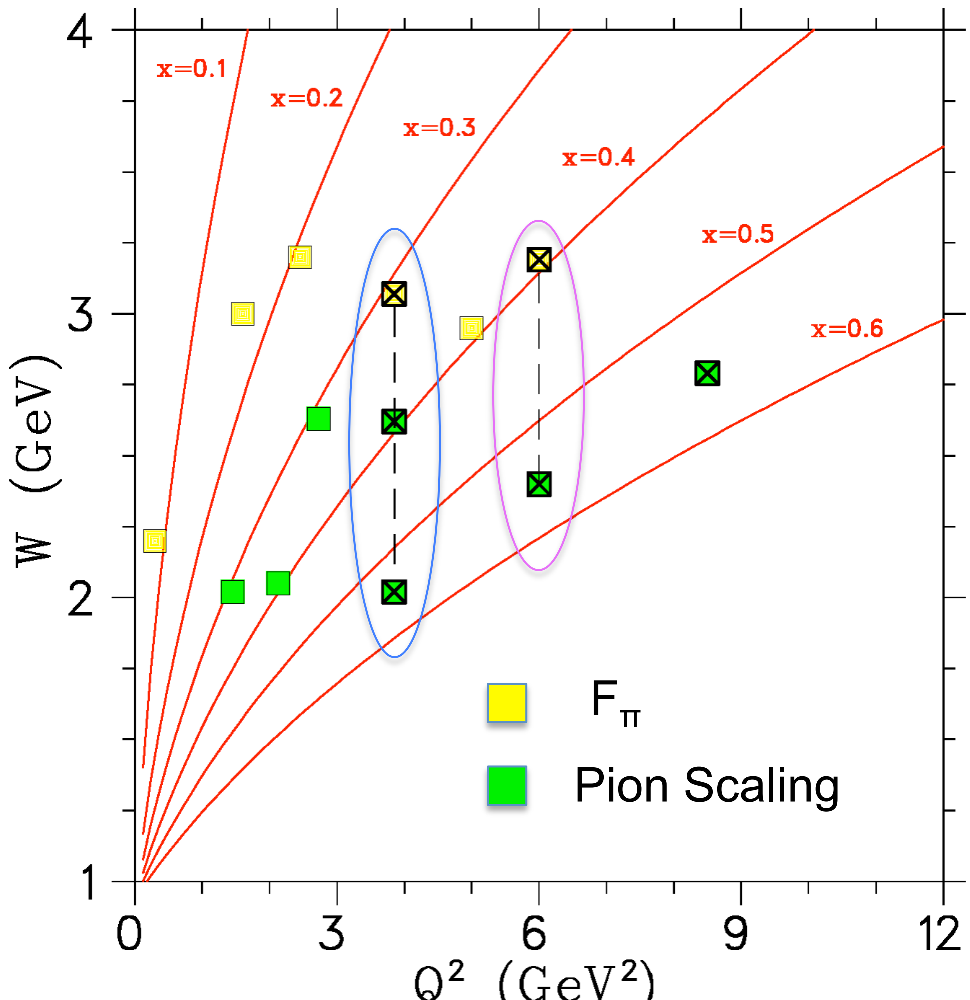
Hall C π^+ Program Kinematics

E12-06-101 (F_π), E12-07-105 (Pion Scaling), PR12-16-003 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



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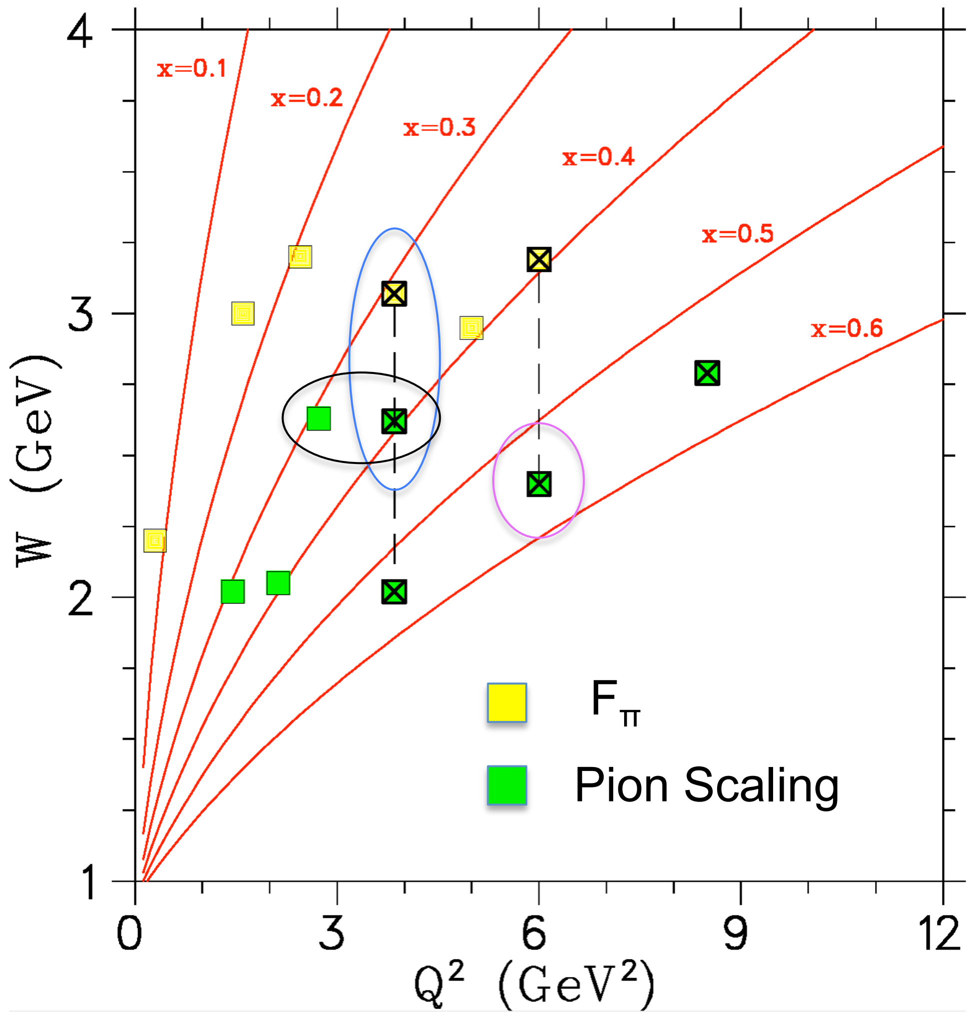
→ Q^2=6.0 GeV^2
-t_{min}=0.21, 0.53 GeV^2

Separated π-/π+ Ratios

→ Q^2=2.12 GeV^2
-t_{min}=0.20 GeV^2

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

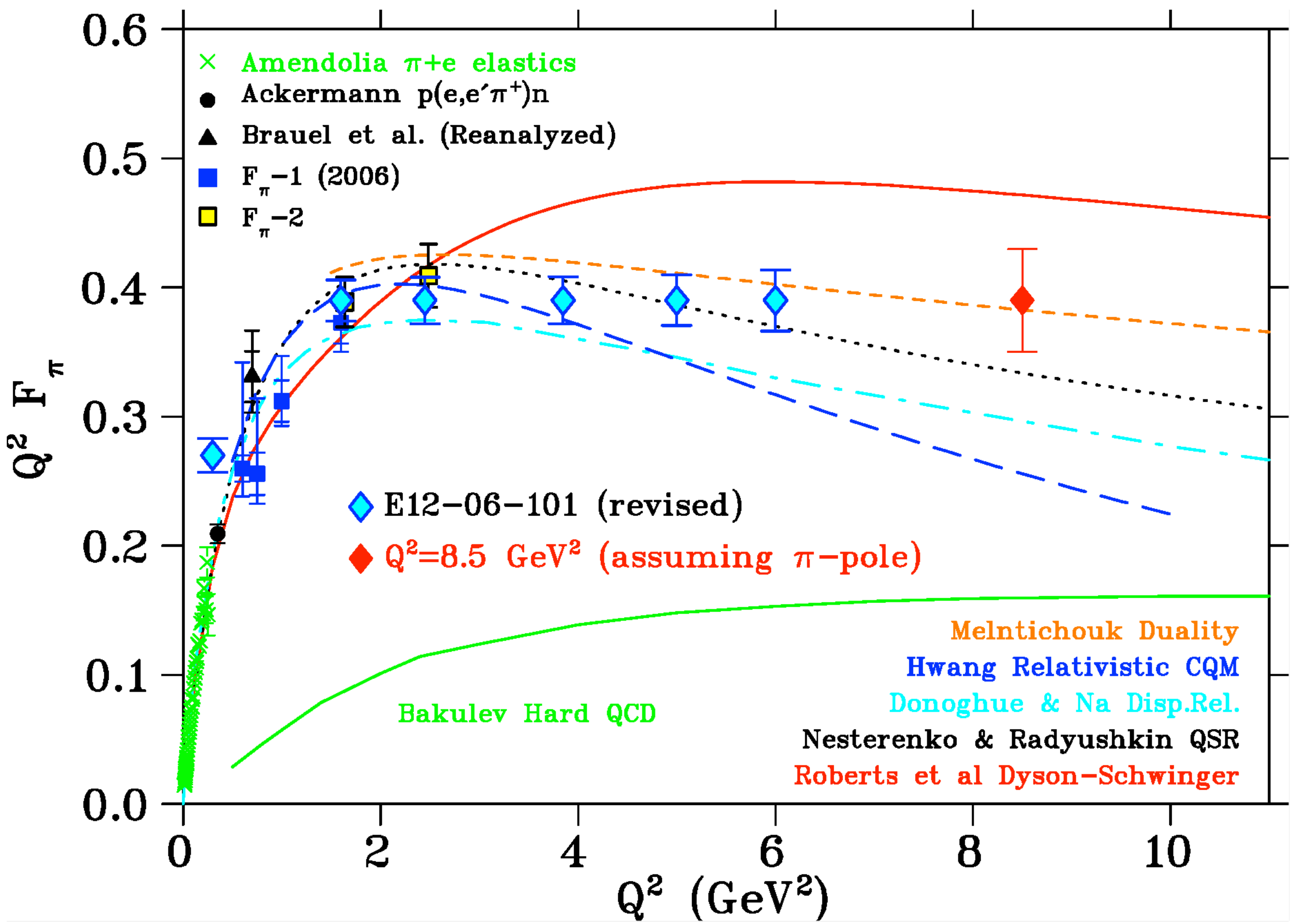
→ Q^2=6.0 GeV^2
-t_{min}=0.53 GeV^2



$F_\pi(Q^2)$ Kinematic Reach

JLab 12 GeV upgrade + HMS/SHMS will allow measurement up to Q^2=8.5 GeV^2

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



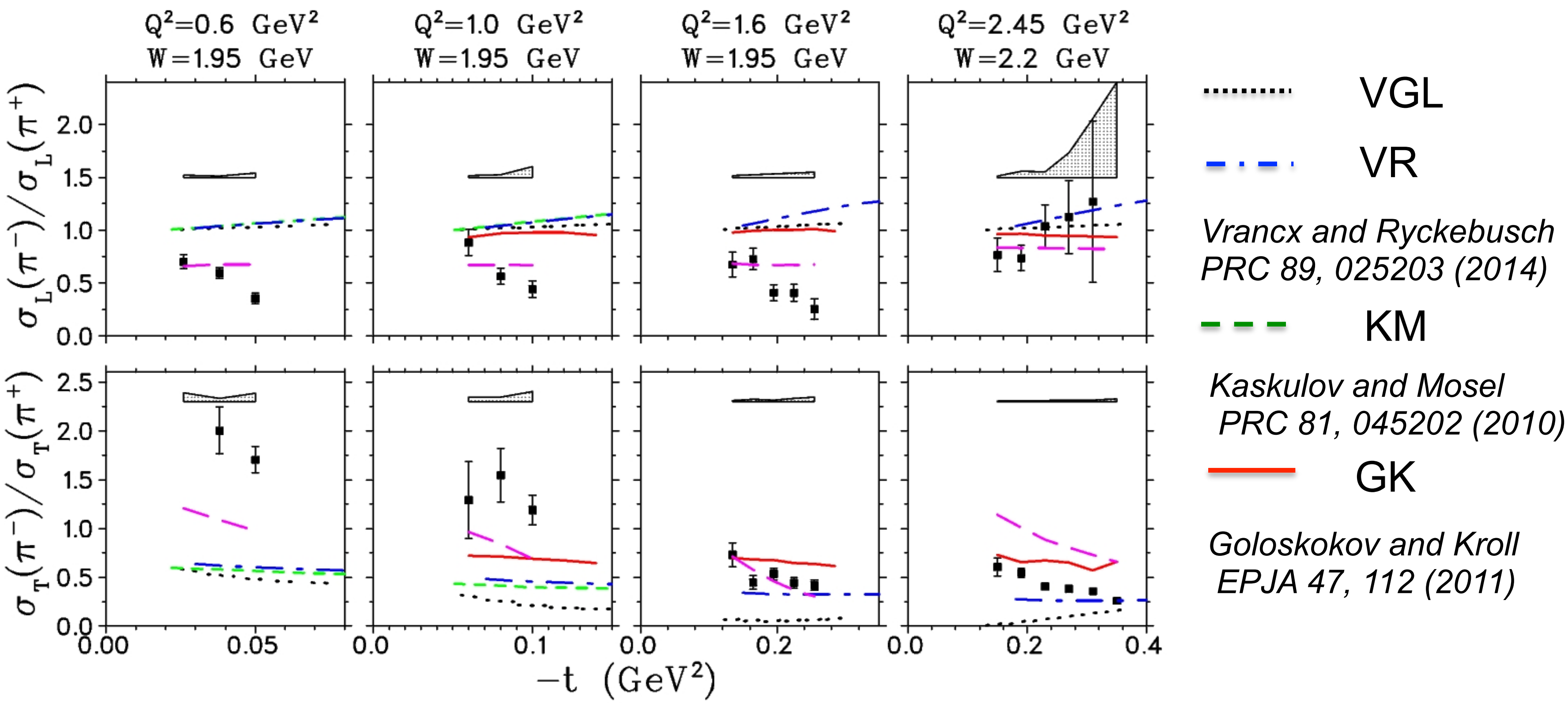
Projected precision using R from VR model

Summary

- The Jefferson Lab pion form factor program has provided precise, reliable measurements up to Q^2=2.45 GeV^2
- The JLab 12 GeV Upgrade + SHMS in Hall C will extend precision measurements up to Q^2=8.5 GeV^2
- Measurements up to Q^2=6 GeV^2 will be relatively close to the pion pole → $-t_{min}$ < 0.2 GeV^2
- A comprehensive program of measurements ($-t$ dependence of form factor extraction, π-/π+ ratios) will allow us to relax $-t_{min}$ constraints
  - Access the pion form factor at the very largest Q^2 accessible at a 12 GeV JLab

Extra

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

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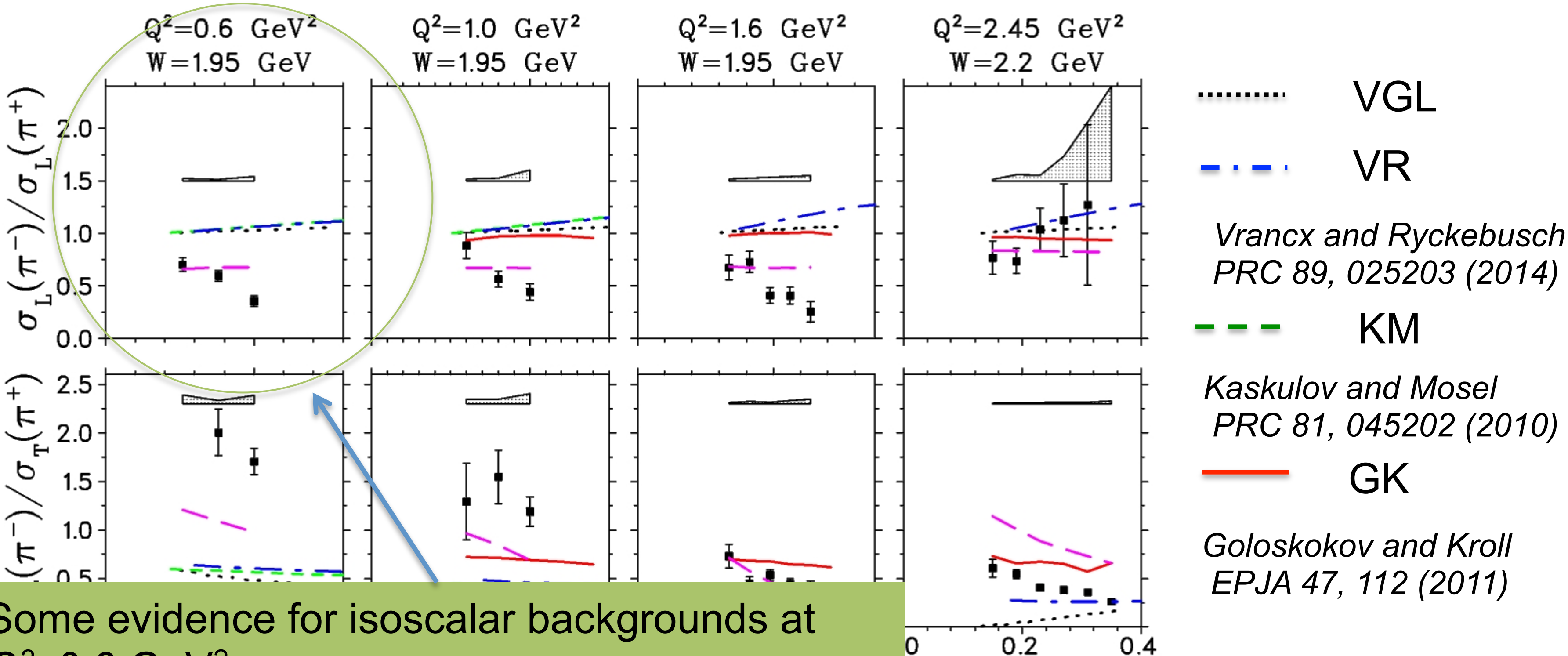
π^-/π^+ Ratios from F_π-1 and F_π-2



Some evidence for isoscalar backgrounds at Q^2=0.6 GeV^2

→ Consistent with form factor extraction issues found during F_π-1 analysis

182501

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