PR12-16-003: Determining the Pion Form Factor from Higher Q^2, High-t Electroproduction Data

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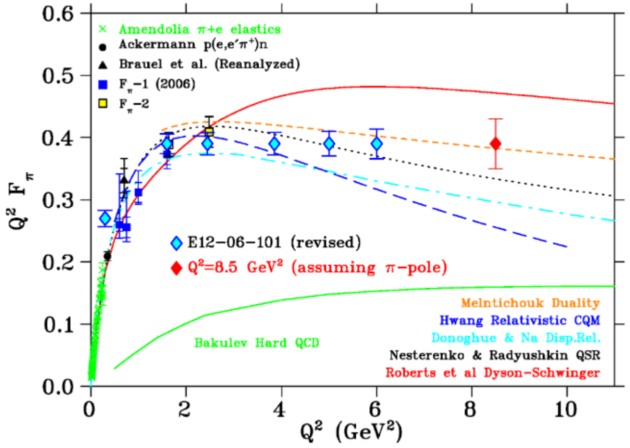
The Catholic University of America

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Program Advisory Committee Meeting (PAC44)

Jefferson Lab, Newport News, 25-28 July, 2016

PR12-16-003 Goals and Request



Goals

- ❑ Enable measurements of pion form factor at low t up to $Q^2 = 6$ GeV^2
- ❑ Allow for measurements of the separated π^+ cross sections as function of Q^2 at fixed x=0.3, 0.4, 0.55
- ❑ Enable pion form factor measurement to the very largest Q^2 accessible at 12 GeV JLab, 8.5 GeV^2

Request to PAC44

- ➢ Confirmation of high-impact status of the π^+ program with L/T separations
- ➢ Linking of experiments E12-06-101 and E12-07-105 measuring separated π^+ cross sections over a range of Q^2, x and t, enabling pion form factor extractions
- ➢ Additional 120 hours (5 days) to be used in conjunction with the already approved experiments to obtain the needed statistics and enhance the validation for the pion form factor measurements to $Q^2 = 8.5$ GeV^2

Dynamical Chiral Symmetry Breaking (DCSB)

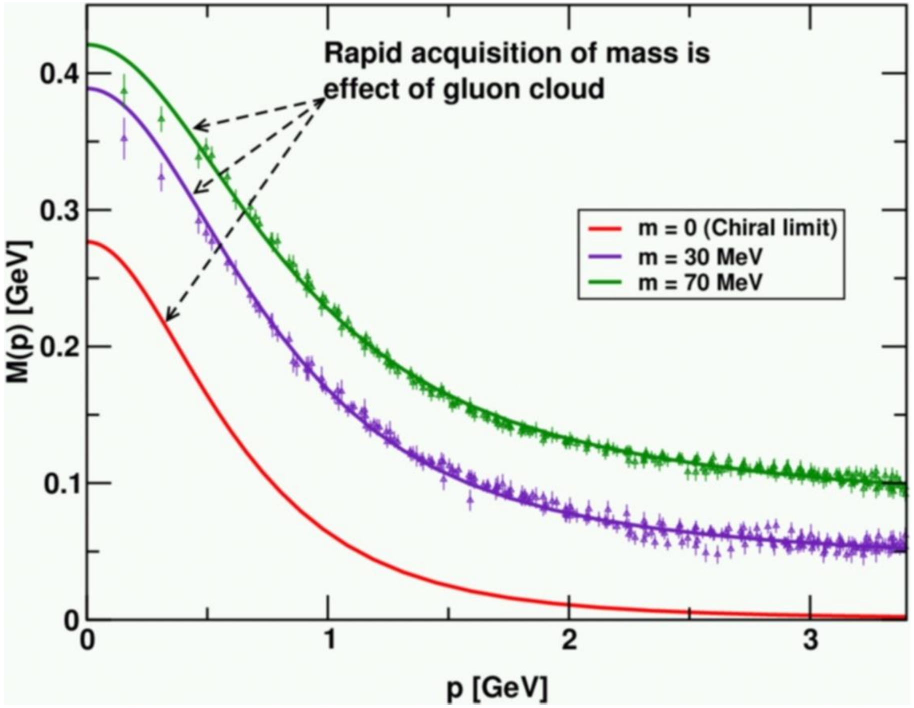
- The pion is both the Goldstone boson and a quark-antiquark bound state
- If QCD was chirally (left-right) symmetric, the pion would have no mass

Pion mass is enigma

- Chiral symmetry of massless QCD is broken dynamically by quark-gluon interactions and explicitly by including light meson masses – this gives the pion its mass

[for a recent review see: J. Phys. G43 (2016) no.7, 073001]

  - Purely dynamical, not spontaneous
    - Add nothing to QCD - *no Higgs field, nothing!*



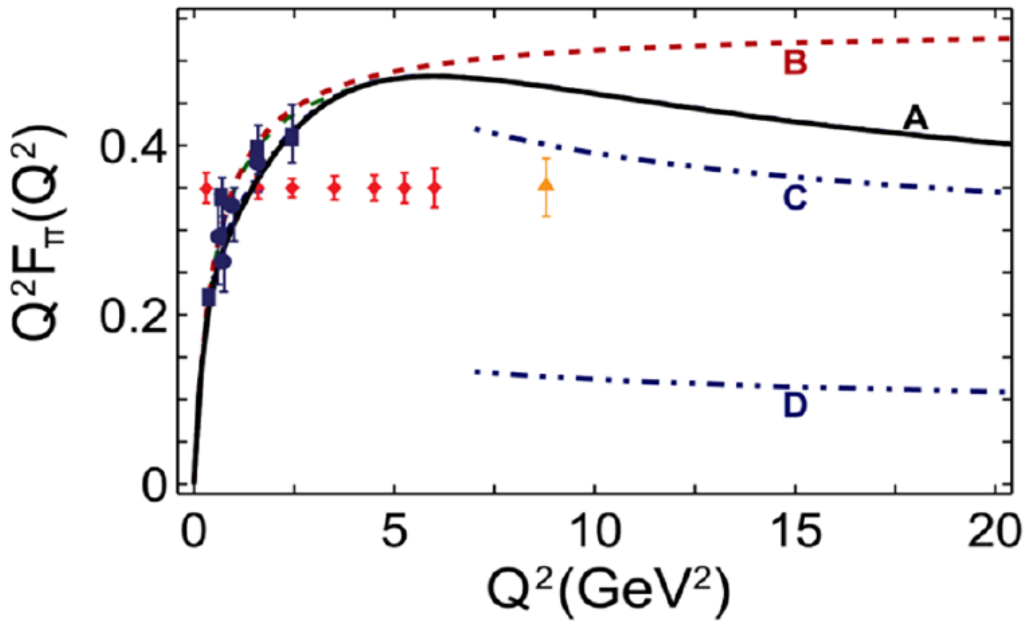
Pion form factor measurements are *key to confirm the mechanism that dynamically generates all of the mass of hadrons* - contribute major step forward towards understanding of QCD

Role of the pion (form factor)

- Pion (and kaons) play a special role in Nature
  - Lightest QCD quark systems - responsible for the long range character of the strong interaction
  - Goldstone boson related to chiral symmetry - chiral symmetry breaking of massless QCD gives pion mass

Pion exists if, and only if, mass is dynamically generated

[2015 NSAC Long Range Plan]



- Form factor is an essential element of hadron structure studies

> - Great theoretical interest, in particular at larger values of Q^2, where one can study non-perturbative dynamics of QCD while searching for transition to perturbative regime

High Impact Pion Form Factor

~2000

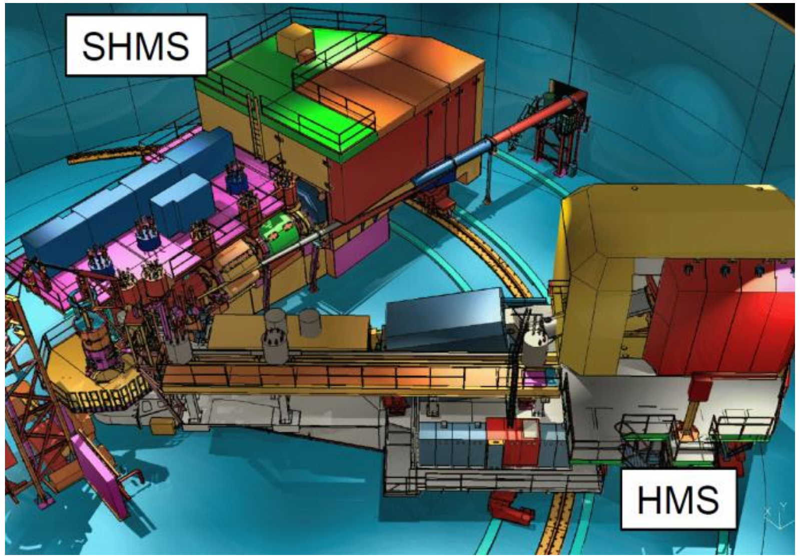
- J. Volmer, et al., Phys. Rev. Lett. **86** (2001) 1713 – **270 citations**
  - Precision F_π results between Q^2=0.60 and 1.60 GeV^2
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. Lett. **97** (2006) 192001 – **195 citations**
  - Precision F_π results at Q^2=1.60 and 2.45 GeV^2
- V. Tadevosyan, et al., Phys. Rev. C**75** (2007) 055205 – **176 citations**
- G. Huber, T. Horn, D. Gaskell, et al., Phys. Rev. C**78** (2008) 045203 – **131 citations**
  - Archival paper of precision F_π measurements at JLab 6 GeV
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. C**78** (2008) 058201 – **47 citations**
  - Precision F_π results at Q^2=2.15 GeV^2 and exploratory at Q^2~4.0 GeV^2

2016

F_π is a flagship and high impact experiment of the 12 GeV JLab

The JLab 12 GeV π^+ experiments:

- ***E12-06-101***: determine F_π up to Q^2=6 GeV^2 in a dedicated experiment
  - Require t_{min}<0.2 GeV^2 and $\Delta\varepsilon$>0.25 for L/T separation
  - Approved for 52 PAC days with "A" rating, high impact



CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for extending precision measurements to higher Q^2

- ***E12-07-105***: probe conditions for factorization of deep exclusive measurements in π^+ data to highest possible Q^2~9 GeV^2 with SHMS/HMS
  - Potential to extract F_π to the highest Q^2~9GeV^2 achievable at Jlab 12 GeV
  - Approved for 36 PAC days with "A-" rating

THE ULTIMATE GOAL:

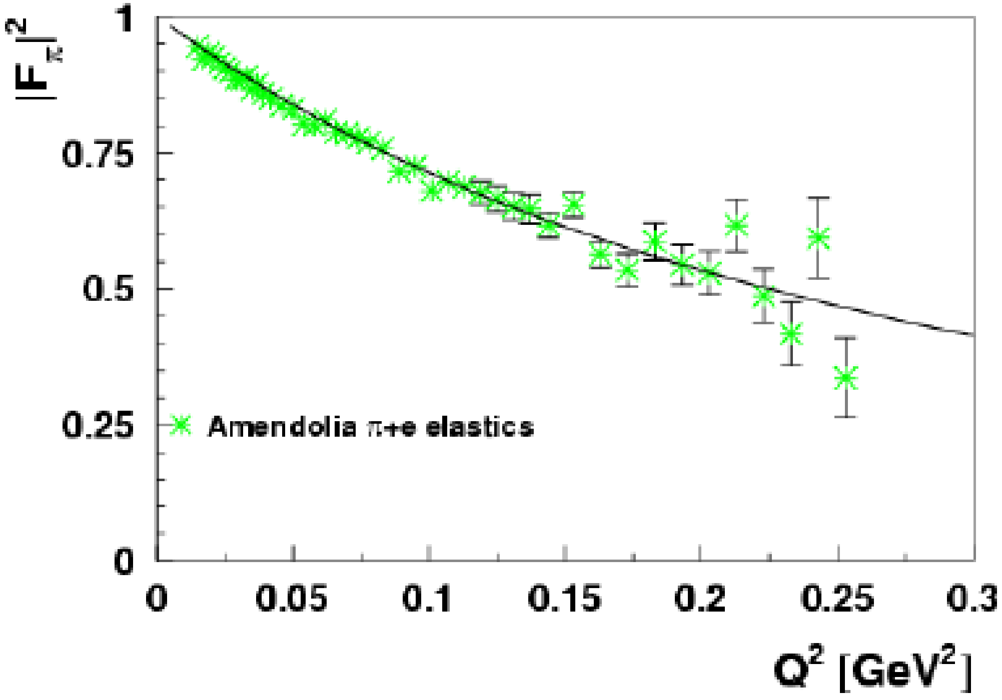
PR12-16-003 enables this goal: → Extraction of high impact F_π to the highest Q^2 at 12 GeV Jefferson Lab

Experimental Determination of the π^+ Form Factor

Through π-e elastic scattering

- At low Q^2, $F_{\pi+}$ 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 constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012$ fm



- The maximum accessible Q^2 is roughly proportional to the pion beam energy
  - $Q^2 = 1$ GeV^2 requires 1000 GeV pion beam

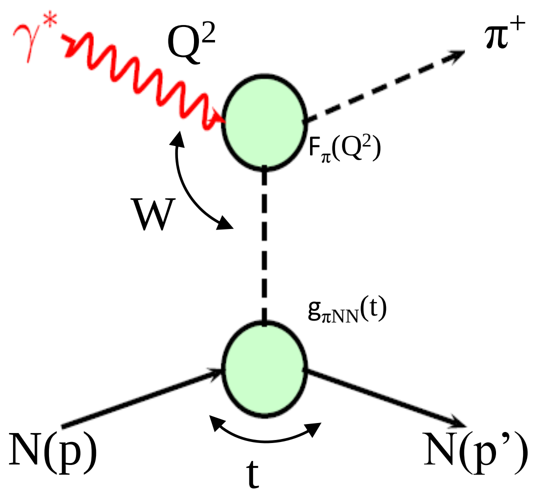
Experimental Determination of the π^+ Form Factor

Through pion electroproduction

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

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

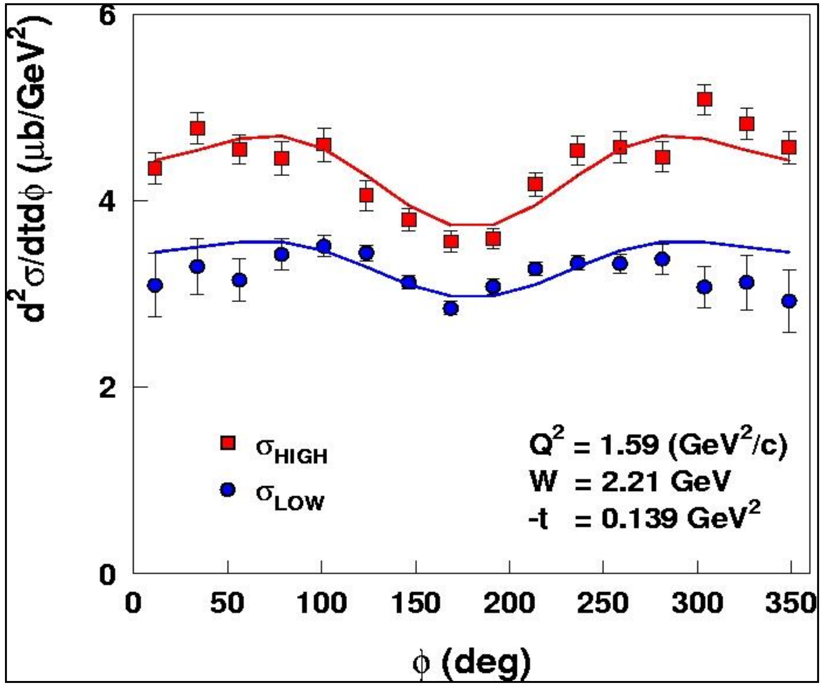
[In practice one uses a more sophisticated model]



- Requirements:
  - Full L/T separation of the cross section – isolation of σ_L
  - Selection of the pion pole process
  - Extraction of the form factor using a model
  - Validation of the technique - model dependent checks

L/T Separation Example

- σ_L is isolated using the Rosenbluth separation technique
  - Measure the cross section at two beam energies and fixed W, Q^2, -t
  - Simultaneous fit using the measured azimuthal angle (ϕ_π) allows for extracting L, T, LT, and TT



- Careful evaluation of the systematic uncertainties is important due to the $1/\varepsilon$ amplification in the σ_L extraction
  - Spectrometer acceptance, kinematics, and efficiencies

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

σ_L will give us F_π

Magnetic spectrometers a must for such precision cross section measurements

- This is only possible in Hall C at JLab

Extraction of F_π from σ_L Jlab data

- JLab 6 GeV F_π experiments used the VGL/Regge model as it has proven to give a reliable description of σ_L across a wide kinematic domain

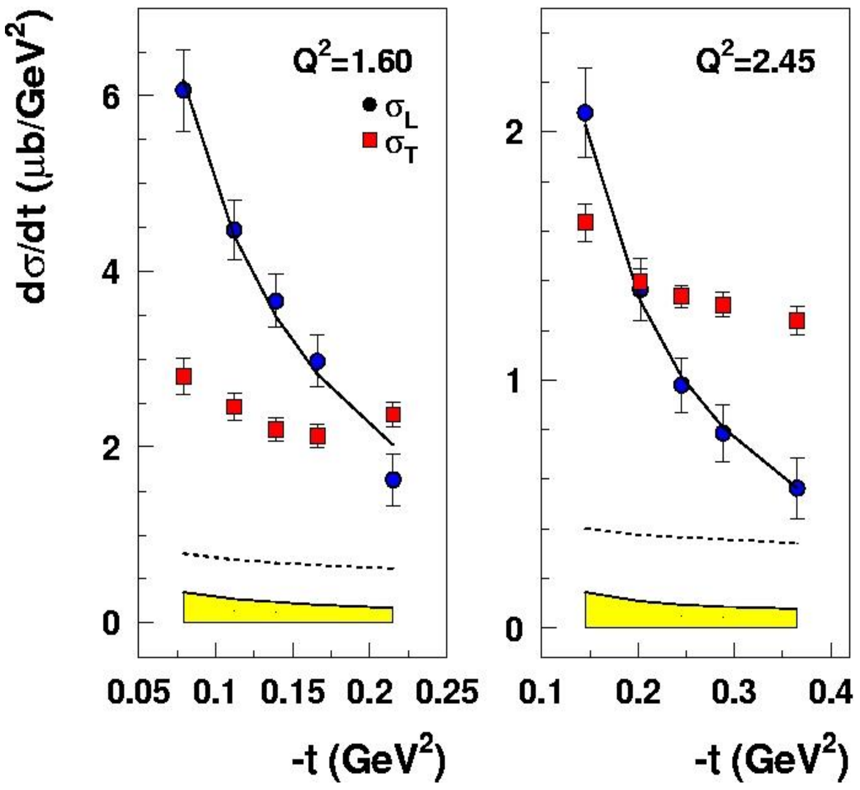
  *[Vanderhaeghen, Guidal, Laget, PRC **57**, (1998) 1454]*

  - Feynman propagator replaced by π and ρ trajectories
  - Model parameters fixed by pion photoproduction data
  - Free parameters: $\Lambda_\pi^2, \Lambda_\rho^2$

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

Fit of σ_L to model gives F_π at each Q^2

*[Horn et al., PRL **97**, (2006) 192001]*



$$\Lambda_\pi^2 = 0.513,\ 0.491\ GeV^2$$

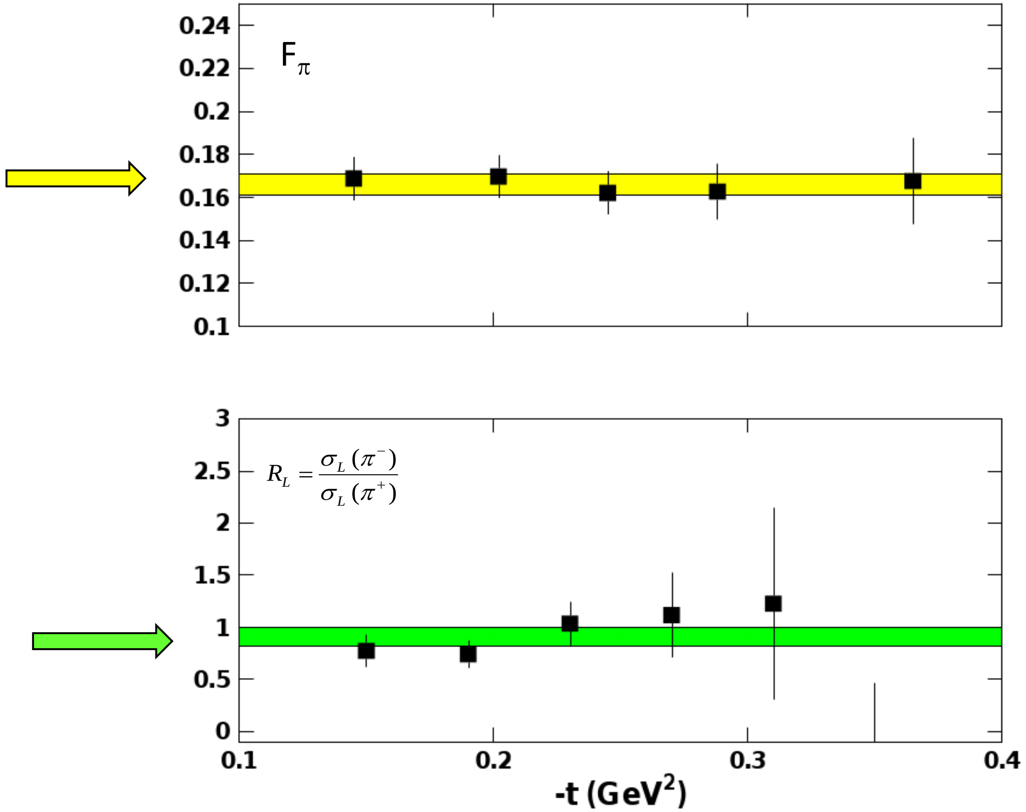
$$\Lambda_\rho^2 = 1.7\ GeV^2$$

Experimental Considerations

Experimental studies over the last decade have given more *confidence* in the electroproduction method yielding the physical pion form factor

Experimental studies include:

- Check consistency of model with data
  - F_π values seem robust at larger -t (>0.2) – increased confidence in applicability of model to the kinematic regime of the data
- Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
  - R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance
- Extract F_π at several values of t_{min} for fixed Q^2 (not shown here)



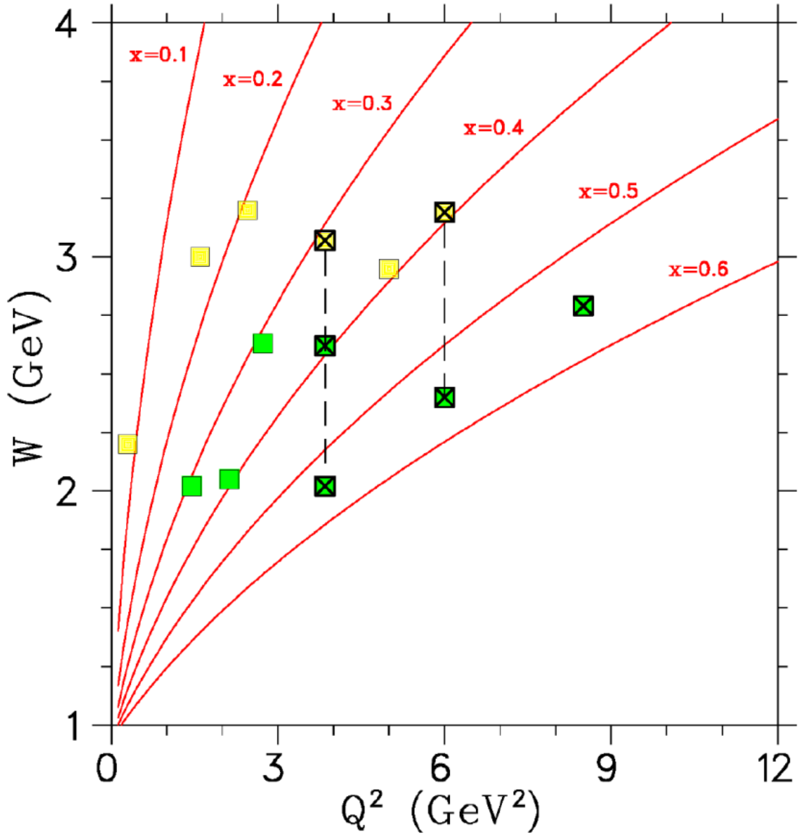
$$R_L = \frac{\sigma(n(e,e'\pi^-)p)}{\sigma(p(e,e'\pi^+)n))} = \frac{|A_v - A_s|^2}{|A_v + A_s|^2}$$

Optimization of two experiments into one program

- An optimization of the kinematics of E12-06-101 and E12-07-105 now allows to extend pion form factor data to the highest possible Q^2 achievable at 12 GeV JLab

JLab 12 GeV F_π Program features:

- Reliable F_π extractions from existing data to the highest possible Q^2
- Validation of F_π extraction at highest Q^2
- Separated cross sections as function of Q^2 at fixed x=0.3, 0.4, 0.55



- The optimized program also addresses several points raised by previous PACs

Previous PAC comments

PAC30

Issues: Since the measurement requires a large number of measurements at different energy and spectrometer settings, a careful optimization of the schedule is strongly recommended. The use of a longer target envisaged in the proposal requires a proper understanding of the corresponding variation in the acceptance. This does not look an issue since the simulated variation is smooth. On the other hand a longer target, but not beyond 10 cm, may allow a reduction in the beam current that could be a benefit for operation in other halls. Given the delicate nature of acceptance issues in Rosenbluth separations that require adequate understanding of the spectrometer performance, it is clear and acknowledged by the proponents that the experiment could only run after an adequate commissioning of the new SHMS.

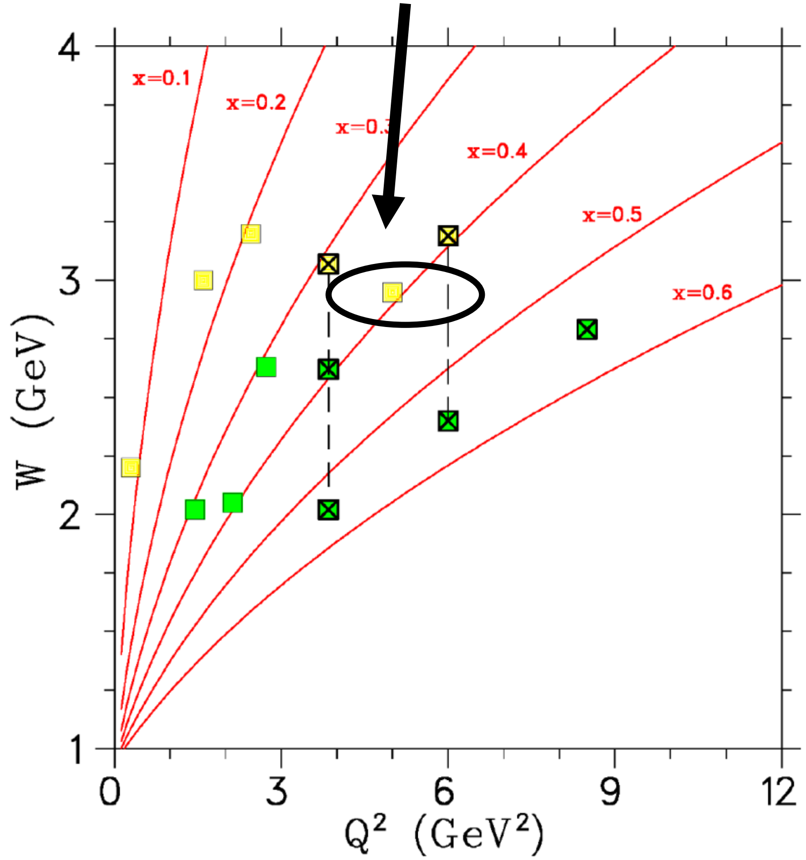
PAC32

Issues: A detailed study to determine whether or not meson electroproduction can provide information on GPDs is important. The PAC believes that the kinematics might not be fully optimized. The experiment could better overlap the F_π-experiment. The collaboration should consider whether the highest x / Q^2 point fully justifies the large time required.

Optimization of the schedule (PAC30)

- ❑ Considerable time saved by eliminating points at Q^2=4.46 GeV^2 (E12-06-101) and Q^2=5.5 GeV^2 (E12-07-105) – moved Q^2=5.25 GeV^2 point of E12-06-101 to Q^2=5.0 GeV^2 to also serve in x-scan

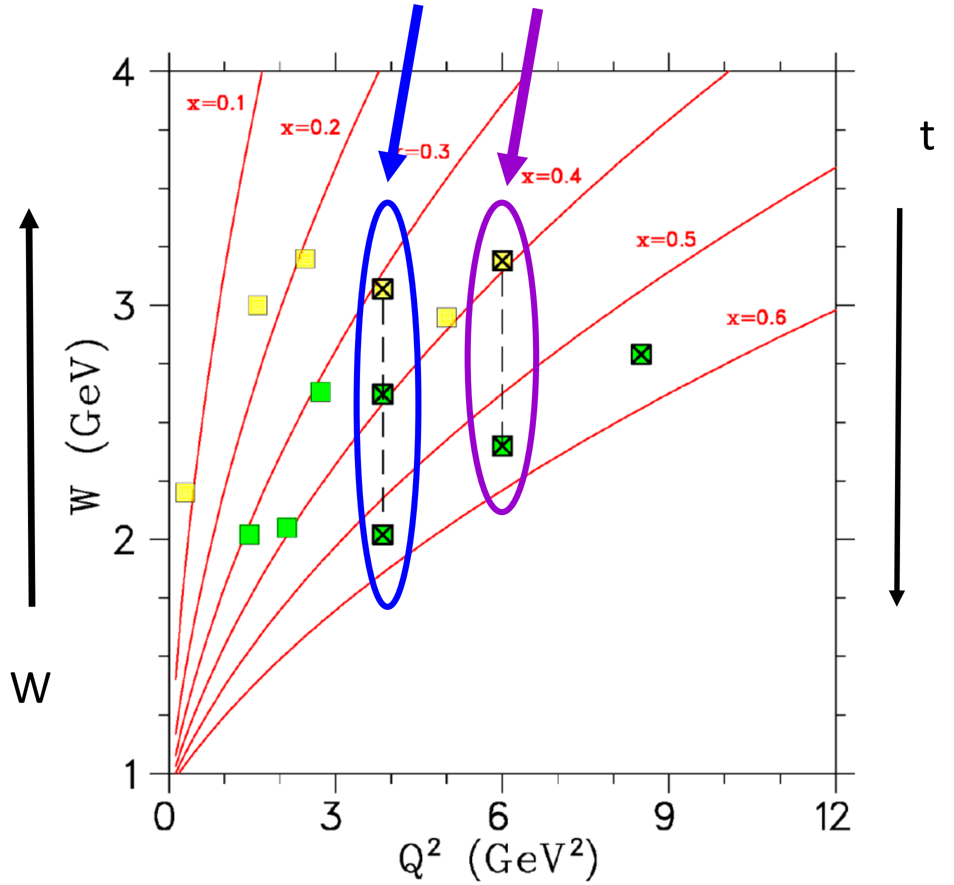
- ❑ Additional optimizations:
  - ➢ Revised all settings to minimize the number of settings requiring special Linac gradients
  - ➢ Reduced the most forward angle requirements
  - ➢ Increased target cell length from 8 cm to 10 cm allowing for reduction in max beam current from 85 μA (with 8 cm target assumed for PAC35/38) to 70μA.



Optimization between the two experiments (PAC32)

To achieve better overlap between the two experiments, move Q^2=6.6 point of E12-07-105 to 6.0 GeV^2 and re-arrange intermediate points to common Q^2=3.85 GeV^2

- t-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



Note: W increases as t decreases

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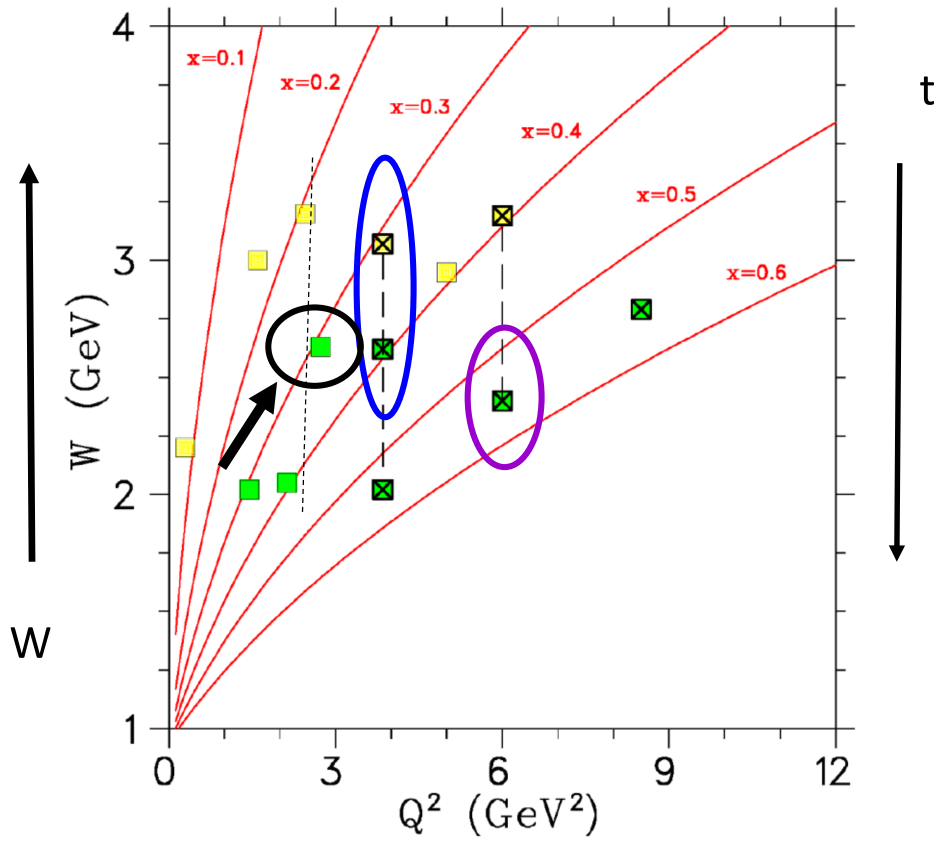
- t-scans at fixed Q^2
  - Q^2=3.85 GeV^2
    - t_{min}=0.12, 0.21, 0.49 GeV^2
  - Q^2=6.0 GeV^2
    - t_{min}=0.21, 0.53 GeV^2
  - Q^2=2.12 GeV^2
    - t_{min}=0.20 GeV^2

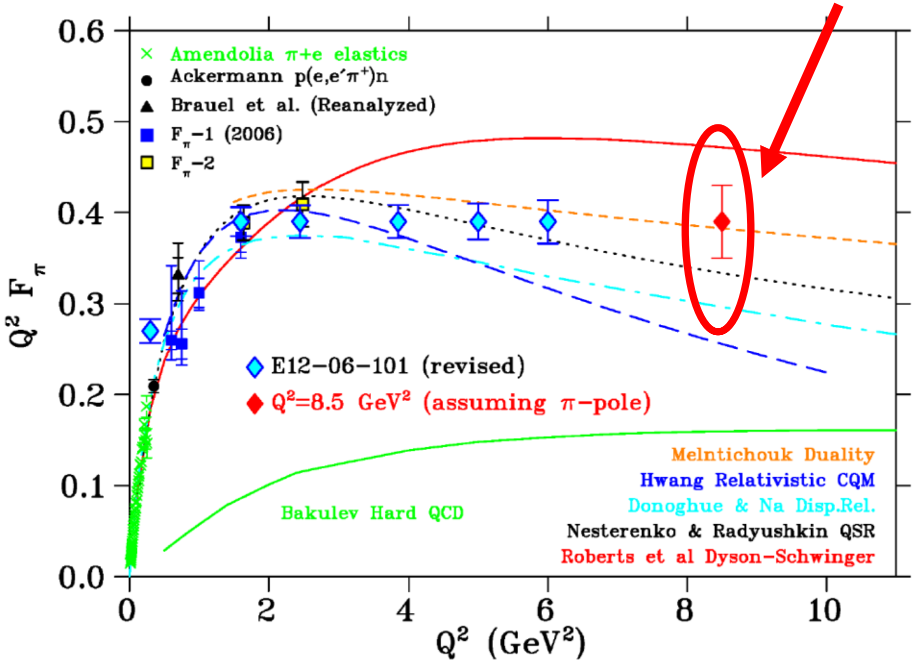


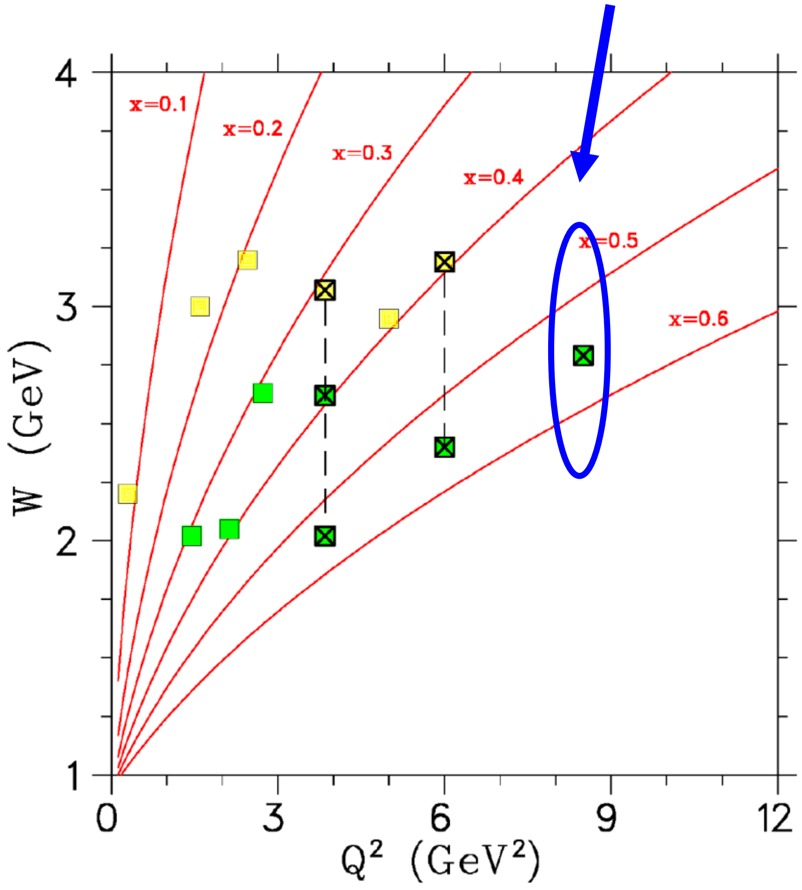
Note: W increases as t decreases

Justification of the beam time for the highest x/Q^2 point (PAC32)

Moved the previous E12-07-105 point at Q^2=9.1 GeV^2 to Q^2=8.5 GeV^2 to extend F_π extraction to the highest possible Q^2 at JLab 12 GeV

- Benefits from reduced uncertainties due to higher rate and more favorable $\Delta\varepsilon$ magnification
- Some beam time added for statistics needed for F_π extraction





Potential physics outcome justifies the beam time requirement

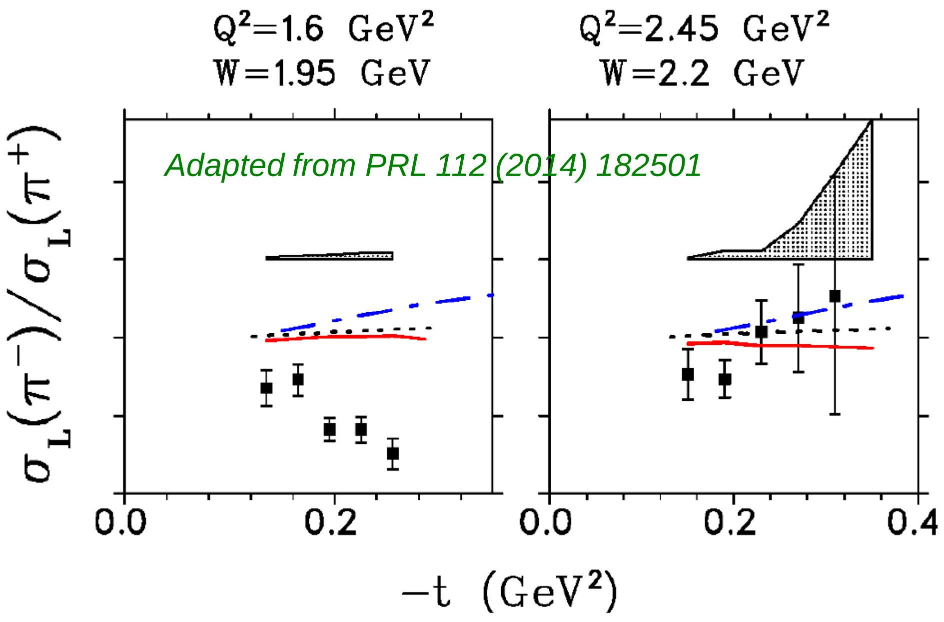
Method check: include validation of the F_π extraction

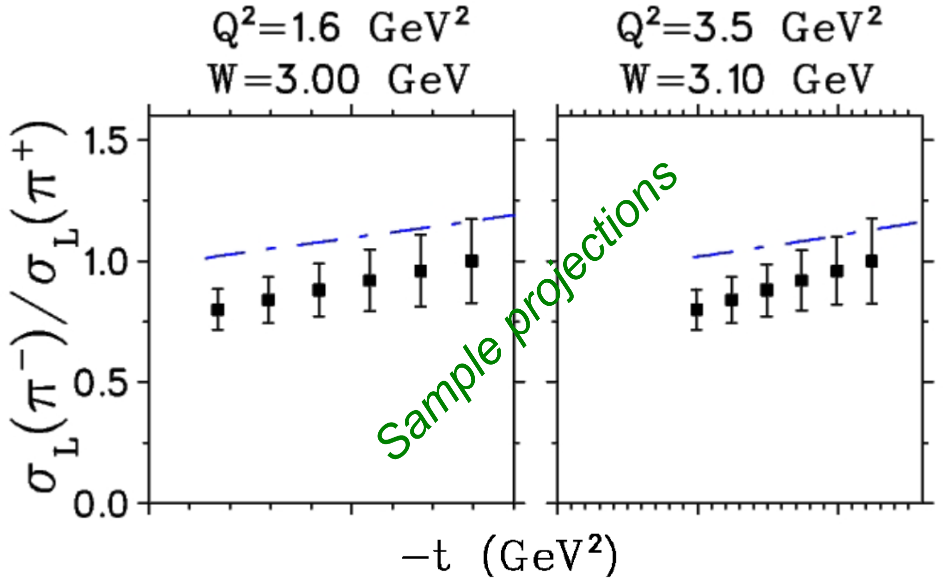
- Check consistency of model with data

- Extract F_π **at several values of t_{min}** for fixed Q^2
  - at Q^2=3.85 and 6.00 GeV^2 (and 2.12 GeV^2)
  - Combining with 6 GeV data - at Q^2=1.6 and 2.45 GeV^2

- Verify that the pole diagram is the dominant contribution in the reaction mechanism
  - **L/T separated π^-/π^+ ratios** to validate form factor extraction at Q^2=1.6, 3.85, 5. and 6.0 GeV^2

PR12-16-003: Additional 5 days needed to validate F_π extraction at high Q^2

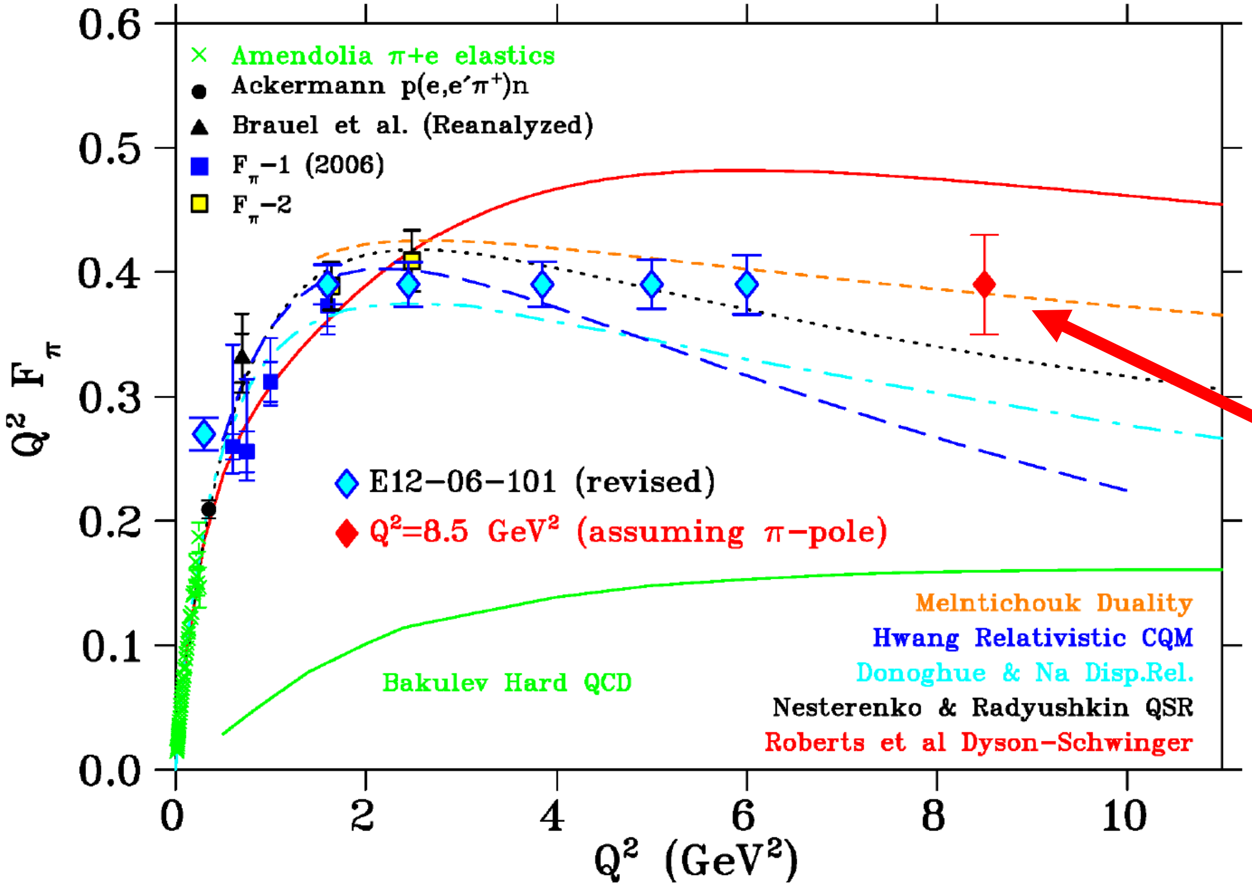




$$R_L = \frac{\sigma(n(e,e'\pi^-)p)}{\sigma(p(e,e'\pi^+)n))} = \frac{|A_v - A_s|^2}{|A_v + A_s|^2}$$

Projected Uncertainties

statistical uncertainty per t-bin range: 1.6-3.6%



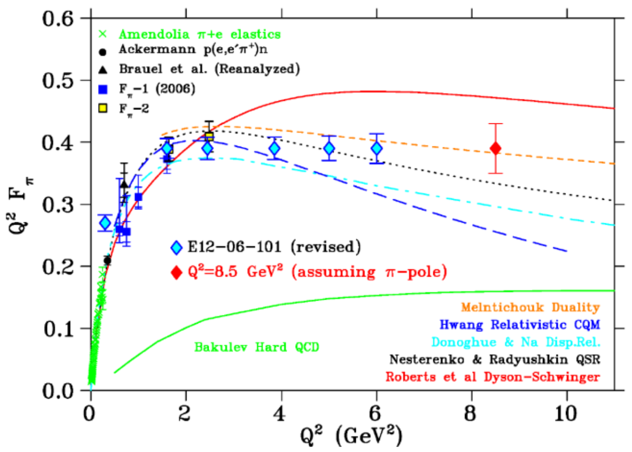
$$\frac{\Delta F_\pi}{F_\pi} = \frac{1}{2}\frac{1}{(\epsilon_1-\epsilon_2)}\sqrt{\left(\frac{\Delta\sigma_1}{\sigma_1}\right)^2(r+\epsilon_1)^2+\left(\frac{\Delta\sigma_2}{\sigma_2}\right)^2(r+\epsilon_2)^2}$$

Statistical and systematic uncertainty projections assuming the VR [T. Vrancx, J. Ryckebusch PRC89, 025203 (2014)] model cross section

Q^2 (GeV^2)	$-t_{min}$ (GeV^2)	$r \equiv \sigma_T/\sigma_L$	$\Delta\epsilon$	$\Delta F_\pi/F_\pi$ (%)
E12-06-101				
0.30	0.005	0.68	0.406	4.9
1.60	0.029	0.36	0.409	4.1
2.45	0.048	0.37	0.326	4.6
3.85	0.120	0.55	0.365	4.7
5.00	0.209	0.78	0.395	5.0
6.00	0.212	0.70	0.268	6.1
Optimized E12-07-105				
8.50	0.544	1.71	0.274	10.2

- Projections are sensitive to the assumption of *r*, which may be conservative
- Systematic uncertainties:
  - Point-to-point: 0.6%
  - t-correlated: 1.6%
  - Overall normalization: 3.3%

E12-06-101, E12-07-105 AND PR12-16-003 together

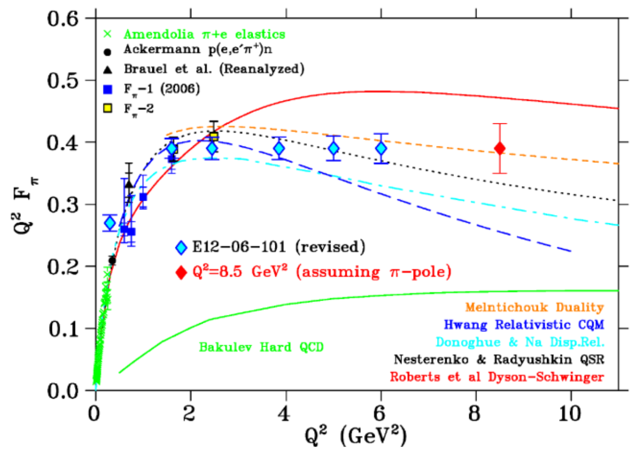


- ❑ Address all earlier PAC comments
- ❑ Enable measurements of pion form factor at low t up to Q^2 = 6 GeV^2
- ❑ Allow for measurements of the separated π^+ cross sections as function of Q^2 at three fixed values of x
- ❑ Enable pion form factor measurement to the very largest Q^2 accessible at 12 GeV JLab, 8.5 GeV^2

Together these will provide a comprehensive and coherent program of charged pion electroproduction, L/T-separated cross section measurements

F_π measurement at Q^2=8.5 GeV^2 will contribute greatly to our understanding of QCD

Request to PAC44



- Confirmation of high-impact status of the π^+ program with L/T separations
- Linking of the two experiments E12-06-101 and E12-07-105 measuring separated π^+ cross sections over a range of Q^2, x and t, enabling the pion form factor extraction
- Additional 120 hours (5 days) to be used in conjunction with the already approved experiments to obtain the needed statistics and enhance the validation for the pion form factor measurements to Q^2 = 8.5 GeV^2