Probing the Strong Interaction with Pion Electroproduction

Nucleon vs. Pion Form Factors

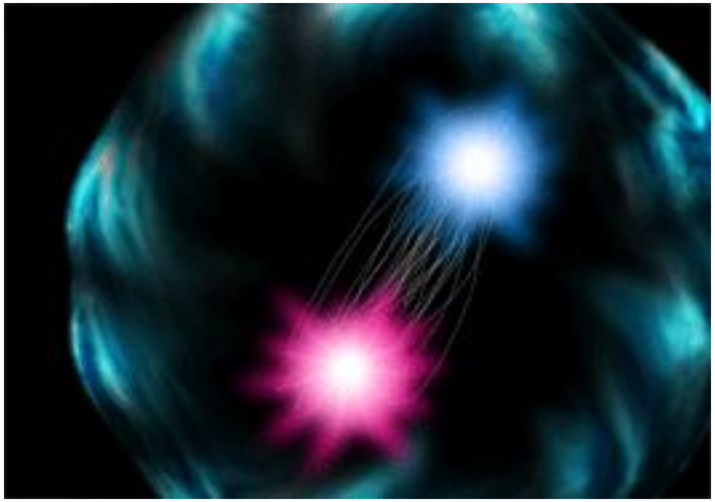
- Earlier, focused on nucleon (proton and neutron) form factors
- Motivation
  - Understand structure of the nucleon at short and long distances
  - Understand the nature of the strong interaction (Quantum Chromodynoamics) at different distance scales
- The pion provides a simpler system for trying to understand QCD
  - 2 quark system vs. 3 quarks (nucleon)
  - Asymptotic form of the pion form factor can be calculated exactly → this is not true for nucleons

Pion Form Factor

Pion particularly attractive as a QCD laboratory

→ Simple, 2 quark system

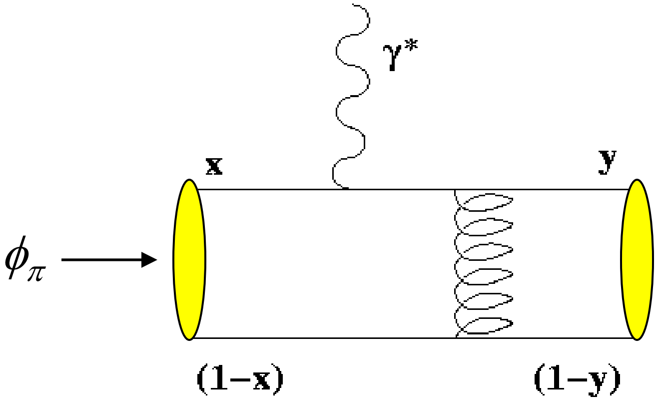
→ ***Electromagnetic structure (form factor) can be calculated exactly at large energies (small distances)***



Drawbacks:
→ No "free" pions
→ Measurements at large momentum transfer difficult

pQCD and the Pion Form Factor

At large Q^2, pion form factor (F_π) can be calculated using perturbative QCD (pQCD)

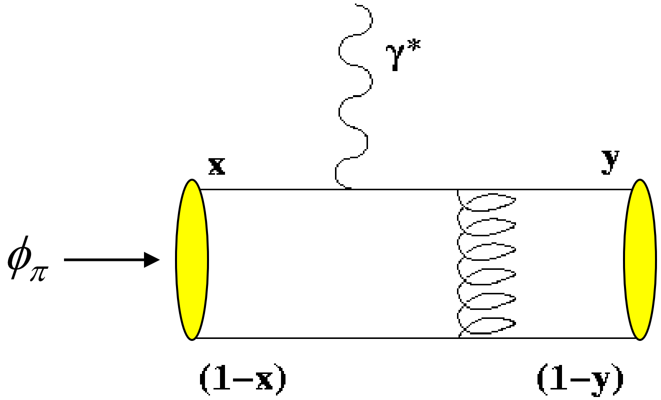


pQCD and the Pion Form Factor

At large Q^2, pion form factor (F_π) can be calculated using perturbative QCD (pQCD)

at asymptotically high Q^2,
the pion wave function becomes

and F_π takes the very simple form



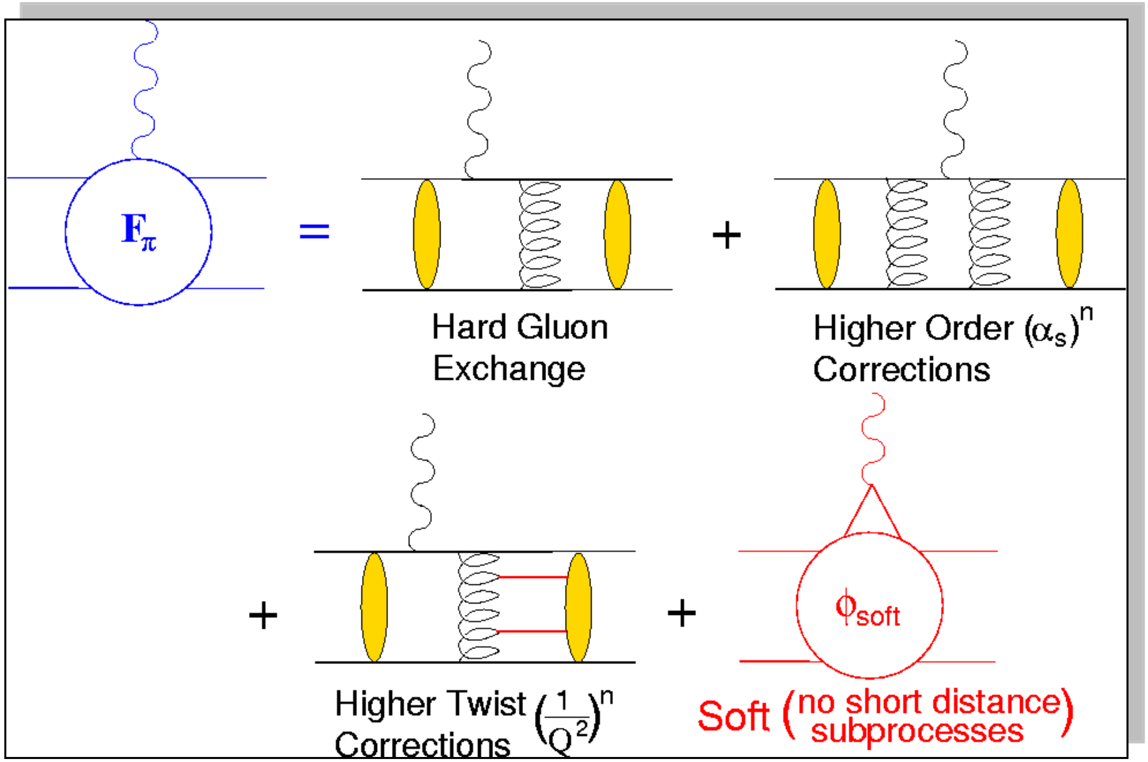
f_π=93 MeV is the $\pi^+ \rightarrow \mu^+ \nu$ decay constant.

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

Pion Form Factor at Finite Q^2

At finite momentum transfer, higher order terms contribute

→ Calculation of higher order, “hard” (short distance) processes difficult, but tractable



There are “soft” (long distance) contributions that cannot be calculated in the perturbative expansion

→Understanding the interplay of these hard and soft processes is a key goal!

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

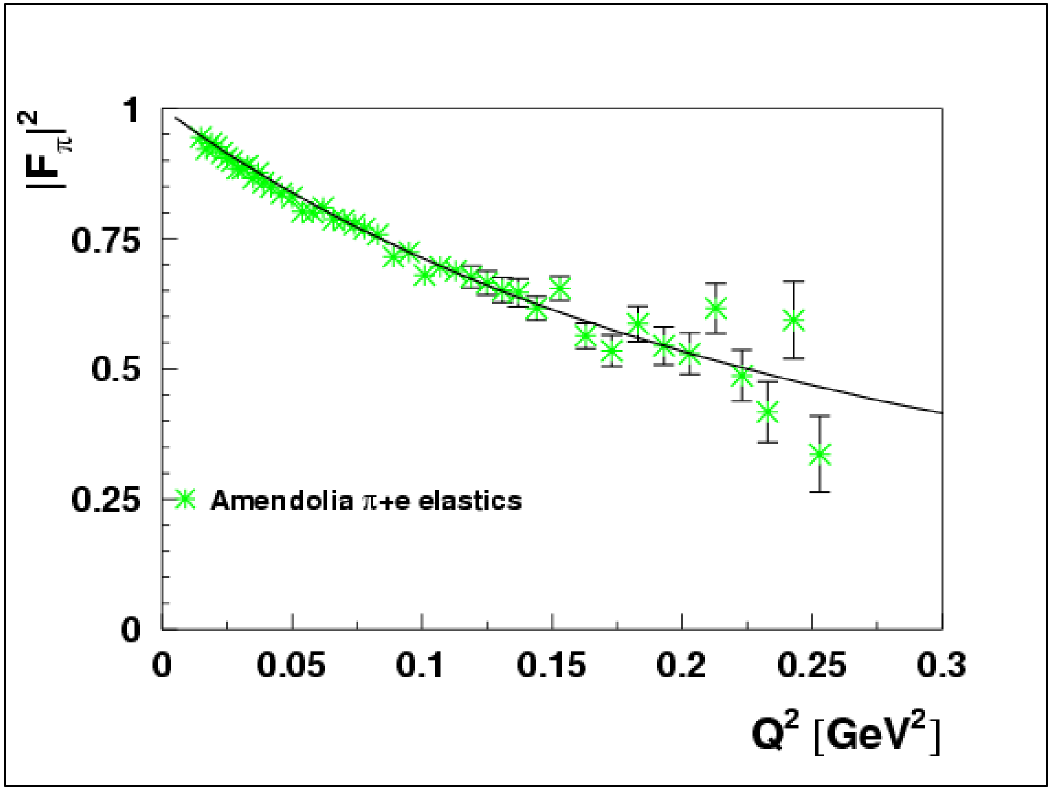
→CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia et al, NPB277, 168 (1986)]*

→ Data used to extract 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

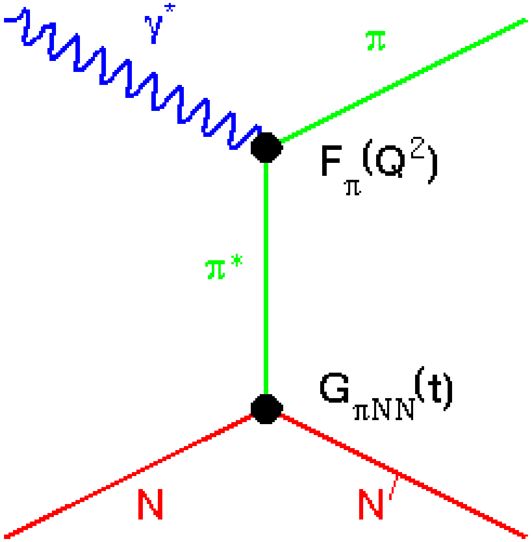
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion $p(e,e'\pi^+)n$

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

→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

Pion Cross Section

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

***t* = four-momentum transferred to nucleon**

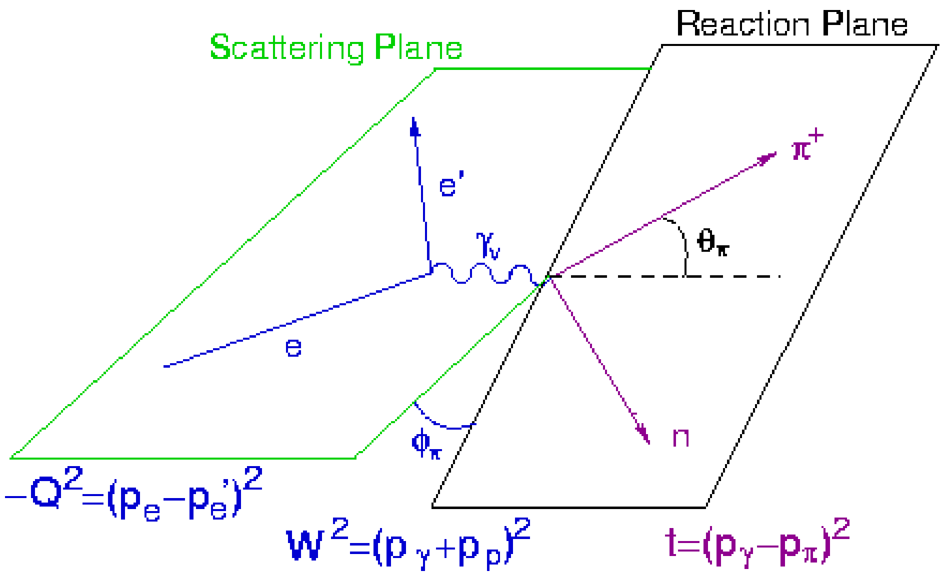
= (mass)^2 of struck virtual pion

W = total energy in virtual photon-target center of mass

***Q*^{2}= -(mass)^2 of virtual photon**

ε= virtual photon polarization, 0→1

ϕ= azimuthal angle between reaction plane and scattering plane



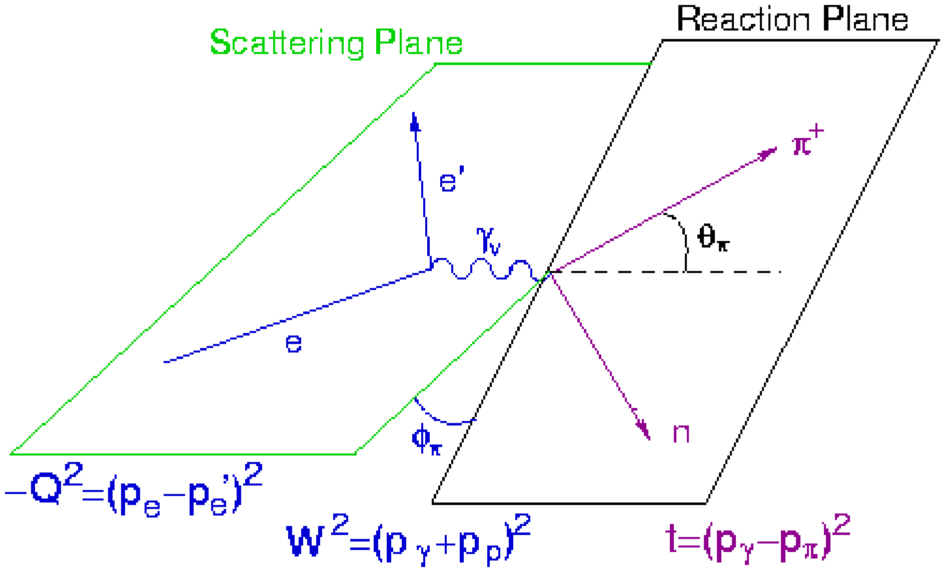
Pion Cross Section

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

For electroproduction, $t<0$

Magnitude of $-t$ smallest when pion emitted along direction of virtual photon

At fixed W, $-t_{min}$ increases as Q^2 increases



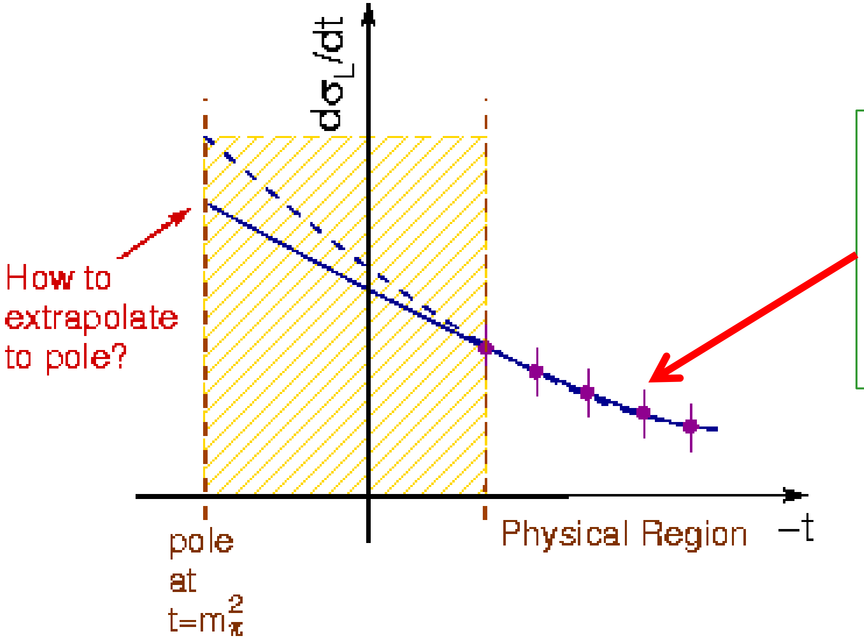
At small $-t$, the pion pole process dominates σ_L

F_π^2 in Born term model

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

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

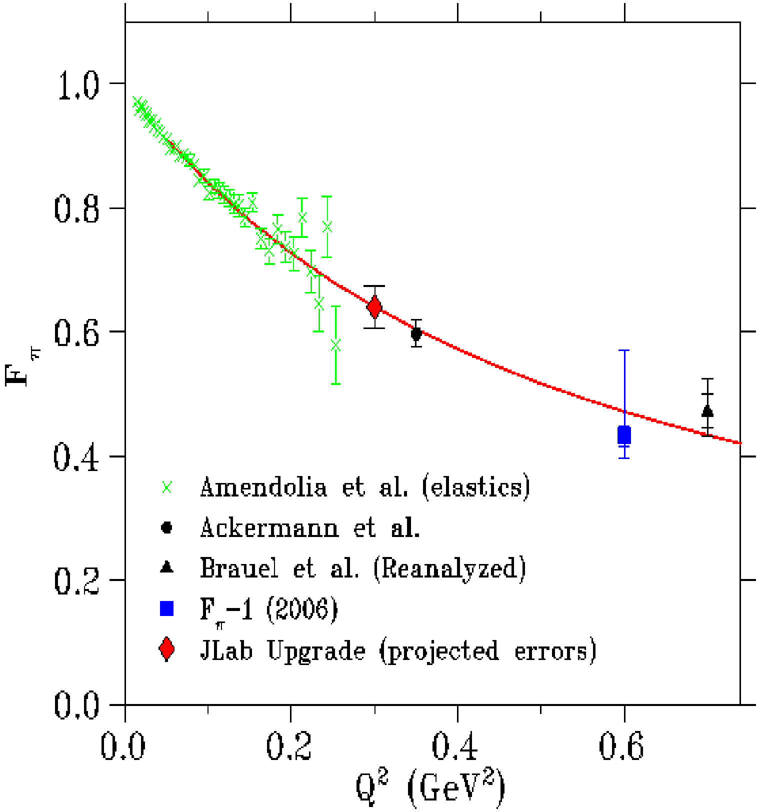
Fitting/constraining a ***model*** incorporating FF is a more robust technique

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

Check of Pion Electroproduction Technique

- Does electroproduction really measure the physical form-factor?
- Test by making $p(e,e'\pi^+)$ measurements at same kinematics as π+e elastics
- Looks good so far

  - *Electroproduction data at $Q^2 = 0.35$ GeV^2 consistent with extrapolation of SPS elastic data*

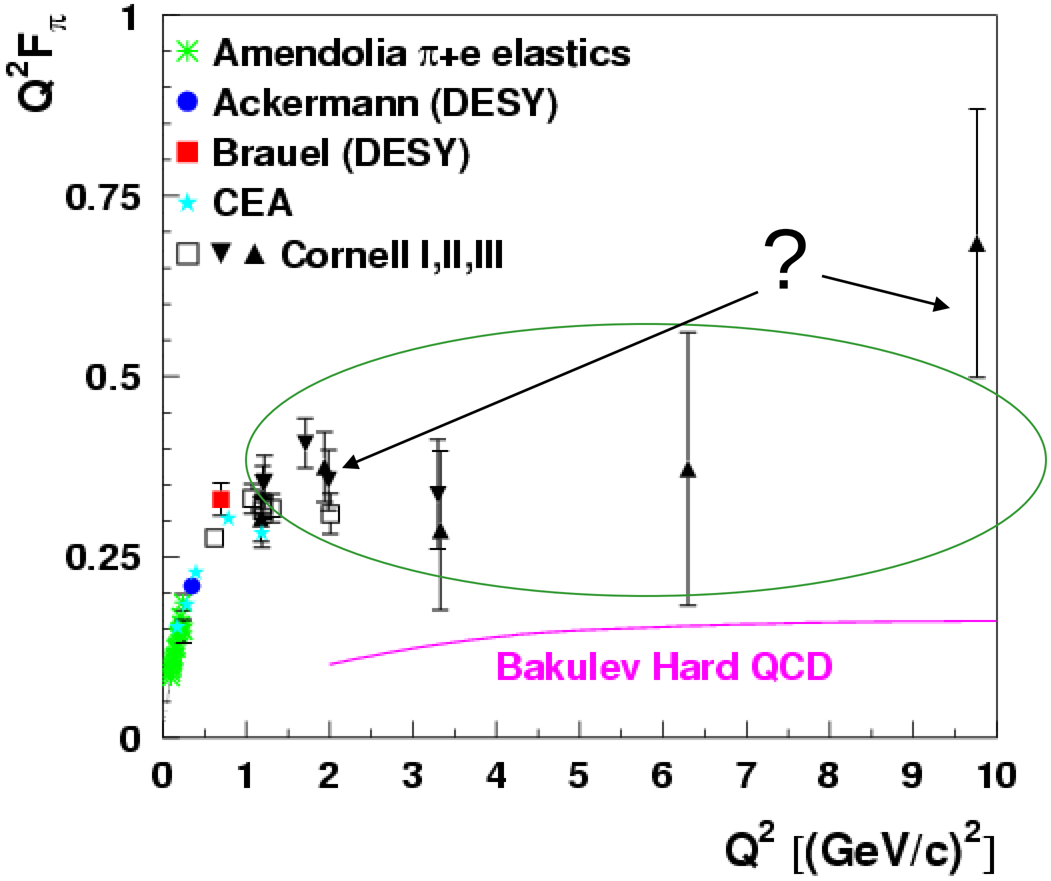


An improved test will be carried out after the JLAB 12 GeV upgrade

→ **smaller Q^2 (=0.30 GeV^2)**

→ **$-t$ closer to pole (=0.005 GeV^2)**

$F_{\pi^+}(Q^2)$ Measurements before 1997



Data above Q^2=1 GeV^2 questionable

→ Extracted F_π from ***unseparated*** cross sections, *no experimental isolation of σ_L*

→ Used *extrapolation of σ_T* fit at low Q^2 to calculate σ_L

→ Largest Q^2 points also taken at large $-t_{min}$

Theoretical guidance suggests non-pole contributions grow dramatically for $-t_{min}>0.2$ GeV^2 *[Carlson and Milana PRL 65, 1717(1990)]*

Pole term may not dominate!

F_π Program at Jefferson Lab at 6 GeV

Two F_π experiments have been carried out at JLab

F_π-1: $Q^2=0.6\text{-}1.6$ 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

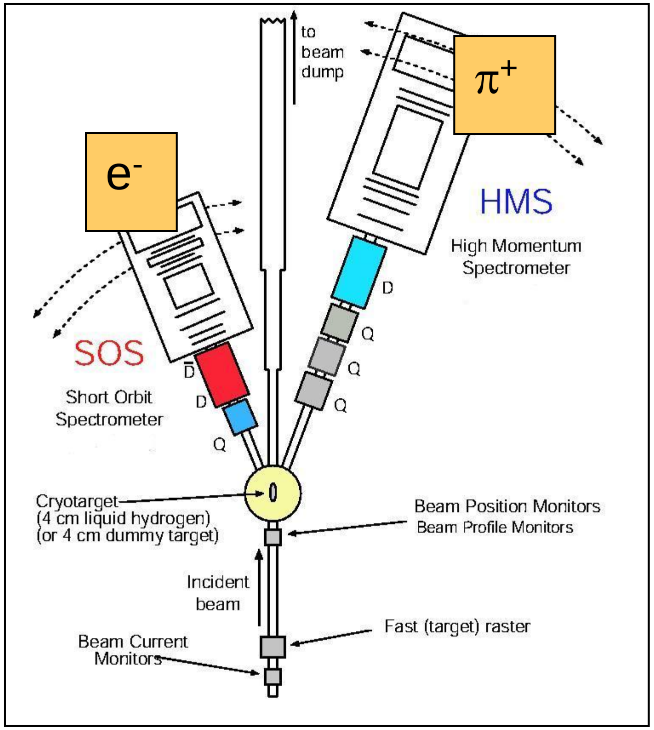
→ Both experiments ran in experimental Hall C: F_π-1 in 1997 and F_π-2 in 2003

JLab F_π Experiment Details

Reaction:

$e + p \rightarrow e' + \pi^+ + n$

beam (→ e) SOS (→ e') HMS (→ π^+) undetected (→ n)



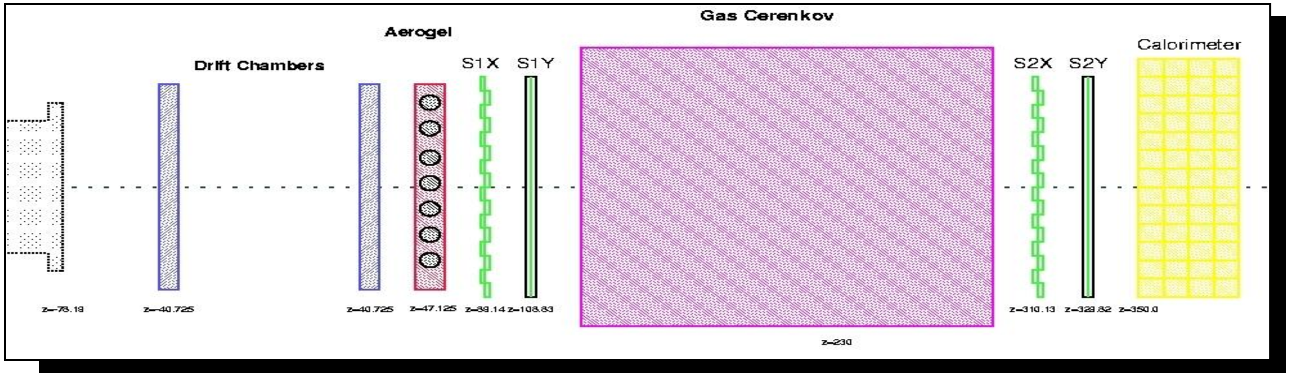
Electron ID in SOS:

→Threshold gas Cerenkov detector

→Lead-glass detector ($E/p_{reconstructed}$)

Pion ID in HMS:

→Aerogel Cerenkov detector

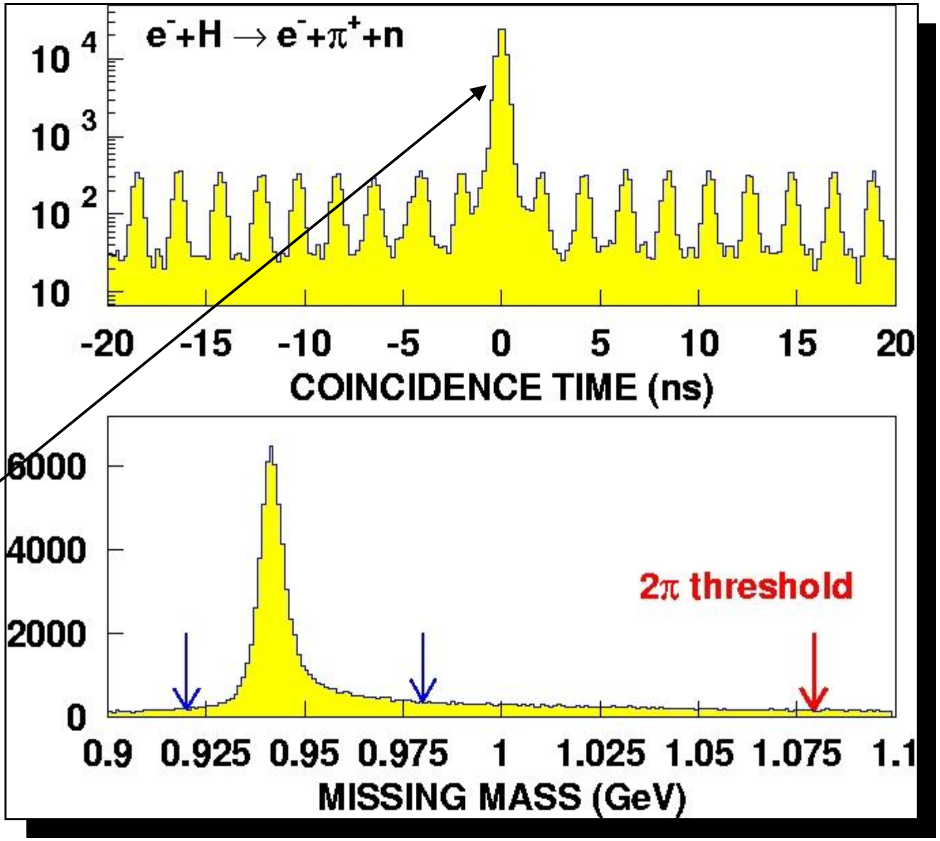


$p(e,e'\pi^+)n$ Event Selection

1. Select electrons in SOS and pions in HMS
2. Reconstruct undetected neutron mass

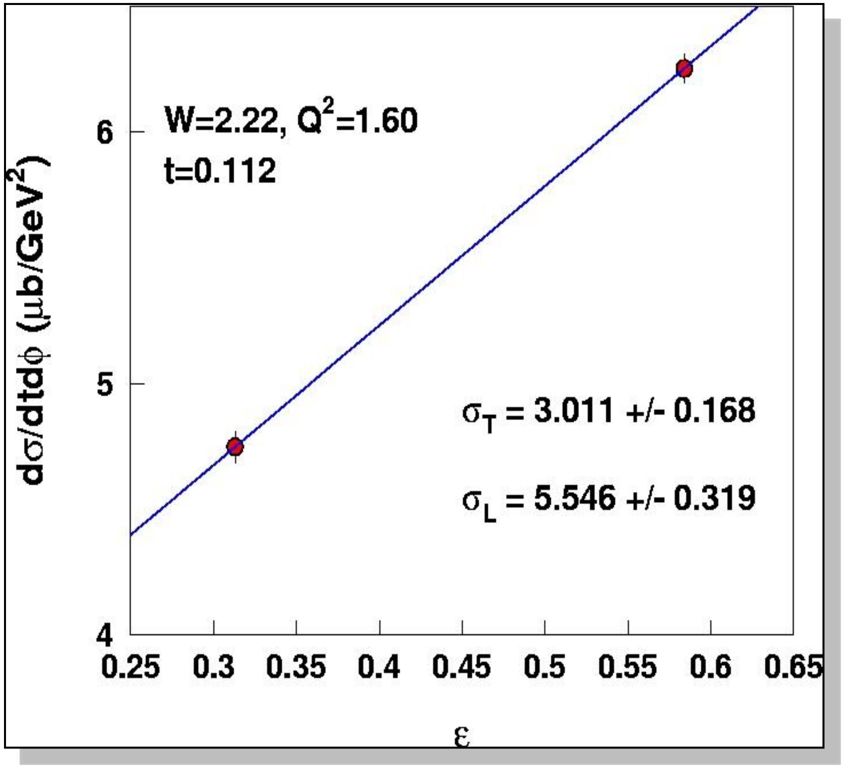
$$M_n^2 = (P^\mu_{e-beam} + P^\mu_p - P^\mu_{e'} - P^\mu_\pi)^2$$

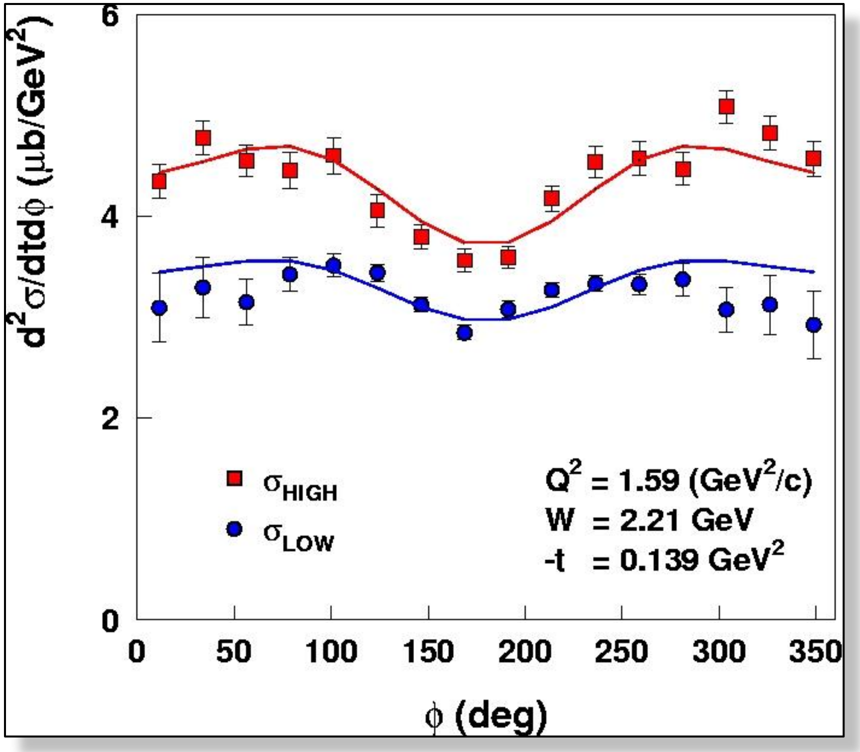
3. Identify events that arrived simultaneously in HMS and SOS



Measuring σ_L

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





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

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

Model for F_π Extraction

Model is required to extract $F_\pi(Q^2)$ from σ_L

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

1. The experimentalist would like to use a variety of models to extract $F_\pi(Q^2)$ from the electroproduction data, so that the model dependence can be better understood.

2. The Vanderhaeghen-Guidal-Laget (VGL) Regge model *[Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)]* is the only reliable model available for our use at present.

3. It would be useful to have additional models for the pion form factor extraction.

The experimental $F_\pi(Q^2)$ result is not permanently "locked in" to a specific model.

F_π Extraction from JLab data

VGL Regge Model

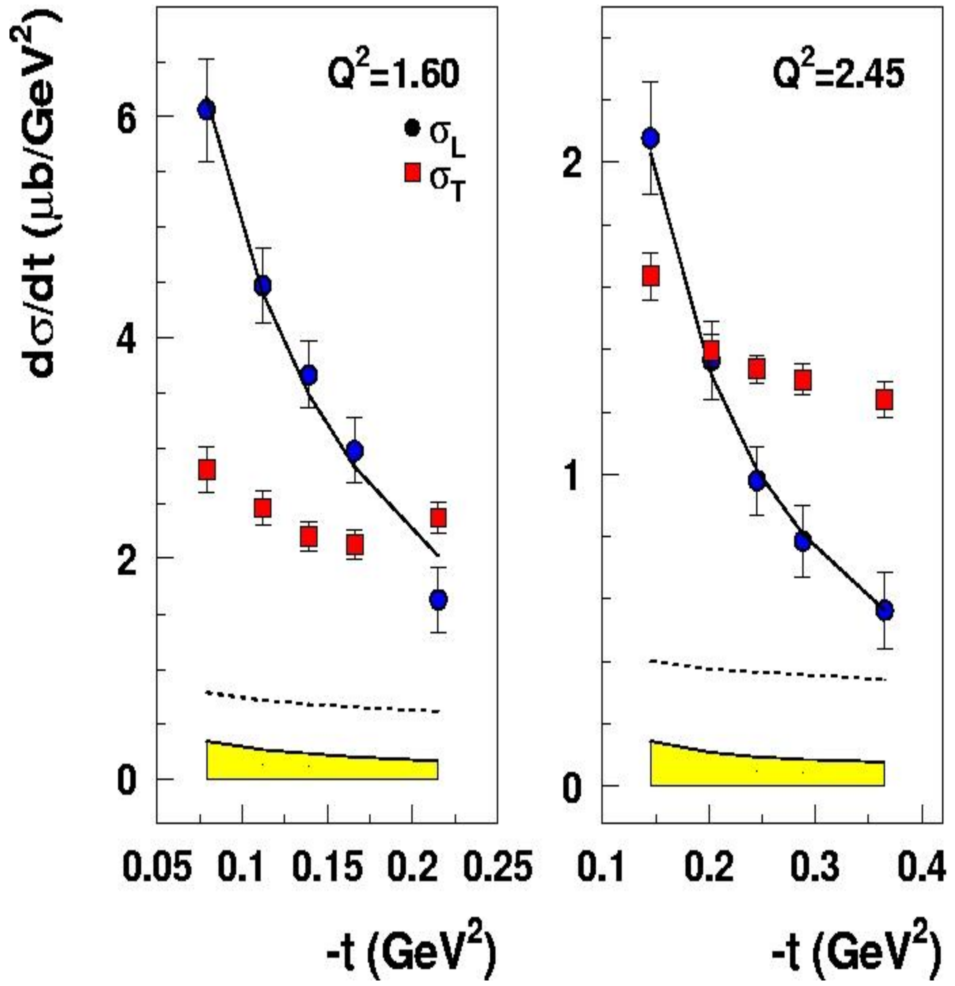
Feynman propagator $\left(\frac{1}{t-m_\pi^2}\right)$ replaced by π and ρ Regge propagators

→Represents the exchange of a <u>series</u> of particles, compared to a <u>single</u> particle

Model parameters fixed from pion photoproduction

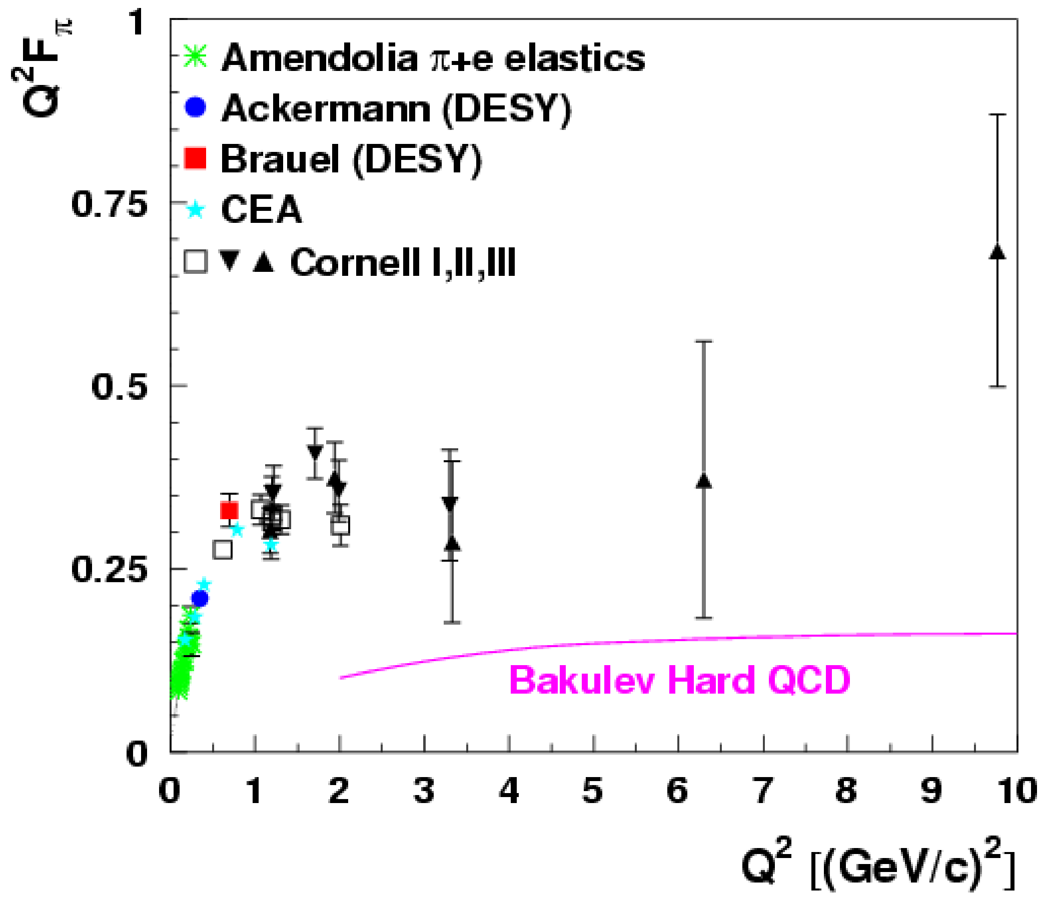
Free parameters: Λ_π , Λ_ρ *(trajectory cutoff)*

Horn et al, PRL97, 192001,2006

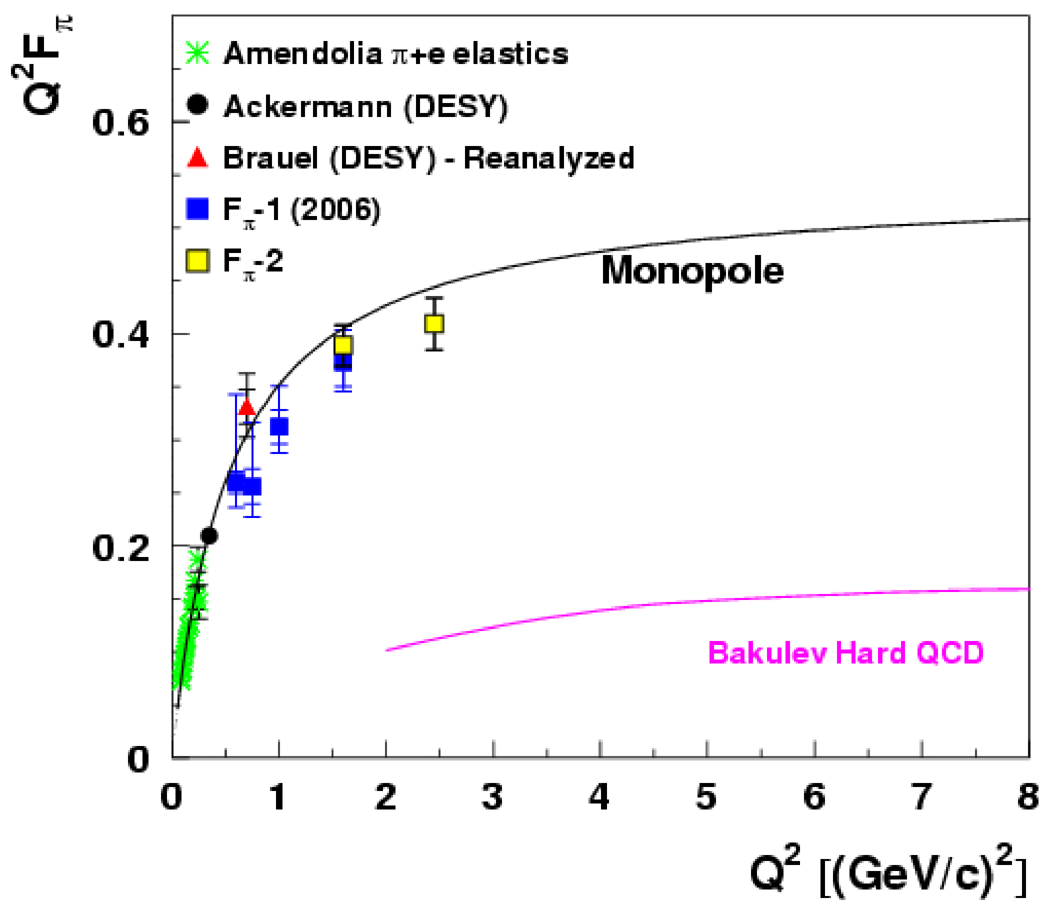


Λ_π^2=0.513, 0.491 GeV^2, Λ_ρ^2=1.7 GeV^2

$F_{\pi^+}(Q^2)$ in 2012

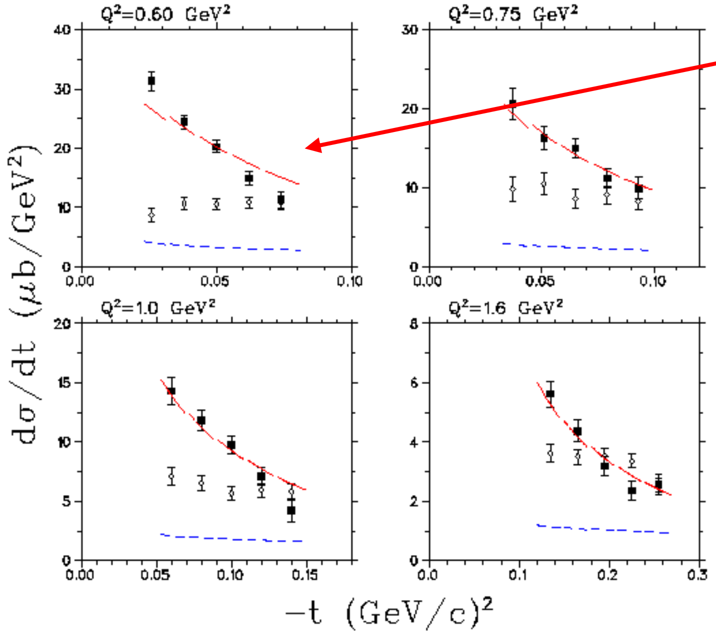


$F_{\pi^+}(Q^2)$ in 2012



- Only true *L-T* separated data shown
- Trend suggested by extractions from unseparated cross sections still holds
  - Far from asymptotic limit
- Monopole curve reflects soft physics at low Q^2
  - ~1 sigma deviation at Q^2=2.5 GeV^2

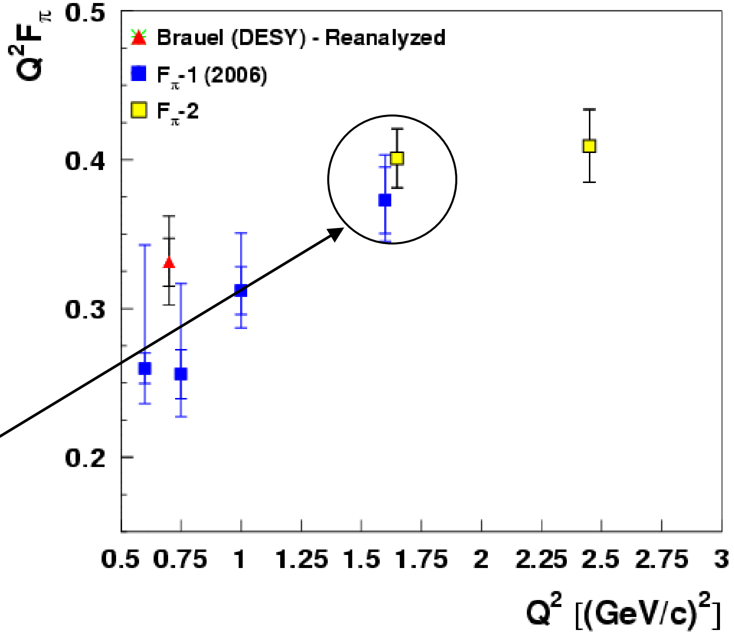
Model/Intepretation Issues



VGL Regge model does not describe –*t* dependence of F_{π}-1 σ_L at lowest Q^2

→ Leads to large systematic errors for F_{π}

→Underscores the need for additional models



Even if model describes data, does it give the “physical” form factor?

→ Test by extracting FF at different distances from –t pole

→ Ex: F_{π}-2, $-t_{min}=0.093$ GeV^2

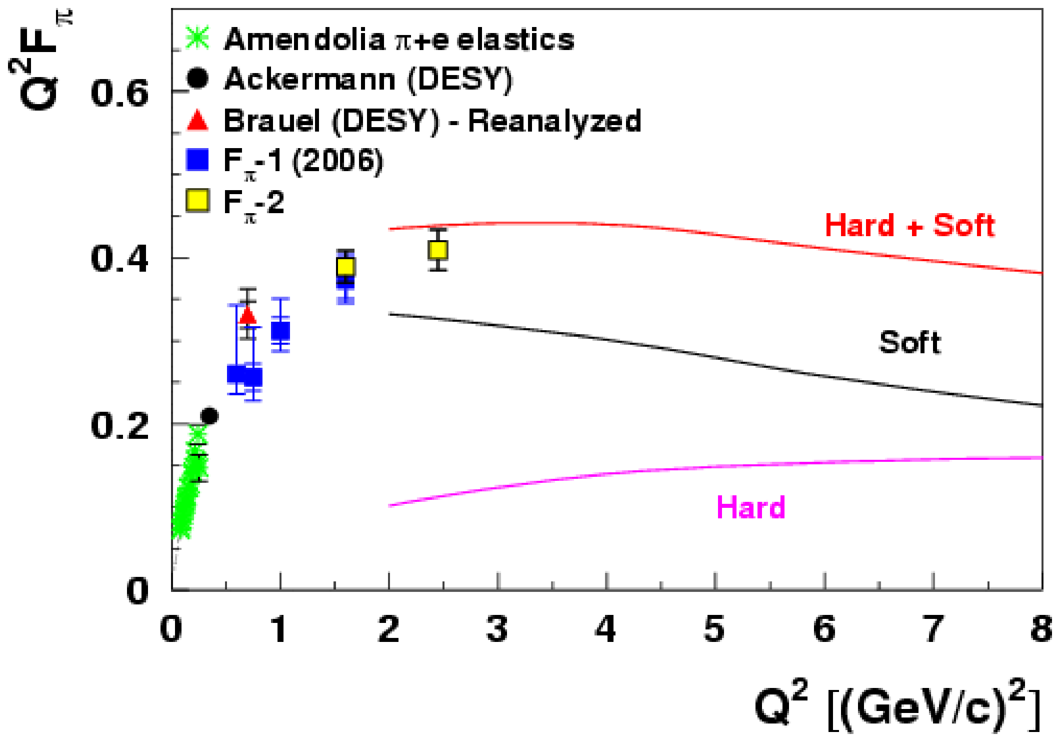
F_{π}-1, $-t_{min}=0.15$ GeV^2

pQCD and the Pion Form Factor

Calculation including only perturbative contributions dramatically under-predicts form factor

Good agreement with data only achieved after including “soft” model dependent contribution

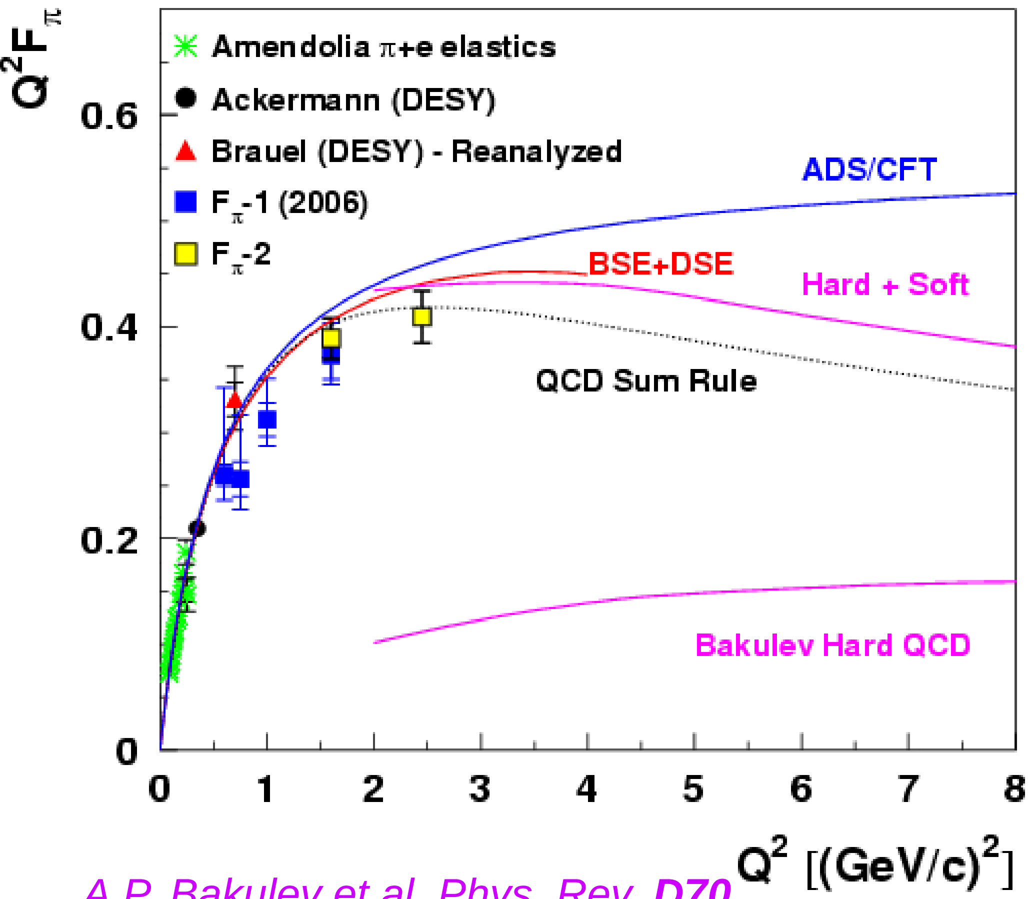
→Modeled using “local duality” – equivalence of hadronic and partonic descriptions



$$F_\pi = \int (\text{Free quark spectral density})$$

A.P. Bakulev, K. Passek-Kumericki, W. Schroers, & N.G. Stefanis, PRD **70** (2004) 033014.

$F_{\pi^+}(Q^2)$ Models



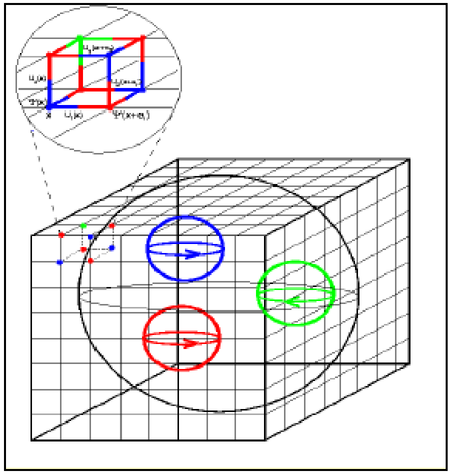
A.P. Bakulev et al, Phys. Rev. ***D70*** *(2004)*

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, hep-th/0702205
→ Anti-de Sitter/Conformal Field Theory approach

Lattice QCD

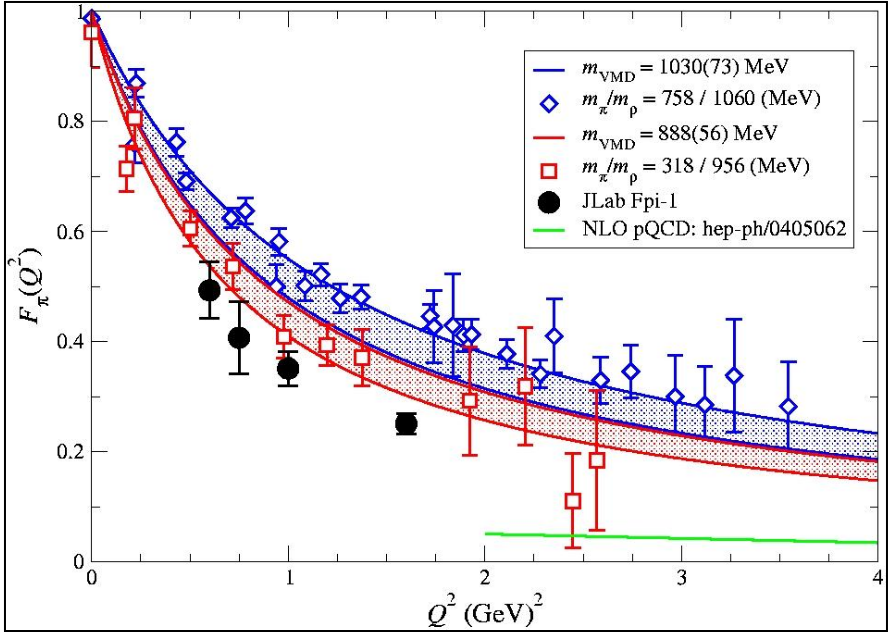


Lattice calculations solve QCD from first principles, numerically

→Space-time is discretized on a finite grid
→Extrapolate to continuous system

Calculations extremely CPU intensive
→Calculation yields pion mass of ~ 318 MeV (physical mass ~ 140 MeV)
→Form factor agrees with experimental data, but error bars still large

F. Bonnet et al., hep-lat/0411028



F_π Program at 6 GeV

JLab F_π program has built on pioneering $H(e,e'\pi^+)$ measurements of the 1970's

→ Facilities at JLab (beam, spectrometers) improved precision of cross sections

→Improved reliability of F_π extraction by isolating σ_L

→Where possible, tested the "electroproduction technique" as a valid method for extracting F_π

At 6 GeV, $Q^2=2.5\ GeV^2$ is the ultimate reach of the F_π program

Larger Q^2 requires the JLab 12 GeV upgrade

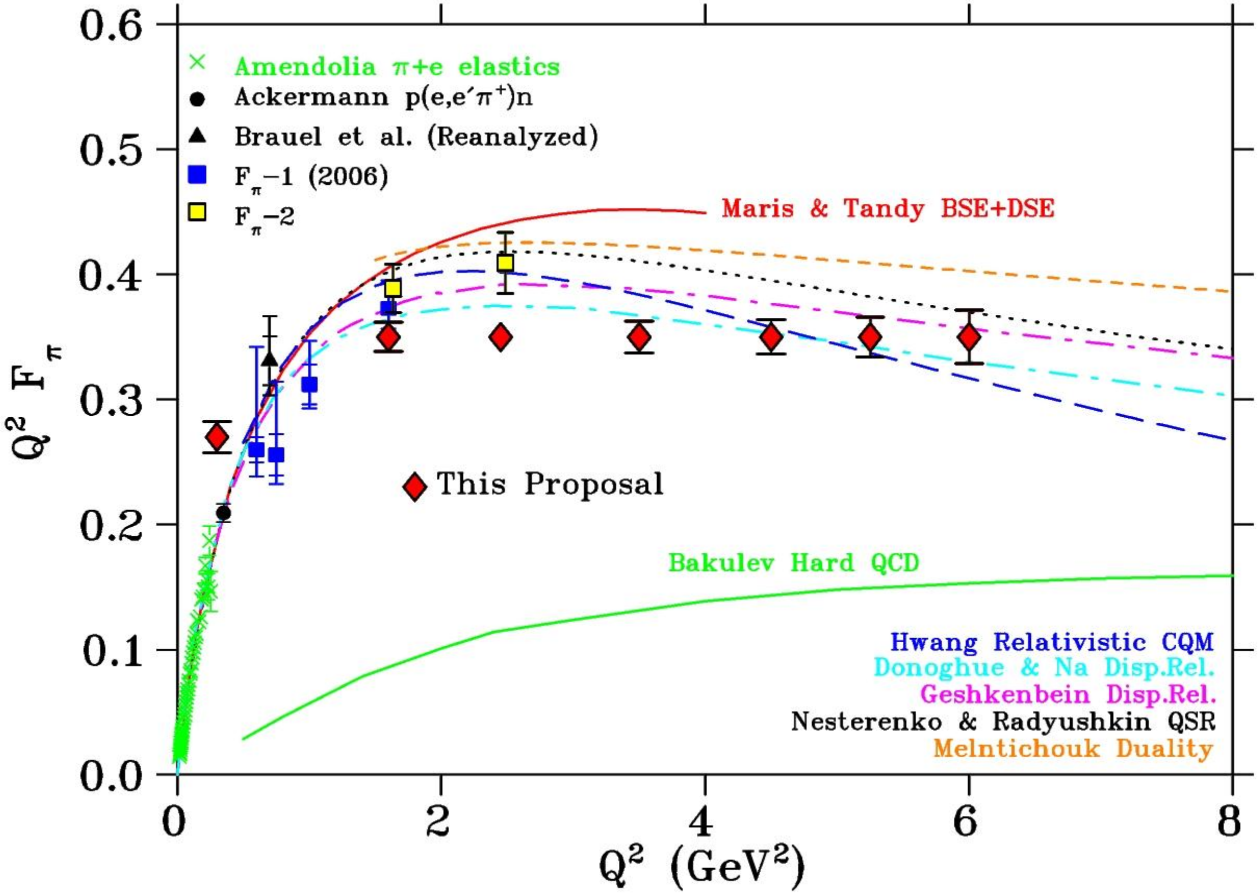
$F_\pi(Q^2)$ after JLAB 12 GeV Upgrade

JLab 12 GeV upgrade will allow measurement of F_π up to $Q^2=6$ GeV^2

Will we see the beginning of the transition to the perturbative regime?

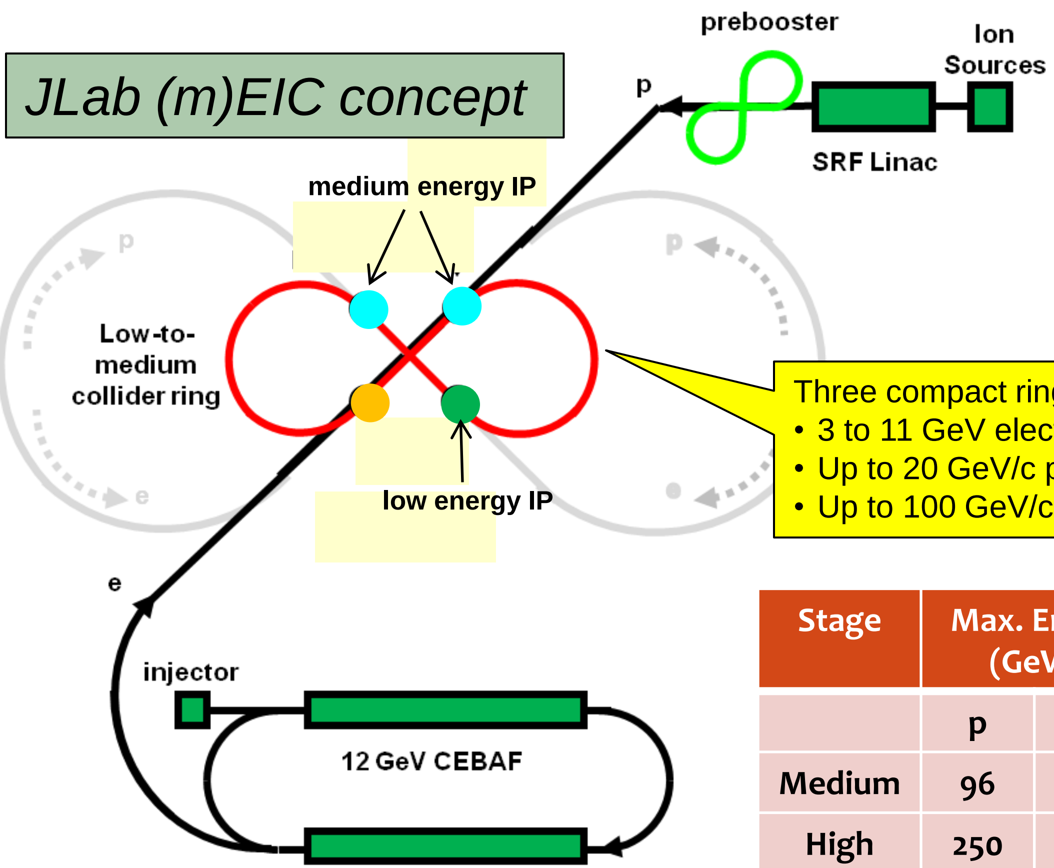
Additional point at $Q^2=1.6$ GeV^2 will be closer to pole: will provide constraint on $-t_{min}$ dependence

$Q^2=0.3$ GeV^2 point will be best direct test of agreement with elastic π+e data



F_π at an Electron-ion collider

Accessible Q^2 for $\boldsymbol{F_\pi}$ measurement with “fixed target” → $E_{beam}/2$
→ Giving the “target” some energy and momentum dramatically broadens the experimentally accessible phase space

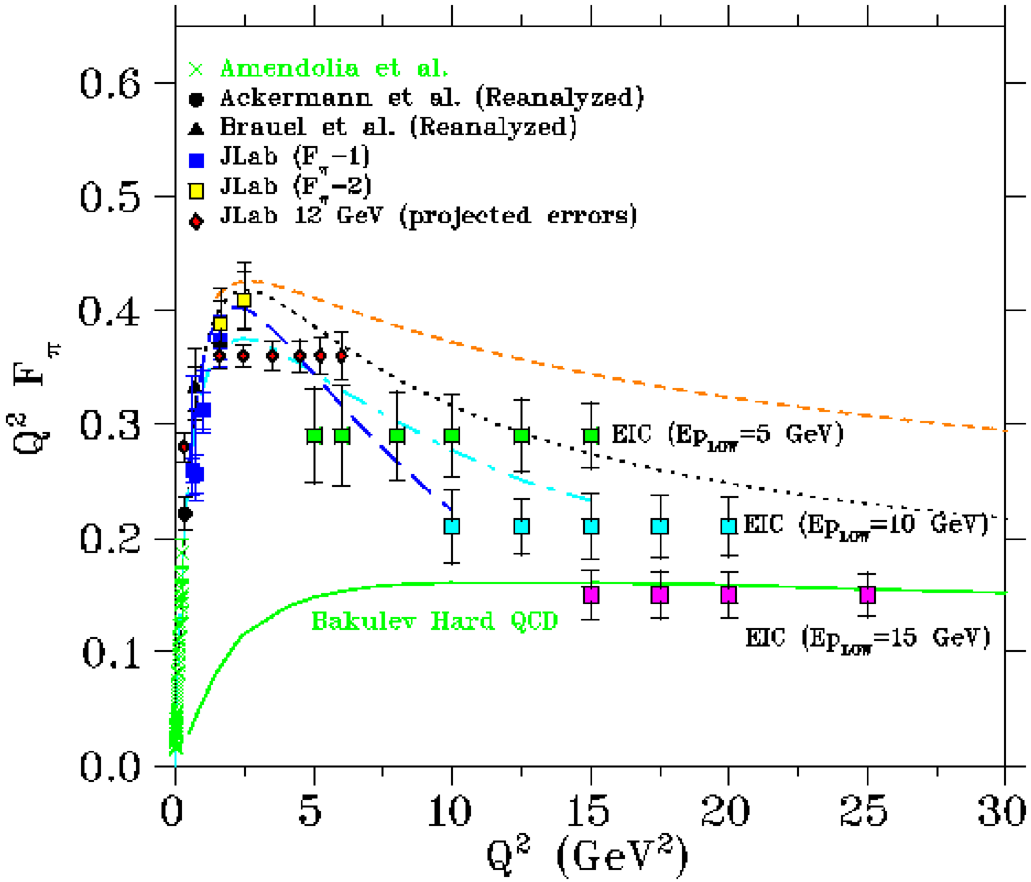

JLab (m)EIC concept

Preliminary $\boldsymbol{F_\pi}$ studies done using parameters similar to those proposed for JLab-based “medium energy” design

Three compact rings:
- 3 to 11 GeV electron
- Up to 20 GeV/c proton (warm)
- Up to 100 GeV/c proton (cold)

Stage	Max. Energy (GeV/c)		Ring Size (m)	Ring Type		IP #
	p	e		p	e	
Medium	96	11	1000	Cold	Warm	3
High	250	20	2500	Cold	Warm	4

F_π at EIC - Kinematic Reach



Assumptions:

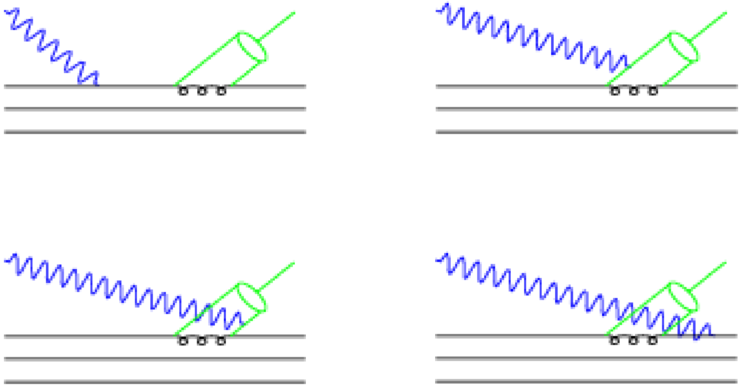
1. High ε: 5(e^-) on 50(p).
2. Low ε proton energies as noted.
3. Δε~0.22.
4. Scattered electron detection over 4π.
5. Recoil neutrons detected at $\theta<0.35^o$ with high efficiency.
6. Statistical unc: $\Delta\sigma_L/\sigma_L$~5%
7. Systematic unc: 6%/Δε.
8. Approximately one year at $L=10^{34}$.

Excellent potential to study the **QCD transition** over nearly the whole range from the strong QCD regime to the hard QCD regime.

F_π at larger Q^2

- In the near future, 12 GeV JLab will yield the ultimate reach for the electroproduction technique for measuring F_π
- Can we extend measurements to larger Q^2 with “existing” accelerators?
- Beyond nucleon pole backgrounds, an additional concern has been pQCD backgrounds to the pion pole process
  - Keeping pQCD backgrounds small (in addition to the general philosophical goal of staying close to pion pole) partially dictates maximum Q^2 available at JLab
  - Relaxing this constraint would allow us to access significantly larger Q^2
- Requires theoretical input ***AND*** supplemental experiments to help verify calculations

pQCD Contributions to $H(e,e'\pi^+)$



In addition to Born terms, pQCD processes can also contribute to π^+ production

Carlson and Milana ***[PRL 65, 1717 (1990)]*** calculated these contributions for Cornell kinematics
→ Asymptotic form for F_π
→ King-Sachrajda nucleon distribution

For $-t>0.2$ GeV^2, pQCD contributions grow rapidly
→This helps set the constraint on maximum accessible Q^2
(fixed W, $-t_{min}$ grows w/Q^2)

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**

F_π at Larger Q^2 and larger $-t_{min}$

If larger $-t_{min}$ were useable, we could measure F_π up to **Q^2=9 GeV^2** at 12 GeV

→ *E12-07-105, T. Horn and G. Huber, spokespersons*

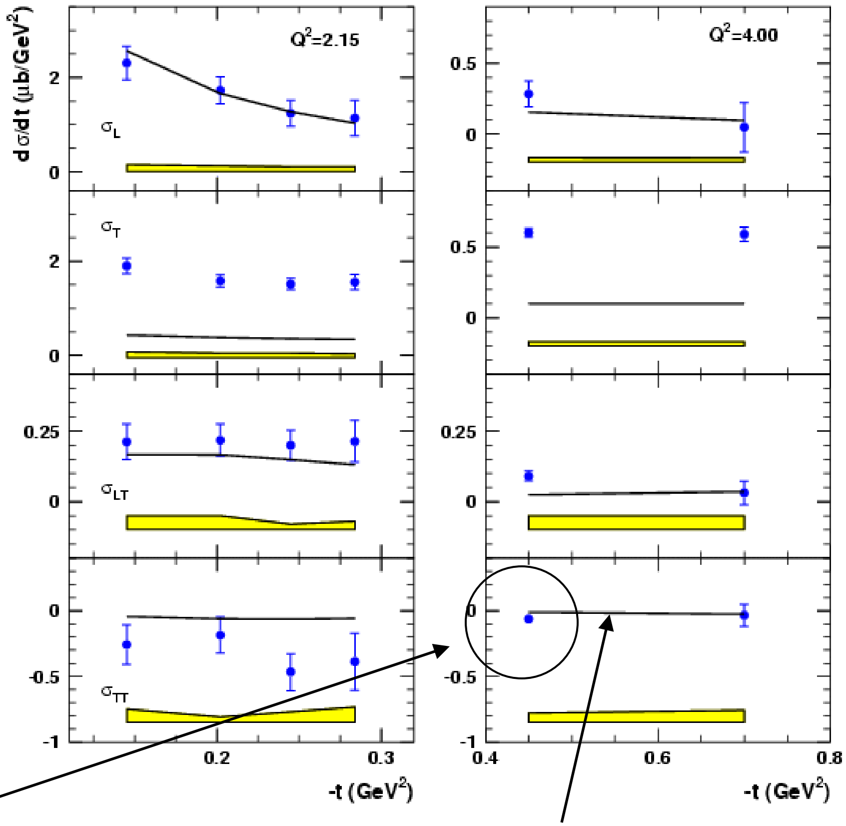
Even at 6 GeV, data at $Q^2=4$ GeV^2 already exist!

Needed:

→*L/T* separated π^0 cross sections

→Transverse target asymmetries

Horn et al, Phys.Rev.C78:058201 (2008)



$-t_{min}$ = 0.45 GeV^2

Separated π^+ cross sections at $Q^2=4$ GeV^2

H(e,e'π^0) and *H(e,e'π^+)*

Same diagrams/GPDs that contribute to π^+ production also contribute to π^0

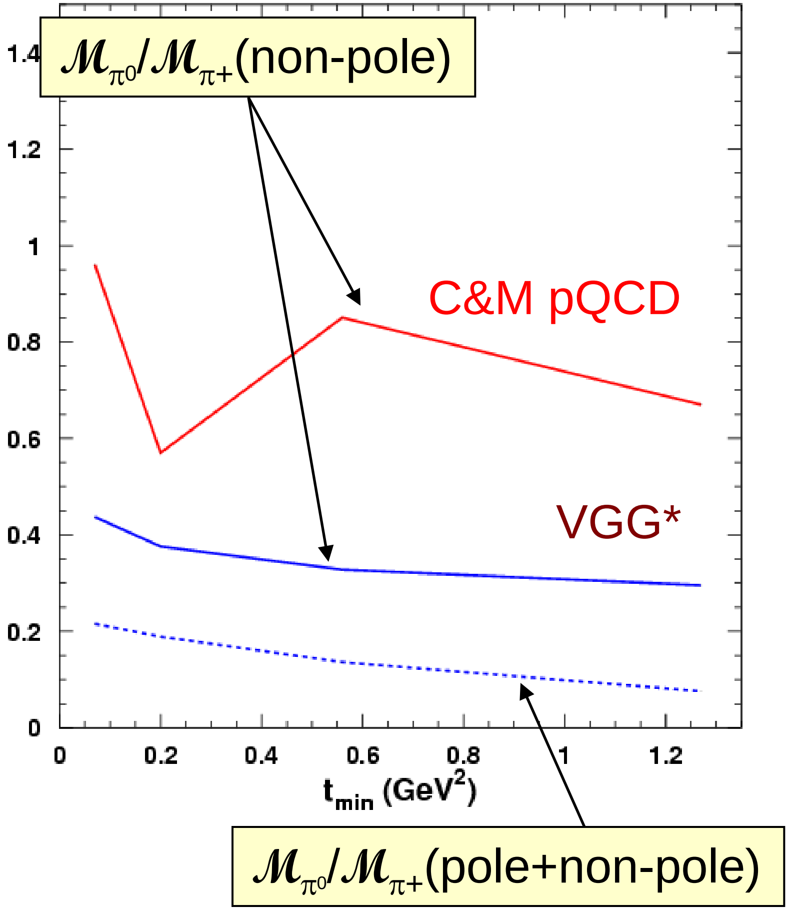
Measurement of σ_L for π^0 could shed some light on non-pole contributions at large *-t*

π^0

$$A_{p\pi^o} \sim (e_u \tilde{H}^u - e_d \tilde{H}^d)$$
$$B_{p\pi^o} \sim (e_u \tilde{E}^u - e_d \tilde{E}^d)$$

π^+

$$A_{p\pi^+} \sim (\tilde{H}^u - \tilde{H}^d)(e_u + e_d)$$
$$B_{p\pi^+} \sim (\tilde{E}^u - \tilde{E}^d)(e_u + e_d)$$



Transverse Target Asymmetry

Non-pole contribution can also be constrained using the transverse target asymmetry

$$A_{p\pi^+} \sim (\tilde{H}^u - \tilde{H}^d)(e_u + e_d)$$

$$B_{p\pi^+} \sim (\tilde{E}^u - \tilde{E}^d)(e_u + e_d)$$

$$A_\perp \sim \mathrm{Im}(AB^*) \longleftarrow$$

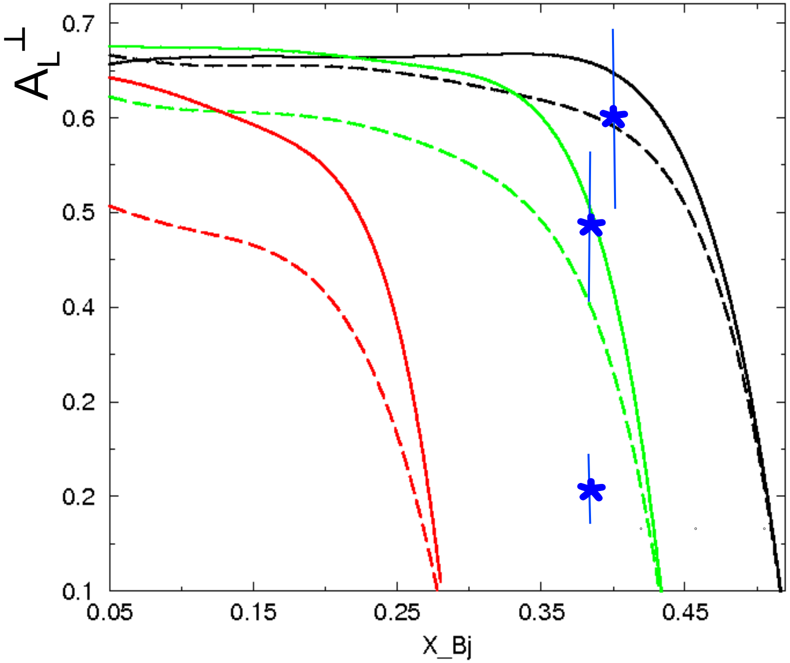
Asymmetry measures interference between pole and non-pole contributions

Experimentally difficult → need “double” Rosenbluth separation to eliminate contributions from transverse photon

$$\sigma = \sigma_T + \epsilon_L \sigma_L + \sqrt{\frac{1}{2}\epsilon(\epsilon+1)}\sigma_{LT}\cos\phi + \epsilon\sigma_{TT}\cos 2\phi$$

$$\sigma_{Py} = -P_y\left[\sigma^y_{TT} + \epsilon\sigma^y_{TT'}\cos 2\phi + 2\epsilon\sigma^y_L + \sqrt{2\epsilon(1+\epsilon)}\sigma^y_{LT}\cos\phi\right]$$

$A_{\square}$ Measurement with ^{3}He



Solid: asymptotic pion distribution amp.
Dashed: CZ pion dist. amp.

t = -0.5 GeV^2 **t = -0.3 GeV^2**
t = -0.1 GeV^2

Polarized ^{3}He target → effective neutron target
e+n → e'+p+π⁻

Proposed U. New Hampshire ^{3}He target:
Luminosity = 1.2 10^{37}/cm^2/s
P_{targ} = 65%

18 day measurement with conventional spectrometers

Q^2=4.0, W=2.8, x=0.365			
-t (GeV^2)	R= σ_L/σ_T	$A_L^\perp$	$\delta A_L^\perp$
0.2	1.0	0.2	0.04
0.4	1.0	0.5	0.08
0.6	1.5	0.6	0.10

Pion Form Factor Summary

- Recent data from JLab at 6 GeV improve interpretability and precision of moderate Q^2 data set
- JLab 12 GeV Upgrade will allow us to hopefully begin seeing the transition to the perturbative regime
- Studying this transition will give us insight into the best way to describe bound hadrons using effective models at low Q^2
- Access to larger Q^2 requires,
  - Radical change in technology (electron-ion collider!)

and/or

  - Supplementary measurements of other reactions + theoretical input