Precision Measurement of The Pion Form Factor

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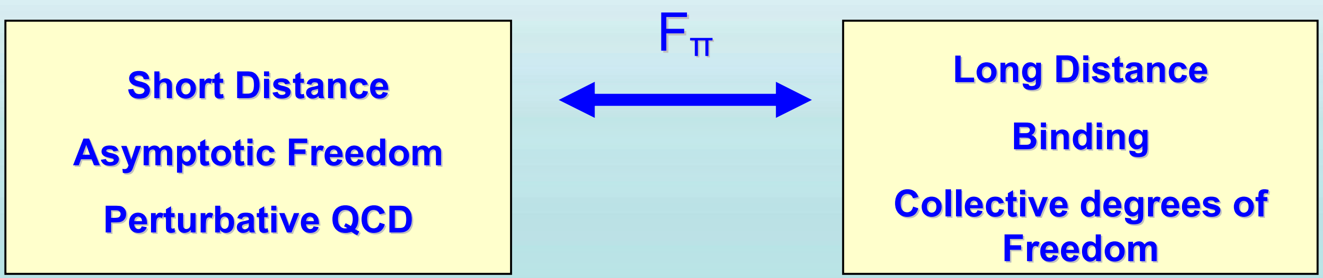
- Pion Form Factor via Pion Electroproduction
- Precision Measurements in Hall C JLab
- Results (F_{π}-2)

Hadronic Form Factors in QCD

- Fundamental issue: quantitative description of hadrons in terms of underlying constituents
  - Theory: Quantum Chromo-Dynamics (QCD) describes strong interactions
  - Degrees of freedom: quarks and gluons



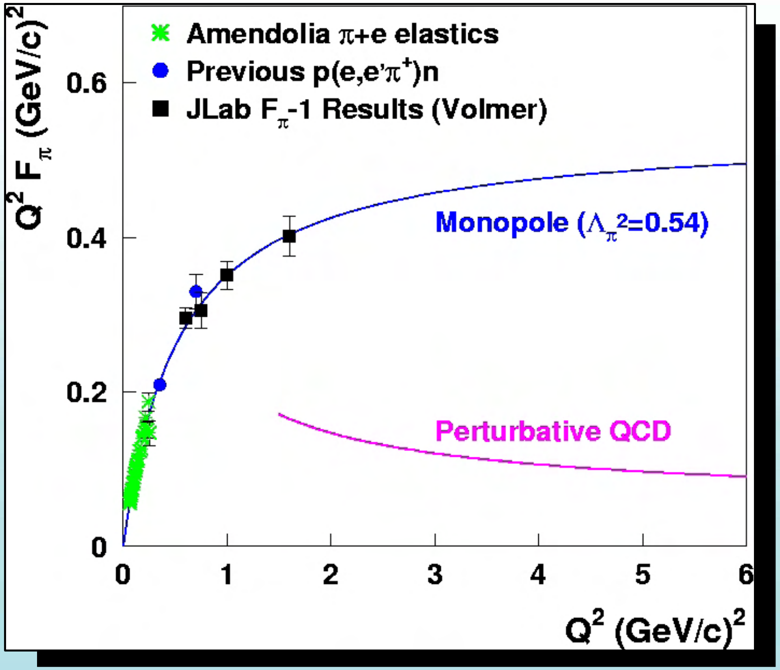
- Studies of short/long distance scales:
  - Theory – QCD framework, GPD's, lattice, models
  - Experiments – form factors, neutral weak nucleon structure

Pion Electromagnetic Form Factor $F_\pi(Q^2)$ and pQCD

- Good observable for studies of hadronic structure
  - Simple valence structure, $q\bar{q}$
  - "Hydrogen atom" of QCD
- High Q^2 scaling predicted by Farrar-Jackson (*PRL* ***43*** *(1979) 246*)

$$F_\pi \to 8\pi \frac{\alpha_s f^2\pi}{Q^2}$$

f^2_π=133 MeV is the $\pi+\to\mu+\nu$ decay constant



- Small Q^2: vector meson dominance gives reasonable description with normalization $F_\pi(0)$=1 by charge conservation

Summary F_π Calculations

- Limits on F_π well defined and many model calculations available for transition region
- Key Point: Know there is asymptotic limit, but how to get there and what governs transition?

Long distance

Low Q^2

?? →

Short distance

High Q^2

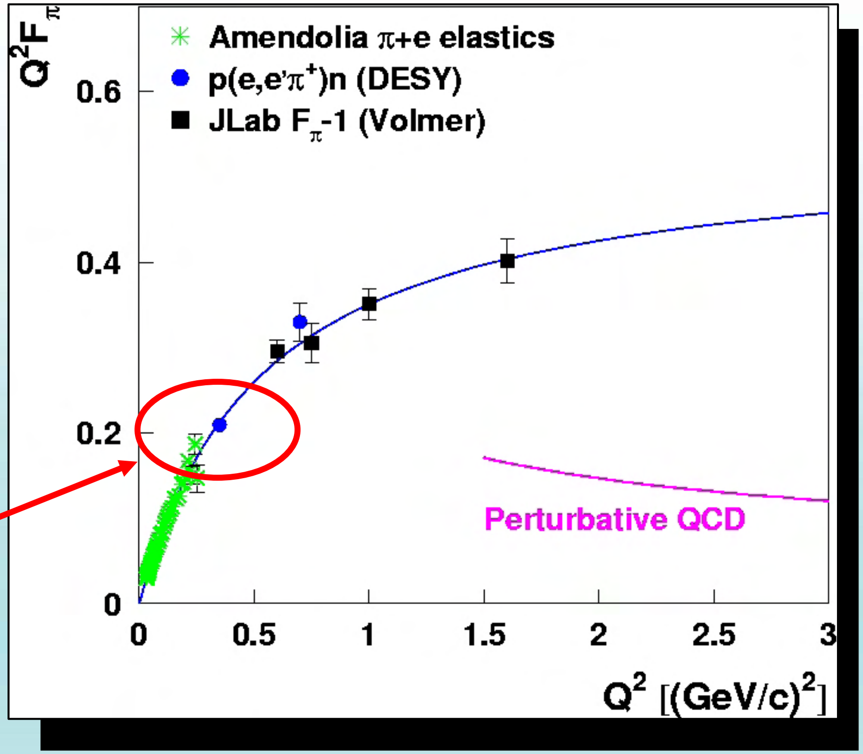
$$F_\pi(0) = 1$$

$$F_\pi \rightarrow \frac{8\pi\alpha f^{2}\pi}{Q^{2}}$$

- **Need experimental data to study behavior of QCD in transition from long distance to short distance scales**

F_π via Pion Electroproduction

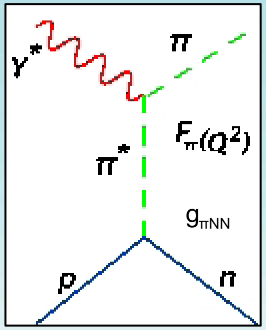
- F_π can be measured directly from π+e scattering (*S.R. Amendolia et al., NP **B277** (1986)*) up to Q^2~0.3 GeV^2
- No "free pion" target – to extend measurement of F_π to larger Q^2 values use "virtual pion cloud" of the proton
- Method check - Extracted results are in good agreement with π+e data



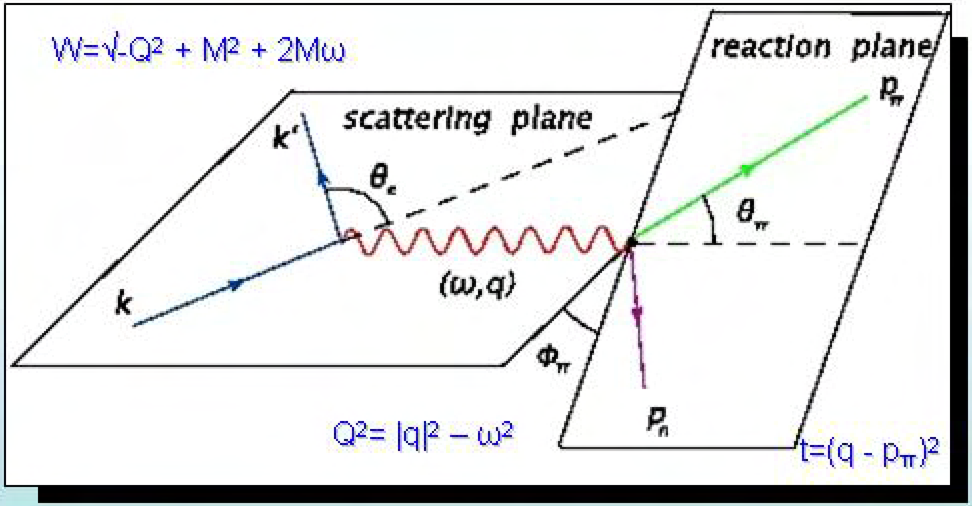
S.R. Amendolia et al., Nucl. Phys. **B277** (1986)

P. Brauel, et al., Z. Phys. **C3** (1979) 101.

J. Volmer et al PRL **86** (2001)



Extracting F_π from Pion Electroproduction Data



- The lab cross section can be expressed in terms of virtual photon flux (Γ_v), Jacobian ($\mathcal{J}$) and virtual photon cross section.

$$\frac{d\sigma}{dE\,d\Omega_e\,d\Omega_\pi} = \Gamma_v\,\mathcal{J}(t,\varphi \rightarrow \Omega_\pi)\,\frac{d^2\sigma}{d\Omega_\pi}$$

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

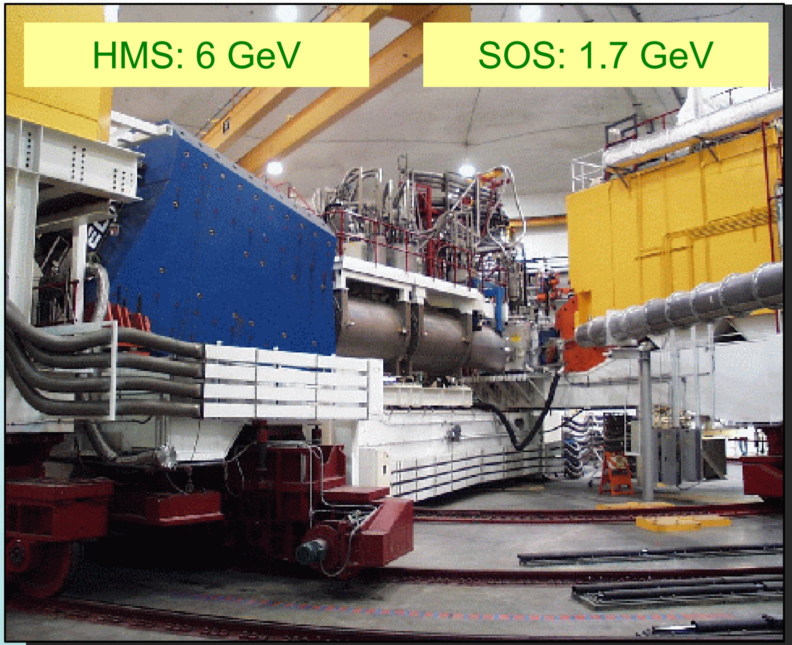
- In t-pole approximation:

$$\sigma_L \propto \frac{-t\,g^2_{\pi NN}(t)}{\left(t-m_\pi^2\right)^2}\,Q^2\,F_\pi^2(Q^2,t)$$

- In the analysis F_π is **extracted** from σ_L data using a model incorporating pion electroproduction (VGL/Regge)

Precision F_π data up to Q^2=2.45 GeV^2 (F_π-2)

- Extension of F_π-1 at highest possible value of Q^2 with 6 GeV beam at JLab
  - New data at higher W
  - Repeat Q^2=1.60 GeV^2 closer to $t=m_\pi$
- Successfully completed in Hall C at JLab 2003
  - Coincidence measurement: HMS detects pions, SOS detects electrons
  - Pion electroproduction from H and ^{2}H
  - Extracted σ_L σ_L, σ_T, σ_{TT}, and σ_{LT} at W=2.22 GeV



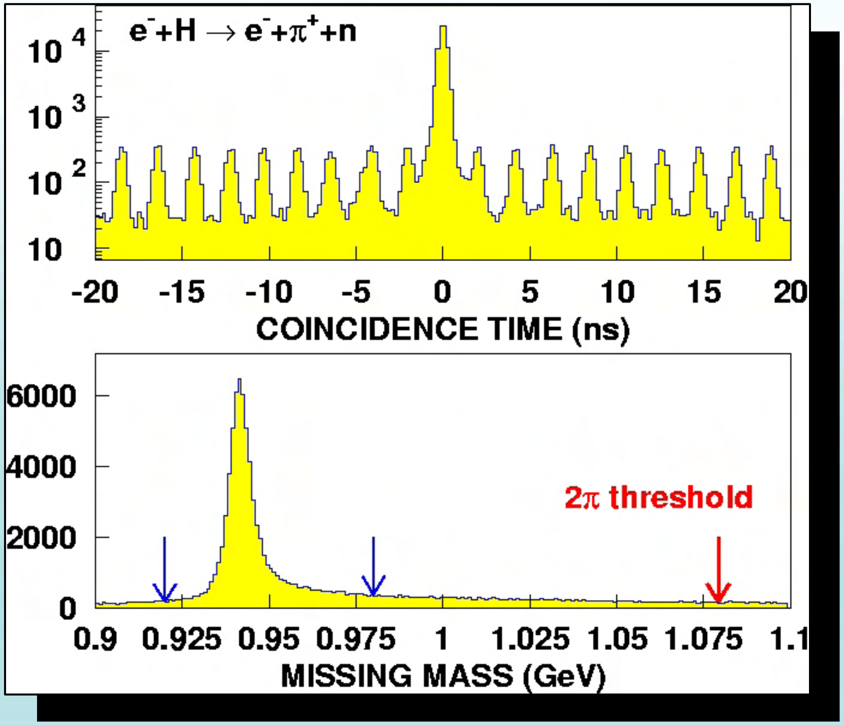
Exp	Q^2 (GeV^2)	W (GeV)	|t| (Gev)^2	E_e (GeV)
F_π-1	0.6-1.6	1.95	0.03-0.150	2.445-4.045
F_π-2	1.6,2.45	2.22	0.093,0.189	3.779-5.246

Good Event Selection

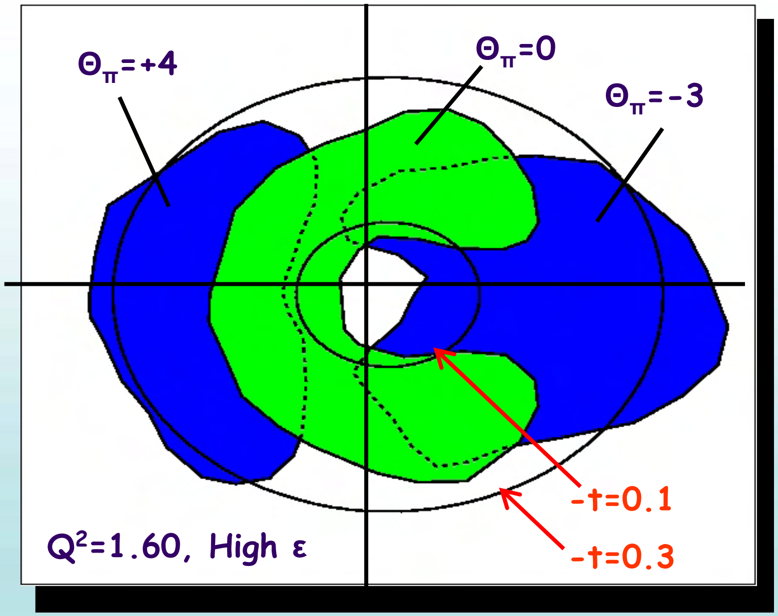
- Coincidence measurement between charged pions in HMS and electrons in SOS
    - Coincidence time resolution ~200-230 ps
    - Cut: ± 1ns

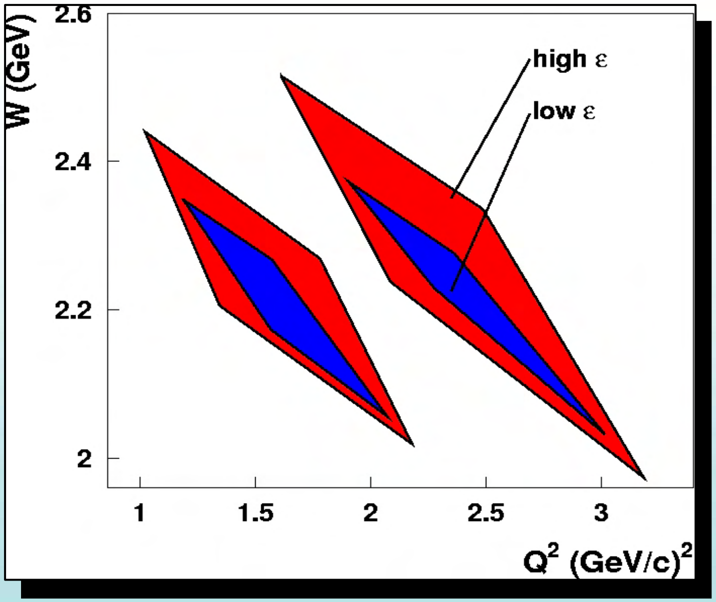
- Protons in HMS rejected using coincidence time and Aerogel Cerenkov
- Electrons in SOS identified by gas Cerenkov /Calorimeter

- Exclusive neutron final state selected with missing mass cut: 0.92 ‹ MM ‹ 0.98 GeV



F_π-2 Kinematic Coverage



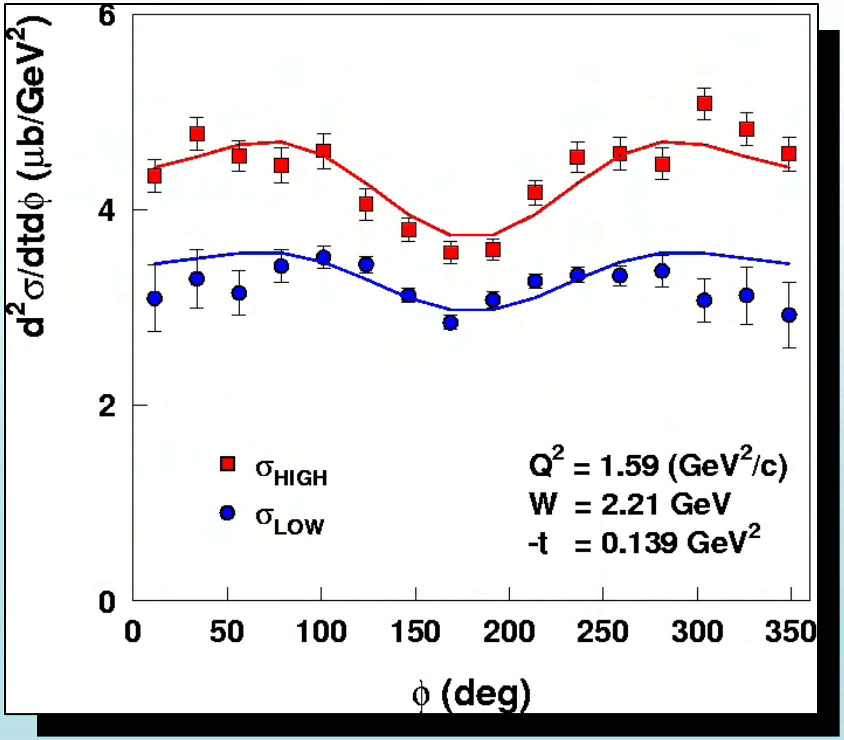


- Have full coverage in ϕ BUT acceptance not uniform
- Measure σ_{TT} and σ_{LT} by taking data at three angles: $\theta_{\pi q}=0^o$, $+4^o$, -3^o
- W/Q^2 phase space covered at low and high ε is different
- For L-T separation use cuts to define common W/Q^2 phase space

F_π-2 Data Analysis

- Compare experimental yields to Monte Carlo of the experiment
  - Model for $H(e,e'\pi^+)$ based on pion electroproduction data
  - Radiative effects, pion decay, energy loss, multiple scattering
  - COSY model for spectrometer optics

$$\sigma_{exp} = \frac{Y_{exp}}{Y_{SIMC}} \sigma_{model}$$

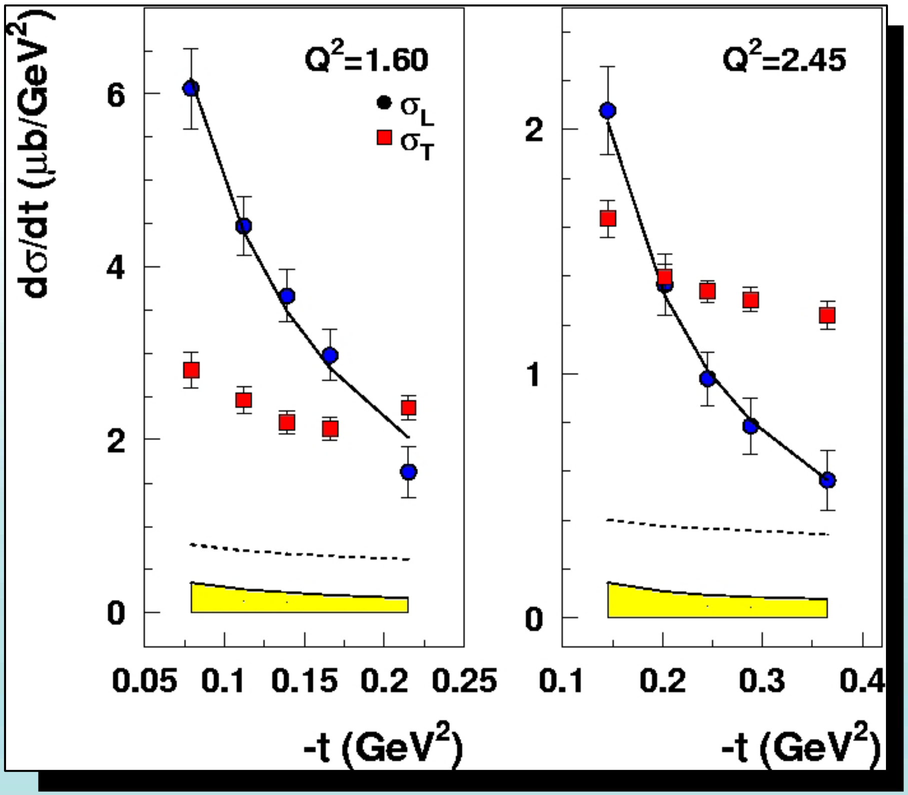


- Extract σ_L by simultaneous fit using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε).

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

Comparison to VGL/Regge Model

- Pion electroproduction in terms of exchange of π and ρ like particles *(**V**anderhaeghen, **G**uidal, **L**aget, PRC **57** (1998) 1454)*
  - Model parameters fixed from pion photoproduction
  - Free parameters: F_π, F_ρ
  - ρ exchange does not significantly influence σ_L at small –t



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

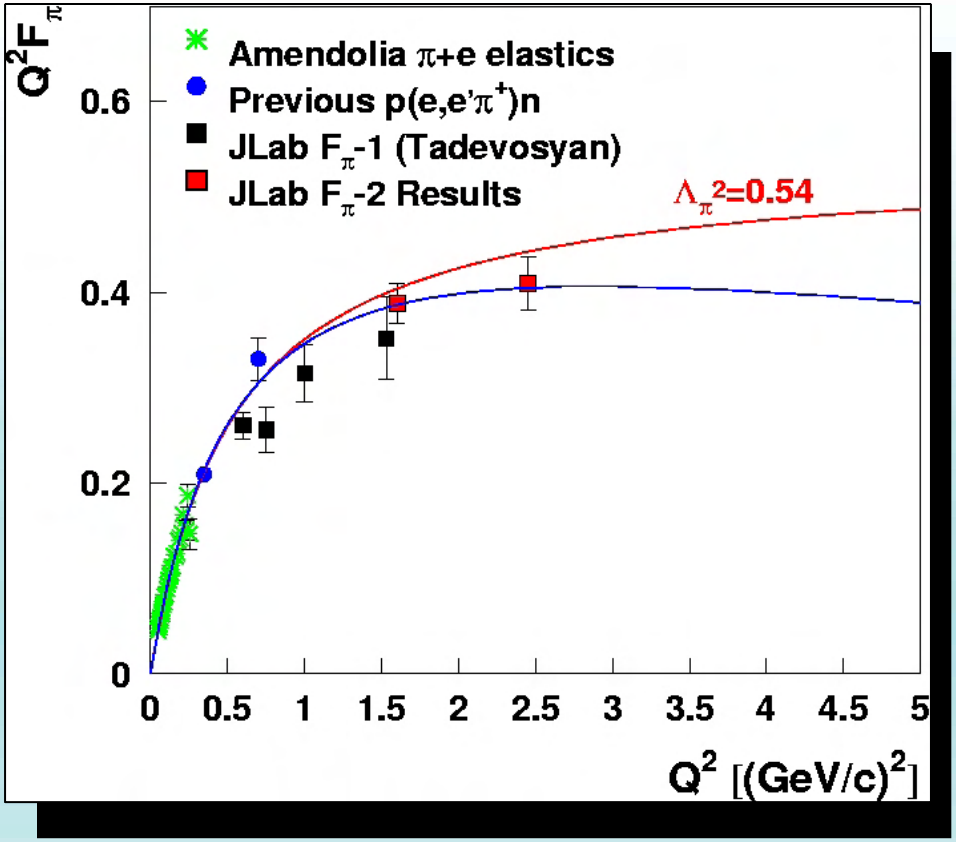
Λ_π^2=0.513, 0.491 GeV², Λ_ρ^2=1.7 GeV²

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

- Points include 1.0(0.6)% point-to-point systematic uncertainty (dominated by acceptance)
- 3.5 % normalization (correlated) uncertainty (radiative corrections, pion absorption, pion decay, kinematic uncertainties)
- 1.8(1.9)% "t-correlated" uncertainties, influence t-dependence at fixed ε

F_π-2 Results

- Data point at Q^2=1.60 GeV^2 to check model dependence of F_π extraction
  - Agreement between F_π-1 (W=1.95 GeV) / F_π-2 (W=2.22 GeV) to ~5%
  - Note: new point is closer to the pion pole by ~40%
- JLab F_π data below monopole form, Λ^2_π=0.54 GeV^2
  - Indicates relative contribution of hard/soft physics at moderate Q^2



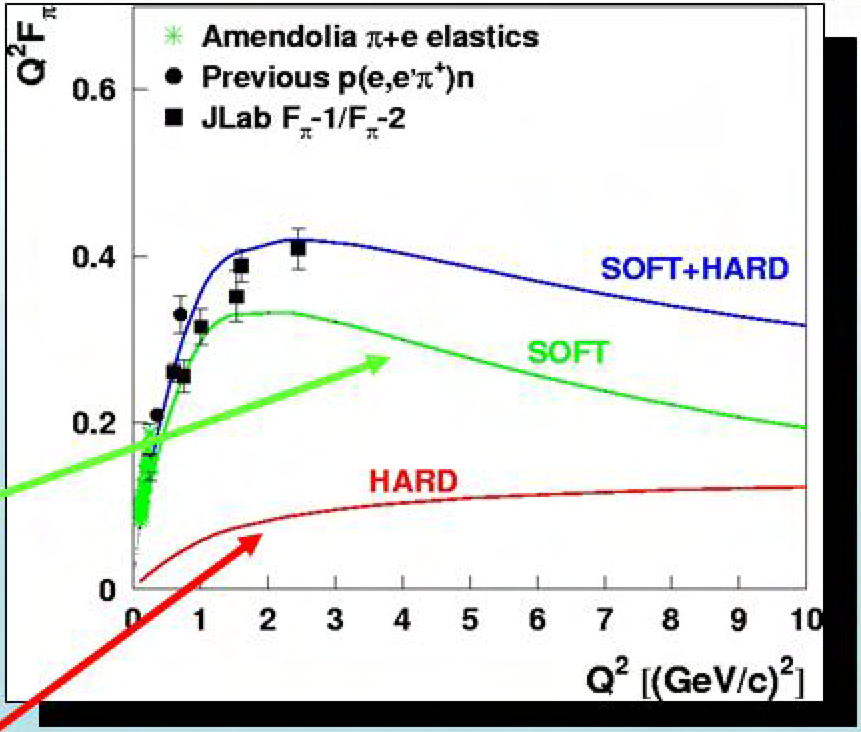
Hard and Soft Contributions

- QCD Sum Rules
  - Interpolate between perturbative and non-perturbative regions using dispersion relations and Operator Product Expansion
- SOFT: QCD SR → Local Quark-Hadron duality relation

$$F_\pi^{soft} = 1 - \frac{1 + 6s_0/Q^2}{(1 + 4s_0/Q^2)^{3/2}}$$

- HARD: Based on interpolation between value at Q2=0 and asymptotic behaviour

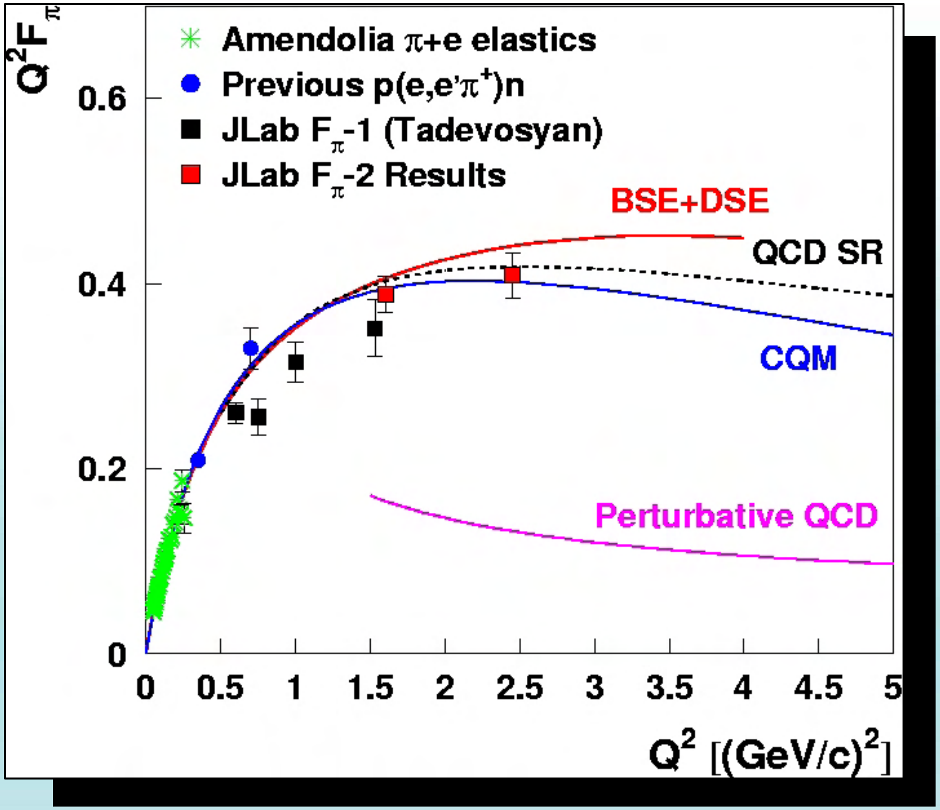
$$F_\pi^{hard} = \frac{\alpha_s}{\pi} \frac{1}{(1 + Q^2/2s_0)}$$



V.A. Nesterenko and A.V. Radyushkin, Phys. Lett. B115 (1982) 410

Compare F_π Models

- Variety of models on the market – how do we know which one is "right"?
- F_π-2 result in a region of Q^2 where calculations start to diverge
  - BUT cannot rule out any calculations yet
- Still far from pQCD prediction



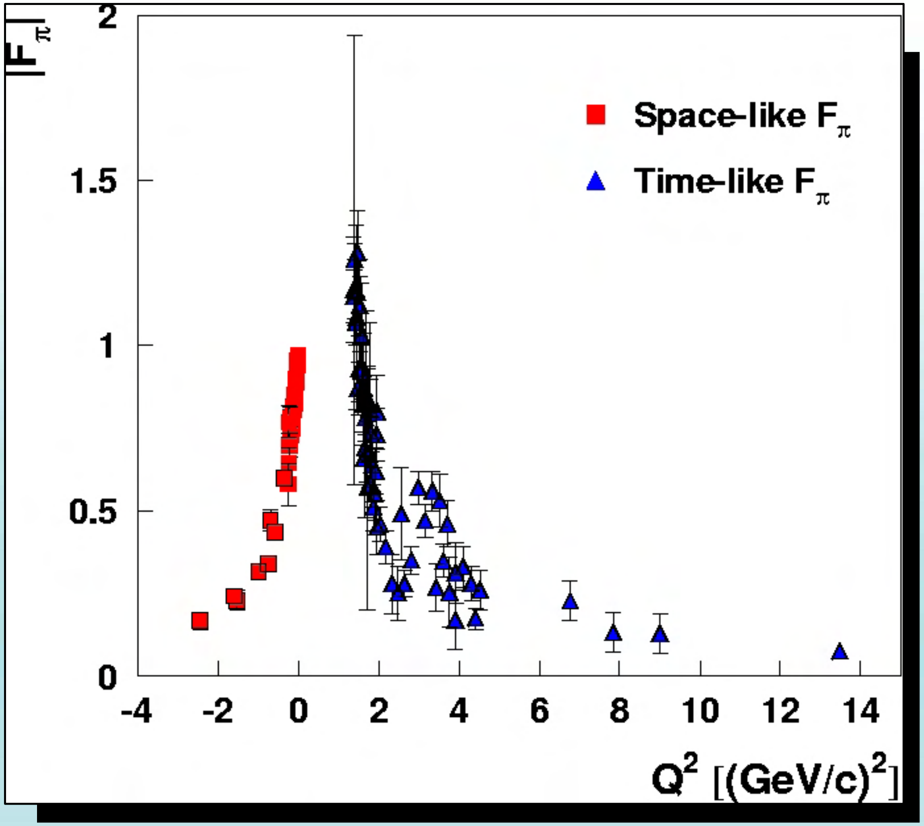
V.A. Nesterenko and A.V. Radyushkin, Phys. Lett. **B115** (1982) 410

P. Maris and P. Tandy Phys Rev **C61** (2000)

C.-W. Hwang, Phys Rev **D64** (2001)

F_π Time-like and Space-like

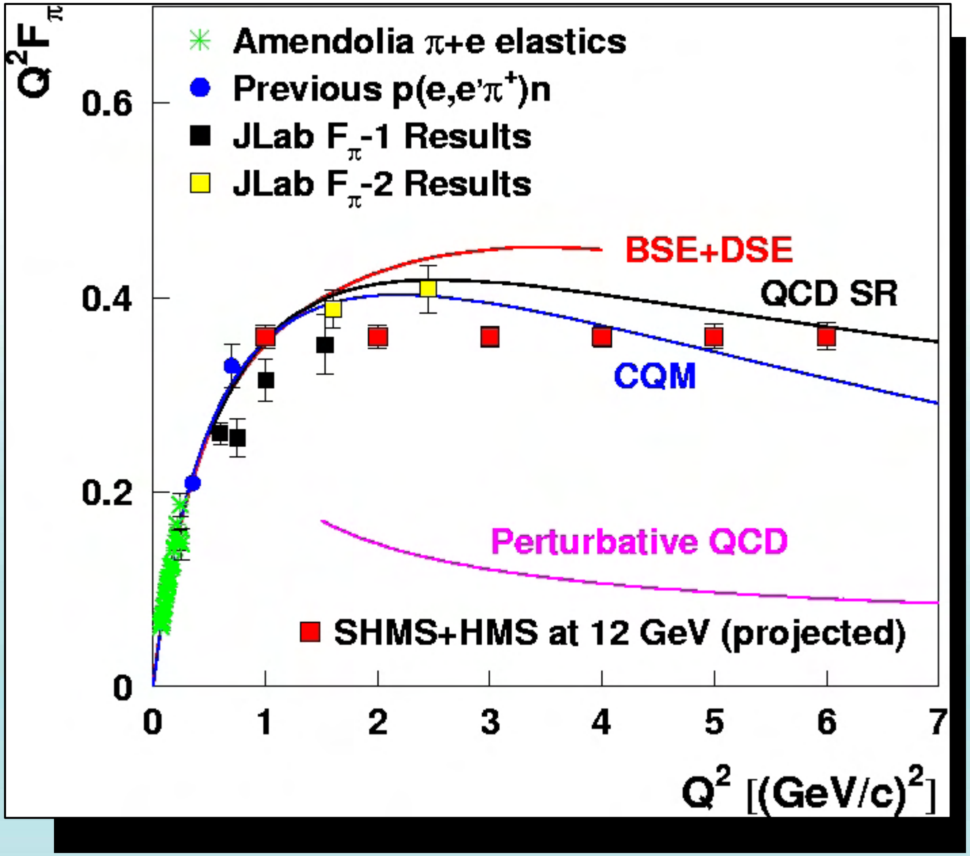
- Expect same asymptotic prediction for both space-like and time-like data
  - The way one gets there may be different
- Calculations in time-like region complicated by explicit resonances



Timelike data from P.K. Zweber Ph.D. thesis (2006)

F_π at 12 GeV

- Significant progress on theoretical front expected in next 5 years – Lattice, GPD etc.
- Experiments need higher energy electron beam to reach the kinematic region where pQCD expectation may be approached
- SHMS+HMS in Hall C will allow F_π to be measured up to Q^2~6 GeV^2 – 12 GeV proposal



- Small forward angle crucial for F_π experiment since need to reach low –t values.

Summary

- F_π good observable to study transition region to perturbative QCD
  - Contribution of soft and hard physics

- F_π-2 results up to $Q^2 = 2.45\ GeV^2$
  - Data will constrain models describing the treatment of non-perturbative physics at higher Q^2
  - Still far from pQCD prediction
  - Good agreement with data point at Q^2=1.60 GeV^2 gives confidence in reliability of extraction method

- Studies of F_π at higher electron beam energy will allow us to reach the kinematic range where pQCD expectation may be approached
  - Measurement at JLab with 11GeV beam up to Q^2~6 GeV^2

JLab F_π-2 Collaboration

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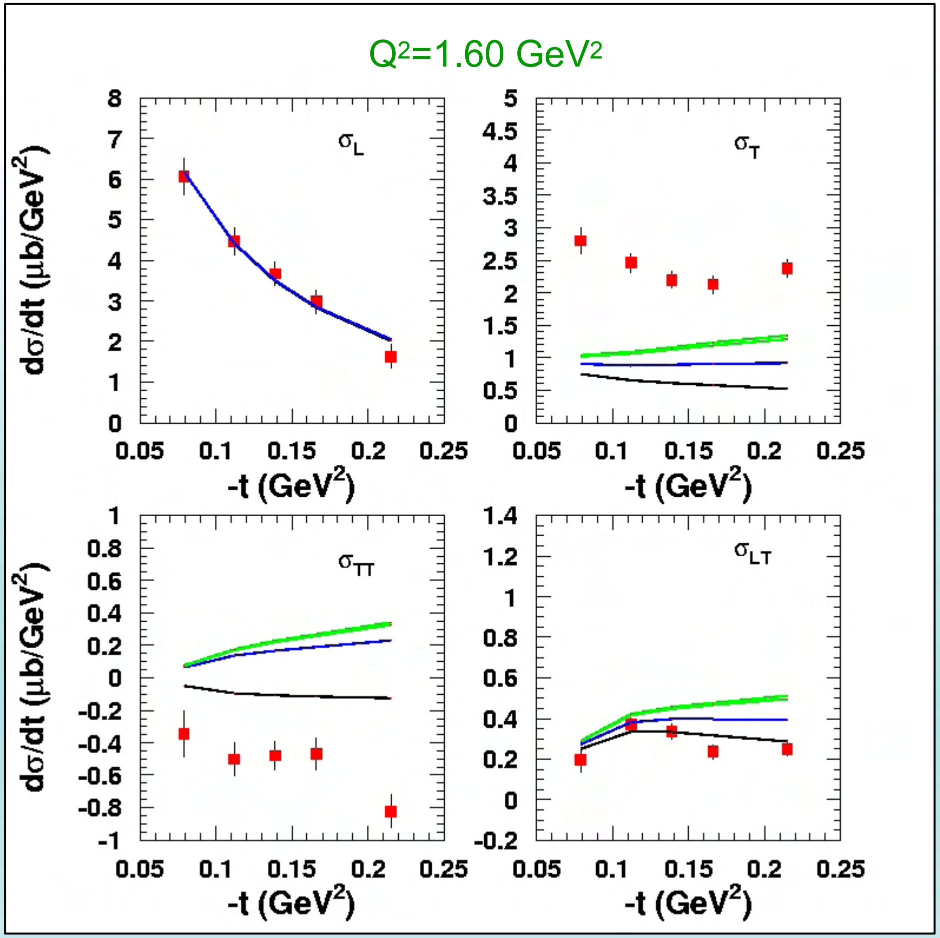
California State University, Sacramento, CA, USA

Comparison to VGL – ρ trajectory

- Influence of ρ cutoff on cross sections – vary Λ_ρ between 1.1 and 5 GeV^2
  - σ_T, σ_{TT} systematically underpredicted
  - Little influence on σ_L

Q2 (GeV/c)^2	|t| (Gev/c)^2	ρ exchange effect
1.60	0.06-0.21	0.5-1.0%
2.45	0.11-0.37	0.5-3.0%



Λ_π^2=0.513, 0.491 GeV^2

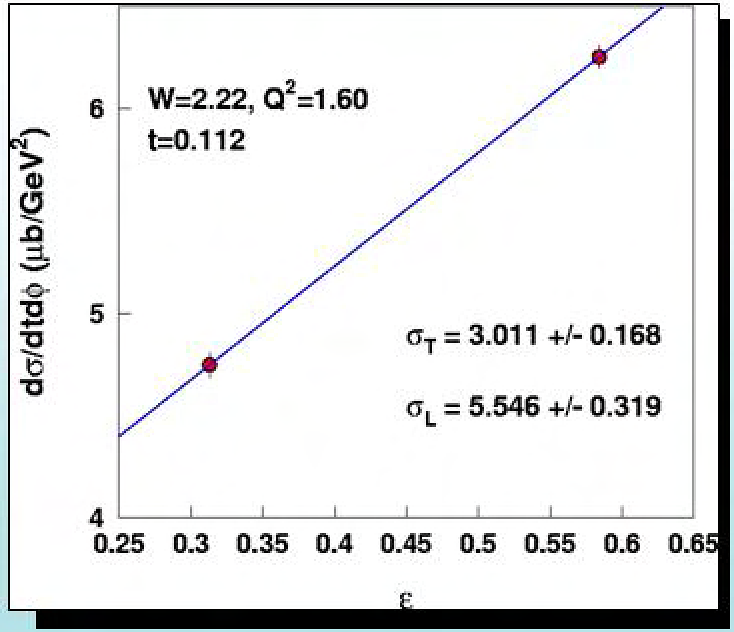
F_π-2 Uncertainties

- Uncertainty in separated cross sections has both statistical and systematic sources
- Statistical uncertainty in ranges between 1 and 2%

Source	Pt-Pt	Scale	t-correlated
Acceptance	1.0(0.6)%	1.0%	0.6%
Radiative Corrections	0.1%	2.0%	0.4%
Pion Absorption	-	2.0%	0.1%
Pion Decay	0.03%	1.0%	-
Model Dependence	0.2%	-	1.1(1.3)%
Kinematics	0.2%	-	1.0%
HMS Tracking	0.1%	1.0%	0.4%
Charge	-	0.5%	0.3%
Target Thickness	-	0.8%	0.2%
Detection Efficiency	-	0.5%	0.3%

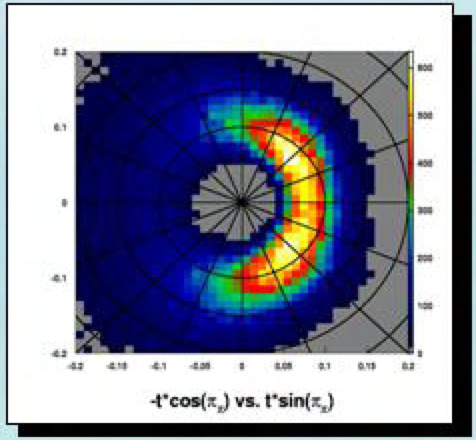
- Point-to-point errors amplified by $1/\Delta\varepsilon$ in L-T separation
- Scale errors propagate directly into separated cross section
- Uncertainties in spectrometer quantities parameterized using over-constrained $^1H(e,e'p)$ reaction
  - Beam energy and momenta to <0.1%
  - Spectrometer angles to ~0.5mrad
- Spectrometer acceptance verified by comparing e-p elastic scattering data to global parameterization
  - Agreement better than 2%

"Simple" Longitudinal-Transverse Separation



- For uniform φ-acceptance, σ_{TT}, $\sigma_{LT} \rightarrow 0$ when integrated over φ
- Determine $\sigma_T + \varepsilon\, \sigma_L$ for high and low ε in each t-bin for each Q^2
- Isolate σ_L, by varying photon polarization, ε

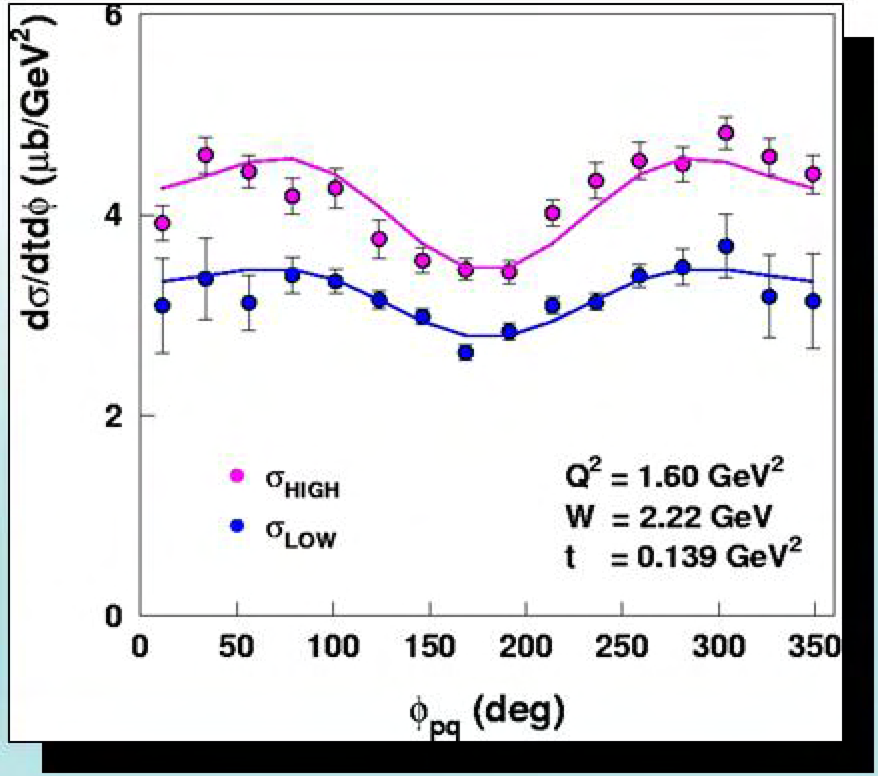
$$\varepsilon = \left(1 + 2\left(1 + \frac{\omega^2}{Q^2}\right)\tan^2\left(\frac{\theta_e}{2}\right)\right)^{-1}$$



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

"Real" Cross Section Separation

- Cross Section Extraction
  - φ acceptance not uniform
  - In reality, must measure σ_{LT} and σ_{TT}
- Extract σ_L by simultaneous fit using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε)



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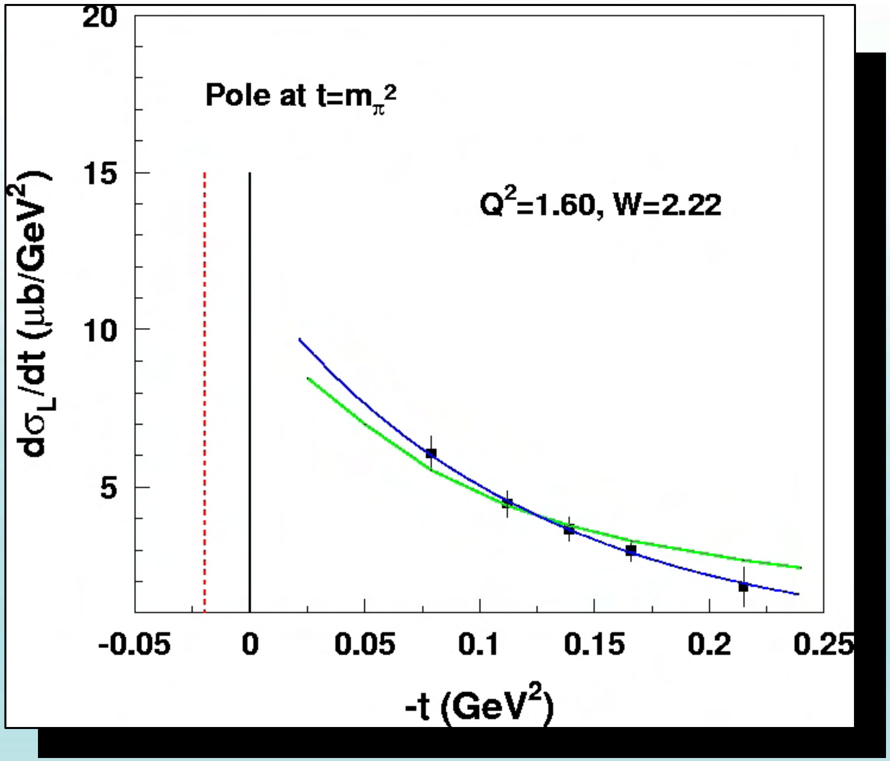
Extracting F_π from σ_L Data



- In t-pole approximation:

$$\sigma_L \propto \frac{-t\, g^2_{\pi NN}(t)}{\left(t-m_\pi^2\right)^2} Q^2 F_\pi^2(Q^2,t)$$

- Want smallest possible –t to maximize contribution from π-pole to σ_L
- Need to know t-dependence of σ_L to extract F_π

→ • In the analysis F_π is extracted using a model incorporating pion electroproduction (VGL/Regge)

VGL Regge Model

- Pion electroproduction in terms of exchange of π and ρ like particles *(PRC **57** (1998) 1454)*
  - Model parameters fixed from pion photoproduction
  - Free parameters: F_π
  - ρ exchange does not significantly influence σ_L at small –t

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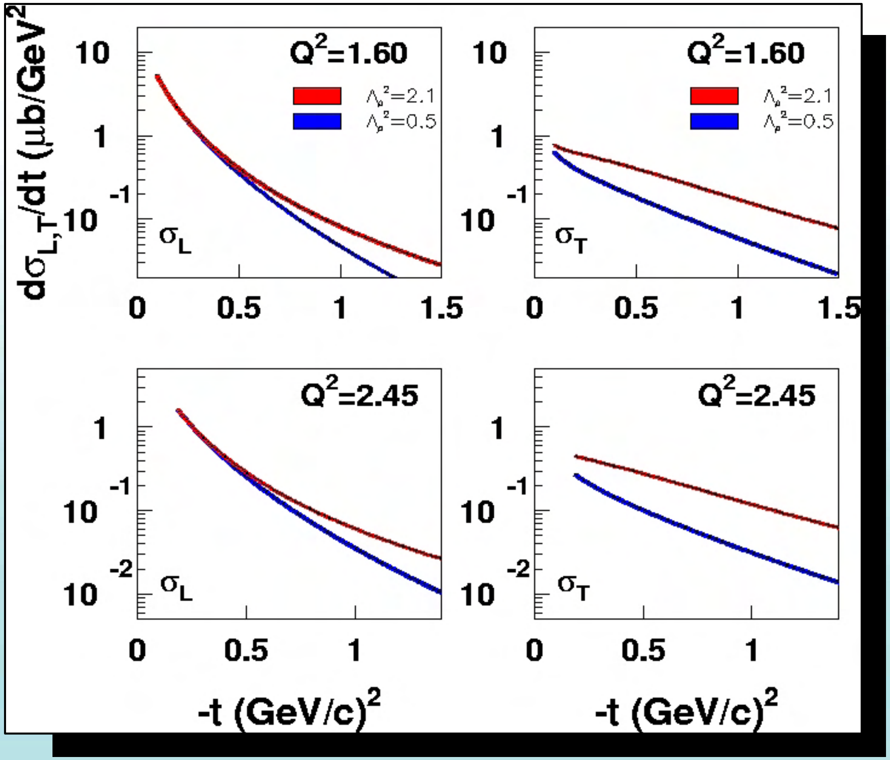
Fit to σ_L to model gives F_π at each Q^2



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1.60	0.06-0.21	0.5-1.0%
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Precision F_π Data From JLab (F_π-1)

- Ran in Hall C at JLab in 1998, thesis students: J. Volmer and K. Vansyoc
  - Measured pion electroproduction from H and ^{2}H
  - Extracted σ_L σ_L, σ_T, σ_{TT}, and σ_{LT} at W=1.95 GeV, Q^2 = 0.6, 0.75, 1.0, 1.6 GeV^2

- F_π was determined by comparing σ_L to a Regge calculation by Vanderhaeghen, Guidal, Laget (VGL, PRC **57**(1998)1454)
  - Model parameters fixed from pion photo-production, free parameters: F_π and F_ρ.

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

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