The Pion Form Factor

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for the F_π-2 Collaboration

- Pion Form Factor in pQCD
- The transition to the asymptotic regime
  - -> Pion Electroproduction
  - -> Cross Section Extraction
- Results and new directions

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Hadronic Form Factors in QCD

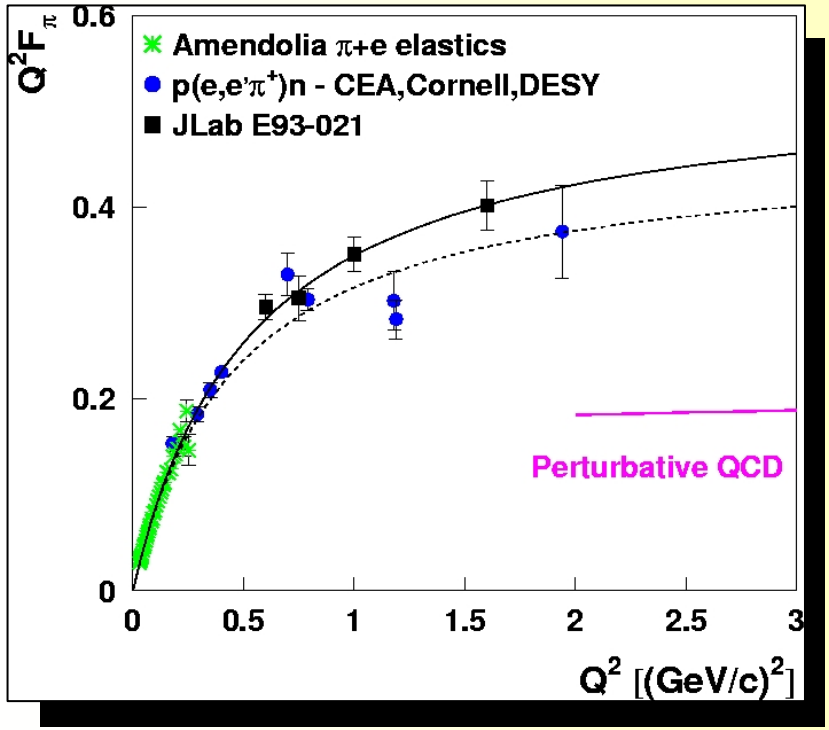
- Fundamental issue: Quantitative description of hadrons in terms of underlying constituents.
  - Theory: QCD describes strong interactions
  - Degrees of freedom: quarks and gluons

- However, consistent analysis of different length scales in a single process not easy.

- Studies of short/long distance scales
  - Theory – QCD framework, GPD's and effective models
  - Lattice calculations – still in progress
  - Experiments – form factors, neutral weak nucleon structure, charge structure of 2-quark systems

Pion Form Factor in QCD

- Why pions? - Simplest QCD system ($q\bar{q}$) - "Hydrogen Atom of QCD"
- Good observable for study of interplay between hard and soft physics in QCD

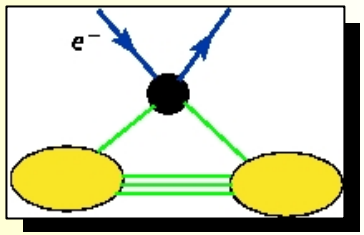


- Large Q^2 behavior predicted by Brodsky-Farrar

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

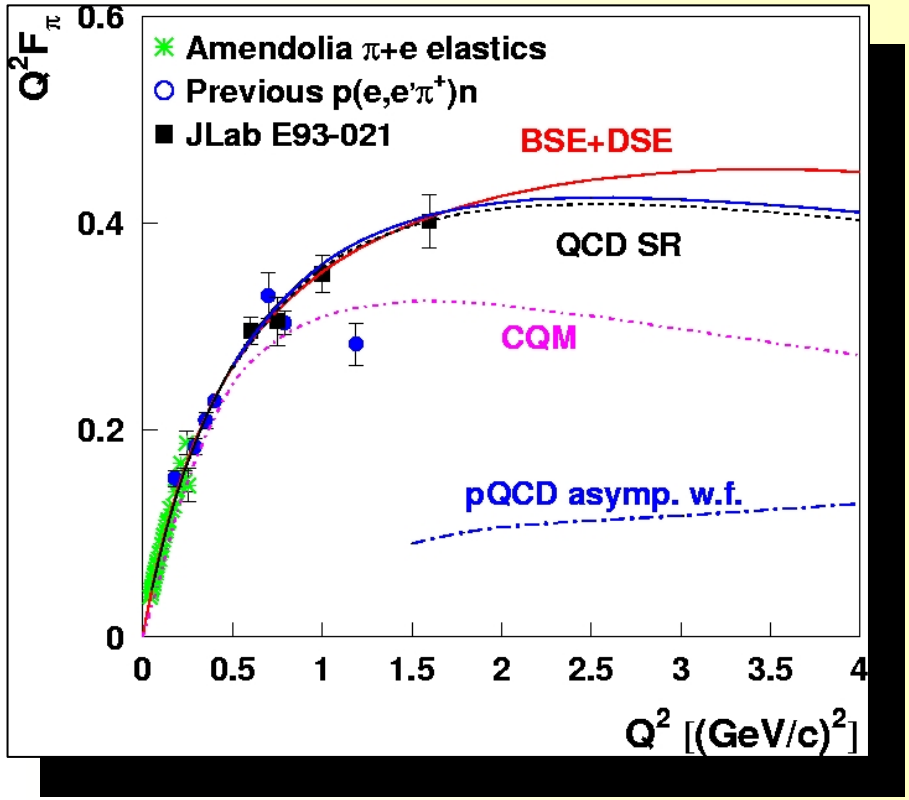
- At small Q^2 vector meson dominance gives accurate description with normalization $F_\pi(0)=1$ by charge conservation – data fits well so where is pQCD?

Nonperturbative Physics



Feynman Mechanism

- At moderate Q^2 nonperturbative corrections to pQCD can be large – Braun et al calculate ~30% at Q^2=1 GeV^2 to F_π
- Need a description for transition to asymptotic behavior
- Variety of effective models on the market – how do we know which one is "right"? – experimental studies to constrain models

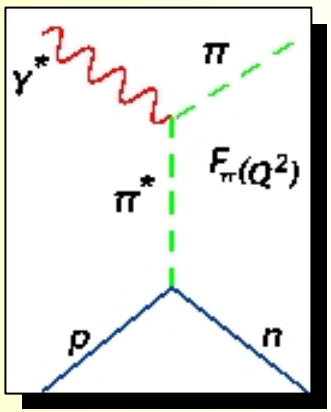


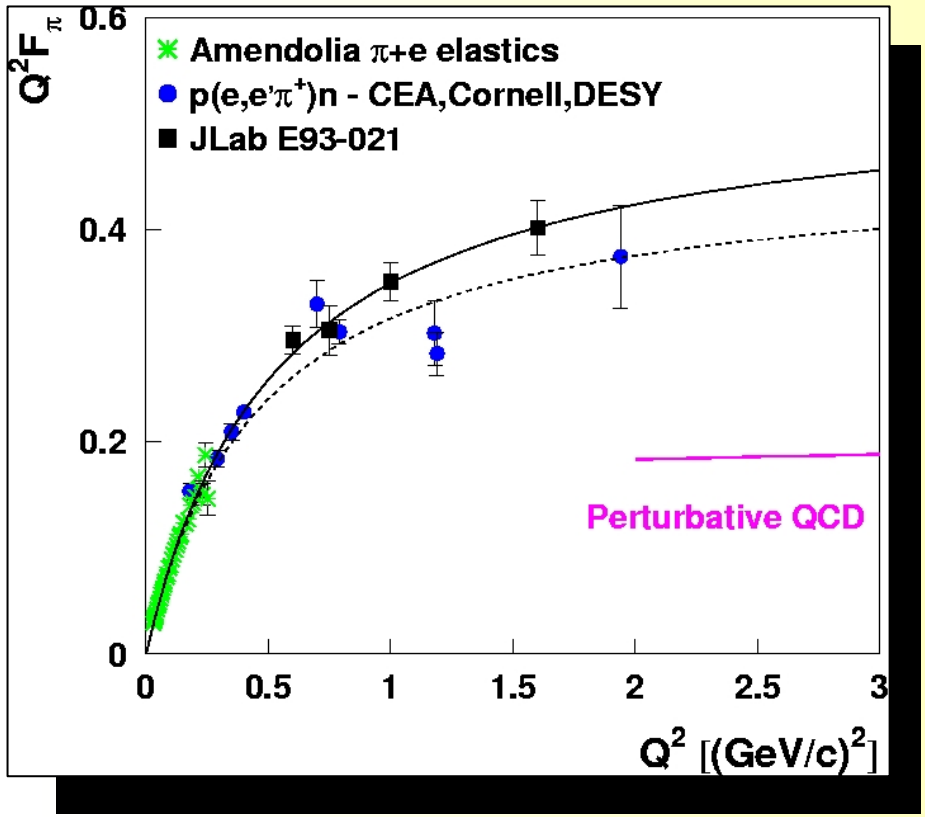
Effective models and pQCD prediction of F_π

Pion Form Factor via Electroproduction

- Charge radius well known from π+e scattering
- No "free pion" target – to extend measurement of F_π to larger Q^2 values use "virtual pion cloud" of the proton

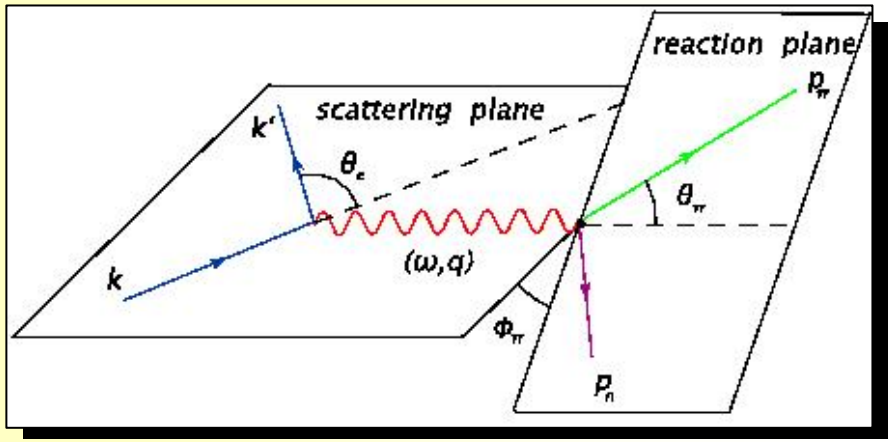
- Method check - Extracted results are in good agreement with π+e data





J. Volmer et al. Phys Rev. Lett. 86 (2001) 1713-1716

Extraction of the Pion Form Factor



- Extraction of F_π requires a model incorporating pion electroproduction

- In t-pole approximation:

$$\sigma_L \propto \frac{-t\, g^2_{\pi NN}}{(t-m^2_\pi)^2} F^2_\pi(Q^2)$$

  - Want smallest possible –t for proximity to π-pole
  - Need to know t-dependence

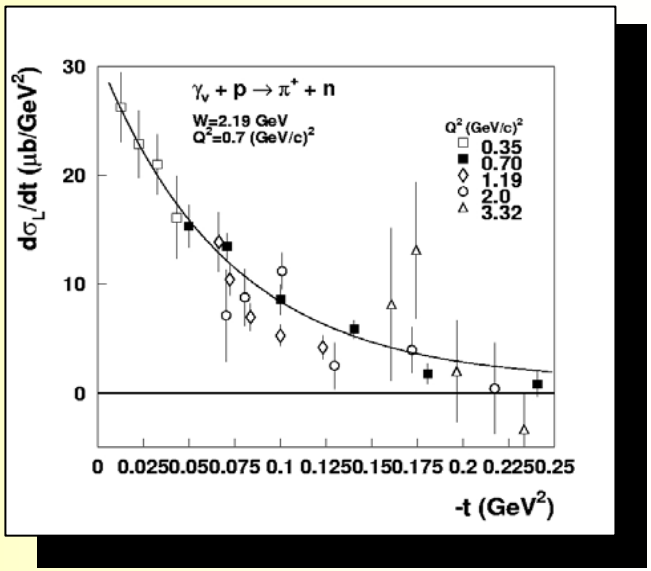
- Pole dominance tested using π+/π- from D(e,e'π) – if pure pole then $\frac{\sigma_L^{\pi+}}{\sigma_L^{\pi-}} = 1$

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

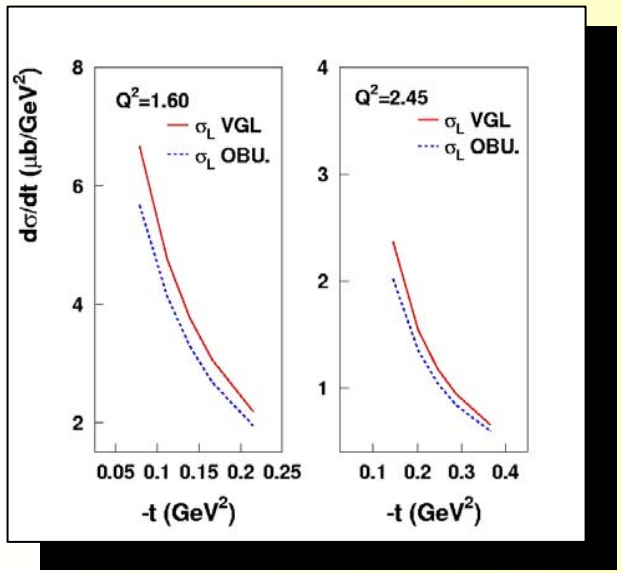
Extracting F_π from σ_L data

- DESY (Brauel et al) used Born term model for t-dependence of the data
- F_π-1/F_π-2 at JLab use VGL/Regge model – Fπ is the only free parameter adjusted at each Q^2 to reproduce σ_L data
- New cross section calculation by I. Obukhovsky et al –includes baryon s-poles by nonlocal extension of contact term, include quark form factor with Λ_q=0.95

P. Brauel, ZP C3, 101 (1978)

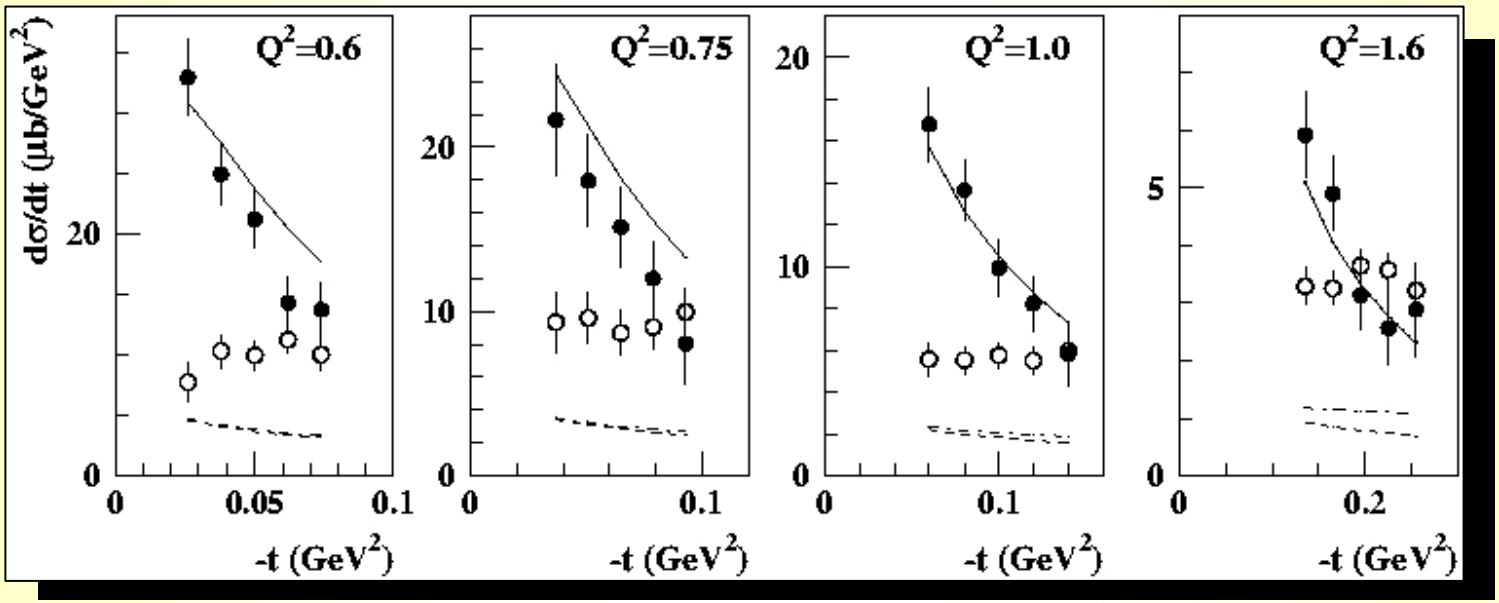


I. Obukhovsky et al hep-ph/0506319
M. Vanderhaeghen, M Guidal, J-M Laget Phys Rev C57 (1998)



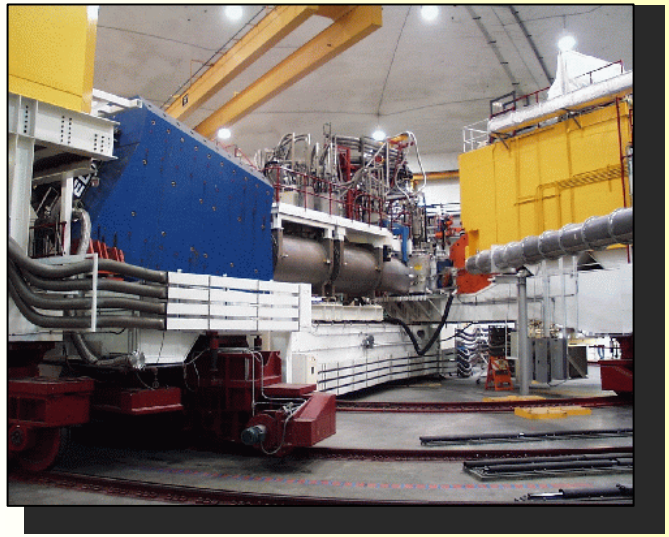
F_π-1 (E93-021)

- Data taken in 1998, thesis students: J. Volmer and K. Vansyoc
- Q^2=0.6-1.6 GeV^2 at W=1.95 GeV
- Transverse cross section smaller and slightly steeper t-dependence in σ_L than in Regge model – attributed to resonance background contribution



F_π-2 (E01-004)

- Successfully completed in Hall C in 2003
- Extension of E93-021 (F_π-1)
  - Completed in 1997 – J. Volmer et al PRL 86 (2001)

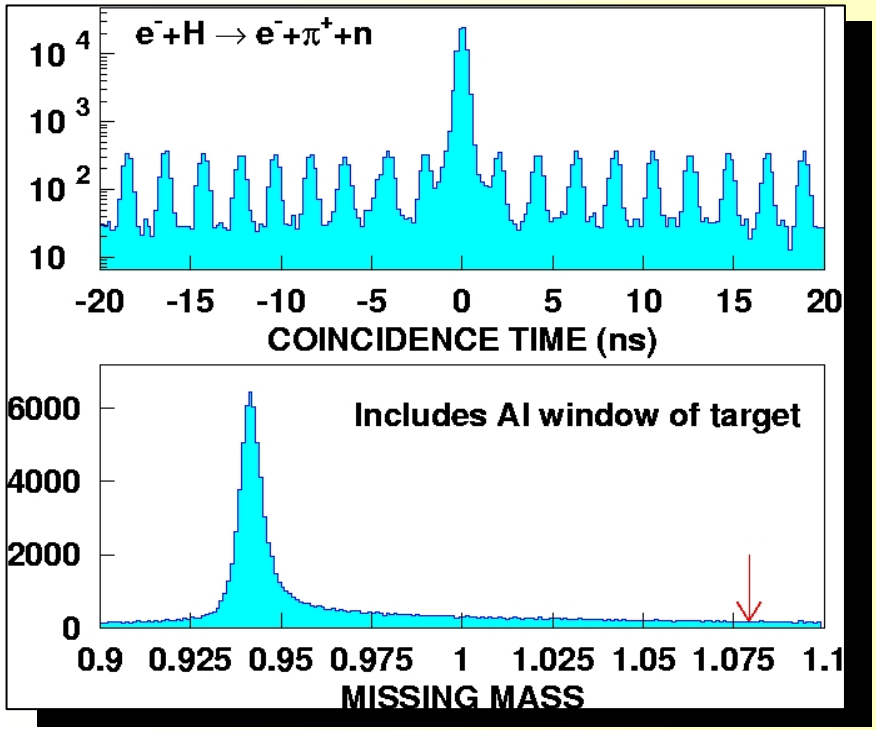


- New data at higher W
- Constraint on soft models for F_π at higher Q^2
- Repeat Q^2=1.60 GeV^2 closer to $t=m_\pi$ pole allows study of model dependence in extraction of F_π

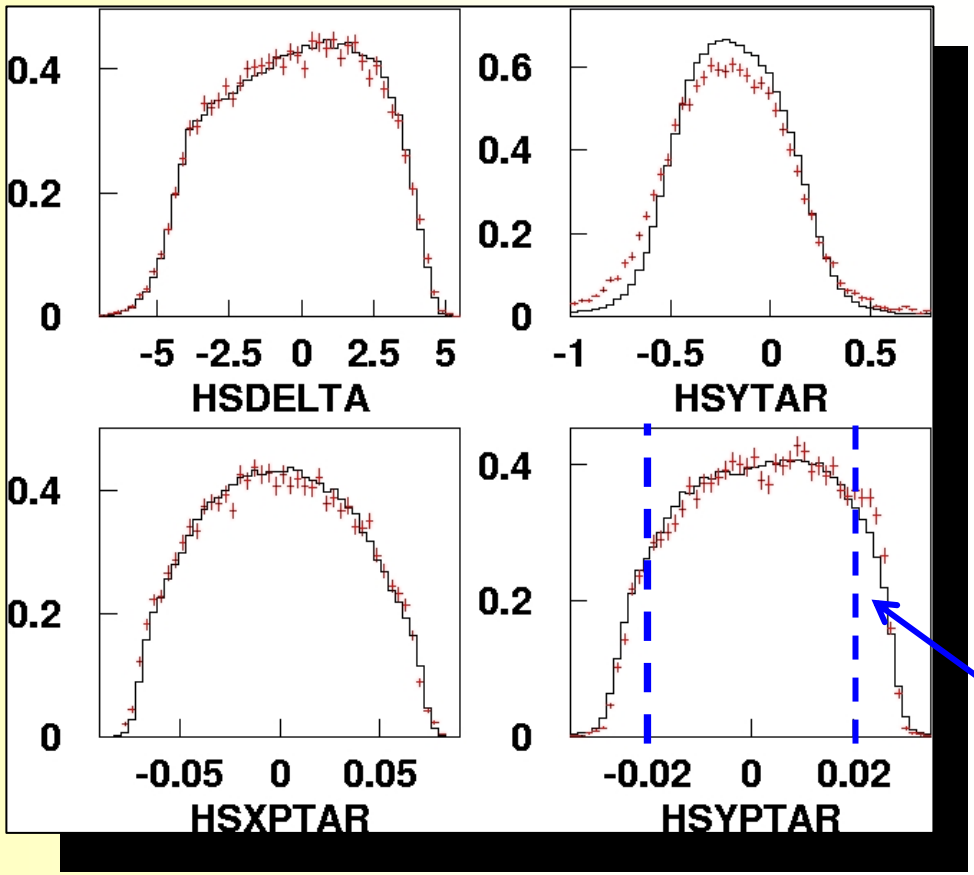
Exp	Q2 $(GeV/c)^2$	W (GeV)	|t| $(Gev/c)^2$	E_e (GeV)
Fπ-1	0.6-1.6	1.95	0.03-0.150	2.445-4.045
Fπ-2	1.6,2.5	2.22	0.093,0.189	3.779-5.246

Good Event Selection

- Coincidence measurement between charged pions in HMS and electrons in SIS
- π^+ detected in HMS – Aerogel Cerenkov and Coincidence time for PID
  - π^- selected in HMS using Gas Cerenkov
- Electrons in SOS – identified by Cerenkov /Calorimeter
- After PID cuts almost no random coincidences



Acceptance Studies

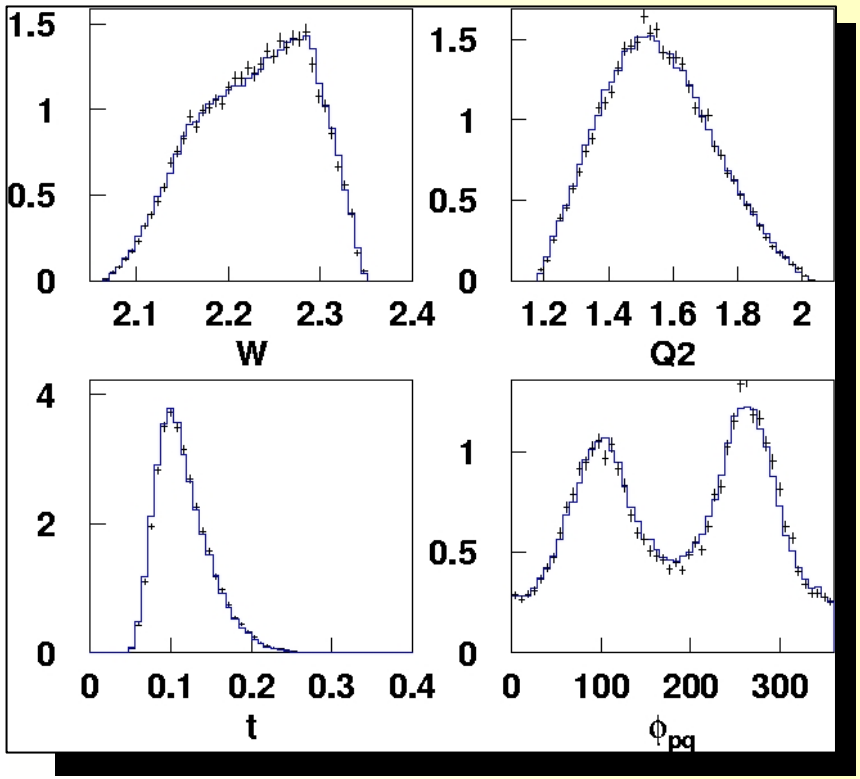


- t-bin closest to $t=m_{\pi}$ very sensitive to offsets
- Found that cross section significantly sensitive to Y'_{tar} acceptance
- Acceptance edges currently under study – in cross section extraction limit to well understood region

Acceptance Cut

Cross Section Extraction

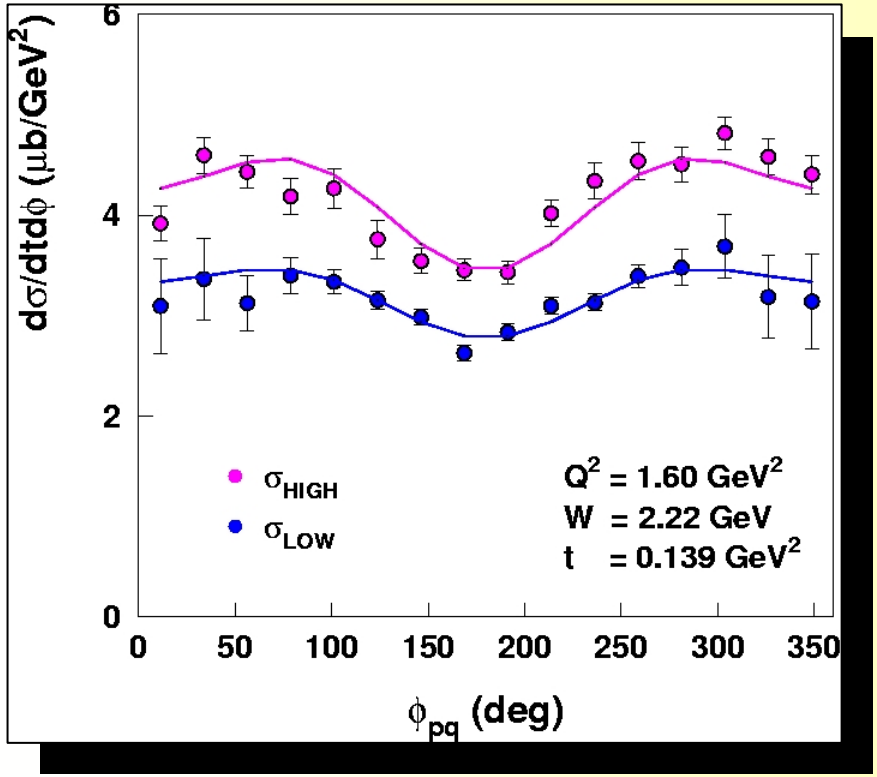
- Cross Section Extraction requires Monte Carlo Model of spectrometer optics and acceptance
- Compare Data to Hall C Monte Carlo - SIMC
  - COSY model for spectrometer optics
  - Model for H(e,e'π^+)
  - Radiative Corrections, pion decay
- Experimental cross section extracted by iterating model until achieve agreement with data



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

Cross Sections Unseparated

- Cross Section Extraction
  - Data binned in t and φ
  - Average W, Q^2 for each bin at both high and low epsilon
- Extract σ_L by simultaneous fit using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε)

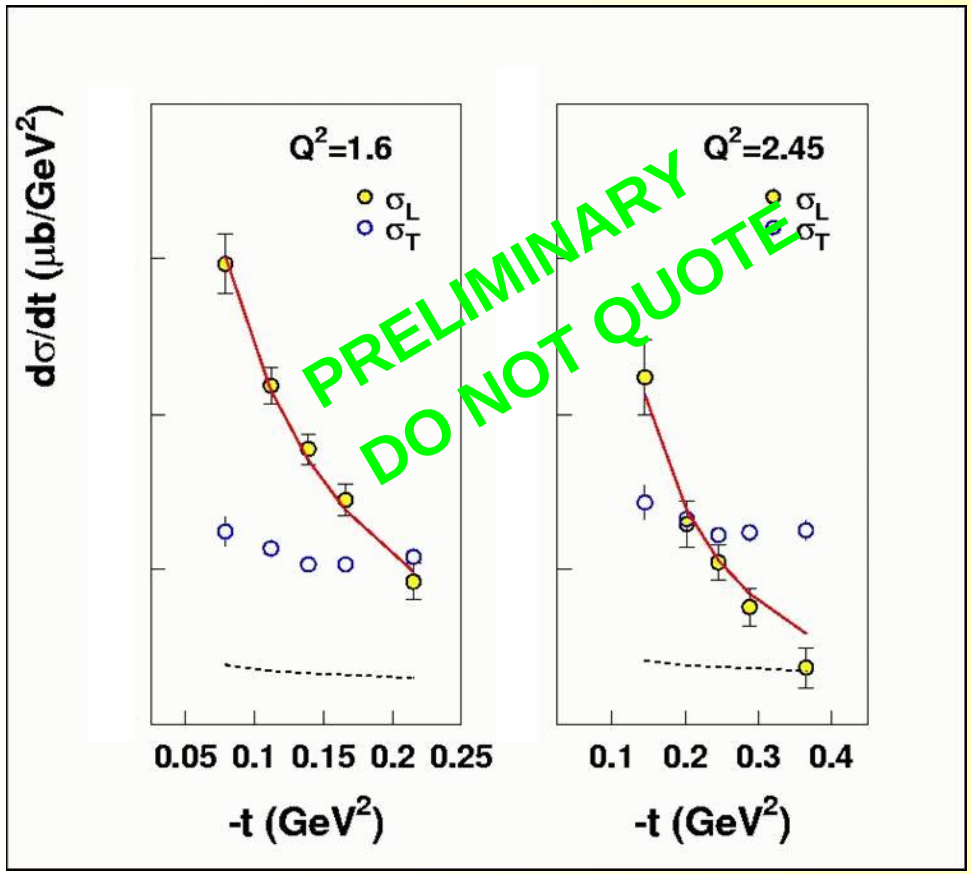


$$\frac{d^2\sigma}{dtd\varphi} = \varepsilon \frac{d\sigma_L}{dtd\varphi} + \frac{d\sigma_T}{dtd\varphi} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dtd\varphi} \cos\varphi_\pi + \varepsilon \frac{d\sigma_{TT}}{dtd\varphi} \cos 2\varphi_\pi$$

Preliminary Results

- F_π-2 Separated cross sections
  - Y'_{tar} acceptance cut applied
  - Compare to VGL/Regge model with Λ_π^2=X.XXX Λ_ρ^2=1.7

Point-to-point Systematic	Error
Acceptance	3-4.5%
Radiative Corrections	1%
Kinematics	1%
Target Density	0.5%
Charge	0.5%
Model Dependence	0.5%
Cut Dependence	0.5%
Detection Efficiency	0.5%



- Statistical Error only

Preliminary F_π Results

- Increase in dynamic coverage in Q^2
- Datapoint at Q^2=1.60 GeV/c to check model dependence of mass pole extrapolation

- To Do:
  - (more) Acceptance Studies
  - Radiative Correction Tests
  - Model Dependence – model iteration
  - Kinematic uncertainties
  - Theory uncertainties
  - Pole dominance: π^+/π^- ratios

PRELIMINARY
DO NOT QUOTE

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 Fπ 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.

PRELIMINARY

DO NOT QUOTE

Summary

- F_π good observable to study transition region to pQCD
- Results from F_π-1 shows Q^2F_π clearly not asymptotic yet
  - $\pi-/\pi+$ suggests dominance of pion exchange
- F_π-2 results in a region of Q^2 where F_π calculations begin to diverge
  - Data will constrain models describing the treatment of soft physics at higher Q^2
- Studies of F_π at 12 GeV will allow us to reach the kinematic range where pQCD expectation may be approached