The Pion Form Factor

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- Calculation of the Pion Form Factor
  -> The road to a hard place
- F_π measurement via pion electroproduction
  -> Extracting F_π from $H(e,e'\pi^+)$ data
  -> F_π-2 in Hall C
- Preliminary Cross Sections

Hall C Workshop, 5 Jan 2006

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

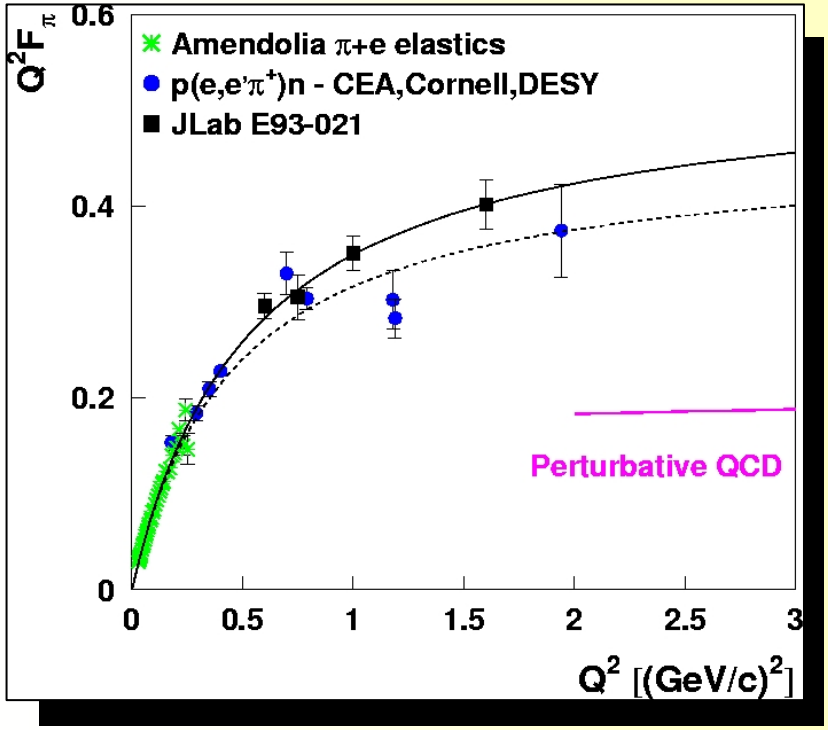
- But, consistent analysis of different length scales in a single process not easy

Short Distance Asymptotic Freedom	⟷	Long Distance Binding, collective dof

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

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

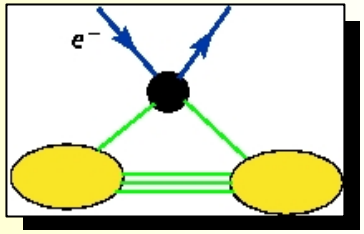


- Large Q^2 behavior predicted by Brodsky-Farrar

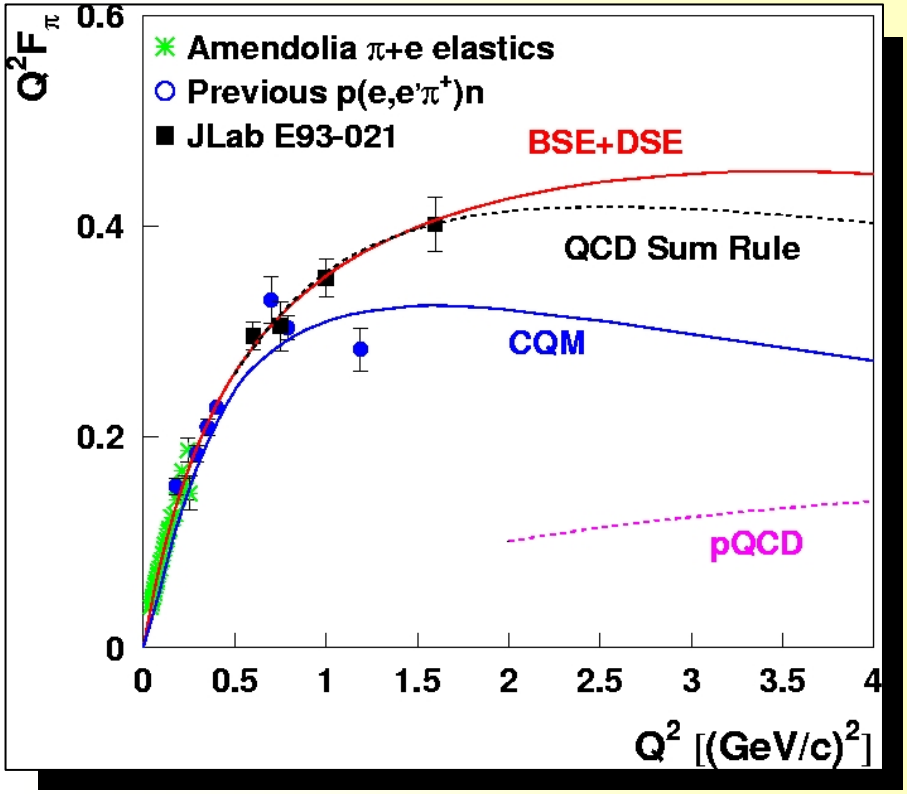
$$F_\pi \rightarrow \frac{8\pi f^2\pi}{Q^2}$$

- 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 F_π models on the market – how do we know which one is "right"?

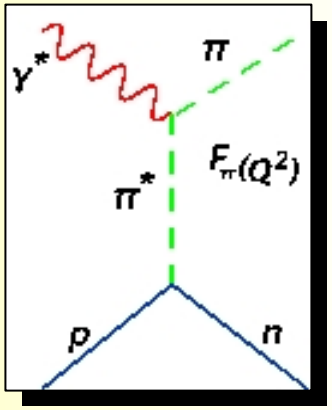
V.A. Nesterenko and A.V. Radyushkin, Phys. Lett. B115 (1982) 410

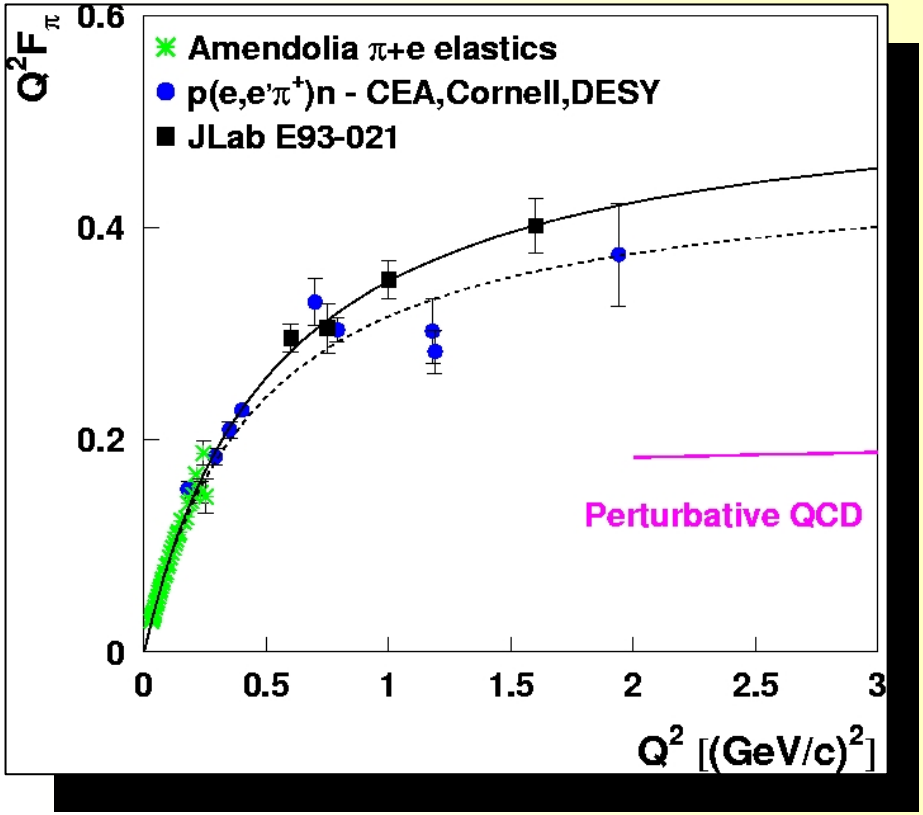
P. Maris and P. Tandy Phys Rev C61 (2000)

F. Cardarelli et al. Phys. Lett. B357 (1995) 267.

Pion Form Factor via Electroproduction

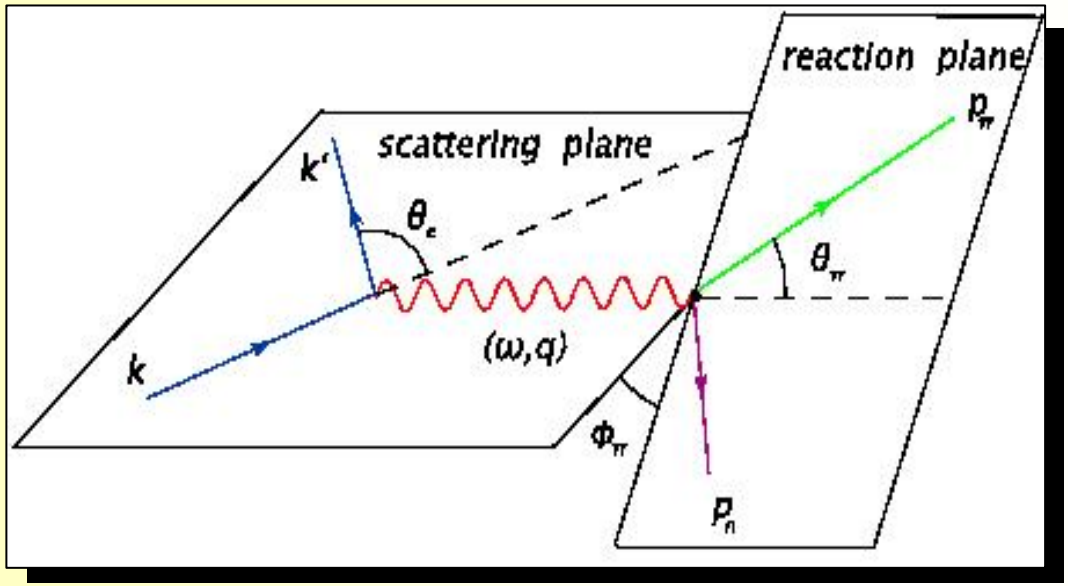
- Charge radius well known from π+e scattering
- No "free pion" target – to extend measurement of F_π to larger Q^2 values use "virtual pion cloud" of the proton
- Method check - Extracted results are in good agreement with π+e data





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

Pion Electroproduction Kinematics



- Hadronic information determined by Lorentz invariants

$$Q^2 = |\vec{q}|^2 - \omega^2$$

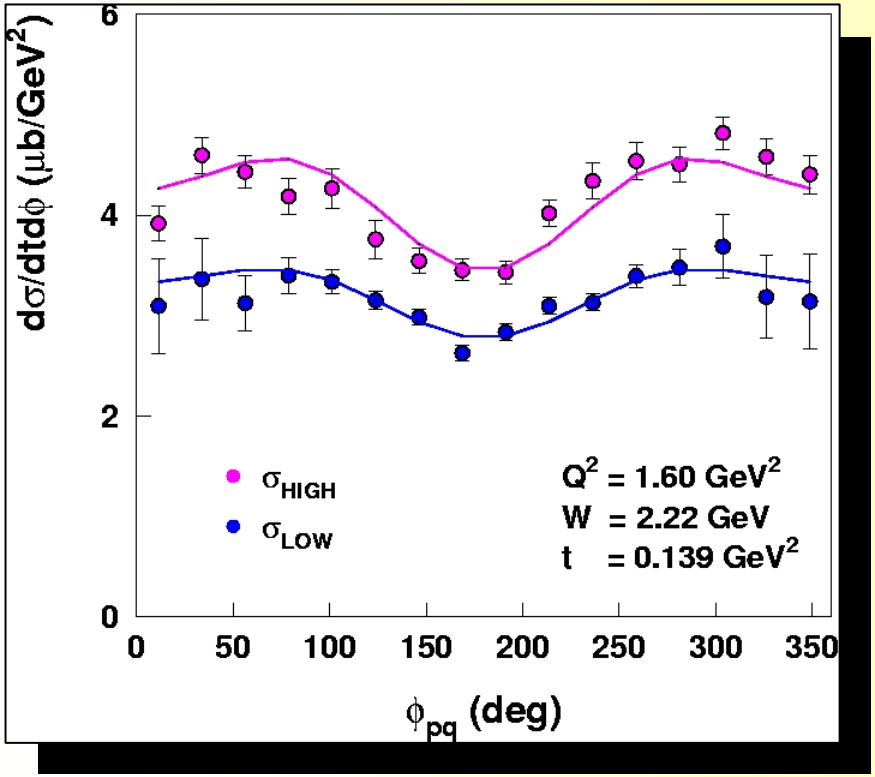
$$W = \sqrt{-Q^2 + M + 2M\omega}$$

$$t = (q - p_\pi)^2$$

- p_π = momentum of scattered pion
- θ_π = angle between scattered pion and virtual photon
- φ_π = angle between scattering and reaction plane

Cross Section Separation

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



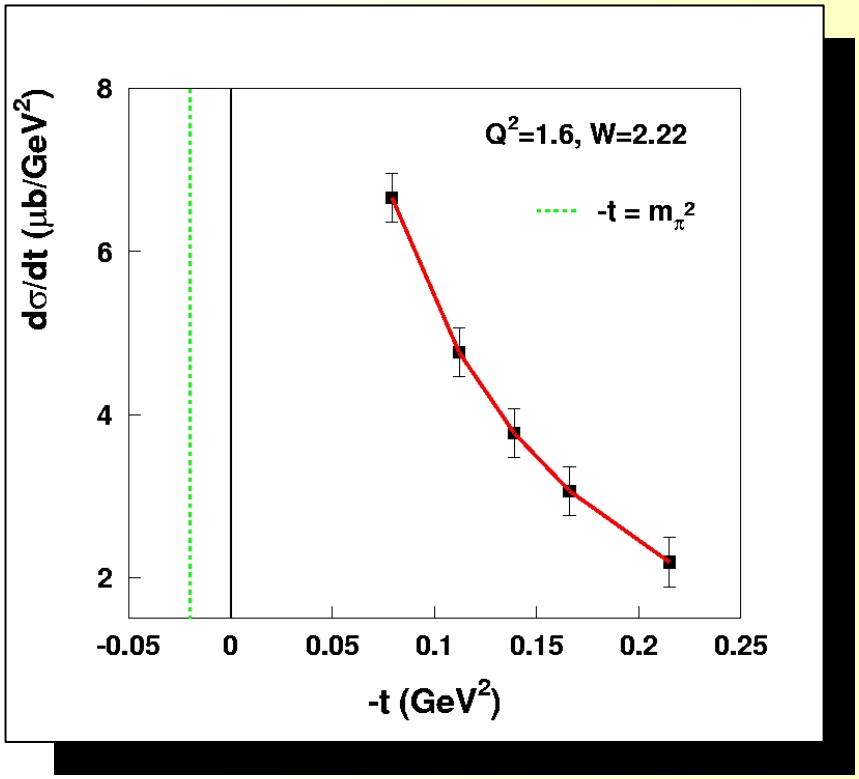
$$\frac{d^2\sigma}{dt\,d\varphi} = \varepsilon \frac{d\sigma_L}{dt\,d\varphi} + \frac{d\sigma_T}{dt\,d\varphi} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt\,d\varphi}\cos\varphi_\pi + \varepsilon\frac{d\sigma_{TT}}{dt\,d\varphi}\cos 2\,\varphi_\pi$$

Extracting F_π from σ_L data

- In t-pole approximation:

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

- Extraction of F_π requires a model incorporating pion electroproduction – VGL Regge model
  - One recent model based on constituent quark model by *Obukhovsky et al.*

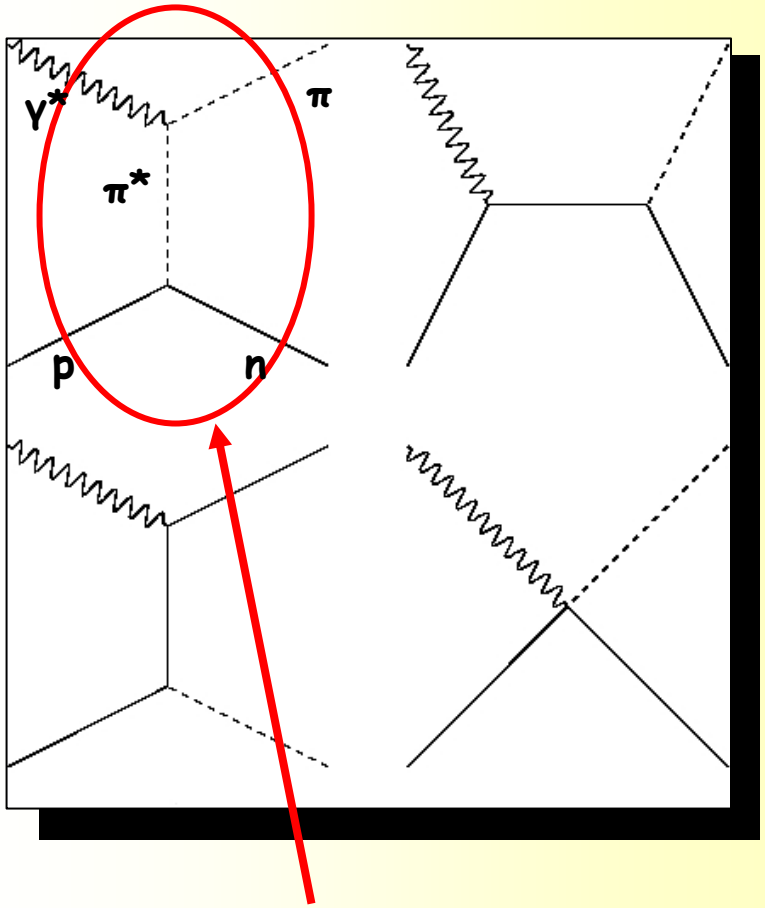


Competing Reaction Channels

- Extraction of F_π relies on dominance of t-channel, BUT there are other diagrams
  - t-channel purely isovector
  - Background: isoscalar

$$R = \frac{\sigma_L^{\pi^-}}{\sigma_L^{\pi^+}} = \frac{|A_v - A_s|^2}{|A_v + A_s|^2}$$

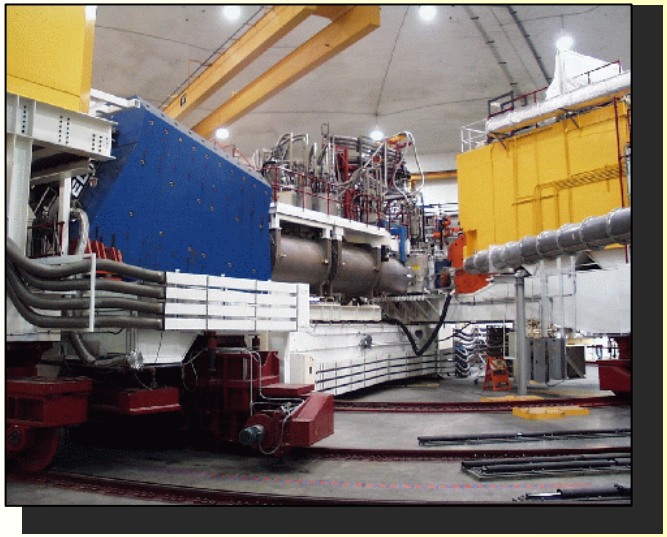
- Pole dominance tested using π^-/π^+ from $D(e,e'\pi)$
  - G-parity: If pure pole then necessary R=1



t-channel process

F_π-2 (E01-004)

- Goal:
  - Separate σ_L/σ_T via Rosenbluth separation for extracting F_π using pole dominance
- Experiment
  - Successfully completed in Hall C in 2003
  - Measure $^1H(e,e',\pi^+)$ and $^2H(e,e'\pi^\pm)NN$



- Extension of F_π-1
  - Higher W
  - Repeat Q^2=1.60 GeV^2 closer to $t=m_\pi$ pole
  - Highest possible value of Q2 at JLab

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

F_π-2 Collaboration

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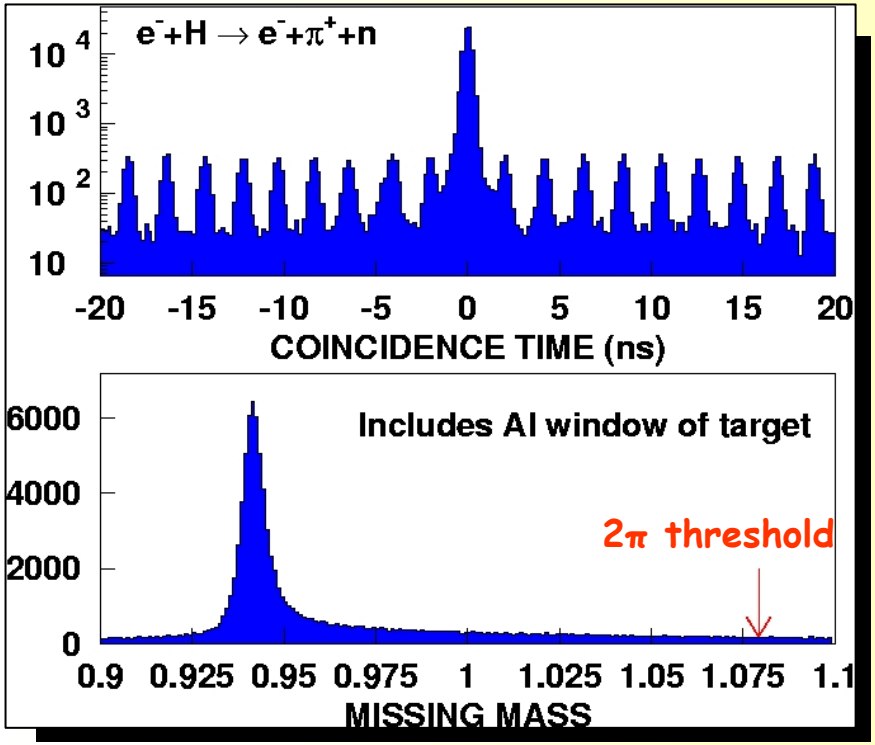
Good Event Selection: Coincidence Time

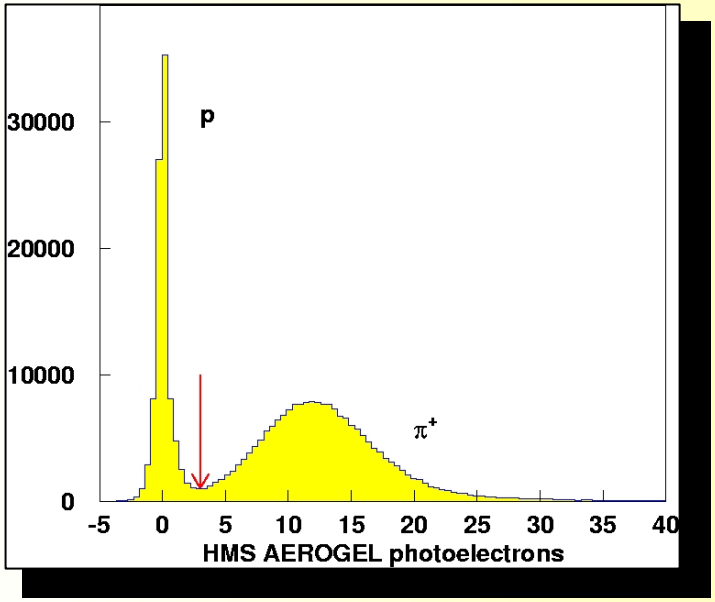
- Coincidence measurement between charged pions in HMS and electrons in SOS
  - Coincidence time resolution ~200-230 ps
- π^+ detected in HMS – Aerogel Cerenkov and Coincidence time for PID
  - π^- selected in HMS using Gas Cerenkov
- Electrons in SOS – identified by Cerenkov /Calorimeter

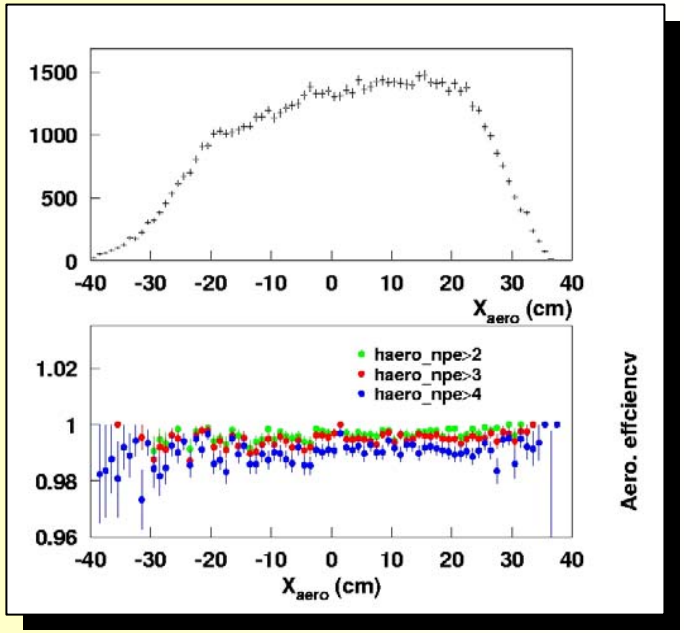


- After PID cuts almost no random coincidences

Pion Selection: HMS Aerogel

- Cannot distinguish p/π^+ at momenta ~ 3 GeV by TOF or gas Cerenkov
- Tune detection threshold for particle of interest
  - **n=1.03 for proton rejection in F_π-2**

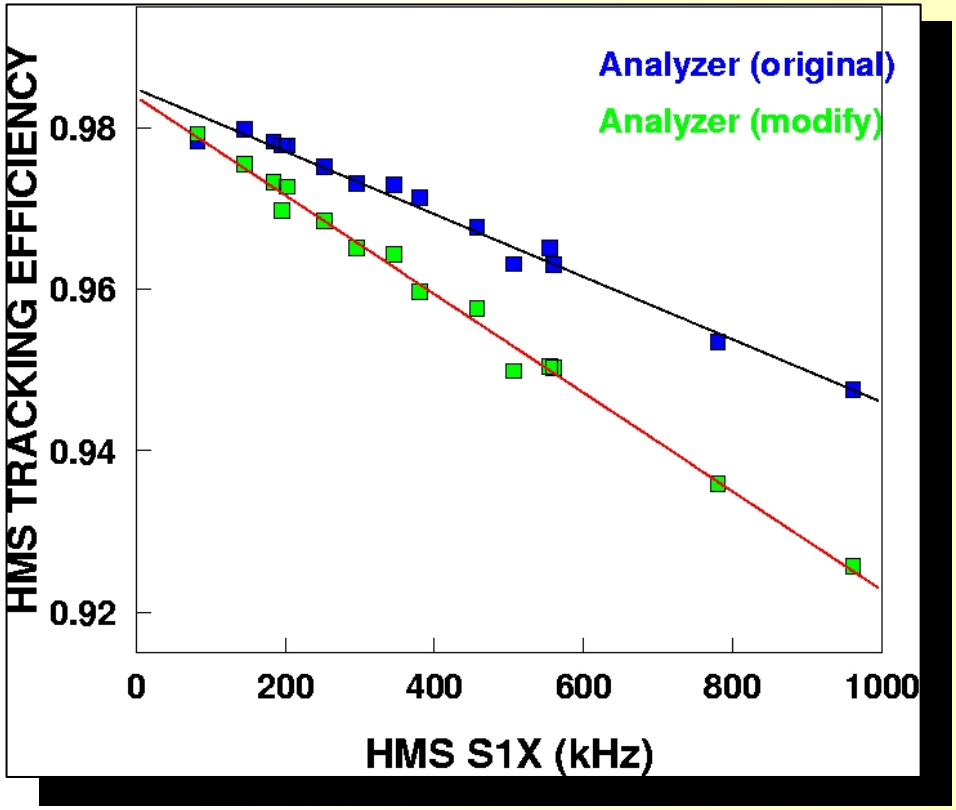




- Aerogel Cut Efficiency (npe=3) 99.5%
- Proton Rejection 1:300
- Note: cannot distinguish K^+/π^+ here

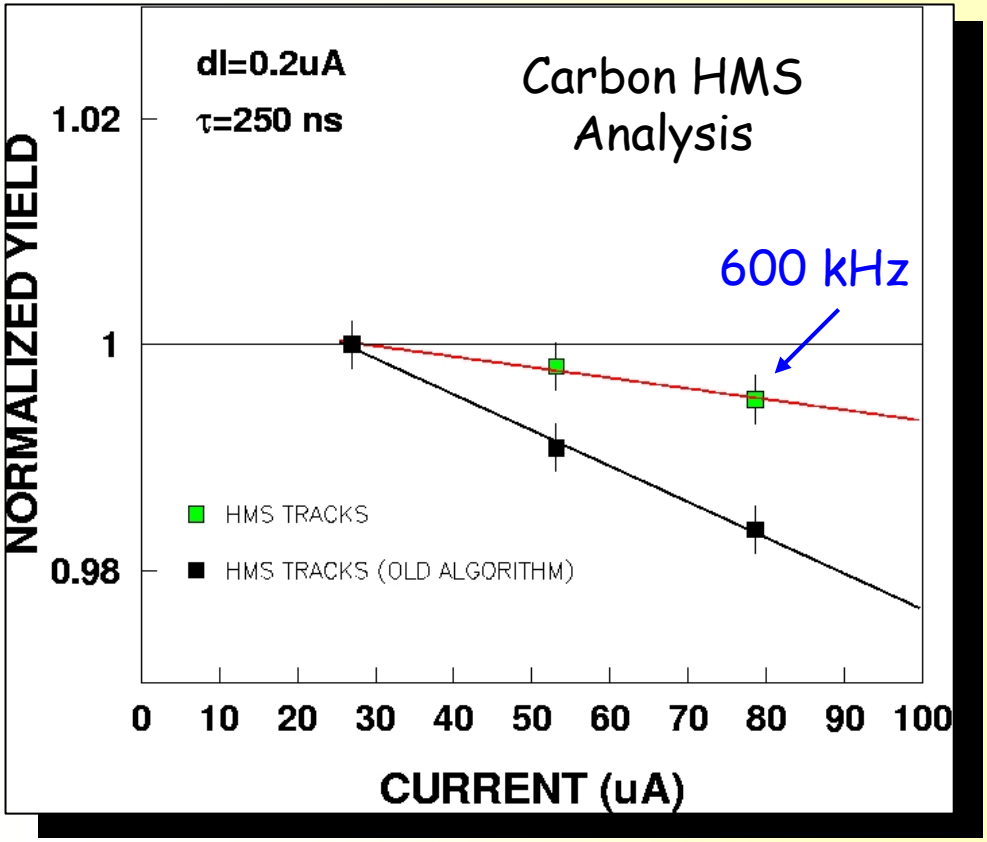
HMS Tracking Efficiency

- At high rates: multiple particles within allowed timing window
  - Consider efficiency for one good track
- Original efficiency algorithm: biased towards single tracks
  - But there are multiple track events with lower intrinsic efficiency
- Overall tracking efficiency was too good



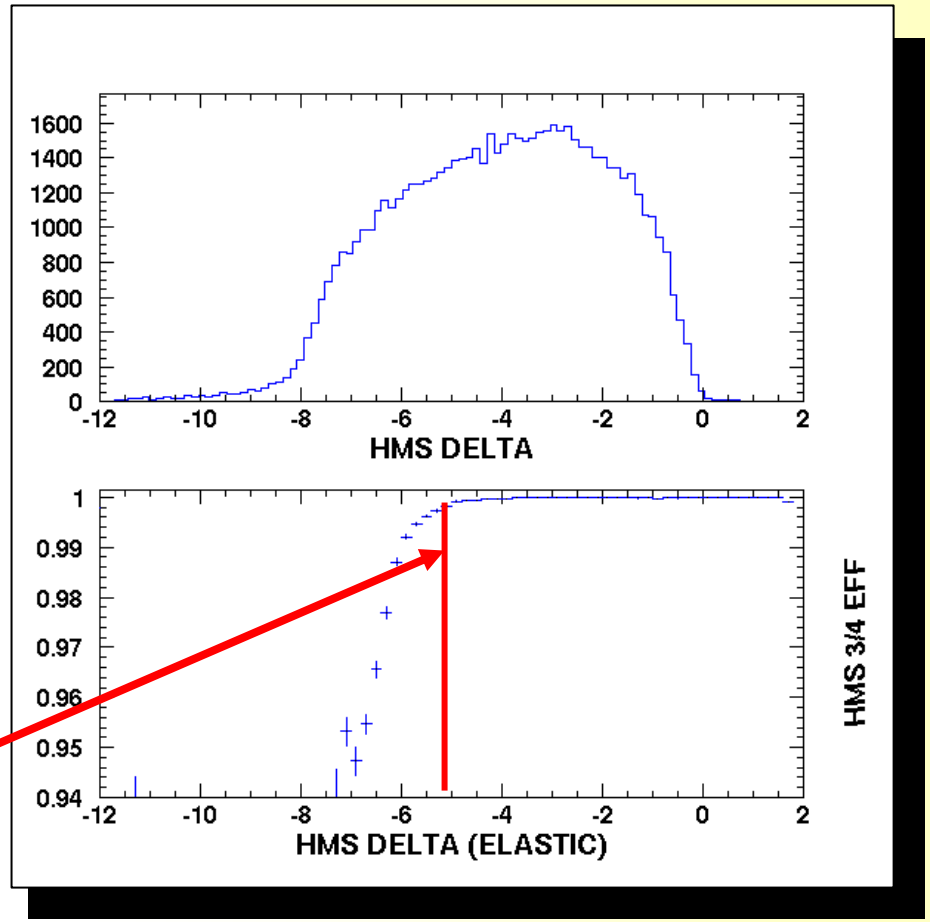
Target Density - Luminosity Scans

- Three scans on H, D, Al and carbon – beam currents between 20-90 uA
  - HMS rates: 100-1000 kHz
  - SOS rates: < 100 kHz
- Include modified tracking efficiency calculation
- Small rate dependence for carbon at very high rates (~1%/600kHz)



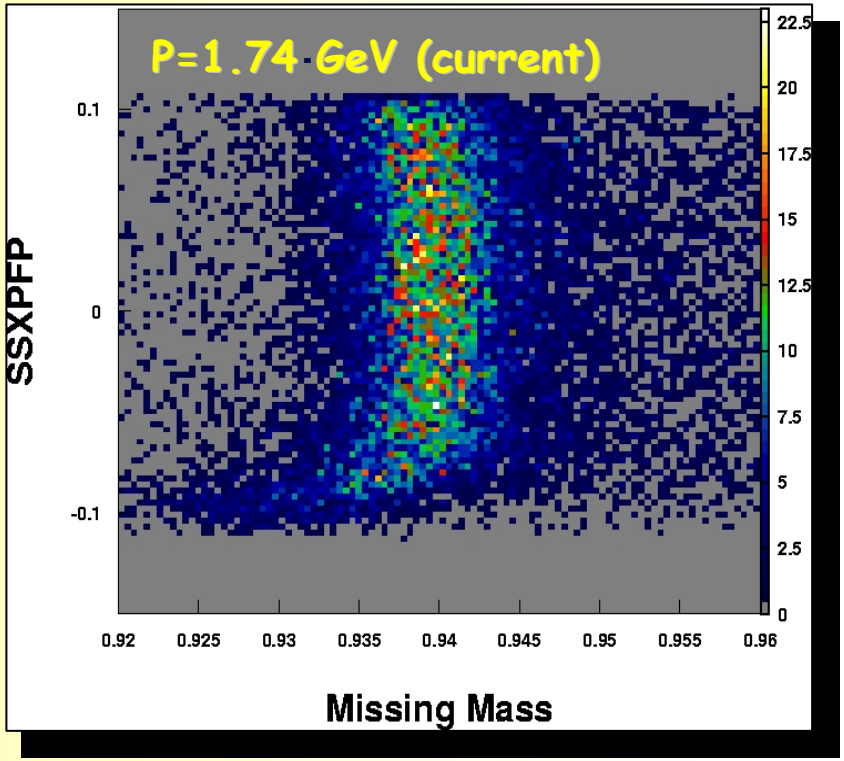
HMS Trigger Efficiency

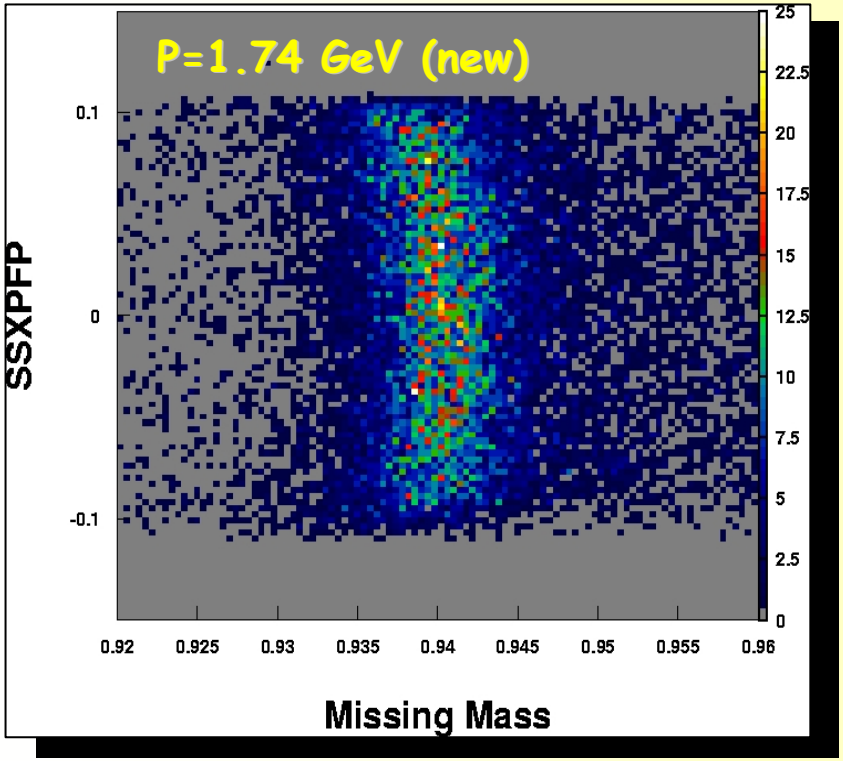
- Localized scintillator inefficiency at negative HMS acceptance
  - Both elastic and $\pi^{\pm}$ data
- Could be problem if apply global efficiency correction
- F_{π}-2 acceptance ±5% - can avoid region by applying cut



F_{π}-2 acceptance cut

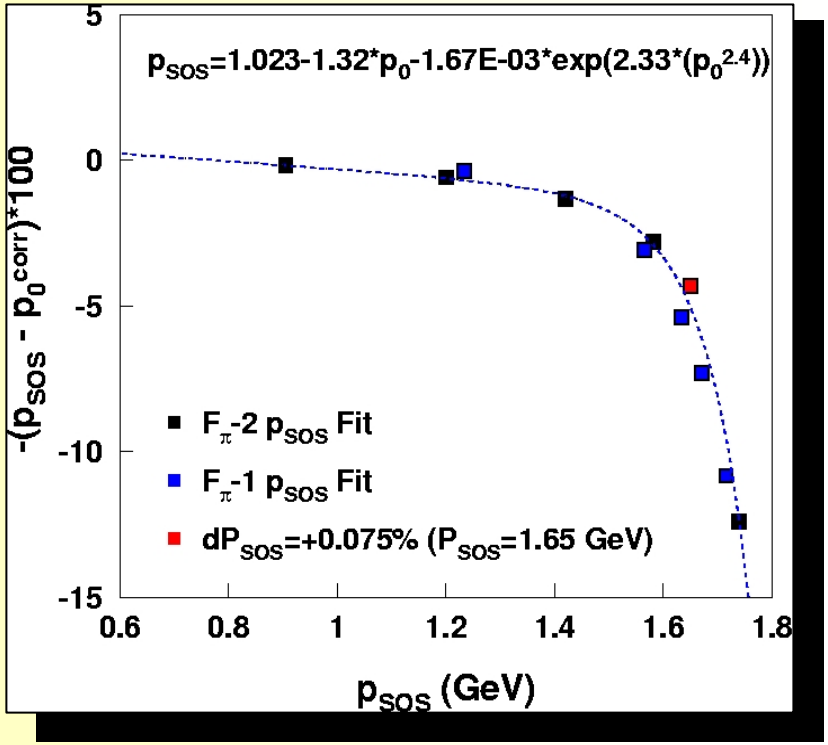
SOS Saturation Correction (1)



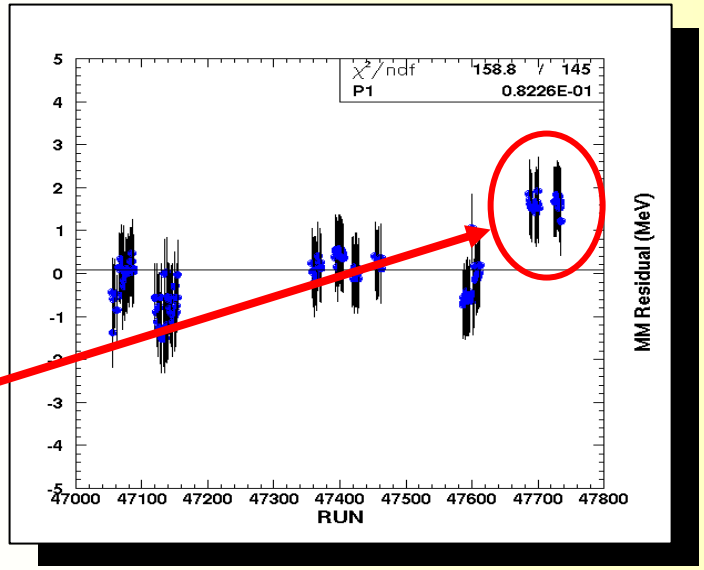


- Current SOS saturation correction not enough at large SOS momenta (~ 1.6 GeV)
- Can eliminate correlation using new SOS delta matrix elements + small correction

SOS Saturation Correction (2)

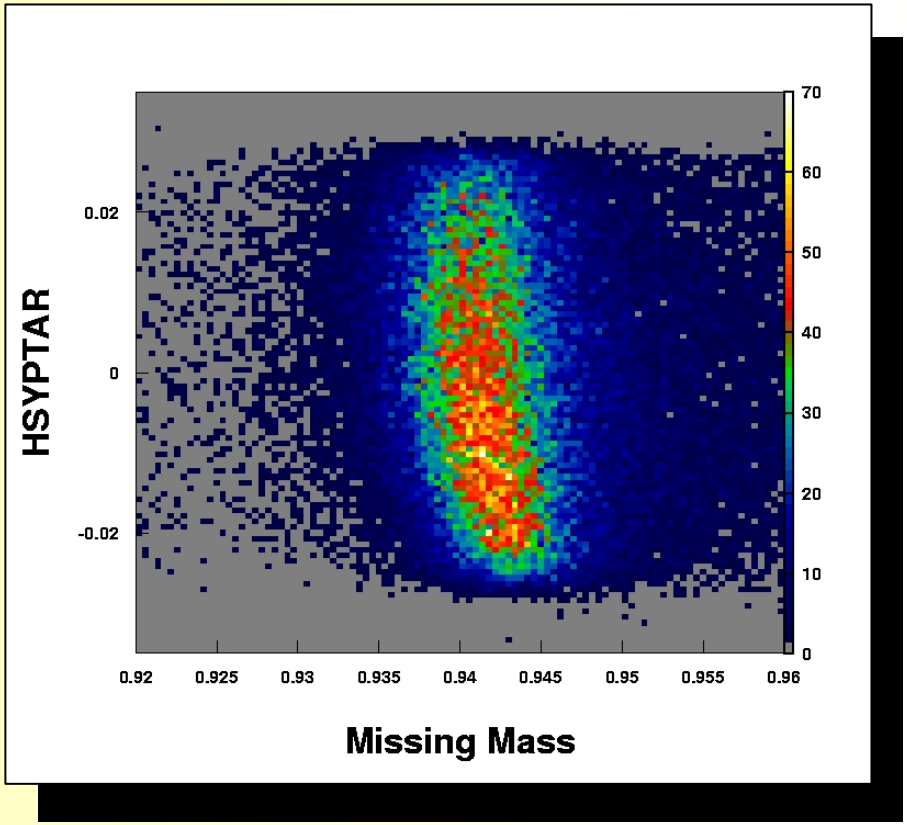


- Need additional correction to SOS saturation parametrization
  - Relevant for SOS momenta ~1.6 GeV
  - Consistent with elastics



- Problem: Missing mass high ~2MeV (p_{SOS}=1.65 GeV)

HMS – More Correlations

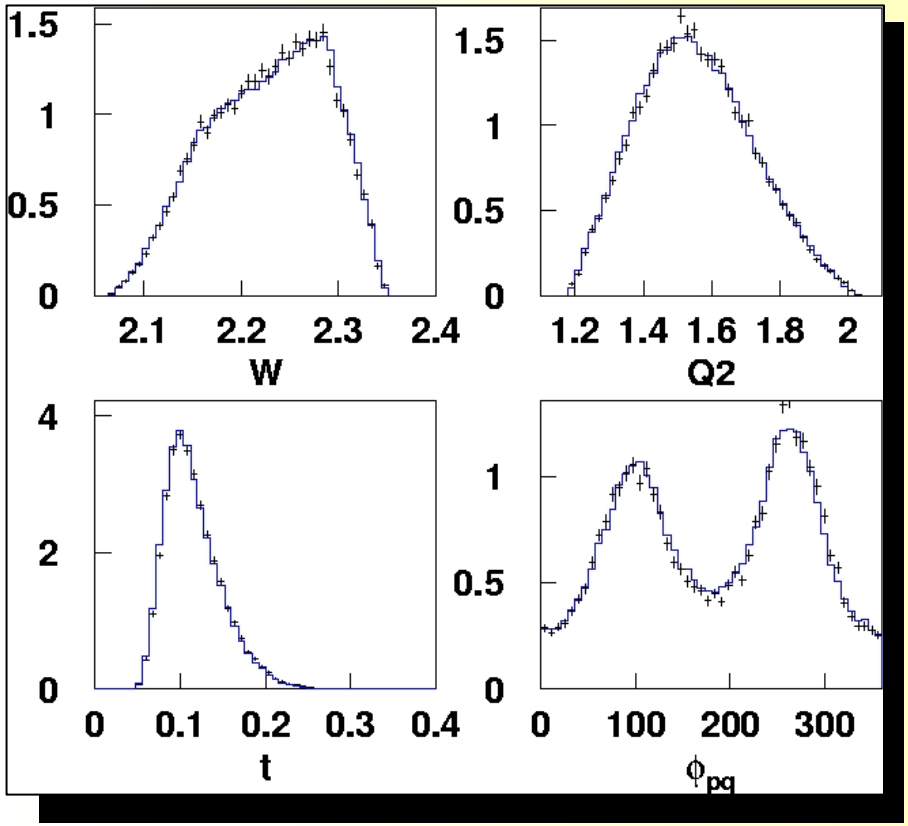


- Problem: missing mass correlated with Y'_{tar} in both elastic and π data – spectrometer optics
- Can be eliminated by modification to HMS δ
  - Simulation suggests effect from Q3 current/field offset
- Do not see in elastic data due to different illumination

Cross Section Extraction

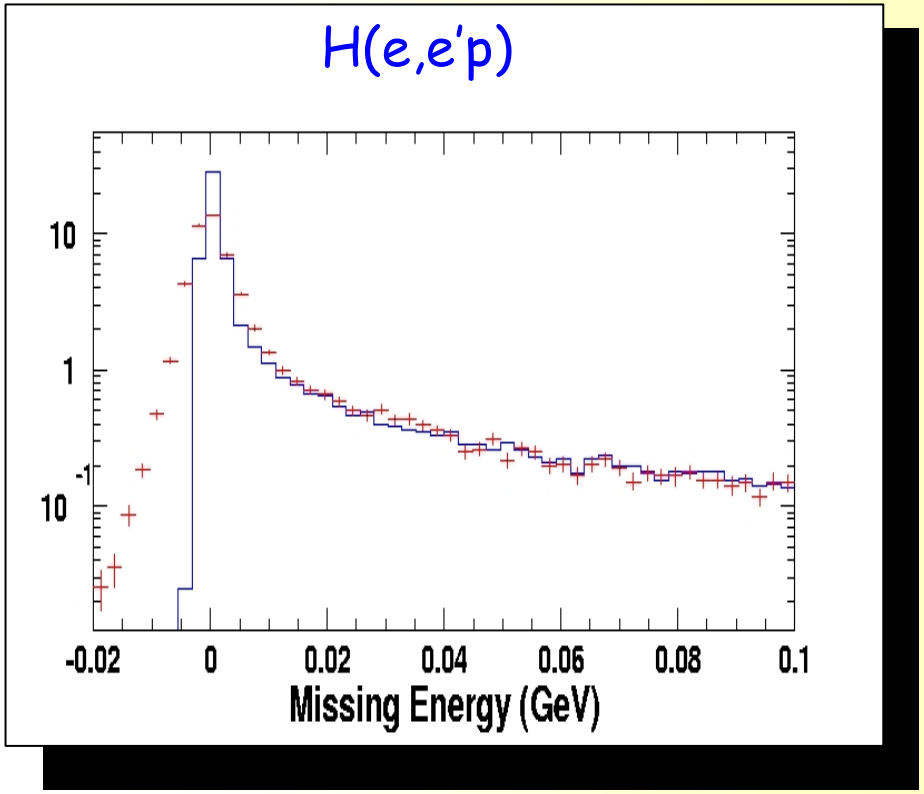
- Monte Carlo Model of spectrometer optics and acceptance
- Compare Data to Hall C Monte Carlo - SIMC
  - COSY model for spectrometer optics
  - Model for $H(e,e'\pi^+)$
  - Radiative Corrections, pion decay
- Iterate model until achieve agreement with data

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



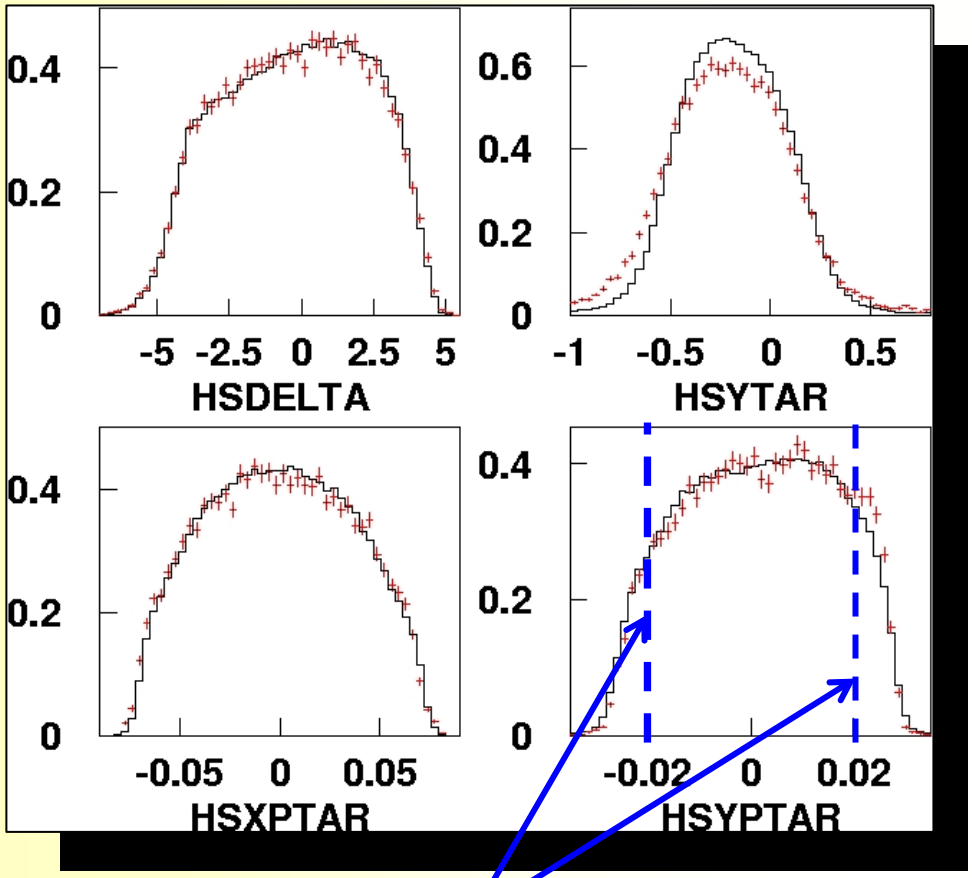
SIMC – Radiative Corrections

- Charged particles radiate in presence of electric field
  - External: radiate independently – no interference terms
  - Internal: Coherent radiation in field of primary target nucleon
- Description of elastic data looks good



- Pion radiation important, changes SIMC yield ratio ~3.5%
  - Point-to-point uncertainty ~1% based on radiative tail studies between ε points.

Y'_{tar} Acceptance Cut



- Investigate various aspects regarding Y'_{tar} acceptance
  - Resolution √
  - Correlations √
  - Matrix element fits and corrections √
  - Different binning in -t
- This talk: Limit to well understood Y'_{tar} acceptance region in cross section extraction

Preliminary Results - Compare VGL/Regge Model

- F_π-2 Separated cross sections
  - Y'_{tar} acceptance cut applied
  - Compare to VGL/Regge model with $\Lambda_\pi^2=$, $\Lambda_\rho^2=1.7$

PRELIMINARY

Point-to-point Systematic	Error	Goal
Acceptance	3-4%	1-2%
Radiative Corrections	1%	1%
Kinematics	1%	1%
Target Density	0.5%	0.1%
Charge	0.5%	0.5%
Model Dependence	0.5%	0.5%
Cut Dependence	0.5%	0.5%
Detection Efficiency	0.5%	0.5%

- Statistical Error only

To Do - For Final Result

- Studies of rate dependent corrections and relevant correlation - done
- Finalize Systematic Studies - in progress
  - Y' acceptance
  - Radiative processes
- Theory Uncertainties - in progress
  - Models for F_π extraction (VGL/Obukhovsky)
- Pole dominance : $\pi+/\pi-$ ratios - in progress