Probing Pion Structure with L/T-Separated Cross Sections in Hall C at Jefferson Lab

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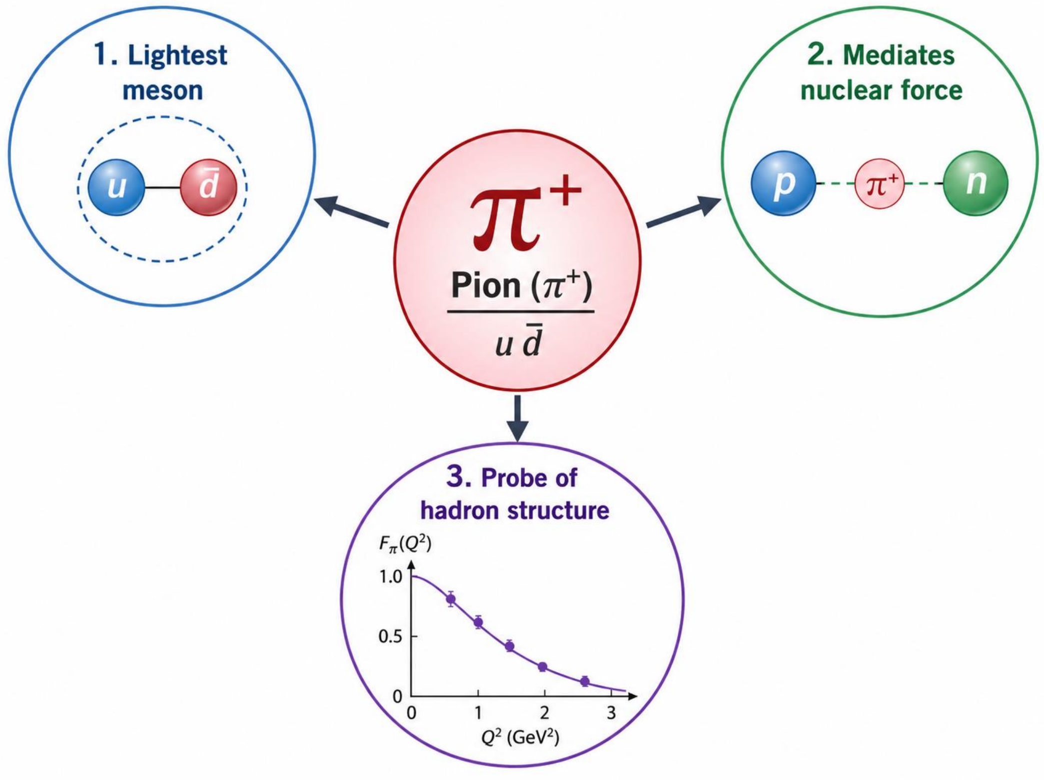
Scientific Motivation

- The interaction of quarks and gluons is successfully described by **Quantum Chromodynamics (QCD).**
- **But unable to construct the quantitative description of hadrons in terms of the underlying constituents, quarks and gluons.**

- **Pion** is the lightest meson and provides an ideal testing ground for our understanding of the bound $q\bar{q}$ hadronic system.
- **Pions mediate the residual strong force that helps bind nucleons inside the nucleus.**
- **Form factor** $(F(Q^2))$ is an important observable that can be studied to understand the internal structure of hadrons.
- **Measuring the pion form factor at various Q^2 (up to $8.5\,\mathrm{GeV}^2$) checks the validity of QCD-based theories, including the transition region between perturbative and non-perturbative approaches.**

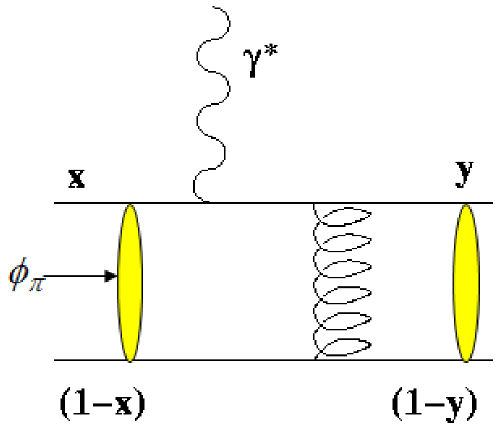


The Pion in perturbative QCD

- Form Factor describes transverse spatial position of partons within hadrons.

- At very large Q^2, pion form factor (F_π) can be calculated using pQCD;

$$F_\pi(Q^2) = \frac{4}{3}\pi\alpha_s \int_0^1 dxdy \frac{2}{3}\frac{1}{xyQ^2}\phi(x)\phi(y)$$



- At asymptotically high Q^2, the pion distribution amplitude becomes;

$$\phi_\pi(x) \rightarrow \frac{3f_\pi}{\sqrt{n_c}}x(1-x)$$

- And F_π takes the very simple form;

$$Q^2F_\pi(Q^2) \rightarrow 16\pi\alpha_s(Q^2)f_\pi^2 \qquad (Q^2 \rightarrow \infty)$$

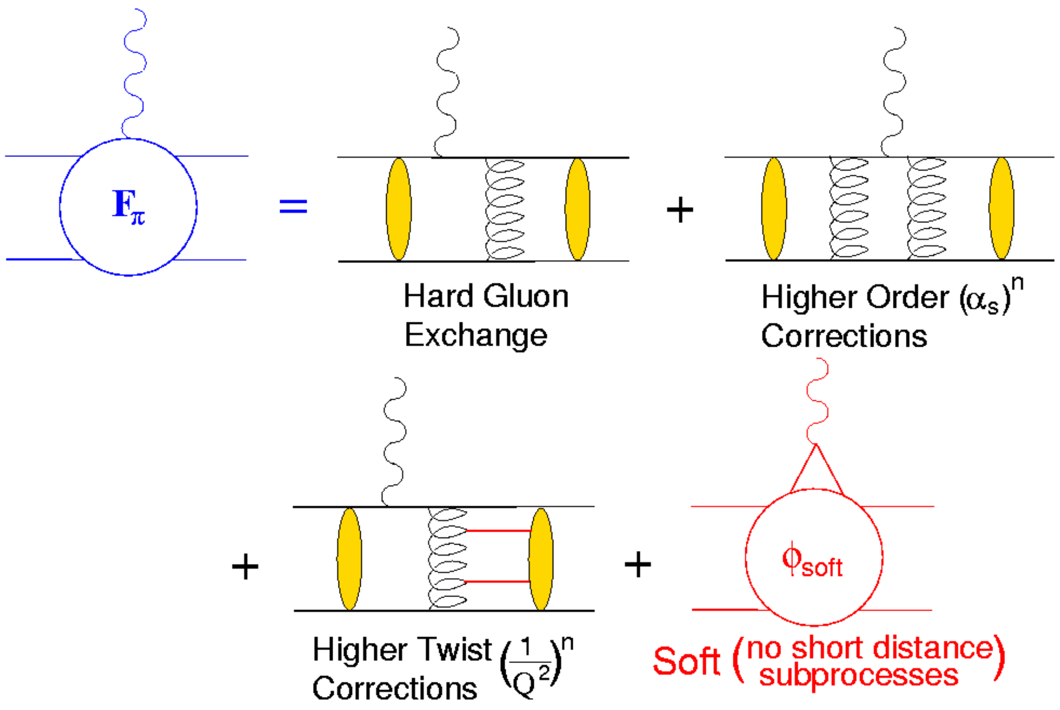
[G.P. Lepage, S.J. Brodsky, Phys.Lett. 87B(1979)359].

- Q^2F_π should behave like $\alpha_s(Q^2)$ even for moderately large Q^2
- Pion form factor seems to be best tool for experimental study of nature of the quark-gluon coupling constant renormalization

[A.V. Radyushkin, JINR 1977, arXiv:hep–ph/0410276]

Pion in Accessible Q^2 Region

- **At experimentally accessible Q^2, both the ”hard” and “soft” components (e.g., transverse momentum effects) contribute.**
- The interplay of hard and soft contributions is poorly understood
- Different theoretical viewpoints on whether higher-twist mechanism dominate until very large momentum transfer or not.
- The pion elastic and transition form factors are experimentall accessible over a wide kinematic range.
- Hall C at Jefferson Lab is only facility in the world with the capacity to perform F_π measurement.



Pion Form Factor Measurement

- Above $Q^2 > 0.3\text{GeV}^2$, F_π is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e, e'\pi^+)n$

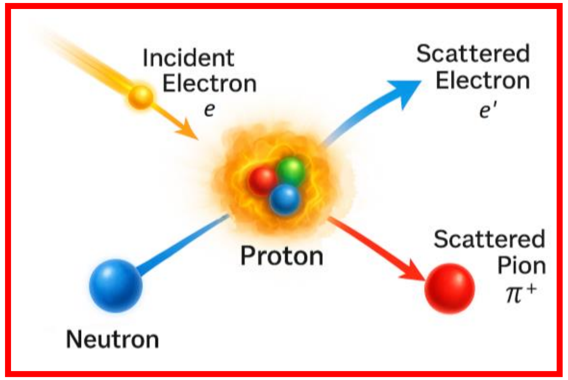
- Indirect measurement – Form factor extraction requires a model.

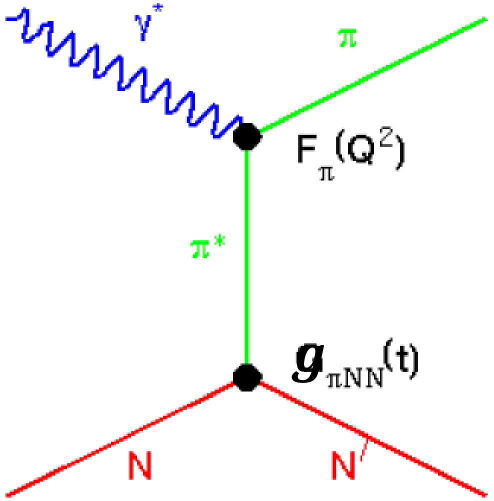
- Need to extract σ_L from the total cross-section.

- As an illustration of how σ_L connects to $F_\pi^2(Q^2, t)$, we consider a simple Born Term Model;

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

- In reality, we use other available models such as VGL, CKY and PKT for $F_\pi^2(Q^2, t)$ extraction.





Rosenbluth Separation Technique

- **Rosenbluth separation required to isolate σ_L for L/T separation.**

- The physical cross-section for the electroproduction process is given by;

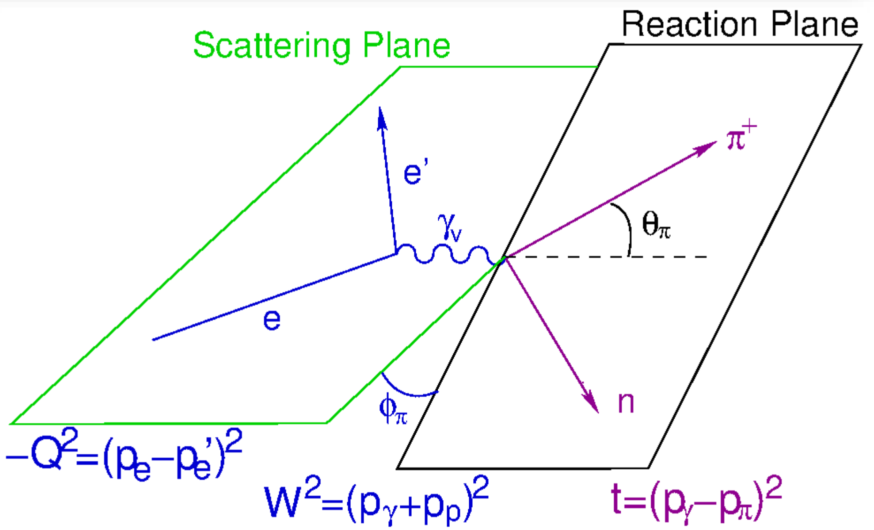
$$2\pi \frac{d^2\sigma}{dt d\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$

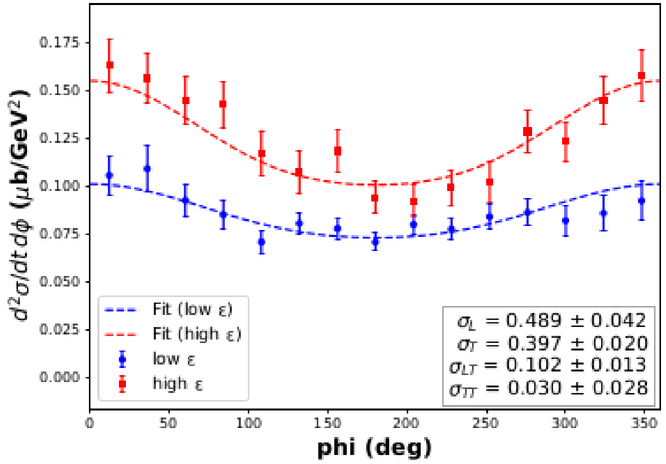
- Here "ϵ" is polarization of virtual photon.

$$\epsilon = \left[1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2} . \tan^2\frac{\theta_{e'}}{2}\right]^{-1}$$

- Perform two scattering measurements with different beam energies "E_e" to vary "ϵ" and separate different cross-section terms.

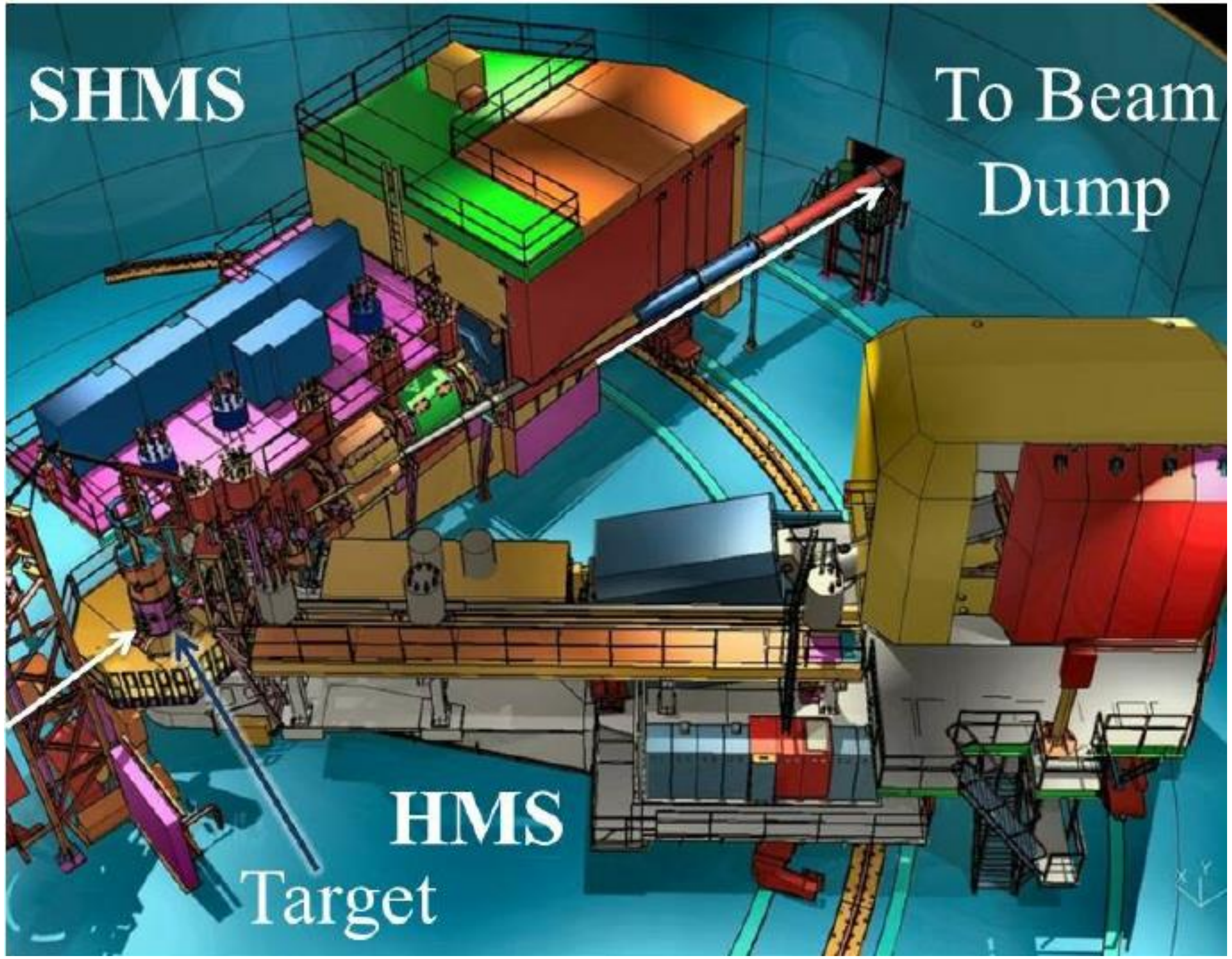
- Careful attention must be paid to systematic studies such as spectrometer acceptance, kinematics, efficiencies, etc.





Pion-LT Experiment at JLab

- Specially designed to measure precise cross-sections and form factors for mesons.
- Experimental setup contains a target and two detector arms.
- Target can be Liquid H_2, Liquid D_2 or solid targets.
- Two detectors are;
  - High Momentum Spectrometer (HMS)
  - Super High Momentum Spectrometer (SHMS)



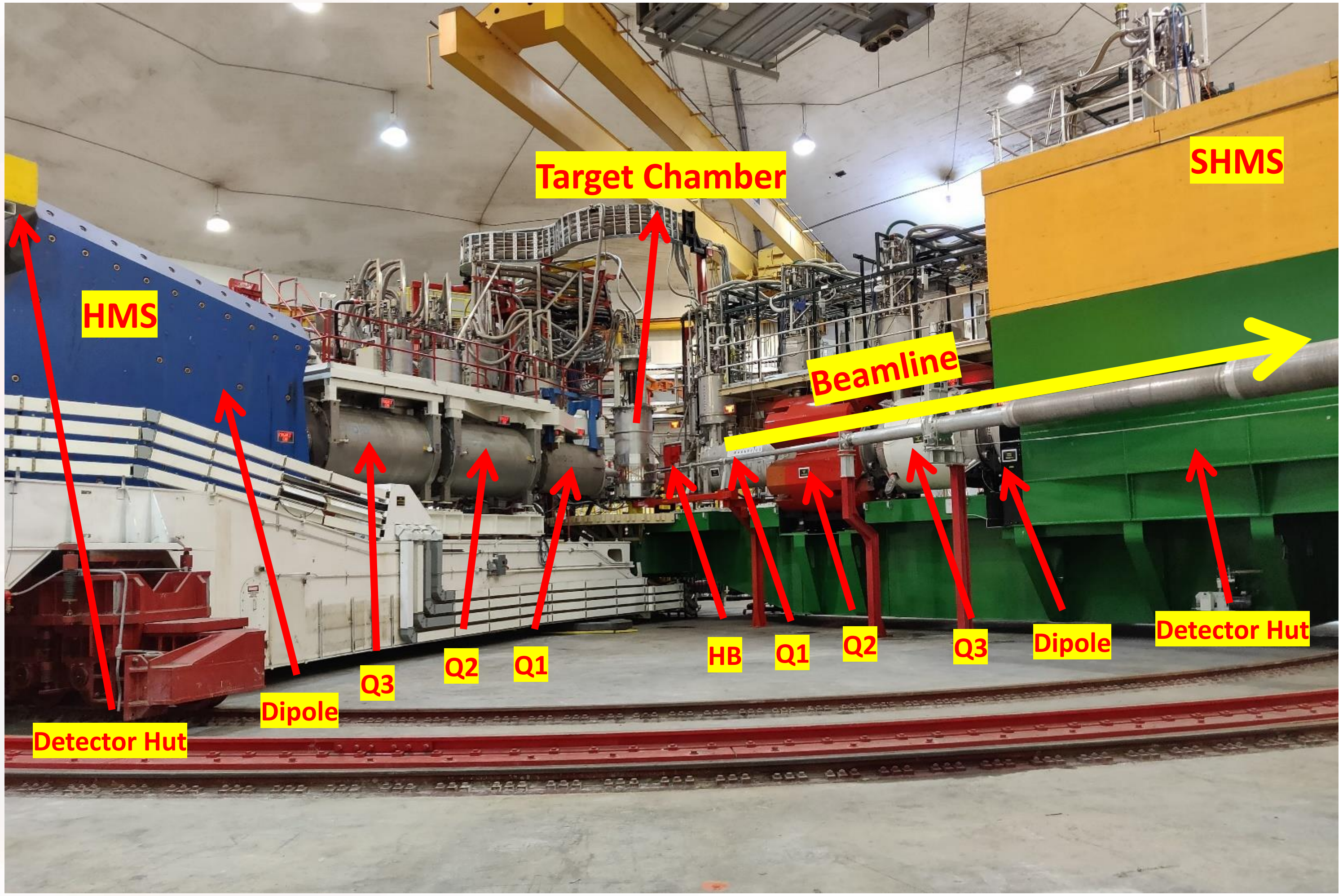
Hall C Spectrometers

- Both spectrometers are movable and have sets of quadrupole (Q), dipole (D) superconducting magnets and a Detector Hut.

- Both spectrometers are rotatable and contain similar detector packages.

Spec	Angle range (deg)	Momentum range
HMS	10.5 – 90	0.5 – 7 GeV
SHMS	5.5 – 40	0.5 – 11 GeV

- Took coincidence data; simultaneously detected **electrons in HMS** and **pions in the SHMS**



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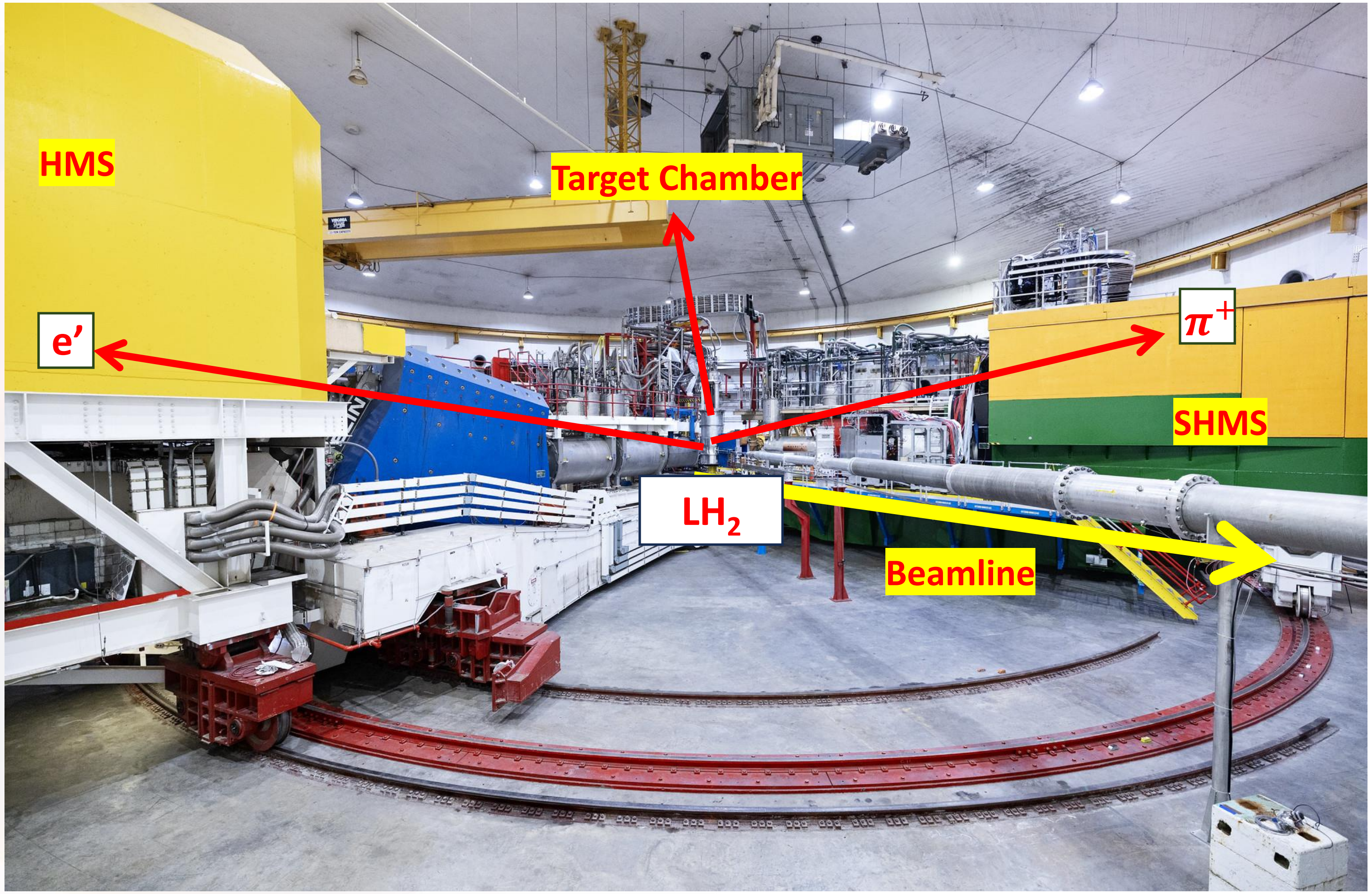


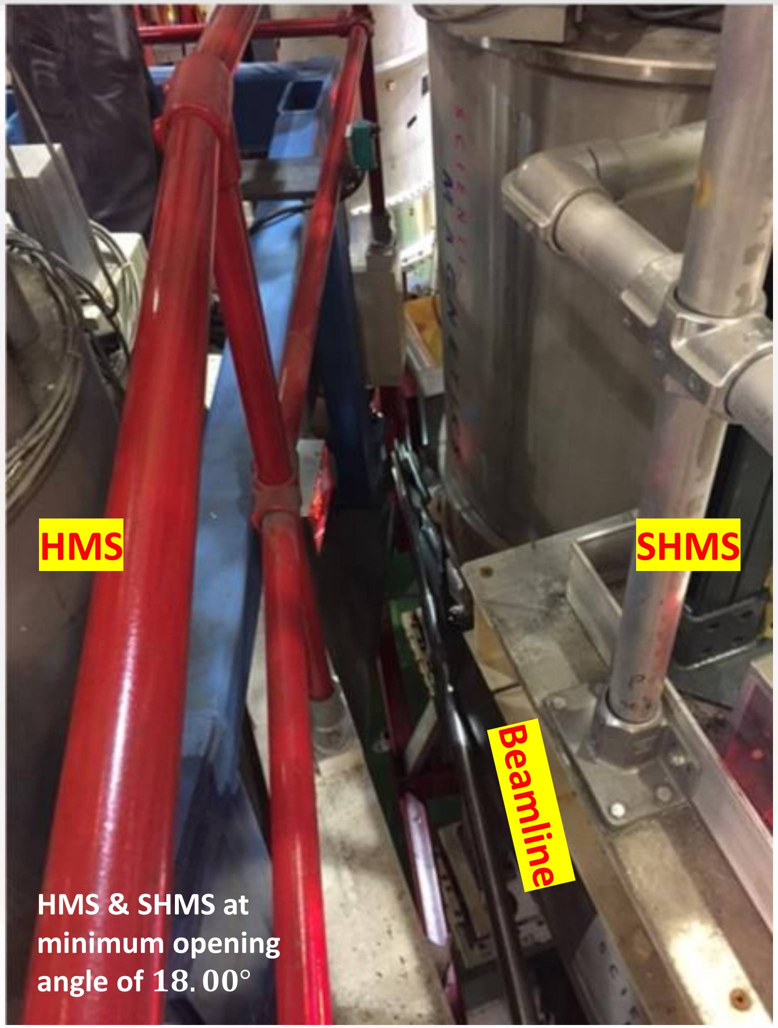
Hall C Spectrometers

- This experiment has in large part driven the forward angle requirements of SHMS and HMS

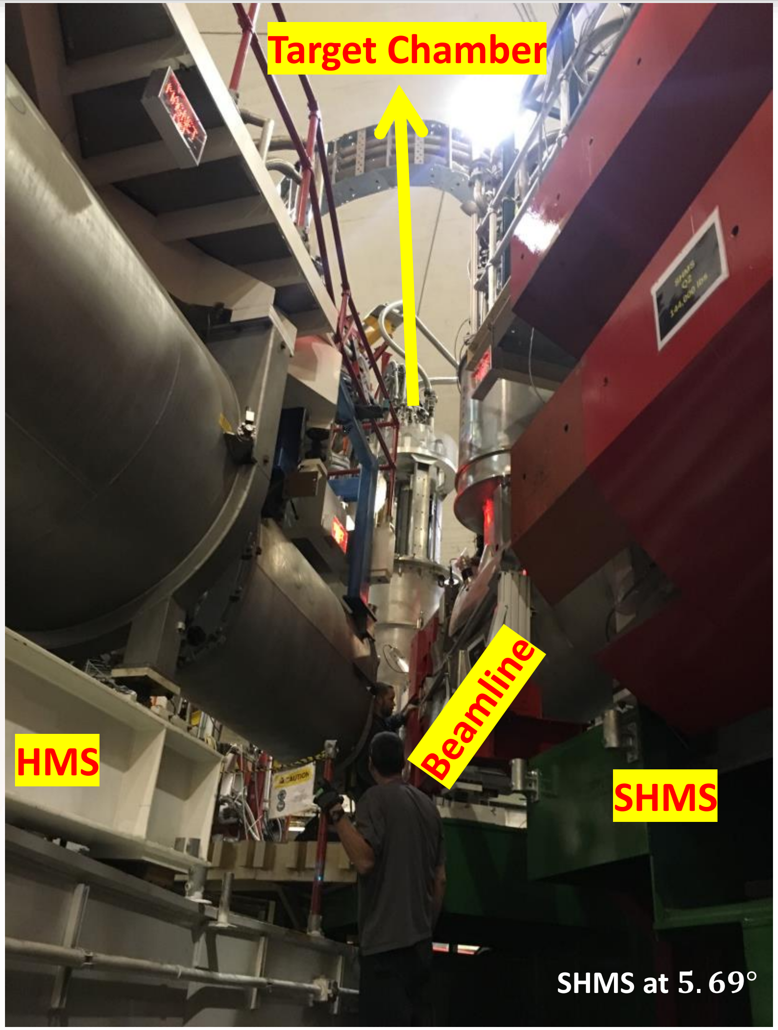
- The **minimum opening angle** between SHMS and HMS was, $18.00°$, reached for this experiment.
  - HMS moved to $11.01°$ deg and SHMS moved $18.00°$ away at $6.99°$

- In this experiment, we pushed **SHMS to** $5.50°$.
  - Several kinematic settings used the SHMS at its minimum angle of $5.50°$

Thank you to the Hall C scientific and technical staff members who made all of this possible



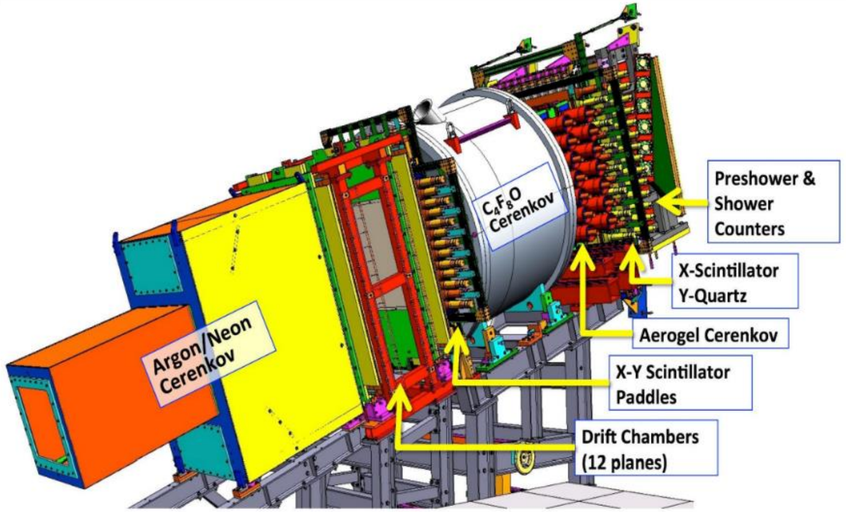
HMS & SHMS at minimum opening angle of $18.00°$

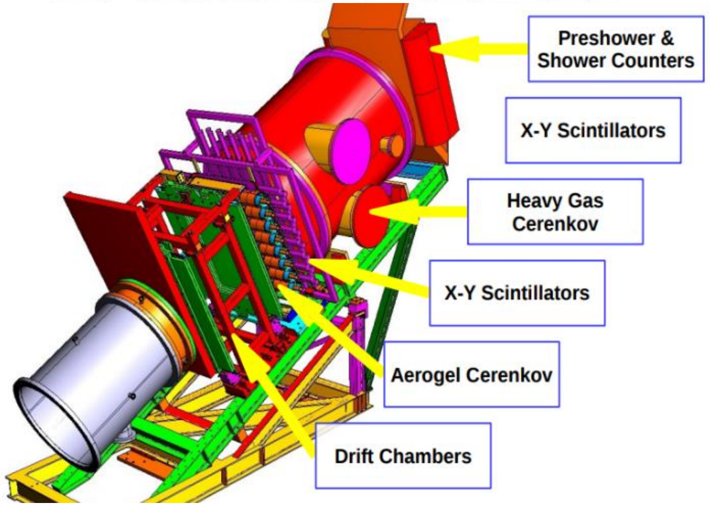


SHMS at $5.69°$

Detectors

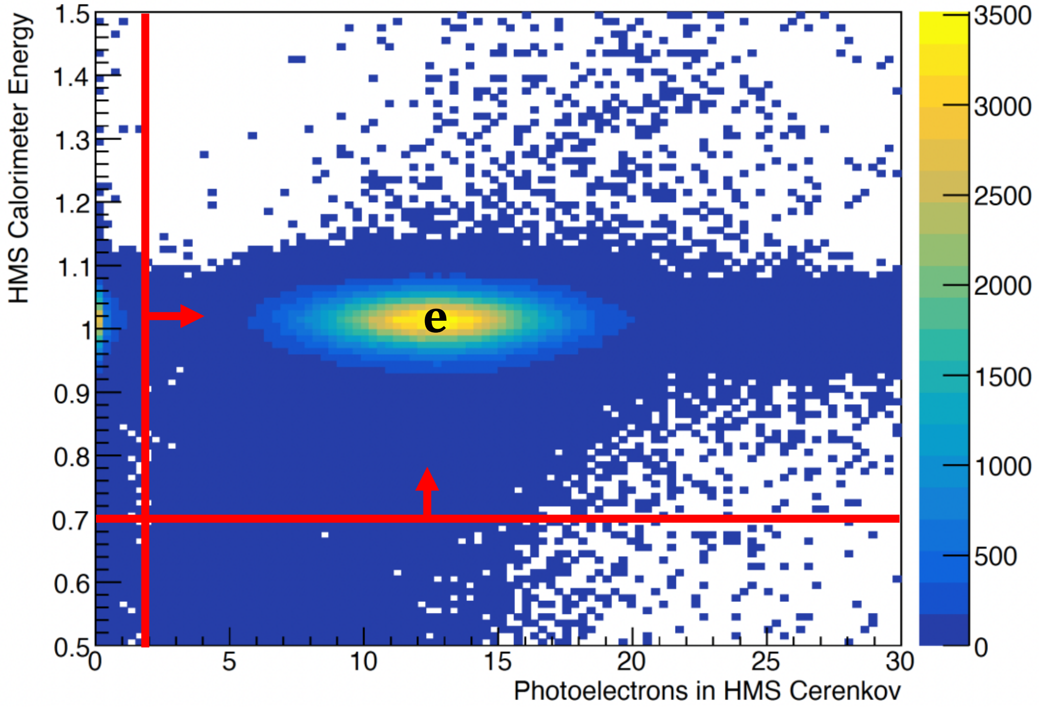
Detectors	Purpose	Notes
Noble Gas Cerenkov (NGC)	Particle ID Trigger '$e^{\pm}/\pi^{\pm}$' at high momentum	Vary Ar/Ne mixture to set index at '$\pi^{\pm}$' threshold. Only used in SHMS.
Heavy Gas Cherenkov (HGC)	Particle ID Trigger '$\pi^{\pm}/K^{\pm}$' discrimination	C_4F_8O - Vary pressure to set n at $\pi^{\pm}$ threshold (here n = 1.011 – 1.030 at 1 atm)
Aerogel Cerenkov	Particle ID Trigger 'K^{+}/p' discrimination	n = 1.011, 1.015, 1.03, 1.05
Drift Chambers	Momentum measurement, Tracking	5mm max. Drift, 300 micron resolution
Hodoscopes	Trigger, Time reference, Measure β	X-Y Scintillators
Calorimeters (EM-Preshower and Shower Counters)	Particle ID, Trigger, $e^{\pm}$ Tagging	



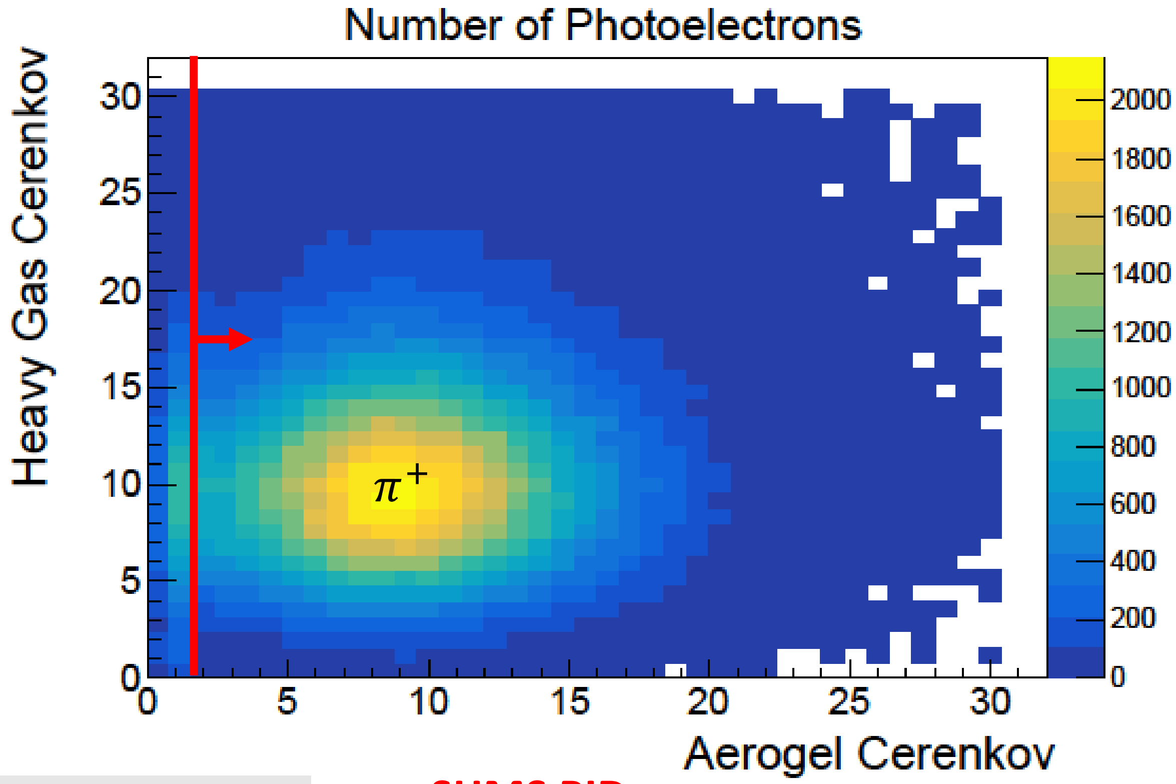


Event Selection Criteria

- Purpose is to select the clean pion events sample in coincidence with the electrons to measure the cross-sections.
- Cuts must be tight, but not so close as to sacrifice efficiency across the acceptance.
- Overall, detector efficiencies are greater than ~98%.



HMS PID



SHMS PID

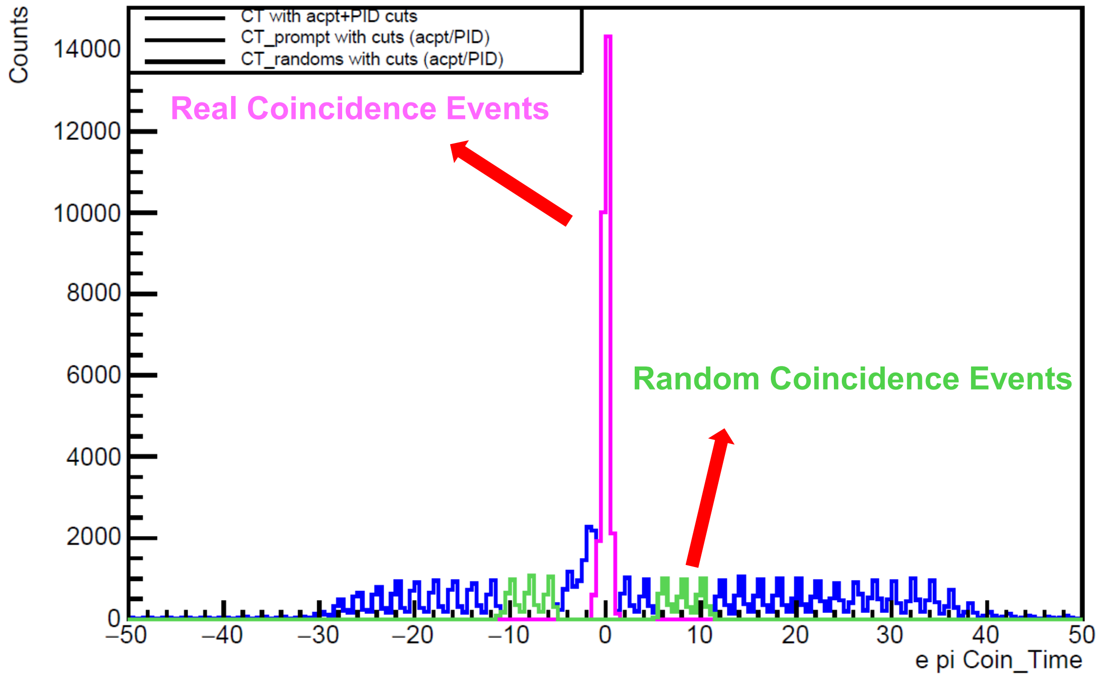
Q2 = 3.85, W = 2.62, t = 0.21 (2 epsilons)

Event Selection Criteria

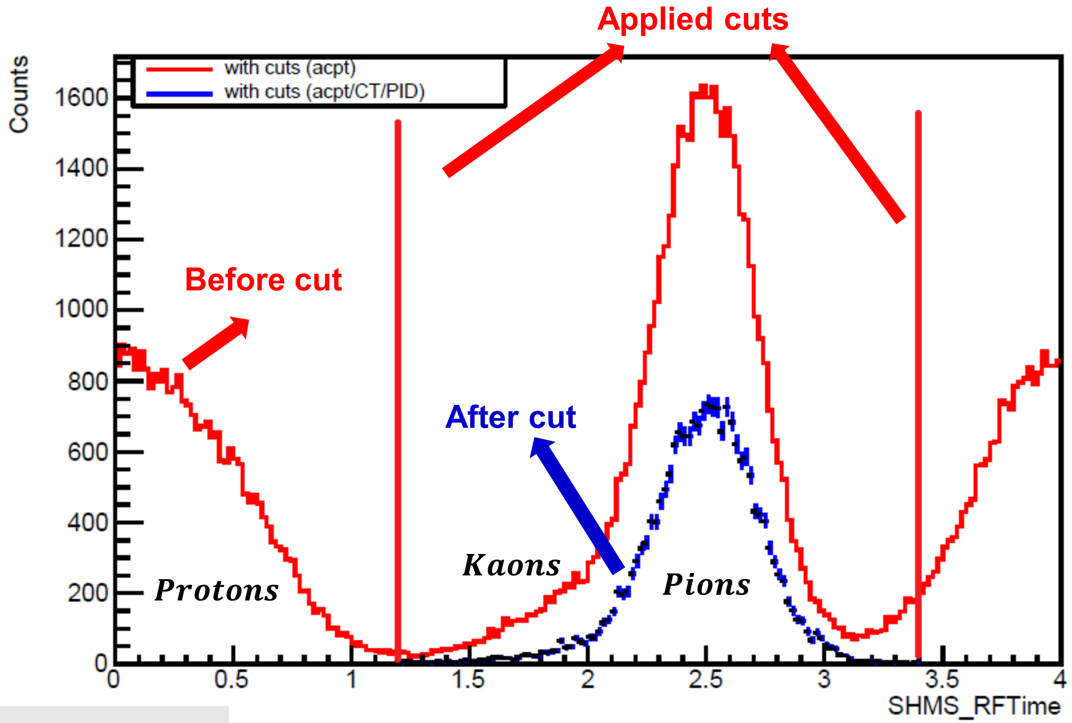
- CoinTime (CT) is given as:

$$t_{coin} = t_{HMS} - t_{SHMS}$$

- Used to eliminate random background caused by random coincidences.



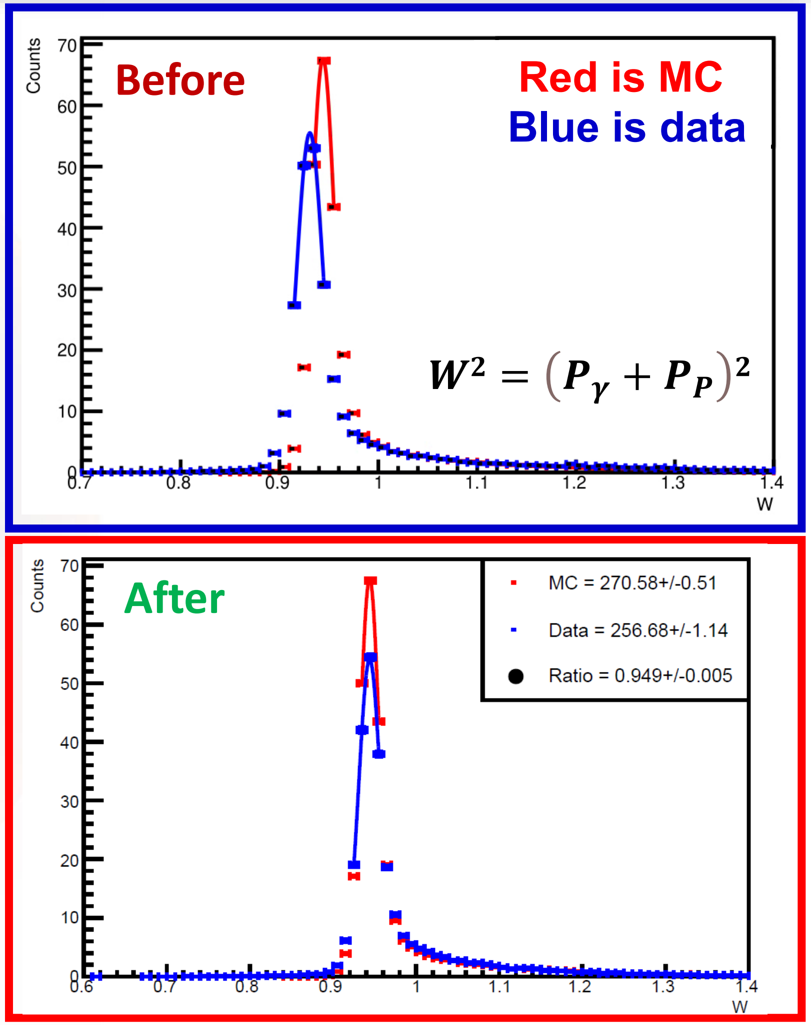
- RF time refers to the time difference between a detected event and the nearest preceding RF signal of the electron linac.
- Enables the differentiation between pions, kaons, and protons due to their distinct velocities.



Q2 = 3.85, W = 2.62, t = 0.21 (2 epsilons)

Elastic *ep* Reaction Study

- **Collected elastic ep data to identify possible kinematic offsets** by comparing measured quantities with the well-known elastic reaction expectations.
- **Pupose of the kinematic offset study is to quantify and correct small shifts in reconstructed kinematics** and to help **manage systematic uncertainties**.
- **looked at distributions of the missing variables ($E_M, \overrightarrow{P_M}, W$) to find deviations from expected values based on kinematics.**
- **The E_M , the components of $\overrightarrow{P_M}$, and W are correlated to different spectrometer quantities (momentum , angle, beam energy), and thus offsets can be extrapolated from them.**
- **By adjusting the beam energy, momentum and angles, missing variables ($E_M, \overrightarrow{P_M}, W$) can be moved to better agree between data and SIMC.**
- **Offsets are doing a good job and peaks are in agreement with each other.**
- **Applied the determined kinematic offsets to the physics data for cross-section measurement.**

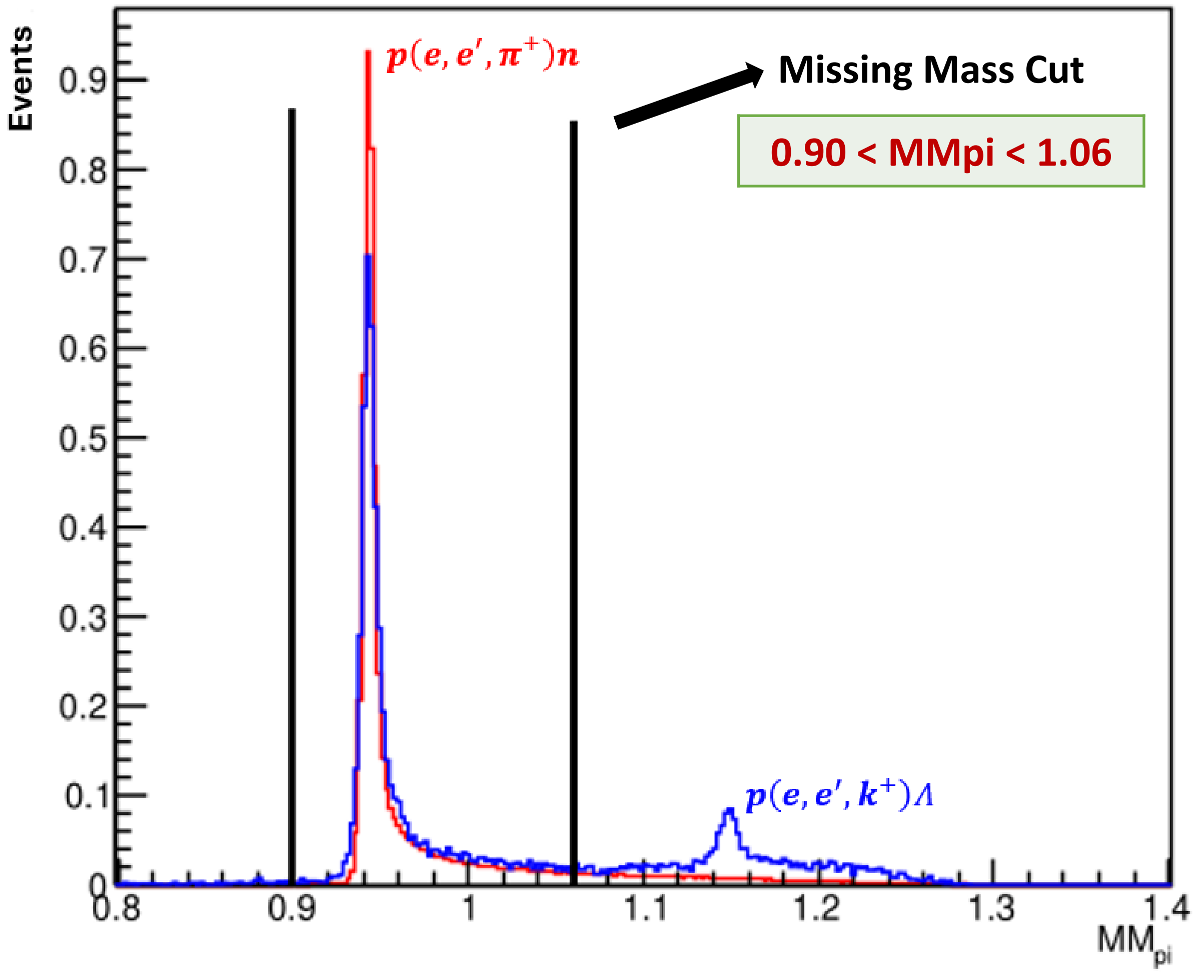


Selection of Event Sample

- Selected electrons in HMS in coincidence with pions in the SHMS.
- Missing particle reconstruction (neutron).

$$M_m = \sqrt{(E_e + m_P - E_{e'} - E_{\pi^+})^2 - (p_e - p_{e'} - p_{\pi^+})^2}$$

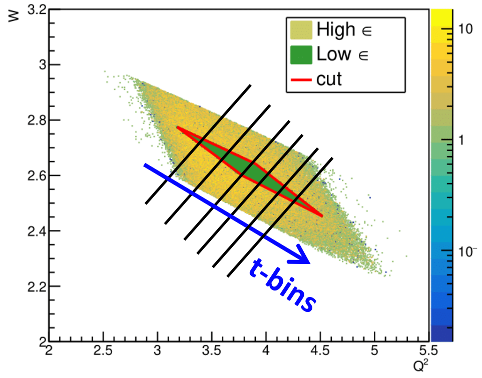
- Blue represents the experimental data missing mass plot.
- Red represents the Monte Carlo missing mass plot.
- To eliminate the remaining background, a missing-mass cut was applied to both the Monte Carlo and experimental data.



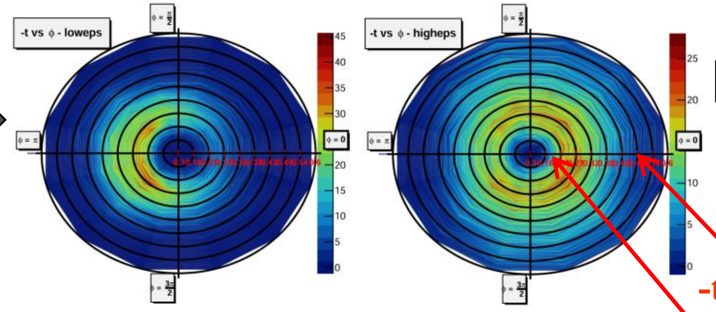
Q^2 = 3.85 GeV^2, W = 2.62 GeV (2 epsilons)

L/TSeparation Iteration Procedure

Diamond cut



Improve φ coverage by taking data at multiple π (HMS) angles, $-2^o<\theta_{\pi q}<2^o$.



$\theta_{\pi q}=0$ $\theta_{\pi q}=+2$

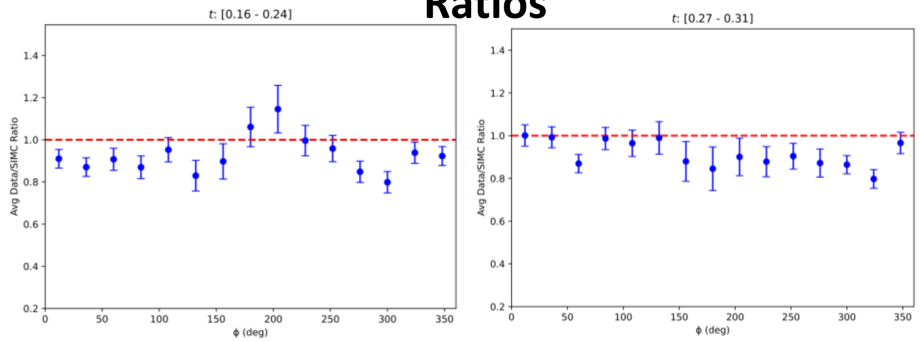
Q2 = 3.85, W = 2.62, t = 0.21 (2 epsilons)

For each π HMS setting, form ratio:

$$R=\frac{Y_{EXP}}{Y_{SIMC}}$$

Combine ratios for π settings together, propagating errors accordingly.

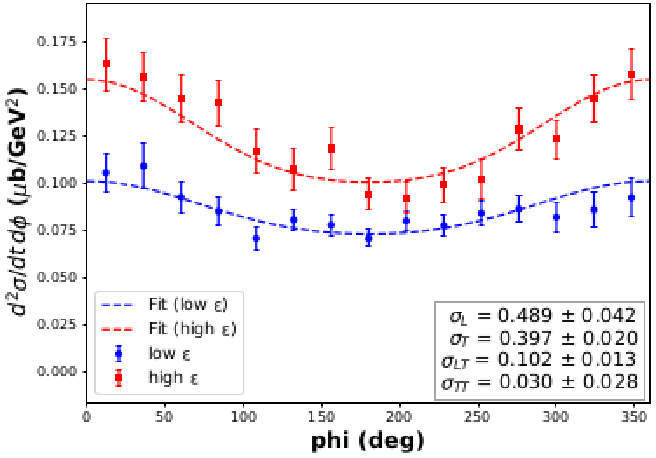
Ratios



$$\frac{d^2\sigma}{dtd\varphi}_{EXP}=\left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\frac{d^2\sigma}{dtd\varphi}_{SIMC}$$

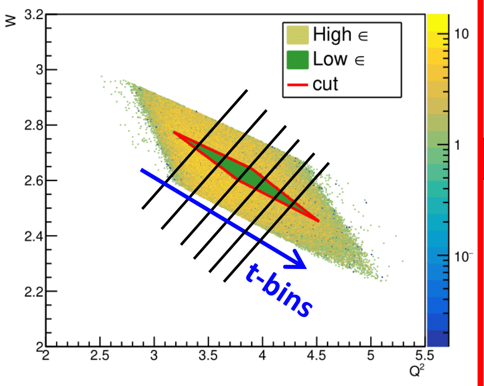
$$2\pi\frac{d\sigma}{dtd\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos2\phi$$

Extract via simultaneous fit of L,T,LT,TT



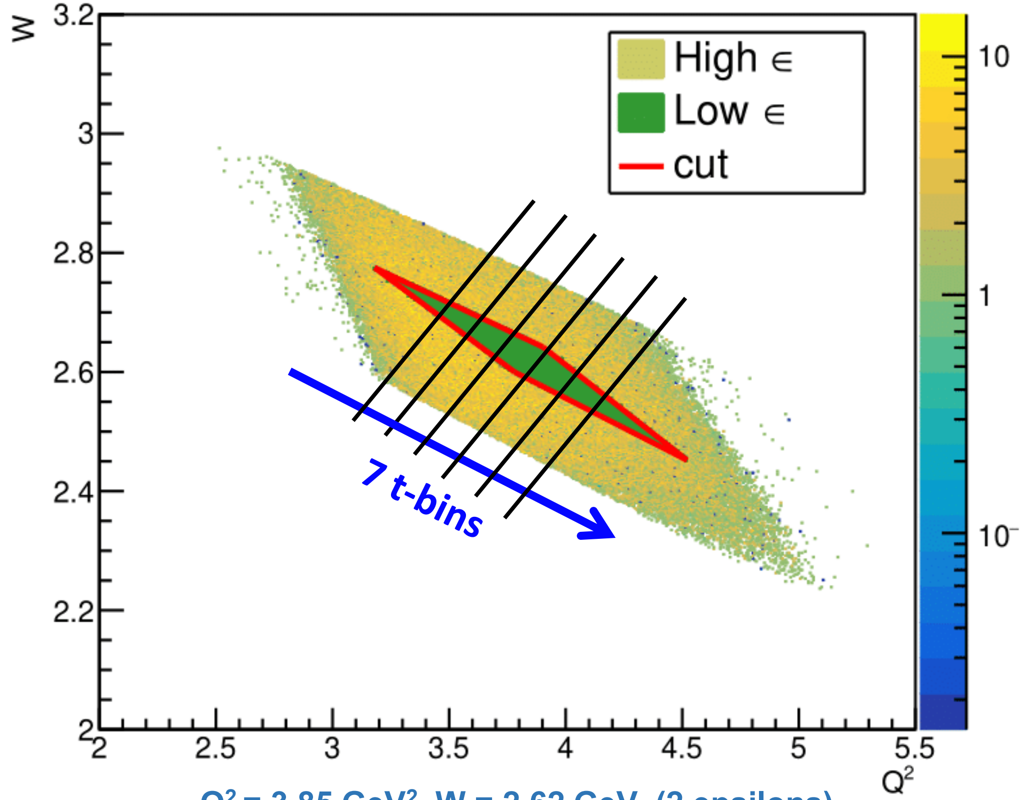
Importance of Diamond Region

Diamond cut



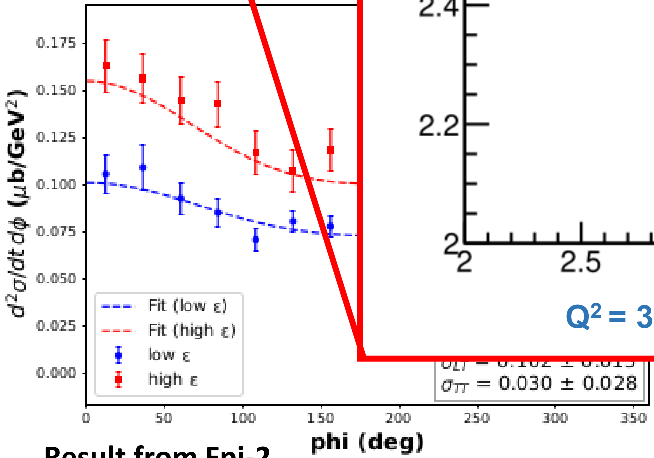
Improve φ coverage by taking data at
n

For each π HMS setting, form ratio:



Q^2 = 3.85 GeV², W = 2.62 GeV (2 epsilons)

- **Electron spectrometer acceptance is larger for high ϵ.**
- **Selected an overlapped phase-space region.**
- **Divided data into 7 t-bins based on data statistics.**
- **Purpose is to ensure consistency across different kinematic settings and measure the t-dependence**



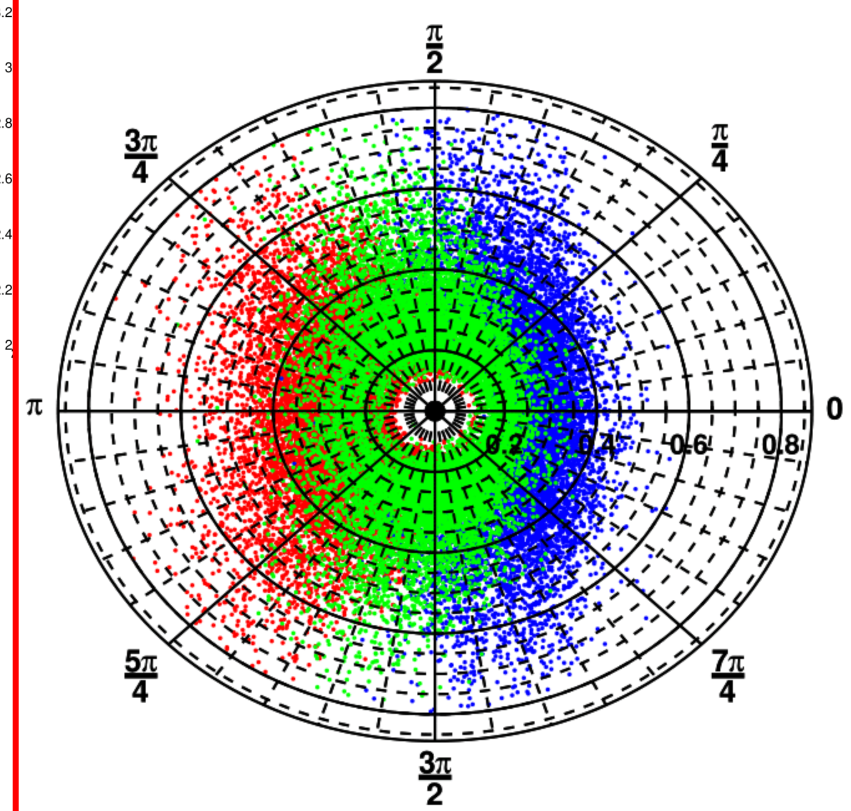
Result from Fpi-2

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

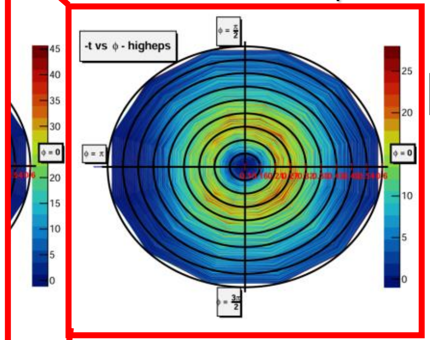
Full ϕ-Coverage

Diamond cut

Improve φ coverage by taking data at
…S) angles, $-2^o<\theta_{\pi q}<2^o$.

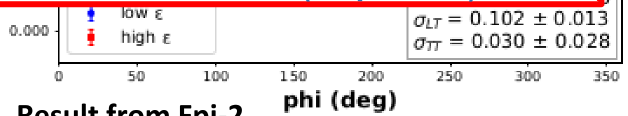


Q2 = 3.85, W = 2.62, t = 0.21 (2 epsilons)



$\theta_{\pi q}$=+2

…2.62, t = 0.21 (2 epsilons)



Result from Fpi-2

For each ε HMS setting, form ratio:

- To get full-ϕ coverage, data is taken on two degrees on the right and left of the central angle by rotating the pion arm.
- **Red corresponds to the right angle pion arm setting**
- **Green corresponds to the central angle pion arm setting**
- **Blue corresponds to the left angle pion arm setting**
- Divided data into 15 ϕ-bins to measure the ϕ dependence.

$$2\pi\frac{d\sigma}{dt\,d\phi} = \ldots \frac{\ldots}{dt} + \frac{\ldots}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{\ldots}{dt}\cos\phi + \epsilon\frac{\ldots}{dt}\cos 2\phi$$

Normalized Yield Calculation

- ❑ The goal is to calculate the experimental cross-sections using the ratio method.

$$\frac{d^2\sigma}{dtd\phi}_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\frac{d^2\sigma}{dtd\phi}_{SIMC}$$

- ❑ Calculated normalized bin-by-bin data yield.

$$Y_{EXP} = \frac{N}{Q_{\text{eff}}}$$

where,

$$Q_{\text{eff}} = Charge \times Tracking\ Eff \times Detector\ Eff \times EDTM\ Live\ Time \times Boiling\ Corr \times other\ normalization\ factors \ldots\ldots$$

- ❑ Same cuts, binning, and kinematic selections criteria is applied to Monte Carto (SIMC) to calculate the normalized bin-by-bin SIMC yields.

Normalization Factors	Comments
Charge	Calculated run-by-run
HMS & SHMS Tracking Efficiencies	> 98%
Live Time Correction	>98%
HMS Cerenkov Efficiency	>99%
HMS Calorimeter Efficiency	>99%
SHMS Aerogel Efficiency	>98%
HMS & SHMS Hodoscope Efficiency	>98%
RF Efficiency	>99%
Boiling Correction Factor	Calculated run-by-run
Coin Blocking Correction	Calculated run-by-run
Pion Absorption Correction	~97%

Normalized Yield Calculation

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- Same cuts, binning, and kinematic selections criteria is applied to Monte Carto (SIMC) to calculate the normalized bin-by-bin SIMC yields.
- Calculated ratios (DATA/SIMC) for each t & phi-bin setting-by-setting, separately.

$$R(t,\varphi) = \frac{Y_{\text{EXP}}}{Y_{\text{SIMC}}}$$

- Combined data from each pion arm angle setting per ϵ by calculating their error-weighted average.

Normalization Factors	Comments
Charge	Calculated run-by-run
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Live Time Correction	>98%
HMS Cerenkov Efficiency	>99%
HMS Calorimeter Efficiency	>99%
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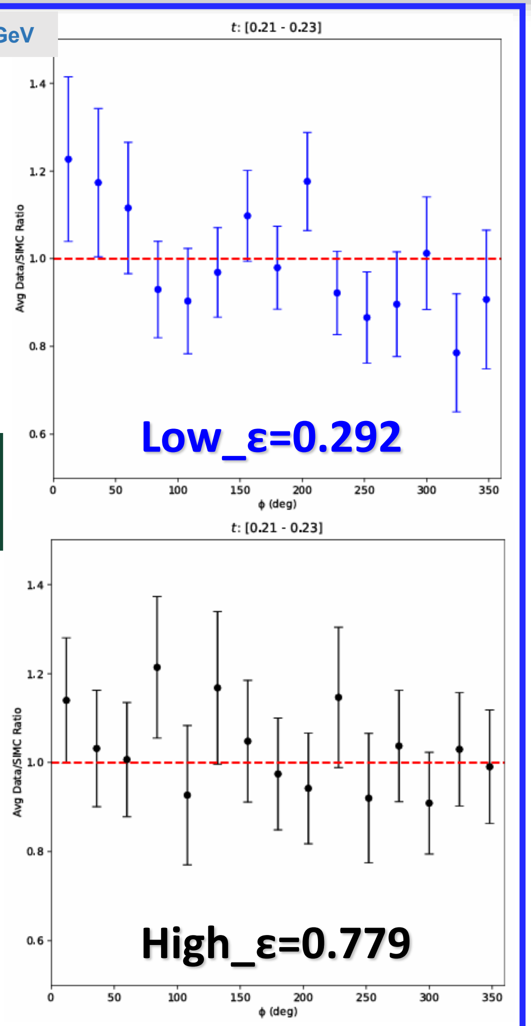
RF Efficiency	>99%
Boiling Correction Factor	Calculated run-by-run
Coin Blocking Correction	Calculated run-by-run
Pion Absorption Correction	~97%

Jefferson Lab
Thomas Jefferson National Accelerator Facility

High & Low-epsilon Data/MC Ratios

$Q^2 = 3.85\ \mathrm{GeV}^2$, $W = 2.62$ GeV

$$R(t,\varphi) = \frac{Y_{\mathrm{EXP}}}{Y_{\mathrm{SIMC}}}$$

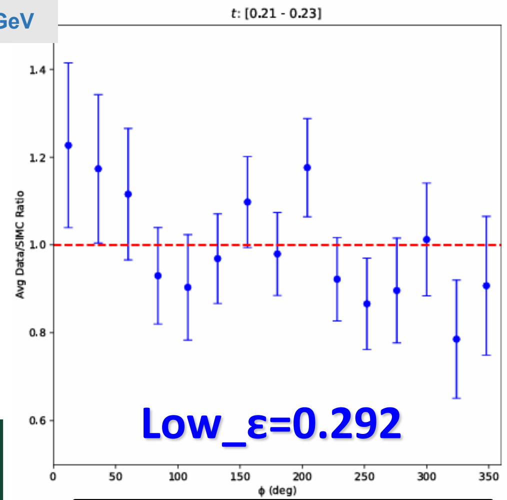


University of Regina Go far, together.

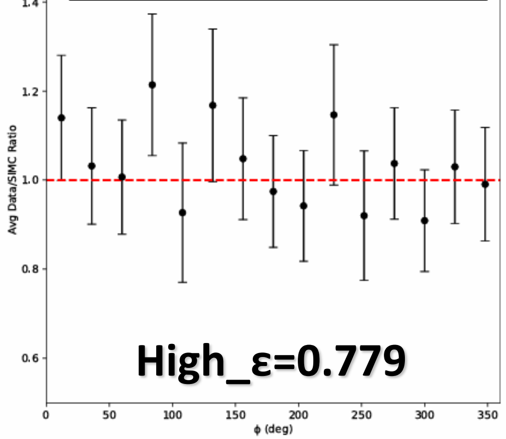
High & Low-epsilon Data/MC Ratios

Q² = 3.85 GeV², W = 2.62 GeV

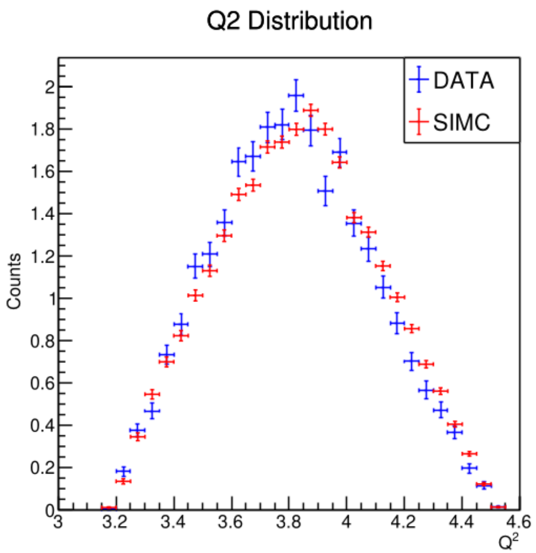
$$R(t,\varphi) = \frac{Y_{\text{EXP}}}{Y_{\text{SIMC}}}$$



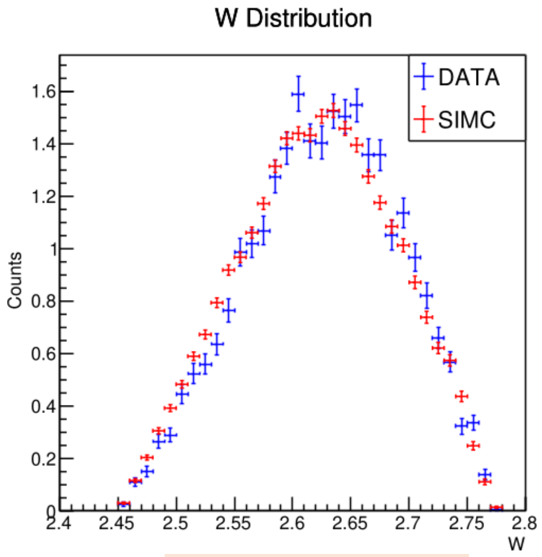
Ratios are consistent



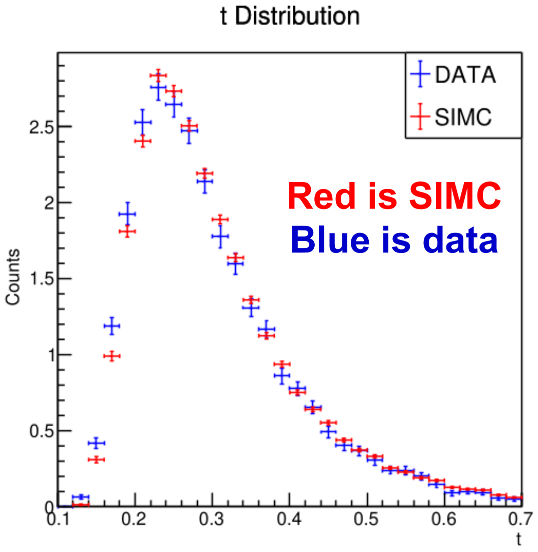
Compared kinematic and spectrometer variables between data and SIMC to verify that the SIMC model reliably reproduces the measured distributions.



$$Q^2 = -(P_e - P_{e'})^2$$



$$W^2 = (P_\gamma + P_P)^2$$



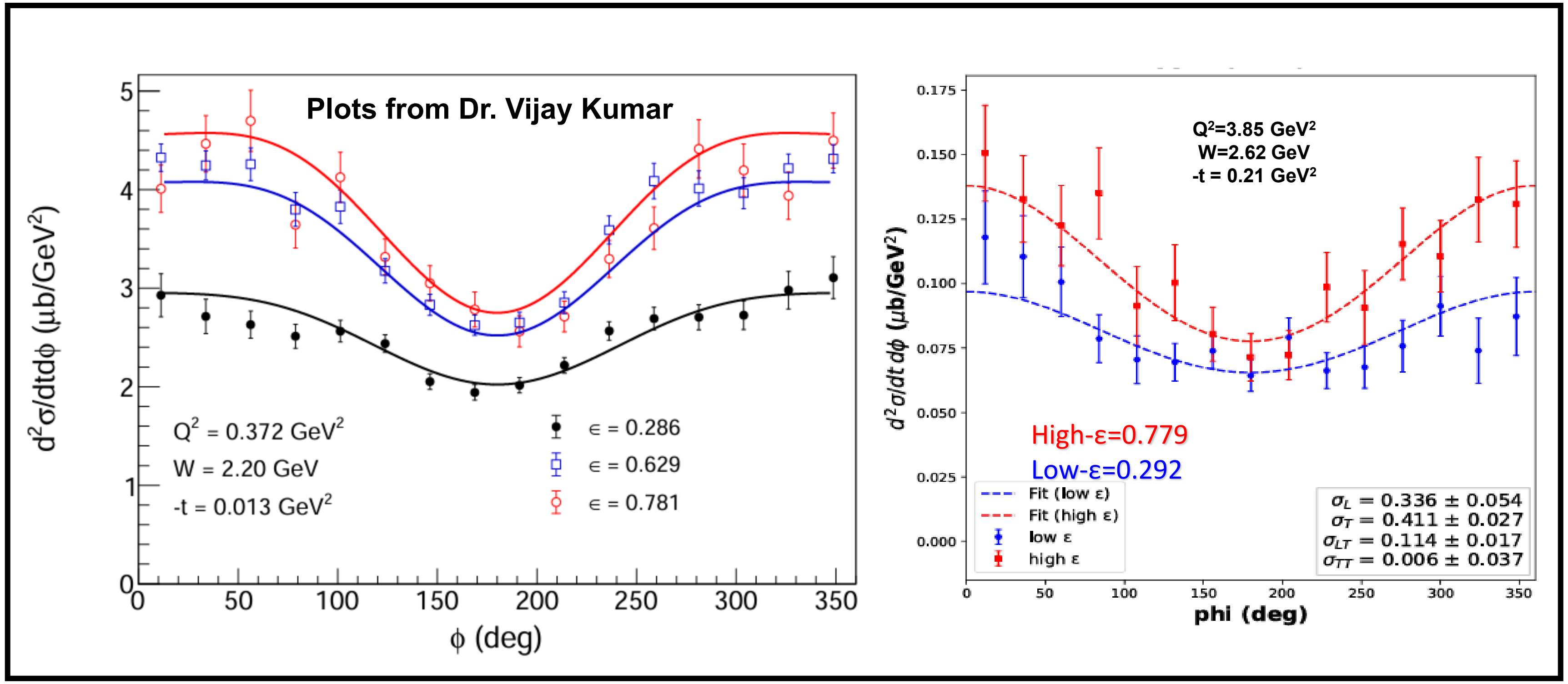
$$t = (P_\gamma - P_\pi)^2$$

Red is SIMC
Blue is data

Q² = 3.85 GeV², W = 2.62 GeV (low-epsilons)

L/T Separated Cross-section Measurements

- This L/T Separation technique is model-dependent.
- Requires the SIMC empirical model to reproduce data.
- Only reliable if SIMC reproduces the data well in both shape and normalization.
- Fit the Rosenbluth equation to extract the cross-section components.
- Need to iteratively tune L/T/LT/TT empirical model until MC reproduces experimental data.



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

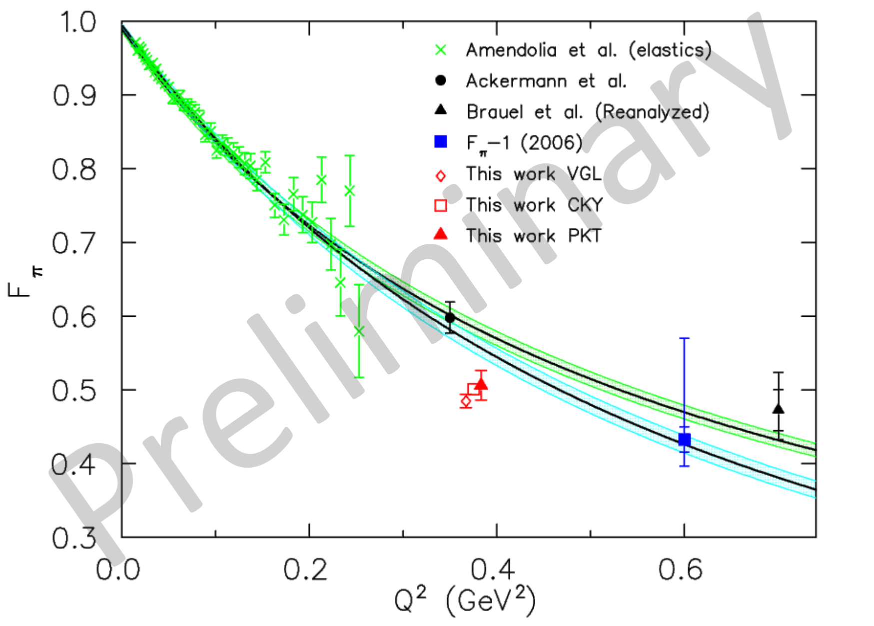
Model Dependence & Future Extraction of F_π

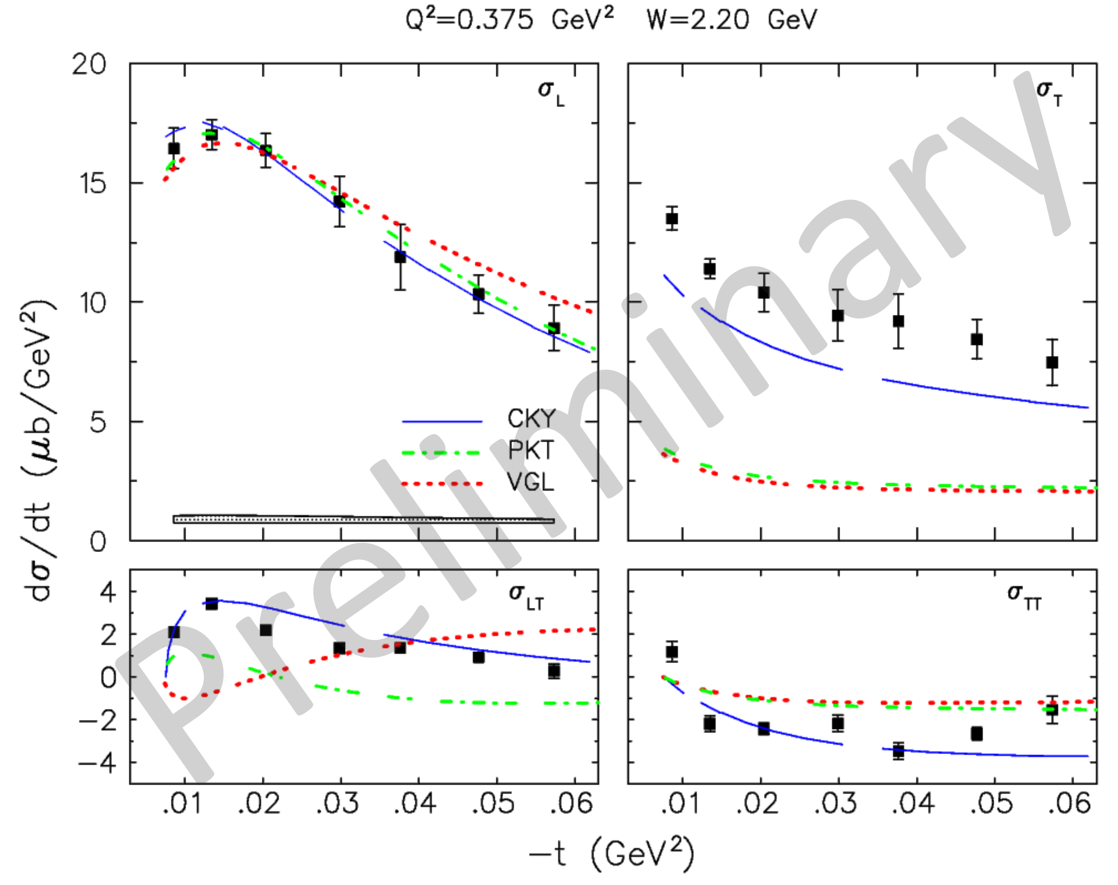
- **Our philosophy is to publish our experimentally measured $\frac{d\sigma_L}{dt}$, so that updated values of $F_\pi(Q^2)$ can be extracted as improved theoretical models become available.**
- Jefferson Lab F_π experiments have primarily used three models for form-factor extraction:
  - **VGL Regge Model** — Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)
    - VGL model has proven to give a **reliable description of σ_L** over a across a wide kinematic domain.
    - However, VGL **significantly underestimates** σ_T, indicating the need for improved models to fully describe the separated cross-section data.
  - **CKY Regge Model** — Choi, Kong, Yu, JKPS 67, L1089 (2015)
    - **This motivated the development of the CKY model**, aimed at improving the description of σ_T without degrading the successful description of σ_L.
  - **PKT Model** — Perry, Kizilersu, Thomas, PLB 807, 135581 (2020)
    - A **modern pion electroproduction model** was developed to improve theoretical consistency and study model dependence in the extracted $F_\pi(Q^2)$.
    - The PKT model provides an alternative framework for comparing how different reaction models affect the form-factor extraction.

- **More theoretical models are welcome**, especially those capable of describing both σ_L and σ_T consistently.

Results from Low-Q^2 Pion-LT Experiment

- **CKY model describes the t–dependence of σ_L very well.**
- **The VGL and PKT models dramatically underestimate the σ_T**
- **CKY model provides much better T/L ratio, as expected.**
- **CKY model is also doing good job for σ_{LT} and σ_{TT} .**
- **The results are consistent with the elastic fits of Amendolia et al. - ~one standard deviation below**



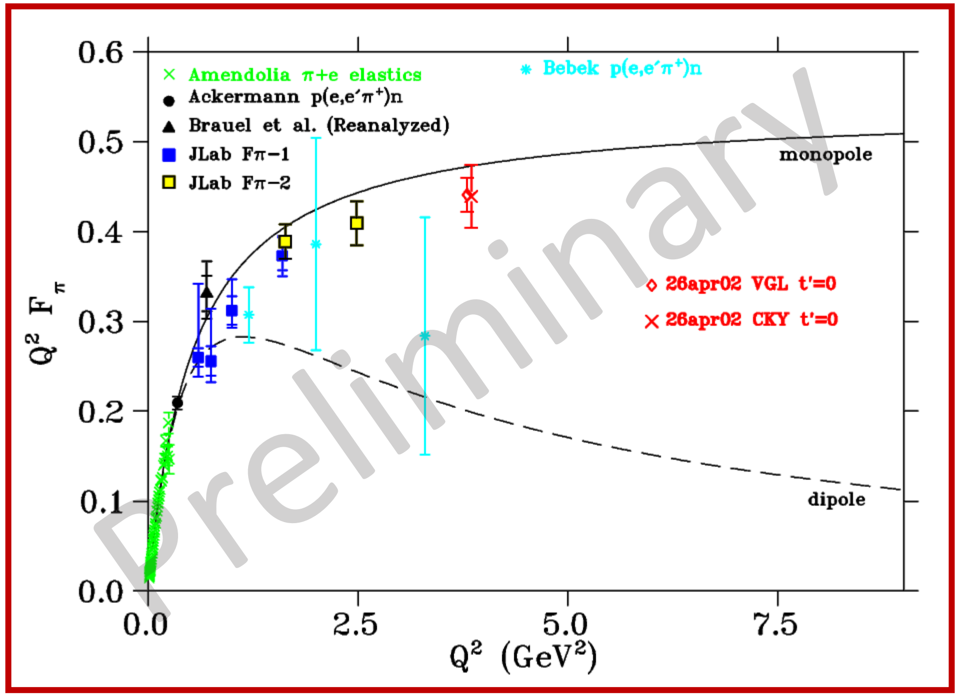


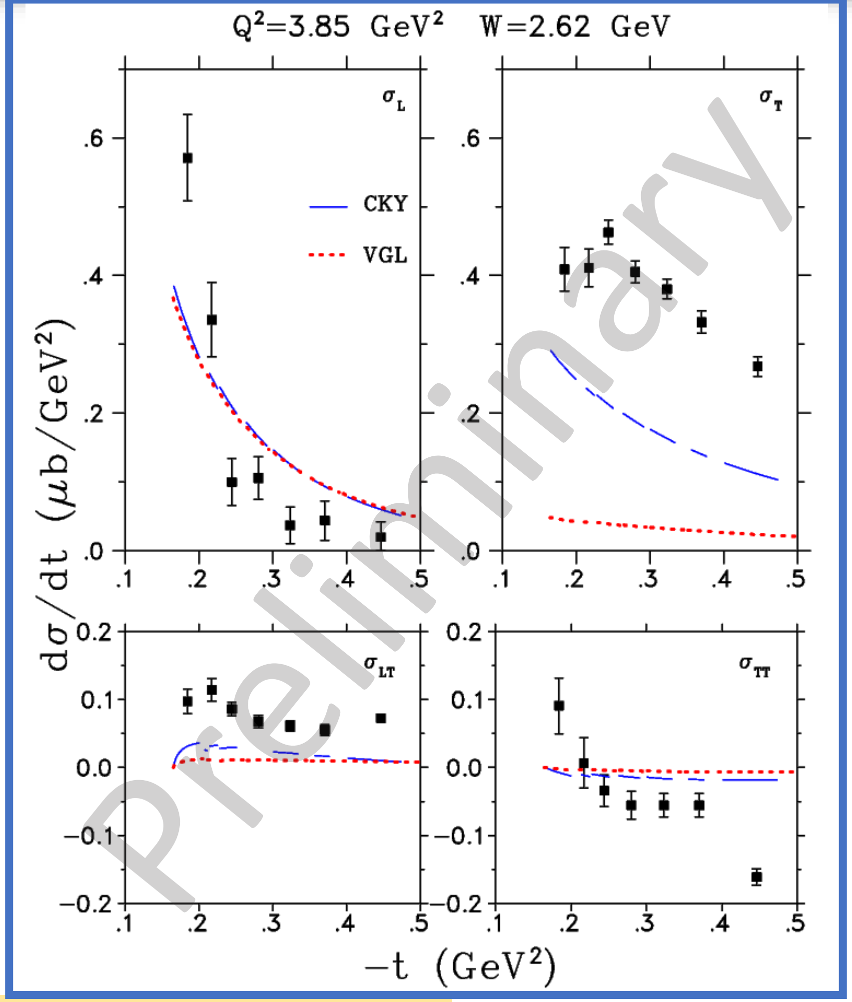
Plots from Dr. Vijay Kumar

Model is evaluated at precise kinematics of data. Discontinuities indicate change in (Q^2,W) for each t-bin.

Results from Moderate-Q^2 Pion-LT Experiment

- The VGL model struggles to describe the t-dependence of σ_L well, and dramatically underestimates T/L ratio.
- The CKY model also struggles to describe the t-dependence of σ_L well, but has a better T/L ratio.
- Comparison with PKT Model is in progress.





Model is evaluated at precise kinematics of data. Discontinuities indicate change in (Q^2,W) for each t-bin.

Summary and Future Plans

- E12–19–006 (12 GeV Flagship Experiment) is expected to provide the definitive $p(e, e'\pi^+)n$ L/T–separation data set and will remain important for decades to come.

- Preliminary L/T separation is completed for Q^2=0.37 GeV^2 and Q^2=3.85 GeV^2 physics settings.

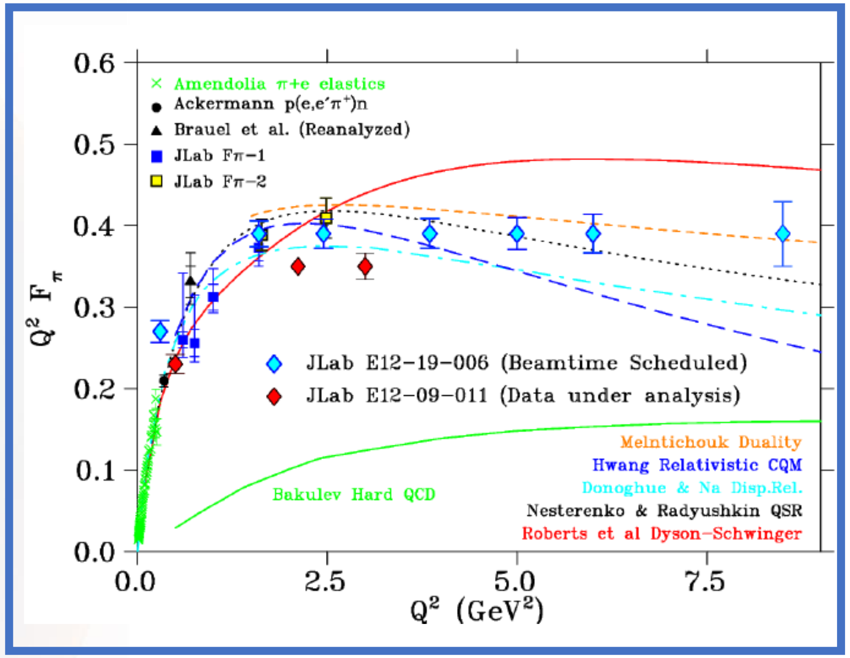
- Systematic uncertainty studies still need to be done for Q^2=3.85 GeV^2.

- Will analyze the other two Q^2=3.85 physics settings to calculate the L/T separated cross-sections using the Rosenbluth technique and extract the pion form factor.

- Will do a detailed comparison with existing VGL, CKY, and PKT theoretical models.

- Results will help to understand the dependence of the Form factor and in validating theoretical models.

- Expected to be graduated in fall 2026. Publications are expected soon.



Projected Results

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