Exploring Hadronic Structure: Precision Rosenbluth Separation for the Pion Form Factor at Jefferson Lab

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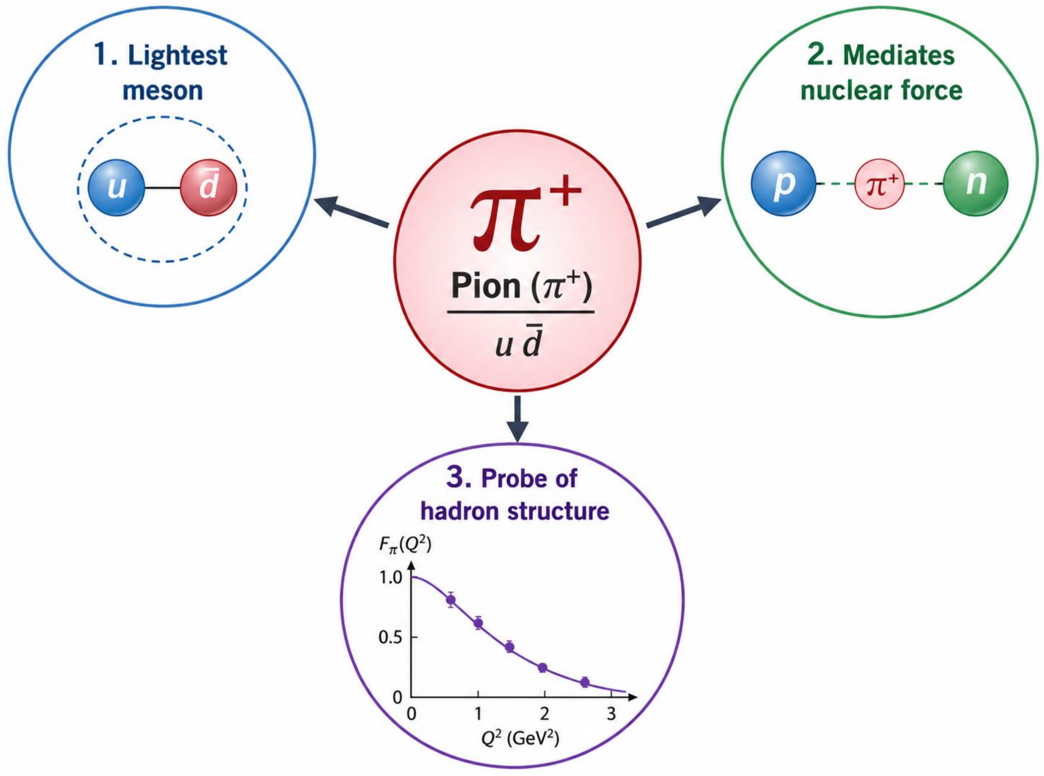
CAP Congress 2026

June 23rd, 2026

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 by describing the transverse spatial position of partons within 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**.



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

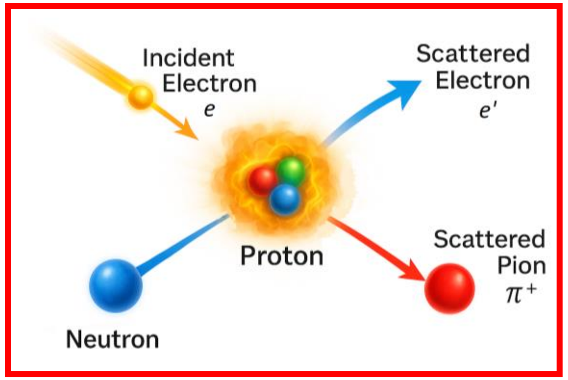
- Indirect measurement – Form factor extraction requires a model.

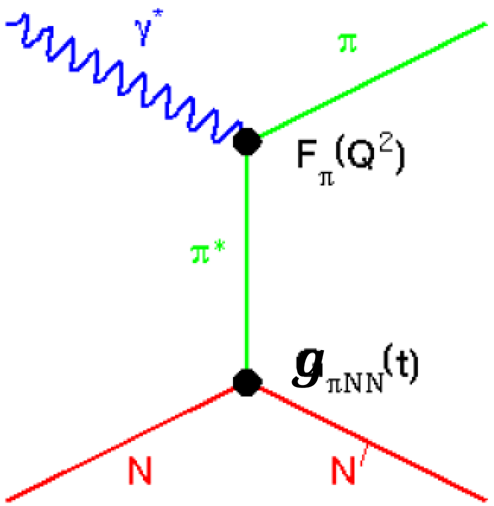
- Need to extract σ_L from the total cross-section.

- 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 Regge base model such as VGL, CKY and PKT Models for $F_\pi^2(Q^2, t)$ extraction.





Rosenbluth Separation Technique

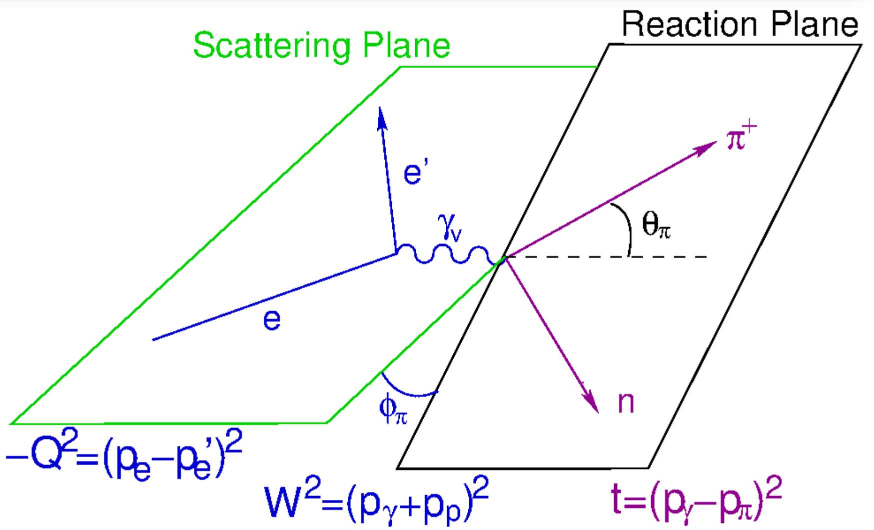
- **Rosenbluth separation required to isolate σ_L for L/T separation.**
- The physical cross-section for the electroproduction process is given by;

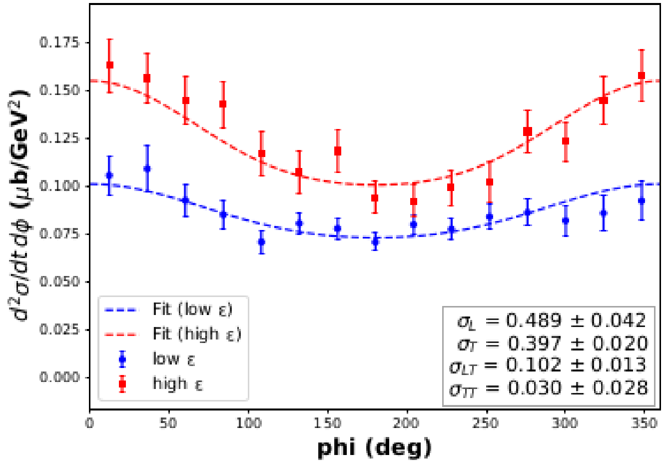
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

- Here "ϵ" is polarization of virtual photon.

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

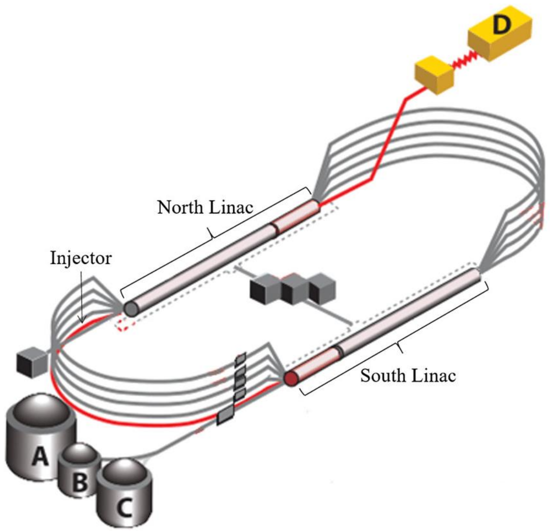
- Perform two scattering measurements with different beam energies "E_e" to vary "ϵ" and separate different cross-section terms.
- Careful attention must be paid to systematic studies such as spectrometer acceptance, kinematics, efficiencies, etc.

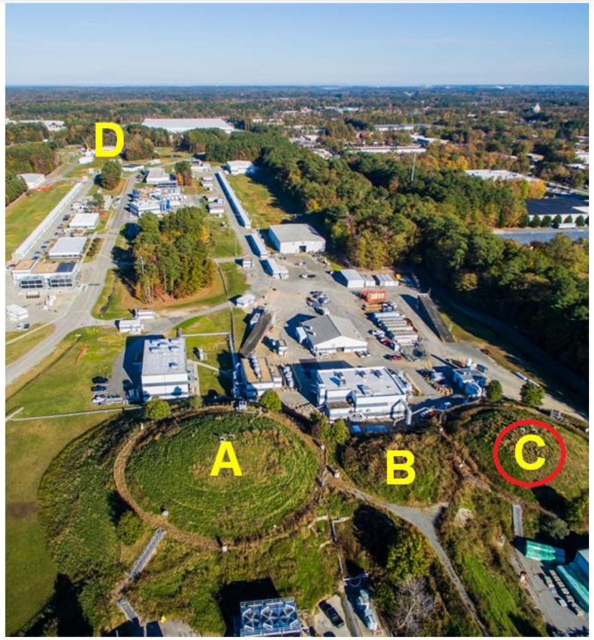




Pion-LT Experiment at JLab

- Located at Newport News, Virginia, USA.
- 2 Superconducting LINACs configured as "Racetrack".
- Continuous Electron Beam Accelerator Facility (CEBAF).
- Capable of $12 GeV$ beam up to $200 \mu A$.
- Four experimental halls, all running unique experiments and capable of running simultaneously.





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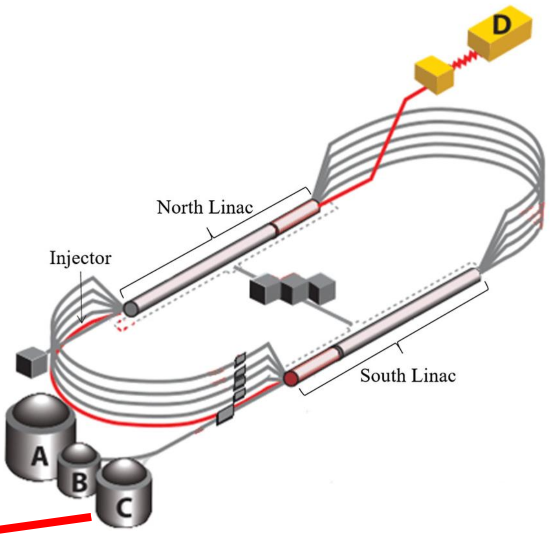
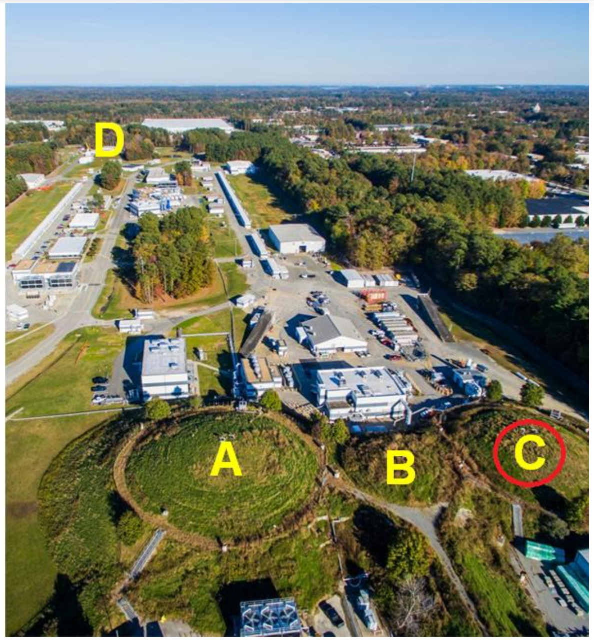
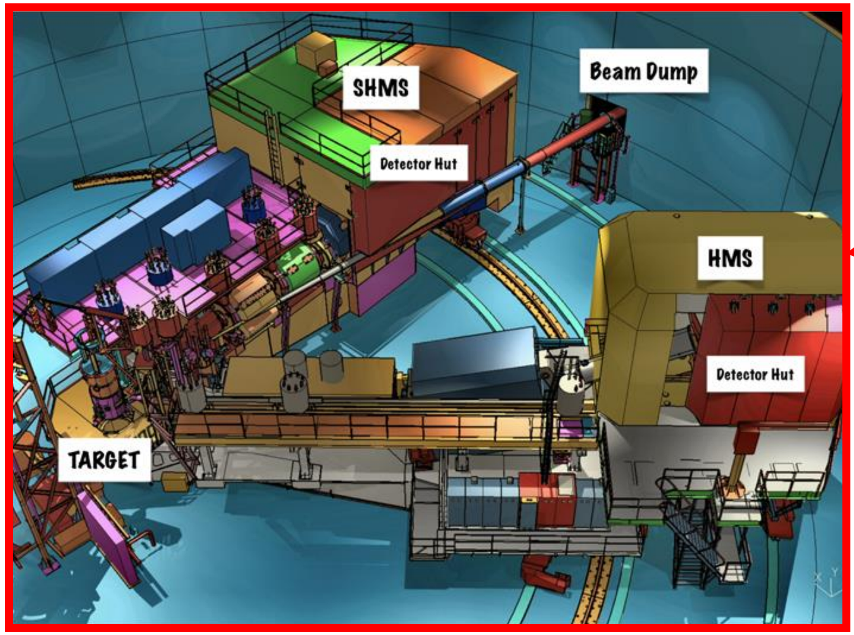






- Specially designed to measure precise cross-sections and form factors for mesons.
- Hall C has a target and two detector arms.
- Target can be Liquid H_2, Liquid D_2 or solid targets.
- Two detectors are;
  - High Momentum Spectrometer (HMS)
  - Super High Momentum Spectrometer (SHMS)

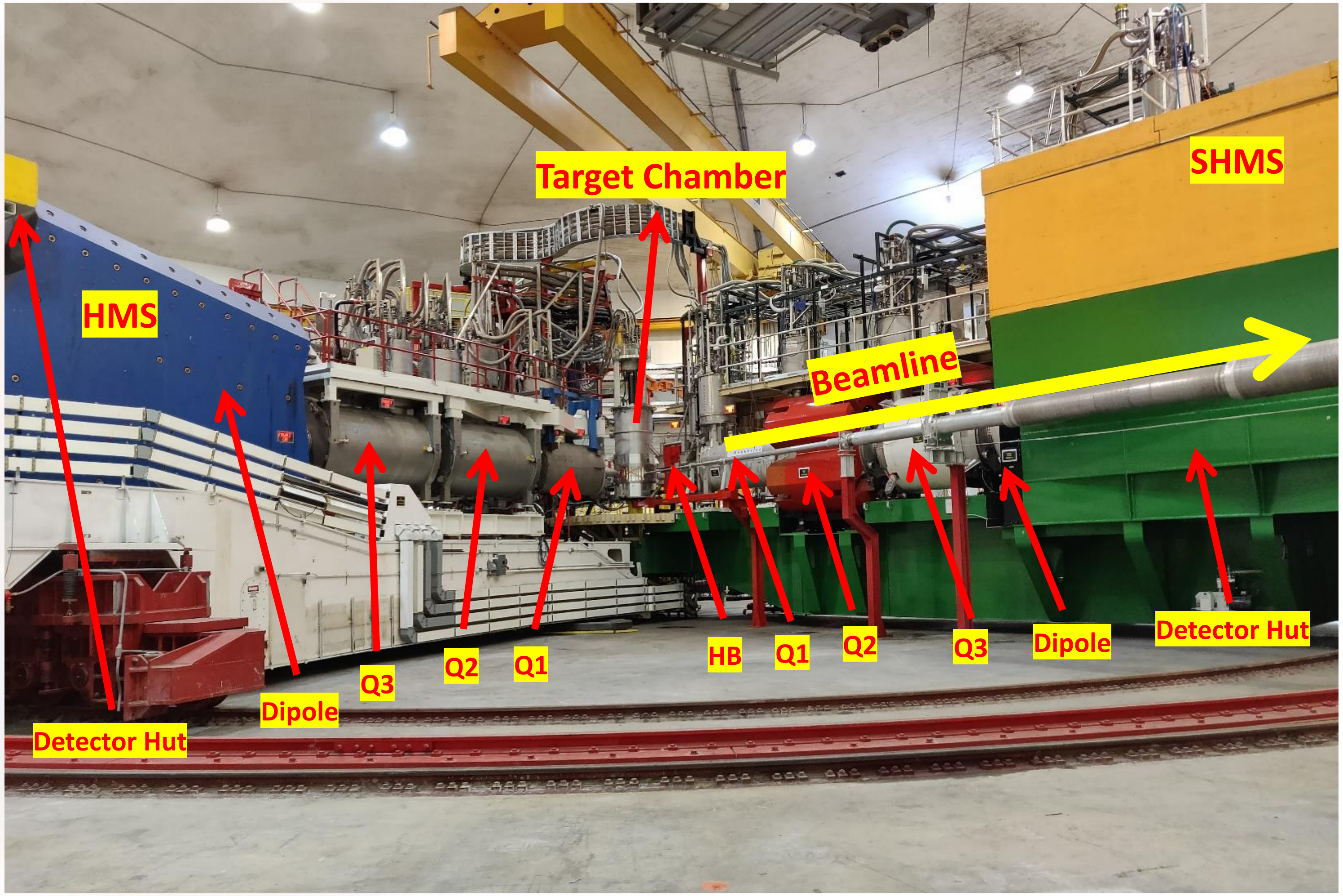
Hall C Spectrometers

- 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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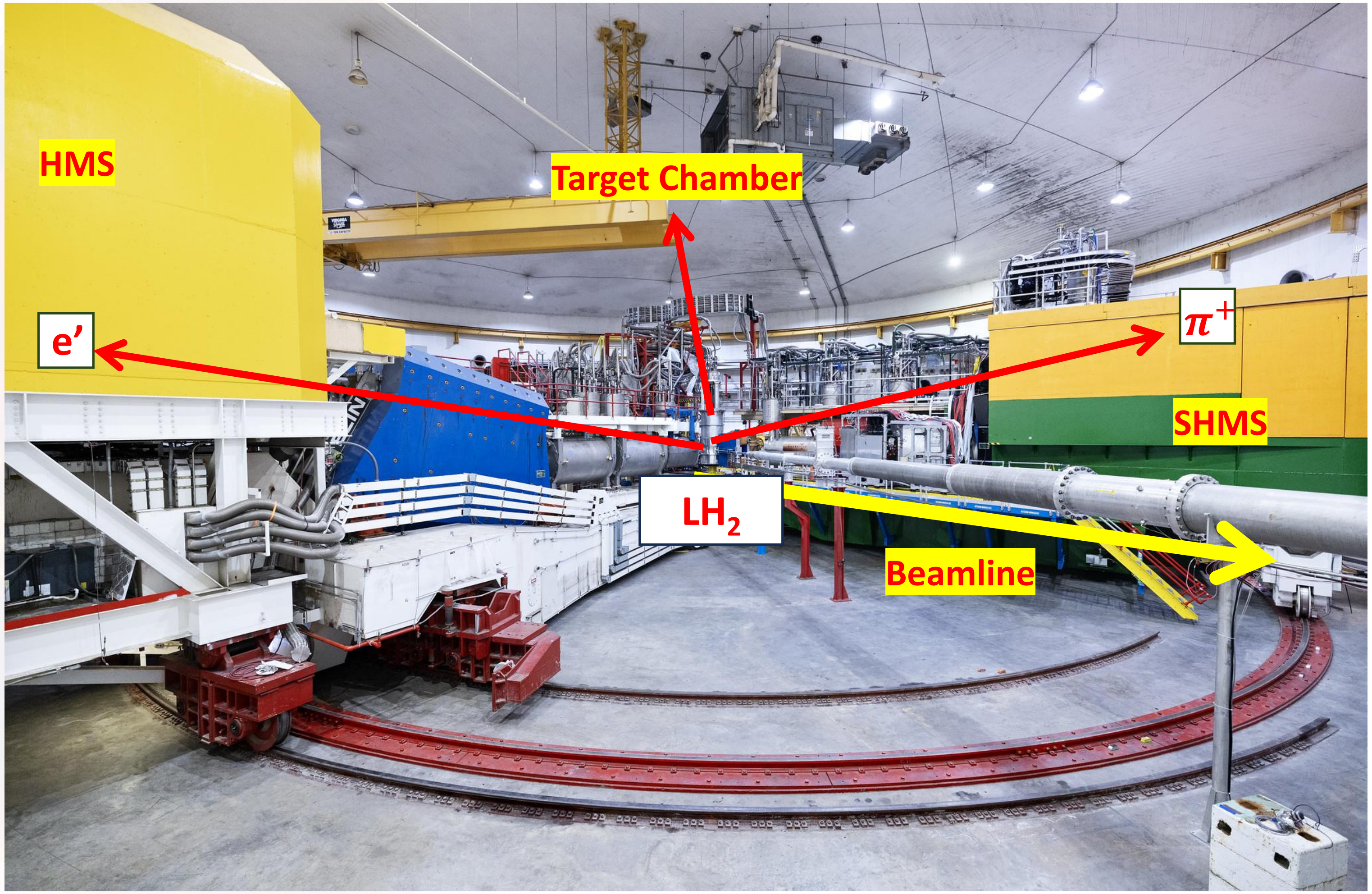
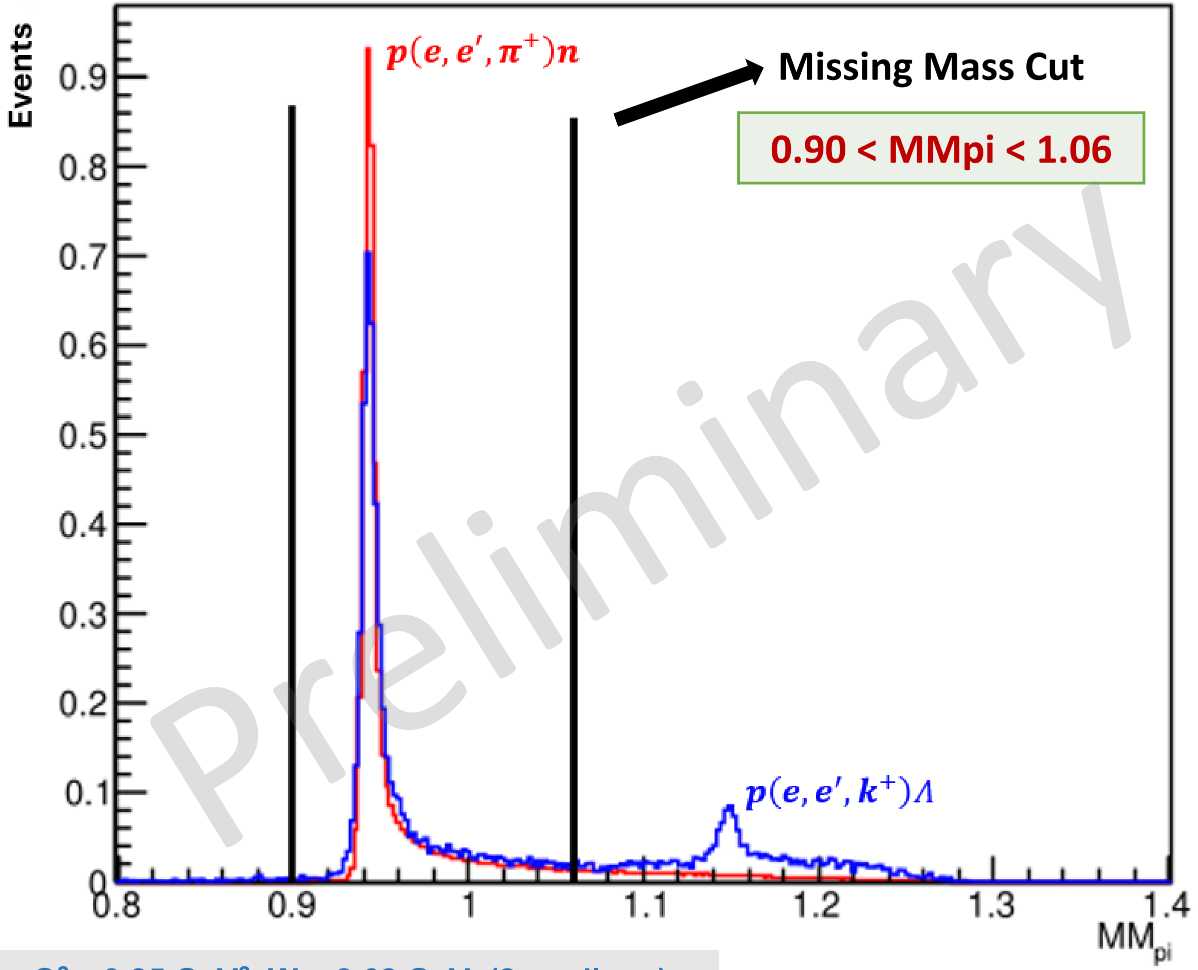


Selection of Event Sample

- 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)

Cross-section Measurements

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

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

- The same cuts and kinematic selection criteria were applied to both the data and the Monte Carlo.
- This technique is model-dependent.
- Requires the Monte Carlo empirical model to reproduce data.
- Only reliable if Monte Carlo reproduces the data well in both shape and normalization.

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- This technique is model-dependent.
- Requires the Monte Carlo empirical model to reproduce data.
- Only reliable if Monte Carlo reproduces the data well in both shape and normalization.

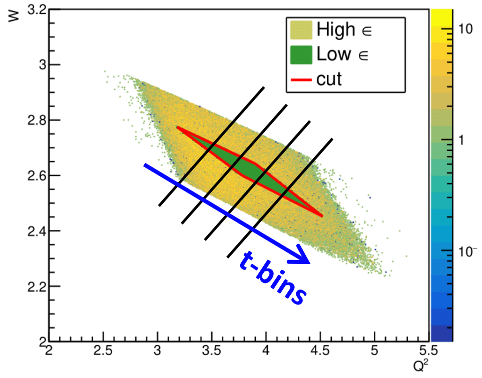
- Fit the Rosenbluth equation to extract the cross-section components.

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

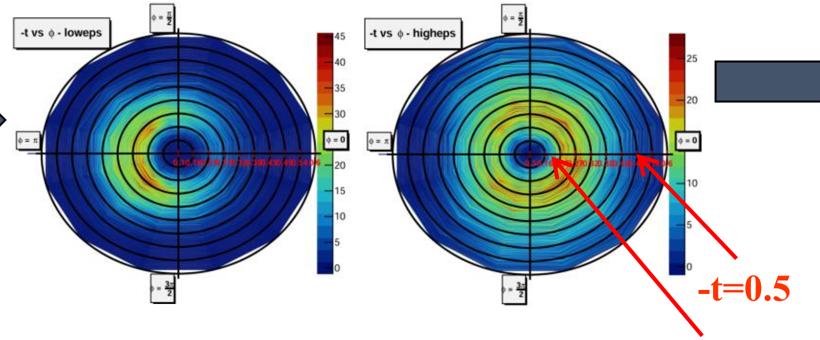
- Need to iteratively tune L/T/LT/TT empirical model until Monte Carlo reproduces experimental data.

L/T Separation Iteration Procedure

Diamond cut



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



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

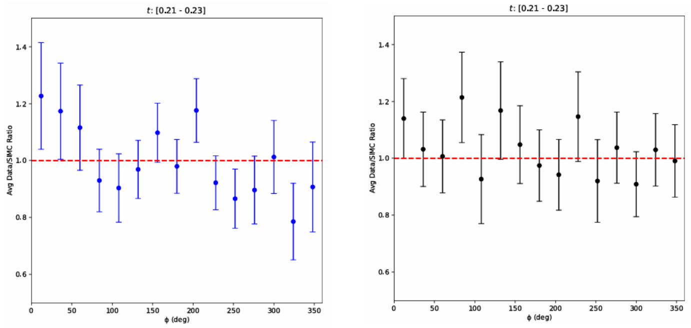
$Q^2 = 3.85$ GeV^2, W = 2.62 GeV (2 epsilons)

For each π HMS setting, form ratio:

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

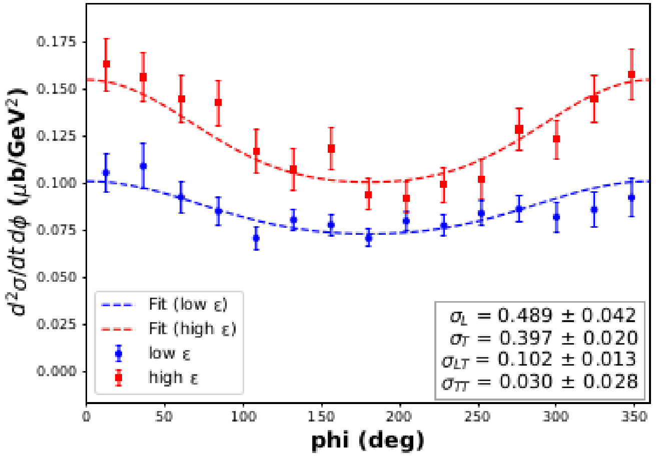
Combine ratios for π settings together, propagating errors accordingly.

Ratios



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

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



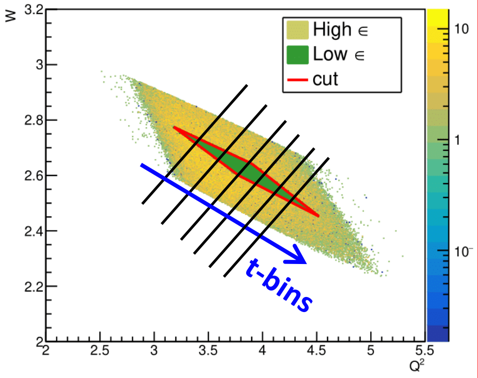
Extract via simultaneous fit of L,T,LT,TT

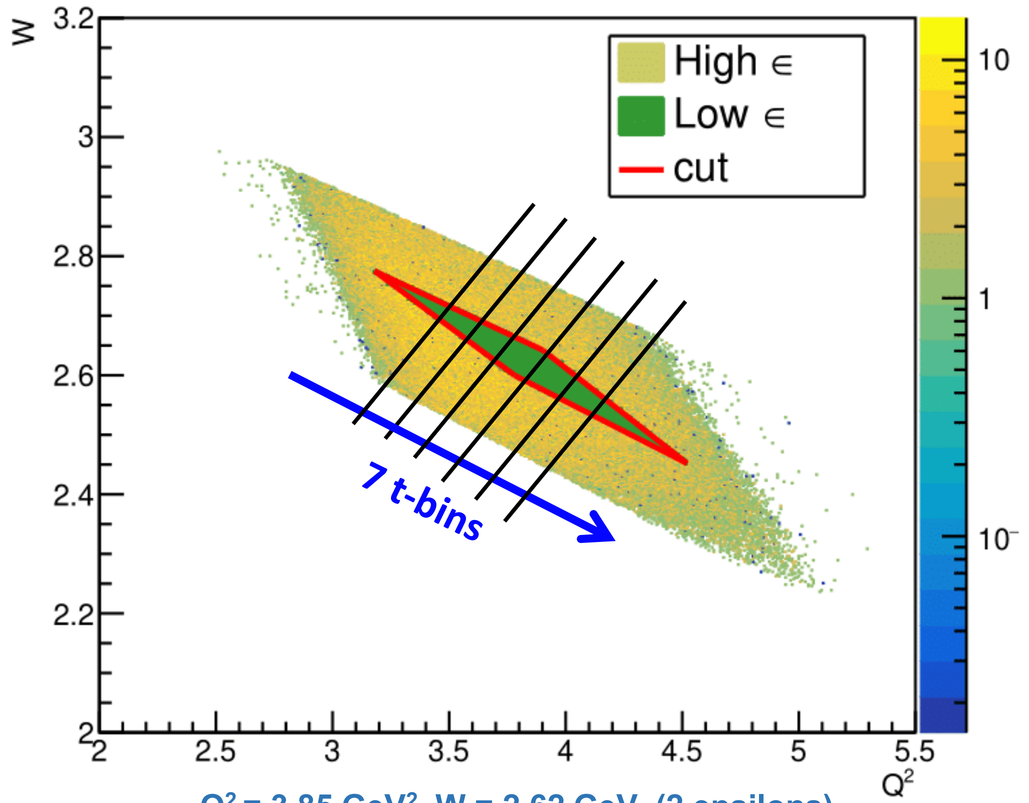
Importance of Diamond Region

Improve φ coverage by taking data at

For each π HMS setting, form ratio:

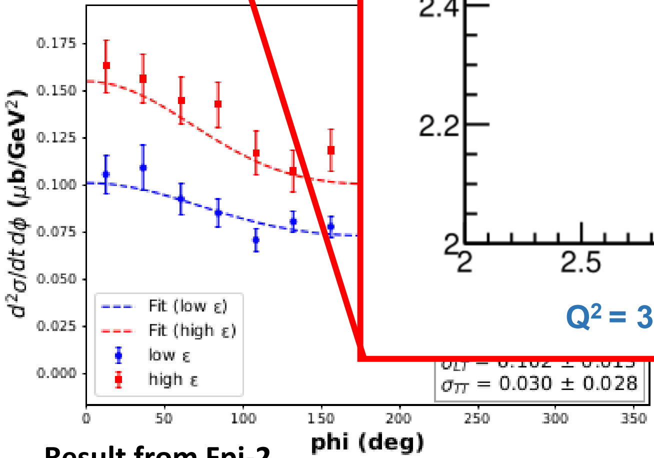
Diamond cut





Q^2 = 3.85 GeV^2, 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

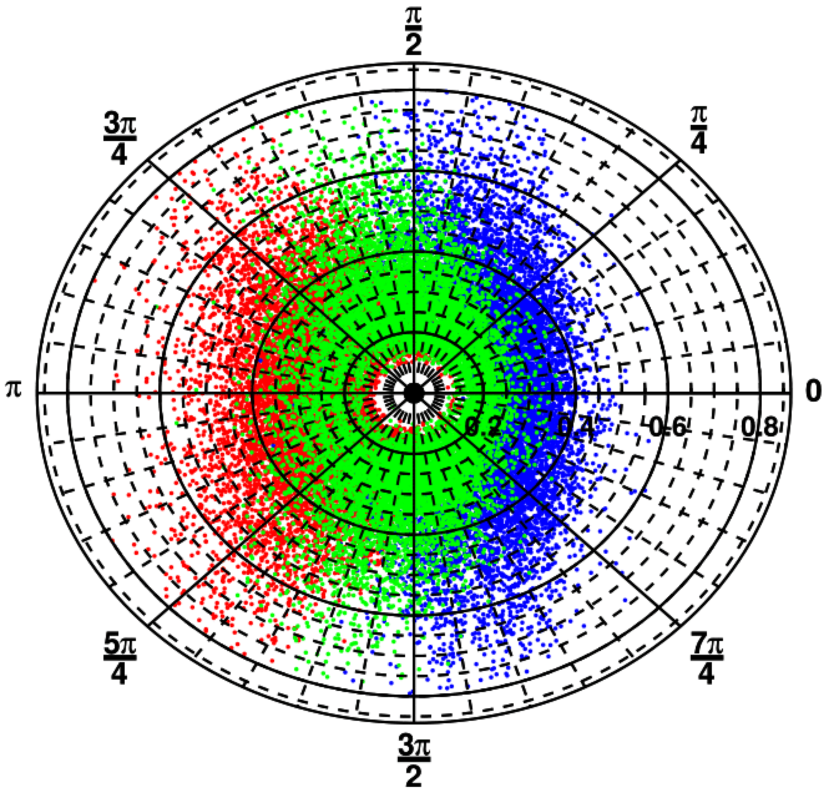
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Full ϕ-Coverage

Diamond cut

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

For each ε HMS setting, form ratio:



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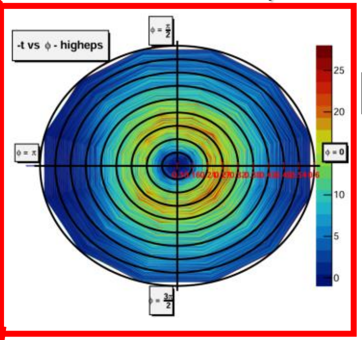
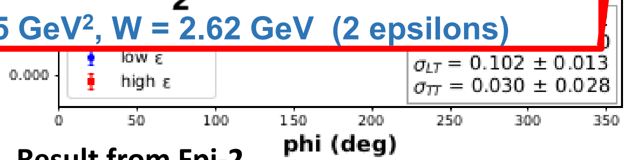


$\theta_{\pi q}$=+2

2.62, t = 0.21 (2 epsilons)



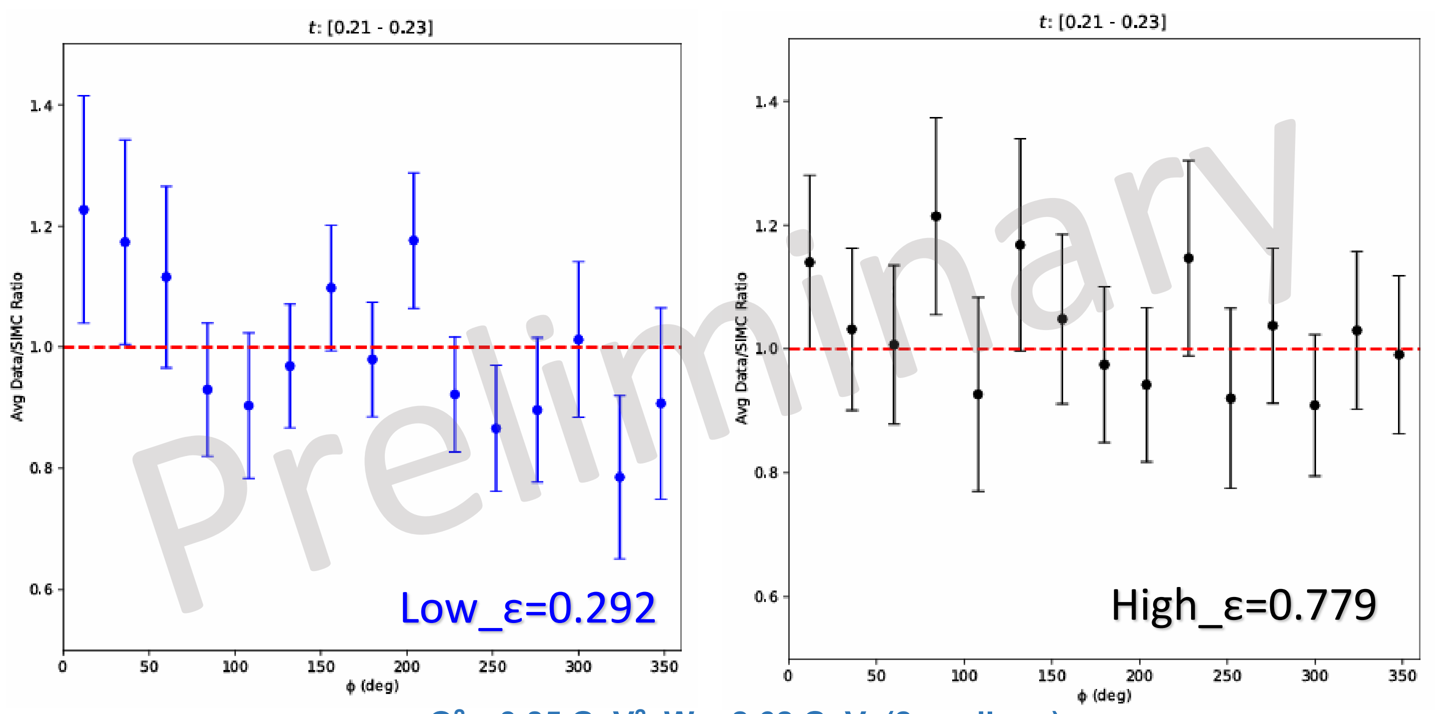
Result from Fpi-2

- 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.

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

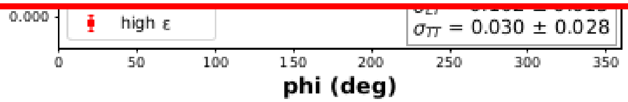
Low and High Epsilon Data/MC Ratios

Improve φ coverage by taking data at



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

Ratios are consistent



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Combine ratios for π settings together, propagating errors accordingly.

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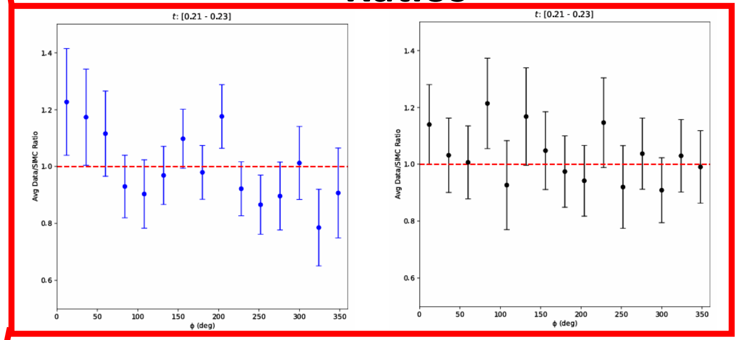

$$\left.\frac{d^2\sigma}{dt d\varphi}\right|_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\left.\frac{d^2\sigma}{dt d\varphi}\right|_{SIMC}$$

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

L/T Separa… ts

In…
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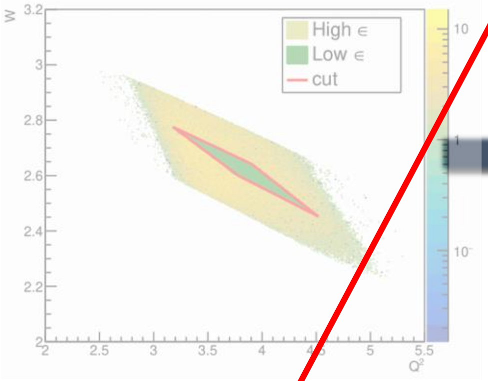
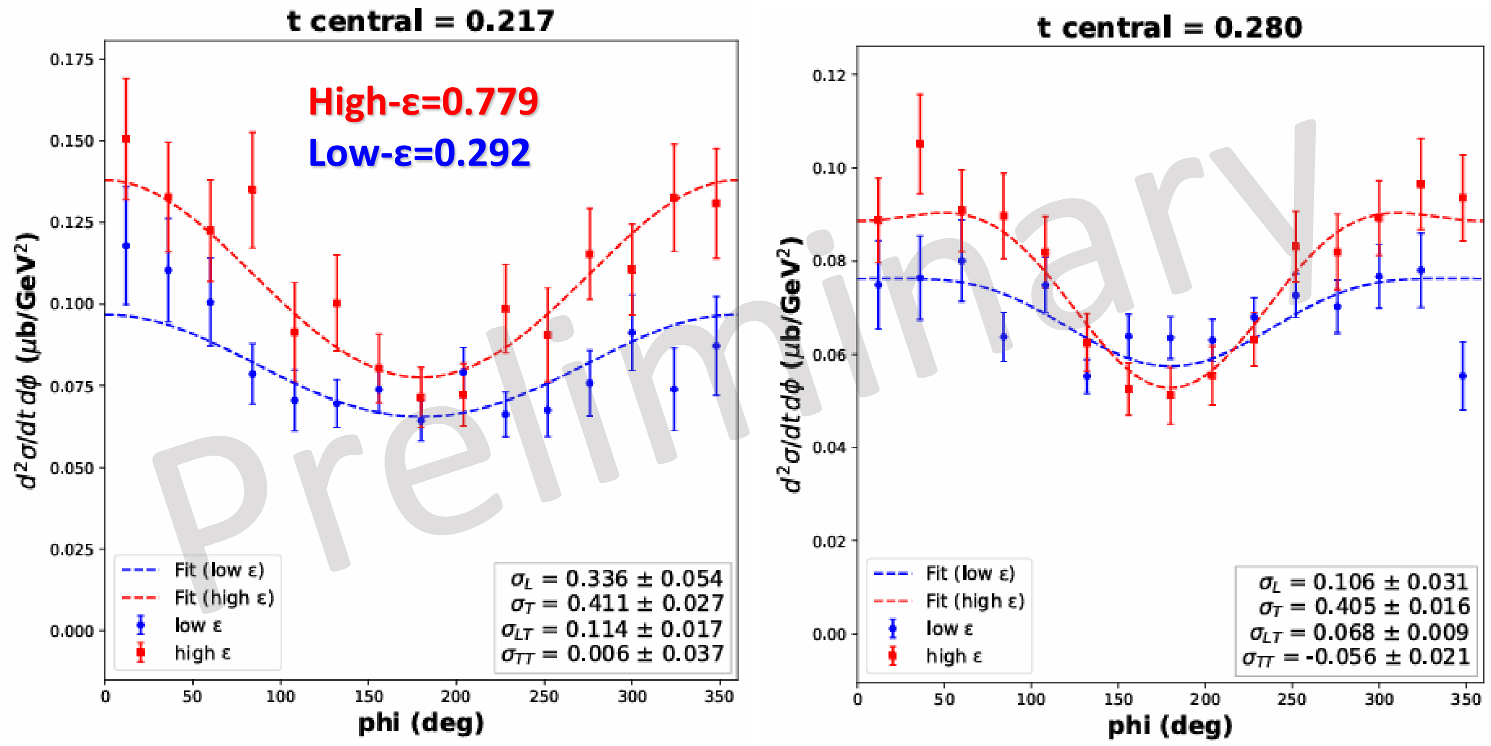
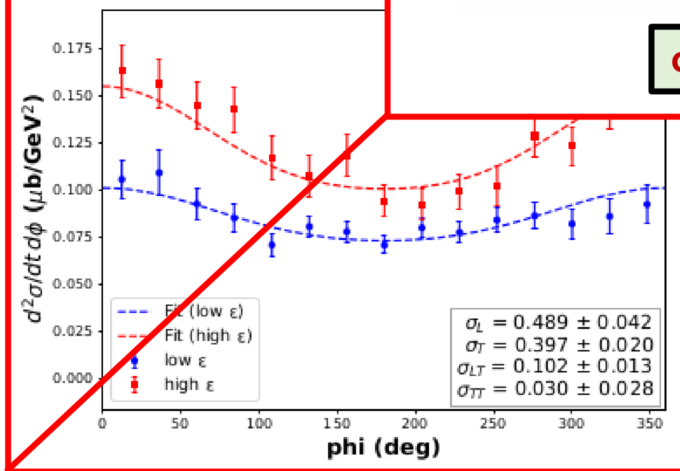




σ_L drops as we go to higher t

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



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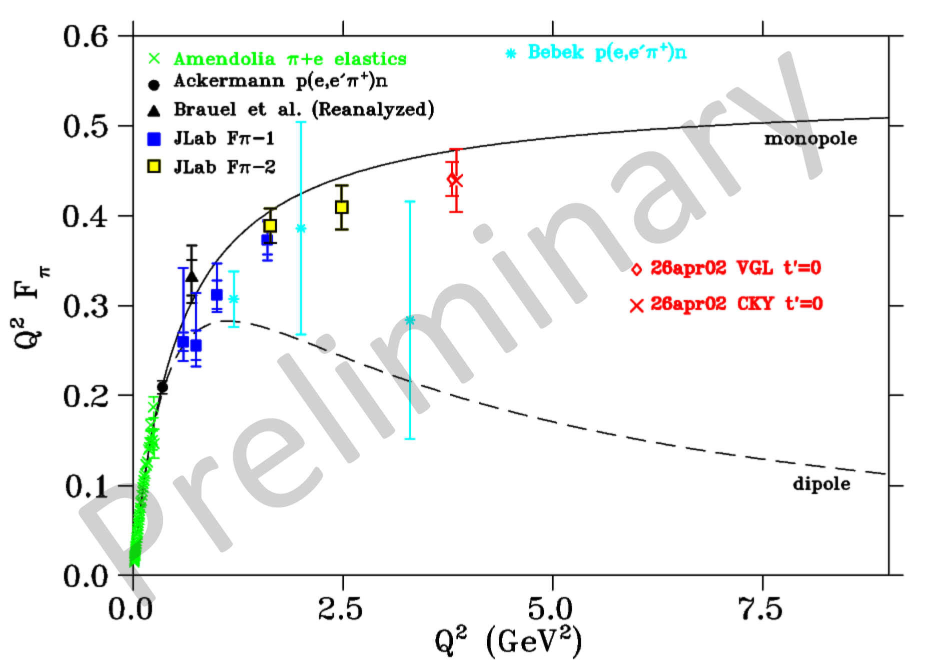
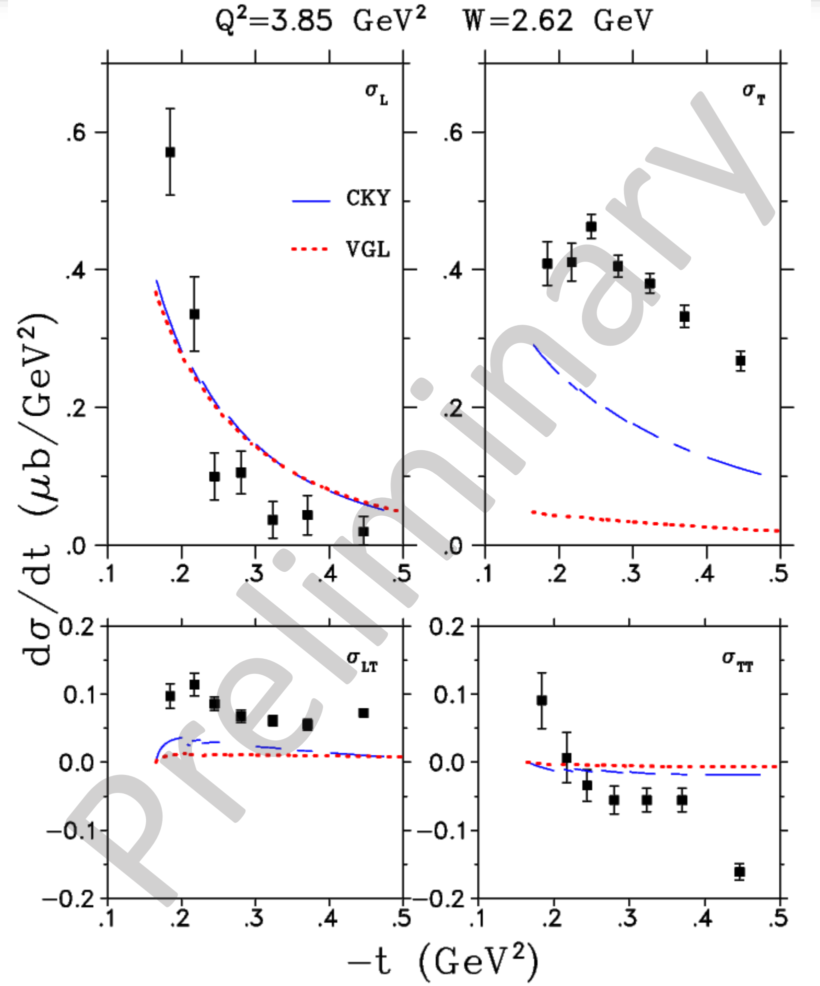
Results from Moderate-Q^2 Pion-LT Experiment

- 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

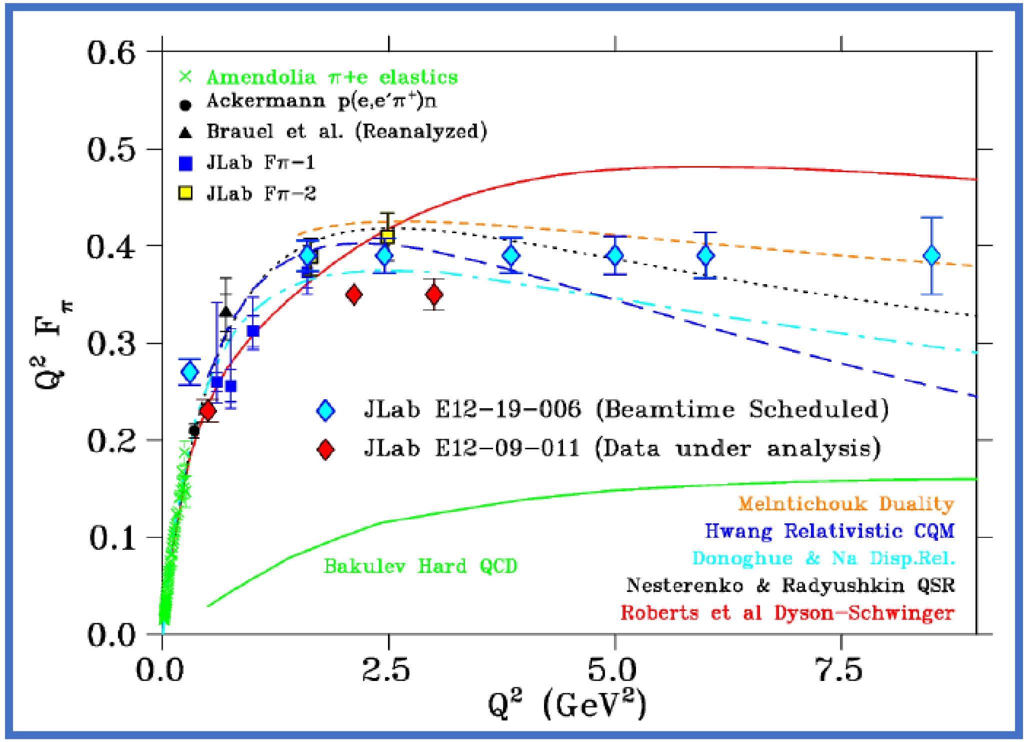
- **E12–19–006 (12 GeV Flagship Experiment) is expected to provide the definitive $p(e, e'\pi^+)n$ L/T–separation data set and will remain important for decades to come.**

- **Preliminary L/T separation is completed for Q^2=3.85 GeV^2, W=2.62 GeV physics setting.**

- **Systematic uncertainty studies still need to be done.**

- **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.**



Projected Results

Acknowledgement

- **Spokespersons:**
  Dave Gaskell (JLab), Garth Huber (URegina), Tanja Horn (CUA),
- **Graduate Students:**
  Nathan Heinrich (URegina), Muhammad Junaid (URegina),
  Nermin Sadoun (URegina), Kathleen Ramage (UofG)
- **Pion-LT/Kaon-LT Collaboration:**
  Nacer Hamdi, Sameer Jain, Stephen Kay, Vijay Kumar, Pete Markowitz, Rachel Montgomery, Gabriel Niculescu, Ioana Niculescu, Alicia Postuma, Julie Roche, Chi Kin Tam, Richard Trotta, Ali Usman

We gratefully acknowledge support from **Natural Sciences and Engineering Research Council of Canada (NSERC) SAPIN-2026-00043**

THANKS

NSERC CRSNG

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We gratefully acknowledge support from **Natural Sciences and Engineering Research Council of Canada (NSERC) SAPIN-2026-00043**