Measurement of Charged Pion Form Factor at Jefferson Lab

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Scientific Motivation

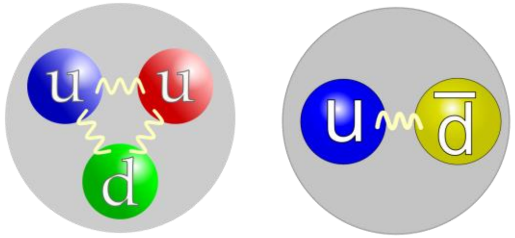
- Hadrons are classified into two groups:
  - **Baryons** combination of quark-quark-quark states (qqq or $\overline{qqq}$).
  - **Mesons** combination of quark-antiquark states ($q\bar{q}$).

- 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.**

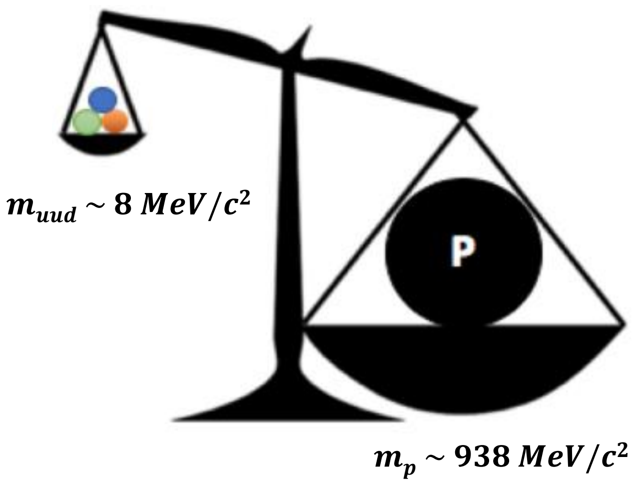
- **Form factor** is an important observable that can be studied to understand the internal structure of hadrons.

- **Mesons** give an ideal testing ground for our understanding of bound $q\bar{q}$ hadronic system.
  - **Pion** is the lightest meson with only two valence quarks: up (u) and anti-down ($\bar{d}$).



Baryon (proton, p)

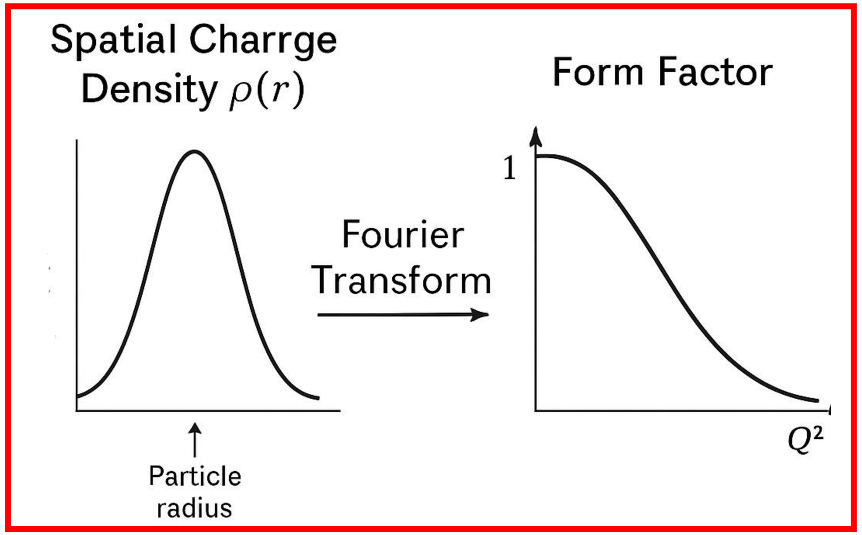
Meson (pion, π^+)



What is Form Factor?

- Form Factor ($F(Q^2)$) describes the transverse spatial position of partons within hadrons.
- $F(Q^2)$ is the Fourier transform of the particle's spatial charge density ($\rho(r)$).

$$F(Q^2) = \int \rho\,(r) e^{iQ\cdot r} d^3 r$$



- At low Q^2, the form factor directly relates to particle's charge radius $\langle r^2 \rangle$.

$$\langle r^2 \rangle = -6 \frac{dF(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

- At high Q^2, form factor follows predictions from perturbative QCD and helps to understand nature of the quark-gluon coupling constant renormalization.

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

- Measuring the pion form factor at various Q^2 checks the validity of QCD-based theories, including the transition region between perturbative and non-perturbative approaches.

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Pion Form Factor Measurement

Direct Measurement:

- Elastic Scattering of electrons from pions gives

$$e + \pi^{+} \rightarrow e' + \pi^{+\prime}$$

- **Limitation:** Pion ($\boldsymbol{\pi}^{\pm}$) targets not possible due to short lifetime ($\sim 2.6 \text{ x } 10-8 s$)
- Even scattering high energy pion beam (1 TeV, if some facility could be constructed) can access only $Q^2 \sim 1 GeV^2$

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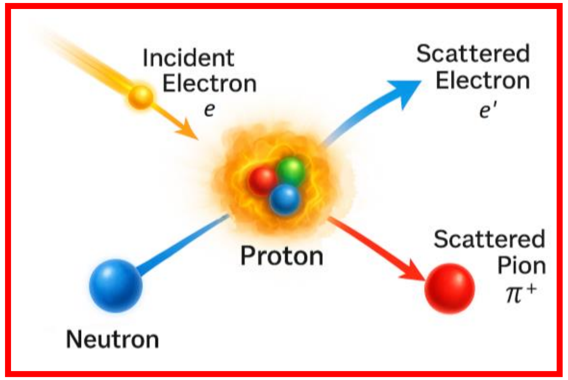


Indirect Measurement:

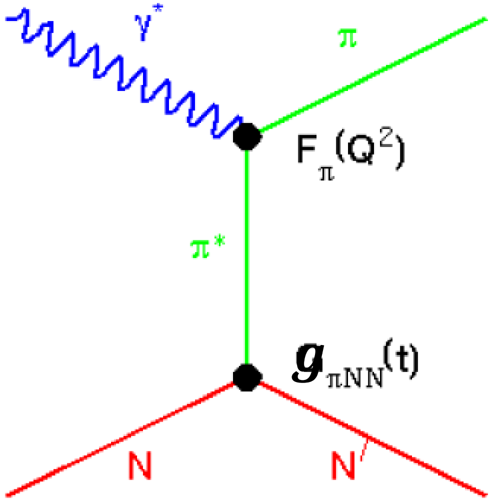
- Above $Q^2 > 0.3\text{GeV}^2$, F_π is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e, e'\pi^+)n$

- Indirect measurement – Form factor extraction requires a model.

- 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-model for $F_\pi^2(Q^2, t)$ extraction.



Rosenbluth Separation

- **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.

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

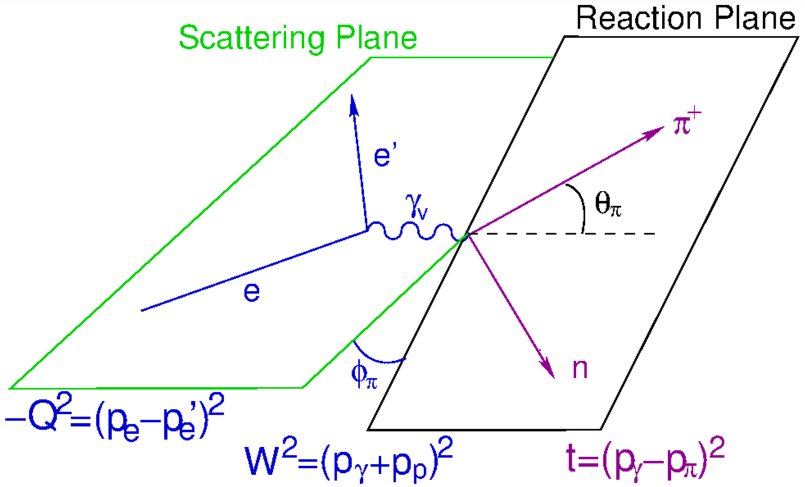
- Perform two scattering measurements with different beam energies "E_e" to vary "ϵ" and separate different cross-section terms.

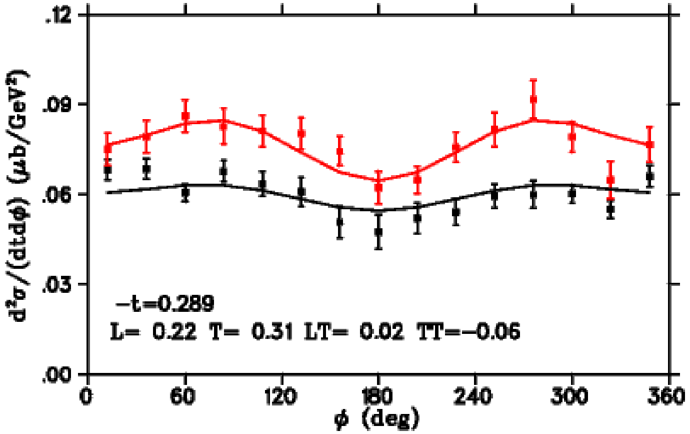
- Careful control of point-to-point systematics crucial, $^{1}/_{\Delta\epsilon}$ error amplification in σ_L.

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2}\frac{1}{\sigma_L}\sqrt{\Delta\sigma_1^2 + \Delta\sigma_2^2}$$

Where "$\sigma_1 = \sigma_T + \epsilon_1\,\sigma_L$" and "$\sigma_2 = \sigma_T + \epsilon_2\,\sigma_L$".

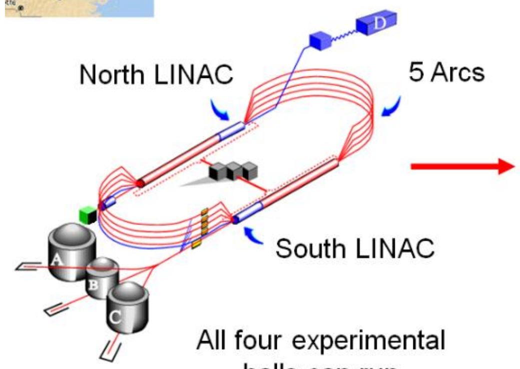
- Careful attention must be paid to systematic studies such as spectrometer acceptance, kinematics, efficiencies, etc.

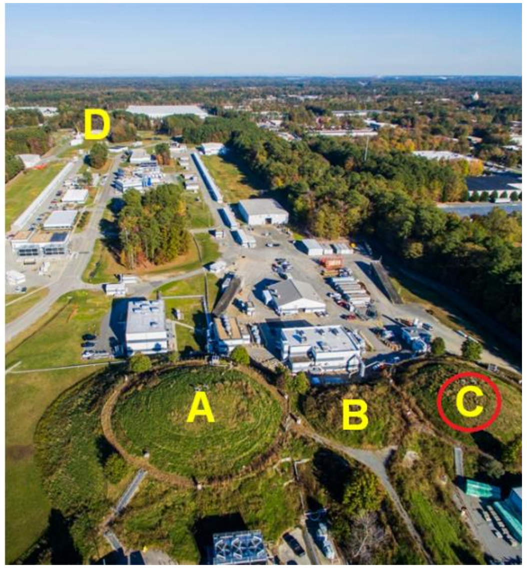




Experimental Facility

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





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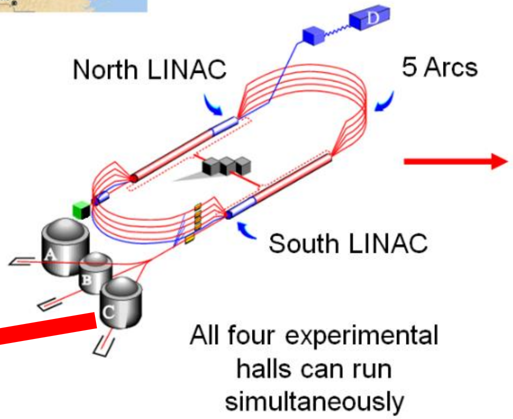
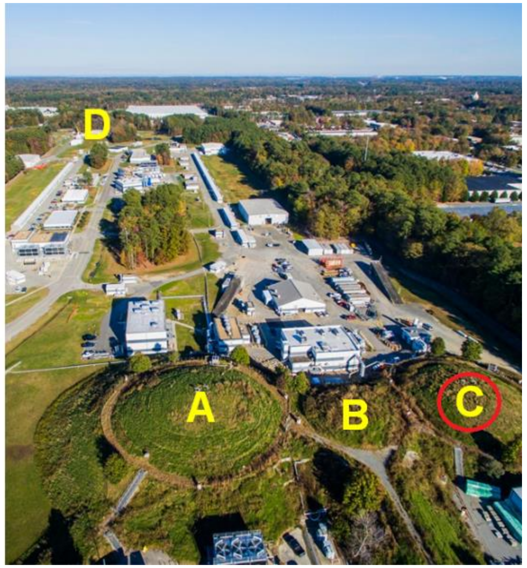
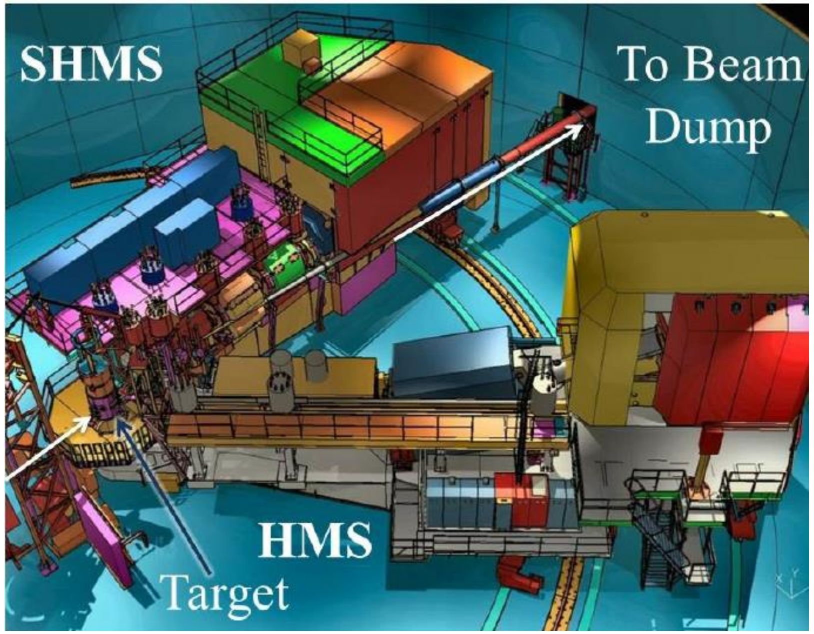






- Specially designed to measure precise cross-sections and form factors for mesons.
- Experimental setup contains a target and two detector arms.
- Target can be Liquid H_2, Liquid D_2 or solid targets.
- Two detectors are;
  - High Momentum Spectrometer (HMS)
  - Super High Momentum Spectrometer (SHMS)

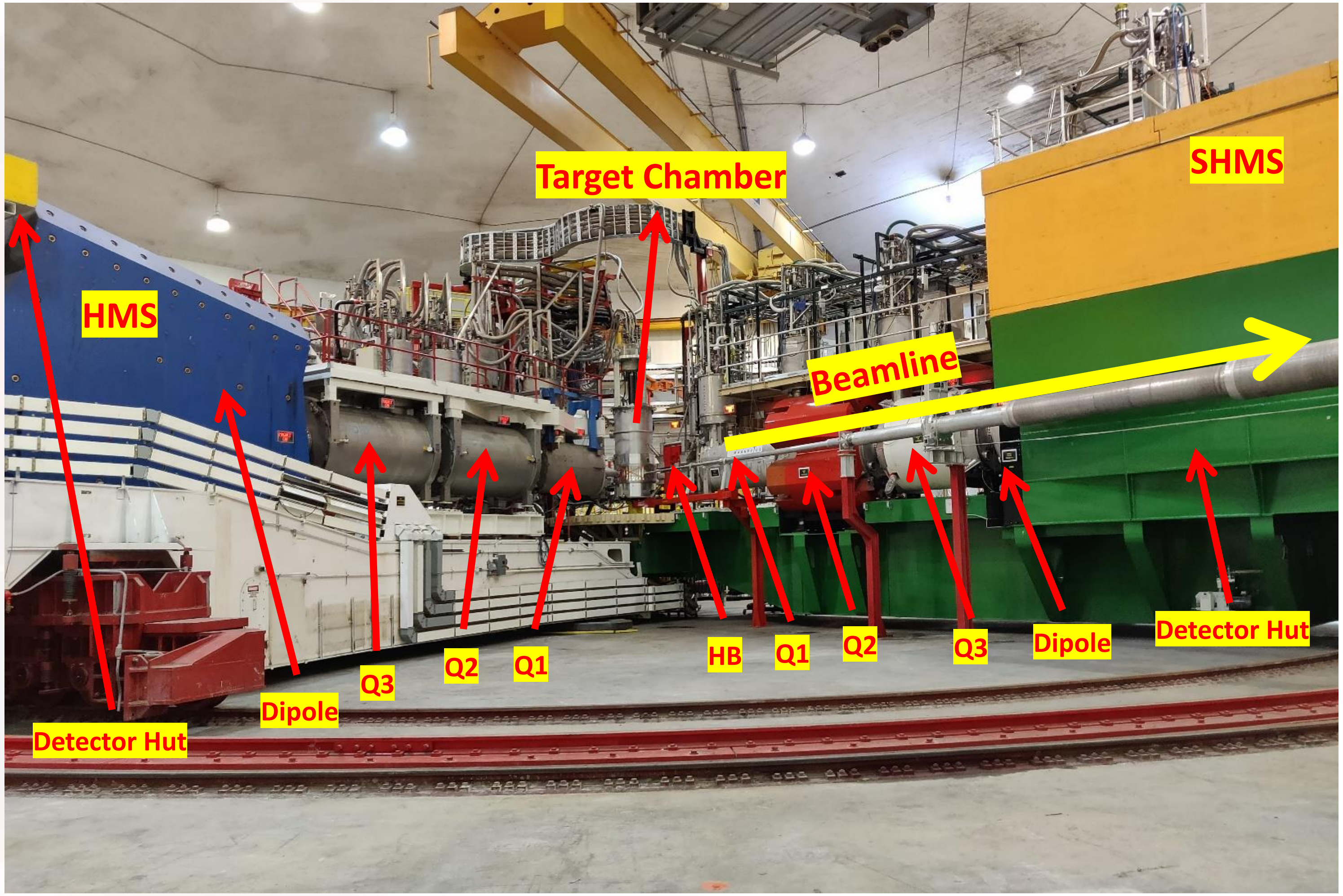
Hall C Spectrometers

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

- Both contain similar detector packages, including DC, hodoscopes, Cherenkov, and calorimeter detectors.

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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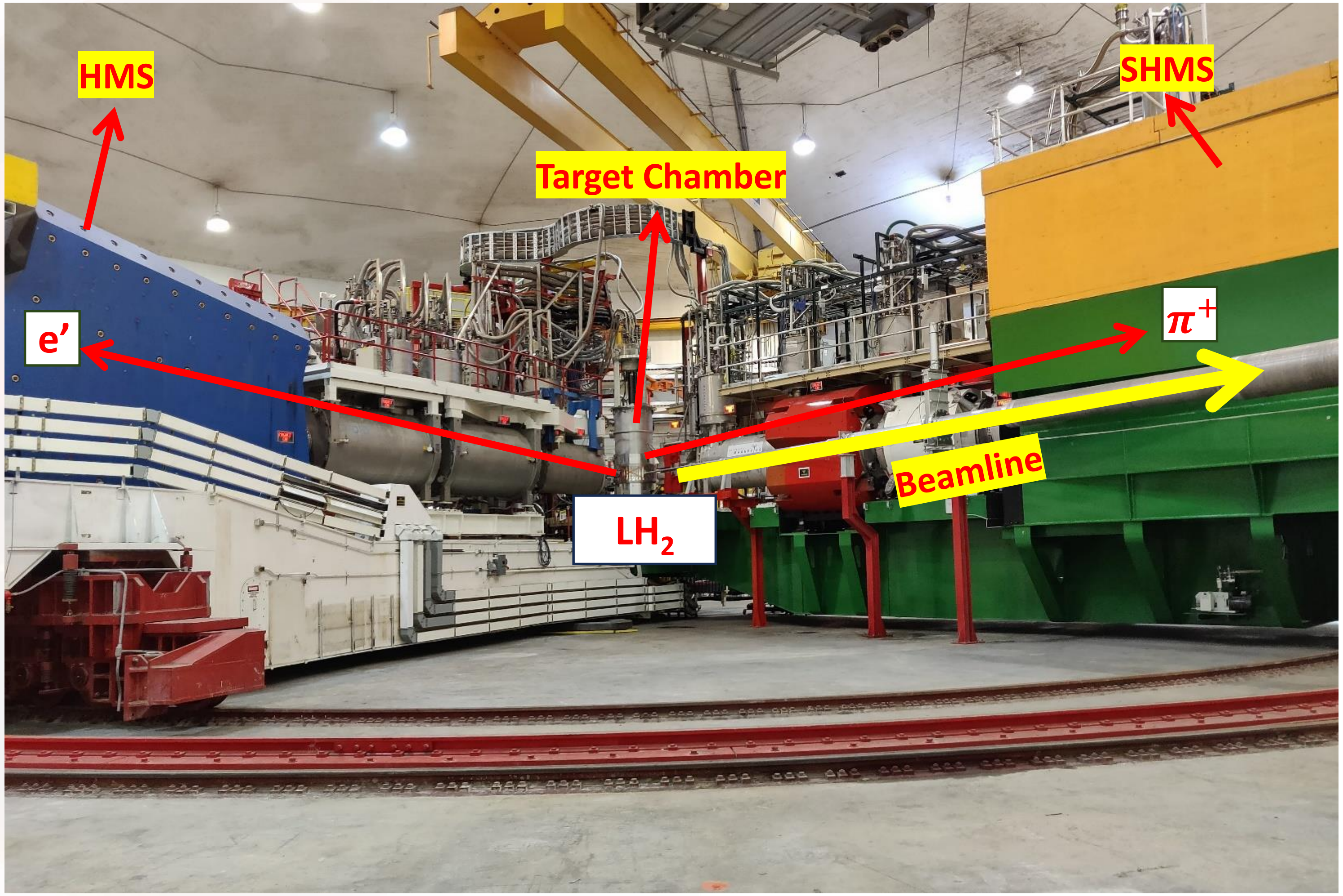

List of Physics Data Sets

Physics Settings	Planned Studies	Assigned to
$Q^2 = 1.45, W = 2.02, -tmin = 0.11$ $Q^2 = 1.60, W = 3.08, -tmin = 0.11$	$x = 0.31$ Scaling Study F_π Study	Junaid & Nathan Junaid
$Q^2 = 2.12, W = 2.05, -tmin = 0.19$ $Q^2 = 2.45, W = 3.20, -tmin = 0.05$ $Q^2 = 2.73, W = 2.63, -tmin = 0.12$	$x = 0.39$ Scaling Study F_π Study $x = 0.31$ Scaling Study	Nathan Junaid Nathan
$Q^2 = 3.85, W = 2.02, -tmin = 0.49$ $Q^2 = 3.85, W = 2.62, -tmin = 0.21$ $Q^2 = 3.85, W = 3.07, -tmin = 0.12$	F_π Study, $x = 0.55$ Scaling Study F_π Study, $x = 0.39$ Scaling Study F_π Study, $x = 0.31$ Scaling Study	Junaid & Nathan Junaid Nathan
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$Q^2 = 8.50, W = 2.79, -tmin = 0.55$	F_π Study, $x = 0.55$ Scaling Study	Junaid & Nathan

- **Blue Settings will be analyzed by both of us to cross check our results.**

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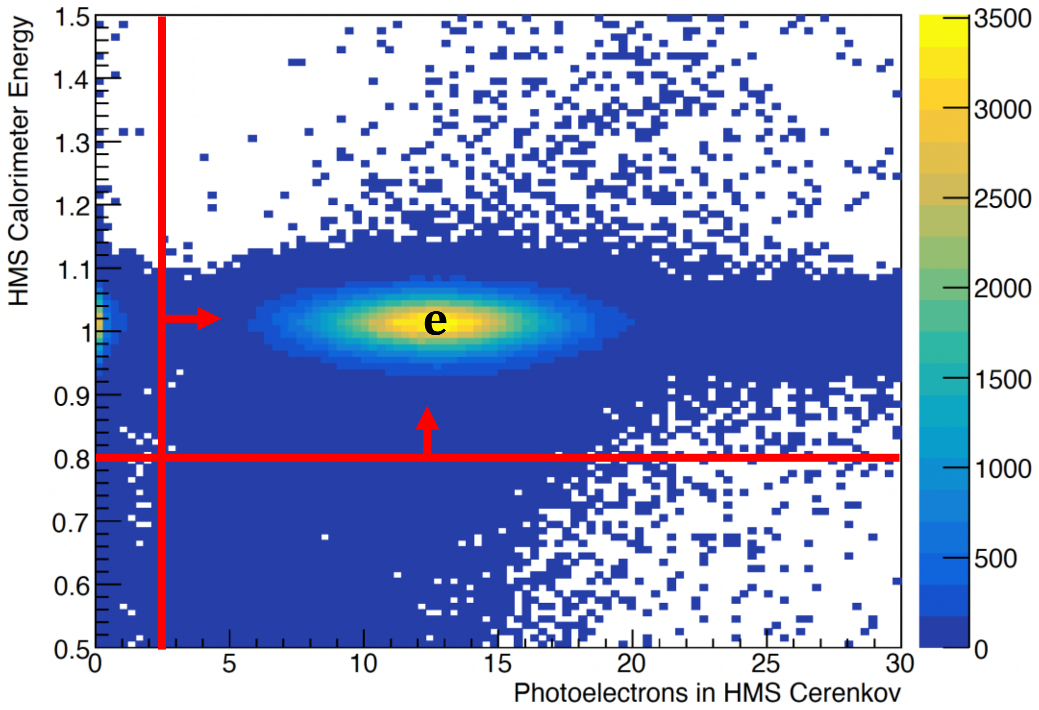
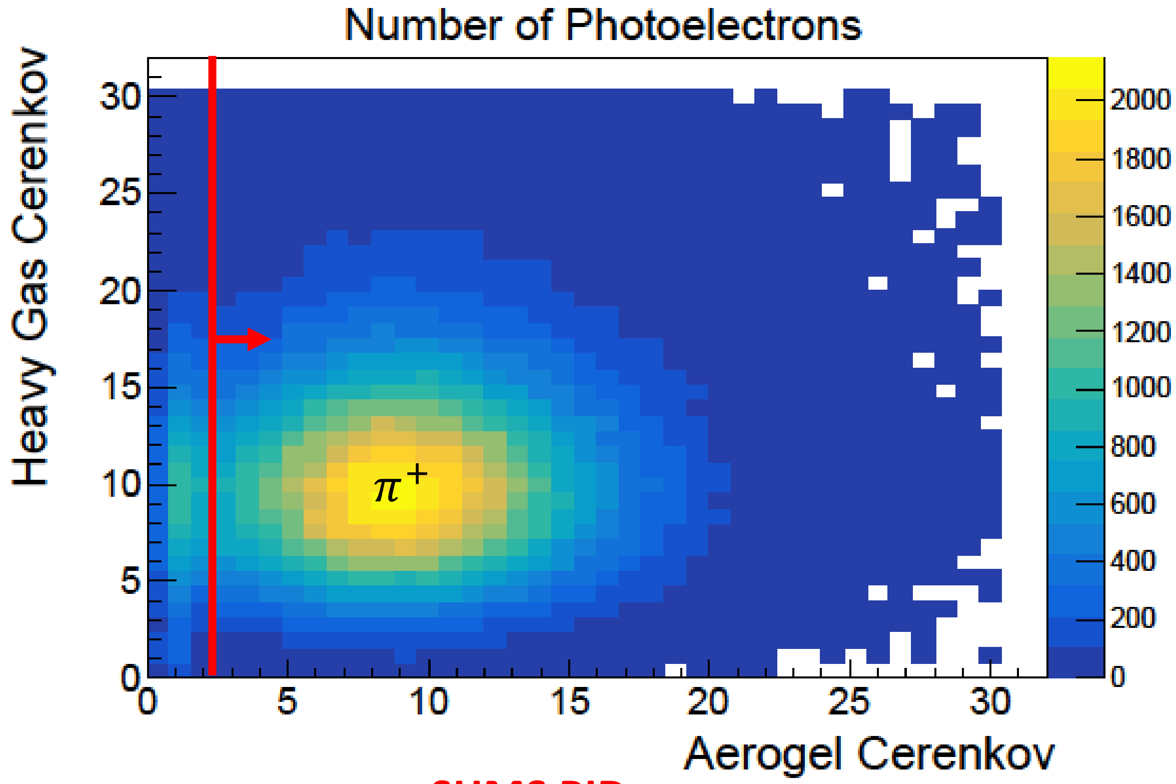
University of Regina Go far, Together.

Particle Identification (PID)

- 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



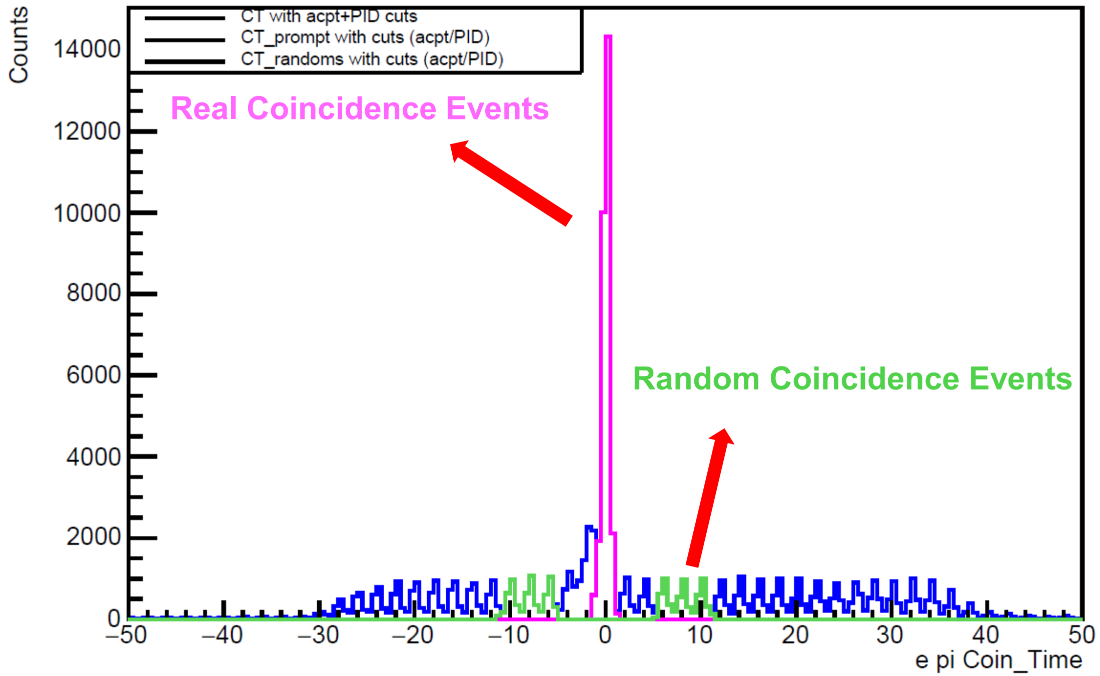
SHMS PID

Event Selection and Missing Mass

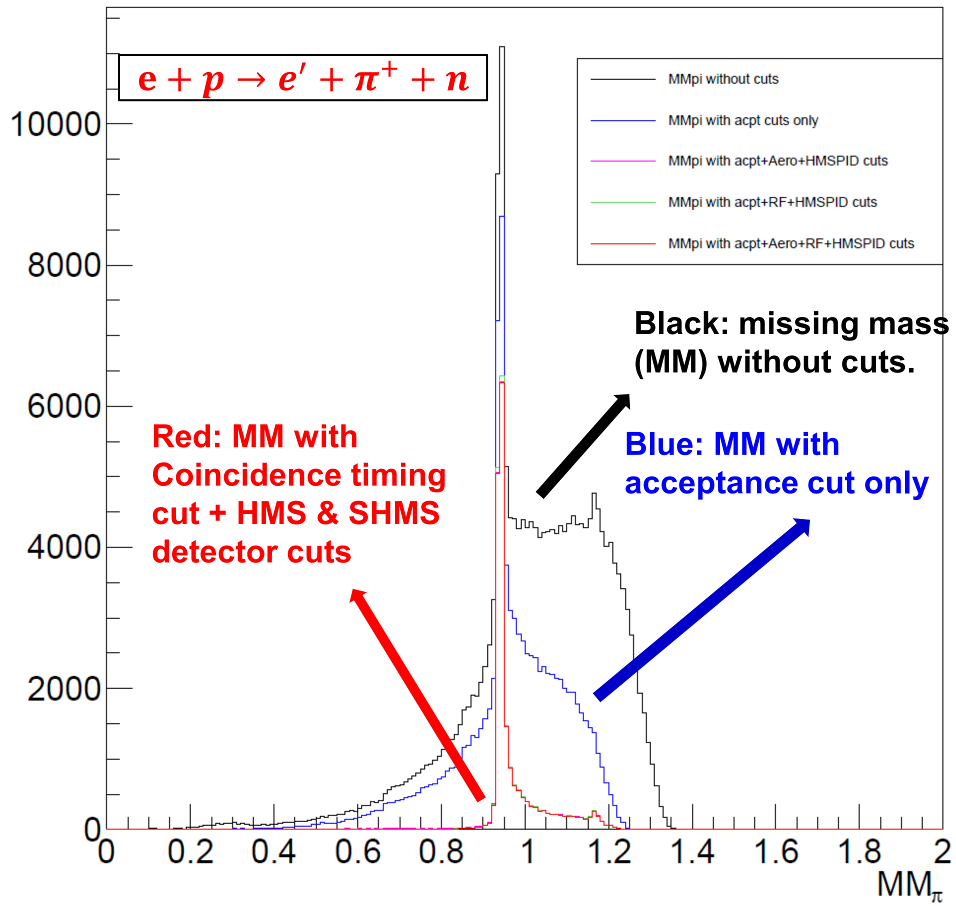
- **CoinTime (CT) is given as:**

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

- **Used to eliminate random background caused by random coincidences.**



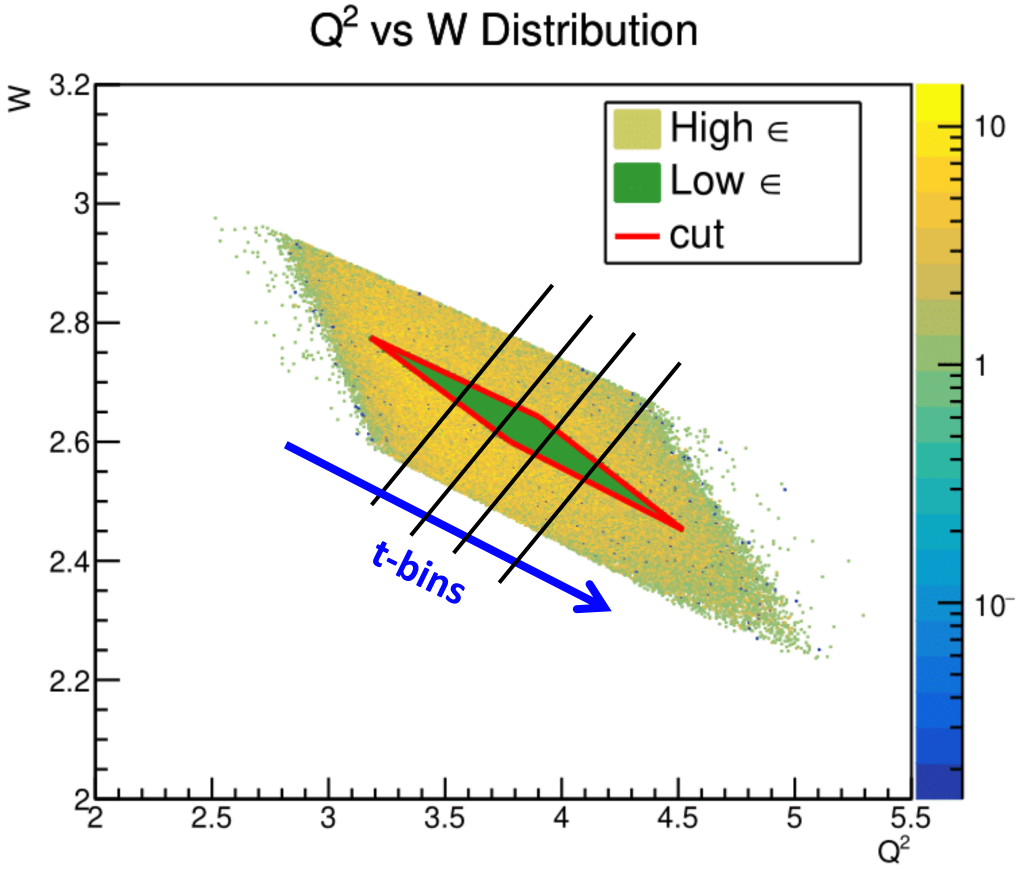
$$M_m = \sqrt{(E_e + m_P - E_{e'} - E_{\pi^+})^2 - (p_e - p_{e'} - p_{\pi^+})^2}$$



EBeam=5.986, Q2=3.85, W=2.02, x=0.55, θ_SHMS=15.79

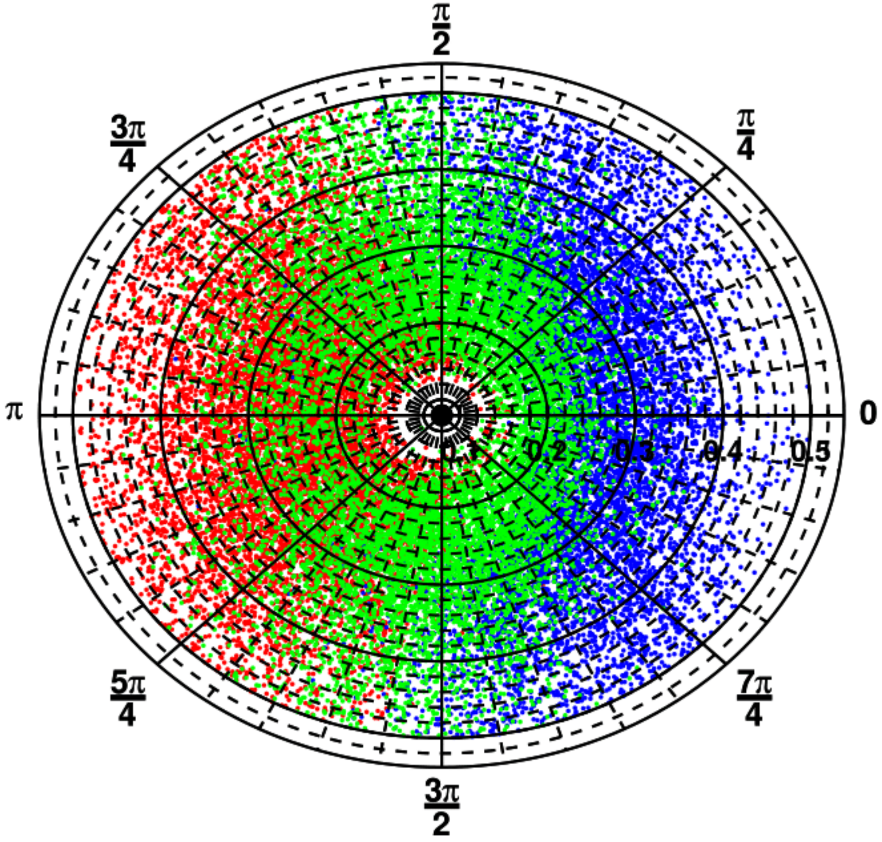
Importance of Diamond Region

- Electron spectrometer acceptance is larger for high ϵ.
- Selected an overlapped phase-space region.
- Divided data into 5 t-bins based on data statistics.
- Purpose is to measure the t-dependence



EBeam=5.986, Q2=3.85, W=2.02, x=0.55, θ_SHMS=15.79 (Center)

Full ϕ-Coverage



Radial axis $-t$
Azimuthal angle - ϕ

- 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 equal ϕ-bins to measure the ϕ dependence.

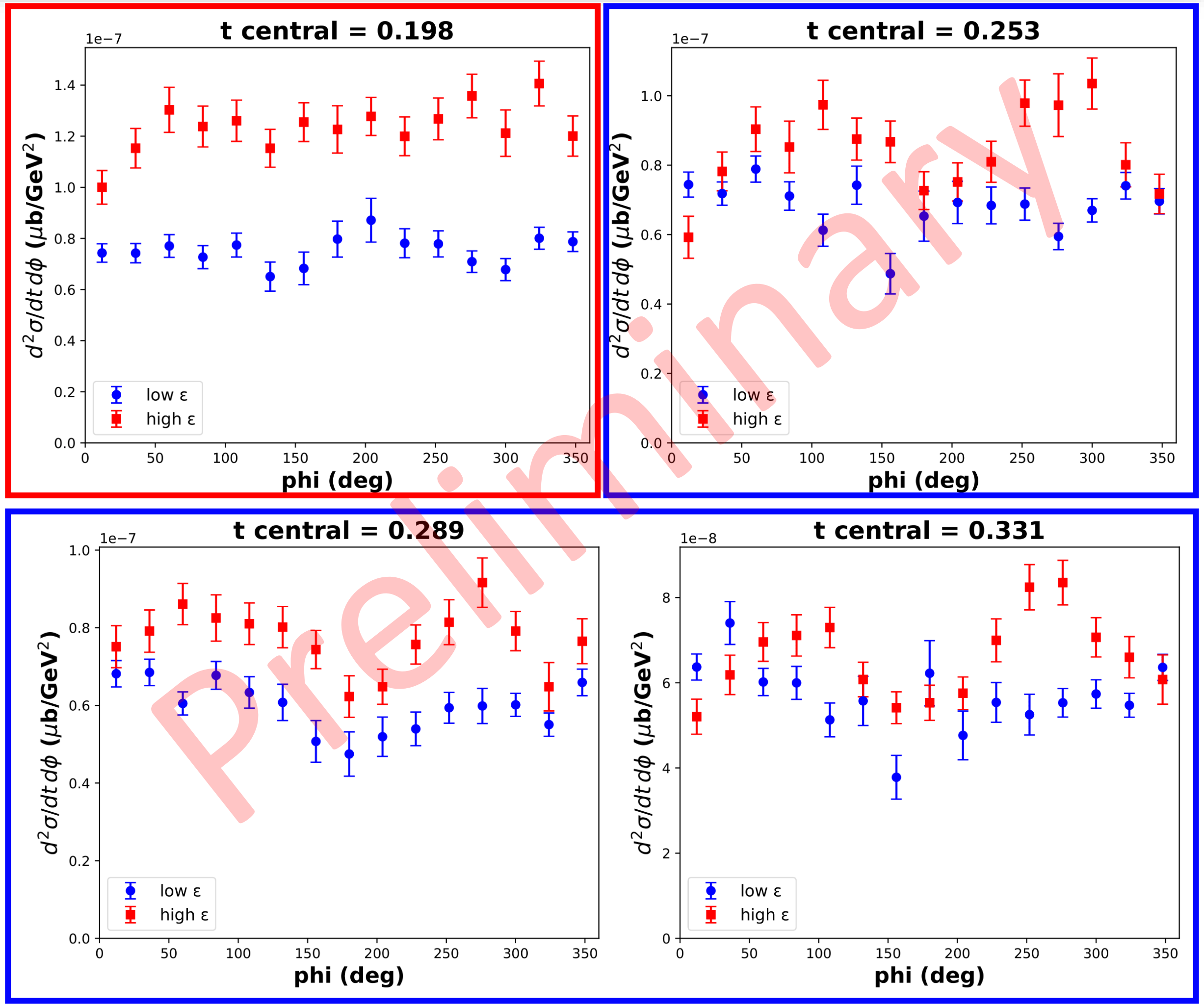
EBeam=5.986, Q2=3.85, W=2.02, x=0.55, θ_SHMS=15.79 (Center)

Unseparated Cross-sections

- ❑ Calculated normalized data yield.
- ❑ Calculated normalized Monte Carlo (SIMC) yields.
- ❑ Combined data from each pion arm angle setting per ϵ by calculating their error-weighted average.
- ❑ Calculated unseparated cross-sections.

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

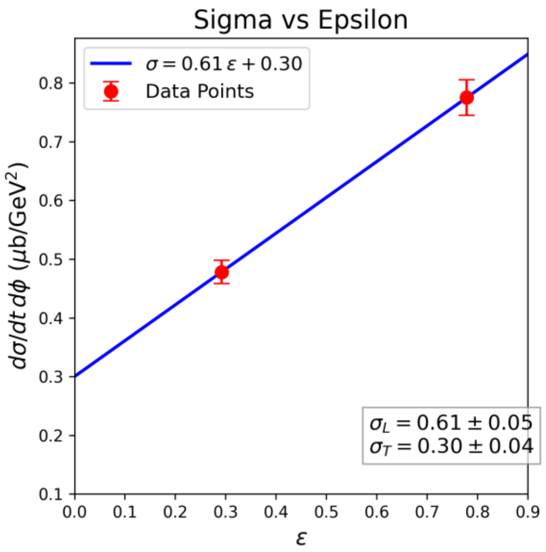
- ❑ σ_l is larger as compared to σ_t
- ❑ σ_l is dropping as we go to higher t.



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

LT-Separated Cross-sections

- ‘Simple’ longitudinal-transverse:



Slope gives σ_L
Intercept gives σ_T

In our case, we also have interference terms that correspond to azimuthal oscillations

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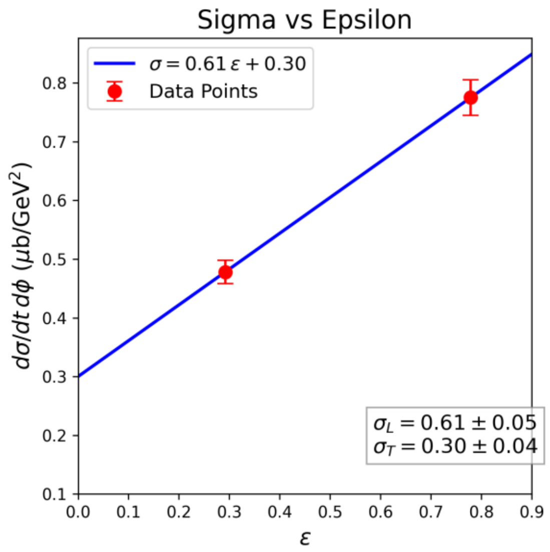

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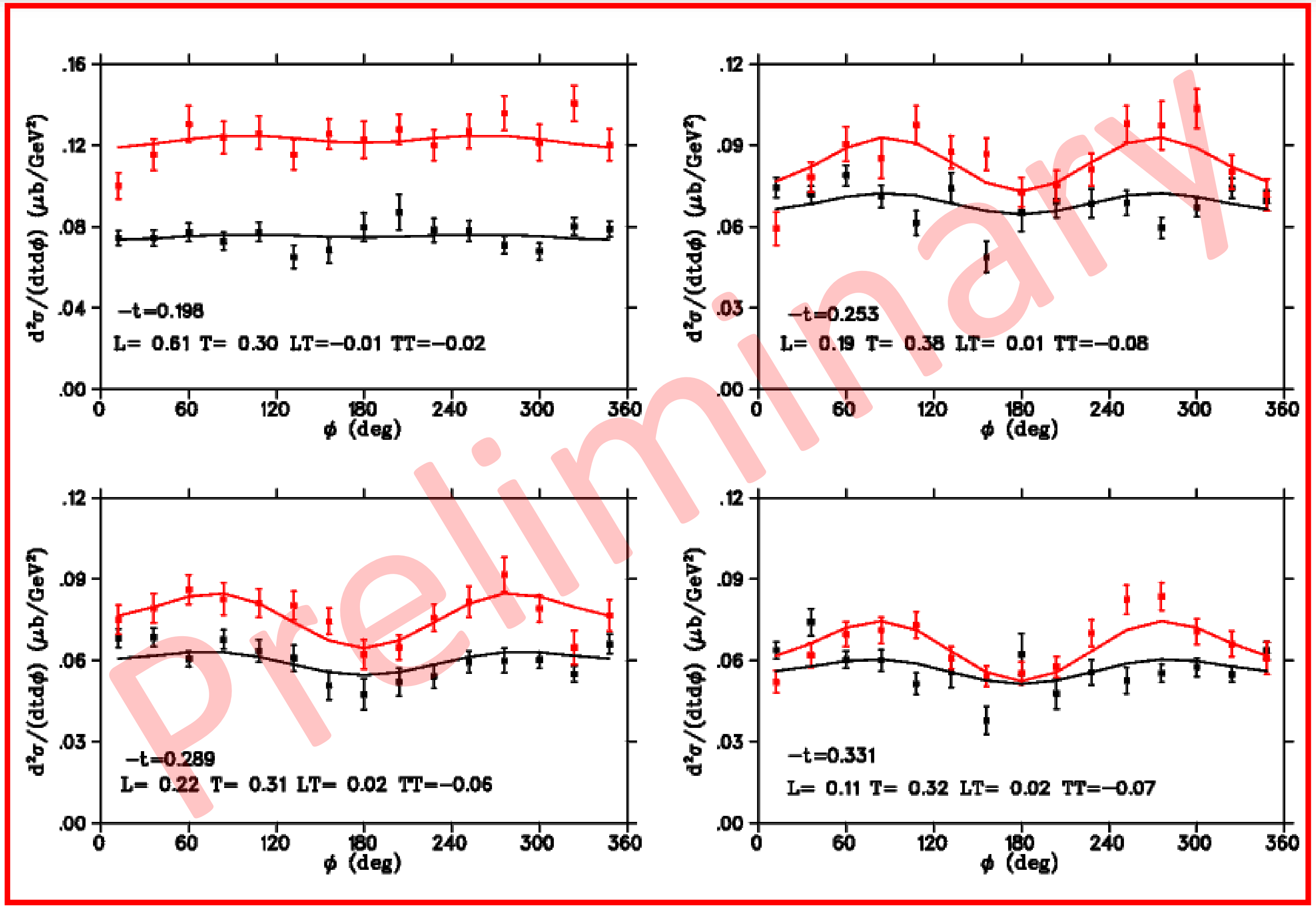

Q2 = 3.85, W = 2.62, t = 0.21 (2 epsilons)

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

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

Summary and Future Plans

- E12–19–006 (12 GeV Flagship Experiment) is expected to provide the definitive $\mathrm{p}(\mathrm{e}, e'\pi^{+})\mathrm{n}$ L/T–separation data set and will remain important for decades to come.
- Systematic studies are almost finalized.
- Next Step will be optimization of fit parameters for the functions defining longitudinal, transverse, and interference cross-section terms.
- Then calculate the separated cross-sections (longitudinal, transverse, and interference terms) using the Rosenbluth technique and extract the pion form factor.
- Analysis is expected to be completed in 2026.
- Results will help to understand the dependence of the Form factor and in validating theoretical models.
- It is expected as many as 9 publications will come from this data.

THANKS

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Kaon-LT and Pion-LT Collaboration

- **Spokespeople**

  Garth Huber, Dave Gaskell, Tanja Horn, Pete Markowitz

- **Key Members**

  Richard Trotta, Alicia Postuma, Portia Switzer, Stephen Kay, Vijay Kumar, Nathan Heinrich, Abdennacer Hamidi, Julie Roche, Ali Usman

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