Measurement of $e + p \rightarrow e' + \pi^+ + \Delta^0$ reaction at Jefferson Lab Hall C

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Contents

- Introduction & Motivation
- Experiment
- Beam Spin Asymmetry
- L/T Separated Cross-Section
- Summary

Where is Regina?

Regina is named after Queen Victoria, and is capital of the province of Saskatchewan

Albert Memorial bridge in Regina holds world record of longest bridge on shortest span on water.

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, Muhammad Junaid, Jacob Murphy

- Institutions

cua

University of Regina

OHIO UNIVERSITY

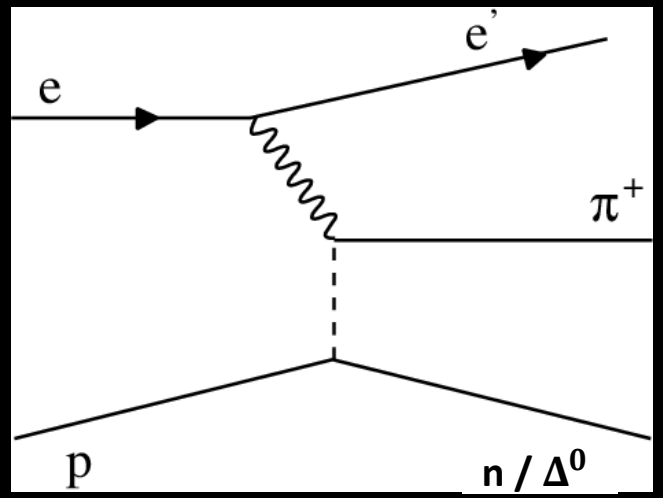
Jefferson Lab

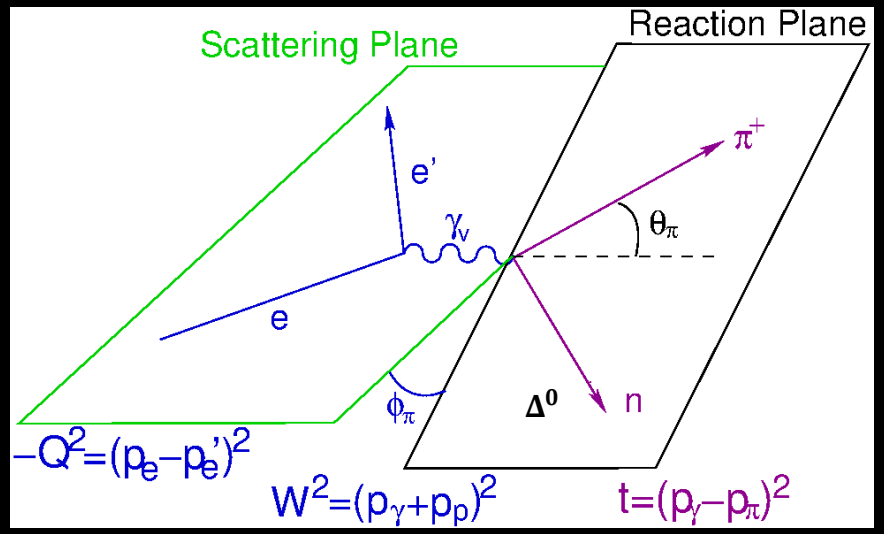
Introduction

- Pion is the lightest meson with two valence quarks.
- Pion electroproduction reaction is studied through ***"Exclusive Pion Electroproduction".***

$$e + p \rightarrow e' + \pi^+ + n \; or \; \Delta^0$$

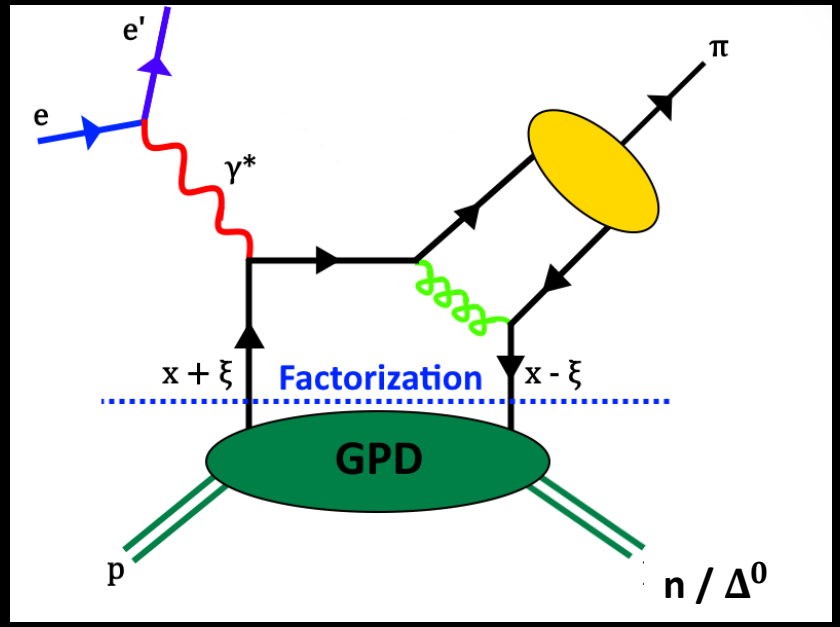
- **To study hadron structure, need a precise measurement of this rection.**
- **Important Kinematic Quantities**
  - $Q^2, W, -t \; and \; \phi$





Physics Motivation

- Meson production can be described by the t-channel meson pole term.
- At sufficiently high Q^2, the process should be understandable in terms of the “handbag” diagram.
- Non-perturbative (soft) physics is represented by GPDs.
  - Factorized from QCD perturbative (hard) processes for longitudinal photons.
- Measurements of GPDs require
  - Confirmation of applicability of hard-soft QCD factorization mechanism at intermediate Q^2.

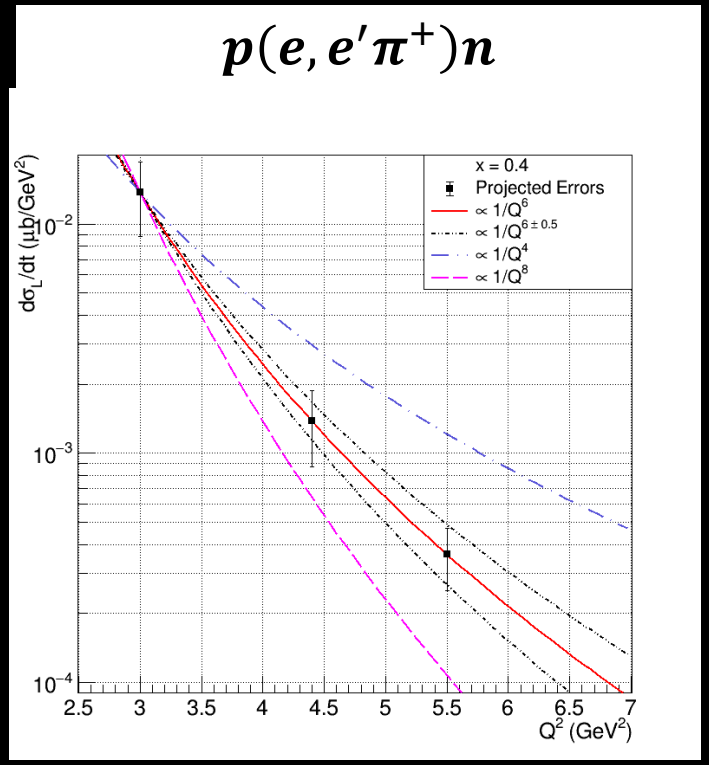


Factorization and Q^n Scaling

- QCD counting rule predicts $1/Q^n$ dependence of $p(e, e'\pi^+)n$ cross-section in Hard Scattering Regime.
  - σ_L to leading order, scales as $1/Q^6$
  - σ_T expected to scale at least as $1/Q^8$
  - At large Q^2, $\sigma_L \gg \sigma_T$

Is this empirically true for $p(e, e'\pi^+)\Delta^0$?

- Study hard-soft factorization for GPD extraction
  - if σ_L becomes large, would allow leading twist GPD study.
  - If σ_T becomes large, could allow for transversity GPD study



L/T Separated Cross Section

- Exclusive pion electroproduction reaction

$$e + p \rightarrow e' + \pi^+ + n \; or \; \Delta^0$$

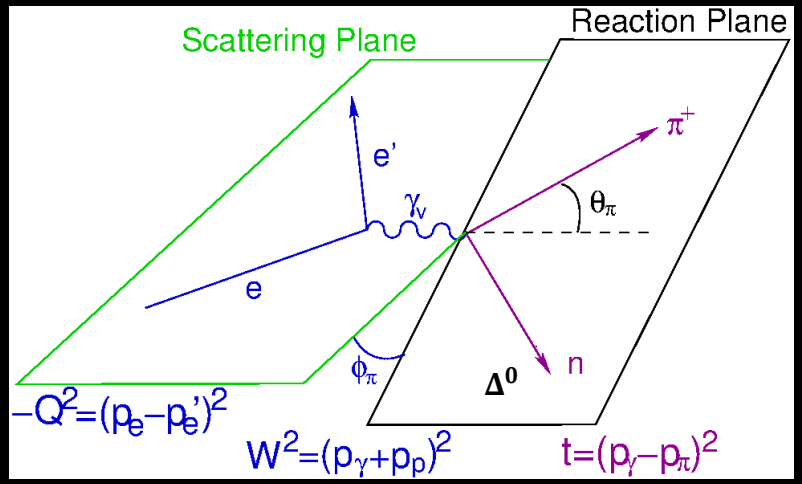
- Differential cross-section is dictated by virtual photon polarization ϵ.

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

- "ϵ" is polarization of virtual photon

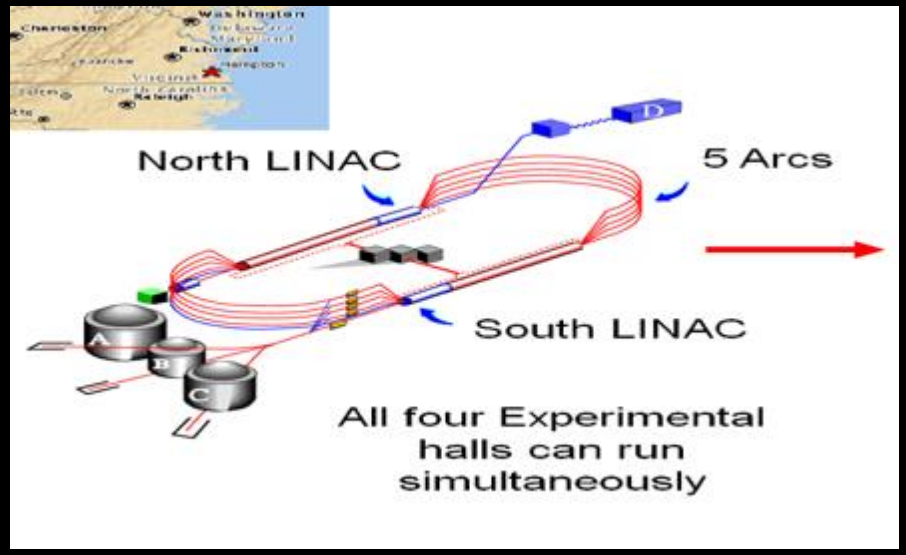
$$\epsilon = \left[1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2} . tan^2 \frac{\theta_{e'}}{2}\right]^{-1}$$

- Cross-section is separated by performing two scattering measurements at different "ϵ" value with fixed Q^2 and W.



Hall C at Jefferson Lab is capable of doing L/T separated cross-section and scaling study measurements at wide range of kinematics ($Q^2, W, -t$)

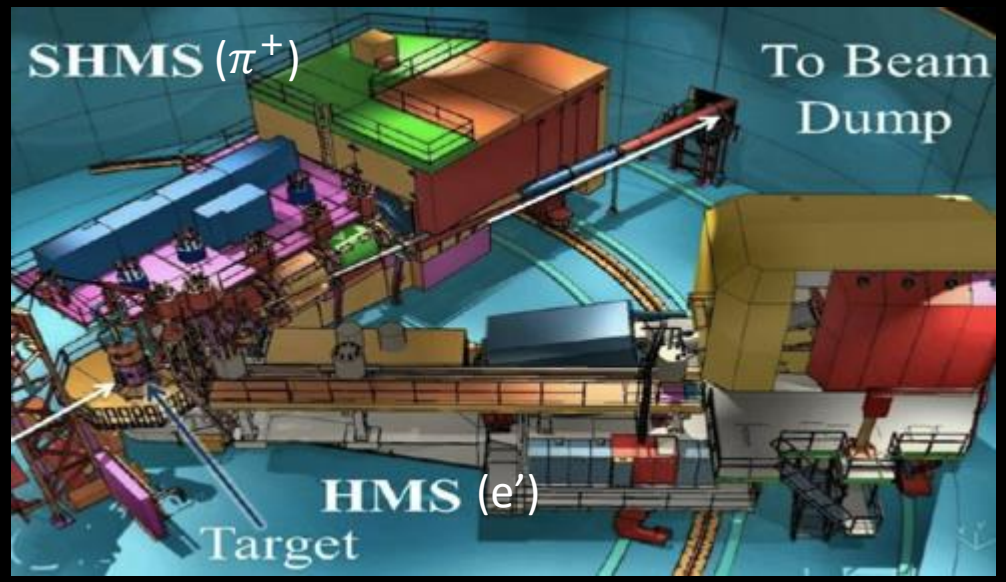
Thomas Jefferson National Accelerator Facility



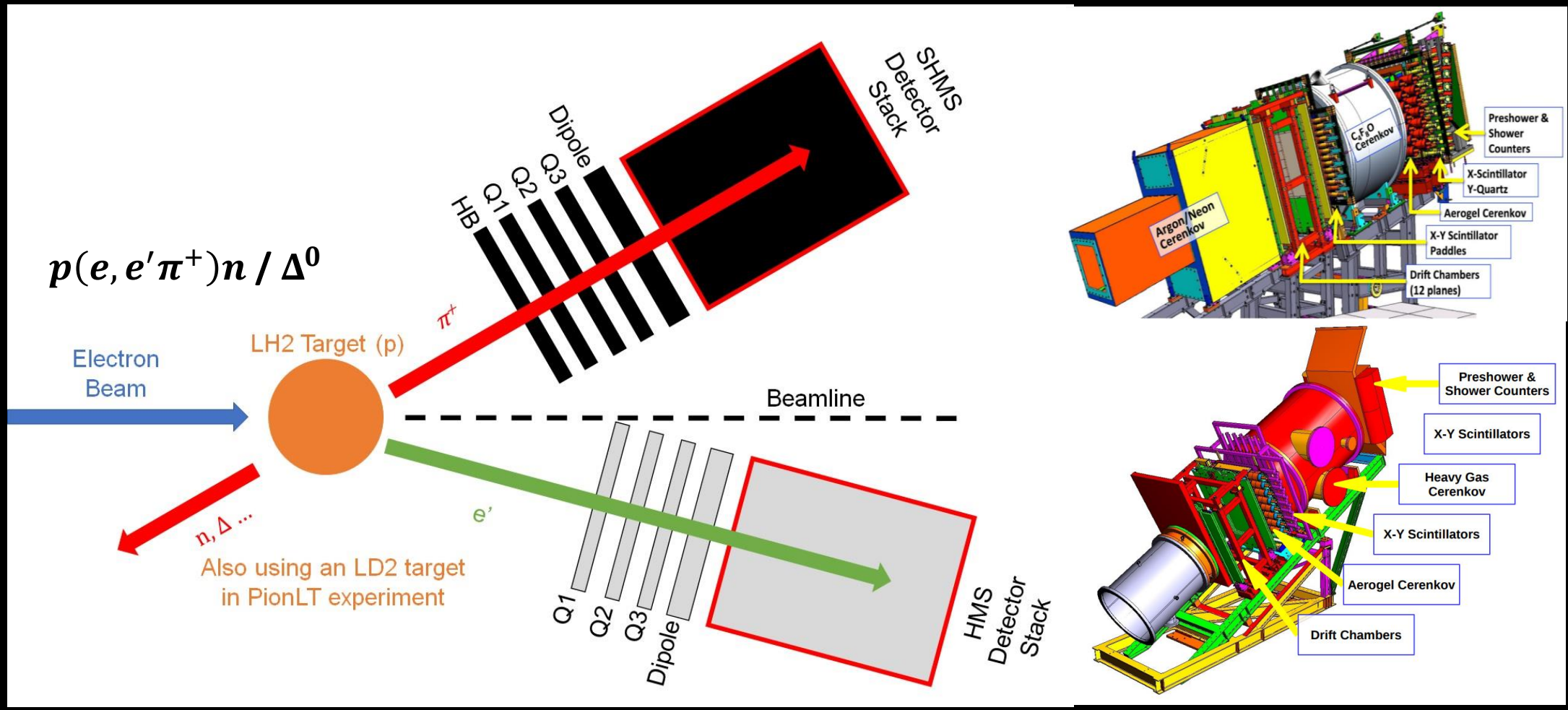
- Consists of two superconducting electron LINACs.
- Capable of delivering high luminosity beam to four halls.
- Variable beam energies and high current (critical for L/T separation).

Hall C

- Specifically designed to measure precise cross-sections.
- Two advanced rotatable magnetic spectrometers (HMS and SHMS).
- Particles of specific momentum are studied by using a magnet system.

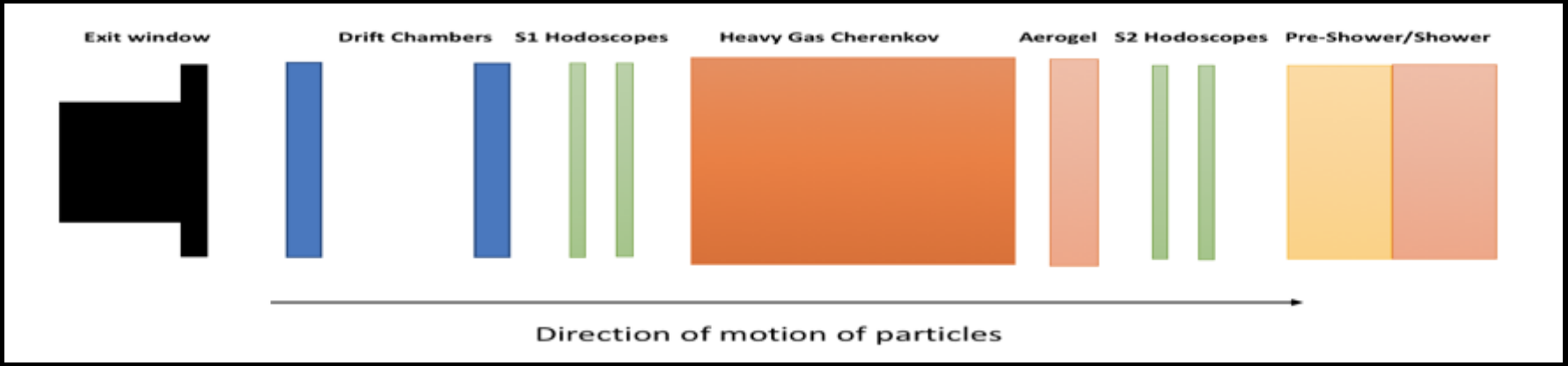


Schematic View of Hall C



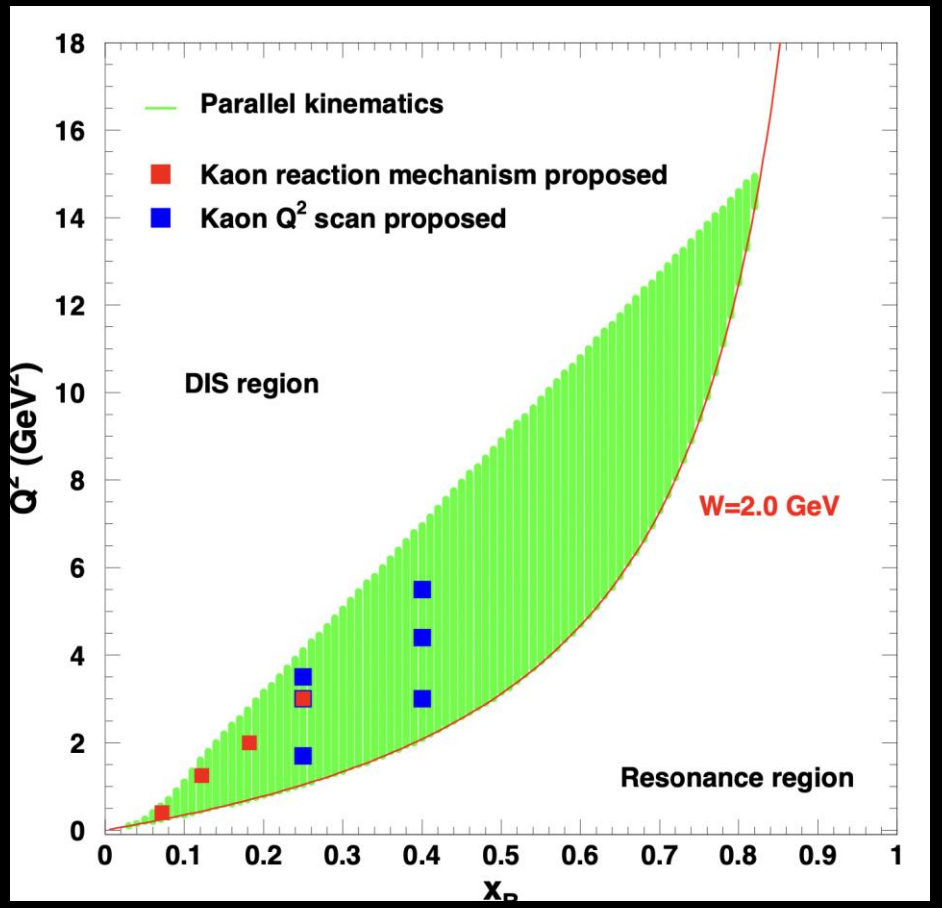
SHMS Detector System

DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Aerogel Cerenkov	Particle ID, K+/p discrimination	n= 1.011,1.015, 1.03,1.05
Heavy-Gas Cerenkov	Particle ID, Trigger. $\pi^{\pm}/K^{\pm}$ discrimination	C_4F_{10} - Kept at roughly 1 atm pressure
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Preshower / Shower Counters	Particle ID, Trigger. Electron tag	



Kaon-LT Experiment (E12-09-011)

- First dedicated experiment ot study exclusive kaon electroproduction reaction.
  - Data collected 2018-2019 (~ 60 % complete)
- $p(e, e'K^+)\Lambda$ cross-section is ~ 1/10 times $p(e, e'\pi^+)n$ cross-section.
  - Give access to high statistic exclusive pion electroproduction data.
- Ideal dataset to study $p(e, e'\pi^+)\Delta^0$ reaction.



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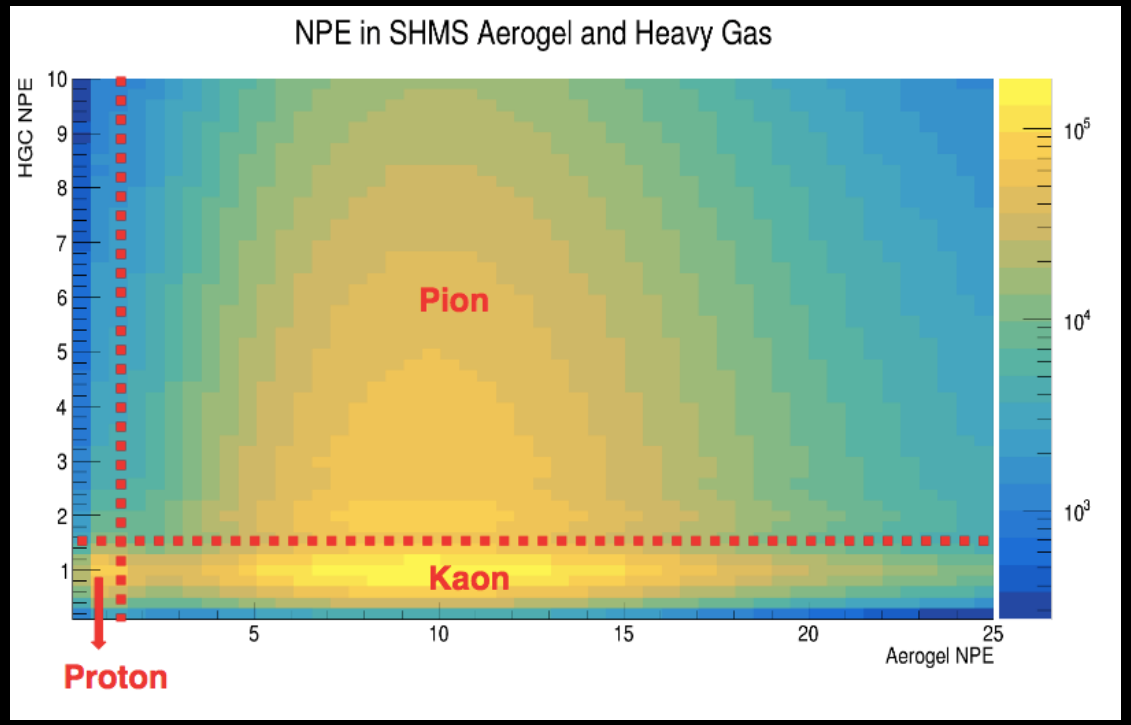
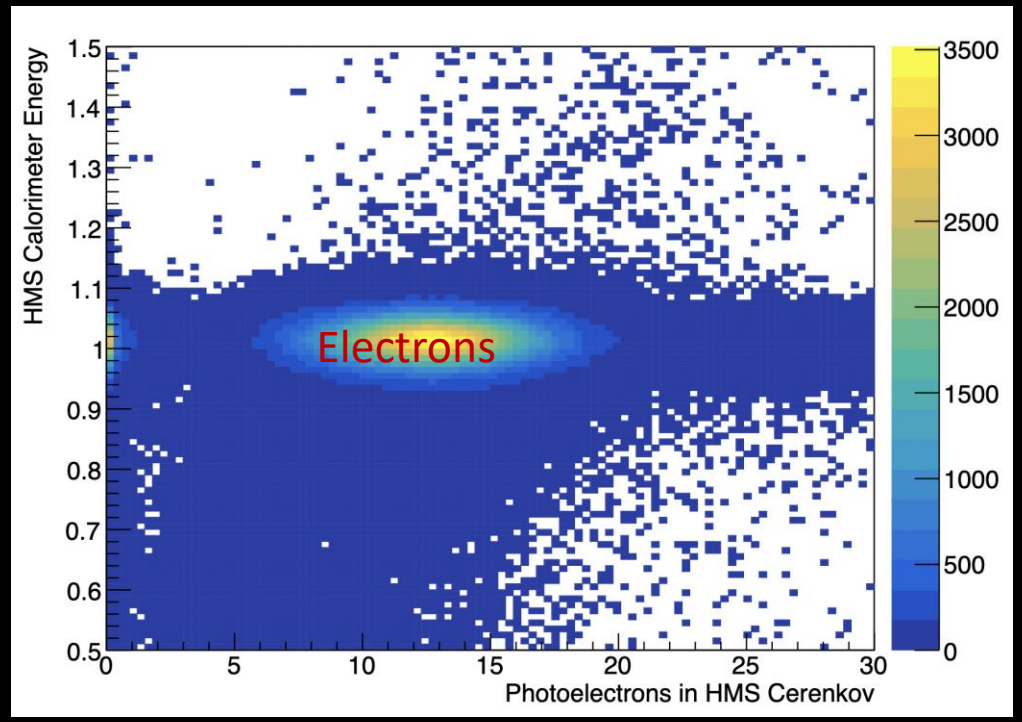
E (GeV)	Q^2 (GeV^2)	W (GeV)	x_B	ε_{High} / ε_{Low}
10.6/8.2	5.5	3.02	0.40	0.53/0.18
10.6/8.2	4.4	2.74	0.40	0.72/0.48
10.6/8.2	3.0	3.14	0.25	0.67/0.39
10.6/6.2	3.0	2.32	0.40	0.88/0.57
10.6/6.2	2.115	2.95	0.21	0.79/0.25
4.9/3.8	0.5	2.40	0.09	0.70/0.45

Particle ID

- Pion Selection



- Electron Selection

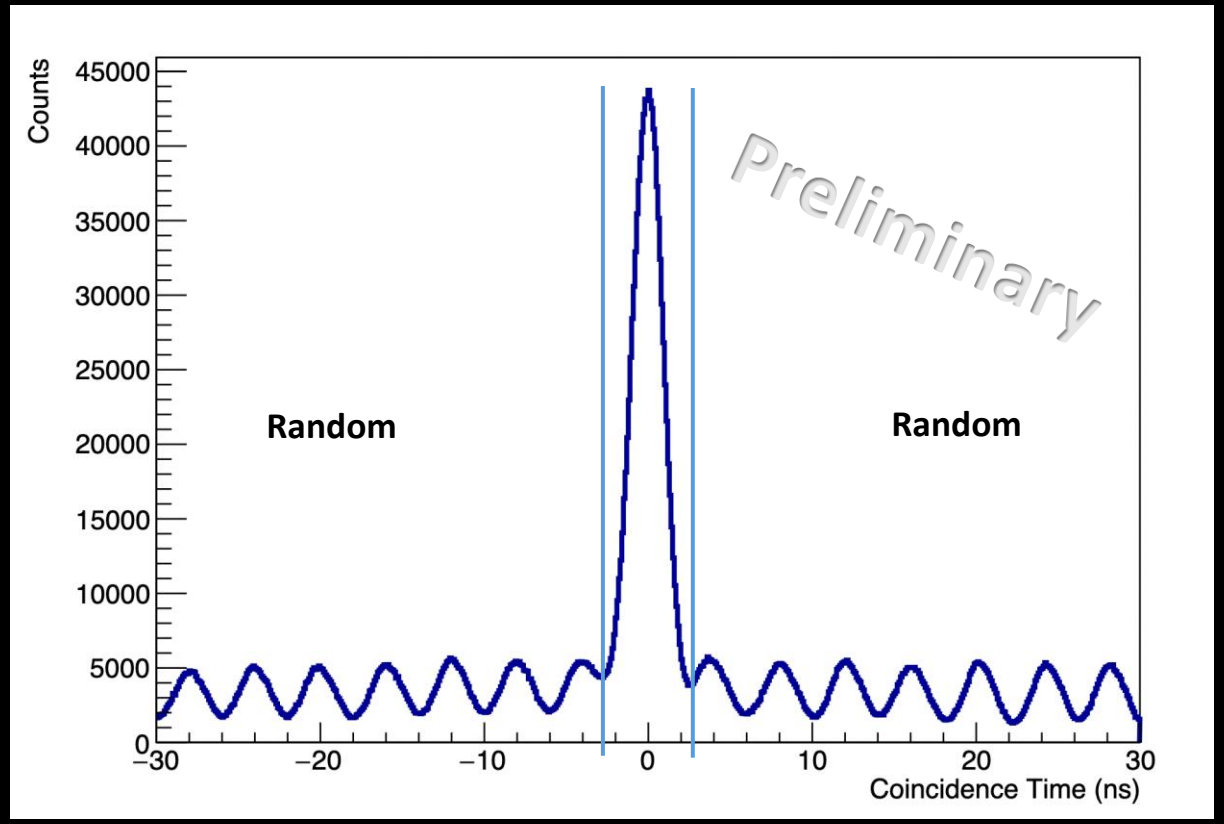


$$Q^2 = 2.115\,, W = 2.95$$

Event Selection

- $e' - \pi^+$ Coincidence

$$e' - \pi^+ \, Coin \, Time = HMS_{time} - SHMS_{time}$$

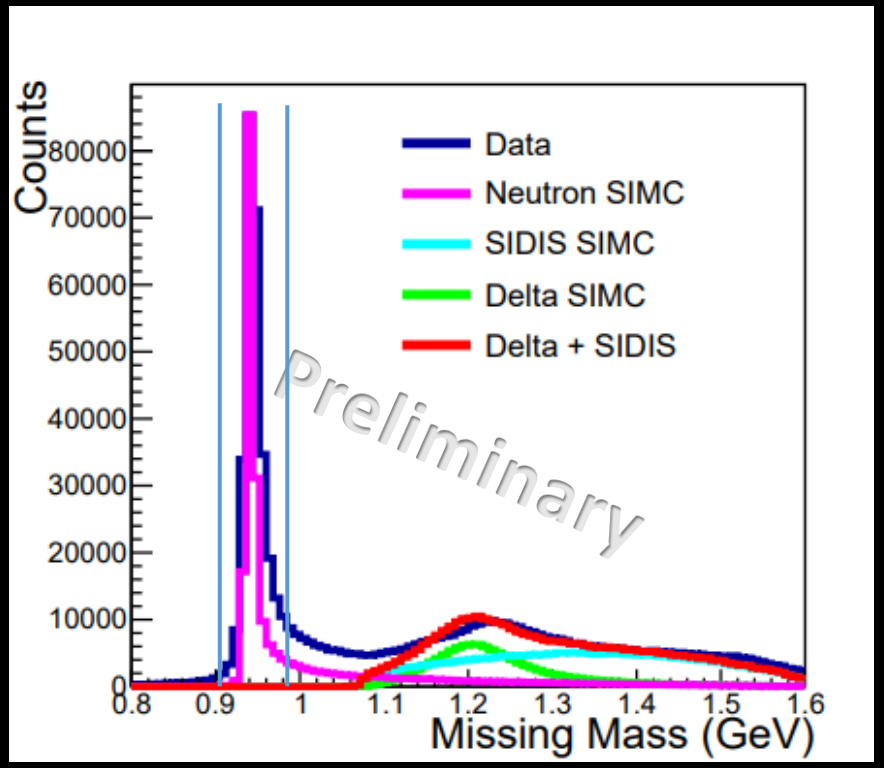


$$Q^2 = 2.115 \, , W = 2.95$$

Event Selection

- Missing Mass

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



$$Q^2 = 2.115\,, W = 2.95$$

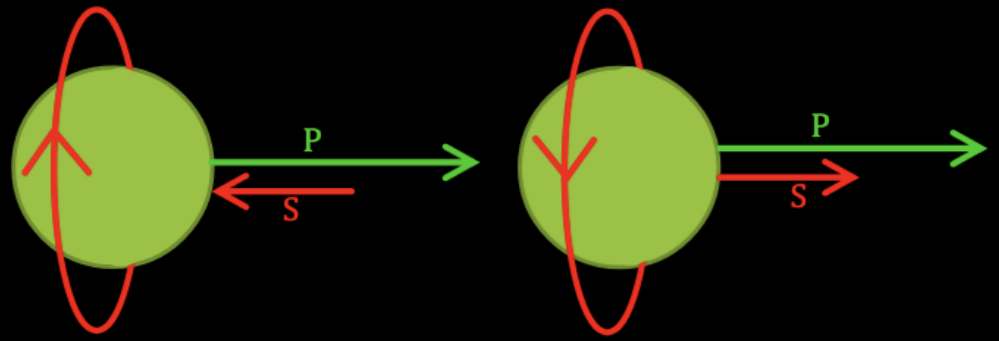
Beam Spin Asymmetry

Goals

- **Calculate asymmetry for high ϵ data**
  - **High statistics and full ϕ coverage**
- **Study and estimate SIDIS background**
- **Extract $\frac{\sigma_{LT'}}{\sigma_0}$ for a wide range of kinematics**

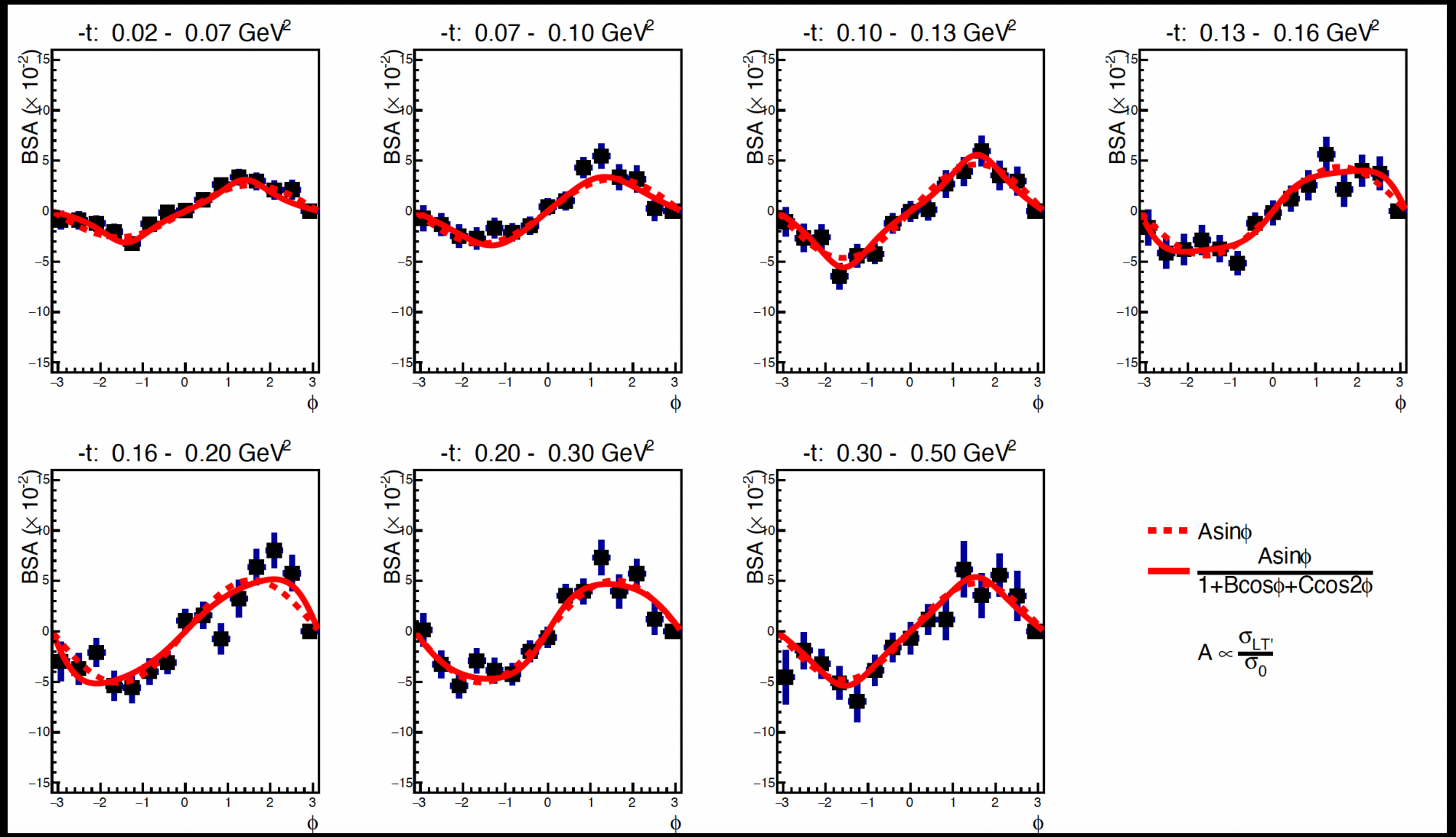
Beam Spin Asymmetry

- Difference in cross-section based on helicity (+1, -1) of incident electron.
- Caused by interference between transversely and longitudinally polarized virtual photons.
- Beam polarization "*P*" is measured at source ($P = 89^{+1}_{-3}\ \%$)
- Acceptance and efficiencies cancel in the ratio.



$$\boldsymbol{BSA} = \left[\frac{1}{P}\left(\frac{\sigma^{+} - \sigma^{-}}{\sigma^{+} + \sigma^{-}}\right)\right] = \left[\frac{1}{P}\left(\frac{Y^{+} - Y^{-}}{Y^{+} + Y^{-}}\right)\right] \propto \frac{\boldsymbol{\sigma^{LT'}}}{\boldsymbol{\sigma^{0}}}$$

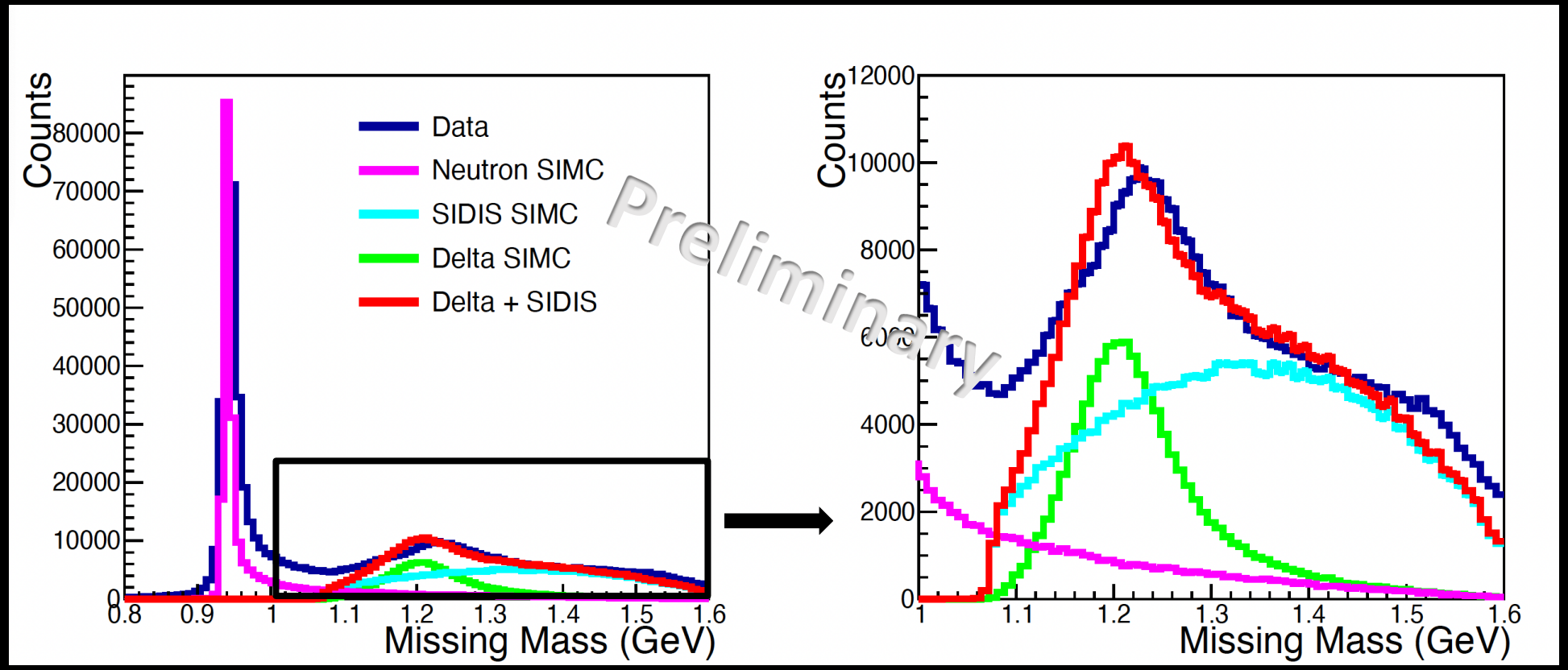
BSA - $p(e, e'\pi^+)n$



$Q^2 = 2.115\,, W = 2.95$

Event Selection - Δ^0

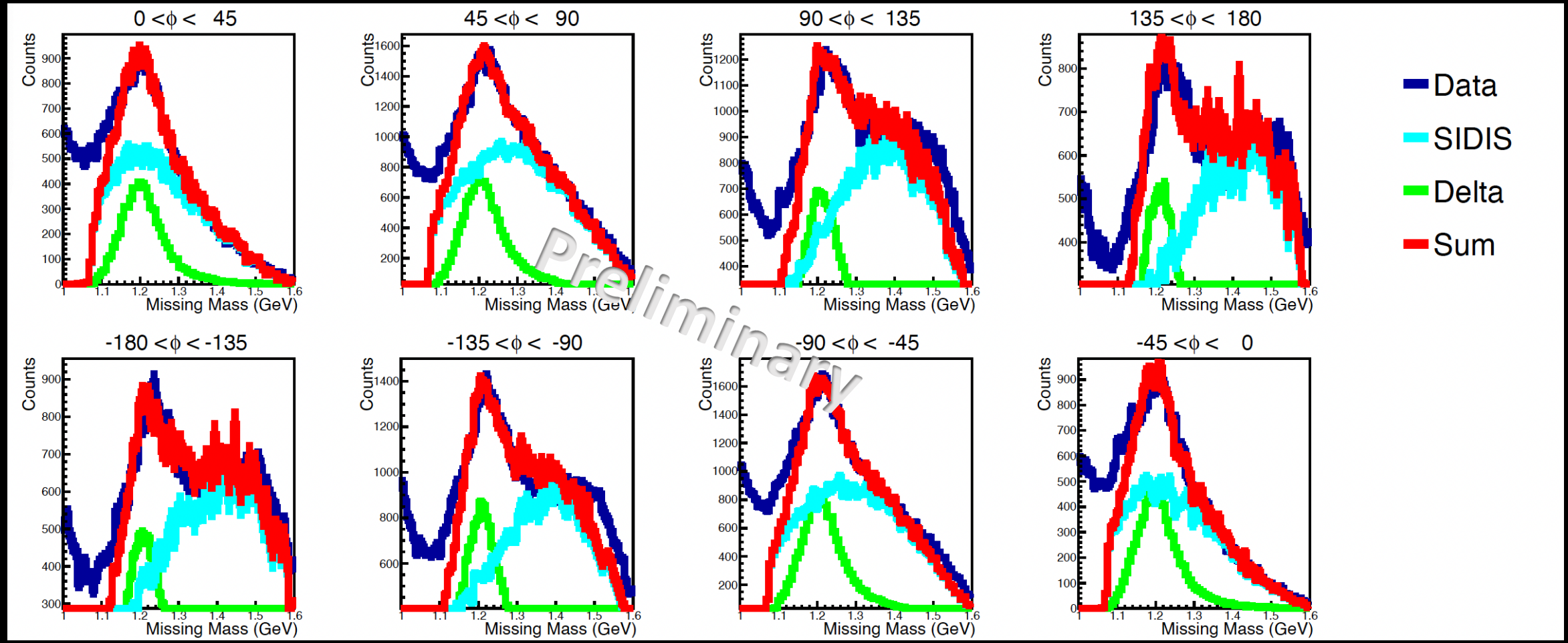
$$M_m = \sqrt{(E_e + m_p - E_{e'} - E_{\pi^+})^2 - (p_e - p_{e'} - p_{\pi^+})^2}$$



$Q^2 = 2.115\,, W = 2.95$

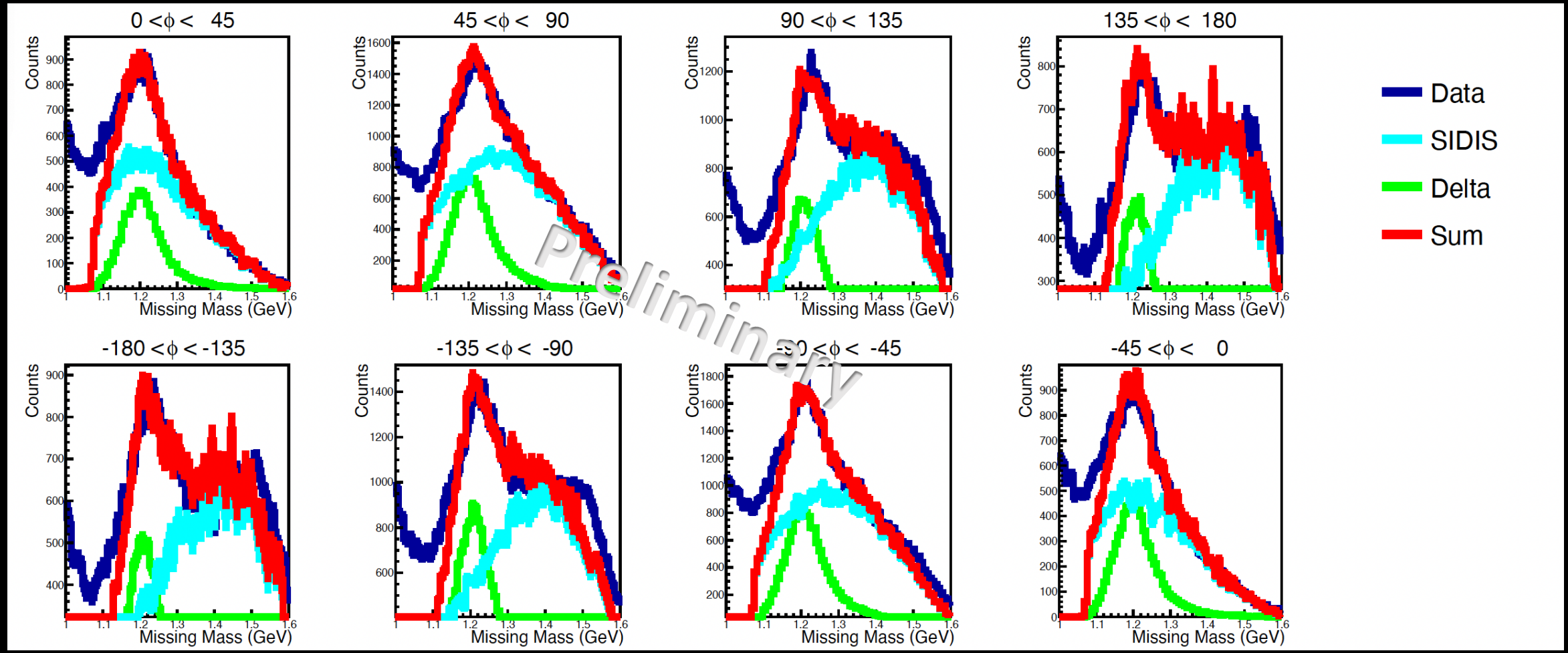
SIDIS MC provided by P. Bosted (Hall C SIDIS collaboration)

Δ^0 Shape Study (Helicity +1)



$Q^2 = 2.115\,, W = 2.95$

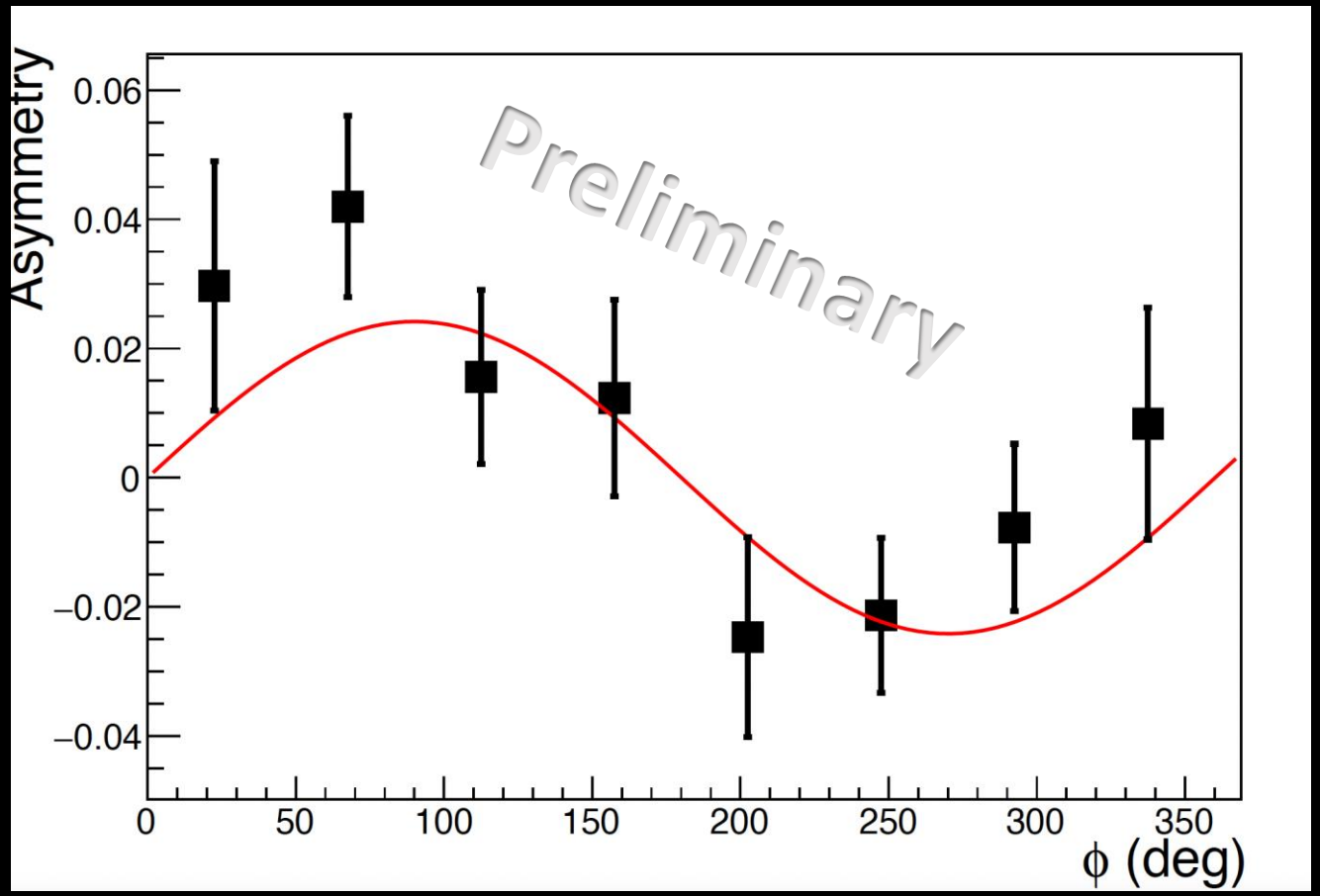
Δ^0 Shape Study (Helicity -1)



$Q^2 = 2.115\,, W = 2.95$

BSA - $p(e, e'\pi^+)\Delta^0$

- BSA is calculated by integrating $p(e, e'\pi^+)\Delta^0$ MC missing mass.
- Small asymmetry observed
  - ~ 1.5 σ from zero.
- Only statistical errors shown here.



$Q^2 = 2.115\,, W = 2.95$

Outlook - BSA

- Full kinematics for BSA analysis

E (GeV)	Q^2 (GeV^2)	W (GeV)	x_B
10.6	5.5	3.02	0.40
10.6	4.4	2.74	0.40
10.6	3.0	3.14	0.25
10.6	3.0	2.32	0.40
10.6	2.115	2.95	0.21

- Extract the $\frac{\sigma_{LT'}}{\sigma_0}$ and compare it with theory models
  - Regge based models
  - GPD based models

- Compare $p(e, e'\pi^+)\Delta^0$ results with parallel BSA analysis of $p(e, e'\pi^+)n$.
  - Also compare with CLAS12 results.

L/T Separated Cross-Section

Goals

- **Carefully understand all systematics**
  - **Acceptance, Efficiencies**
- **Calculate Normalized yield**
- **Perform an L/T separation for a wide range of kinematics.**

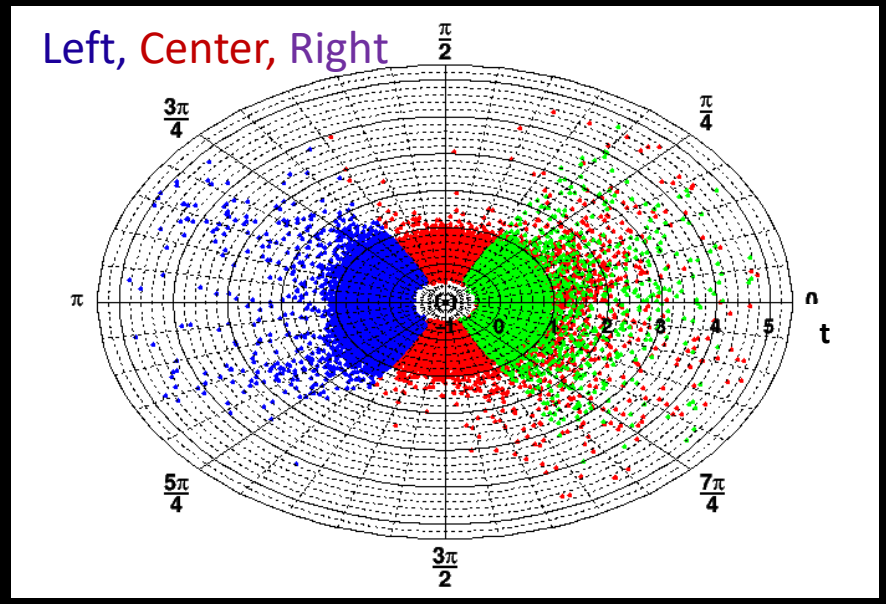
ϕ Coverage for L/T Separation

- Hall C 12 GeV upgrade was motivated by extreme forward angle requirements for L/T separation experiments.
- To get a full ϕ coverage, data is taken three degrees on the left and right of the *Q-vector* (in pion arm).
- *Measurements are only possible due to small angle capibilities of SHMS.*

ϕ Coverage for L/T Separation

- To get a full ϕ coverage, data is taken three degrees on the left and right of the *Q-vector* (in pion arm).
- To control systematics, an excellent understanding of spectrometer is required
  - Over constrained $p(e, e'p)$ elastic scattering is used to calibrate spectrometer acceptance, momenta, kinematic offset and efficiencies.

$Q^2 = 4.4\,, W = 2.74$



Radial axis – t

Azimuthal angle - ϕ

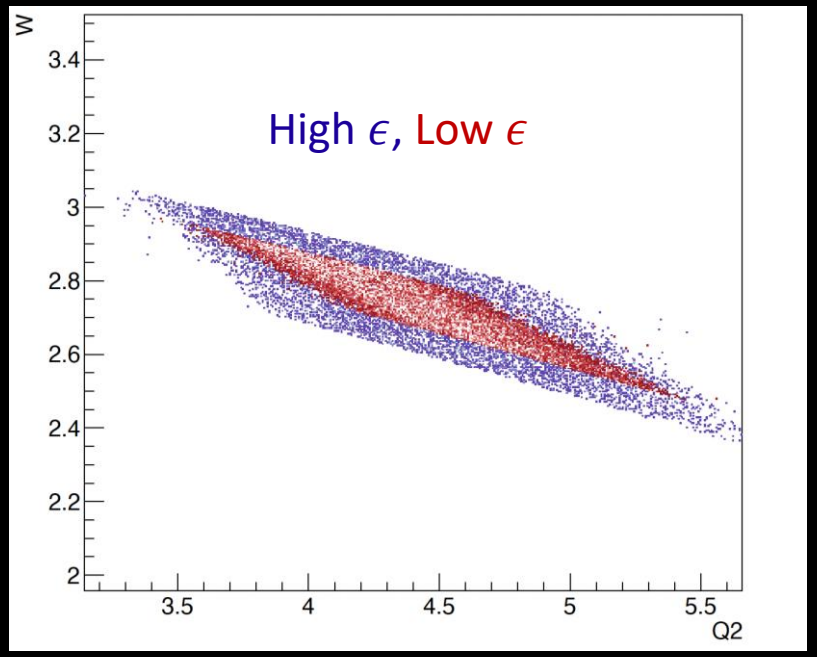
Rosenbluth (L/T) Separation

- σ_L and σ_T are separated through Rosenbluth Separation technique

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

- Cross-section is separated by performing two scattering measurements at different "ϵ" value with fixed Q^2 and W.
- Cuts are placed on low and high ϵ setting to select overlap region in Q^2 and W.
- Total uncertainty budget is very small due large error amplification.
  - Error amplification by a factor ~ 2-4.

$Q^2 = 4.4\,, W = 2.74$



Error Estimation

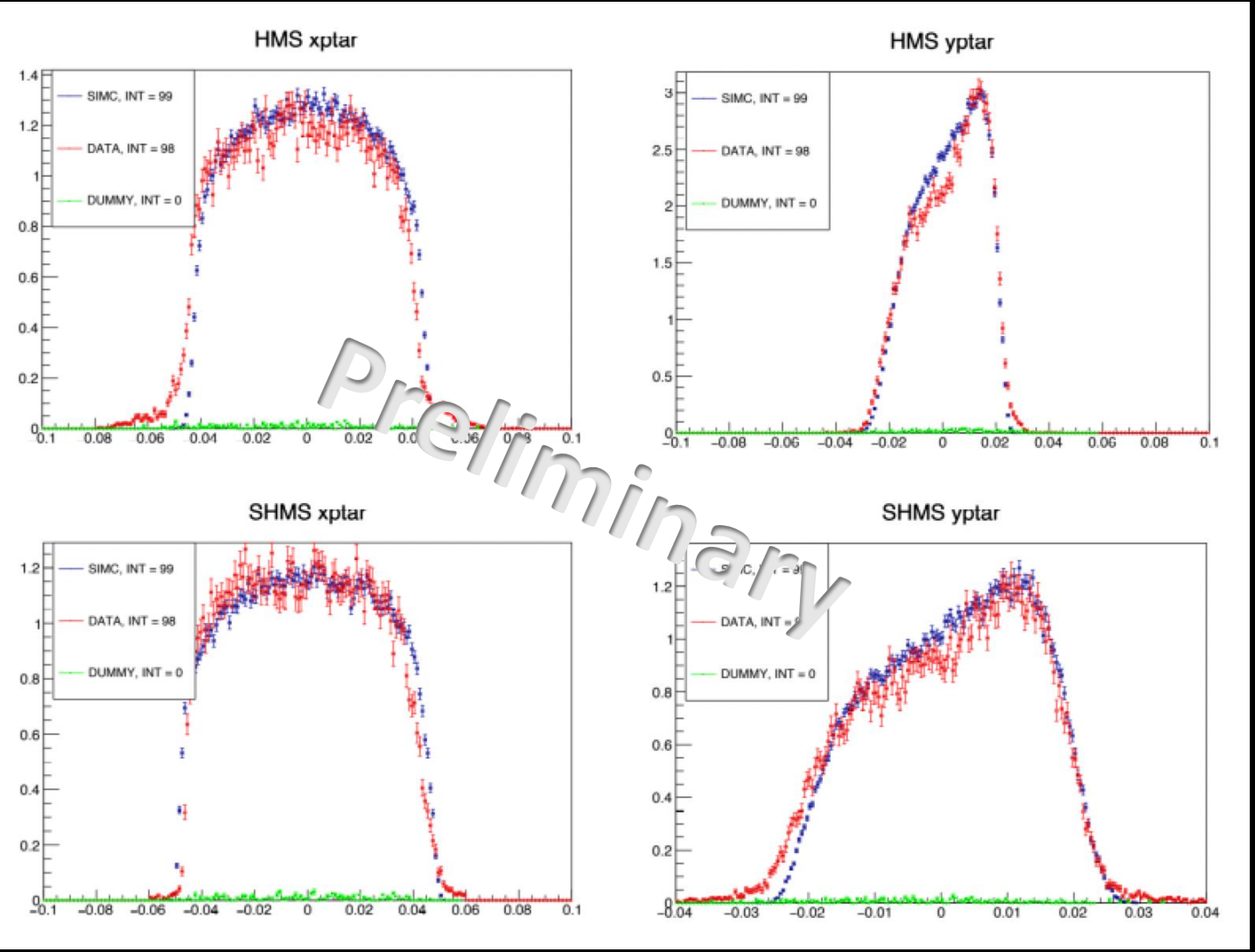
$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2}\frac{1}{\sigma_L}\sqrt{\Delta\sigma_1^2 + \Delta\sigma_2^2}$$

Systematic Studies - Acceptance

- Target quantities are reconstructed from the focal plane quantities.
  - Xptar → vertical euler angle
  - Yptar → Horizontal euler angle

- Both HMS and SHMS show reliable comparison between data and simulation.

- $E_{beam} = 8.2\ GeV$



Relative Yield

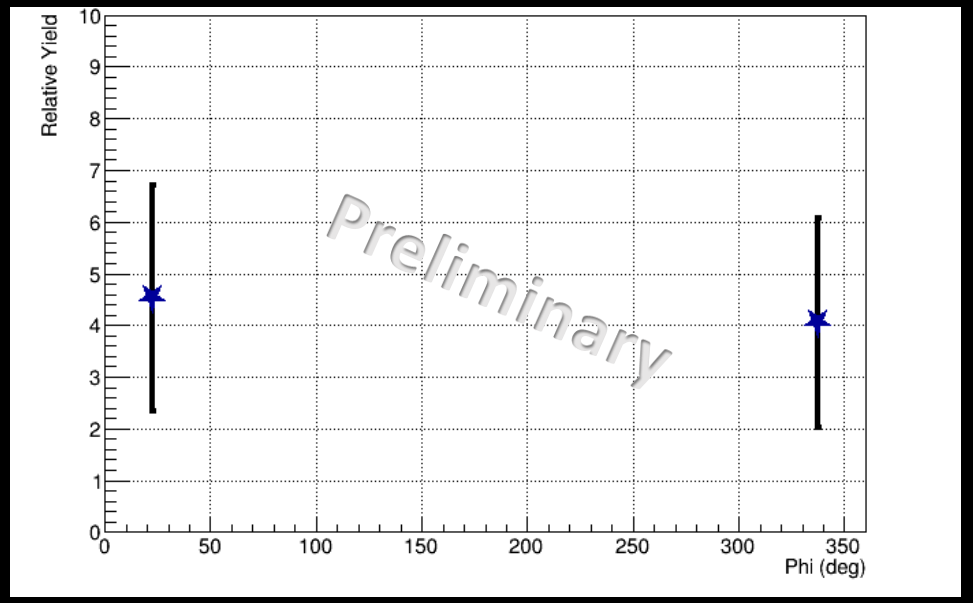
- Relative for $p(e, e'\pi^+)n$ and $p(e, e'\pi^+)\Delta^0$ is calculated as

$$Yield_{rel} = \frac{Y_{low\ \epsilon}/Y_{high\ \epsilon}}{Y_{low\ \epsilon}/Y_{high\ \epsilon}}$$

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

$\Rightarrow p(e, e'\pi^+)\Delta^0$

- Results shows large ϵ dependence for $p(e, e'\pi^+)n$ reaction.
  - σ_L dominates for this channel.
- Large double ratio value indicate $p(e, e'\pi^+)\Delta^0$ reaction is dominated by σ_T.



$low\ \epsilon = 0.25, \quad high\ \epsilon = 0.79$

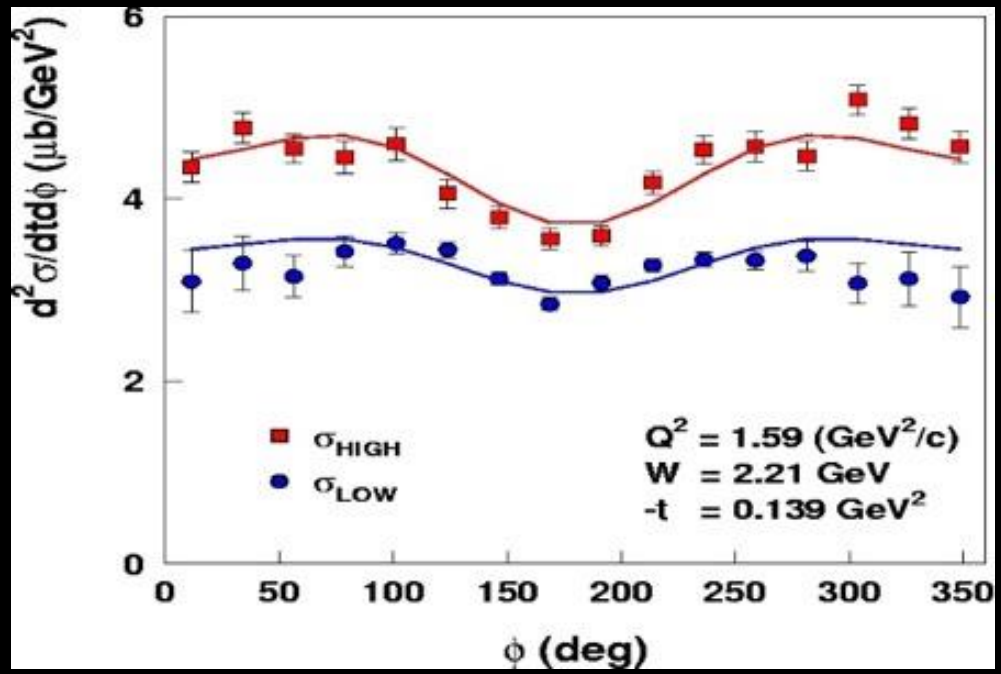
$Q^2 = 2.115, W = 2.95$

Next Steps - L/T/LT/TT Separated Cross-Section

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

- Differential cross-section is calculated for each ϵ setting with fixed value of Q^2, W and $-t$.

- Rosenbluth equation is fitted to the data to extract separated cross-sections.



Horn et al. (PRL 97, 192001)

Summary and Outlook

- Kaon-LT Experiment is gives access to high statistic exclusive pion electroproduction data.

- Analysis in progress for $p(e, e'\pi^+)\Delta^0$ Beam spin asymmetry and L/T separated cross-section.
  - Shape study for Δ^0 missing mass has been done to understand SIDIS contribution.
  - A large number of systematic studies are completed.

- Will be the first measurement of $p(e, e'\pi^+)\Delta^0$ L/T separated cross-section.
  - **The n/Δ^0 ratio of separated cross-section can give access to transition GPDs.**

- Need theory support for both BSA and L/T separated cross-section.

- Potential to increase statistics and kinematic range with JLab upgrade and EIC.

Thank You !!!

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