Probing Hadron Structure through $e + p \rightarrow e' + \pi^{+} + \Delta^{0}$ reaction at Jefferson Lab

Ali Usman

On behalf of Kaon-LT / Pion-LT collaboration

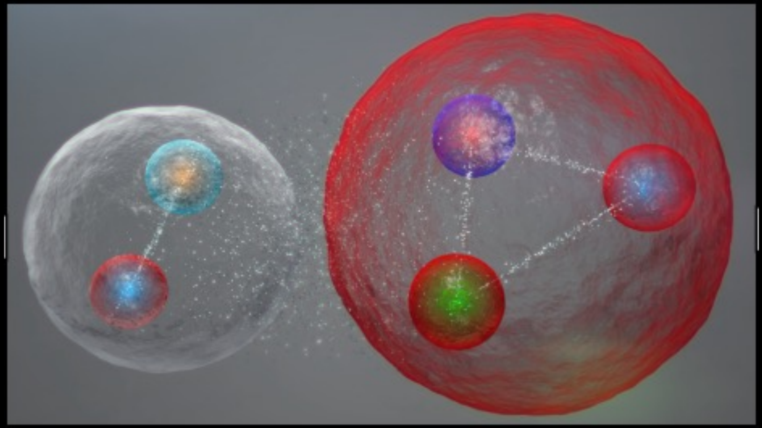
CAP Congress (Saskatoon 2025)

CRSNG NSERC

University of Regina

Jefferson Lab

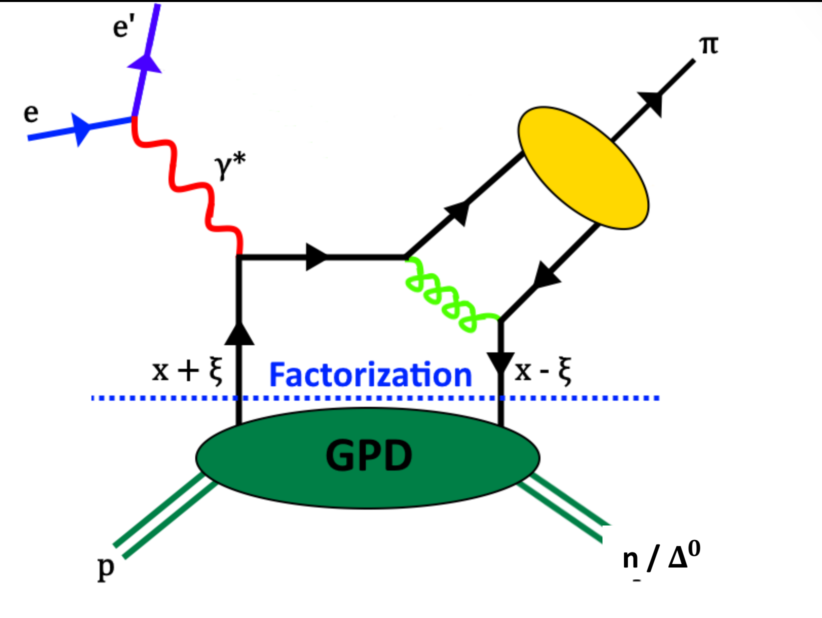
Generalized Parton Distributions (GPDs)



- Hadron structure is poorly understood within QCD framework.

- GPDs describe the 3D structure of hadrons via quark-gluon degrees of freedom.
  - Longitudinal momentum distribution (PDFs)
  - Transverse spatial distribution (Form factors)

- While significant work has been done for the study of ground state nucleon GPDs, little is known about the $N \rightarrow \Delta$ transition GPDs.
  - Only one measurement from CLAS12 with exclusive $\pi^{-}\Delta^{++}$ (Diehl et al. PRL 131 021901)
  - Pioneering theory work on Transition GPDs for exclusive $\pi\Delta$ electroproduction (Kroll, Passek-Kumericki PRD 107, 054009)



Exclusive Pion Electroproduction

- Exclusive pion electroproduction reaction

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

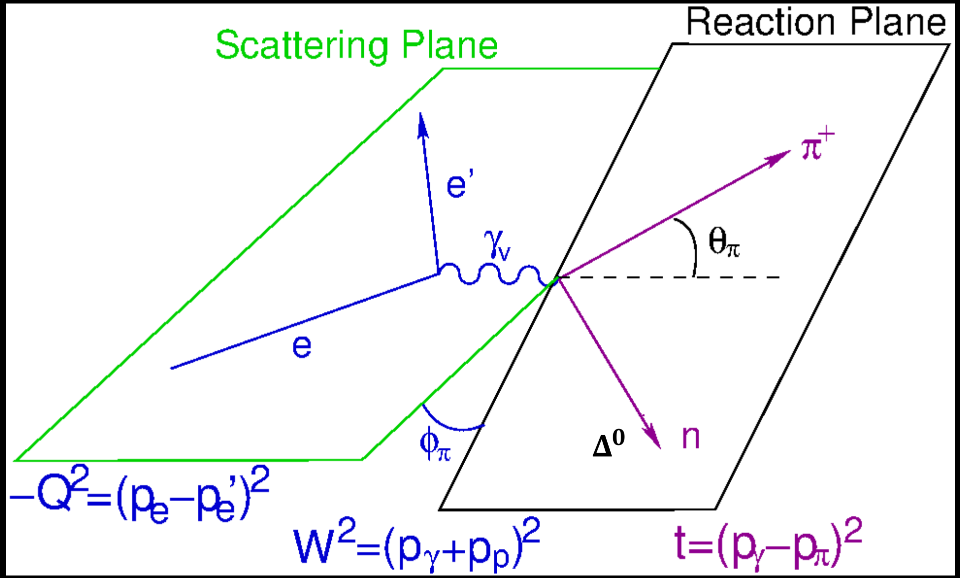
- Differential cross-section is dictated by virtual photon polarization ϵ.

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

- "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, $\sigma_{LT'}$, is extracted using a polarized electron beam.



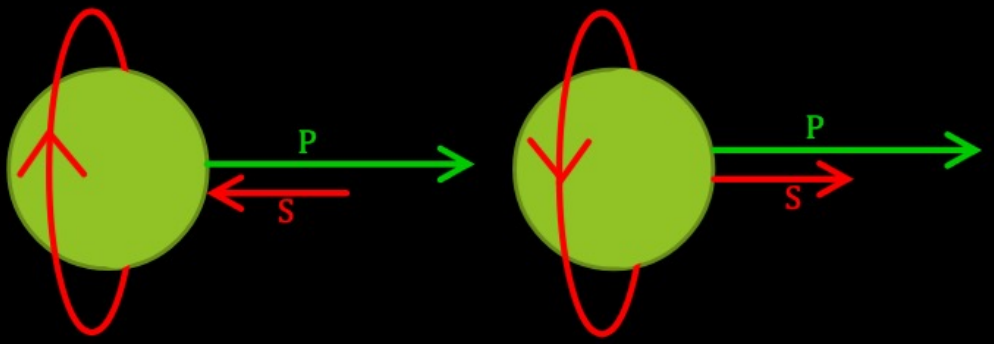
Beam Spin Asymmetry (BSA)

- BSA is difference in cross-section based on helicity (+1, -1) of incident electron.
- $\sigma_{LT'}$ interference between transversely and longitudinally polarized virtual photons
  - Can be accessed through Beam Spin Asymmetry (A_{LU})

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

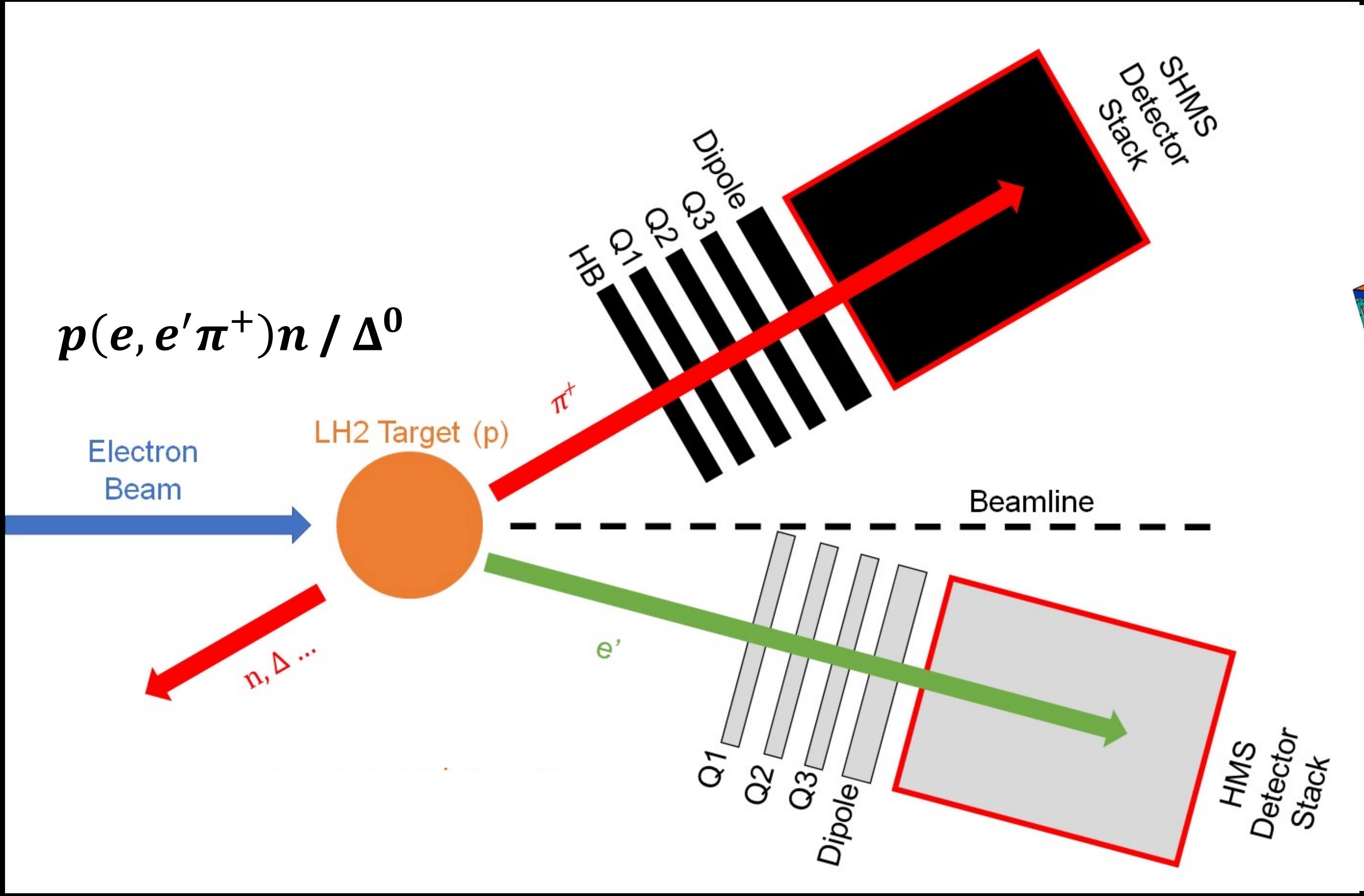
Unpolarized cross-section

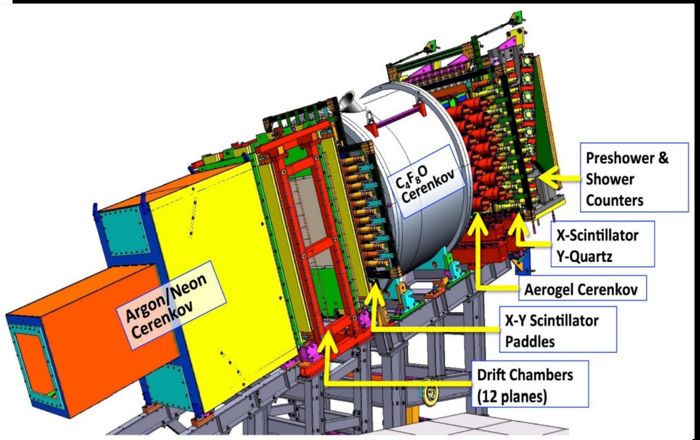
- Acceptance and efficiencies cancel in the ratio.
- Beam polarization "*P*" is measured at source ($P = 89^{+1}_{-3}$ % - Gaskell and Wood)

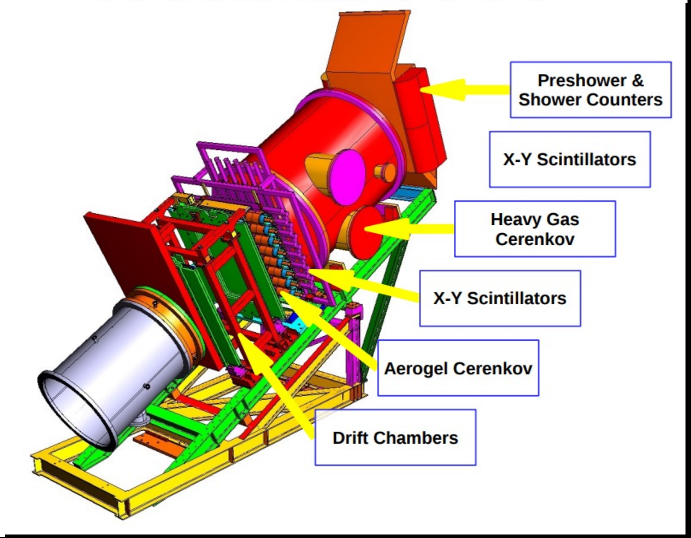


Experimental Hall C @ Jefferson Lab

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







Kaon-LT Experiment (E12-09-011)

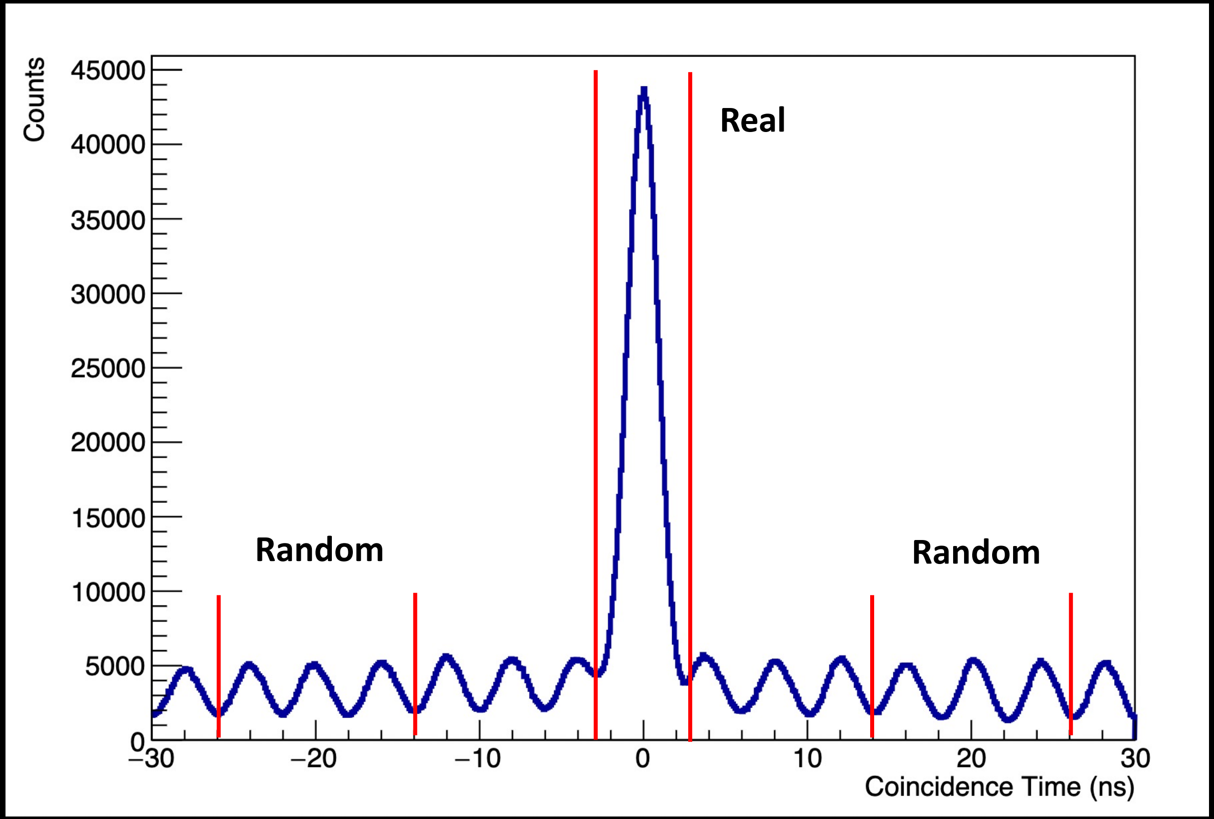
- First dedicated experiment to study exclusive kaon electroproduction reaction.
  - Data collected 2018-2019
- $p(e, e'K^+)\Lambda$ cross-section is ~ 1/10 times $p(e, e'\pi^+)n$ cross-section.
- Ideal dataset to study $p(e, e'\pi^+)\Delta^0$ reaction.
  - Experiment kinematics are designed to have the Λ missing mass region in center of phase space.
- For BSA, only 10.6 GeV data is used.
  - This dataset has full azimuthal (ϕ) coverage.

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	2.32	0.40	0.88/0.57
10.6/6.2	3.0	3.14	0.25	0.67/0.39
10.6/6.2	2.115	2.95	0.25	0.79/0.25
4.9/3.8	0.5	2.40	0.09	0.70/0.45

Event Selection

- $e' - \pi^+$ Coincidence

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

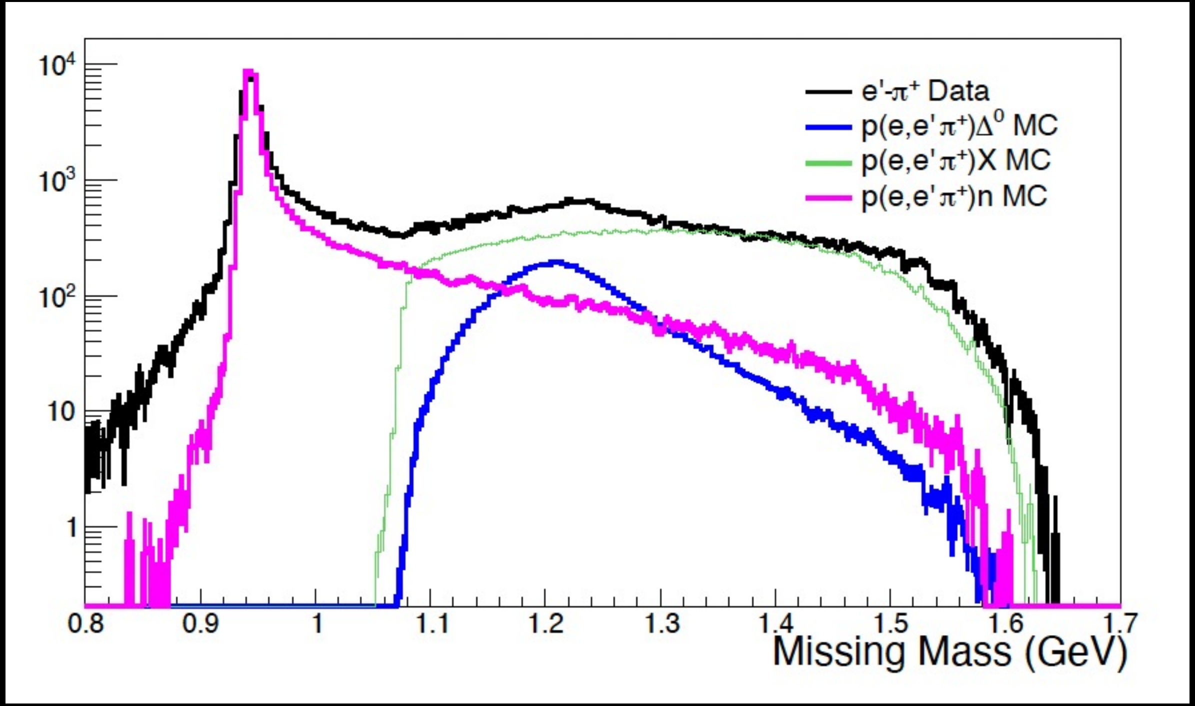


$$Q^2 = 2.115 \ , W = 2.95$$

Missing Mass

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

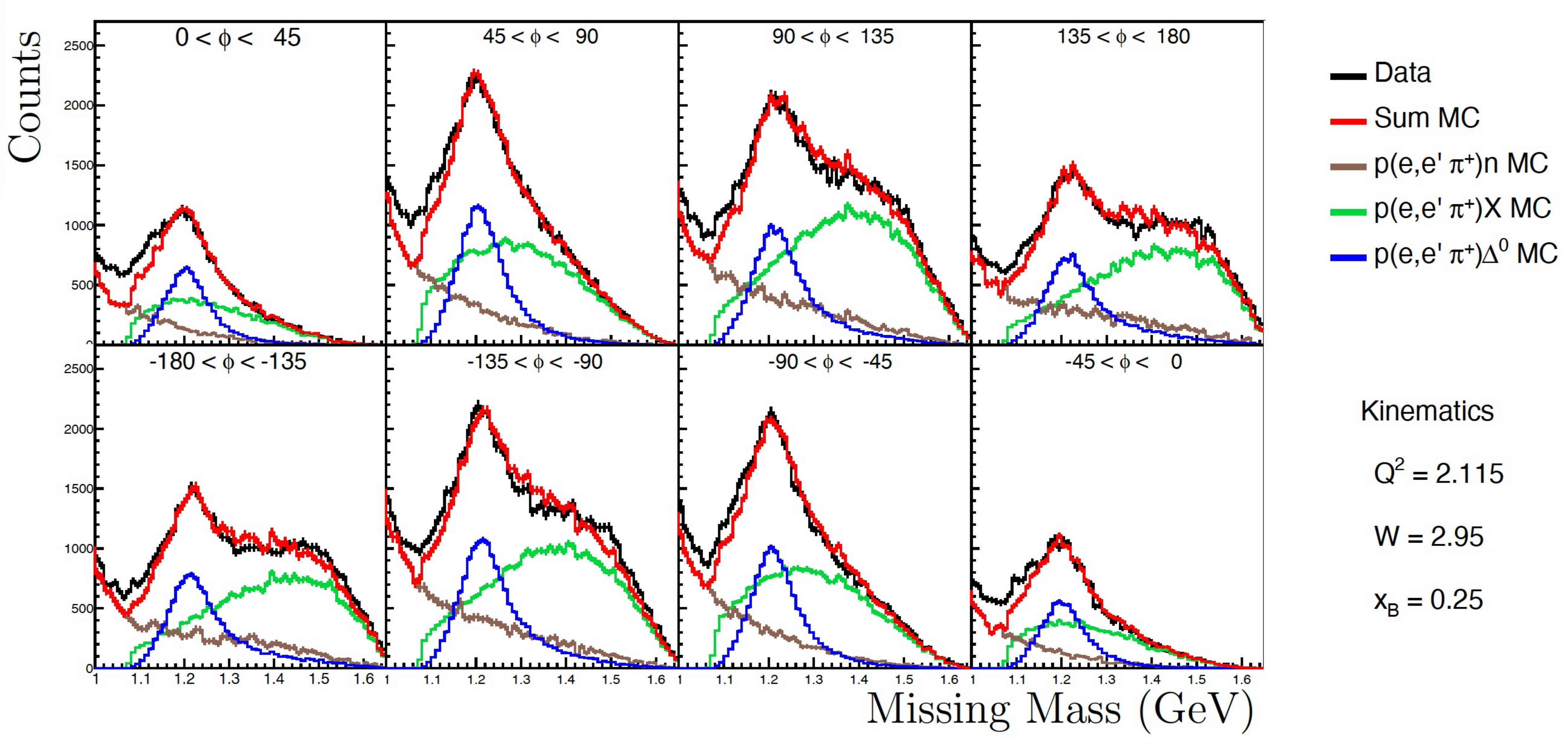
$p(e, e'\pi^+)n$ MC is subtracted by fitting it to the data in the neutron peak region.



$p(e, e'\pi^+)X$ MC is subtracted by fitting it to the data in the region (1.45-1.60 GeV).

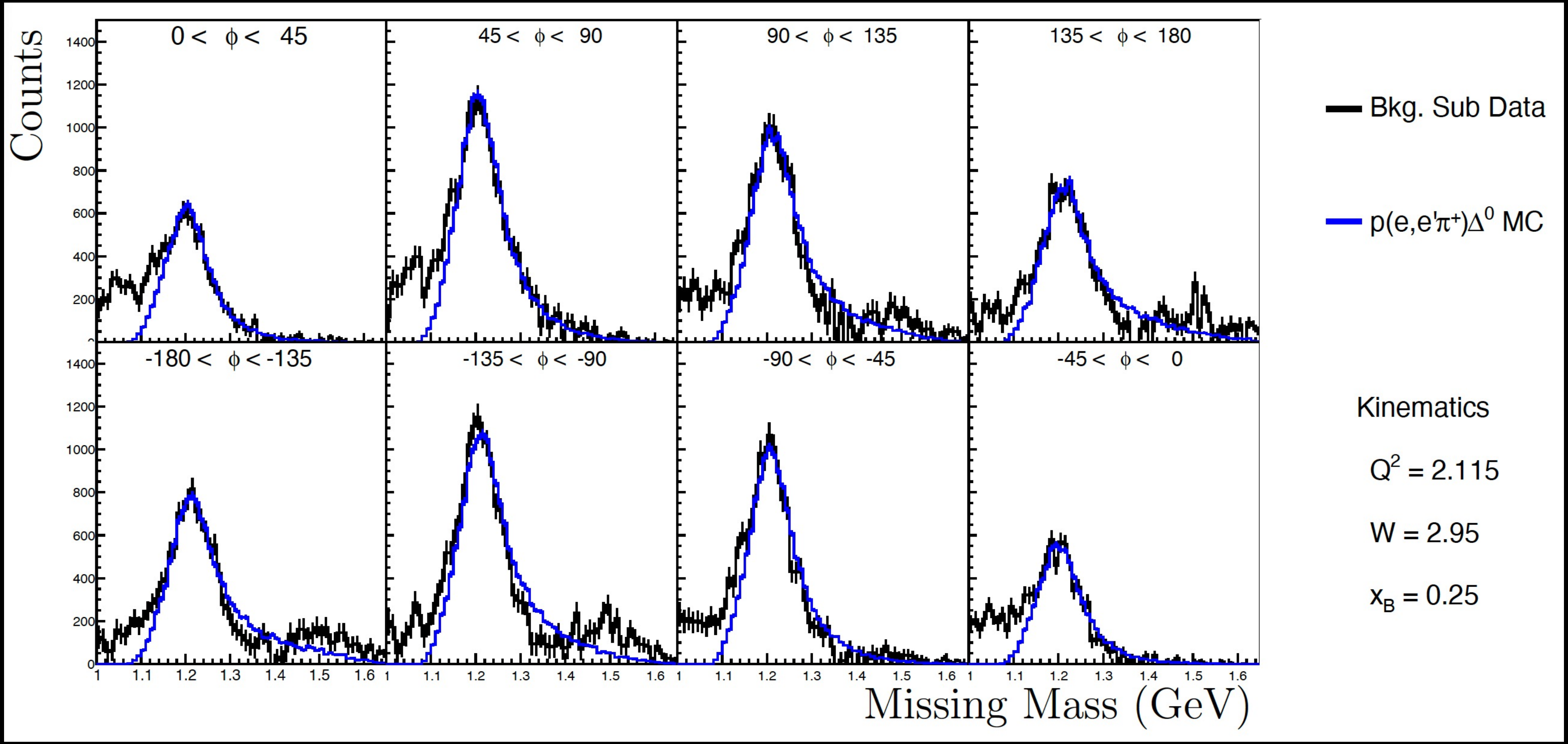
$p(e, e'\pi^+)\Delta^0$ is fitted to the background subtracted data in the region (1.15-1.30 GeV).

Δ^0 Shape Study – Combined Fit



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

Δ^0 Shape Study – Signal Selection



$Q^2 = 2.115, W = 2.95$

$-t - \phi$ binning

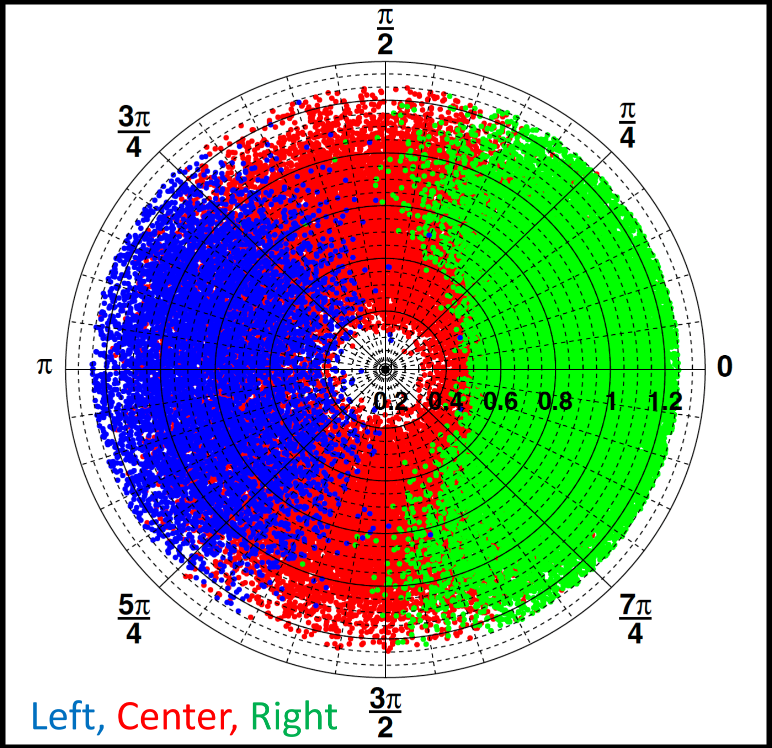
- $-t$ binning is dictated by statistics for each kinematic setting.
  - High statistics settings (3 bins)
  - Low statistics settings (1 or 2 bin)

- 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 capabilities of SHMS (up to 5.5°).*

- *For beam spin asymmetry, ϕ dependence is measured by binning the data in 8 equal size ins (for each SHMS setting).*

$Q^2 = 5.5, W = 3.02$



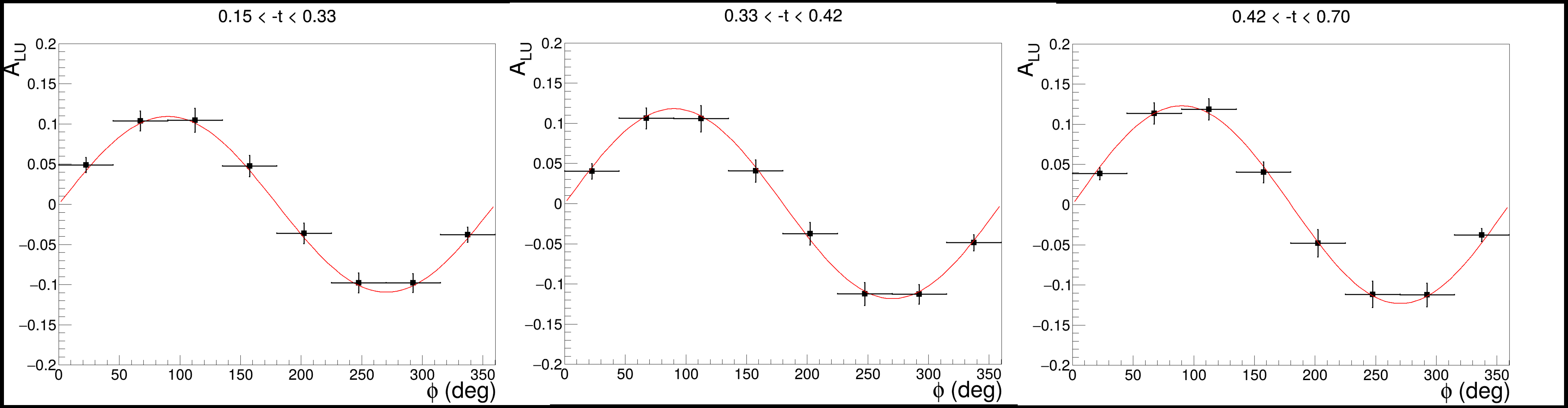
Radial axis – t

Azimuthal angle - ϕ

A_{LU} vs ϕ

- BSA is calculated by integrating $p(e, e'\pi^+)\Delta^0$ missing mass (1.11 - 1.40 GeV).

$$A_{LU} = \left[\frac{1}{P}\left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right)\right] \qquad \delta_{stat} = \frac{2}{P}\sqrt{\frac{Y^+ . Y^-}{(Y^+ + Y^-)^3}}$$



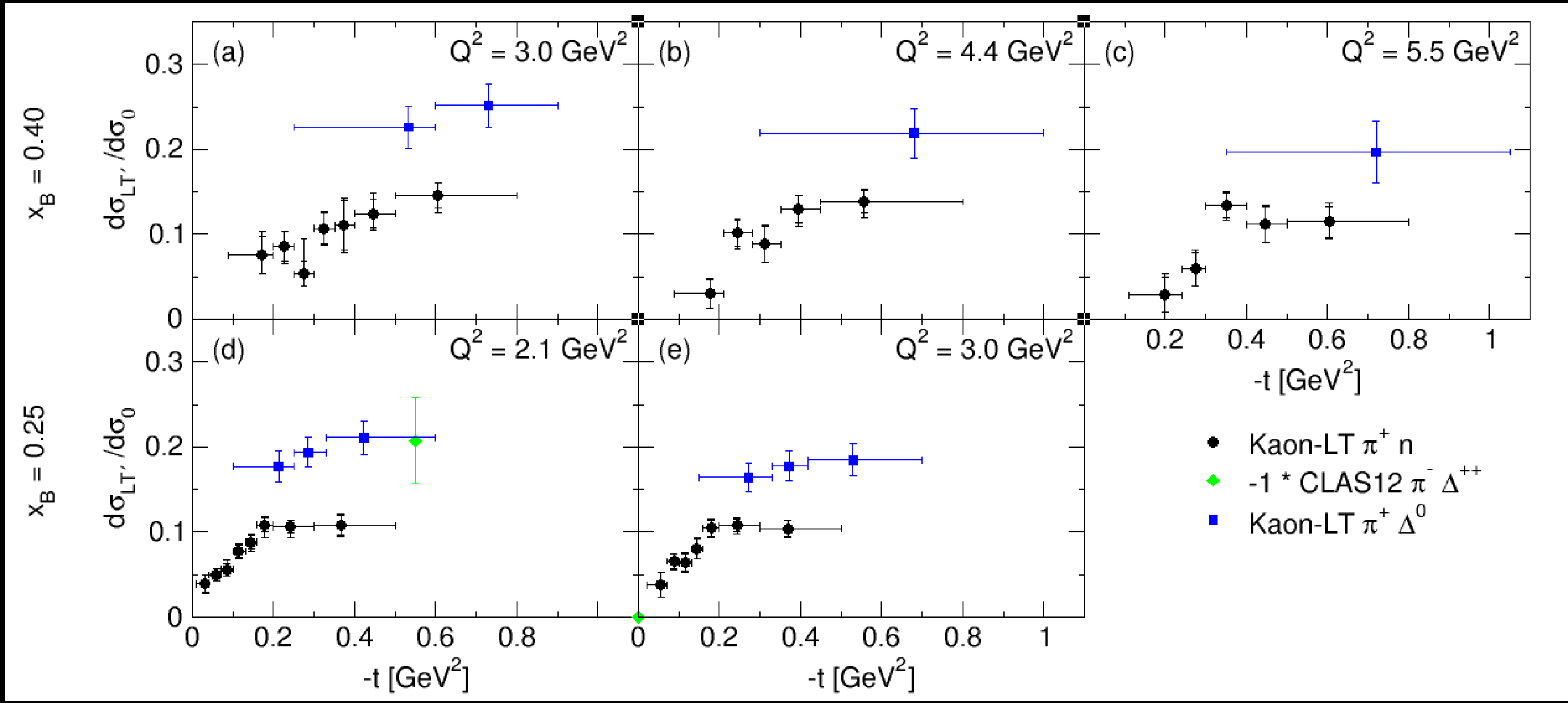
- Only statistical errors shown here.

$$Q^2 = 3.0\ GeV^2, W = 3.14\ GeV$$

$\sigma_{LT'}/\sigma_0$ vs -t

- Within limited –t coverage, $\sigma_{LT'}/\sigma_0$ show similar trend for both π^+n and $\pi^+\Delta^0$
- The $\sigma_{LT'}/\sigma_0$ magnitude for $\pi^+\Delta^0$ is approximately double than the $\pi^+\ n$ across different settings.

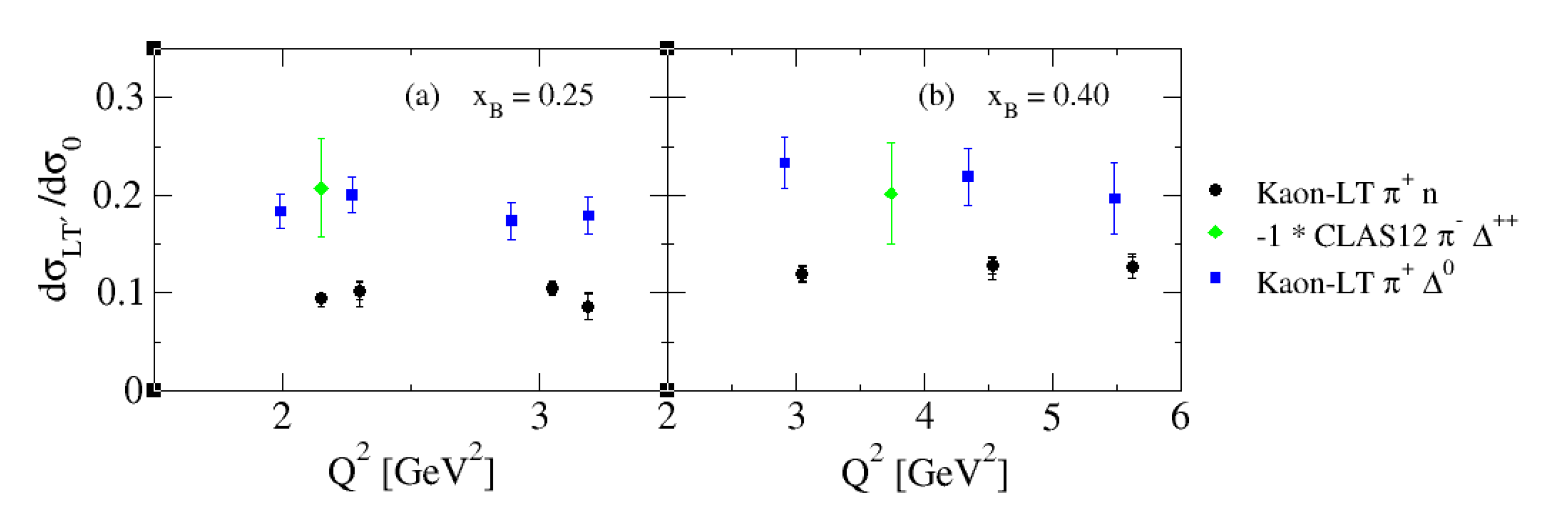
$$A_{LU} = \sqrt{2\epsilon(1-\epsilon)}\ \frac{d\sigma_{LT'}}{d\sigma_0}$$



- Only statistical errors shown here

$\sigma_{LT'}/\sigma_0$ vs Q^2

- The Q^2-dependence show polarized cross-section ($\sigma_{LT'}$) drops at same rate as unpolarized σ_0.
- The $\sigma_{LT'}/\sigma_0$ magnitude for $\pi^+\Delta^0$ and $\pi^-\Delta^{++}$ is comparable but opposite sign.



- Only statistical errors shown here

Summary

- Studying parton interaction is essential to understanding the hadron internal structure.
  - Experimental measurement of exclusive pion electroproduction is a powerful tool for GPD study.
- Kaon-LT Experiment gives access to high statistic exclusive pion electroproduction data at wide range of kinematics.
- **First ever measurement of Beam Spin Asymmetry for the $p(e, e'\pi^+)\Delta^0$ reaction.**
  - $\pi^+ \Delta^0$ BSA is approximately double in magnitude than $\pi^+ n$ (both from Kaon-LT)
  - $\pi^+ \Delta^0$ BSA has similar magnitude but opposite sign than $\pi^- \Delta^{++}$ from CLAS12.
- Systematic error analysis is currently on-going.
  - Final publication anticipated in Fall 2025.

Thank You !!!

CRSNG
NSERC

NSF

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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, Muhammad Junaid, Abdennacer Hamidi, Julie Roche

cua DEUS MEA LUX EST

University of Regina

Jefferson Lab

UNIVERSITY of York

UNIVERSITY of VIRGINIA

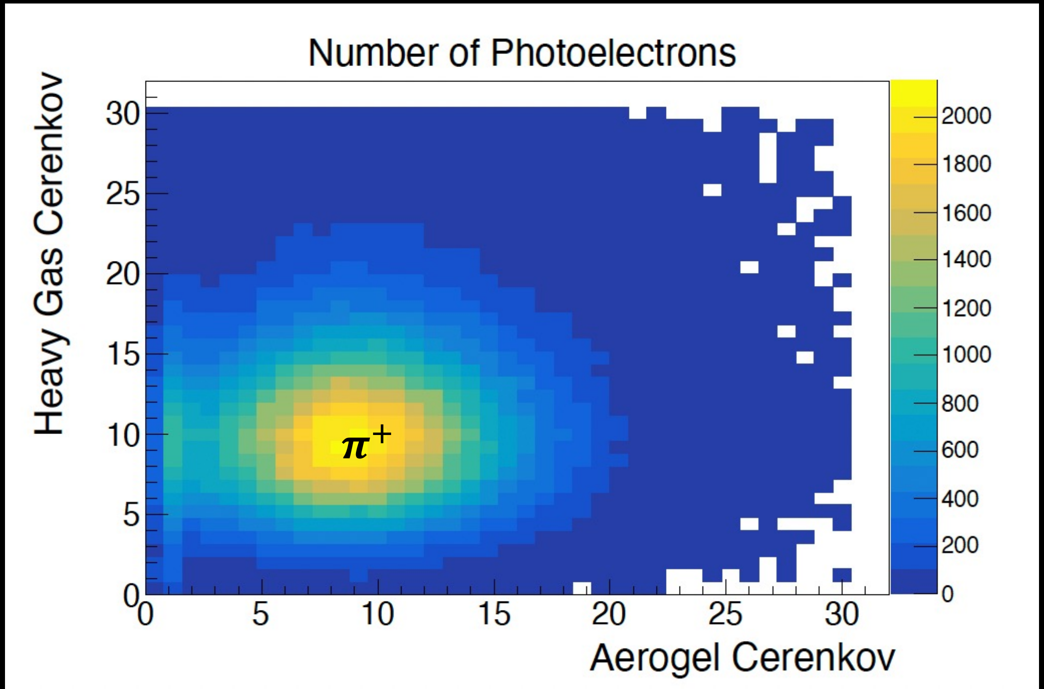
FIU

OHIO UNIVERSITY 1804

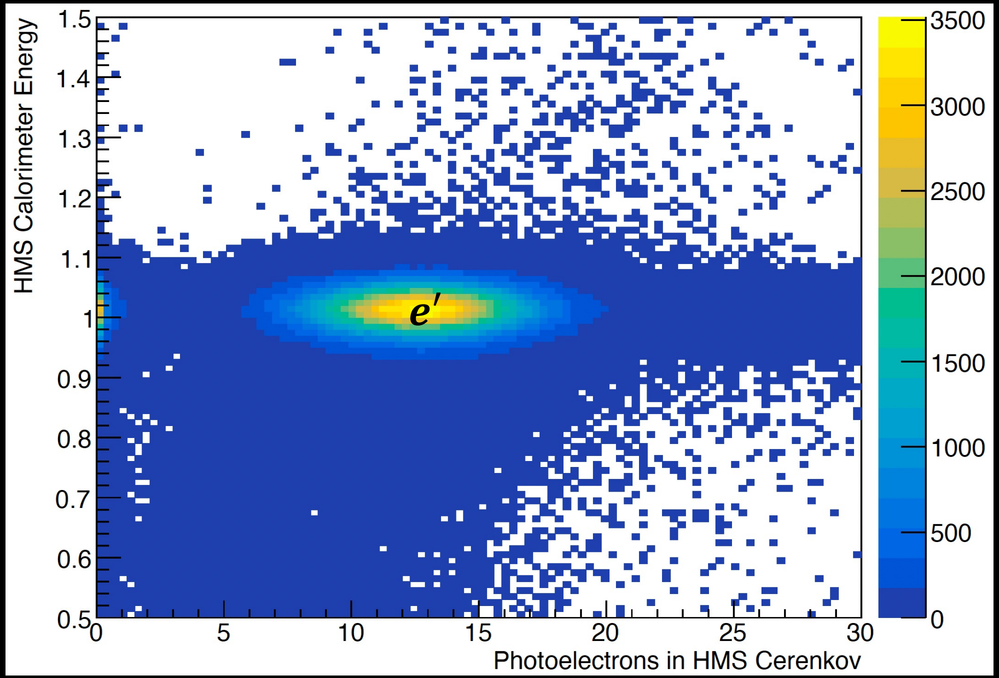
Backup

Particle ID

Pion Selection (SHMS)



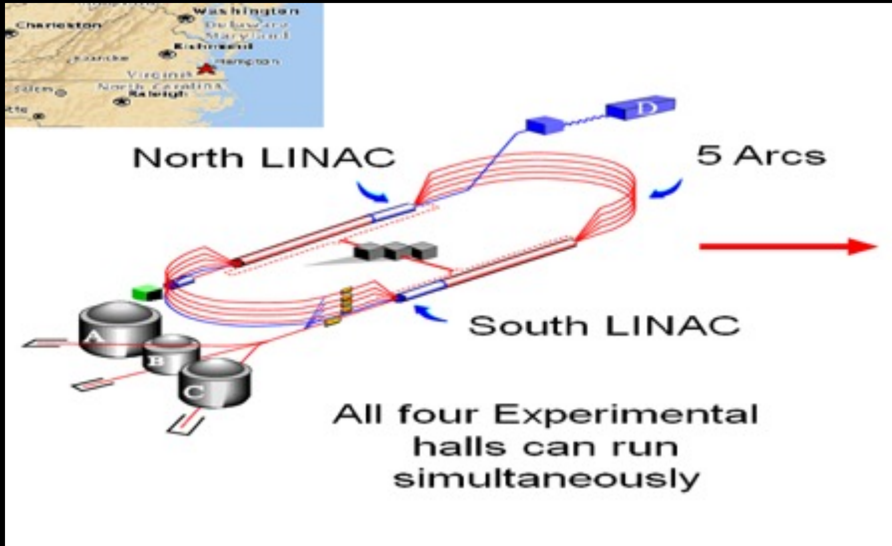
Electron Selection (HMS)



P.hgc.npeSum > 2.0	**H.cer.npeSum > 3.0**
P.aero.npeSum > 3.0	H.cal.etottracknorm > 0.7

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

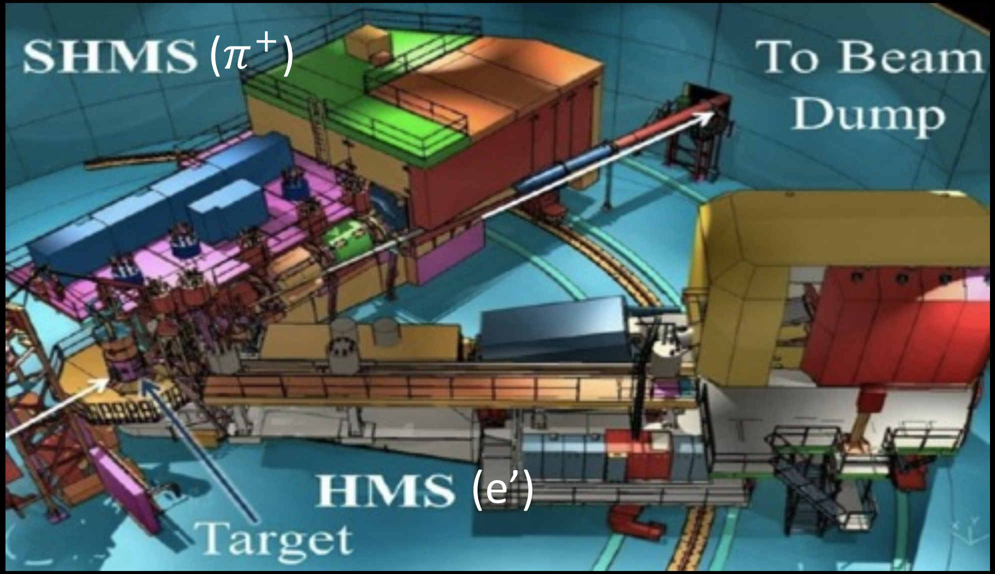
Thomas Jefferson National Accelerator Facility



- Consists of two superconducting electron LINACs.
- Capable of delivering high luminosity beam to four experimental halls.
- Variable beam energies and high current.

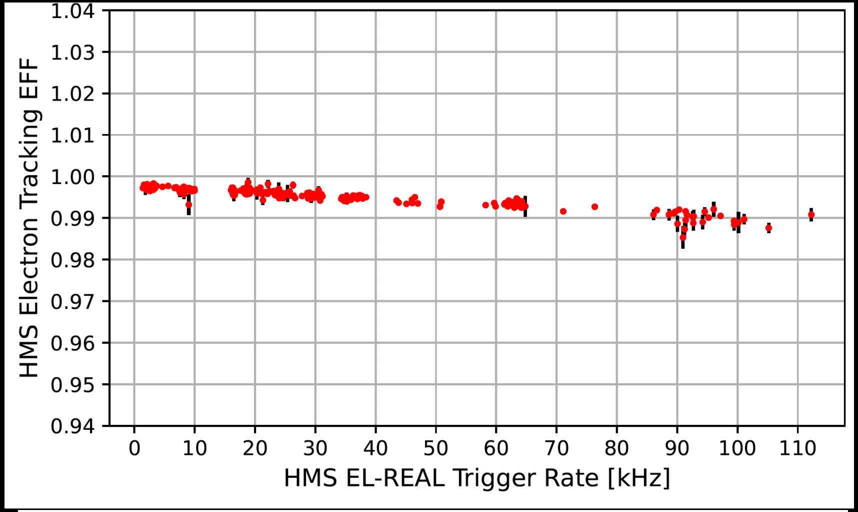
Hall C

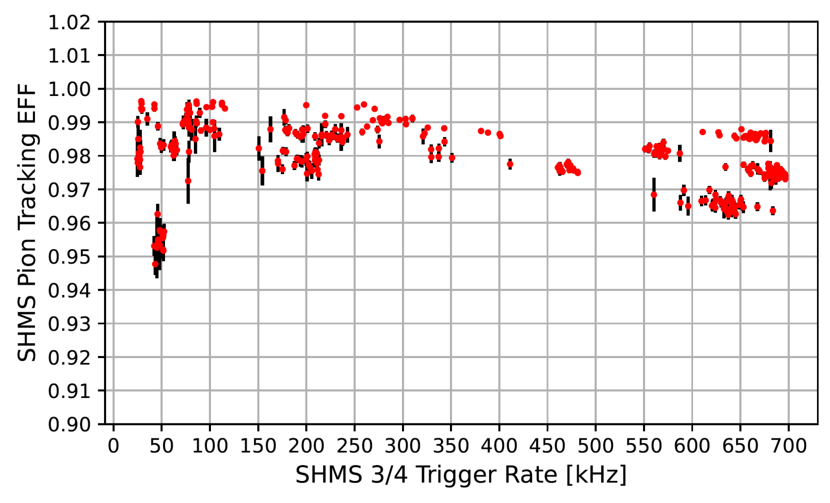
- Specifically designed to measure precise cross-sections.
- Two advanced rotatable magnetic spectrometers (HMS and SHMS).
- Particles of specific momentum are studied by using a magnet system.



Detector Performance – Tracking

- Drift chambers are used for tracking of particles in each spectrometer.
- Electron tracking efficiency in the HMS is stable over a range of rates.
- Pion tracking efficiency in the SHMS shows larger rate dependence.
  - Larger scatter is caused by different experimental conditions (SHMS angle, background rates etc)
- Track parameter optimization study was performed to improve SHMS tracking efficiency.



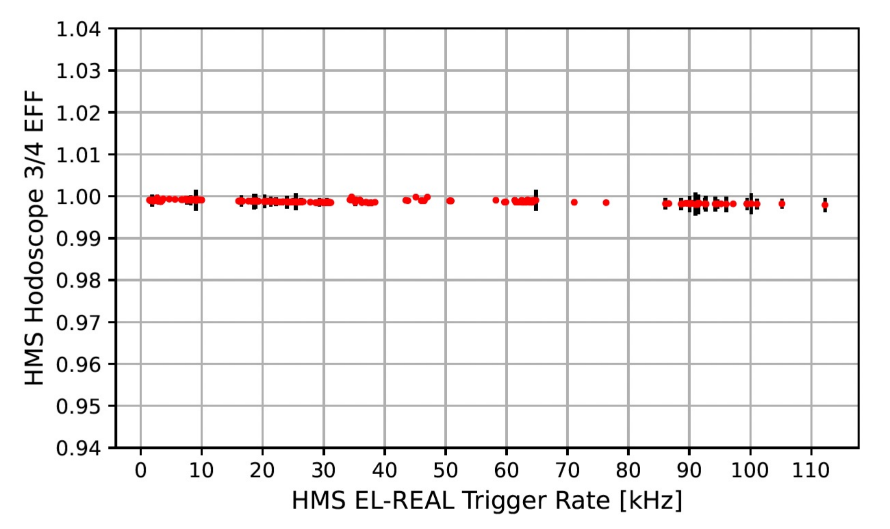


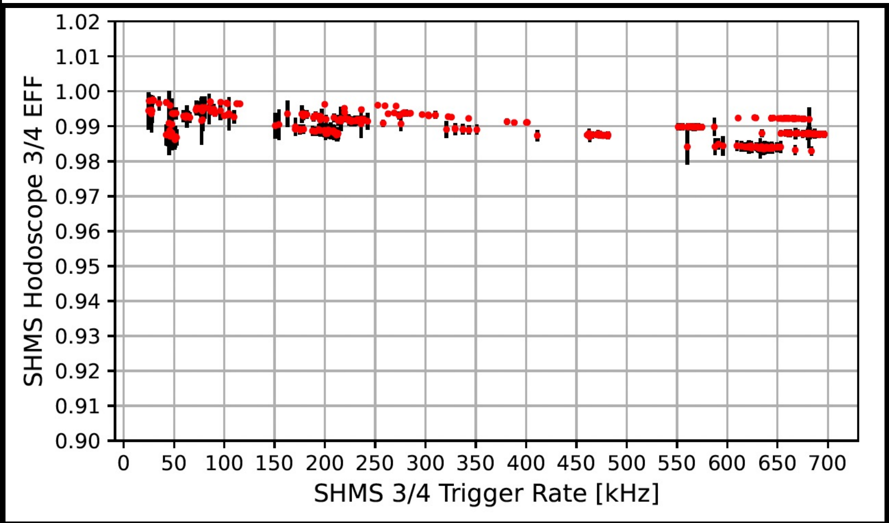
Detector Performance – Hodoscopes

- Hodoscopes are primary detectors for trigger in both spectrometers.

- HMS hodoscope efficiency is very stable and high.
  - Due to lower rates and larger forward angle.

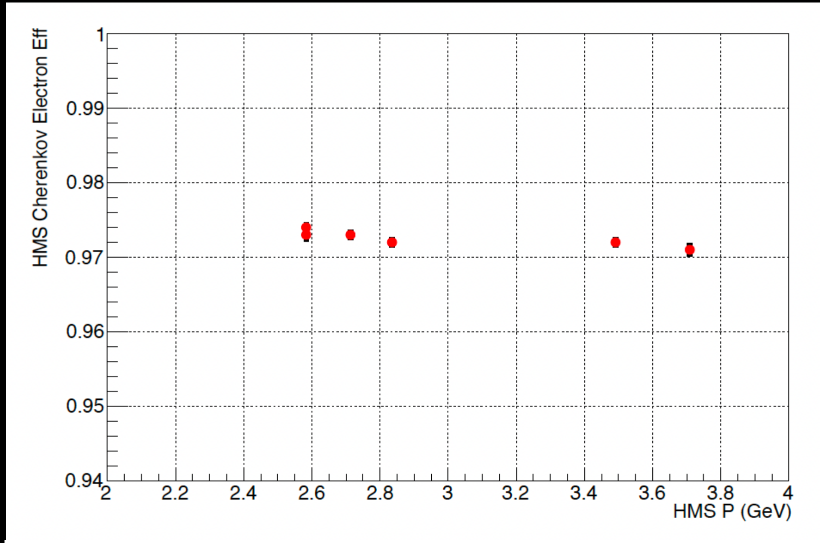
- SHMS hodoscope efficiency fluctuates between 98-100%.
  - Quartz plane has lower efficiency.
  - High rates and lower forward angle.

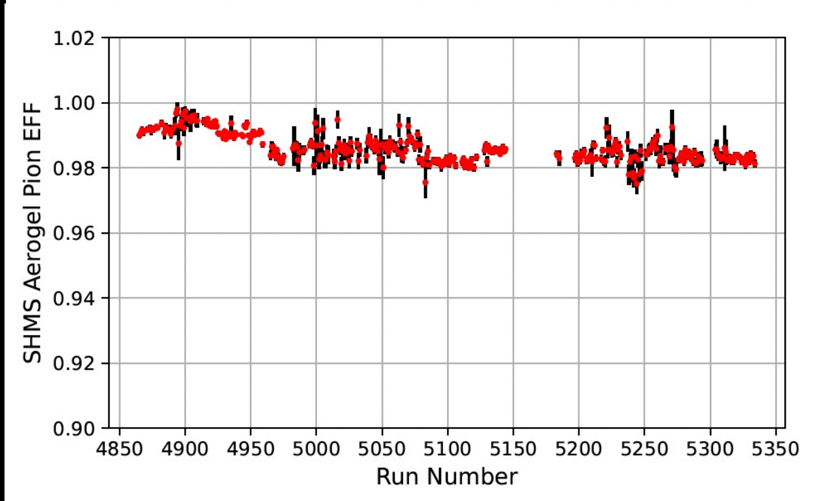




Detector Performance – Cherenkovs

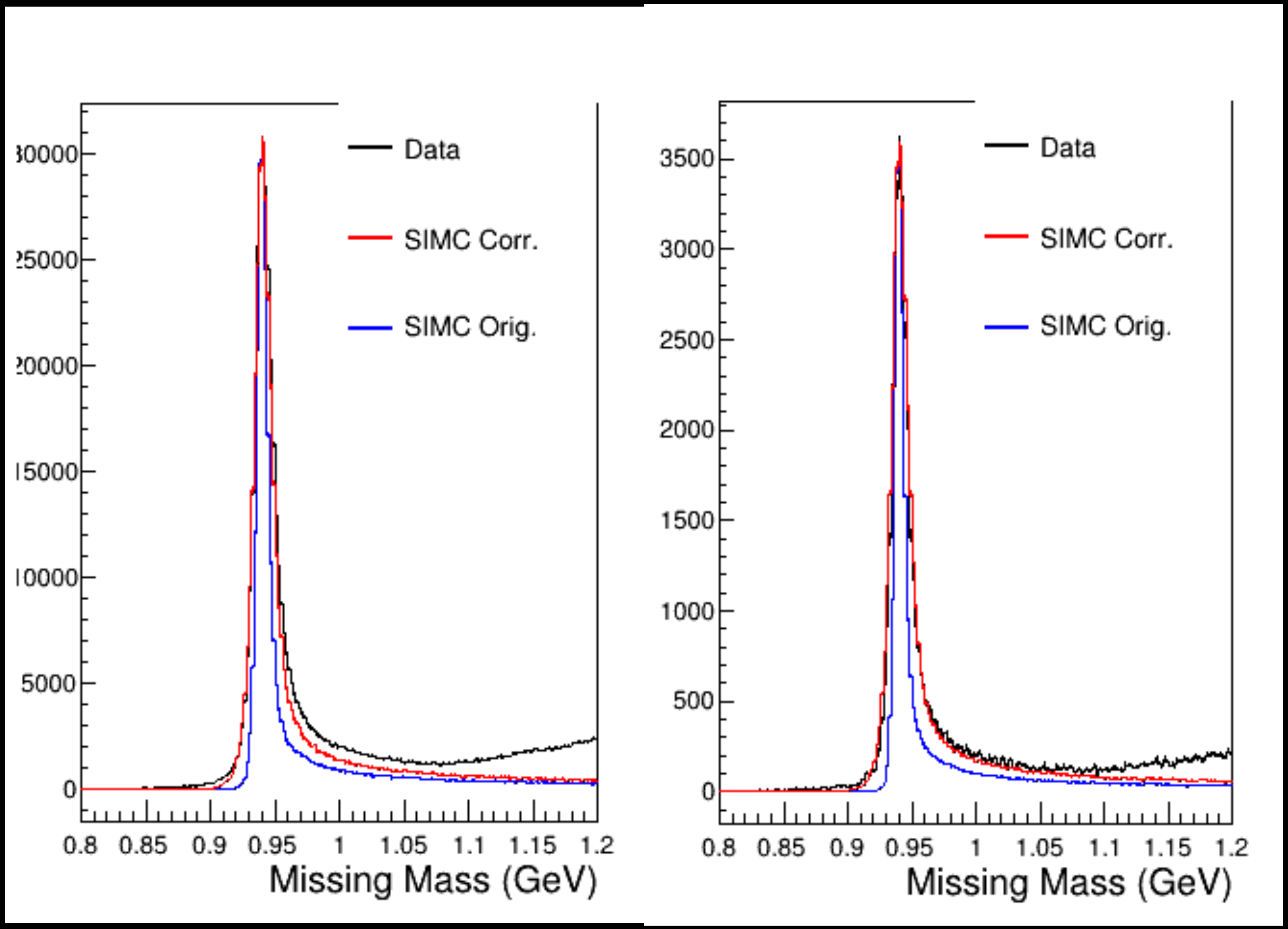
- Cherenkovs are used as PID detectors in both spectrometers.
- HMS Cherenkov efficiency study was unfeasible on physics data.
  - Due to high background rates.
- Elastic singles H(e,e’)p data was used with lower background rates.
  - Light leak is the source of ~2.5% inefficiency.
- SHMS aerogel efficiency study was performed for all physics data.
  - Overall results show high efficiency for pions
  - Small fluctuations caused by different index of refraction aerogel trays





Monte Carlo Resolution Correction

- Hall C Monte Carlo (SIMC) drift chamber resolution has been optimized.
- Resolution difference b/w data and MC vary for different kinematics.
  - A global correction factor is used for all data.
- A systematic uncertainty is on-going to evaluate the remaining resolution difference.

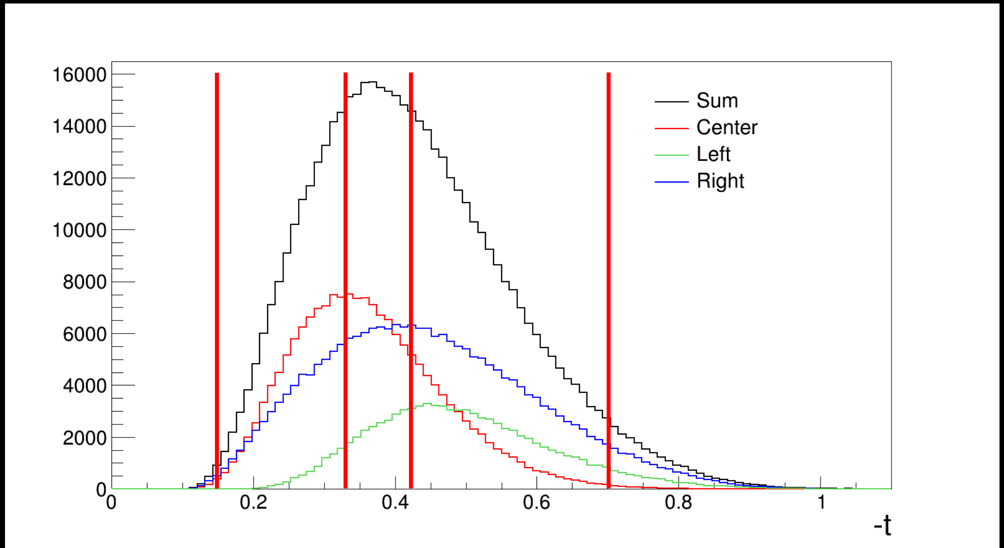


$Q^2 = 2.115, W = 2.95$

$Q^2 = 4.4, W = 2.74$

-*t*-binning

- The –*t* dependence is sensitive to different production mechanisms.
- Multiple t-bins for 3 of the 5 settings
  - High statistics settings (3 bins)
  - Low statistics settings (1 or 2 bin)



$Q^2 = 3.0\,, W = 3.14$

Systematic Error Analysis

Systematic error analysis (currently in-progress) is divided into three main categories.

- Beam Polarization Error
  - Fixed error ($^{+1}_{-3}$ %) calculated during the measurement of beam polarization.

- Fitting dependent Error
  - Recalculate asymmetry using $\pi^+\Delta^0$ simulation yields instead of background subtracted data.
  - Recalculate asymmetry by varying the π^+n and π^+-SIDIS background

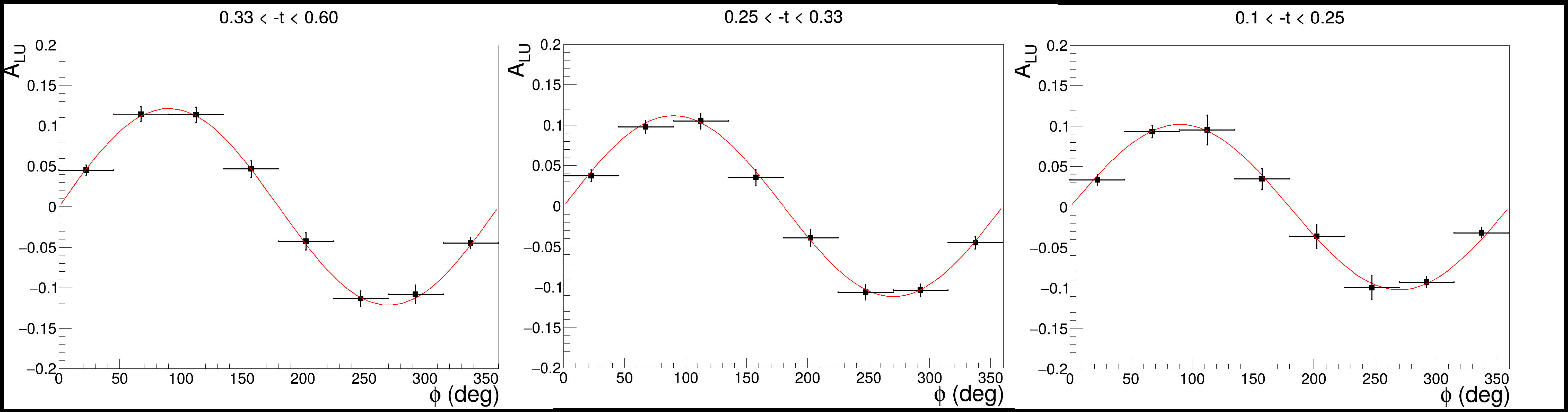
- Cut dependent Error
  - Recalculate asymmetry by varying the SHMS Heavy Gas cut
  - Recalculate asymmetry by varying missing mass selection cut

- Preliminary results show **f**itting dependent error has the largest contribution to the total error.

A_{LU} vs ϕ

- BSA is calculated by integrating $p(e, e'\pi^{+})\Delta^{0}$ missing mass (1.11 - 1.40 GeV).

$$A_{LU} = \left[\frac{1}{P}\left(\frac{Y^{+}-Y^{-}}{Y^{+}+Y^{-}}\right)\right] \qquad \delta_{stat} = \frac{2}{P}\sqrt{\frac{Y^{+}.Y^{-}}{(Y^{+}+Y^{-})^{3}}}$$



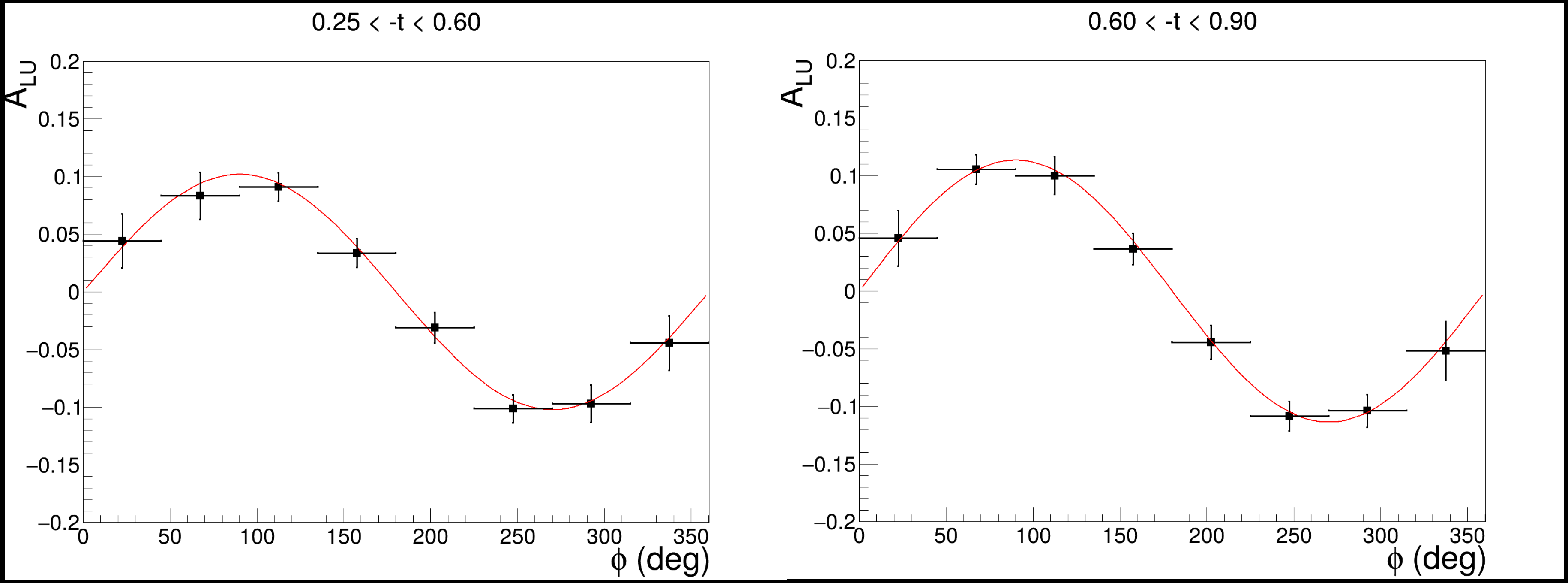
- Only statistical errors shown here.

$$Q^{2} = 2.1\ GeV^{2}, W = 2.95\ GeV$$

A_{LU} vs ϕ

- BSA is calculated by integrating $p(e, e'\pi^+)\Delta^0$ missing mass (1.11 - 1.40 GeV).

$$A_{LU} = \left[\frac{1}{P}\left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right)\right] \qquad \delta_{stat} = \frac{2}{P}\sqrt{\frac{Y^+ . Y^-}{(Y^+ + Y^-)^3}}$$



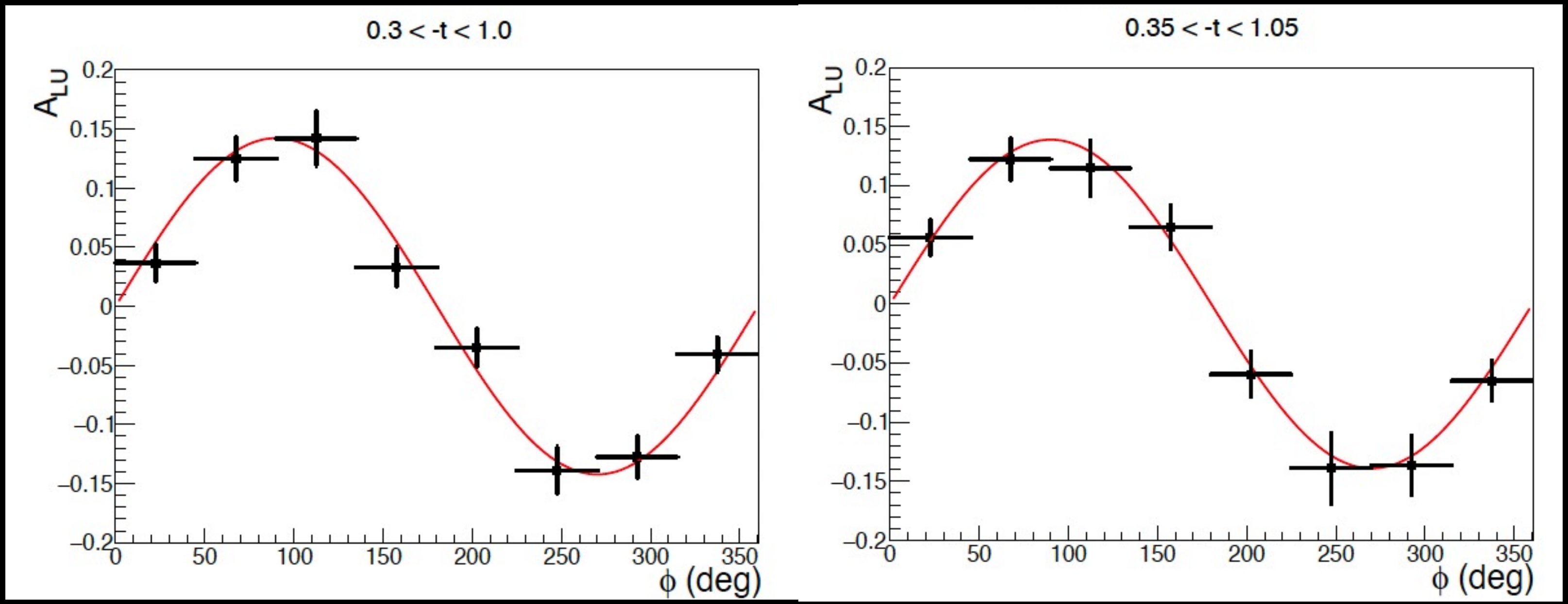
- Only statistical errors shown here.

$$Q^2 = 3.0\ GeV^2, W = 2.32\ GeV$$

A_{LU} vs ϕ

- BSA is calculated by integrating $p(e, e'\pi^+)\Delta^0$ missing mass (1.11 - 1.40 GeV).

$$A_{LU} = \left[\frac{1}{P}\left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right)\right] \qquad \delta_{stat} = \frac{2}{P}\sqrt{\frac{Y^+ . Y^-}{(Y^+ + Y^-)^3}}$$



$Q^2 = 4.4\ GeV^2$ $\qquad$ $Q^2 = 5.5\ GeV^2$

- Only statistical errors shown here.

Beam Polarization

- Beam Polarization
  - No dedicated measurement in Hall C during the Kaon-LT experiment
  - Compared polarization measurements at the injector and dedicated measurement in Hall B

- Injector Measurement via Mott polarimeter
  - 90.13% +/- 0.51% (stat.) +/- 0.90% (sys.)

- Hall B Measurement via Moller polarimeter
  - 89.37% +/- 1.56% (stat.) +/- 3% (sys.)

- Error in the Hall C beam polarization comes from
  - Source uncertainty
  - Beam energy uncertainty
  - Linac imbalance