Charged pion electroproduction reaction studies at Jefferson Lab

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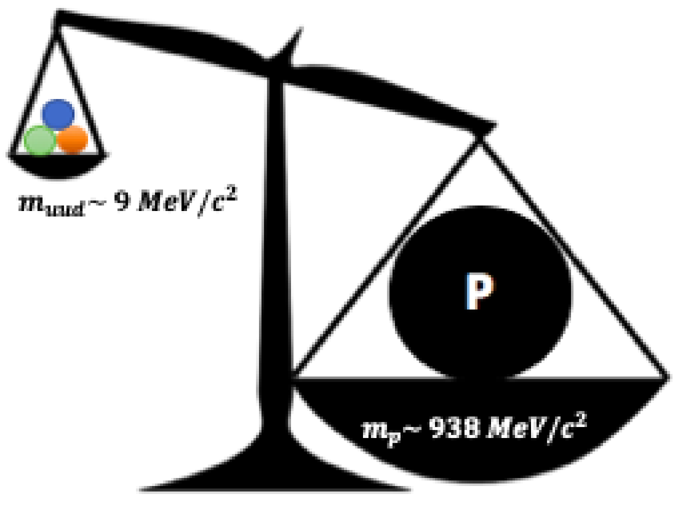
2023 CAP Congress

Physics Motivation

- Two well known hadronic states:
  - Baryons ($qqq\ or\ \bar{q}\bar{q}\bar{q}$)
  - Mesons ($q\bar{q}$)
- Interactions of quarks and gluons are described by Quantum Chromodynamics (QCD).
- Poorly understood hadron properties:
  - Mass and Spin



Open Questions

- ❑ How fundamental properties of hadrons arise from their constituent quarks and gluons?
- ❑ Which theoretical model precisely predicts the parton (quark-gluon) interactions in color confinement regime?

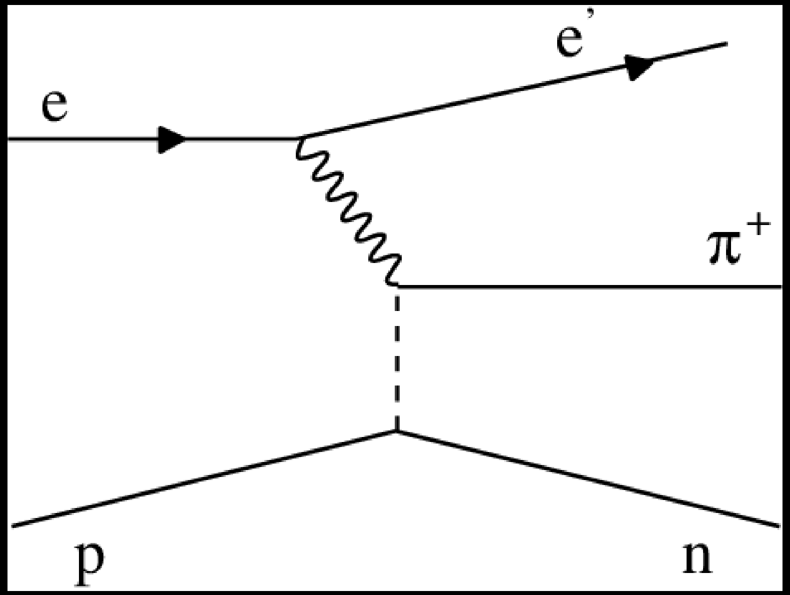
- Mesons give an ideal testing ground for our understanding of bound $q\bar{q}$ system.

Pion – A Unique Meson

- Pion is lightest meson with only two valence quarks (up and down).
- Pion is positronium atom of QCD.
- The residual nuclear force is carried by pions inside a nucleus.
- Pions can be produced by scattering electrons off the virtual pion cloud inside the proton.
- ***Exclusive Pion Electroproduction***

$$e^- + p \rightarrow e^{-\prime} + \pi^+ + n \; or \; \Delta^0$$

- To study hadron structure, need a precise measurement of the cross-section of this reaction.

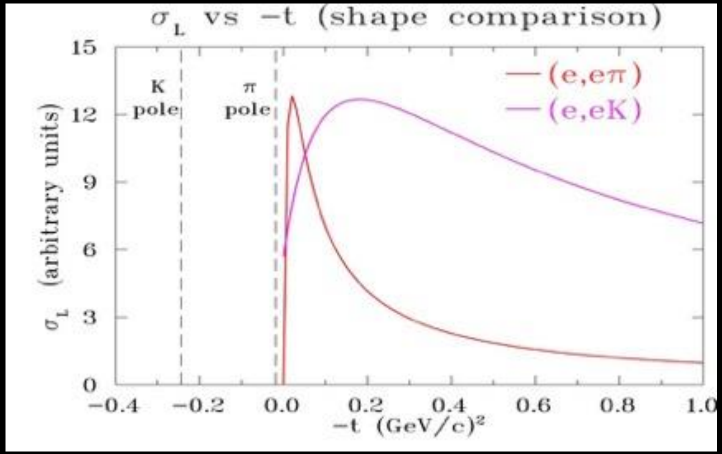


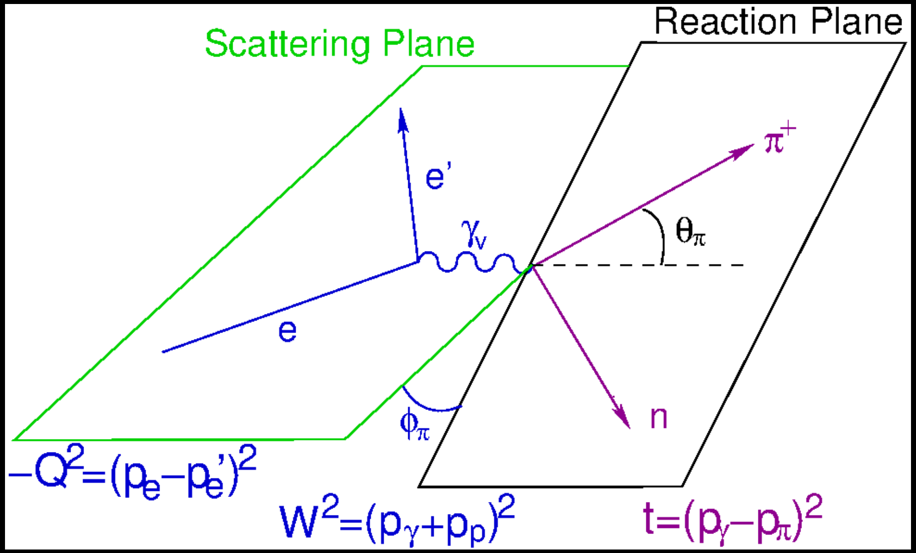
Pion Electroproduction Reaction

- In exclusive pion electroproduction, cross-section is dictated by virtual photon polarization ϵ.

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

- At low -t, σ_L dominates the total cross-section.





- $-Q^2$ is the square of four momentum carried by virtual photon.
- W^2 is the square of hadronic invariant mass
- t is the square of four momentum transfer from virtual photon to hadronic system (Mandelstam variable)
- ϕ_e is the azimuthal angle between two planes

Rosenbluth (L/T) Separation

- "Rosenbluth Separation technique" is used to separate σ_L and σ_T terms.

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

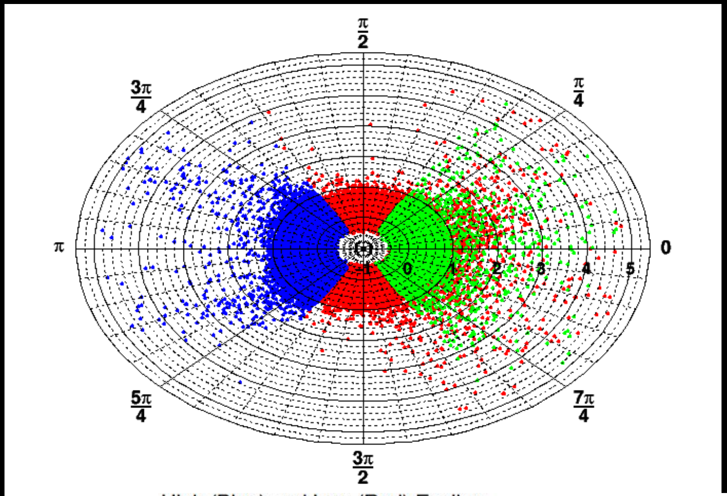
- "ϵ" is polarization of virtual photon

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

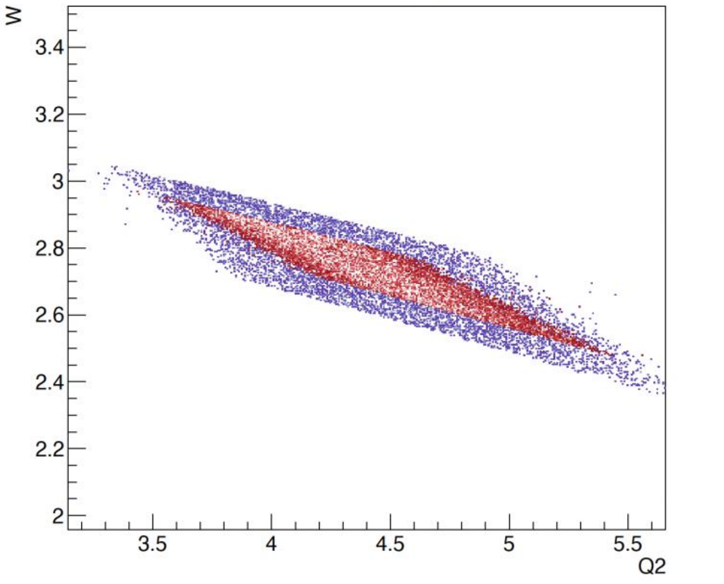
- Cross-section is separated by performing two scattering measurements at different "ϵ" value with fixed Q^2 and W.

Error Estimation

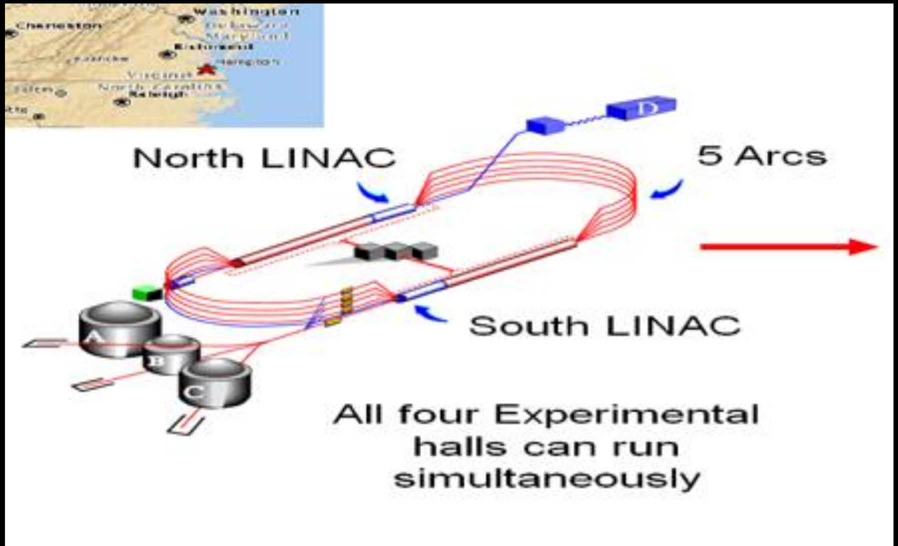
$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2} \frac{1}{\sigma_L} \sqrt{\Delta\sigma_1^2 + \Delta\sigma_2^2}$$



High (Blue) and Low (Red) Epsilon



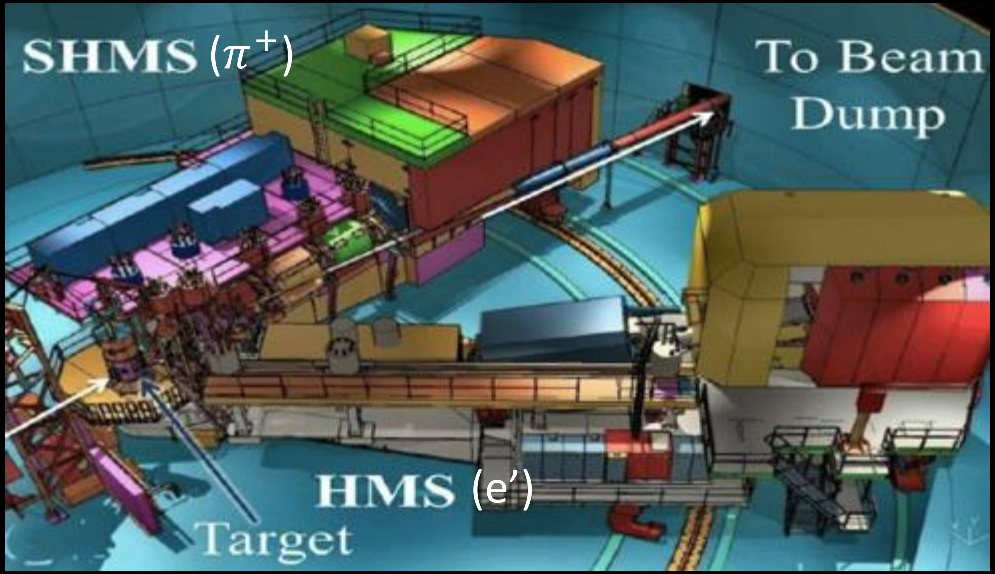
Thomas Jefferson National Accelerator Facility



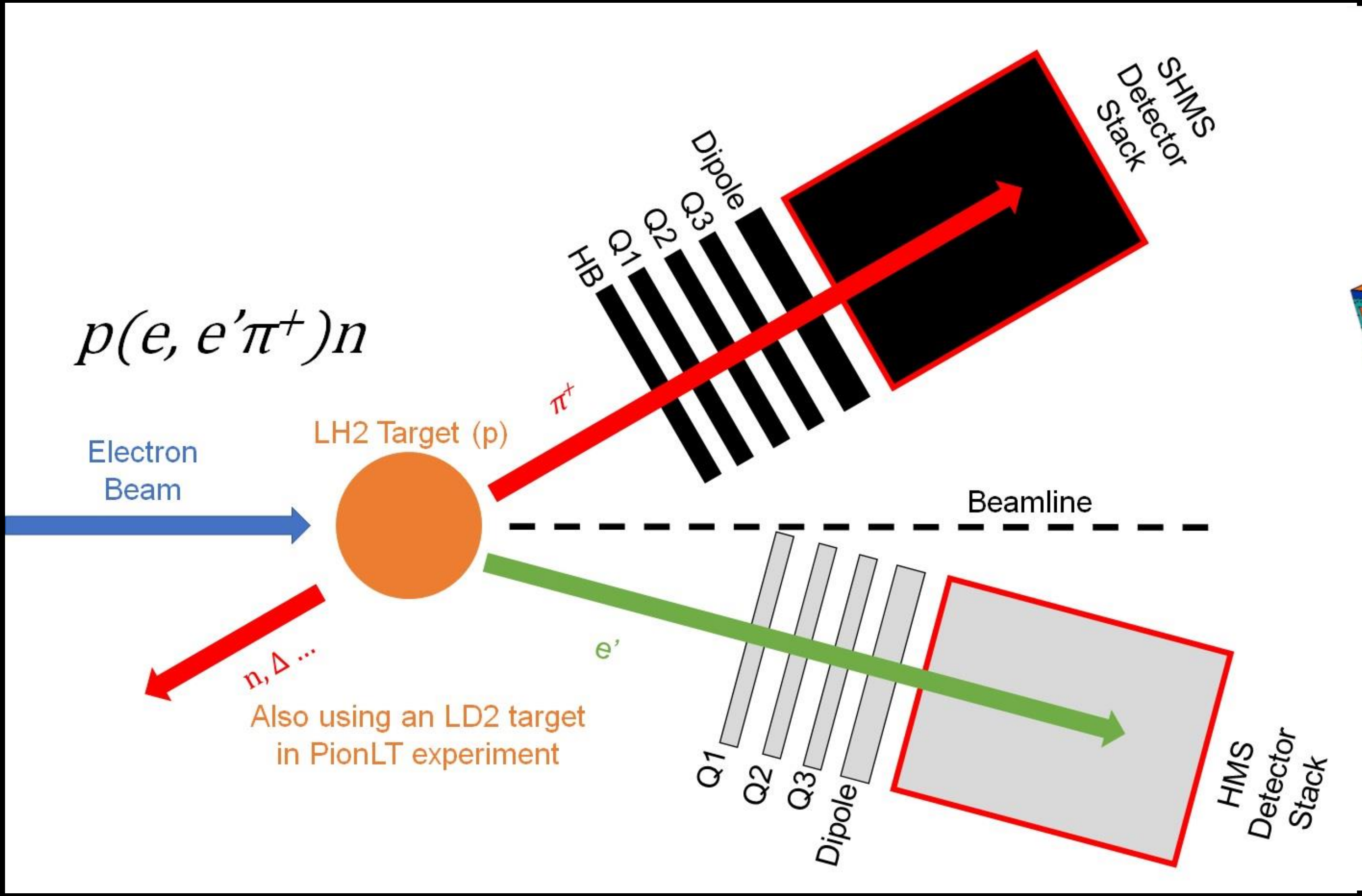
- Located in Newport News, VA
- Consists of two superconducting electron LINACs.
- Capable of delivering a 12 GeV electron beam of up to 200 μA.

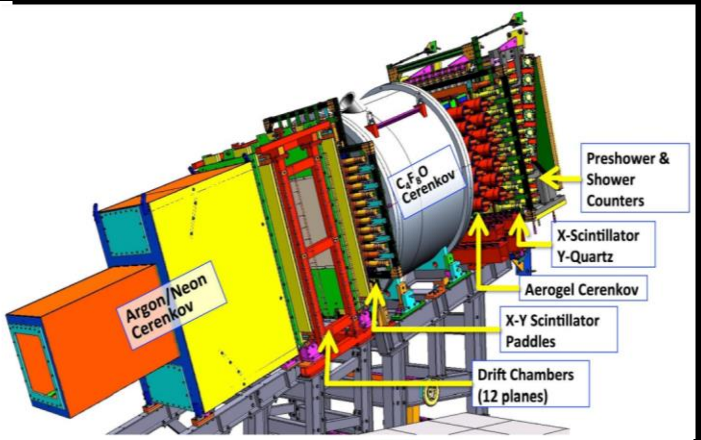
Hall C

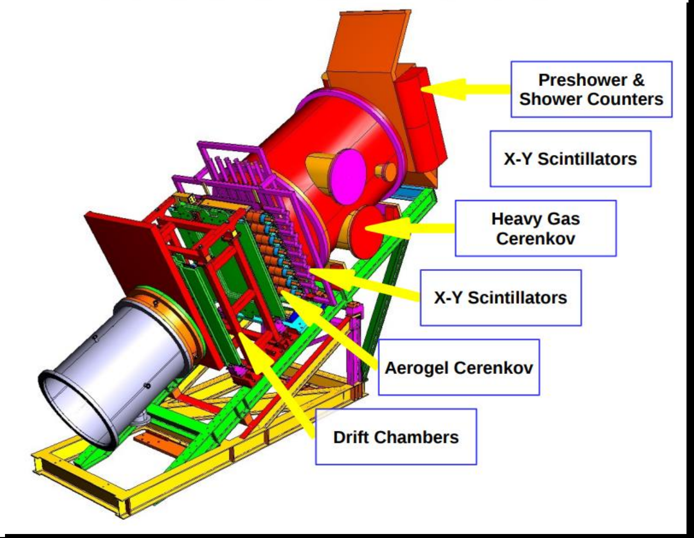
- Specifically designed to measure precise cross-sections.
- Two advanced rotatable magnetic spectrometers (HMS and SHMS).
- Particles of specific momentum are studied by using a magnet system.



Schematic View of Hall C





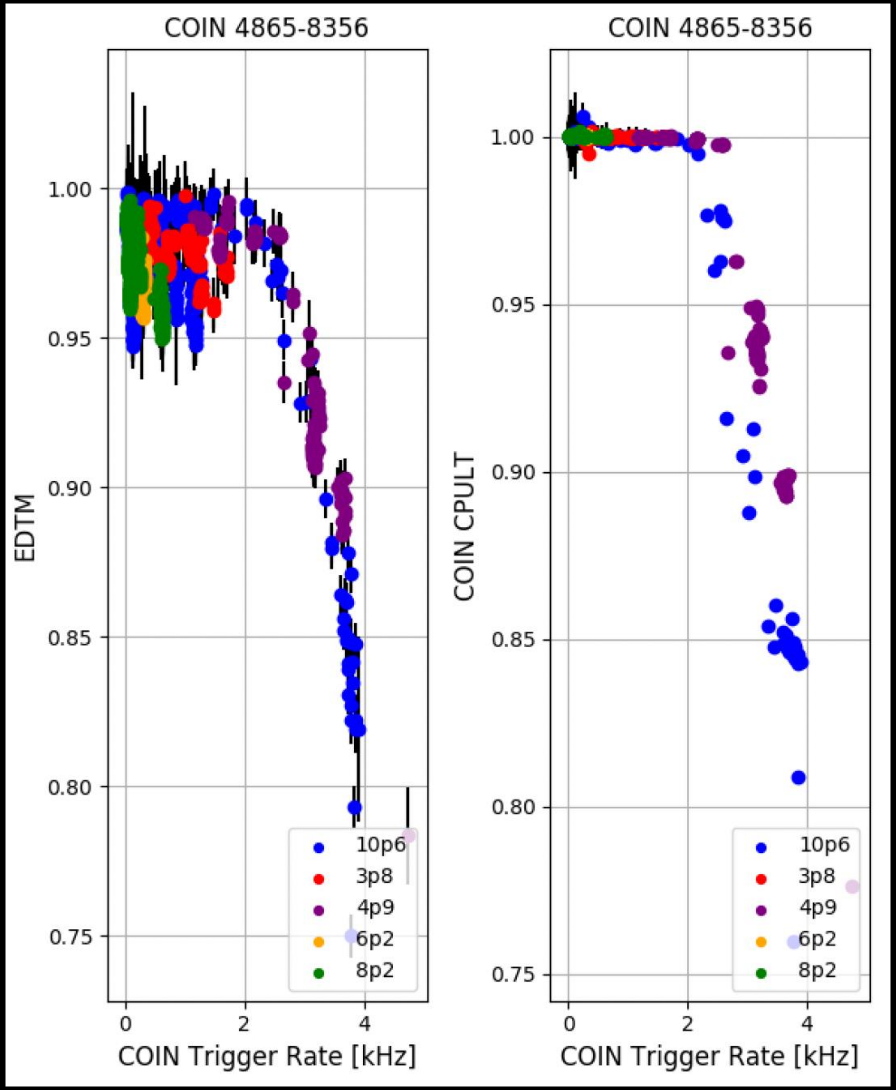


Systematic Studies – DAQ

- CPU Live Time
  - Measure of DAQ live time
  - Results show expected trend
    - Live time decrease with increase in rate.

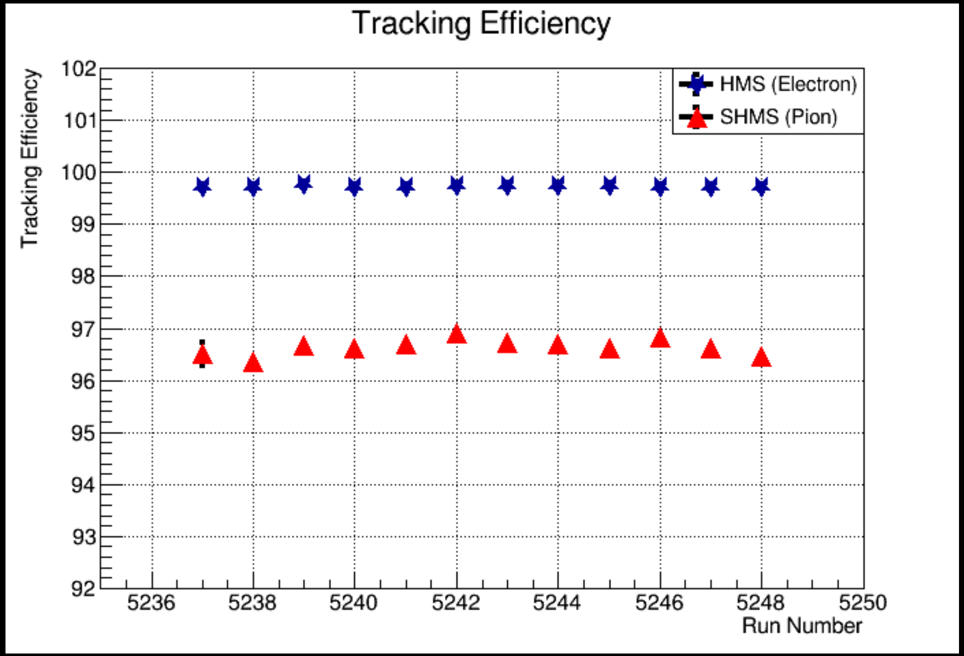
- EDTM Live Time
  - Measure of total live time (CPU live time and electronic dead time)
  - Same trend as the CPU live time

$$EDTM\ Live\ Time = \frac{EDTM_{recorded}}{EDTM_{sent}}$$

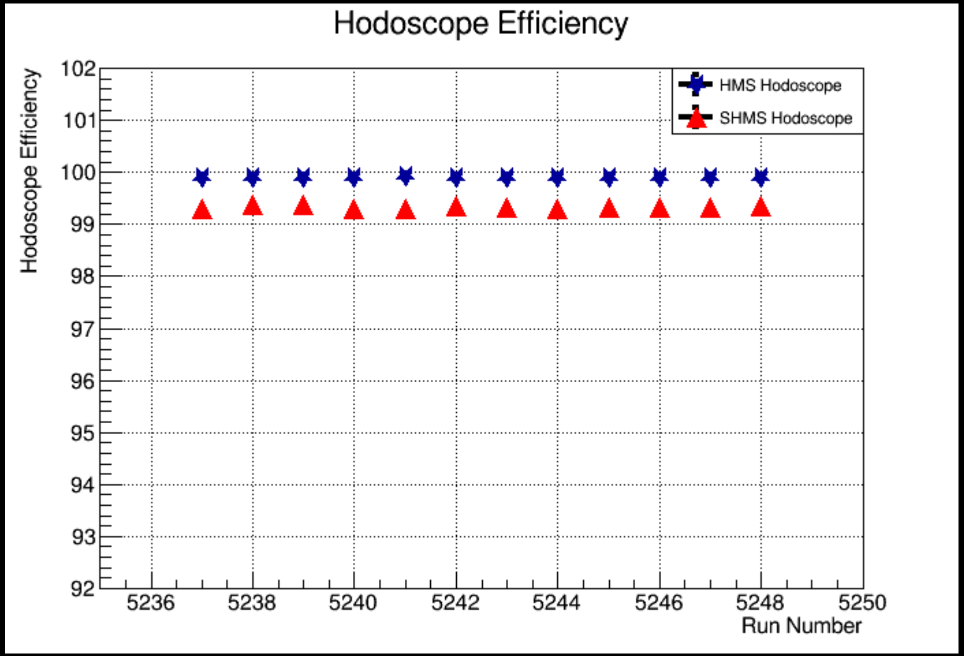


Systematic Studies – Detectors

- Tracking Efficiency



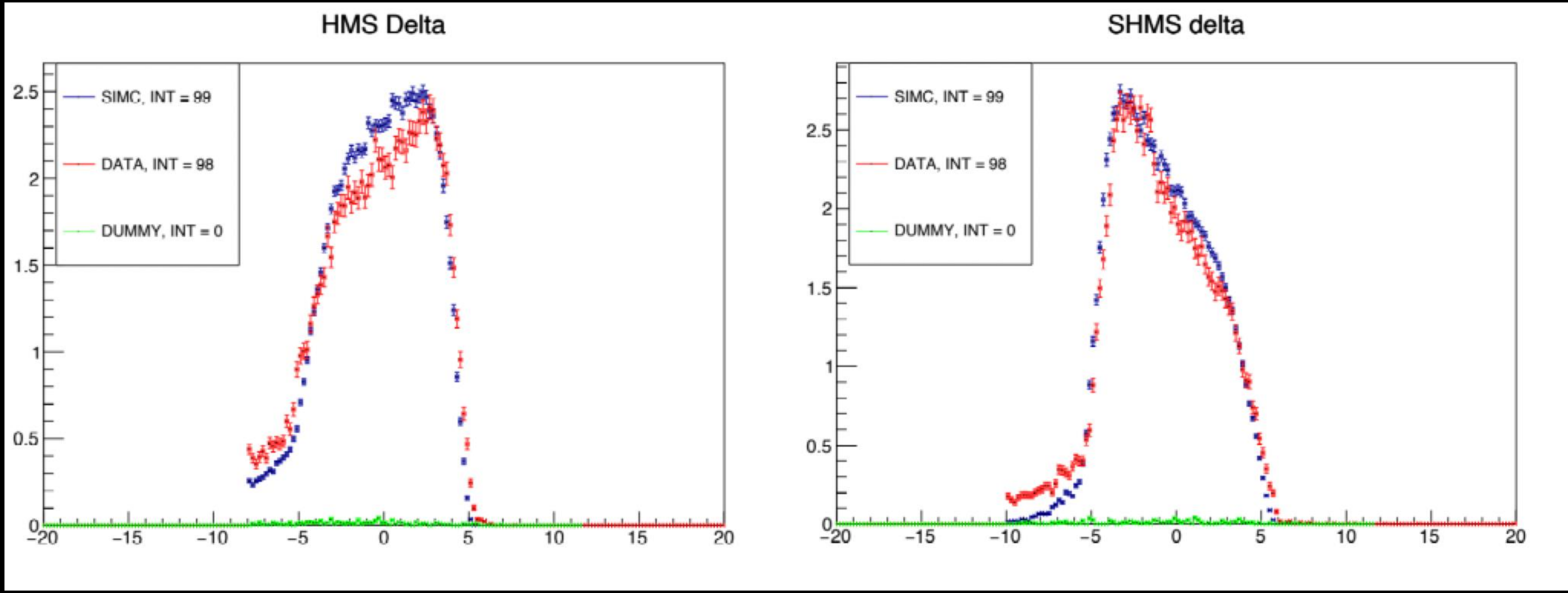
- Hodoscope Efficiency



Systematic Studies - Acceptance

- Delta is measure of momentum spread (in percentage) from the central momentum of spectrometer

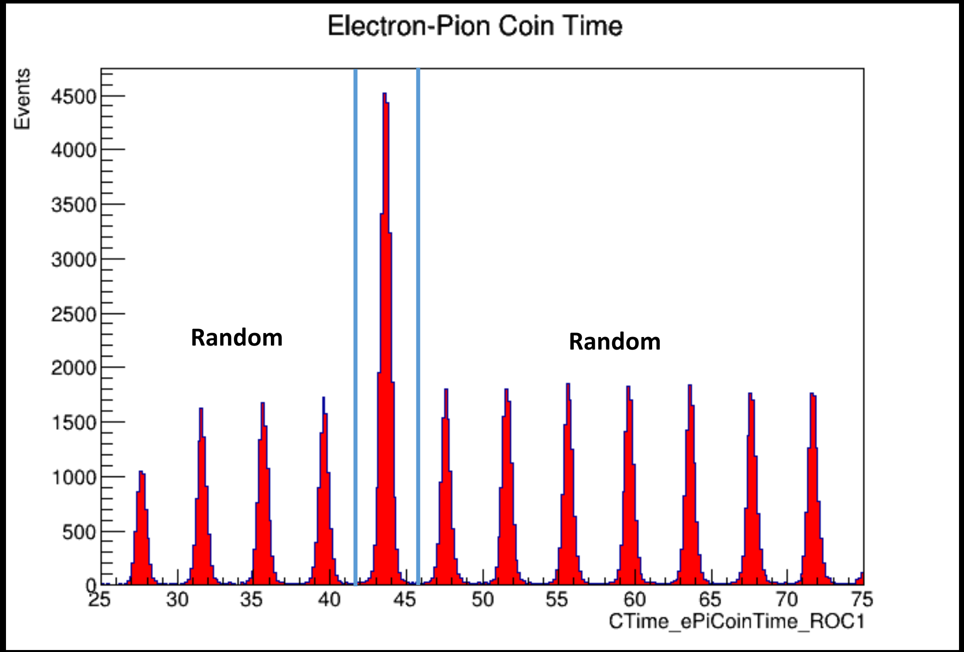
$$\delta = \frac{P_{particle} - P_{central}}{P_{central}} * 100$$



Event Selection

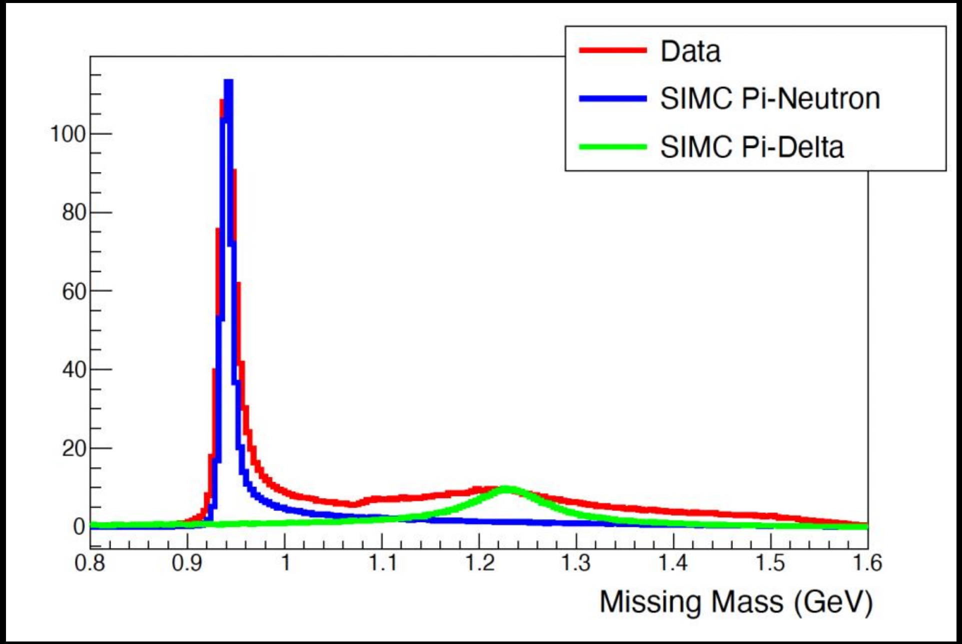
- $e' - \pi^+$ Coincidence

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



- Missing Mass

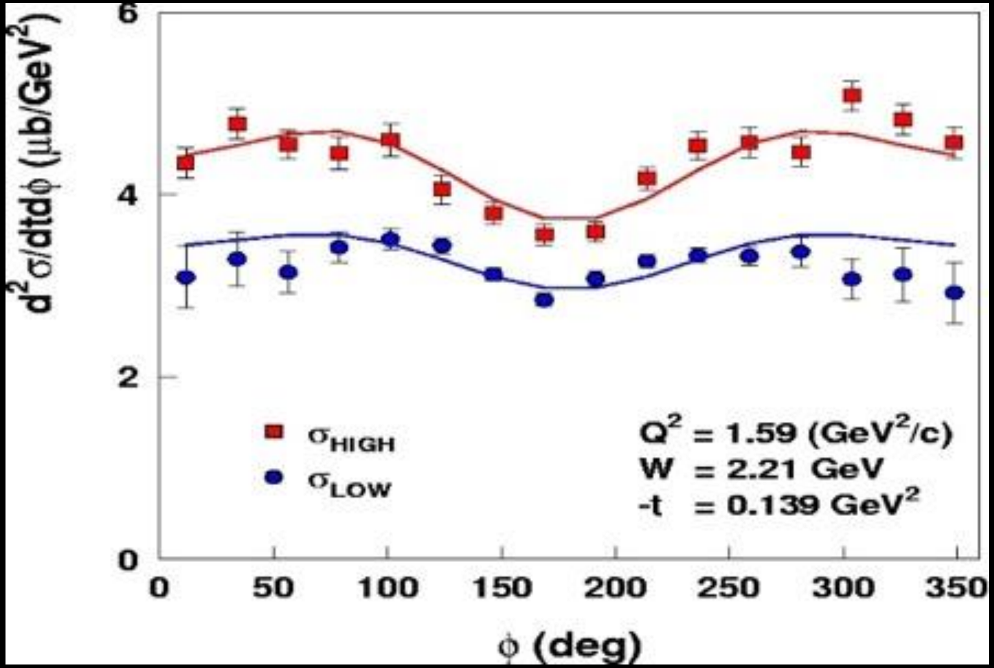
$$M_m = \sqrt{\left(E_e + m_p - E_{e'} - E_{\pi^+}\right)^2 - (p_e - p_{e'} - p_{\pi^+})^2}$$



L/T/LT/TT Separated Cross-Section

- For $\boldsymbol{\theta_{\pi q} \neq 0}$, cross-section can be decomposed into four structure functions.

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



Horn et al. (PRL 97, 192001)

Summary and Outlook

- Pion is a simple and important meson to study hadronic structure.

- Precise separated cross-section of the exclusive pion electroproduction reaction gives access to many physics observables.
  - Form Factors
  - GPDs
  - BSA

- Kaon-LT experiment gives access to unique data of $p(e, e'\pi^+)\Delta^0$
  - L/T separation of this data will allow us to extract N → N* transition GPDs.

- Results to be published in 2024.

Collaborators

cua

University of Regina

FIU

OHIO UNIVERSITY

Jefferson Lab

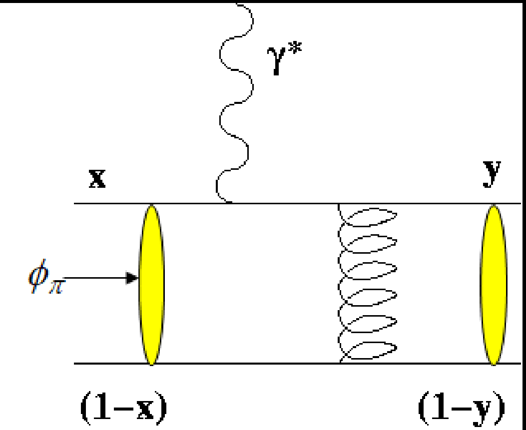
CRSNG NSERC

This research is funded by Natural Sciences and Engineering Research Council of Canada (NSERC) FRN: SAPIN-2021-00026

Backup

The Pion in perturbative QCD

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



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

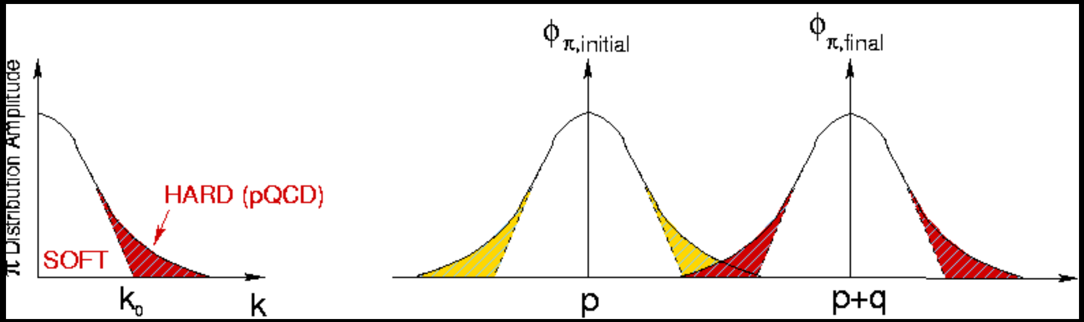
at asymptotically high Q^2, the pion distribution amplitude becomes

$$\phi_\pi(x) \underset{Q^2\to\infty}{\longrightarrow} \frac{3f_\pi}{\sqrt{n_c}}x(1-x)$$

and F_π takes the very simple form

$$Q^2F_\pi(Q^2) \underset{Q^2\to\infty}{\longrightarrow} 16\pi\alpha_s(Q^2)f_\pi^2$$

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



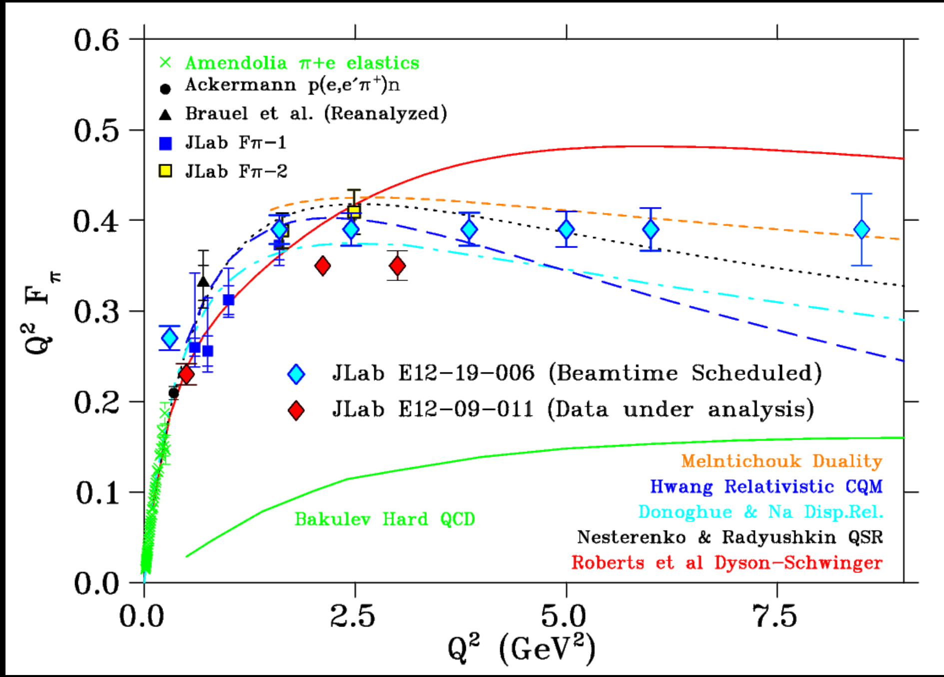
- This only relies on asymptotic freedom in QCD, *i.e.* $(\partial\alpha_S/\partial\mu) < 0$ as $\mu\to\infty$.
- **Q^2F_π should behave like $\alpha_s(Q^2)$ even for moderately large Q^2.**
- Can study the renormalization of α_S quark-gluon coupling, and QCD's transition between asymptotic freedom and confinement.

F_π Results and Projections

- F_π is a key variable in our understanding of strong QCD.
- Two proposed experiments at Jefferson Lab Hall C will extend current F_π results up to Q^2 of 8.5 GeV^2.

E12-09-011

- Data Collected in 2018-19
- Analysis in progress
- Results expected in 2023-24



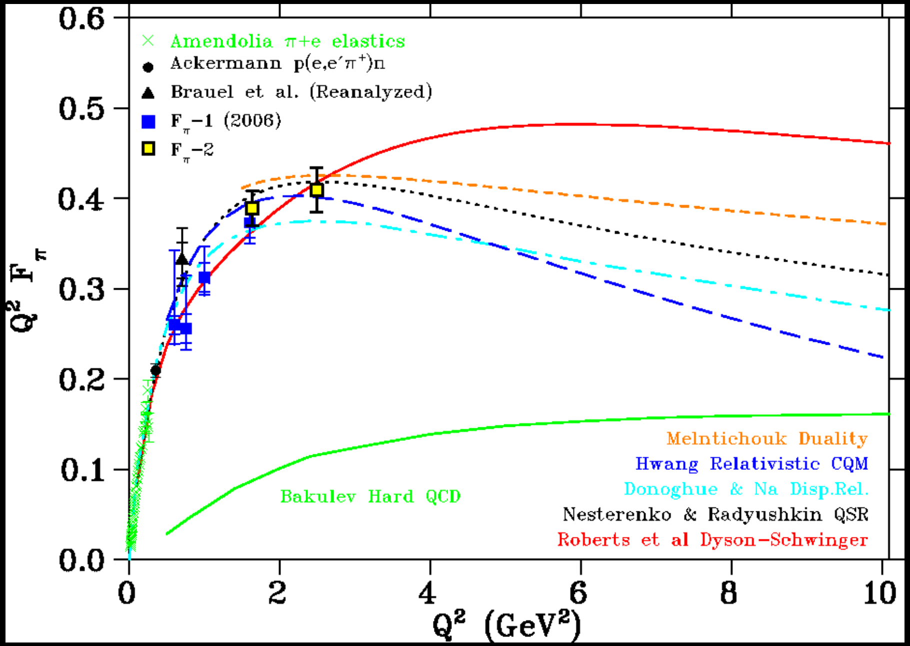
E12-19-006

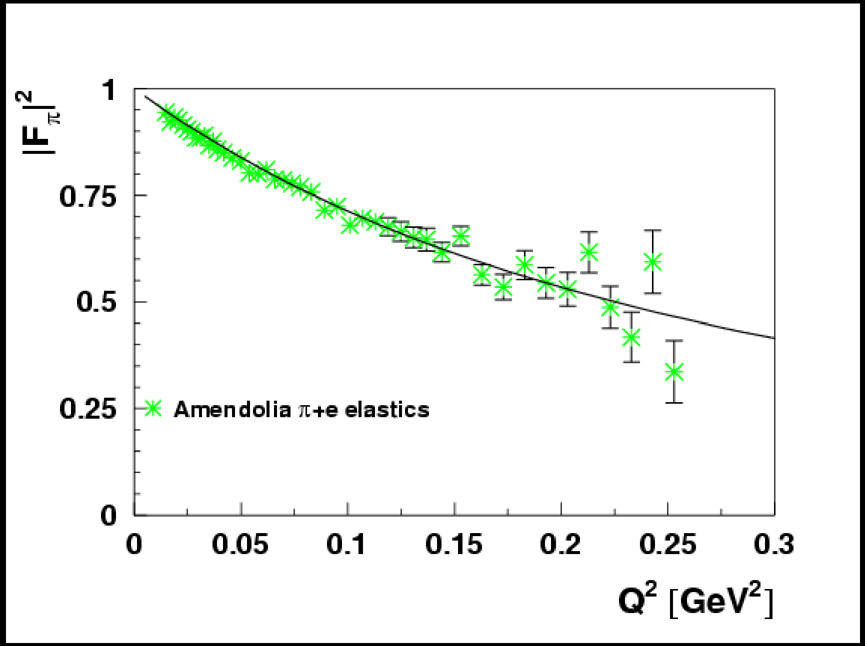
- Data collection scheduled in 2021-22
- Results will be published in ~2025-26.

This is the beginning of exciting QCD physics era which extends beyond Jefferson Lab

F_π at low Q^2

- F_π at low Q^2 has been previously measured at CERN using π^+ beam.
- At high Q^2, this measurement is not possible as Q^2 of 1 GeV^2 will require 1 TeV π^+ beam.





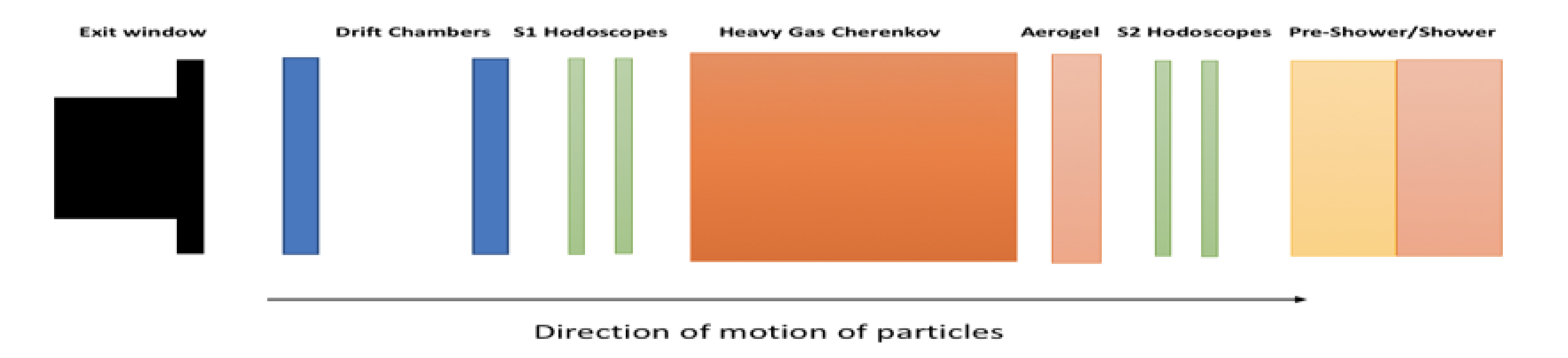
CEBAF

- Electrons are stripped off from the hydrogen atom using electric filed.
- The electrons are accelerated and entered into LINAC from the injector.
- The LINACs increases the energy of the beam evey time the pass through using electric field.

- The arcs steer the beam from one LINAC to other using mangetic field.
- The accelerator provides a beam of 1.5 GHz frequency.
- The electron gains energy after passing through the LINACs every time.
- A refrigeration unit provides liquid helium to cool down superconducting cavities.

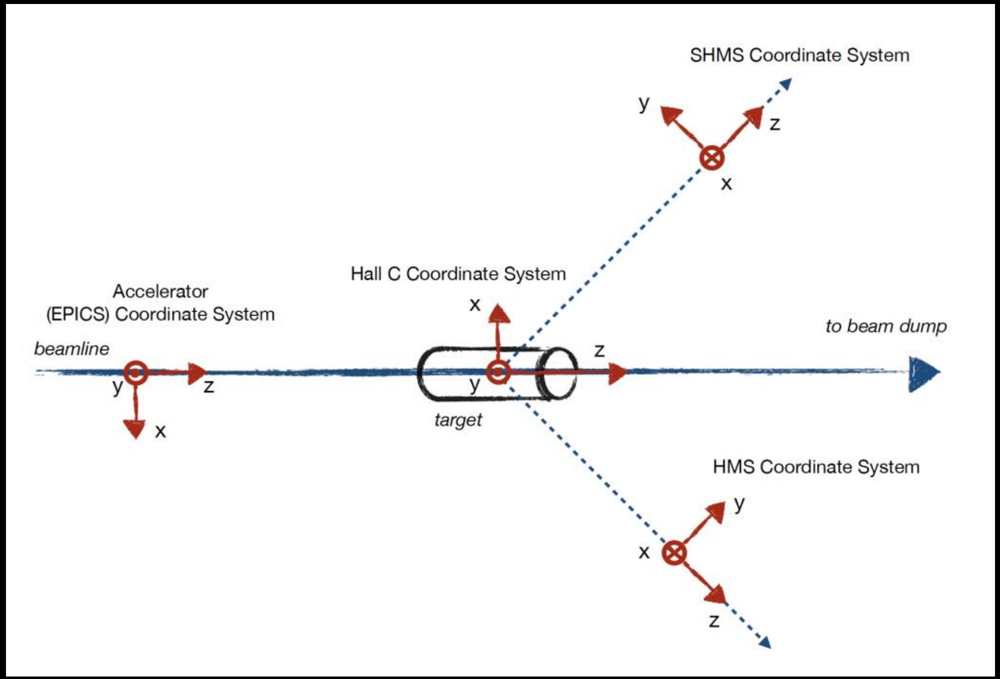
SHMS Detector System

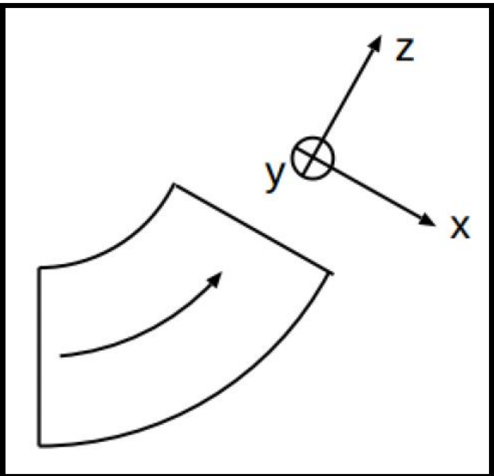
DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Aerogel Cerenkov	Particle ID, K+/p discrimination	n= 1.011,1.015, 1.03,1.05
Heavy-Gas Cerenkov	Particle ID, Trigger. $\pi^{\pm}/K^{\pm}$ discrimination	C_4F_{10} - Kept at roughly 1 atm pressure
Drift Chambers	Momentum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



Hall C Co-ordinate System

- Accelerator Co-ordinates
  - Left Handed System
- Hall C Co-ordinates
  - Left Handed System
- Spectrometer Co-ordinates
  - Right Handed System
- Target Co-ordinates
  - Right handed system



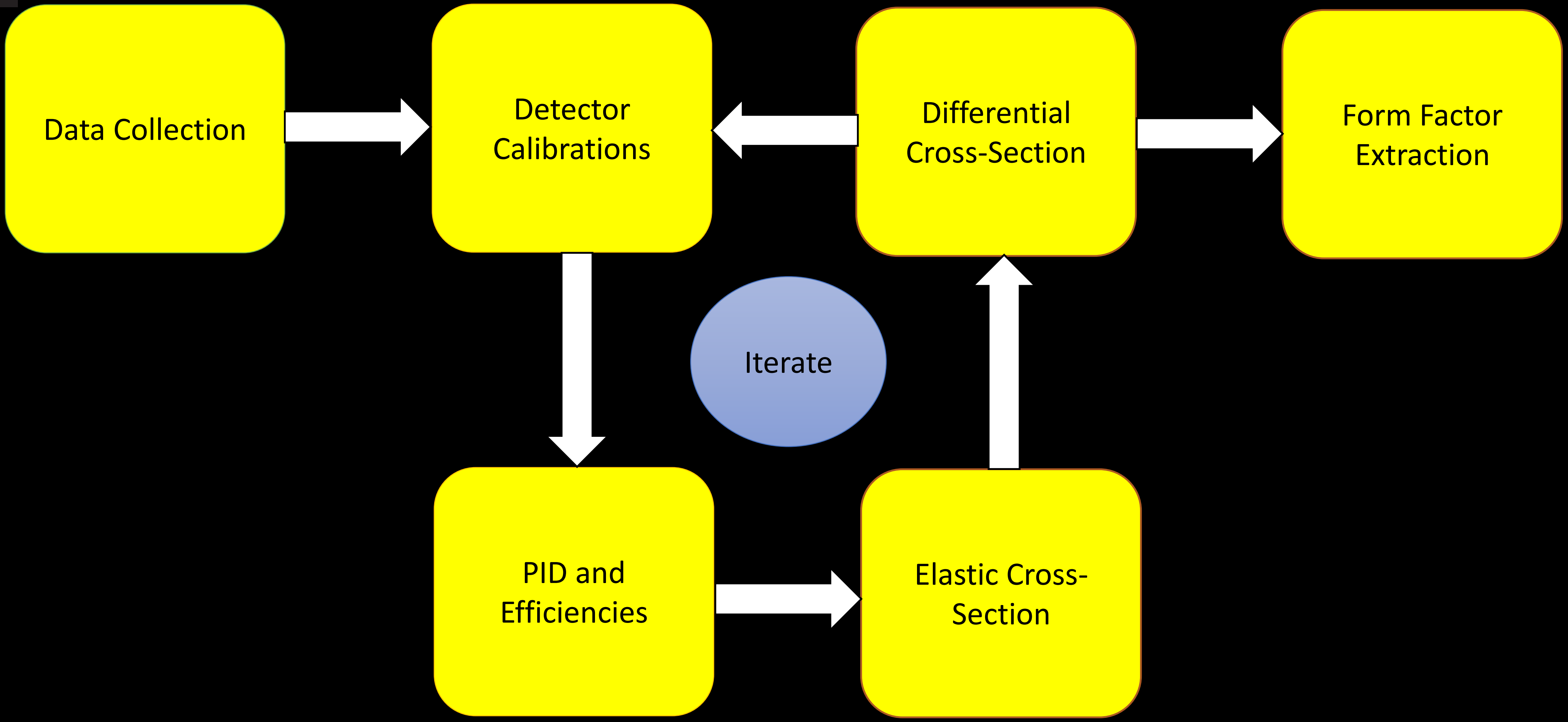


Kaon-LT Experiment

E (GeV)	Q^2 (GeV^2)	W (GeV)	$x = Q^2 / 2m_p (E - E')$	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

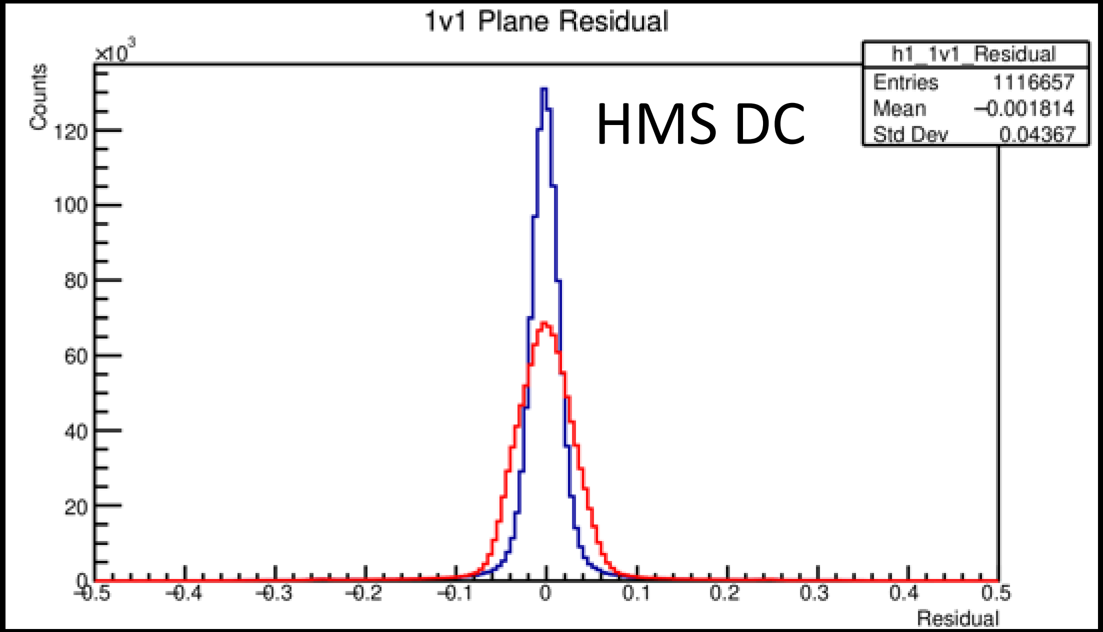
$\theta_{SHMS} = 5.69$

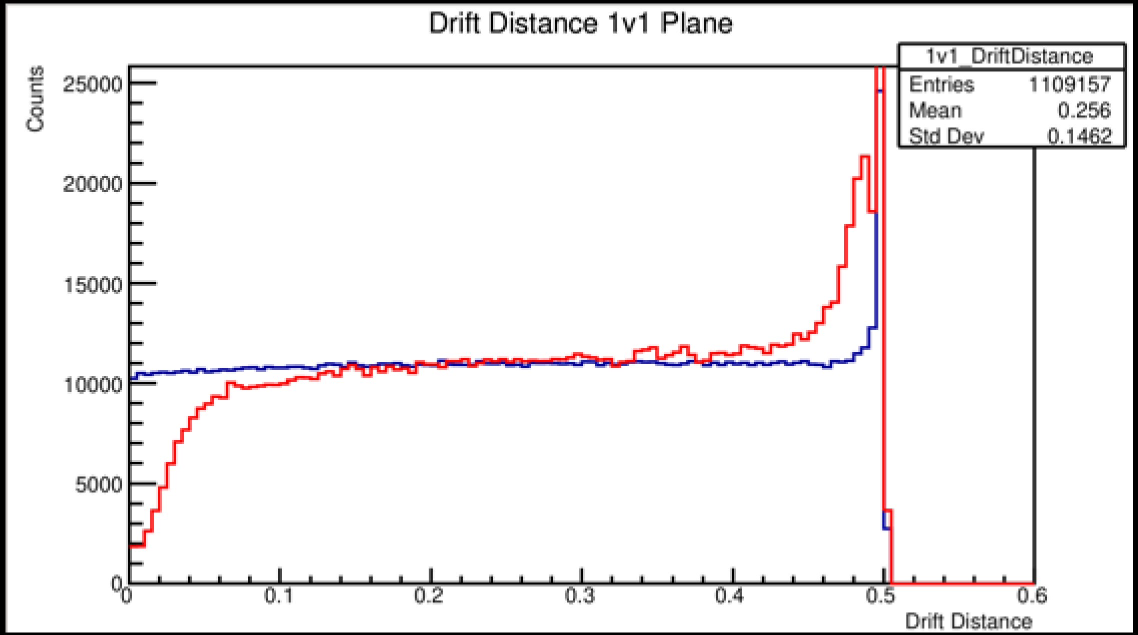
Analysis Flow



Calibrations - Drift Chambers

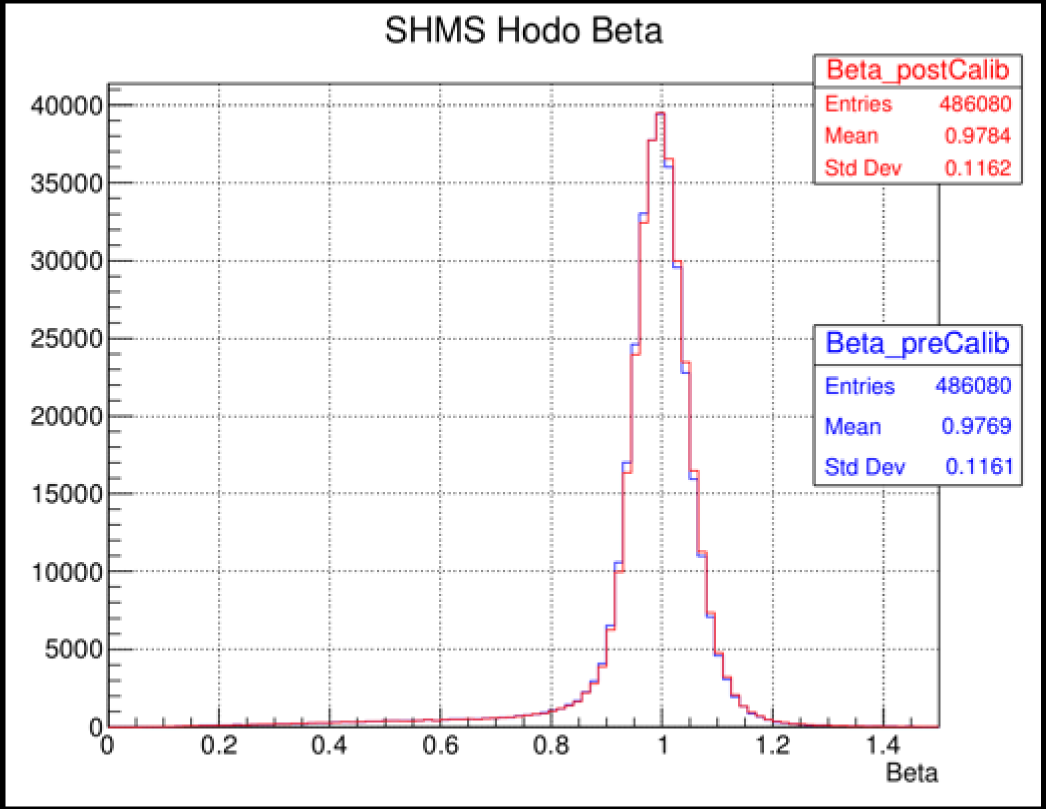
- Residual is the difference between final track position and the hit location obtained from individual drift chamber planes.

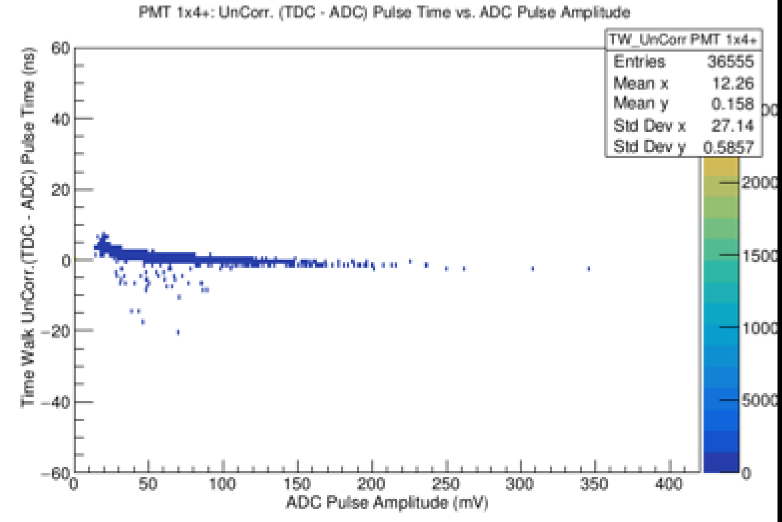


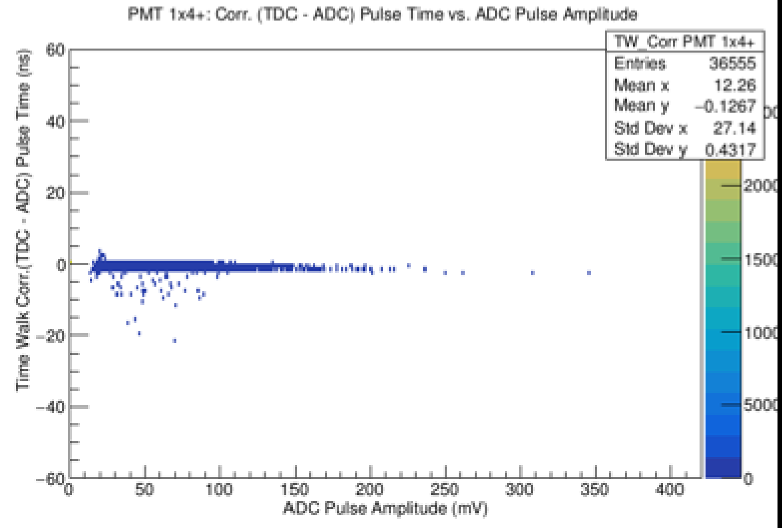


Calibrations - Hodoscope

$$\beta_{shms} = \frac{1}{c}\frac{\Delta l(h_2 - h_1)}{\Delta t(h_2 - h_1)}$$

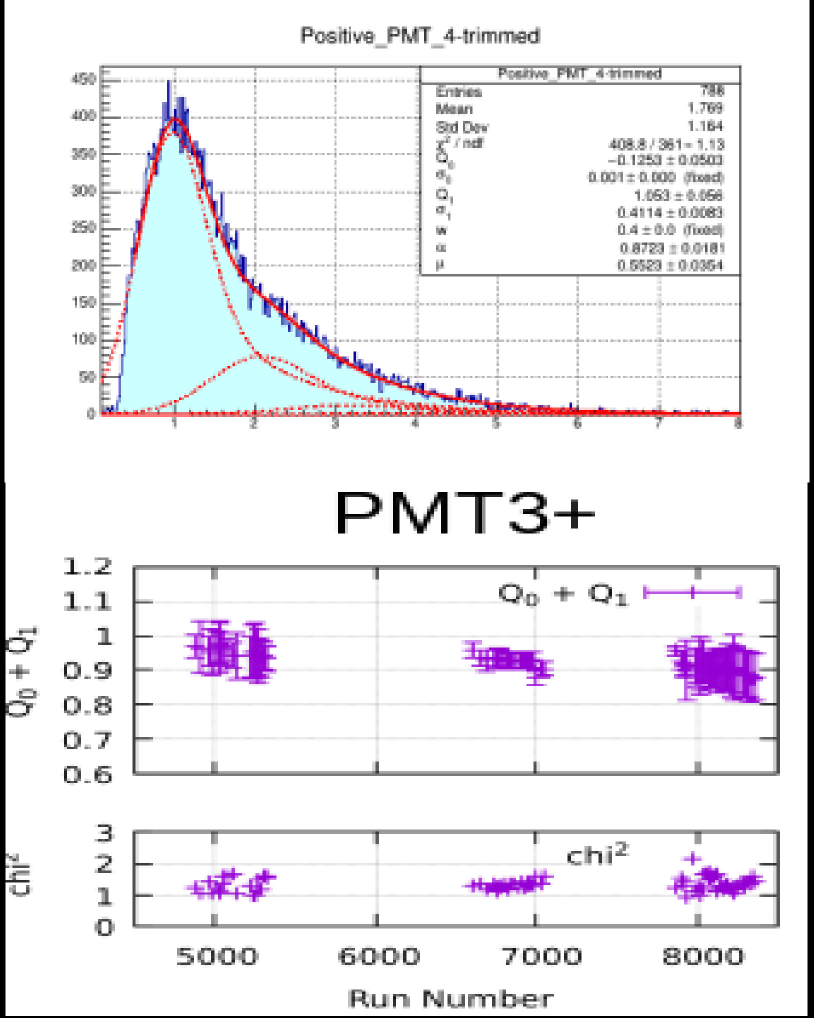






Calibrations - Aerogel

- Kaon-LT Experiment used dedicated equipment for kaon/pion separation.
- Multiple trays of different refractive indices (1.011-1.030) were used throughout the experiment.
- PMT spectra were plotted and fitting algorithm was validated.
- Accounted for the experimental background.
- Analyzed stability of the parameters throughout different run periods.



Plots and study by V. Berdnikov & P. Stepanov

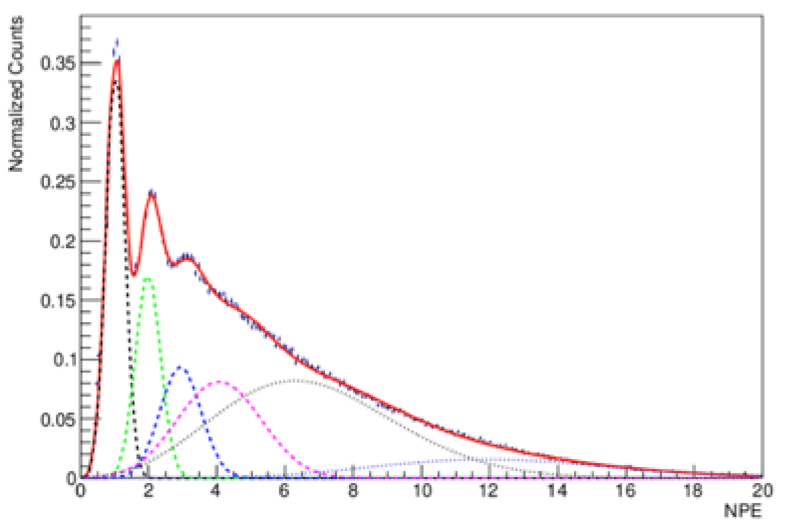
Calibrations - HGC

- Calibrations scripts improved by doing cross checks.
- New technique to study multiple NPEs as well as the poissonian background.
- Checked the stability of calibration parameters throughout multiple run periods.
- Kinematic Details

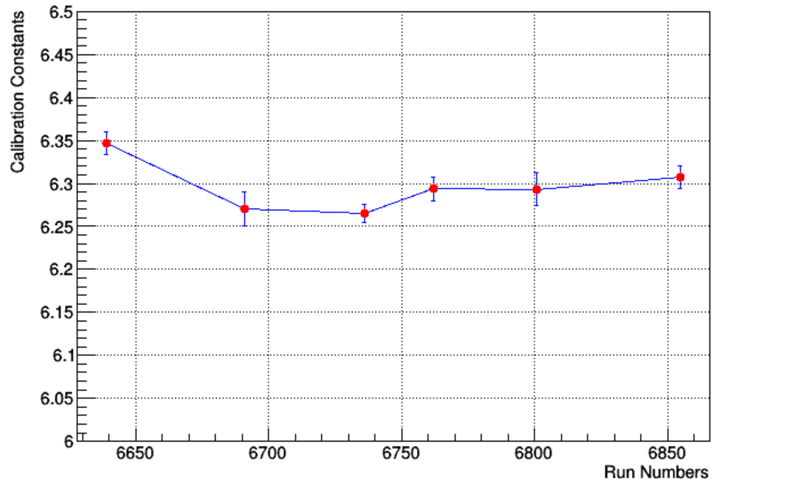
Run # 7045	E_{beam} = 4.9 *GeV*
P_{SHMS} = +2.583 *GeV/c*	$\theta_{SHMS} = 6.01$
Q^2 = 0.5	W = 2.4

- More details can be found at

https://hallcweb.jlab.org/doc-public/ShowDocument?docid=1100



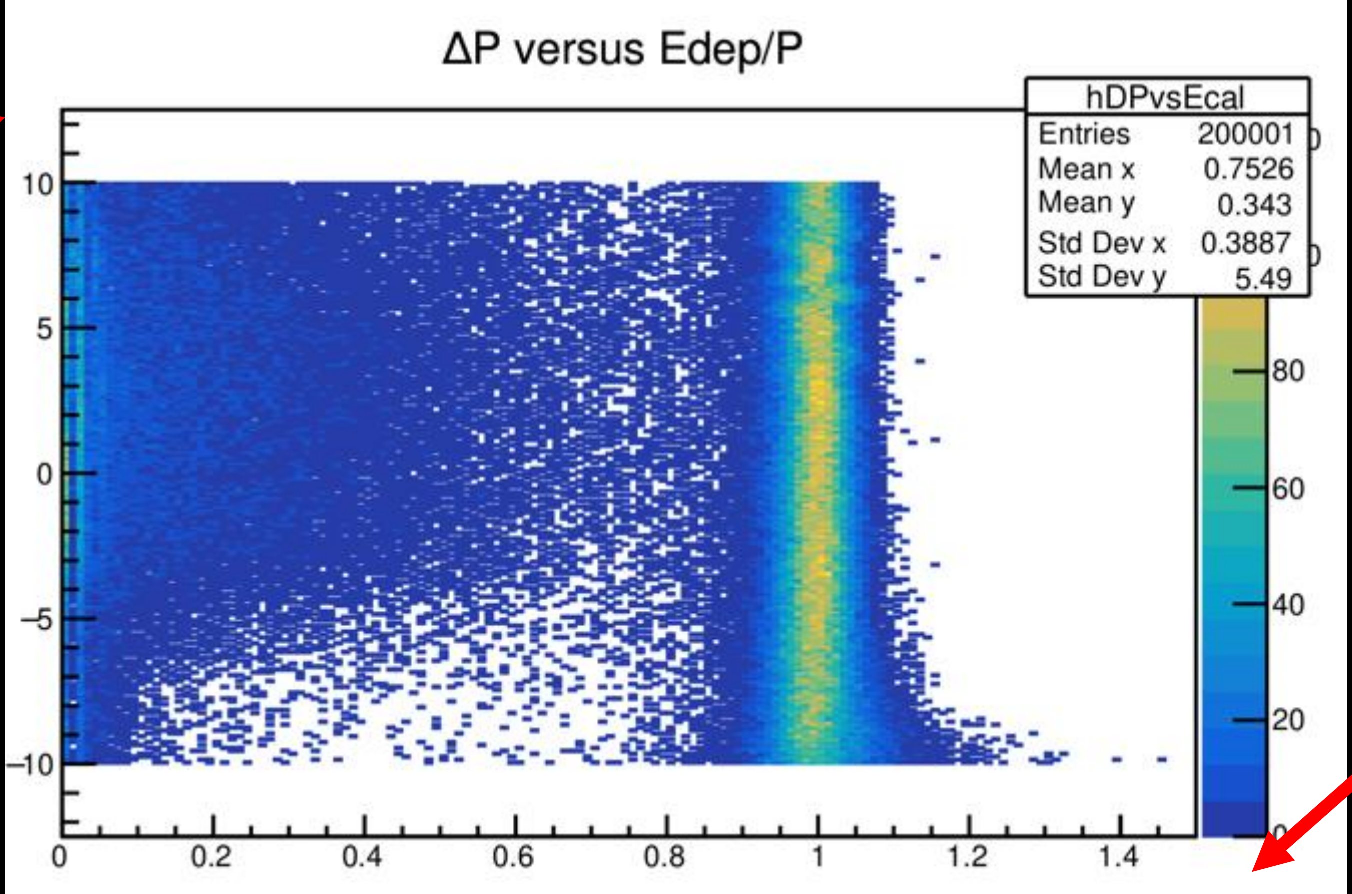
PMT 1



Plots and Study by V. Kumar

Calibrations - Calorimeter

- Momentum distribution for electrons.



- Deviation of particle momentum from spectrometer central momentum

- E/p - Normalized energy
- Deposited energy/ particle momentum
- Expect E/p = 1 for e^-

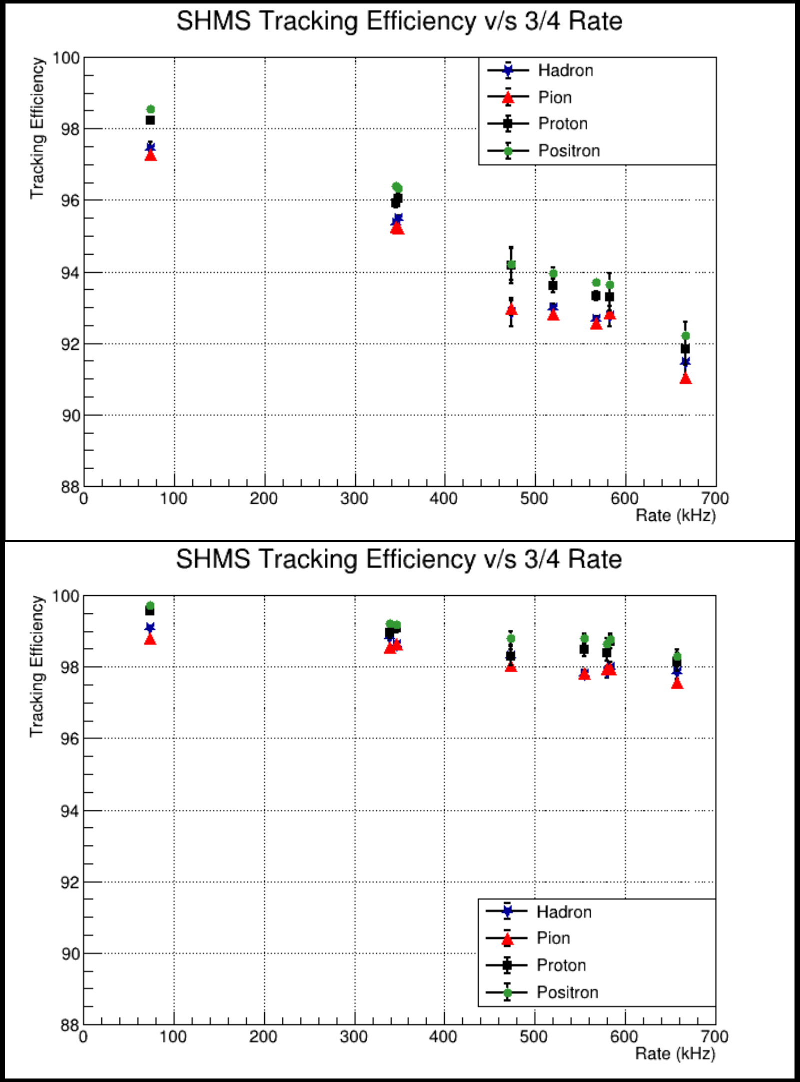
Tracking Efficiency

- The tracking efficiency is defined as follows:

$$\epsilon_{tracking} = \frac{Trig\ \&\ PID\ \&\ TR}{Trig\ \&\ PID}$$

- The SHMS tracking efficiency has improved after the optimization of tracking parameters.

- Efficiency slope for default and new parameters changed from -9.7%/MHz to -2.0%/MHz.



PID Studies

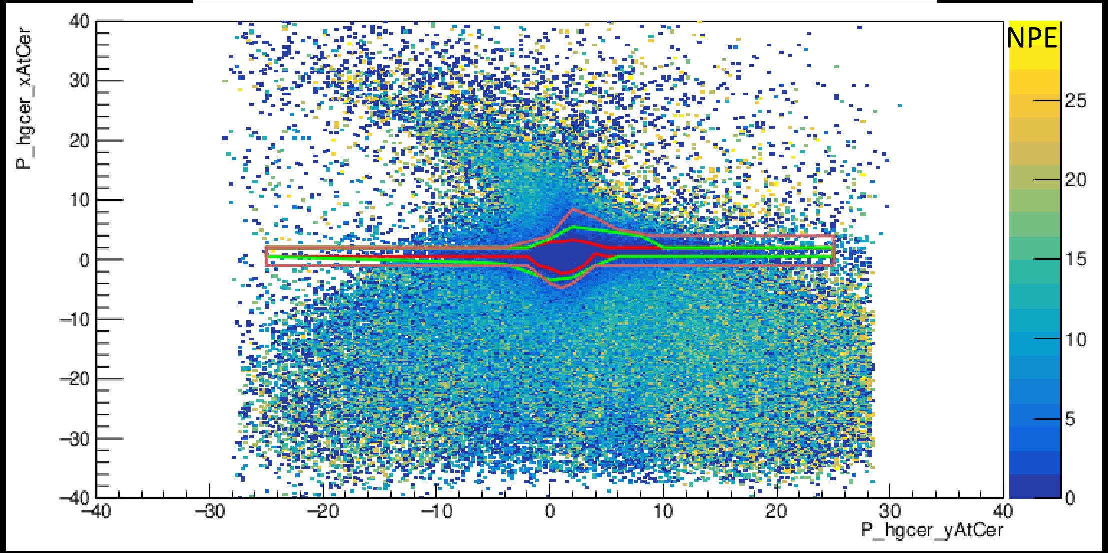
- Hole in the center region of mirrors in Heavy Gas Cherenkov during 2018 is well known.

- Required precision by Kaon-LT Experiment needs a unique approach to deal with this issue.

- Dividing Cherenkov into various regions to understand efficiencies.

$$x_{\text{HGC}} = x_{\text{Focal Plane}} + x'_{\text{Focal Plane}} * z_{\text{HGC}},$$

$$z_{\text{HGC}} = 156.27 \text{ cm},$$



- Kinematic Details

Run # 5018 (Before 2019 realignment) E_{beam} = 10.6 *GeV*

P_{SHMS} = +6.053 *GeV/c* $\theta_{SHMS} = 12.46$

- HGC Regions

1st region → NPE <= 1.5 2nd Region → 1.5 < NPE < 5.0

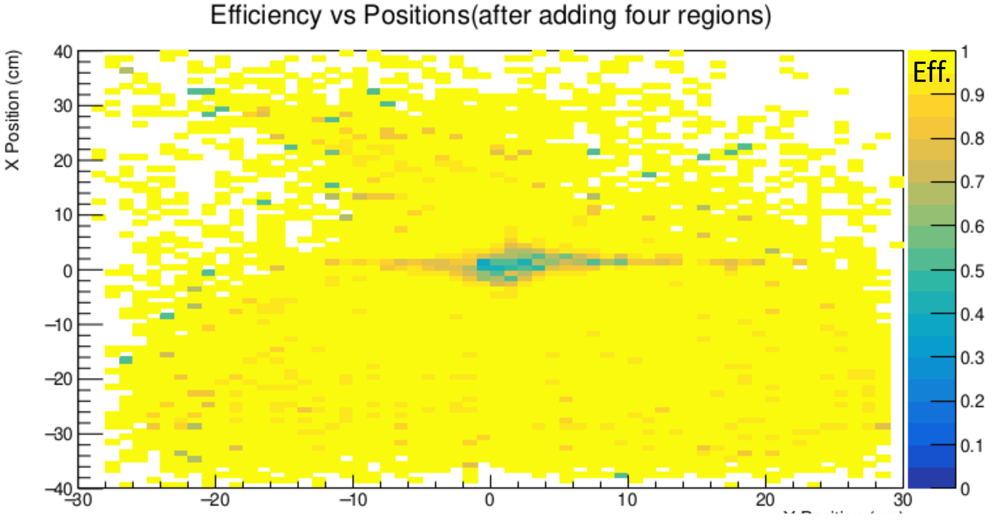
3rd Region → 5.0 < NPE < 7.0 4th Region → NPE > 7.0

Plots and Study by V. Kumar

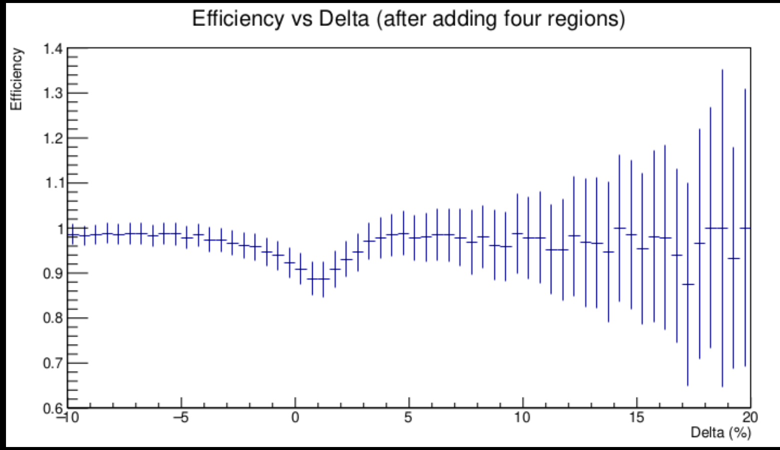
PID Studies

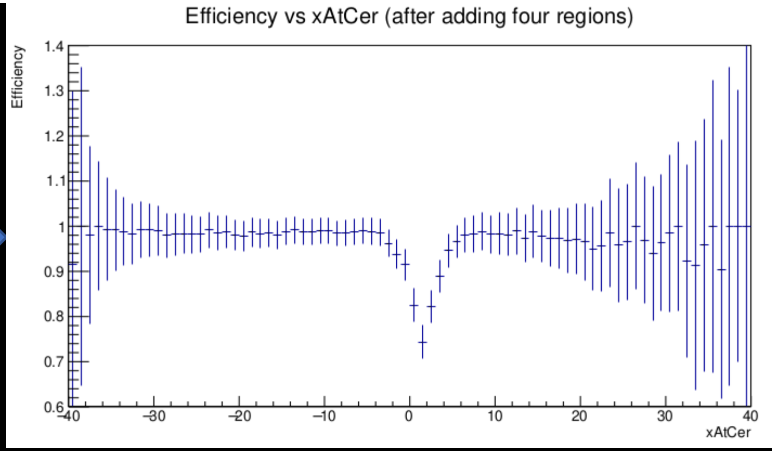
- Efficiency plotted vs XatCer makes the efficiency dip more sharp than vs. Delta
  - Corresponds more closely to the actual configuration of the mirror setup

- Will perform a (Xcer, Ycer) 2D efficiency study for HGC, for both the 2018 and 2019 mirror configurations.



$$\text{efficiency} = \frac{[\text{Particle ID}][\text{Tracks}][\text{Beta}][\text{Timing}][\text{HGC}]}{[\text{Particle ID}][\text{Tracks}][\text{Beta}][\text{Timing}]} \times 100\%,$$

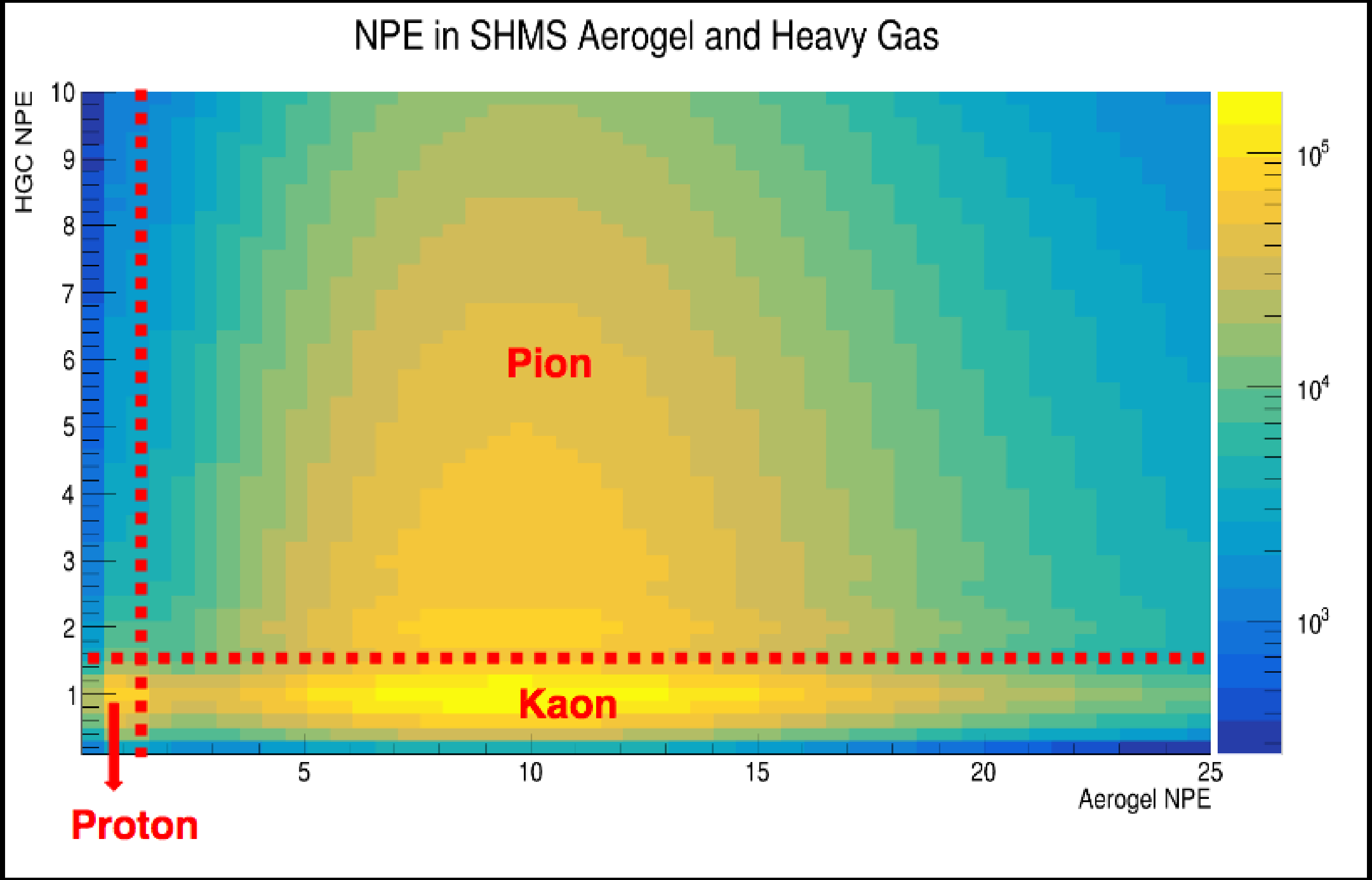




Plots and Study by V. Kumar

Pion Production in Kaon-LT Experiment

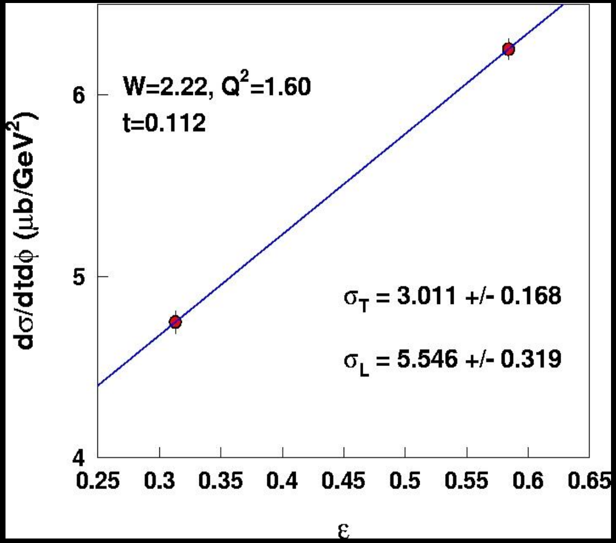
- A lot pions are produced in Kaon-LT Experiment which can be observed in the distribution of number of photoelectrons (NPE) in HGC and Aerogel Cherenkov.



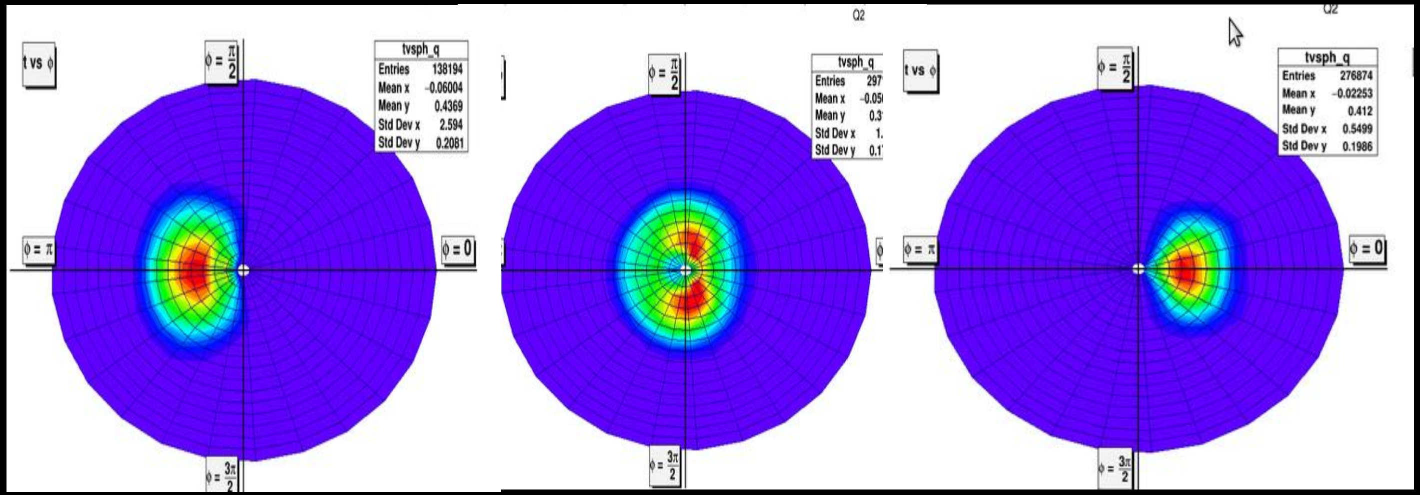
Rosenbluth Separation Technique

- "Rosenbluth Separation technique" is used to separate the longitudinal and transverse cross-section terms.
- In parallel kinematics

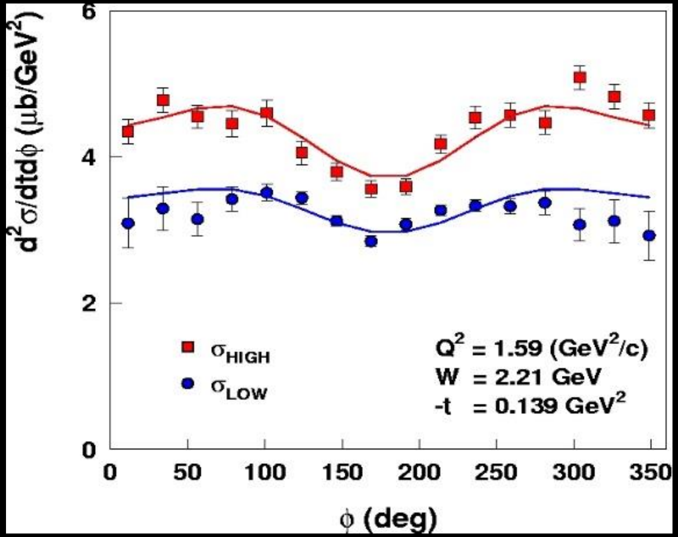
$$2\pi \frac{d^2\sigma}{dt d\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt}$$



$E_{beam} = 10.6\ GeV$ $Q^2 = 3.0\ GeV$ $W^2 = 3.14\ GeV$



$\theta_{SHMS} = 12.42$ $\theta_{SHMS} = 9.42$ $\theta_{SHMS} = 6.65$



Pion Form Factor

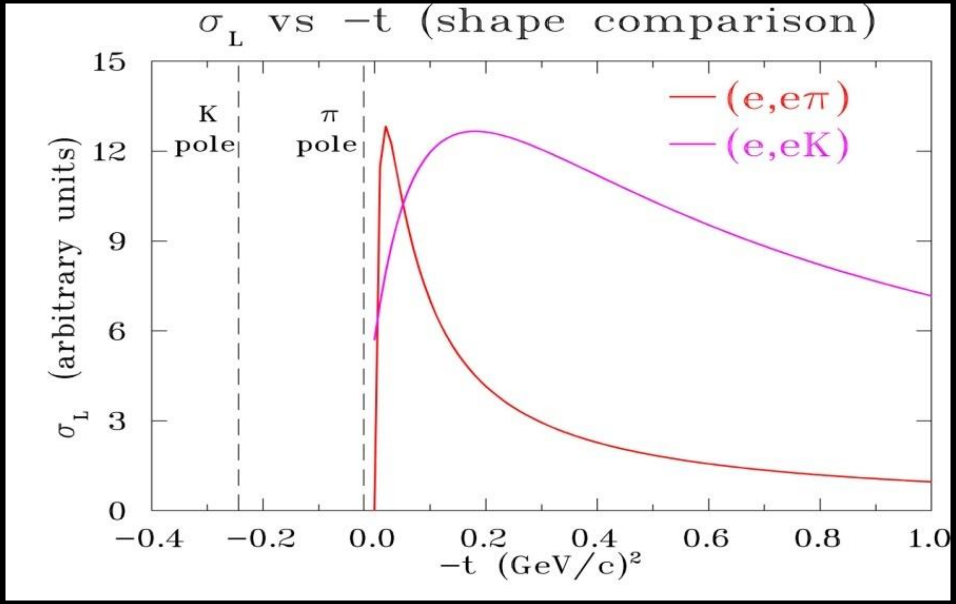
- Pion form factor decreases with increase in energy (i.e. F_π is minimal at infinite momentum).
- in pQCD, F_π can be written as

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

- In Born term model F_π appear as

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

Coupling constant — Form Factor



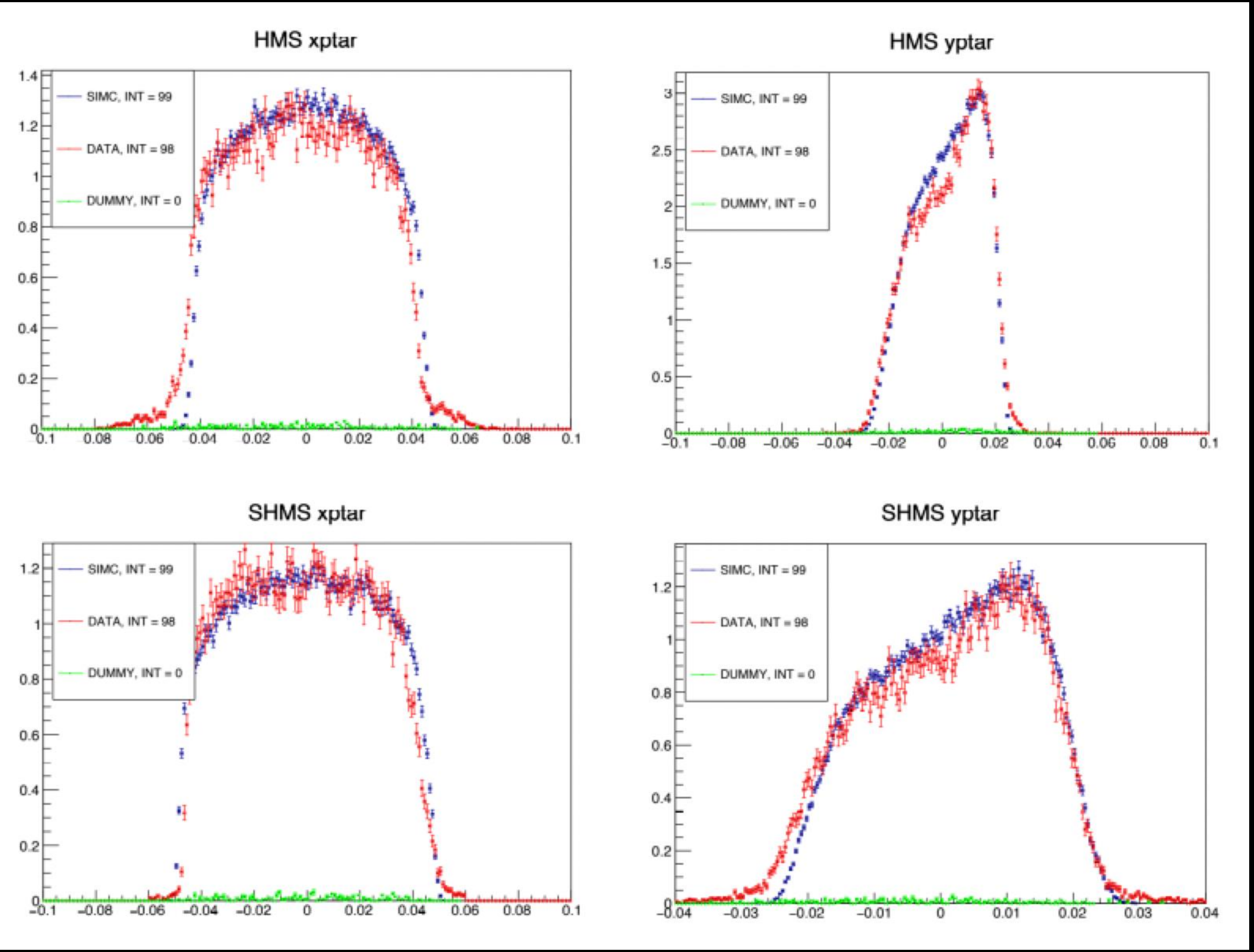
- F_π is cleanest case for studying transition from non-perturbative QCD to the perturbative QCD region.

Target Variables Comparison

- $E_{beam} = 8.2\ GeV$
- Heep Coin

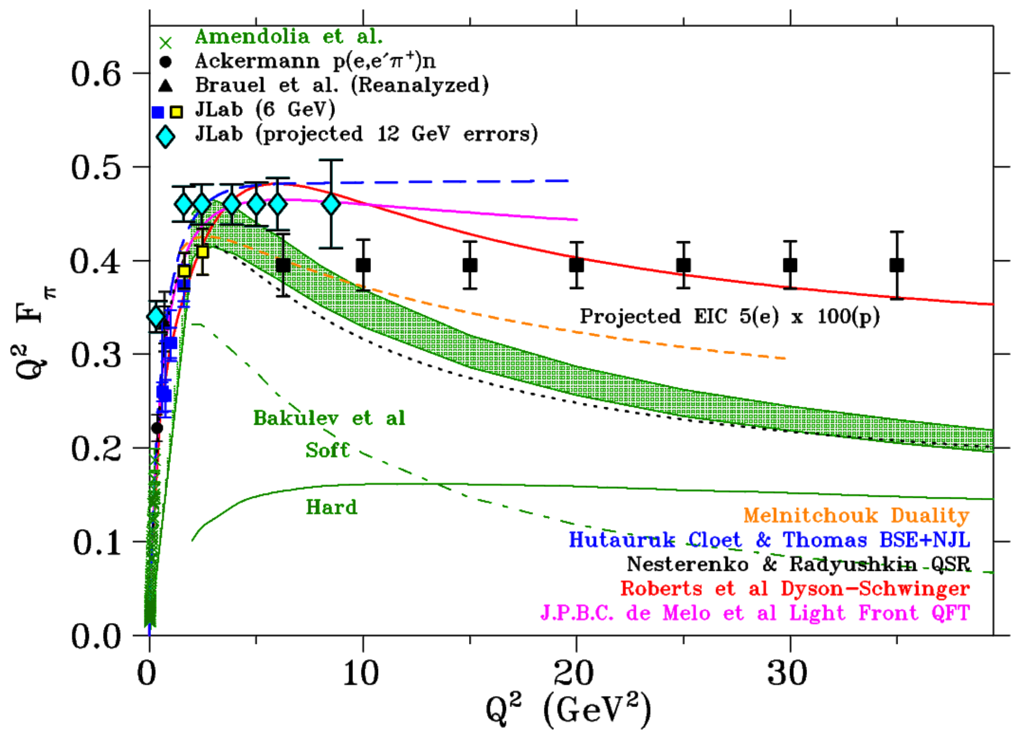
- Target quantities are reconstructed from the focal plane quantaties.

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



F_π at EIC

- Electron-Ion collider is upcoming facility to be built at BNL.
- F_π can be measured by e-p collisions with different energy combinations are available.
- Our group has already started simulations which will extend F_π results up to Q^2 of 35 GeV^2.



Kaon Form Factor

- Kaon-LT Experiment gives access to highest possible Q^2 data (i.e Q^2~5.5 GeV^2).

- Will perform pole dominance studies and attempt to extract F_K at Q^2 up to 5.5 GeV^2.

- Includes both $p(e,e'K^+)\Sigma^0$ as well as $p(e,e'K^+)\Lambda^0$ which allows us to perform ratio between two channels.

- Low Q^2 data will help compare with results from Fermilab and CERN which used K⁺ beam