# Semi-inclusive and Exclusive $\pi^0$ Electroproduction Physics with NPS

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On behalf of the NPS Collaboration

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# Outline

- $\pi^0$ Physics
  - TMD Background
  - Validation of Factorization theorem
  - E12-13-007, E12-23-014, and E12-13-010 in Hall C
- $\pi^0$ in parallel with DVCS
  - NPS experiment setup as it relates to the $\pi^0$
- NPS RG-1a analysis plan
  - Current Status
  - RG-1a kinematic coverage
- Current status of the $\pi^0$ with the NPS
  - Initial missing mass observation
  - Heading towards L/T separation of exclusive $\pi^0$
- Next Steps

# SIDIS Pion Physics Considerations

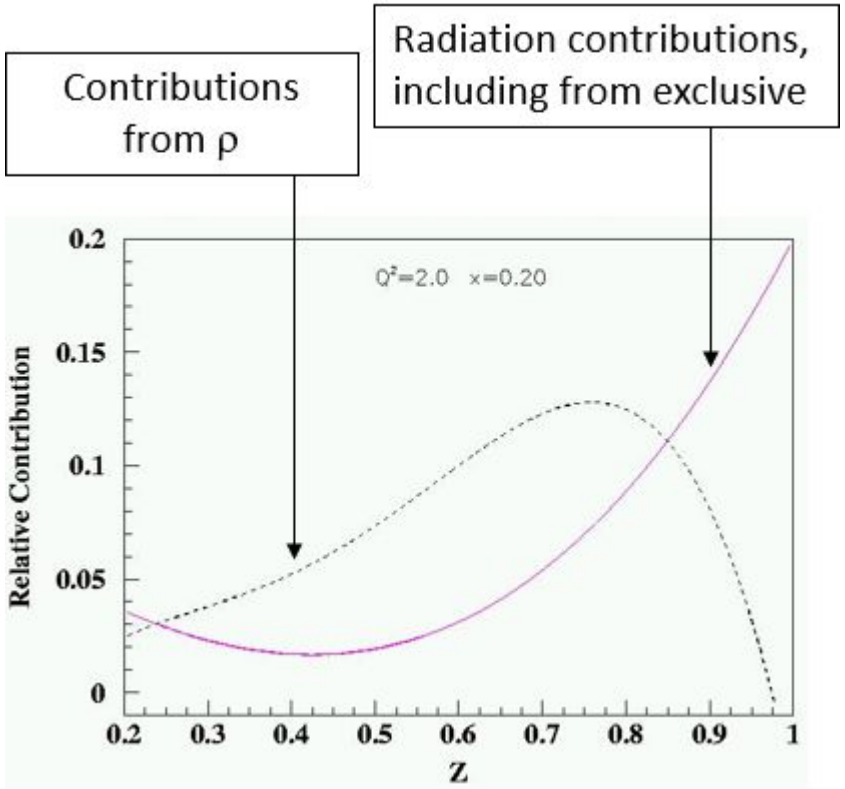
- Low-energy (x,z) factorization, or possible convolution in terms of quark distribution and fragmentation functions, at JLab-12 GeV must be well validated to substantiate the SIDIS science output
  - Many questions at intermediate-large z (~0.2-1) and low-intermediate $Q^2$ (~2-10 $GeV^2$) remain

Advantages of (e,e'$\pi^0$) beyond (e,e'$\pi^{+/-}$)?

(e,e'$\pi^0$):

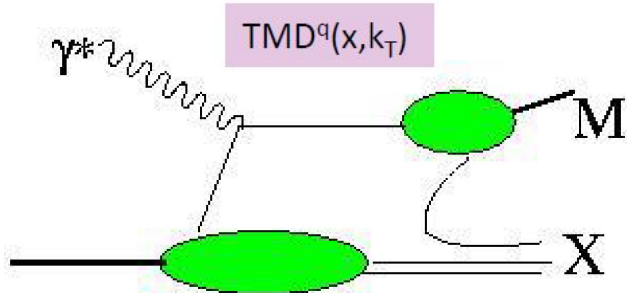
- No diffractive $\rho$ contributions
- No exclusive pole contributions
- Reduced resonance contributions
- Proportional to average D

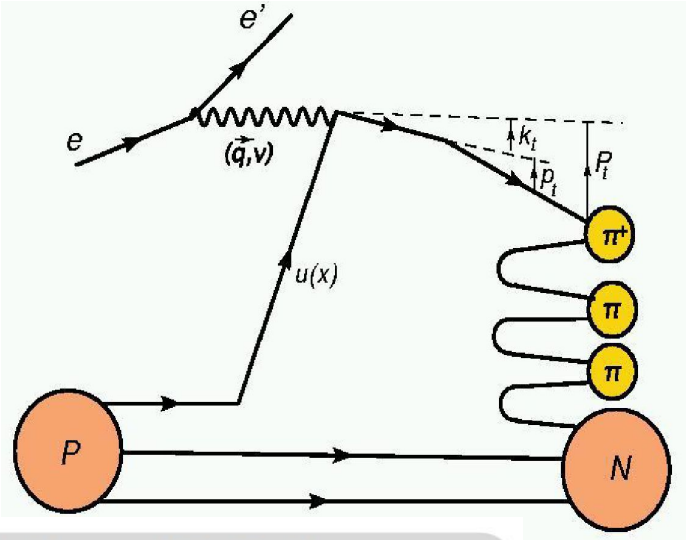
Non-trivial contributions to (e,e'$\pi^+$) Cross Sections:



# E12-13-007: Basic (e,e'$\pi^o$) cross sections

- Linked to framework of Transverse Momentum Dependent Parton Distributions (TMDs)
- Basic cross sections are a fundamental test of understanding SIDIS in 12 GeV kinematics and essential for most future experiments and their interpretation




- Validation of factorization theorem
- Target-mass corrections and ln(1-z) re-summations require precision large-z data
- Transverse momentum widths of quarks with different flavor (and polarization) can be different

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

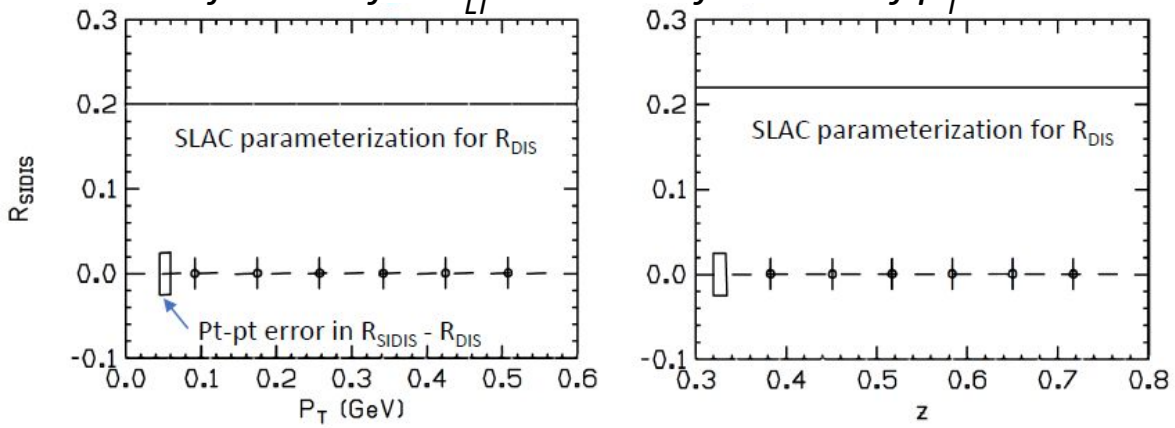
- **Advantages of (e,e'π°) beyond (e,e'π$^{+/-}$)**
  - Experimental and theoretical advantages to validate understanding of SIDIS
  - Can verify: $\sigma^{\pi^0}(x,z) = \frac{1}{2}(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
  - Confirms understanding of flavor decomposition/$k_T$ dependence

**E12-13-007 goal**: Measure the basic SIDIS cross sections of π° production off the proton, including a map of the $P_T$ dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate flavor decomposition and the $k_T$ dependence of (unpolarized) up and down quarks

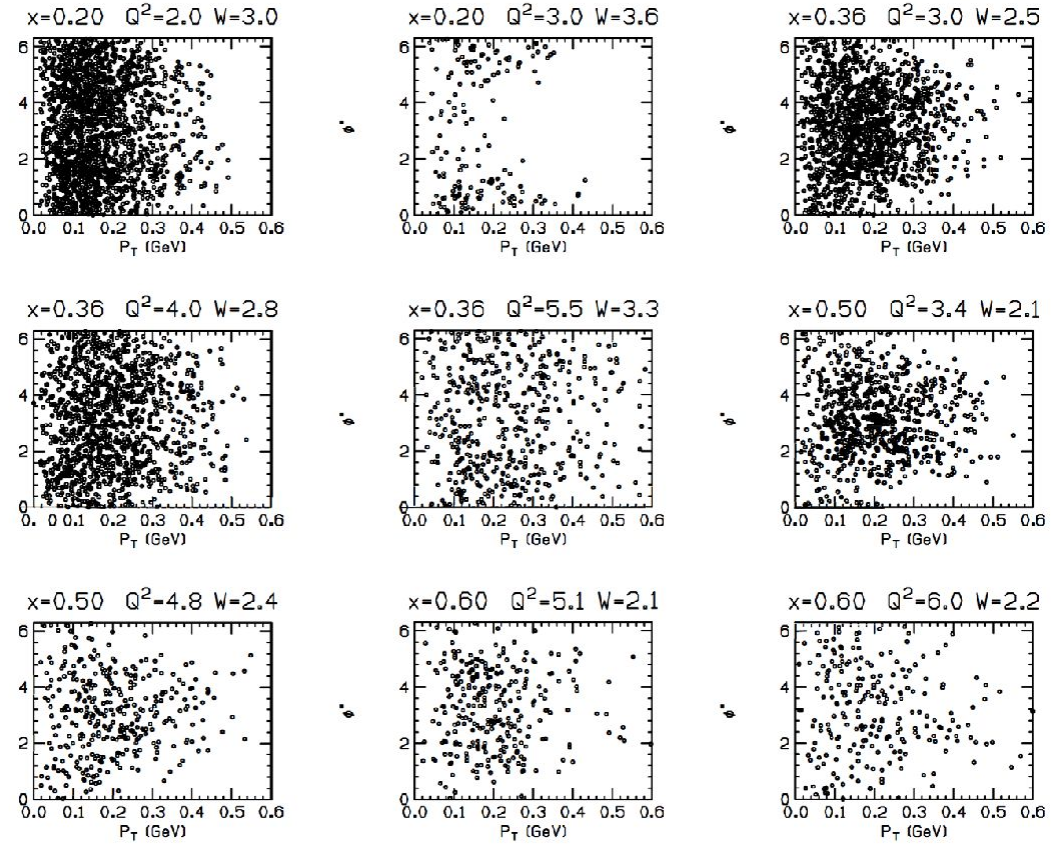
# E12-23-014: R = $\sigma_L/\sigma_T$ , p/d ratios, $P_{h\perp}$ dependence, and azimuthal asymmetries with $\pi^0$ SIDIS

- Measure $R_{LT}= \sigma_L/\sigma_T$, the ratios of d/u cross sections, the transverse momentum dependence of the cross section, and the spin-independent and beam-spin-dependant modulations of the cross section
  - Data taken on both Hydrogen and Deuterium targets to allow for precision ratio of proton to deuteron
- Physics goals are driven by the need to more fully understand the production processes that enter SIDIS for better understanding of the 3D nucleon structure
  - Dynamic and target higher twist, deep-exclusive processes, VM, CSV

*Projections for $R_{LT}$ SIDIS as a function of $p_T$ and z*

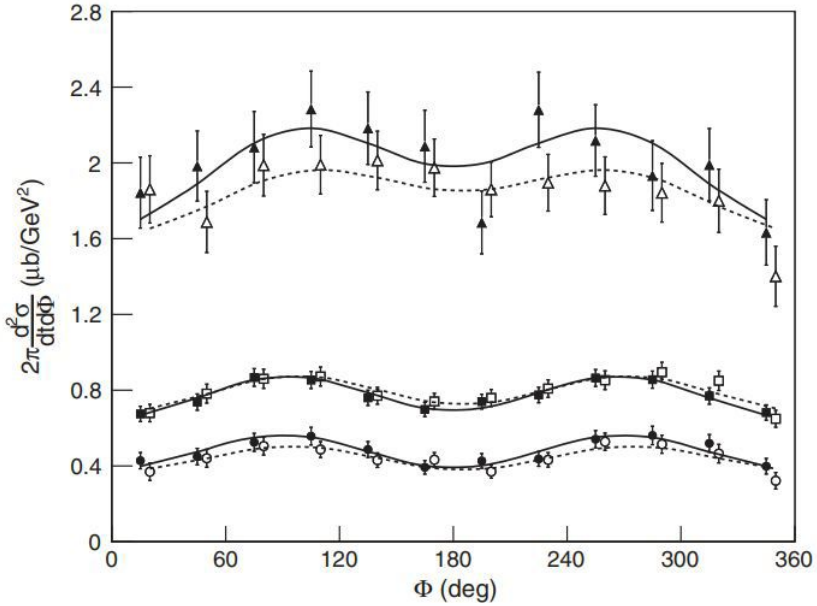



*Angles for which NPS has good acceptance in ($z,p_T$)*

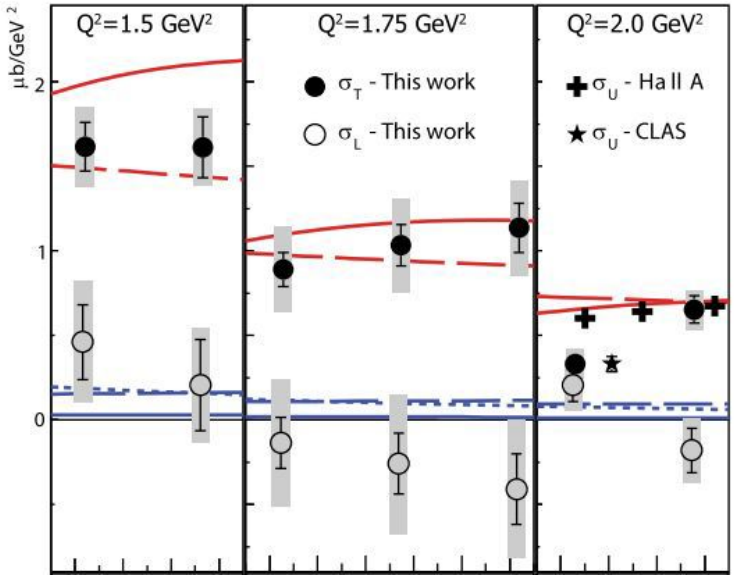


# Early Insights into Exclusive $\pi^0$ and Factorization

- $\pi^0$ Electroproduction Cross Section at Hall A at Jefferson Lab
  - L/T-separated $\pi^0$ cross sections measured at Hall A, covering $1.5 < Q^2 < 2$ and $x_B = 0.36$
  - VGG model (short dashed lines) predicts a small longitudinal cross-section, matching data
  - Models with chiral-odd GPD and twist-3 PDAs also in good agreement for both L/T
  - Indicates potential access to transversity GPDs of the nucleon through exclusive $\pi^0$ electroproduction for $Q^2 \geq 1.5$ GeV$^2$




The cross sections extracted at low ϵ are shown in open symbols and high ϵ in solid symbols




Higher transverse contribution; transversity GPD models agree well with data. Suggests pQCD regime isn't reached

"M. Defurne et al, PRL 117 (2016) no.26, 262001"

# E12-13-010 Exclusive $\pi^0$ Electroproduction with NPS in Hall C

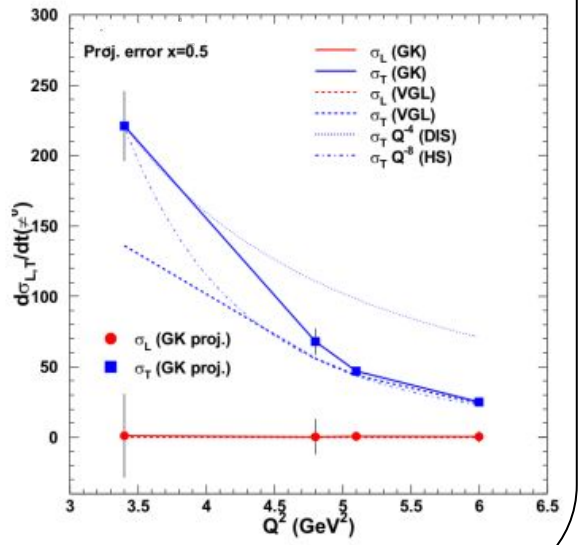
- An extension and compliment to the kinematic settings examined in Hall A
  - Increased the $Q^2$ reach to even higher values at fixed $x_B$
  - Also Expanded the kinematic coverage to smaller values of $x_B$
  - E12-13-010 also provides data on $\sigma_L$ and $\sigma_T$ at higher $Q^2$ for reliable interpretation of 12 GeV GPD data

- Motivation for $\pi^0$ electroproduction towards GPDs:
  - Sensitive to transversity GPDs ( $\tilde{H}_q$ , $\tilde{E}_q$ ), which are less accessible in vector meson production.
  - Offers insights into parton helicity flipping (chiral-odd GPDs).
  - No need for polarized targets or beams to access these polarized distributions.

**E12-13-010 goal:** Perform an L/T separation of the exclusive $\pi^0$ electroproduction cross section as a function of $Q^2$ .

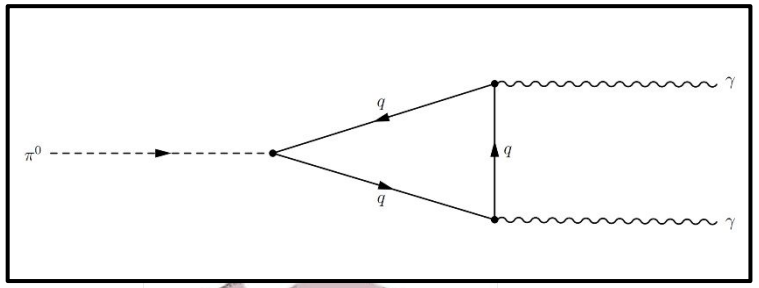
**$\pi^0$ Exclusive Cross Sections**

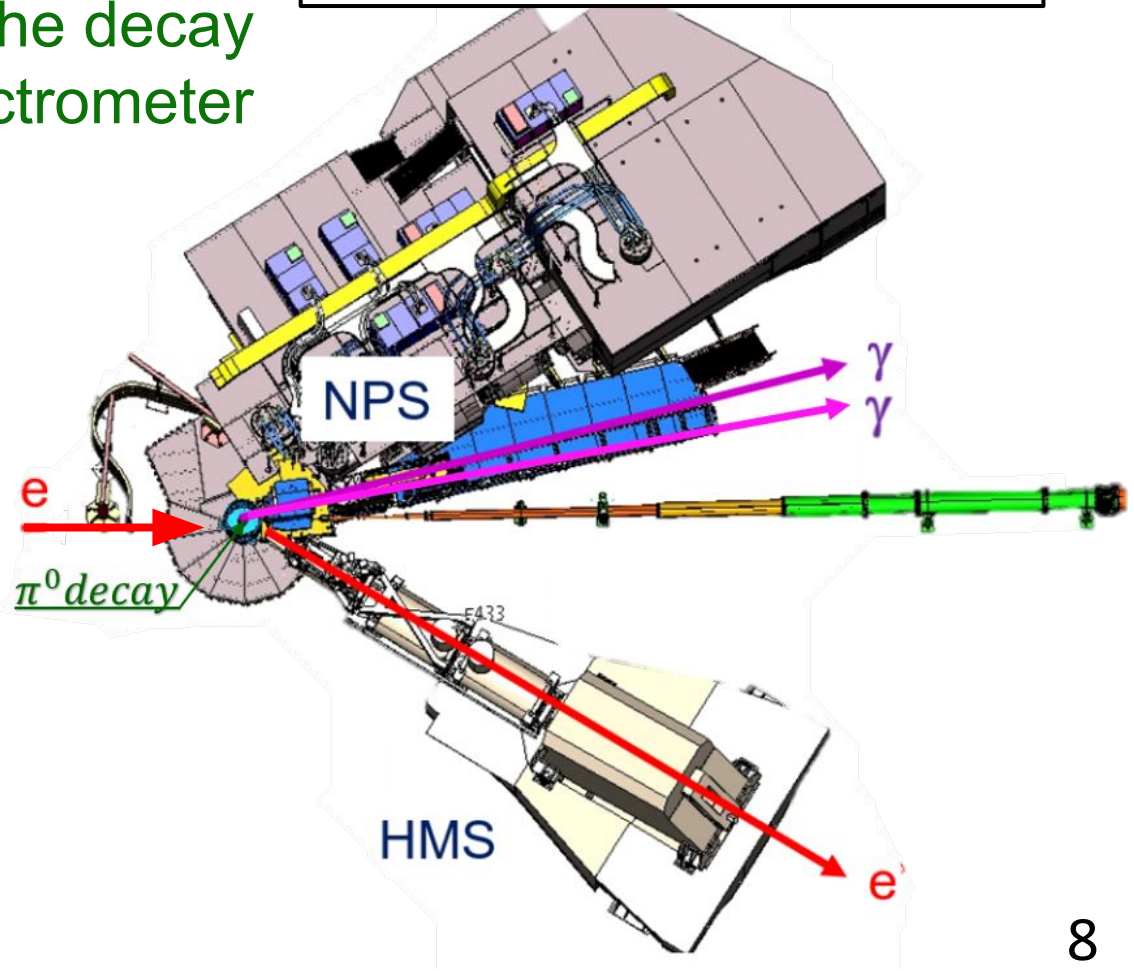
- Relative L/T contribution to $\pi^0$ cross section important in probing transversity
- Results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in $\pi^0$ production is non-zero up to $Q^2$=2 GeV$^2$
  - *12 GeV projections: confirm $Q^2$/t dependence*



# Semi-inclusive and Exclusive $\pi^0$ with NPS in Hall C

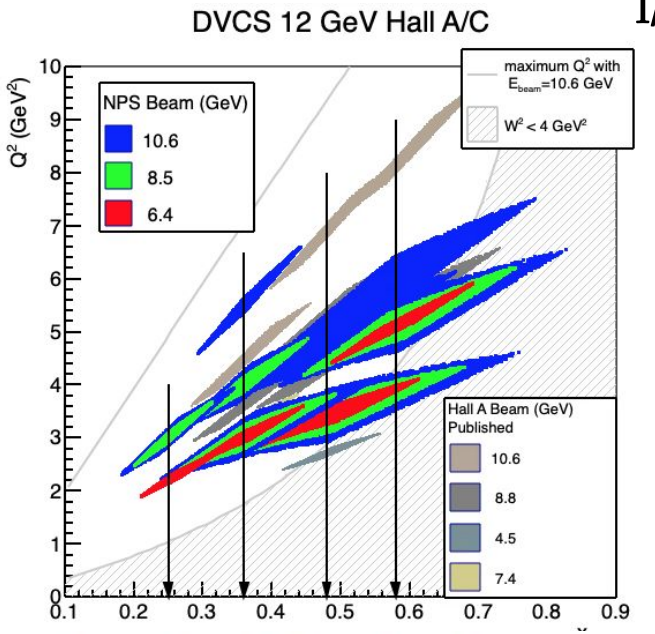
- These experiments were part of the NPS RG1-a and detected in coincidence scattered electrons in the existing HMS and photons from the decay of the $\pi^0$ using the Neutral Particle Spectrometer (NPS)
- The NPS detected photons corresponding to $\pi^0$ electroproduction close to the direction of $\vec{q}$, the exchanged virtual photon three-momentum transfer
  - Average lifetime of $8.5\times10^{-17}$ seconds.
  - The HMS Spectrometer benefits from relatively small point-to-point uncertainties, which are crucial for meaningful L/T separations

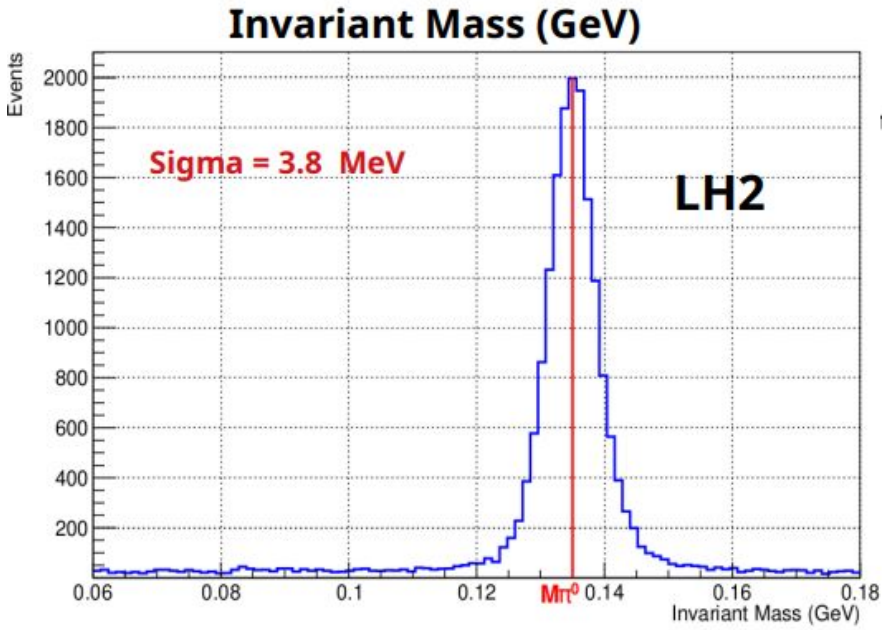


# Analysis Game Plan

- ✅ The overall analysis for the NPS RG-1a is in progress with the Pass-1 having been run just prior to the Holiday break.
- ✅ Initial calibrations of the HMS subdetectors and beamline components have been finalized.
  - HMS Optics Calibration
  - Beam Charge/Position Measurements
  - Coincidence Timing Corrections
- ✅ These calibrations are being done to maximize the acceptance of the overall experimental apparatus
- ❑ Next steps will include waveform analysis and further refinements of the NPS detector Calibrations along with the $\pi^0$ analysis
- ❑ The $\pi^0$ is also providing useful information for calibration of the NPS detector itself
  - Supplemental to the elastic calibration. $\pi^0 \rightarrow \gamma\gamma$ Calibration
- ❑ Stay tuned for more details!

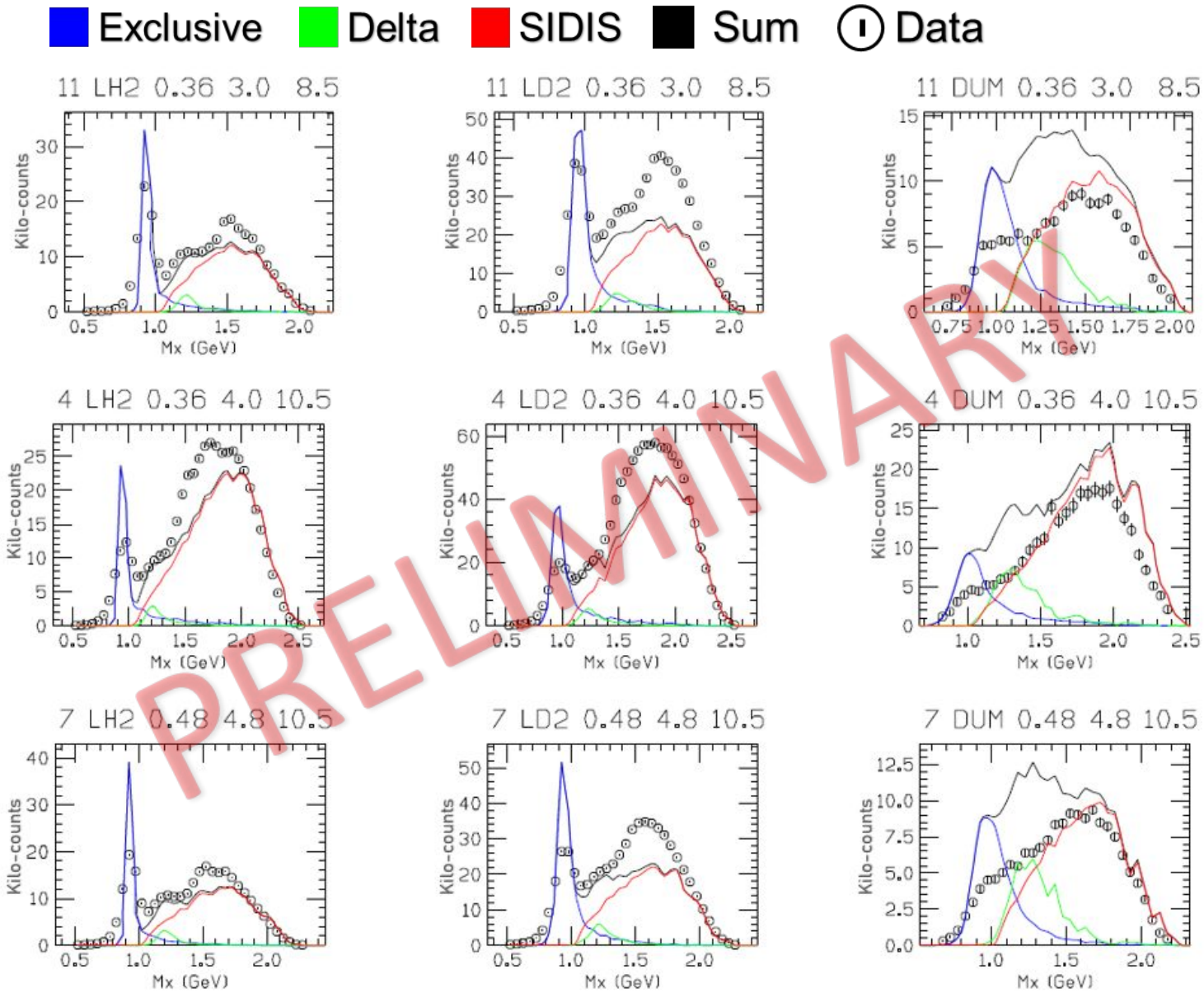



Credit: Wassim Hamdi

# $\pi^0$ Missing Mass

- Example of the $\pi^0$ missing mass statistics from three of the 56 different kinematics from the Pass-1 data analysis
  - Two cryogenic targets were used ($LD_2$ and $LH_2$) along with a dummy/ empty Al target for background subtractions
- The colored curves represent the SIMC predictions for exclusive, Delta ,and Sidis (solid black curve is the sum) and the open circles are the measured data
- NPS Fiducial cuts were applied to both SIMC and data



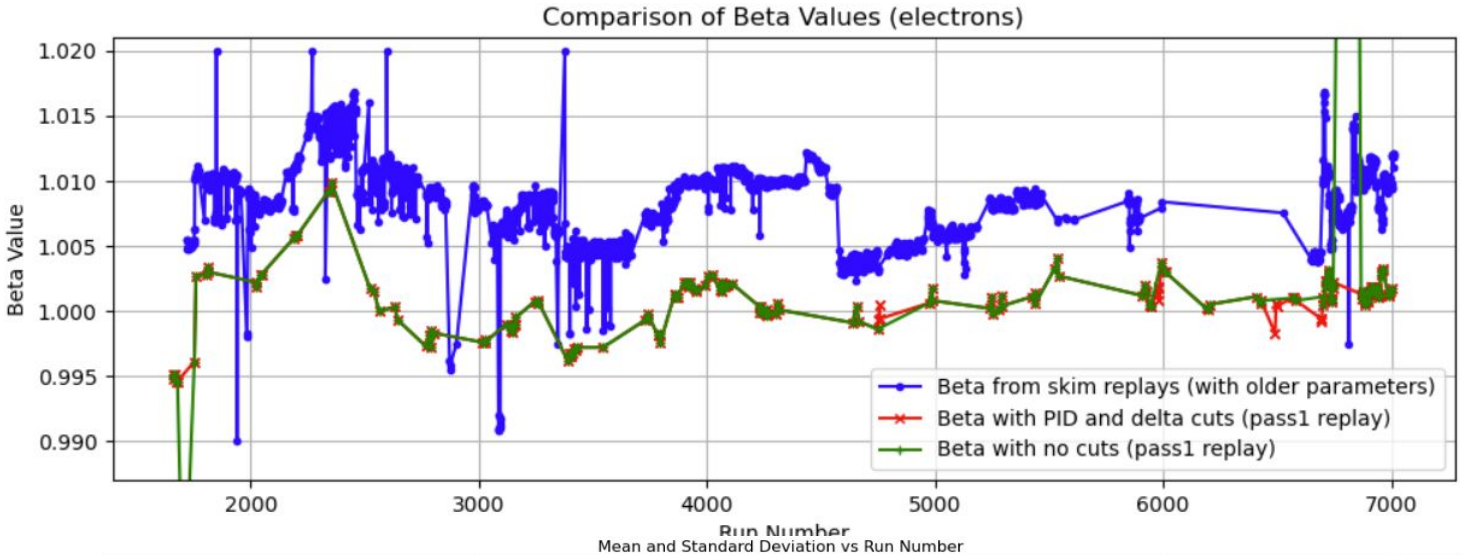


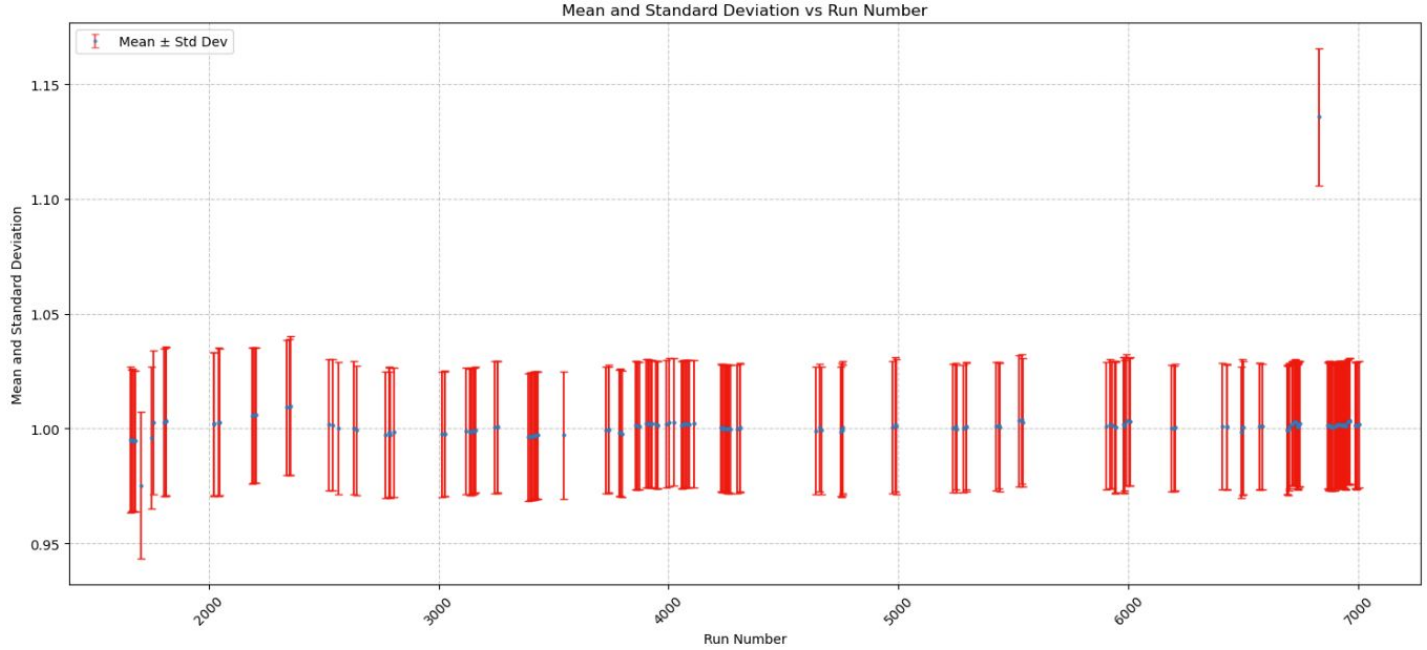

Credit: Peter Bosted

# HMS Beta Value Stability in Pass1



- Extracted HMS Beta during the RG1-a run period
- Refinement in the HMS calibrations, PID cuts, timing corrections, etc. showed good improvement over the values used for online running
  - Both Pass-0 (online analysis) and Pass-1 replay shown for comparison
  - Beta values are consistent across the experiment and the values were improved ~80% with the Pass-1 calibrations applied

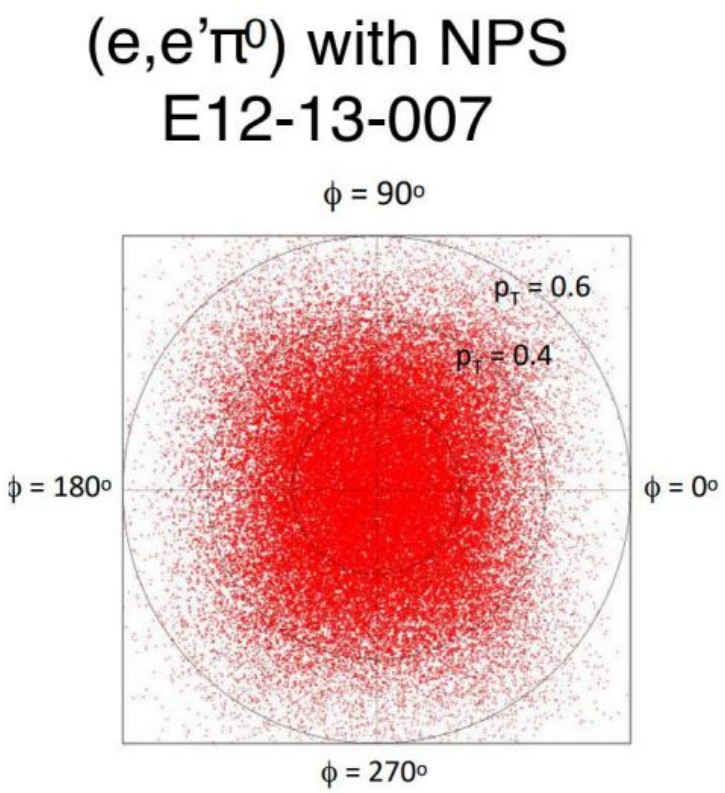



Credit: Avnish Singh

# Next Steps

- After the initial replay of the data with the pass-1 calibrations verified, the next steps will be to refine the code used to reconstruct the 4-vector of the candidate $\pi^0$ decays
  - Using two photon hits detected in the NPS over all the kinematics and select good events
  - Refining the selection criteria and comparing to simulated acceptance of the NPS detector to determine efficiencies (comparing probabilities of edge case events clustering)
- Once the good events are selected, full analysis of the kinematic bins will continue
  - Accumulate the $\pi^0 \rightarrow \gamma\gamma$ accidental-subtracted invariant mass spectra in bins of x, e-$\pi^0$ missing mass, helicity and transverse momentum, etc.
  - Also since RG-1a ran on two different targets we can also compare the output from the LD2 vs LH2 targets



# Summary

- Hall C E12-13-007, E12-23-014, and E12-13-010 give probes for TMDs and will allow for a L/T separation measurement across a large kinematic range, along with SIDIS cross section of $\pi^0$
  - Also can show validation of Low-energy (x,z) factorization
- The NPS RG-1a experiments (2023-2024) ran in Hall C at JLab using the NPS detector in combination with the HMS spectrometer to detect photons corresponding to $\pi^0$ electroproduction
- There was good coverage of the desired kinematic range in $X_b$ and $Q^2$ despite the challenges which were overcome
- HMS subdetector calibrations have been finalized with Pass-1 replay complete, analysis is in progress
- The $\pi^0$ missing mass peak has been preliminarily identified from online running analysis and is being refined in Pass-1
- $\pi^0$ reconstruction ongoing

Thank you to the NPS Collaboration
Thanks to all my colleagues
at JLab and elsewhere
Thank you all for your time