Semi-inclusive and Exclusive π^0 Electroproduction Physics with NPS

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On behalf of the NPS Collaboration

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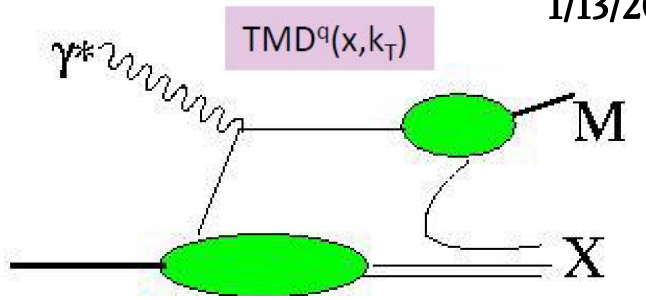
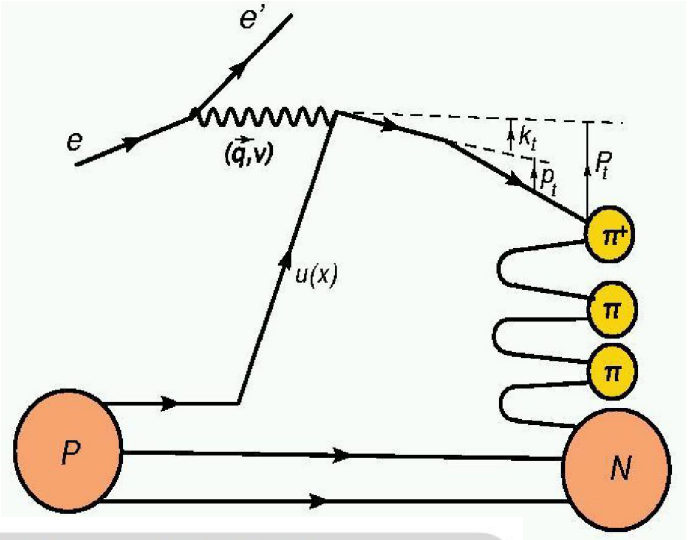
Outline

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

E12-13-007: Basic (e,e'π^o) cross sections

- Linked to framework of Transverse Momentum Dependent Parton Distributions
- 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

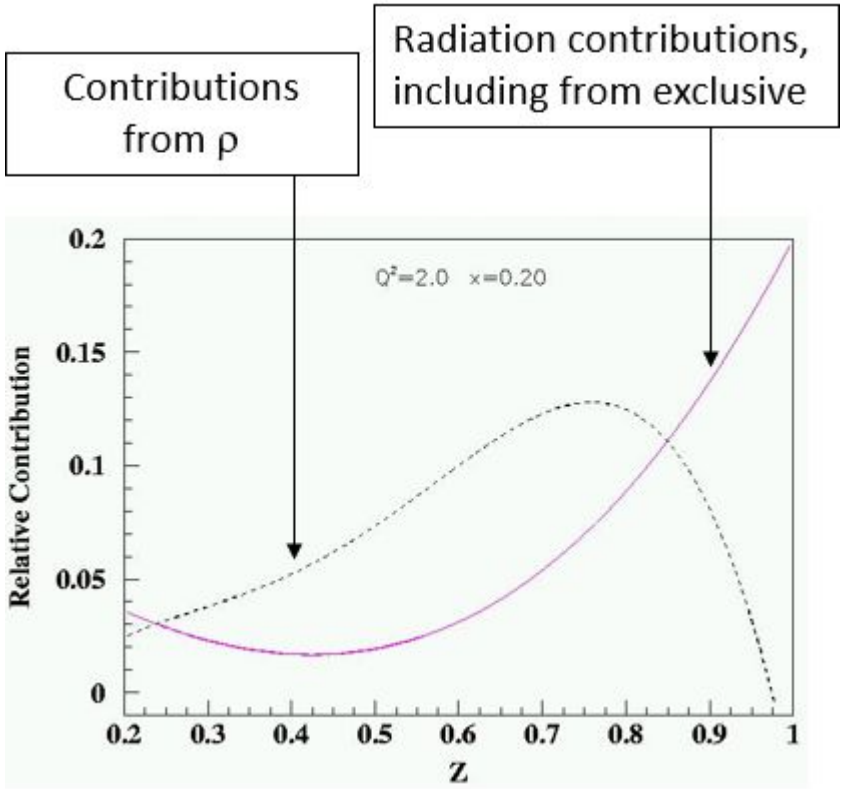
Physics Considerations

- 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 Q2 (~2-10 GeV2) remain

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

(e,e'π^0):
- No diffractive ρ contributions
- No exclusive pole contributions
- Reduced resonance contributions
- Proportional to average D

Non-trivial contributions to (e,e'π^+) Cross Sections:

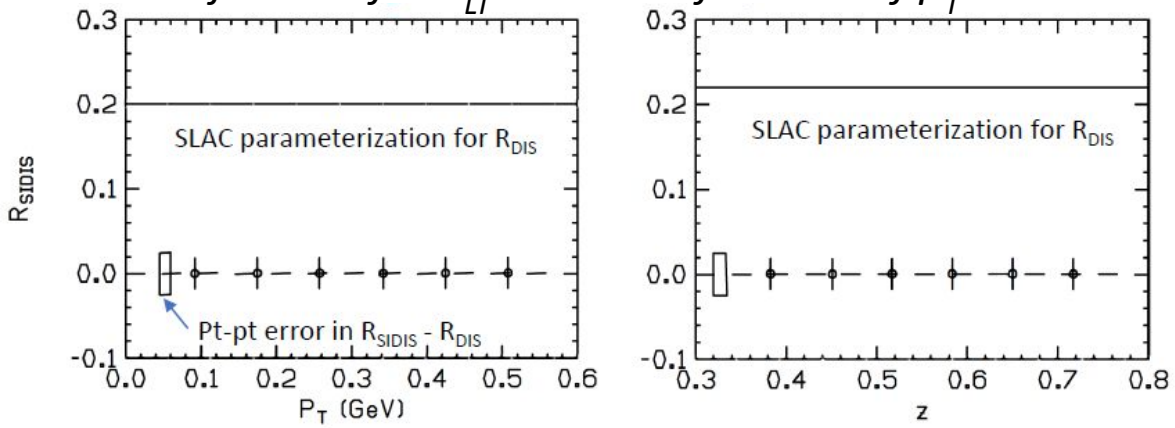


E12-13-007 & E12-23-014 goal: basic SIDIS cross sections, validate SIDIS framework at JLab energies

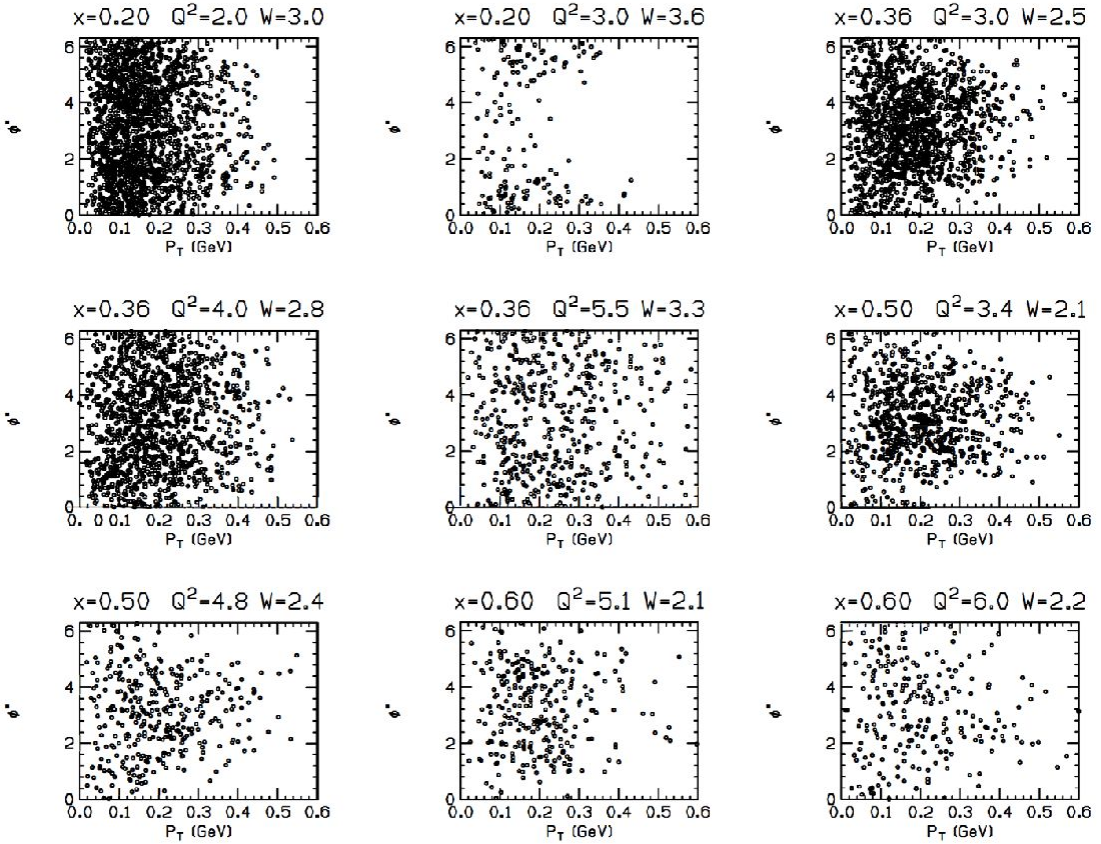
E12-23-014: R = σ_L/σ_T , p/d ratios, $P_{h\perp}$ dependence, and azimuthal asymmetries with π^0 SIDIS

- Measure R_{LT}= σ_L/σ_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

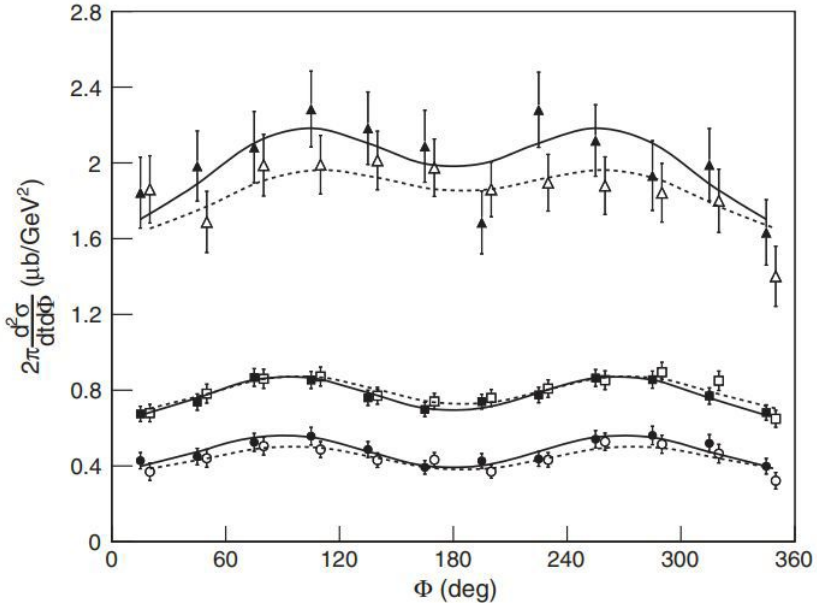


Angles for which NPS has good acceptance in (z,p_T)

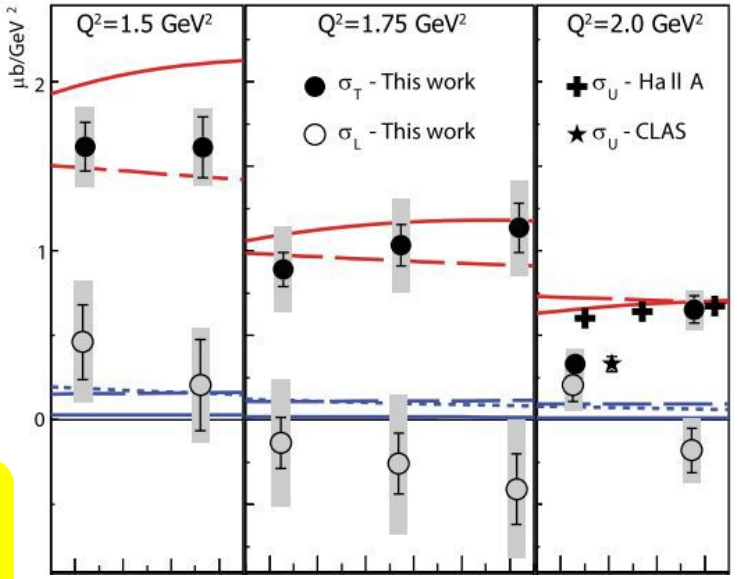


Early Insights into Exclusive π^0 and Factorization

- π^0 Electroproduction Cross Section at Hall A at Jefferson Lab
  - L/T-separated π^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 π^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"

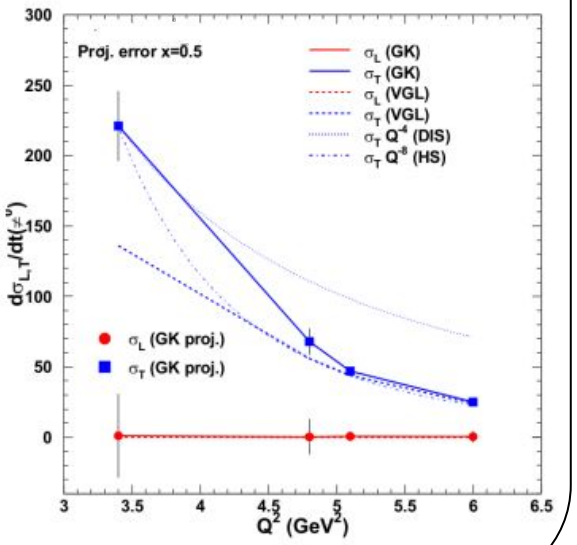
E12-13-010 goal: Perform an L/T separation of the exclusive π^0 electroproduction cross section as a function of Q^2 .

E12-13-010 Exclusive π^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 σ_L and σ_T at higher Q^2 for reliable interpretation of 12 GeV GPD data
- Motivation for π^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.

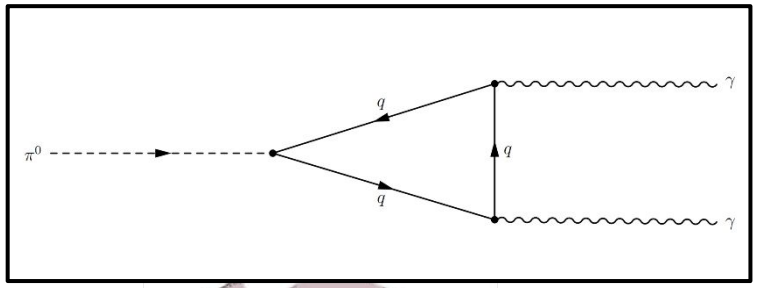
π^0 Exclusive Cross Sections

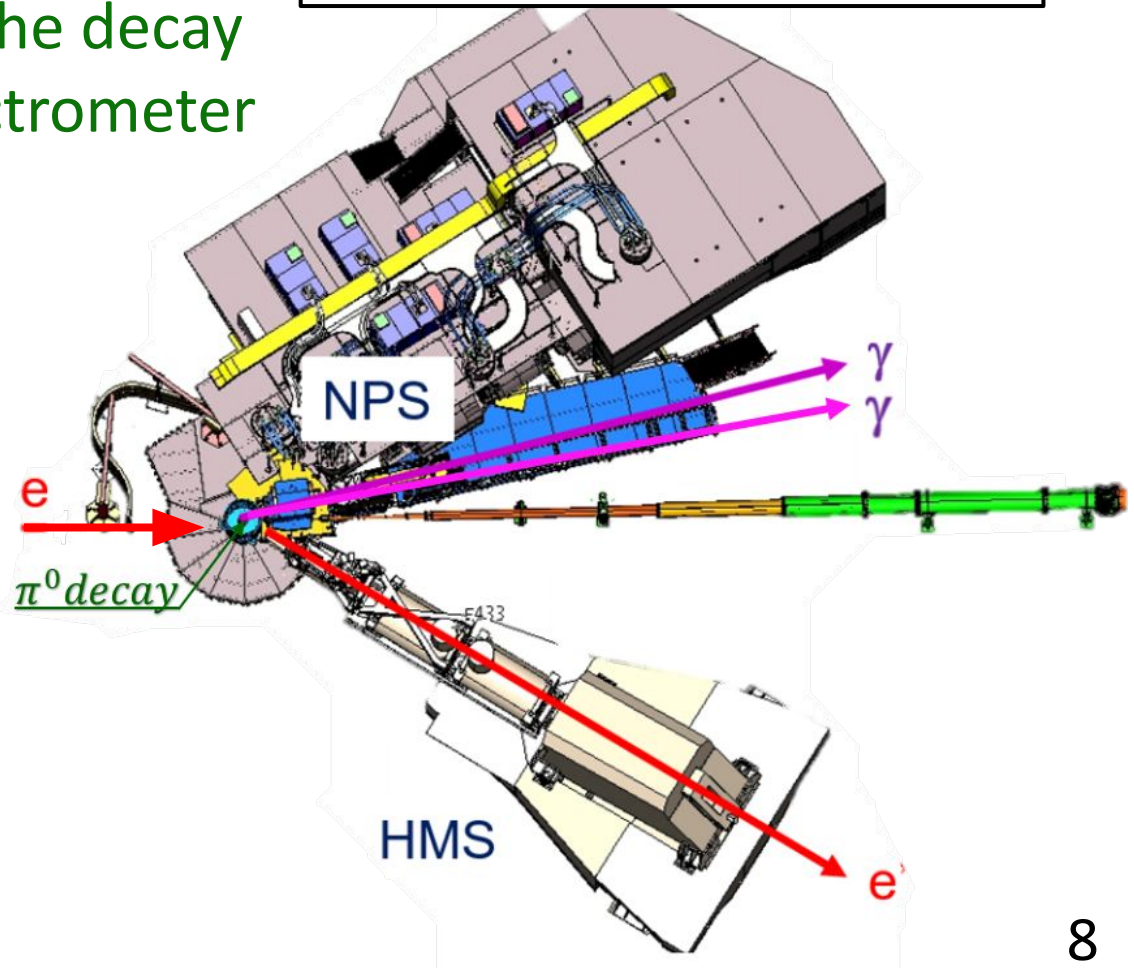
- Relative L/T contribution to π^0 cross section important in probing transversity
- Results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in π^0 production is non-zero up to Q^2=2 GeV^2
  - *12 GeV projections: confirm Q^2/t dependence*



Semi-inclusive and Exclusive π^0 with NPS in Hall C

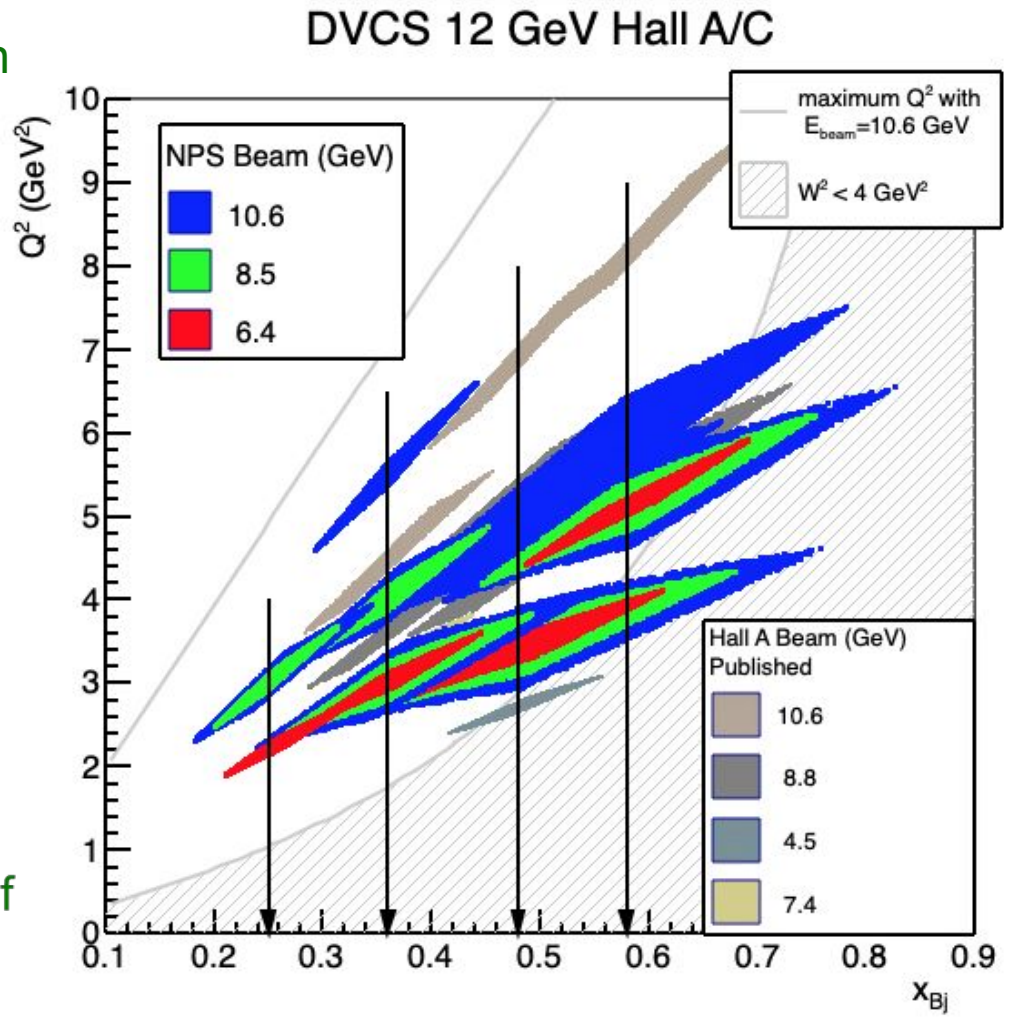
- These experiments were part of the NPS RG1-a and detected in coincidence scattered electrons in the existing HMS and photons from the decay of the π^0 using the Neutral Particle Spectrometer (NPS)
- The NPS detected photons corresponding to π^0 electroproduction close to the direction of $\vec{q}$, the exchanged virtual photon three-momentum transfer
  - Average lifetime of 8.5×10^{-17} seconds.
  - The HMS Spectrometer benefits from relatively small point-to-point uncertainties, which are crucial for meaningful L/T separations





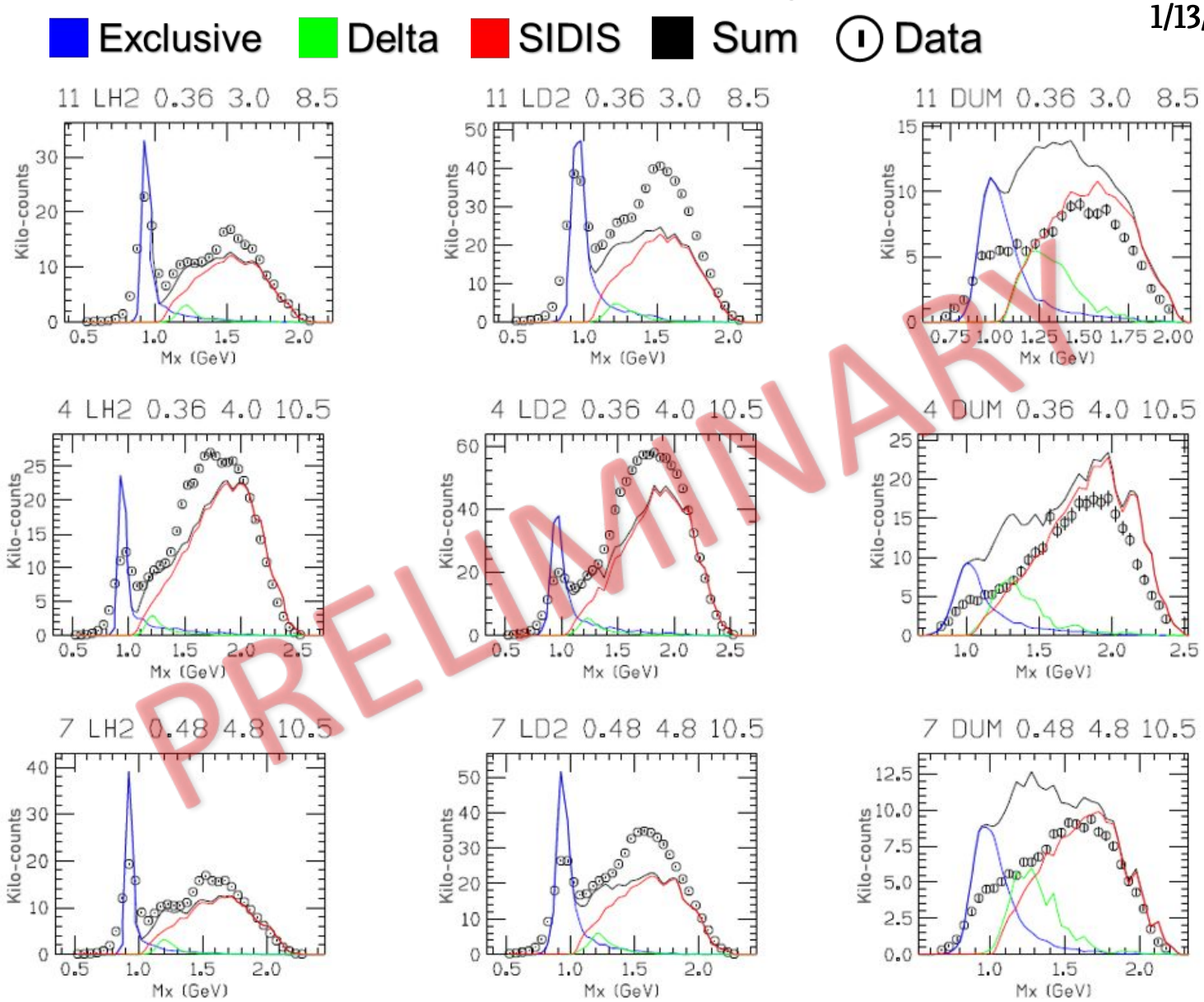
Analysis Game Plan

- ✅ The overall analysis for the NPS RG-1a is in progress with the Pass-1 having been run over the Holiday break.
- ✅ Initial calibrations of the HMS subdetectors and beamline components have been finalized.
  - HMS Optics Calibration
  - Beam Charge 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 π^0 analysis
- ❑ The π^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!



π^0 Missing Mass

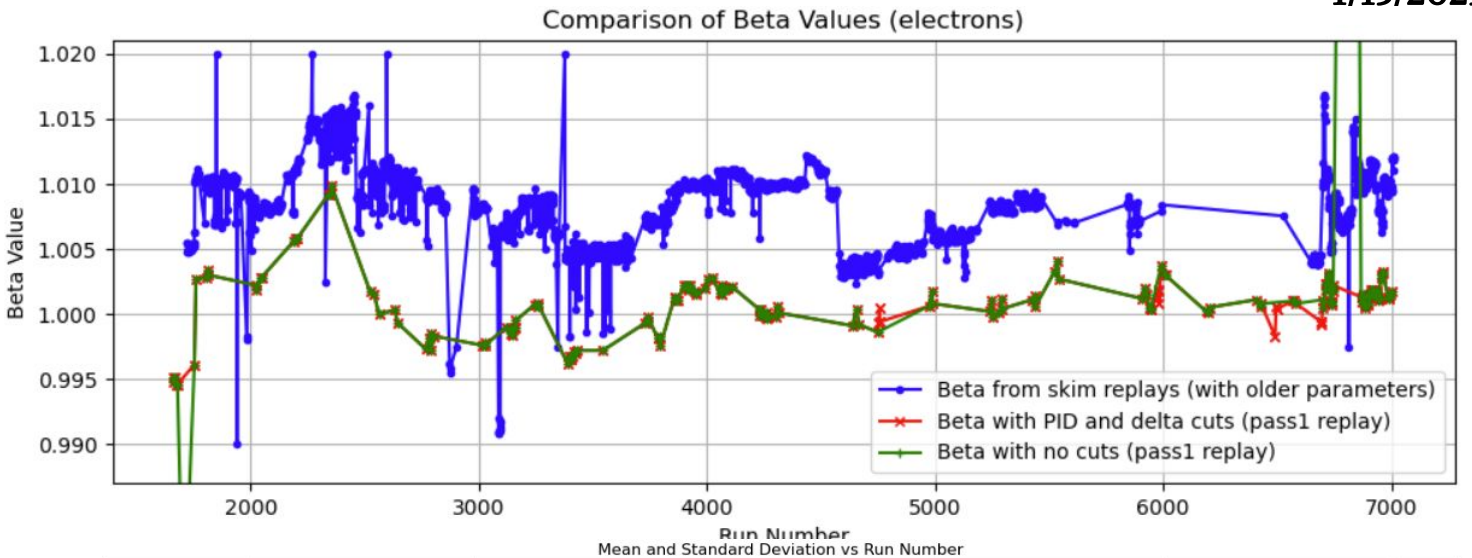
- Example of the π^0 missing mass statistics from different kinematics from the Pass-1 data analysis
  - Two cryogenic targets were used (LD_2 and LH_2) along with a dummy/ empty Al target for background subtractions
- The colored curves represent the SIMC predictions for exclusive, Delta ,and Sidis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

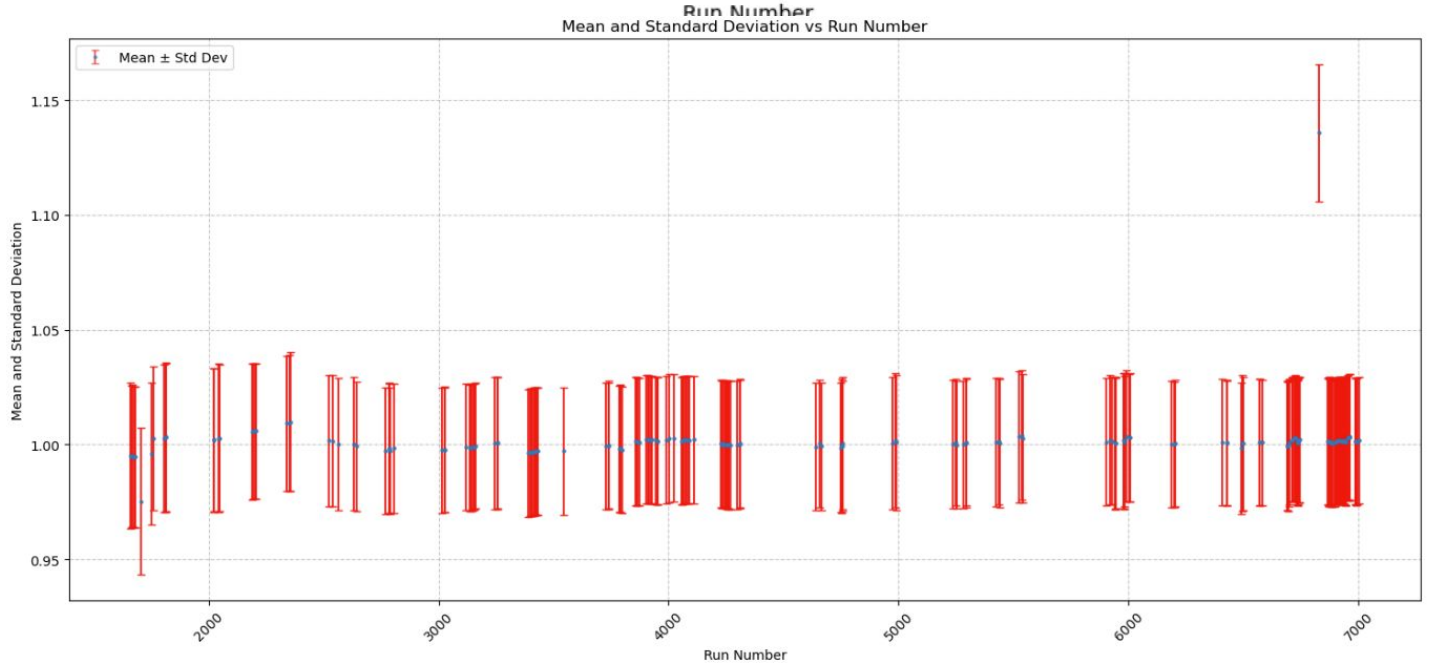


Credit: Peter B.

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

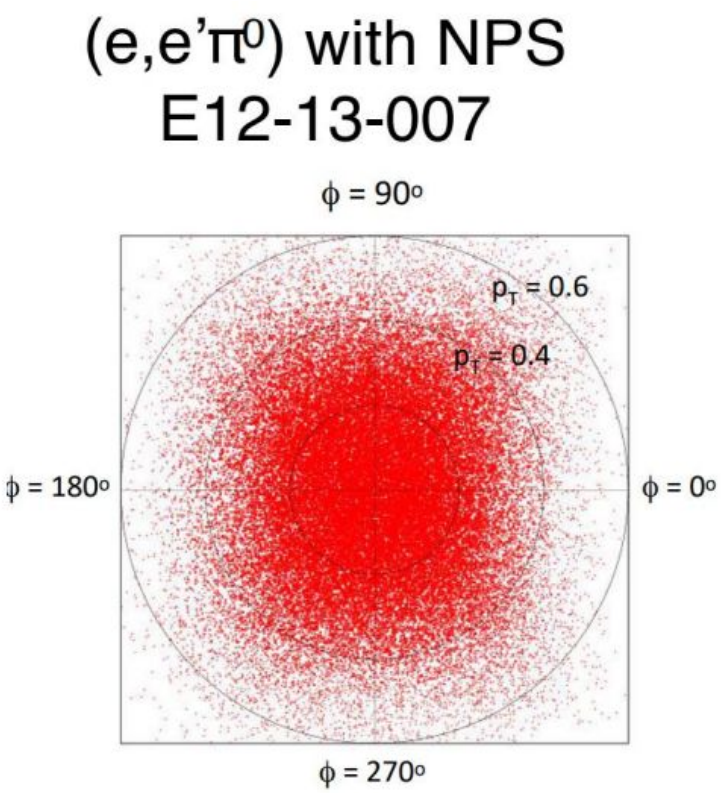




Credit: Avnish S.

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 π^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-π^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
  - 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 π^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 π^0 missing mass peak has been preliminarily identified from online running analysis and is being refined in Pass-1
- π^0 reconstruction ongoing

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