Measurements of the Cosϕ and Cos2ϕ Moments of the Unpolarized SIDIS π^{+} Cross-section at CLAS12

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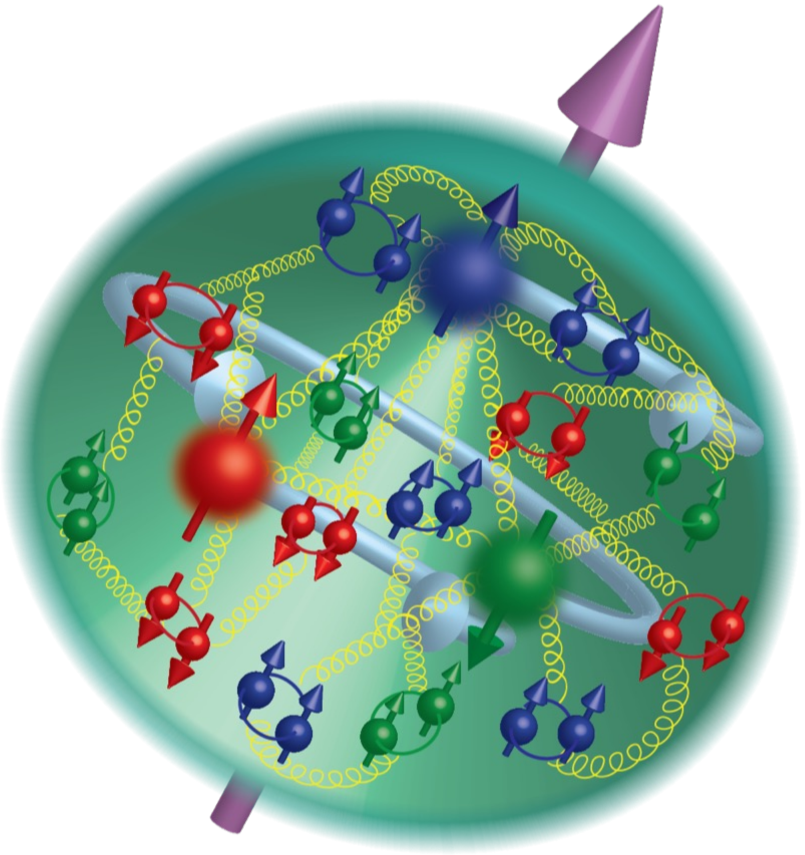
Linkedin

UCONN | UNIVERSITY OF CONNECTICUT Argonne NATIONAL LABORATORY U.S. DEPARTMENT OF ENERGY Office of Science Jefferson Lab clas

Motivation

- Semi-Inclusive Deep Inelastic Scattering: access to 3D structure of nucleons in momentum space
- Azimuthal modulations of unpolarized SIDIS cross-section for charged pion electroproduction can give access to the Cahn and Boer-Mulders effects
  - **Boer-Mulders Effect:** Sensitive to the correlation between the quark's transverse momentum and intrinsic transverse spin in an unpolarized nucleon
  - **Cahn Effect:** Sensitive to the transverse motion of quarks inside the nucleon
- A non-zero Boer-Mulders requires quark orbital angular momentum contributions to the proton spin

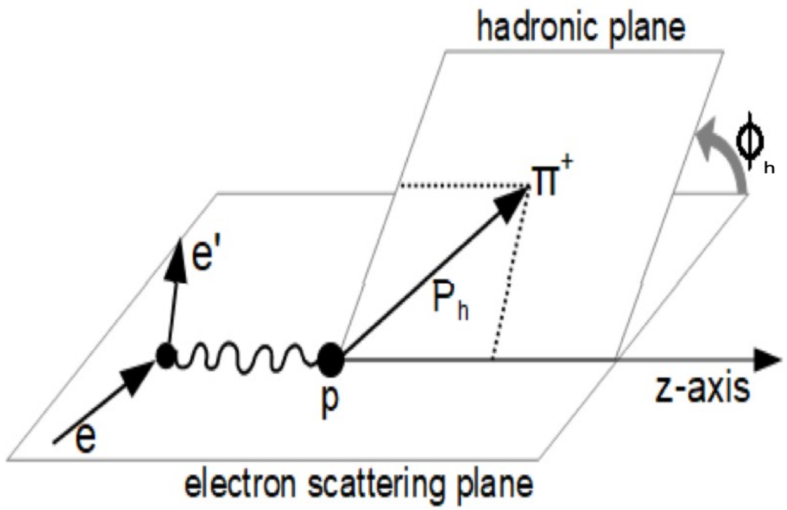


SIDIS Cross-Section and Boer-Mulders

Reaction Studied: ep→eπ⁺(X)

$$\frac{d^5\sigma}{dx\, dQ^2\, dz\, d\phi_h\, dP_{h\perp}^2} =$$

$$\underbrace{\frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)(F_{UU,T}+\epsilon F_{UU,L})}_{A_0}\left\{1+\underbrace{\frac{\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos\phi_h}}\cos\phi_h+\underbrace{\frac{\epsilon F_{UU}^{\cos 2\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\right\}$$



The Boer-Mulders and Cahn effects are present in the Structure Functions:

BOER-MULDERS EFFECT

leading twist

$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}h_1^\perp H_1^\perp + \dots\right]$$

CAHN EFFECT

Interaction dependent terms neglected

next to leading twist

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M_h}x\, h\, H_1^\perp - \frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M}f_1 D_1 + \dots\right]$$

Event Selection

Particle ID (PID):

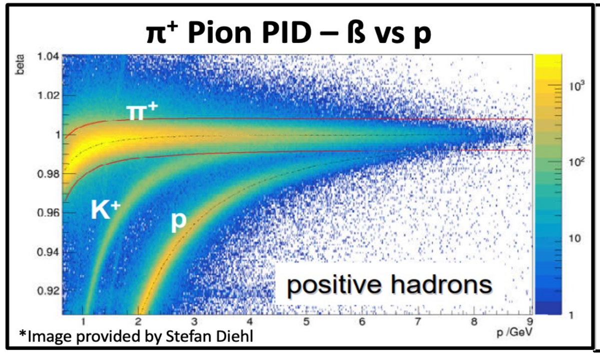
- **Electron ID:** Based on Electromagnetic Calorimeter (PCAL) and Cherenkov Counters (HTCC)
- **Hadron (π^+) ID:** Based on Time-Of-Flight Counters (TOF) and the correlation of velocity (ß) and momentum

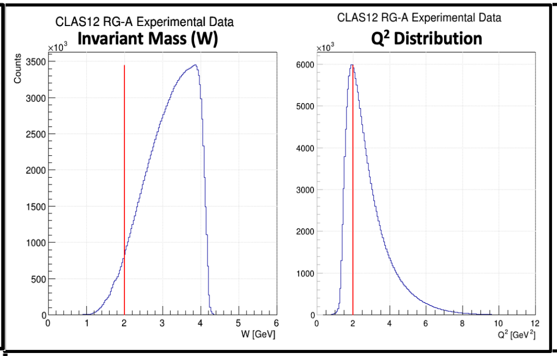
Using Data from RG-A Fall 2018 (Pass 2)

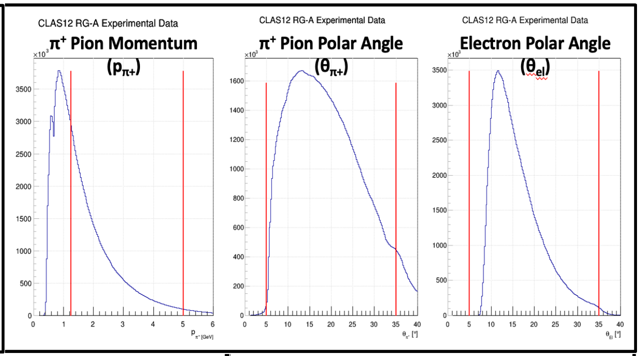
10.6 GeV Polarized Beam
Unpolarized Liquid Hydrogen Target
Inbending Forward Tracking Only

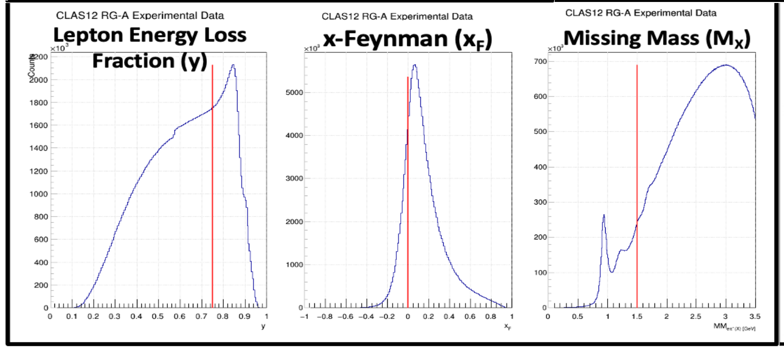
Analysis Cuts:

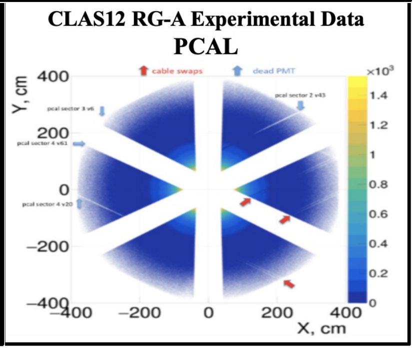
- **SIDIS Cuts:**
  - W > 2 GeV
  - $Q^2 > 2$ GeV^2
- **Other Analysis Cuts:**
  - $p_{\pi+}$ Cut: 1.25 GeV < $p_{\pi+}$ < 5 GeV
  - θ-angle Cut: 5° < $\theta_{particle}$ < 35°
  - y < 0.75 (minimize other background processes)
  - $x_F > 0$ (minimize contributions from target fragmentations)
  - Missing Mass Cut: $M_x > 1.5$ GeV (limit on exclusive events)
  - Fiducial Cuts (e.g., accounts for bad channels present in data)











Analysis Procedure

Experimental extraction of cross-section

$$\frac{d^5\sigma}{dQ^2 dy\, dP_T dz\, d\phi_h} = \underbrace{\frac{1}{N_0\left(N_A \cdot \rho \cdot \frac{t}{A_w}\right) \cdot \Gamma_v \cdot BC \cdot \Delta Q^2 \Delta y\, \Delta P_T \Delta z\, \Delta\phi_h}}_{\boxed{\text{Normalization factors that only impact } A_0}} \cdot \underbrace{\frac{N}{RC \cdot \eta}}_{\boxed{\textbf{Needed to measure } A_{UU}^{\cos\phi_h} \textbf{ and } A_{UU}^{\cos 2\phi_h}}} \Longrightarrow A_0(1 + A_{UU}^{\cos\phi_h} \cos\phi_h + A_{UU}^{\cos 2\phi_h} \cos 2\phi_h)$$

- η = Acceptance Correction →
- RC = Radiative Correction →
- N = Bin Yields

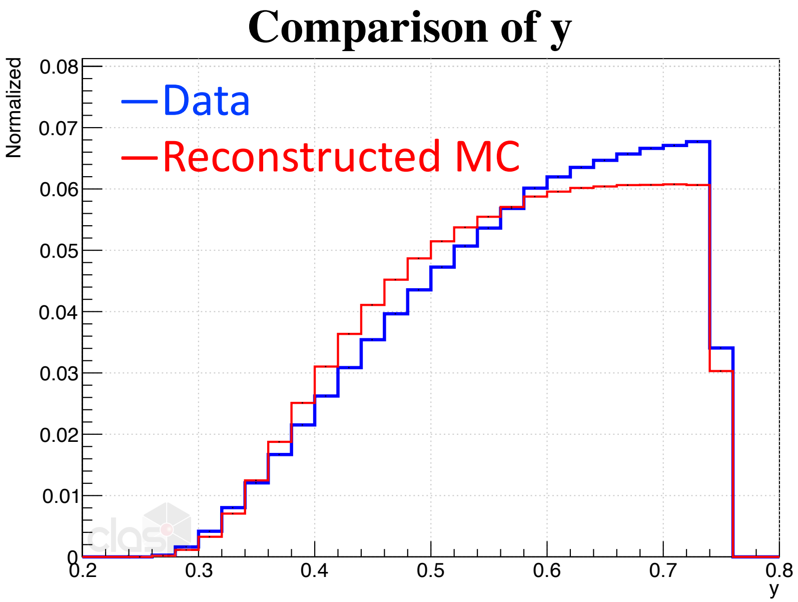
Require Monte Carlo (MC) Simulations

Acceptance corrections uses LEPTO (6.5) event generator

Radiative corrections uses "SIDIS-RC EvGen" — Event Generator*

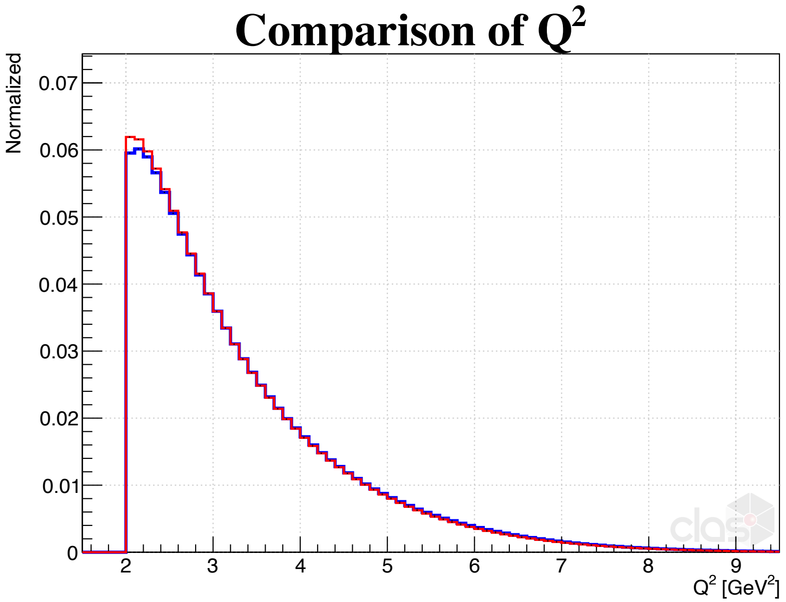
*See: arXiv:2210.03785v3 [hep-ph] 7 Mar 2023

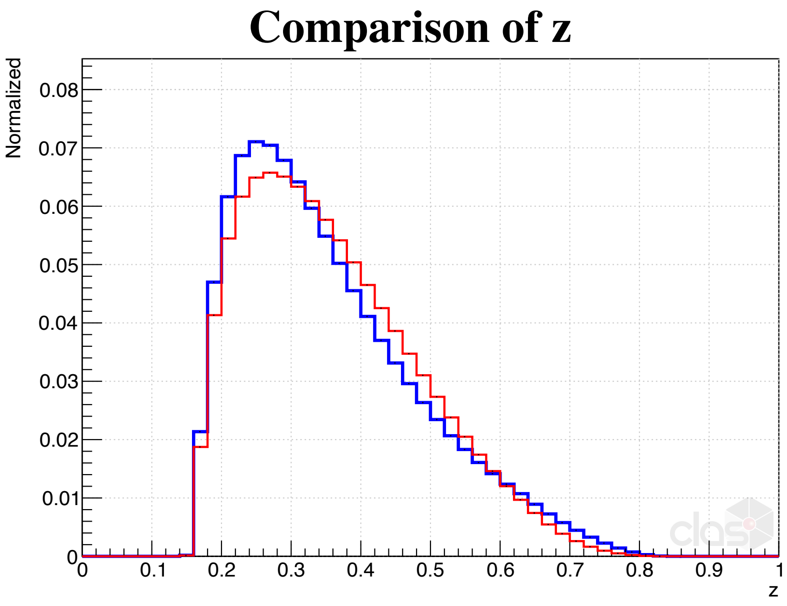
Data and Monte Carlo Comparison

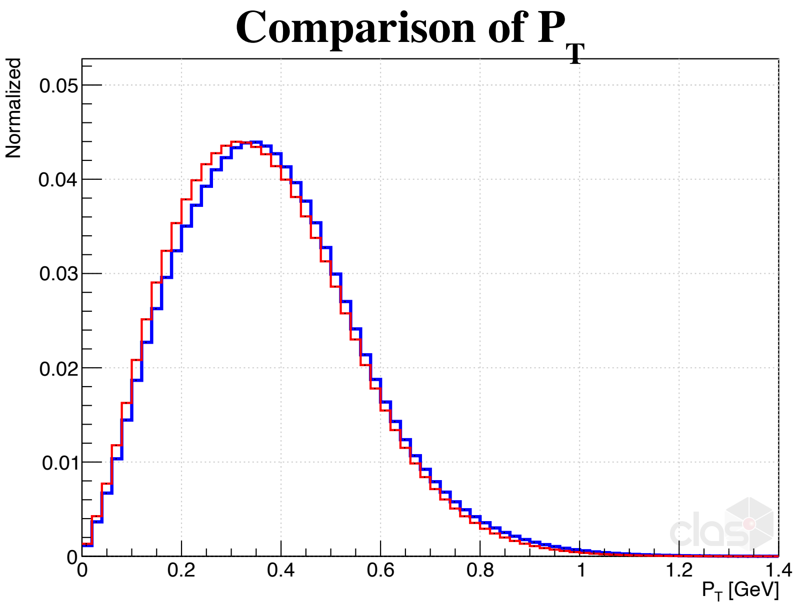


Reconstructed MC SIDIS π^+ Events (No radiative effects)

- These distributions have reasonable agreement
- Mismatch in high y is likely caused by the lack of radiative effects

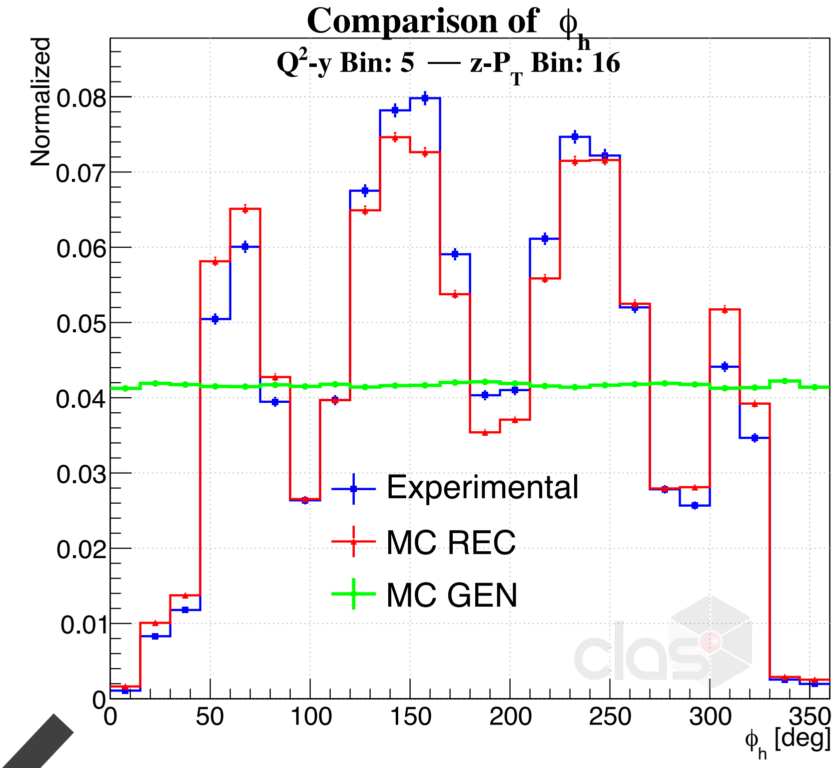


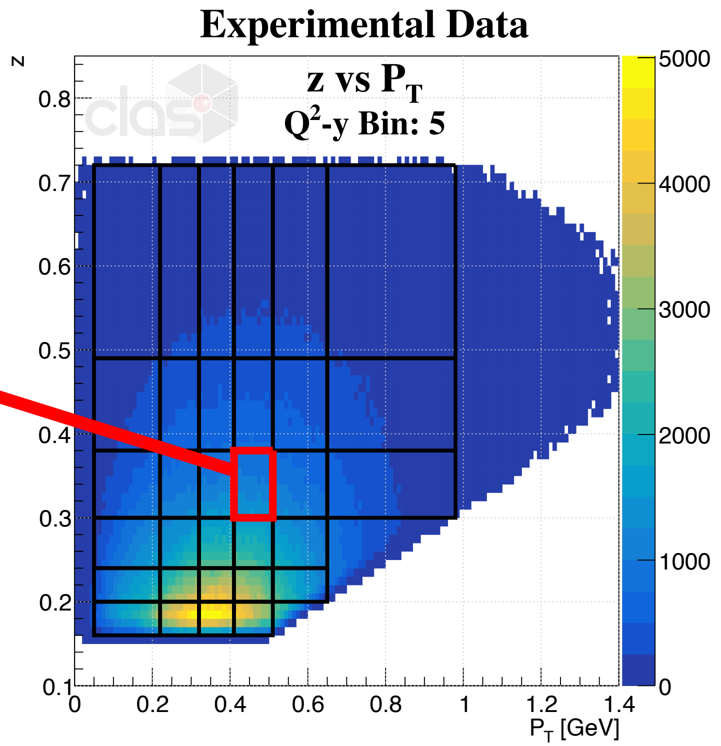


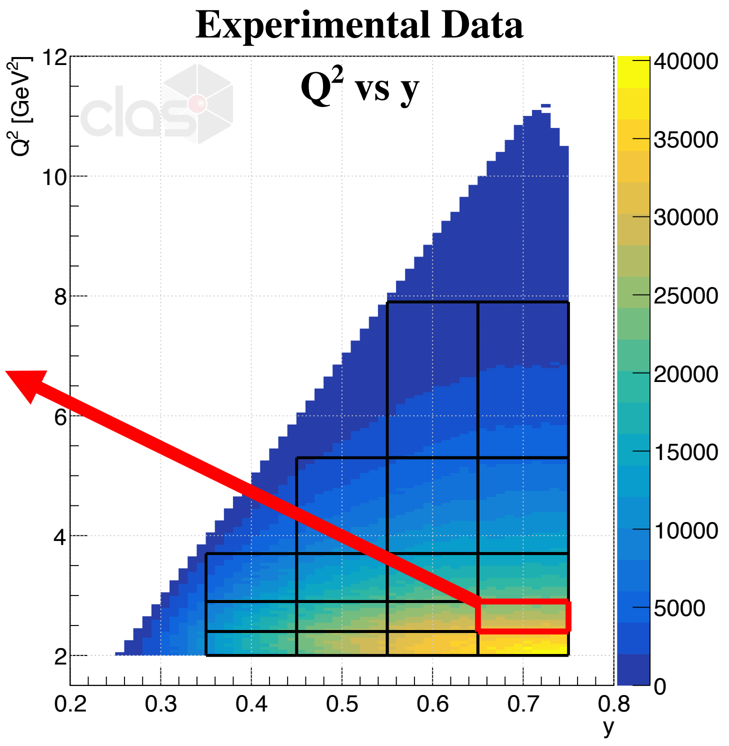


Multidimensional Analysis Procedures

17 Q^2-y Bins Total – 22-34 z-P_T Bins (per Q^2-y bin) — Total: 486 Bins (with 24 ϕ_h bins each)







Apply Multidimensional Acceptance and Radiative Corrections

Fit with

$$A(1 + B\cos(\phi_h) + C\cos(2\phi_h))$$

Where the parameters B, C give the cosine moments of the cross section

$$A_{UU}^{\cos\varphi_h} = B$$
$$A_{UU}^{\cos 2\varphi_h} = C$$

The three ϕ_h plots are normalized to their own total number of events

Acceptance Corrections and Bin Migration Study

- **<u>Acceptance Matrix:</u>** $A_{(i,\ j)}$ describes both Acceptance (including geometric acceptance and detector efficiency) and Bin Migration

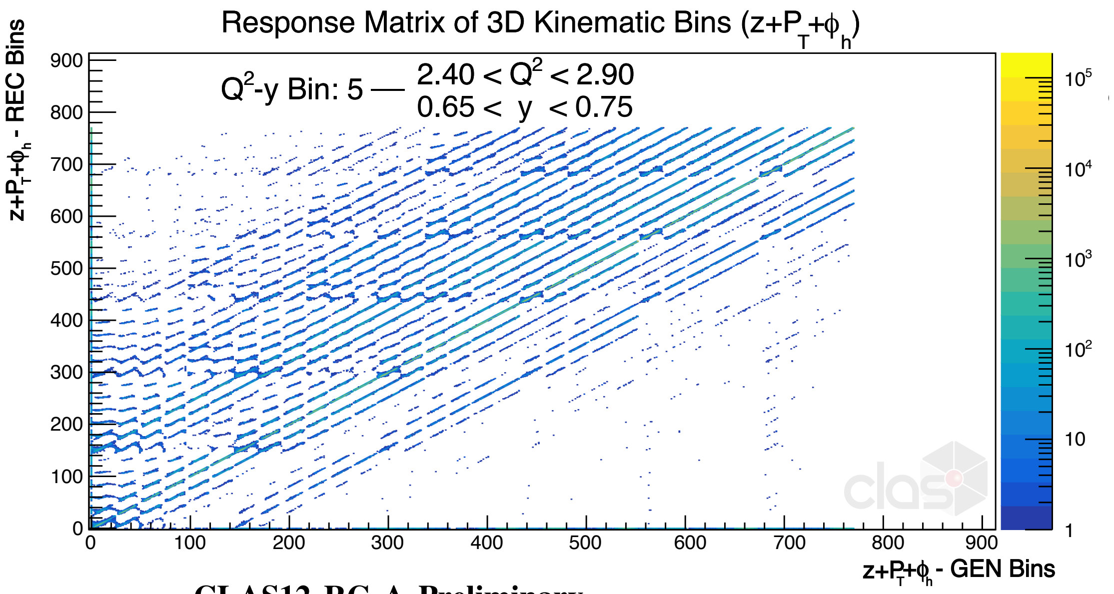
- $$A_{(i,\,j)} = \frac{\text{Number of Events Generated in bin } j \text{ but Reconstructed in bin } i}{\text{Total Number of Events Generated in the } j\text{th bin}}$$

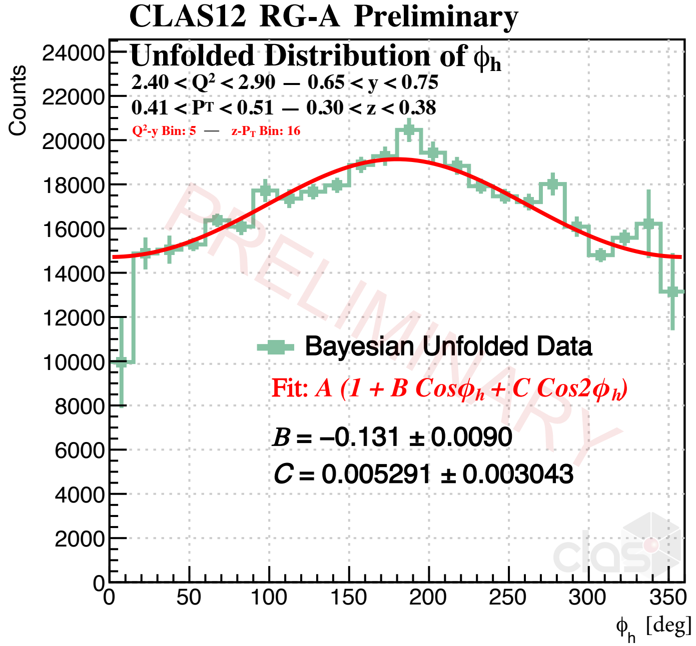
- Acceptance Unfolding:

$$Y_i = A_{(i,\,j)} X_j + \beta_i \Leftrightarrow X_j = A^{-1}_{(i,\,j)} (Y_i - \beta_i)$$

where:

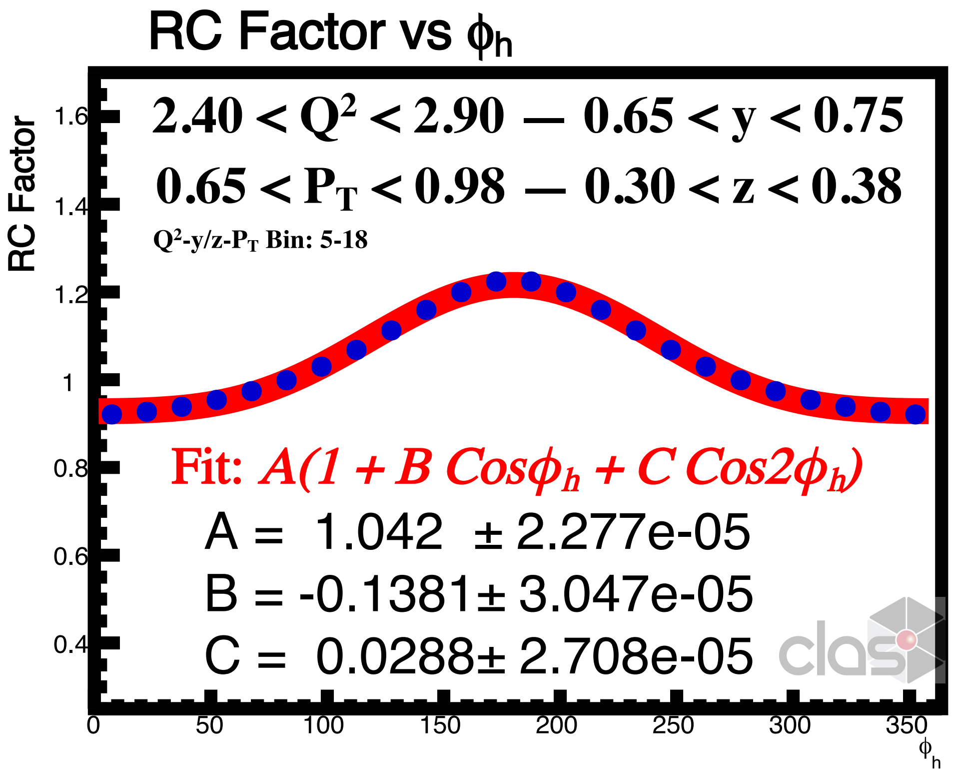
  - Y_i = Number of events experimentally measured in the *i*-th bin
  - X_j = Number of acceptance-corrected events in the *j*-th bin
  - β_i = Number of events from outside the signal region measured in the *i*-th bin





Importance of Radiative Corrections to the Cosine Moments

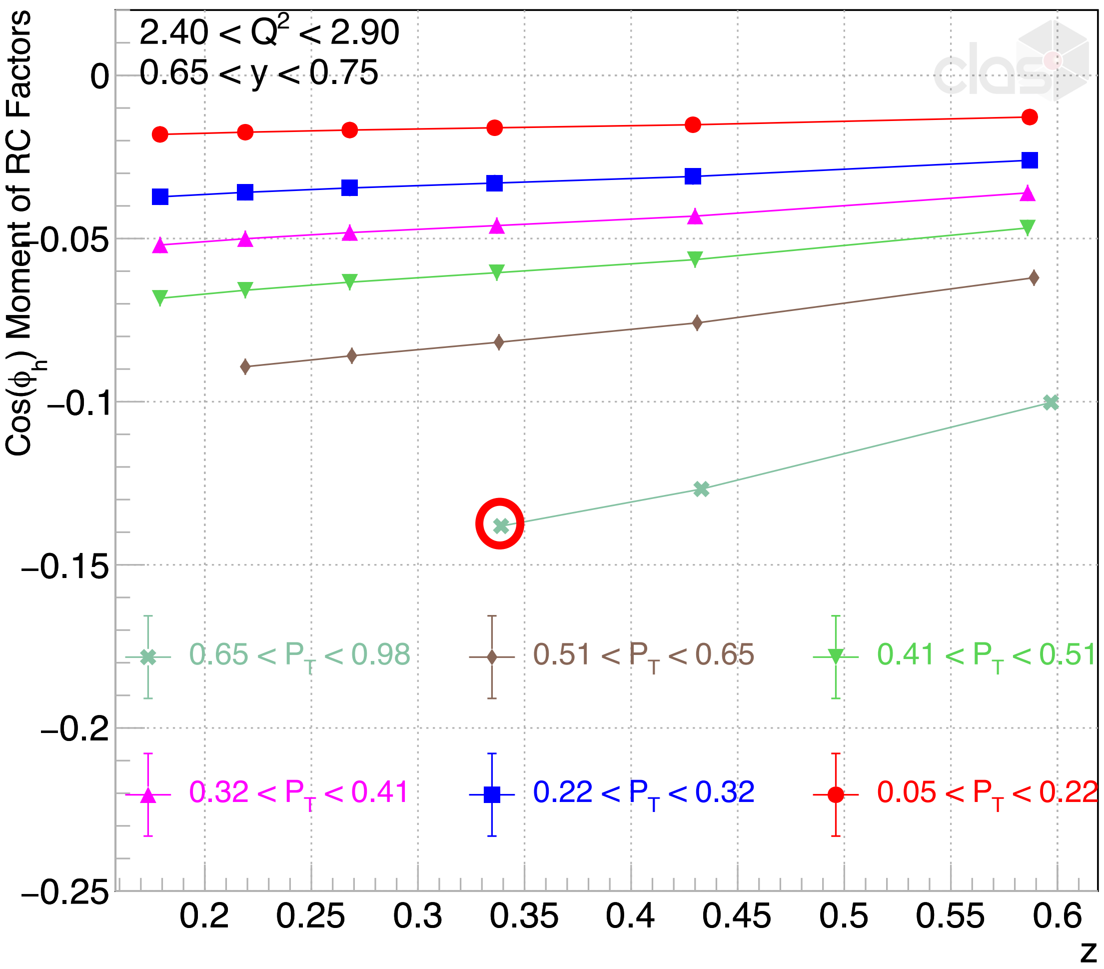
- **RC Factor** $= \frac{\sigma_{RAD}}{\sigma_{BORN}}$ **(From EvGen)**
- RC Factors are calculated for each Q^2-y-z-P_T-ϕ_h bin (using bin centers)
- Will be applied as per bin weights to the differential cross section level



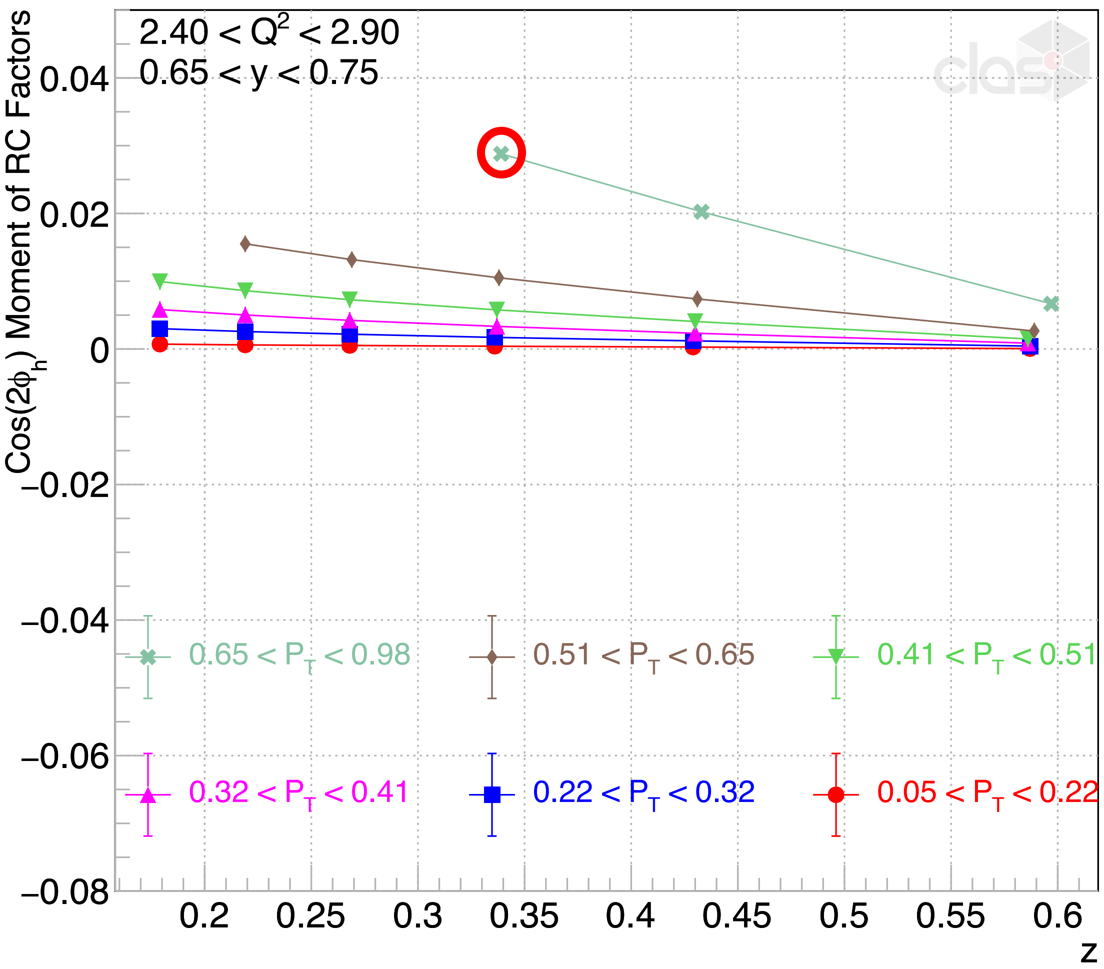
- RC Factors show a cosine-like dependence on ϕ_h
  - Fitting with the same formula for moment extraction can show the impact of these corrections on the final moments

Importance of Radiative Corrections to the Cosine Moments

$Cos(\phi_h)$ Moments of the RC Factors

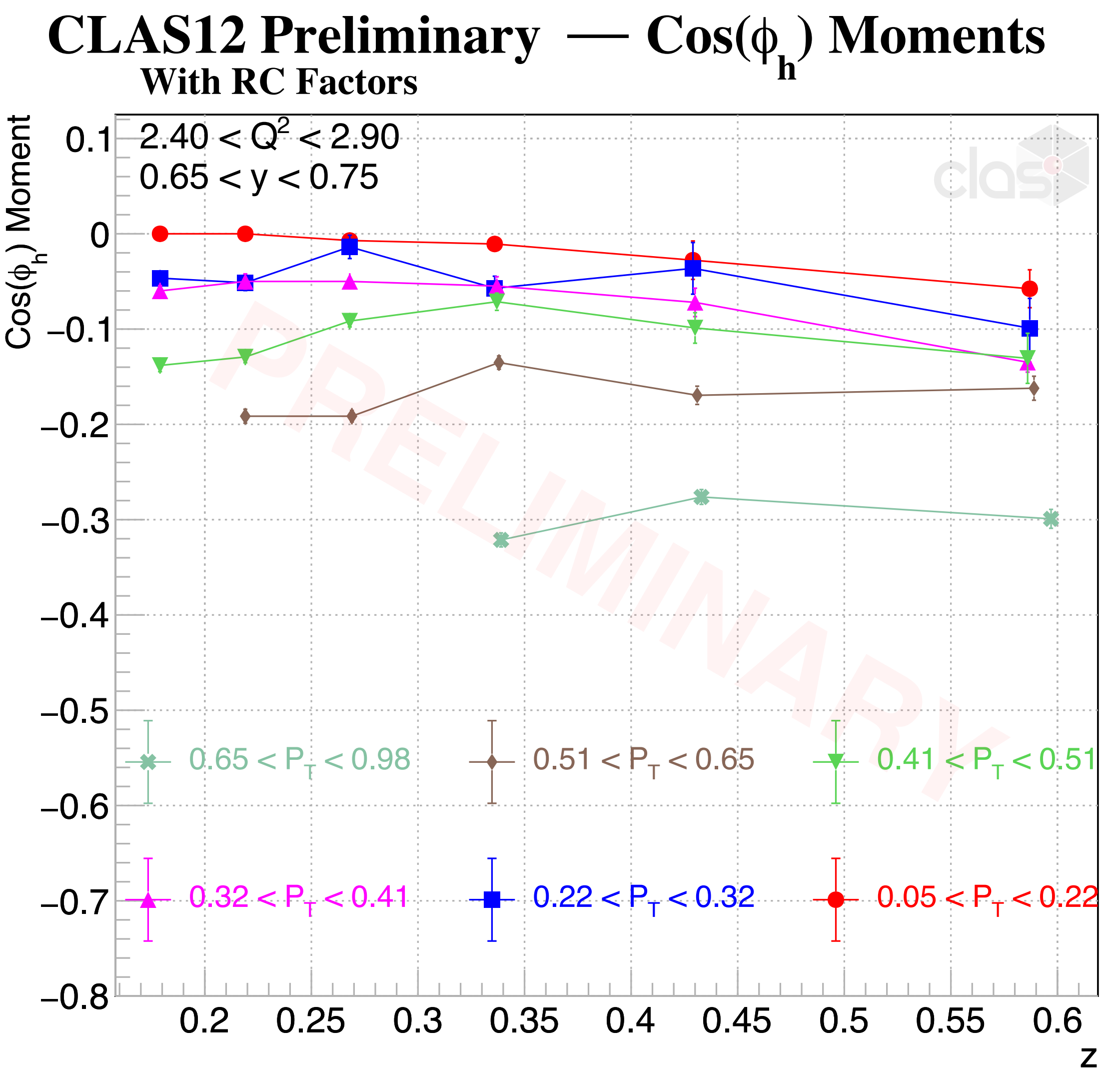


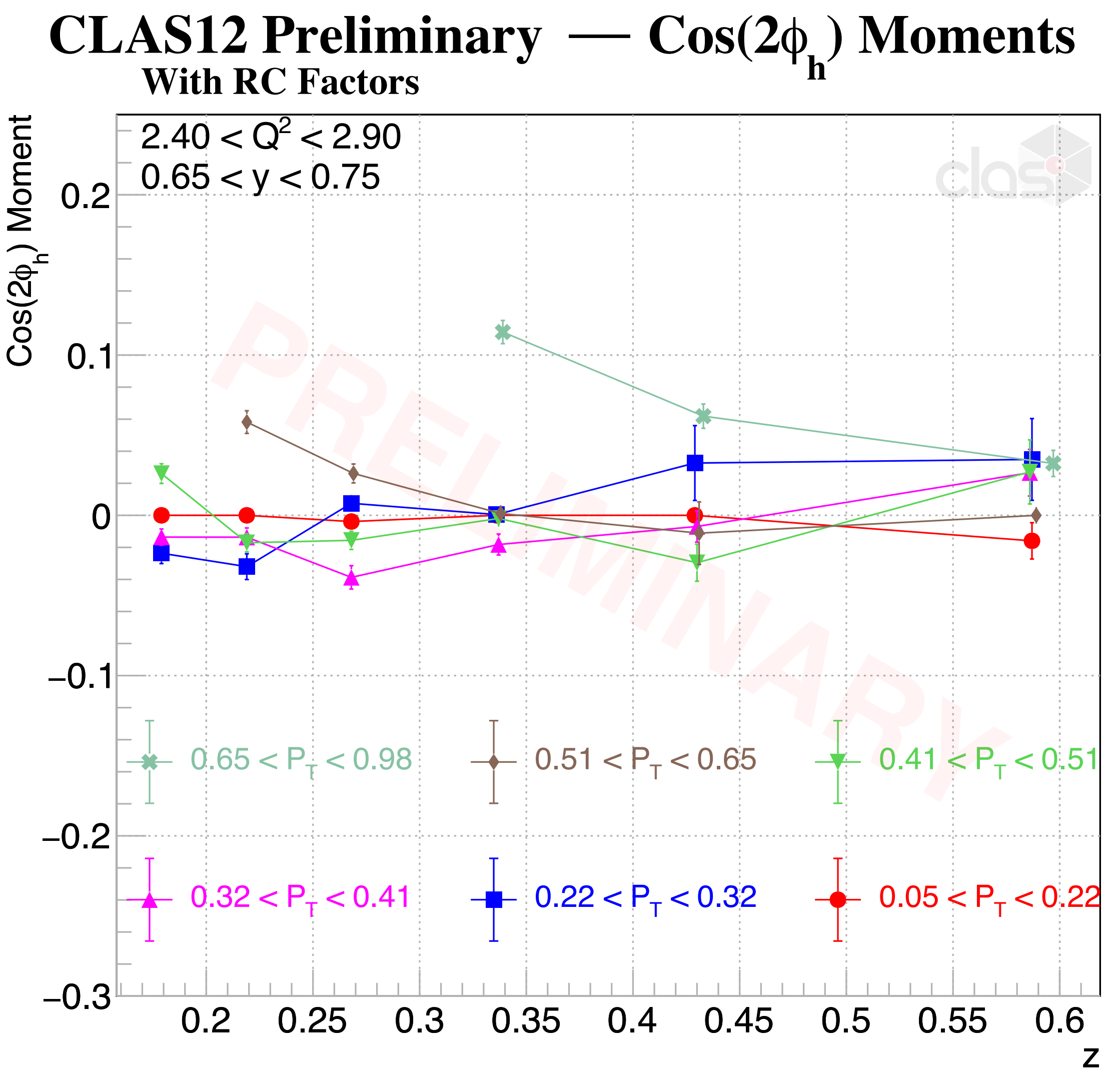
$Cos(2\phi_h)$ Moments of the RC Factors



*Circled point is from the example on the last slide

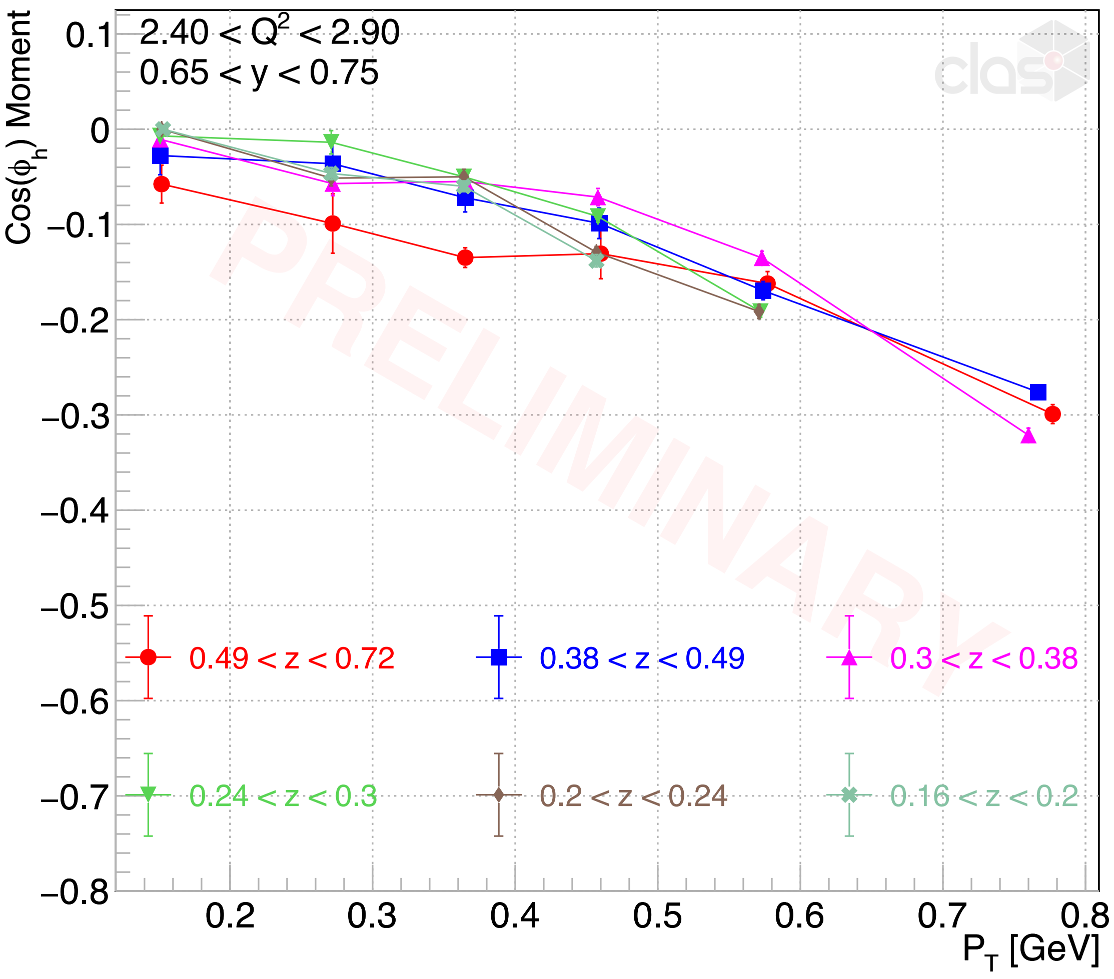
Cosine Moments as Functions of z



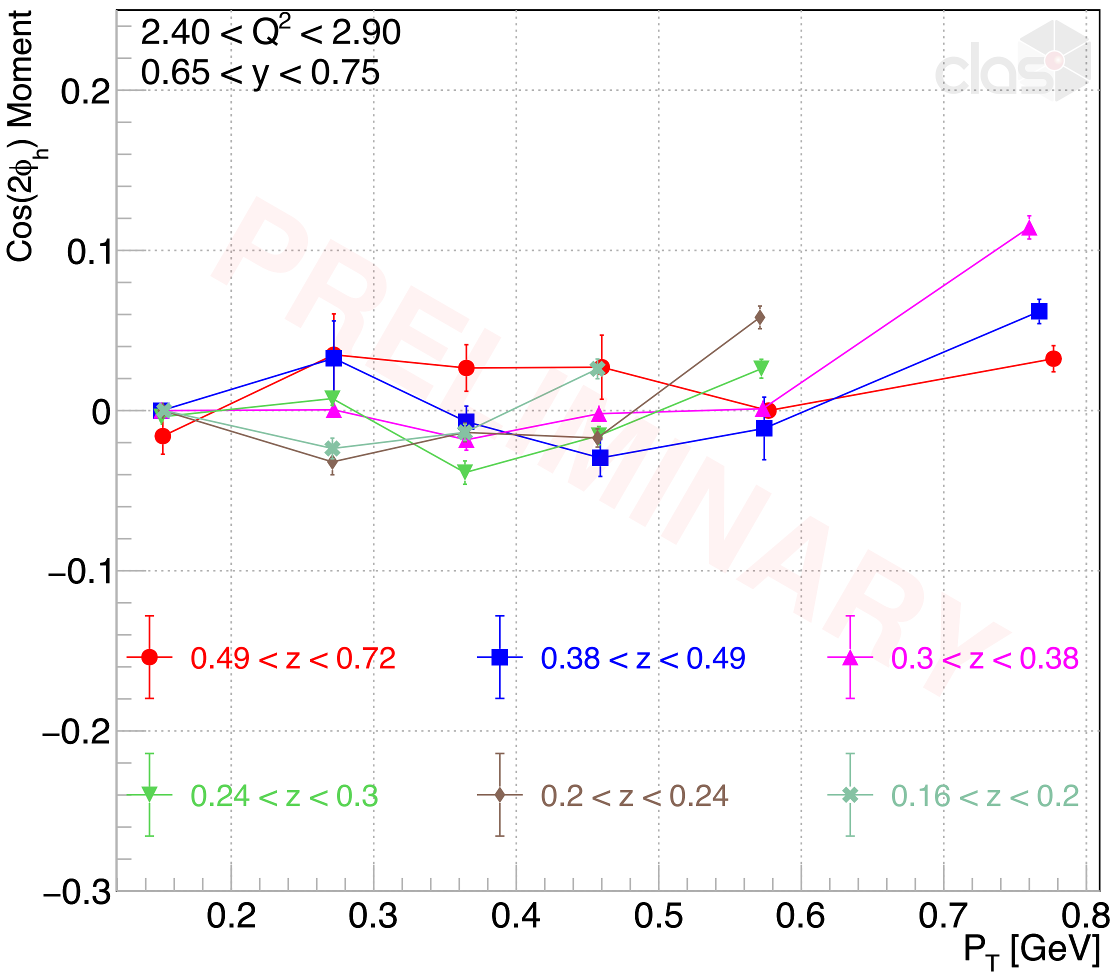


Cosine Moments as Functions of P_T

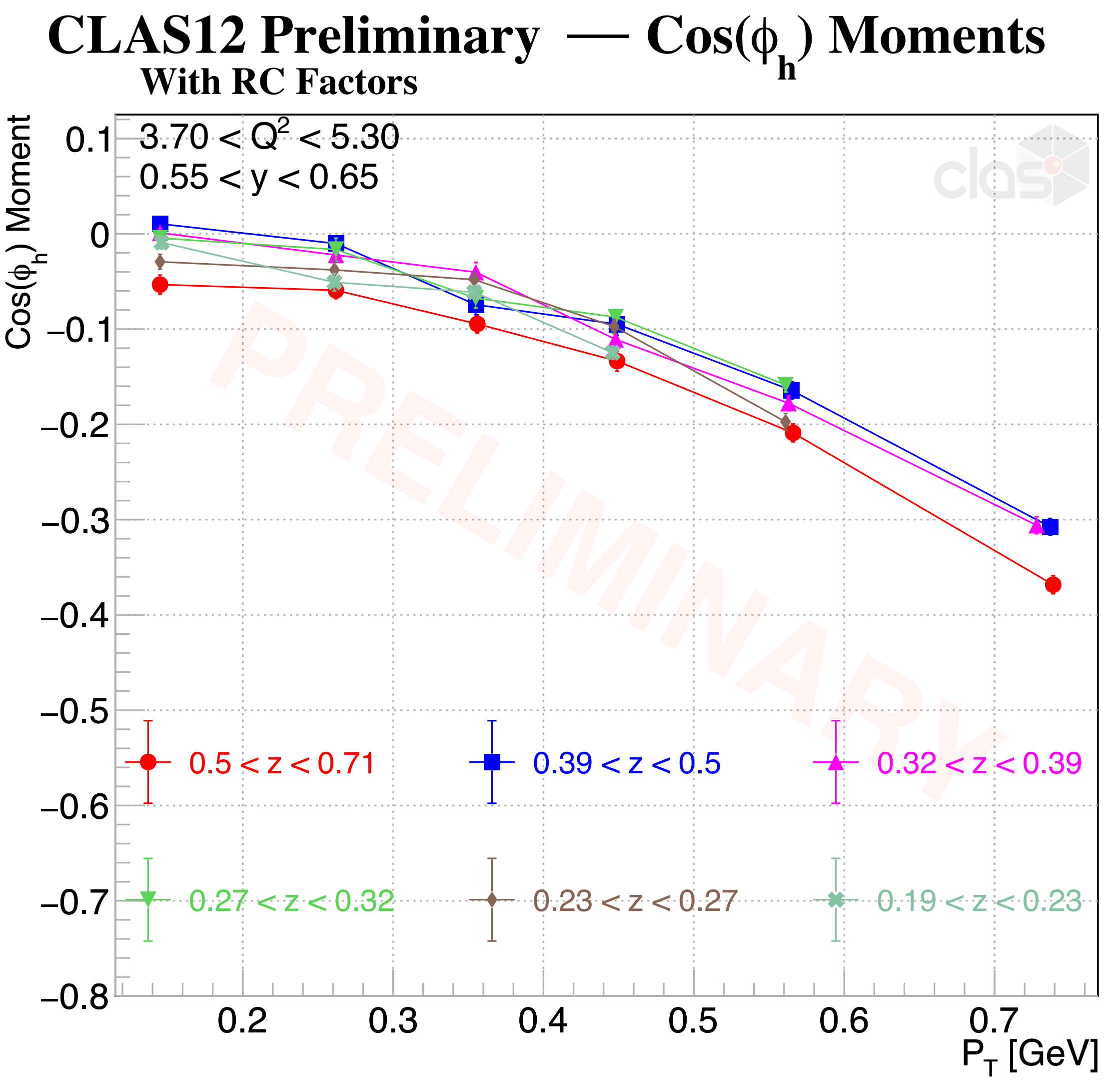
CLAS12 Preliminary — Cos(ϕ_h) Moments
With RC Factors

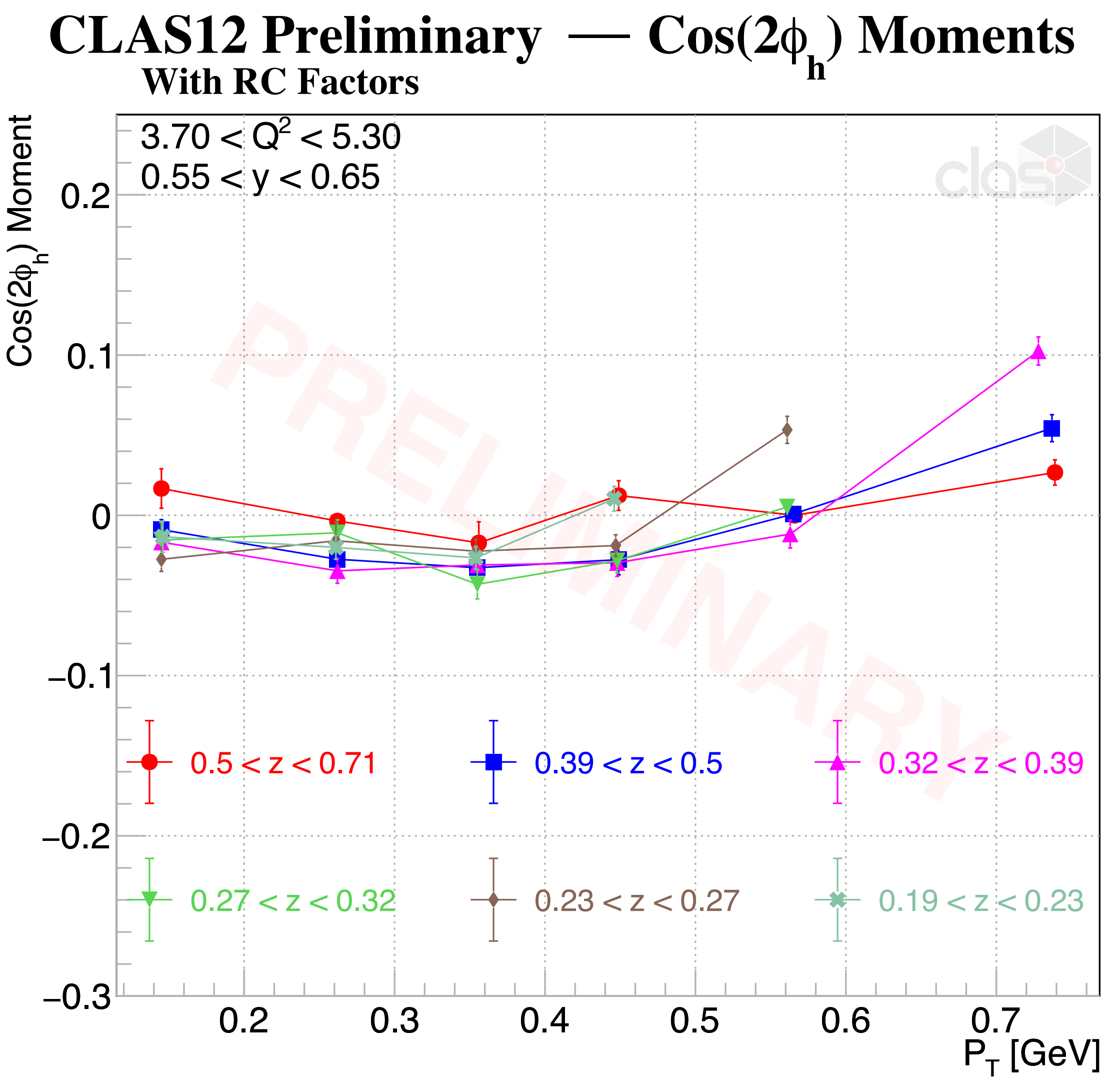


CLAS12 Preliminary — Cos($2\phi_h$) Moments
With RC Factors



Cosine Moments as Functions of P_T — Secondary Example





Summary & Outlook

- Preliminary extraction of the Cosine Moments in 486 Q^2-y-z-P_T bins
  - Unfolded up to 3 dimensions
  - Introduced Radiative Corrections
- Measured Cos(ϕ) Moments with little z dependence and larger P_T dependence
  - Magnitude grows with P_T
- Measured Cos(2ϕ) Moments around 0 except for higher P_T
  - Magnitude decreases with z when not already suppressed for low P_T

➢ **Work in progress:**

- Extend to full 5D Unfolding
- Unfold with radiated Monte Carlo
- Assign systematic uncertainties

Thank you

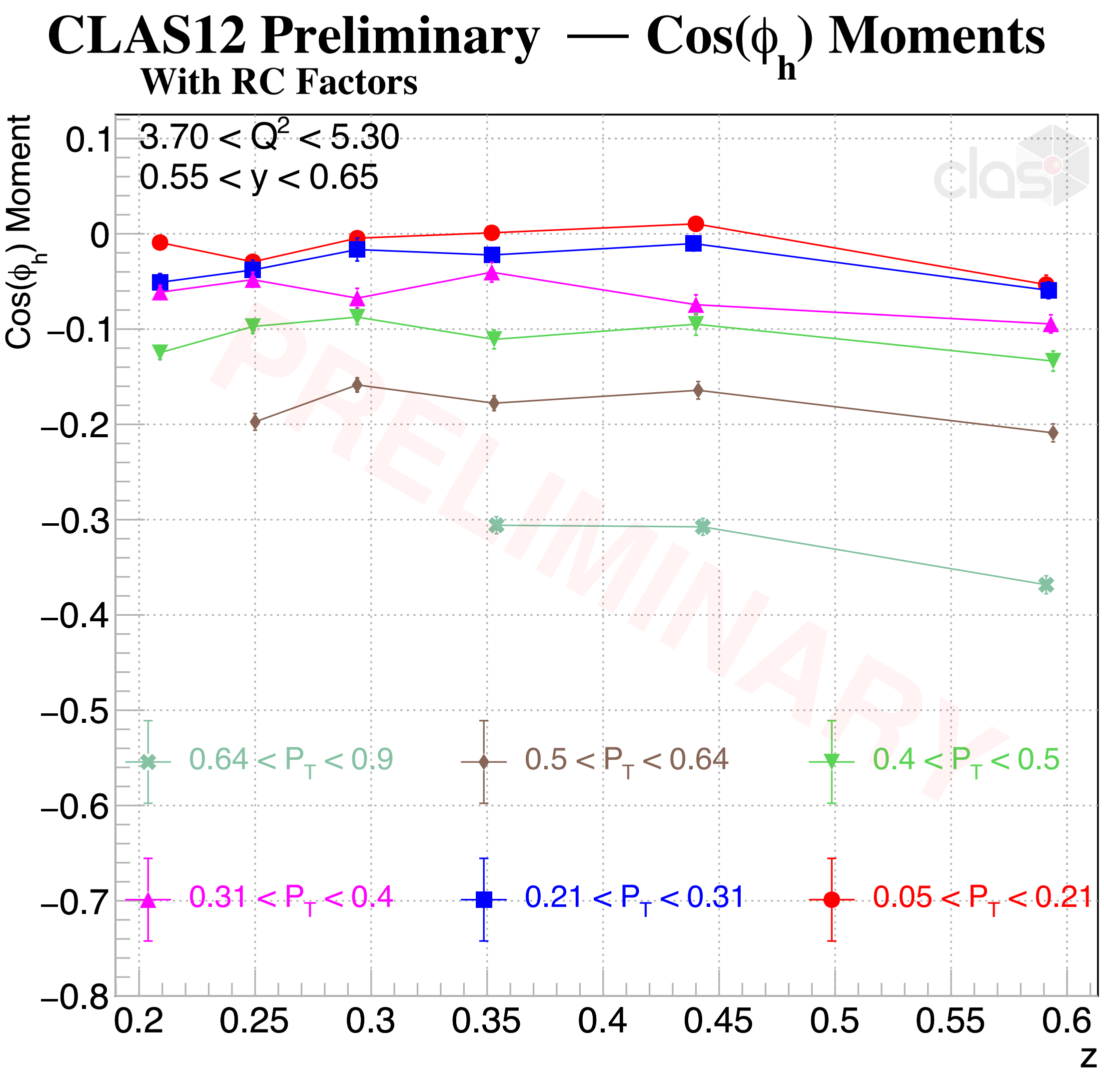
Questions?

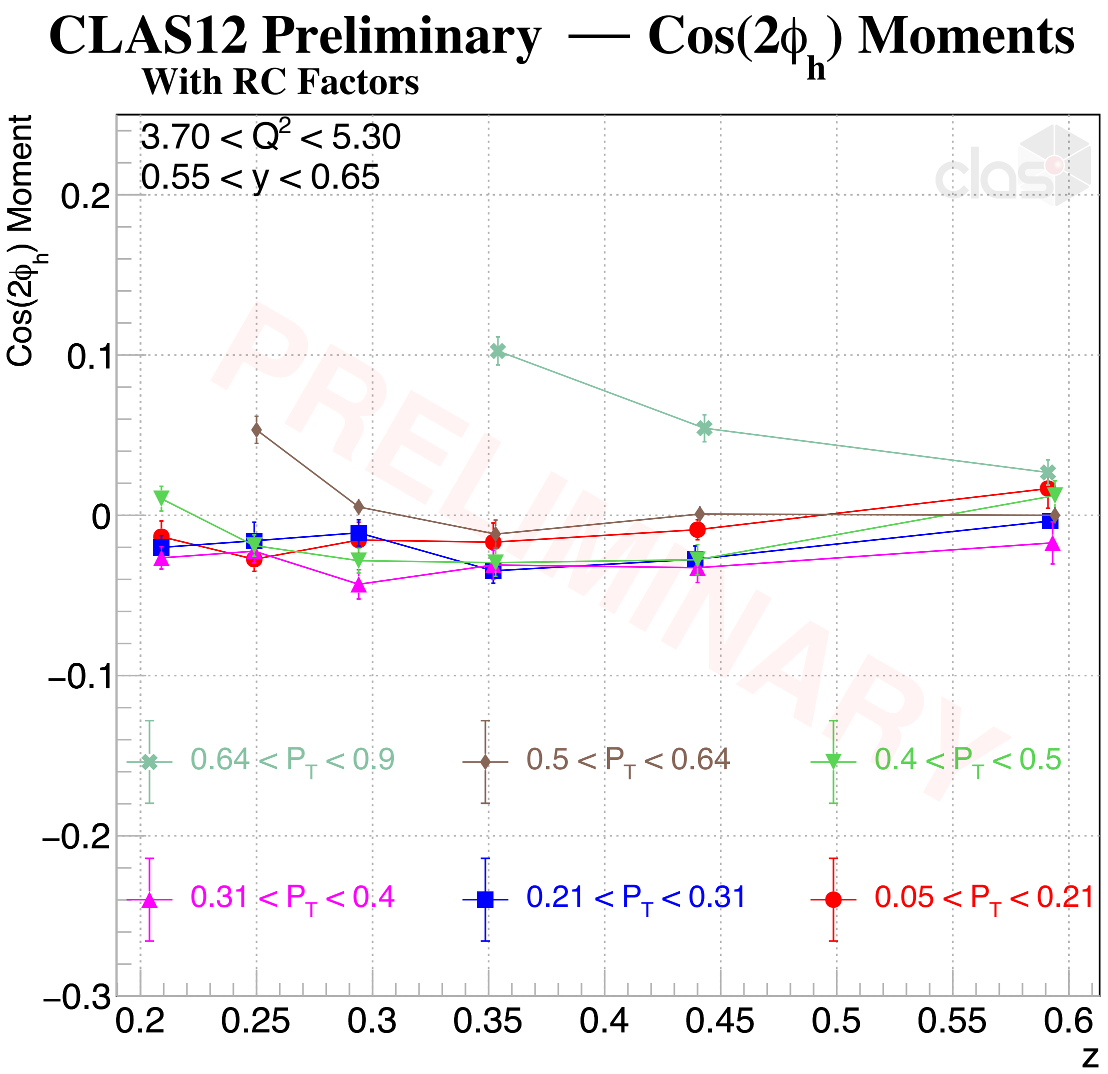
Acknowledgments and Thanks

- Contributions made by other members of the CLAS Collaboration and researchers at Argonne National Lab
- This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract number DE-AC02-06CH11357

Backup Slides

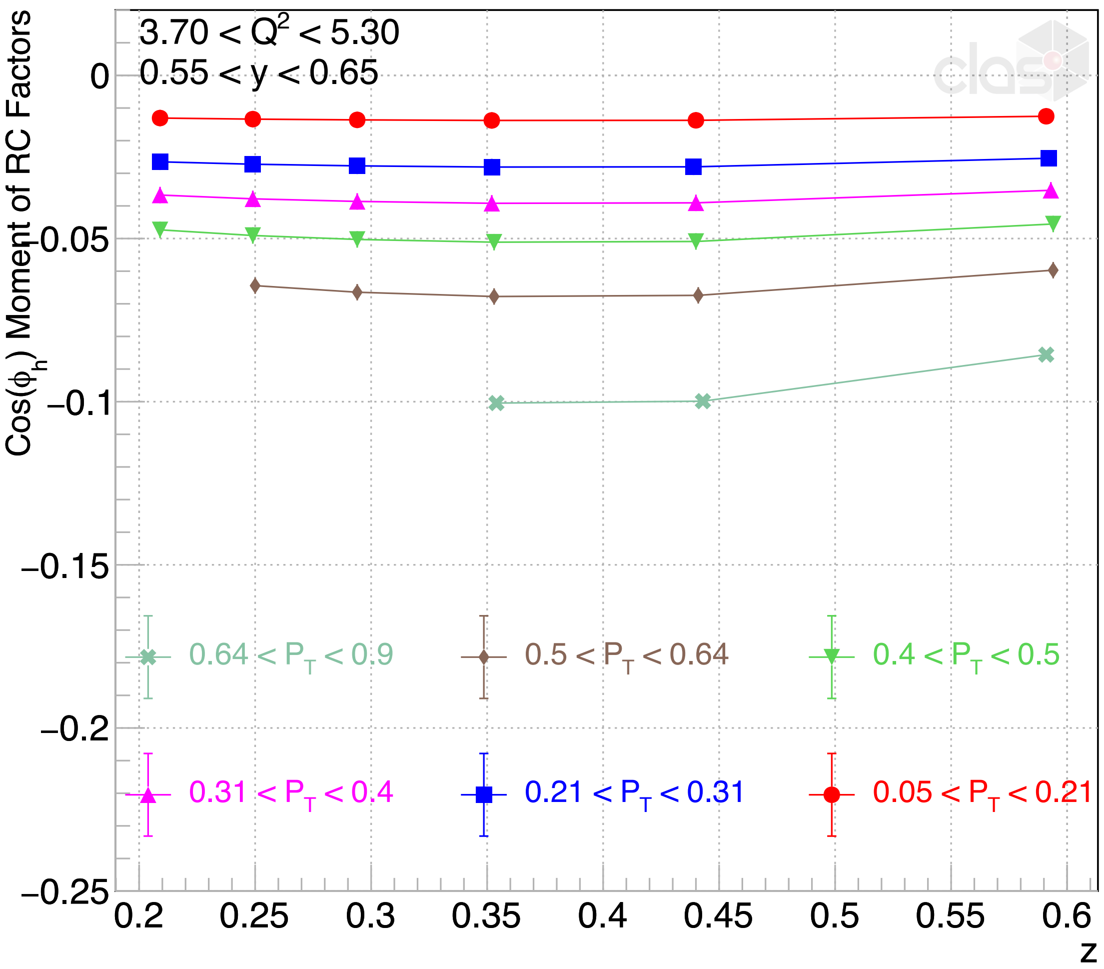
Cosine Moments as Functions of z — Secondary Example



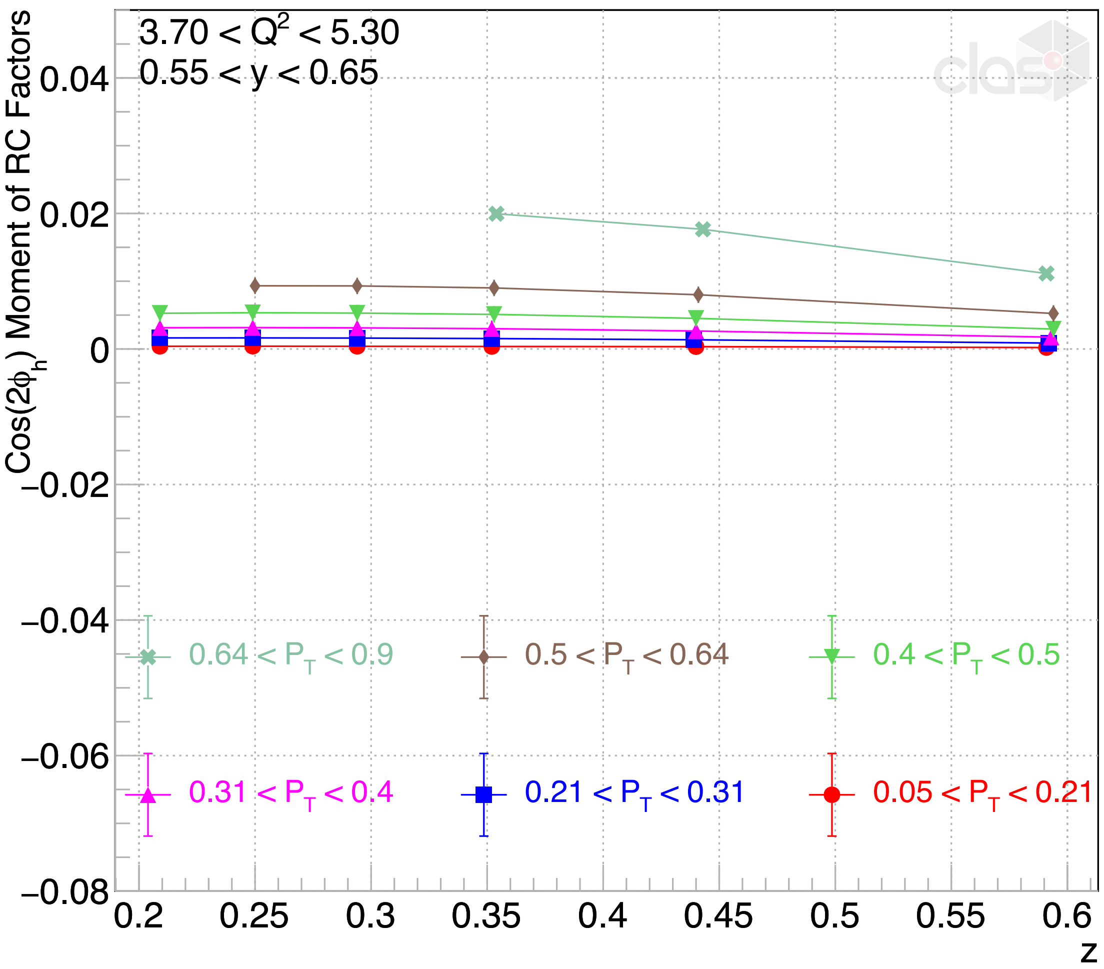


Importance of Radiative Corrections to the Cosine Moments — Secondary Example

Cos(ϕ_h) Moments of the RC Factors



Cos($2\phi_h$) Moments of the RC Factors



SIDIS-RC EvGen Overview

Is an RC Event Generator designed for SIDIS events (ep→e'π⁺X)

- Created by Duane Byer, et al. (Duke University) (see: https://github.com/duanebyer/sidis/tree/8f9881ae958027c01daf3aa588caffcc47f6c11a)

➢ Can generate radiated events and correction factors to go from the radiated cross-section to the Born level

- Generates the scattered lepton, hadron, and radiated photon (for radiated events)
- Just generates the selected SIDIS ($\pi^{+/-}$) process (No exclusive reactions or additional particles)
- Uses a six-fold differential cross-section for the non-radiated events and a nine-fold one for the radiated events
  - The extra 3 degrees of freedom in the radiated events are the photon kinematics
  - Includes ϕ_h modulations (unlike clasdis Monte Carlo)
  - Uses structure functions based on Gaussian and Wandzura-Wilczek-type approximations

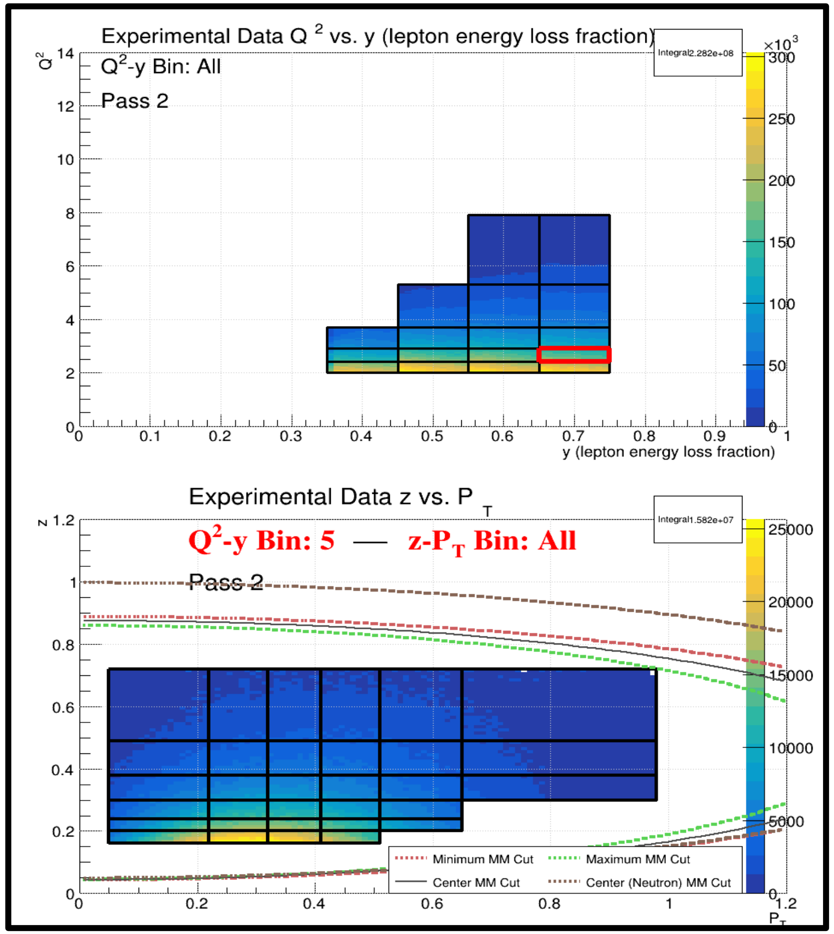
Unpolarized Cross Section used by EvGen:

$$\frac{d\sigma_{\mathrm{SIDIS}}}{dx_{Bj}\,dy\,dz_h\,dP_{hT}^2\,d\phi_h\,d\phi_S} = \frac{\alpha^2}{x_{Bj}yQ^2}\left(1+\frac{\gamma^2}{2x_{Bj}}\right)\times$$
$$\times\left\{\left[c_1\,F_{UU,T} + c_2\,F_{UU,L} + c_3\cos(\phi_h)\,F_{UU}^{\cos(\phi_h)} + c_2\cos(2\phi_h)\,F_{UU}^{\cos(2\phi_h)}\right]\right\}$$

(i) Leading-twist $F_{UU}(x,z,P_{hT}) = \quad \{F_{UU}\equiv F_{UU,T}\}$

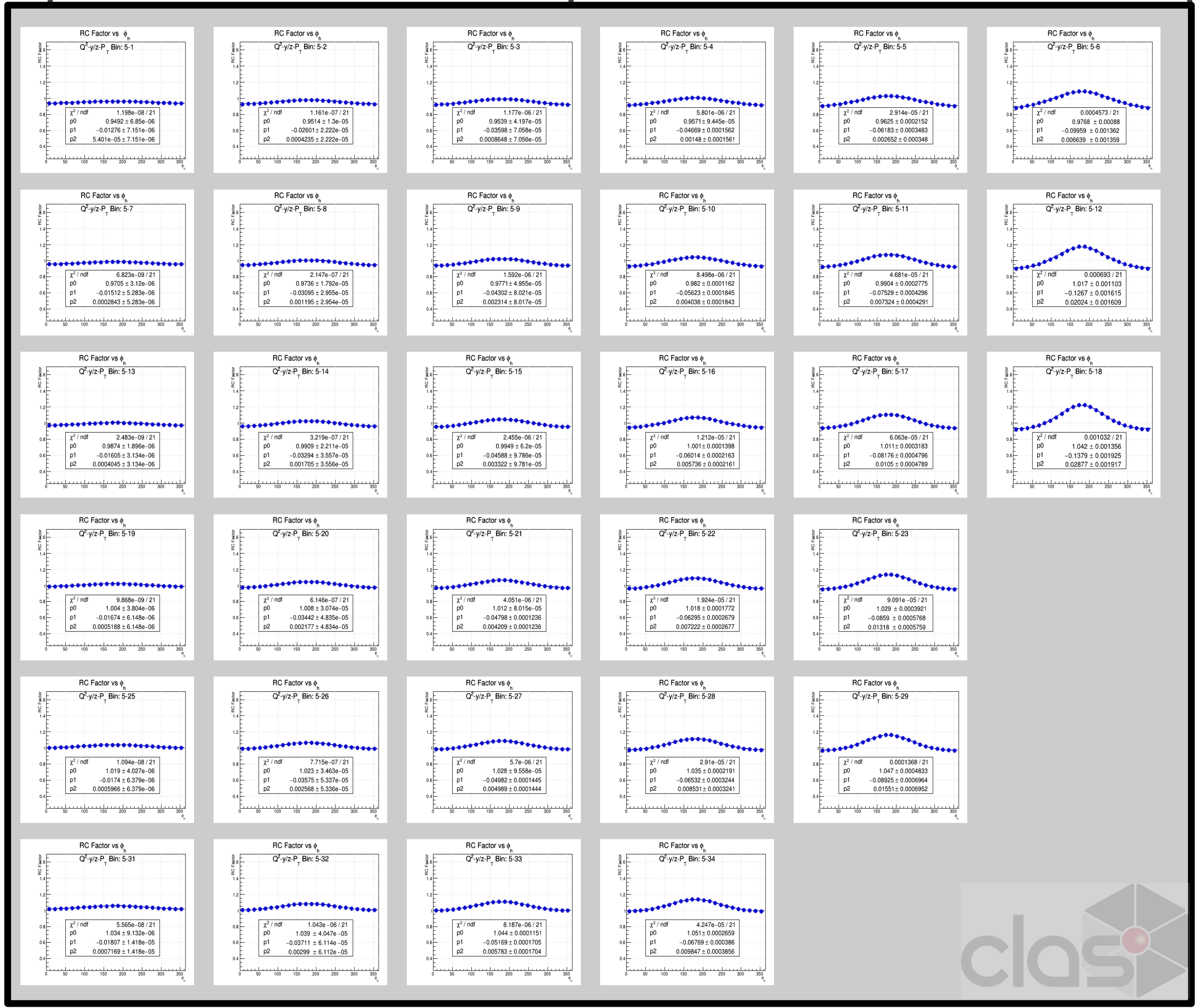
$$= x_{Bj}\sum_a e_a^2\,f_c^a(x_{Bj})\,D_c^a(z_h)\,\frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle}, \qquad (13)$$

Example of Binned RC Factors

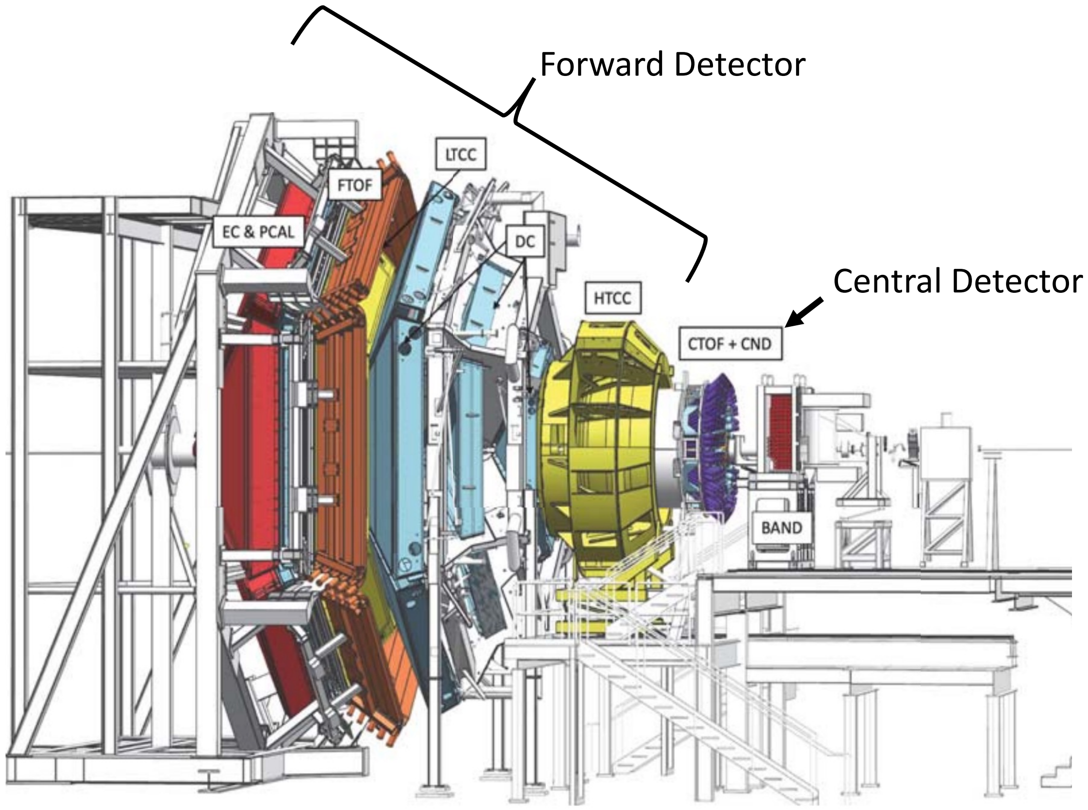


Q^2-y Bin 5 (Low Q^2—High y)

RC Factors as a function of ϕ_h



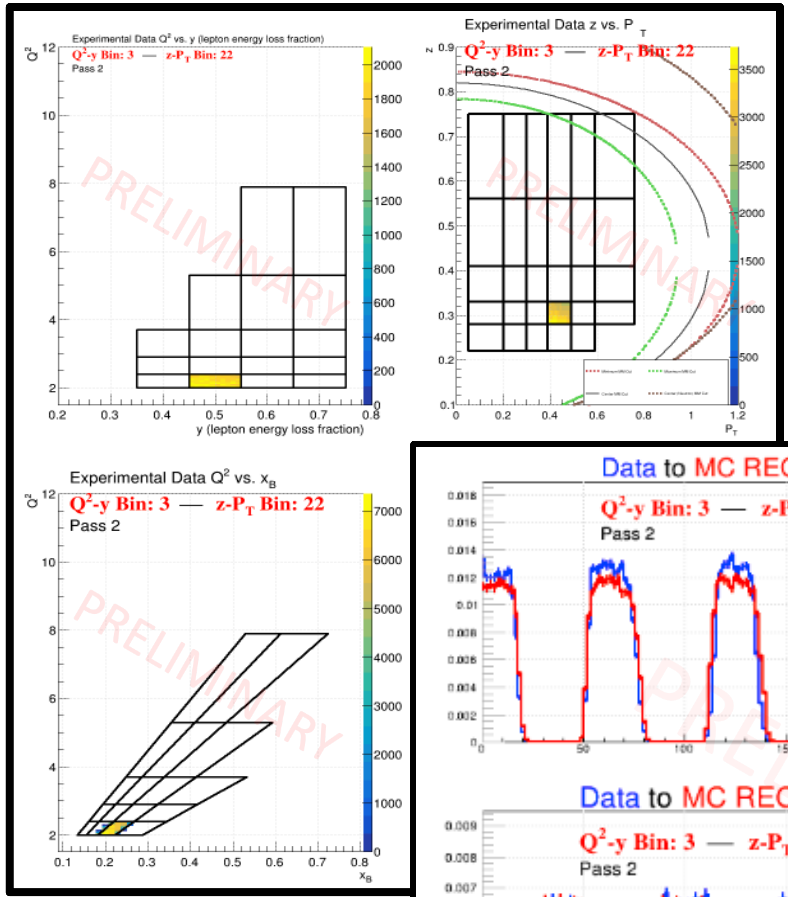
Experimental Setup and Data



CLAS12 Detector

- CLAS12 detector in Hall B at Jefferson Lab
  - Upgrade from the CLAS detector
  - Enabled the higher energy and statistics for our experiments, not previously accessible
- Used a 10.6 GeV polarized electron beam and unpolarized liquid hydrogen target
- Data presented uses forward detector only

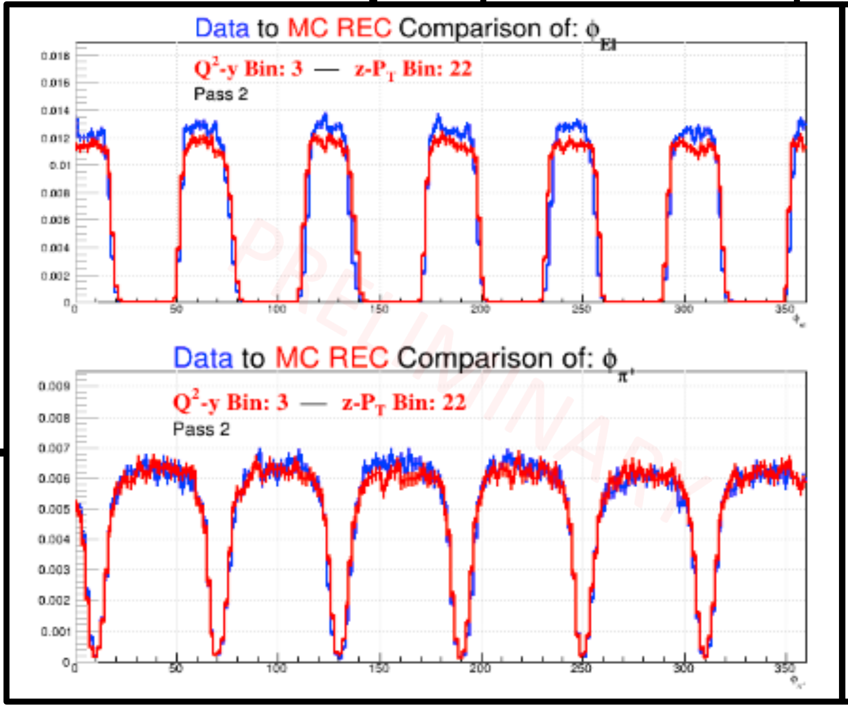
Sector Dependence in ϕ_h Distributions

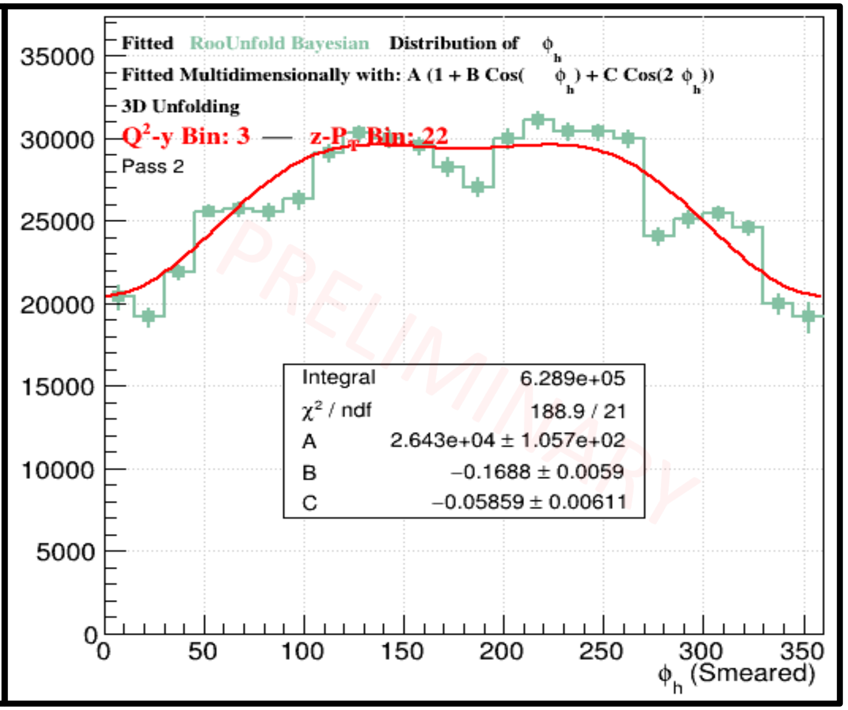


Issue: Some bins seem to have additional modulations AFTER Acceptance Corrections not explained by the Cos(ϕ) and Cos(2ϕ) moments

- The 6 peak structure was found to be related to the forward detector sectors
- This suggested that the effect is related to mismatching in sector acceptance between Data and Monte Carlo

Comparison of Lab ϕ angles of both particles for Data and MC
↓





Solution: Revisit the Fiducial Cuts to improve this agreement

Refinement of Fiducial Cuts (on the Electron)

Drift Chamber Fiducial Cuts

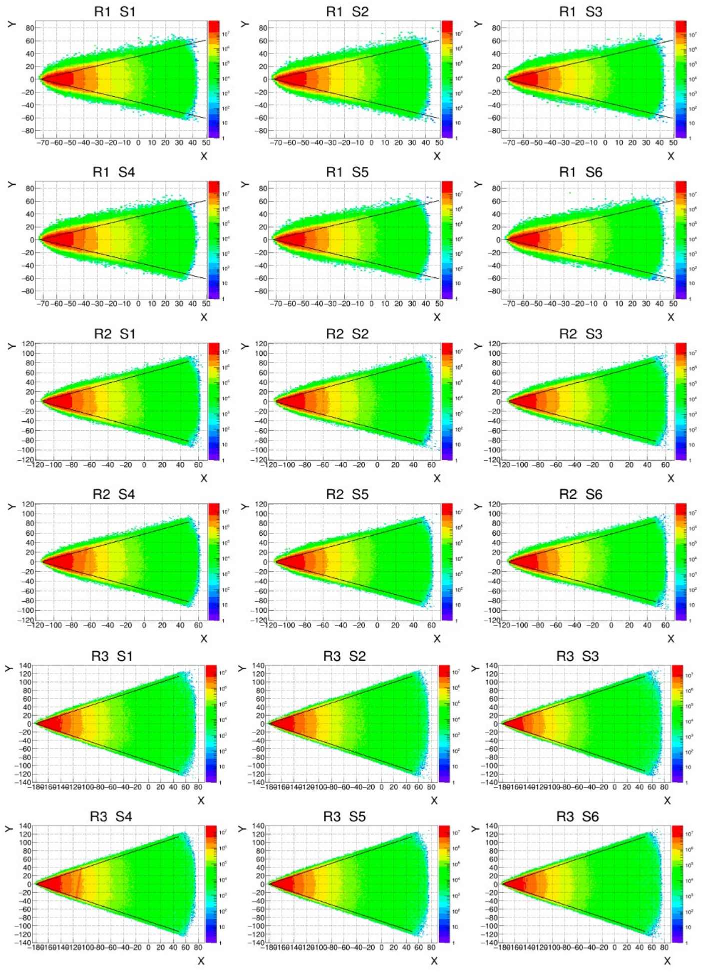
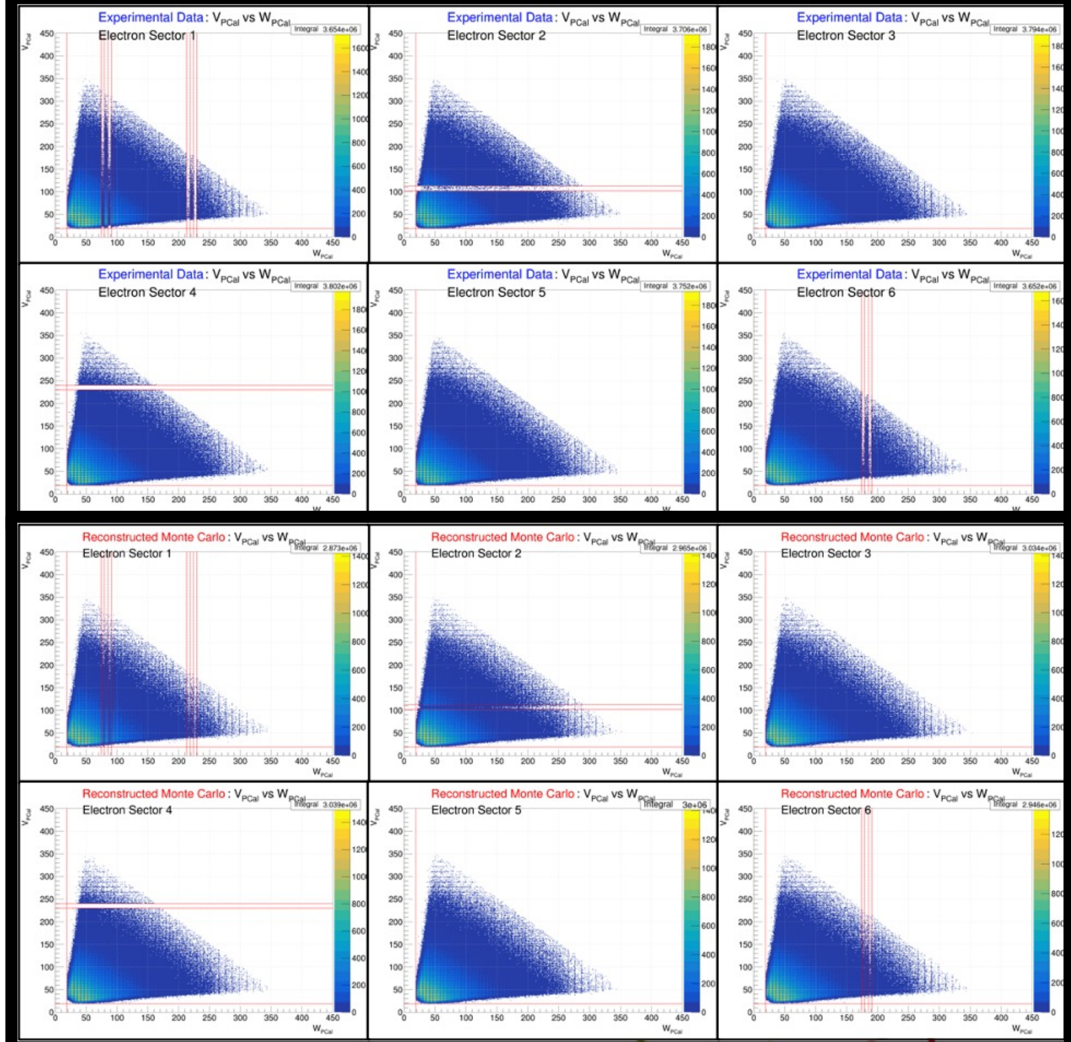


FIG. 10. χ^2 weighted drift chamber occupancy in the x and y detector variables for the three layers (R1, R2, R3) and six sectors. The black lines correspond to the DC fiducial cuts.

PCalorimeter Fiducial Cuts on V and W (also cut on U < 395 cm)



Experimental Data (Before the Cuts)

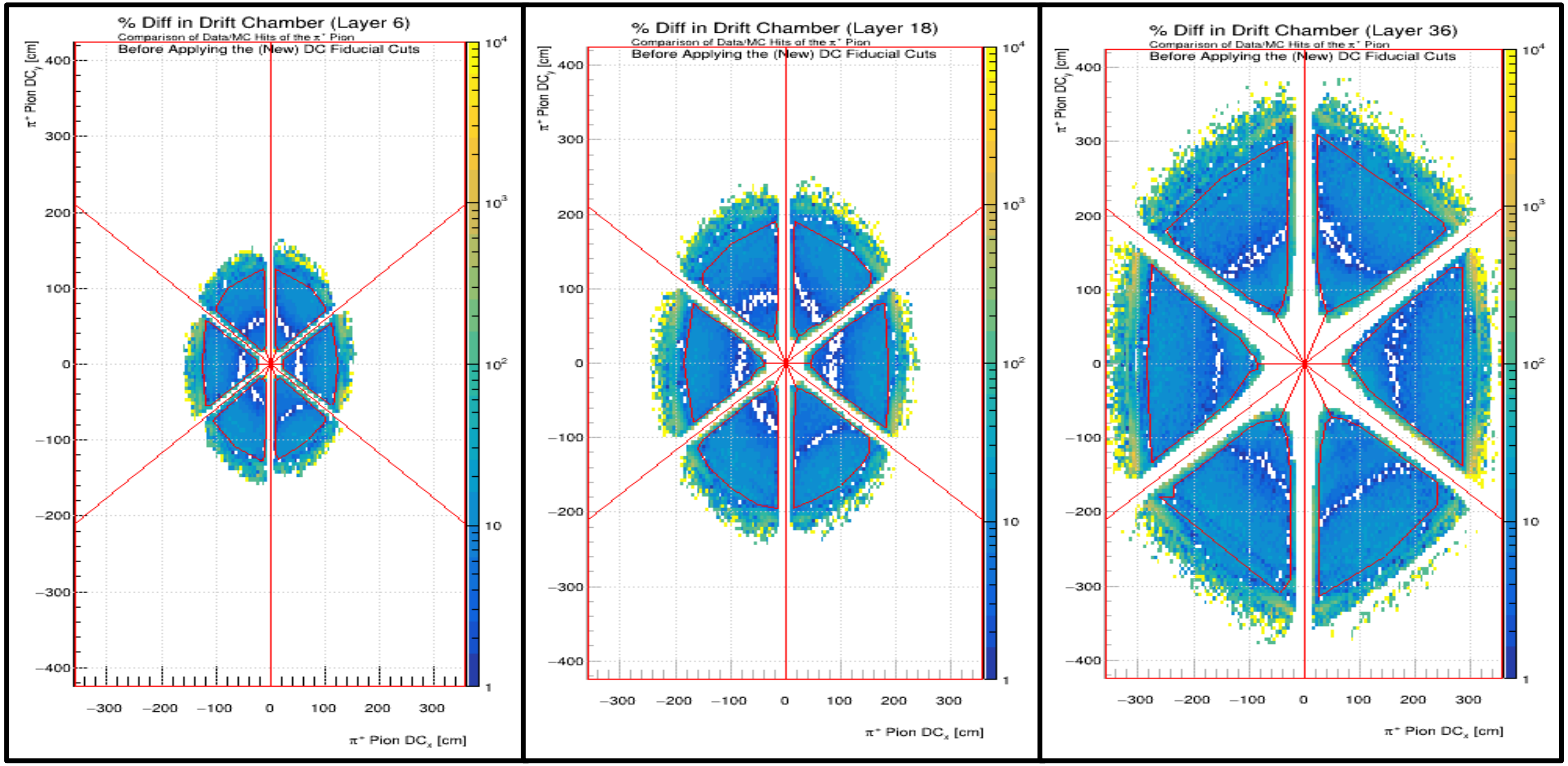
Red lines show cuts to remove the dead channels in data from the simulation

Reconstructed Monte Carlo (Before the Cuts)

*From Valerii Klimenko

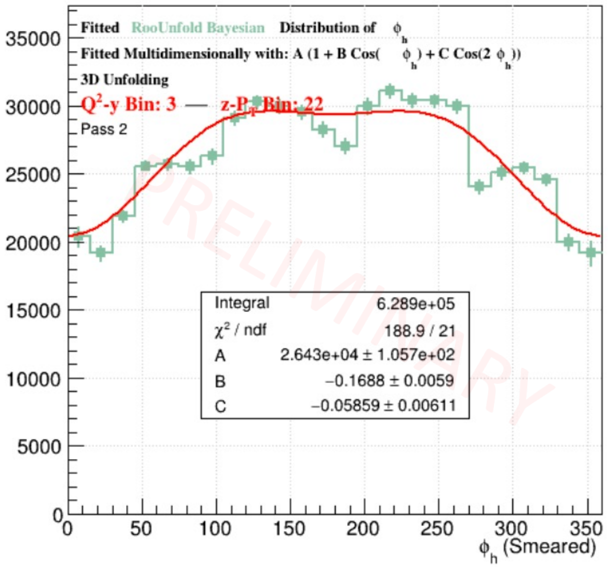
Refinement of Fiducial Cuts (on the π^+ pion)

These images show the % Difference between the normalized event counts of where the π+ pion hits each layer of the Drift Chamber in the Data and Monte Carlo datasets

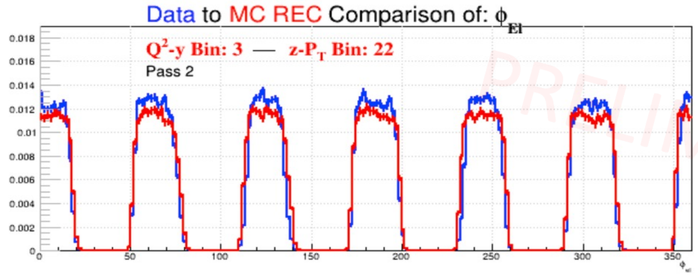


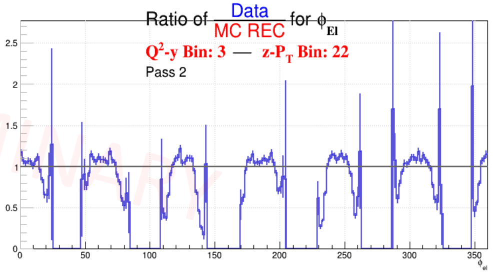
The Red lines show where the cuts are defined for each DC layer

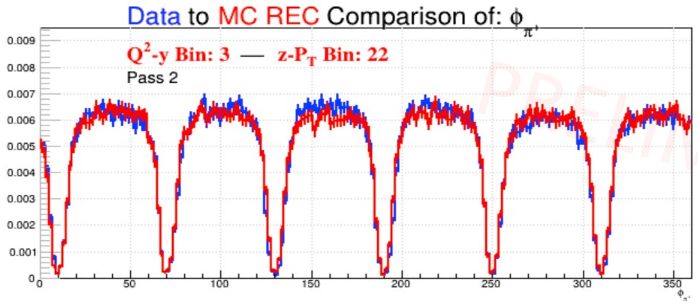
Impact of New Fiducial Cuts

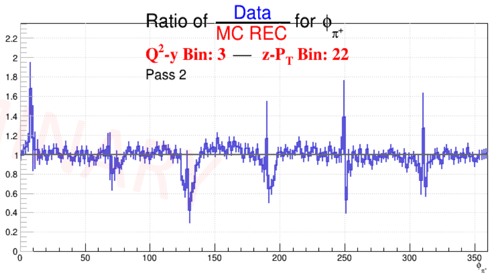


Before New Cuts



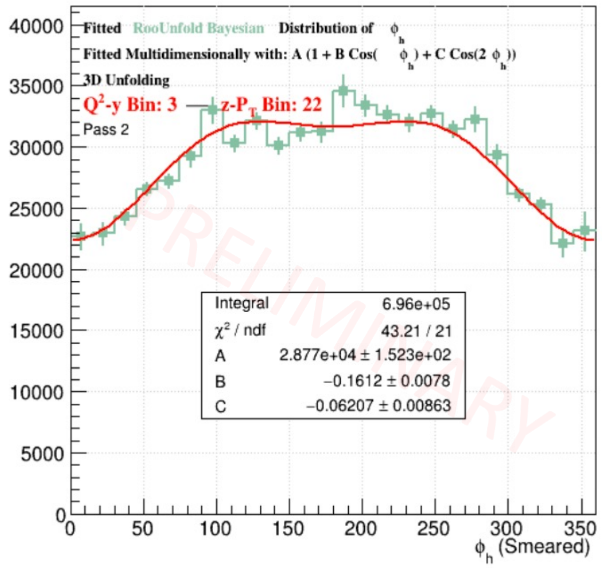






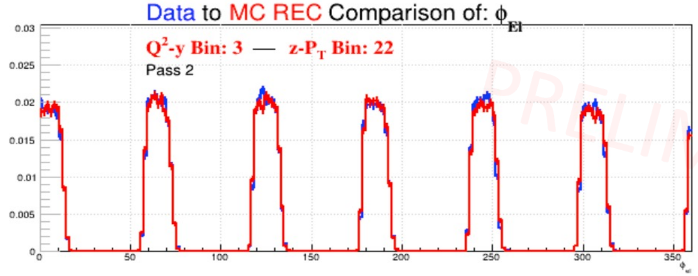
Top Rows:
Lab Angle of Electrons

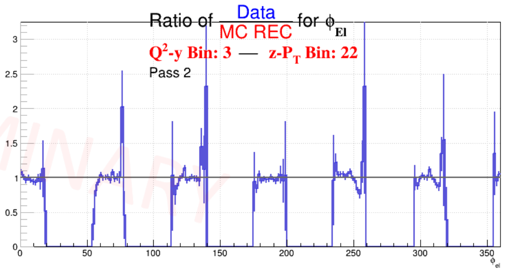
Bottom Rows:
Lab Angle of π^+ Pions



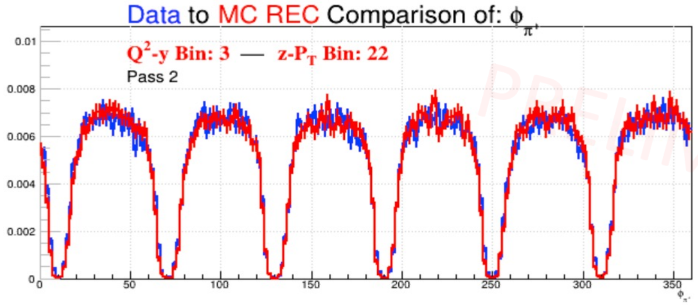
After New Cuts

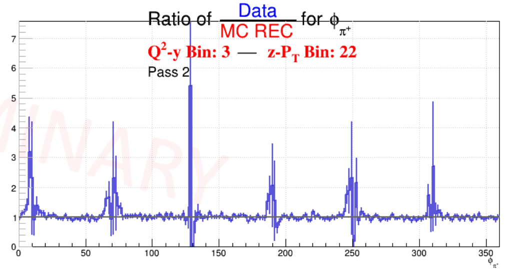
← Much Better χ^2





← Much better agreement between the lab angles of both particles

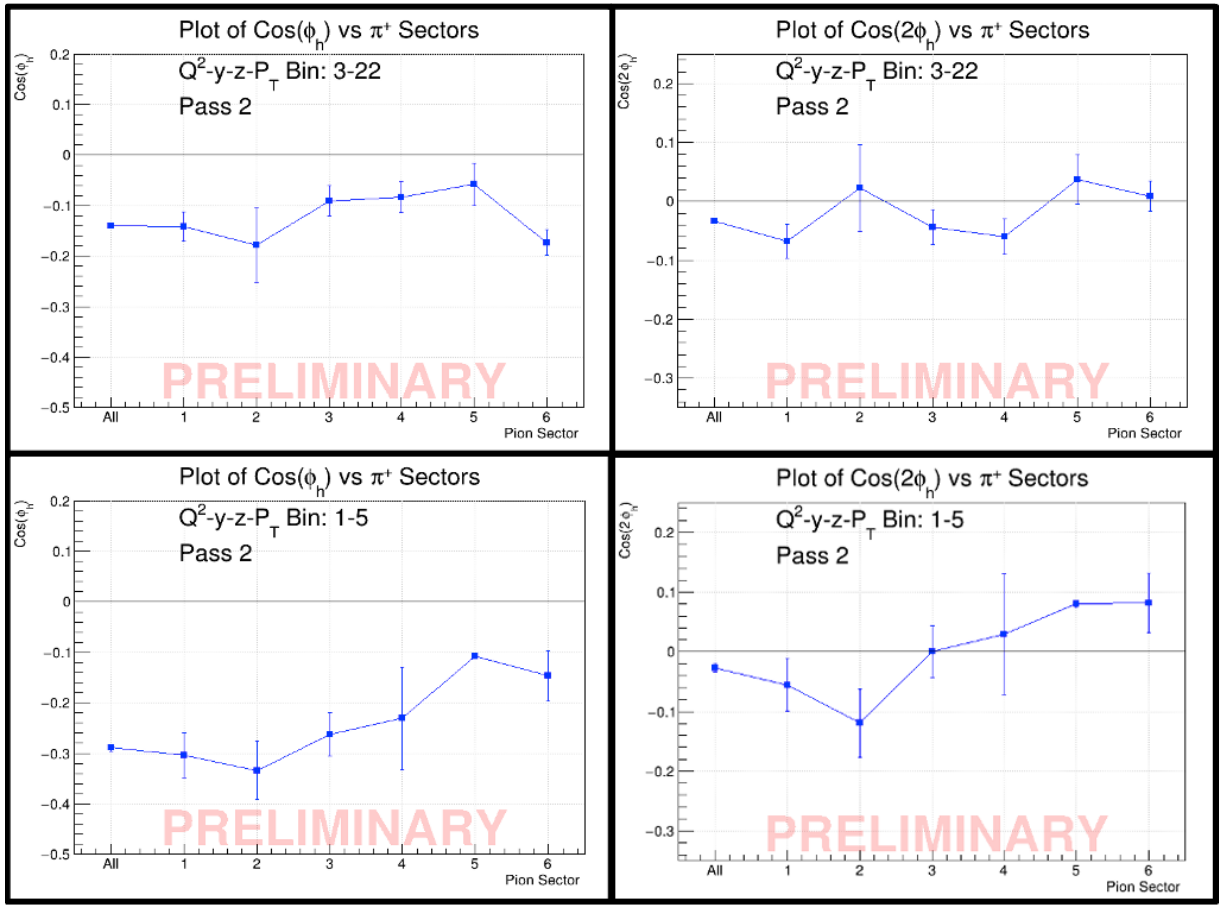




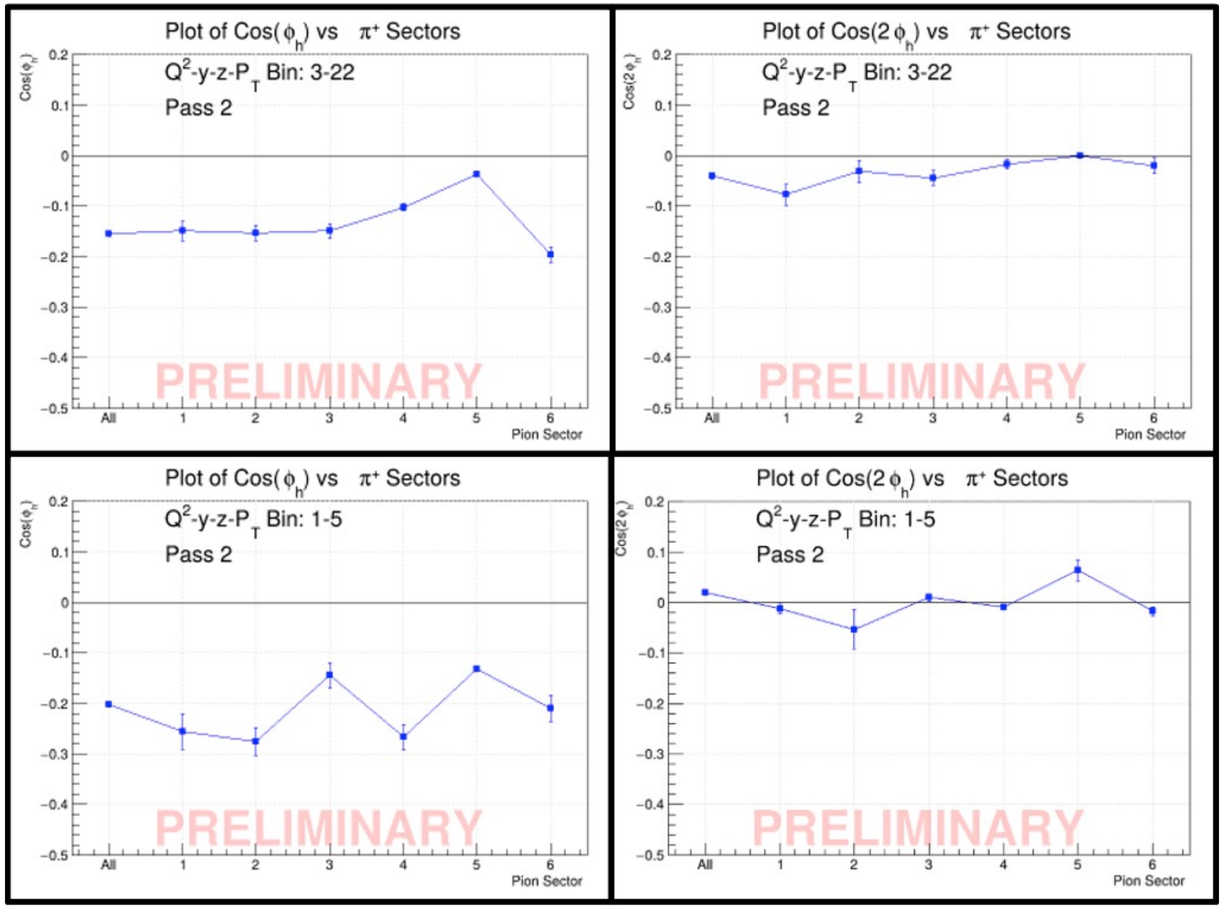
The cuts start to reduce the additional modulations for a smoother distribution of ϕ_h

(Pion) Sector Correlations with Cos(ϕ) and Cos(2ϕ) Measurements

Before Newest Fiducial Cuts



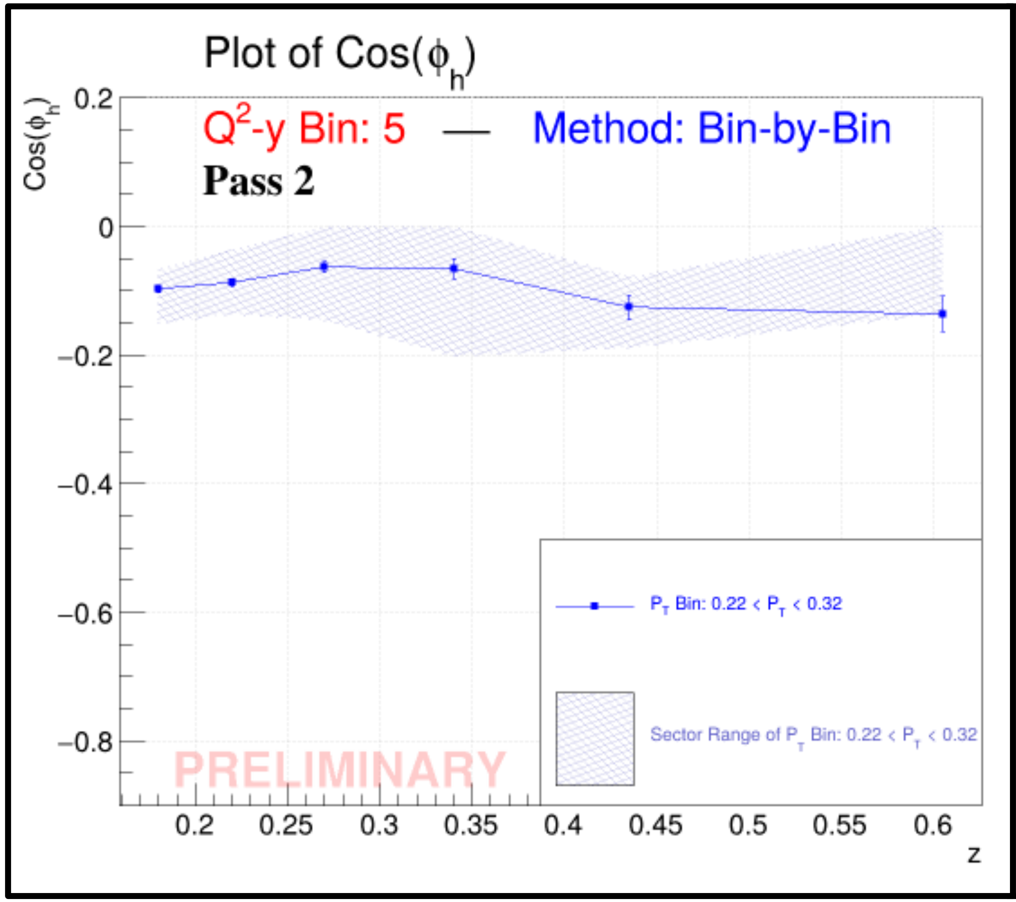
After Newest Fiducial Cuts

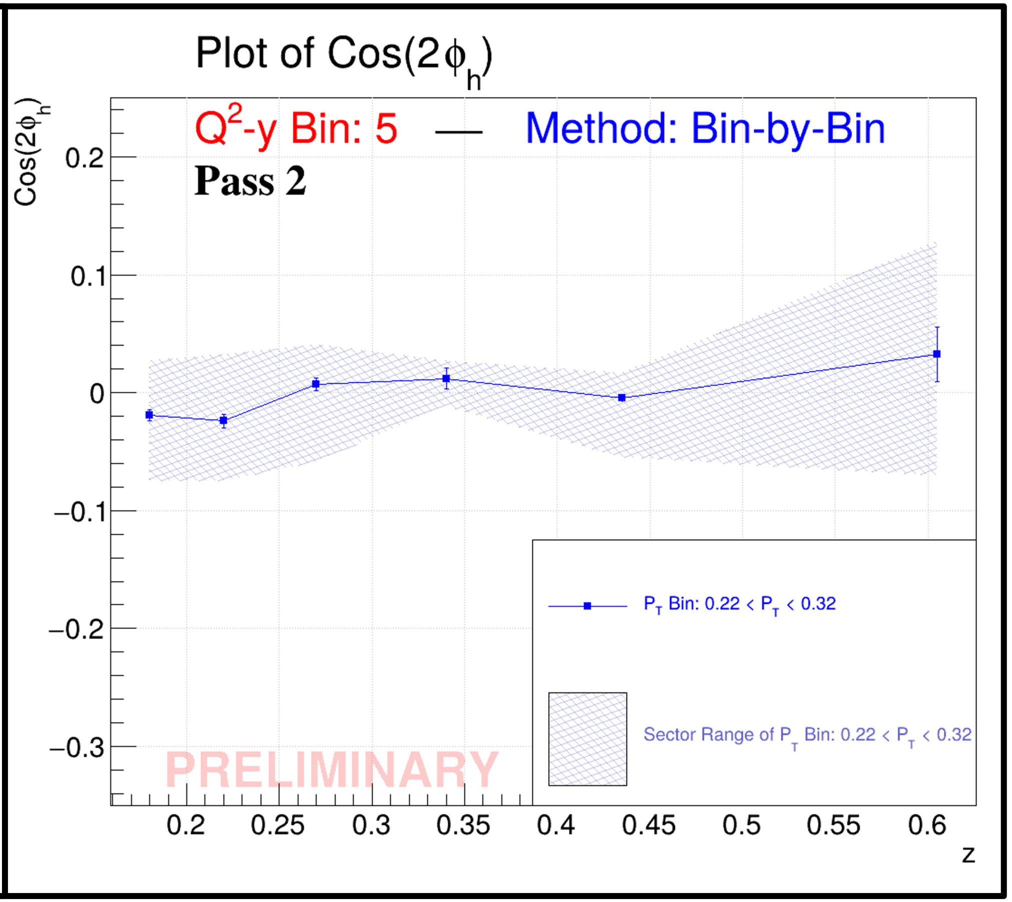


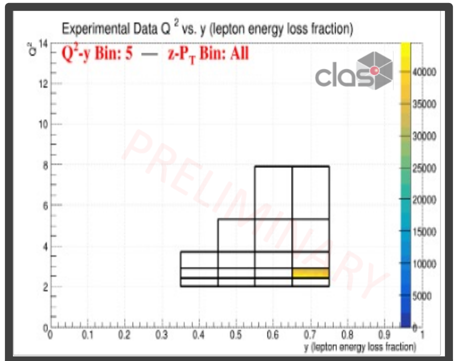
The new Fiducial Cuts reduce Sector dependence across many of my kinematic bins, though some dependence still remains

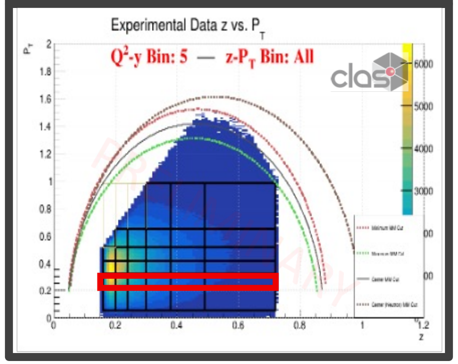
Will plan to account for these dependencies when taking the final measurements

(Pion) Sector Correlations with Cos(ϕ) and Cos(2ϕ) Measurements



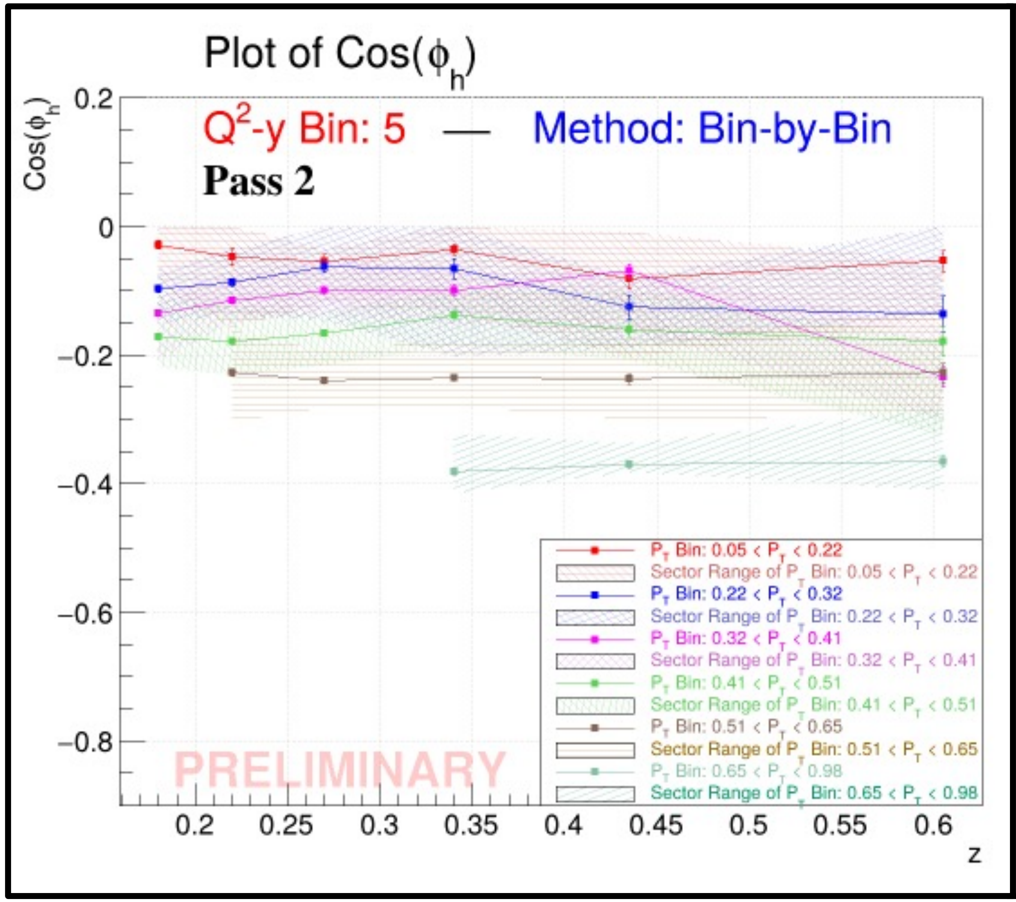


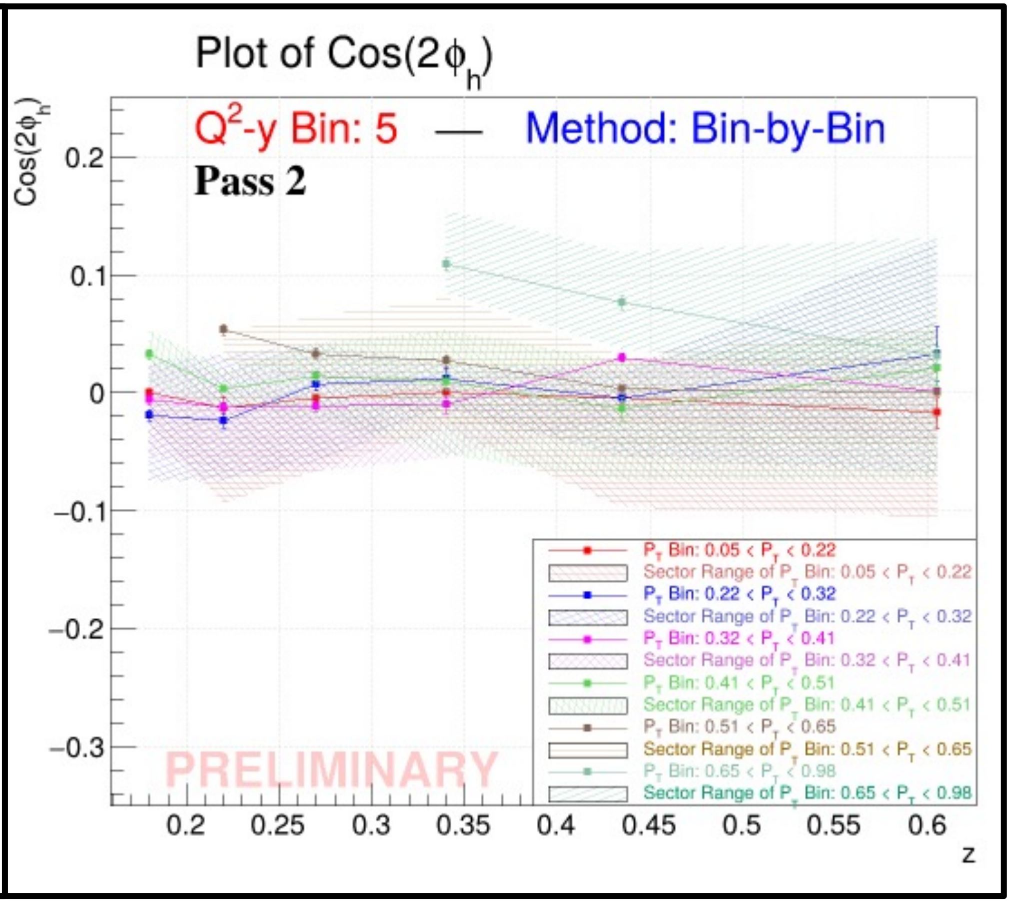


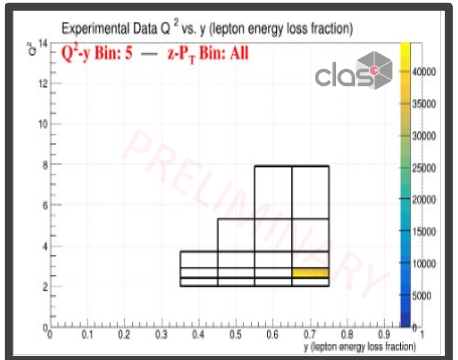


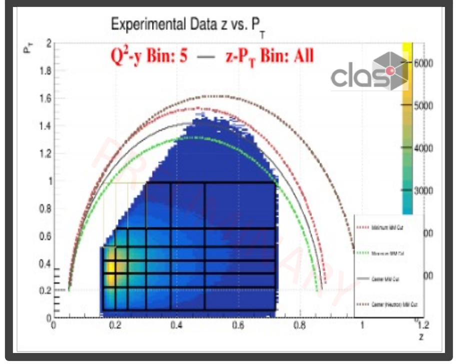
The shaded regions show the ranges of sector dependence on these measurements

(Pion) Sector Correlations with Cos(ϕ) and Cos(2ϕ) Measurements









The shaded regions show the ranges of sector dependence on these measurements

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