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

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November CLAS Collaboration Meeting

LinkedIn

Motivation

- Semi-Inclusive Deep Inelastic Scattering (SIDIS) experiments allow us to address questions about the 3D structure of nucleons
- Azimuthal modulations in 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 (aspect of the proton missing spin puzzle)

SIDIS Cross-Section and Boer-Mulders

The lepton-hadron Unpolarized SIDIS Cross-Section:

$$\frac{d^5\sigma}{dy\,dQ^2\,dz\,d\phi_h\,dP_{h\perp}^2} = \underbrace{\frac{x_B}{y}\frac{2\pi\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)(F_{UU,T}+\epsilon F_{UU,L})}_{A_0}\left\{1+\underbrace{\frac{\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos\phi_h}}\cos\phi_h+\underbrace{\frac{\epsilon F_{UU}^{\cos 2\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\right\}$$

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

leading twist

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

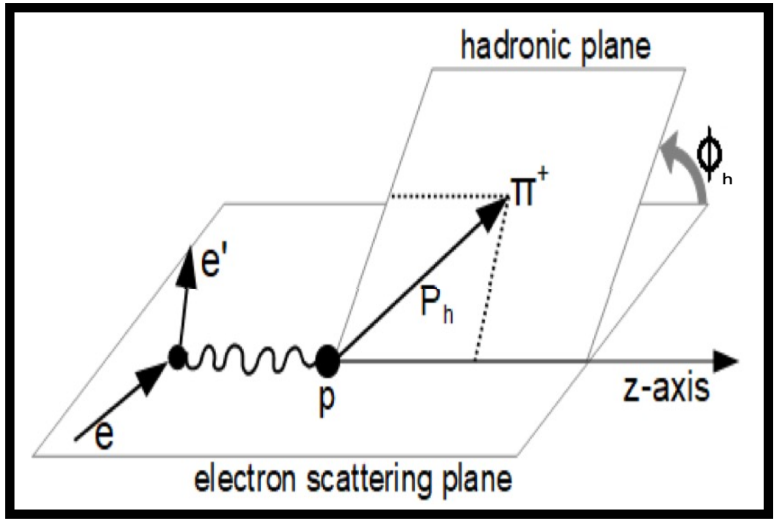
next to leading twist

$$F_{UU}^{\cos\phi_h}\propto\frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M_h}x\,h\,H_1^\perp-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M}f_1D_1+\dots\right]$$

BOER-MULDERS EFFECT

CAHN EFFECT

Interaction dependent terms neglected



Reaction Studied: ep→eπ⁺(X)

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)

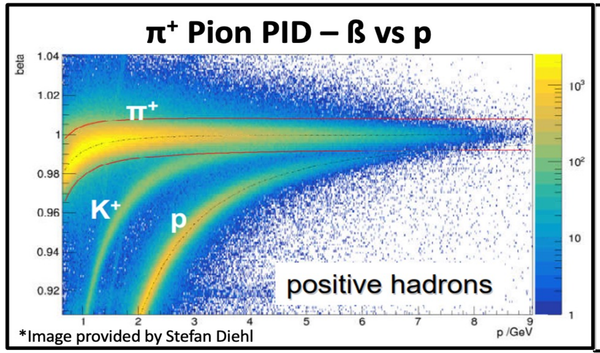
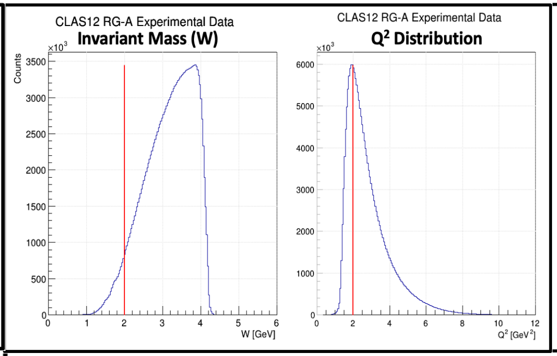
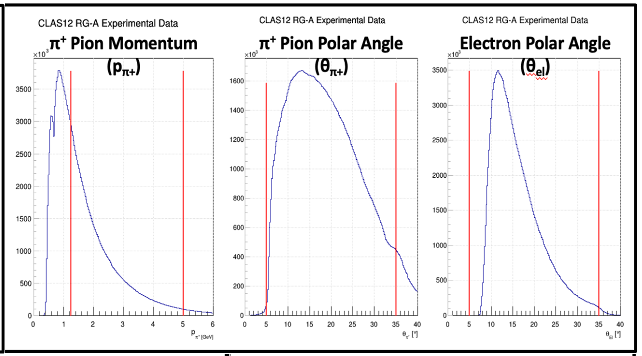
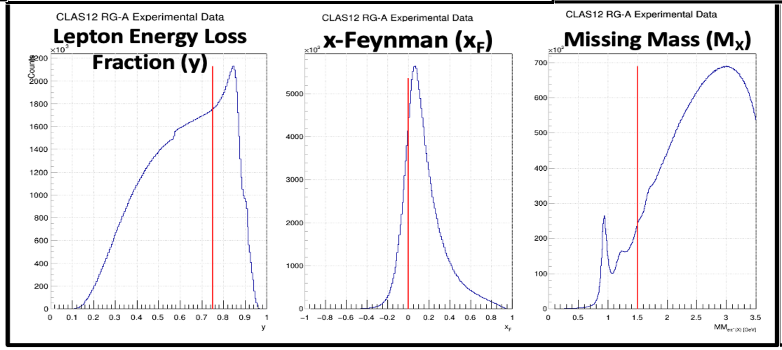
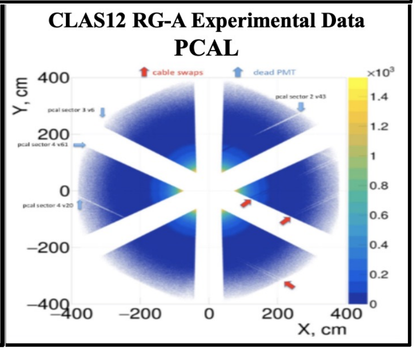


*Image provided by Stefan Diehl









Analysis Procedure

Experimental extraction of cross-section

$$\frac{d^5\sigma}{dQ^2dydP_Tdzd\phi_h} = \frac{1}{\Gamma_\nu}\underbrace{\frac{1}{\Delta Q^2\Delta y\Delta P_T\Delta z\Delta\phi_h}}_{\text{Bin Volume}}\frac{N}{R\cdot BC\cdot\eta\cdot N_0}\underbrace{\frac{1}{(N_A\cdot\rho\cdot t/A_w)}}_{\text{Target Number Density}}$$

Where:

- R = Radiative Correction
- η = **Acceptance Correction** → **Requires Monte Carlo (MC) Simulation**
- N = Bin Yields
- N_0 = Life-time corrected incident electron flux
- BC = factor which evolves bin-averaged differential cross-section

SIDIS MC are generated with LEPTO event generator

MC HIPO files available here:

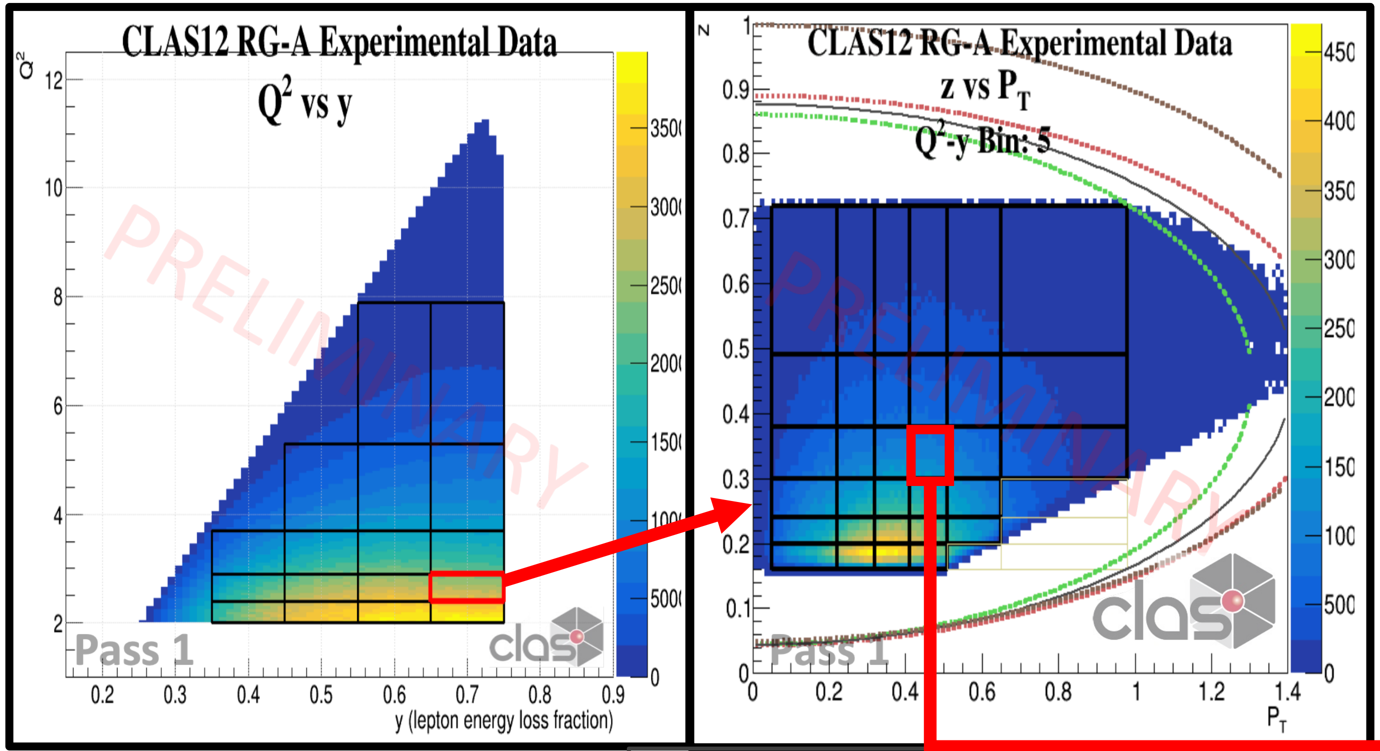
- (1.4T) /lustre24/expphy/volatile/clas12/sdiehl/osg_out/clasdis/inb-clasdis_*.hipo
- (5.8T) /cache/clas12/rg-a/production/montecarlo/clasdis_pass2/fa18_inb/clasdis_rga_fa18_inb_50nA_10604MeV-0*.hipo

Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (5 Dimensions)

17 Q^2-y Bins Total – 25-36 z-P_T Bins (per Q^2-y bin)

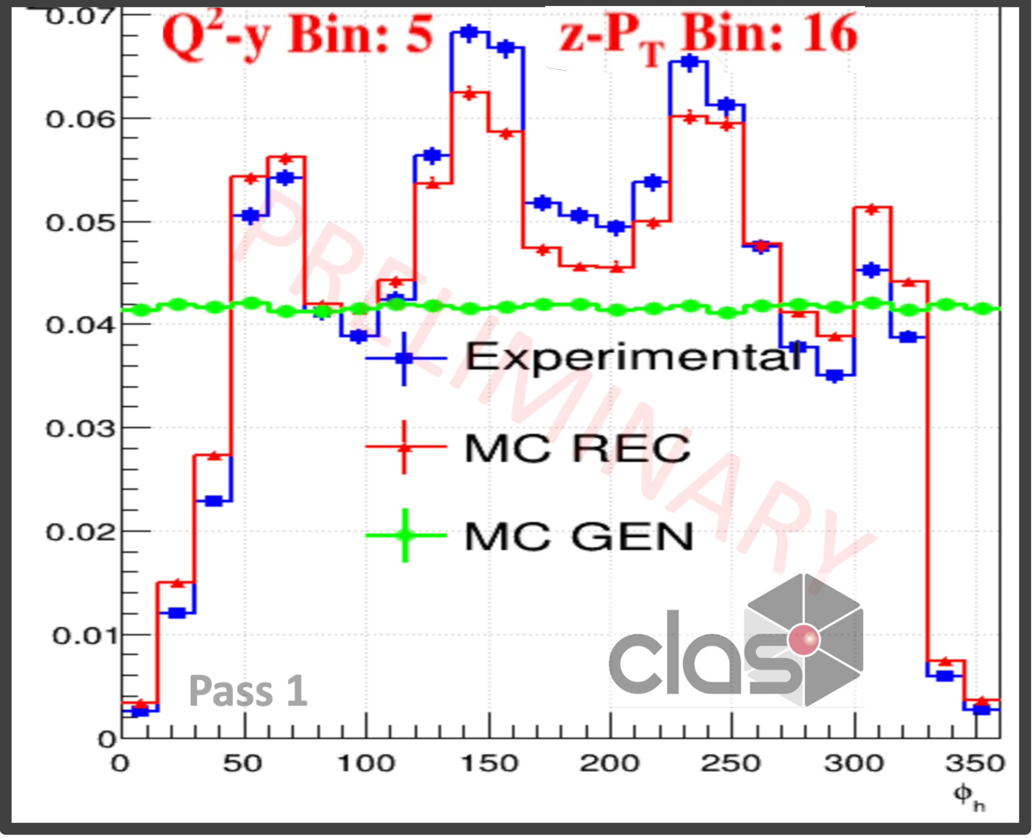
ϕ_h distribution for the Q^2-y-z-P_T bin shown in red



Missing Mass Cut Lines:

Minimum MM Cut	Maximum MM Cut
Center MM Cut	Exclusivity peak

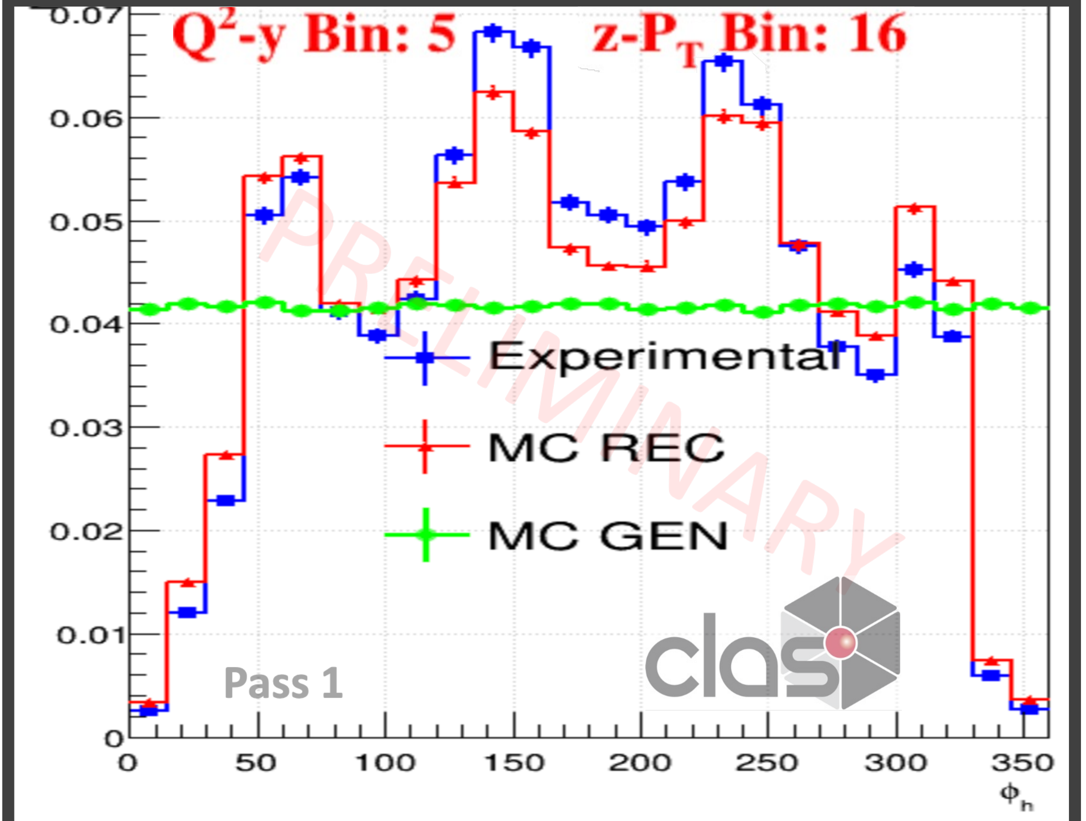
Normalized Comparison of Data, Reconstructed, and Generated ϕ_h



Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (5 Dimensions)

Normalized Comparison of Data, Reconstructed, and Generated φ_h



Apply Multidimensional Acceptance Corrections and convert to a cross-section measurement

ϕ_h fit for every bin

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

Where the parameters A, B, C give the cross-section moments

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

Methods used for Acceptance Corrections:

- **Bin-by-bin Correction**
  - Simple method which just needs the 1D plots shown here
- **Bayesian Unfolding**
  - Bayesian Unfolding Method uses Acceptance Matrices to correct the data

Acceptance Corrections and Bin Migration Study

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

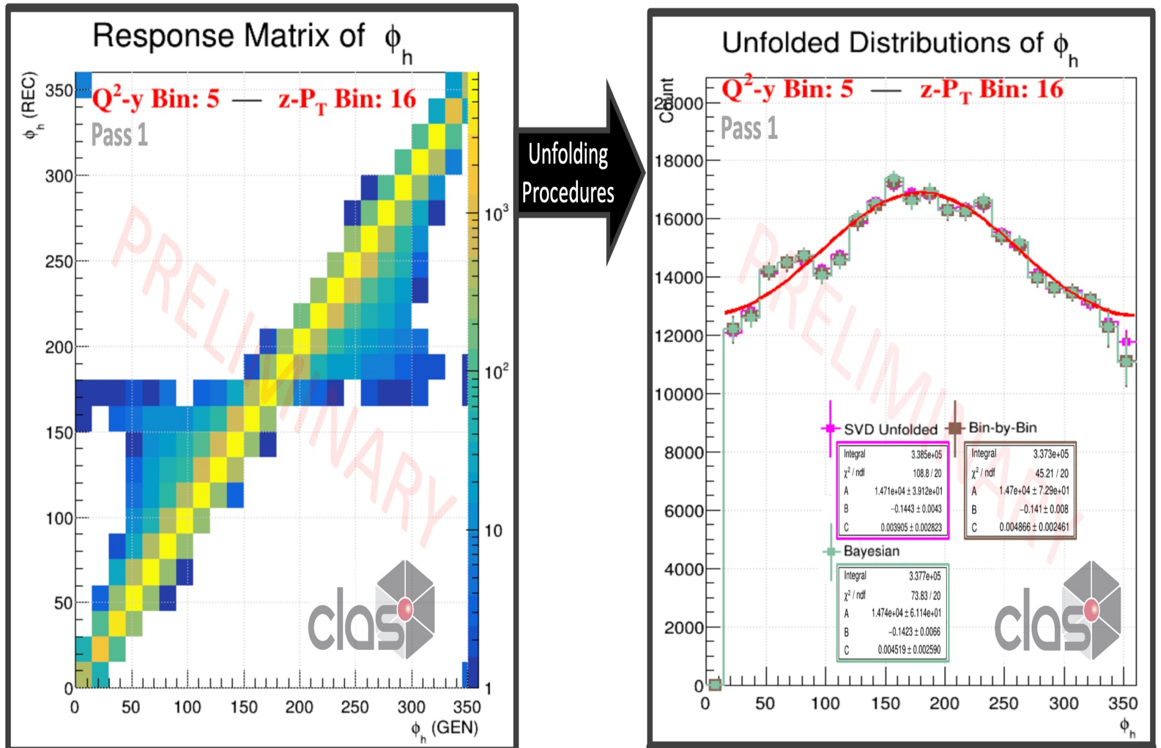
- $$A_{(i,j)} = \frac{\text{Number of Events Generated in bin } j \text{ but Reconstructed in bin } i}{\text{Total Number of Events Generated in the } j\text{th bin}}$$

- 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

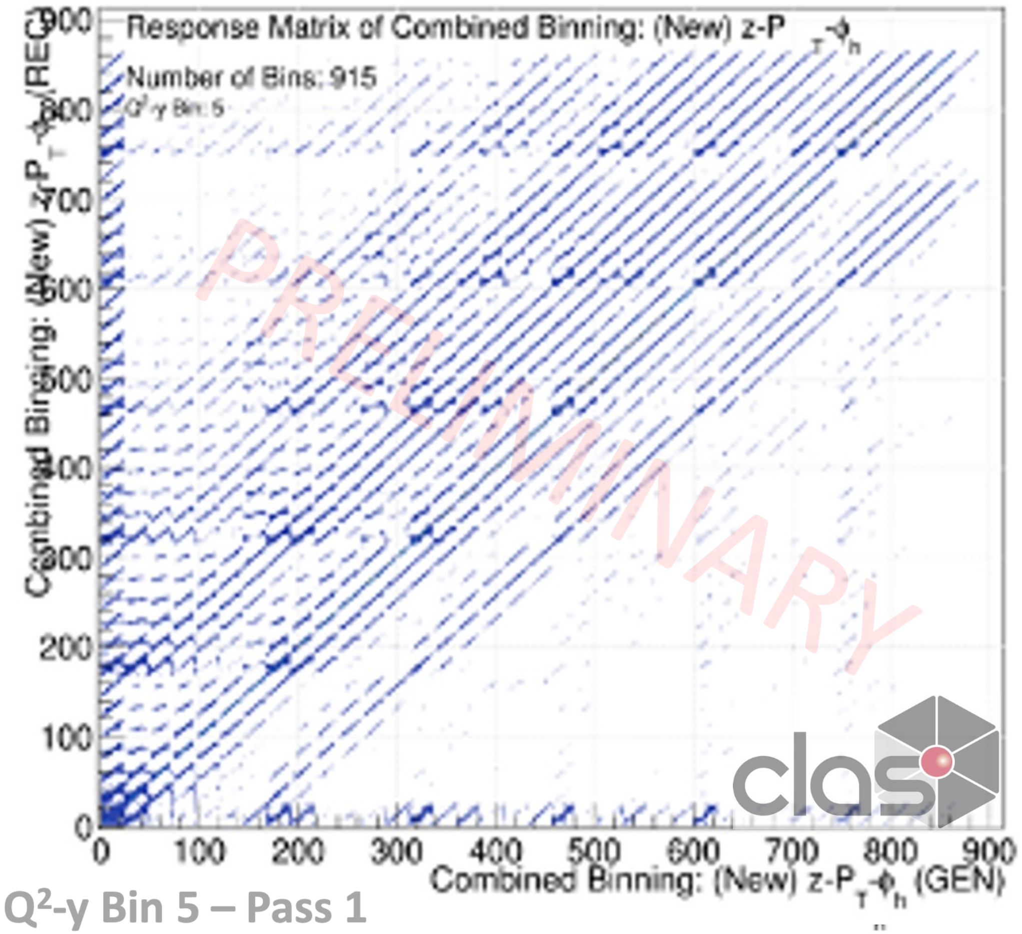
Using the Multidimensional Kinematic Bin from prior example



Parameters shown are from the fits previously described

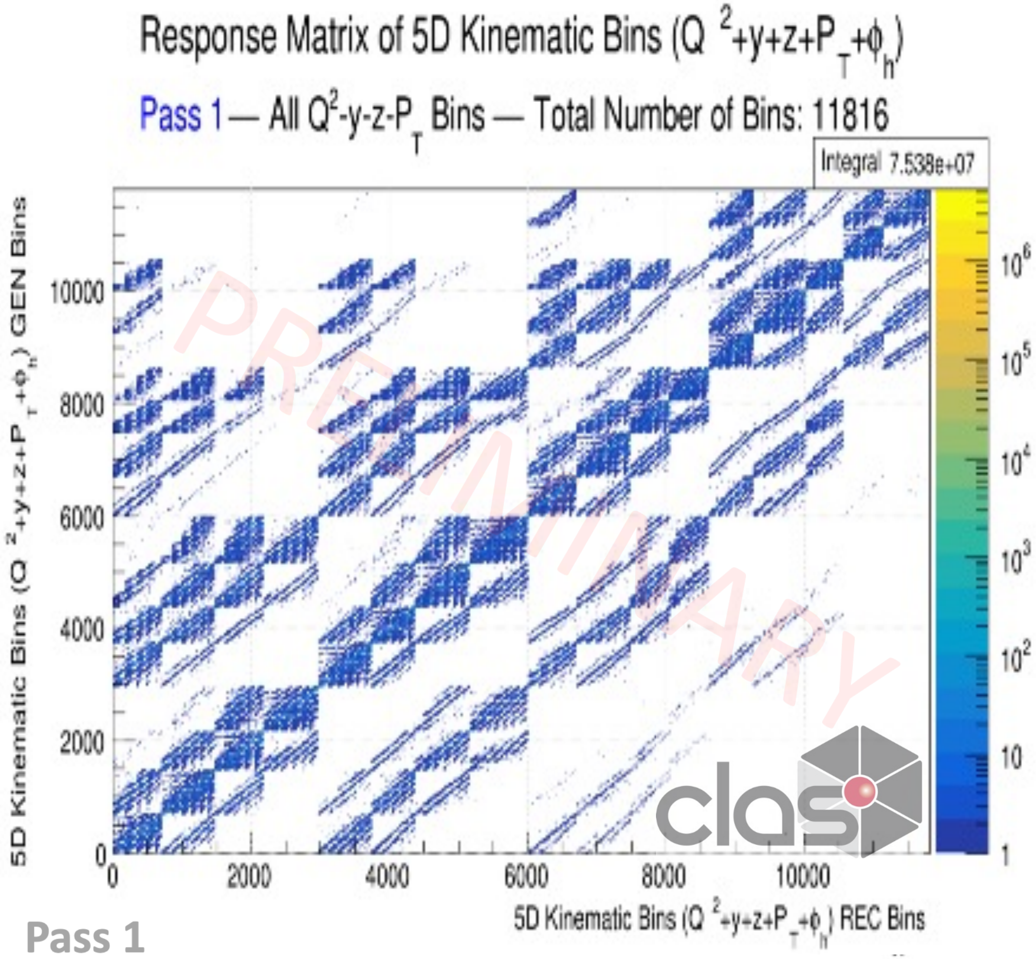
Multi-Dimensional Unfolding

z-P_T-ϕ_h Multidimensional Response Matrix



Q²-y Bin 5 – Pass 1

Q^2-y-z-P_T-ϕ_h Multidimensional Response Matrix

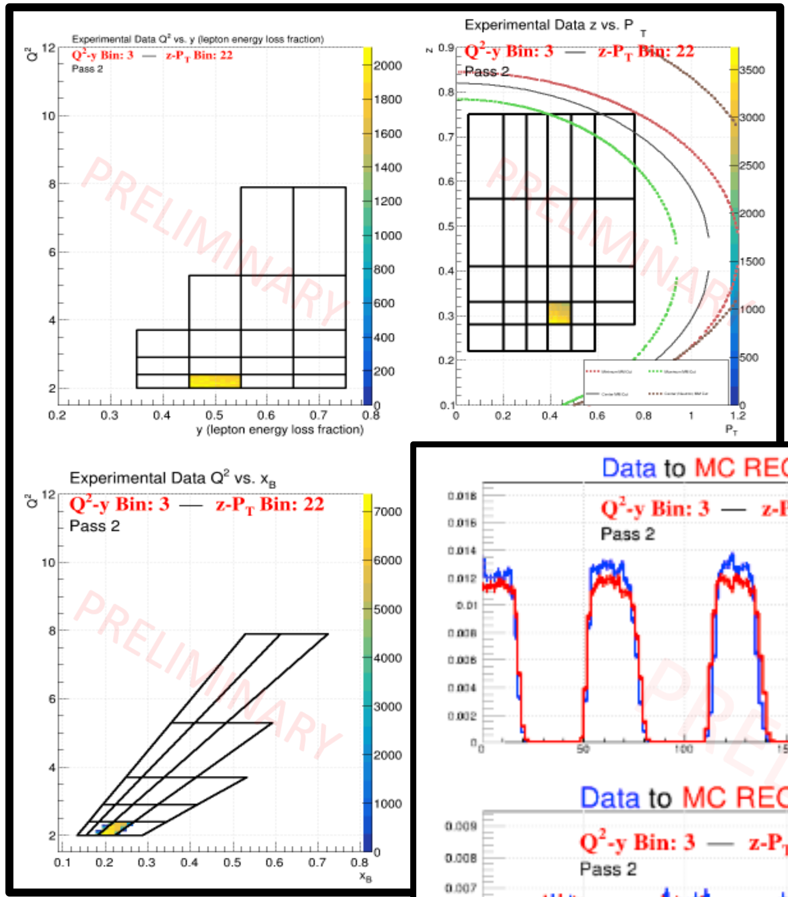


Pass 1

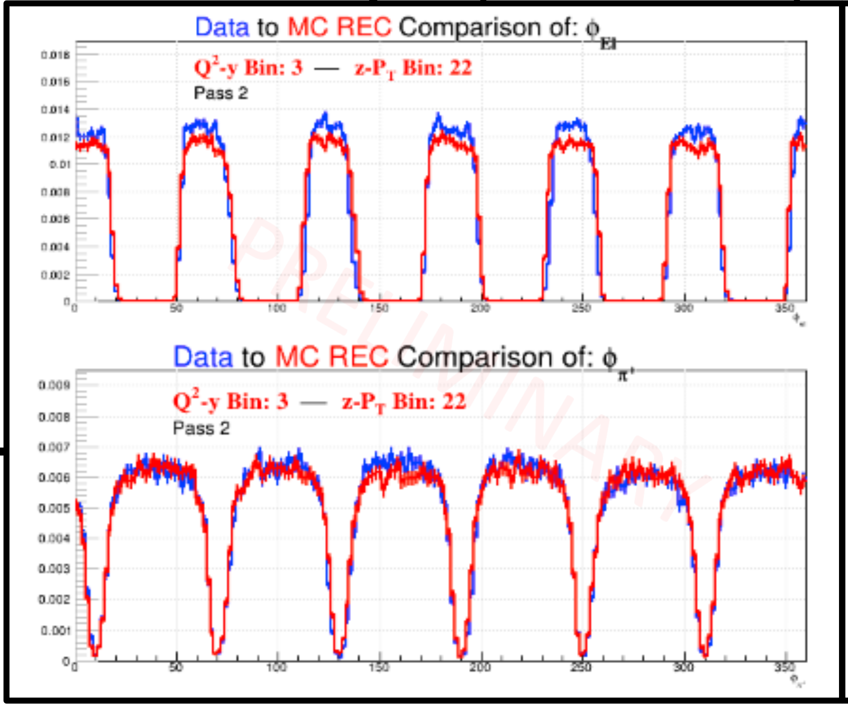
Sector Dependence in ϕ_h Distributions

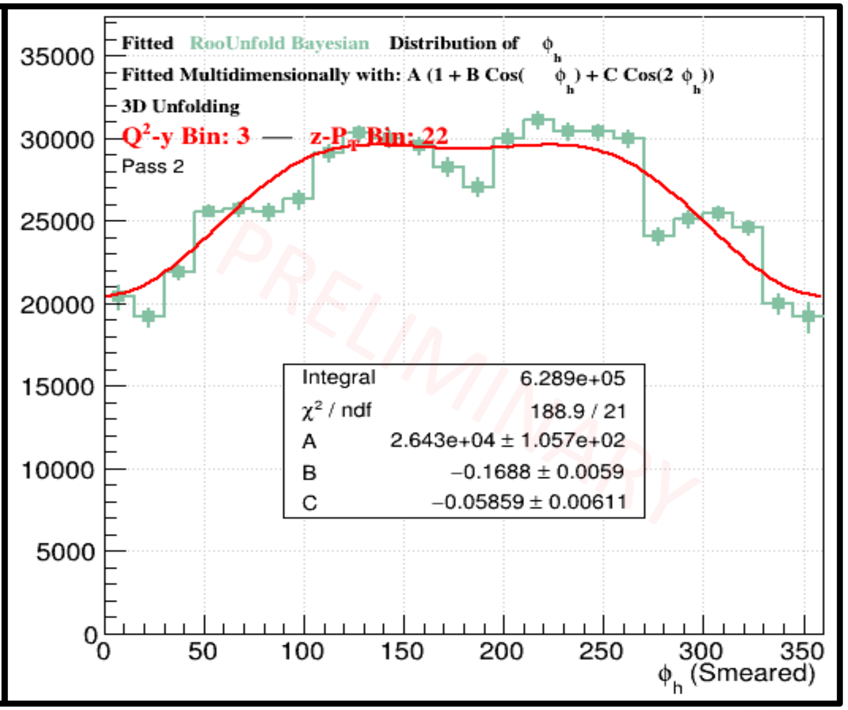
Issue: Some bins seem to have additional modulations AFTER Acceptance Corrections not explained by the Cos(ϕ) and Cos(2ϕ) moments

- 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

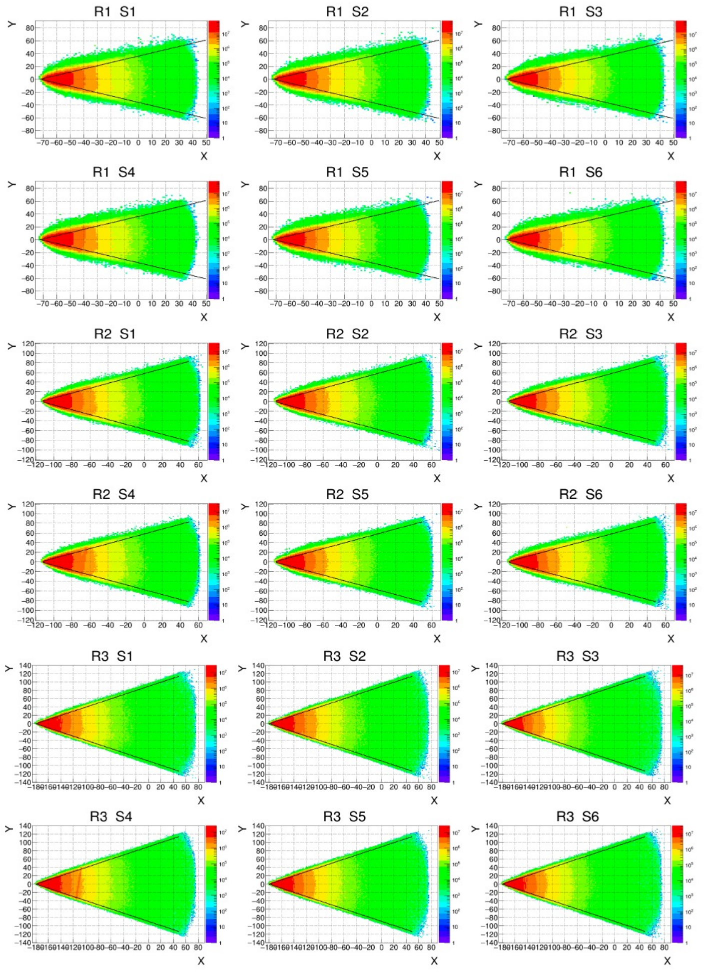
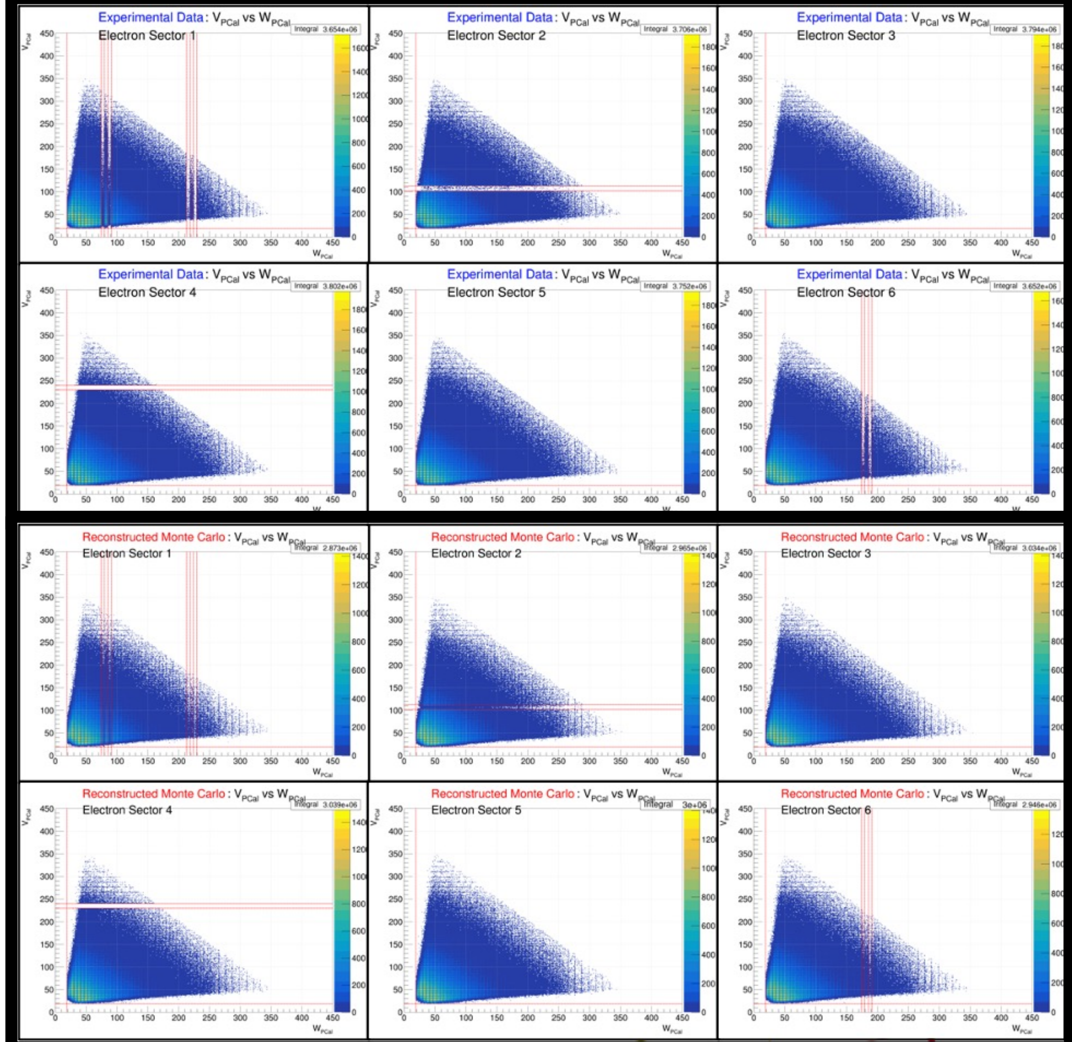


FIG. 10. χ^2 weighted drift chamber occupancy in the x and y detector variables for the three layers (R1, R2, R3) and six sectors. The black lines correspond to the DC fiducial cuts.

*From Valerii Klimenko

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



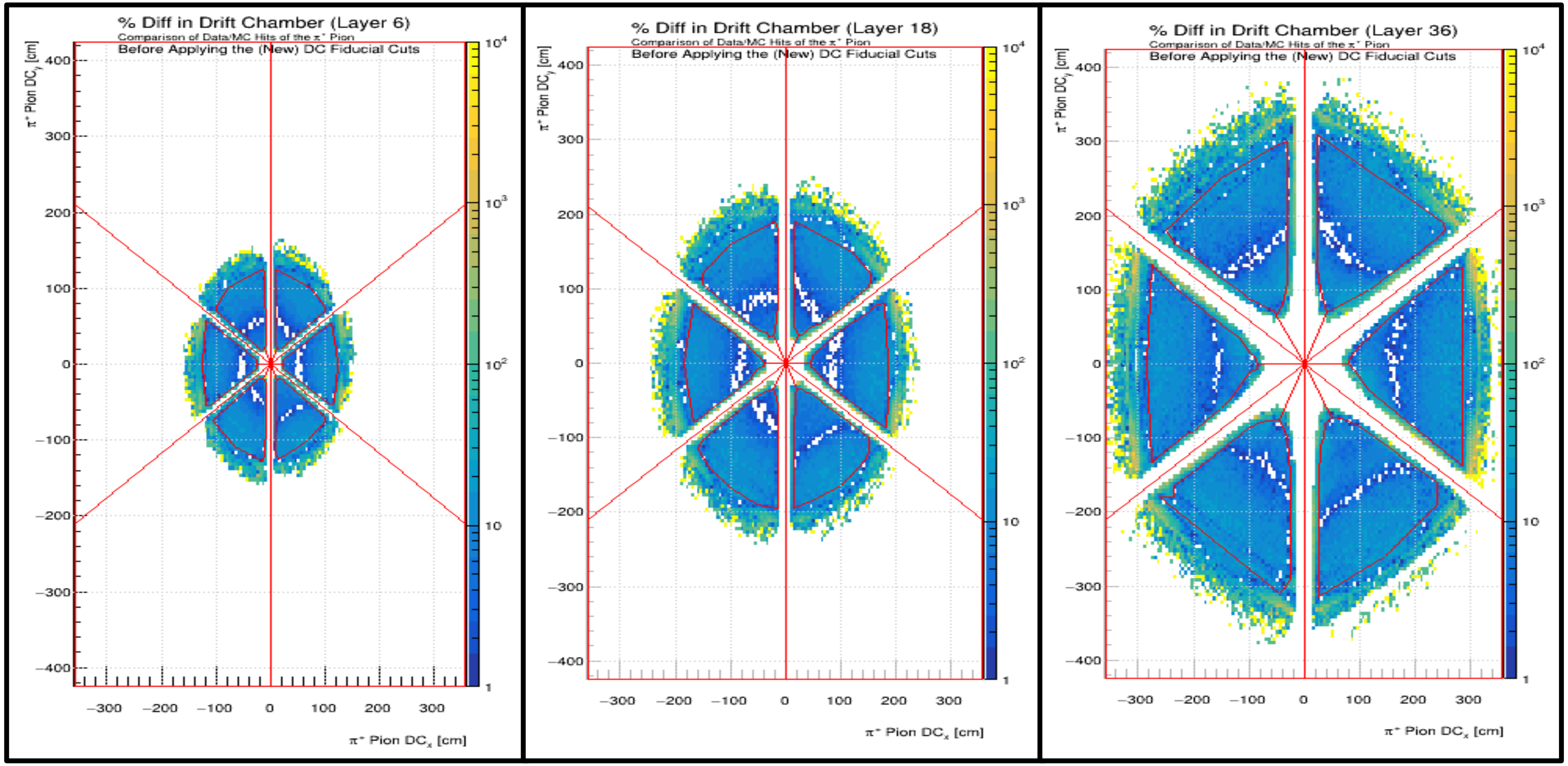
Experimental Data
(Before the Cuts)

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

Reconstructed Monte Carlo
(Before the Cuts)

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

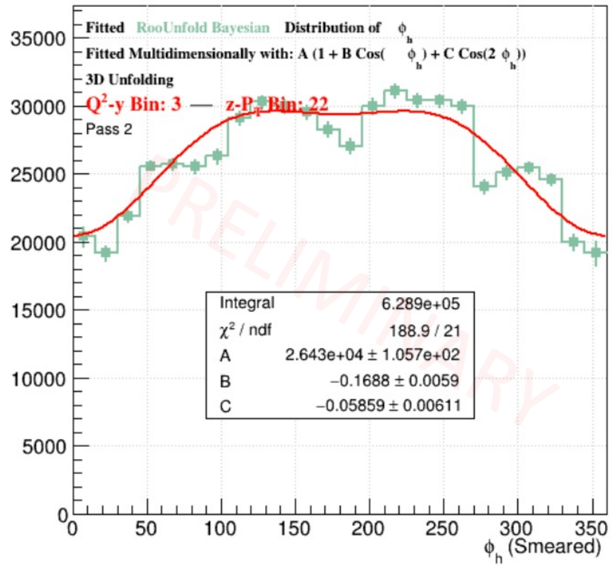
These images show the % Difference between the normalized event counts of where the π+ pion hits each layer of the Drift Chamber in the Data and Monte Carlo datasets

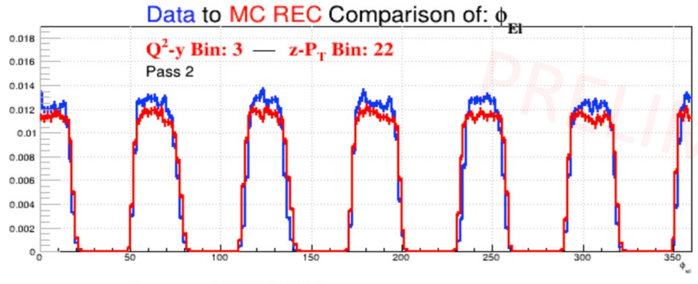


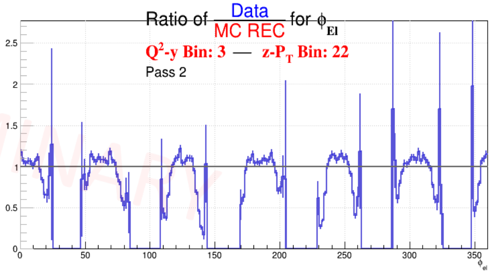
The Red lines show where the cuts are defined for each DC layer

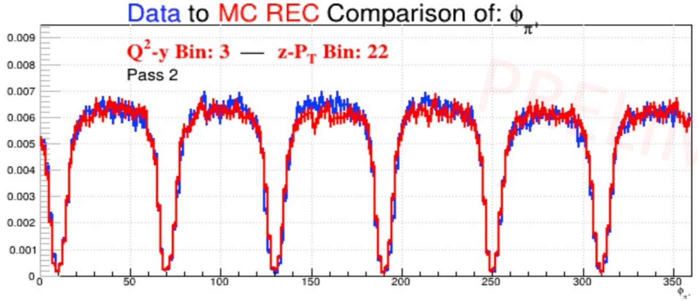
Impact of New Fiducial Cuts

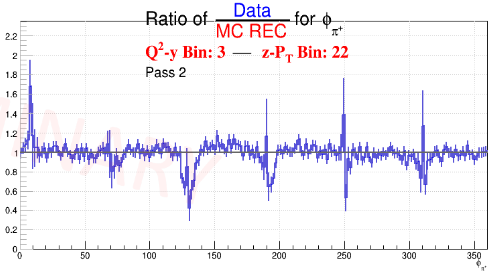
Before New Cuts







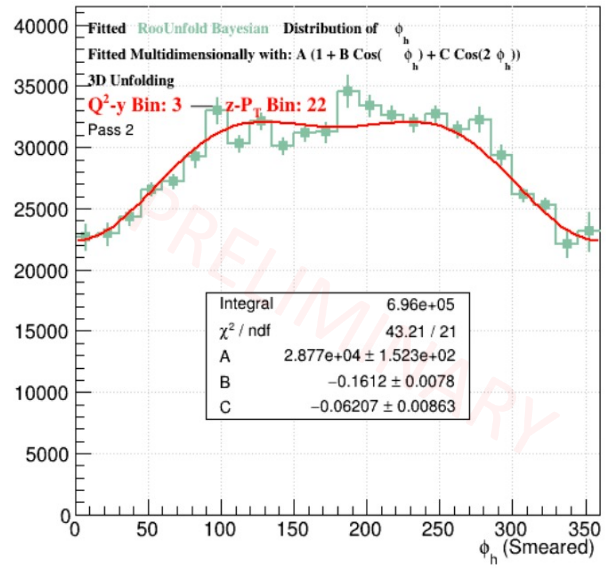




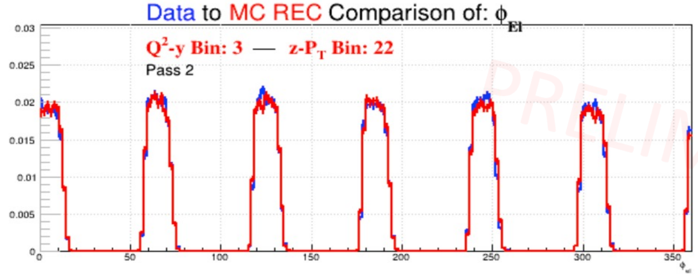
Top Rows:
Lab Angle of Electrons

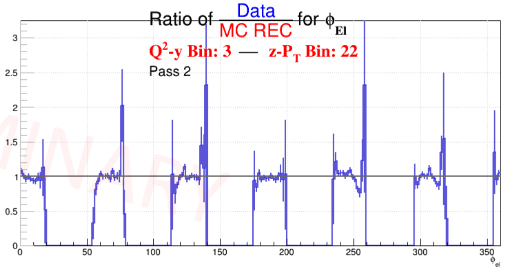
Bottom Rows:
Lab Angle of π^+ Pions

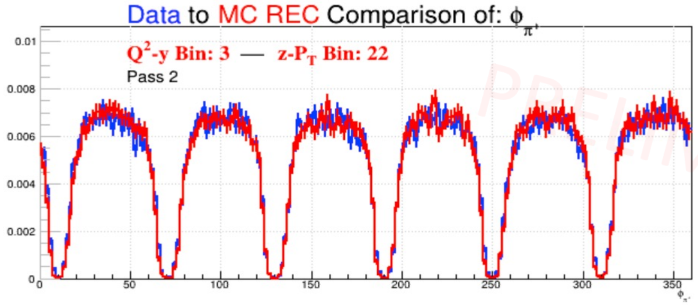
After New Cuts

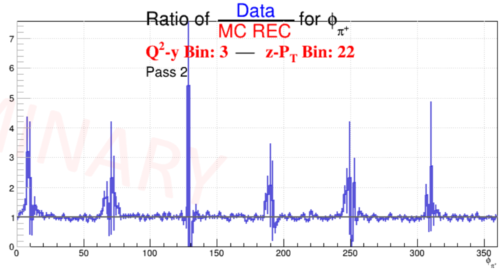


← Much Better χ^2







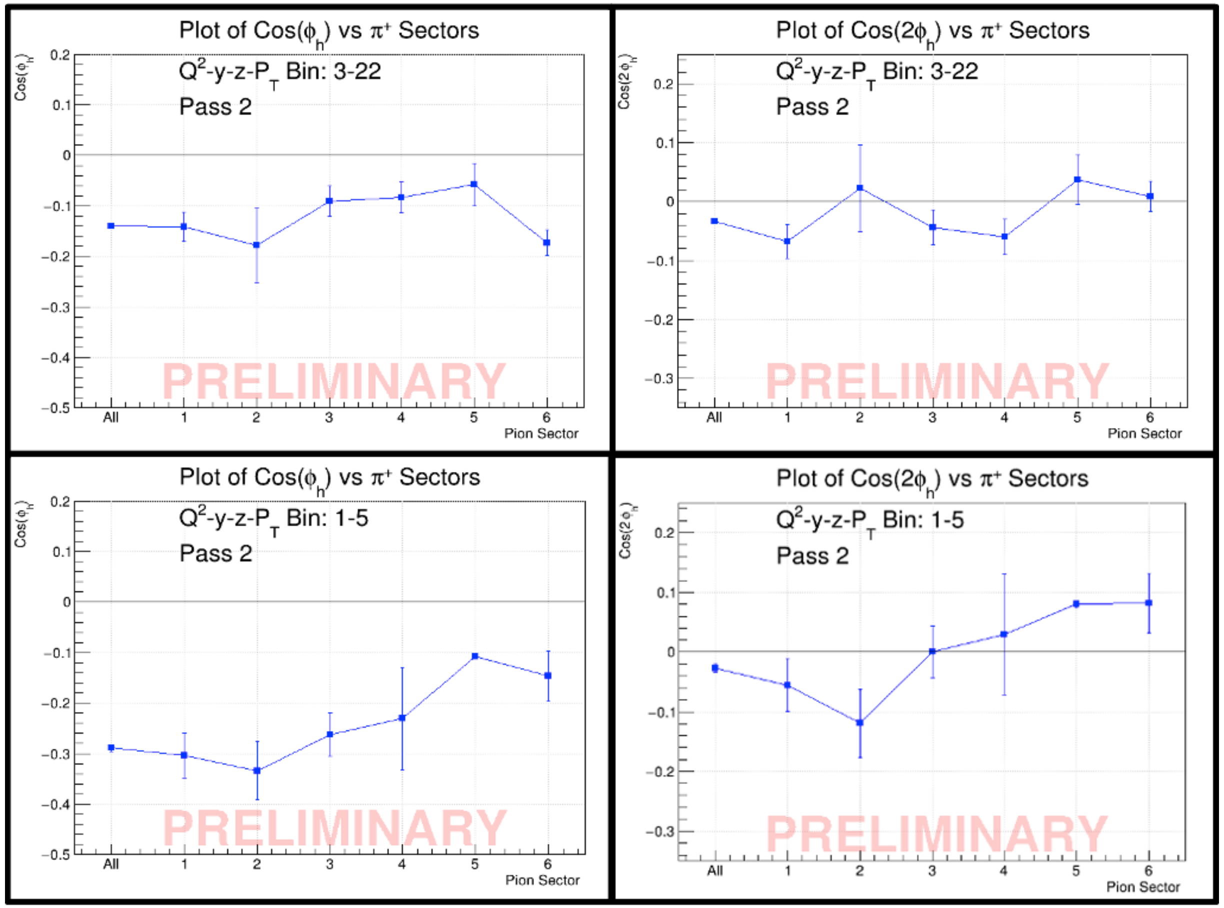


← Much better agreement between the lab angles of both particles

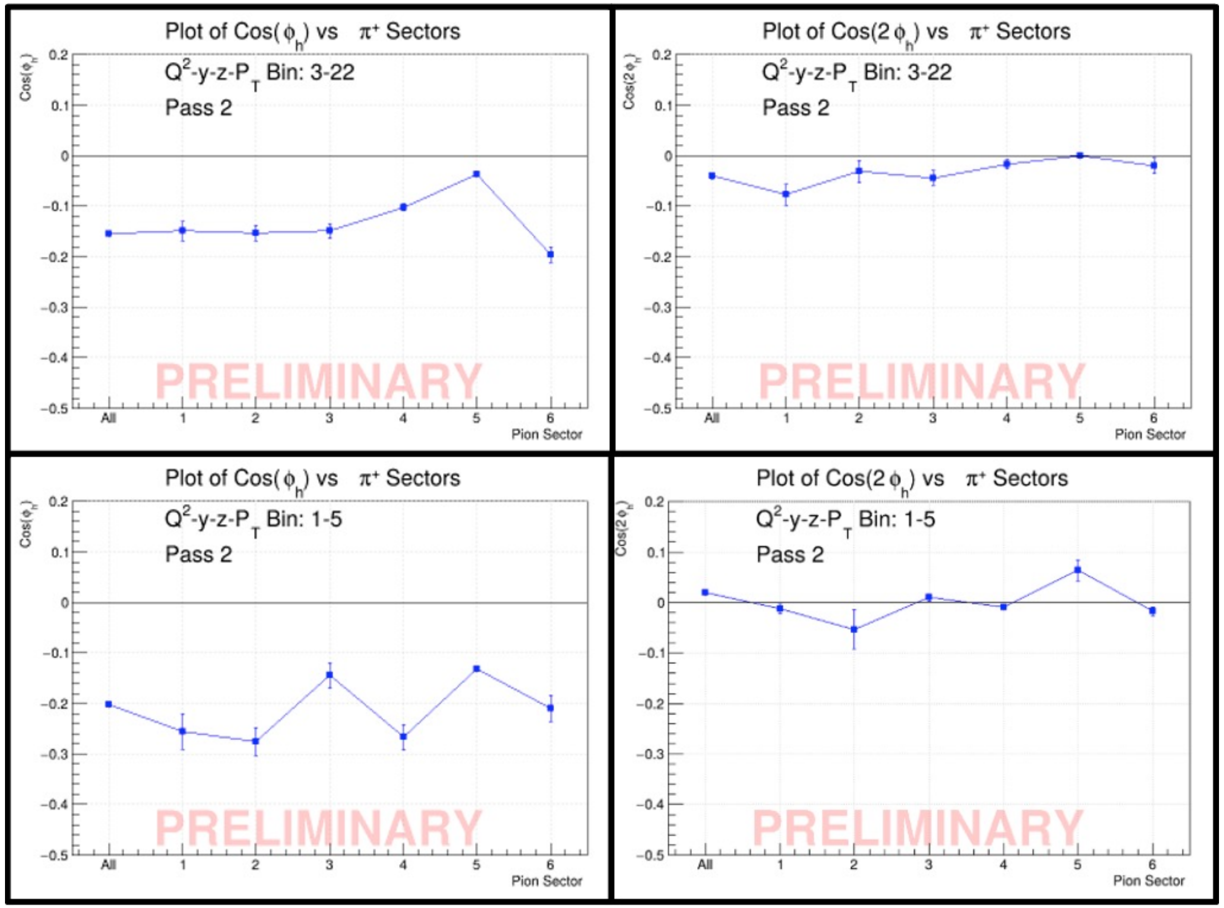
The cuts start to reduce the additional modulations for a smoother distribution of ϕ_h

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

Before Newest Fiducial Cuts



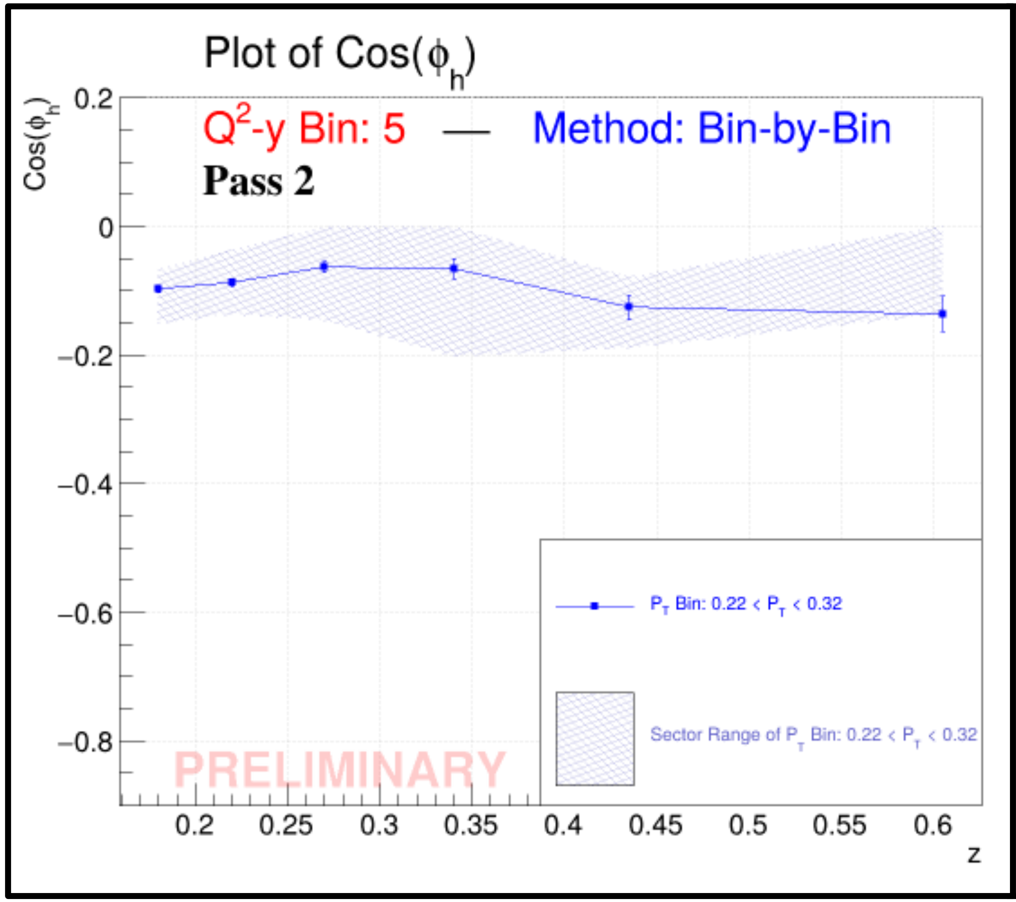
After Newest Fiducial Cuts

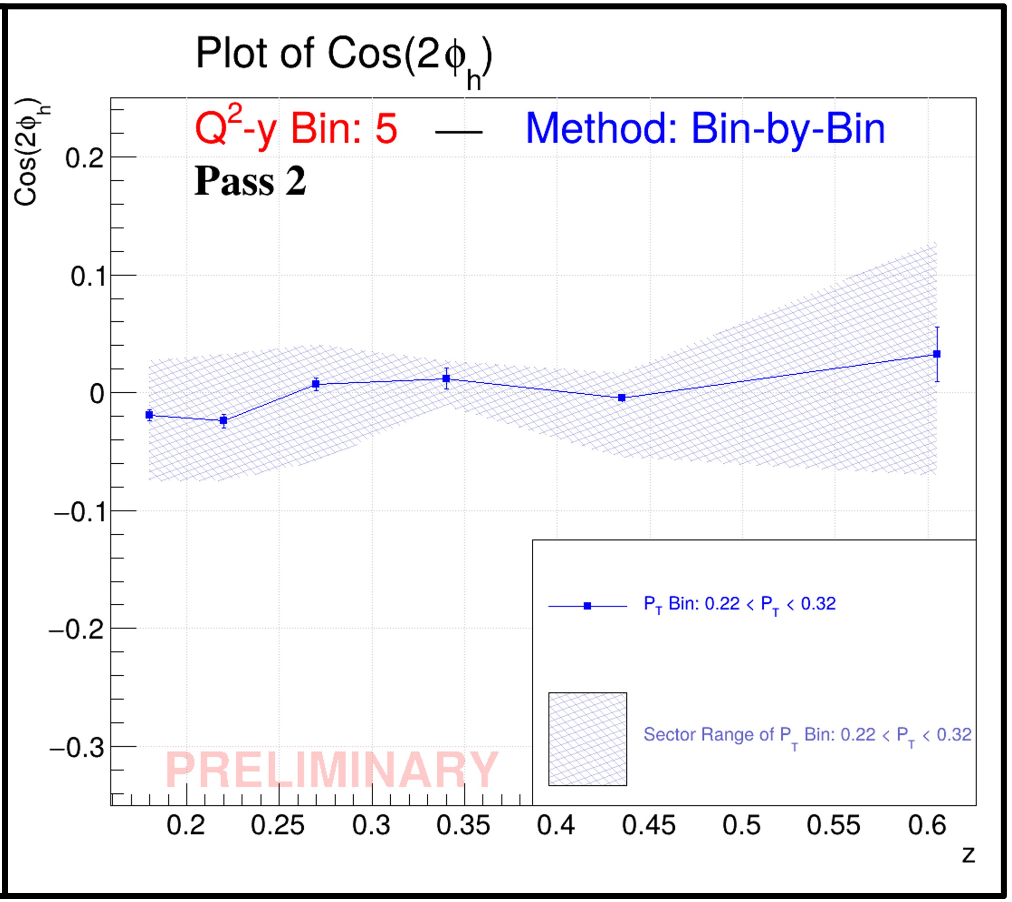


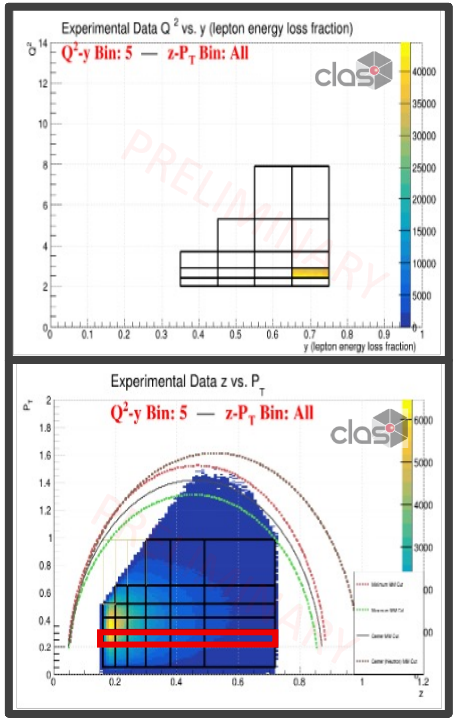
The new Fiducial Cuts reduce Sector dependence across many of my kinematic bins, though some dependence still remains

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

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

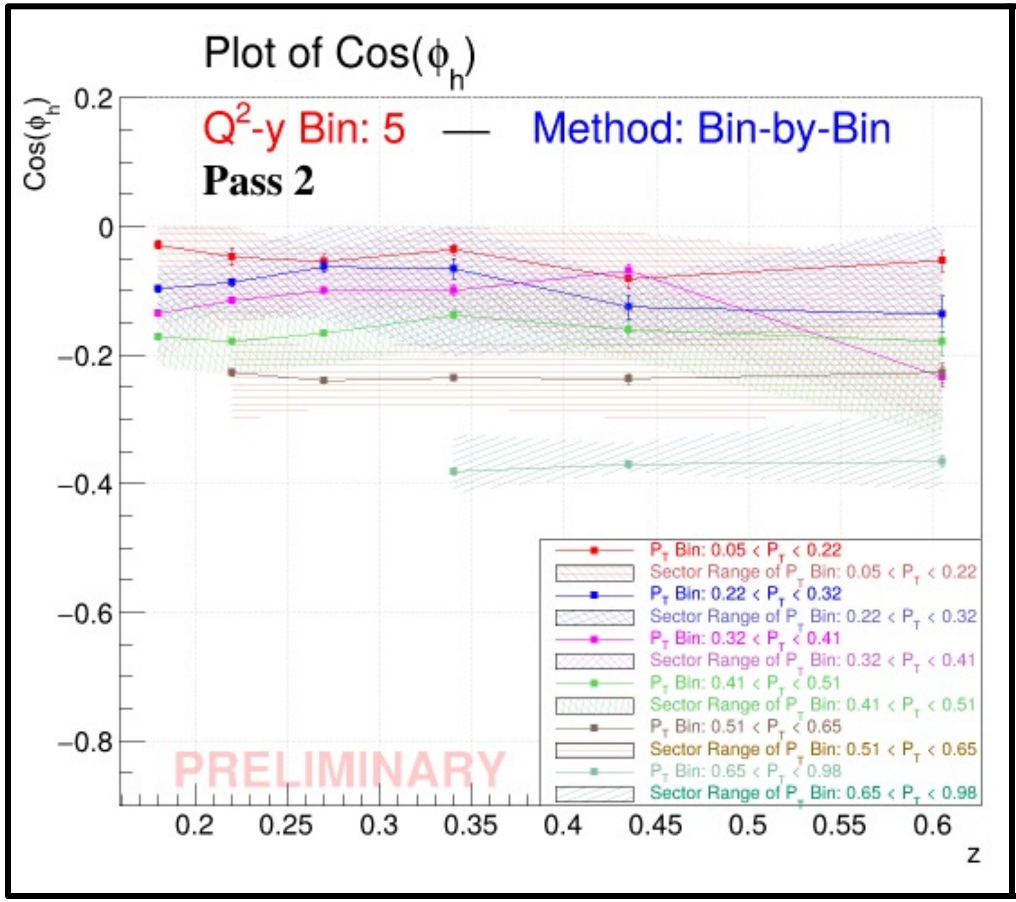


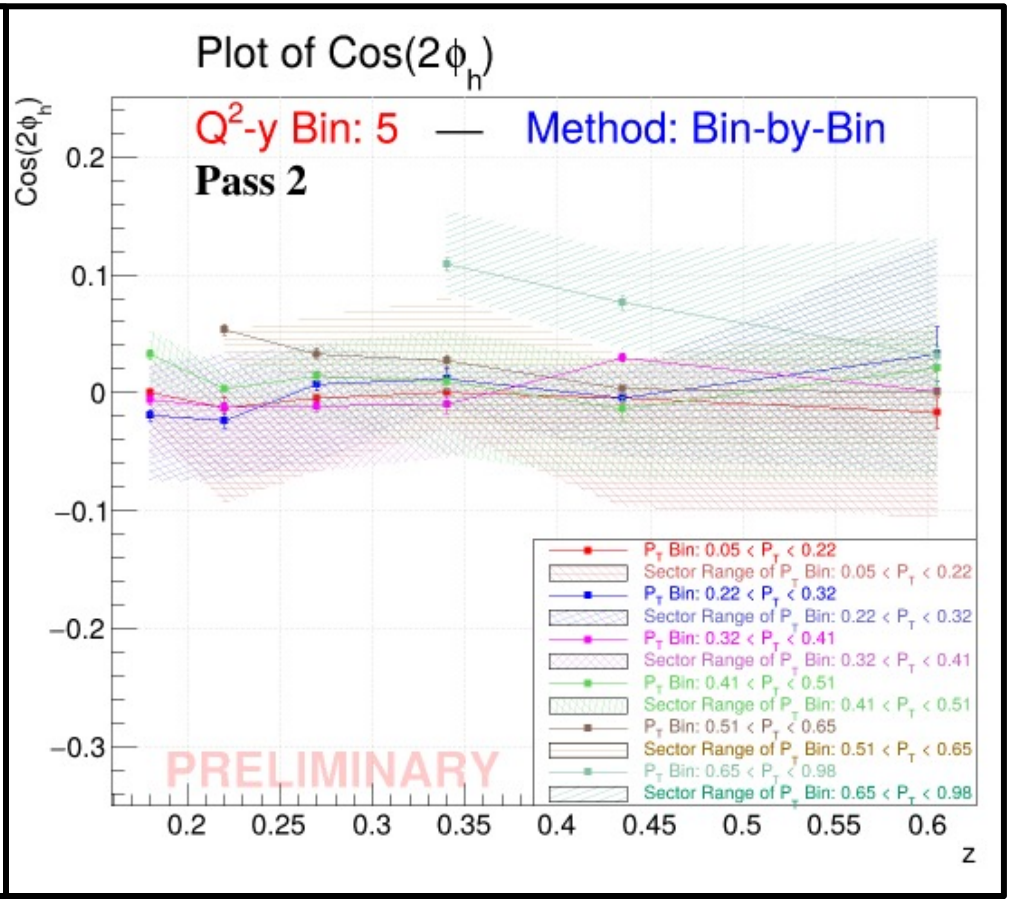


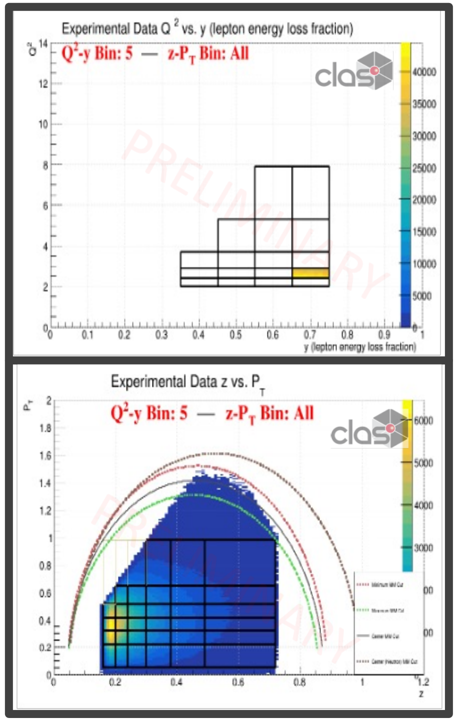


The shaded regions show the ranges of sector dependence on these measurements

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



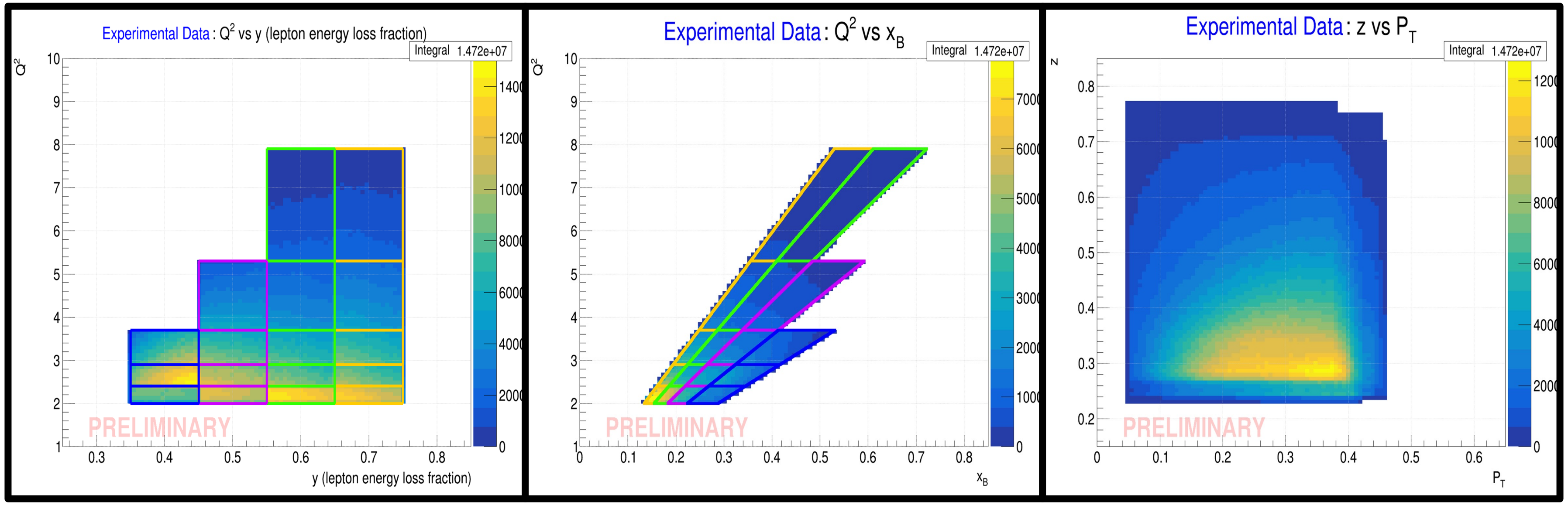




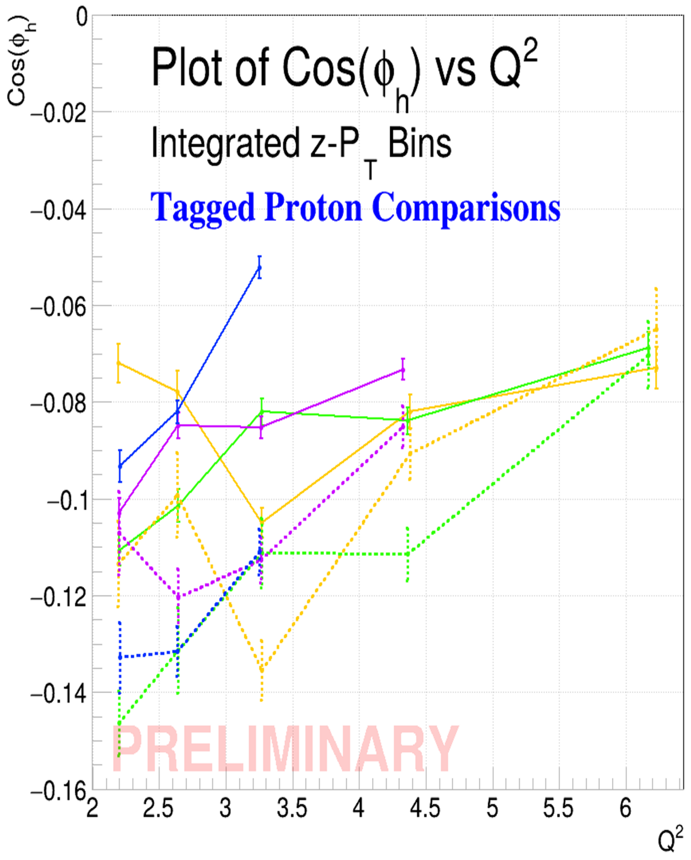
The shaded regions show the ranges of sector dependence on these measurements

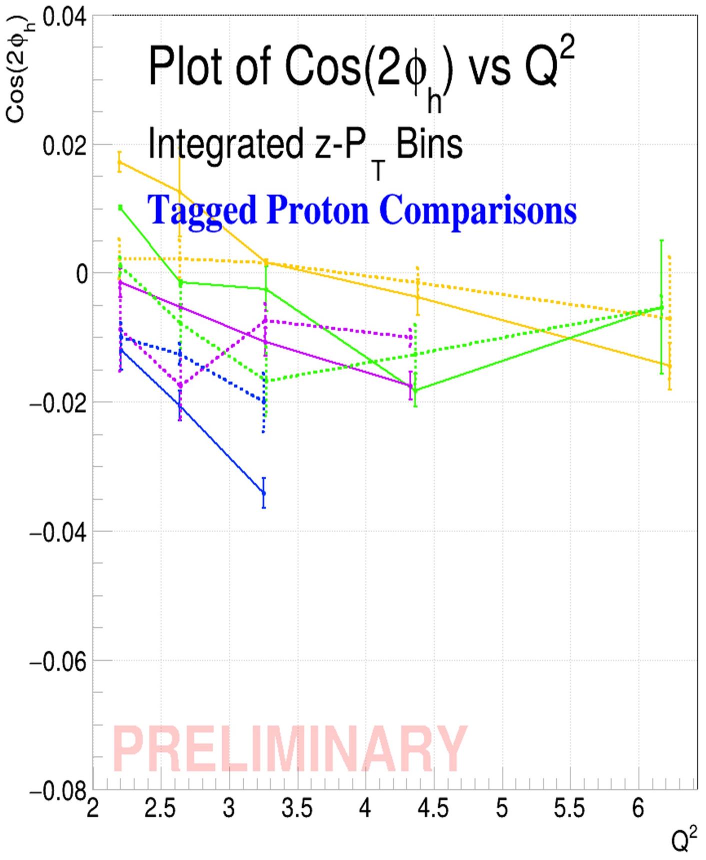
Introduction to Proton Tagging Cuts

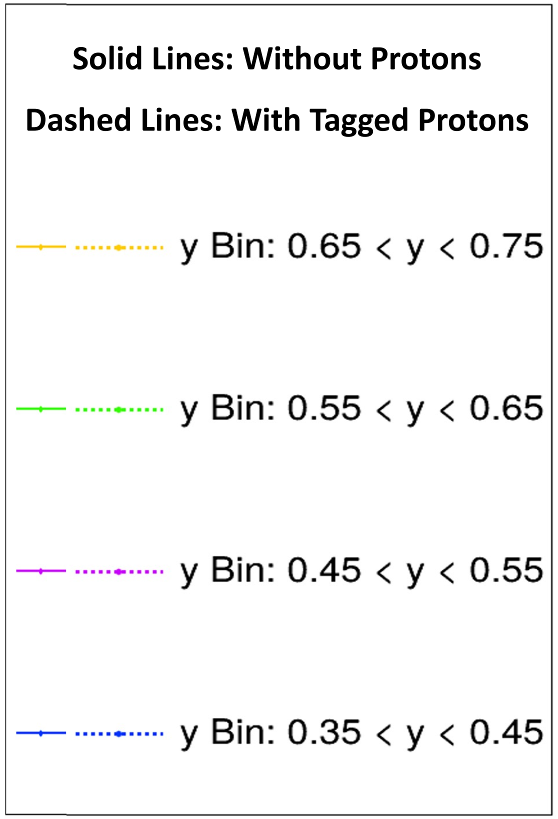
- To study contributions from exclusive ρ^0 productions, a cut was developed with Harut Avakian
  - Cut required the proton to be tagged
  - The cut requires **$M_X > 1.35$ GeV** based on the ep→e'p'(X) events within my SIDIS sample
- To demonstrate the effects of this procedure, the following slides will show the Cosine Moments' dependence on Q^2, x_B, and y in the following regions with/without the Tagged Proton/Cuts
  - Results integrated within z-P_T ranges of **z: 0.23-0.77** and **P_T: 0.05-0.46**

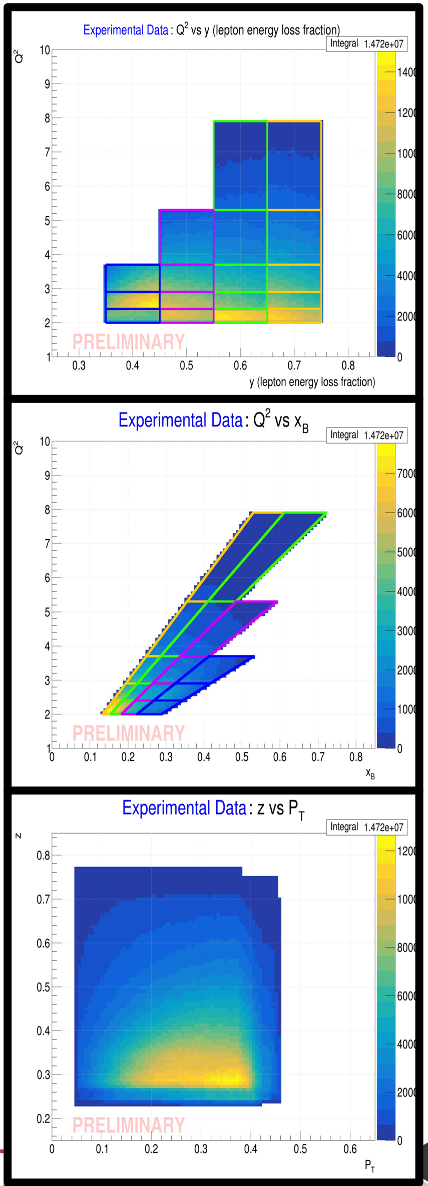


Cos(ϕ) and Cos(2ϕ) as functions of Q^2 and y - Tagged Proton







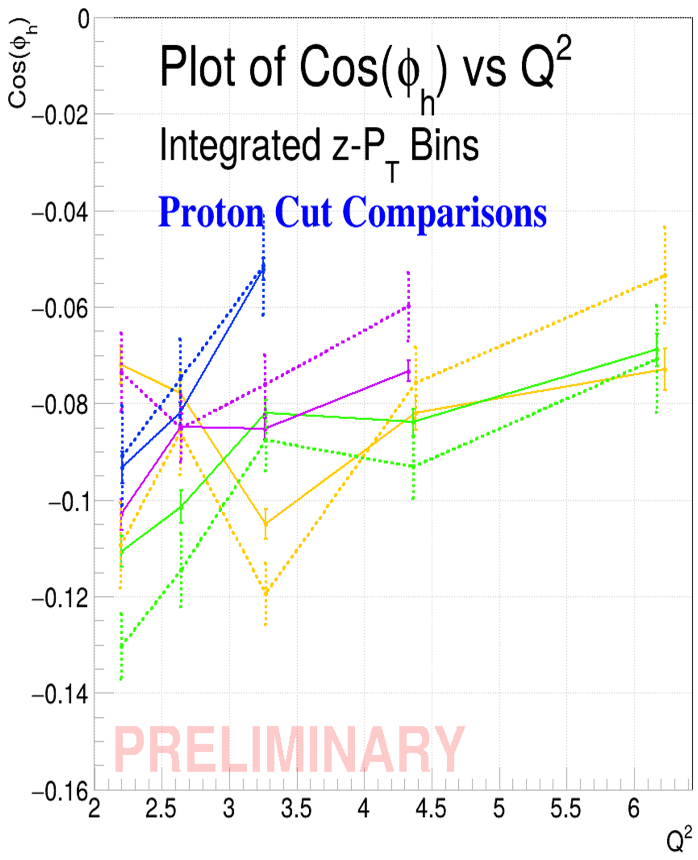


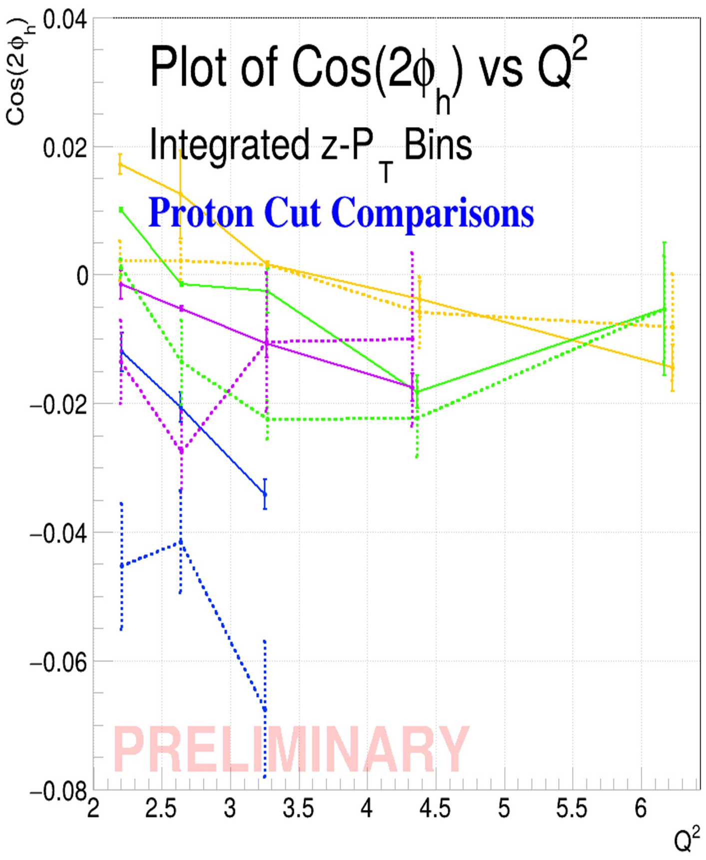
Magnitude of Cos(ϕ) decreases as a function of Q^2 for fixed y

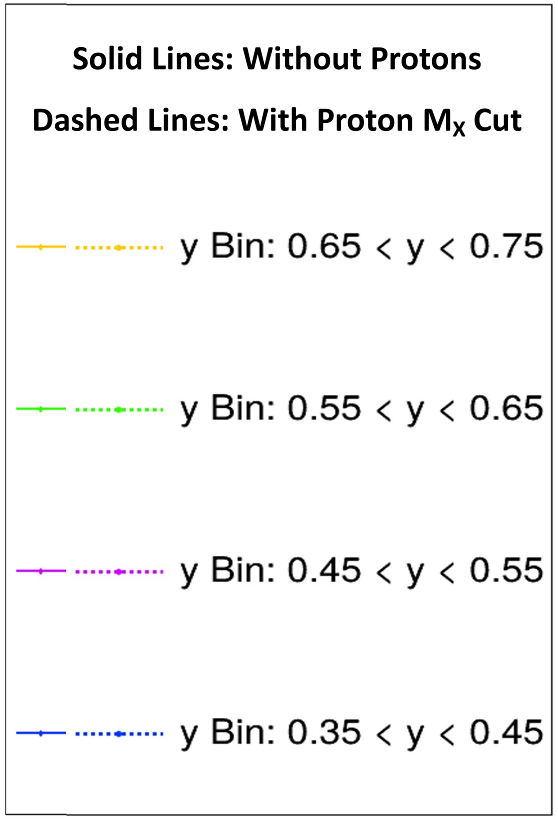
Impact of Just Tagging the Proton on the Moment Measurements:

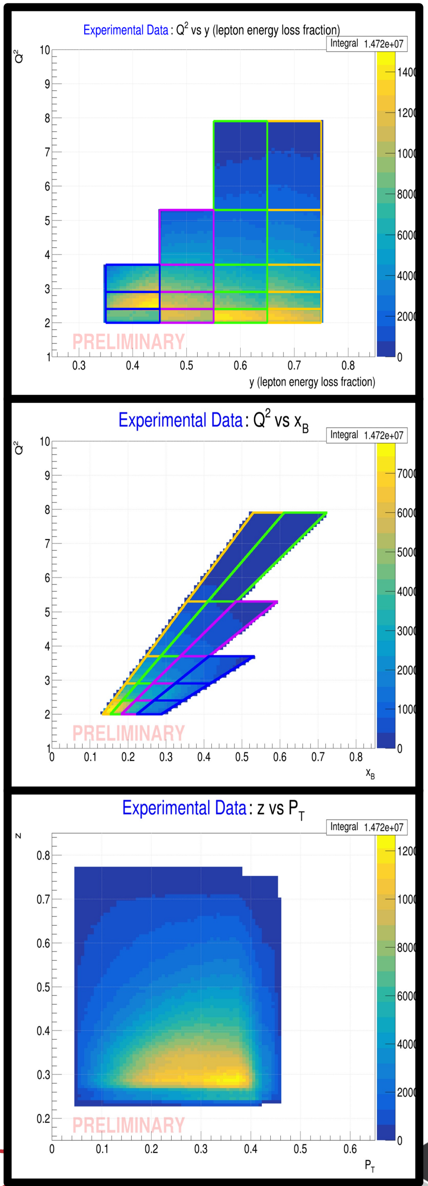
- Magnitude of Cos(ϕ) at lower Q^2 increases with the Tagged Proton (converges back to more similar values at higher Q^2)
- Magnitude of Cos(2ϕ) decreases (especially at lower Q^2) with the Tagged Proton
- Behavior of the moments across different y bins seems consistent aside from the shifts in the magnitudes

Cos(ϕ) and Cos(2ϕ) as functions of Q^2 and y – M_X Cuts







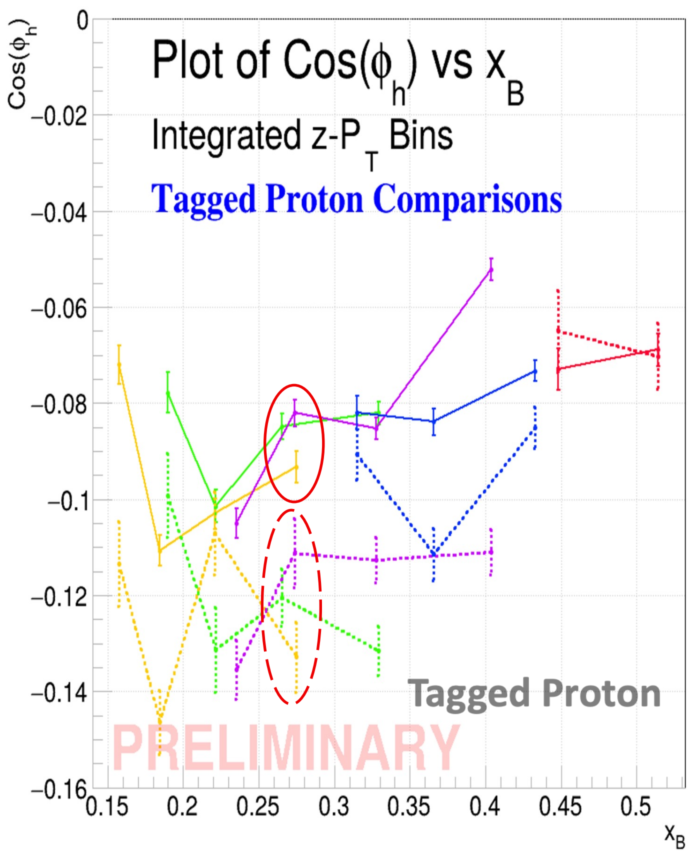


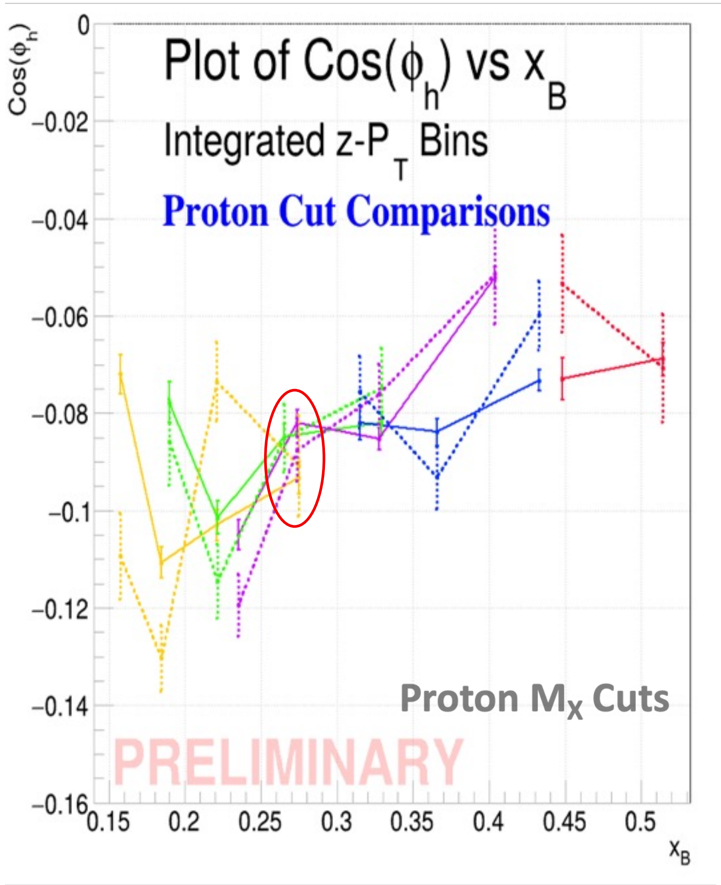
Magnitude of Cos(ϕ) decreases as a function of Q^2 for fixed y

Impact of Proton M_X Cuts on the Moment Measurements:

- Magnitude of Cos(ϕ) decreases in some regions of these plots (namely at higher Q^2/y bins)
- Magnitude of Cos(2ϕ) increases (or at least, becomes more negative)
- **All agree within ranges of statistical uncertainty**

Cos(ϕ) as functions of x_B and Q^2 - Tagged Proton/M_X Cut





Solid Lines: Without Protons

Dashed Lines:

- **(Left Plot) With Tagged Protons**
- **(Right Plot) With Proton M_X Cut**

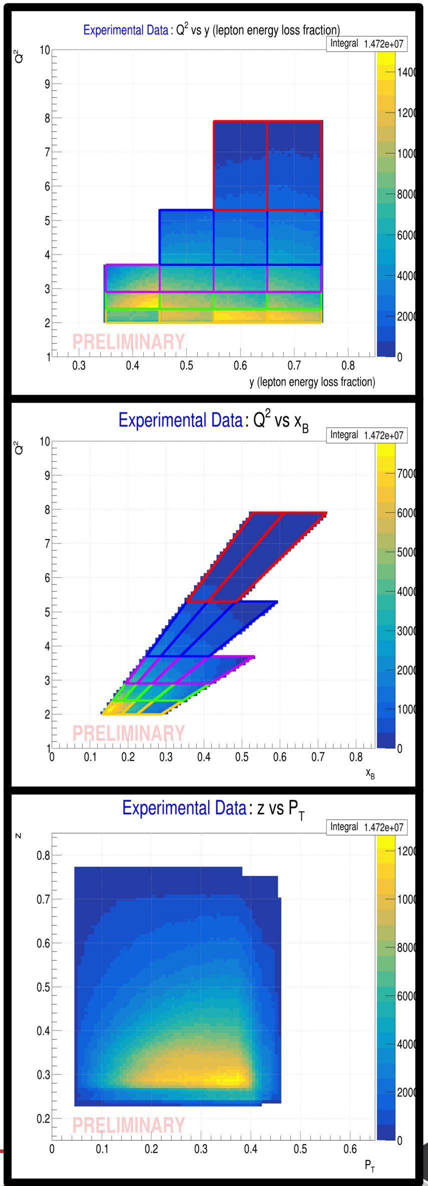
Q^2 Bin: $2.00 < Q^2 < 2.40$

Q^2 Bin: $2.40 < Q^2 < 2.90$

Q^2 Bin: $2.90 < Q^2 < 3.70$

Q^2 Bin: $3.70 < Q^2 < 5.30$

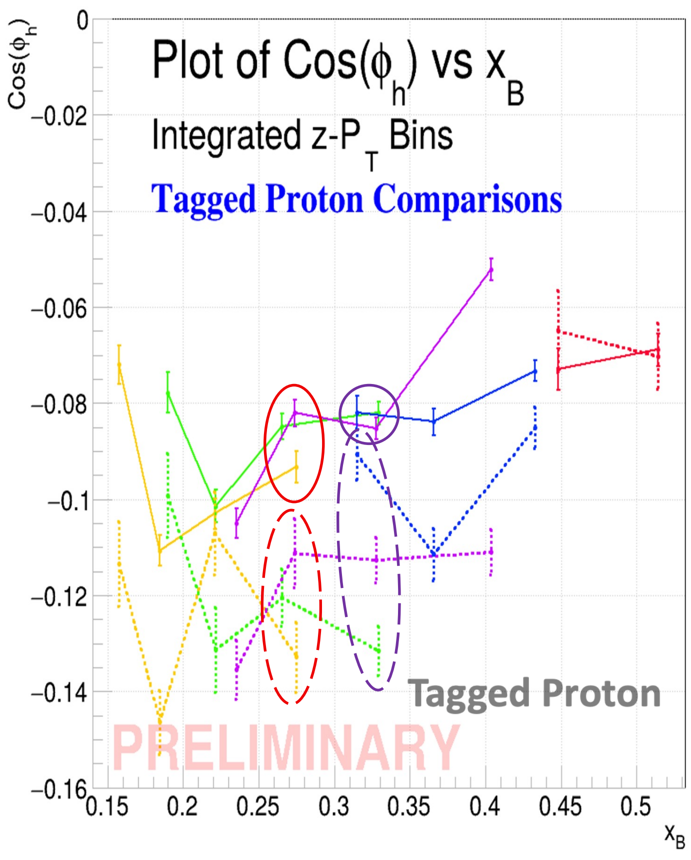
Q^2 Bin: $5.30 < Q^2 < 7.90$

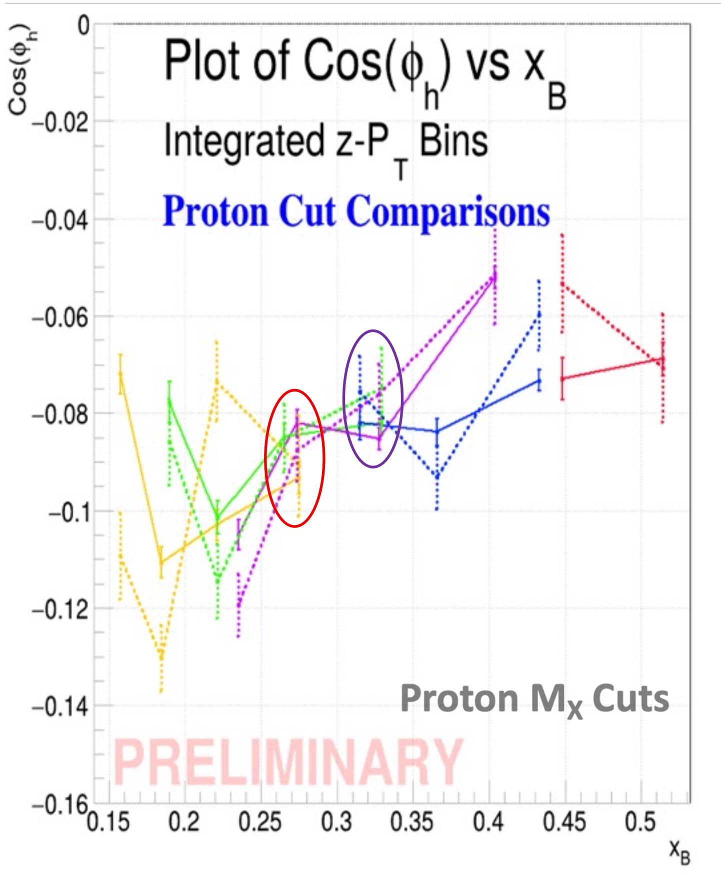


Magnitude of Cos(ϕ) decreases with increasing Q^2 at fixed x_B

Fixed x_B (~0.27): Tagging increases Cos(ϕ) magnitude but Q^2 dependence is mostly within statistical uncertainty

Cos(ϕ) as functions of x_B and Q^2 - Tagged Proton/M_X Cut





Solid Lines: Without Protons

Dashed Lines:

- **(Left Plot) With Tagged Protons**
- **(Right Plot) With Proton M_X Cut**

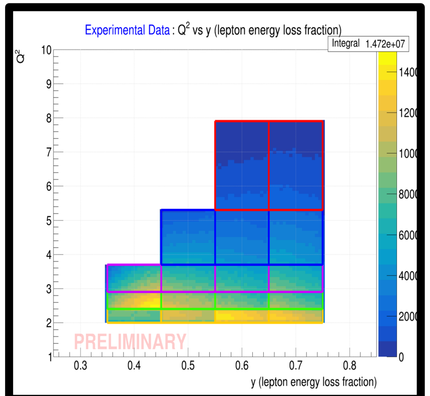
Q^2 Bin: $2.00 < Q^2 < 2.40$

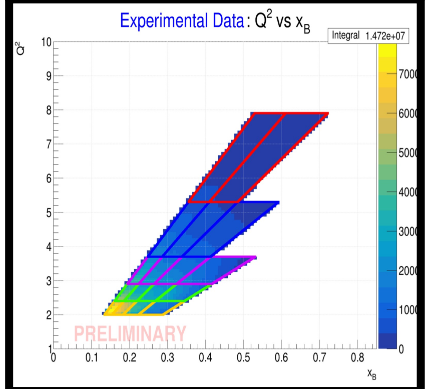
Q^2 Bin: $2.40 < Q^2 < 2.90$

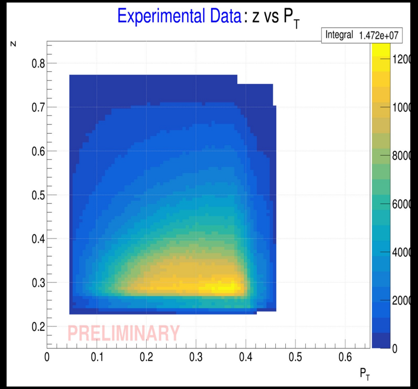
Q^2 Bin: $2.90 < Q^2 < 3.70$

Q^2 Bin: $3.70 < Q^2 < 5.30$

Q^2 Bin: $5.30 < Q^2 < 7.90$







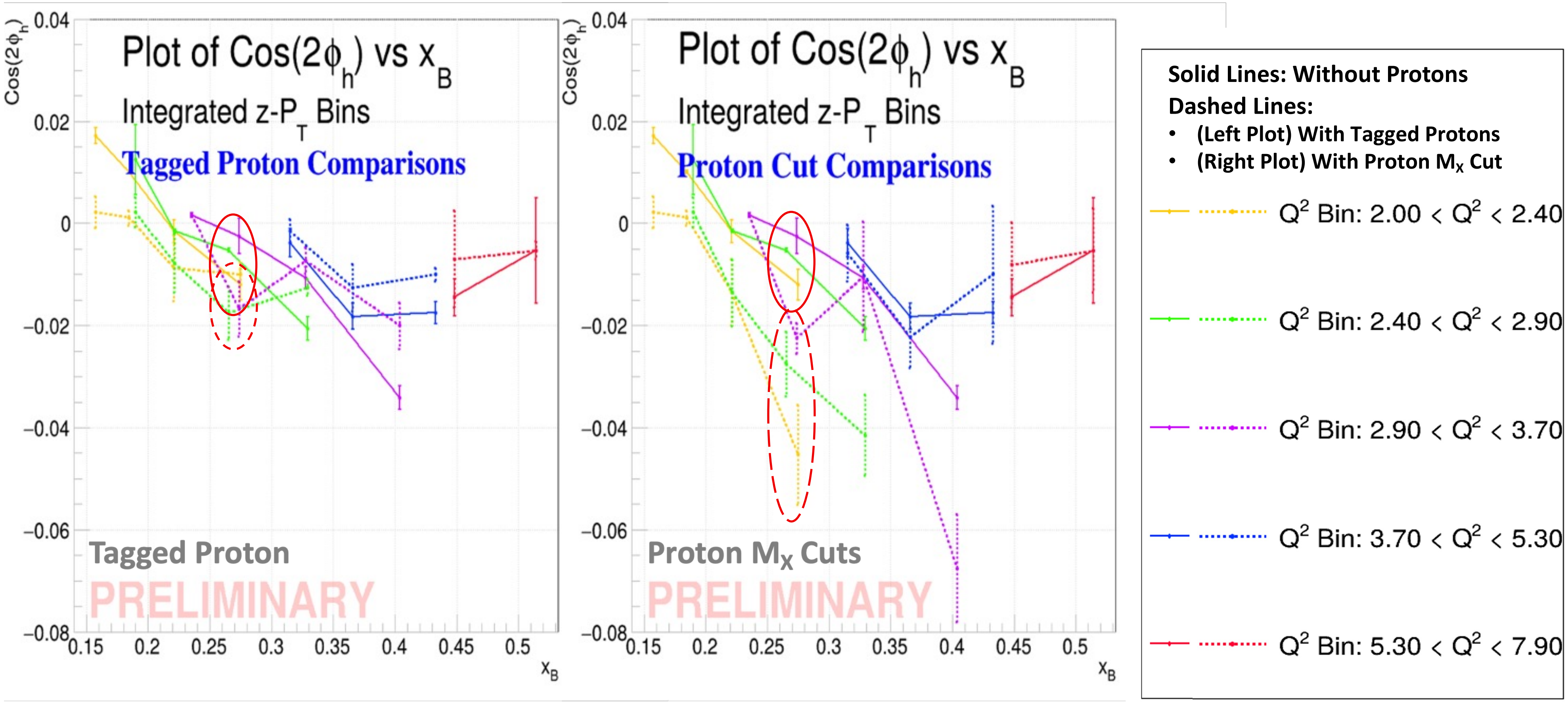
Magnitude of Cos(ϕ) decreases with increasing Q^2 at fixed x_B

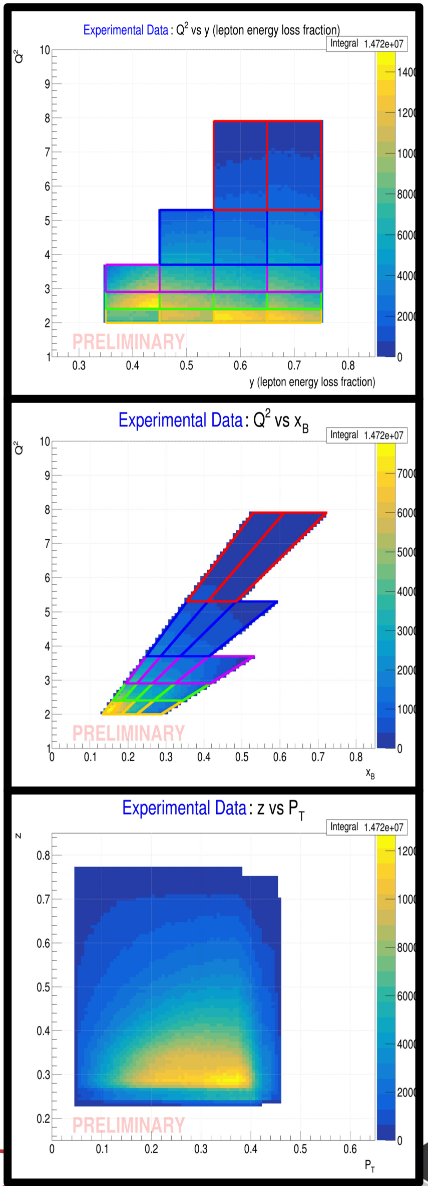
Fixed x_B (~0.27): Tagging increases Cos(ϕ) magnitude but Q^2 dependence is mostly within statistical uncertainty

Fixed x_B (~0.32): Tagging significantly increases Q^2 dependence of Cos(ϕ)

The points with the Proton M_X cut are within the statistical uncertainties of the Untagged Proton measurements

Cos(2ϕ) as functions of x_B and Q^2 - Tagged Proton/M_X Cut



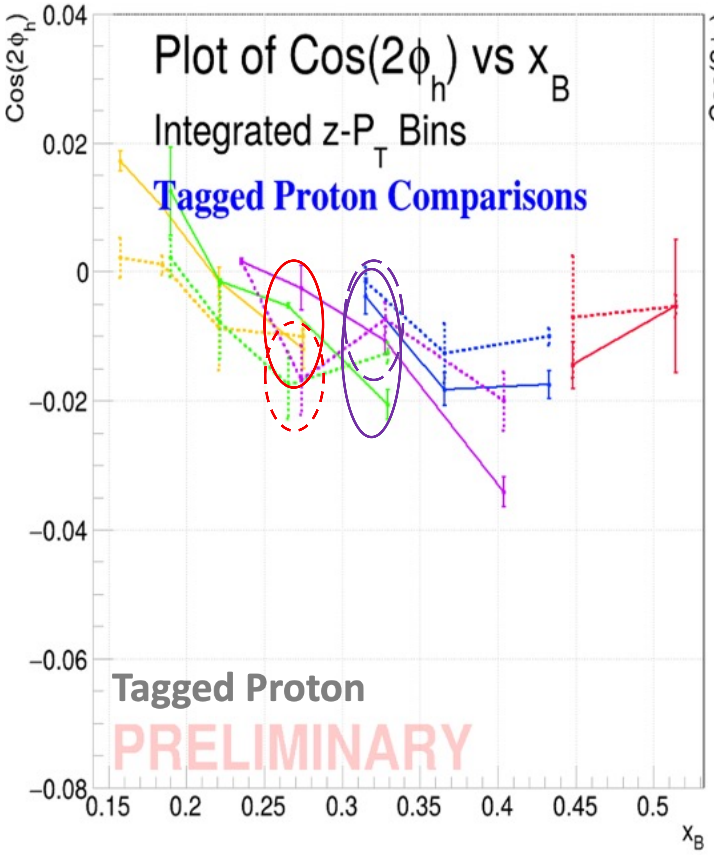


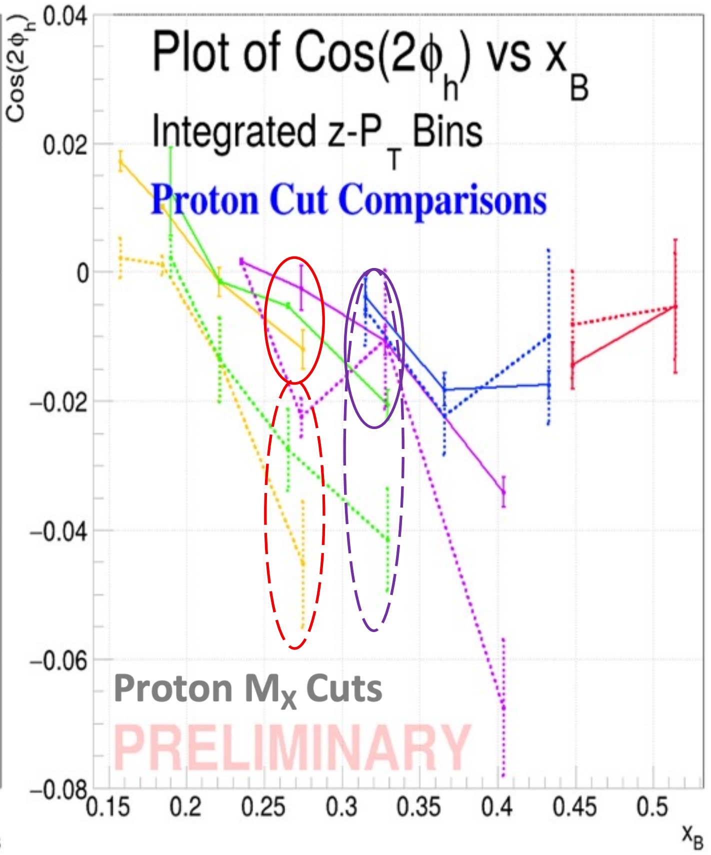
Magnitude of Cos(2ϕ) becomes more negative with increasing x_B at fixed Q^2

Fixed x_B (~0.27): The M_X cut increases Cos(2ϕ) magnitude and increases Q^2 dependence (and uncertainty…)

Tagging slightly increases the magnitude, but this increase and the Q^2 dependence are within statistical uncertainty

Cos(2ϕ) as functions of x_B and Q^2 - Tagged Proton/M_X Cut





Solid Lines: Without Protons

Dashed Lines:

- **(Left Plot) With Tagged Protons**
- **(Right Plot) With Proton M_X Cut**

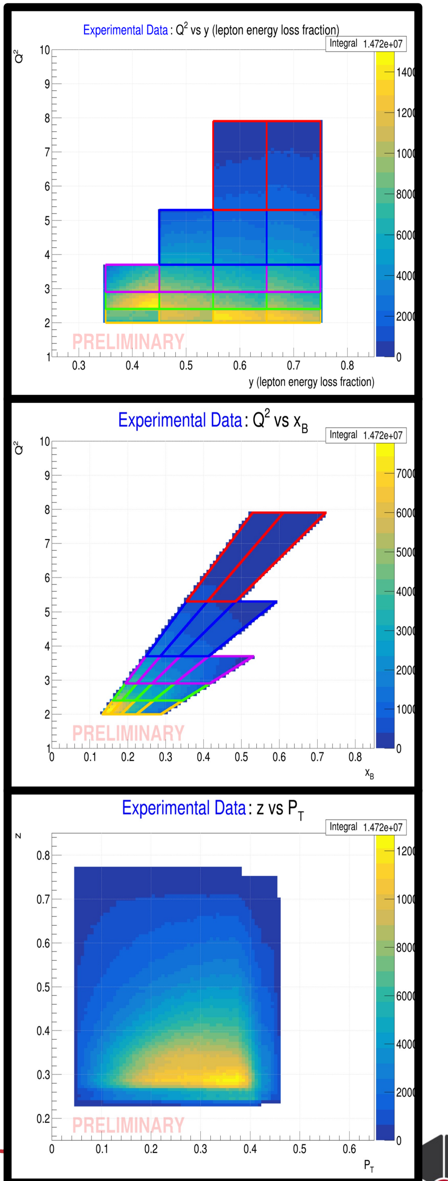
Q^2 Bin: $2.00 < Q^2 < 2.40$

Q^2 Bin: $2.40 < Q^2 < 2.90$

Q^2 Bin: $2.90 < Q^2 < 3.70$

Q^2 Bin: $3.70 < Q^2 < 5.30$

Q^2 Bin: $5.30 < Q^2 < 7.90$



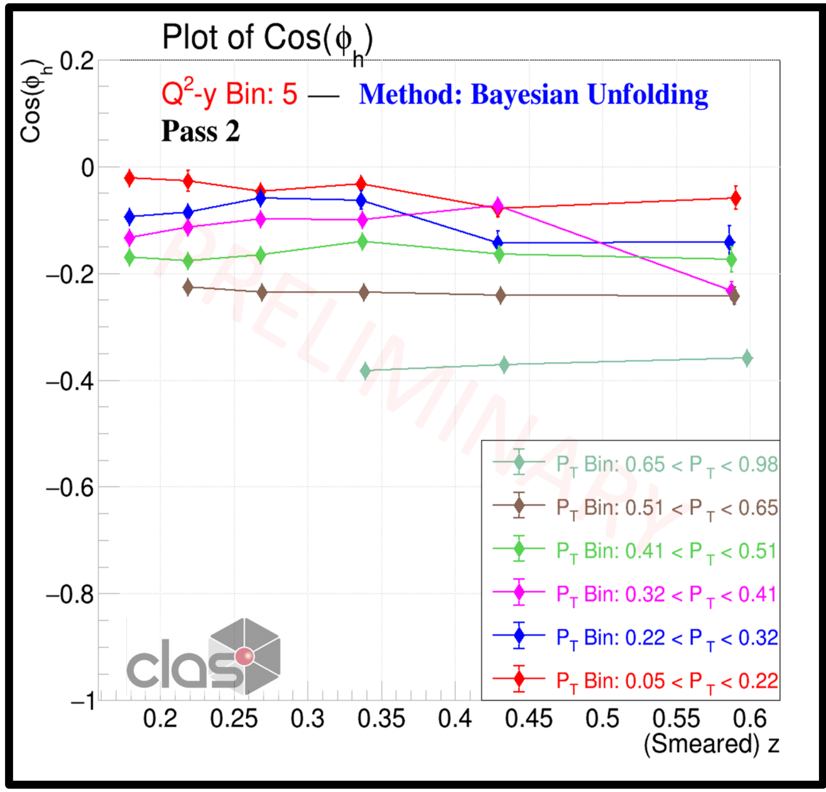
Magnitude of Cos(2ϕ) becomes more negative with increasing x_B at fixed Q^2

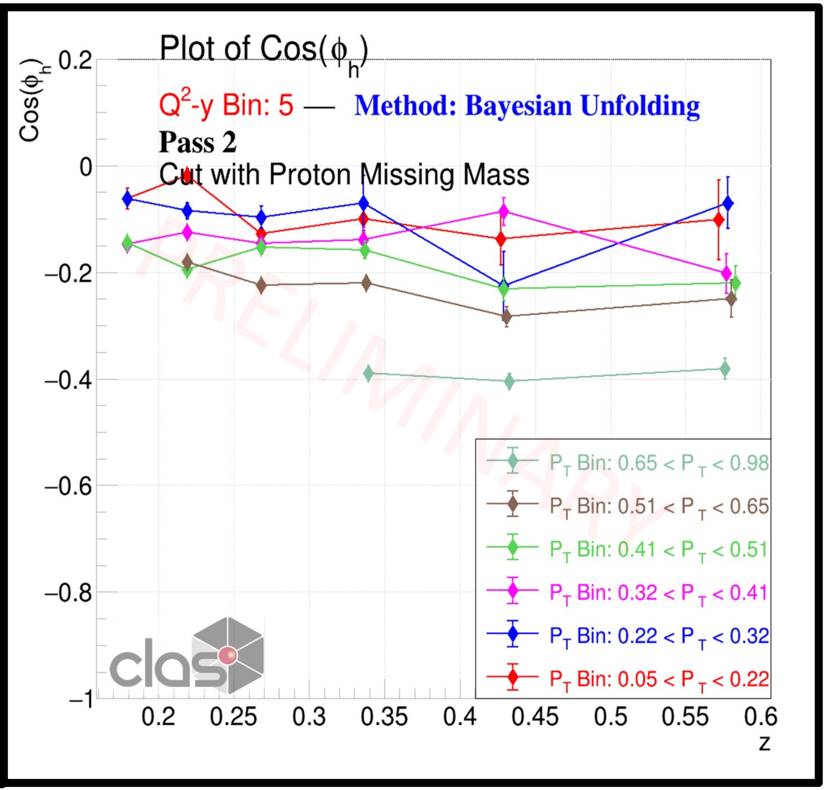
Fixed x_B (~0.27): The M_X cut increases Cos(2ϕ) magnitude and increases Q^2 dependence (and uncertainty…)
Tagging slightly increases the magnitude, but this increase and the Q^2 dependence are within statistical uncertainty

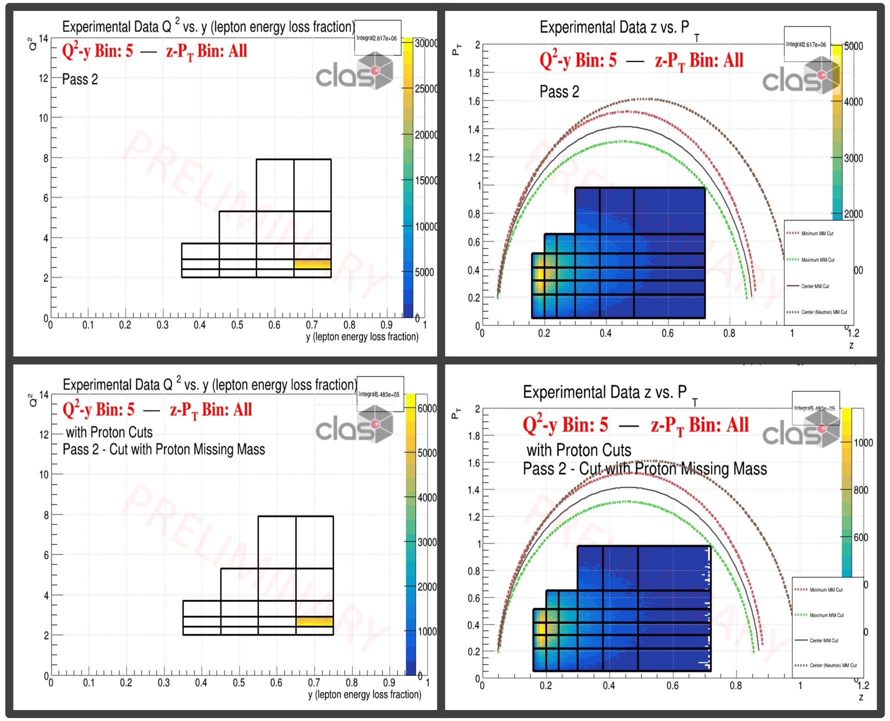
Fixed x_B (~0.32): Both are mostly within statistical uncertainty, with a single exception for low Q^2 with the M_X cut

Cos(ϕ) Moments as Functions of z

Unfolded with Bayesian Method | **Q^2-y Bin 5**







- Magnitude of Cos(ϕ) is consistent with increasing z for fixed P_T
- At fixed z, it increases with higher P_T

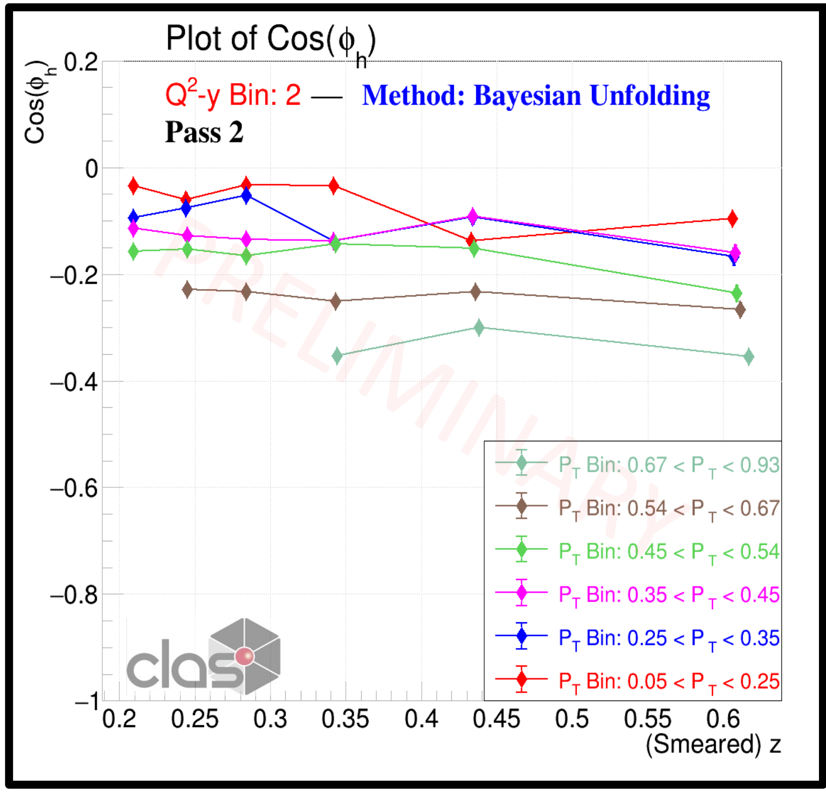
- The Proton M_X Cut causes more fluctuations but is overall consistent with the untagged measurements (differences most likely due to statistics)

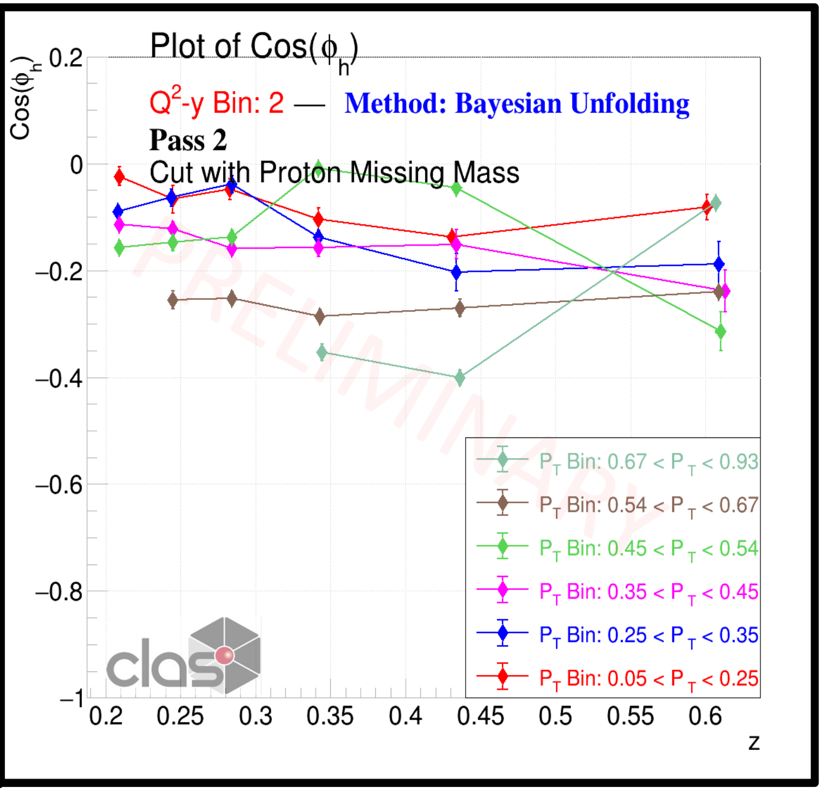
Cos(ϕ) Moments as Functions of z

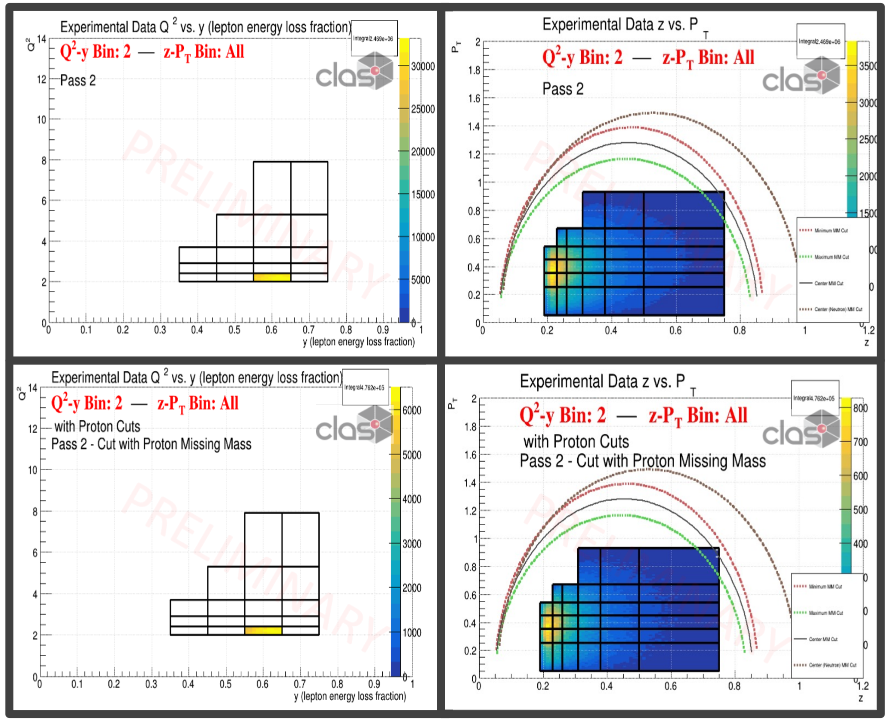
Unfolded with Bayesian Method

Q^2-y Bin 2

Lower Q^2 and y but has consistent x_B





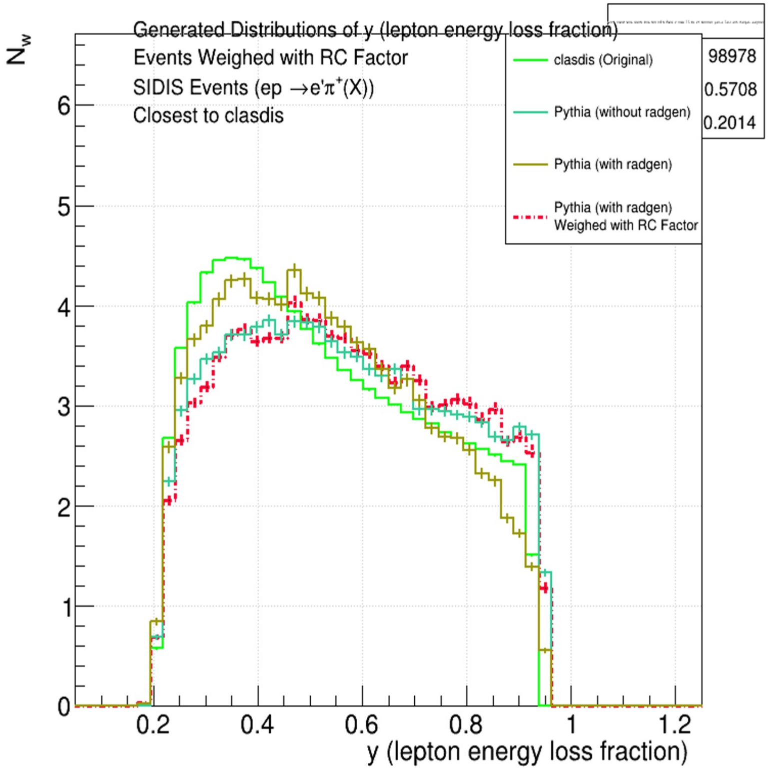


- Magnitude of Cos(ϕ) is consistent with increasing z for fixed P_T
- At fixed z, it increases with higher P_T

- The Proton M_X Cut causes more fluctuations but is overall consistent with the untagged measurements (differences most likely due to statistics)
- **z/P_T dependence is consistent in other Q^2-y bins for a fixed region of x_B**

Outlook on Radiative Effects with RADGEN

- I've been working on incorporating RADGEN into my Monte Carlo Simulations to help develop Radiative Corrections in this analysis
- Using RADGEN requires me to switch from using 'clasdis' to Pythia for event generation
  - The version of Pythia used is a (slightly) modified version of Pythia 6 used by the EIC, with changes having been made to more closely resemble the 'clasdis' and 'claspyth' event generators already available on the OSG



- clasdis (Original) → Uses the existing 'clasdis' generated MC already used in my analysis
- Pythia (without radgen) → Uses the version of Pythia **without** turning on RADGEN
- Pythia (with radgen) → Uses the version of Pythia **with RADGEN** turned on
- Pythia (with radgen) Weighed with RC Factor → Reweighted version of **Pythia (with radgen)** using the correction factor provided by RADGEN
  - If RADGEN is working properly, this distribution should be equivalent to **Pythia (without radgen)**

Currently working on understanding the discrepancies between the non-radiative 'clasdis' and Pythia 6 generated distributions (still investigating details)

Summary

- Improved the amount of available MC statistics through more file production
- Improved the agreement between Data and MC files and reduced sector-dependent fluctuations in corrected ϕ_h distribution with improved fiducial cuts
- Investigating the impact of vector meson contributions via the Proton M_X cuts
- Investigating potential methods of introducing radiative effect through integrating RADGEN into my event generators
- Will be performing full closure tests to assess the reliability of unfolding procedures and assign systematic uncertainties

Thank you

Questions?

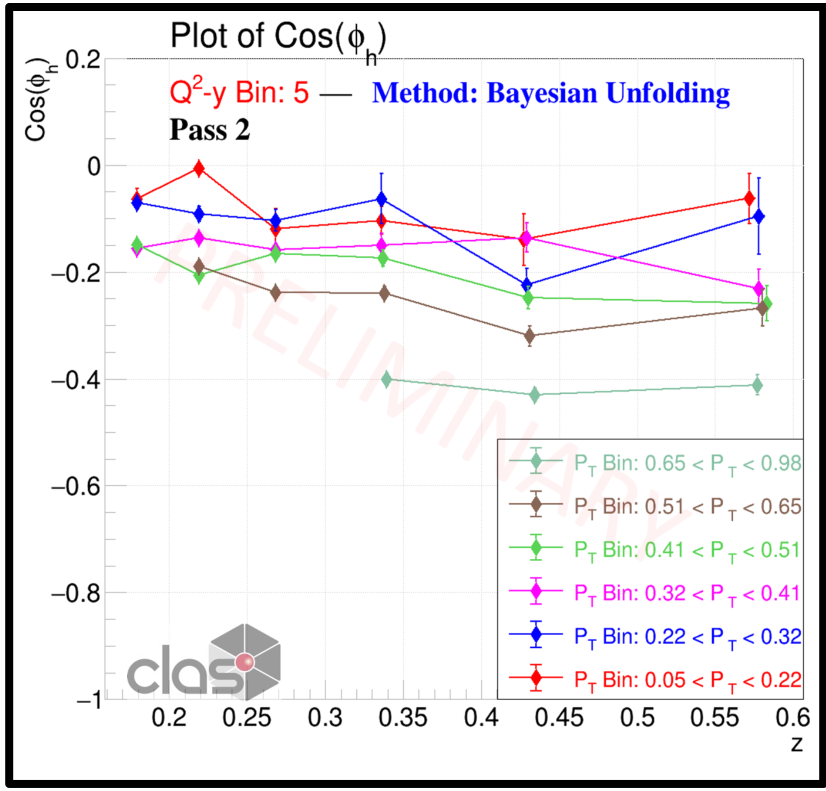
Acknowledgments and Thanks

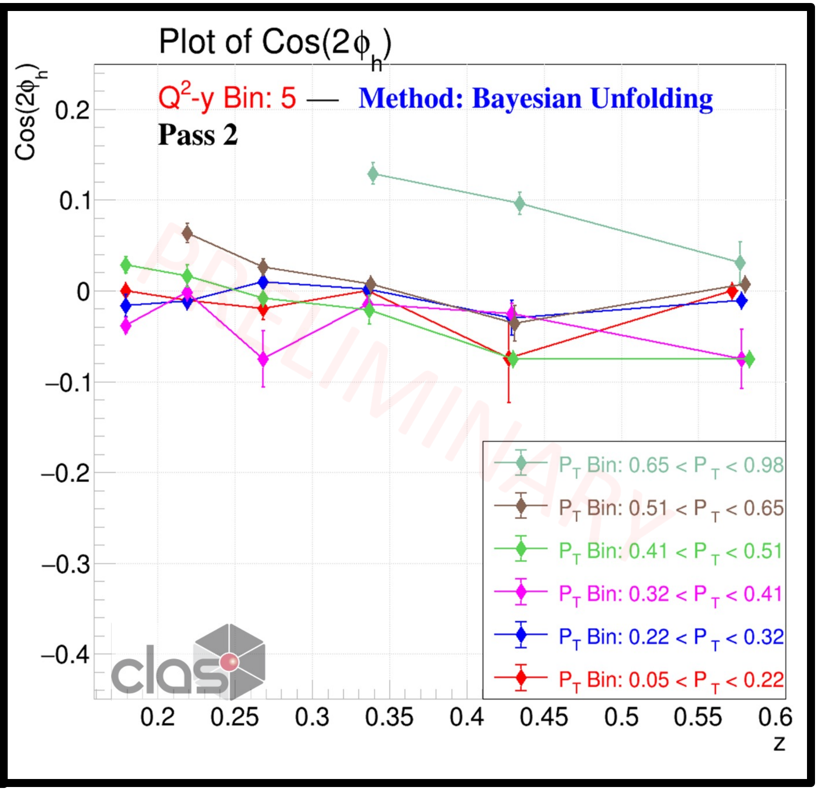
- Contributions made by other members of the CLAS Collaboration and researchers at Argonne National Lab
- This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract number DE-AC02-06CH11357

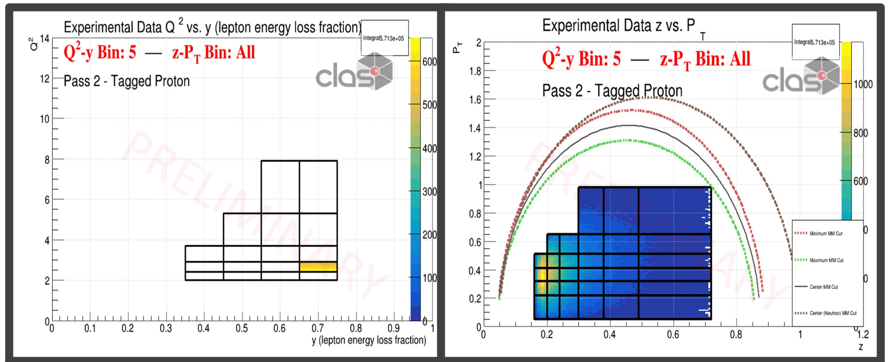
Backup Slides

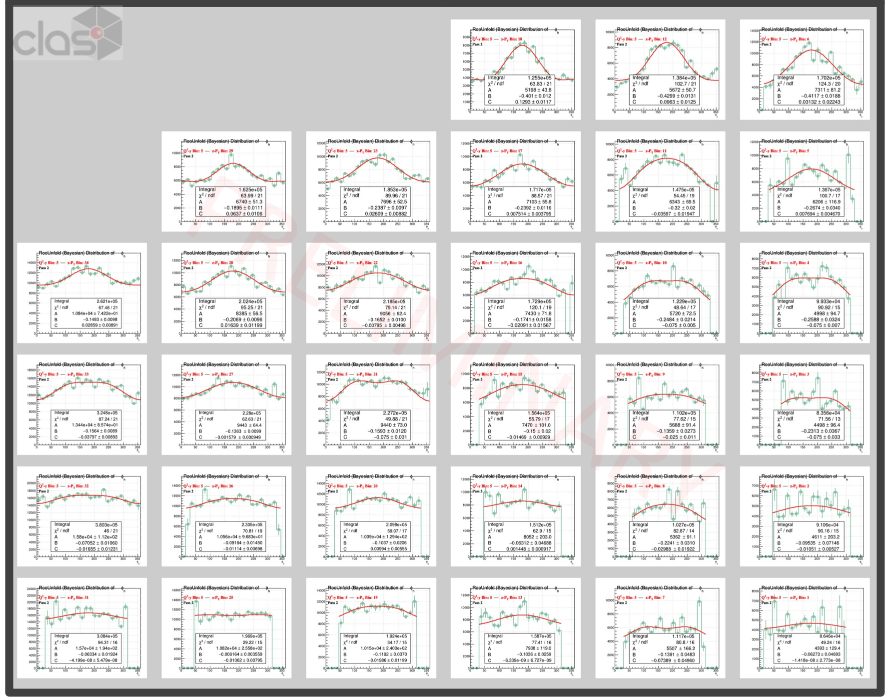
Cosine Moments as Functions of z – Tagged Proton

$B = A_{UU}^{\cos\varphi_h}$ $C = A_{UU}^{\cos 2\varphi_h}$	ϕ_h Plots were fitted with: $A(1 + B\cos(\phi_h) + C\cos(2\phi_h))$
Unfolded with Bayesian Method	Q^2-y Bin 5

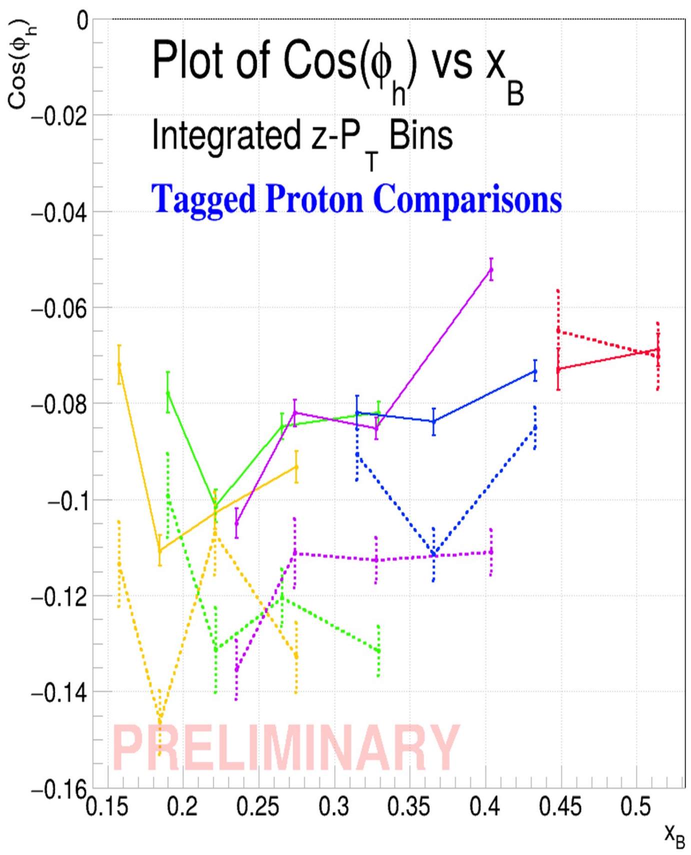


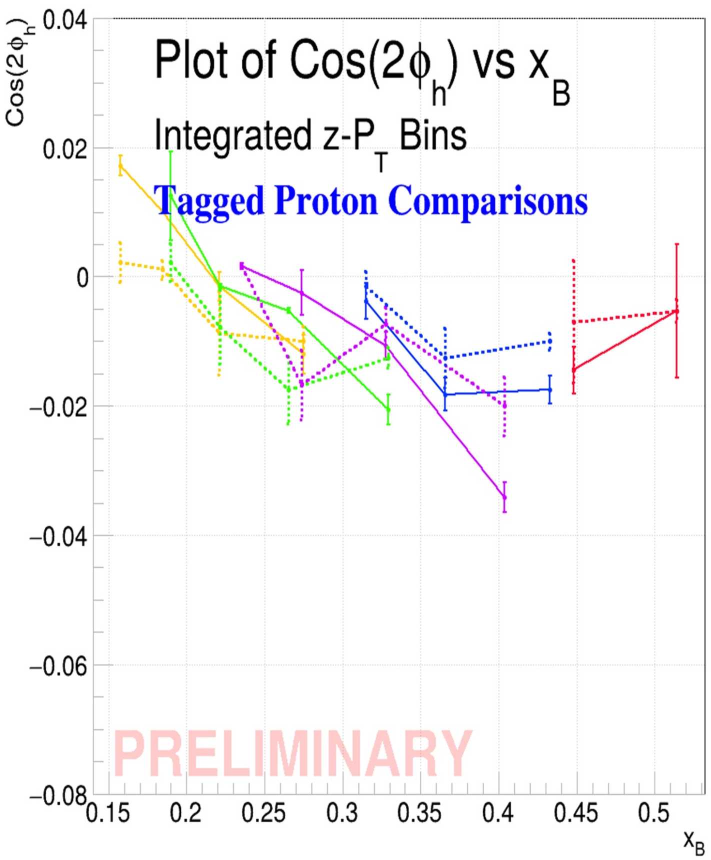


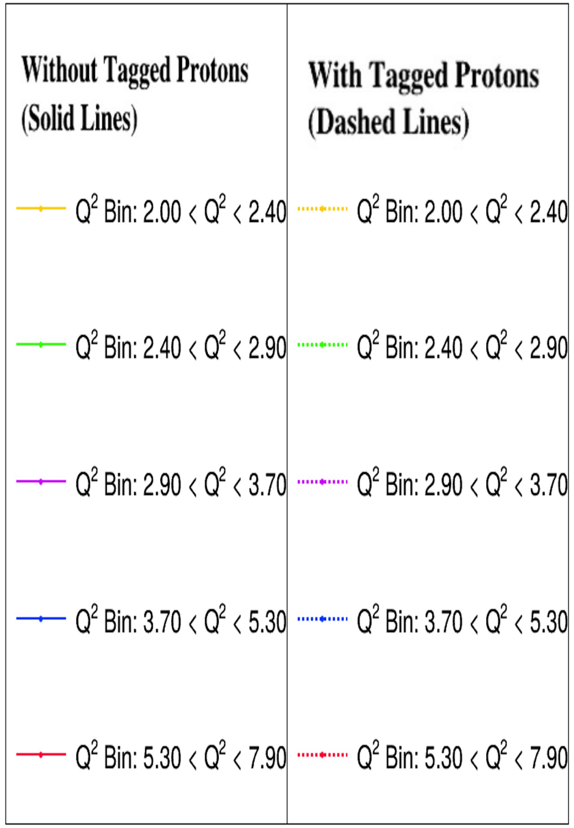


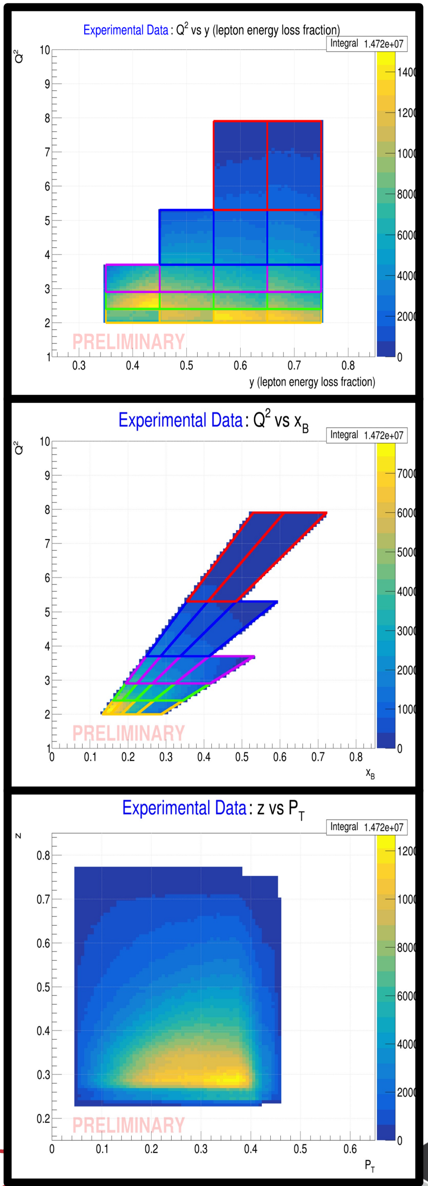


Cos(ϕ) and Cos(2ϕ) Measurements as functions of x_B - Tagged Proton

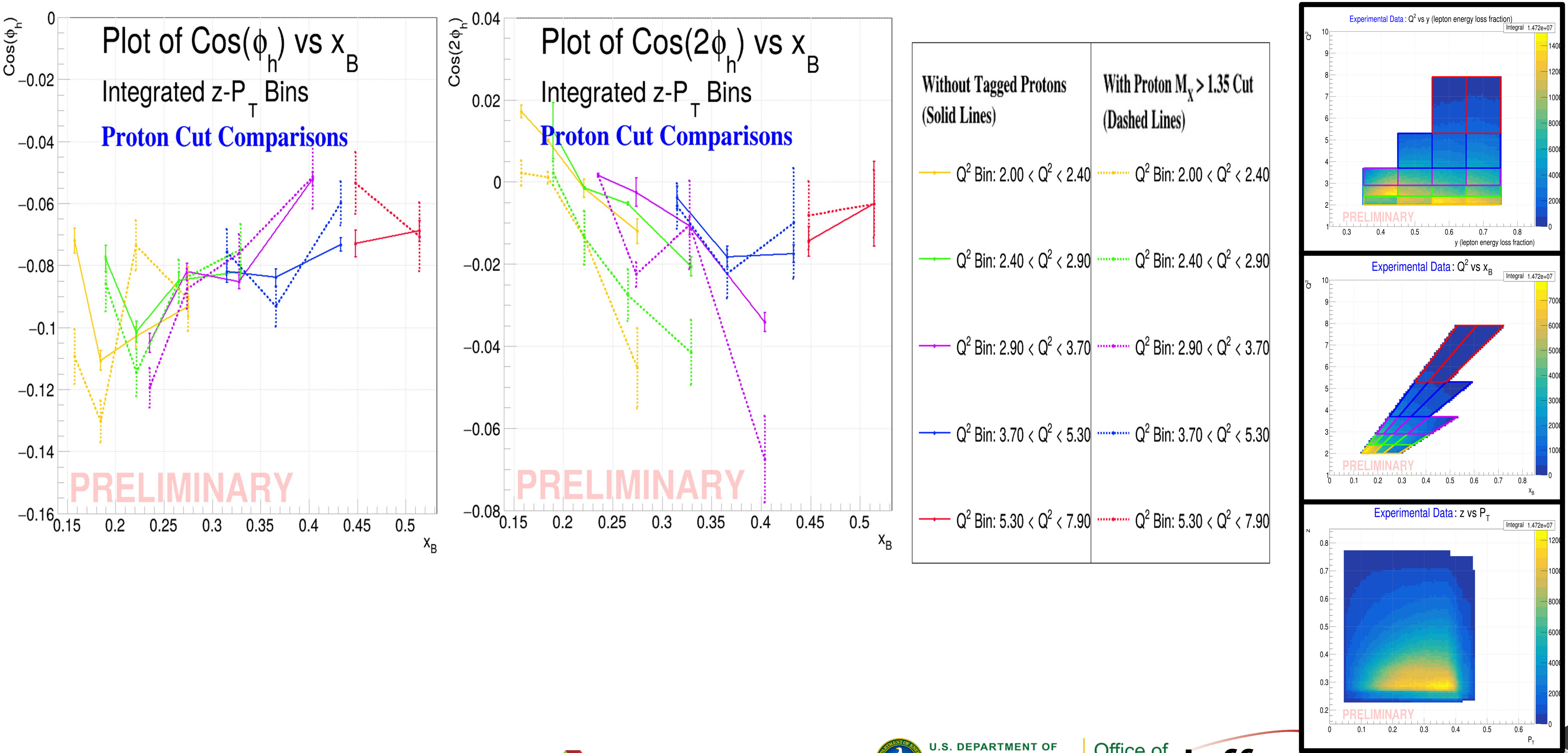








Cos(ϕ) and Cos(2ϕ) Measurements as functions of x_B – Proton Cuts



Configuration of Pythia with RADGEN

- Mainly used the configurations given by the 'claspyth' steering file: input.10.6gev.with-comments
  - Changes to the configurations detailed below

Ranges/Values used for generating Q^2, y, x_B, W^2, and the beam/target proton energies:

- **Q^2:** 0.85 to 20.0 GeV^2 (changed from the claspyth default of 0.00001 to 15.0 GeV^2)
- **y:** 0.15 to 0.95
- **x_B:** 0.05 to 0.95 (from clasdis)
- **W^2:** 4 GeV^2 (min)
- **Beam Energy:** 10.6 GeV
- **Proton Target Energy:** 0 GeV (at rest)

Additional changes added to better match clasdis:

- **Changed the F2-Model/R-Parametrization from "ALLM,1990" to "F2PY,1998"**
- **PARJ(33) = 0.8 changed to 0.3**
- **PARJ(41) = 0.3 changed to 1.2**

***PARJ(33)** defines the energy threshold stopping parton fragmentation and forming two hadrons.
***PARJ(41)** gives the '*a*' parameter of the symmetric Lund fragmentation function

Event Selection (Full PID)

The RG-A Analysis Overview and Procedures note goes into detail about the common particle identification scheme used for RG-A

(See: https://clas12-docdb.jlab.org/DocDB/0009/000949/001/RGA_Analysis_Overview_and_Procedures-08172020.pdf)

Electron PID Criteria:

- Detected in Forward Detector
- > 2 photoelectrons detected in the HTCC
- > 0.07 GeV energy deposited in the PCAL
- Sector dependent sampling fraction cut
- "Diagonal cut" for electrons above 4.5 GeV (HTCC threshold)
- y < 0.75, not strictly an "electron cut", but sets the min electron energy approximately > 2.4 GeV

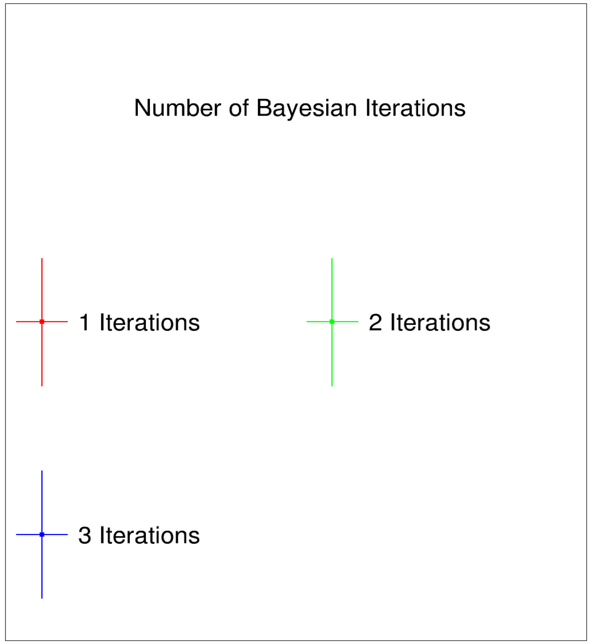
Pion PID Criteria:

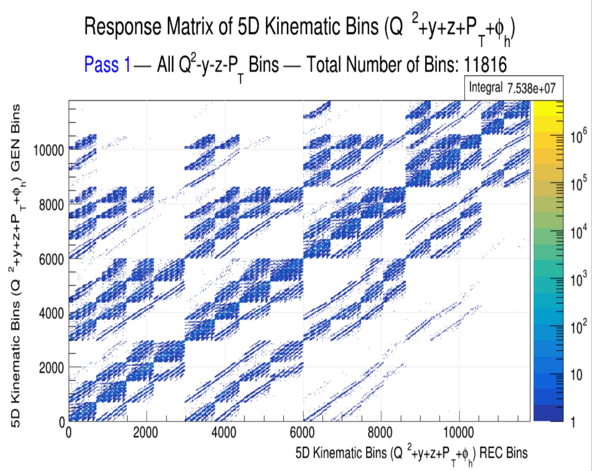
- Detected in Forward Detector
- p > 1.25 GeV
- Refined chi2pid cuts

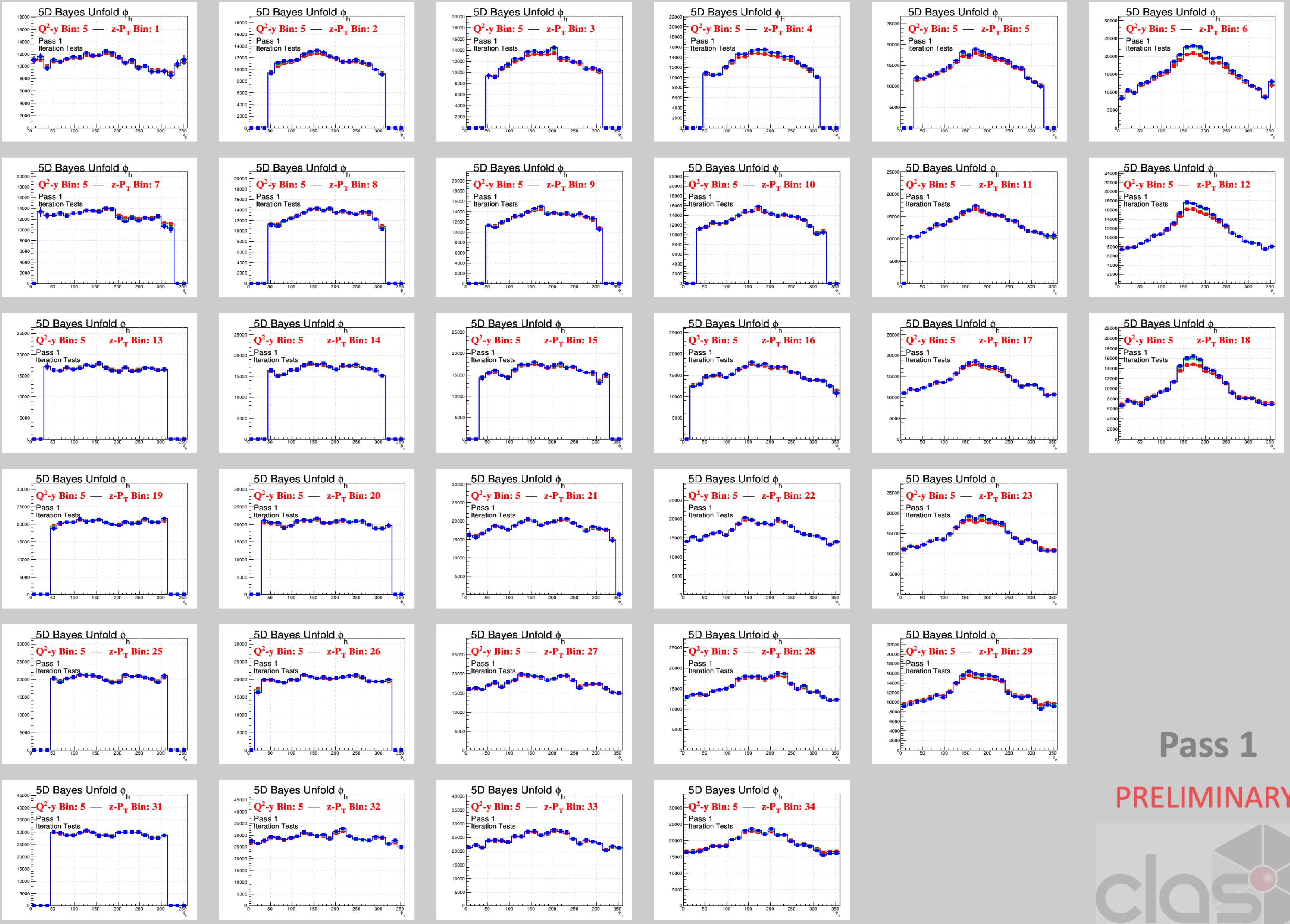
5D Unfolding – Iteration Test

Using Q^2-y-z-P_T-ϕ_h Multidimensional Bins

Q^2-y Bin 5







Pass 1

PRELIMINARY

UCONN

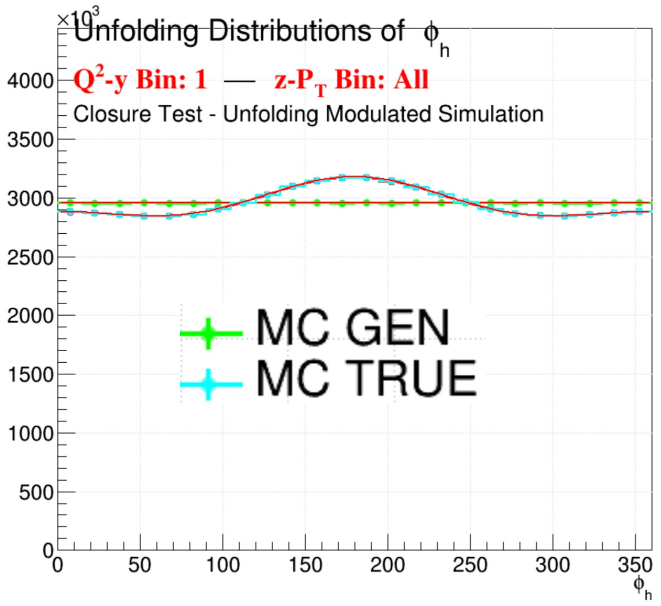
Modulated Unfolding Closure Tests

- Modulated the MC distributions using the formula:

$$Weight = 1 + B\cos(\phi_h) + C\cos(2\phi_h)$$

  - Gives the weight for each MC event based on generated ϕ_h
  - Parameter values currently being used in this image:
    - B = -0.05
    - C = 0.025

(Same for every z-P_T bin)



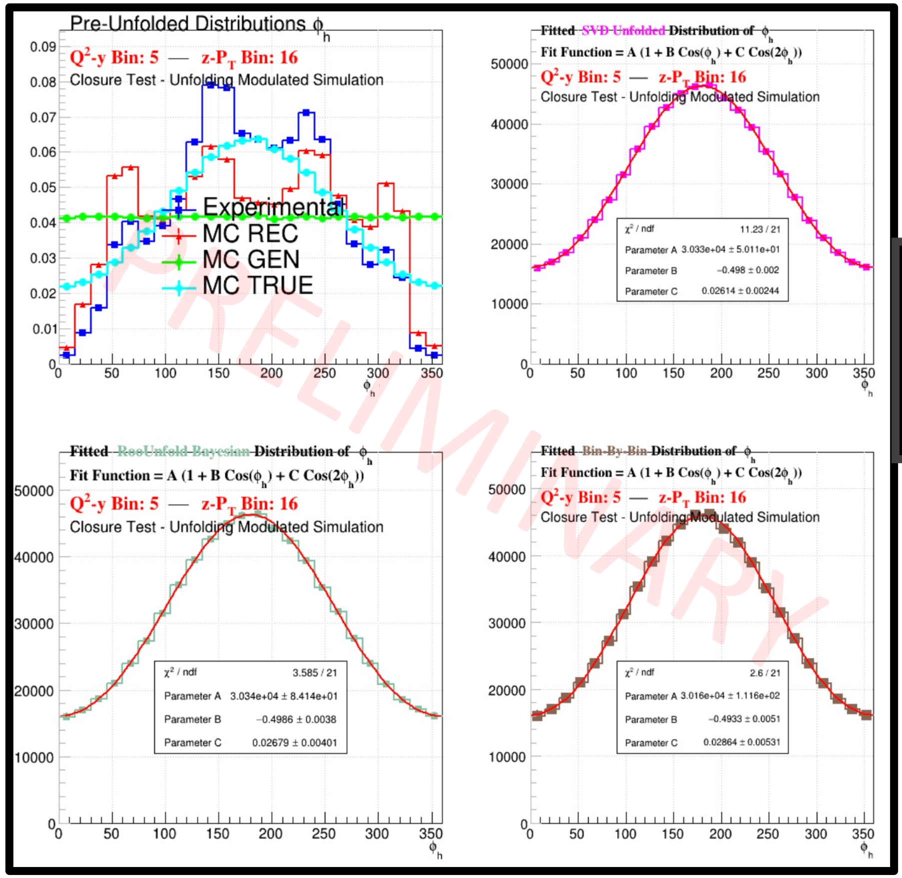
- Modulated MC REC is then unfolded using the un-modulated response matrix (in 1D and Multi-Dim examples) and compared with 'MC TRUE'
  - MC TRUE is the modulated MC GEN distribution
  - Also performed a closure test of unfolding the un-modulated MC REC distribution with the un-modulated response matrix to ensure the method was applied properly

Modulated Unfolding Closure Tests

The parameters used for weighing modulations below are:

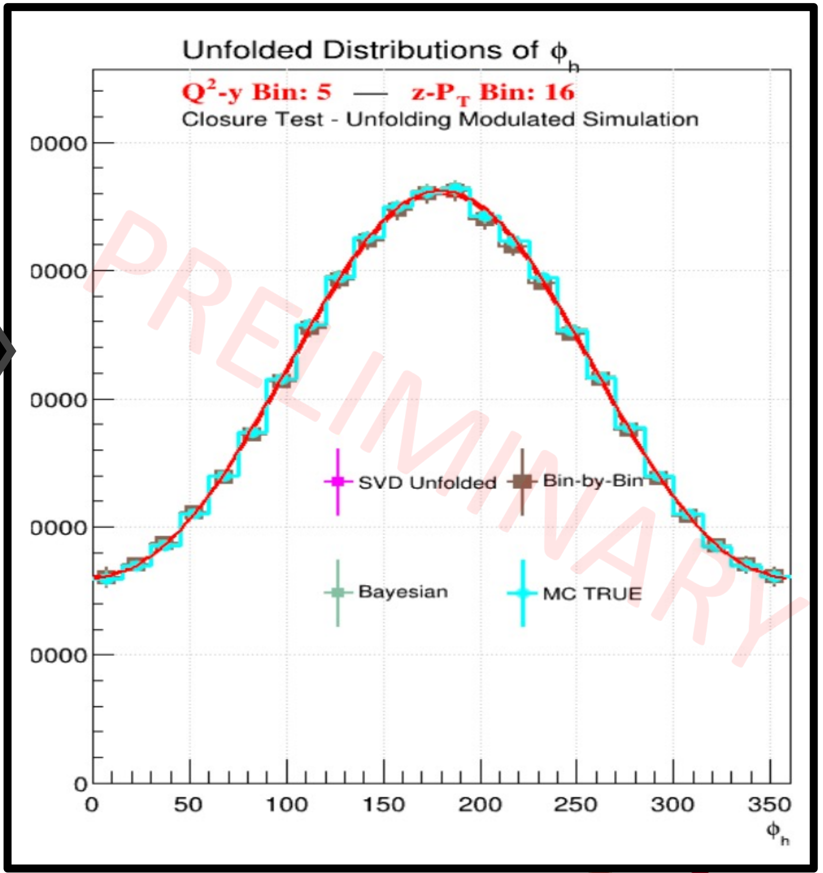
B = -0.5 and C = 0.025

Results show that an **unmodulated** Simulation can correct distributions **with modulations**



Checking that the corrected distributions match MC TRUE

Fits are within the margin of error of the defined parameters



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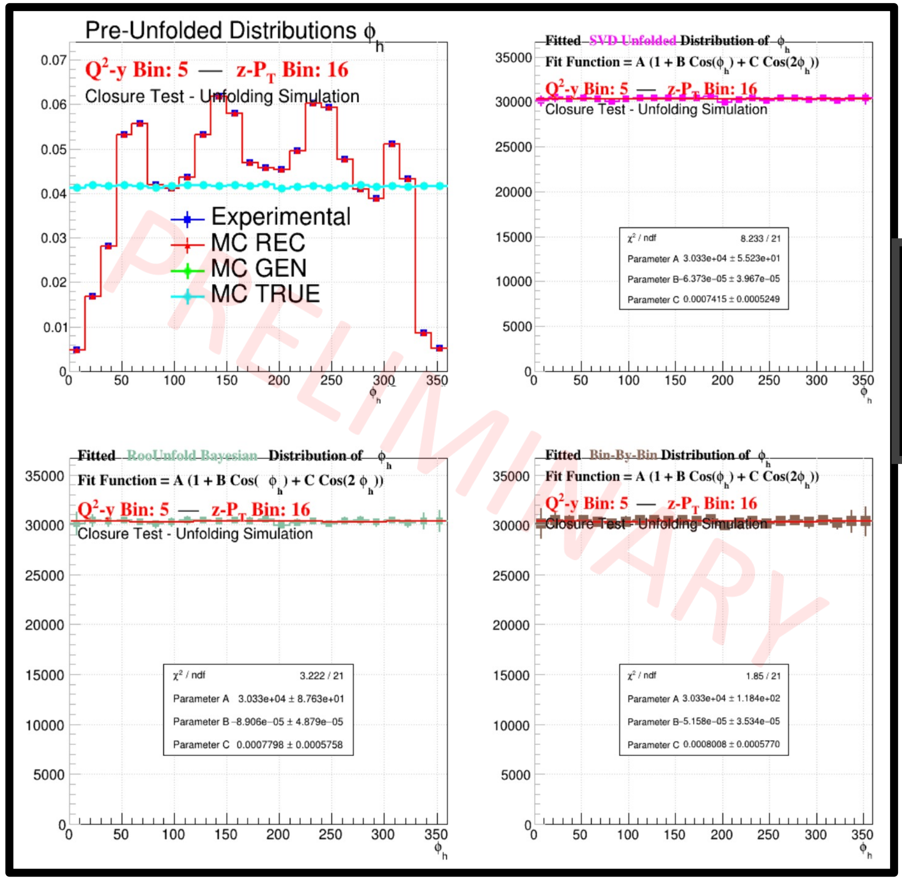
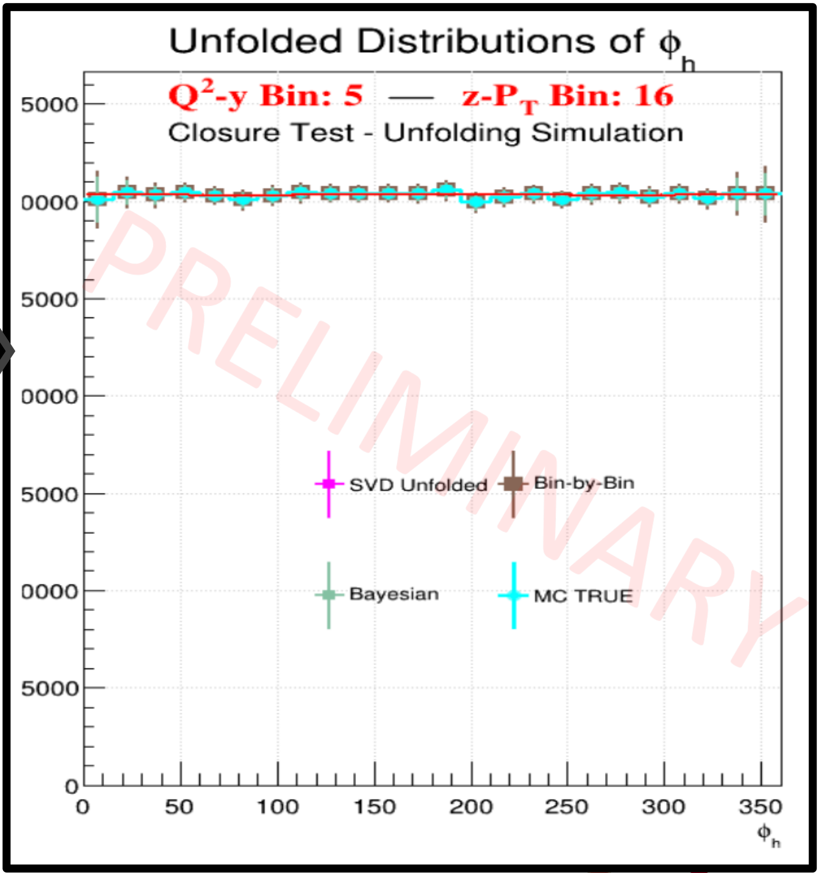
Other Unfolding Closure Tests

Other closure tests being used to check that Unfolding is done properly:

- Replace the experimental data with the reconstructed Monte Carlo (no modulations)
  - Should return the generated (i.e., MC TRUE) distribution



Checking that the corrected distributions match MC TRUE



END

Link to more Images:

https://userweb.jlab.org/~richcap/Interactive_Webpage_SIDIS_richcap/Interactive_Unfolding_Page_Updated.html

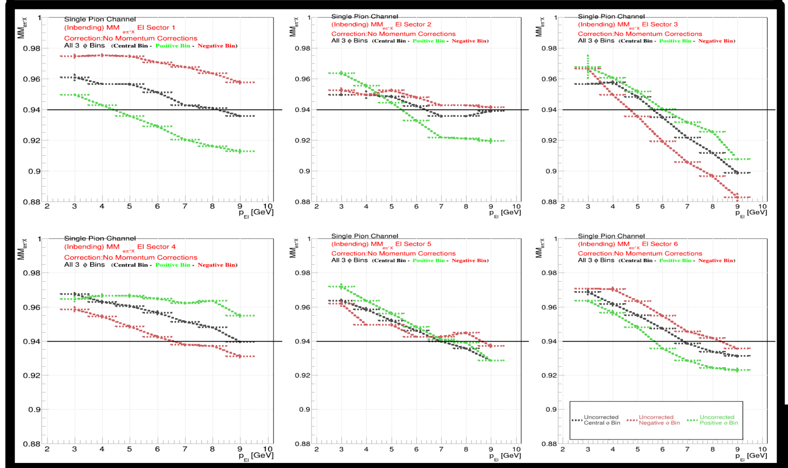
Momentum Corrections from Exclusive Events

- Momentum corrections are developed for the RG-A data being used in this analysis
- Designed to correct for kinematic-dependent reconstruction issues in the experimental data using well-understood reactions
- Use exclusive reactions to correct the particles' momentum as sector-dependent functions of the particles' measured azimuthal angle (ϕ_{lab}) and momentum
  - The primary reaction used for the electron and π^+ pion is **$ep \rightarrow e'\pi^+(N)$**
  - Elastic scattering process also used to help correct the electron momentum
- Developed from momentum 4-vector conservation to calculate the ideal momentum of a particle from exclusive reactions based on the kinematics of the other particle(s)
  - Correction is taken by plotting the difference between this calculation and the measured momentum as functions of the measured momentum and ϕ_{lab}

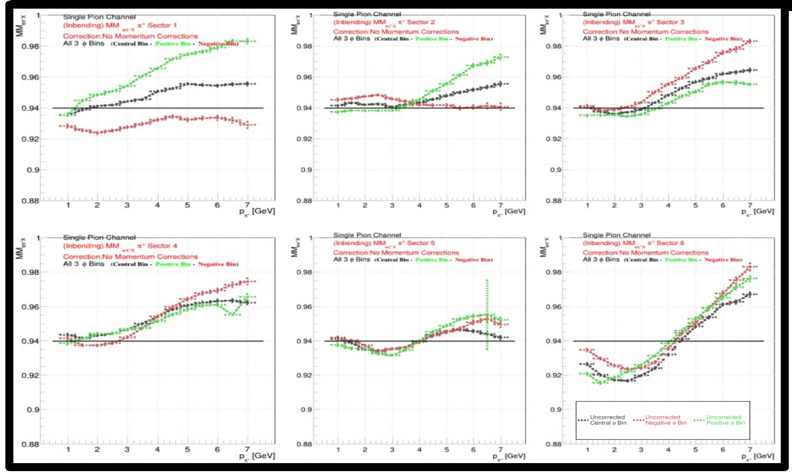
Momentum Corrections from Exclusive Events

These plots show Missing Mass vs. particle momentum in 3 ϕ bins for all 6 sectors of the detector before/after momentum corrections – **Corrections are quadratic functions of ϕ and momentum**

Missing Mass ($MM_{e\pi^+X}$) vs Electron Momentum

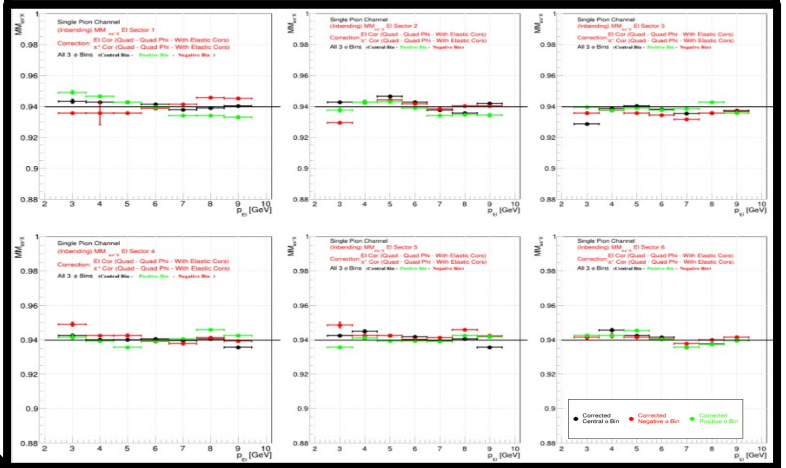


Missing Mass ($MM_{e\pi^+X}$) vs π⁺ Pion Momentum

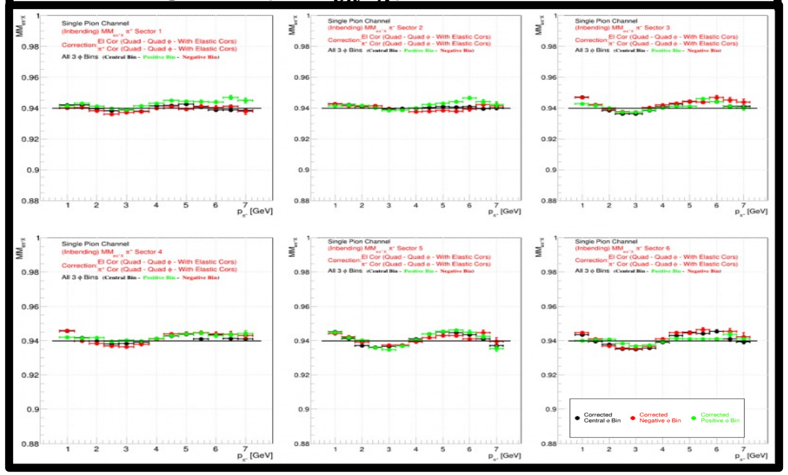


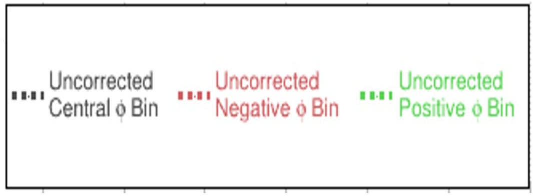
Apply Momentum Corrections

Missing Mass ($MM_{e\pi^+X}$) vs Electron Momentum



Missing Mass ($MM_{e\pi^+X}$) vs π⁺ Pion Momentum





Monte Carlo Smearing

- Momentum Smearing Corrections are designed to match the resolution effects between MC and Experimental data
- Uses exclusive reactions to compare the widths of distributions from the exclusive reactions in both data sets
  - The primary reaction used for the electron and π^+ pion is **$ep \rightarrow e'\pi^+(N)$**
  - Follows a similar process as was used for developing Momentum Corrections for the experimental data
    - i.e., use momentum conservation calculations to derive a ΔP value between the predicted and measured momentums of a particle based on the kinematics of the other measured particle
    - Momentum smearing is focused on correcting the widths of the distributions instead of the peaks
  - Smearing functions are based on ΔP/P vs θ plots

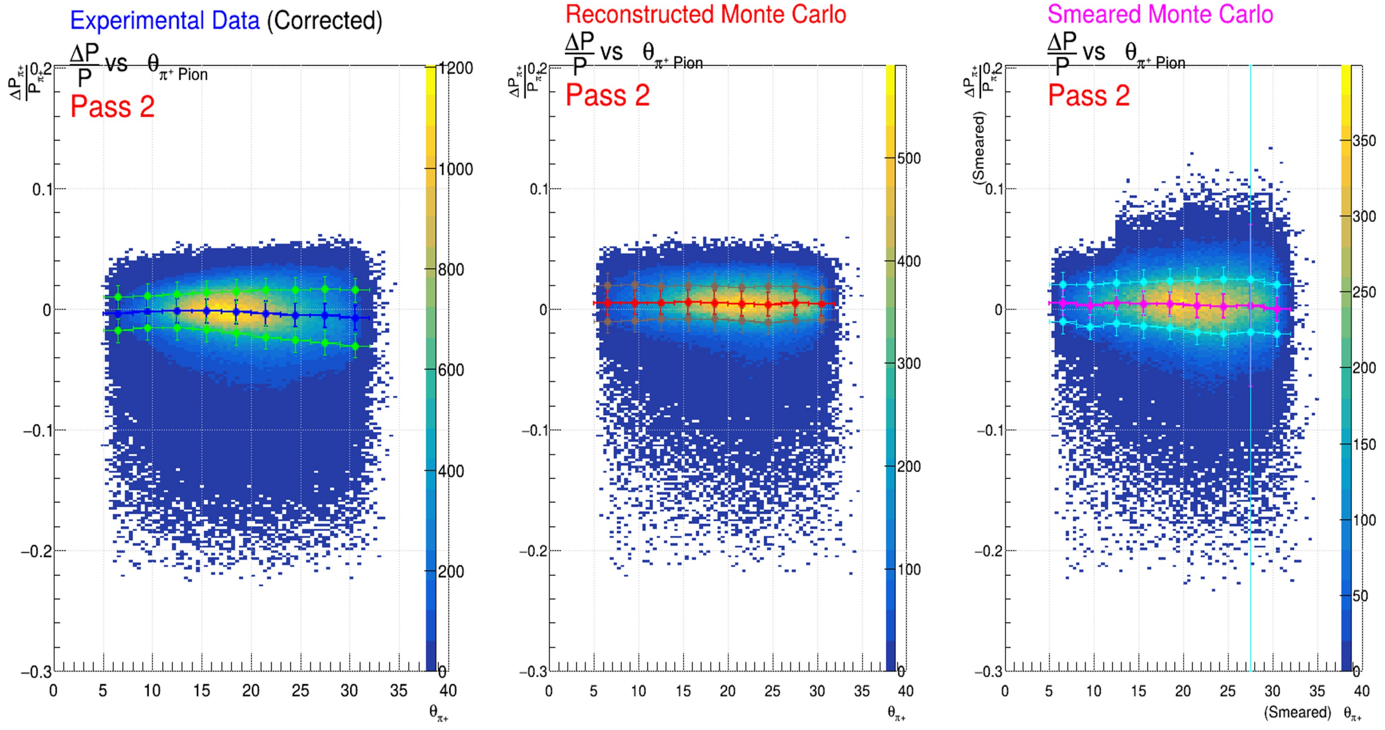
Data and Monte Carlo Comparison (Smearing)

Smearing for the π⁺ Pion

Form of Smearing Function:

$$P_{Smeared} = P_{REC} + gRandom \rightarrow Gaus(0, P_{REC} * \sigma(\theta) * SF)$$

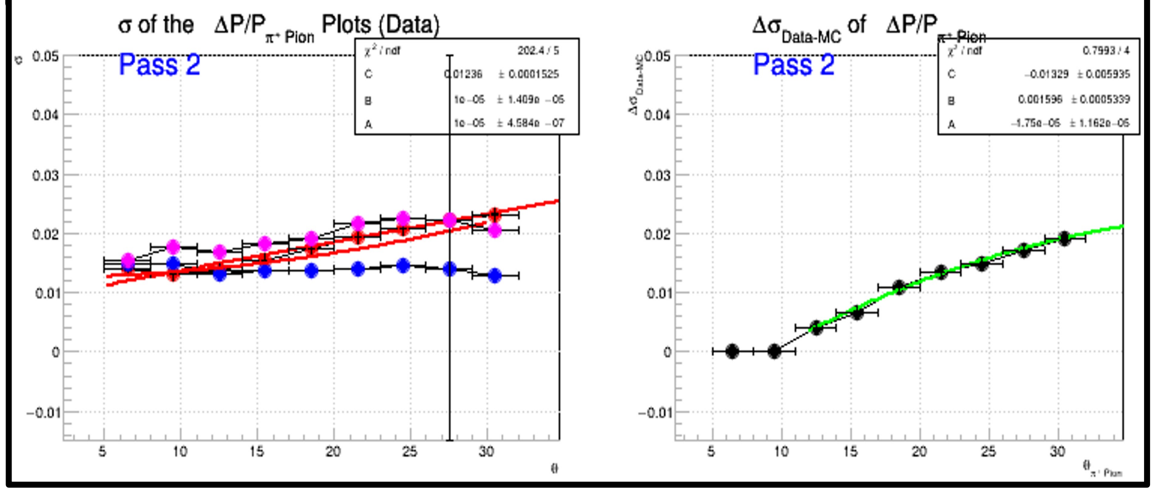
Plots of ΔP/P vs θ for Data, Unsmeared MC, and Smeared MC



Shown with the peak positions and widths of the fitted distributions

- $\sigma(\theta)$ is the difference in the widths of ΔP/P for the Unsmeared MC and Data plots
- *SF* is a constant factor that provides more control over the function's strength

Difference between widths of Smeared MC and Data



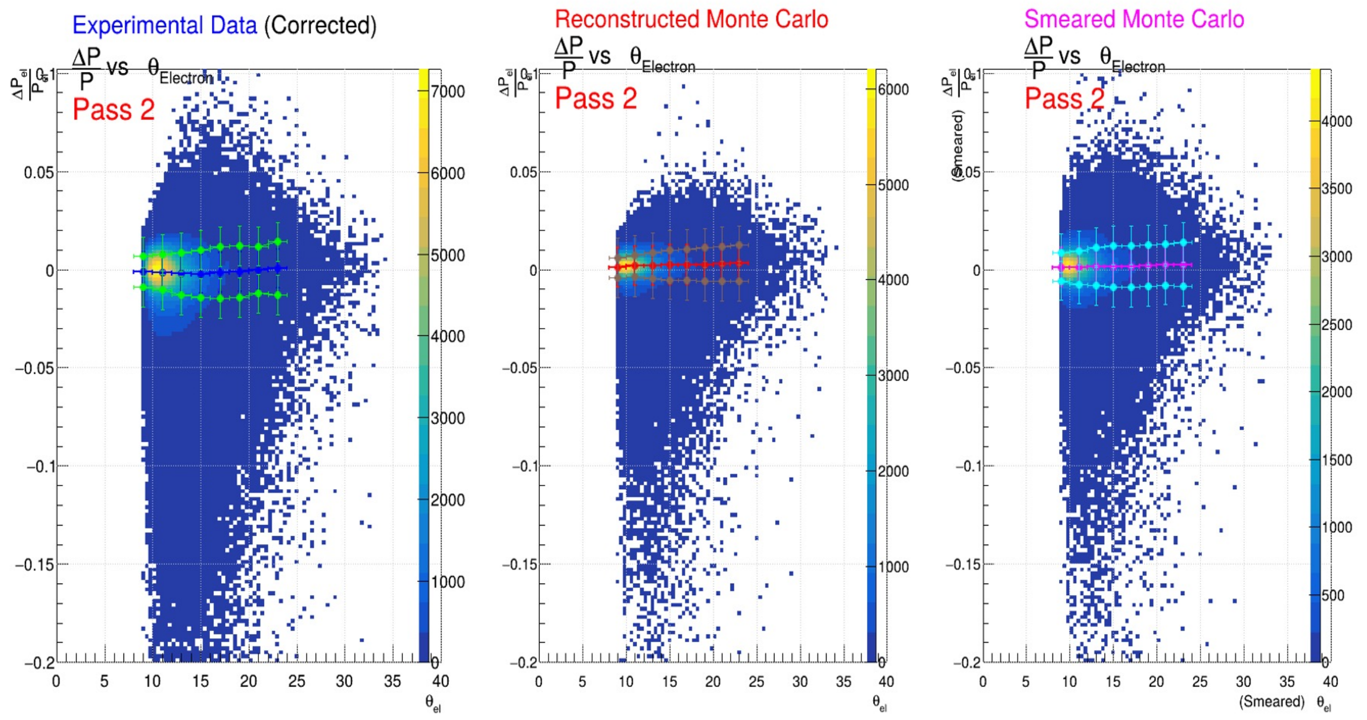
Data and Monte Carlo Comparison (Smearing)

Smearing for the <u>Electron</u>

Form of Smearing Function:

$$P_{Smeared} = P_{REC} + gRandom \rightarrow Gaus(0, P_{REC} * \sigma(\theta) * SF)$$

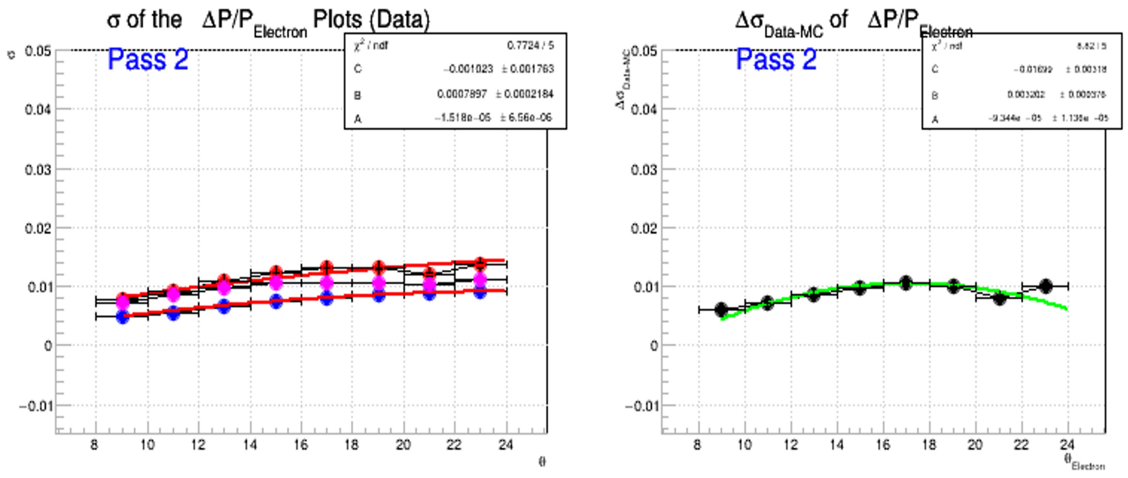
Plots of ΔP/P vs θ for Data, Unsmeared MC, and Smeared MC



Shown with the peak positions and widths of the fitted distributions

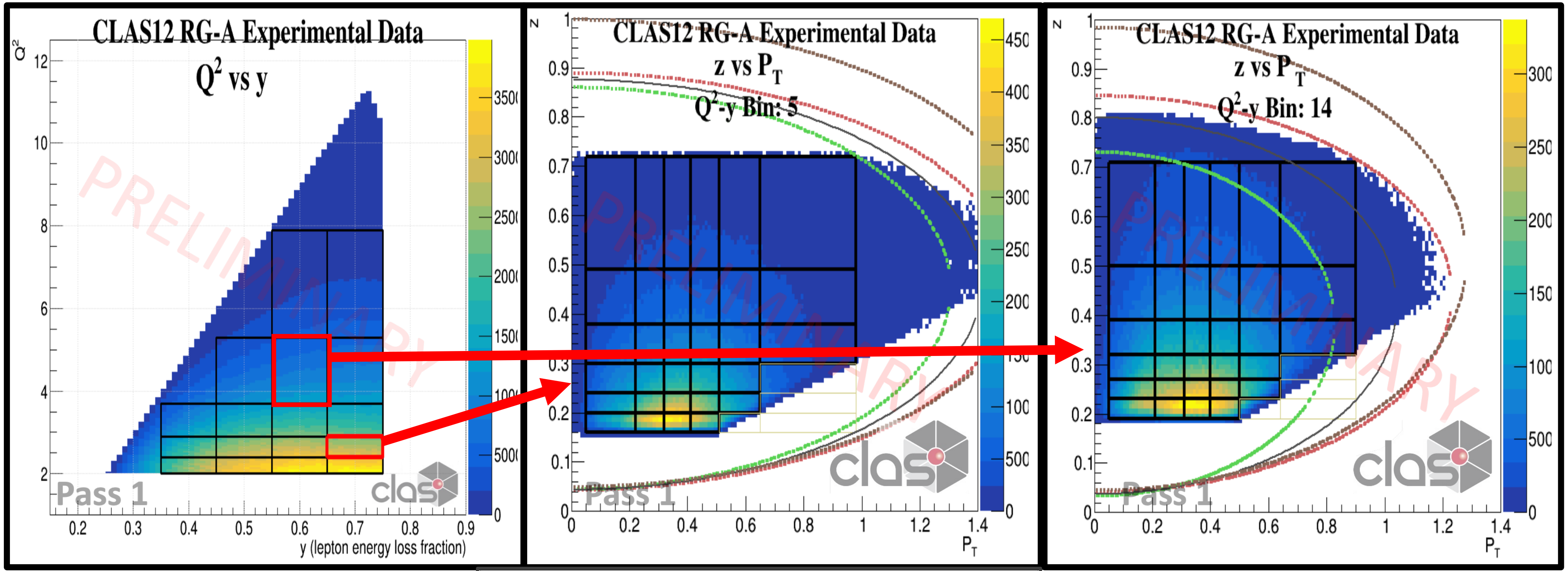
- $\sigma(\theta)$ is the difference in the widths of ΔP/P for the Unsmeared MC and Data plots
- *SF* is a constant factor that provides more control over the function's strength

Difference between widths of Smeared MC and Data



Migrations from Outside Kinematic Regions

Lines drawn here show Missing Mass Cuts in different Q^2-y bins

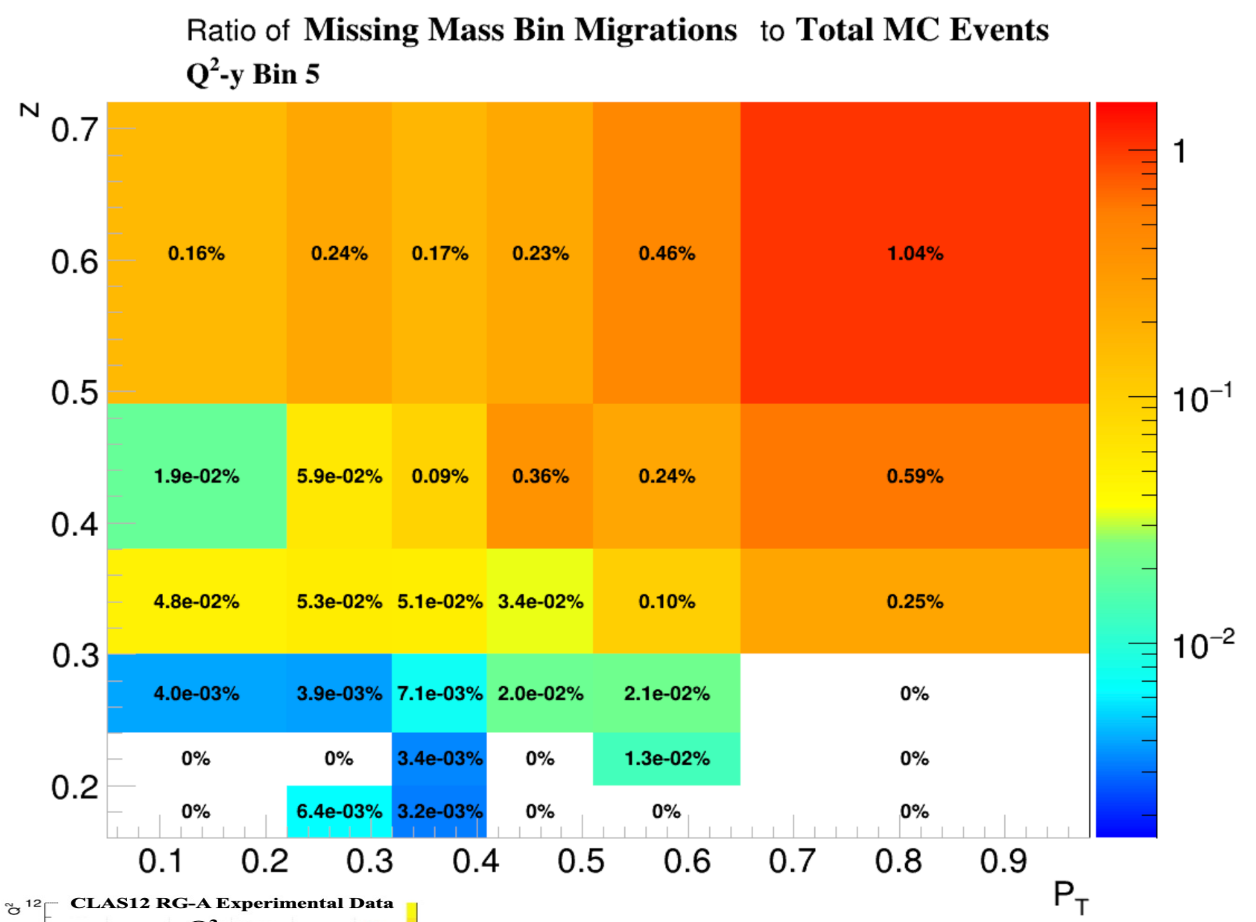


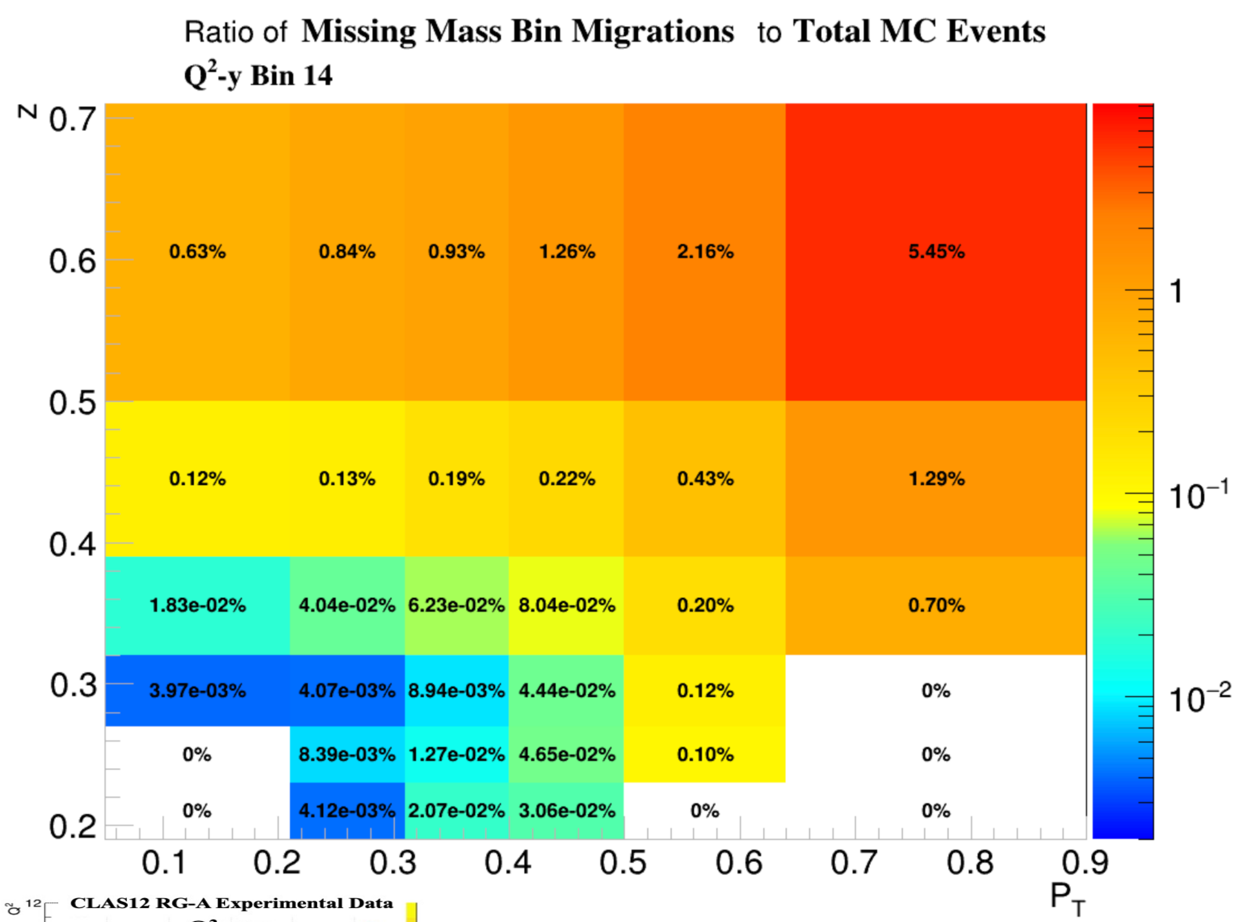
Events migrated from outside the borders of the signal region are removed with ß vector in the unfolding procedure

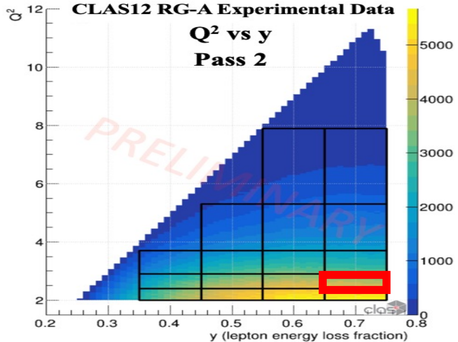
Missing Mass Cut Lines:

Minimum MM Cut	Maximum MM Cut
Center MM Cut	Exclusivity peak

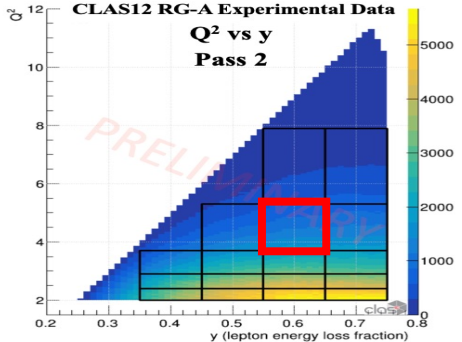
Missing Mass Migration Contributions (Per Q^2-y Bin)







Average Contribution to MC statistics from **Missing Mass Migrations** per z-P_T bin in this Q^2-y region is **0.74%**



Average Contribution to MC statistics from **Missing Mass Migrations** per z-P_T bin in this Q^2-y region is **3.29%**

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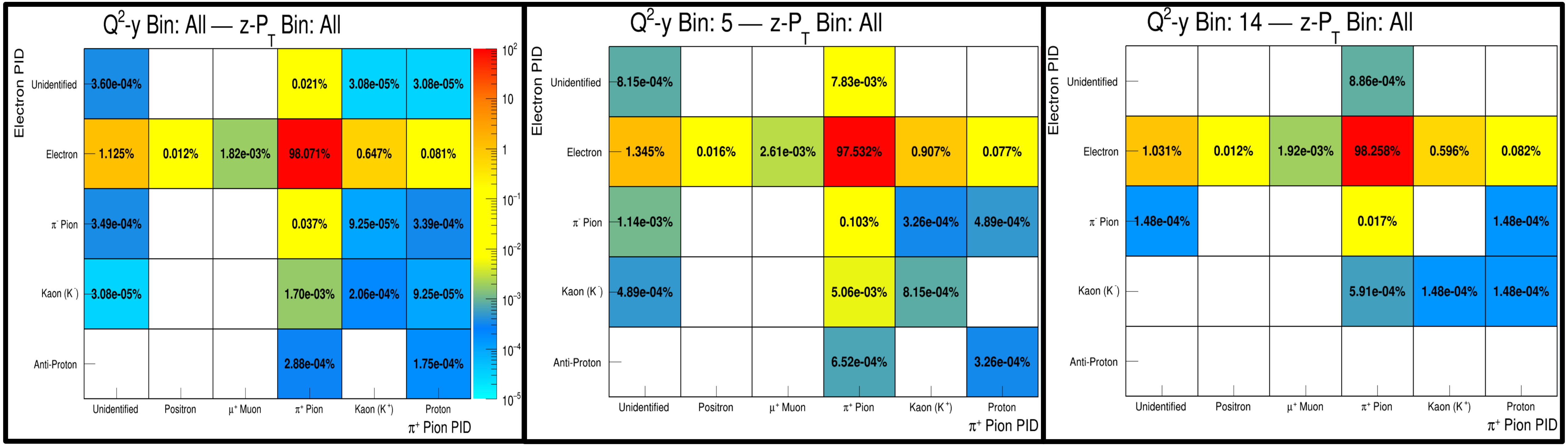
Particle Misidentification

True PID of the MC Events Reconstructed as Electrons/Pions



Meant to model remaining particle misidentification not caught by PID cuts

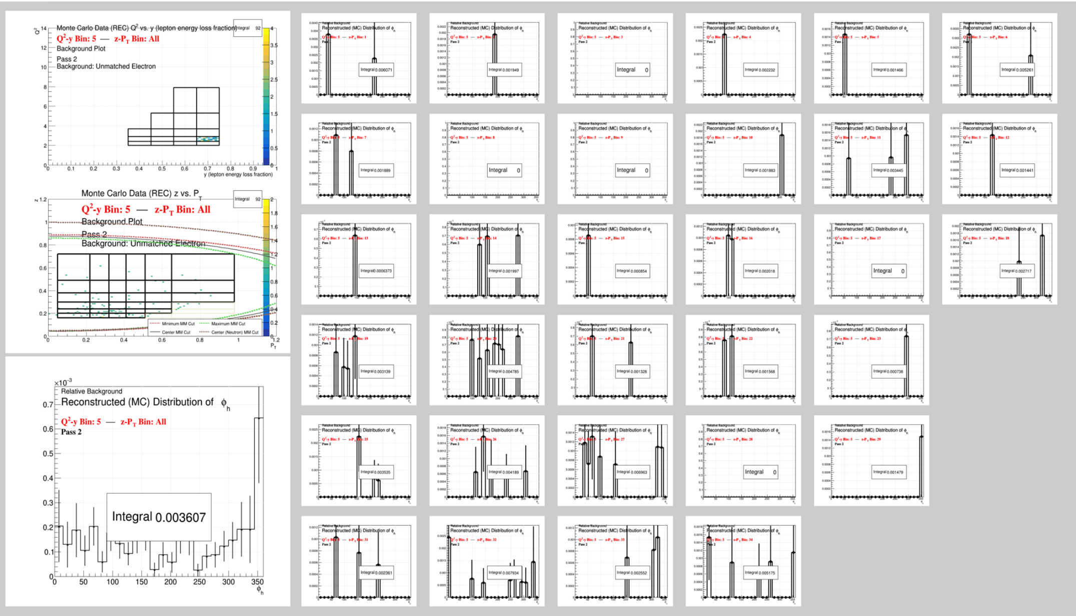
"Unidentified" Particles are those that had a reconstructed particle that could not be matched to a generated particle within the matching criteria used

Integrating over z-P_T: misidentification rate ranges from 1.5-2.5% (depending on Q^2-y bin), the average is ~1.8%

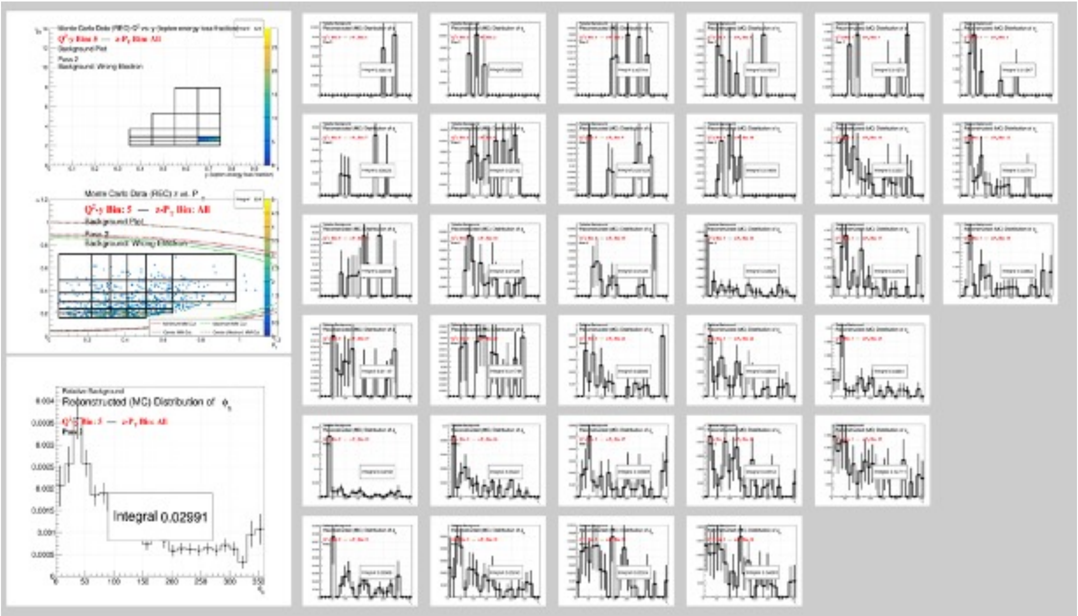
(About 58% of this is from Unidentified Particles on average)

The misidentification rate within individual z-P_T Bins ranges from 0.8-6.5%

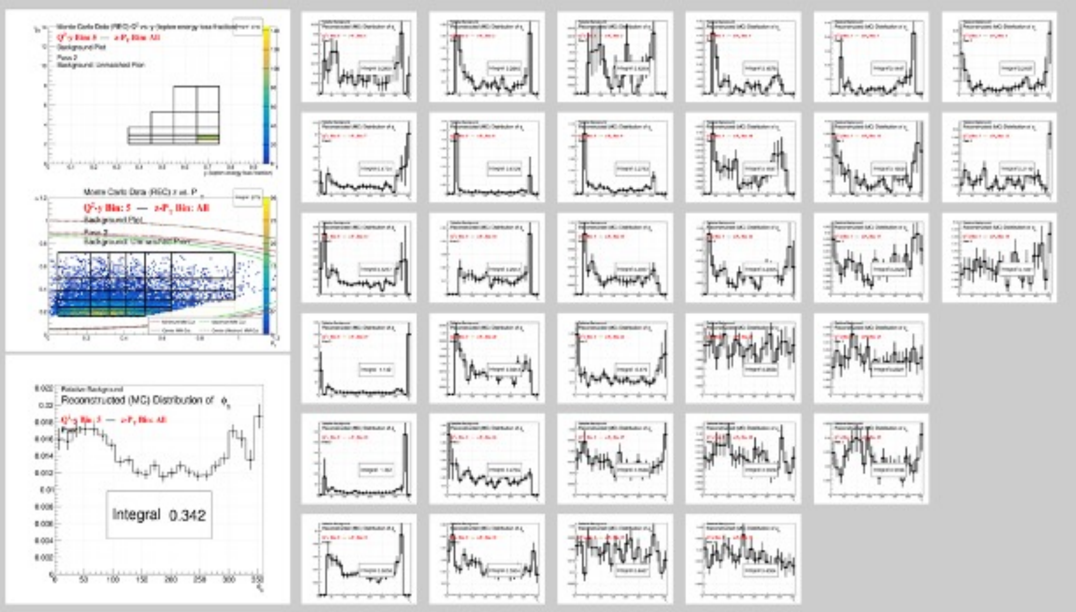
Background (ß) Vector – Particle Mis-Identification (as functions of ϕ_h)



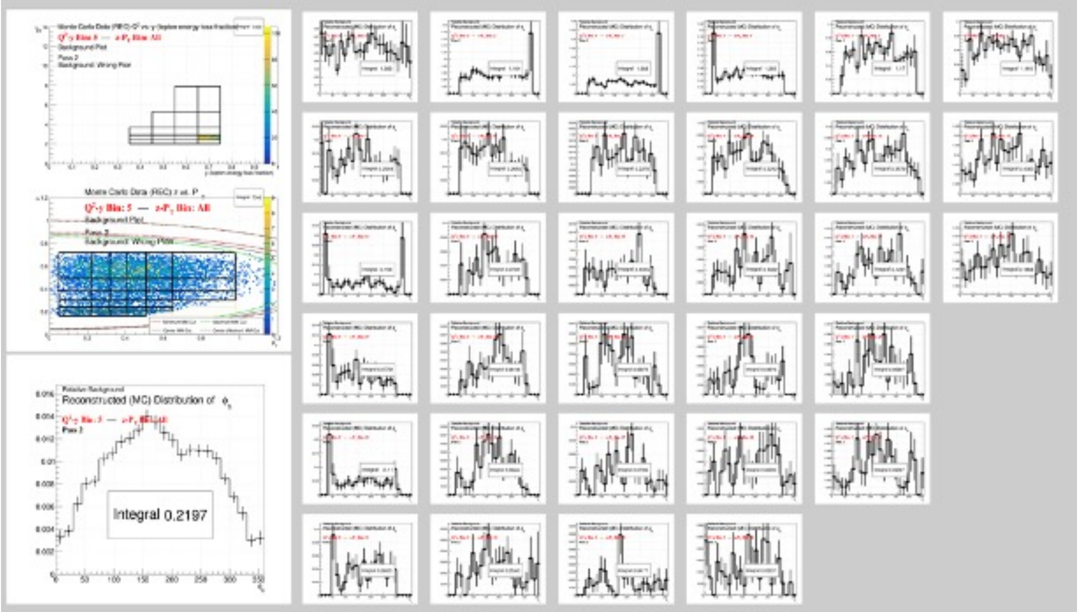
Unmatched
MC REC
Electron
←



Incorrect
PID for
MC REC
Electron
←



Unmatched
MC REC
π^+ Pion
←

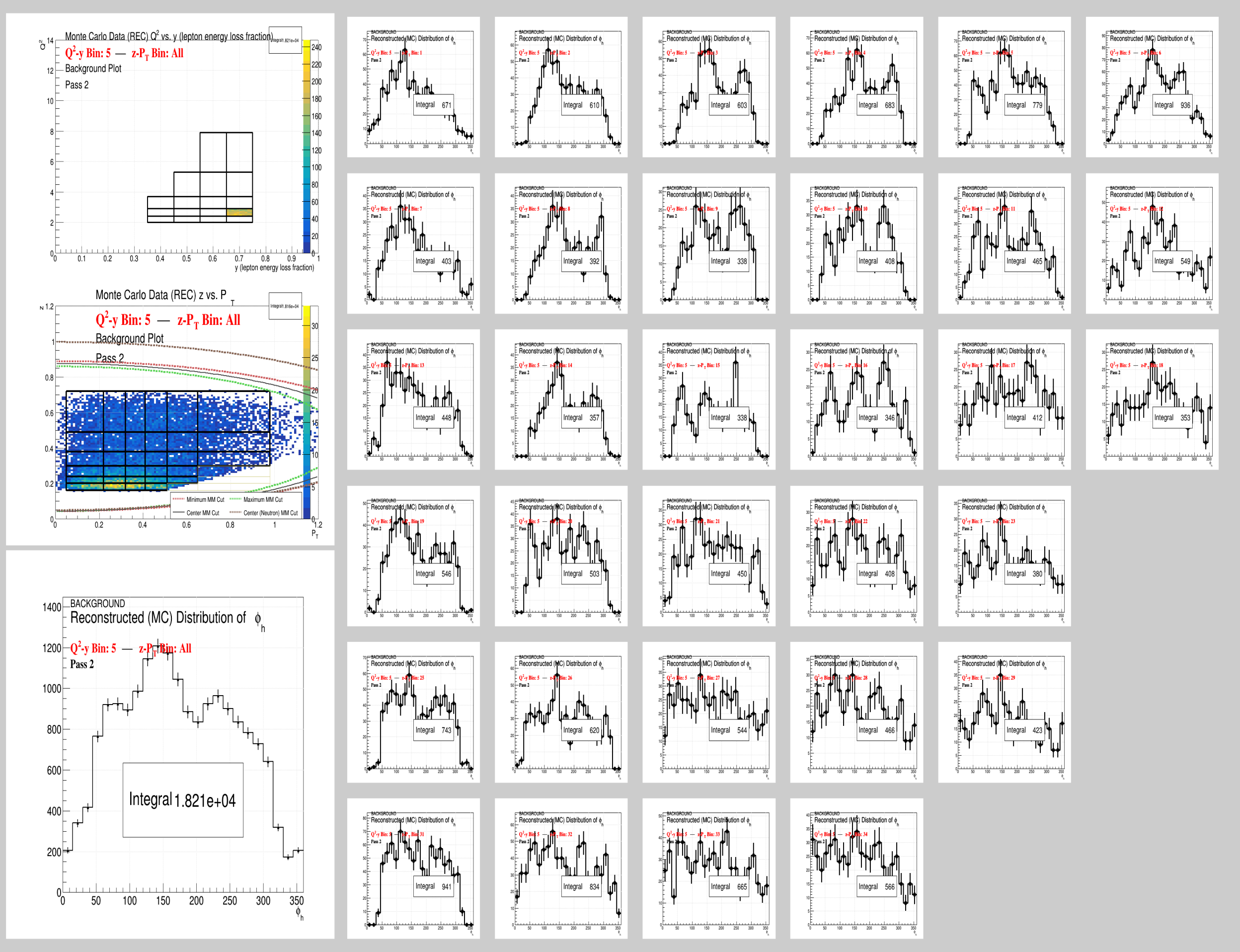


Incorrect
PID for
MC REC
π^+ Pion
←

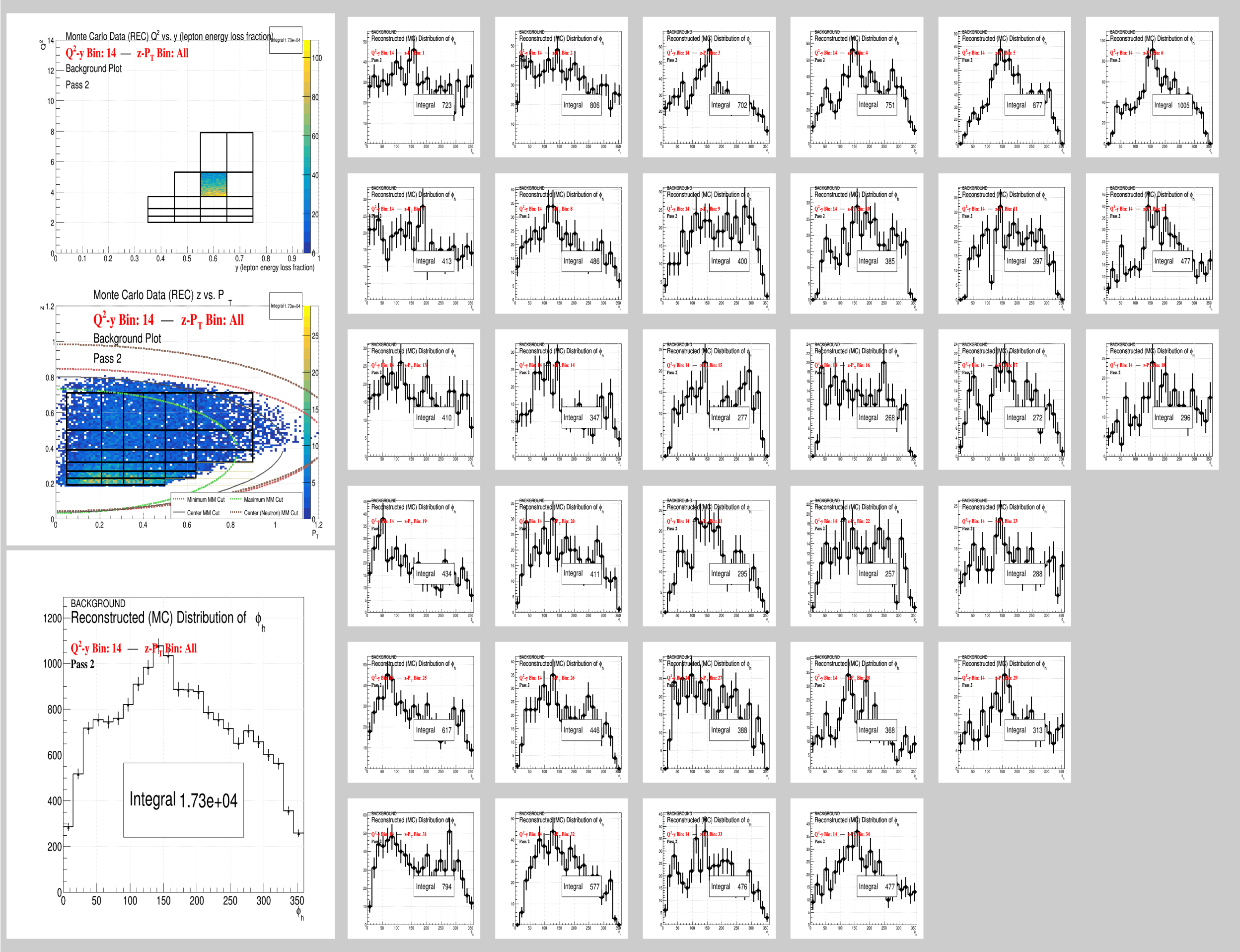
PASS 2

ß Vector – All Contributions (Per Q^2-y Bin)

Q^2-y Bin 5: Events from Generated Missing Mass Cuts make up about 0.87% of the 'Background' shown below



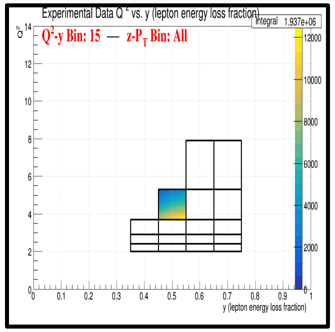
Q^2-y Bin 14: Events from Generated Missing Mass Cuts make up about 18.8% of the 'Background' shown below



Pass 2 Condition

- Momentum/Energy Loss Corrections in Pass 2 have been implemented
- Monte Carlo statistics are still low (using test sample)
  - Planning to run more files soon
  - Also hope to run using RADGEN to start including radiative effects
  - Working side-by-side with Pass 1 in the meantime for better MC statistics

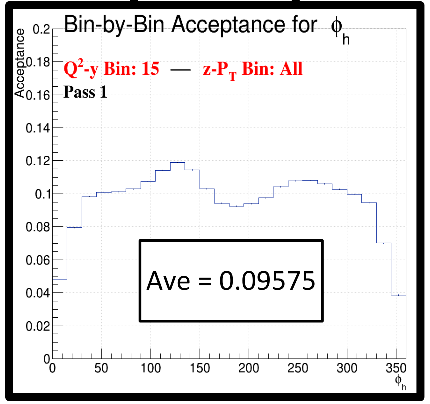
Pass 2 Comparisons - Acceptances



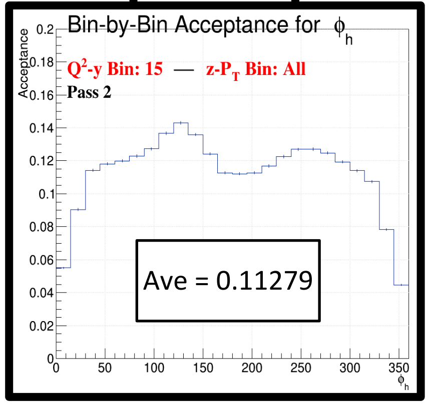
High Q^2
Low y

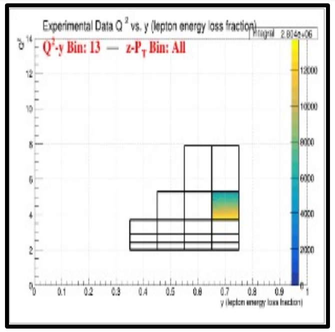
Δ Ave = +0.01704

Pass 1



Pass 2

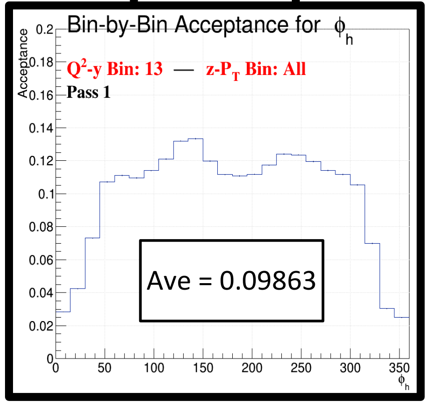




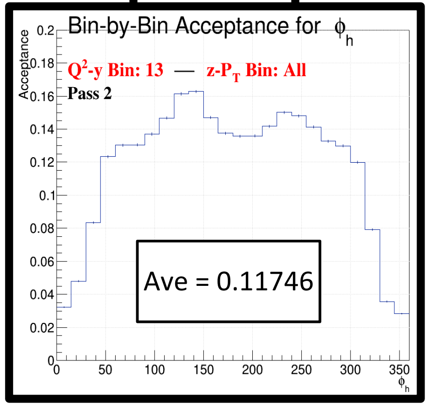
High Q^2
High y

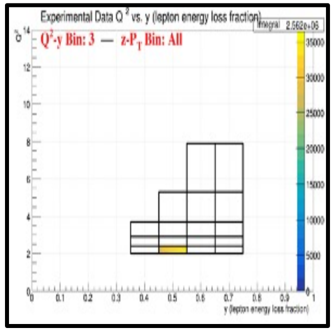
Δ Ave = +0.01883

Pass 1



Pass 2

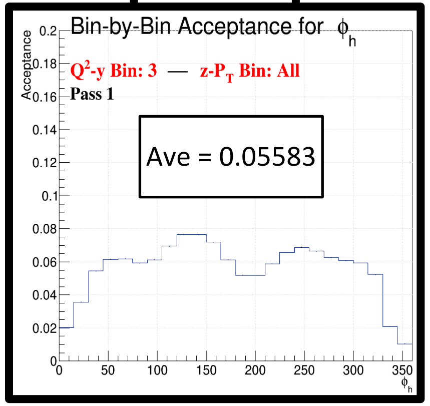




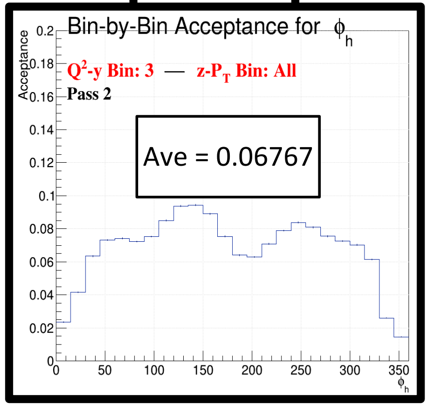
Low Q^2
Low y

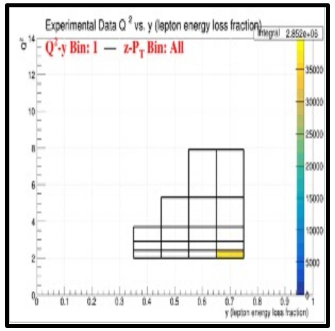
Δ Ave = +0.01184

Pass 1



Pass 2

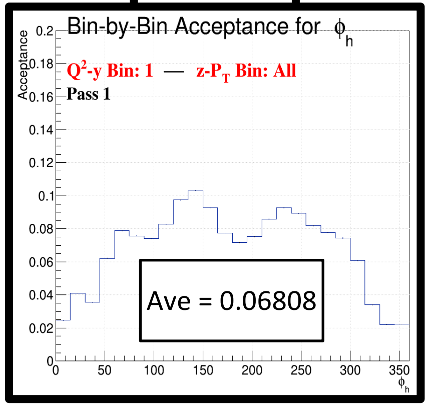




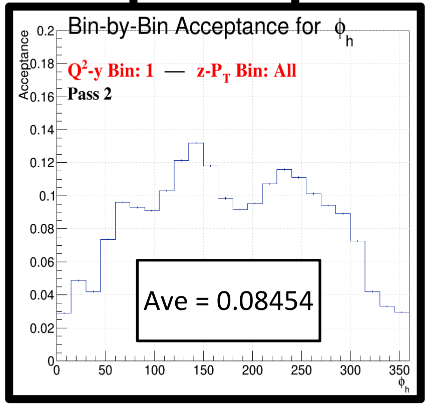
Low Q^2
High y

Δ Ave = +0.01646

Pass 1



Pass 2



Cos(ϕ_h) Moment as Functions of z - Pass 2 Comparison

$$\mathbf{B} = A_{UU}^{\cos\varphi_h}$$

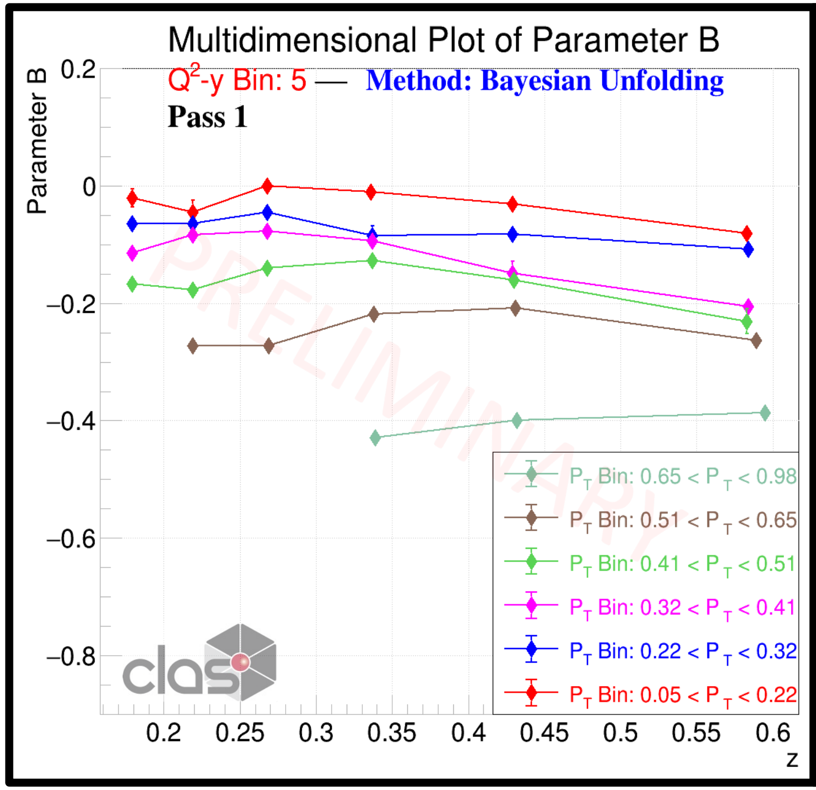
ϕ_h Plots were fitted with:

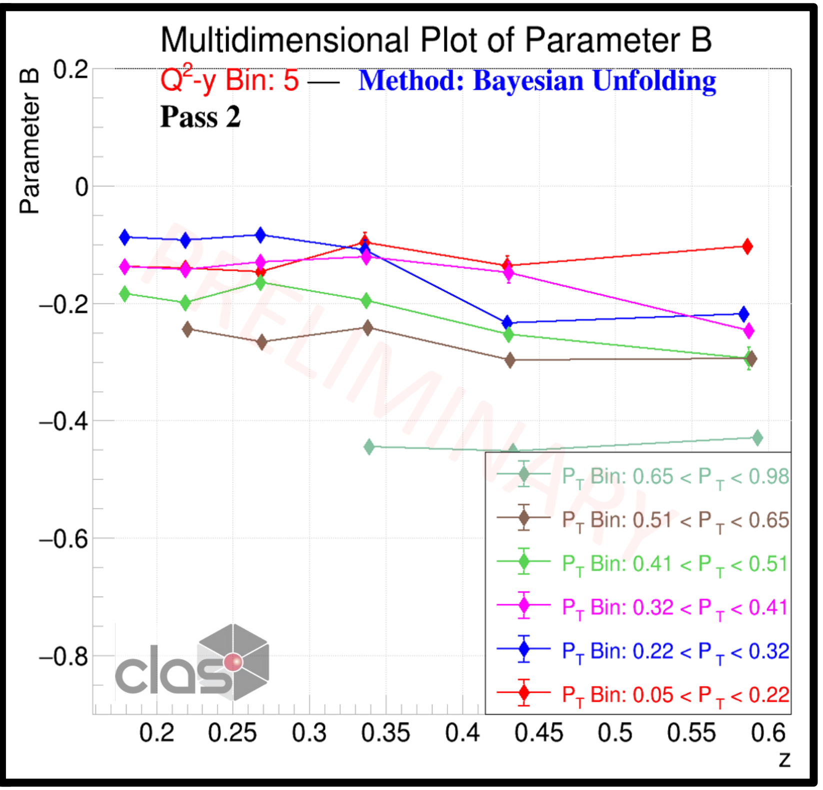
$$A(1 + \mathbf{B}\cos(\phi_h) + C\cos(2\phi_h))$$

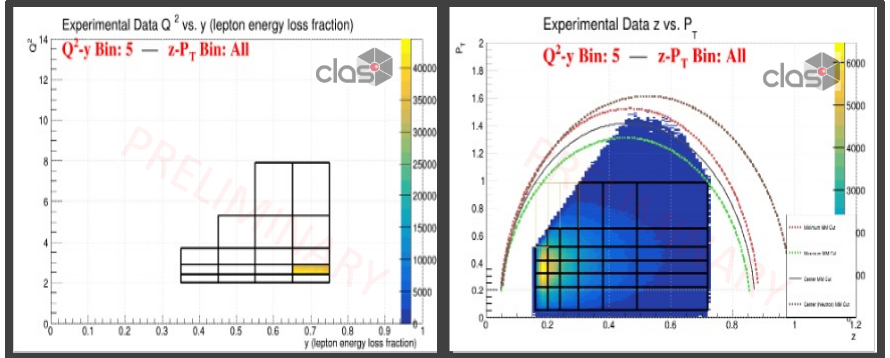
Unfolded with Bayesian Method

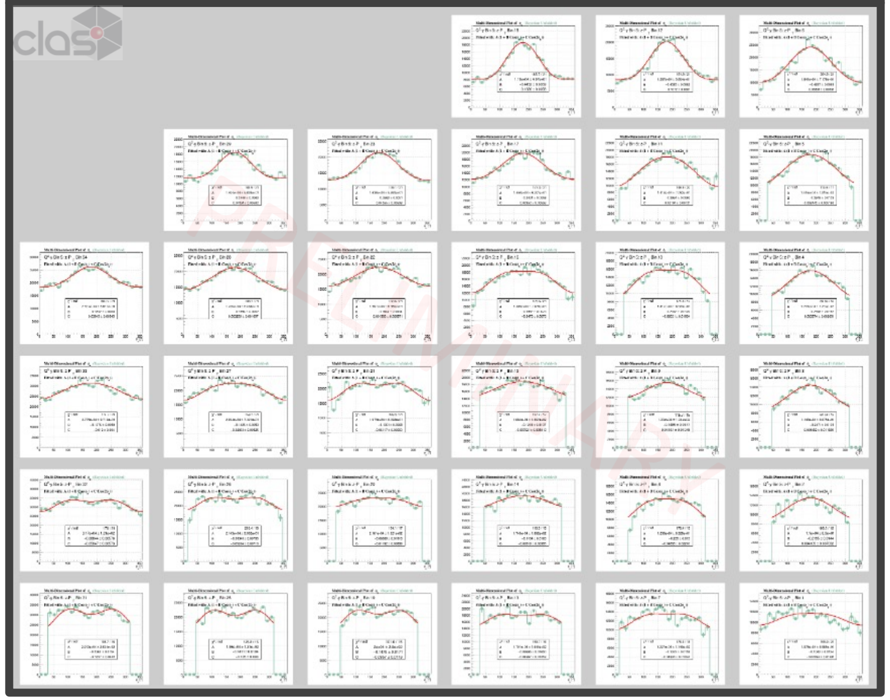
Q^2-y Bin 5

Pass 2









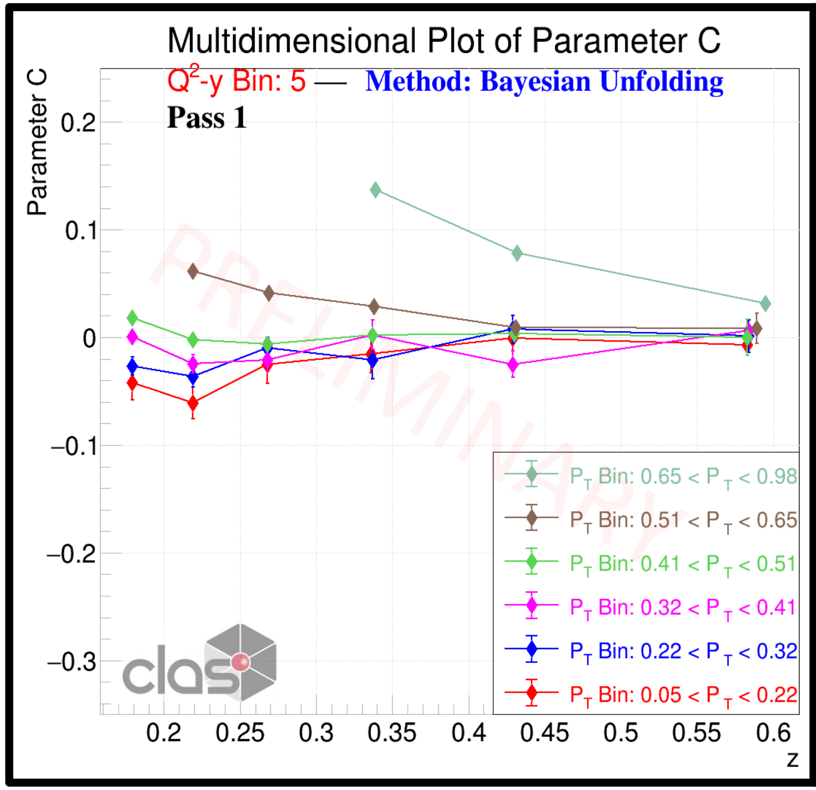
Cos($2\phi_h$) Moment as Functions of z - Pass 2 Comparison

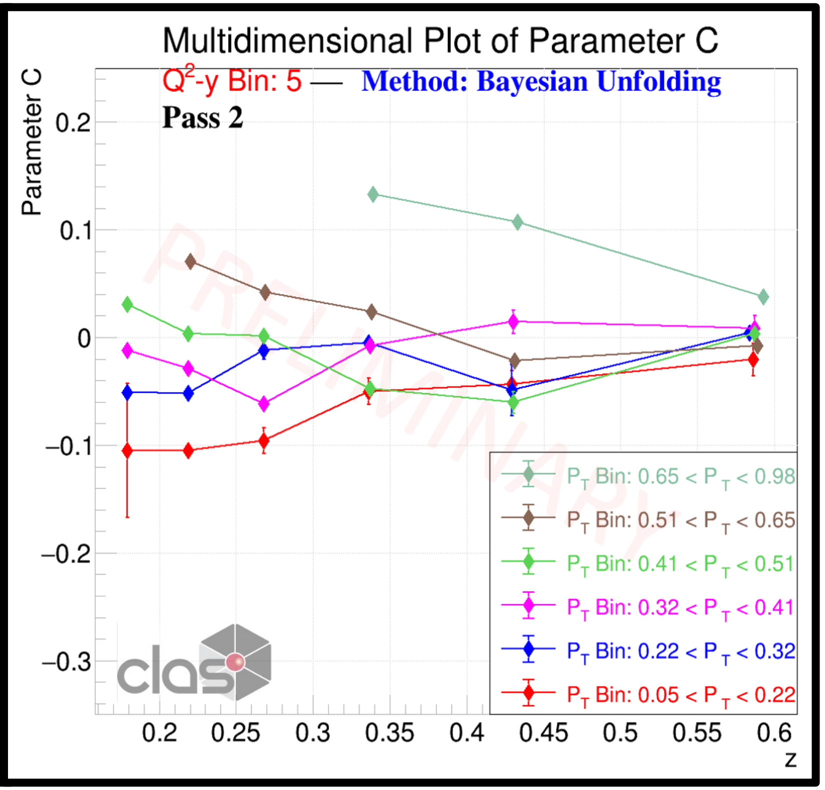
$$C = A_{UU}^{\cos 2\varphi_h}$$

ϕ_h Plots were fitted with:
$A(1 + B\cos(\phi_h) + \mathbf{C}\cos(2\phi_h))$

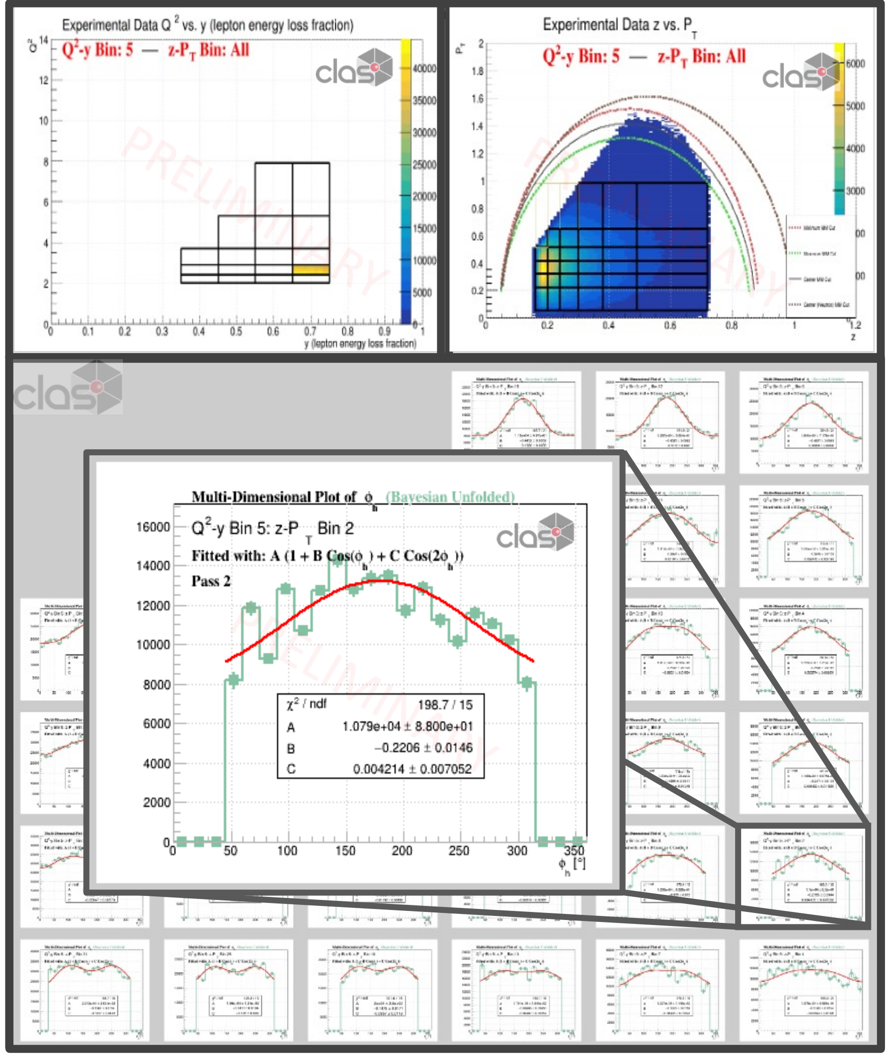
Unfolded with Bayesian Method

Q^2-y Bin 5





Pass 2



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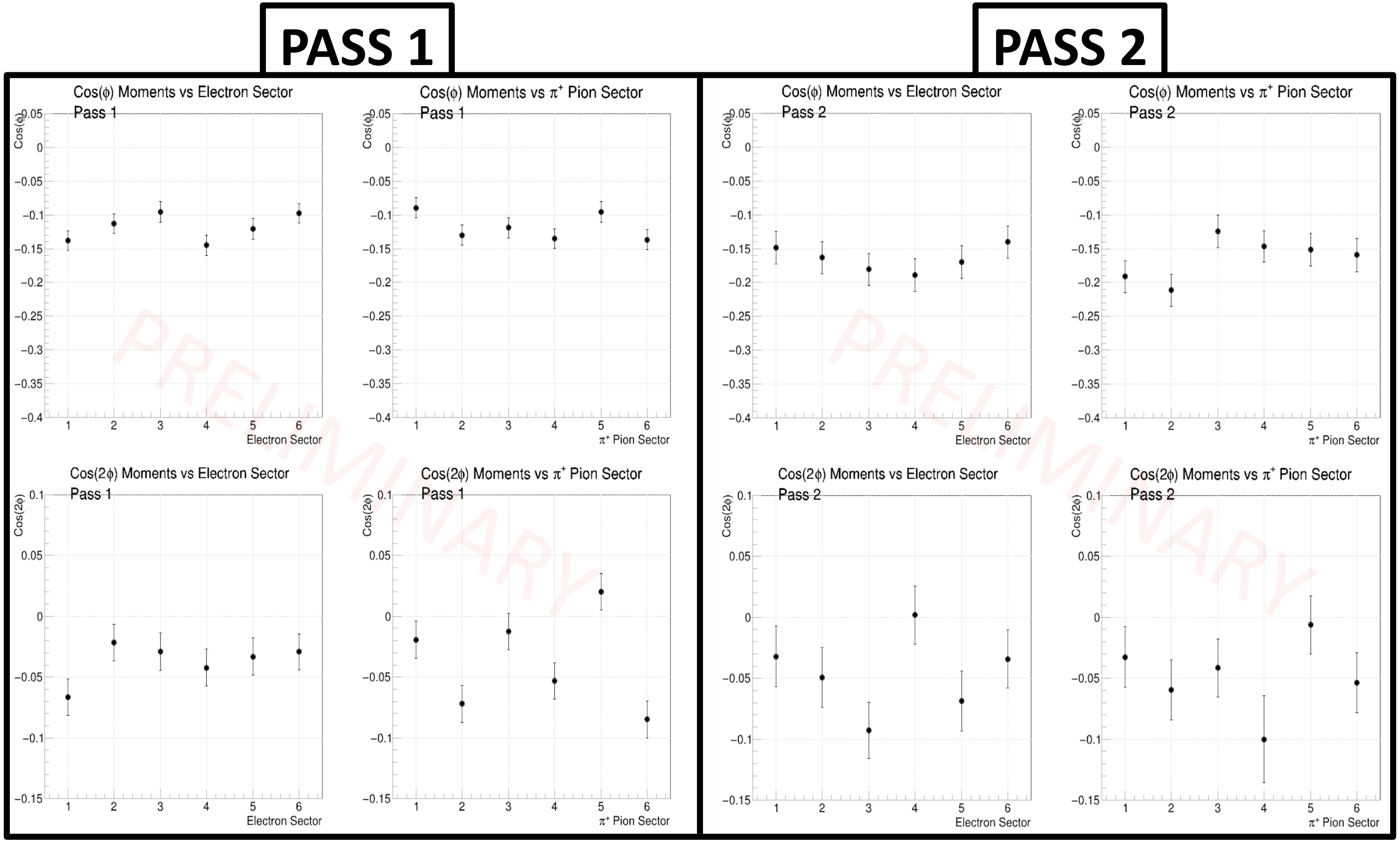
Sector Correlations with Cos(ϕ) and Cos(2ϕ) Measurements

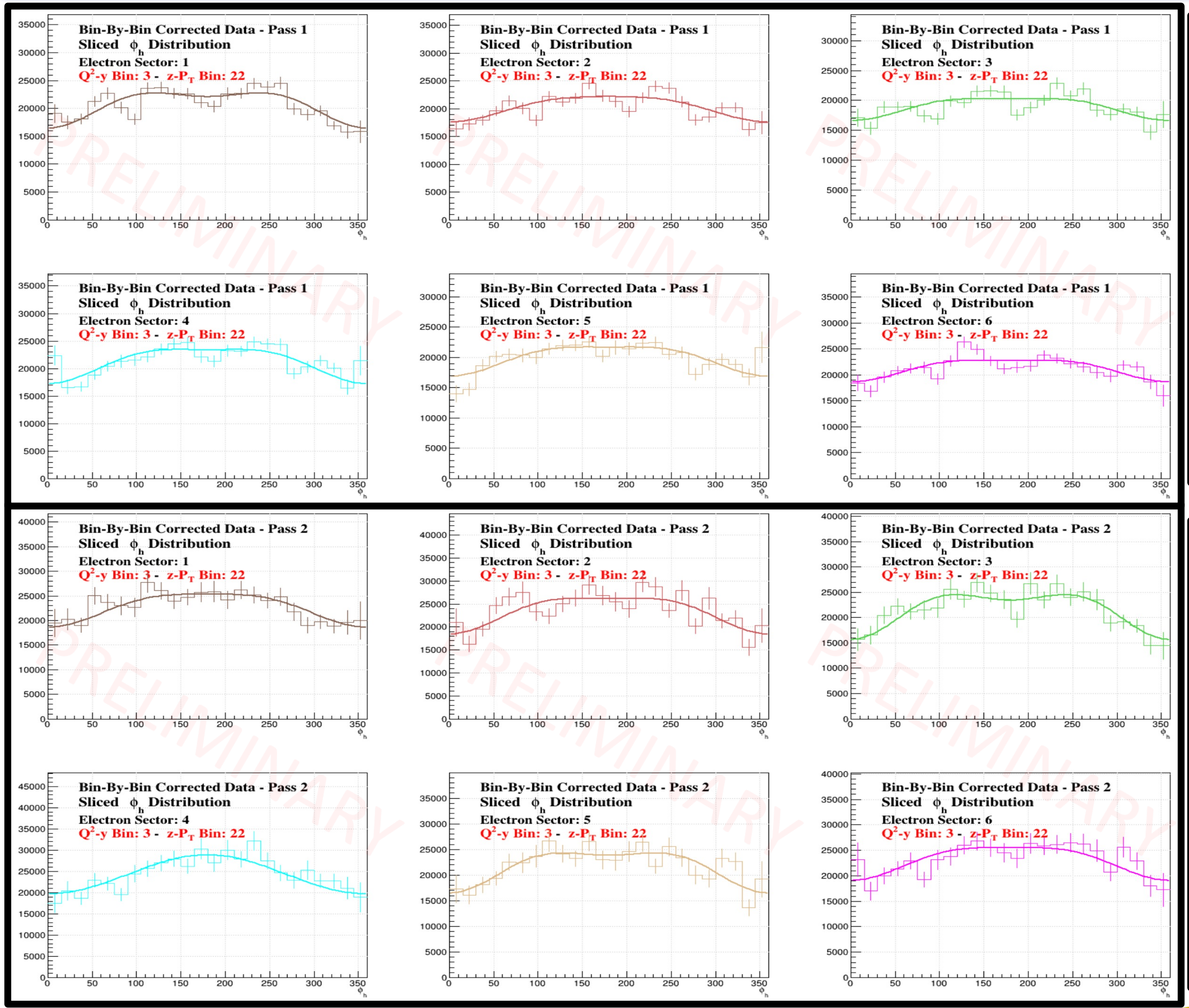


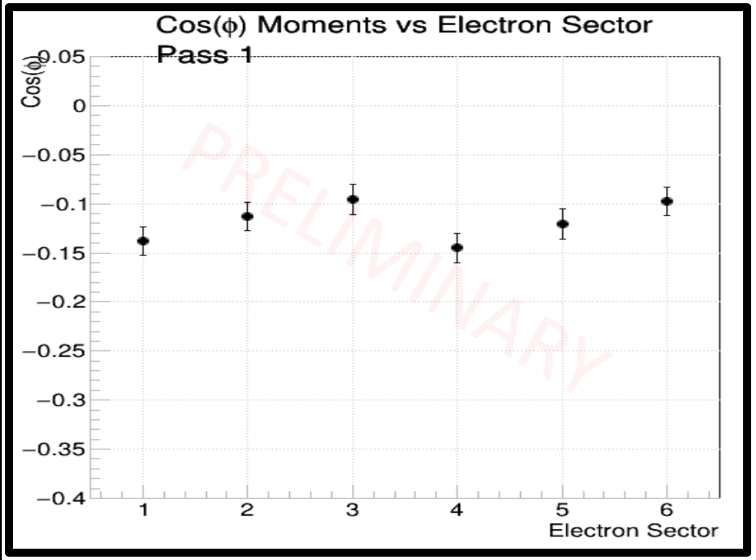
Showing the Cos(ϕ) and Cos(2ϕ) Moments as functions of the particle sector

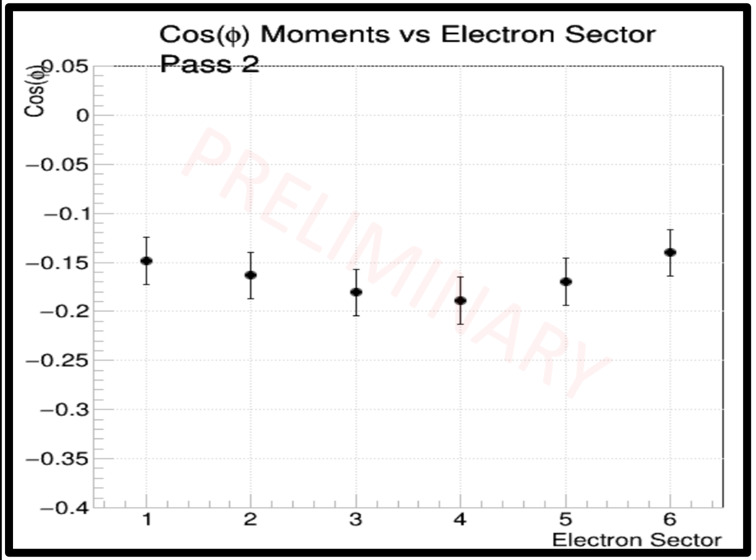
These plots show those differences in Pass 1 and Pass 2 for when the Electron (left plots) or π^+ pion (right plots) are restricted to being detected in a single sector

Images are grouped on the left and right based on Pass version of the data being used

Sector Correlations with Cos(ϕ) Measurements – Pass 1 and 2







Sectors can cause different modulations within the kinematic bins

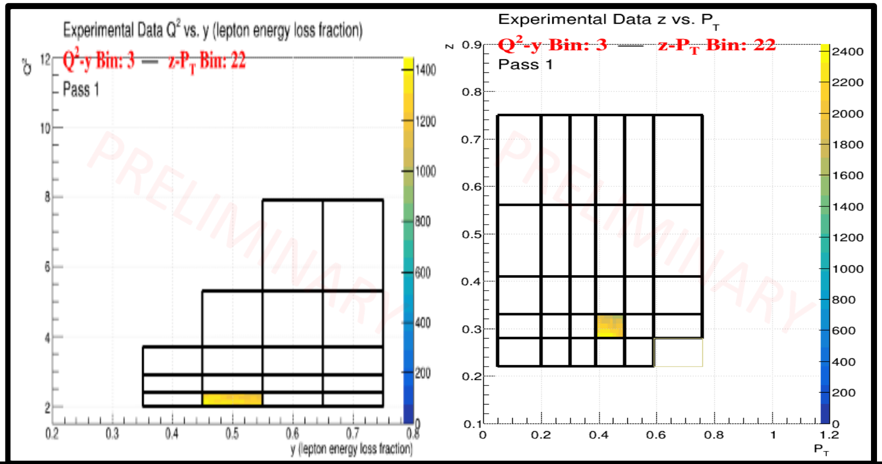
These plots show those differences in Pass 1 (top row) and Pass 2 (bottom row)

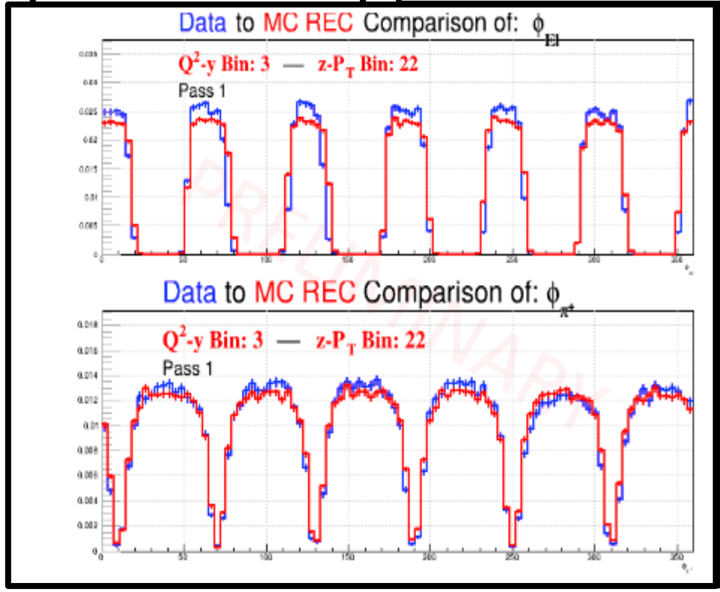
Electron is restricted to being detected in a single sector

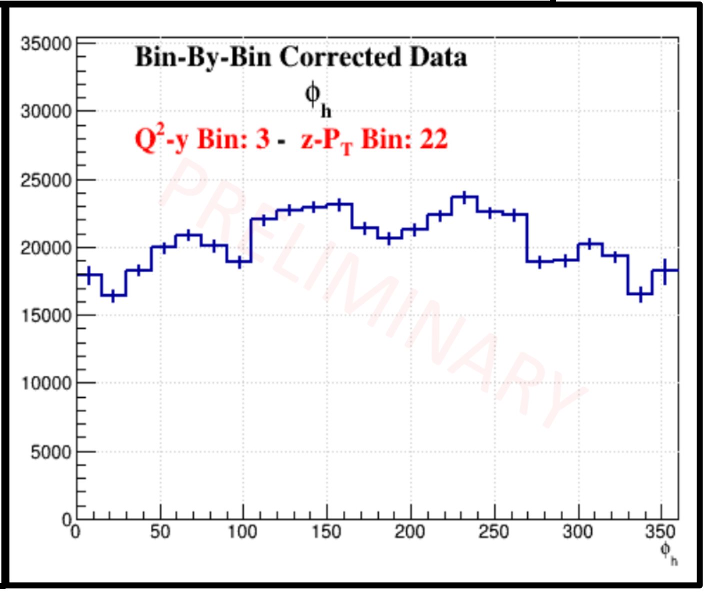
Plotting Cos(ϕ) Moments vs Electron Sector on the right

Sector Dependence of ϕ_h Distributions

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



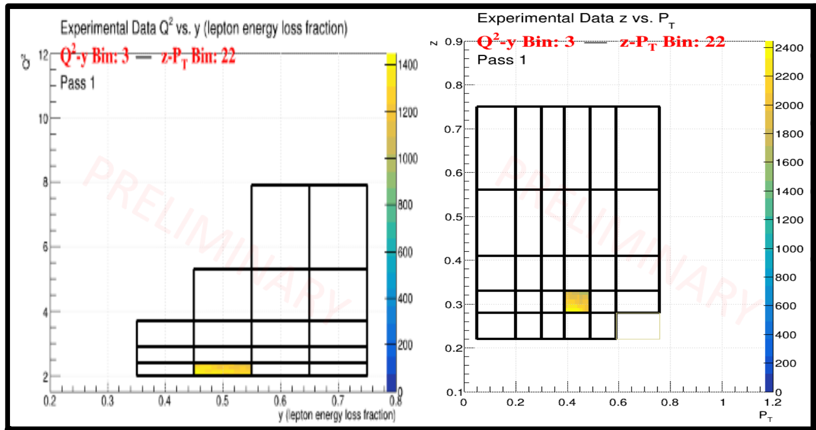


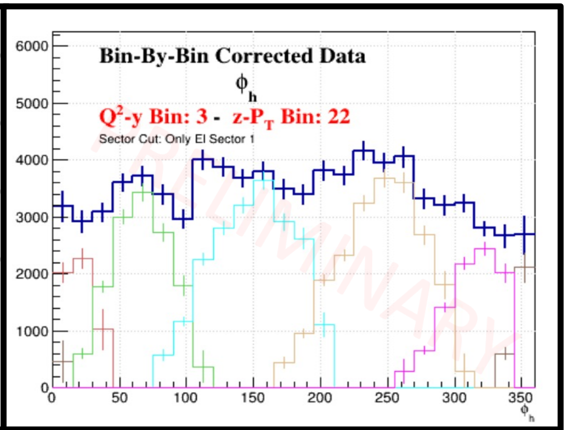


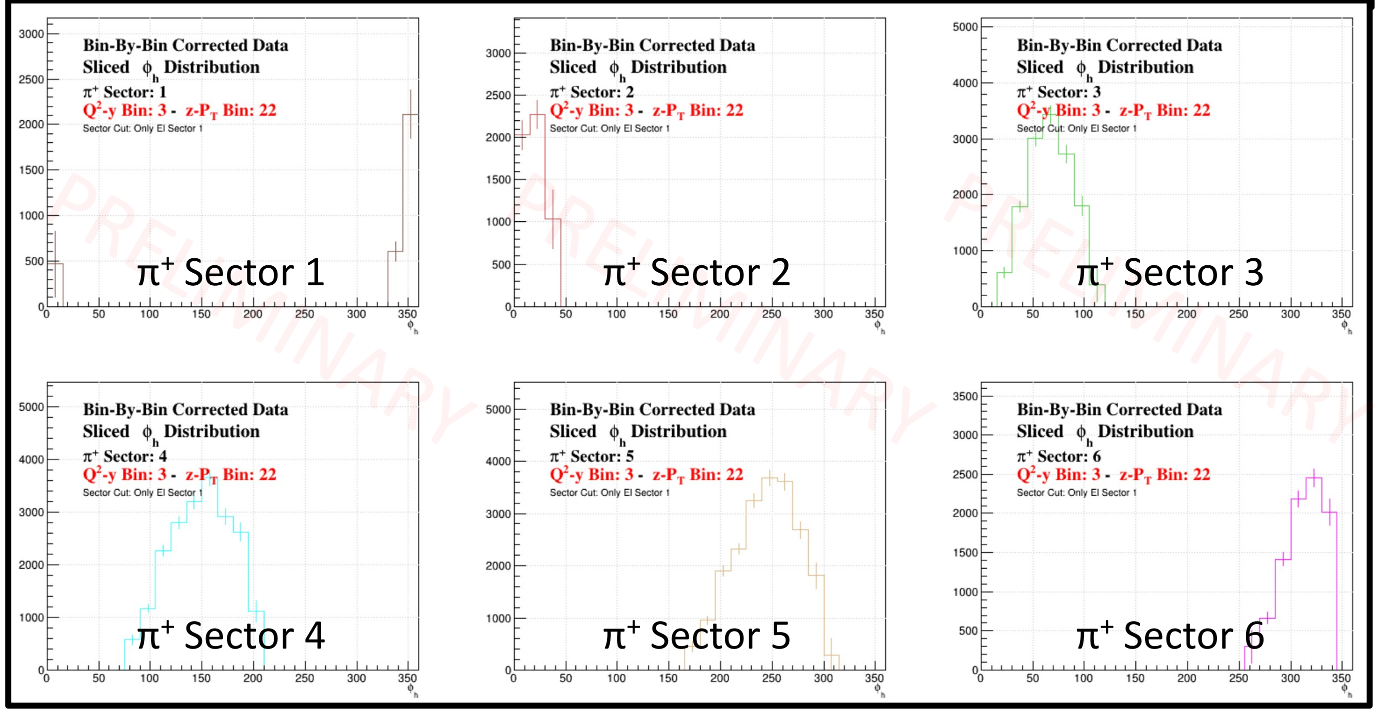
Issue: Some bins seem to have additional modulations AFTER Acceptance Corrections not explained by the Cos(ϕ) and Cos(2ϕ) moments

- The 6 peak structure is related to the forward detector sectors

Sector Dependence of ϕ_h Distributions



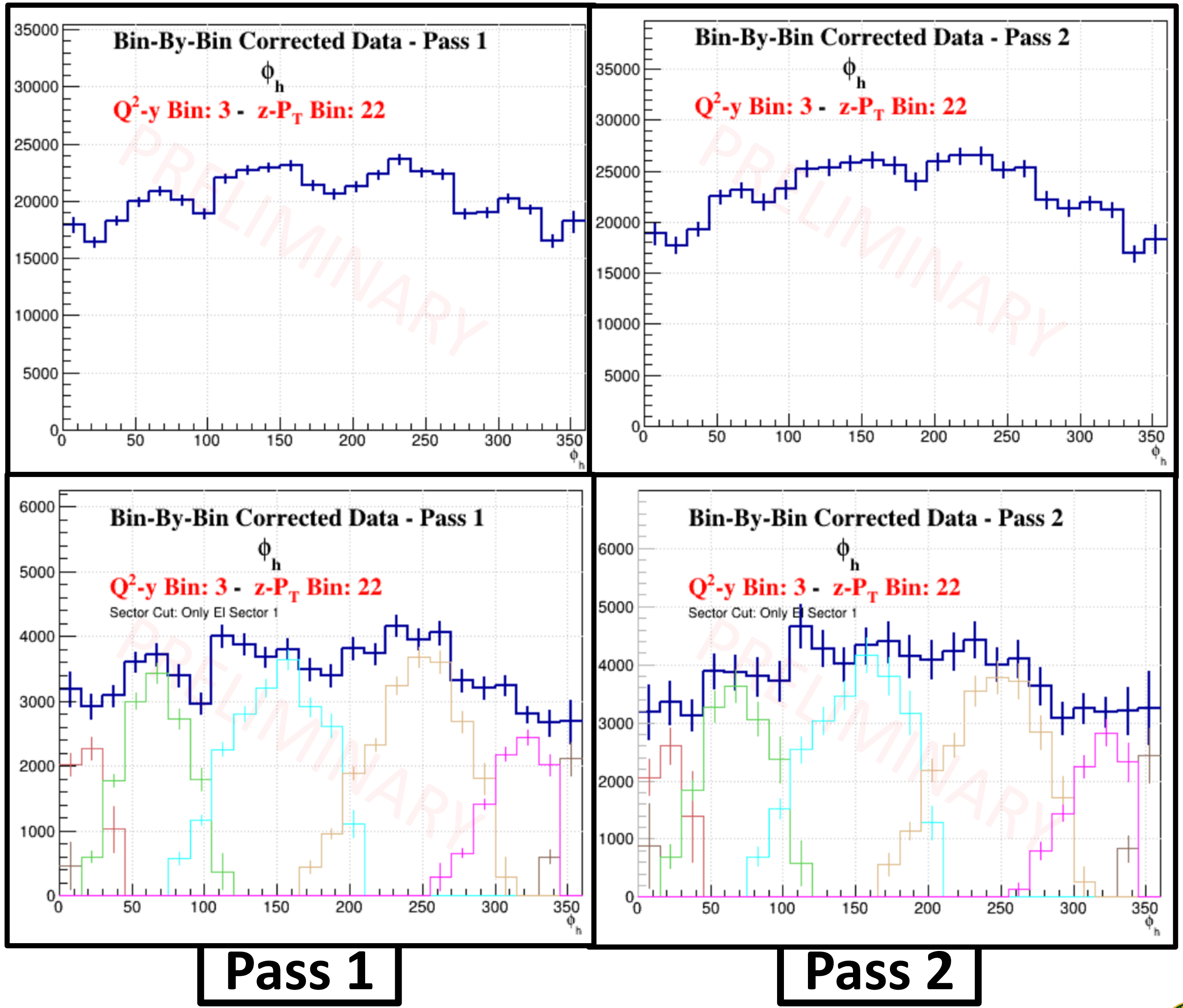




Issue: Some bins seem to have additional modulations AFTER Acceptance Corrections not explained by the Cos(ϕ) and Cos(2ϕ) moments

- The 6 peak structure is related to the forward detector sectors
- **Plots show the ϕ_h distributions separated based on which sector the π+ pion is detected**
- Additional Requirement: Electron in Sector 1
- This suggests that the effect is related to mismatching in sector acceptance between Data and Monte Carlo

Sector Dependence of ϕ_h Distributions – Pass 2 Comparison



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 is related to the forward detector sectors
- **Plots show the ϕ_h distributions separated based on which sector the π+ pion is detected**
- Additional Requirement: Electron in Sector 1
- This suggests that the effect is related to mismatching in sector acceptance between Data and Monte Carlo
- **Also present in Pass 2**