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

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CLAS Collaboration 2023

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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

  o **Boer-Mulders Effect:** Sensitive to the correlation between the quark's transverse momentum and intrinsic transverse spin in an unpolarized nucleon

  o **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)

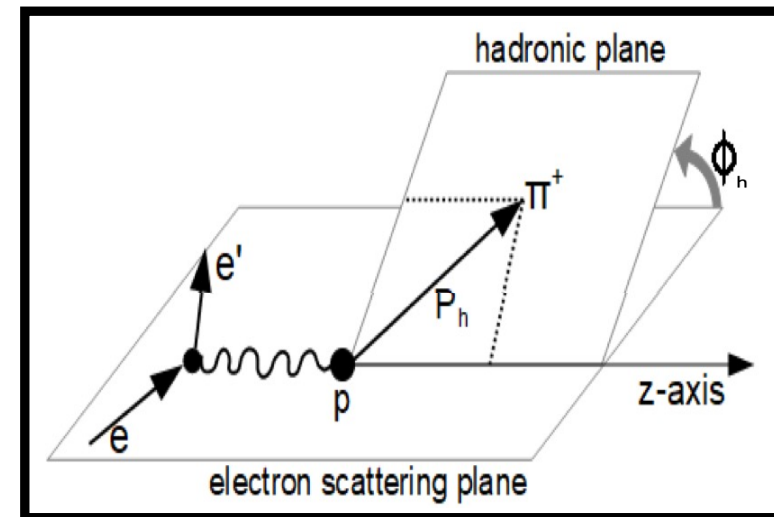**The lepton-hadron Unpolarized SIDIS Cross-Section:**

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

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

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

**Reaction Studied:** ep➔eπ⁺(X)

Data Collection
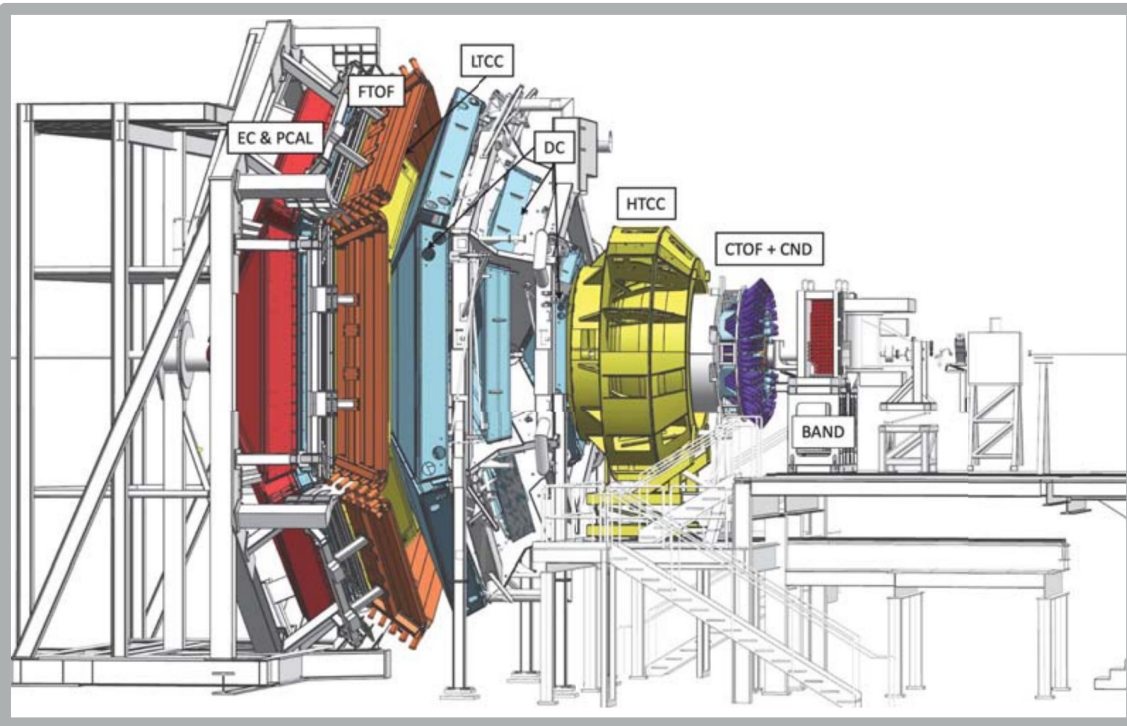
CLAS12 Detector

- CLAS12 detector in Hall B at Jefferson Lab

  o Upgrade from the CLAS detector

  o Enabled the higher energy and statistics for our experiments, not previously accessible

- Data from the Fall 2018 RG-A experiment

  o Used a 10.6 GeV polarized electron beam and unpolarized liquid hydrogen target

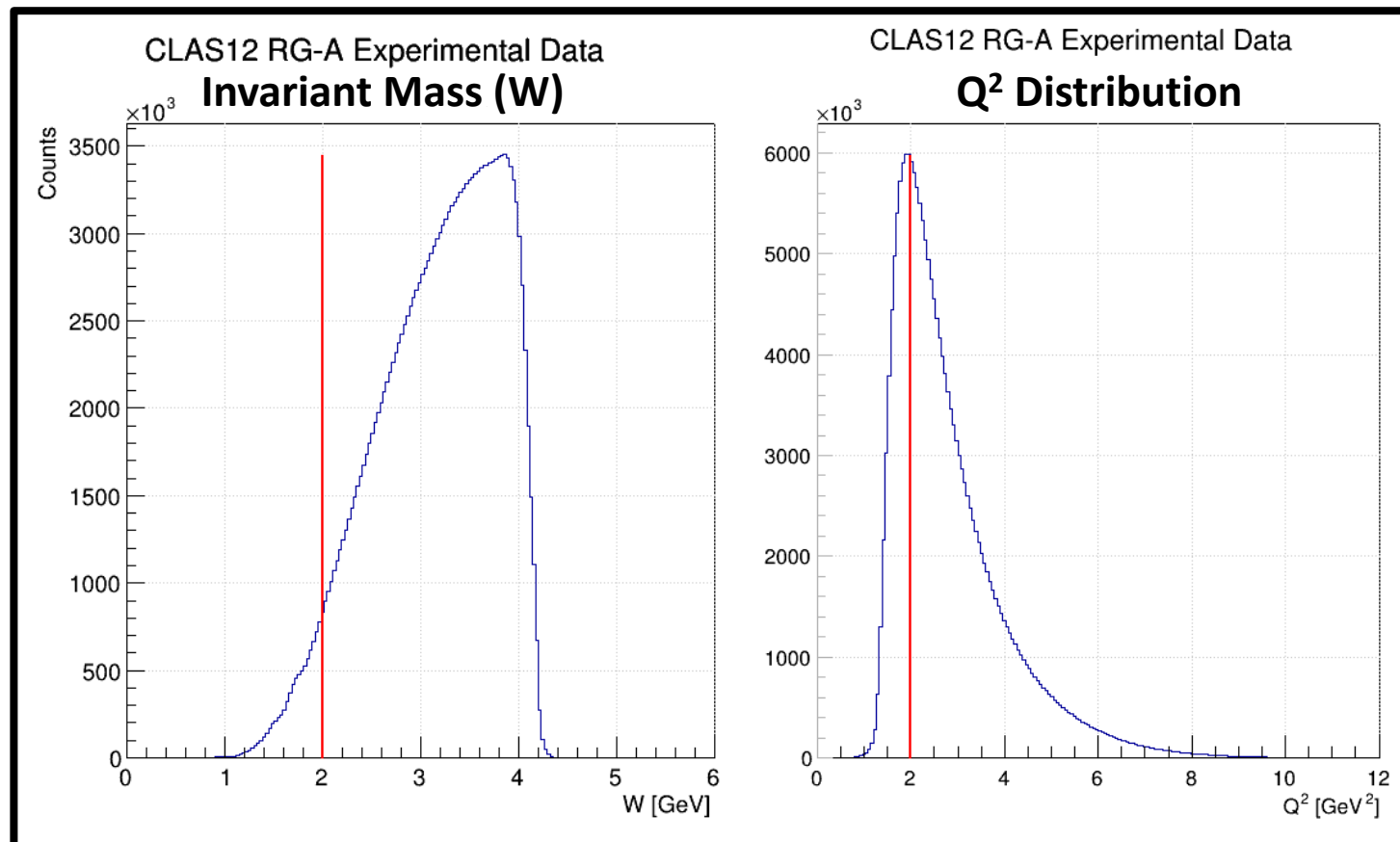- Data presented uses forward tracking only

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
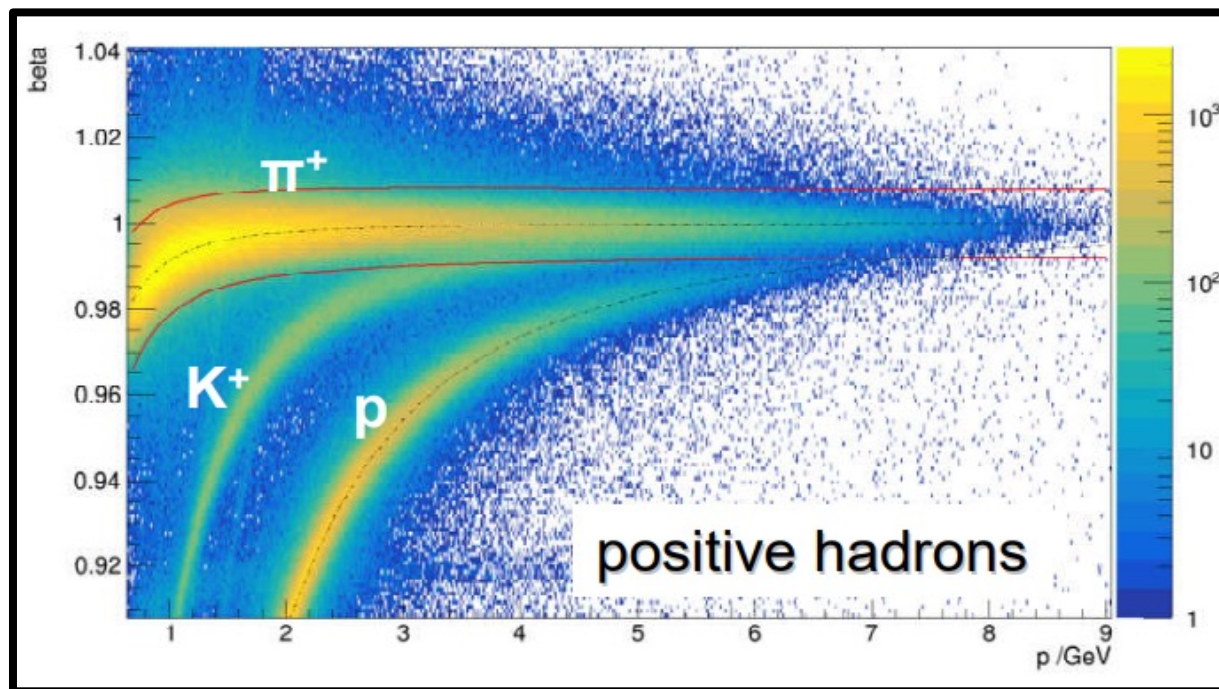
*Image provided by Stefan Diehl

π⁺ Pion PID – ß vs p

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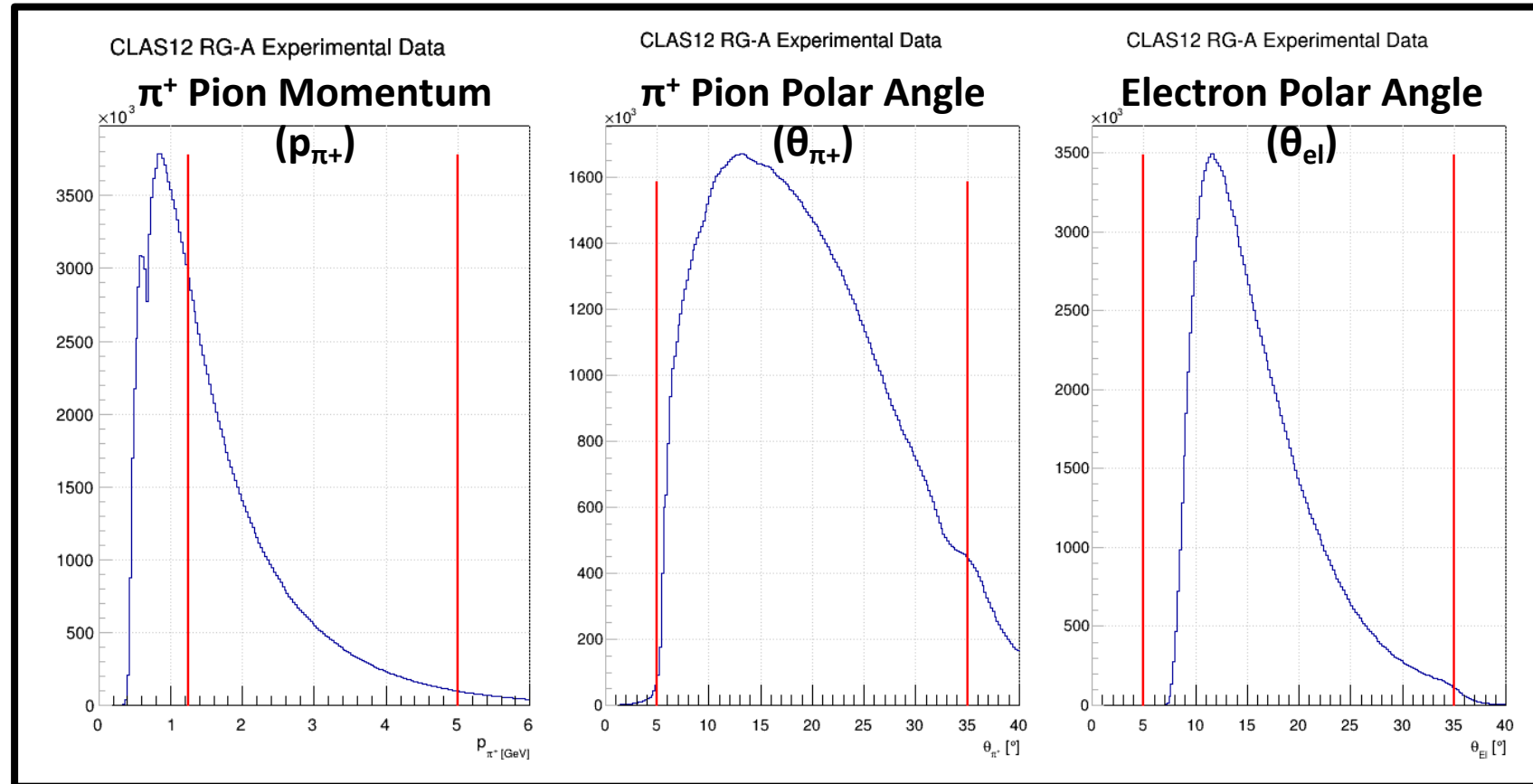
Analysis Cuts:

- **SIDIS Cuts**:
  - W > 2 GeV
  - Q^2 > 2 GeV^2

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  - $Q^2 > 2$ GeV^2

- **Other Analysis Cuts:**
  - $p_{\pi+}$ Cut: 1.25 GeV $< p_{\pi+} < 5$ GeV
  - θ-angle Cut: $5° < \theta_{particle} < 35°$

Event Selection

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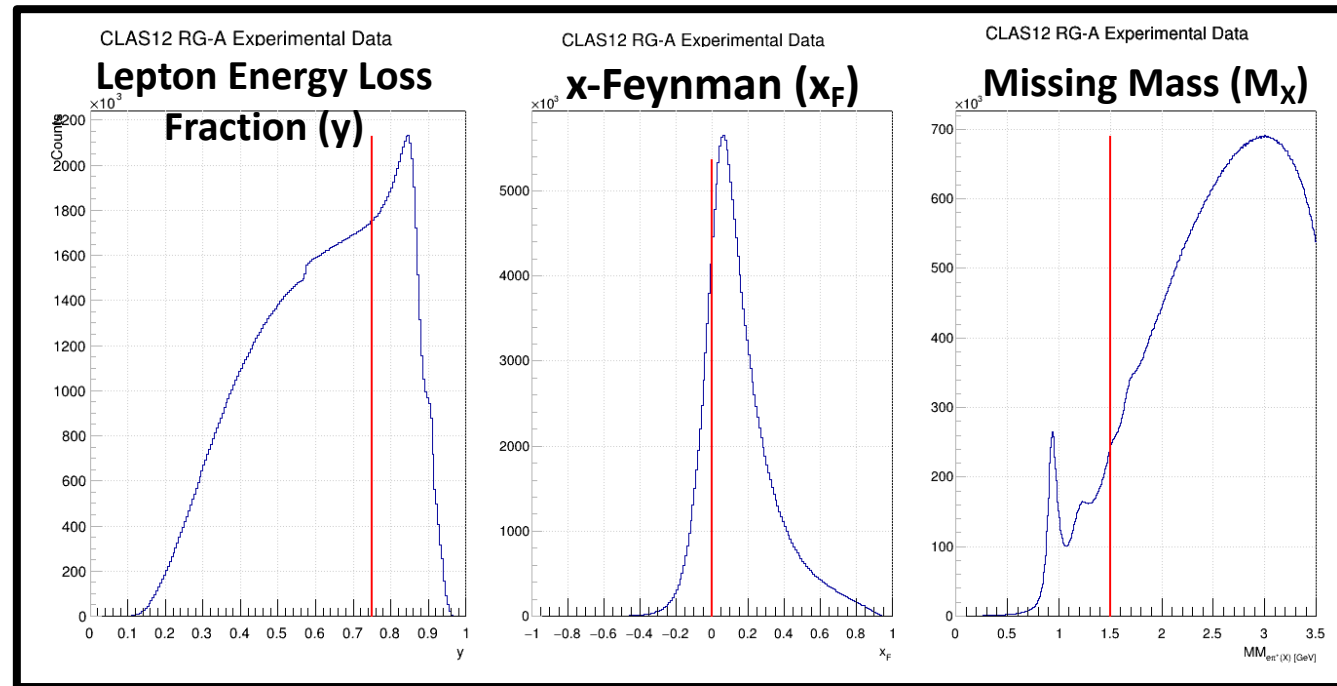- **Hadron (π^+) ID:** Based on Time-Of-Flight Counters (TOF) and the correlation of velocity (ß) and momentum

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  - y < 0.75 (minimize other background processes)
  - x_F > 0 (minimize contributions from target fragmentations)
  - Missing Mass Cut: M_x > 1.5 GeV (limits contributions from exclusive events)

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  - x_F > 0 (minimize contributions from target fragmentations)
  - Missing Mass Cut: M_x > 1.5 GeV (limits contributions from exclusive events)
  - Fiducial Cuts (e.g., accounts for bad channels present in data)

CLAS12 RG-A Experimental Data
PCAL
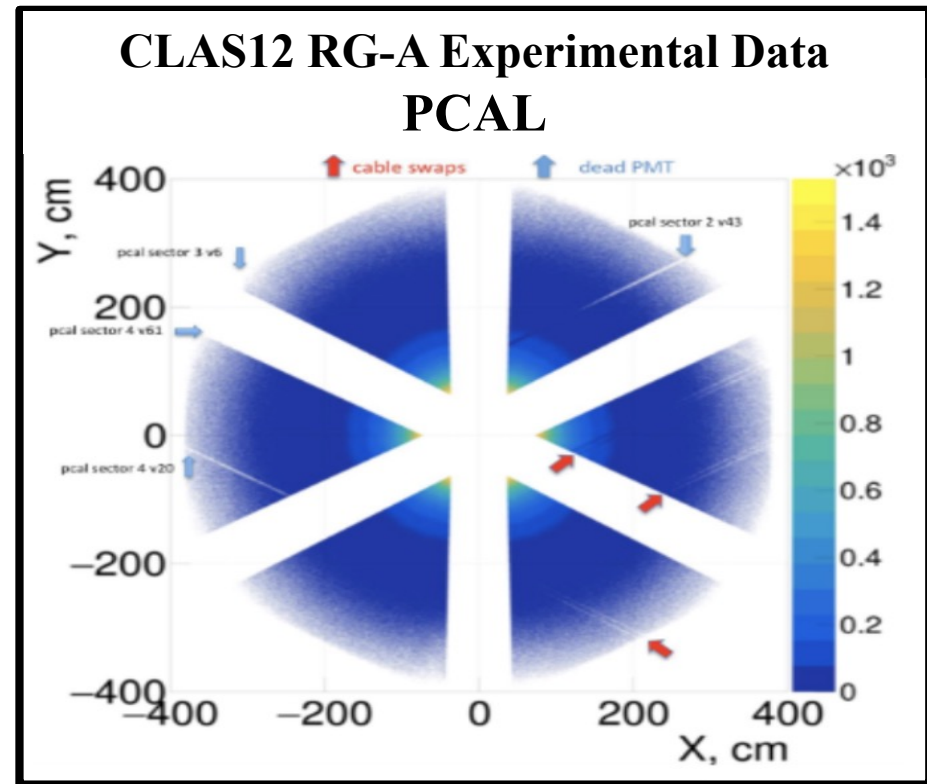
Experimental extraction of cross-section

$$\frac{d^5\sigma}{dQ^2 dy dP_T dz d\phi_h} = \frac{1}{\Gamma_\nu} \frac{1}{\Delta Q^2 \Delta y \Delta P_T \Delta z \Delta \phi_h} \frac{N}{R \cdot BC \cdot \eta \cdot N_0} \frac{1}{(N_A \cdot \rho \cdot t / A_w)}$$
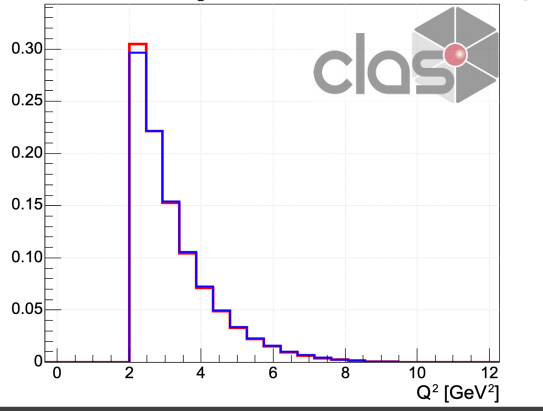
Bin Volume

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

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Data and Monte Carlo Comparison

Q² Comparison

y Comparison

z Comparison

P$_T$ Comparison

Momentum vs Polar Lab Angle Comparison

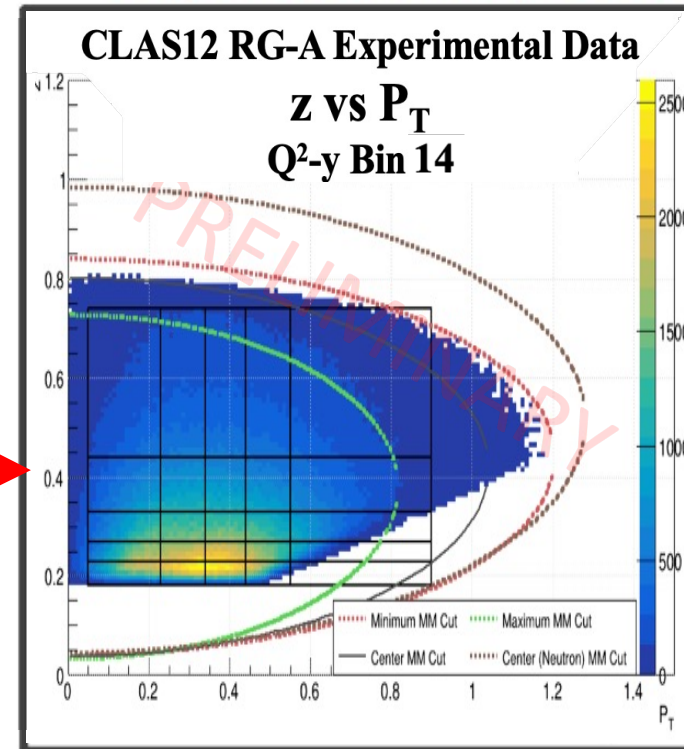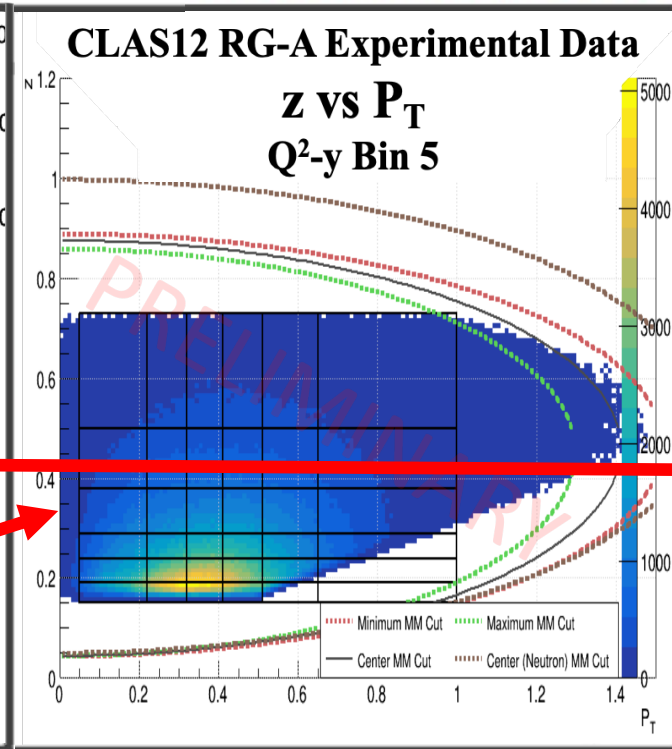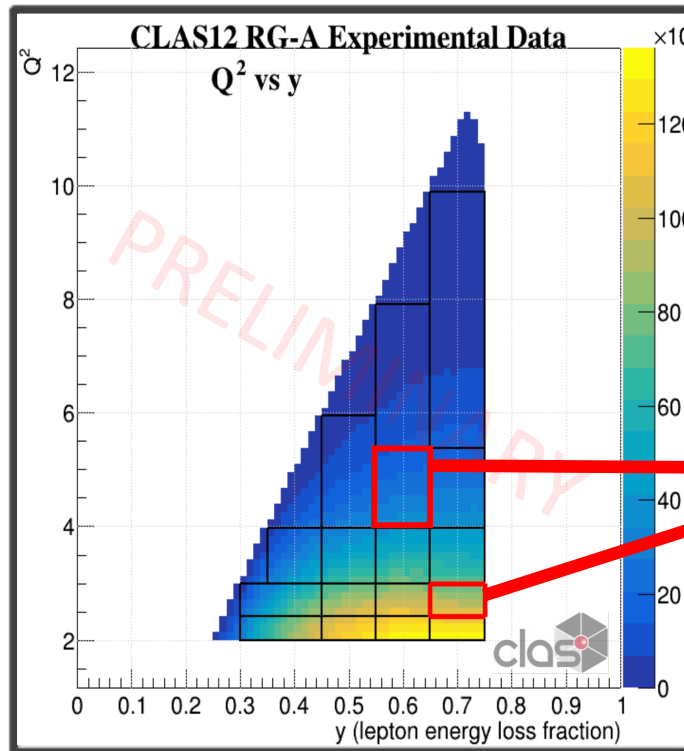Electron Comparison
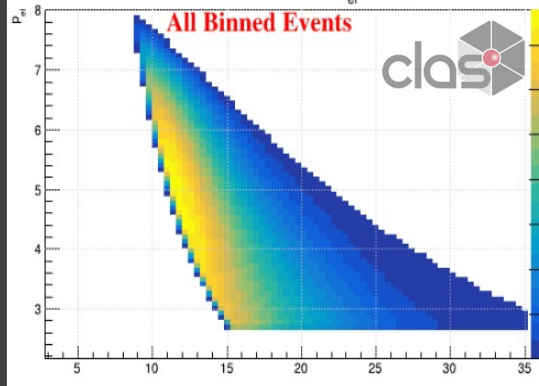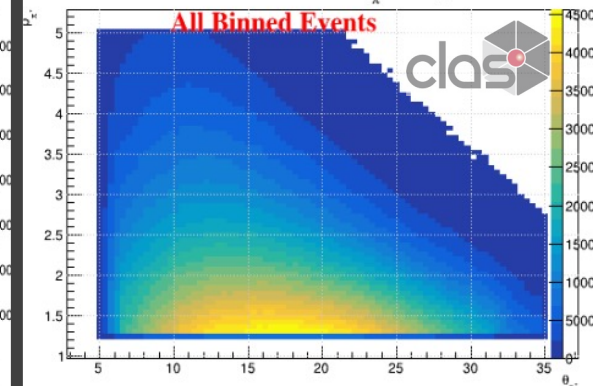
π⁺ Pion Comparison
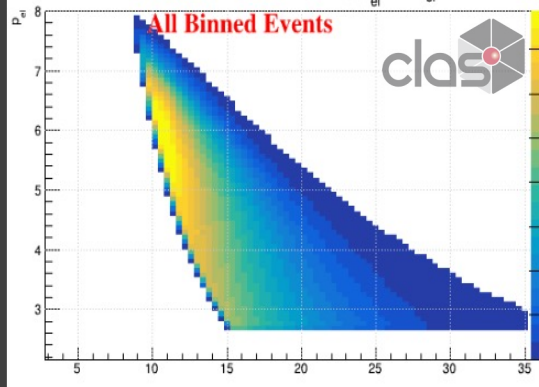
Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (4 Dimensions)

17 Q^2-y Bins Total – 20-42 z-P_T Bins (per Q^2-y bin)

Examples of new binning scheme using Q^2, y, z, and P_T

Missing Mass Cut Lines:

- Minimum MM Cut
- Maximum MM Cut
- Center MM Cut
- Center (Neutron) MM Cut

Ongoing investigations into the binning scheme include how kinematic cuts can affect the events in the edge bins

The example shown is for Missing Mass Cuts from different regions of the Q^2-y Bins
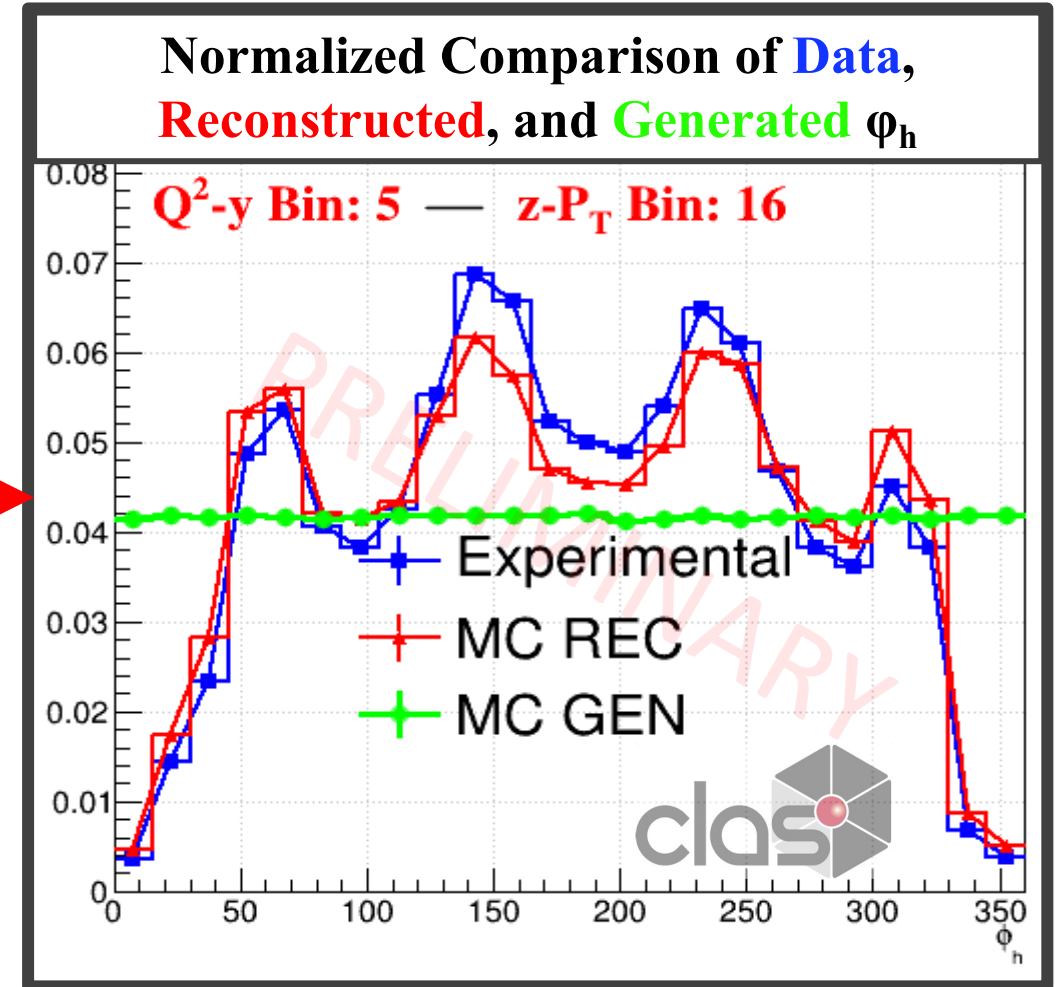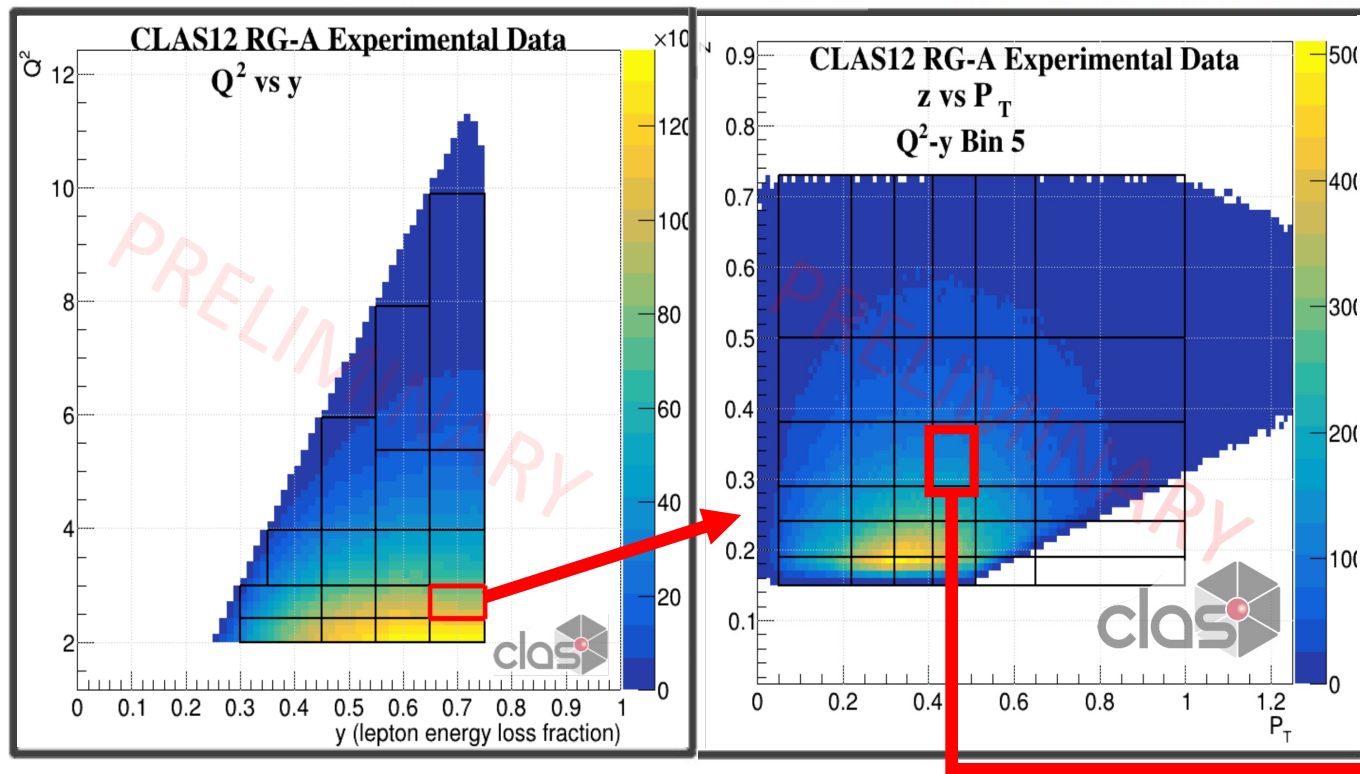
Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (5 Dimensions)

17 Q^2-y Bins Total – 20-42 z-P_T Bins (per Q^2-y bin)

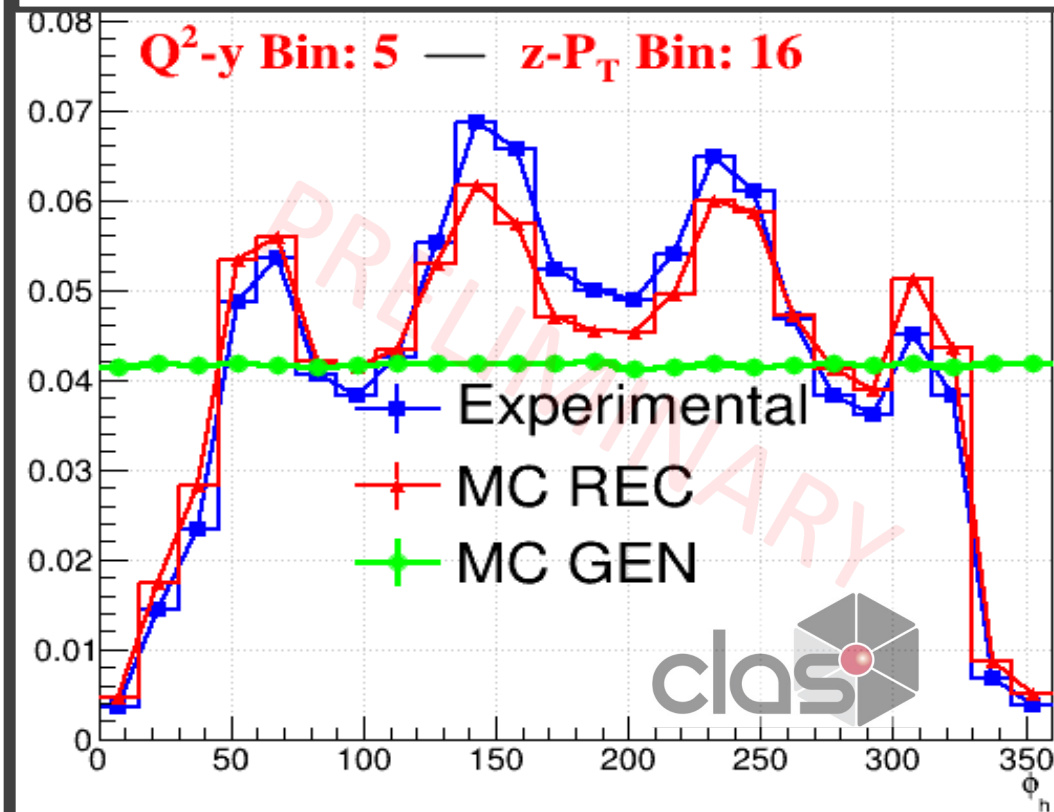ϕ_h distribution for the Q^2-y-z-P_T bin shown in red

Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (5 Dimensions)

Normalized Comparison of **Data**, **Reconstructed**, and **Generated** ϕ_h

Q²-y Bin: 5 — z-P$_T$ Bin: 16

- Experimental
- MC REC
- MC GEN

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
- **(SVD) Singular Value Decomposition**
- **Bayesian Unfolding**
  - Both the SVD and Bayesian Unfolding Methods use Acceptance Matrices to correct the data

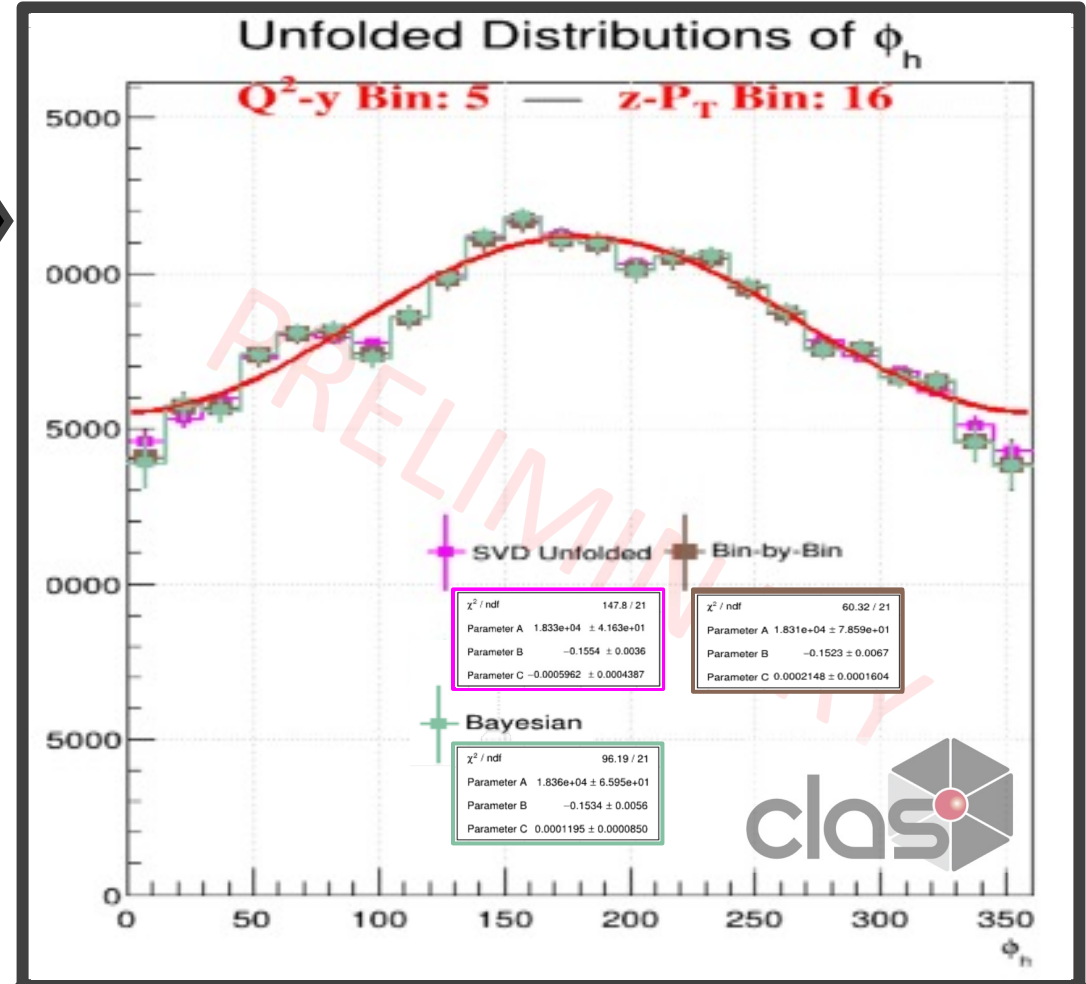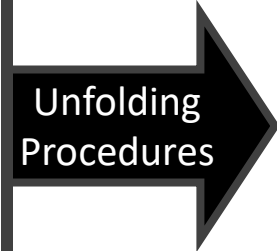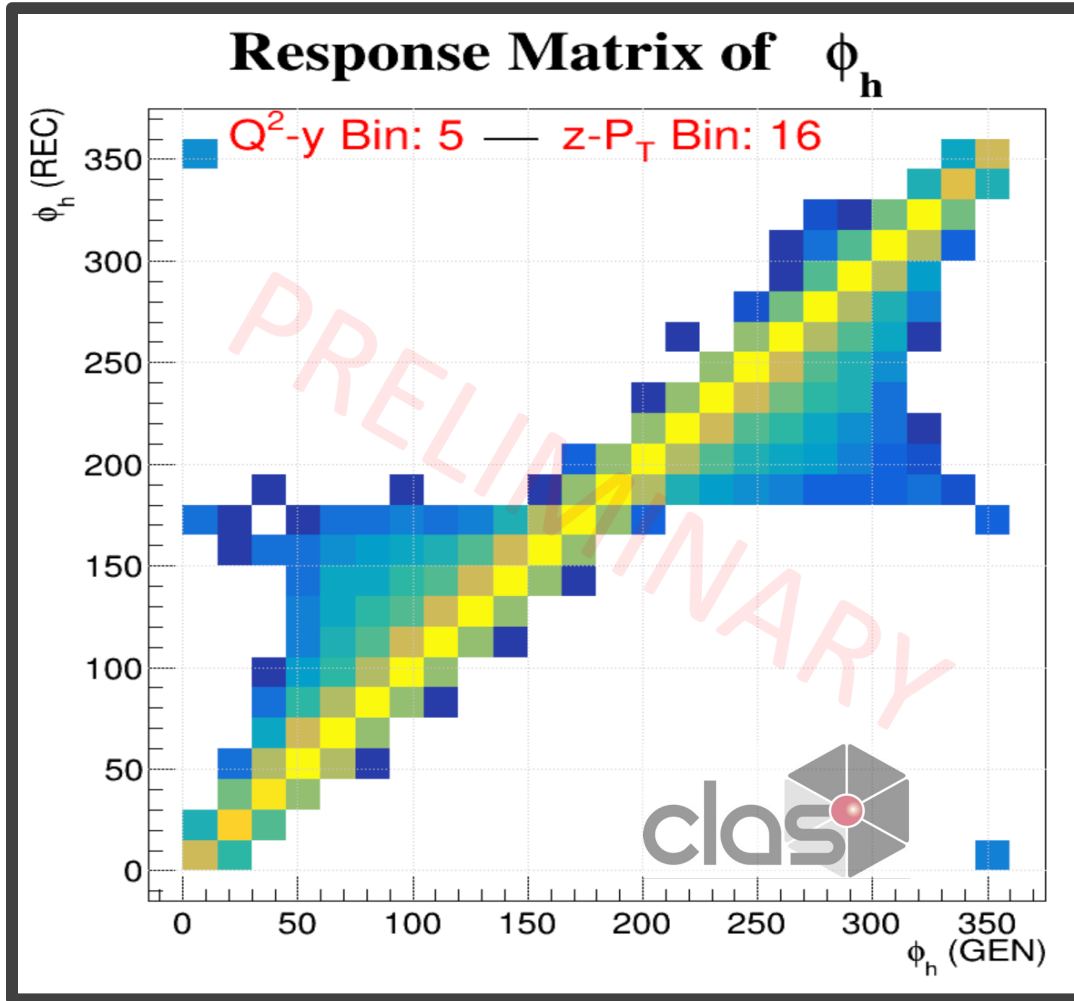# Acceptance Corrections and Bin Migration Study

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

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

- Acceptance Unfolding: $Y_i = A_{(i,\,j)} X_j \iff X_j = A^{-1}_{(i,\,j)} Y_i$

  where:

  o Y_i = Number of events experimentally measured in the i-th bin

  o X_j = Number of acceptance-corrected events in the j-th bin

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Using the Multidimensional Kinematic Bin from prior example
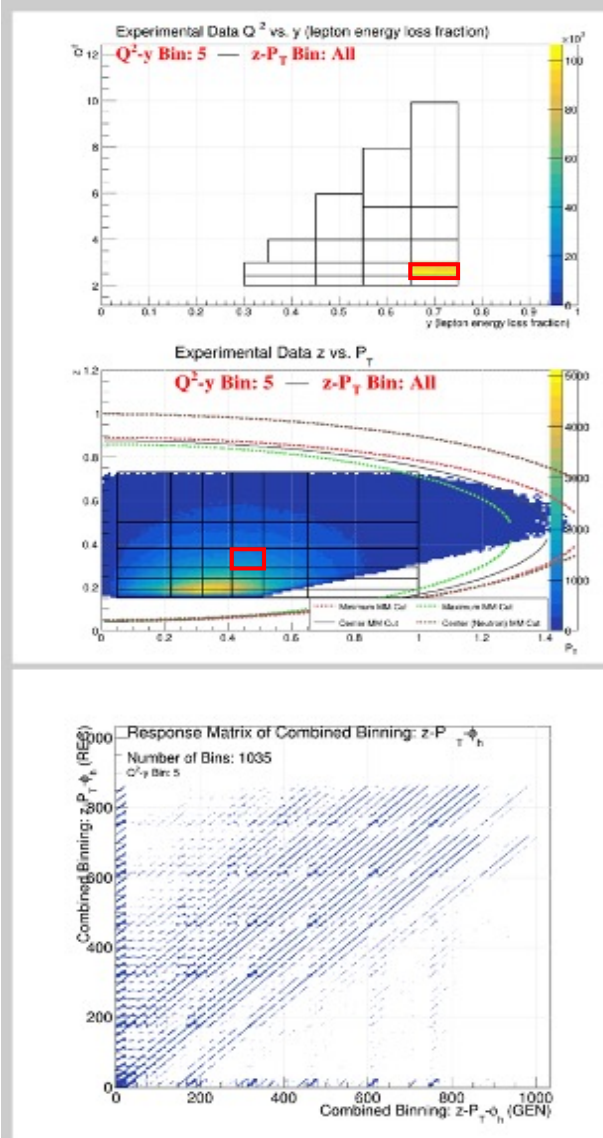

Unfolding Procedures

Parameters shown are from the fits previously described

Example of (3D) Unfolding Procedure

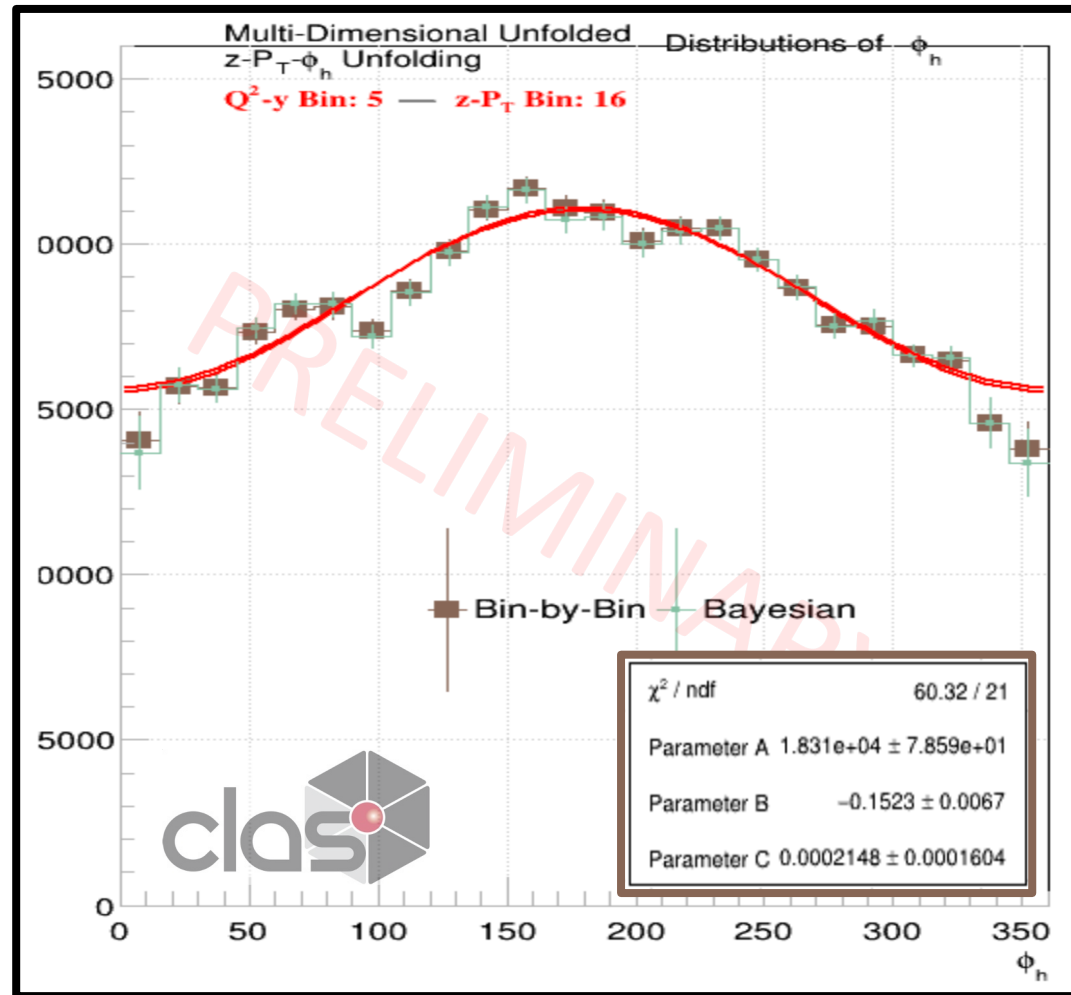**Using the Flattened z-P_T-ϕ_h Multidimensional Bins**

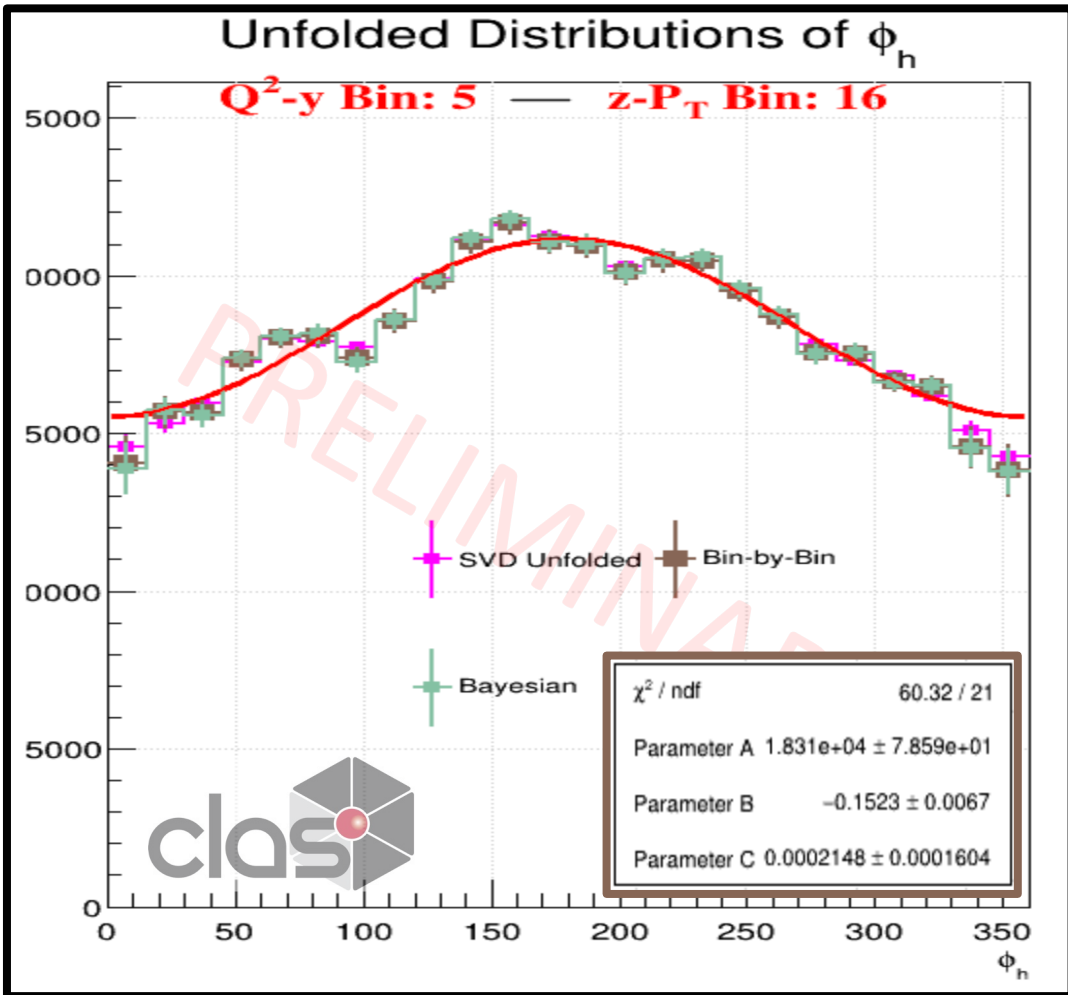**Q^2-y Bin 5**

PRELIMINARY

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Comparisons of 1D and 3D Unfolding Procedure

Using the Multidimensional Kinematic Bin from the prior example for this comparison
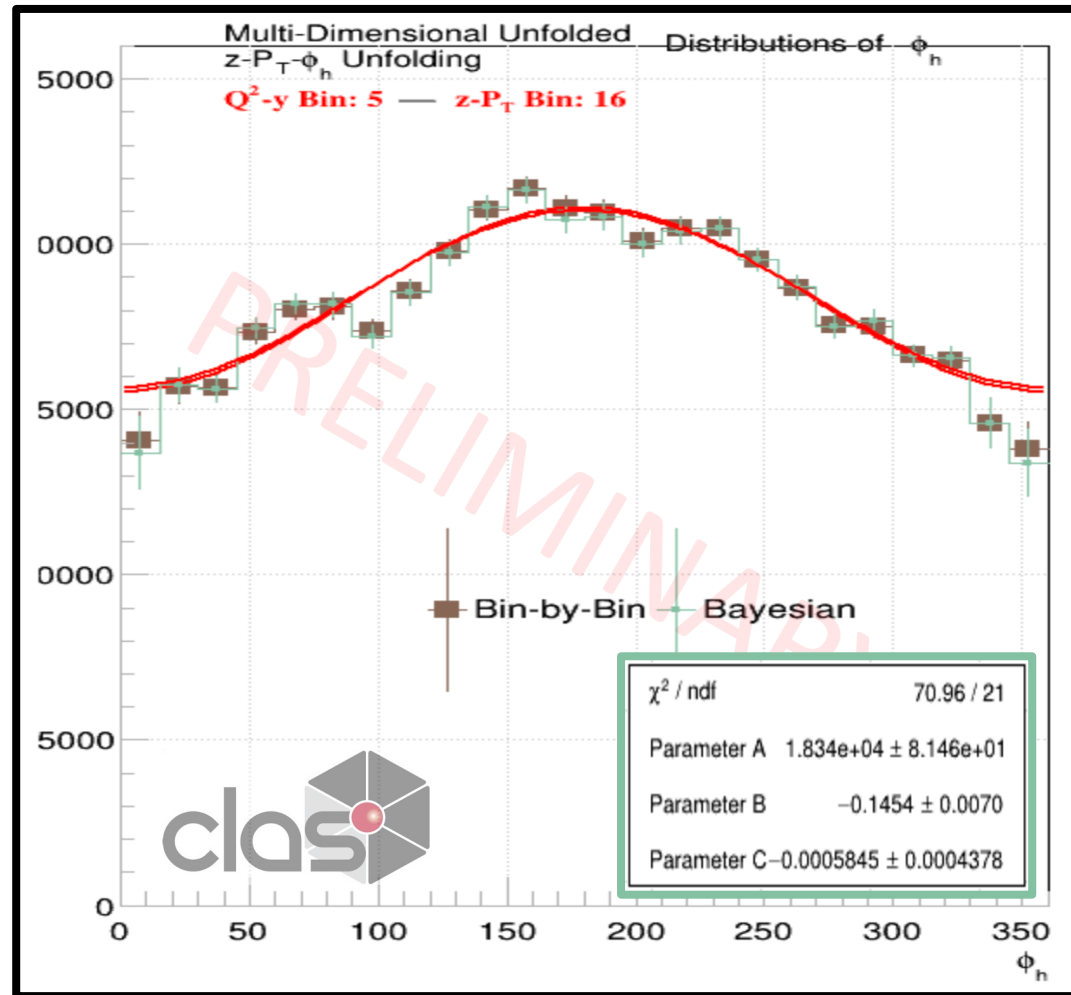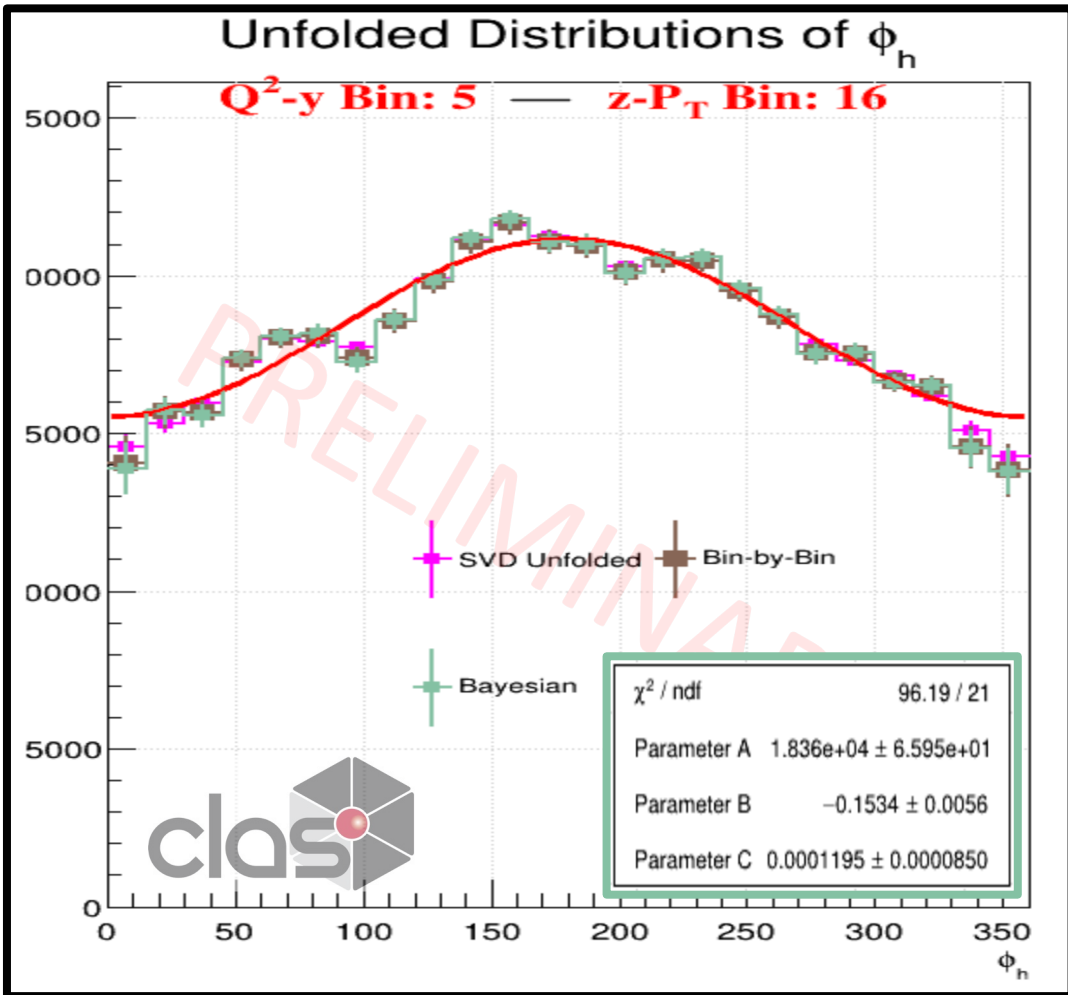

Bin-by-bin Acceptance Correction gives the exact same results

SVD Unfolding has not been able to work so far with the Multidimensional Unfolding procedures

Comparisons of 1D and 3D Unfolding Procedure

Using the Multidimensional Kinematic Bin from the prior example for this comparison

Bin-by-bin Acceptance Correction gives the exact same results

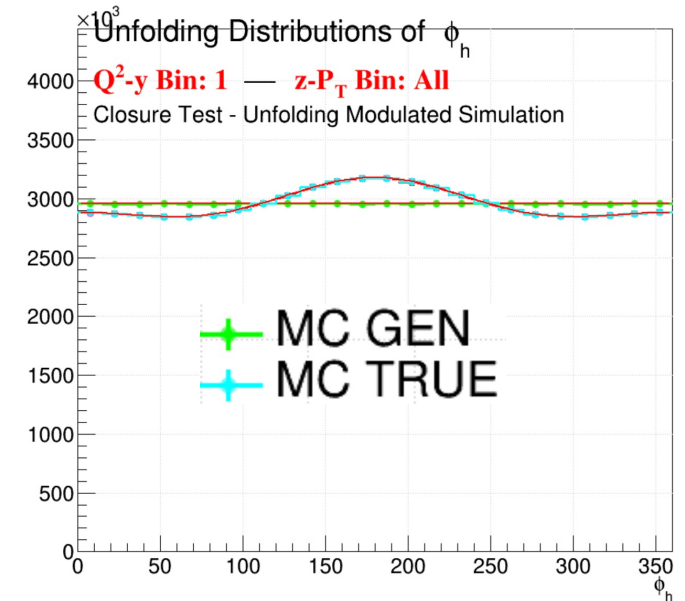**Bayesian Unfolding gives similar results**

SVD Unfolding has not been able to work so far with the Multidimensional Unfolding procedures

Modulated Unfolding Closure Tests

- Modulated the MC distributions using the formula:

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

Unfolding Distributions of ϕ_h
Q^2-y Bin: 1 — z-P$_T$ Bin: All
Closure Test - Unfolding Modulated Simulation
MC GEN
MC TRUE

- Gives the weight for each MC event based on generated ϕ_h

- Parameter values currently being used in this image:

  - B = -0.05   *(Same for every z-P$_T$ bin)*
  - C = 0.025

- 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
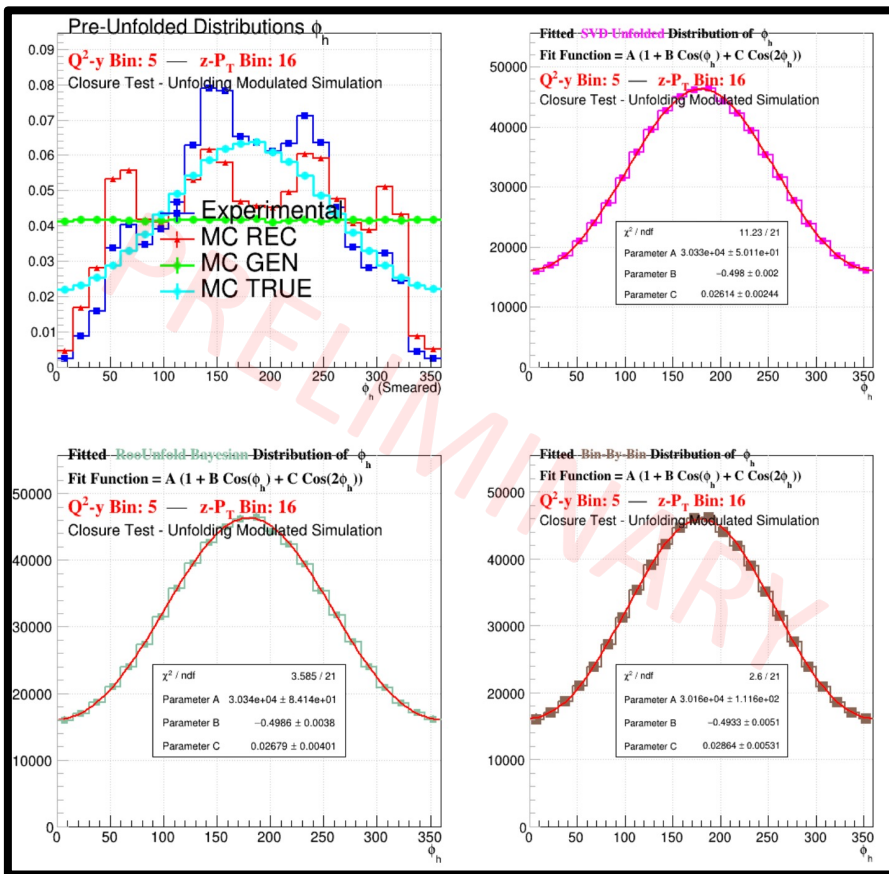
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Modulated Unfolding Closure Tests
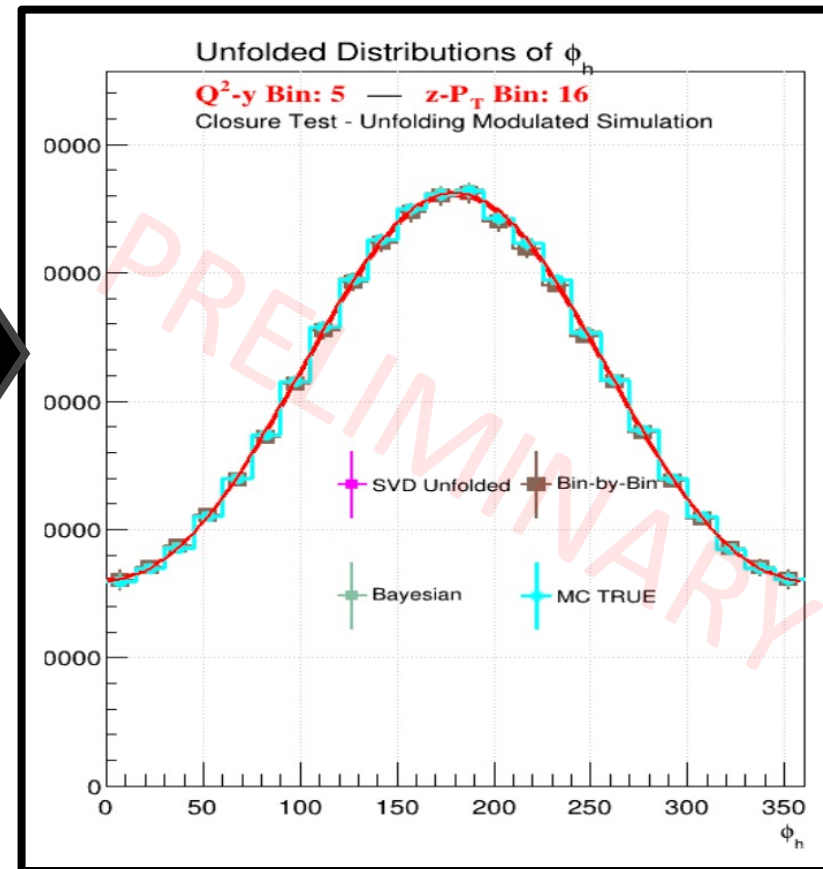
The parameters used for weighing modulations below are:

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

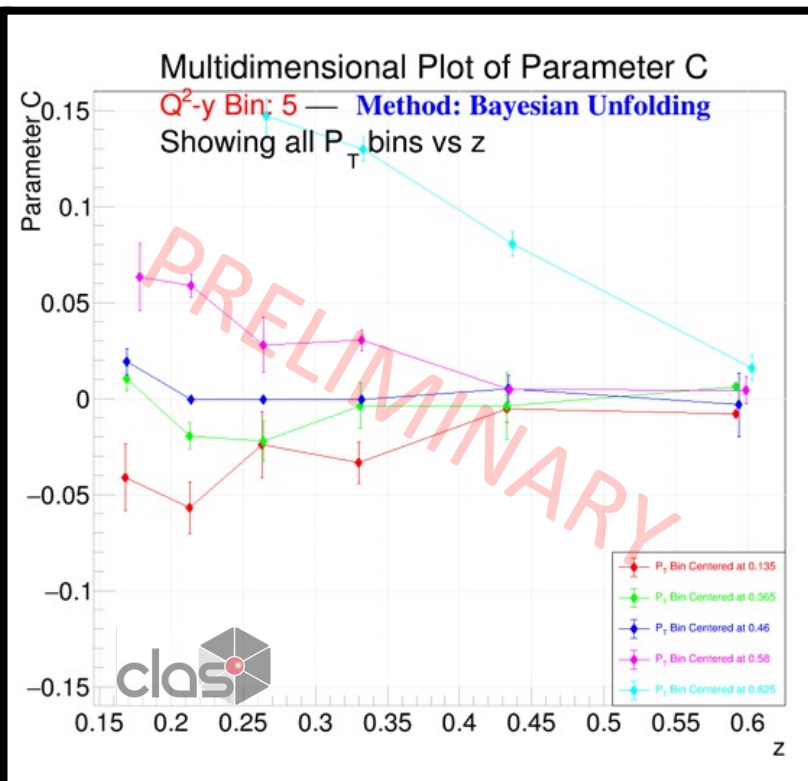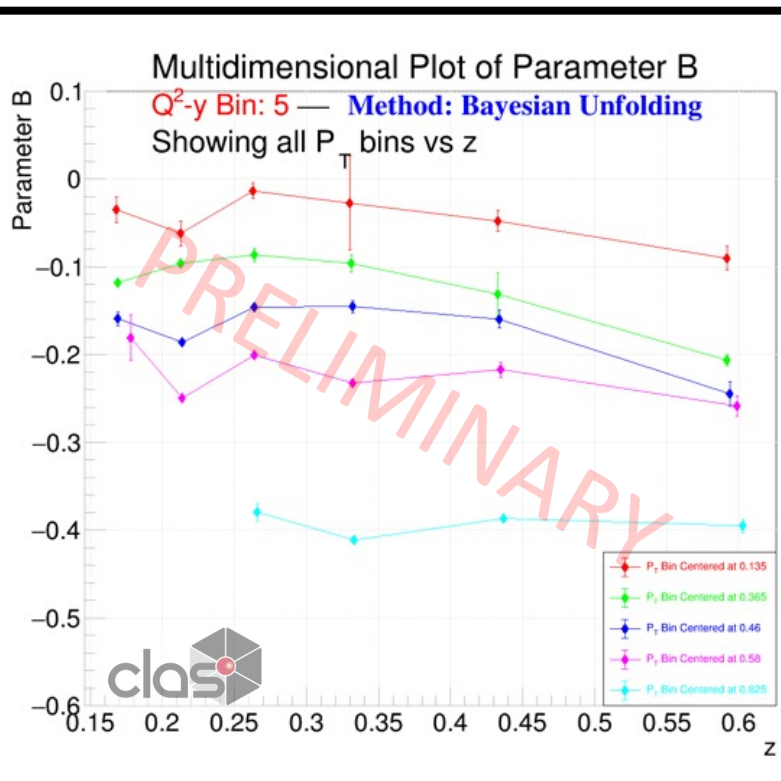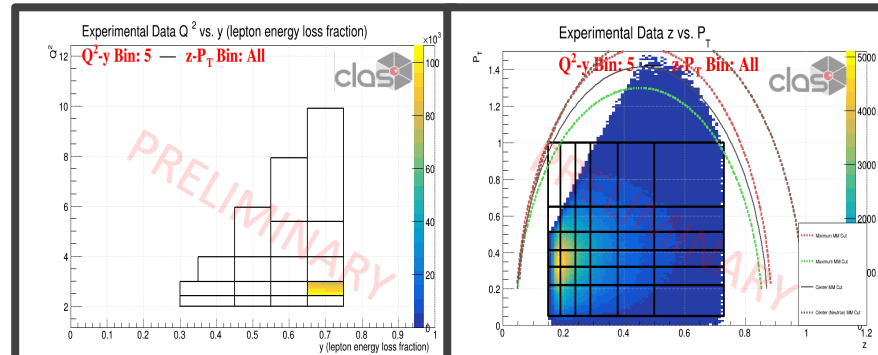Fits are within the margin of error of the defined parameters

Cosine Moments as Functions of z

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

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

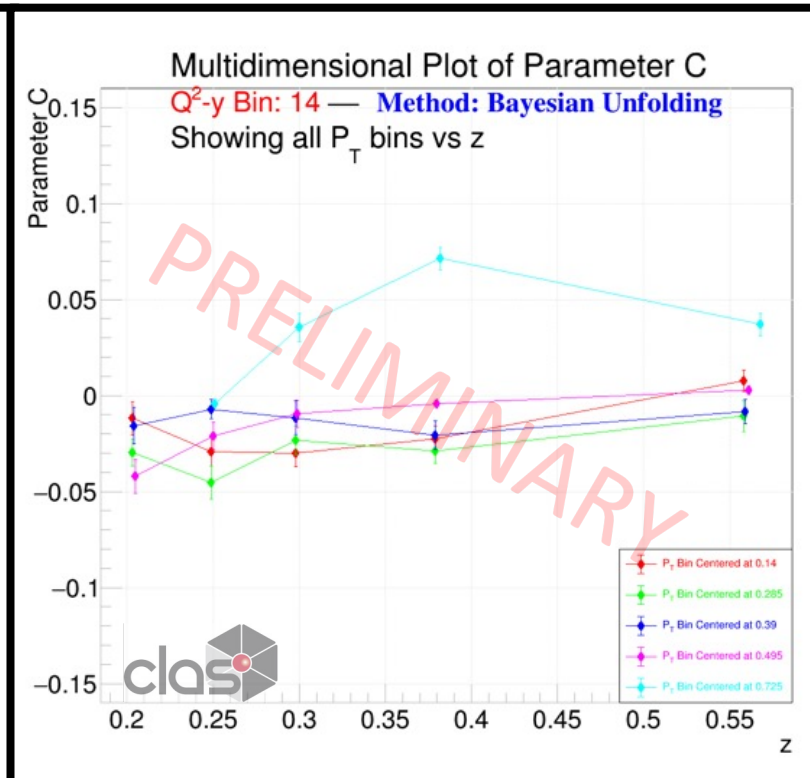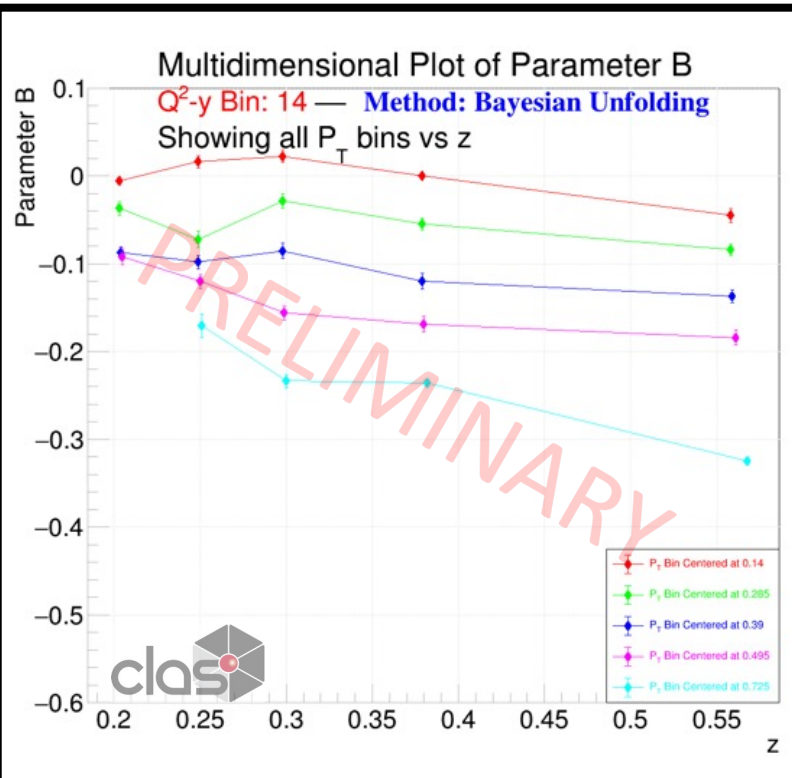**Unfolded with Bayesian Method**   **Q²-y Bin 5**

Cosine Moments as Functions of z

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

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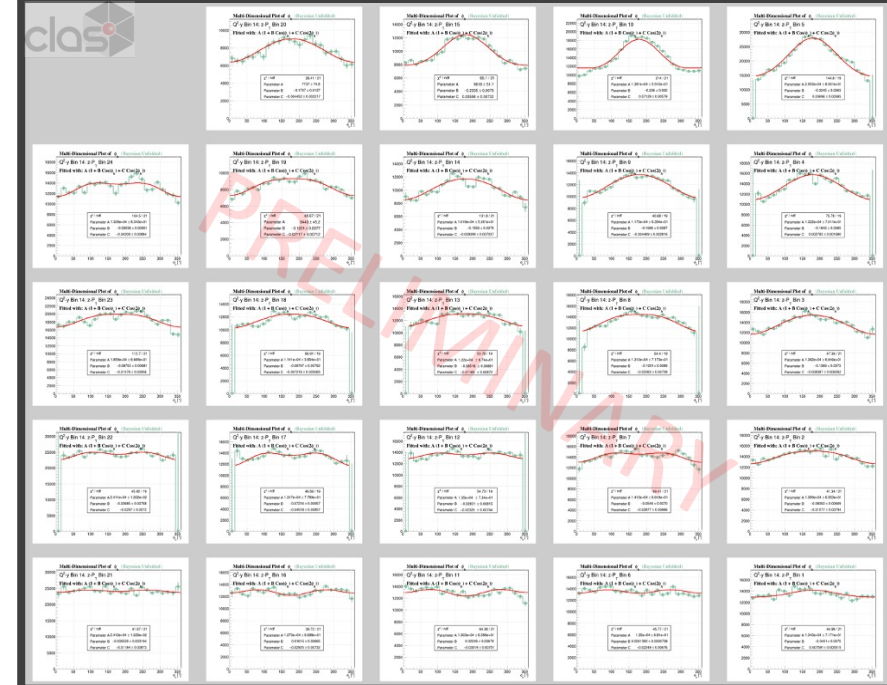$$A(1 + B\cos(\phi_h) + C\cos(2\phi_h))$$

Unfolded with Bayesian Method | **Q²-y Bin 14**

Cosine Moments as Functions of z

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

ϕ_h Plots were fitted with:
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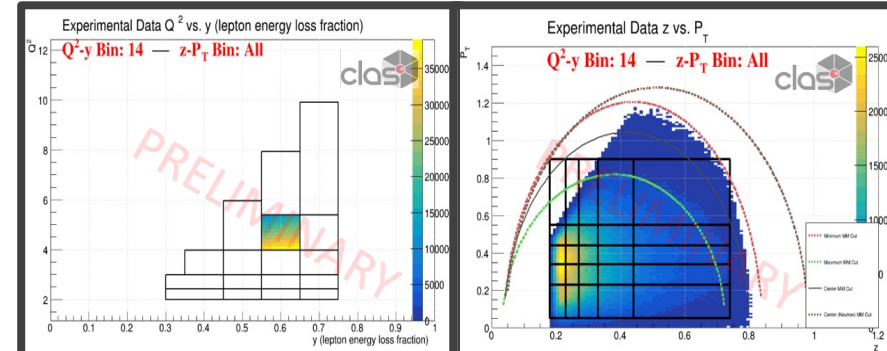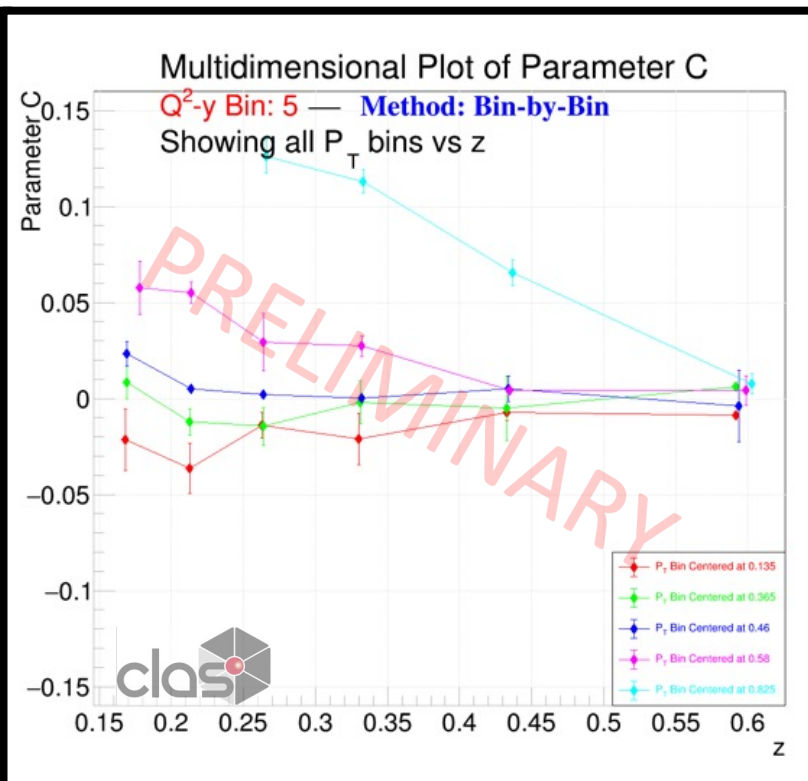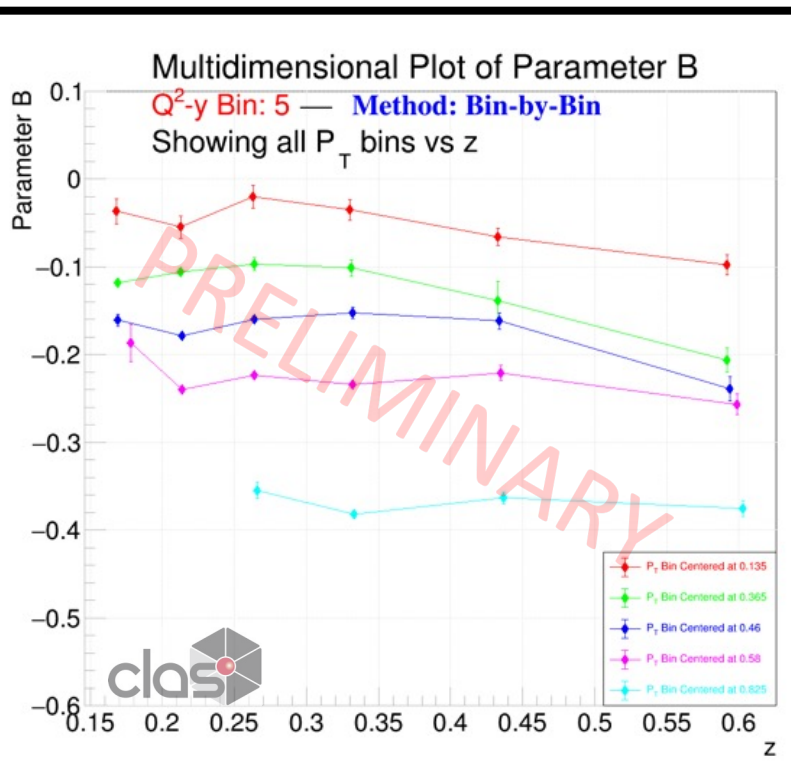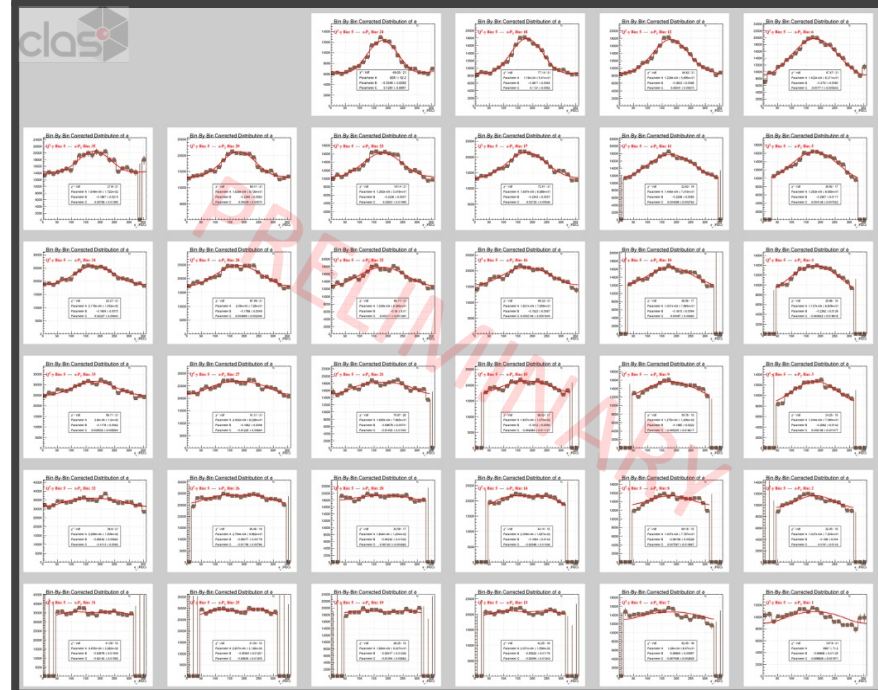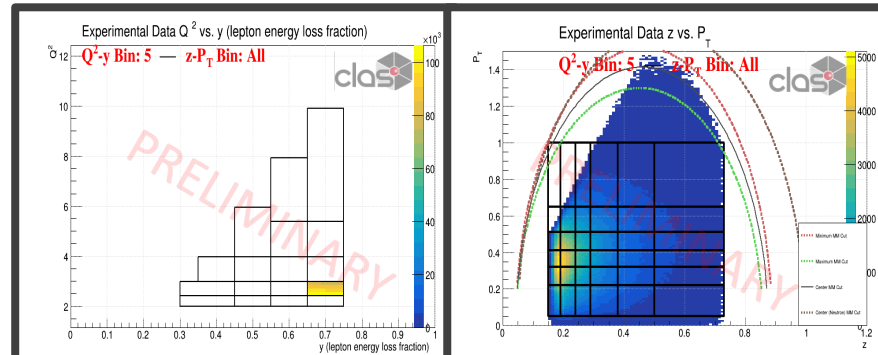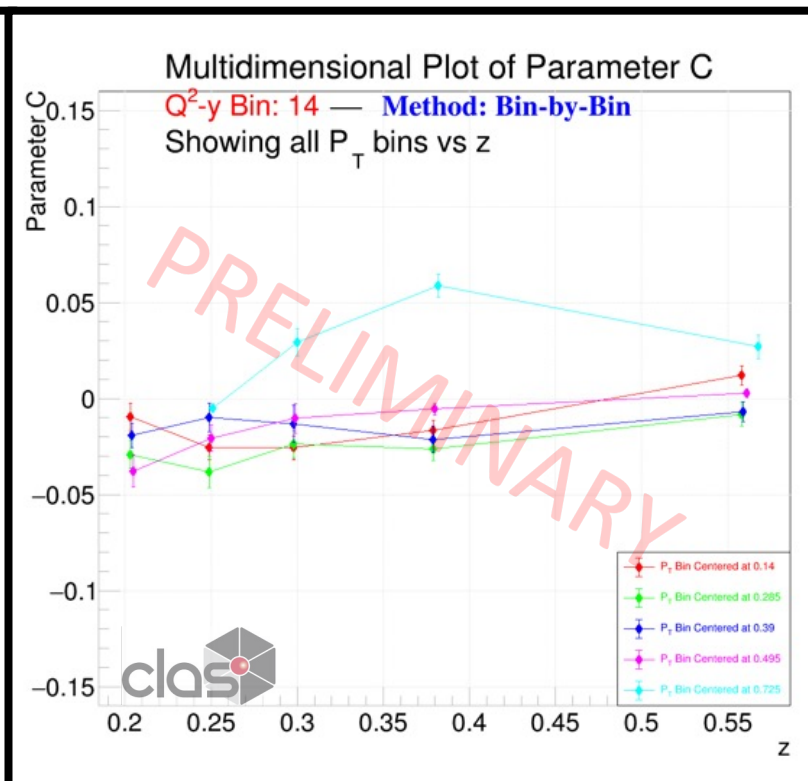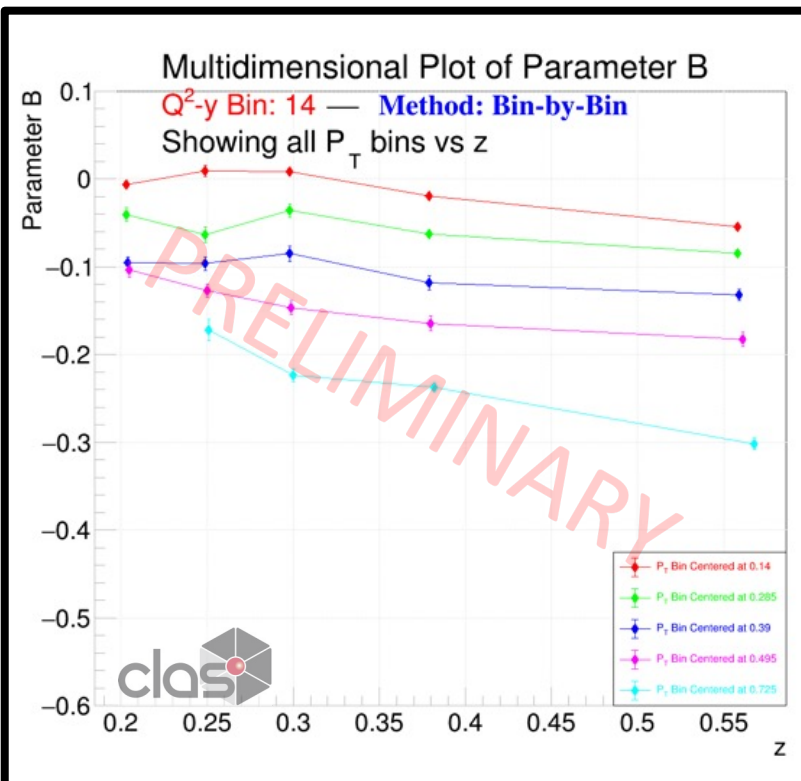**Corrected with Bin-by-bin Method**   **Q²-y Bin 5**

Cosine Moments as Functions of z

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

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

Corrected with Bin-by-bin Method **Q²-y Bin 14**
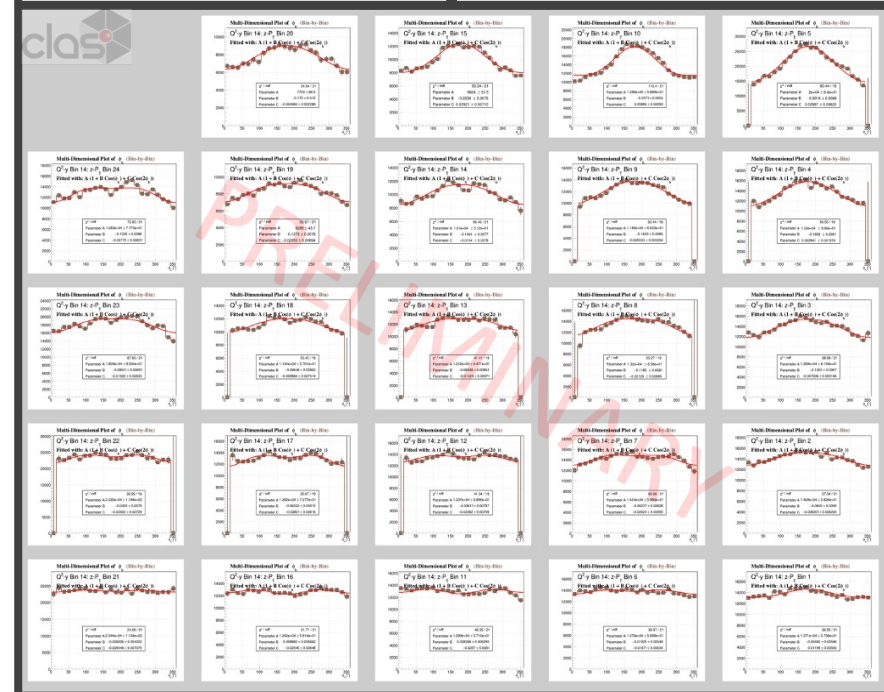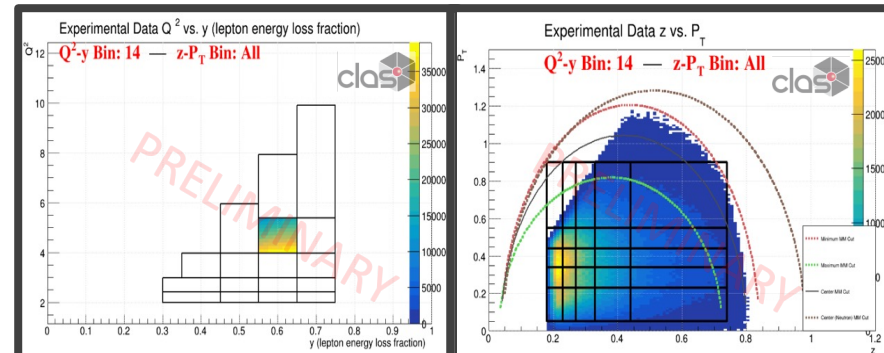
Outlook

- Working on Multidimensional Acceptance Corrections for the simultaneous unfolding of Q^2, y, z, P_T, and ϕ_h variables

- Efforts towards more realistic MC simulations, both on the detector response description and physics process

- Include Radiative and BC Corrections to this analysis

- Final goal is the extraction of multiplicity $(F_{UU,T} + \varepsilon F_{UU,L})$, $F_{UU}^{\cos \varphi_h}$, and $F_{UU}^{\cos 2\varphi_h}$ in terms of in Q^2, y, z, and P_T for the π^+ for all CLAS12 RG-A data

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Thank you

Questions?

Link to more Images:

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

Acknowledgments and Thanks

Backup Slides

More on Boer-Mulders...

quark pol.

	U	L	T
U	f_1		$h^{\perp}_1$
L		g_1	$h^{\perp}_{1L}$
T	$f^{\perp}_T$	g_{1T}	$h_1, h^{\perp}_{1T}$

nucleon pol.

Boer-Mulders

Sivers

Twist-2 TMDs

$$h^{\perp}_1 = P \nearrow^{quark} \quad - \quad P \nearrow^{quark}$$

- **P** is the momentum of the proton
- $\mathbf{k_T}$ is the transverse momentum of the quark
- $\mathbf{s_\perp}$ is the transverse spin of the quark

If the Boer-Mulders term is non-zero, then there is a net transverse quark polarization inside of unpolarized protons

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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
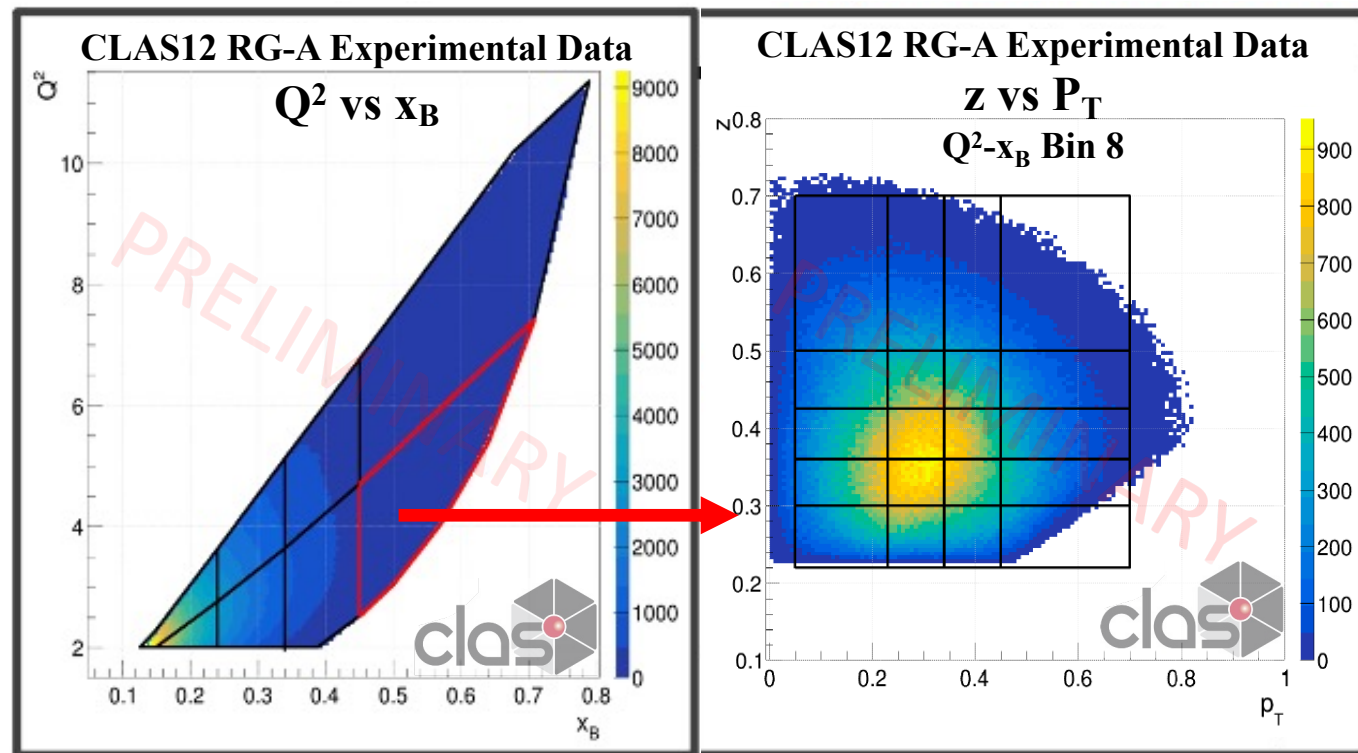
Pion PID Criteria:

- Detected in Forward Detector

- $p > 1.25$ GeV

- Refined chi2pid cuts

Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (4 Dimensions)

8 Q^2-x_B Bins Total – 20-49 z-P_T Bins (per Q^2-x_B bin)

Example of previous binning scheme using Q^2, x_B, z, and P_T
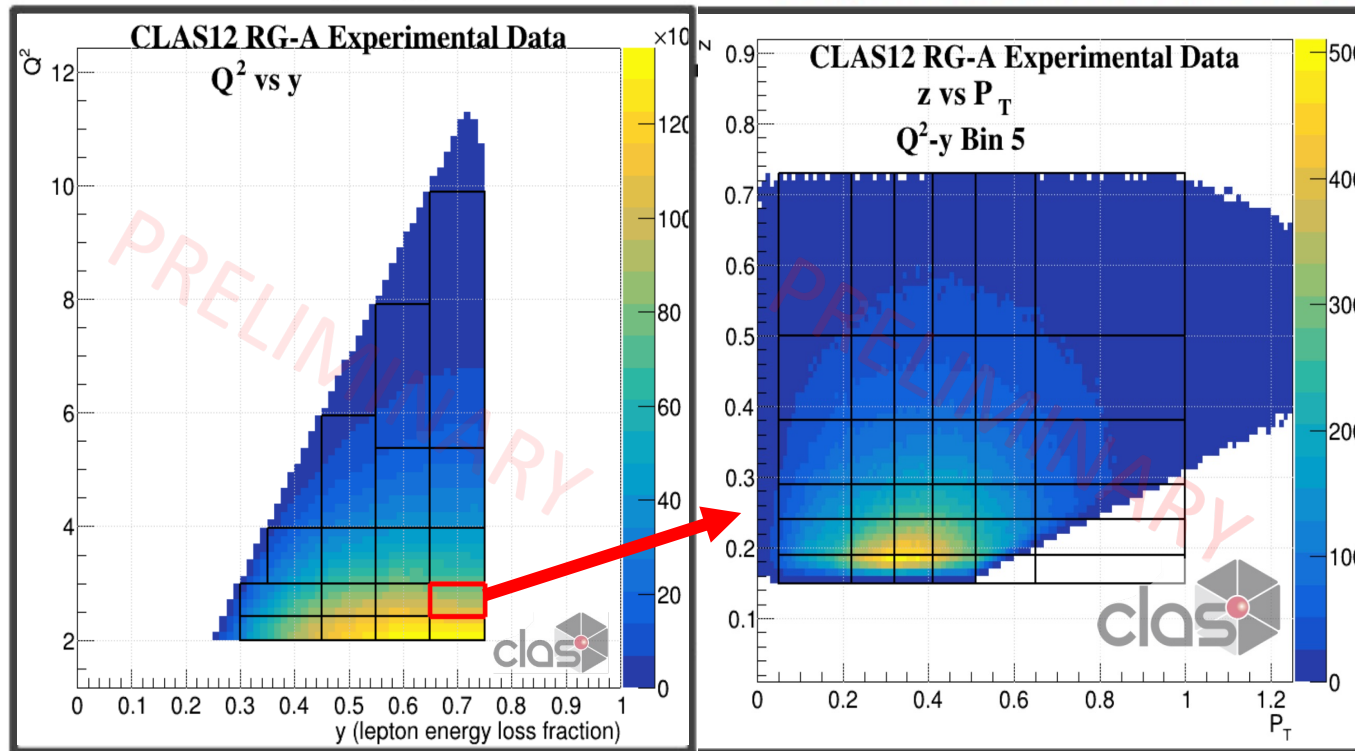

Main Issue was with the irregular shape of the Q^2-x_B Bins

Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (4 Dimensions)

17 Q^2-y Bins Total – 20-42 z-P_T Bins (per Q^2-y bin)

Example of new binning scheme using Q^2, y, z, and P_T

Both the Q^2-y and z-P_T bins are now rectangular which makes the bins easier to work with

Using the Flattened z-P_T-ϕ_h Multidimensional Bins

Unfolded with Bayesian Method

Q²-y Bin 14

PRELIMINARY

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Using Q^2-y-ϕ_h Multidimensional Bins
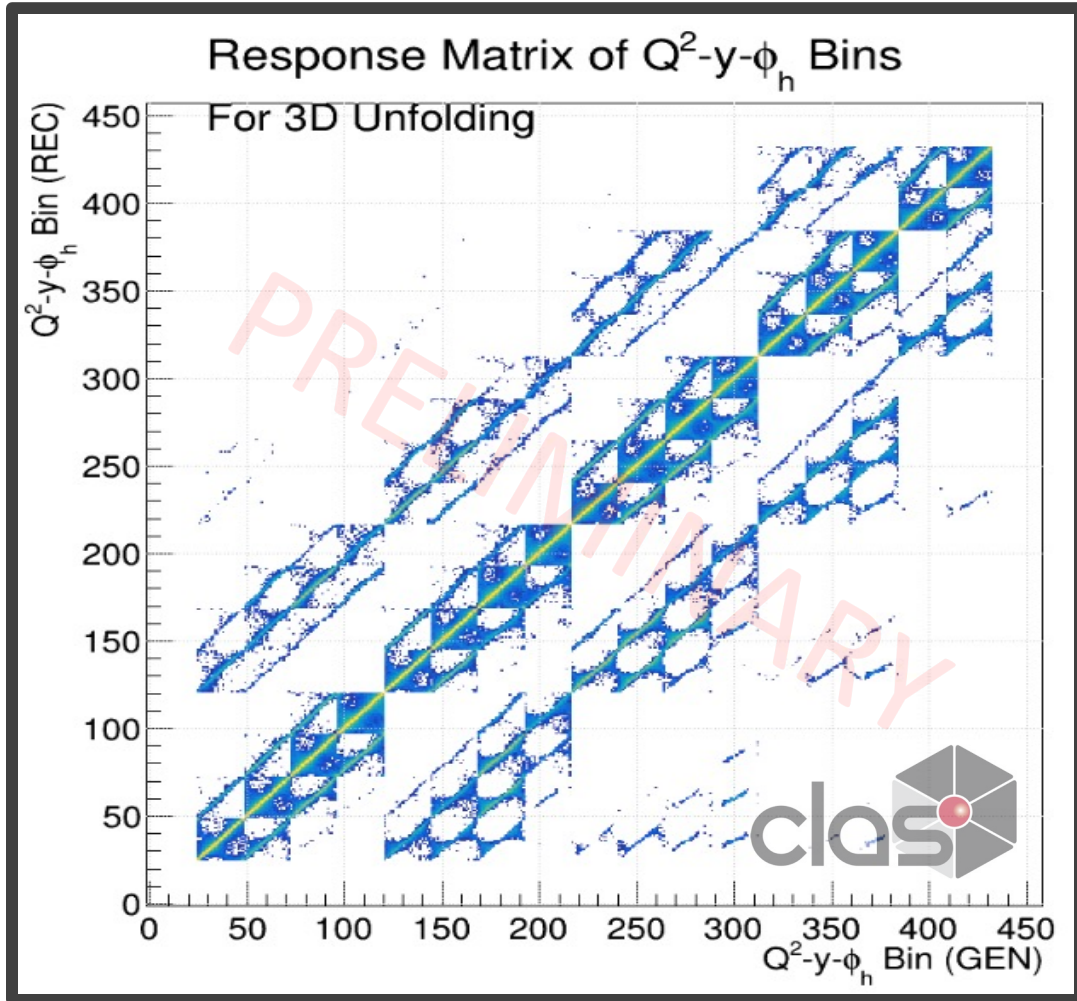
Unfolding Procedure

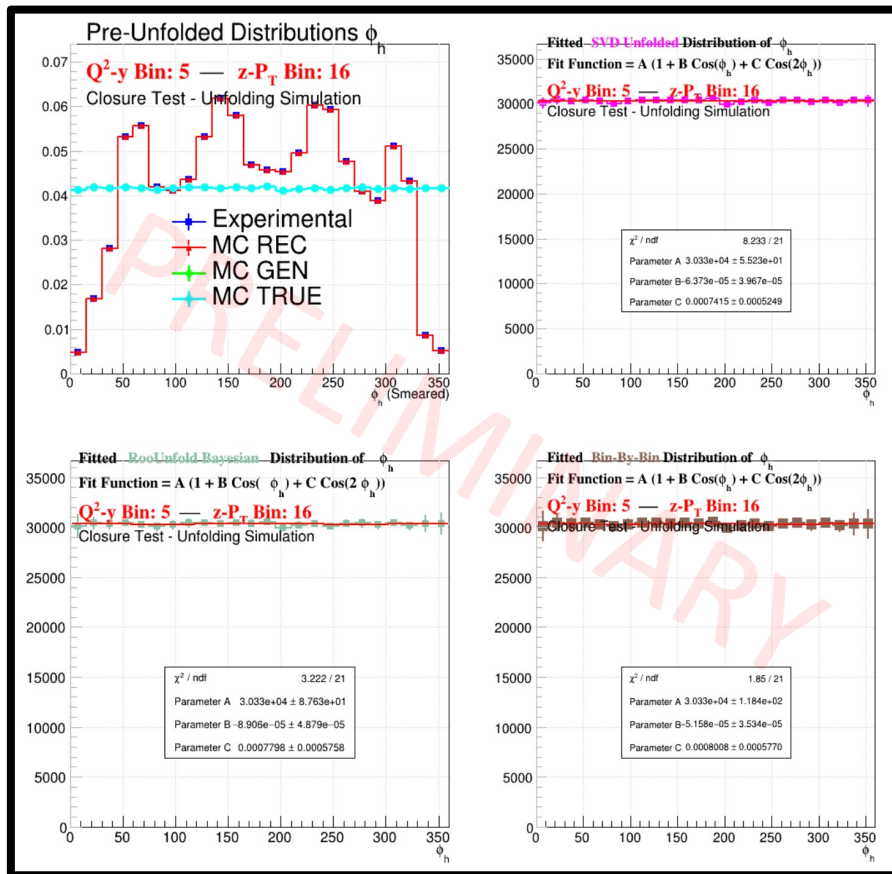**Unfolded with Bayesian Method**
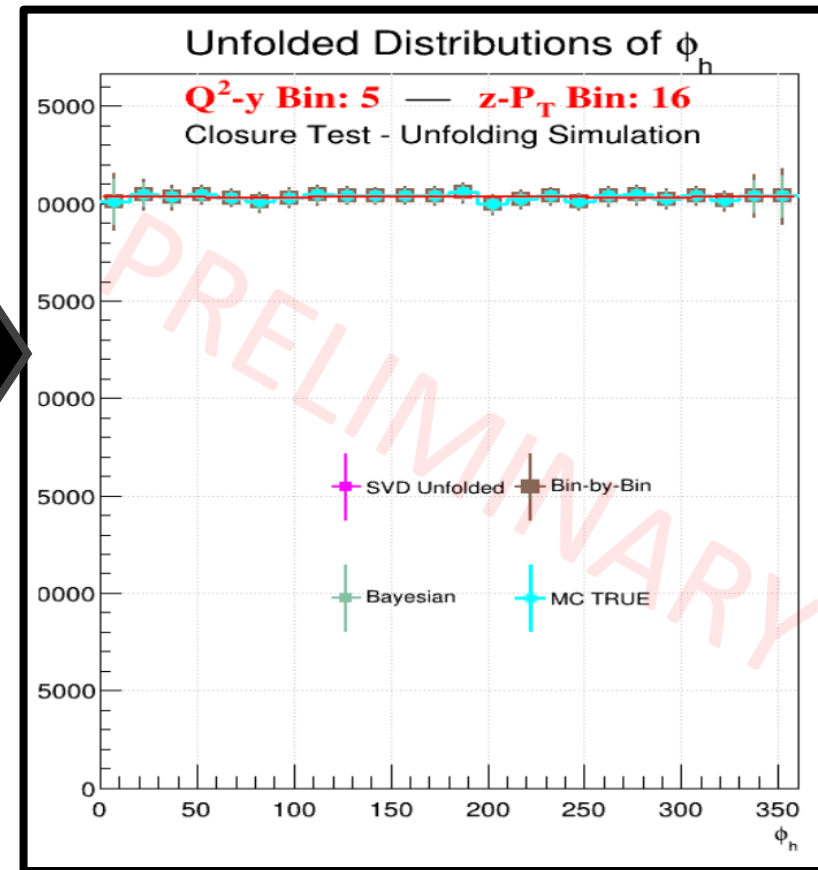
Other closure tests being used to check that Unfolding is done properly:

- Replace the experimental data with the reconstructed Monte Carlo
  - Should return the generated (i.e., MC TRUE) distribution


Checking that the corrected distributions match MC TRUE
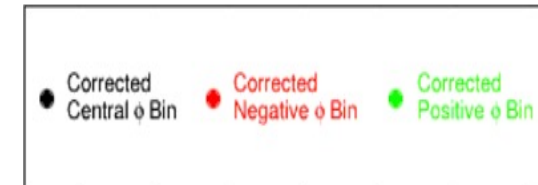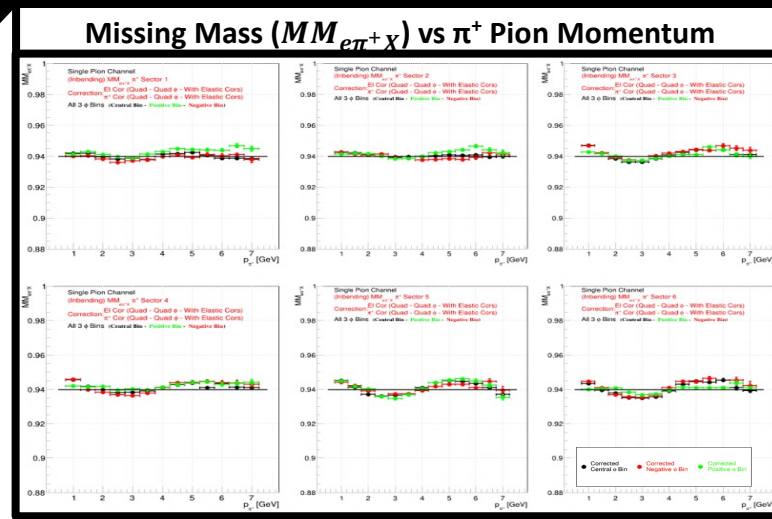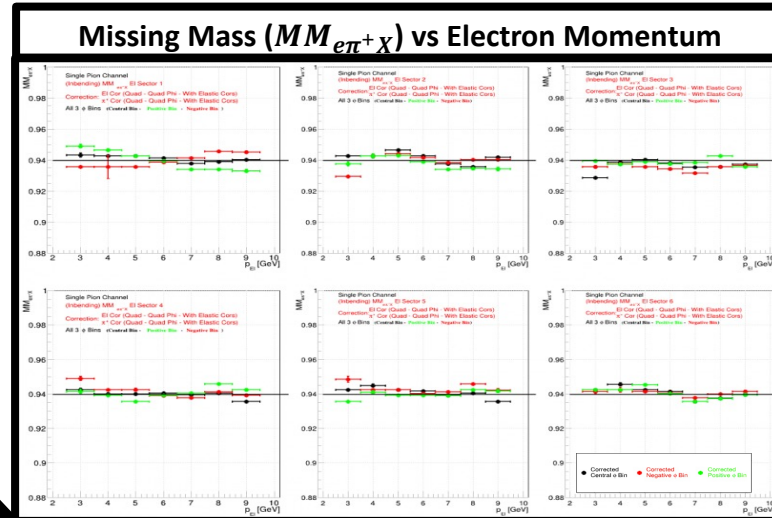
Momentum Corrections from Exclusive Events

- 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}

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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**
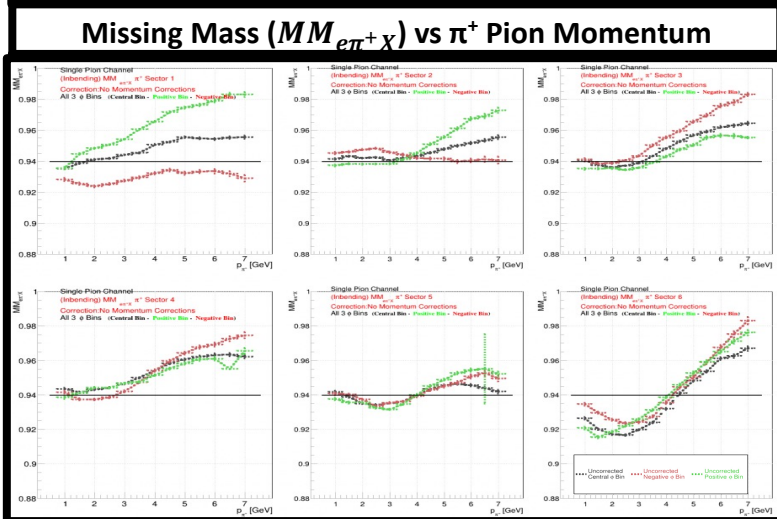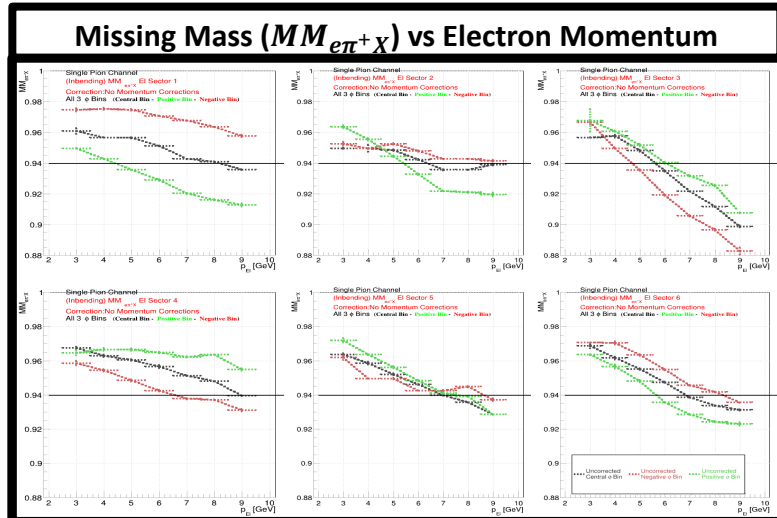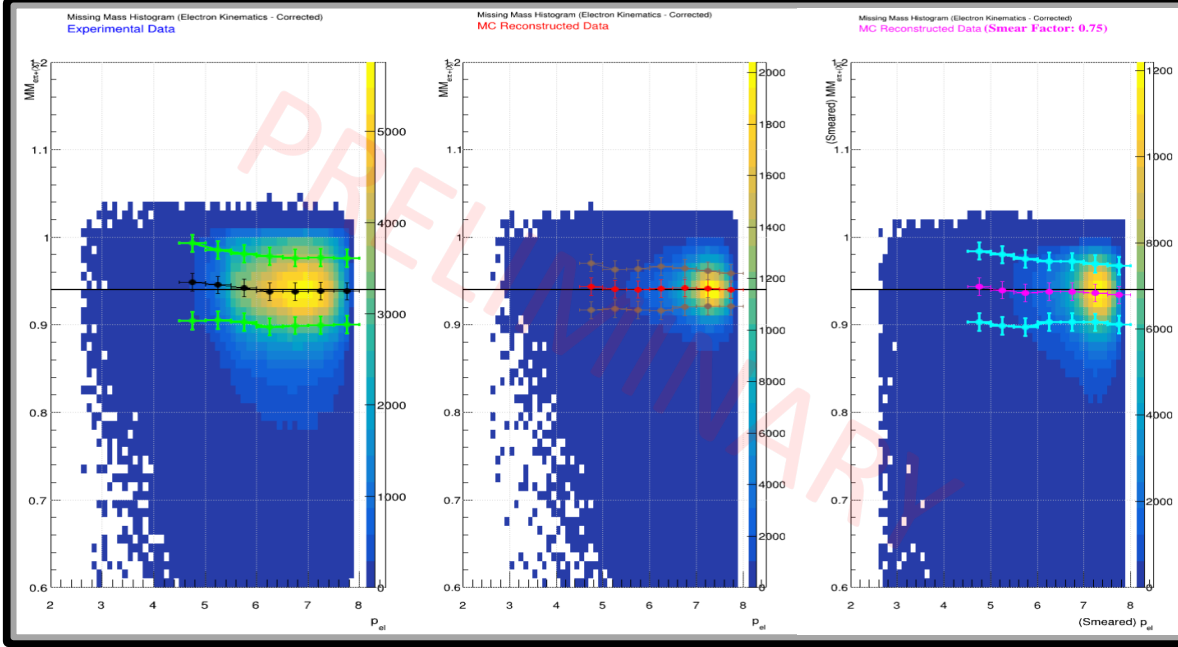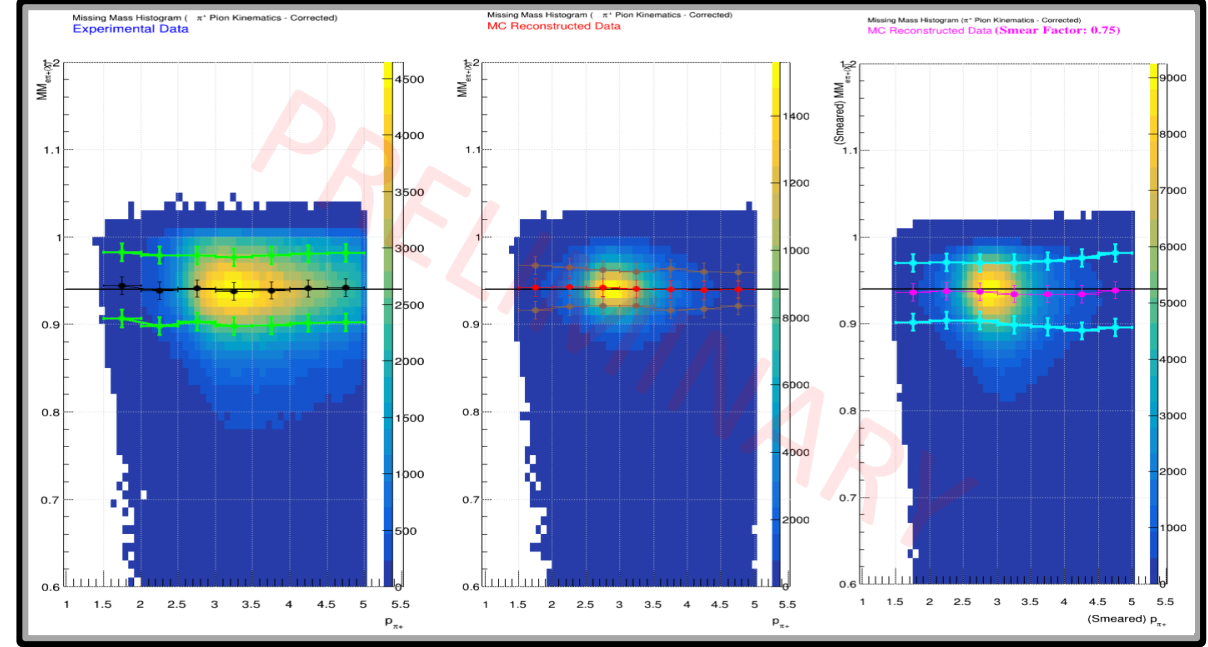

Apply Momentum Corrections

Momentum Smearing
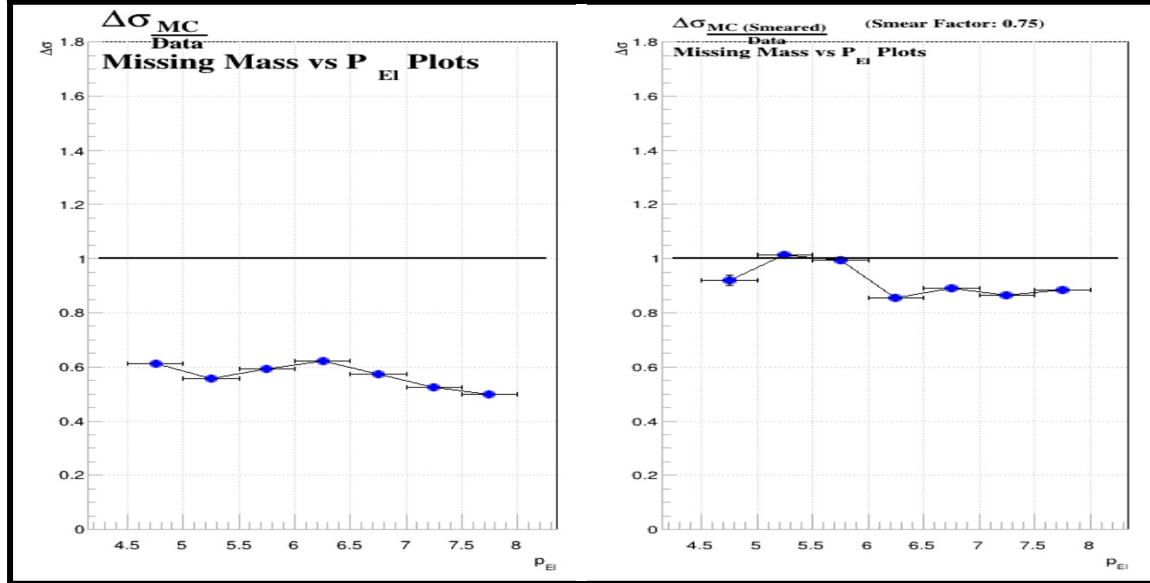
Missing Mass vs Electron Momentum:

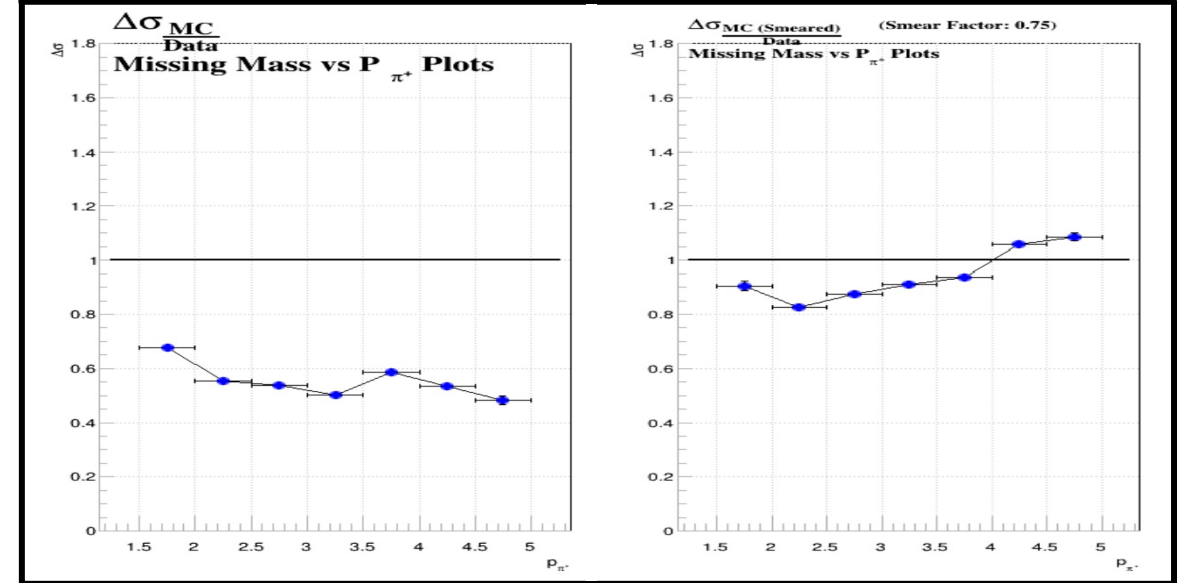**Missing Mass vs π⁺ Pion Momentum:**

- **The momentums of the particles in these plots are <u>CORRECTED</u> (see Momentum Corrections from Exclusive Events)**
- Momentum Smearing is applied in addition to existing MC reconstruction processes
- The momentum smearing functions use 2D Missing Mass plots to check how it improves the MC
  - The widths of the peaks are shown in each plot above
- Momentum smearing is done with the equation: $P_{Smeared} = P_{Generated} - (SF + 1)*(P_{Generated} - P_{Reconstructed})$
  - **SF** is the smear factor used to modify the simulated reconstructed momentum (currently equal to 0.75)
- A properly smeared MC distribution should have approximately the same width as the Experimental data

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Momentum Corrections/Smearing

Ratio of Missing Mass Width vs Electron Momentum:

Ratio of Missing Mass Width vs π⁺ Pion Momentum:

- **The ratio of the Monte Carlo and Experimental data's widths should go to 1 as smearing improves**

- Smearing the momentum also affects the widths of the Missing Mass vs azimuthal/polar angles of the particles

- Development of this correction calls for finding the best smearing parameter for all particle kinematics