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

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LinkedIn

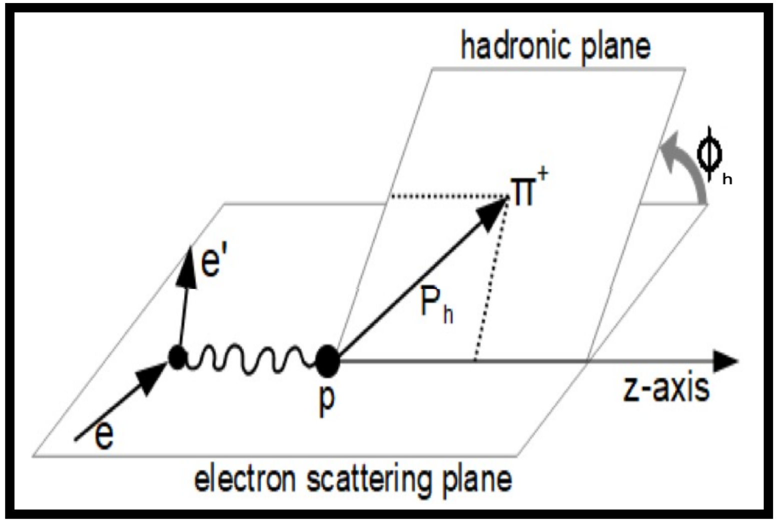
Motivation

- 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

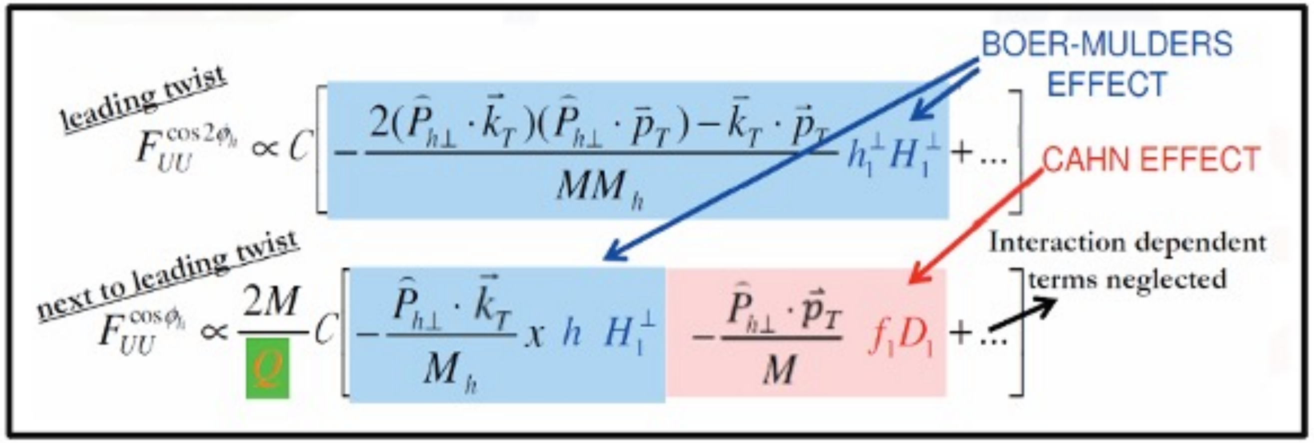
The lepton-hadron Unpolarized SIDIS Cross-Section:

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



Reaction Studied: ep→eπ⁺(X)

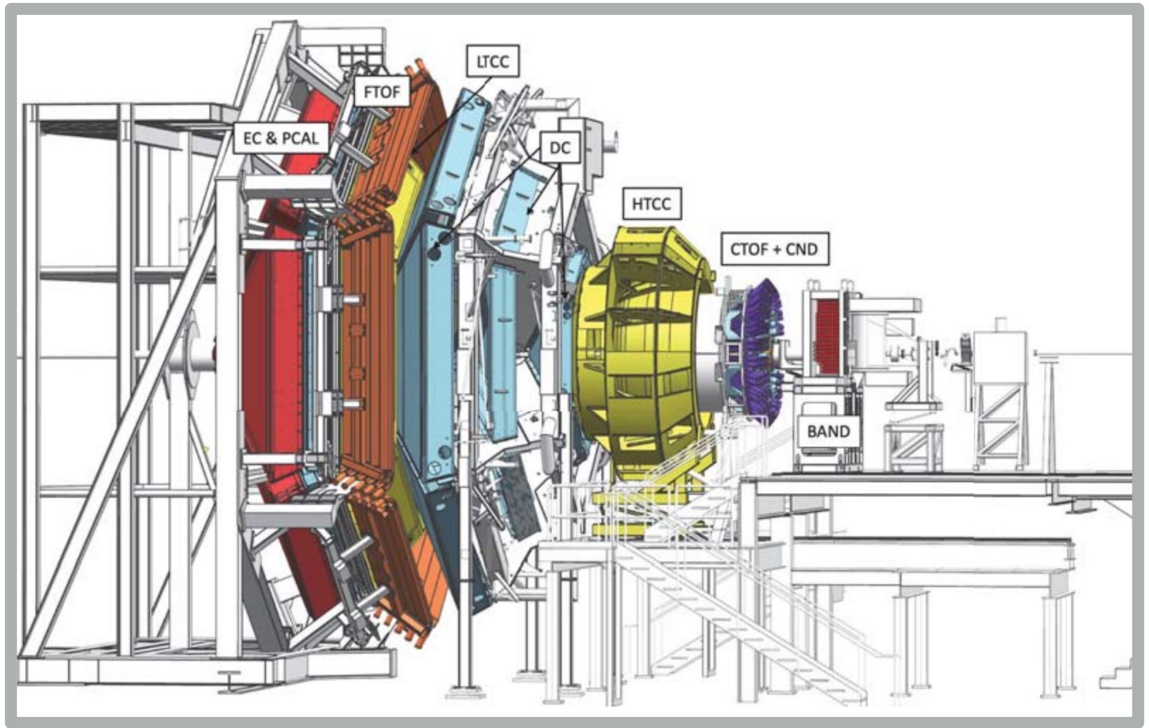
The Boer-Mulders and Cahn effects are present in the Structure Functions:



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

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

Data Collection



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
- Data from the Fall 2018 RG-A experiment
  - Used a 10.6 GeV polarized electron beam and unpolarized liquid hydrogen target
- Data presented uses forward tracking only

Analysis Procedure

Experimental extraction of cross-section

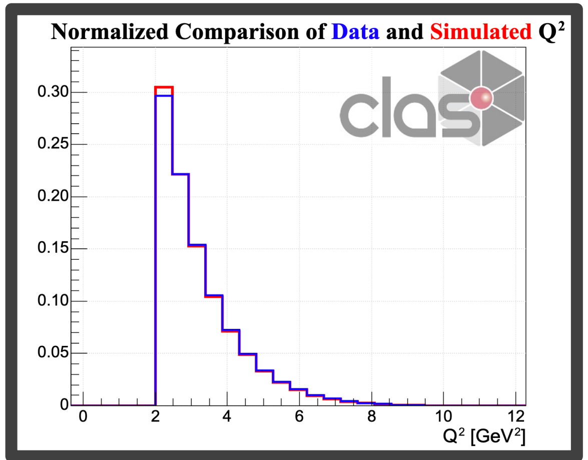
$$\boxed{\frac{d^5\sigma}{dQ^2dydP_Tdzd\phi_h} = \frac{1}{\Gamma_\nu}\underbrace{\frac{1}{\Delta Q^2\Delta y\Delta P_T\Delta z\Delta\phi_h}}_{\text{Bin Volume}}\frac{N}{R\cdot BC\cdot\eta\cdot N_0}\underbrace{\frac{1}{(N_A\cdot\rho\cdot t/A_w)}}_{\text{Target Number Density}}}$$

Where:

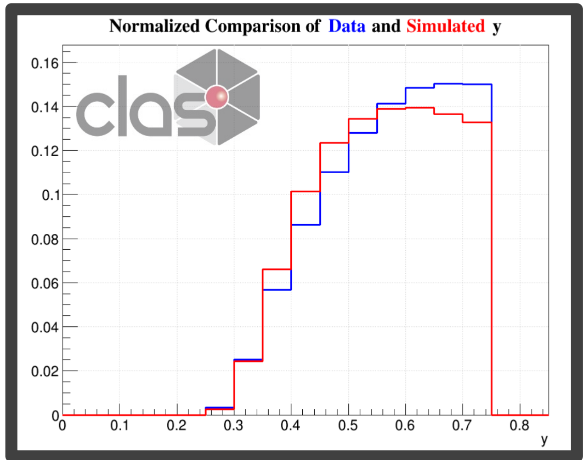
- R = Radiative Correction
- η = **Acceptance Correction** → **Requires Monte Carlo (MC) Simulation**
- N = Bin Yields
- N_0 = Life-time corrected incident electron flux
- BC = factor which evolves bin-averaged differential cross-section

SIDIS MC are generated with LEPTO event generator

Data and Monte Carlo Comparison

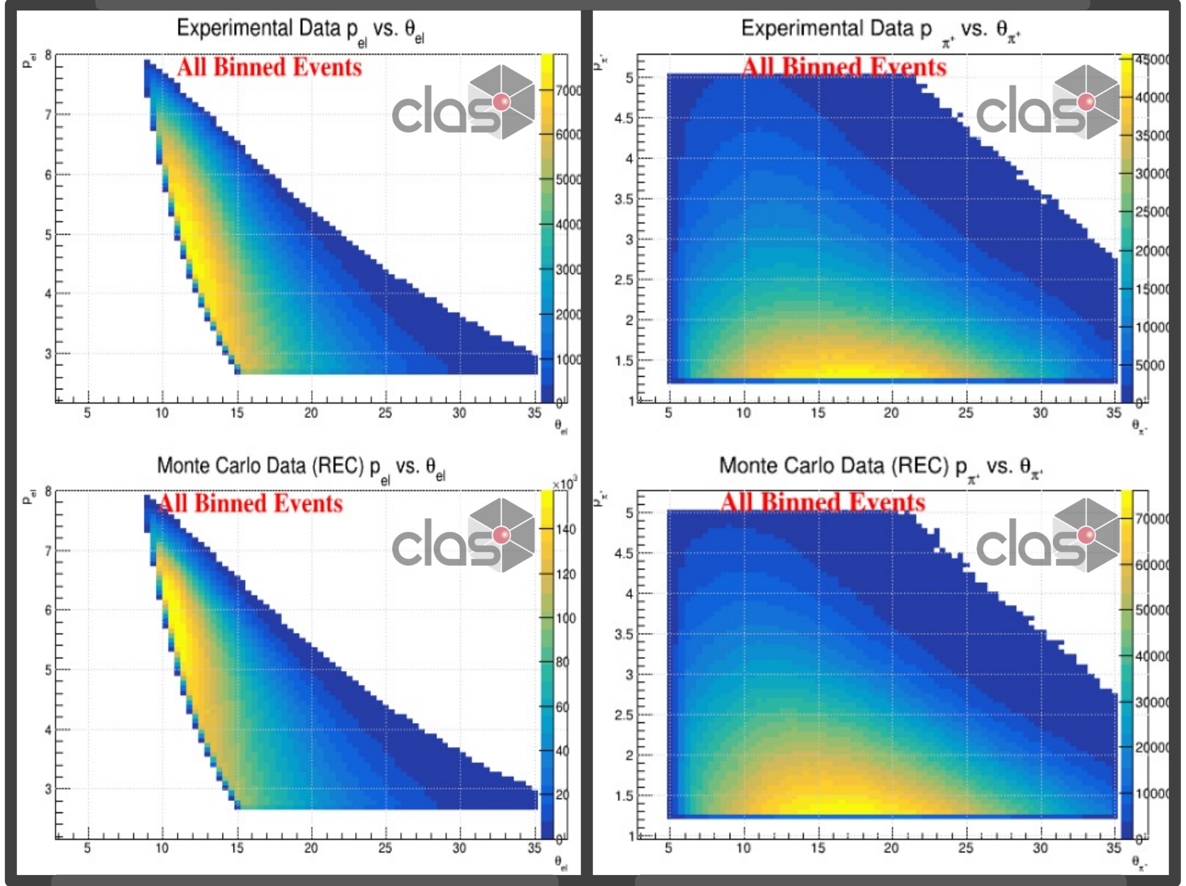


Q^2 Comparison



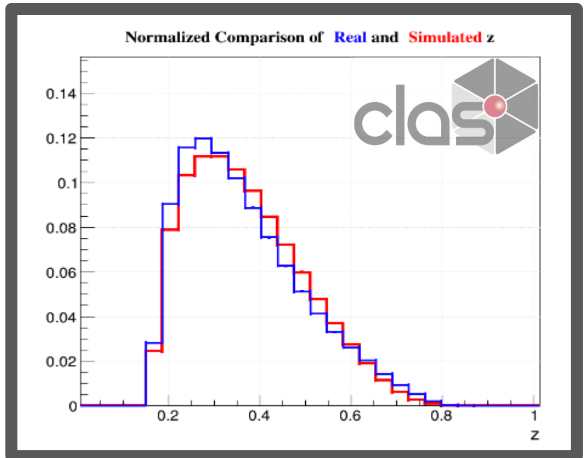
y Comparison

Momentum vs Polar Lab Angle Comparison

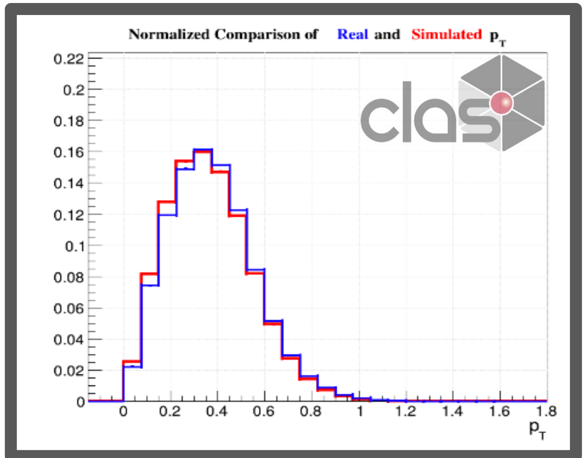


Electron Comparison

π^+ Pion Comparison



z Comparison



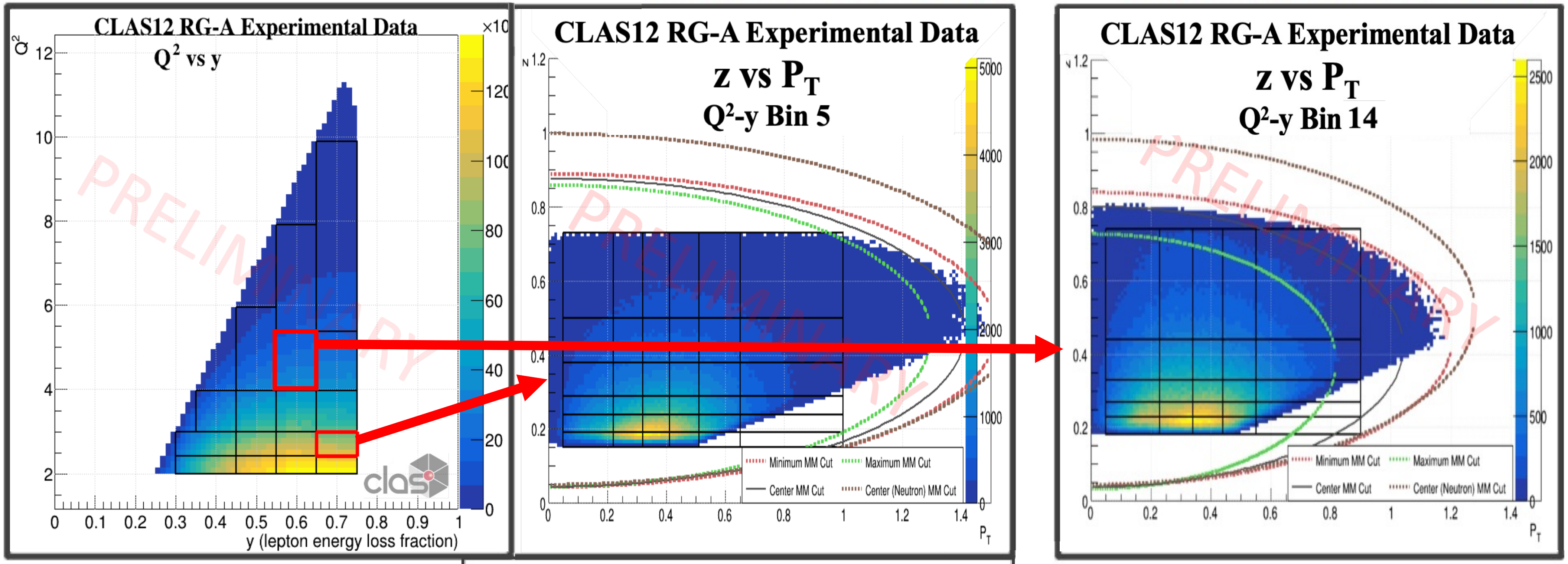
P_T Comparison

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



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

Missing Mass Cut Lines:

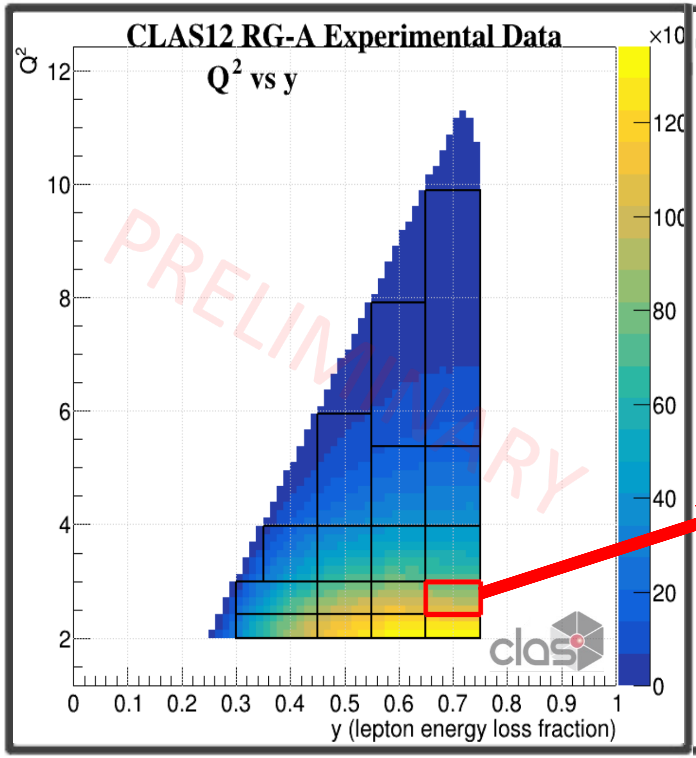
- Minimum MM Cut
- Maximum MM Cut
- Center MM Cut
- Center (Neutron) MM Cut

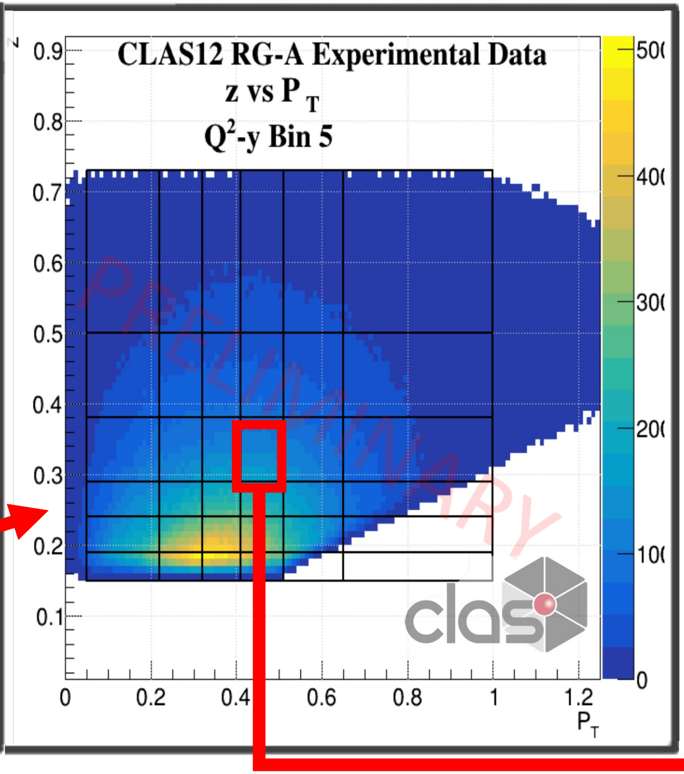
Multidimensional Analysis Procedures

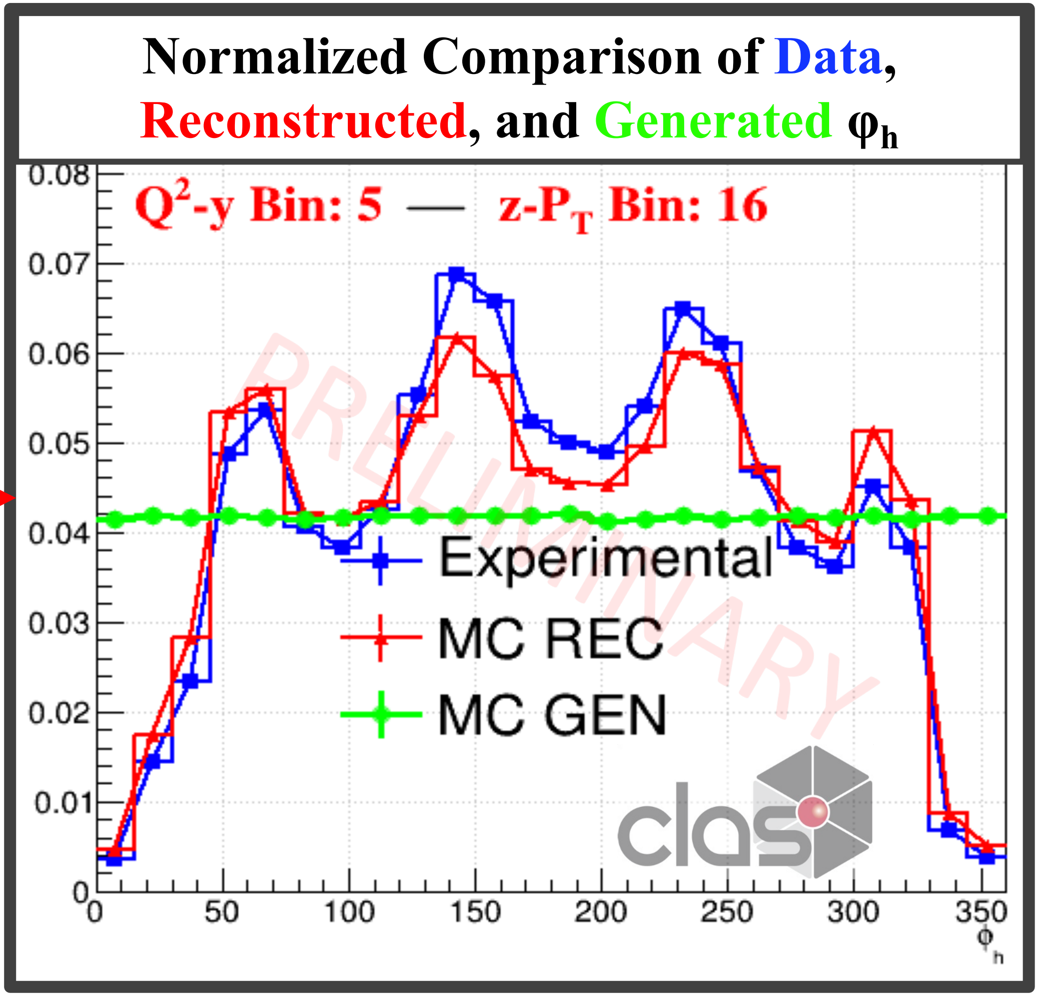
Multidimensional Kinematic Binning (5 Dimensions)

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



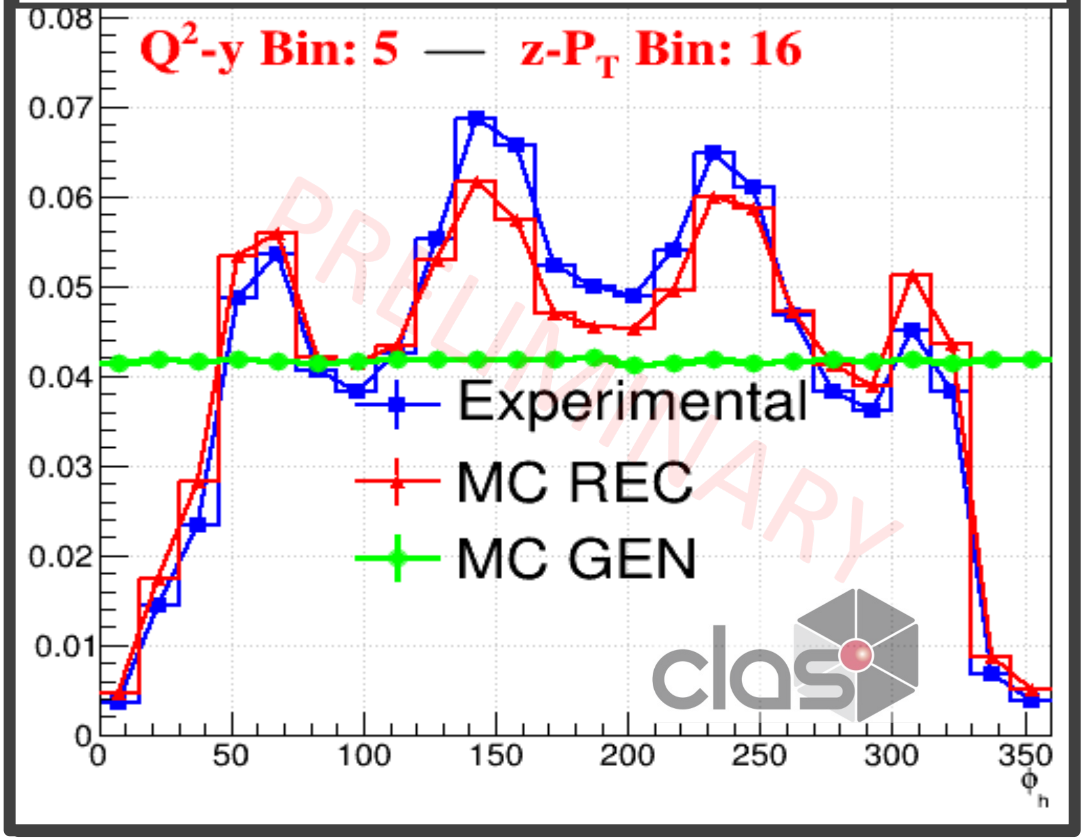



Normalized Comparison of Data, Reconstructed, and Generated φ_h

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

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

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

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

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

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

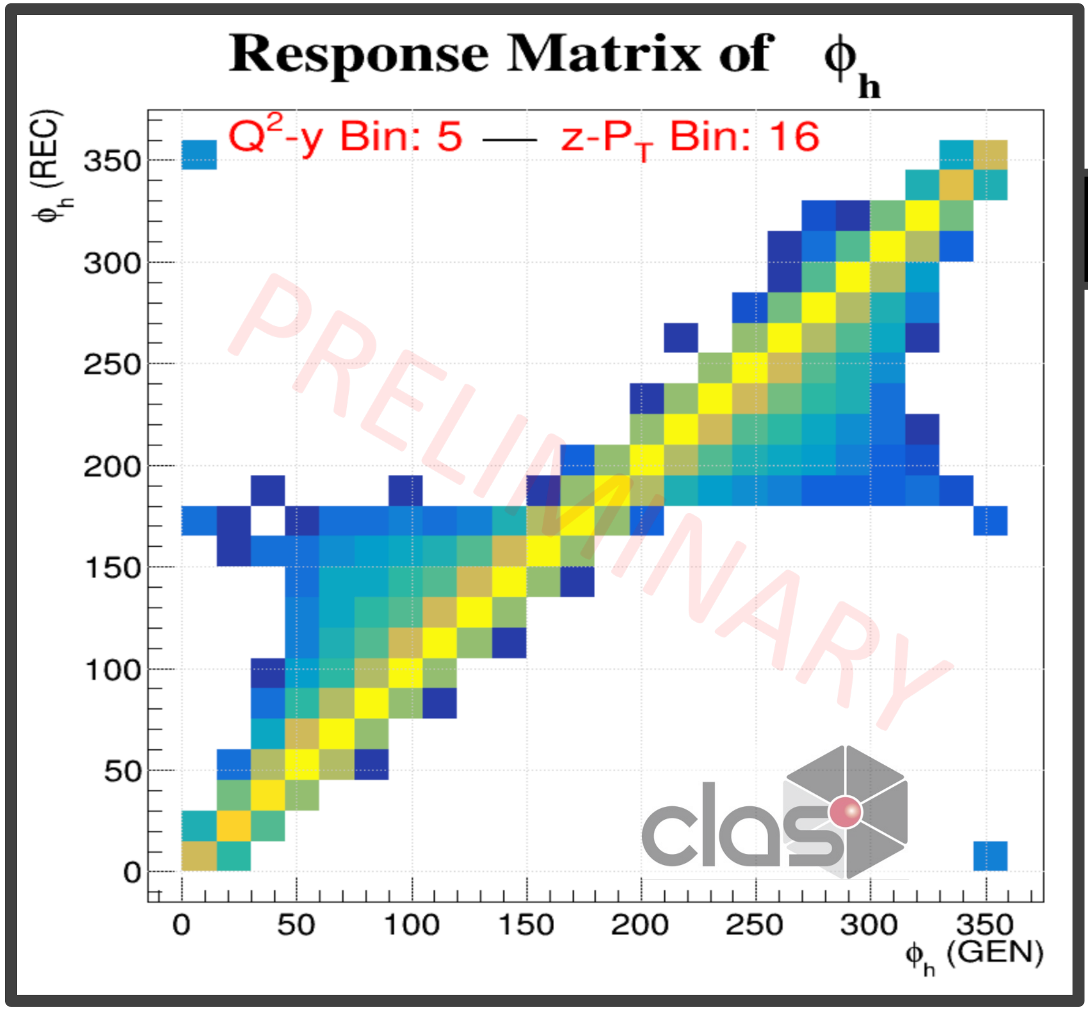
- Acceptance Unfolding: $Y_i = A_{(i,\, j)} X_j \Leftrightarrow X_j = A^{-1}_{(i,\, j)} Y_i$

where:

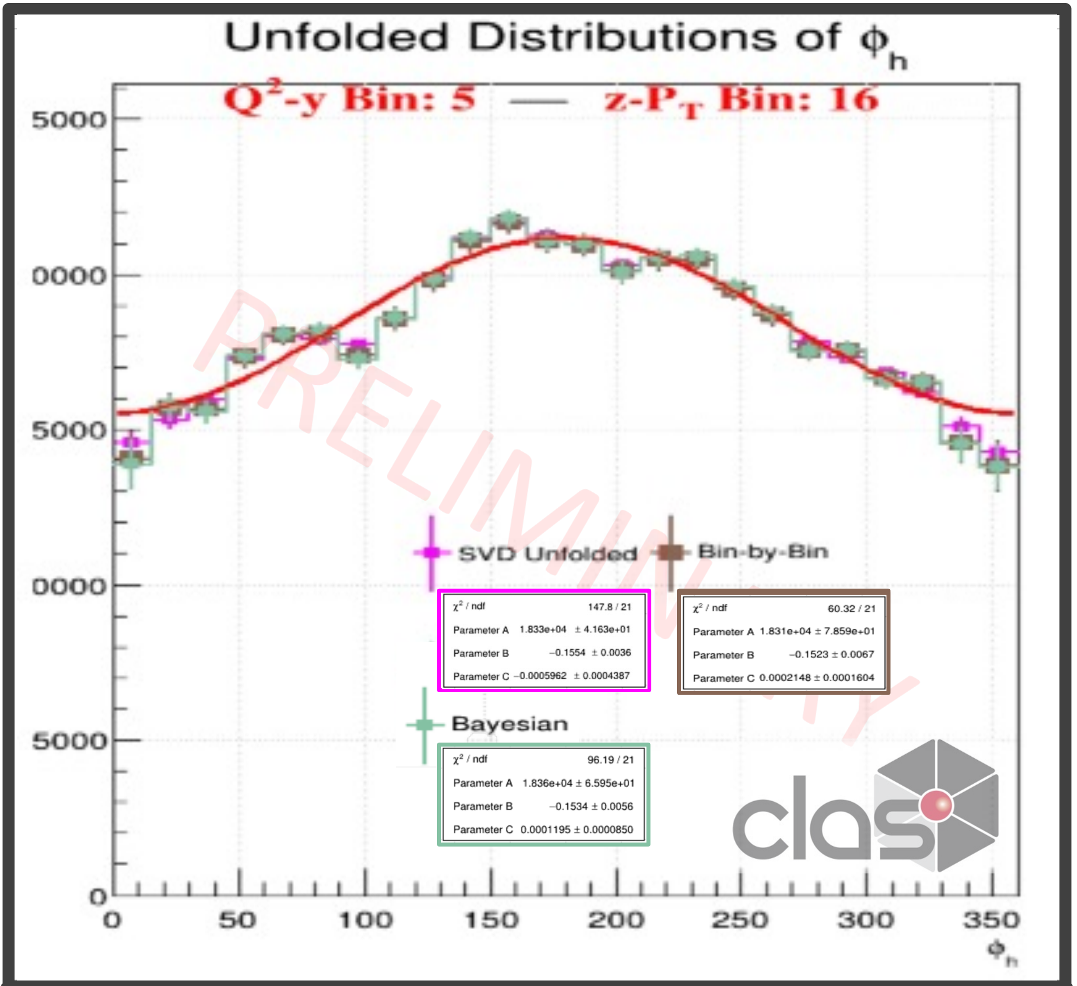
- ○ Y_i = Number of events experimentally measured in the *i*-th bin
- ○ X_j = Number of acceptance-corrected events in the *j*-th bin

Example of (1D) Unfolding Procedure

Using the Multidimensional Kinematic Bin from prior example



Unfolding Procedures



SVD Unfolded

χ^2 / ndf	147.8 / 21
Parameter A	1.833e+04 ± 4.163e+01
Parameter B	−0.1554 ± 0.0036
Parameter C	−0.0005962 ± 0.0004387

Bin-by-Bin

χ^2 / ndf	60.32 / 21
Parameter A	1.831e+04 ± 7.859e+01
Parameter B	−0.1523 ± 0.0067
Parameter C	0.0002148 ± 0.0001604

Bayesian

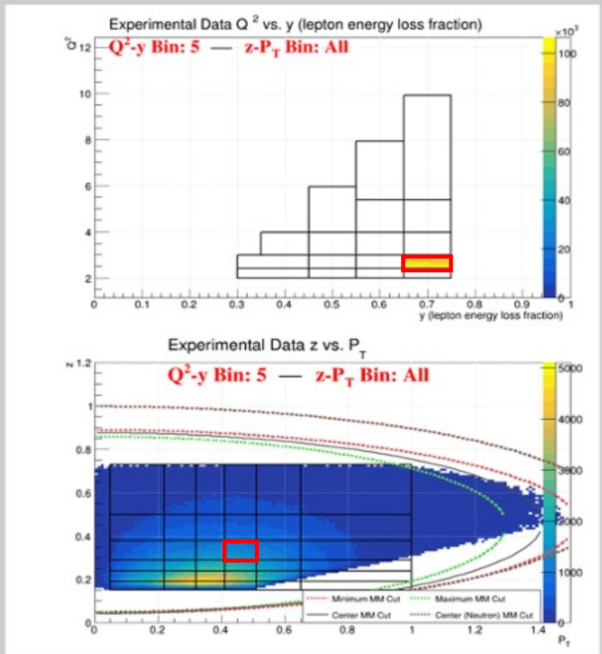
χ^2 / ndf	96.19 / 21
Parameter A	1.836e+04 ± 6.595e+01
Parameter B	−0.1534 ± 0.0056
Parameter C	0.0001195 ± 0.0000850

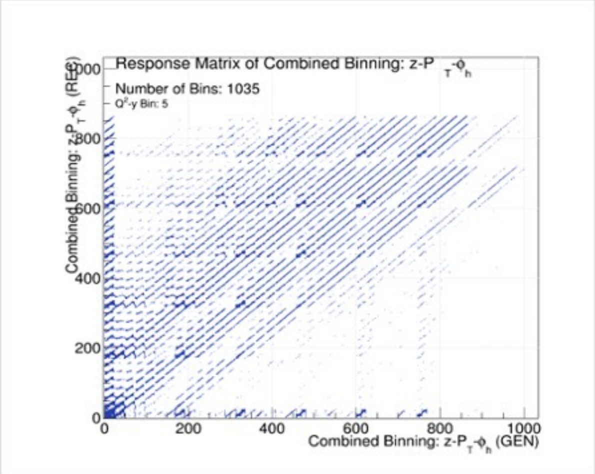
Parameters shown are from the fits previously described

Example of (3D) Unfolding Procedure

Using the Flattened z-P_T-ϕ_h Multidimensional Bins

Q^2-y Bin 5



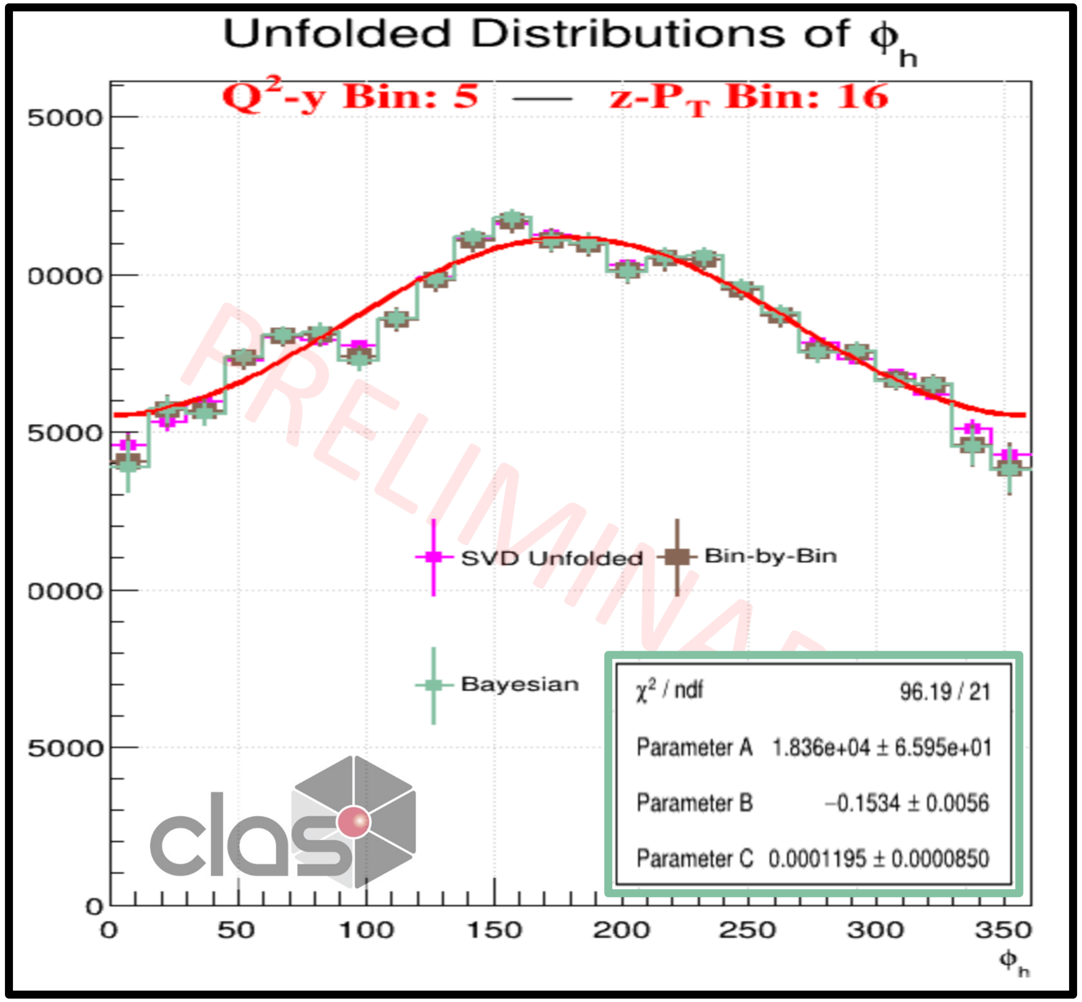


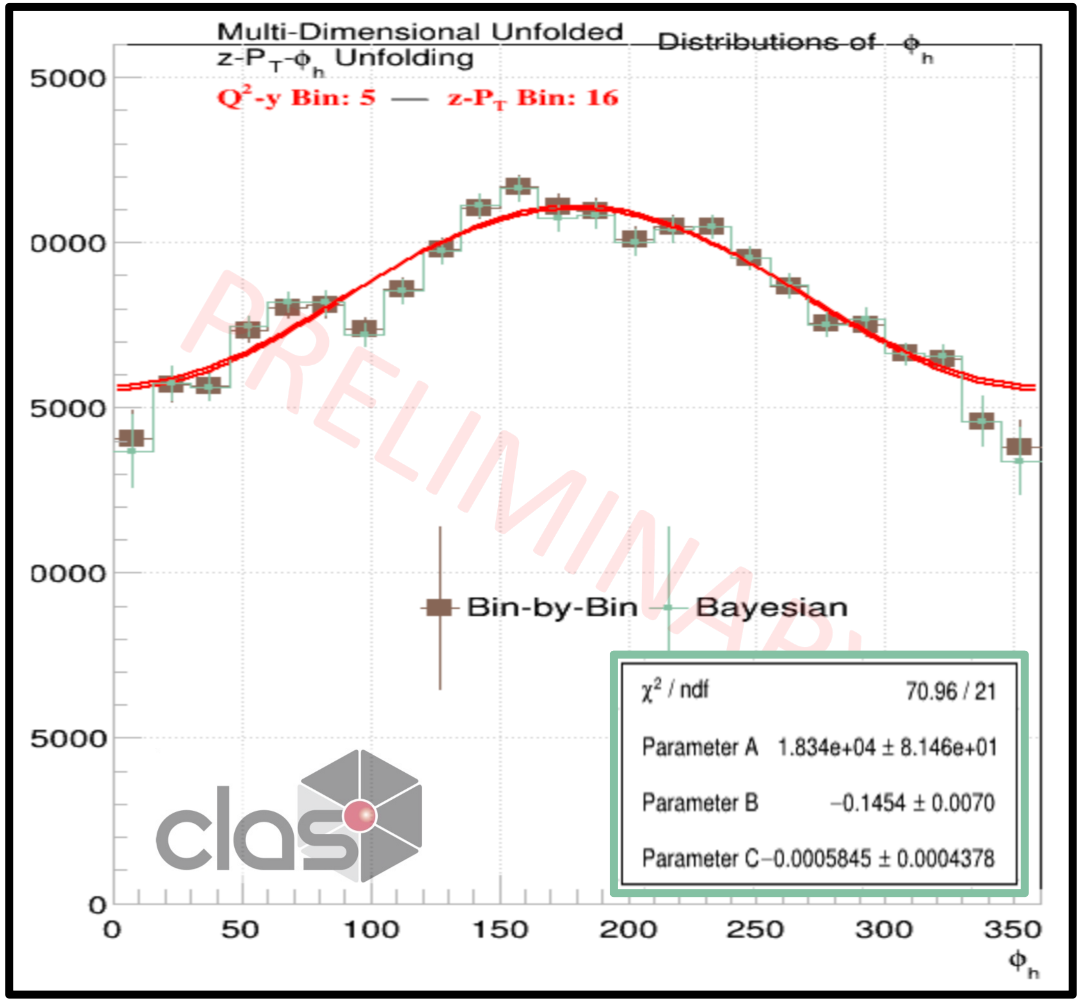
Unfolded with Bayesian Method

PRELIMINARY

Comparisons of 1D and 3D Unfolding Procedure

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



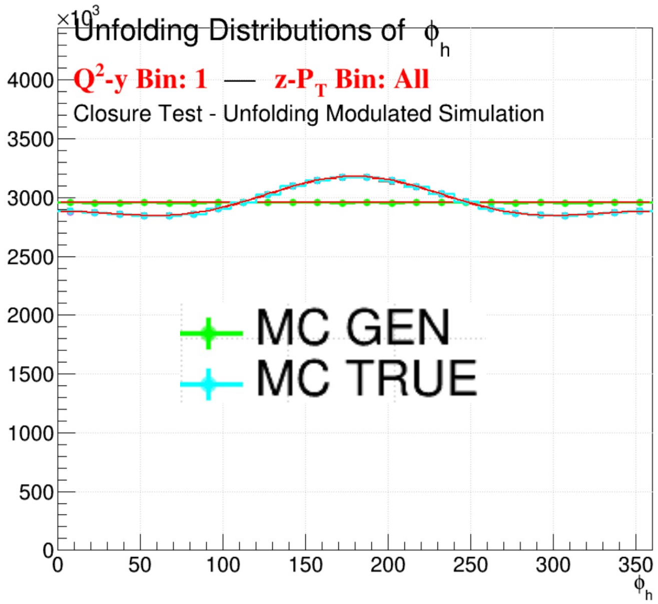


Bin-by-bin Acceptance Correction gives the exact same results

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:

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

  - 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)

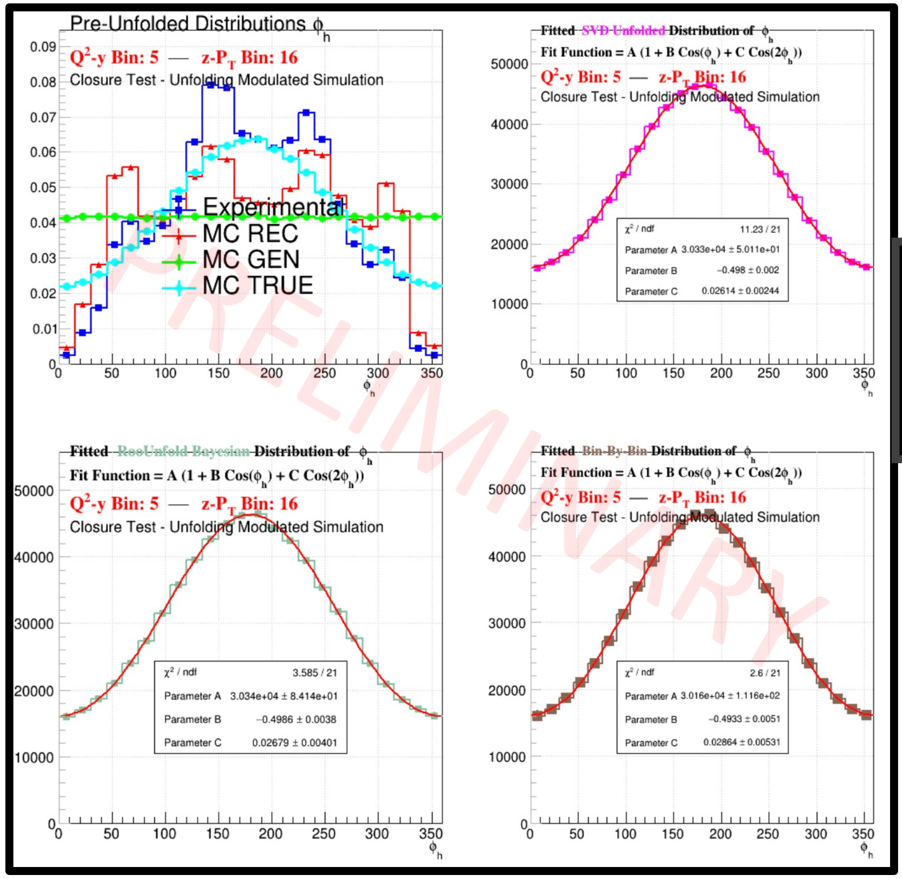
- Modulated MC REC is then unfolded using the un-modulated response matrix (in 1D and Multi-Dim examples) and compared with 'MC TRUE'
  - MC TRUE is the modulated MC GEN distribution
  - Also performed a closure test of unfolding the un-modulated MC REC distribution with the un-modulated response matrix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

Modulated Unfolding Closure Tests

The parameters used for weighing modulations below are:

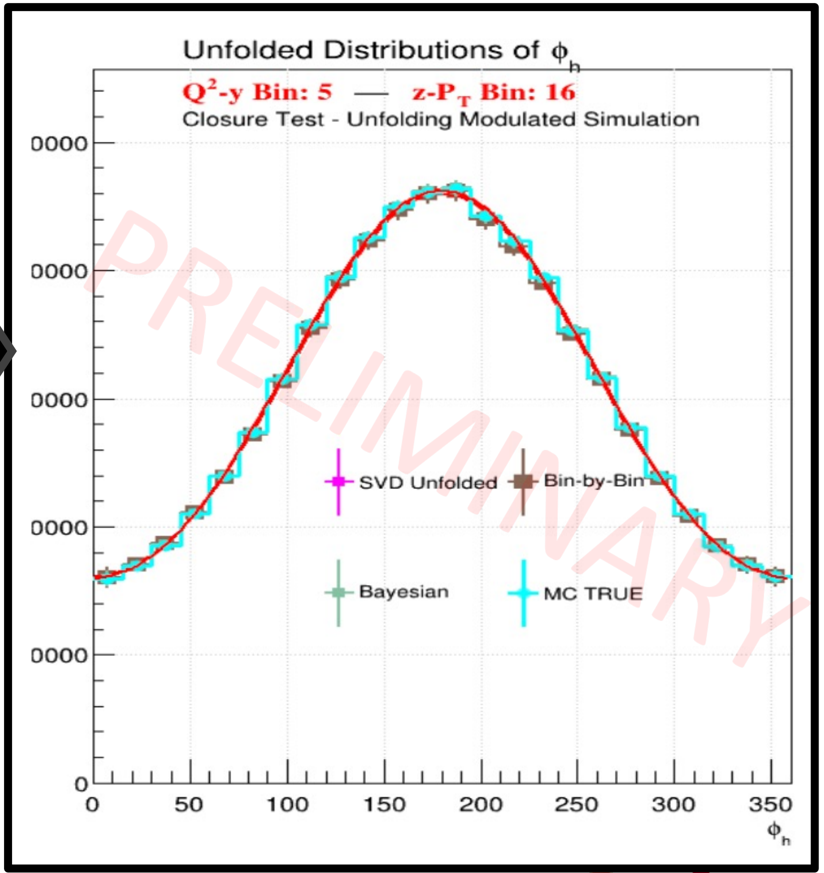
B = -0.5 and C = 0.025

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



Cosine Moments as Functions of z

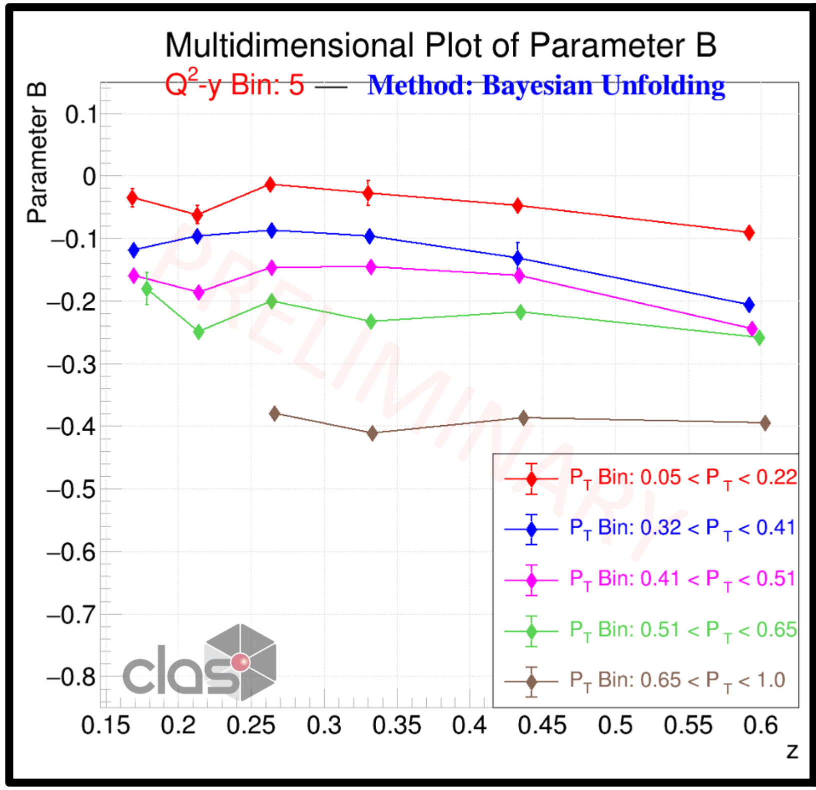
$B = A_{UU}^{\cos\varphi_h}$ $C = A_{UU}^{\cos 2\varphi_h}$

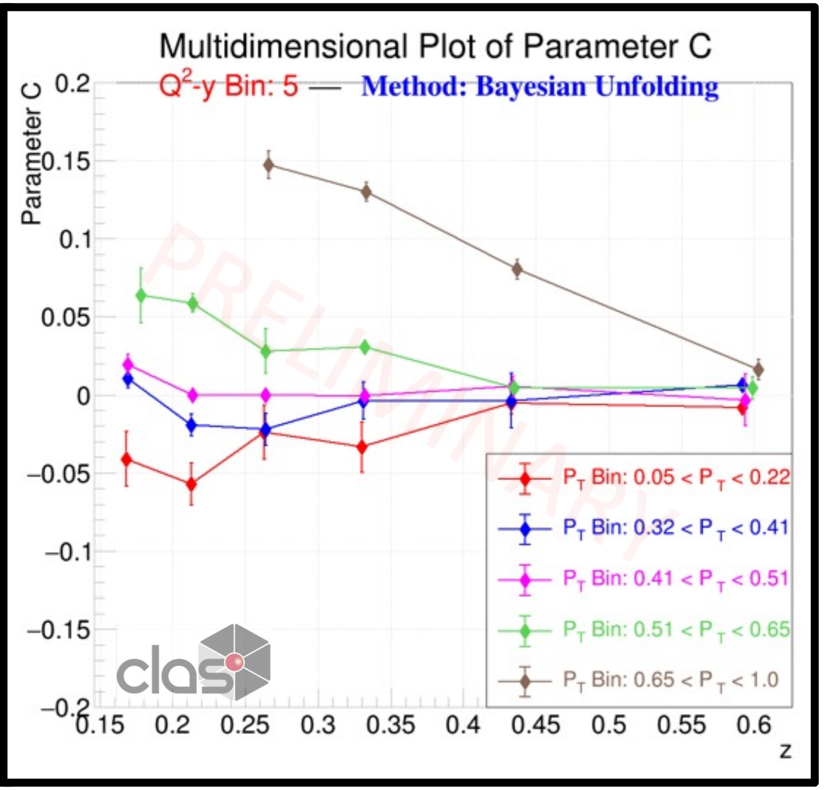
ϕ_h Plots were fitted with:

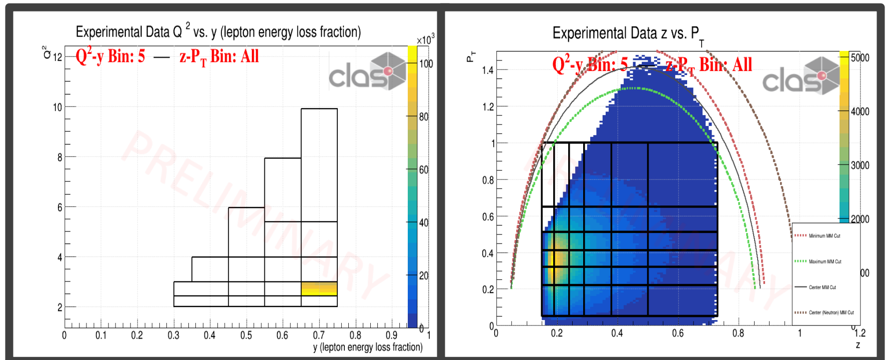
$$A(1 + B\cos(\phi_h) + C\cos(2\phi_h))$$

Unfolded with Bayesian Method

Q^2-y Bin 5







Cosine Moments as Functions of z

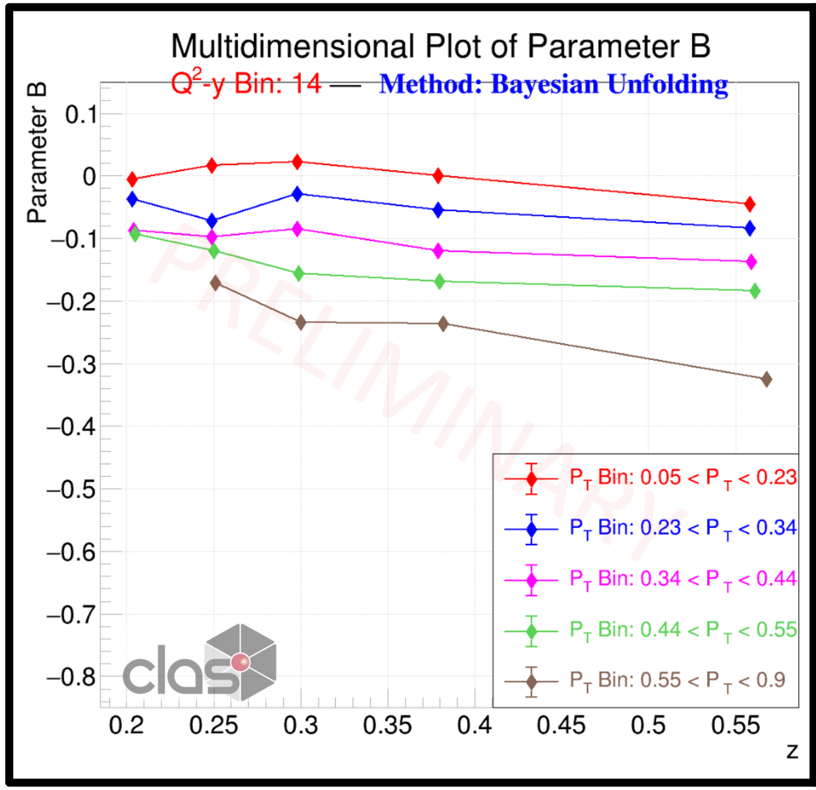
$$B = A_{UU}^{\cos\varphi_h} \qquad C = A_{UU}^{\cos 2\varphi_h}$$

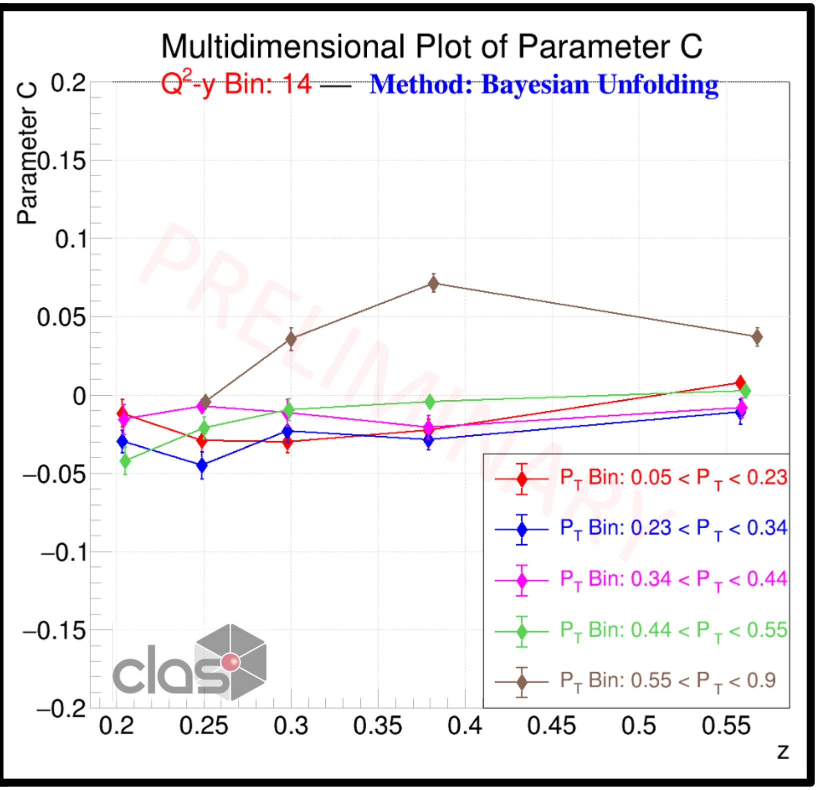
ϕ_h Plots were fitted with:

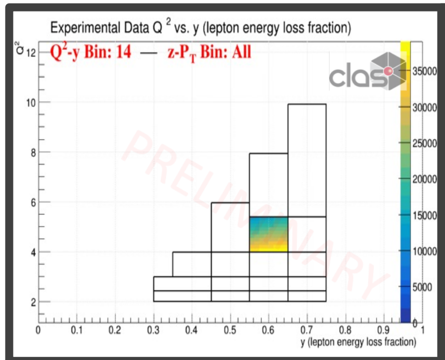
$$A(1 + B\cos(\phi_h) + C\cos(2\phi_h))$$

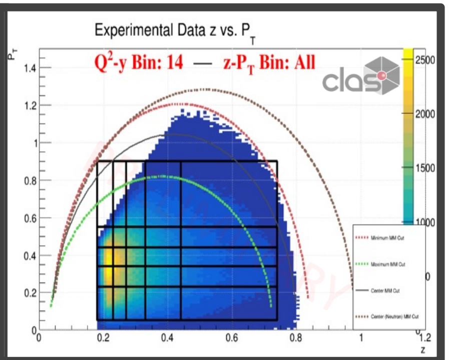
Unfolded with Bayesian Method

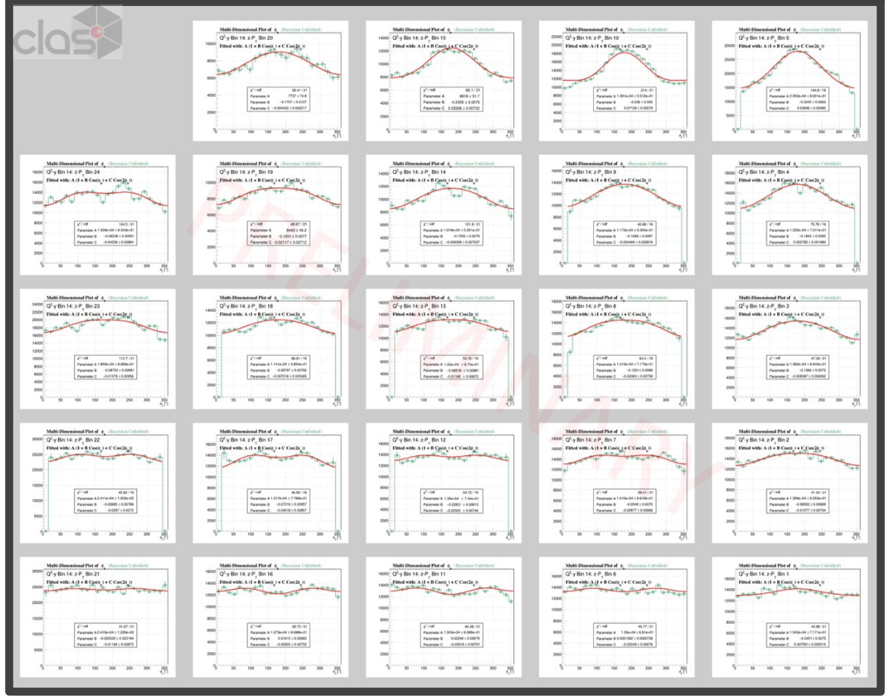
Q^2-y Bin 14











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

Thank you

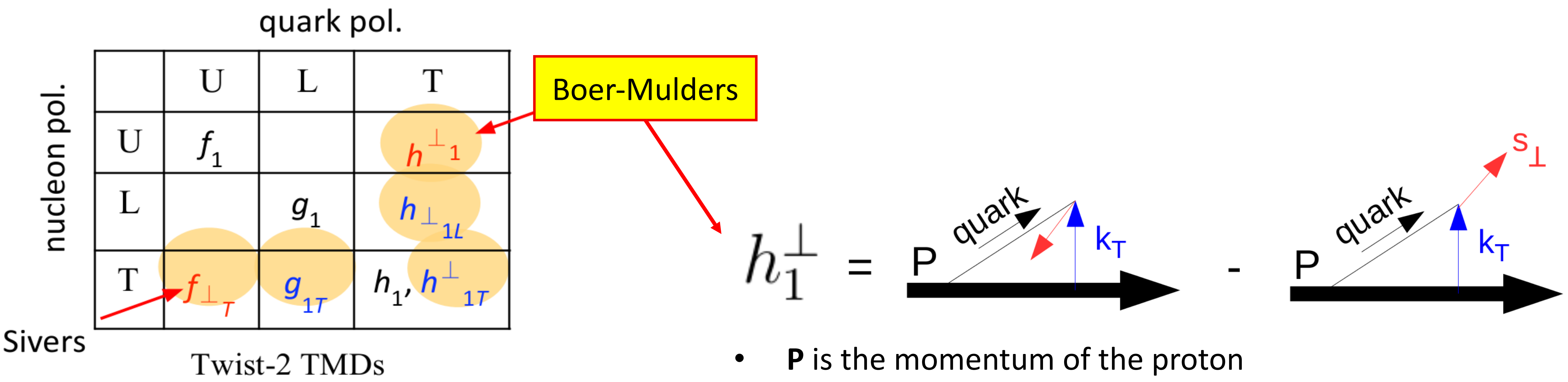
Questions?

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

More on Boer-Mulders…



quark pol.

nucleon pol.	U	L	T
U	f_1		$h^{\perp}{}_1$
L		g_1	$h_{\perp 1L}$
T	$f_{\perp T}$	g_{1T}	$h_1, h^{\perp}{}_{1T}$

Twist-2 TMDs

- **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

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

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

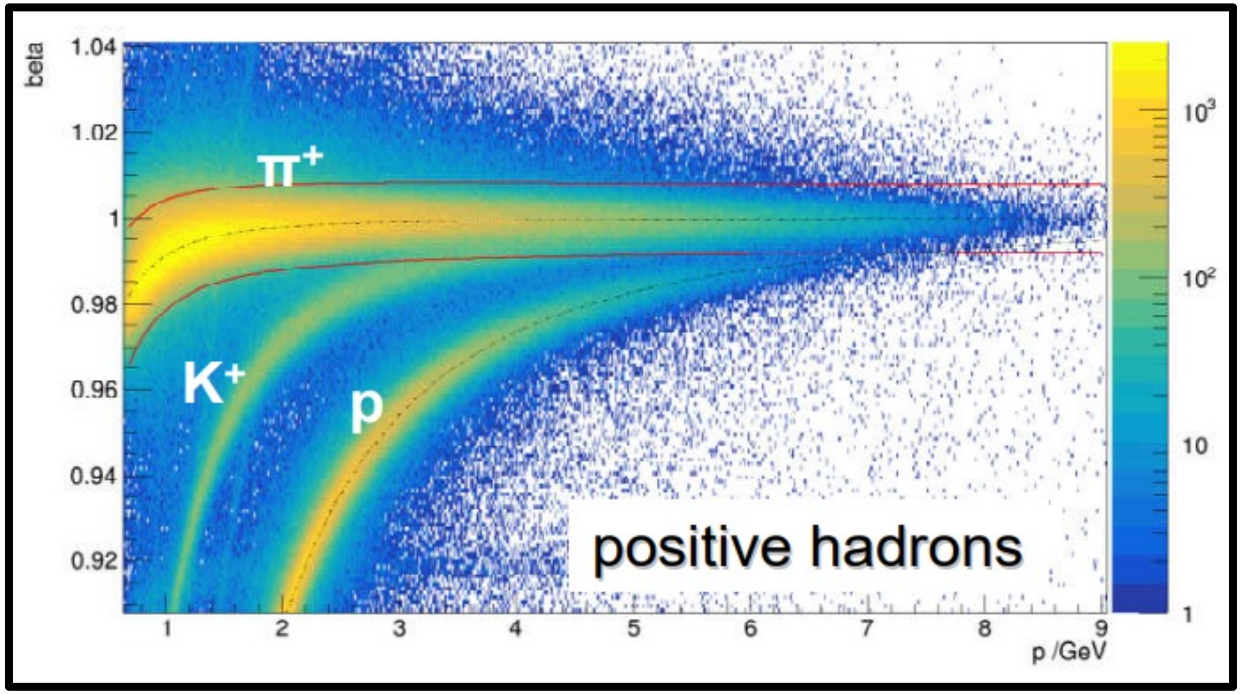


*Image provided by Stefan Diehl

π^+ Pion PID – ß vs p

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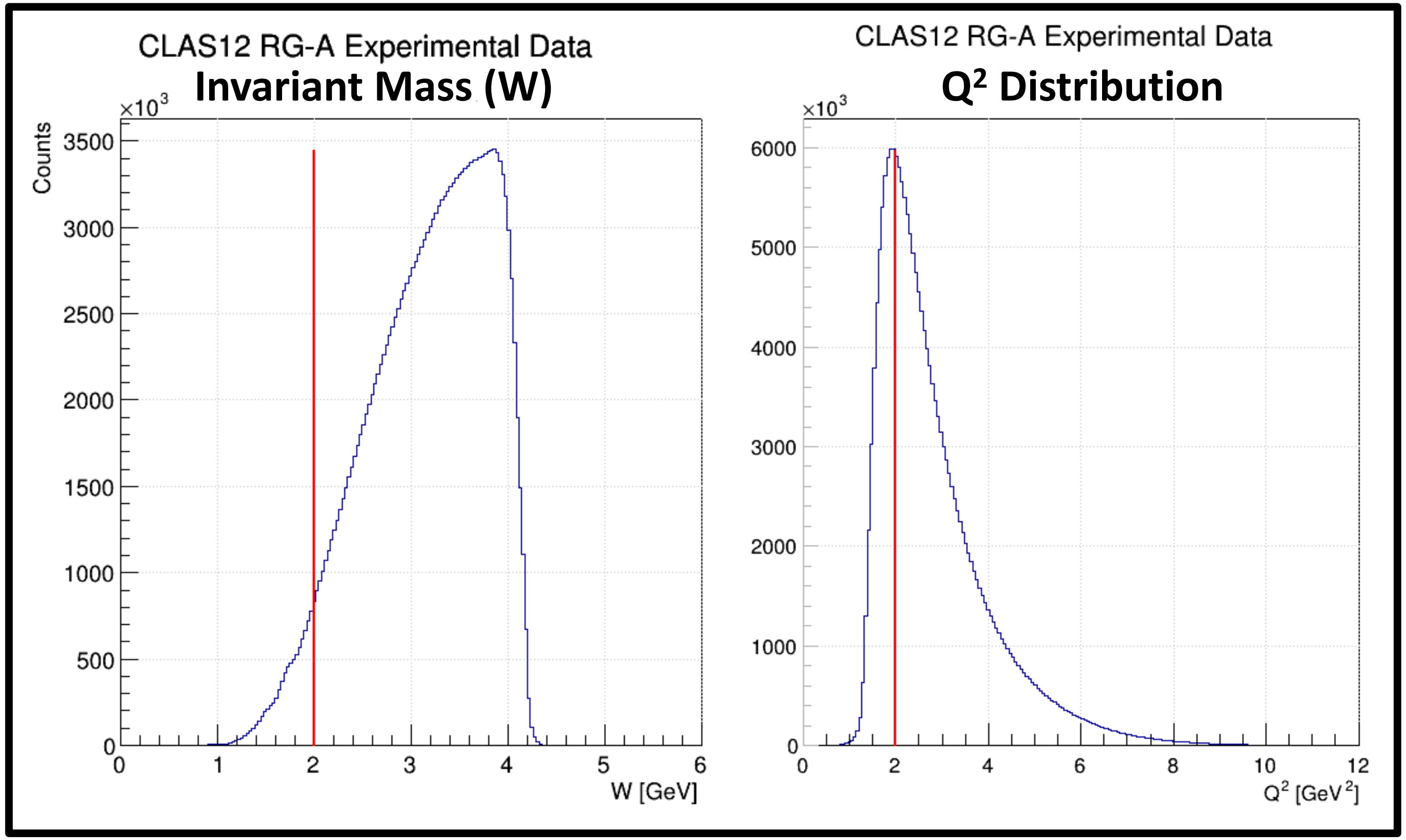
Analysis Cuts:

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



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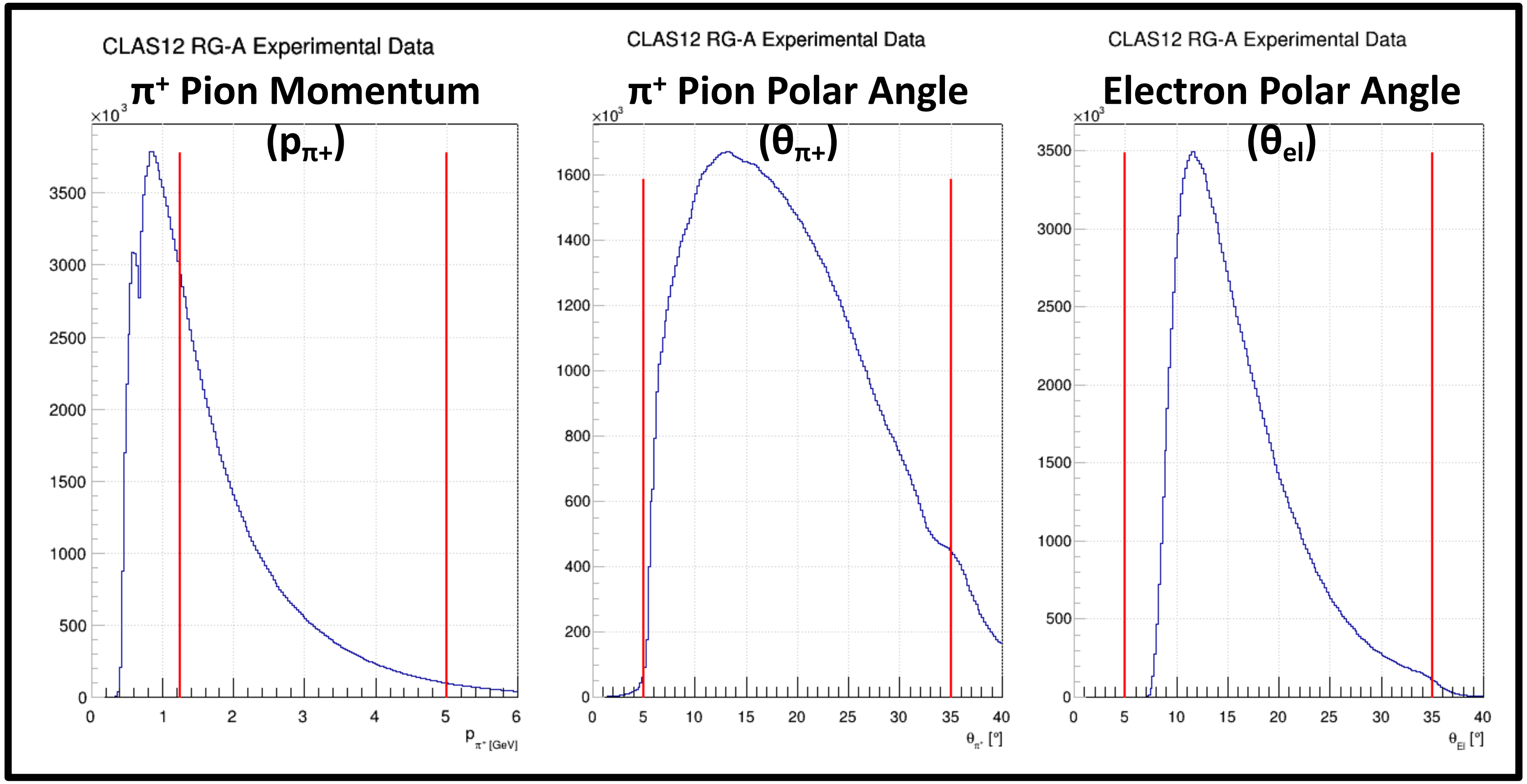
Analysis Cuts:

- **SIDIS Cuts**:
  - W > 2 GeV
  - $Q^2 > 2\ \mathrm{GeV}^2$
- **Other Analysis Cuts:**
  - $p_{\pi+}$ Cut: $1.25\ \mathrm{GeV} < p_{\pi+} < 5\ \mathrm{GeV}$
  - θ-angle Cut: $5° < \theta_{particle} < 35°$



CLAS12 RG-A Experimental Data

π^+ Pion Momentum ($p_{\pi+}$)

CLAS12 RG-A Experimental Data

π^+ Pion Polar Angle ($\theta_{\pi+}$)

CLAS12 RG-A Experimental Data

Electron Polar Angle (θ_{el})

Event Selection

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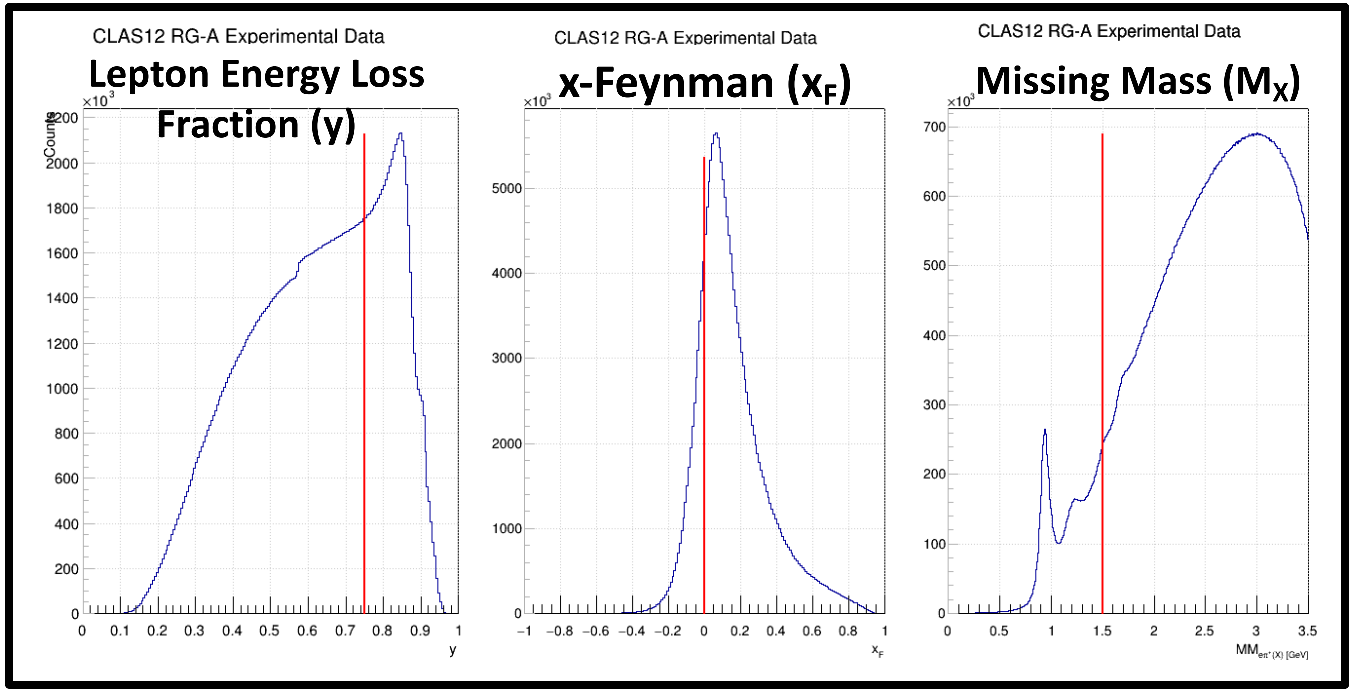
- **Other Analysis Cuts:**
  - $p_{\pi+}$ Cut: 1.25 GeV < $p_{\pi+}$ < 5 GeV
  - θ-angle Cut: 5° < $\theta_{particle}$ < 35°
  - y < 0.75 (minimize other background processes)
  - $x_F > 0$ (minimize contributions from target fragmentations)
  - Missing Mass Cut: $M_x > 1.5$ GeV (limits contributions from exclusive events)



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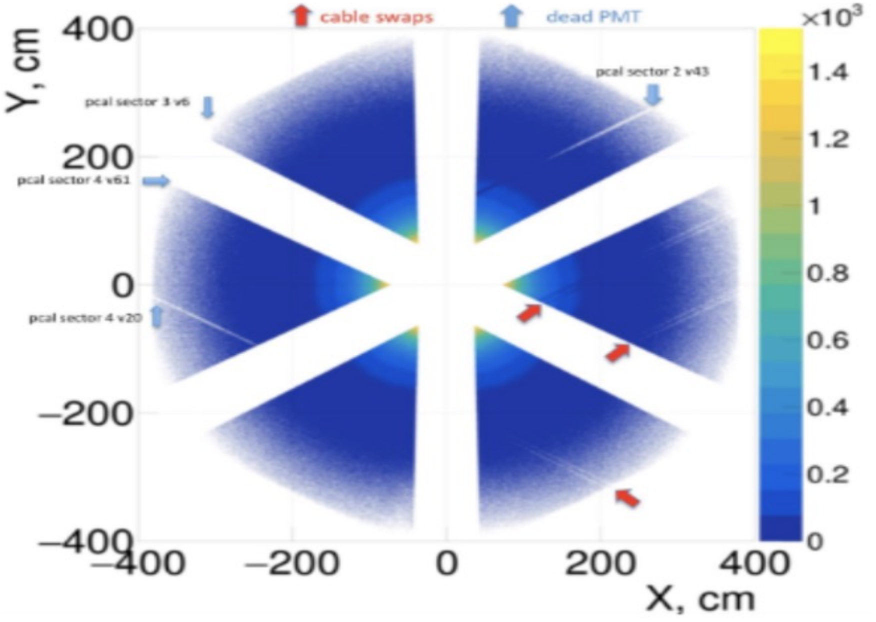
- **Other Analysis Cuts:**
  - $p_{\pi+}$ Cut: $1.25 \text{ GeV} < p_{\pi+} < 5 \text{ GeV}$
  - θ-angle Cut: $5° < \theta_{particle} < 35°$
  - $y < 0.75$ (minimize other background processes)
  - $x_F > 0$ (minimize contributions from target fragmentations)
  - Missing Mass Cut: $M_x > 1.5$ GeV (limits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

CLAS12 RG-A Experimental Data

PCAL

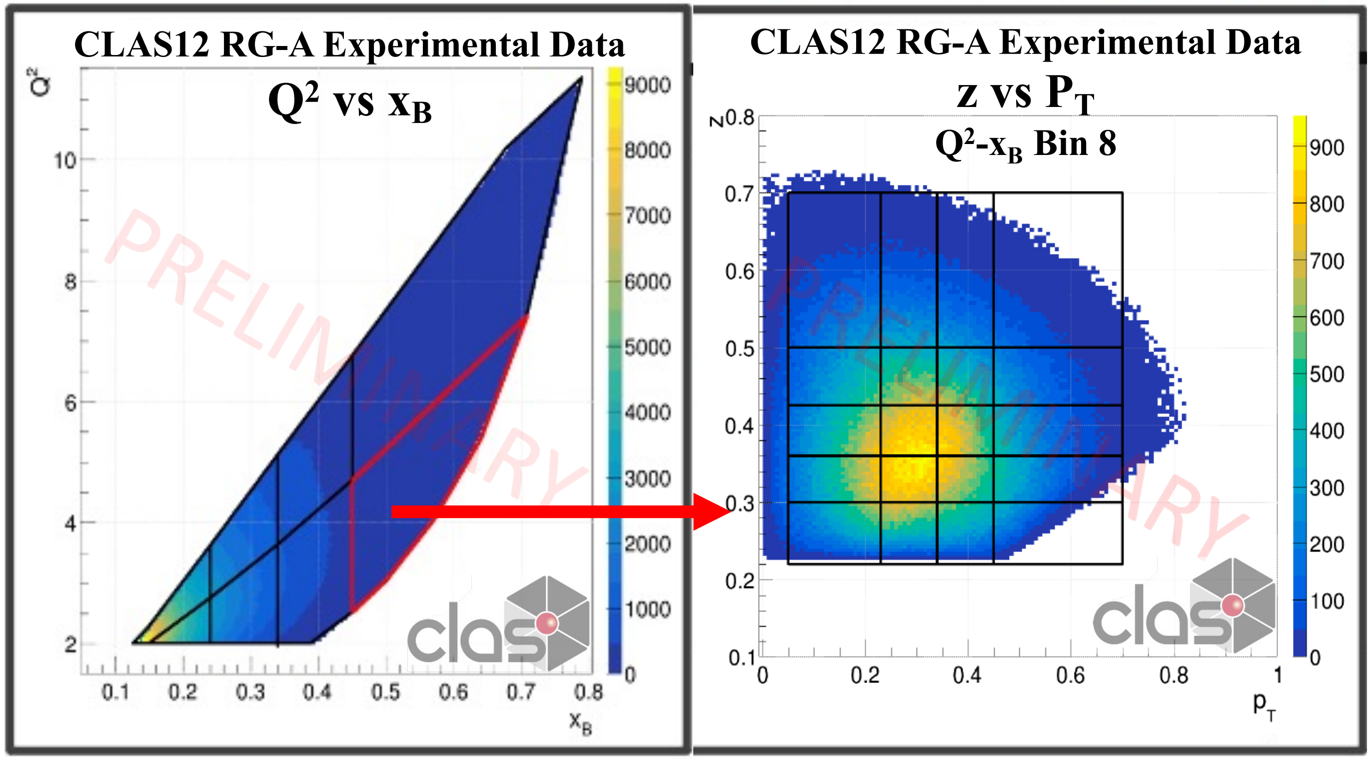


Multidimensional Analysis Procedures

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



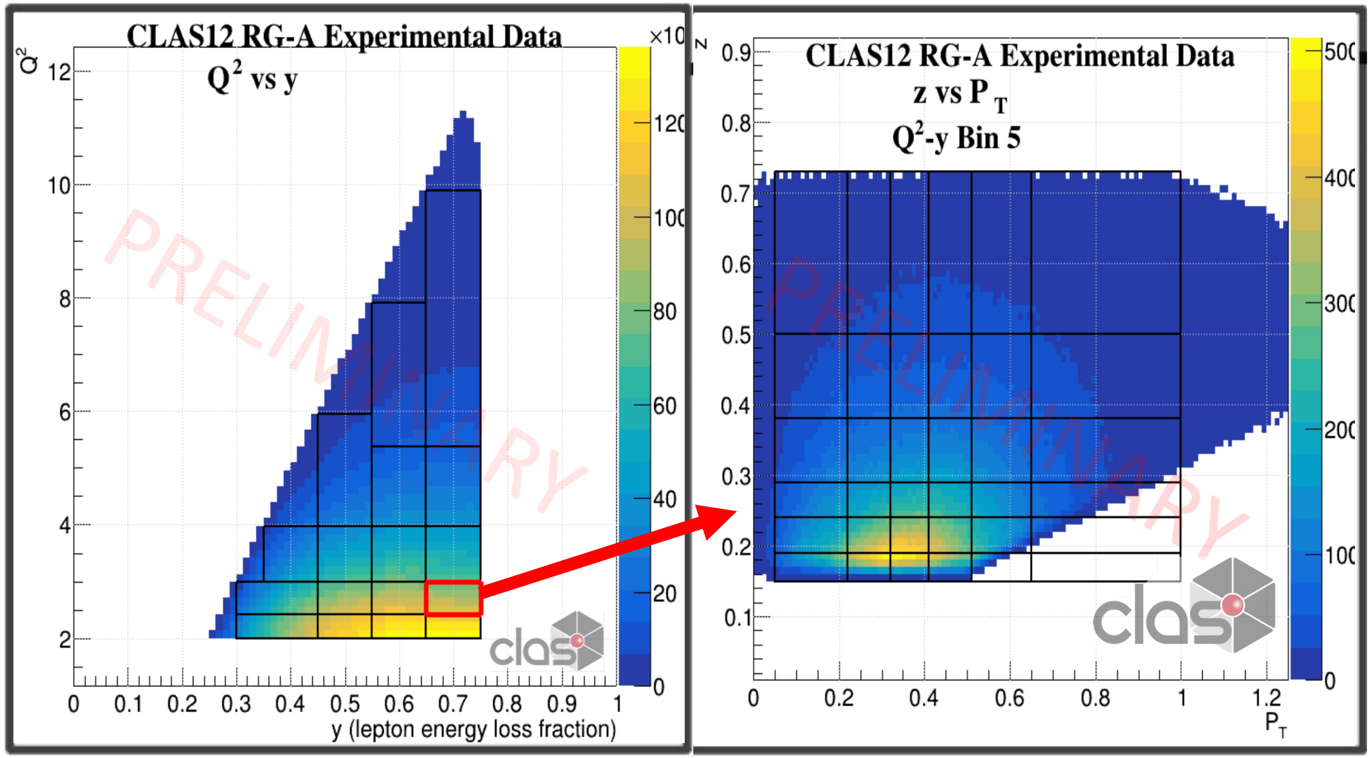
Main Issue was with the irregular shape of the Q^2-x_B Bins

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)

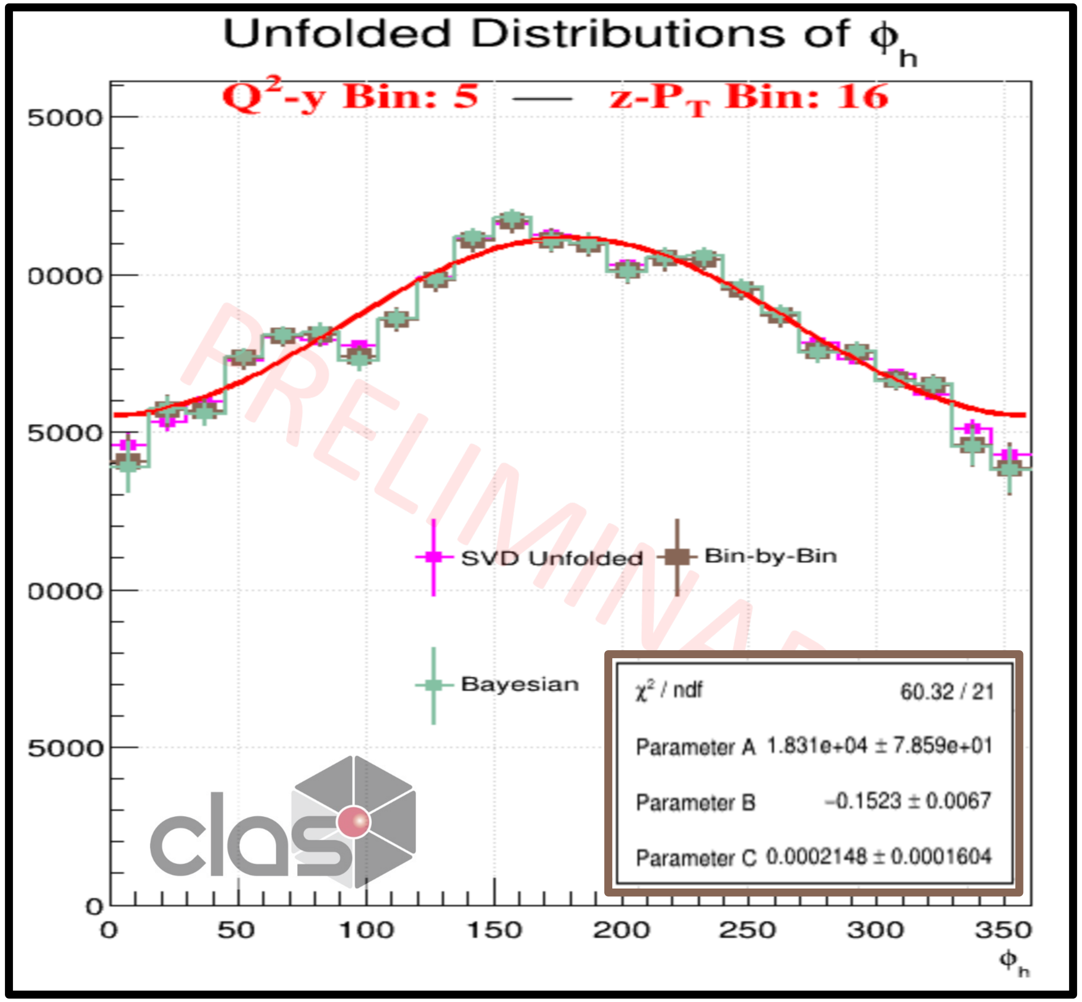
Example of new binning scheme using Q^2, y, z, and P_T

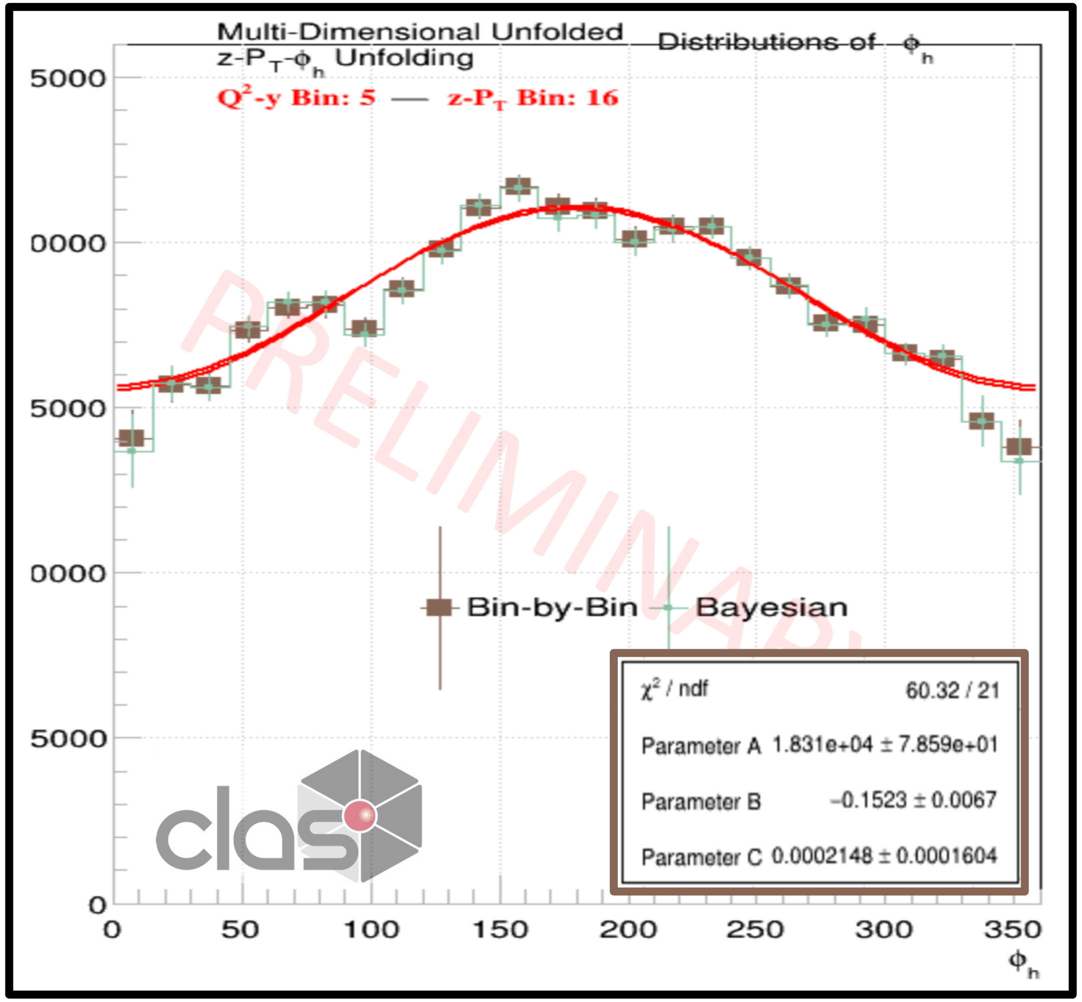


Both the Q^2-y and z-P_T bins are now rectangular which makes the bins easier to work with

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

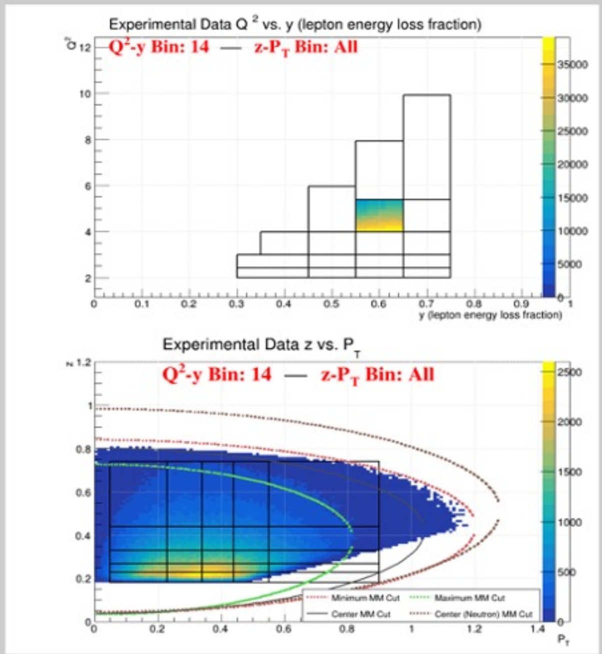
SVD Unfolding has not been able to work so far with the Multidimensional Unfolding procedures

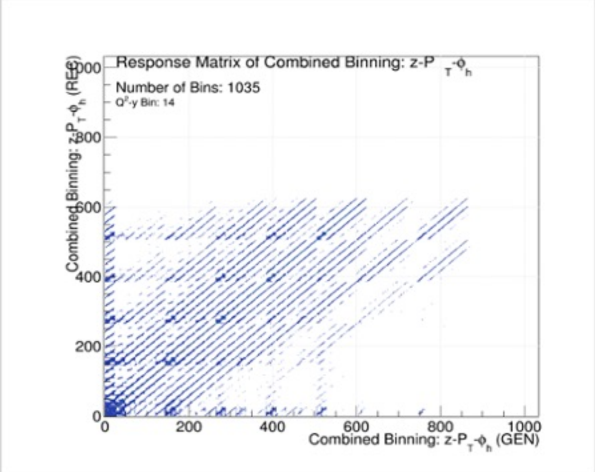
Extra Examples of (3D) Unfolding Procedure

Using the Flattened z-P_T-ϕ_h Multidimensional Bins

Unfolded with Bayesian Method

Q^2-y Bin 14





PRELIMINARY

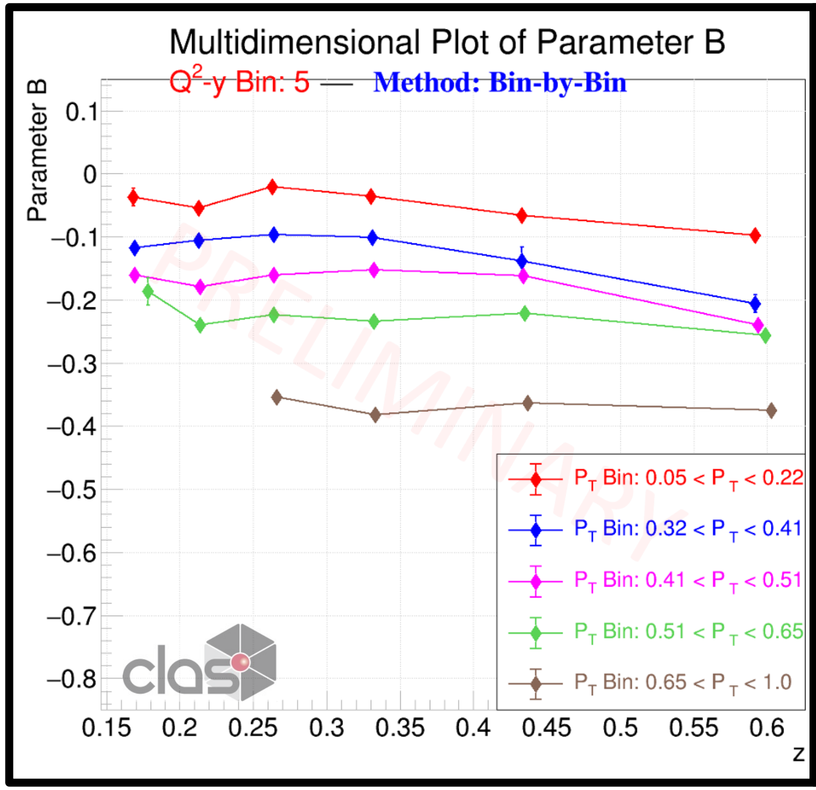
Cosine Moments as Functions of z

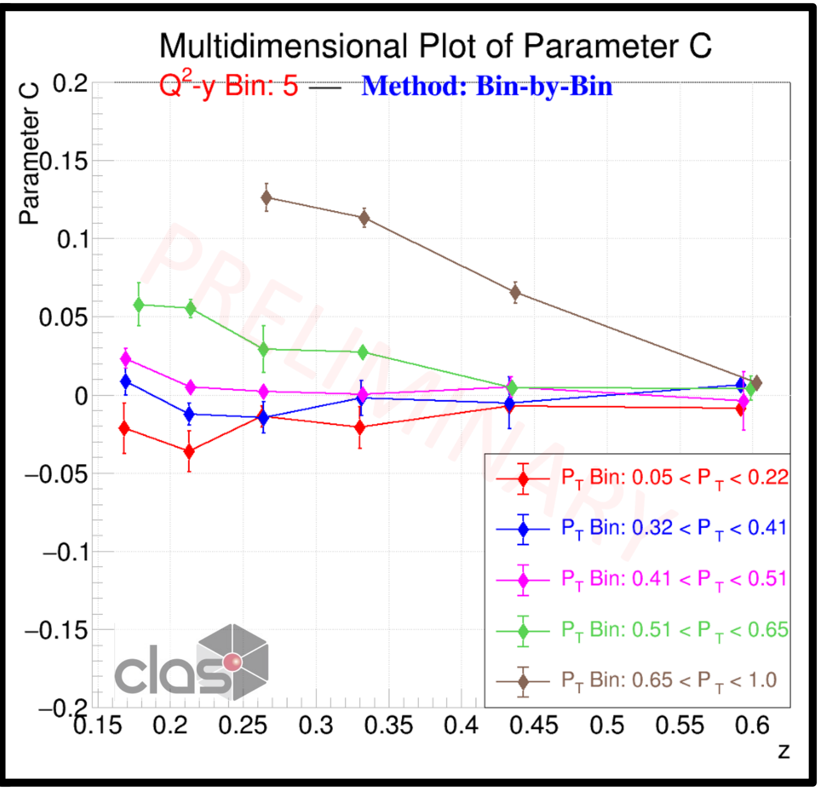
$B = A_{UU}^{\cos\varphi_h}$ $C = A_{UU}^{\cos 2\varphi_h}$

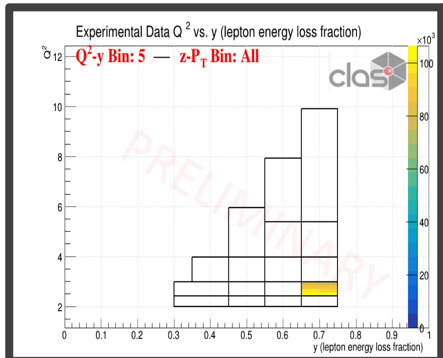
ϕ_h Plots were fitted with:
$A(1 + B\cos(\phi_h) + C\cos(2\phi_h))$

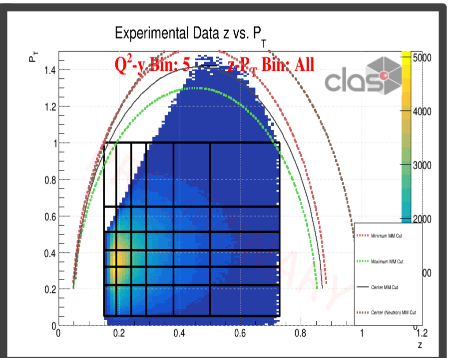
Corrected with Bin-by-bin Method

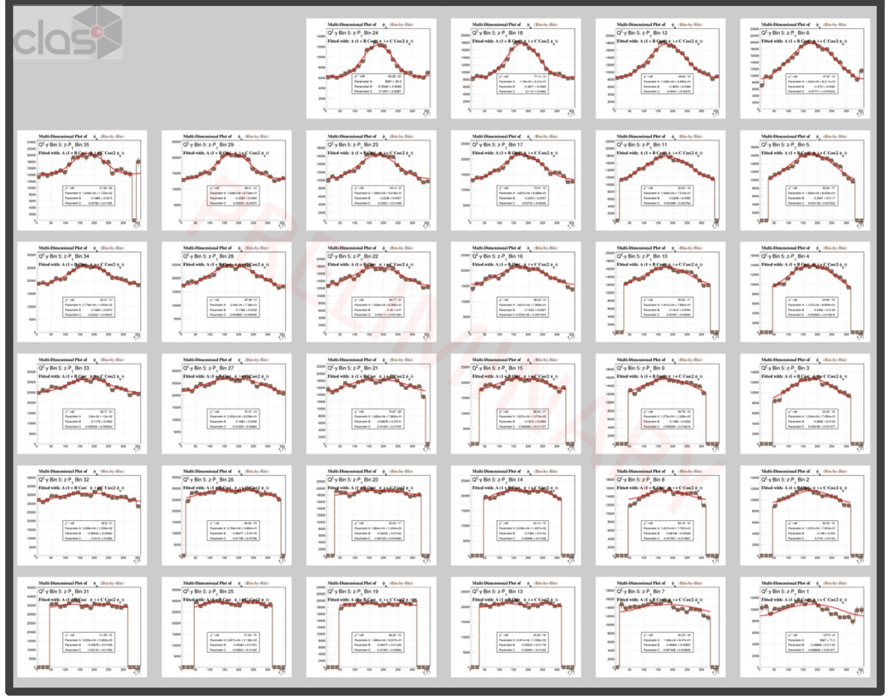
Q^2-y Bin 5











Cosine Moments as Functions of z

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ϕ_h Plots were fitted with:

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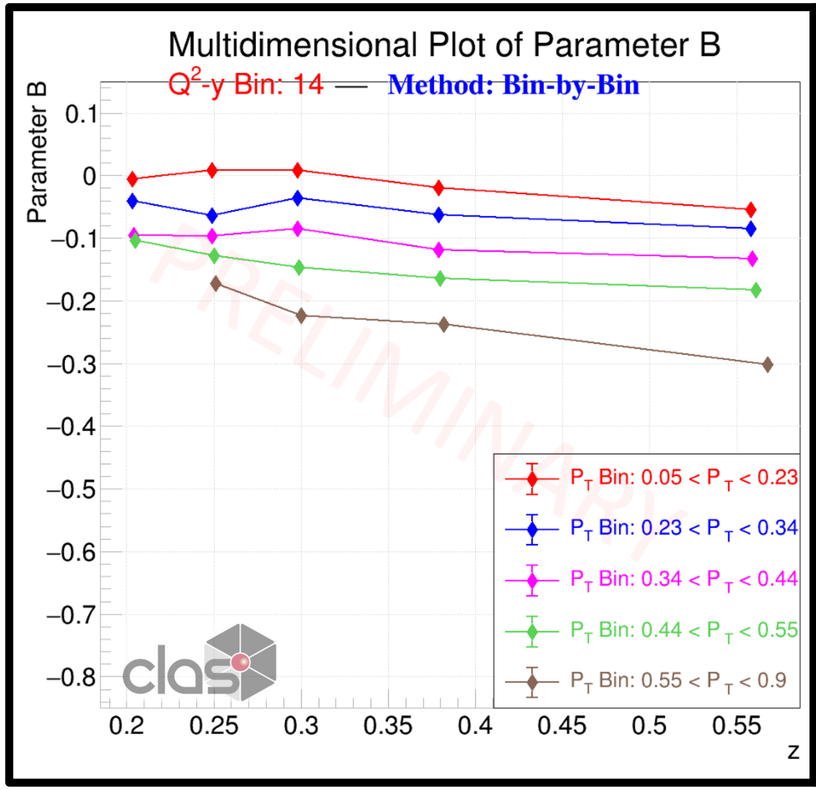
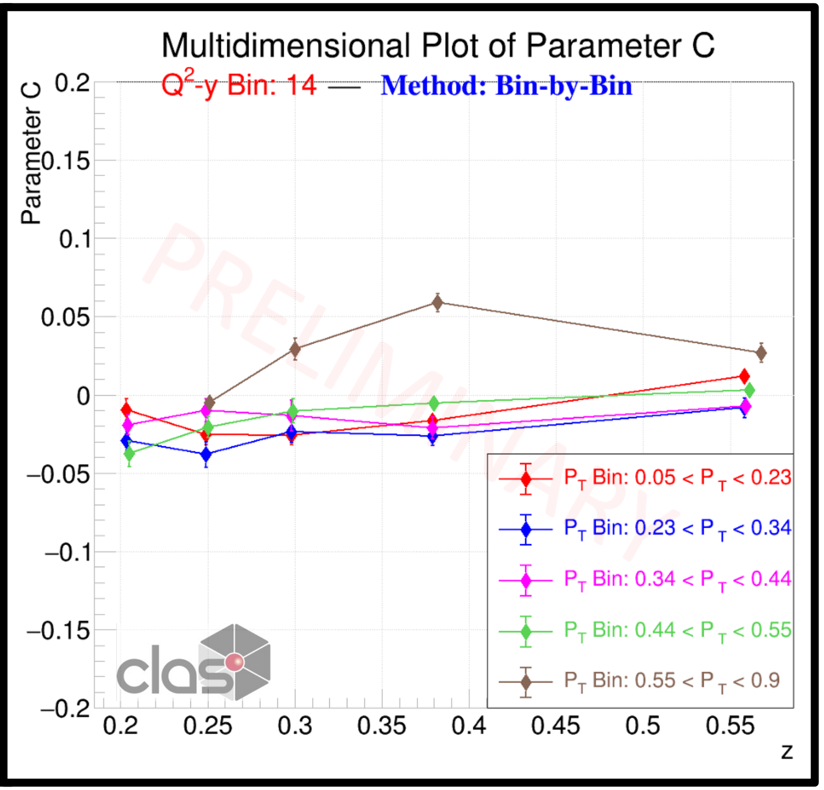
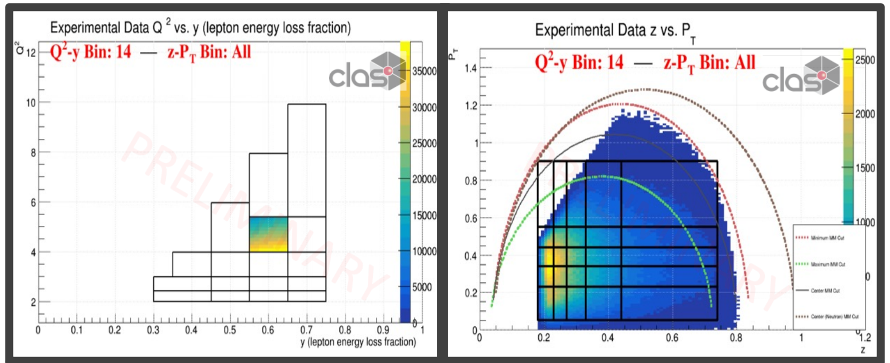
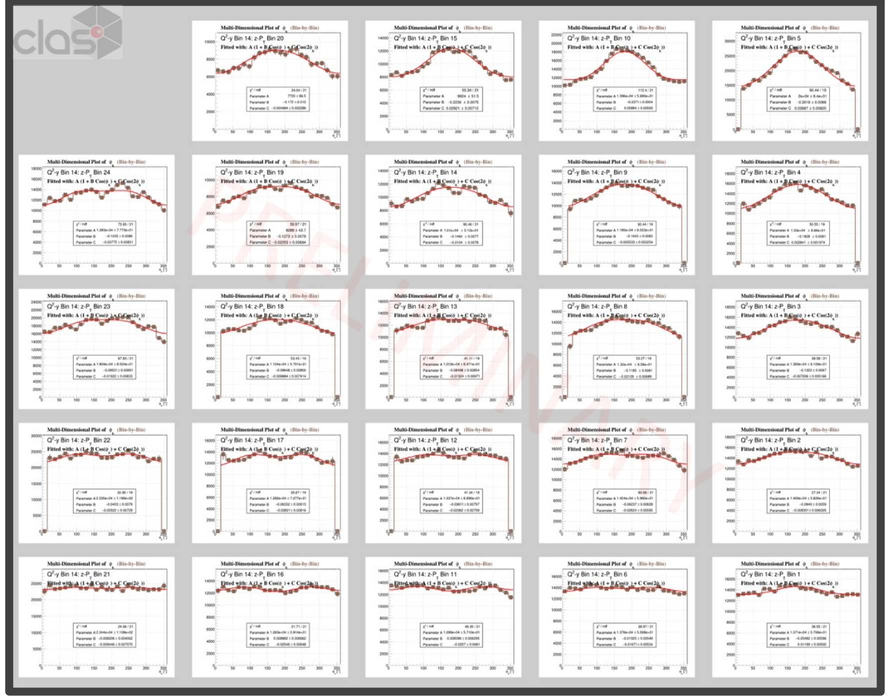
Corrected with Bin-by-bin Method

Q^2-y Bin 14



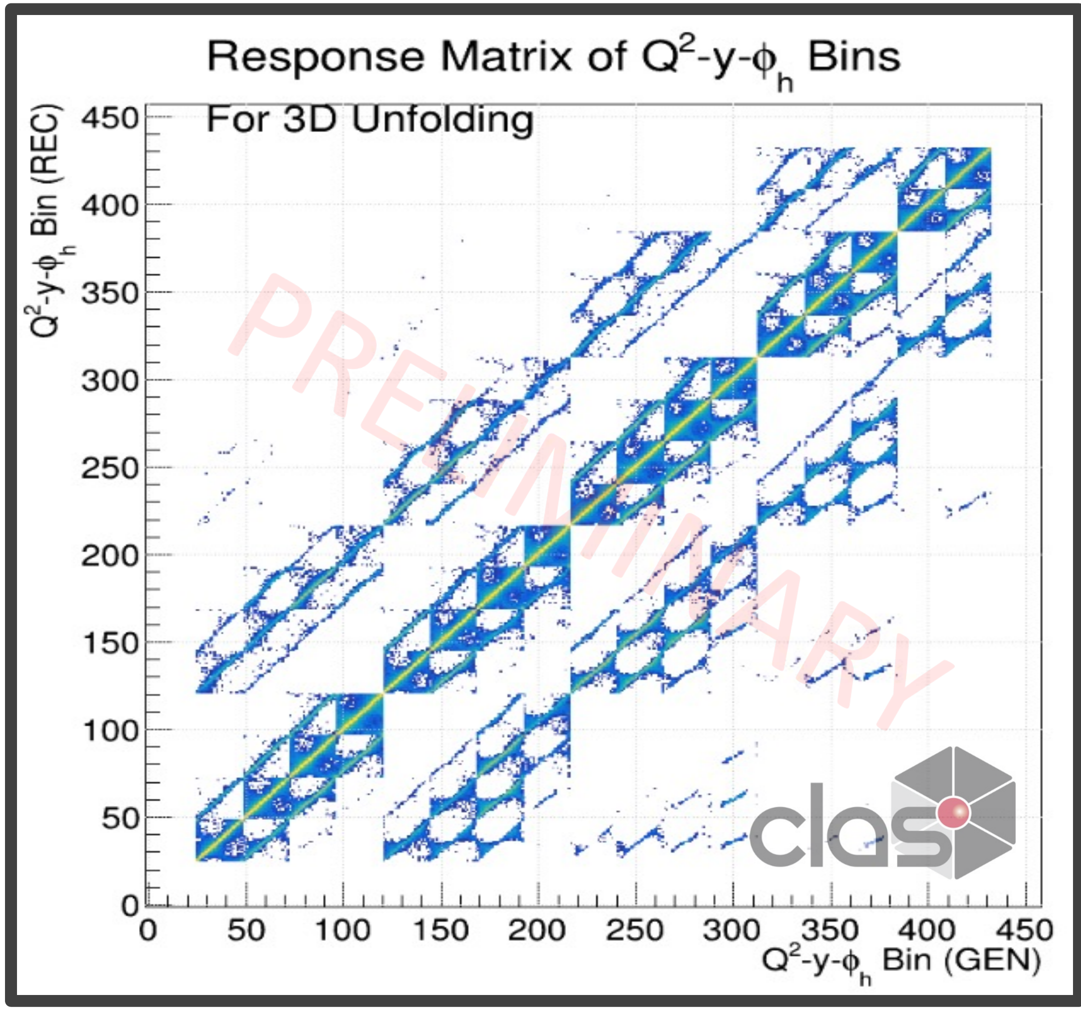






Example of (3D) Unfolding Procedure

Using Q^2-y-ϕ_h Multidimensional Bins



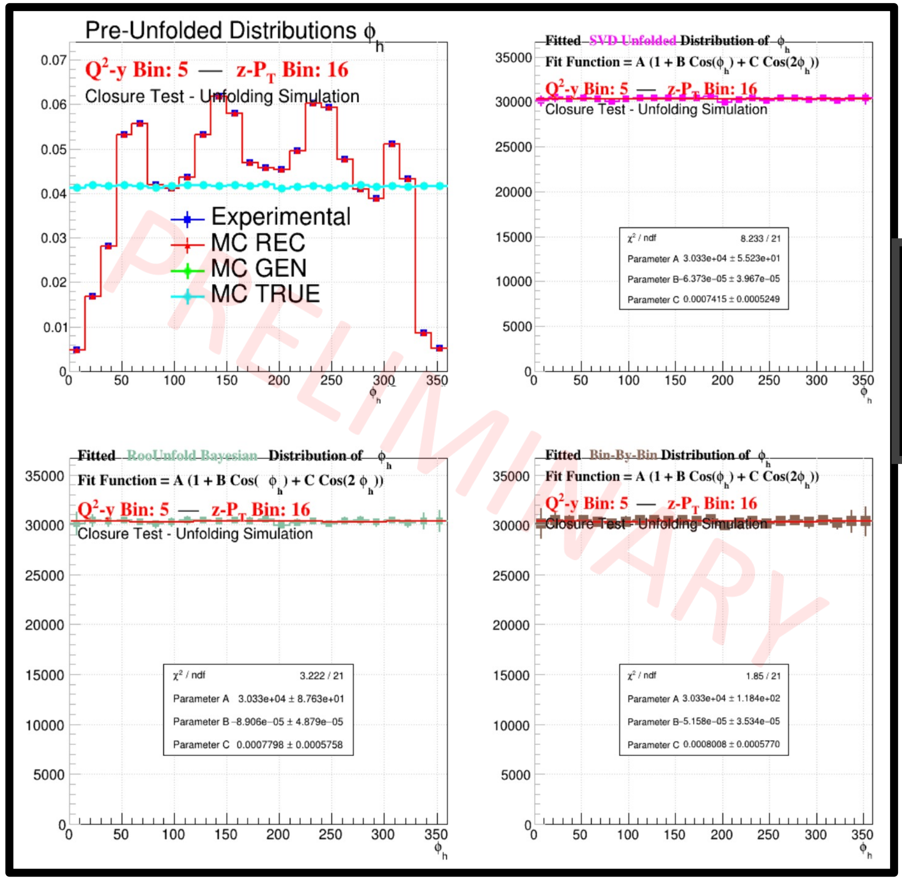
Unfolding Procedure

Unfolded with Bayesian Method

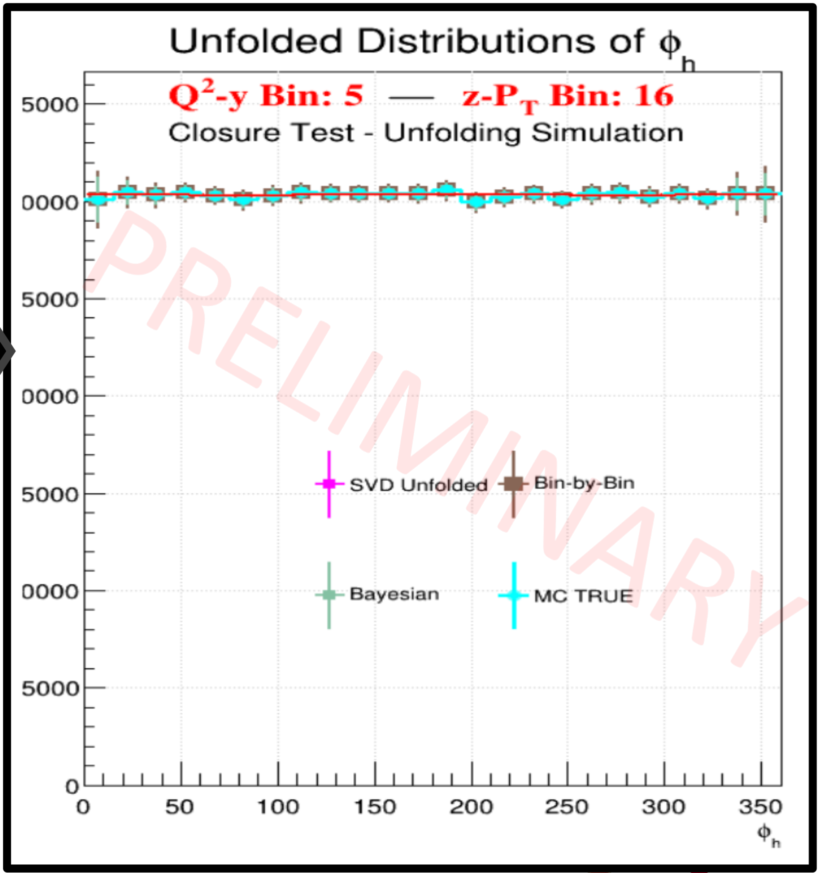
Other Unfolding Closure Tests

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

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



Checking that the corrected distributions match MC TRUE



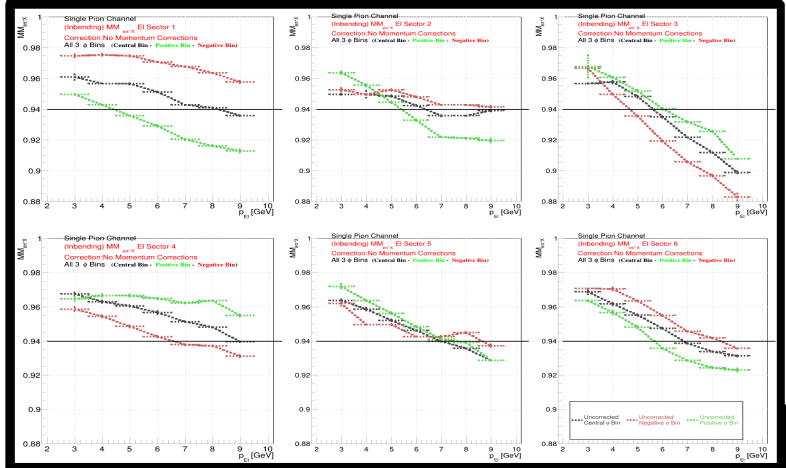
Momentum Corrections from Exclusive Events

- 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}

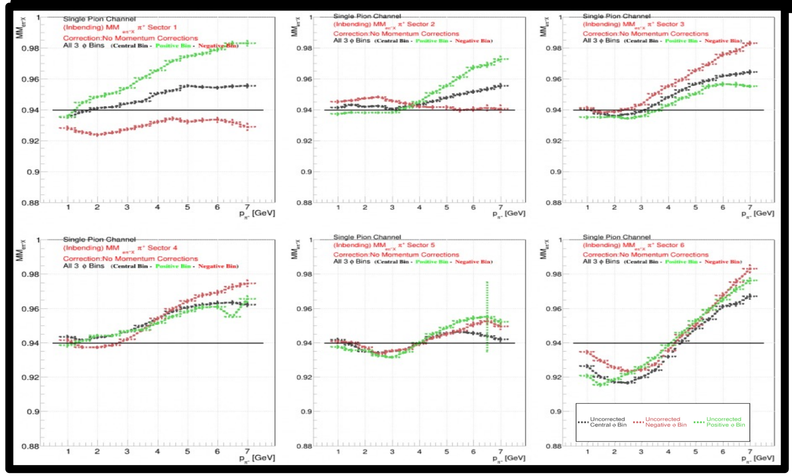
Momentum Corrections from Exclusive Events

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

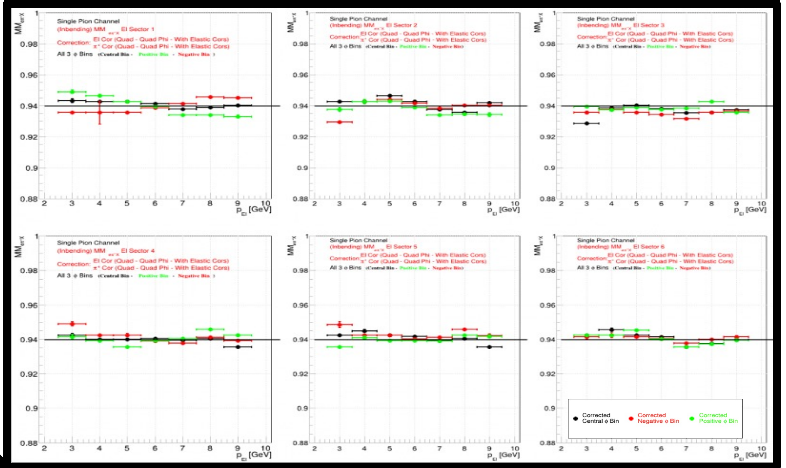


Missing Mass ($MM_{e\pi^+X}$) vs π⁺ Pion Momentum

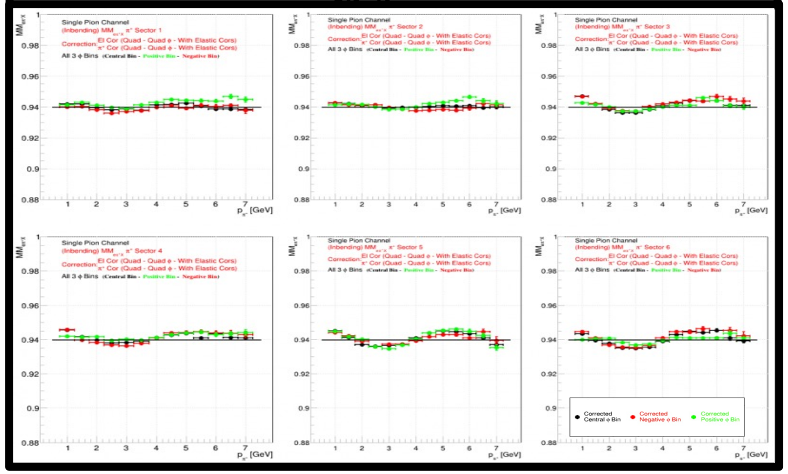


Apply Momentum Corrections

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



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

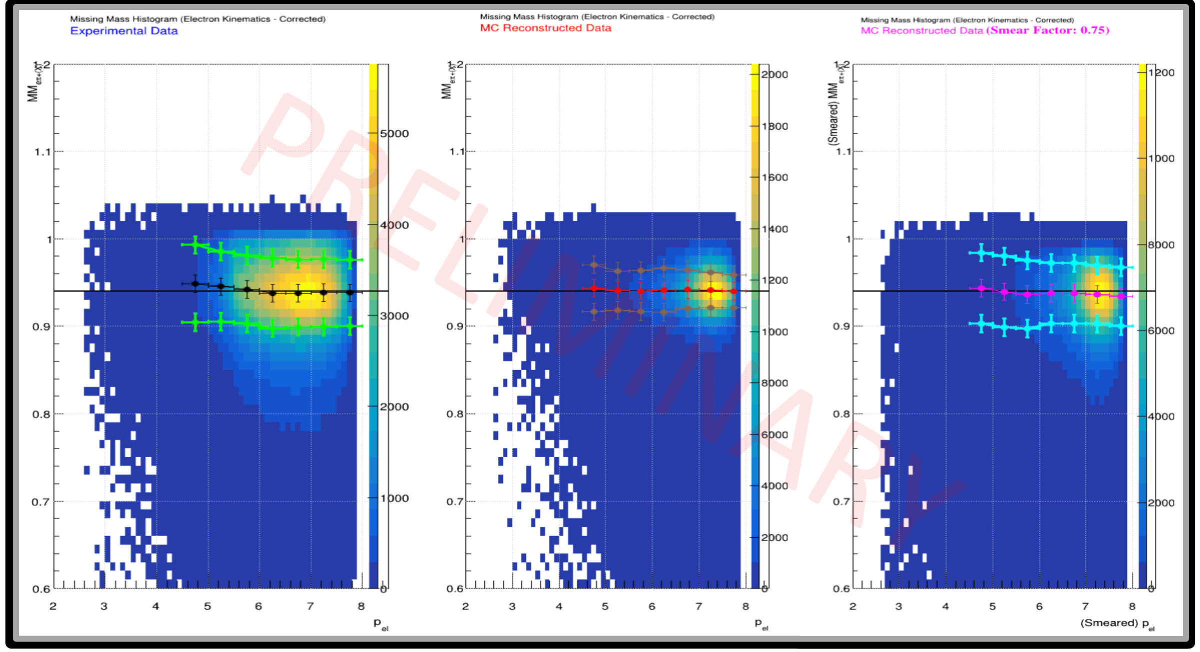


┅ Uncorrected Central ϕ Bin ┅ Uncorrected Negative ϕ Bin ┅ Uncorrected Positive ϕ Bin

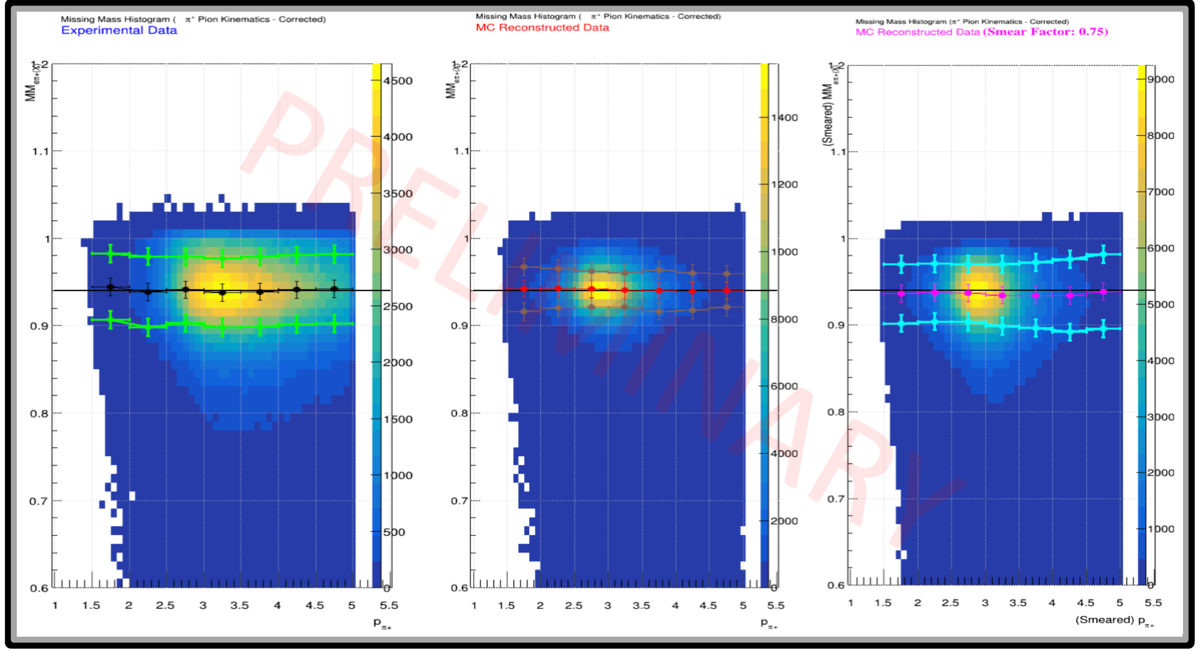
● Corrected Central ϕ Bin ● Corrected Negative ϕ Bin ● Corrected Positive ϕ Bin

Momentum Smearing

Missing Mass vs Electron Momentum:



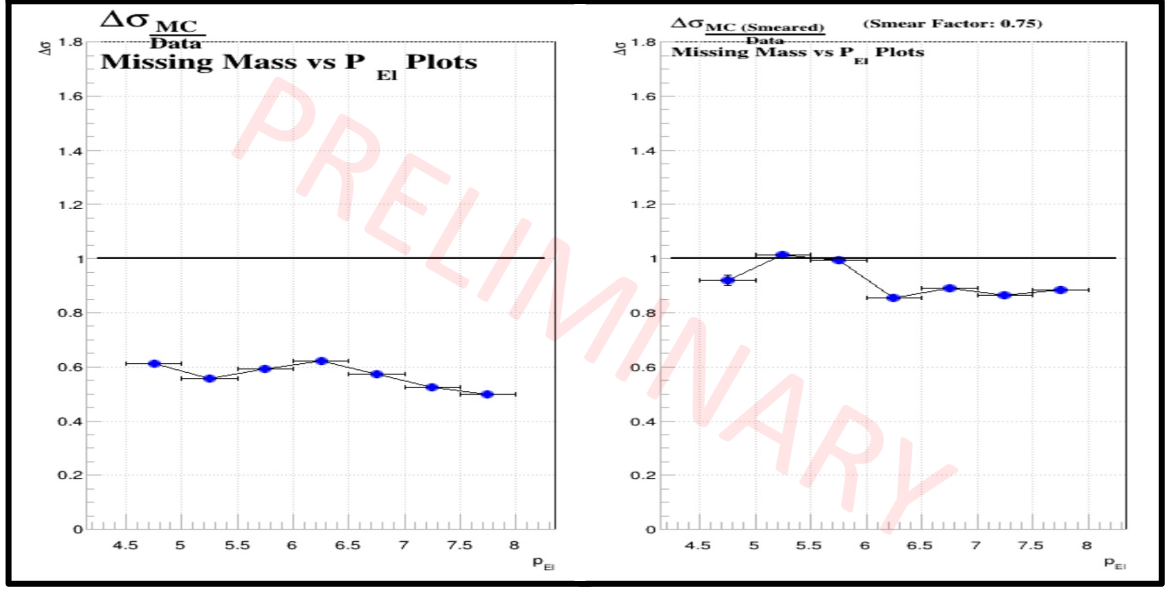
Missing Mass vs π^+ Pion Momentum:



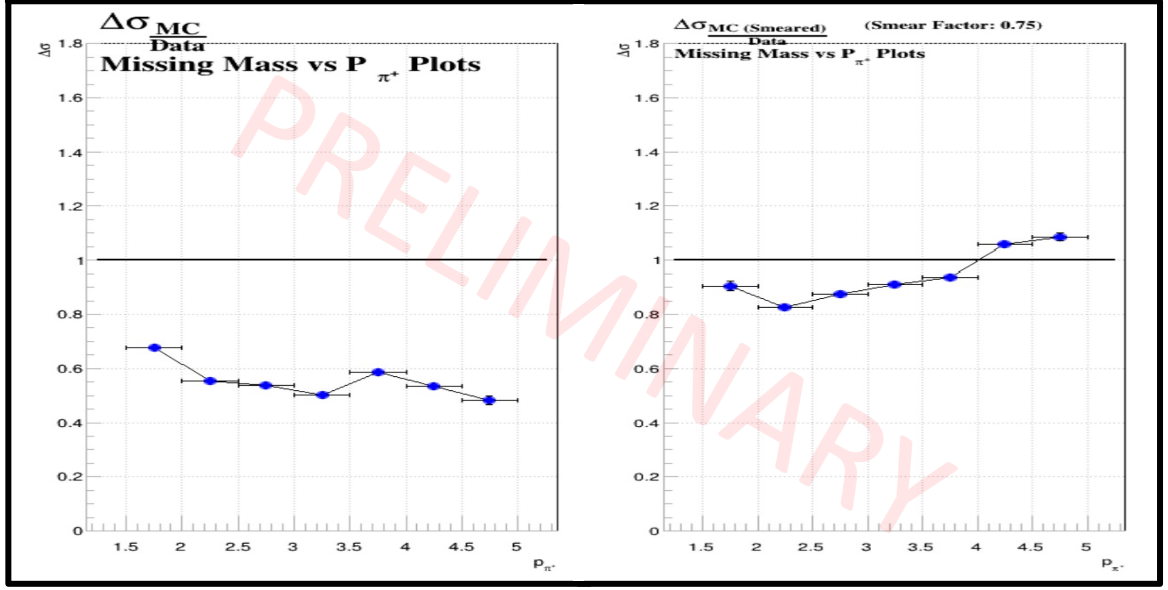
- **The momentums of the particles in these plots are CORRECTED (see Momentum Corrections from Exclusive Events)**
- Momentum Smearing is applied in addition to existing MC reconstruction processes
- The momentum smearing functions use 2D Missing Mass plots to check how it improves the MC
  - The widths of the peaks are shown in each plot above
- Momentum smearing is done with the equation: $\mathbf{P_{Smeared} = P_{Generated} - (SF + 1)*(P_{Generated} - P_{Reconstructed})}$
  - **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

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

END

Link to more Images:

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