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

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Presentation for the CLAS Collaboration

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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
    - **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)

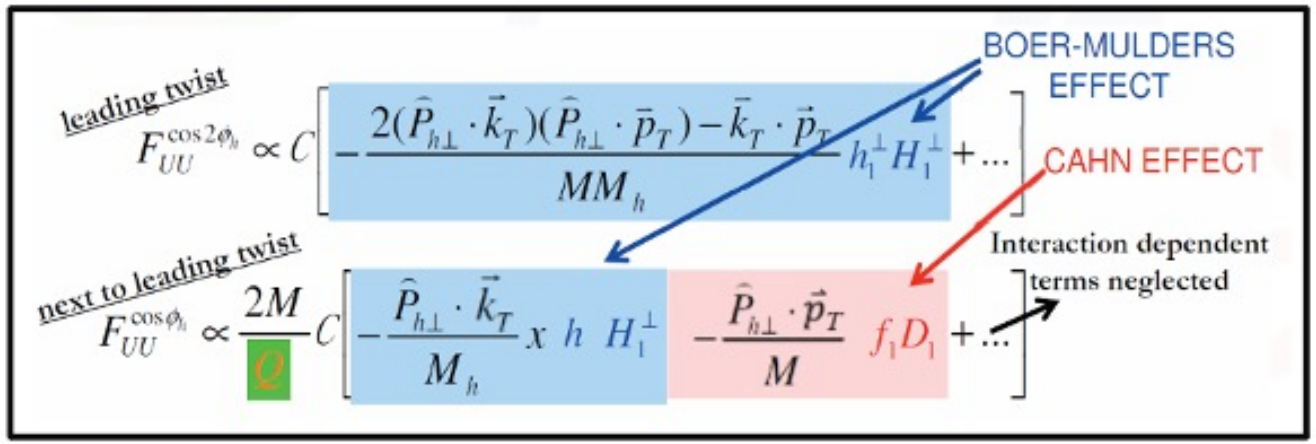
SIDIS Cross-Section and Boer-Mulders

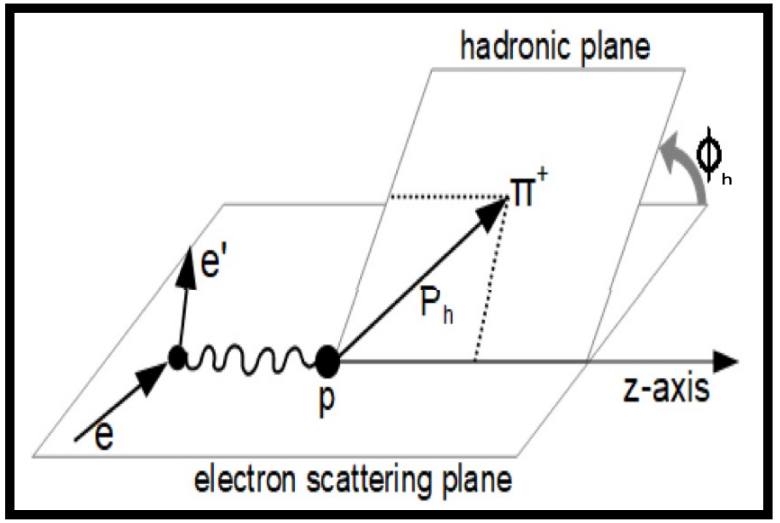
The lepton-hadron Unpolarized SIDIS Cross-Section:

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

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

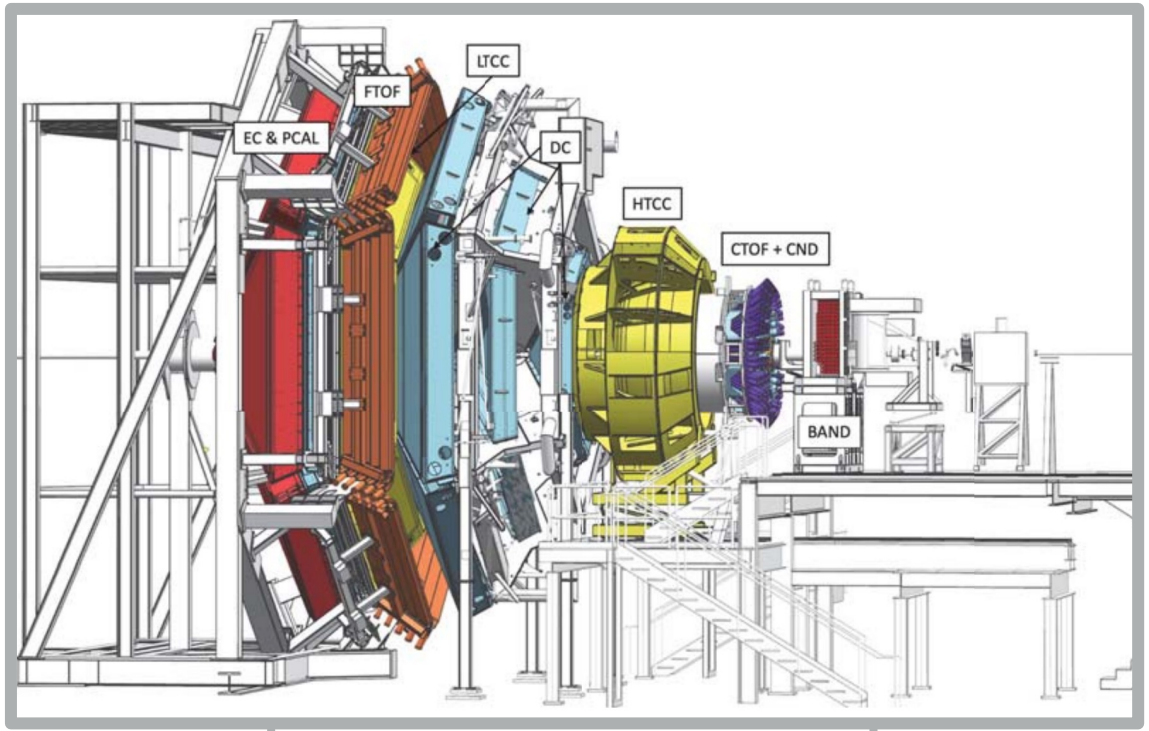
The Boer-Mulders and Cahn effects are present in the Structure Functions:





Reaction Studied: $ep \rightarrow e\pi^+(X)$

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

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

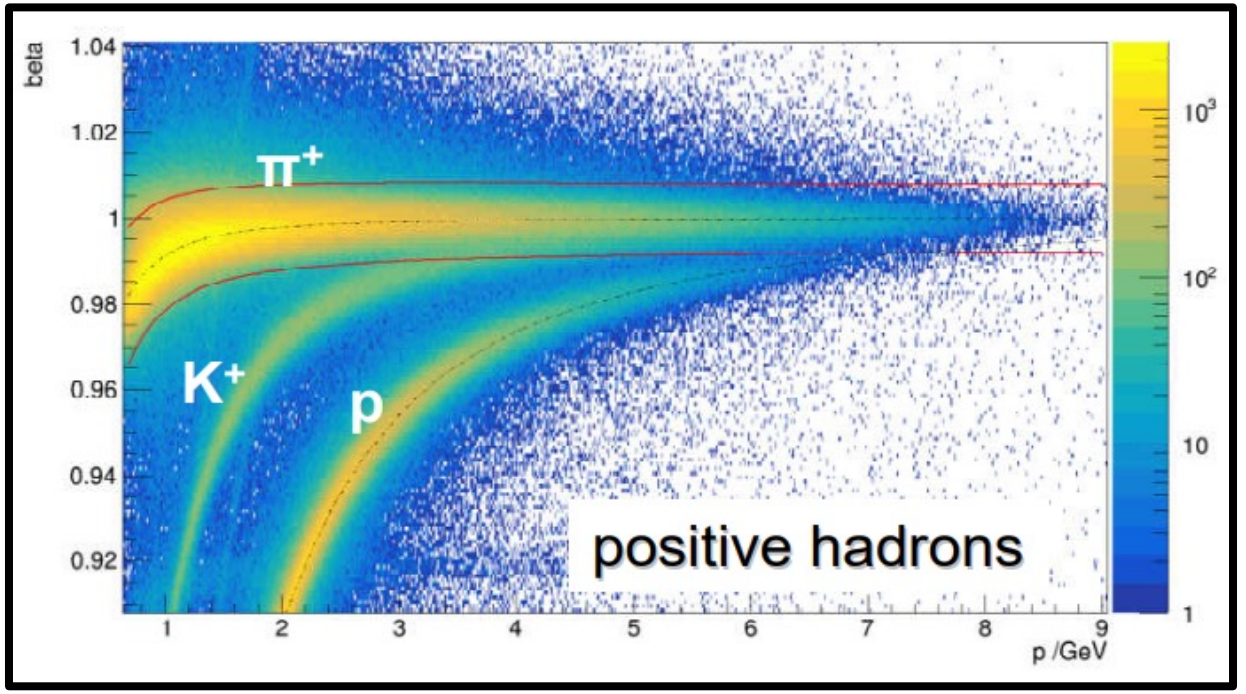


*Image provided by Stefan Diehl

π^+ Pion PID – ß vs p

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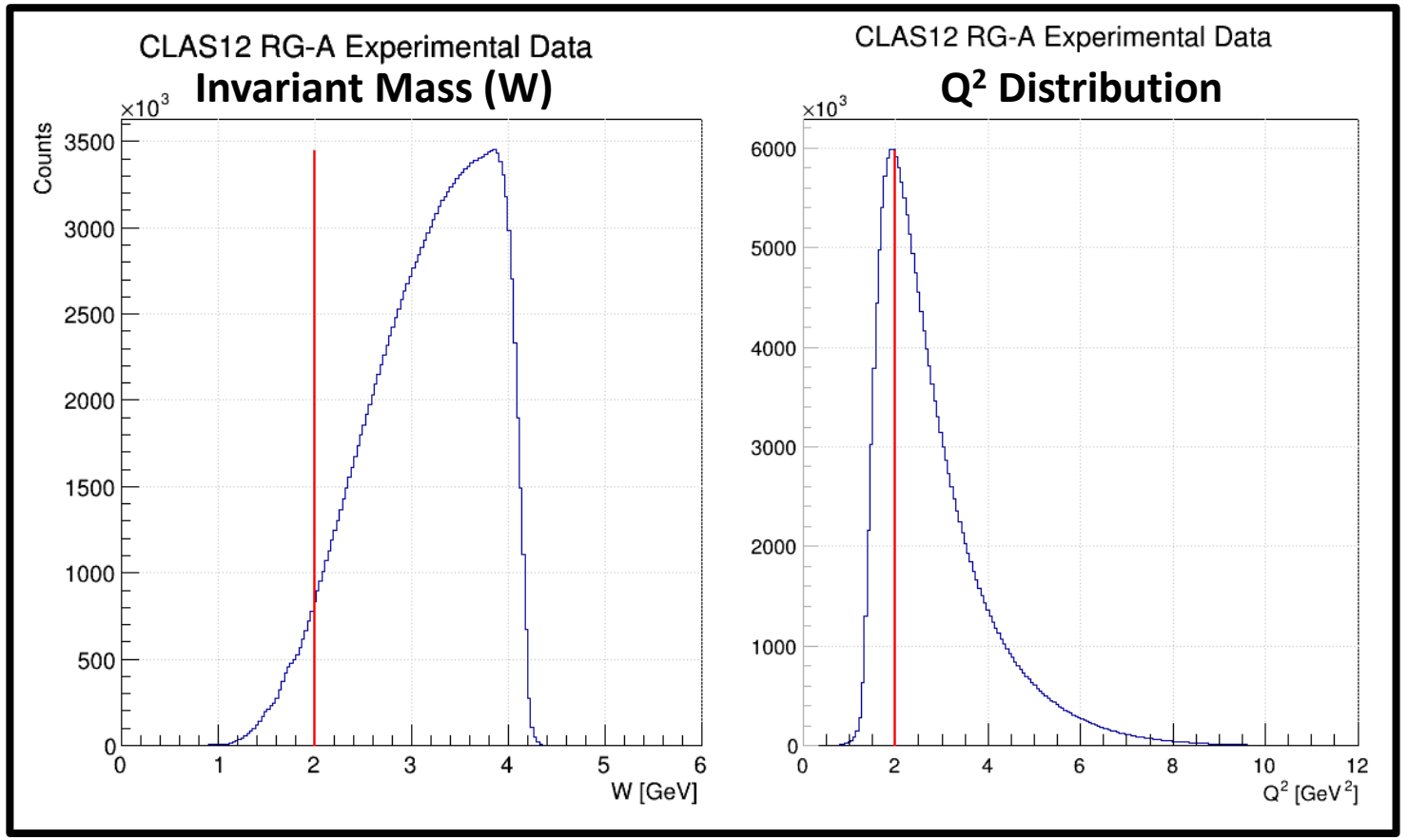
Analysis Cuts:

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



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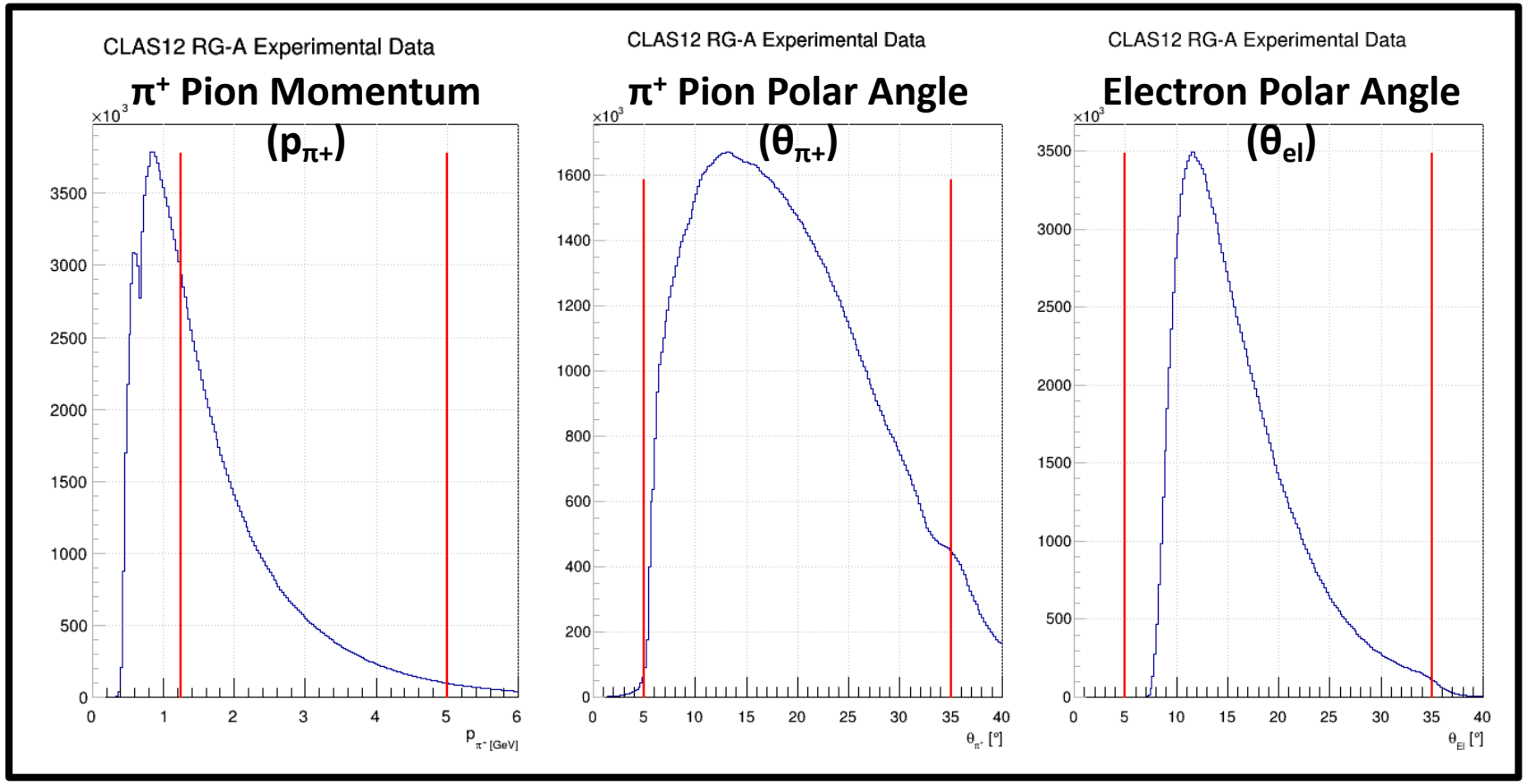
  - $p_{\pi+}$ Cut: 1.25 GeV < $p_{\pi+}$ < 5 GeV
  - θ-angle Cut: 5° < $\theta_{particle}$ < 35°



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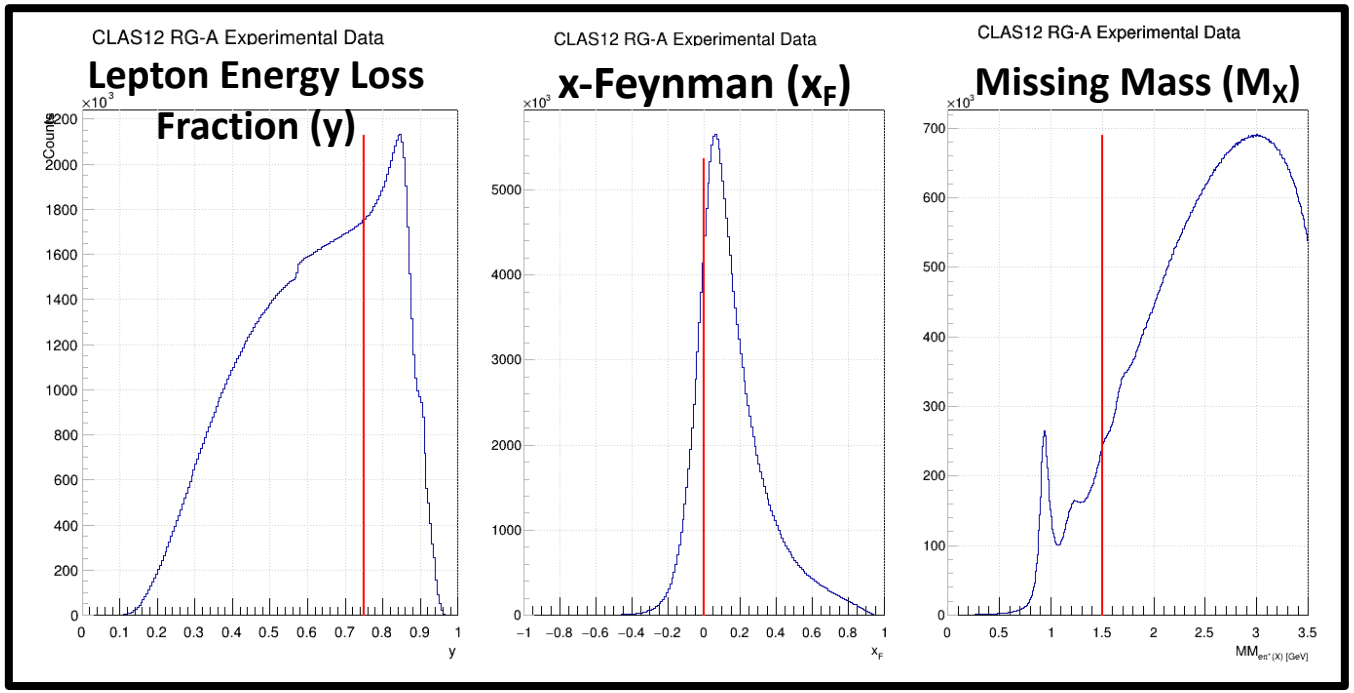
  - $x_F > 0$ (minimize contributions from target fragmentations)
  - Missing Mass Cut: $M_x > 1.5$ GeV (limits contributions from exclusive events)



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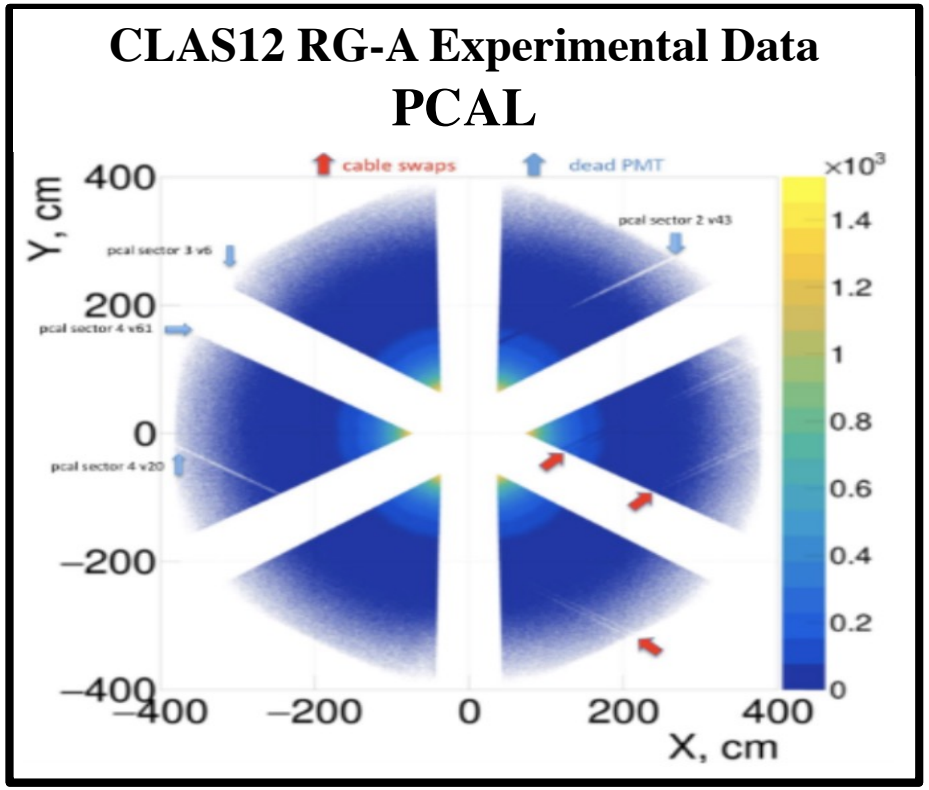
  - Missing Mass Cut: $M_x > 1.5$ GeV (limits contributions from exclusive events)
  - Fiducial Cuts (e.g., accounts for bad channels present in data)



Analysis Procedure

Experimental extraction of cross-section

$$\frac{d^5\sigma}{dQ^2 dx_B dP_T dz d\varphi_h} = \frac{1}{(\Delta Q^2 \Delta x_B \Delta P_T \Delta z \Delta \varphi_h)} \frac{N}{R \cdot BC \cdot \eta \cdot N_0} \frac{1}{(N_A \cdot \rho \cdot t / A_w)}$$

Bin Volume

Target Number Density

Where:

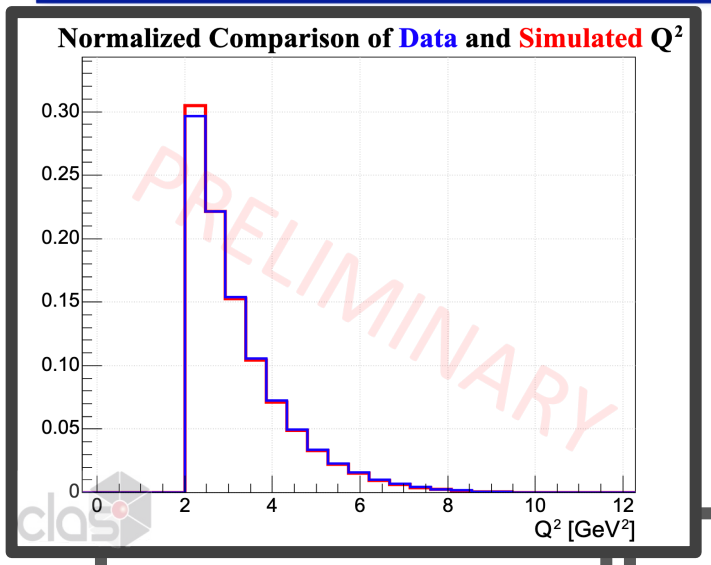
- R = Radiative Correction
- η = **Acceptance Correction** → **Requires Monte Carlo (MC) Simulation**
- N = Bin Yields
- N_0 = Life-time corrected incident electron flux
- BC = factor which evolves bin-averaged differential cross-section

SIDIS MC are generated with LEPTO event generator

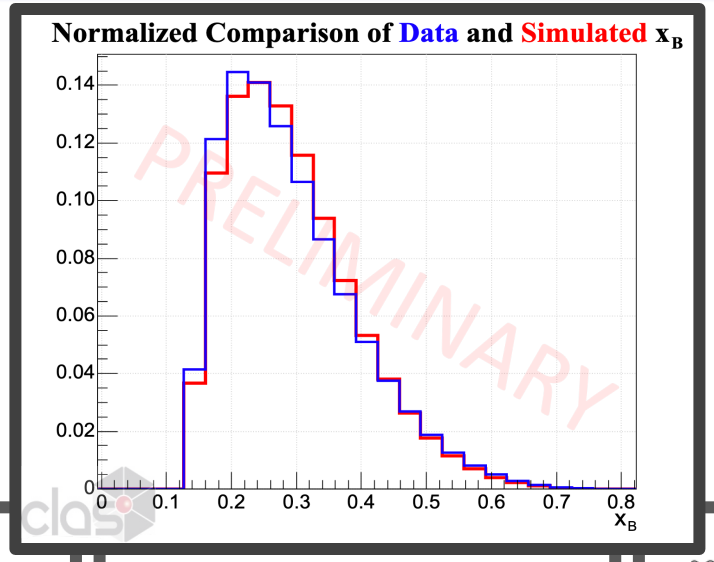
(220) Simulated Files Available Here:

cache/clas12/rg-a/production/montecarlo/clasdis/fall2018/torus-1/v1/bkg45nA_10604MeV/

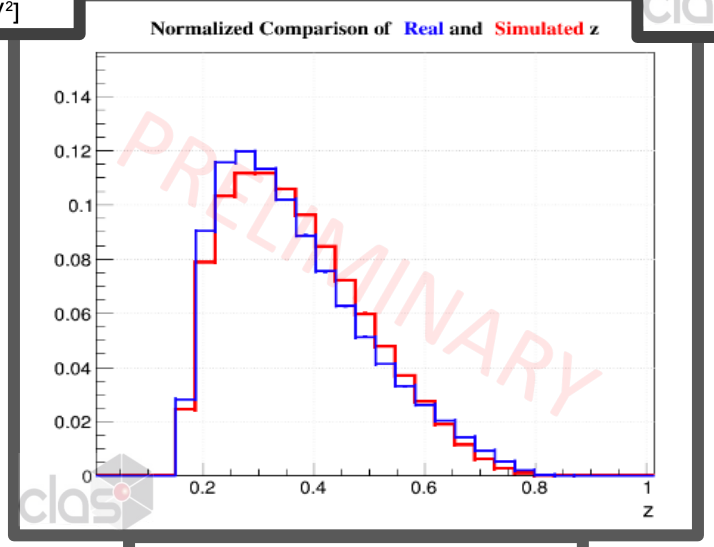
Data and Monte Carlo Comparison



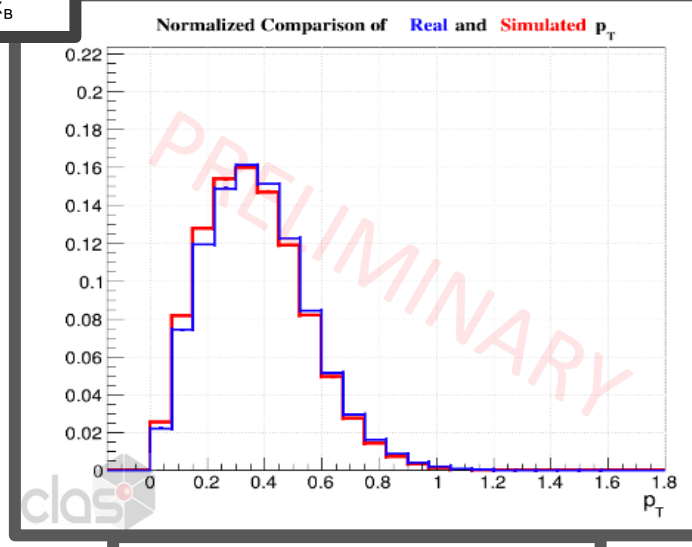
Q^2 Comparison



x_B Comparison



z Comparison



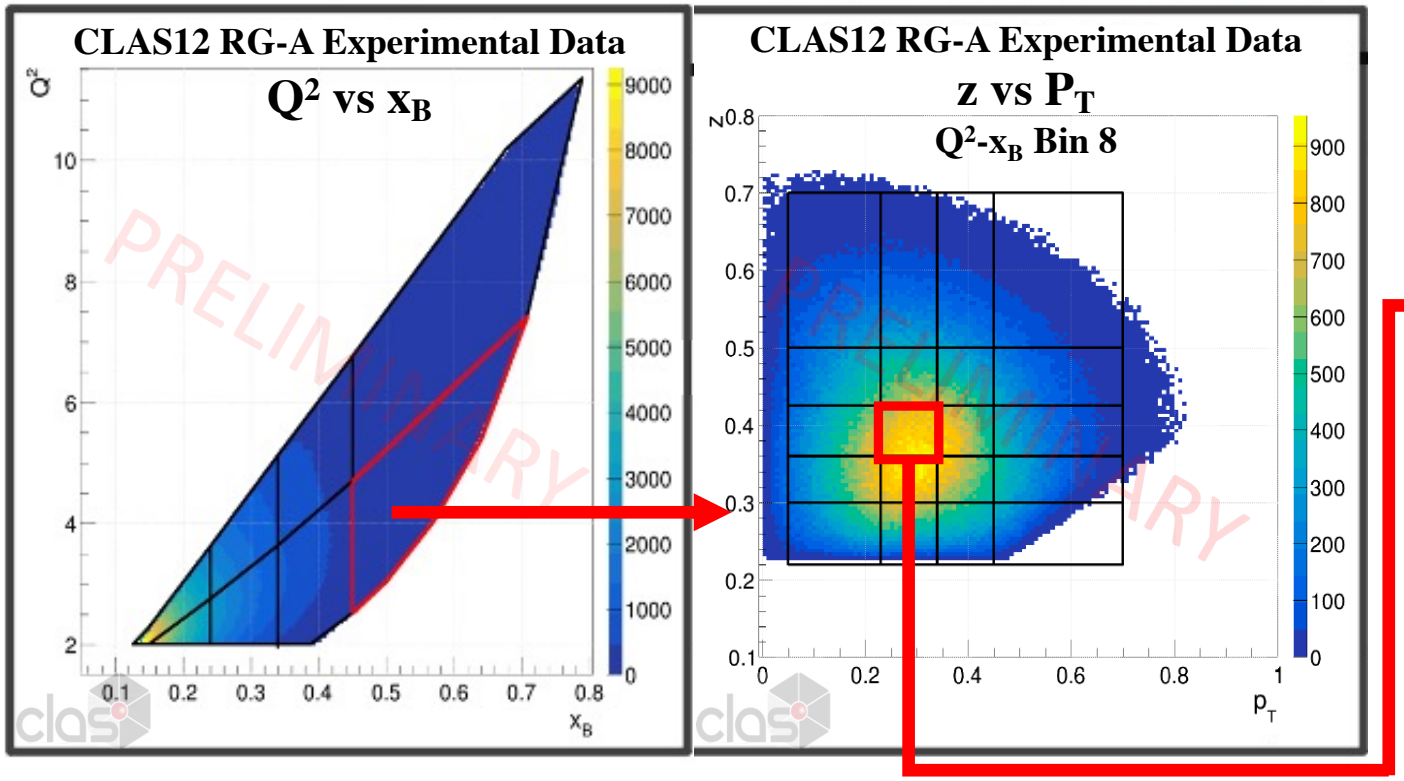
P_T Comparison

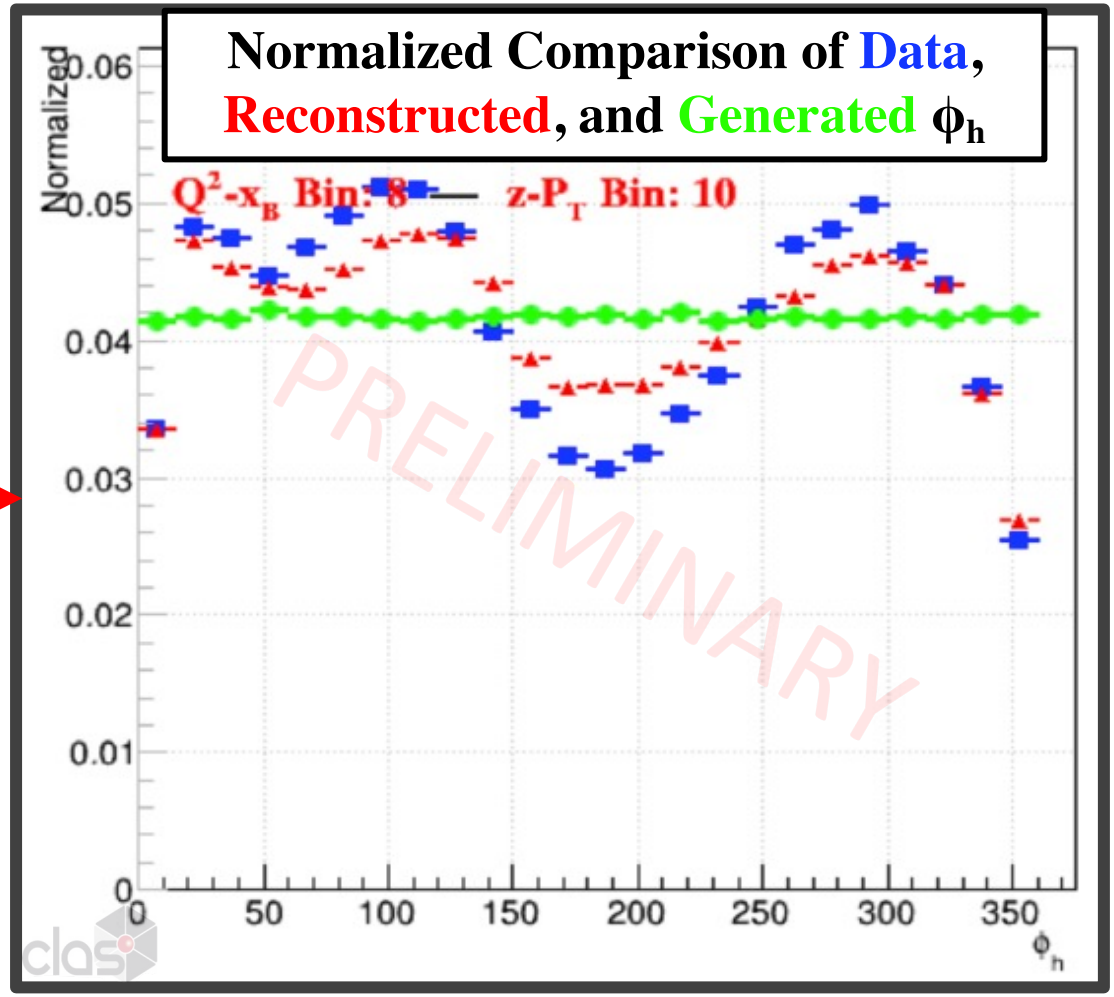
Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (5 Dimensions)

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

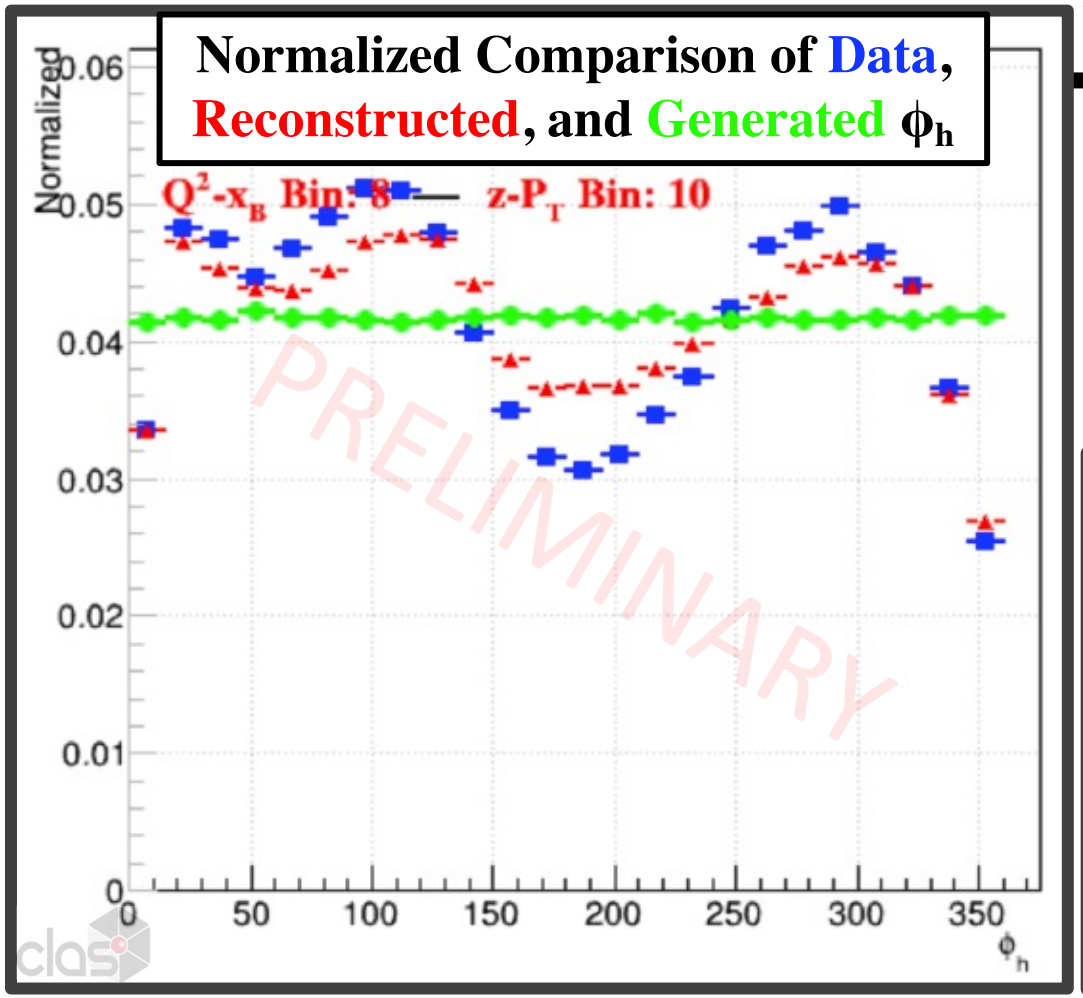
ϕ_h distribution for the Q^2-x_B-z-P_T bin shown in red





Unfolded Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (5 Dimensions)



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

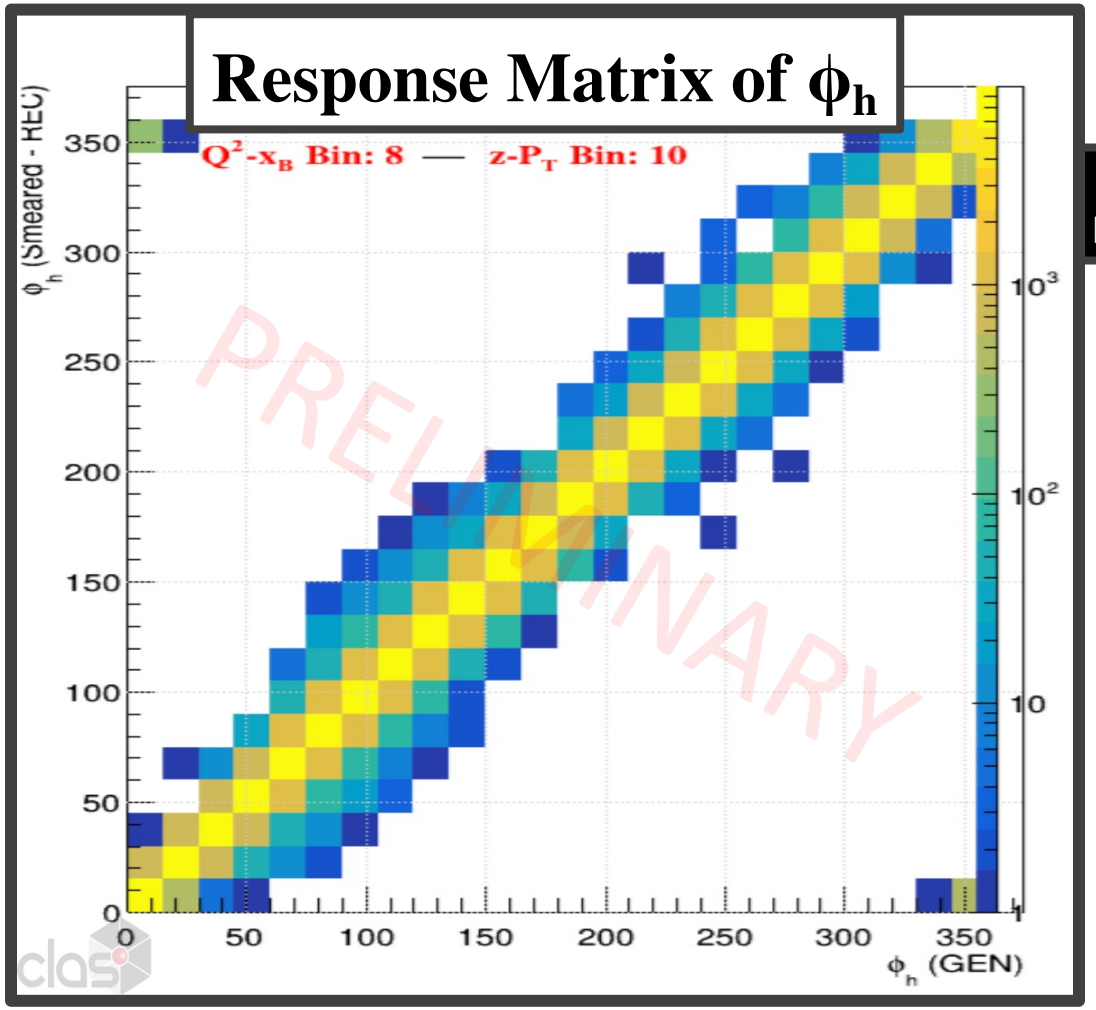
- **Acceptance Matrix:** $A_{(i,\,j)}$ describes both Acceptance (including geometric acceptance and detector efficiency) and Bin Migration
- $$A_{(i,\,j)} = \frac{\text{Number of Events Generated in bin } j \text{ but Reconstructed in bin } i}{\text{Total Number of Events Generated in the } j\text{th bin}}$$
- Acceptance Unfolding: $Y_i = A_{(i,\,j)} X_j \Leftrightarrow X_j = A^{-1}_{(i,\,j)} Y_i$

where:

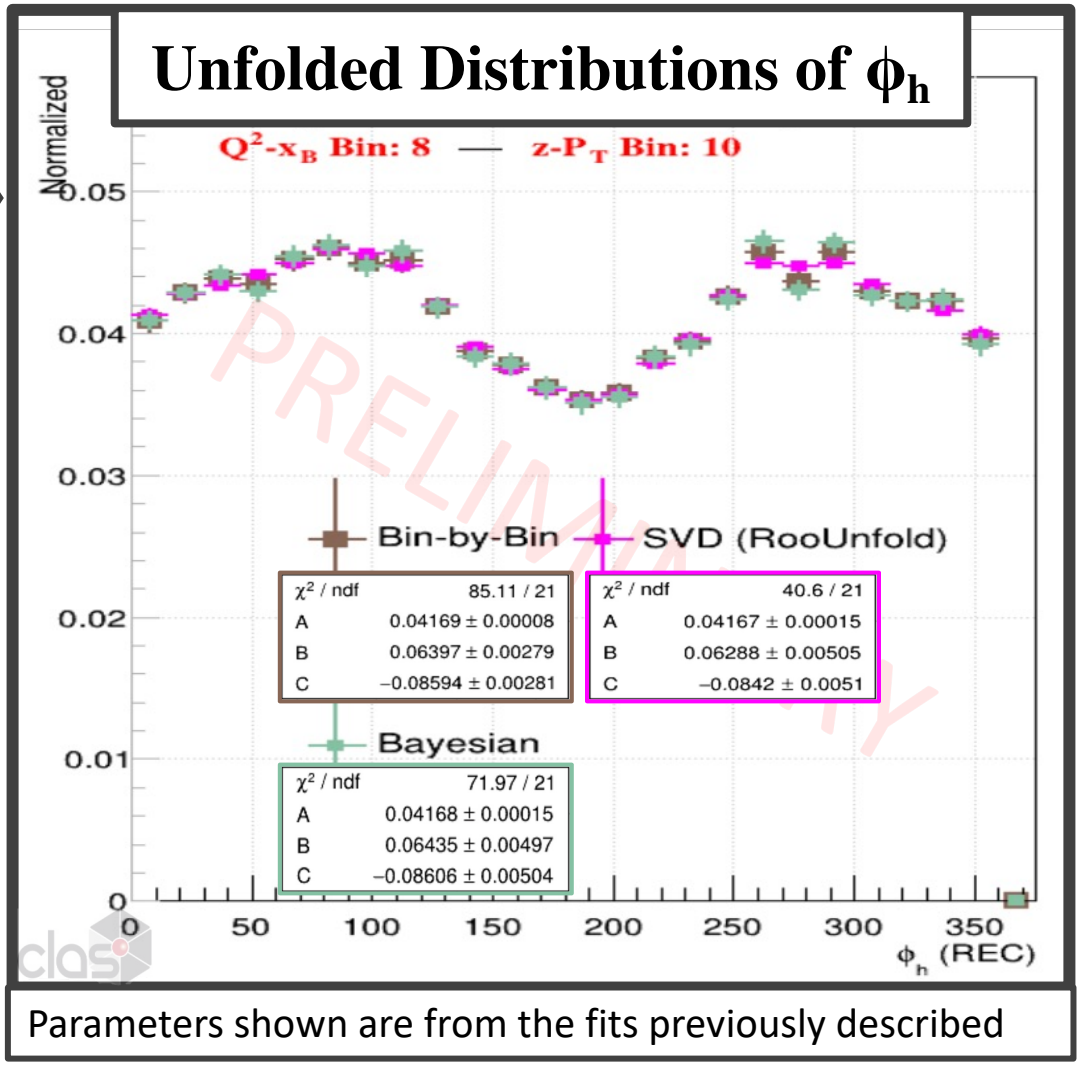
- Y_i = Number of events experimentally measured in the *i*-th bin
- X_j = Number of acceptance-corrected events in the *j*-th bin

Example of Unfolding Procedure

Using the Multidimensional Kinematic Bin from prior example



Unfolding Procedures



Parameters shown are from the fits previously described

Outlook

- Working on Multidimensional Acceptance Corrections for the simultaneous unfolding of Q^2, x_B, 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 analysis
- Long-term goals:
  - 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, x_B, z, and P_T for the π^+ for all CLAS12 RG-A data

Thank you

For more information and updates, see the following web page:

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

Questions?

Acknowledgements

- Contributions made by other members of the CLAS Collaboration
- 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

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)

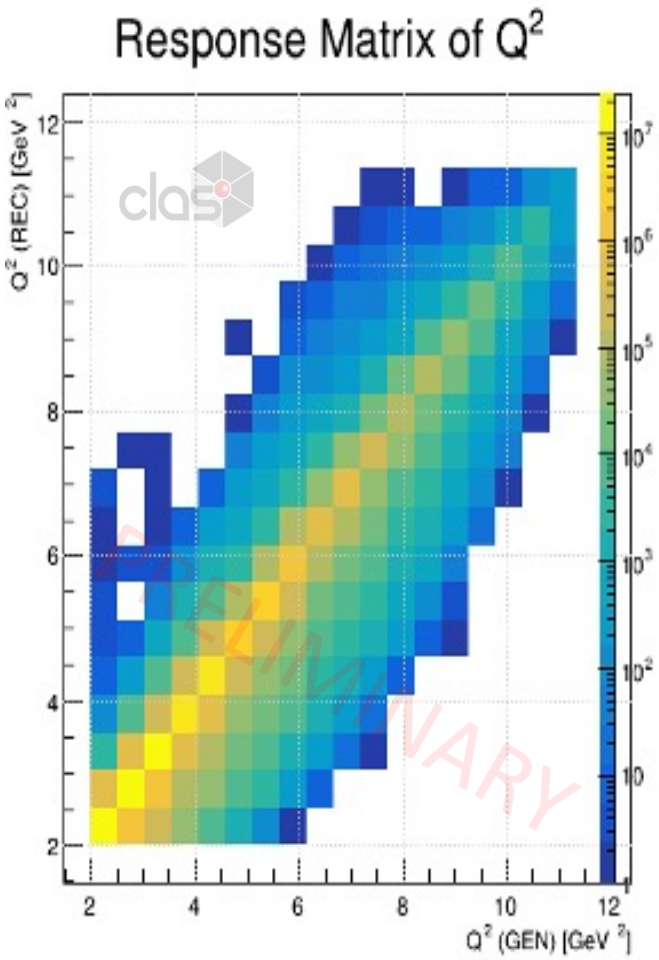
Electron PID Criteria:

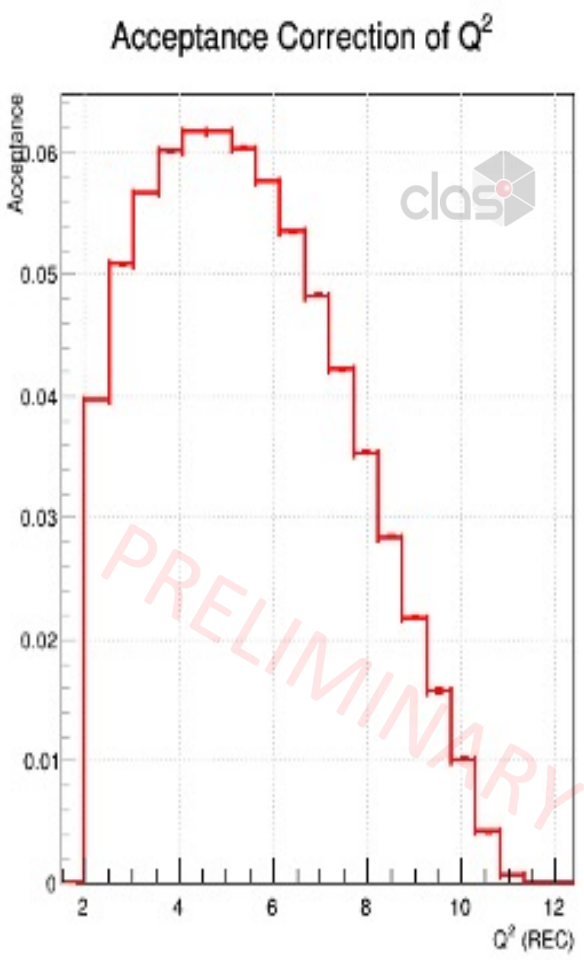
- Detected in Forward Detector
- > 2 photoelectrons detected in the HTCC
- > 0.07 GeV energy deposited in the PCAL
- Sector dependent sampling fraction cut
- "Diagonal cut" for electrons above 4.5 GeV (HTCC threshold)
- y < 0.75, not strictly an "electron cut", but sets the min electron energy approximately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

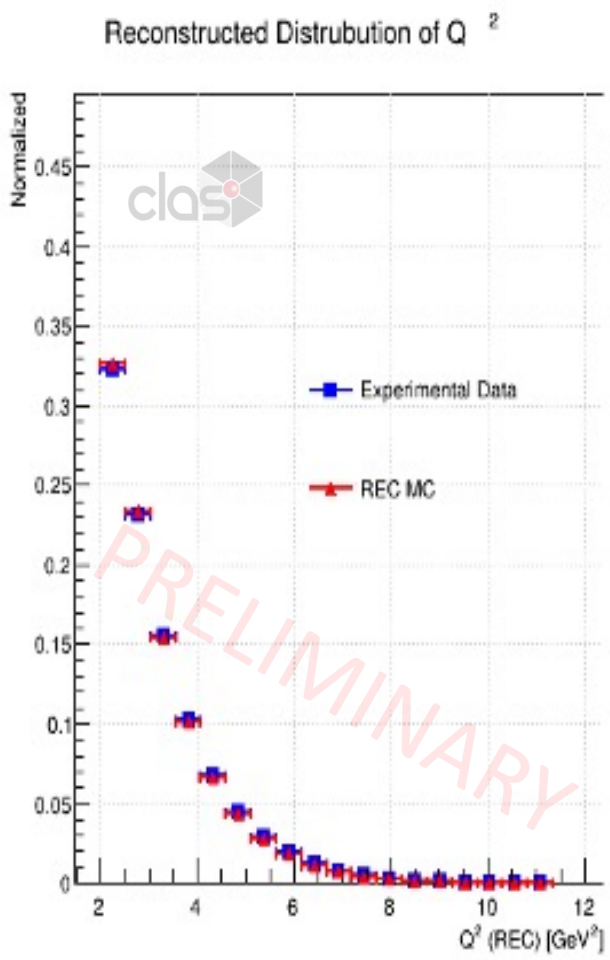
Pion PID Criteria:

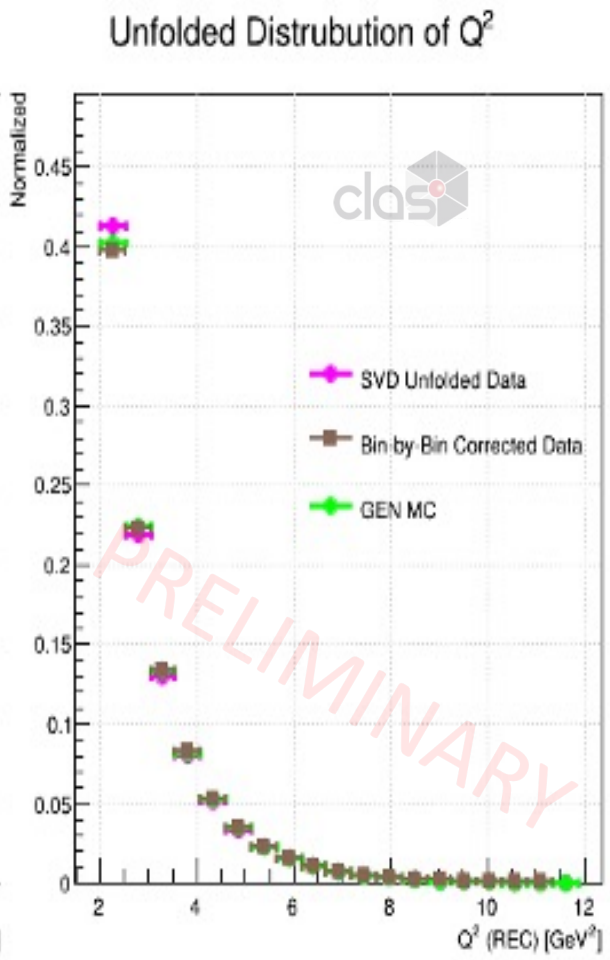
- Detected in Forward Detector
- p > 1.25 GeV
- Refined chi2pid cuts

Example of Unfolding (Q^2)

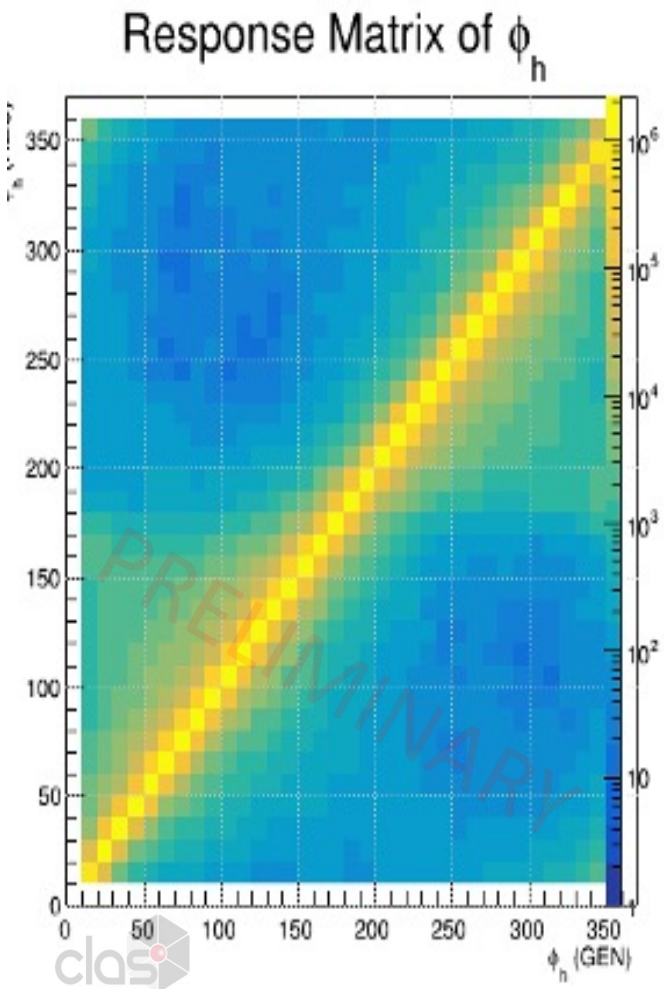


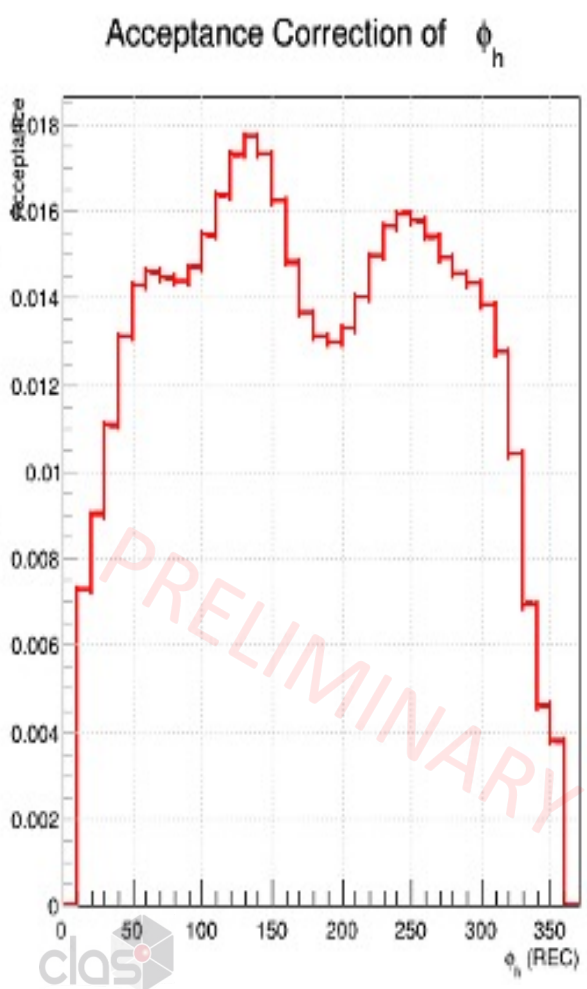


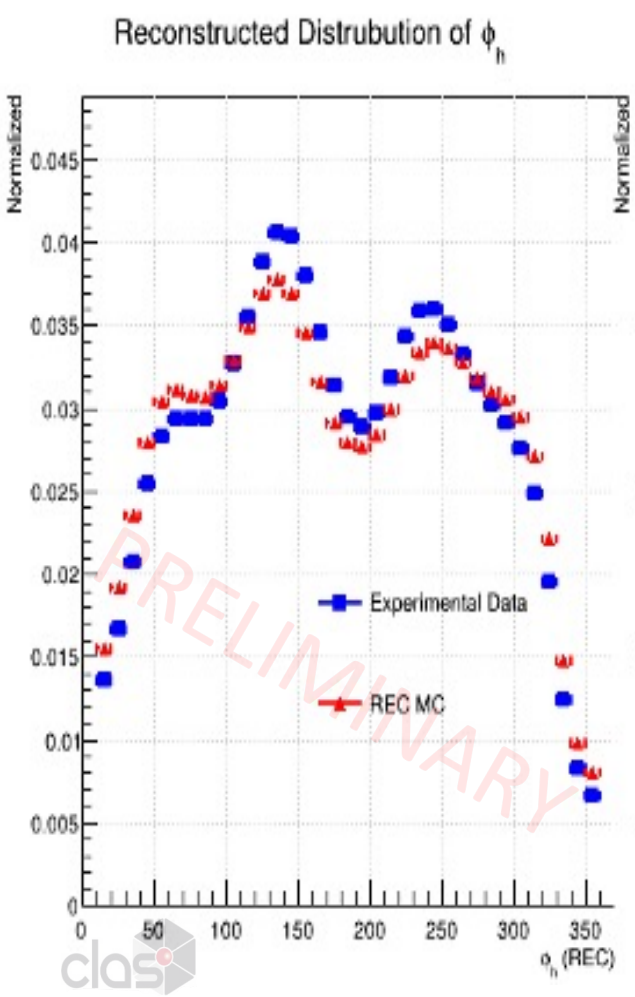


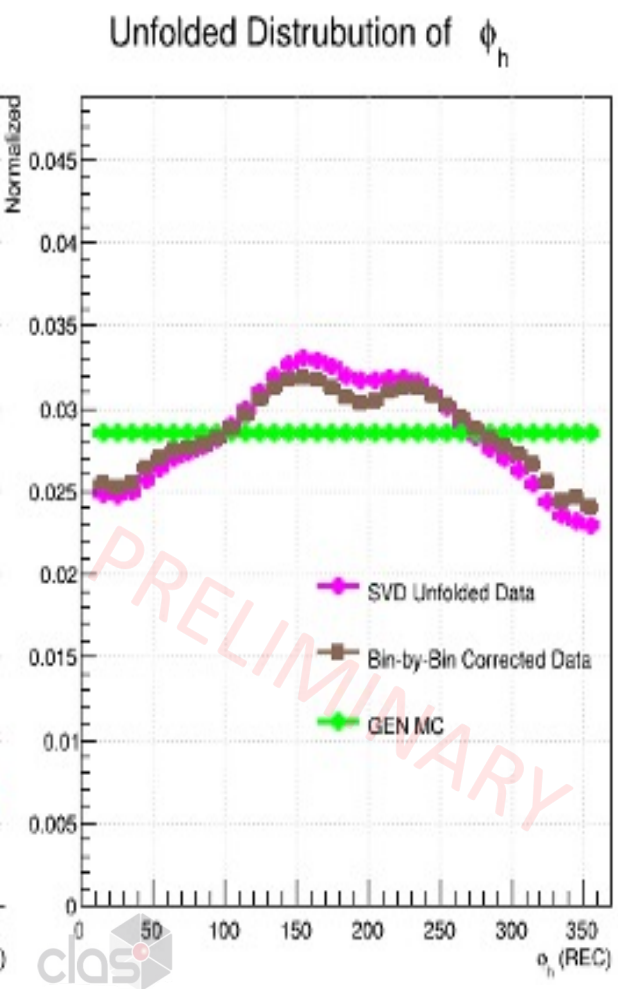


Example of Unfolding (ϕ_h)





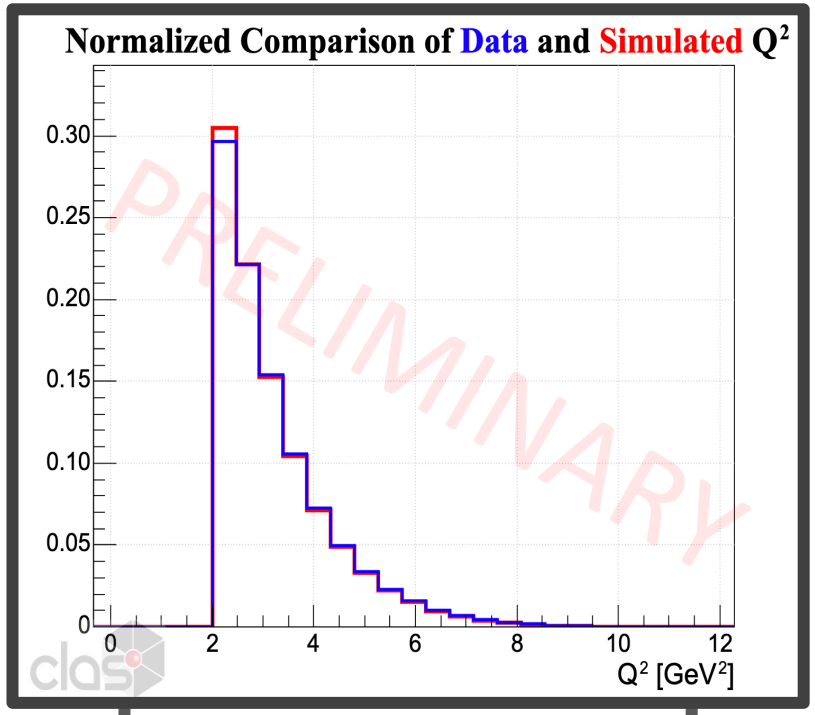




Kinematic Binning and Data-MC Comparison

Other Comparisons

All Events



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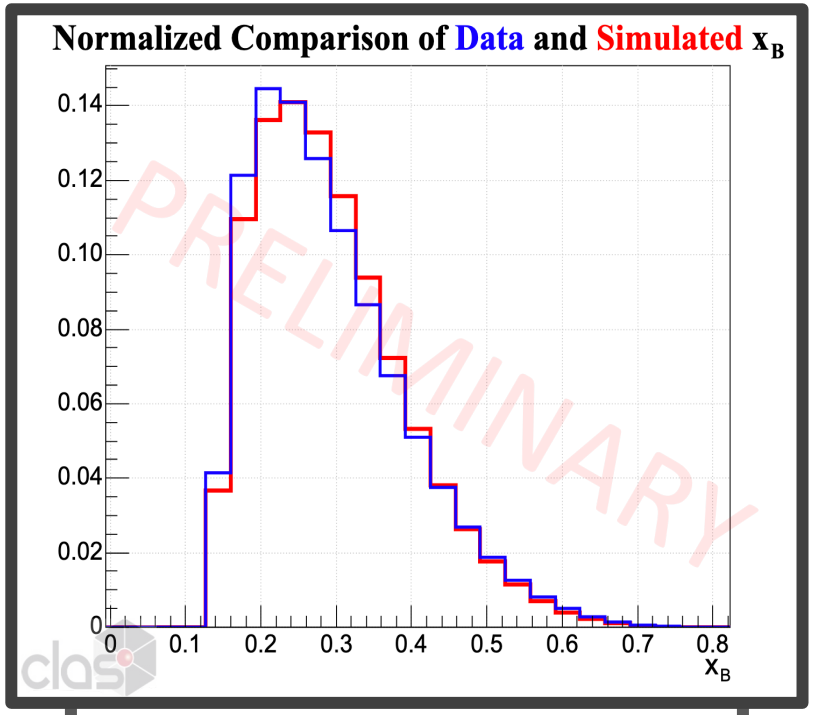

x_B Comparison

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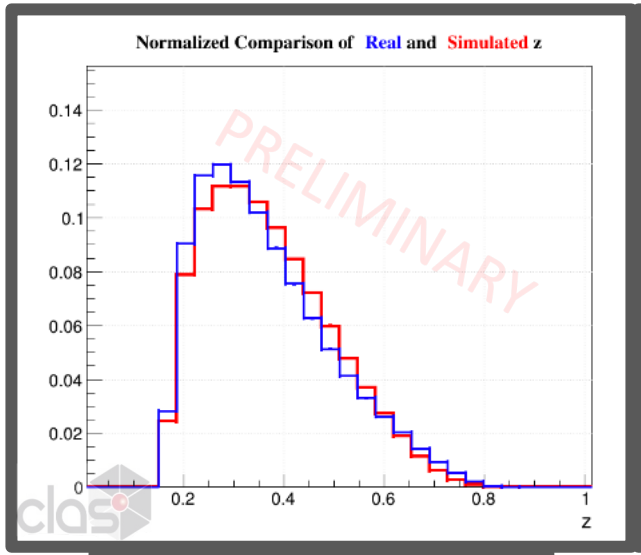
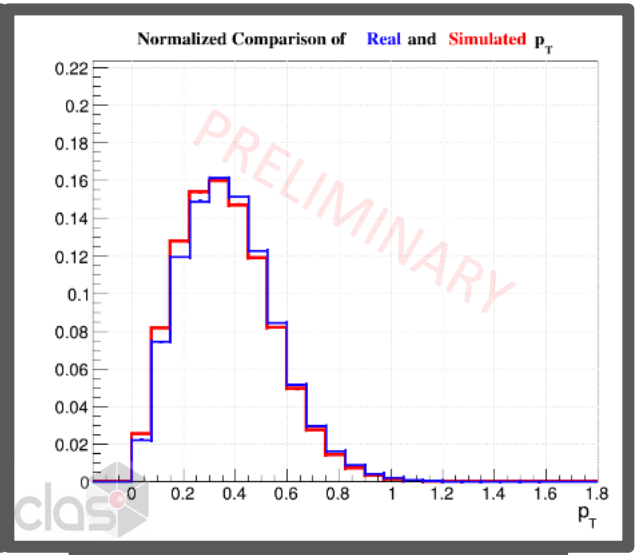
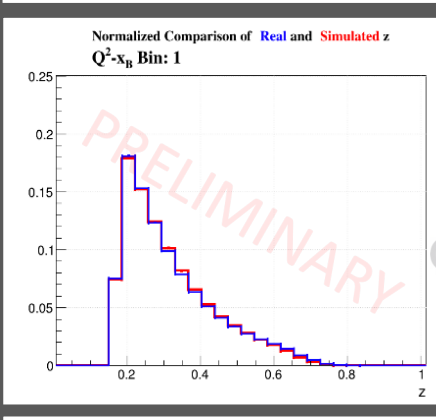
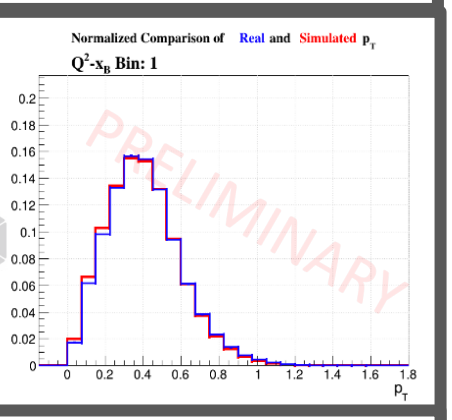
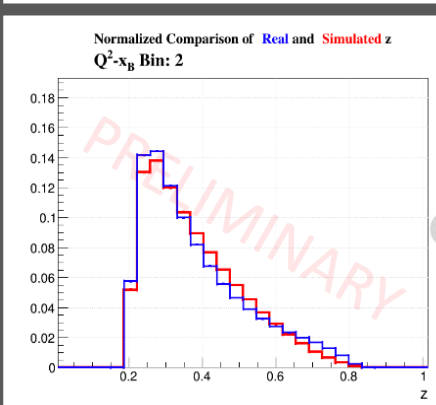
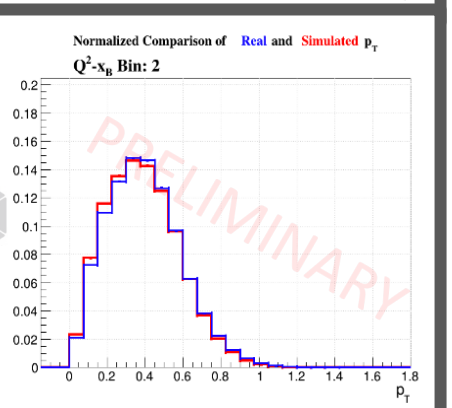


z Comparison



P_T Comparison

	z Comparison	P_T Comparison
Q^2-x_B Bin 1		
Q^2-x_B Bin 2		

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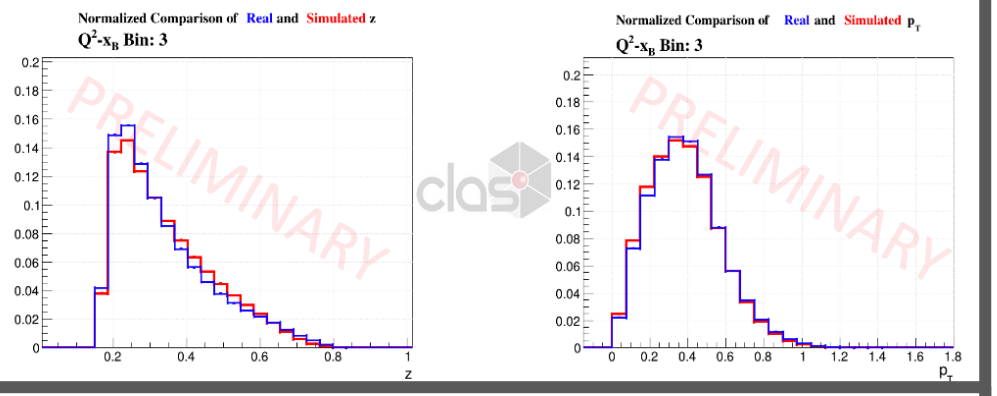
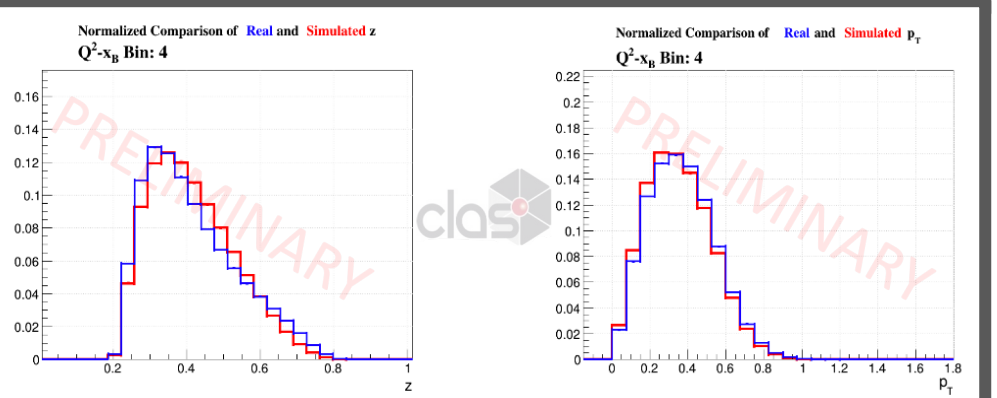
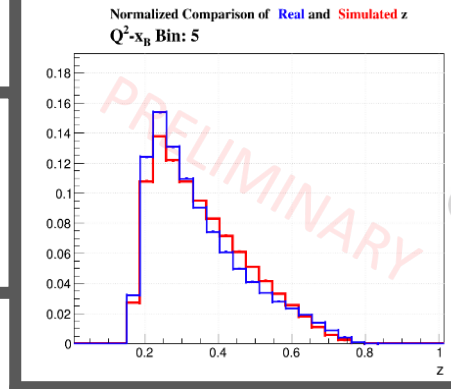
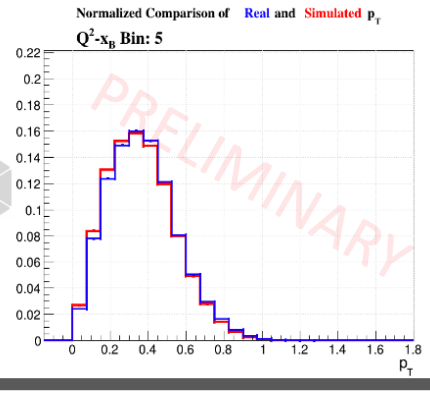
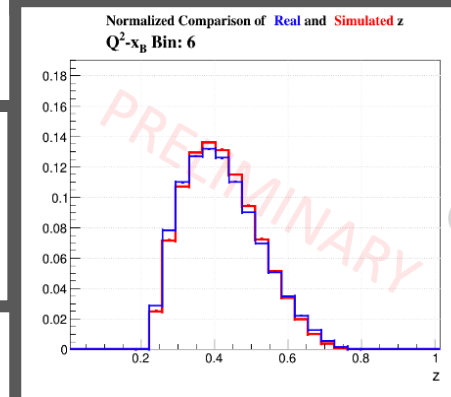
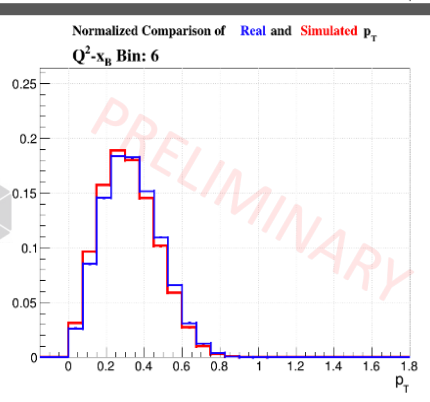
Other Comparisons

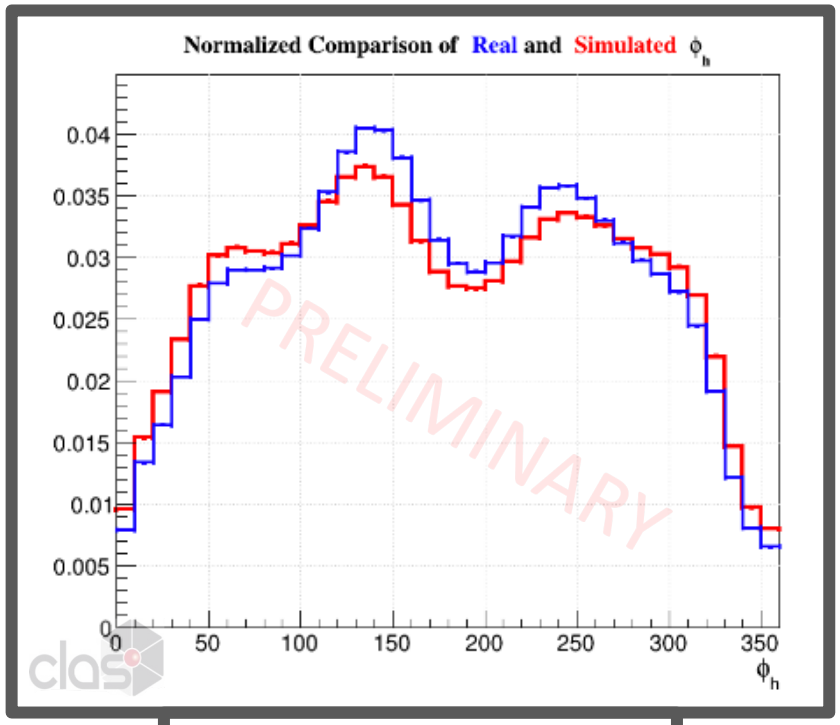
	z Comparison	P_T Comparison
Q^2-x_B Bin 3		
Q^2-x_B Bin 4		

	z Comparison	P_T Comparison
Q^2-x_B Bin 5		
Q^2-x_B Bin 6		

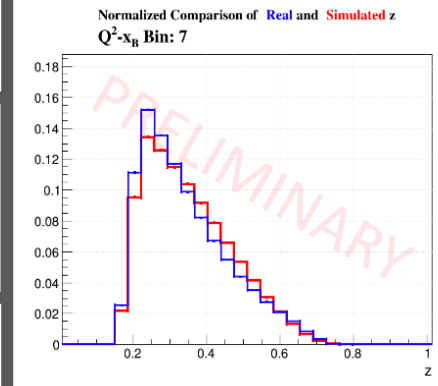
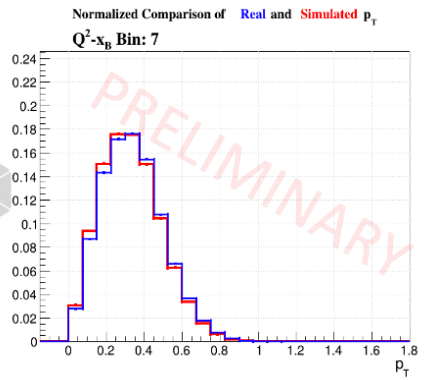
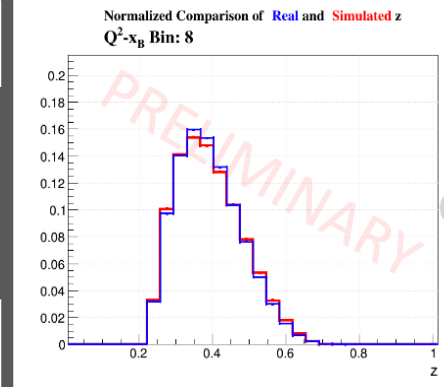
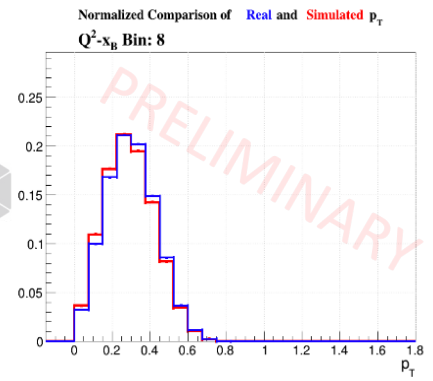
Kinematic Binning and Data-MC Comparison

Other Comparisons

All Events



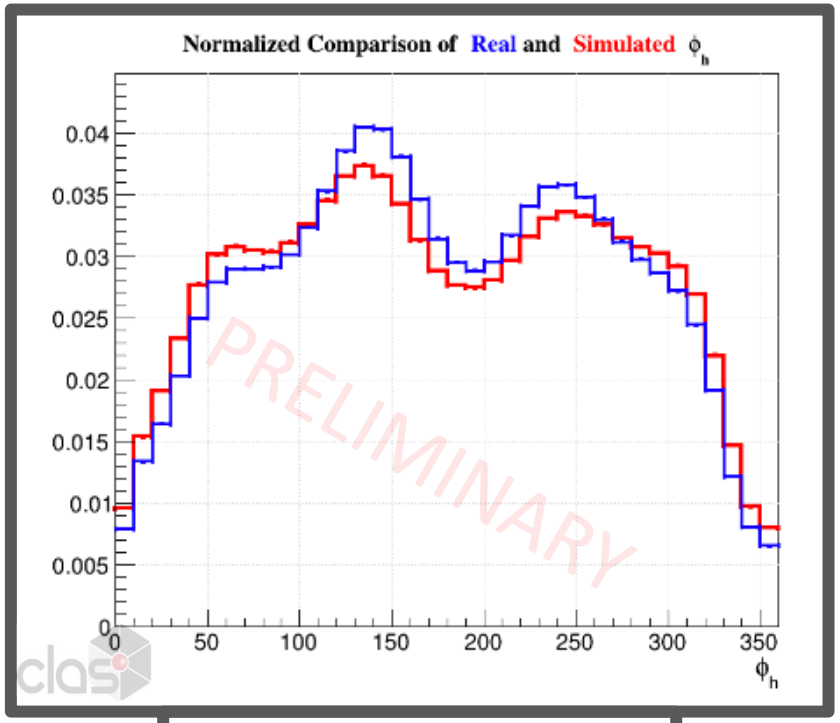
ϕ_h Comparison

	z Comparison	P_T Comparison
Q^2-x_B Bin 7		
Q^2-x_B Bin 8		

Kinematic Binning and Data-MC Comparison

Other Comparison

All Events



ϕ_h Comparison

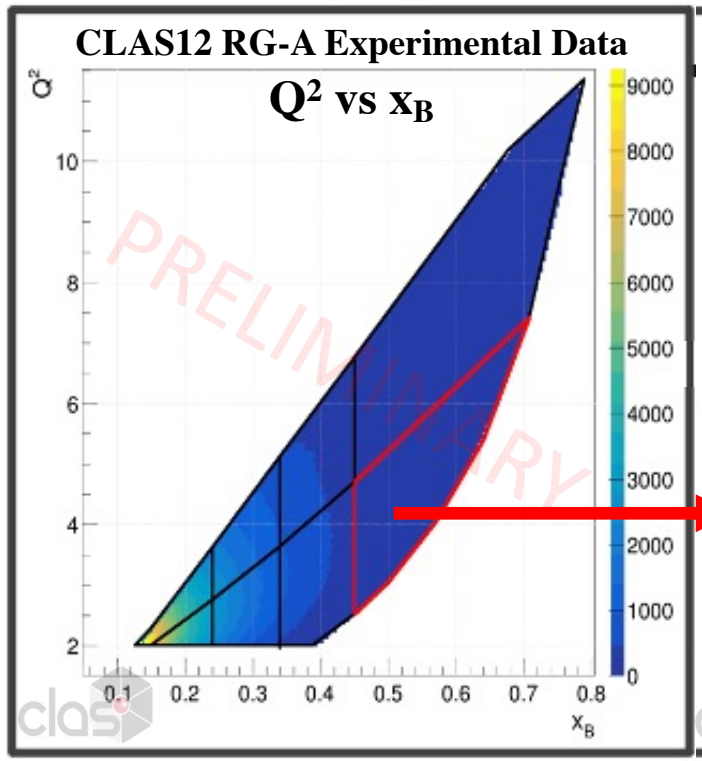
- Some differences between the ϕ_h distributions are expected
- **Reason:** The Monte Carlo Simulation is not initialized with any ϕ_h modulations yet
  - i.e., the ϕ_h distribution is completely flat before reconstruction
- Initial calculations of the cosϕ and cos2ϕ moments will be used to 'update' the simulation in an iterative fashion

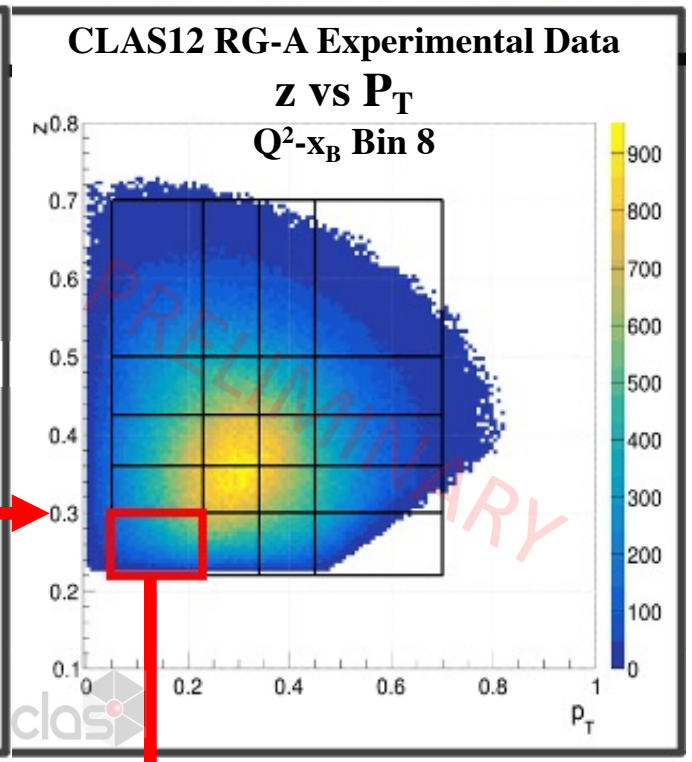
Multidimensional Analysis Procedures

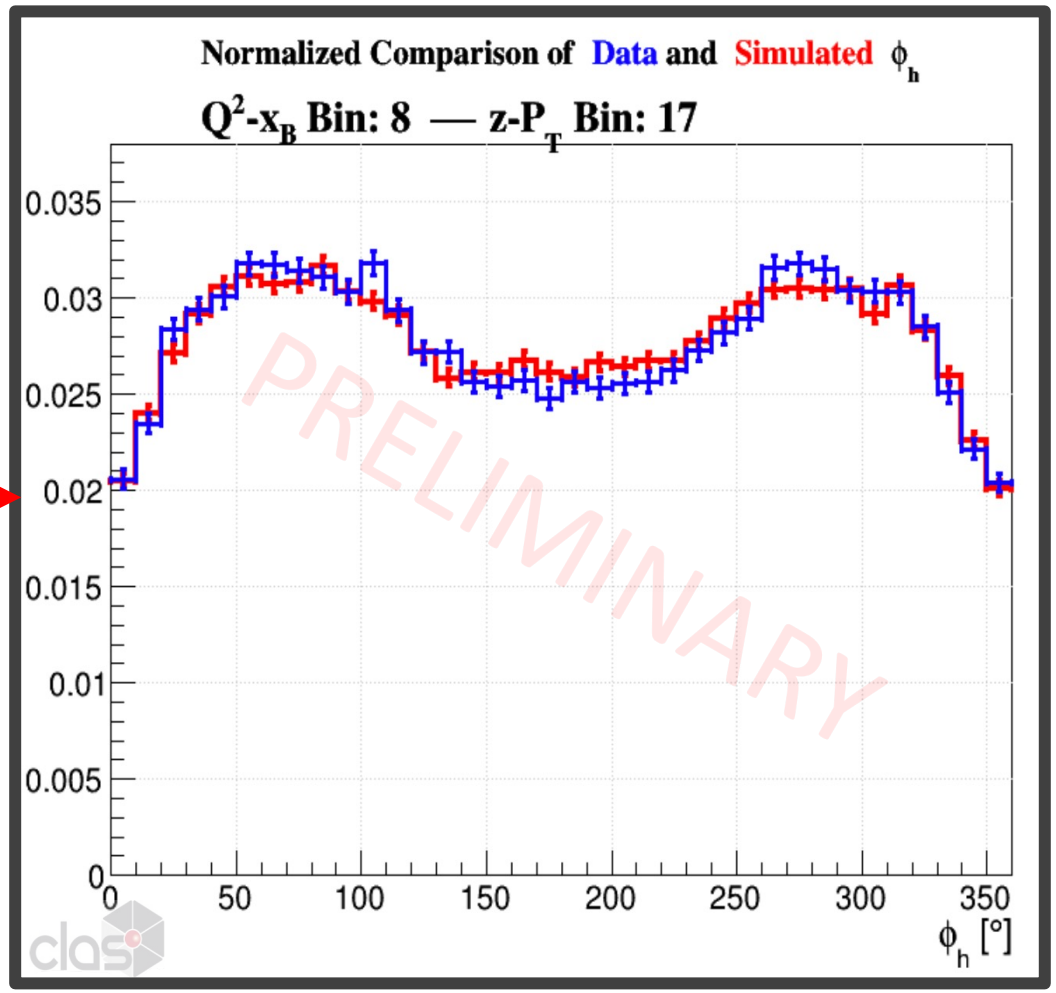
Multidimensional Kinematic Binning (5 Dimensions)

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

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







EXTRA EXAMPLE