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

Richard Capobianco

University of Connecticut

Presentation for the APS meetings

LinkedIn

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

Motivation

- Semi-Inclusive Deep Inelastic Scattering (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:

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

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

leading twist

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

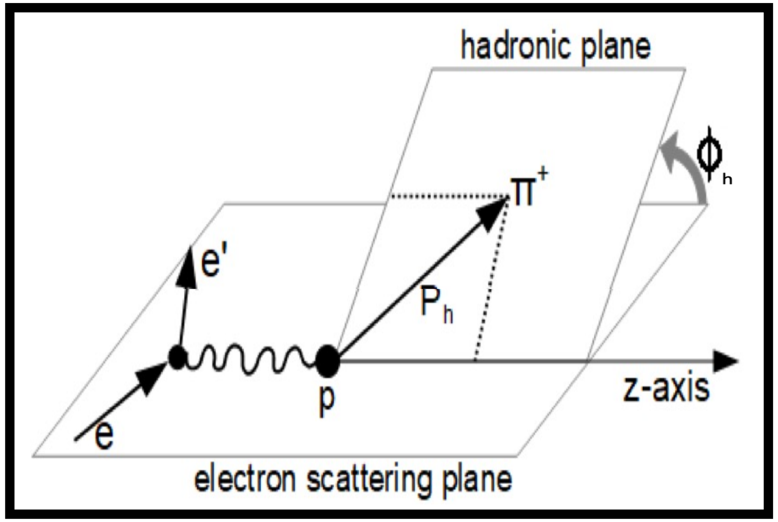
next to leading twist

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

BOER-MULDERS EFFECT

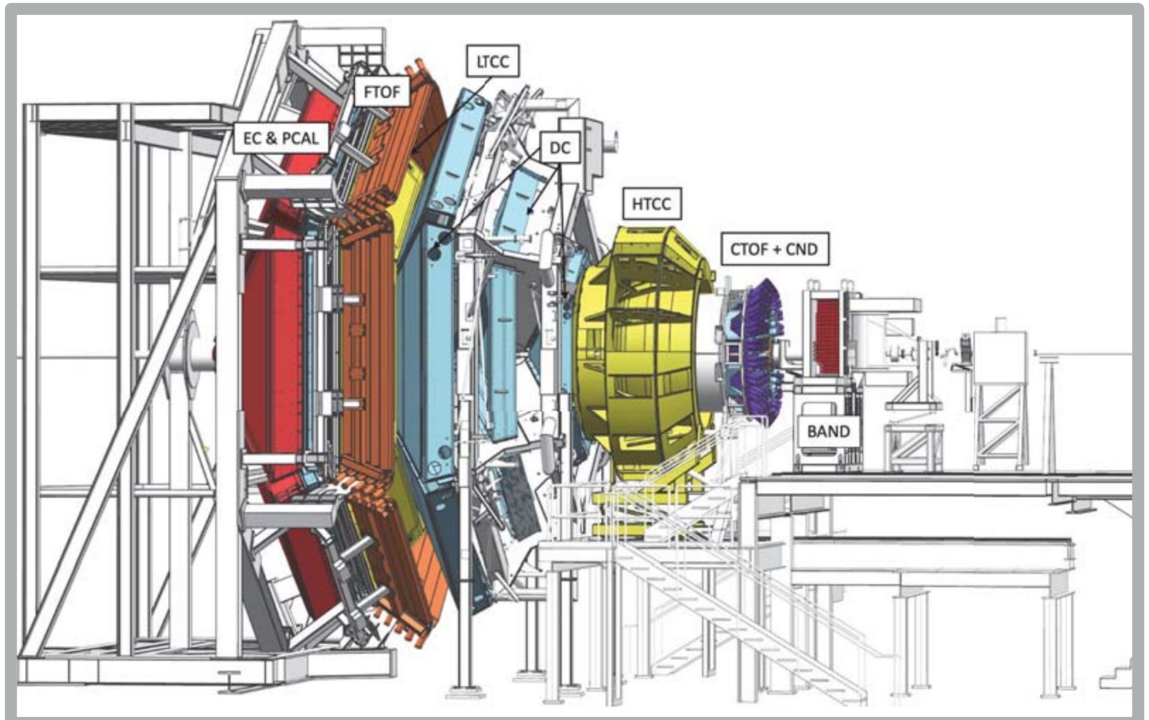
CAHN EFFECT

Interaction dependent terms neglected



Reaction Studied: ep→eπ⁺(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

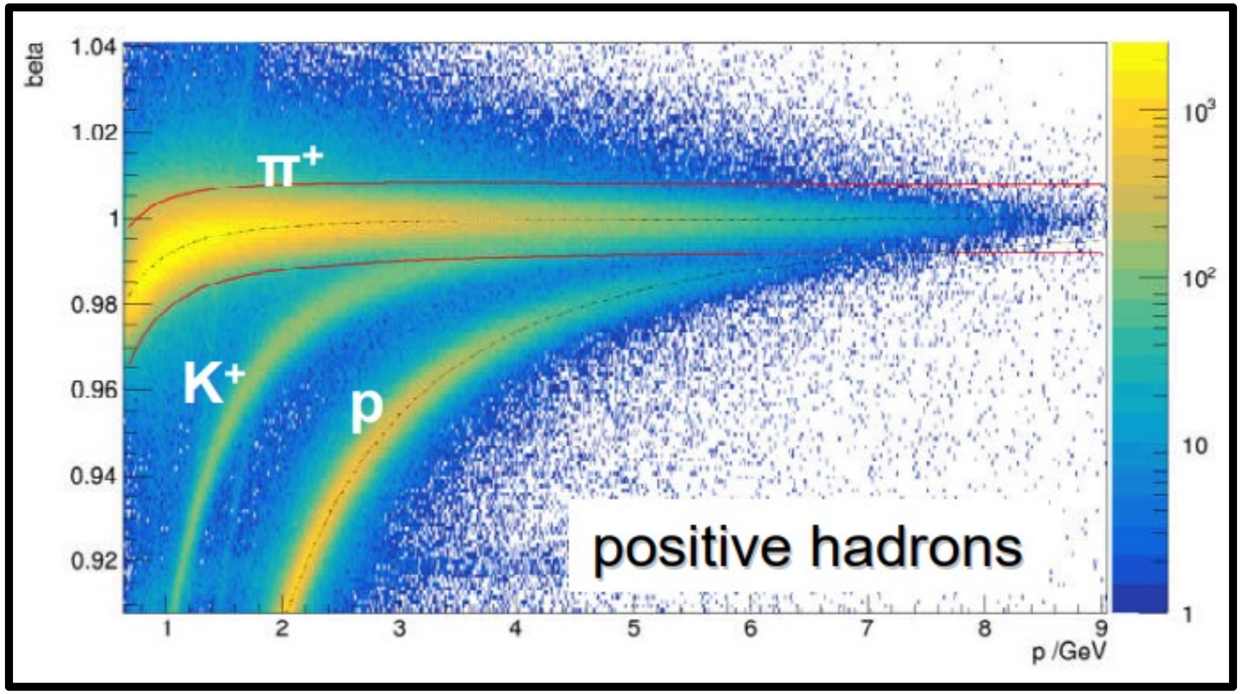


*Image provided by Stefan Diehl

π^+ Pion PID – ß vs p

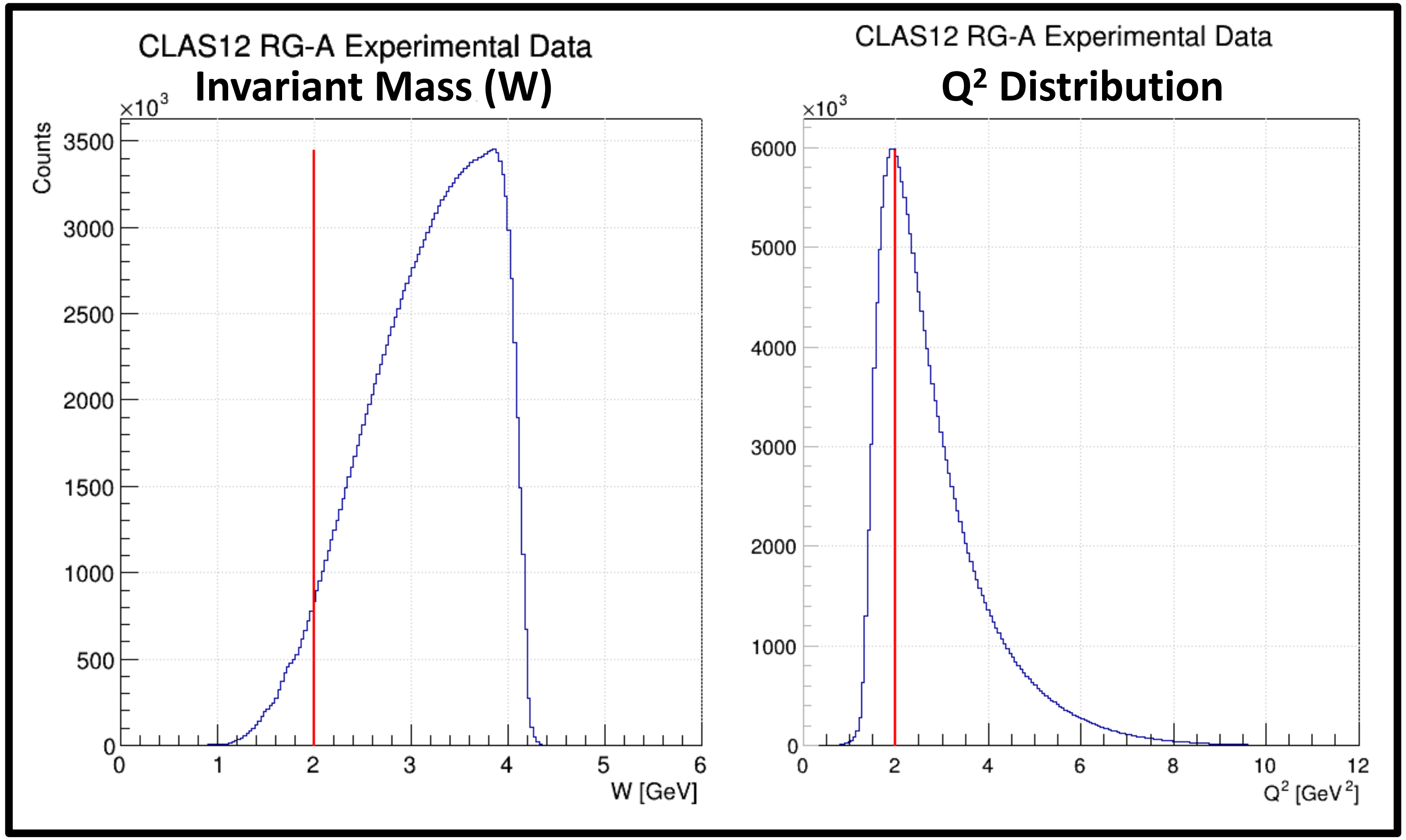
Event Selection

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

Analysis Cuts:

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



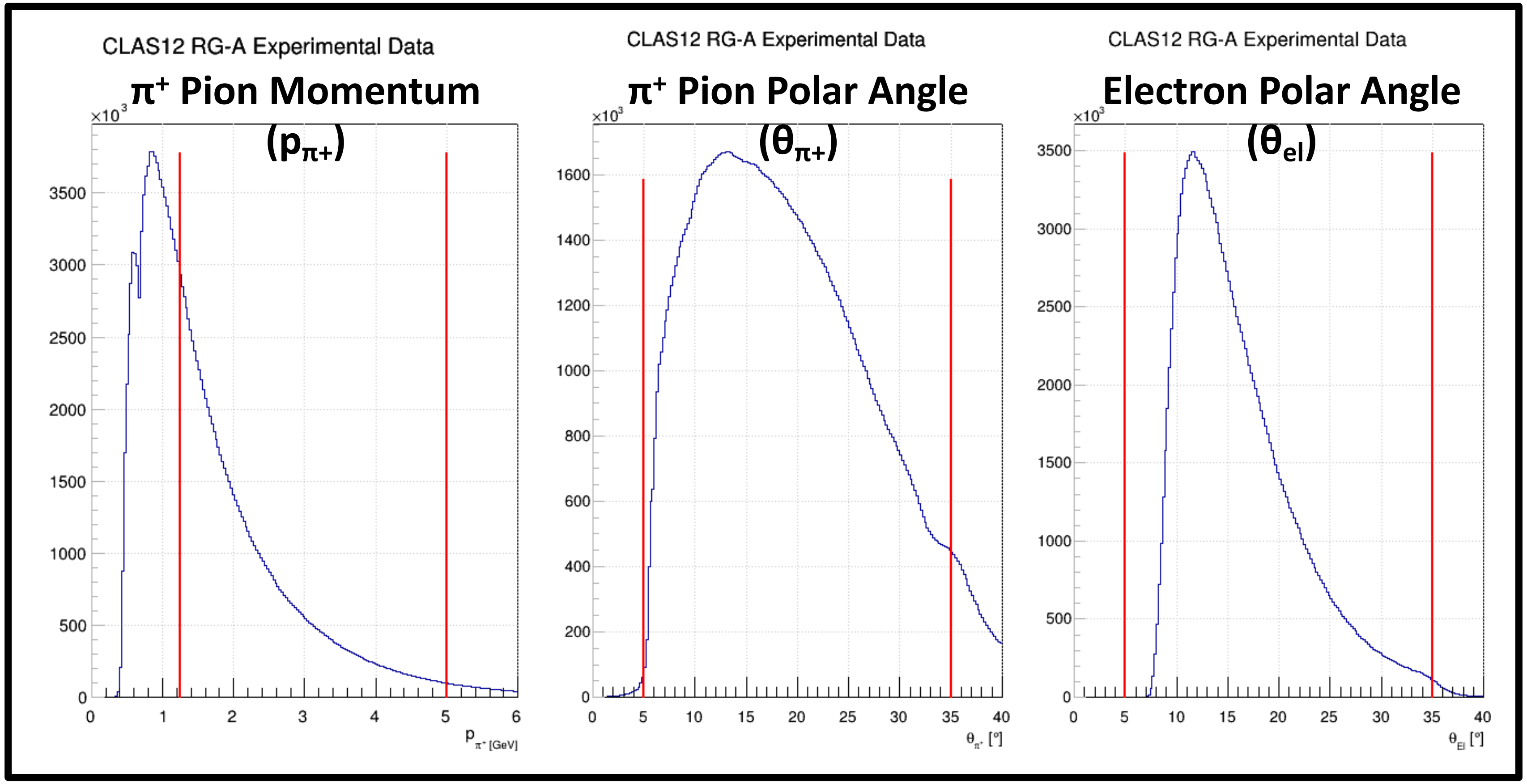
Event Selection

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

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: $5° < \theta_{particle} < 35°$



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

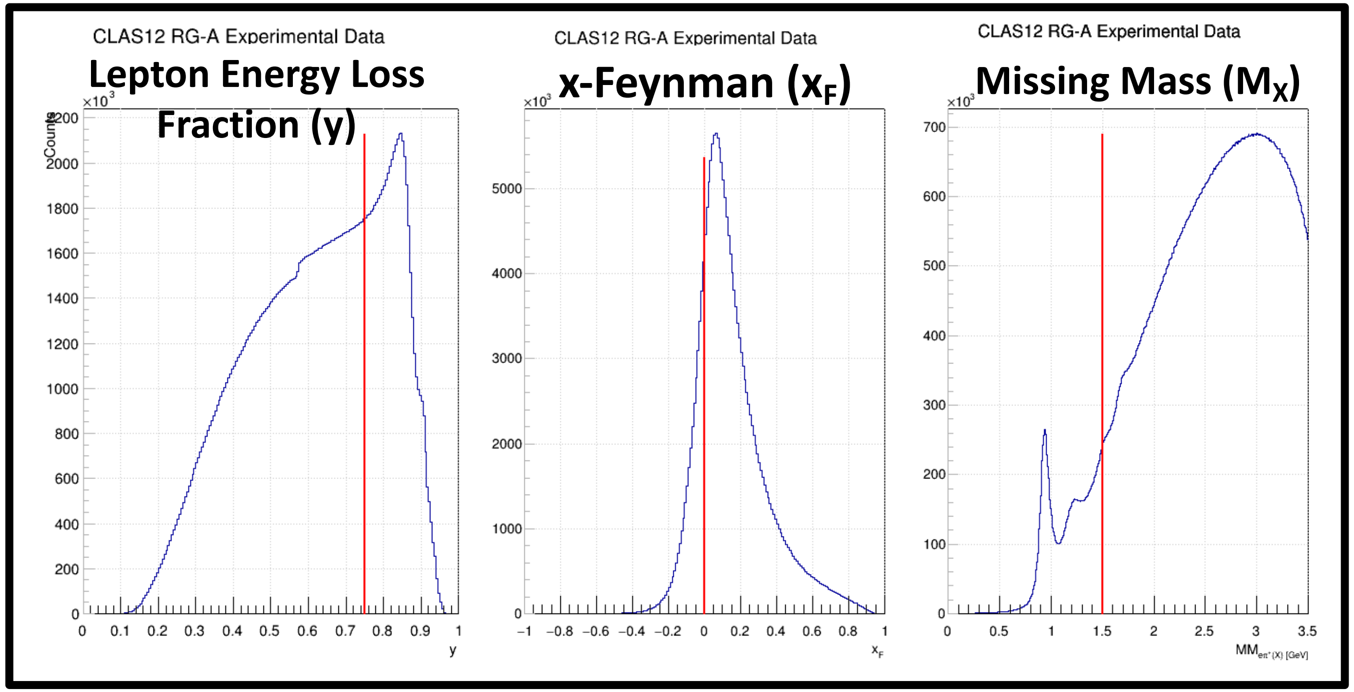
Event Selection

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

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 (limits contributions from exclusive events)



Event Selection

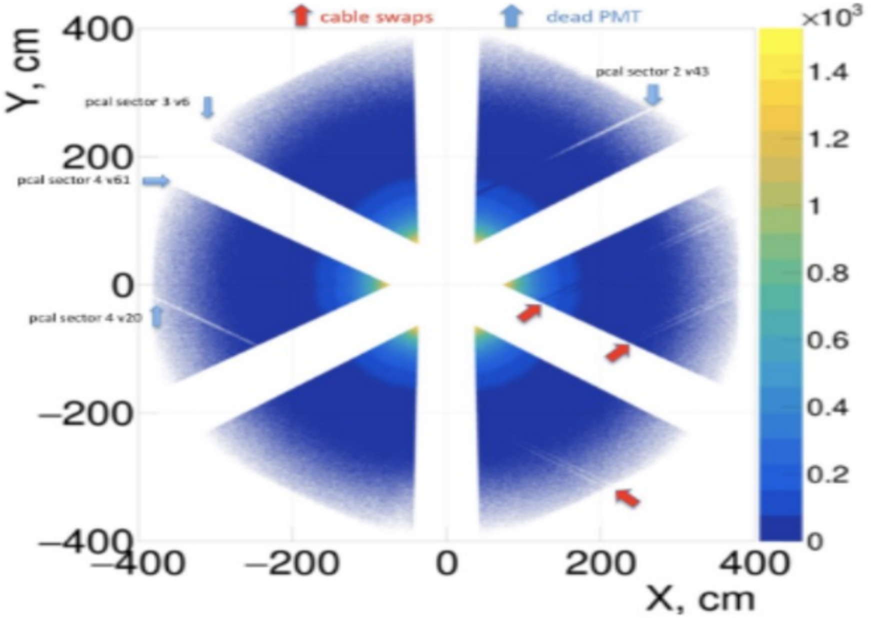
Particle ID (PID):

- **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

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 (limits contributions from exclusive events)
  - Fiducial Cuts (e.g., accounts for bad channels present in data)

CLAS12 RG-A Experimental Data
PCAL



Analysis Procedure

Experimental extraction of cross-section

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

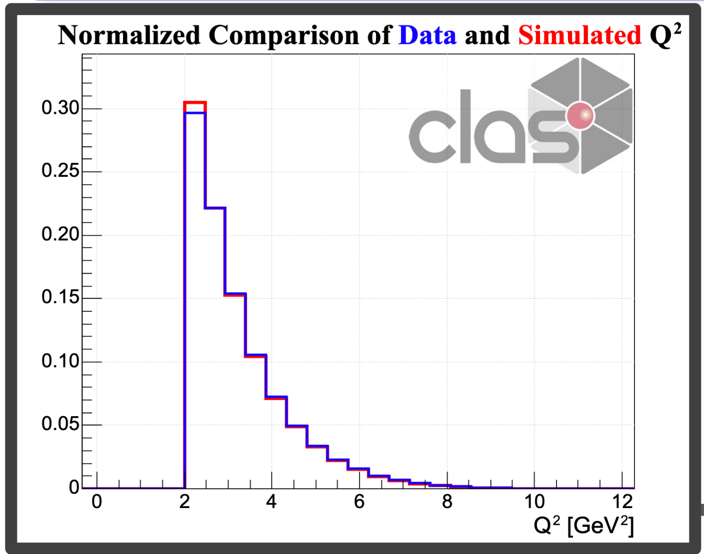
Where:

- 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

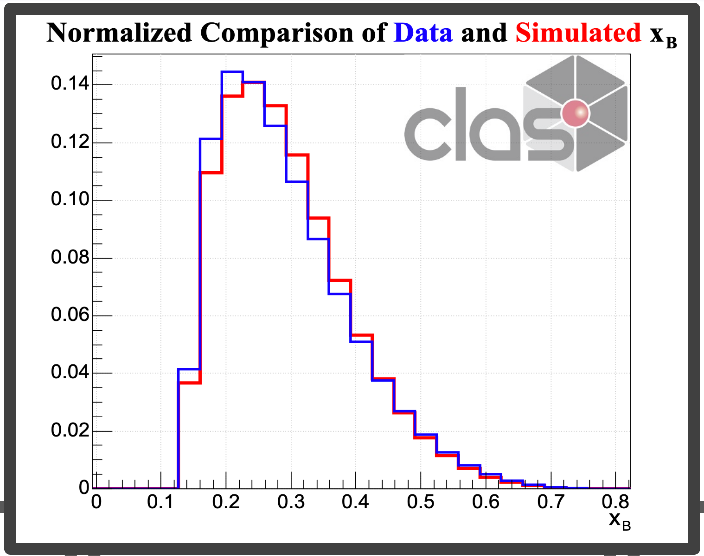
↓

SIDIS MC are generated with LEPTO event generator

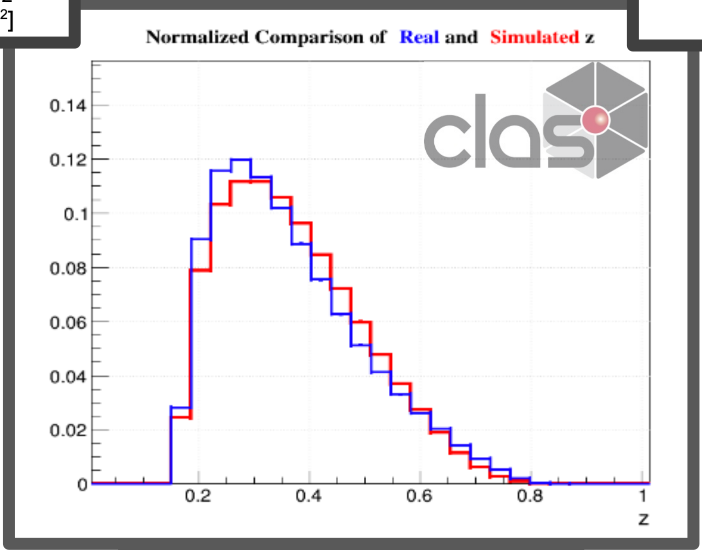
Data and Monte Carlo Comparison



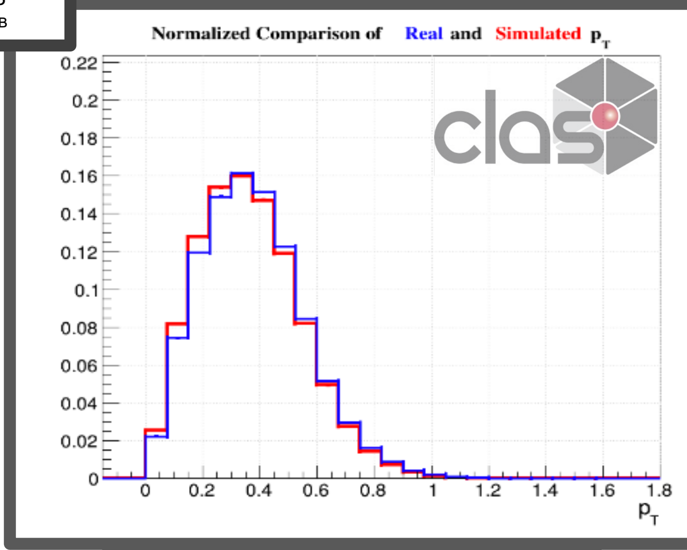
Q^2 Comparison



x_B Comparison



z Comparison



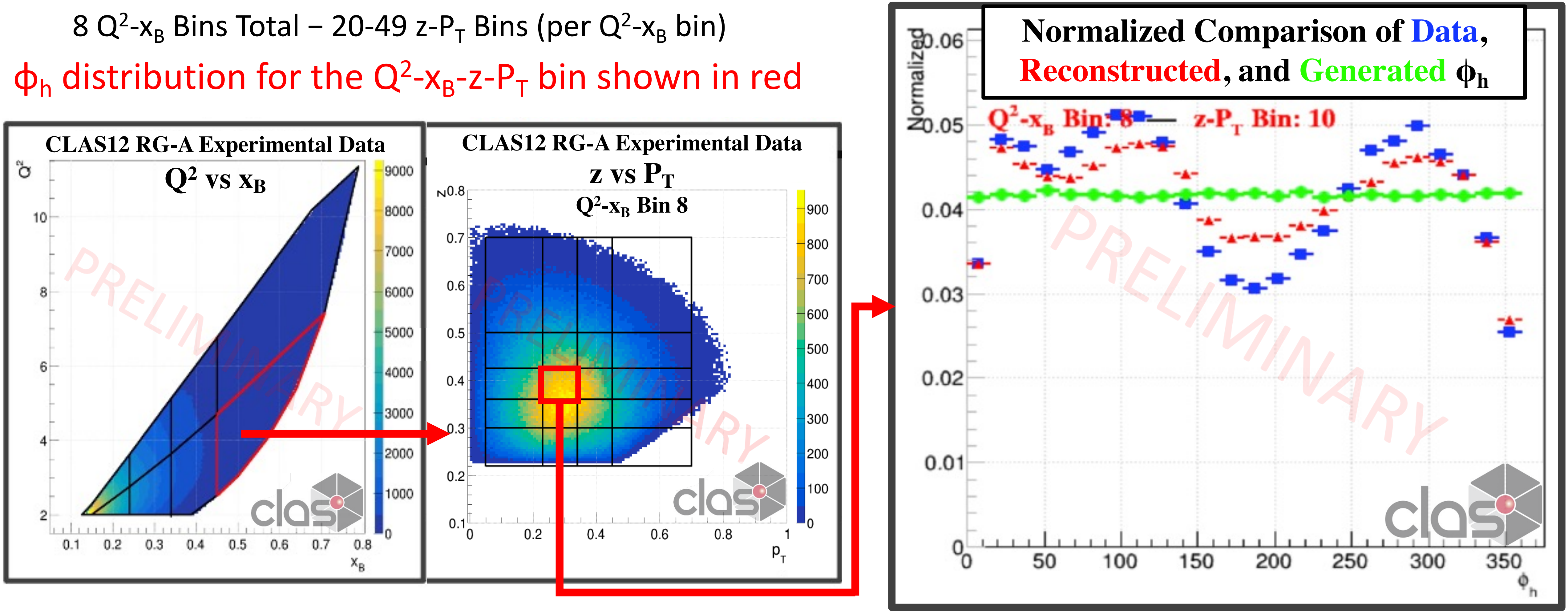
P_T Comparison

Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (5 Dimensions)

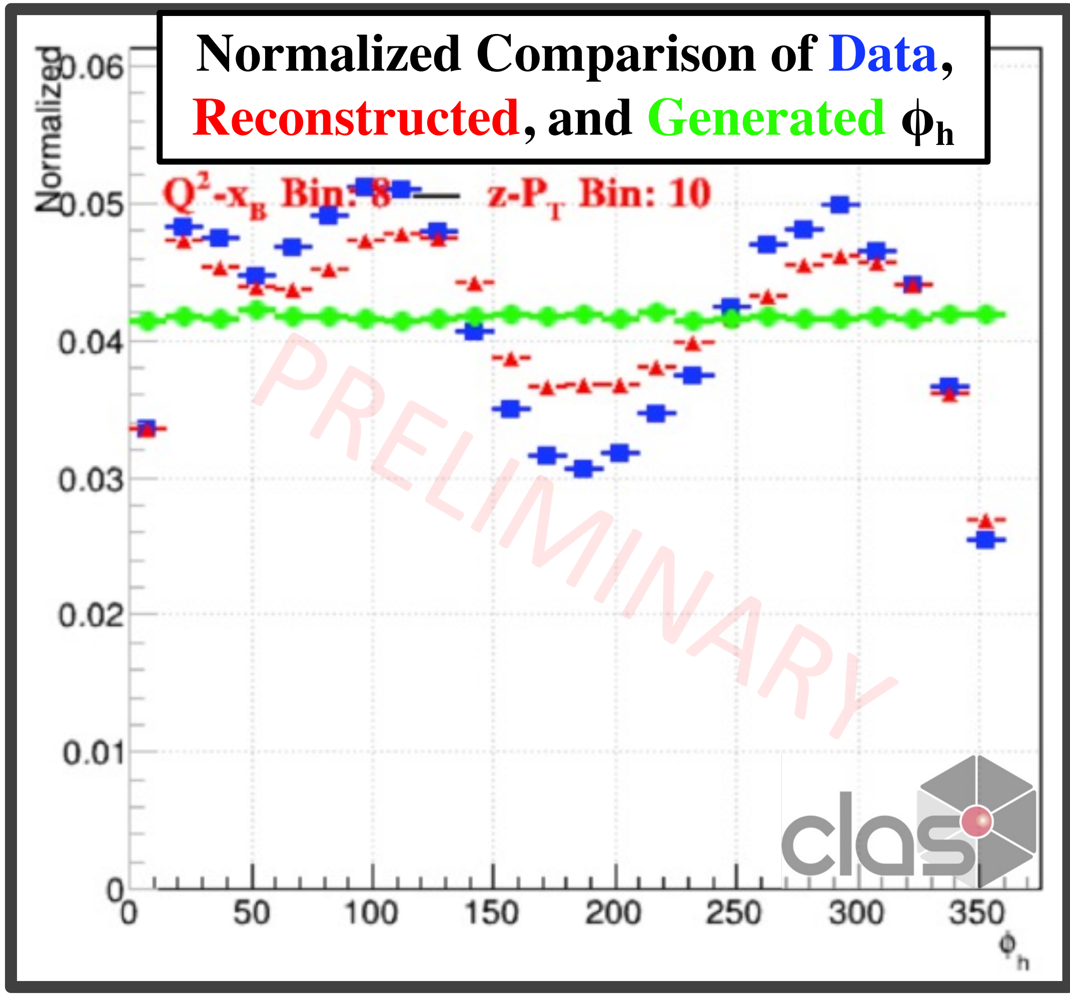
8 Q^2-x_B Bins Total – 20-49 z-P_T Bins (per Q^2-x_B bin)

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



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

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

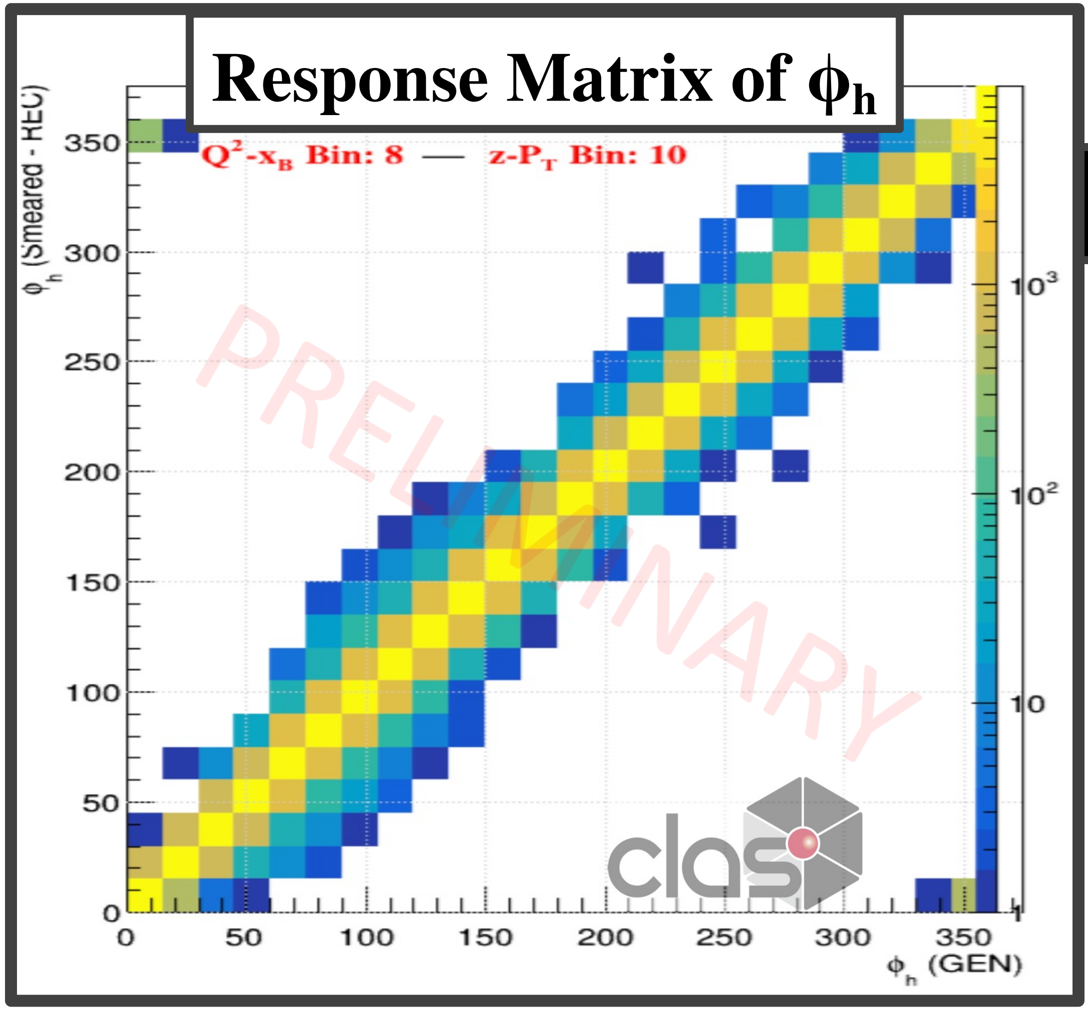
- Acceptance Unfolding: $Y_i = A_{(i,\,j)} X_j \Leftrightarrow X_j = A^{-1}_{(i,\,j)} Y_i$

where:

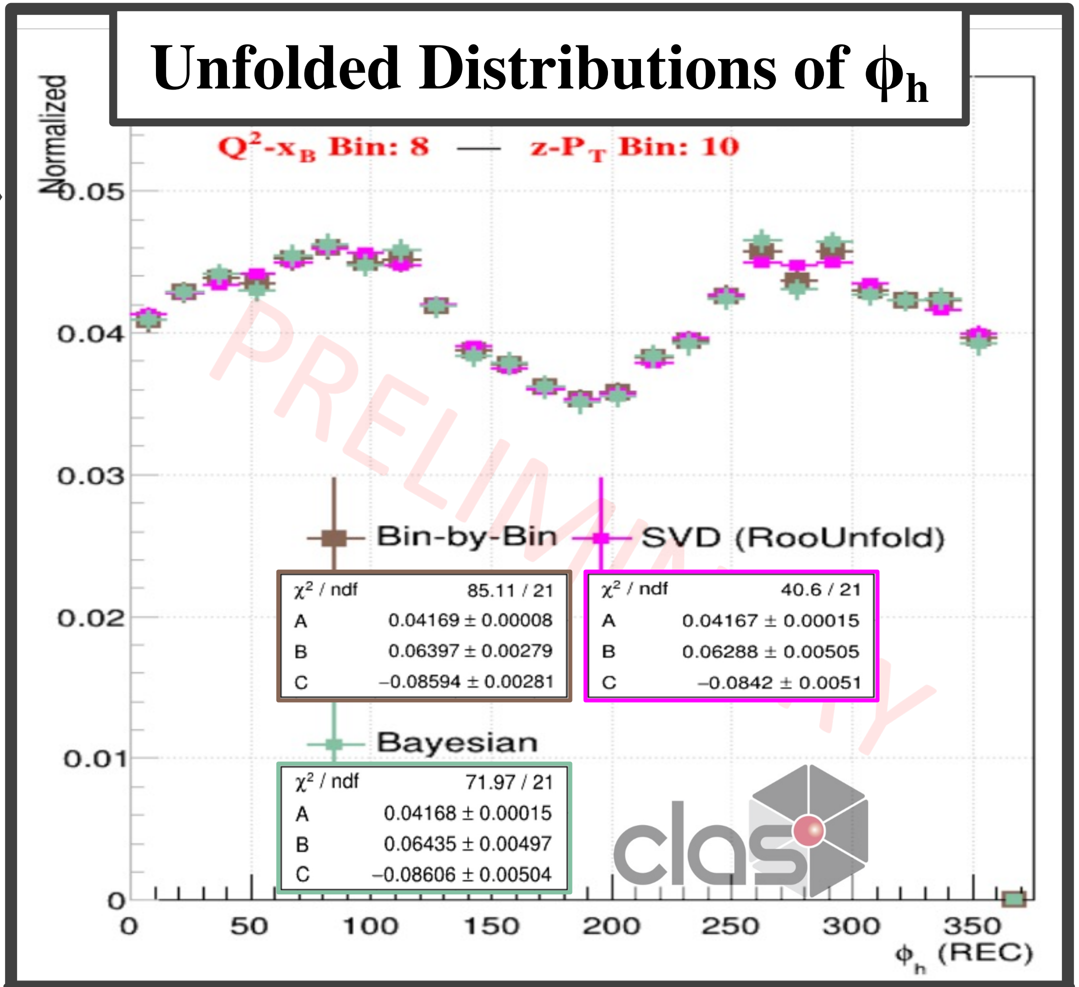
- Y_i = Number of events experimentally measured in the *i*-th bin
- X_j = Number of acceptance-corrected events in the *j*-th bin

Example of Unfolding Procedure

Using the Multidimensional Kinematic Bin from prior example



Unfolding Procedures

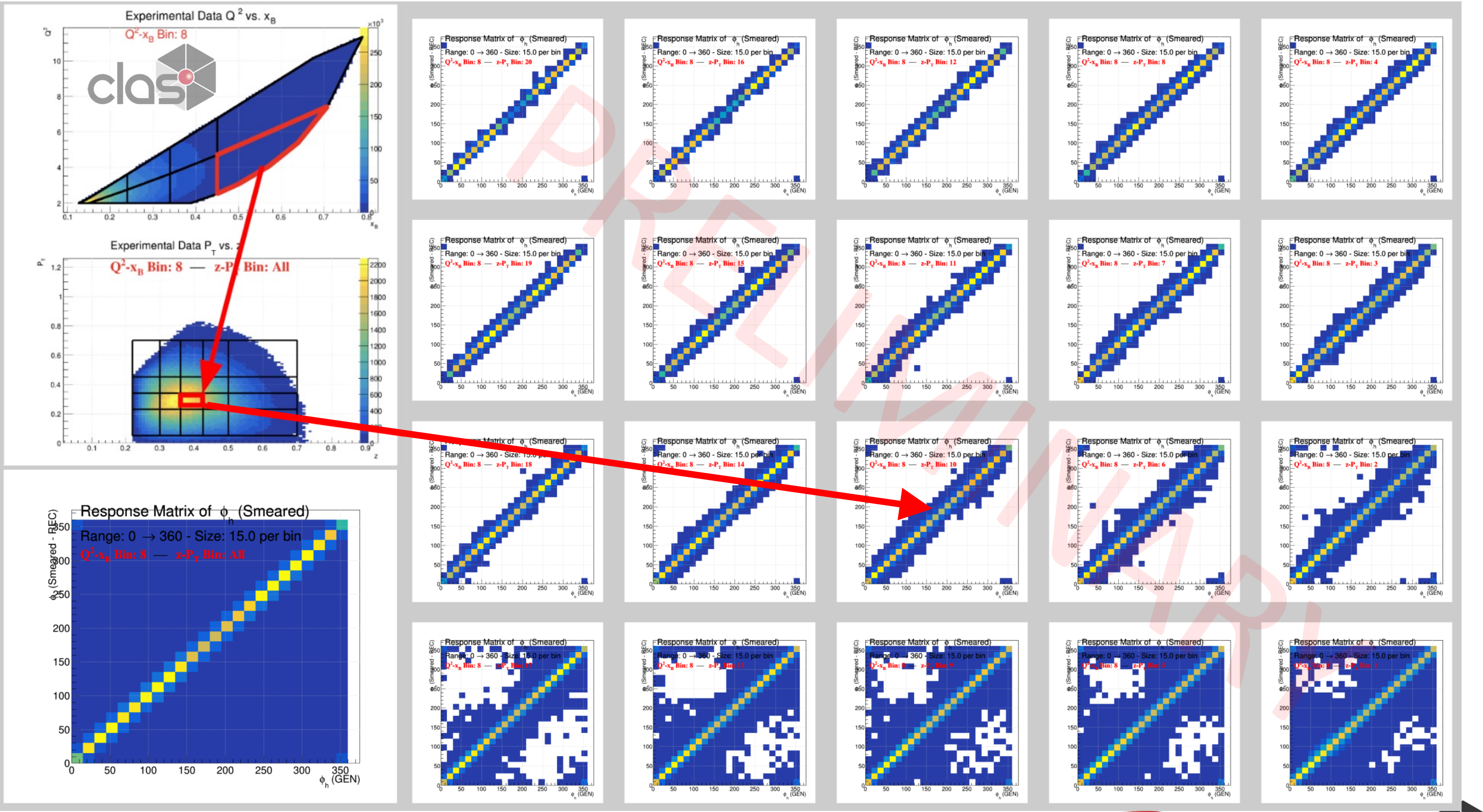


Parameters shown are from the fits previously described

Multiple Examples of the Unfolding Procedure

Response Matrices
in each z-P_T bin for the highlighted Q^2-x_B bin

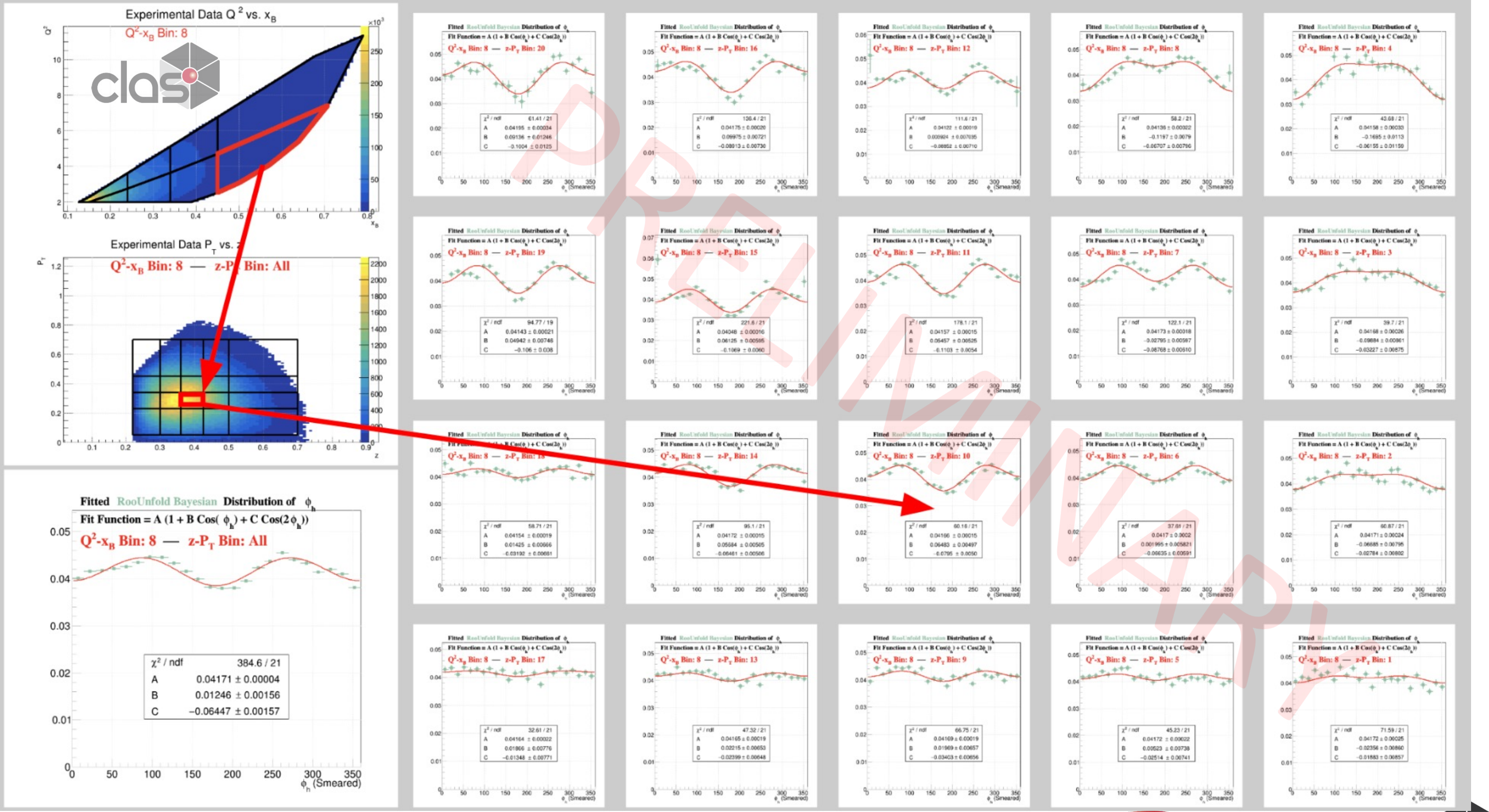
Arrows point to the distribution used in prior examples



Multiple Examples of the Unfolding Procedure

Bayesian Unfolding in each z-P_T bin for the highlighted Q^2-x_B bin

Arrows point to the distribution used in prior examples



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

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

Questions?

Acknowledgements

- Financial support from The Gordon and Betty Moore Foundation and the American Physical Society to present this work at the GHP 2023 workshop
- 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

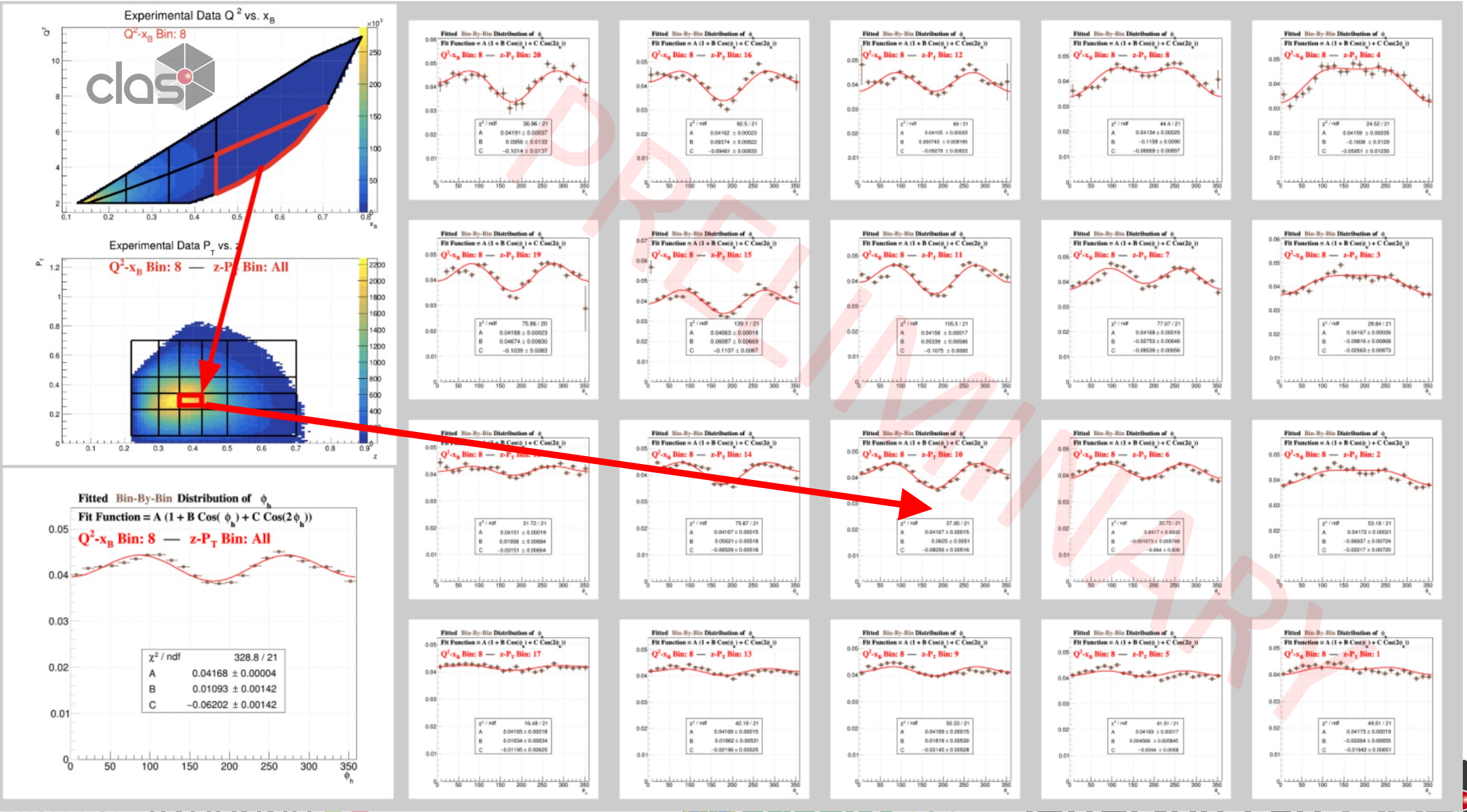
Multiple Examples of the Unfolding Procedure

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

Bin-by-bin Correction in each z-P_T bin for the highlighted Q^2-x_B bin

Arrows point to the distribution used in prior examples

These images are also available at the web address linked above



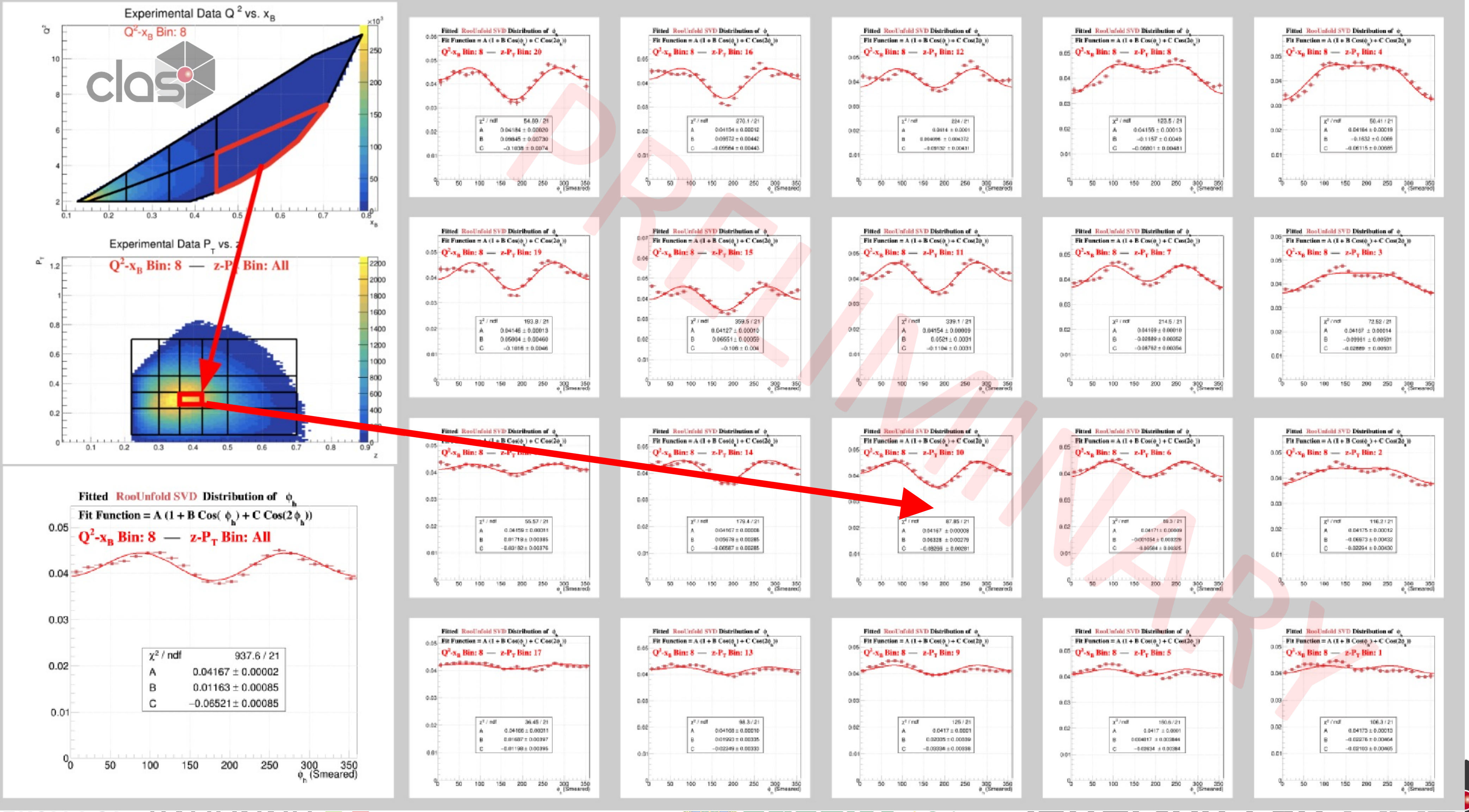
Multiple Examples of the Unfolding Procedure

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

SVD Unfolding in each z-P_T bin for the highlighted Q^2-x_B bin

Arrows point to the distribution used in prior examples

These images are also available at the web address linked above



Multiple Examples of the Unfolding Procedure

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

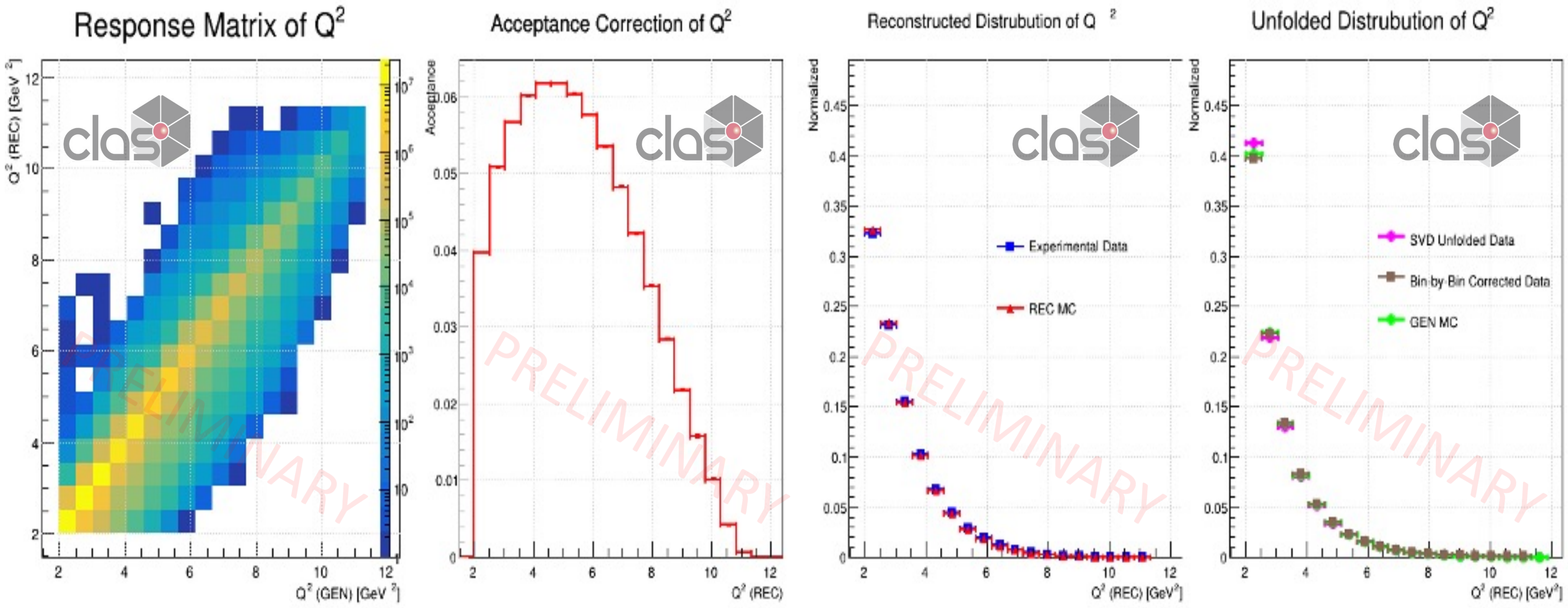
Bayesian Unfolding in each z-P_T bin for the highlighted Q^2-x_B bin

Arrows point to the distribution used in prior examples

DUPLICATE SLIDE

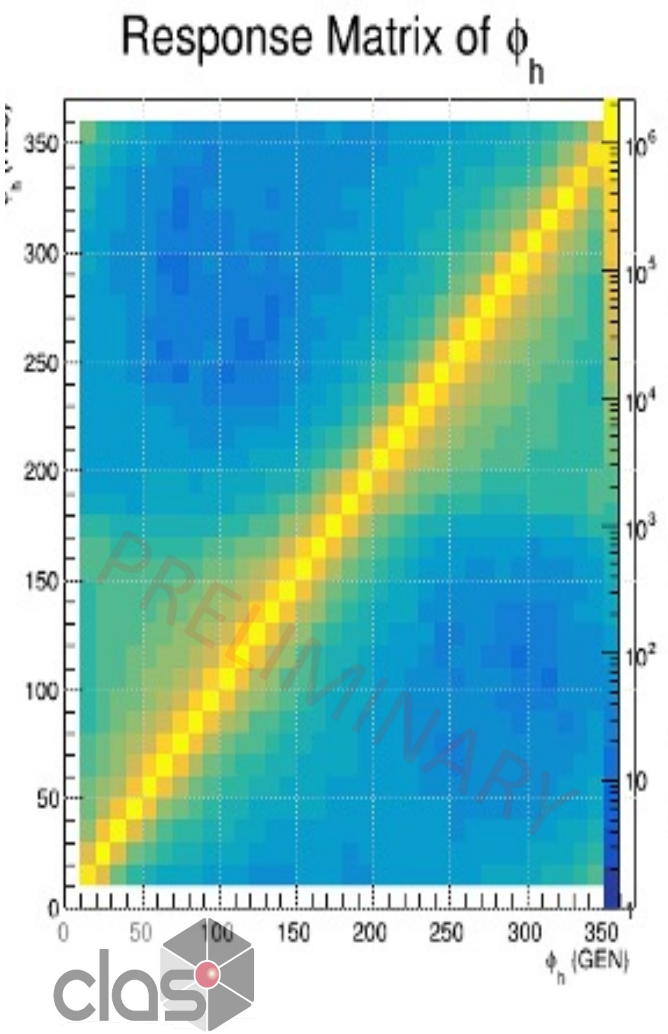
These images are also available at the web address linked above

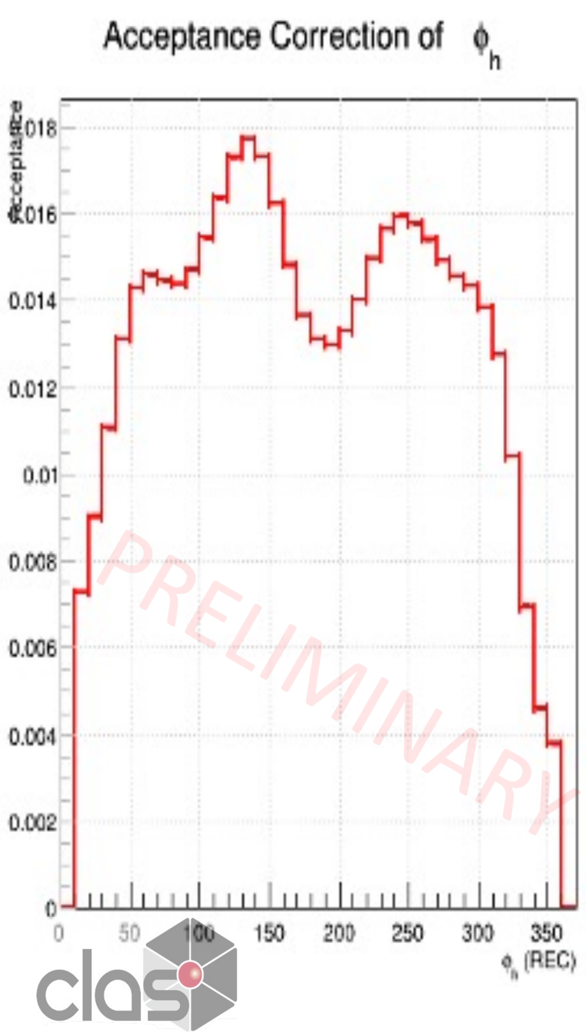
Example of Unfolding (Q^2)

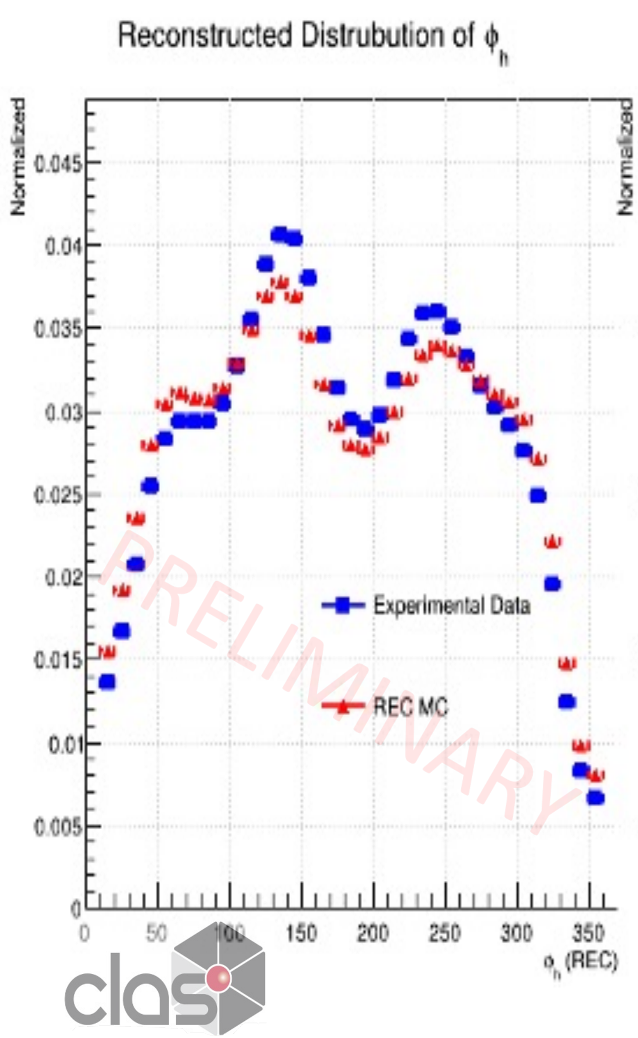


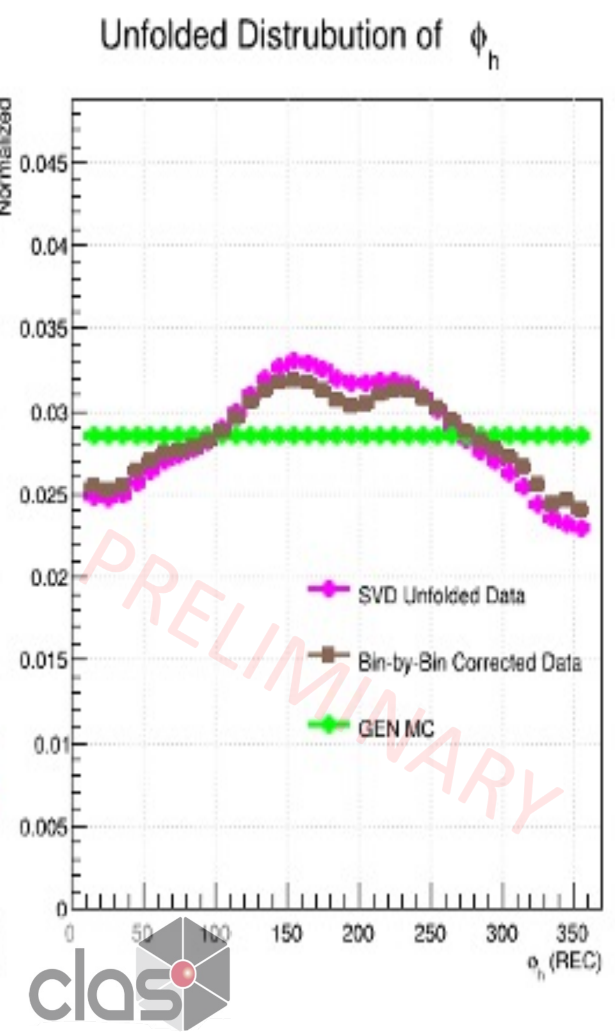
UCONN | UNIVERSITY OF CONNECTICUT Argonne NATIONAL LABORATORY U.S. DEPARTMENT OF ENERGY Office of Science Jefferson Lab

Example of Unfolding (ϕ_h)



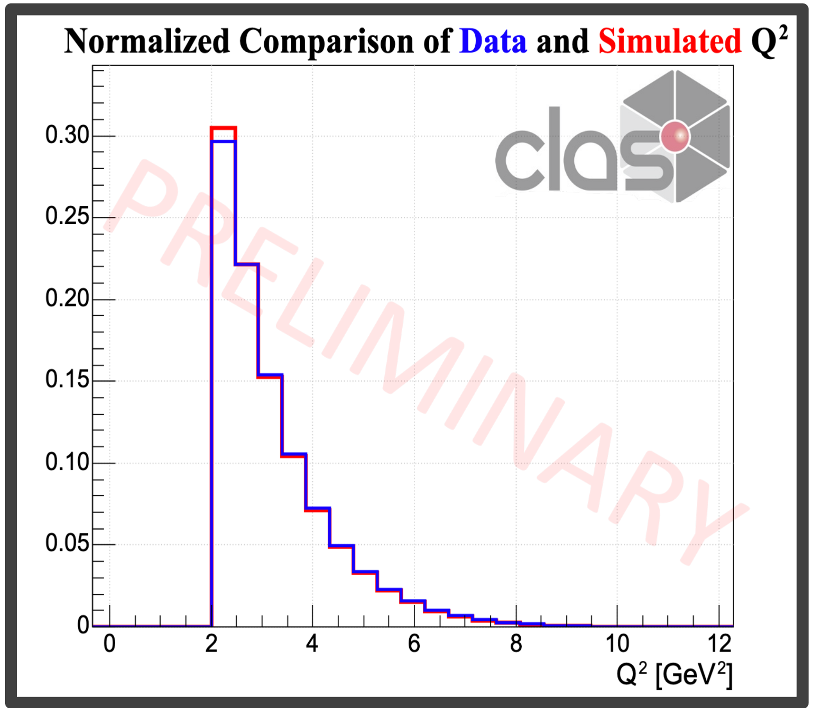




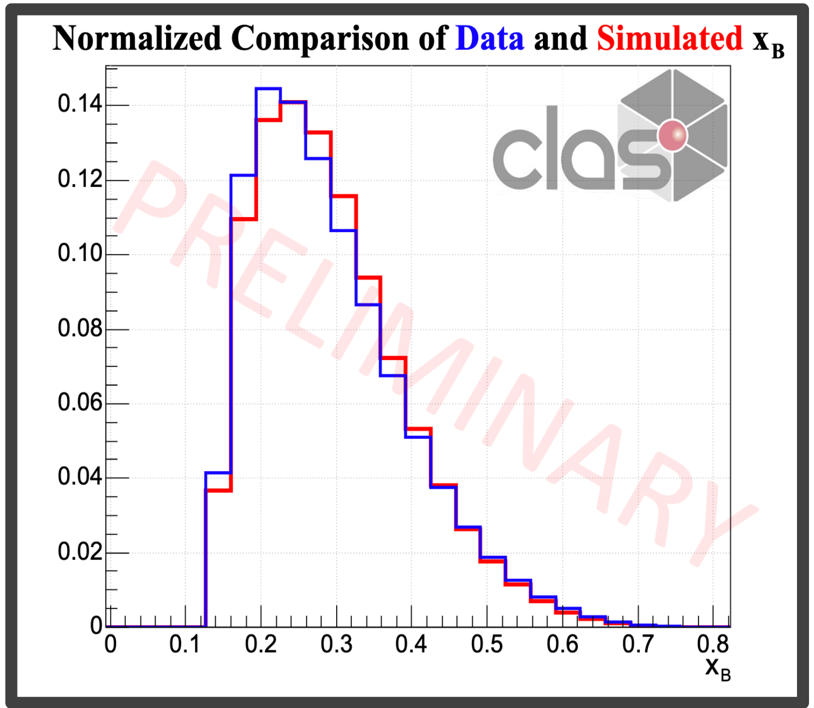


Other Comparisons

All Events



Q^2 Comparison

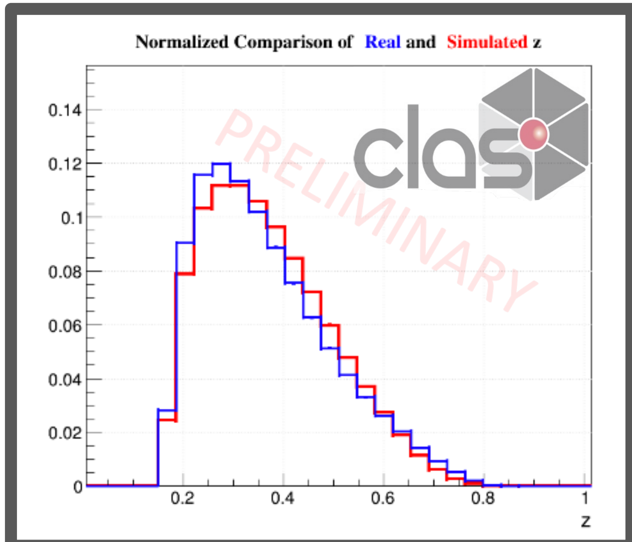


x_B Comparison

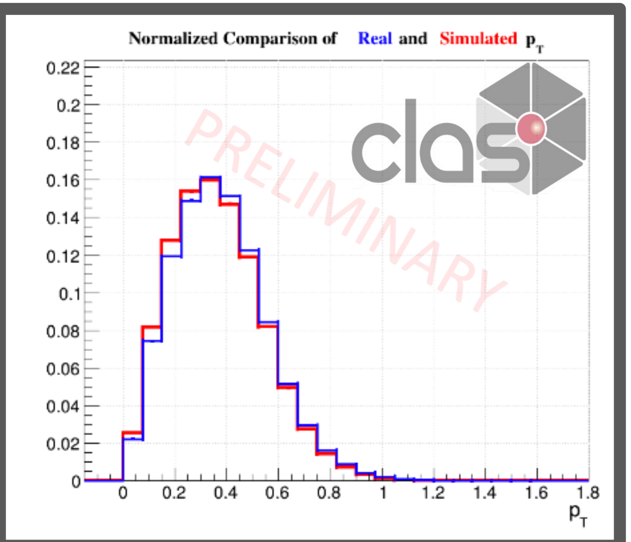
Kinematic Binning and Data-MC Comparison

Other Comparisons

All Events



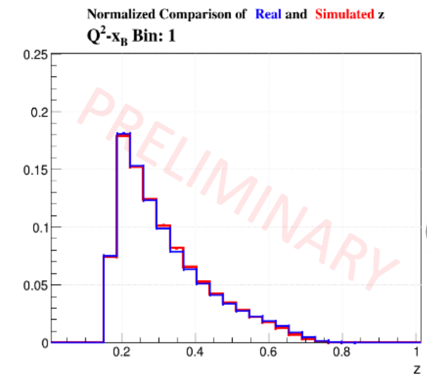
z Comparison

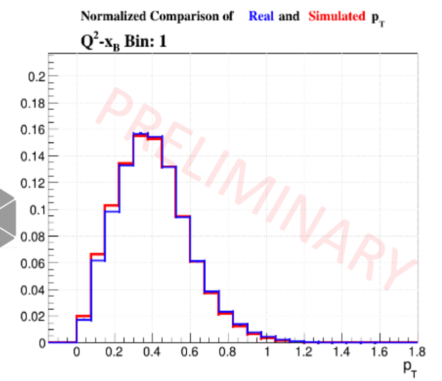


P_T Comparison

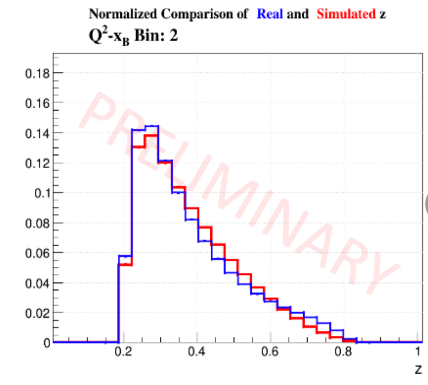
z Comparison | P_T Comparison

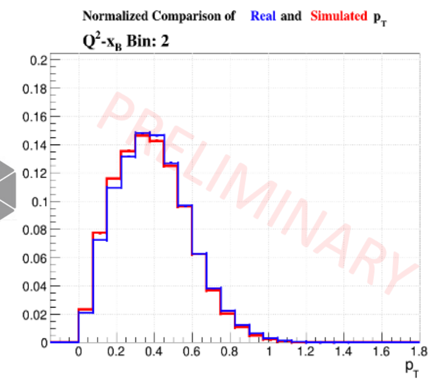
Q^2-x_B Bin 1





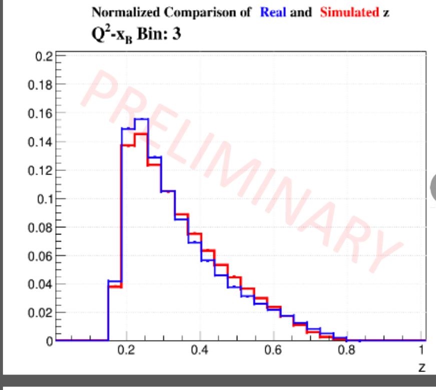
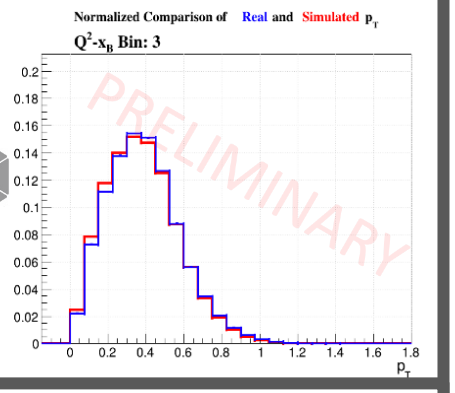
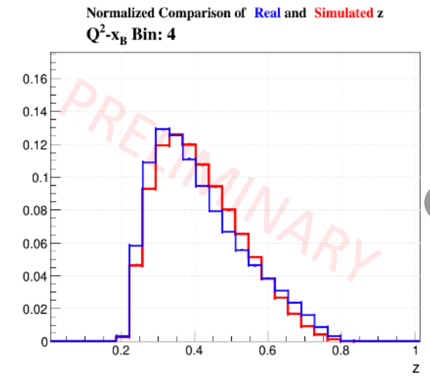
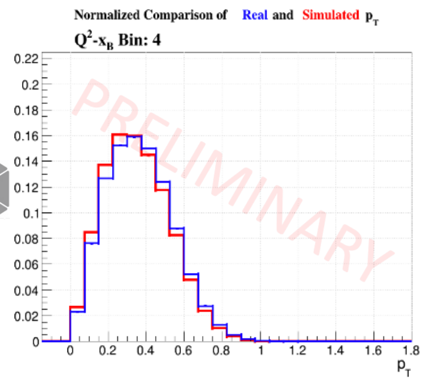
Q^2-x_B Bin 2

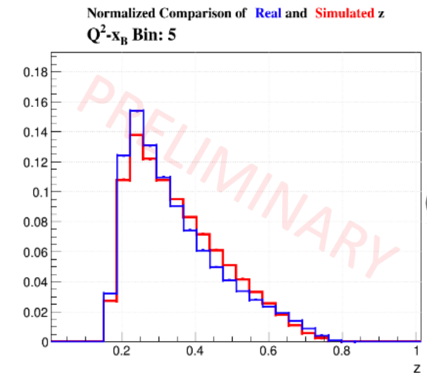
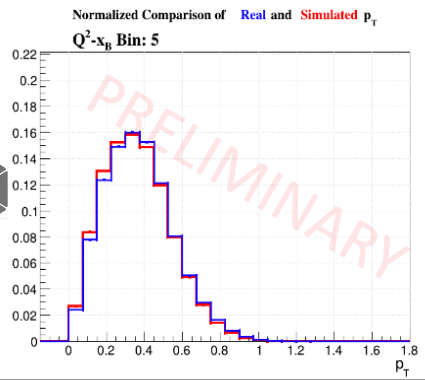
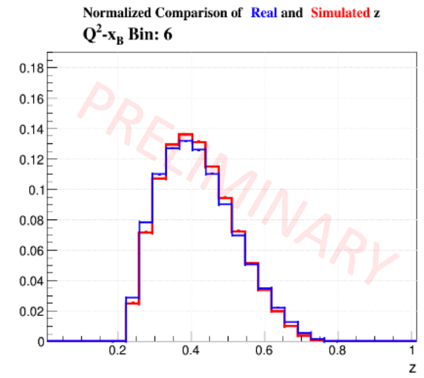
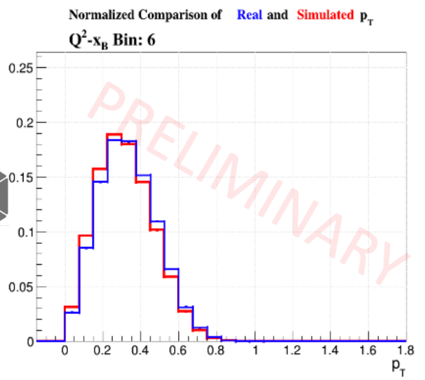




Kinematic Binning and Data-MC Comparison

Other Comparisons

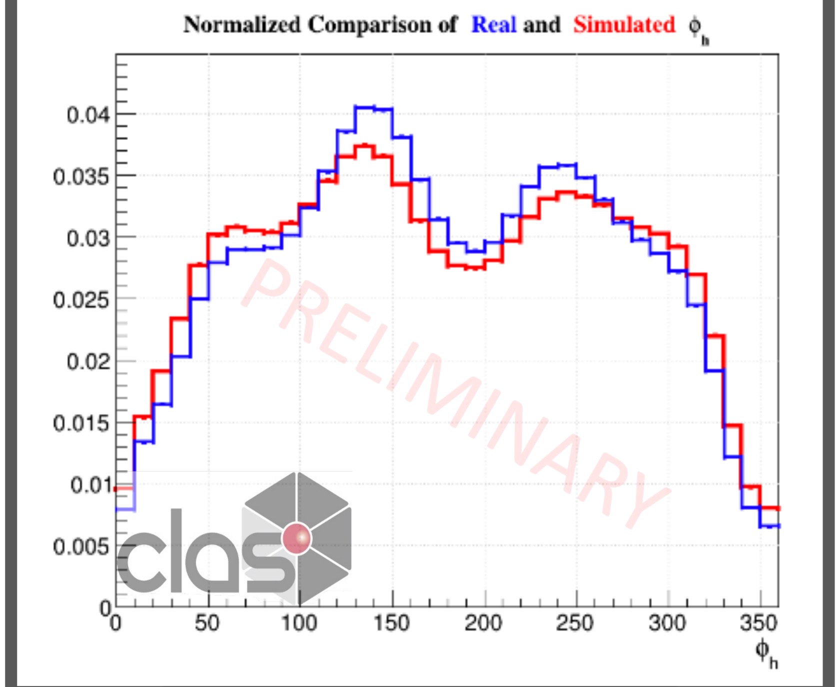
	z Comparison	P_T Comparison
Q^2-x_B Bin 3		
Q^2-x_B Bin 4		

	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

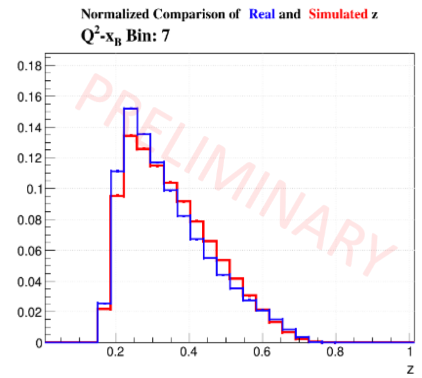


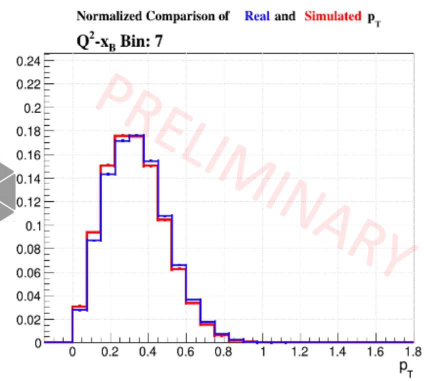
ϕ_h Comparison

z Comparison

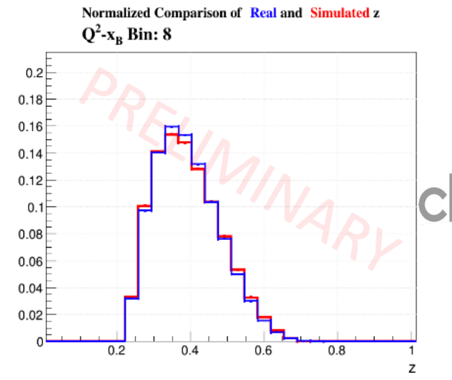
P_T Comparison

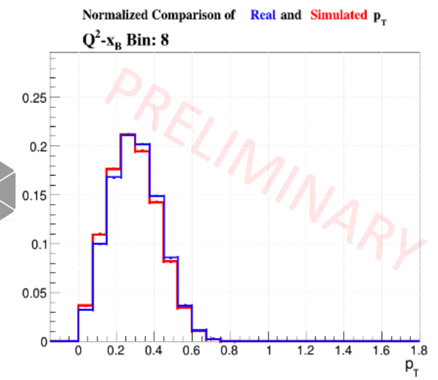
Q^2-x_B Bin 7





Q^2-x_B Bin 8

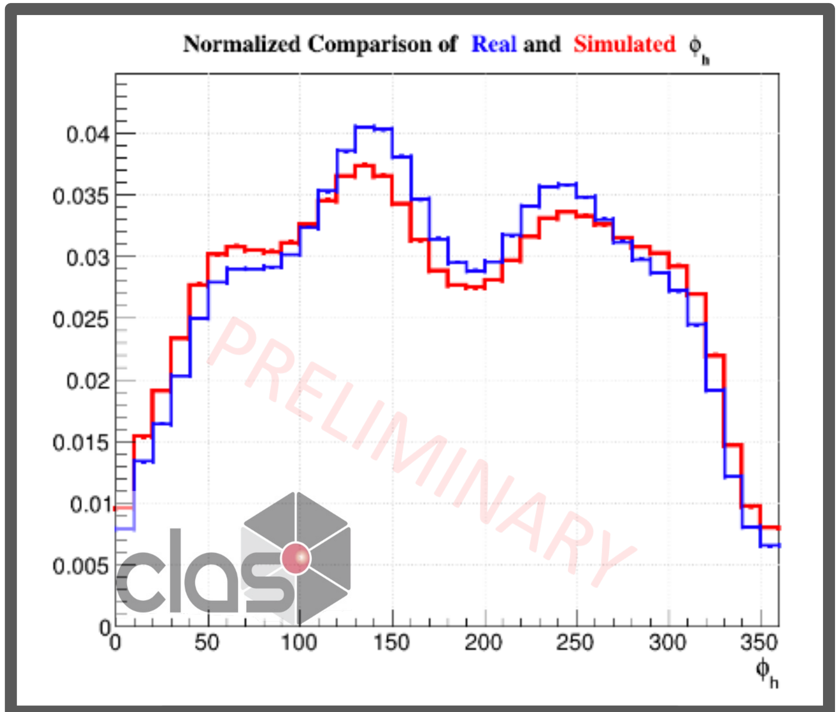




Kinematic Binning and Data-MC Comparison

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

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:

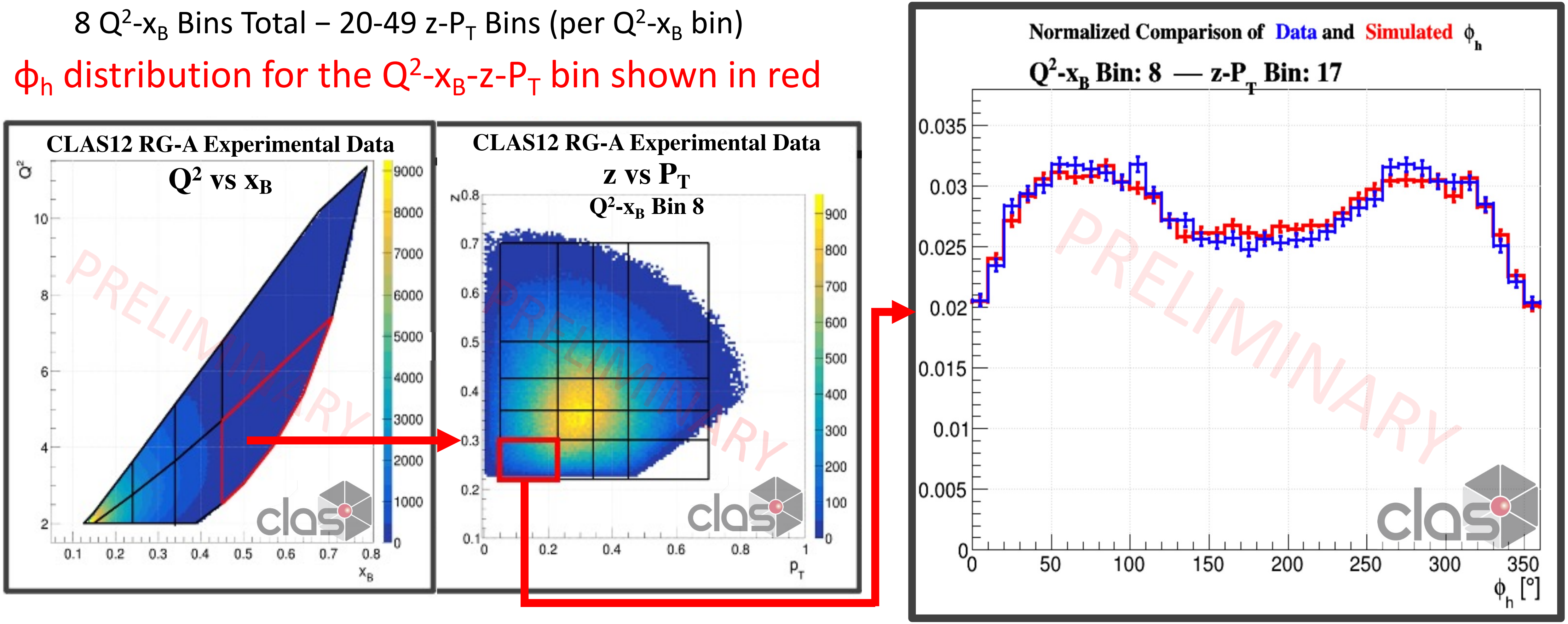
- Detected in Forward Detector
- p > 1.25 GeV
- Refined chi2pid cuts

Multidimensional Analysis Procedures

Multidimensional Kinematic Binning (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

UCONN | UNIVERSITY OF CONNECTICUT   Argonne NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science   Jefferson Lab   clas