

OCTOBER 7, 2026

SIDIS CLAS12&CLAS12 +

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Postdoctoral Appointee

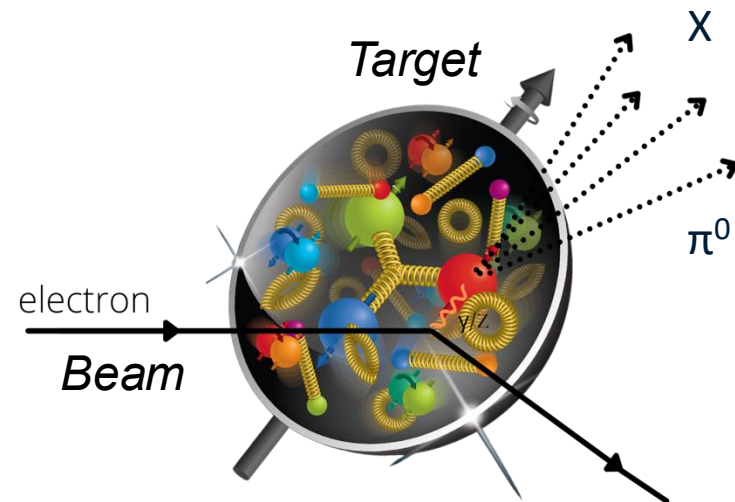


STRUCTURE OF THE TALK

- The current status of the SIDIS π^0 multiplicity analysis
- Projections for kinematic extensions achievable with CLAS12+
- Results for $\cos(\phi)$ and $\cos(2\phi)$ moments of unpolarized SIDIS π^+ with CLAS12
- Potential challenges for these analyses at high luminosity

MOTIVATION

- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** provides access to the **3D momentum structure of the nucleon**, including intrinsic transverse parton motion.
- Azimuthal modulations of unpolarized SIDIS cross-section for charged pion electroproduction can give access to the **Cahn** and **Boer-Mulders** effects
- Extracting $A_{UU}^{\cos \phi_h}$ and $A_{UU}^{\cos 2\phi_h}$ moments help inform us about the transverse momentum structure inside the proton.

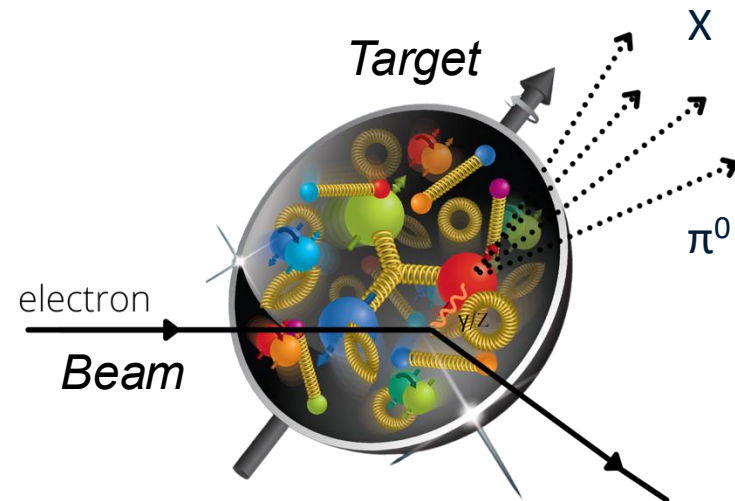


$$\frac{d^5\sigma}{dx dQ^2 dz d\phi_h dP_{h\perp}^2} = \underbrace{\frac{2\pi\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right)}_{A_0} (F_{UU,T} + \epsilon F_{UU,L}) \left\{ 1 + \underbrace{\frac{\sqrt{2\epsilon(1+\epsilon)} F_{UU}^{\cos \phi_h}}{(F_{UU,T} + \epsilon F_{UU,L})}}_{A_{UU}^{\cos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

$$\begin{aligned} \text{leading twist} \quad F_{UU}^{\cos 2\phi_h} &\propto C \left[\underbrace{-\frac{2(\vec{P}_{h\perp} \cdot \vec{k}_T)(\vec{P}_{h\perp} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h}}_{\text{CAHN EFFECT}} h_1^\perp H_1^\perp + \dots \right] \\ \text{next to leading twist} \quad F_{UU}^{\cos \phi_h} &\propto \frac{2M}{Q} C \left[\underbrace{-\frac{\vec{P}_{h\perp} \cdot \vec{k}_T}{M_h}}_{\text{BOER-MULDERS EFFECT}} x h H_1^\perp - \underbrace{\frac{\vec{P}_{h\perp} \cdot \vec{p}_T}{M}}_{\text{Interaction dependent terms neglected}} f_1 D_1 + \dots \right] \end{aligned}$$

MOTIVATION

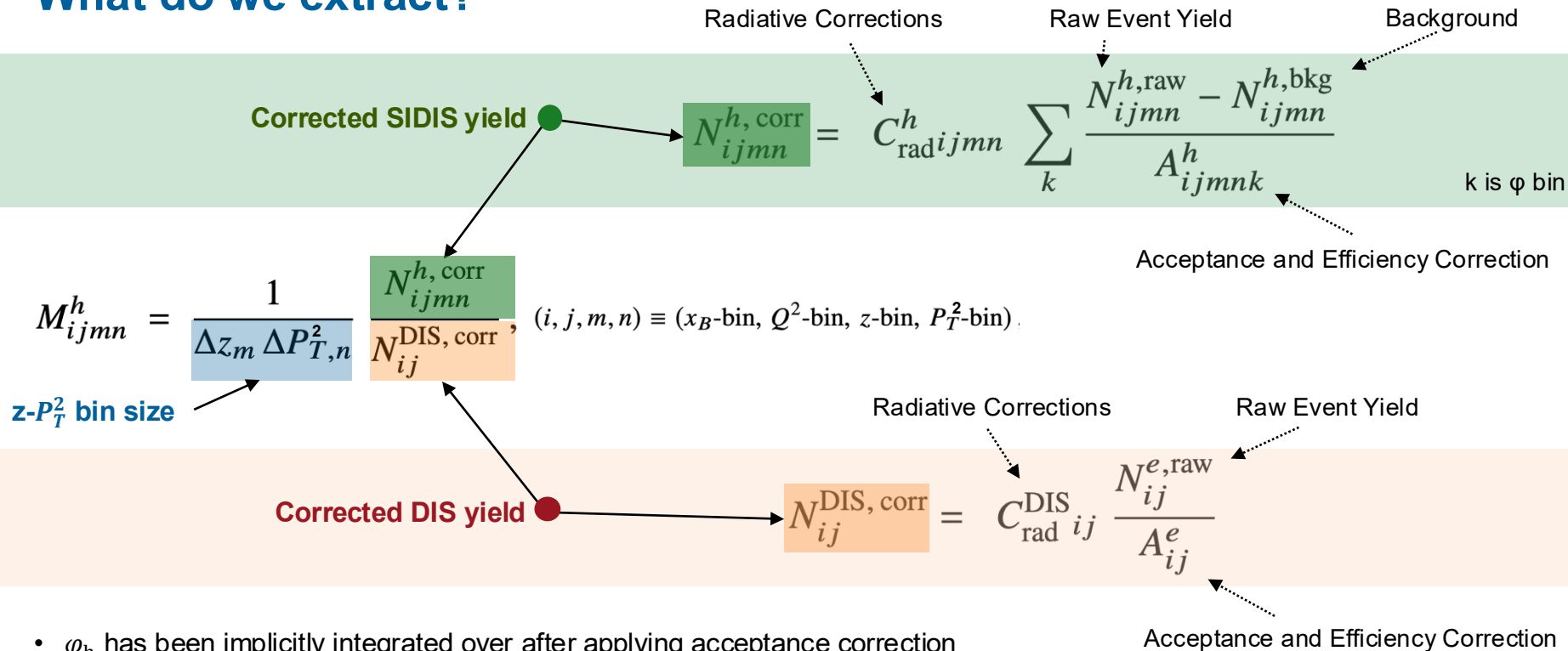
- **Hadron multiplicities** measure the probability of producing a hadron (π^0) per DIS event
- Multiplicity measurements uniquely link hadronization with the proton's internal transverse motion, advancing both FF determinations and our 3D understanding of proton structure
- The **z** - dependence constrains **fragmentation functions (FFs)**: how colored partons turn into color-neutral hadrons
- The **P_T^2** - dependence directly probes the unpolarized **TMD PDFs** revealing the proton's intrinsic transverse momentum dynamics
- It also allows to study isospin invariance as the neutral pion fragmentation function is thought to be dependent on the charged pion fragmentation functions



$$\frac{d^2 M_h}{dz dP_T^2}(x_B, Q^2, z, P_T^2) = \frac{\int_0^{2\pi} d\phi_h \frac{d\sigma^{SIDIS}}{dx dQ^2 dz dP_T^2 d\phi_h}}{\frac{d\sigma^{DIS}}{dx dQ^2}}$$

SIDIS MULTIPLICITY

What do we extract?



- ϕ_h has been implicitly integrated over after applying acceptance correction
- Electron-side efficiencies partially cancel out in the ratio

MULTIPLICITY ANALYSIS PROCEDURE

- Particle Identification
- π^0 yield extraction from two-photons invariant mass fits
- Five-dimensional acceptance and efficiency corrections in $(x_B, Q^2, z, P_T^2, \varphi_H)$
- Fits to the unfolded φ_H distributions with $A + B * \cos(\varphi_H) + C * \cos(2 * \varphi_H)$, followed by integration over φ_H
- Radiative Corrections (see backup slides)
- DIS yield normalization

AZIMUTHAL MODULATIONS EXTRACTION

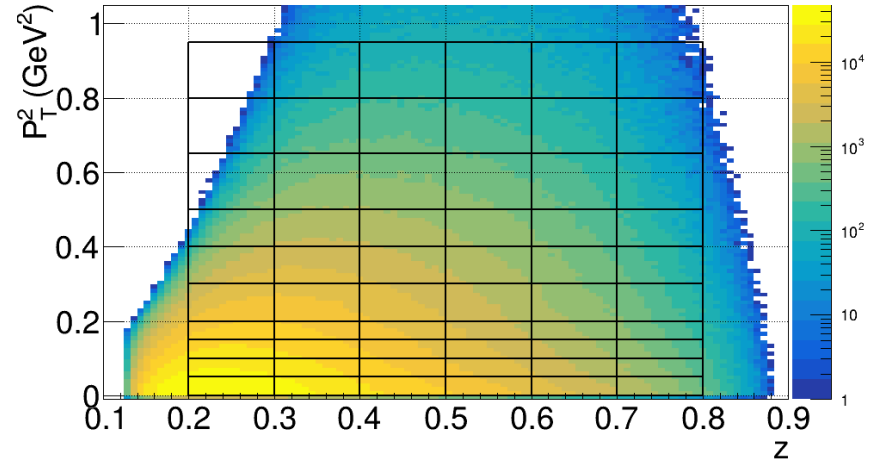
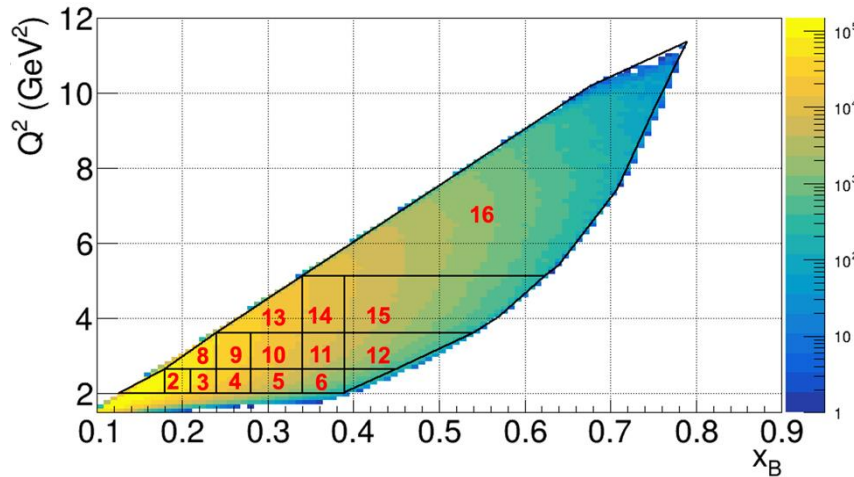
$$\frac{d^5\sigma}{dQ^2 dy dP_T dz d\phi_h} = \frac{1}{N_0 \left(N_A \cdot \rho \cdot \frac{t}{A_w} \right) \cdot \Gamma_\nu \cdot \Delta Q_i^2 \Delta y_i \Delta P_{Ti} \Delta z_i \Delta \phi_{hi}} \cdot \frac{Y_j^{SIDIS}}{A_{i,j} \cdot RC_i \cdot BC_i}$$

- SIDIS event yield: $Y_j^{SIDIS} = Y_j^{SIDIS+Bkg} - Y_j^{Bkg}$ Background: $ep \rightarrow e'p\rho^0 \rightarrow e'p \pi^+ \pi^-$
- A - Acceptance correction
- RC – Radiative correction
- BC – Bin Size Correction

$$\frac{d^5\sigma}{dQ^2 dy dP_T dz d\phi_h} \xrightarrow{\text{Fit with}} A_0 (1 + A_{UU}^{\cos \phi_h} \cos \phi_h + A_{UU}^{\cos 2\phi_h} \cos 2\phi_h)$$

Extract A_0 , $A_{UU}^{\cos \phi_h}$, and $A_{UU}^{\cos 2\phi_h}$ as final measurements

KINEMATICS AND BINNING



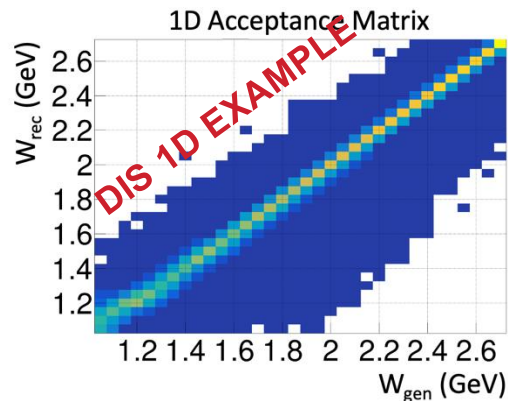
- Large CLAS12 acceptance together with large statistics allow for multidimensional binning
- Semi-Inclusive DIS events selected with following kinematic cuts:

- $W > 2 \text{ GeV}$
- $Q^2 > 2 \text{ GeV}^2$
- $y < 0.75$
- $x_F > 0$ [$x_F = 2P_{h,L}/\sqrt{s}$] : current fragmentation region
- $M_x > 1.5 \text{ GeV}$

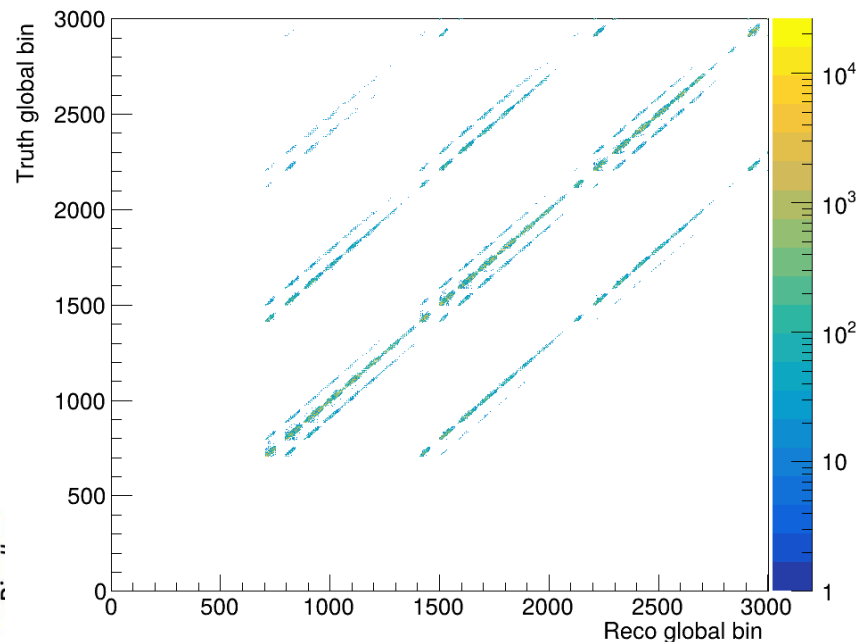
ACCEPTANCE AND EFFICIENCY CORRECTION

Bayesian Deconvolution

- Based on Response Matrix $P(\text{reconstructed in bin } i \mid \text{generated in bin } j)$
total number of generated events
- The algorithm starts from an initial prior (MC) and iteratively updates the unfolded spectrum using Bayes' theorem.
- The implementation provided by the RooUnfold package



Response matrix crop: reco [0,3000], truth [0,3000]

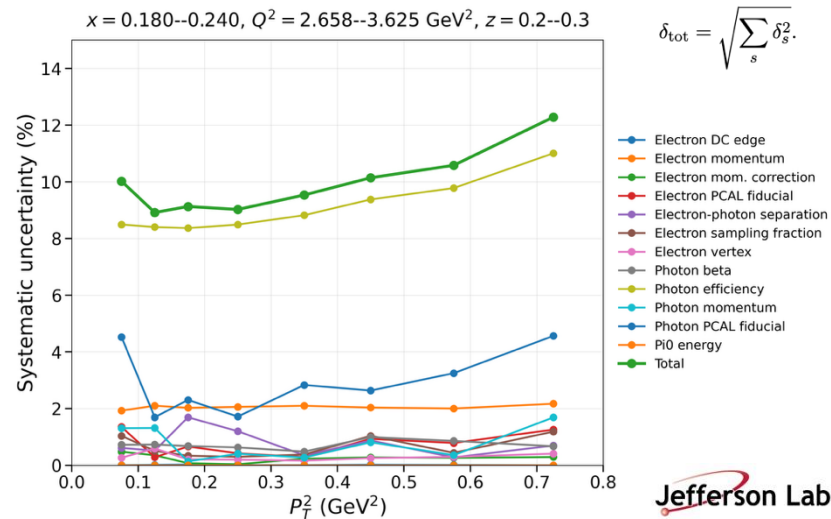


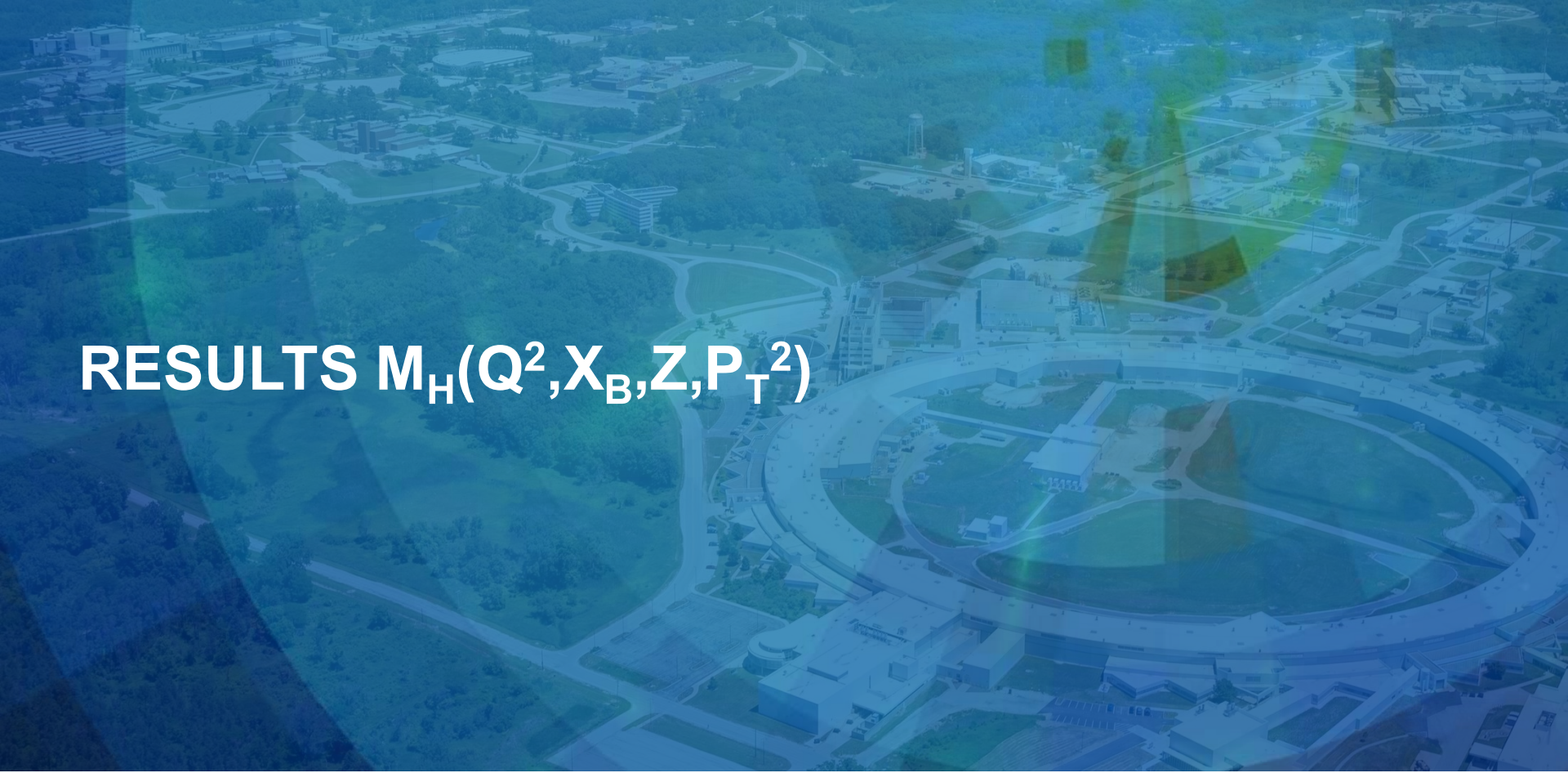
SYSTEMATIC UNCERTAINTY

- Event-selection and efficiency systematics were studied
- Most sources contribute 1–3% uncertainty
- The dominant contribution is currently the detection-efficiency correction (~8%), limited by the statistics of the exclusive $ep \pi^0$ sample used to determine the efficiency
- Deconvolution and radiative correction (RC) systematic uncertainties have not yet been studied

$$\delta_s(\%) = \frac{|M_{\text{low}} - M_{\text{nom}}| + |M_{\text{high}} - M_{\text{nom}}|}{2|M_{\text{nom}}|} \times 100,$$

Systematic source	Loose	Nominal	Strict
Photon momentum	$p_{\gamma 1,2} > 0.45 \text{ GeV}$	$p_{\gamma 1,2} > 0.50 \text{ GeV}$	$p_{\gamma 1,2} > 0.55 \text{ GeV}$
Photon β	$0.87 < \beta_{\gamma 1,2} < 1.13$	$0.90 < \beta_{\gamma 1,2} < 1.10$	$0.93 < \beta_{\gamma 1,2} < 1.07$
π^0 energy	$E_{\pi^0} > 0.10 \text{ GeV}$	$E_{\pi^0} > 0.125 \text{ GeV}$	$E_{\pi^0} > 0.15 \text{ GeV}$
Electron-photon separation	$\theta_{e\gamma 1,2} > 6^\circ$	$\theta_{e\gamma 1,2} > 8^\circ$	$\theta_{e\gamma 1,2} > 10^\circ$
Electron vertex	$-8.5 < v_z < 2.5 \text{ cm}$	$-8.0 < v_z < 2.0 \text{ cm}$	$-7.5 < v_z < 1.5 \text{ cm}$
Electron PCAL fiducial	$L_w, L_v \geq 14$	$L_w, L_v \geq 19$	$L_w, L_v \geq 24$
	$L_u \geq 25$	$30 \leq L_u \leq 395$	$35 \leq L_u \leq 390$
Photon PCAL fiducial	$L_w, L_v \geq 14$	$L_w, L_v \geq 19$	$L_w, L_v \geq 24$
	$L_u \geq 25$	$30 \leq L_u \leq 395$	$35 \leq L_u \leq 390$
Electron DC edge	$R_1 > 4, R_2 > 4,$ $R_3 > 8$	$R_1 > 5, R_2 > 5,$ $R_3 > 10$	$R_1 > 6, R_2 > 6,$ $R_3 > 12$
Electron sampling fraction	$SF > \mu - 4.5\sigma$	$SF > \mu - 3.5\sigma$	$SF > \mu - 2.5\sigma$
Photon efficiency	$C_\gamma - \sigma_{C_\gamma}$	C_γ	$C_\gamma + \sigma_{C_\gamma}$
Electron momentum correction	$1 + 0.95 \text{ dppC}$	$1 + 1.00 \text{ dppC}$	$1 + 1.05 \text{ dppC}$

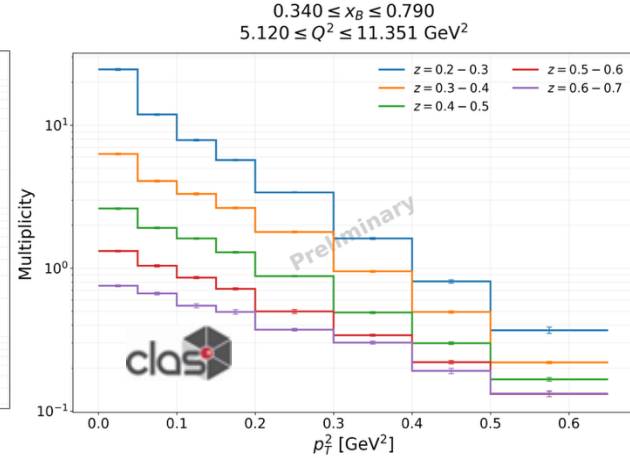
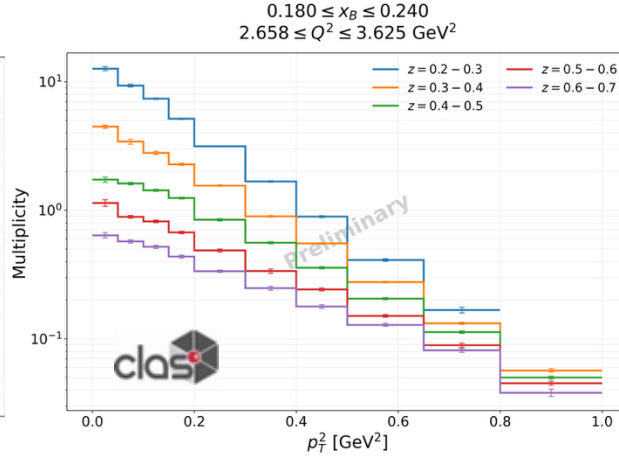
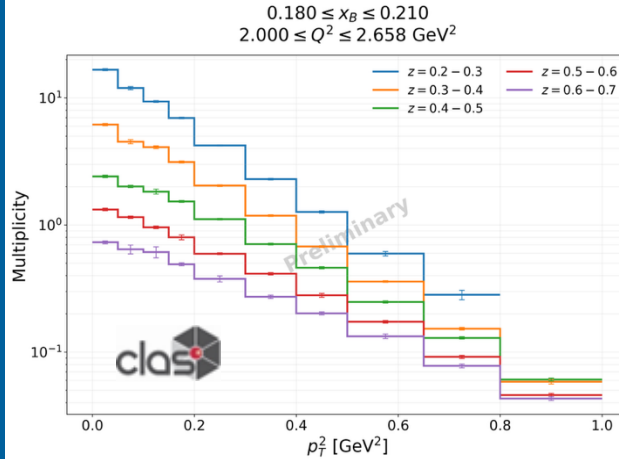




RESULTS $M_H(Q^2, X_B, Z, P_T^2)$

RESULTS

$M_h(p_T^2)$ for selected x- Q^2 bins



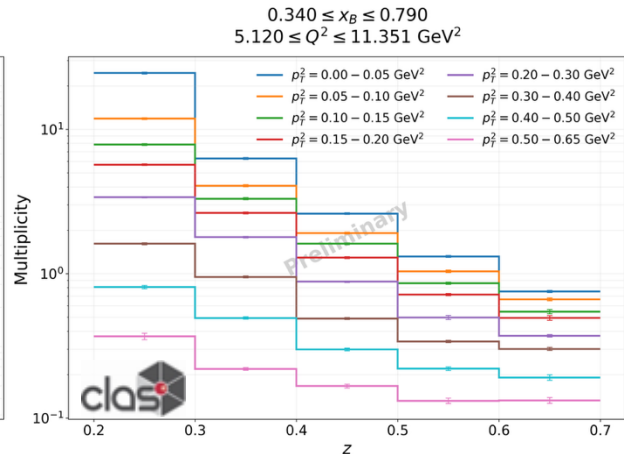
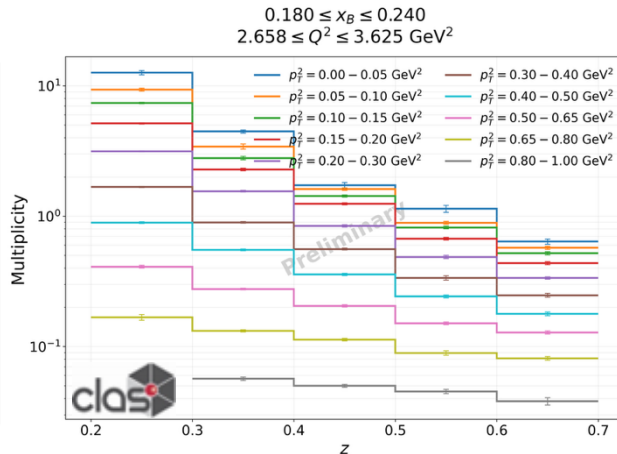
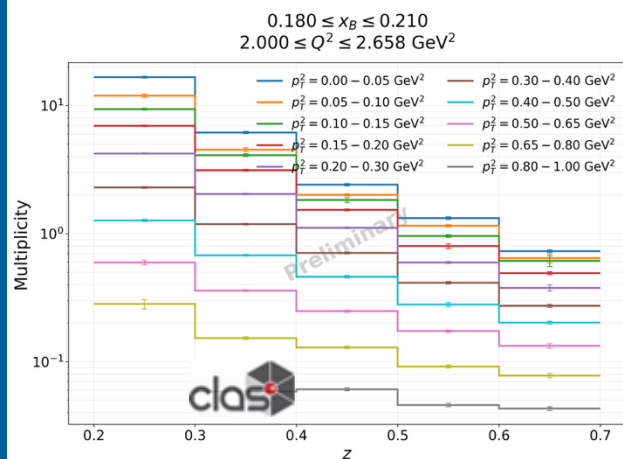
- LO, gaussian approximation:

$$\frac{d^2 M^h}{dz dP_T^2} = \left(\frac{d^4 \sigma}{dx dQ^2 dz dP_T^2} \right) \bigg/ \left(\frac{d^2 \sigma^{\text{DIS}}}{dx dQ^2} \right) = \frac{N}{\pi \langle P_T^2 \rangle} \exp \left(-\frac{P_T^2}{\langle P_T^2 \rangle} \right)$$

- The behavior is consistent with an LO Gaussian model, except for a high- P_T^2 downturn attributable to the phase-space restriction $M_x > 1.5 \text{ GeV}$
- Only statistical uncertainties are shown

RESULTS

$M_h(z)$ for selected x - Q^2 bins

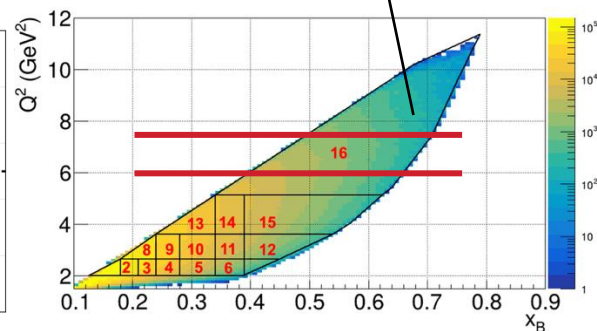
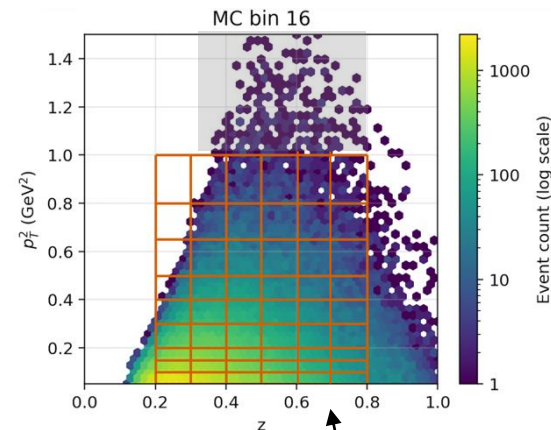
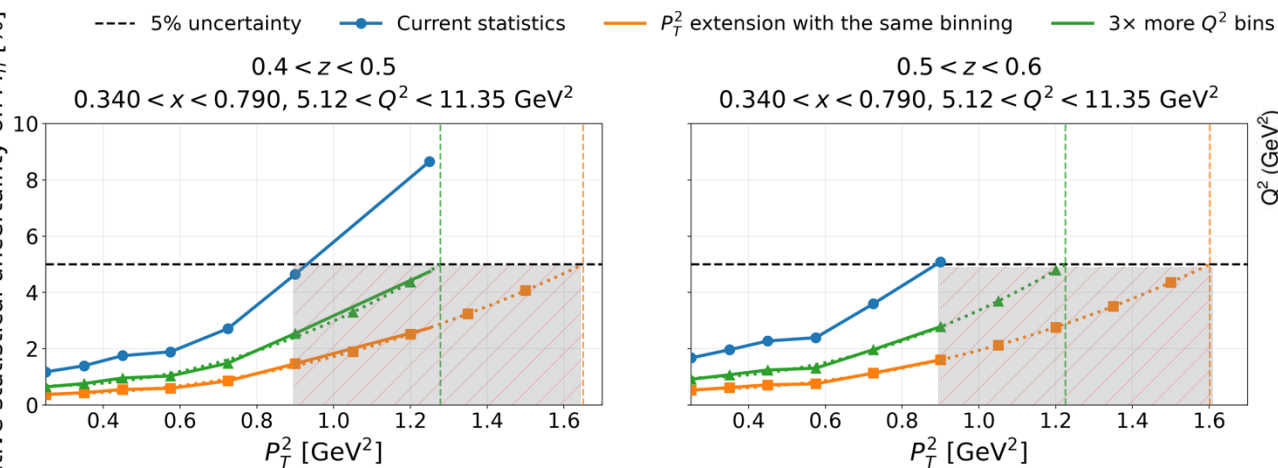


- $\ln(M_h(z))$ is approximately linear
- Only statistical uncertainties are shown

PROJECTIONS WITH 10X STATISTICS

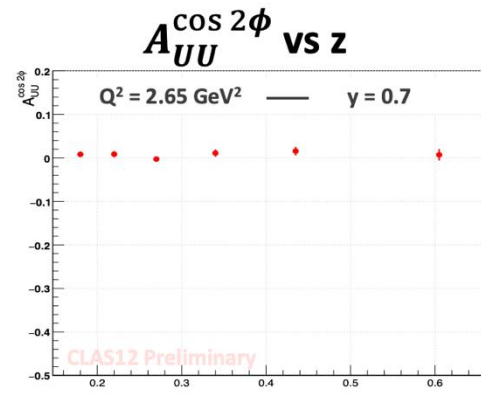
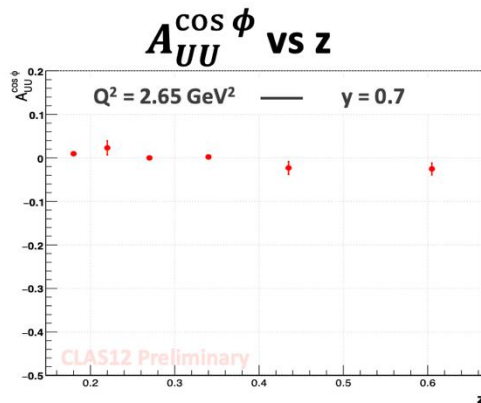
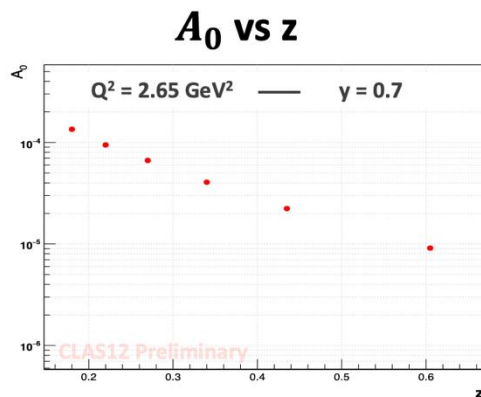
- High- z range is the most sensitive to large k_T through $\vec{P}_T \sim z\vec{k}_T + \vec{p}_T$
- With the current statistics, we can achieve $P_T^2 \sim 0.7 - 0.9 \text{ GeV}^2$
- With increased statistics and the same binning, the coverage extends to roughly $P_T^2 \sim 1.2 - 1.4 \text{ GeV}^2$ depending on z
- With 3 times finer Q^2 binning, the coverage shows extension in P_T^2 up to 1.2 GeV^2

Relative statistical uncertainty on M_h [%]

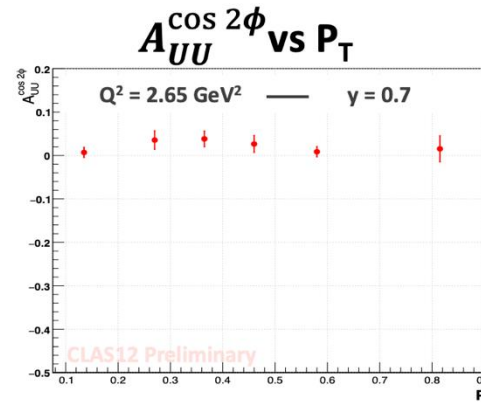
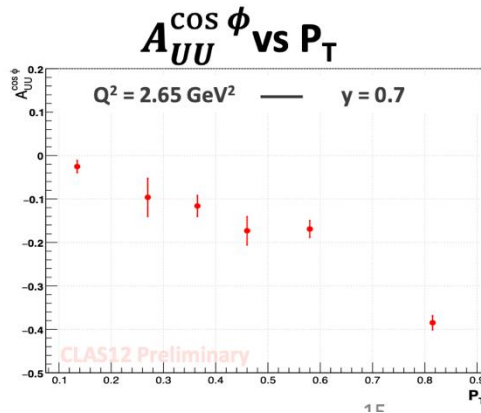
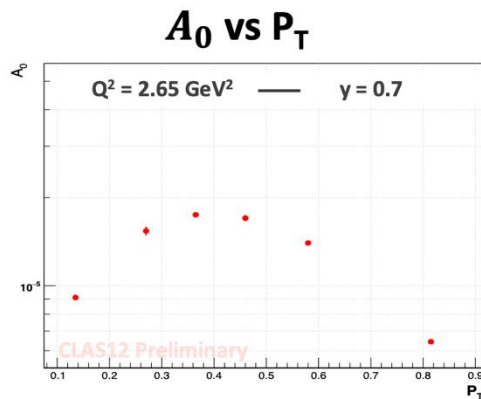


□ $\cos(\phi)$ AND $\cos(2\phi)$ MOMENTS OF
UNPOLARIZED SIDIS PI^+

MOMENT RESULTS



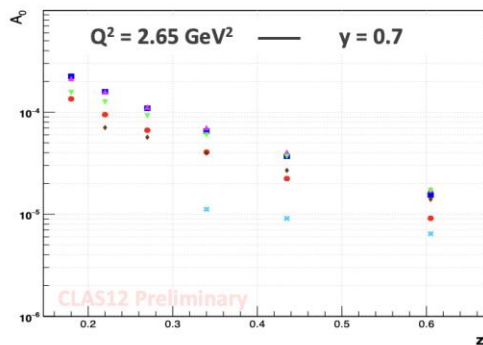
↑ $P_T = 0.135$



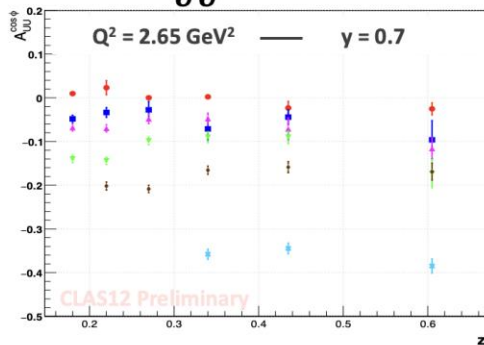
↑ $z = 0.605$

MOMENT RESULTS

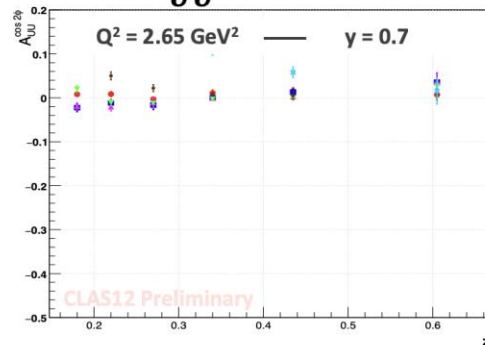
A_0 vs z



$A_{UU}^{\cos \phi}$ vs z

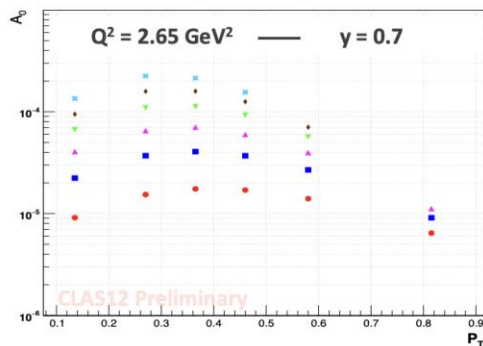


$A_{UU}^{\cos 2\phi}$ vs z

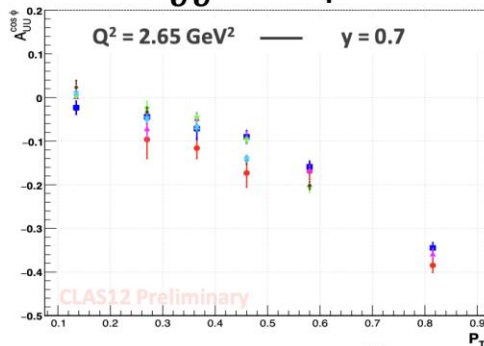


- $P_T = 0.135$
- $P_T = 0.27$
- $P_T = 0.365$
- $P_T = 0.46$
- $P_T = 0.58$
- $P_T = 0.815$

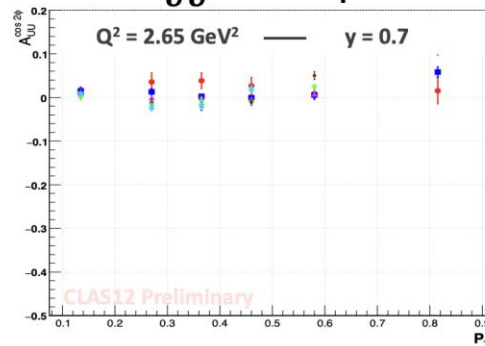
A_0 vs P_T



$A_{UU}^{\cos \phi}$ vs P_T



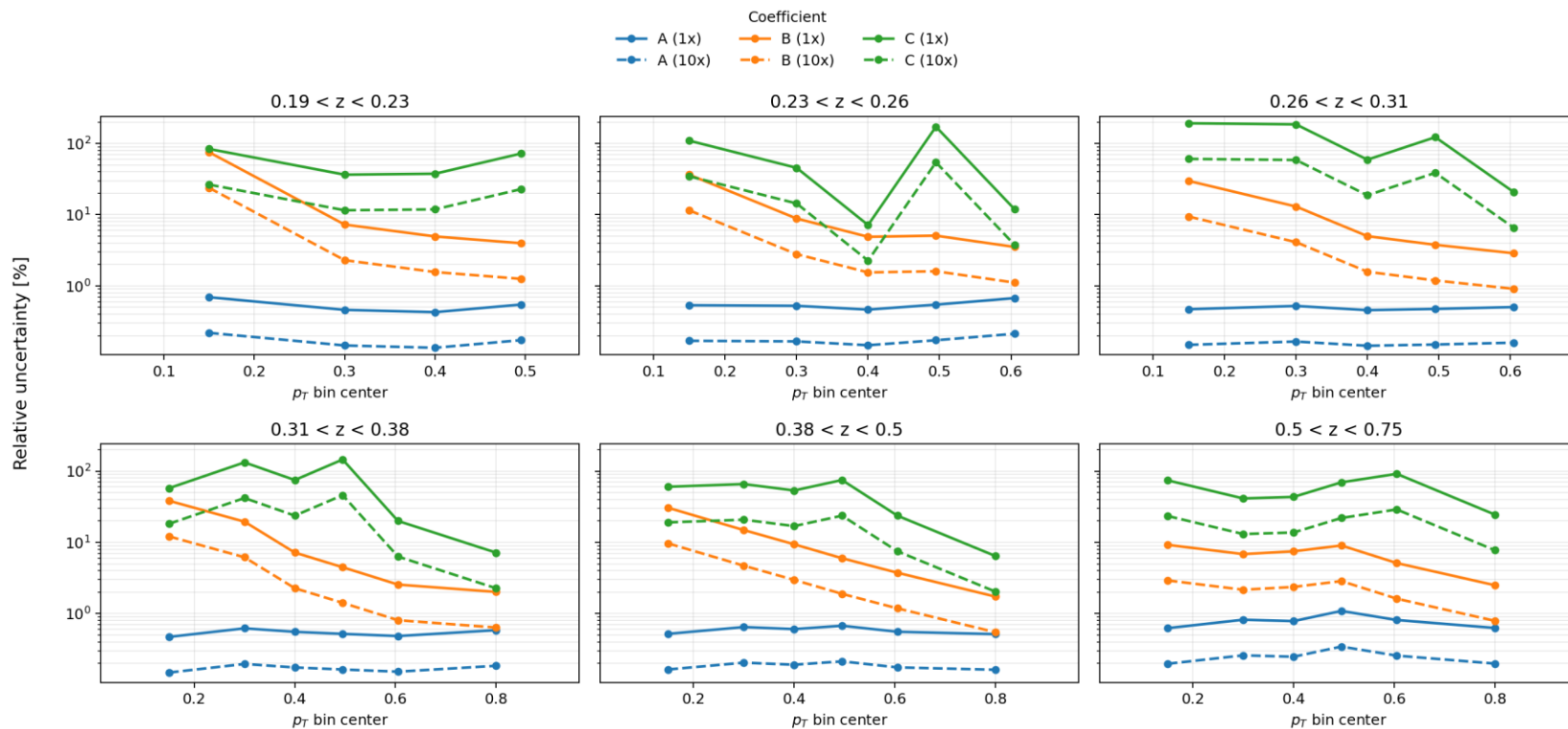
$A_{UU}^{\cos 2\phi}$ vs P_T



- $z = 0.605$
- $z = 0.435$
- $z = 0.34$
- $z = 0.27$
- $z = 0.22$
- $z = 0.18$

STATISTICAL UNCERTAINTY

Q^2 -y bin 2: $2 < Q^2 < 2.4$, $0.55 < y < 0.65$ | $1x$



CHALLENGES

- **Monte Carlo production**

- Reaching $\sim 10\times$ the data statistics required nearly **2 years** of production
- About **50 TB** of simulated data, current campaign covers $1.5 < Q^2 < 10.6 \text{ GeV}^2$
- Full 5D matrix based unfolding becomes increasingly challenging as the binning is expanded
- Unbinned or alternative analysis methods may provide a more scalable approach

- **Radiative Corrections** can reach 20%, dedicated effort on radiated generators is needed

- The dominant systematic uncertainty is currently the detection-efficiency correction, limited by the statistics of the exclusive $ep \pi^0$ sample

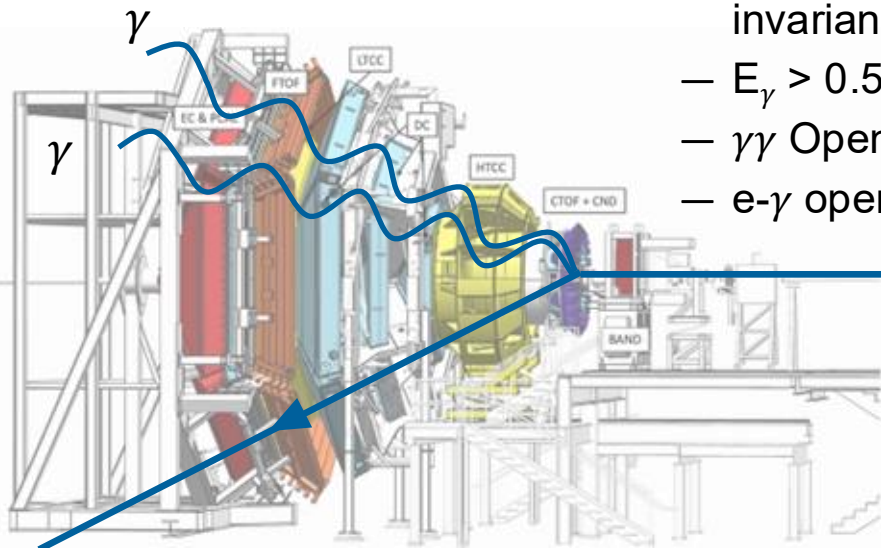


THANK YOU!

CLAS12

Selection of the $ep \rightarrow e\pi^0 X$ reaction with Forward Detector

- π^0 **candidates** are reconstructed from photon pairs invariant mass (registered in Calorimeters)
- $E_\gamma > 0.5$ GeV
- $\gamma\gamma$ Opening angle vs momentum cut
- $e\text{-}\gamma$ opening angle > 8 deg



e' 10.6 GeV electron beam, LH_2 5-cm long hydrogen target

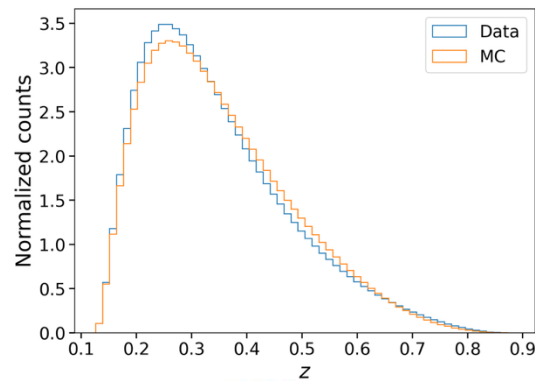
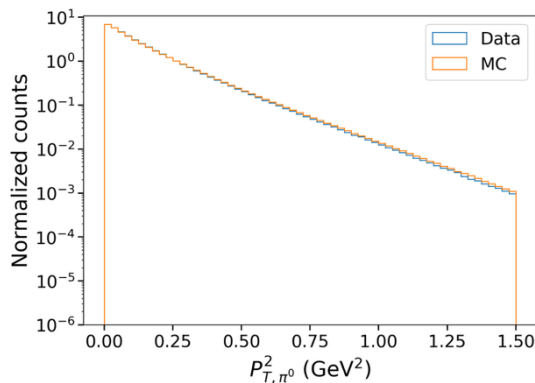
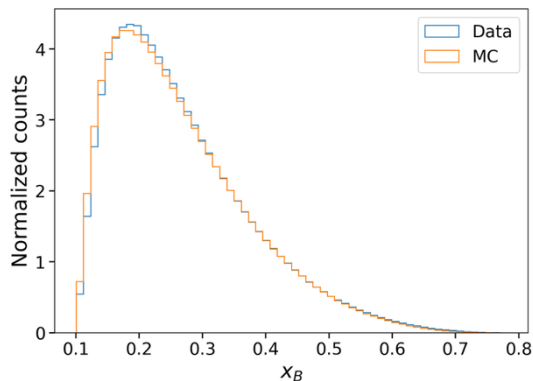
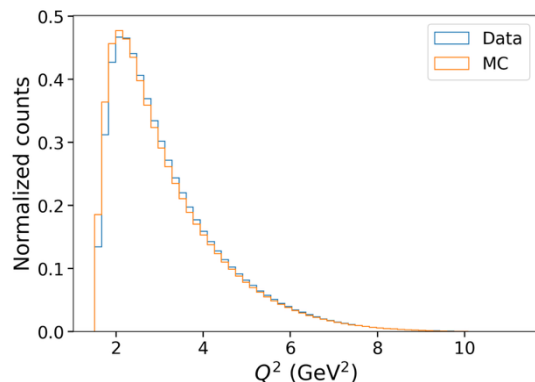
The detector subsystems used for **electron identification**:

- Drift Chambers (track)
- Calorimeters (EM shower)
- Time of Flight (PID)
- Cherenkov counters (PID)

MONTE CARLO

Event Generator used for the Acceptance

- CLASDIS-EG built on LEPTO
- Lund string model as in PYTHIA/JETSET
- LO electroweak DIS (arbitrary lepton polarization); $O(\alpha)$ matrix elements for boson–gluon fusion and gluon radiation; higher-order QCD via parton showers
- QED radiation is not included in the current MC sample
- Hadronization parameters tuned to CLAS12 semi-inclusive data ($Q^2 > 1 \text{ GeV}^2$, $W > 2 \text{ GeV}$)



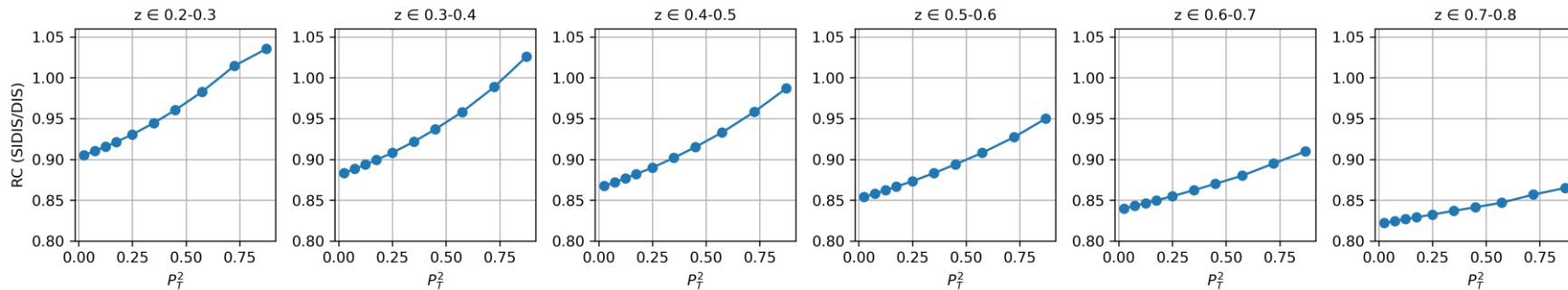
histograms normalized to unit area

RADIATIVE CORRECTIONS

HAPRAD for SIDIS

- π^0 SIDIS structure functions are modeled as the average of the π^+ and π^- structure functions within a Wandzura–Wilczek–type approximation (<https://arxiv.org/abs/1807.10606>)
- The exclusive radiative tail is evaluated using MAID2007 input: <https://maid.kph.uni-mainz.de/maid2007/cross.html>
- Contributions from the ρ and ω channels are not included in the present implementation
- DIS correction is based on Mo-Tsai approach

$$RC_{M_h} = \frac{RC_{SIDIS}}{RC_{dis}}$$

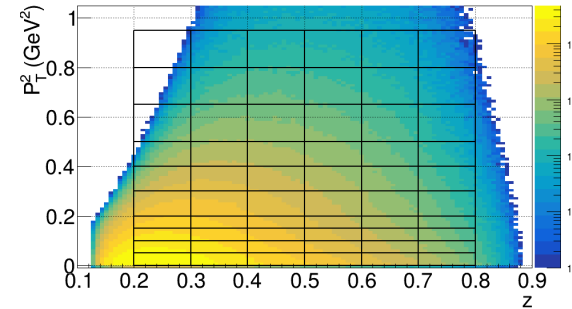
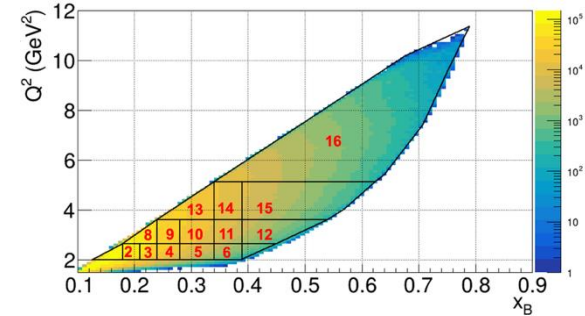
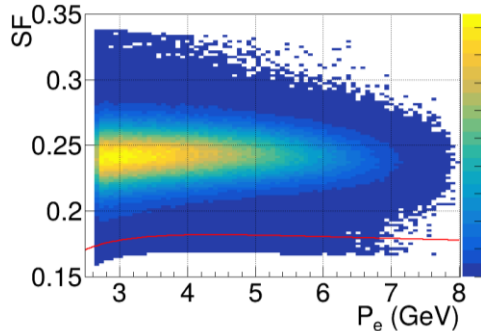


$0.18 < x < 0.21, 2.0 < Q^2 < 2.66 \text{ GeV}^2$

PID AND EVENT SELECTION

Starts with CLAS12 reconstruction algorithm

- Electron
 - $2 < p_e < 8$ GeV
 - $y < 0.75$
 - Z-Vertex cut
 - DC and PCAL fiducial
 - Sampling Fraction
- Photon
 - $E_\gamma > 0.5$ GeV
 - $e\text{-}\gamma$ opening angle > 8 deg
 - $0.9 < \beta < 1.1$
- π^0
 - Candidates are reconstructed from photon pairs
 - $x_F > 0$ [$x_F = 2P_{h,L}/\sqrt{s}$] : current fragmentation region
 - $M_x > 1.5$ GeV
 - $\alpha_{\gamma\gamma} > 6 \cdot \text{Exp}(1 - p_\pi) + 0.5$ deg

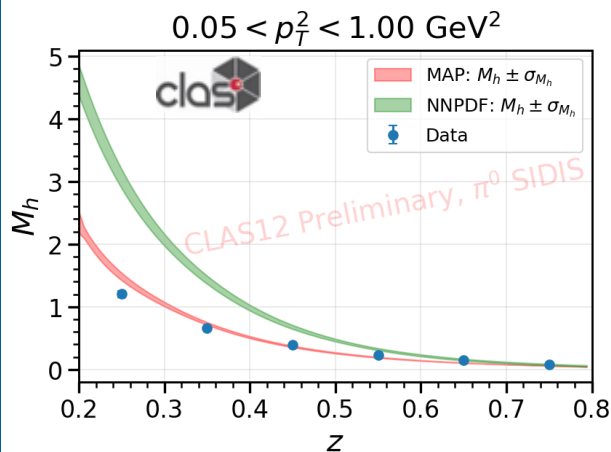


RESULTS

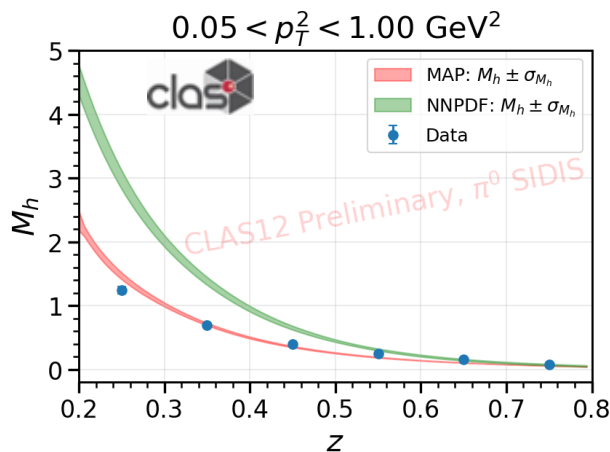
$M_h(z)$ integrated over P_T^2 for selected x- Q^2 bins

P_T^2 integrated multiplicity:

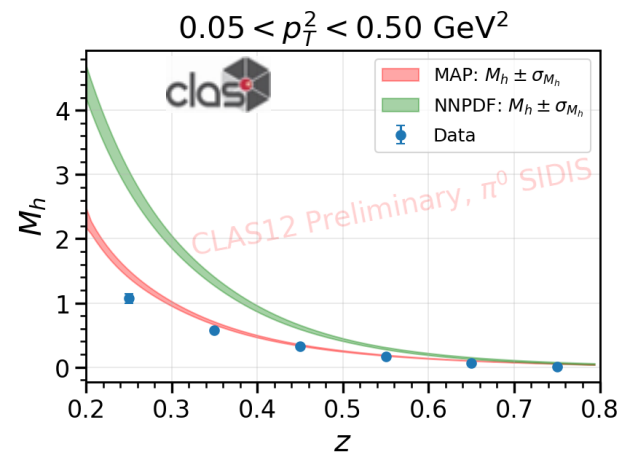
$$M_h = \frac{\sum_q e_q^2 f_q(x) D_q(z)}{\sum_q e_q^2 f_q(x)}$$



0.18 < x < 0.21, 2.0 < Q^2 < 2.66 GeV²



0.24 < x < 0.28, 2.66 < Q^2 < 3.63 GeV²



0.39 < x < 0.62, 3.63 < Q^2 < 5.12 GeV²

- M_h was integrated over the P_T^2 range that preserves full z coverage
- The theoretical curves were computed with CT10nlo PDFs using two fragmentation-function sets:
 - NNFF**, fitted only to single-inclusive hadron production in e^+e^- annihilation
 - MAPFF**, which additionally includes charged-hadron multiplicity data from HERMES and COMPASS
- After integrating over P_T^2 , **multiplicities** vs. z follow the trend of LO predictions using MAPFF FF and CT10nlo PDFs

PHI FIT

