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NEUTRAL PION SIDIS MULTIPLICITY STUDIES AT CLAS12

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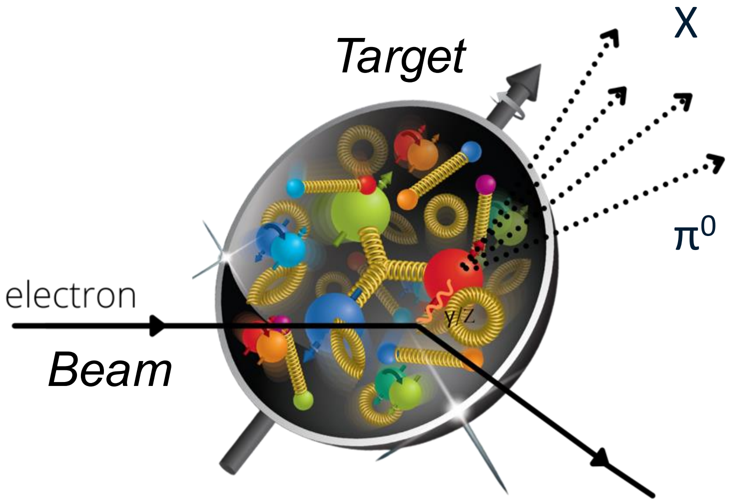
MOTIVATION

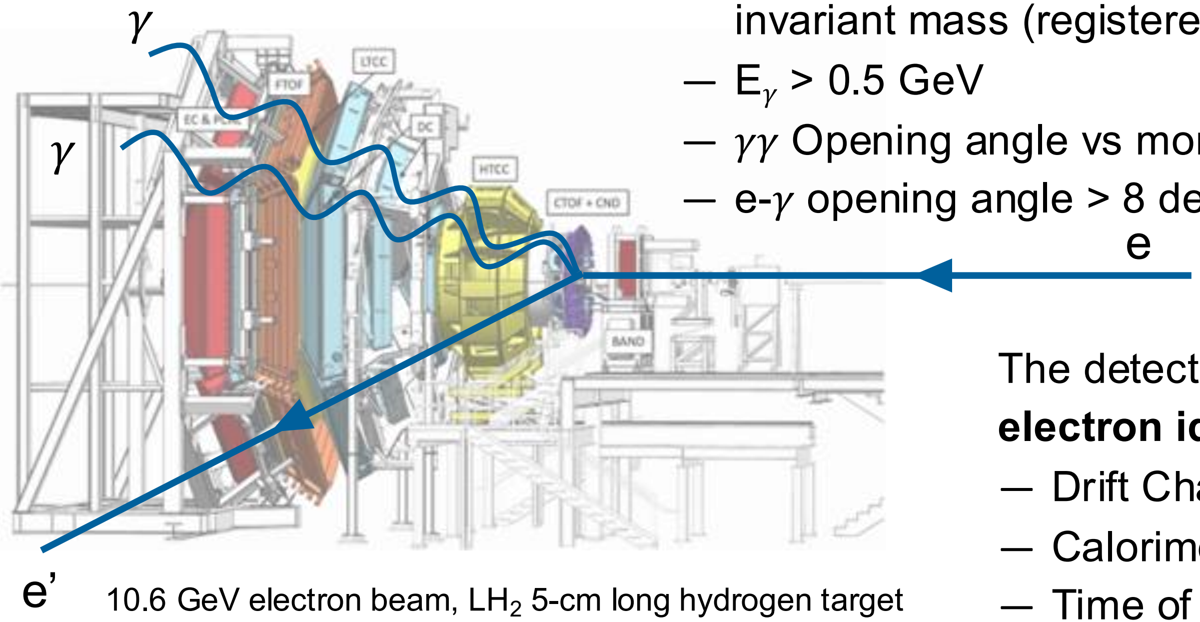
- Neutral pion Semi-Inclusive Deep Inelastic Scattering Multiplicities measure the probability of producing a hadron (π^0) per DIS event
- Multiplicity measurements uniquely link hadronization with the proton's internal transverse motion, advancing both FF determinations and our 3D understanding of proton structure
- The **z** - dependence constrains **fragmentation functions (FFs):** how colored partons turn into color-neutral hadrons
- The $\boldsymbol{P_T^2}$ **-** 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



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

CLAS12

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



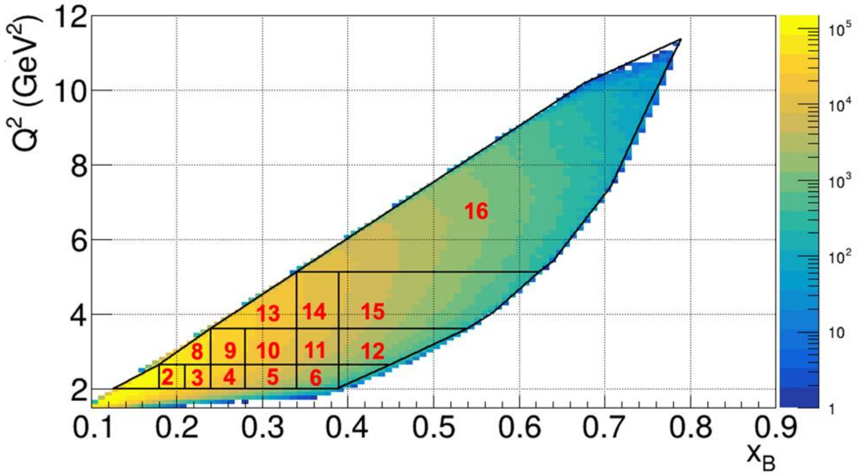
10.6 GeV electron beam, LH_2 5-cm long hydrogen target

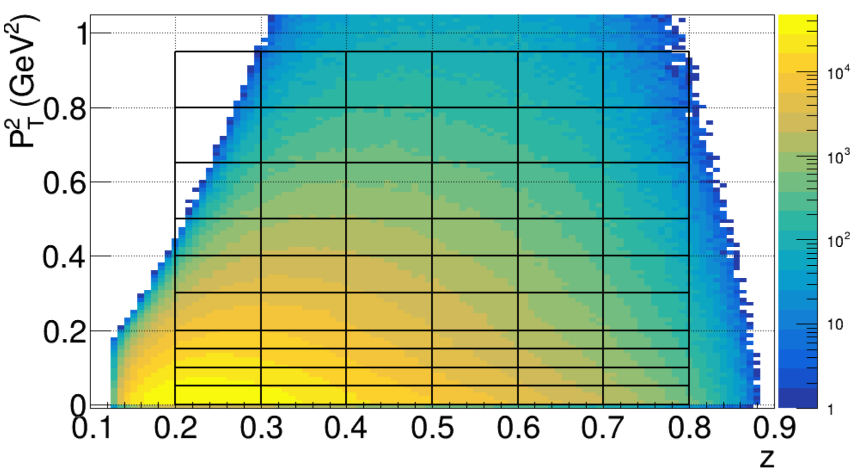
- **π^0 candidates** are reconstructed from photon pairs invariant mass (registered in Calorimeters)
- $E_\gamma > 0.5$ GeV
- $\gamma\gamma$ Opening angle vs momentum cut
- e-γ opening angle > 8 deg

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

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

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

MULTIPLICITY

What do we extract?

Corrected SIDIS yield

Radiative Corrections

Raw Event Yield

Background

$$N^{h,\,\mathrm{corr}}_{ijmn} = C^{h}_{\mathrm{rad}\,ijmn} \sum_{k} \frac{N^{h,\mathrm{raw}}_{ijmn} - N^{h,\mathrm{bkg}}_{ijmn}}{A^{h}_{ijmnk}}$$

k is φ bin

Acceptance and Efficiency Correction

$$M^{h}_{ijmn} = \frac{1}{\Delta z_m \, \Delta P^2_{T,n}} \frac{N^{h,\,\mathrm{corr}}_{ijmn}}{N^{\mathrm{DIS},\,\mathrm{corr}}_{ij}}, \quad (i,j,m,n) \equiv (x_B\text{-bin},\, Q^2\text{-bin},\, z\text{-bin},\, P^2_T\text{-bin})$$

z-P_T^2 bin size

Radiative Corrections

Raw Event Yield

Corrected DIS yield

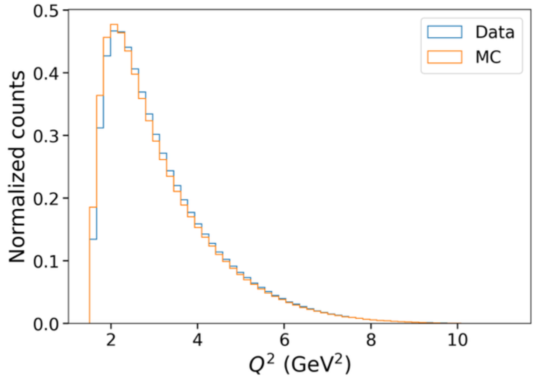
$$N^{\mathrm{DIS},\,\mathrm{corr}}_{ij} = C^{\mathrm{DIS}}_{\mathrm{rad}\;ij} \frac{N^{e,\mathrm{raw}}_{ij}}{A^{e}_{ij}}$$

Acceptance and Efficiency Correction

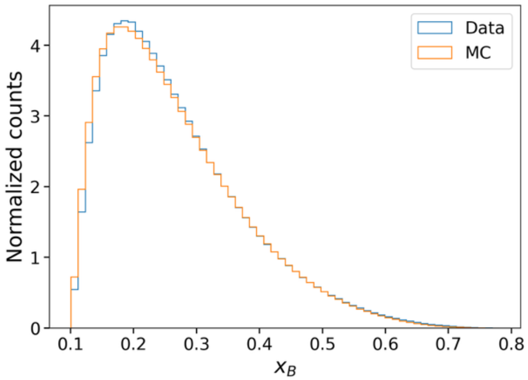
- Electron-side efficiencies partially cancel out in the ratio

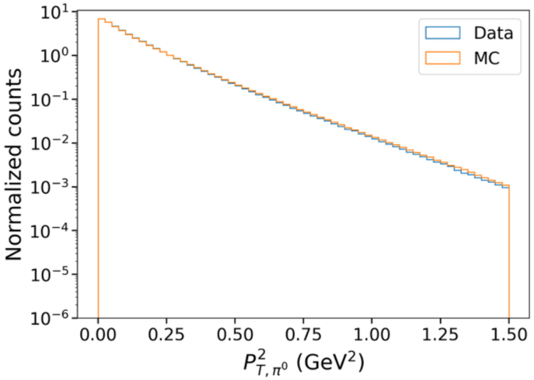
MONTE CARLO

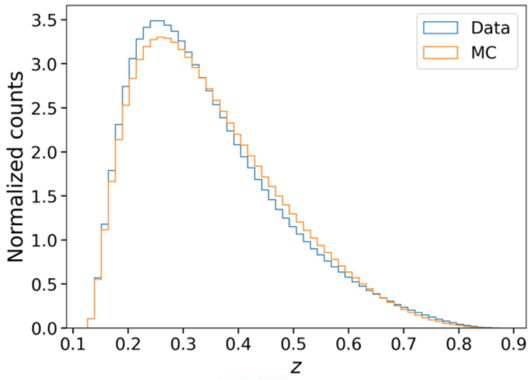
Event Generator used for the Acceptance



- CLASDIS-EG built on LEPTO
- Lund string model as in PYTHIA/JETSET
- LO electroweak DIS (arbitrary lepton polarization); O(α) 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 GeV^2, W > 2 GeV)







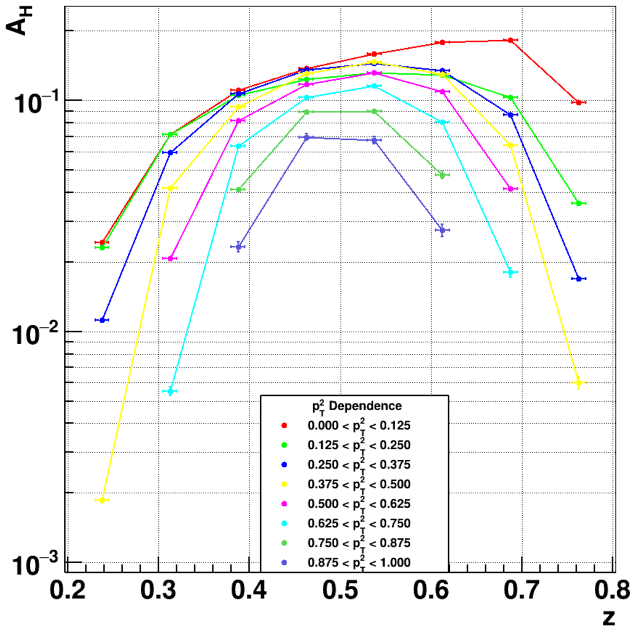
histograms normalized to unit area

ACCEPTANCE AND EFFICIENCY CORRECTION

Deconvolution

- Method: bin-by-bin (efficiency) 5D(x_B, Q^2, z, P_T^2, φ_h) correction
- Per-bin efficiency: $\varepsilon_i = \frac{N_{rec,i}}{N_{gen,i}}$ (reconstructed / generated)
- Deconvolved yield: $y_i = \varepsilon_i \cdot x_i$, where x_i is the measured yield
- Limitation: does not track bin migrations (i -> j); performance depends on generator and detector-simulation accuracy
- Next steps: accumulate more MC to enable matrix-based multidimensional unfolding of migrations

x-Q² Bin 4 : A_H(z)

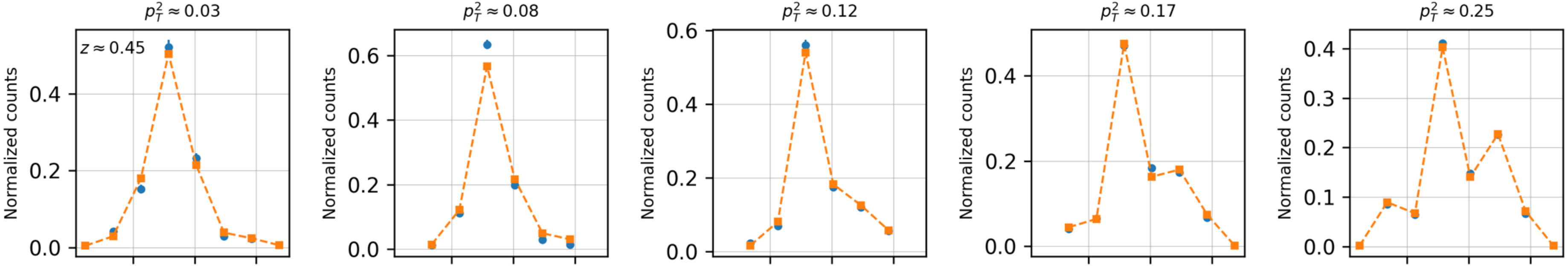


Φ DEPENDENCE

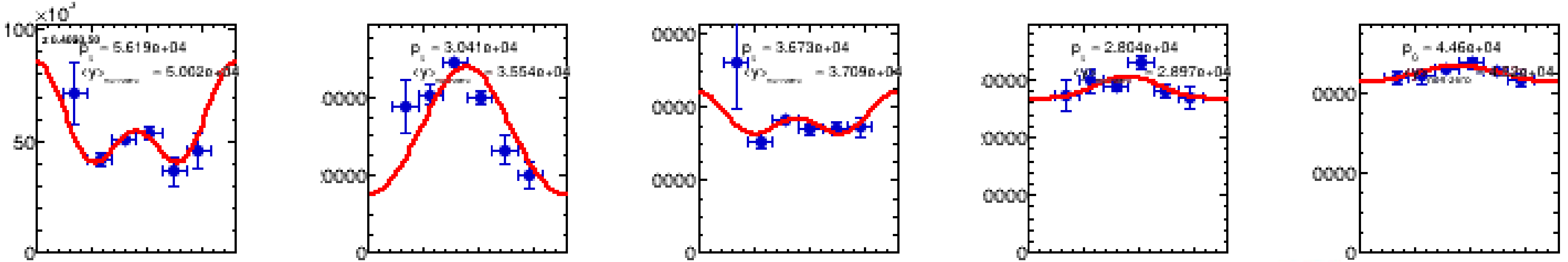
Data and Simulation ϕ_h spectra

- Spectra normalized to the unit area

- Simulation
- Data



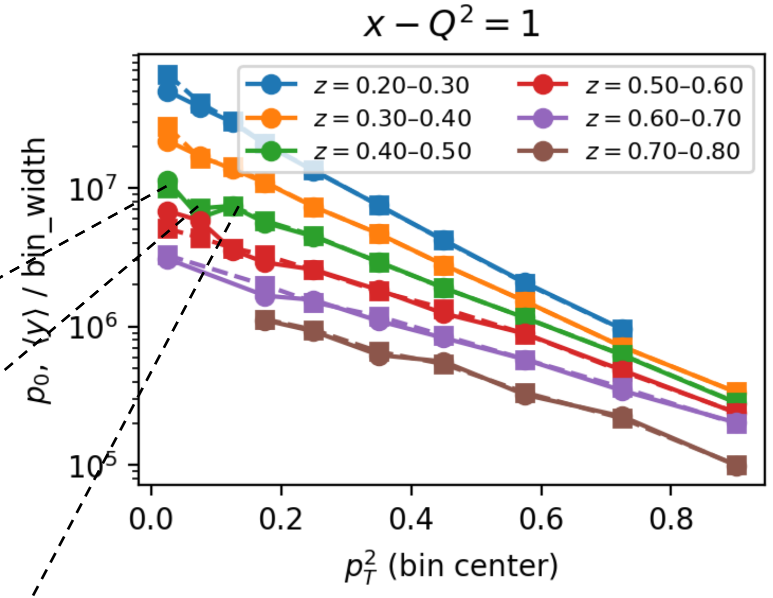
- Acceptance corrected ϕ spectra

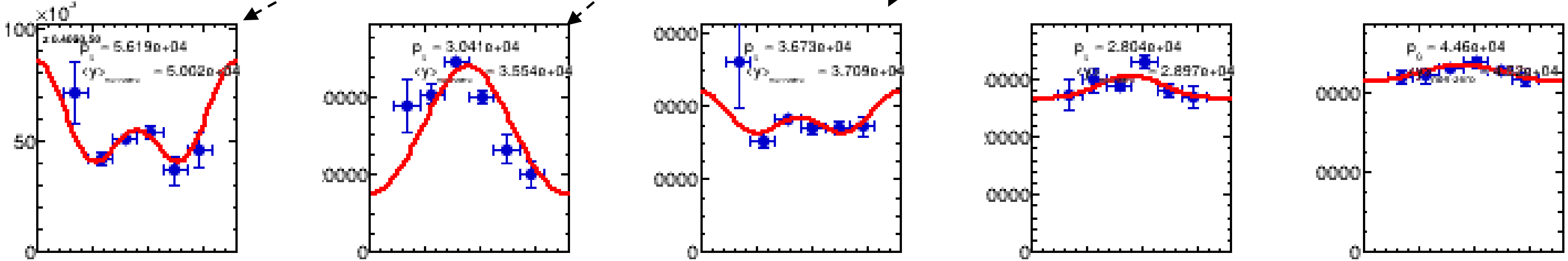


Φ DEPENDENCE

Data and Simulation ϕ_h spectra

- Fits can change the sign and cause structures in Mh
- Greg's AI photo ID may help with coverage and statistics
- If nothing helps, I will drop some data points

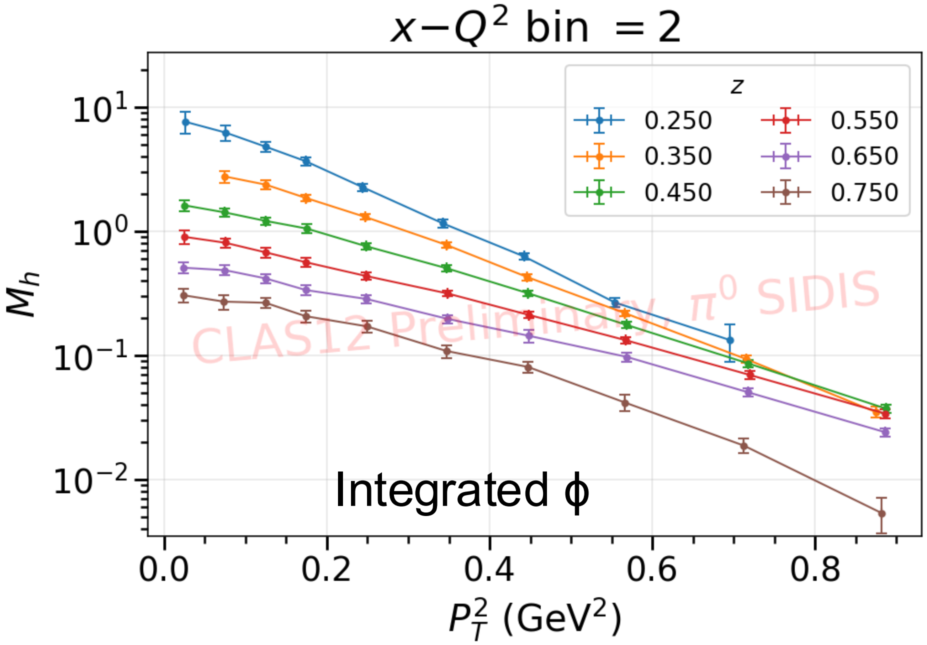


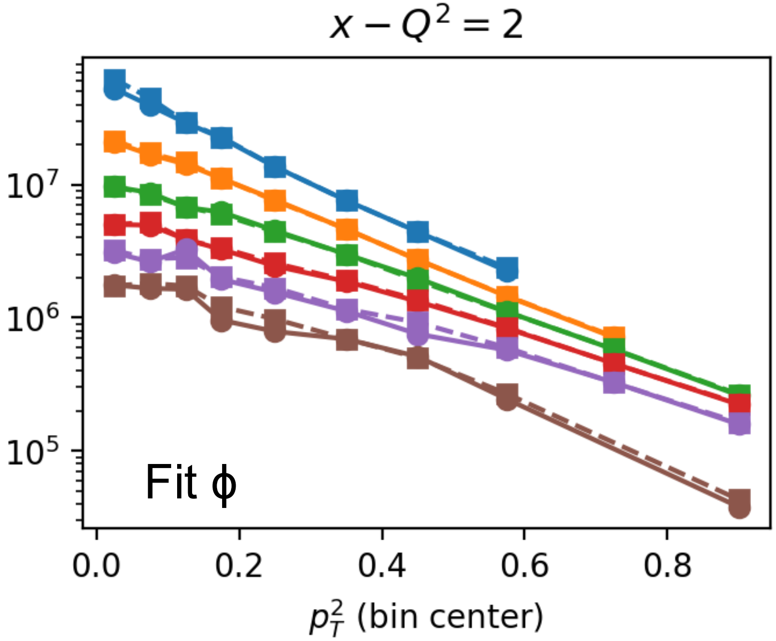


SIDIS YIELD

$N_{sidis}(p_T^2)$ for selected x-Q² = 2

- Left plot is normalized using DIS yield

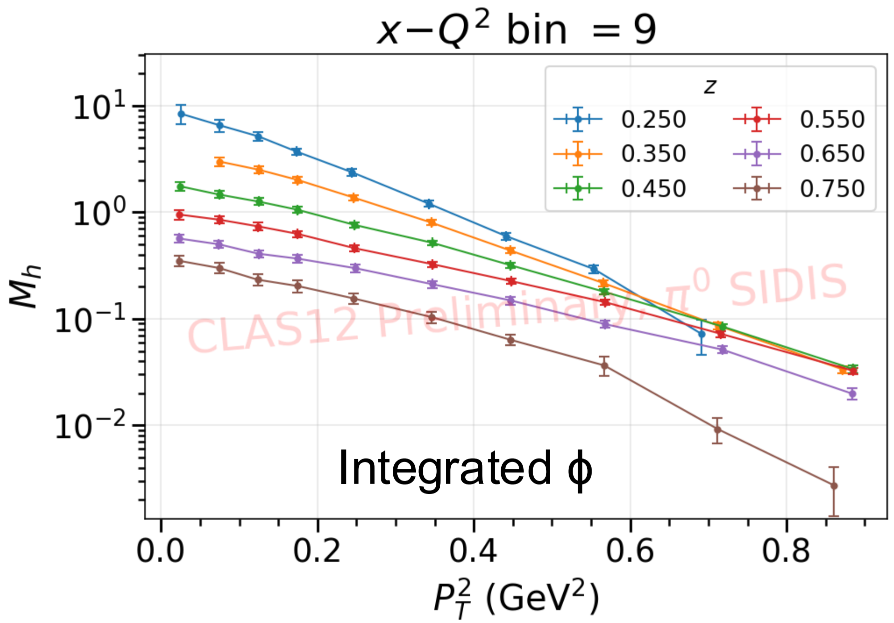


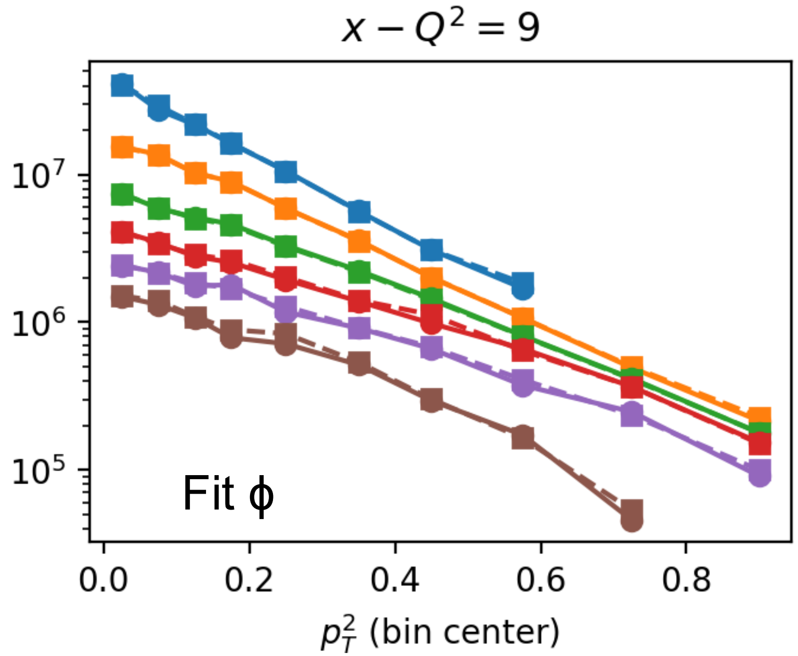


SIDIS YIELD

$N_{sidis}(p_T^2)$ for selected x-Q^2 = 9

- Left plot is normalized using DIS yield

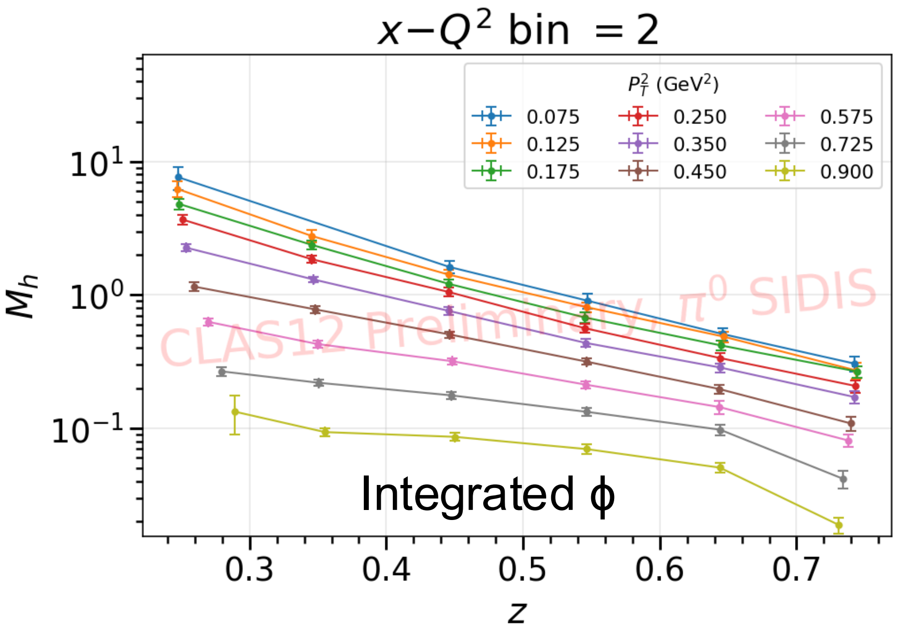


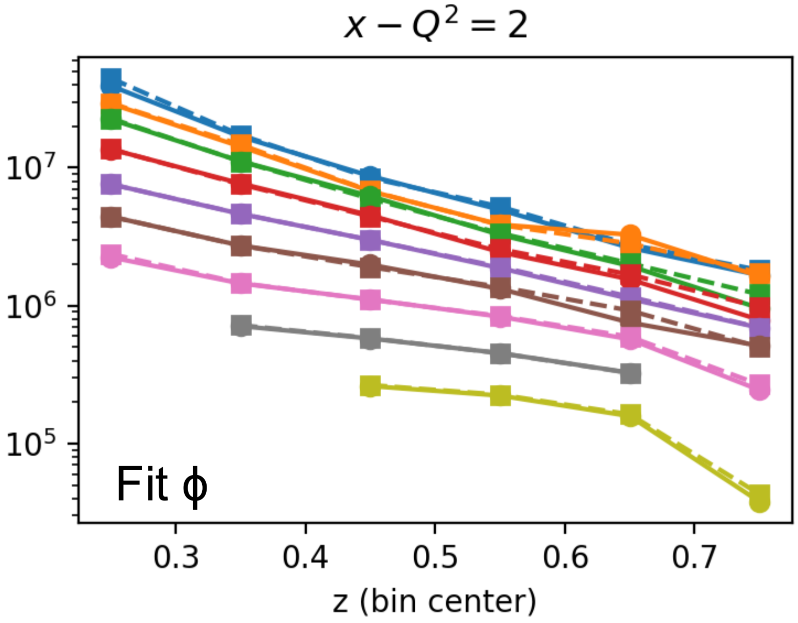


SIDIS YIELD

$N_{sidis}(z)$ for selected x-Q^2 = 2

- Left plot is normalized using DIS yield



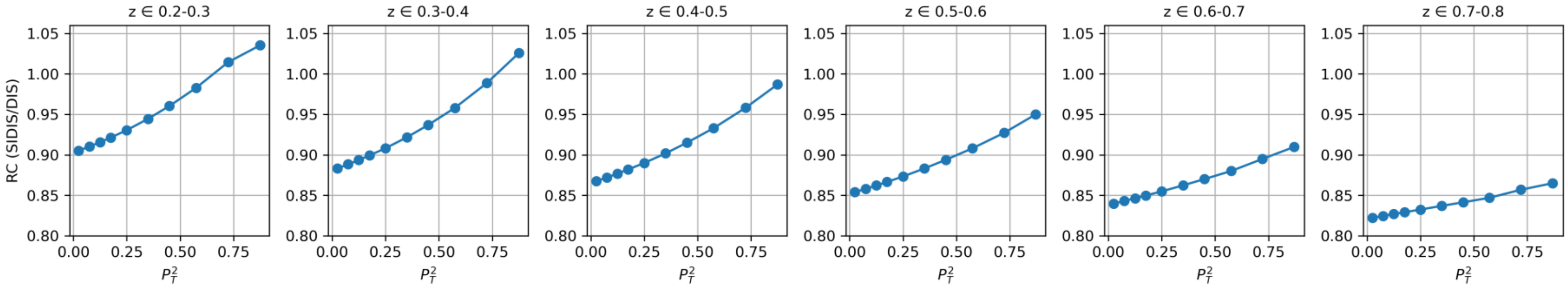


RADIATIVE CORRECTIONS

HAPRAD for SIDIS

$$\mathrm{RC}_{\mathrm{M_h}} = \frac{RC_{SIDIS}}{RC_{dis}}$$

- 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)
- Currently the exclusive radiative tail is evaluated using MAID2007 input: https://maid.kph.uni-mainz.de/maid2007/cross.html
- AAO_RAD will be used when we have enough MC
- Contributions from the ρ and ω channels are not included in the present implementation
- DIS correction is based on Mo-Tsai approach



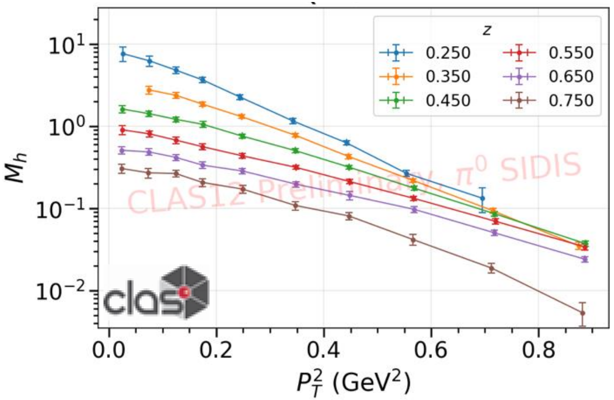
$0.18 < x < 0.21$, $2.0 < Q^2 < 2.66$ GeV^2

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

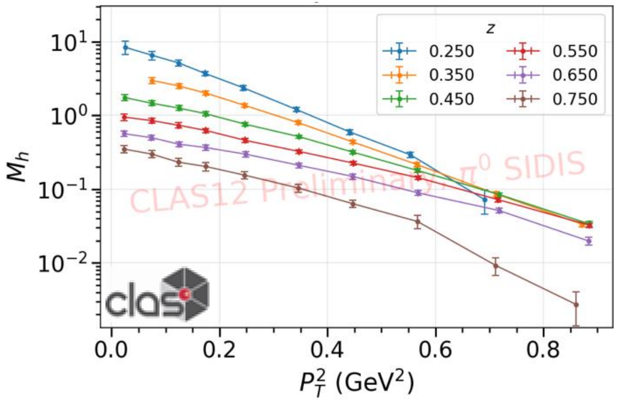
RESULTS

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

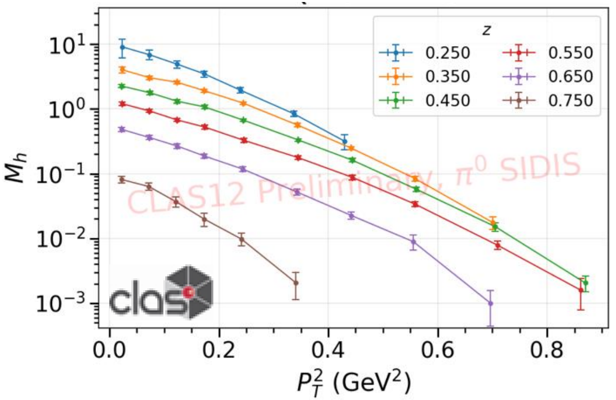
$0.18 < x < 0.21,\ 2.0 < Q^2 < 2.66\ \mathrm{GeV}^2$



$0.24 < x < 0.28,\ 2.66 < Q^2 < 3.63\ \mathrm{GeV}^2$



$0.39 < x < 0.62,\ 3.63 < Q^2 < 5.12\ \mathrm{GeV}^2$



- LO, gaussian approximation:

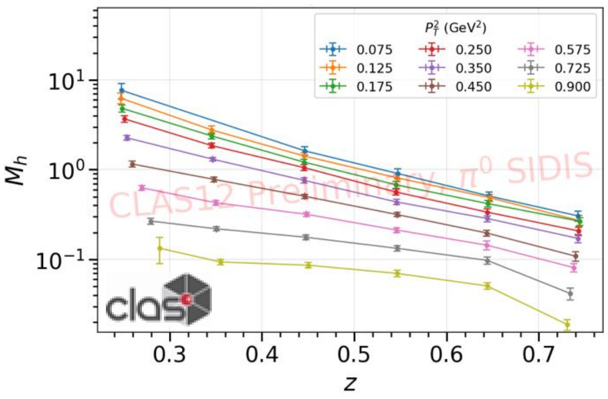
$$\frac{d^2 M^h}{dz\, dP_T^2} = \left(\frac{d^4\sigma}{dx\, dQ^2\, dz\, dP_T^2}\right) \Big/ \left(\frac{d^2\sigma^{\mathrm{DIS}}}{dx\, dQ^2}\right) = \frac{N}{\pi\langle P_T^2\rangle} \exp\left(-\frac{P_T^2}{\langle P_T^2\rangle}\right)$$

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

RESULTS

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

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



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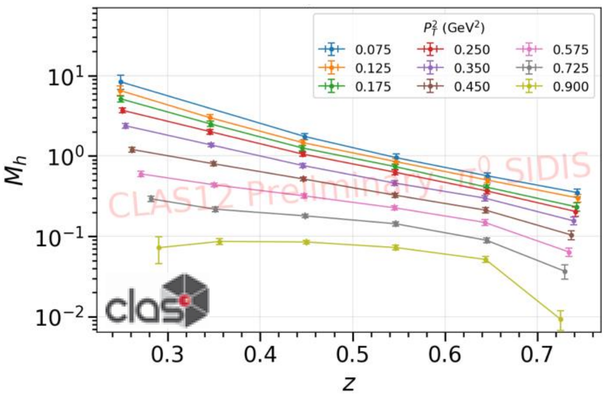

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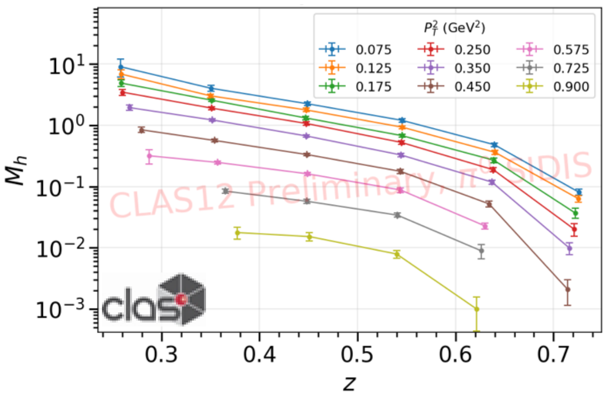


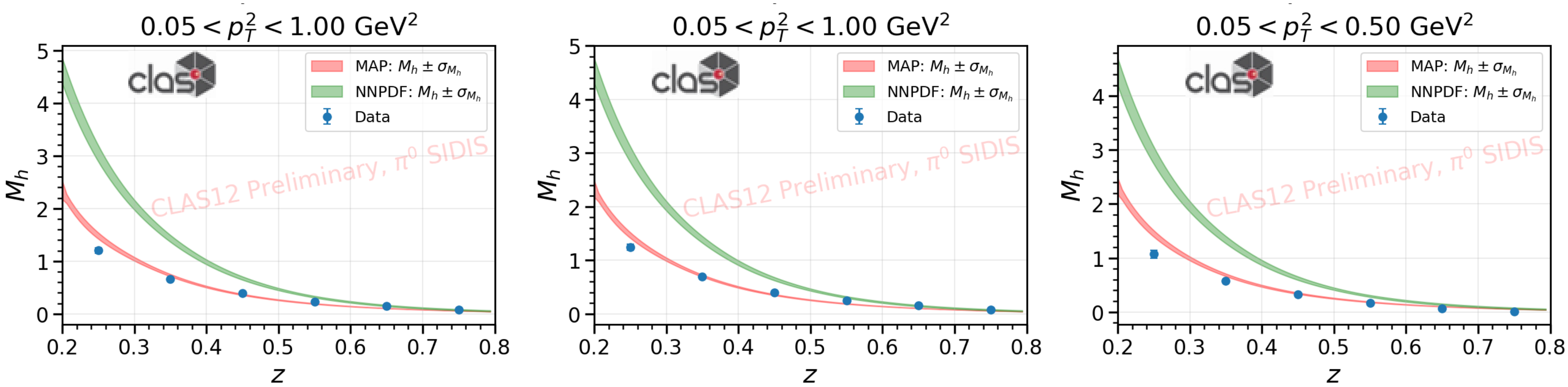
- ln($M_h(z)$) is approximately linear, but drops at large z due to the $M_x > 1.5$ phase-space cut
- Only statistical uncertainties are shown

RESULTS

P_T^2 integrated multiplicity:

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

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



0.18 < x < 0.21, 2.0 < Q^2 < 2.66 GeV^2 0.24 < x < 0.28, 2.66 < Q^2 < 3.63 GeV^2 0.39 < x < 0.62, 3.63 < Q^2 < 5.12 GeV^2

- 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

CONCLUSIONS AND OUTLOOK

- Preliminary Neutral pion SIDIS Multiplicities (x_B, Q^2, z, P_T^2) at CLAS12 are available
- After integrating over P_T^2 , multiplicities vs. z follow the trend of LO predictions using MAPFF fragmentation functions and CT10nlo PDFs
- The data will provide new constraints on unpolarized TMD PDFs and fragmentation functions (FFs) and enabling tests of isospin symmetry in FFs

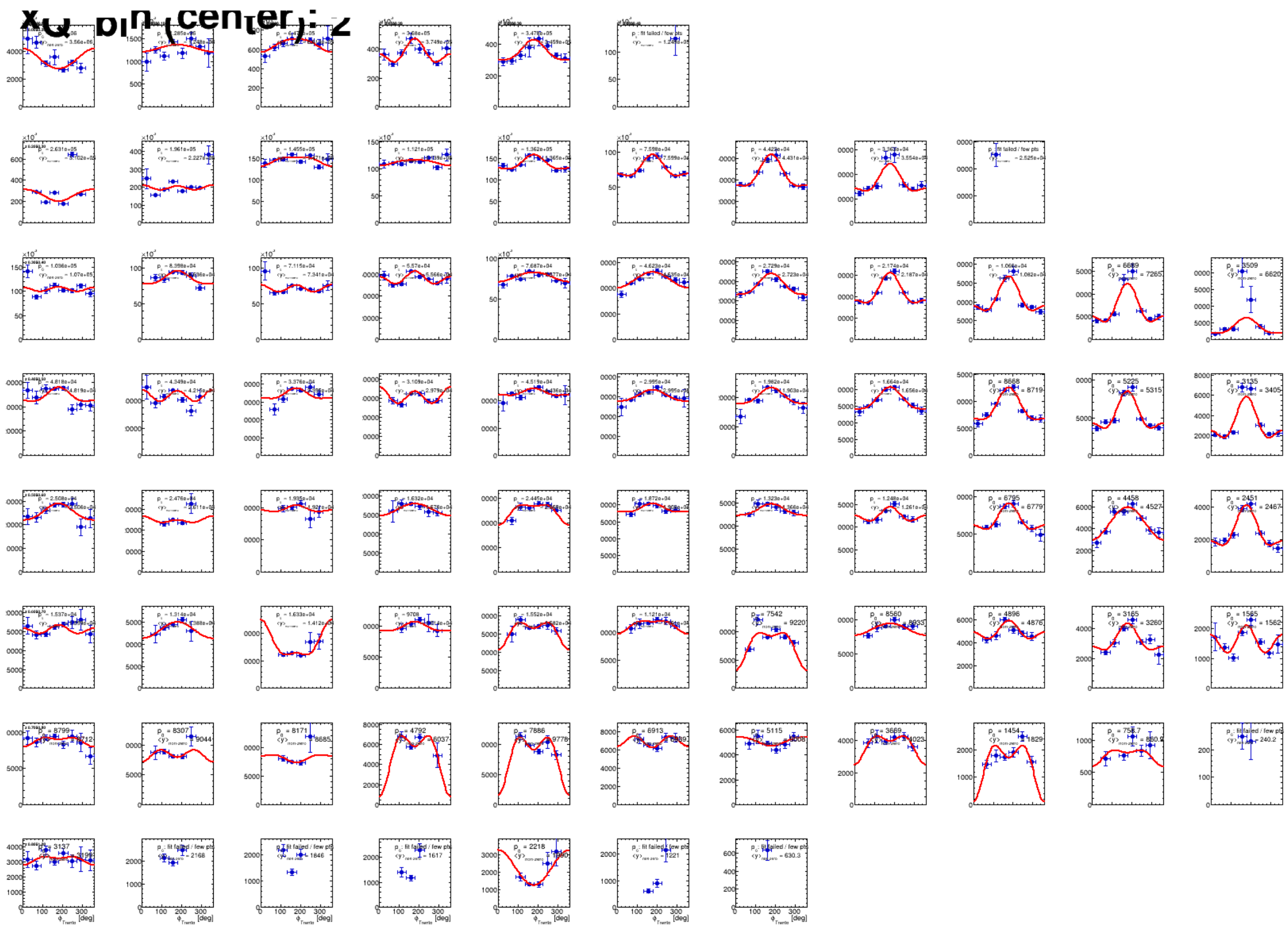
In progress:

- Accumulate more MC to enable matrix-based multidimensional unfolding of migrations
- Estimate systematic uncertainties

THANK YOU!

PHI FITS

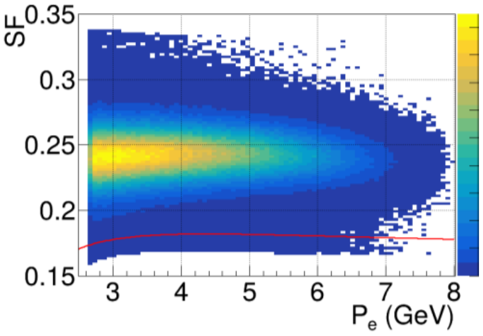
xQ2 =2



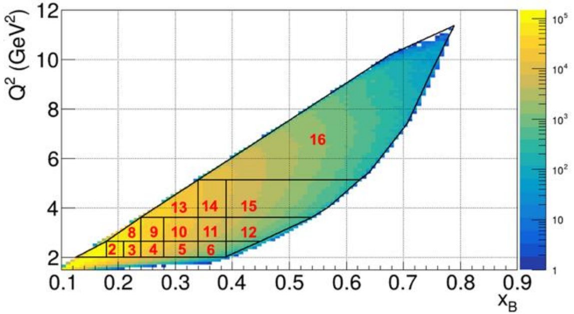
PID AND EVENT SELECTION

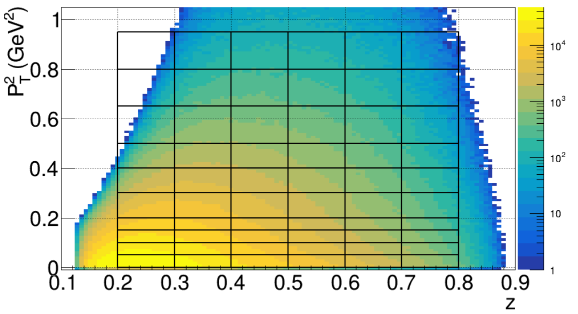
Starts with CLAS12 reconstruction algorithm

- 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-γ 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
  - $\alpha_{\gamma\gamma} > 6 \cdot \mathrm{Exp}(1 - p_\pi) + 0.5$ deg





MULTIPLICITY

What do we extract?

Radiative Corrections

Raw Event Yield

Background

Corrected SIDIS yield

$$N^{h,\,\mathrm{corr}}_{ijmn} = C^{h}_{\mathrm{rad}\,ijmn} \sum_{k} \frac{N^{h,\mathrm{raw}}_{ijmn} - N^{h,\mathrm{bkg}}_{ijmn}}{A^{h}_{ijmnk}}$$

k is φ bin

Acceptance and Efficiency Correction

$$M^{h}_{ijmn} = \frac{1}{\Delta z_m \, \Delta P^2_{T,n}} \frac{N^{h,\,\mathrm{corr}}_{ijmn}}{N^{\mathrm{DIS,\,corr}}_{ij}}, \quad (i, j, m, n) \equiv (x_B\text{-bin},\ Q^2\text{-bin},\ z\text{-bin},\ P^2_T\text{-bin})$$

z-P_T^2 bin size

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