NOVEMBER 18, 2026

π^0 SIDIS MULTIPLICITIES: SYSTEMATICS



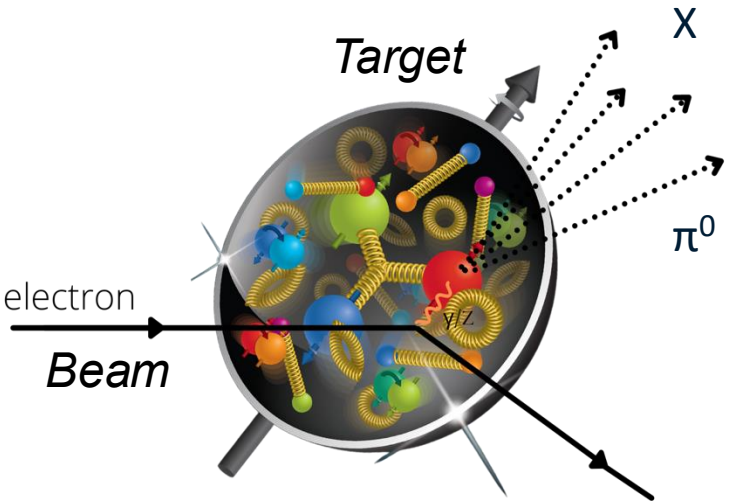
VALERII KLIMENKO
Postdoctoral Appointee

Jefferson Lab

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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 $\boldsymbol{P_T^2}$ **-** 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



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

SIDIS MULTIPLICITY

What do we extract?

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

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

z-P_T^2 bin size

Radiative Corrections

Raw Event Yield

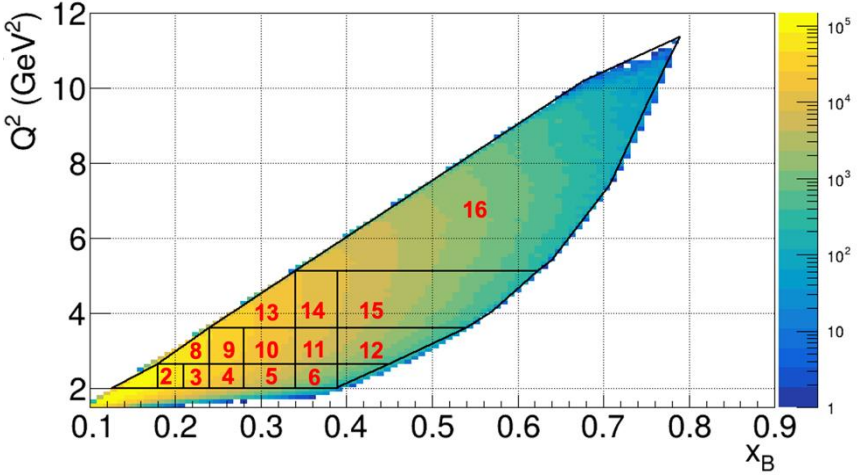
Corrected DIS yield

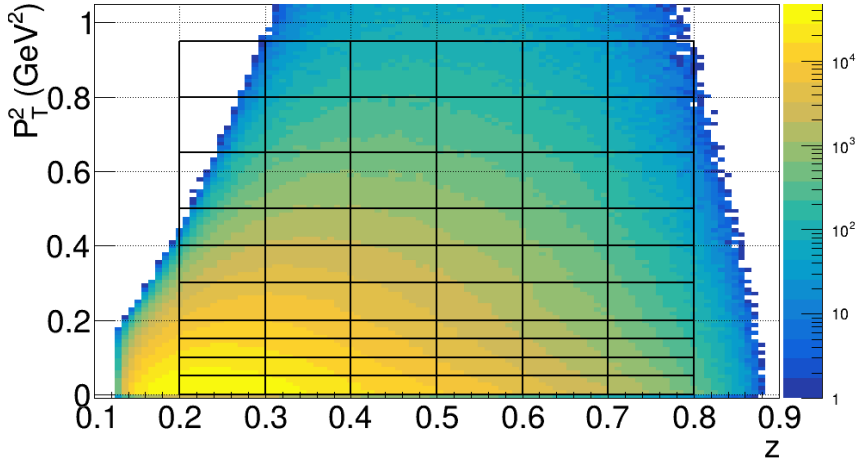
$$N^{\mathrm{DIS,\,corr}}_{ij} = C^{\mathrm{DIS}}_{\mathrm{rad}\ ij} \frac{N^{e,\mathrm{raw}}_{ij}}{A^{e}_{ij}}$$

Acceptance and Efficiency Correction

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

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



SYSTEMATICS

PARTICLE ID SYSTEMATICS

Sources

- SF cut, 1σ variation
- PCAL Fiducial cut (e and g), ± 5
- Photon beta, ± 0.03
- Electron-photon separation, 8 ± 2 deg
- Photon momentum, $0.5 \pm 0.05\ GeV$
- Electron vertex cut, ± 0.5 cm
- Momentum corrections, 5% variation

- Other procedures that estimated separately
  - Photon “efficiency” correction
  - Radiative corrections

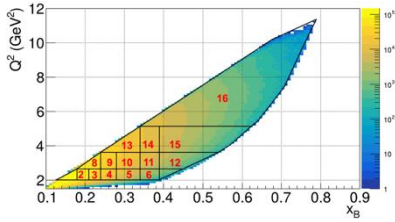
PARTICLE ID SYSTEMATICS

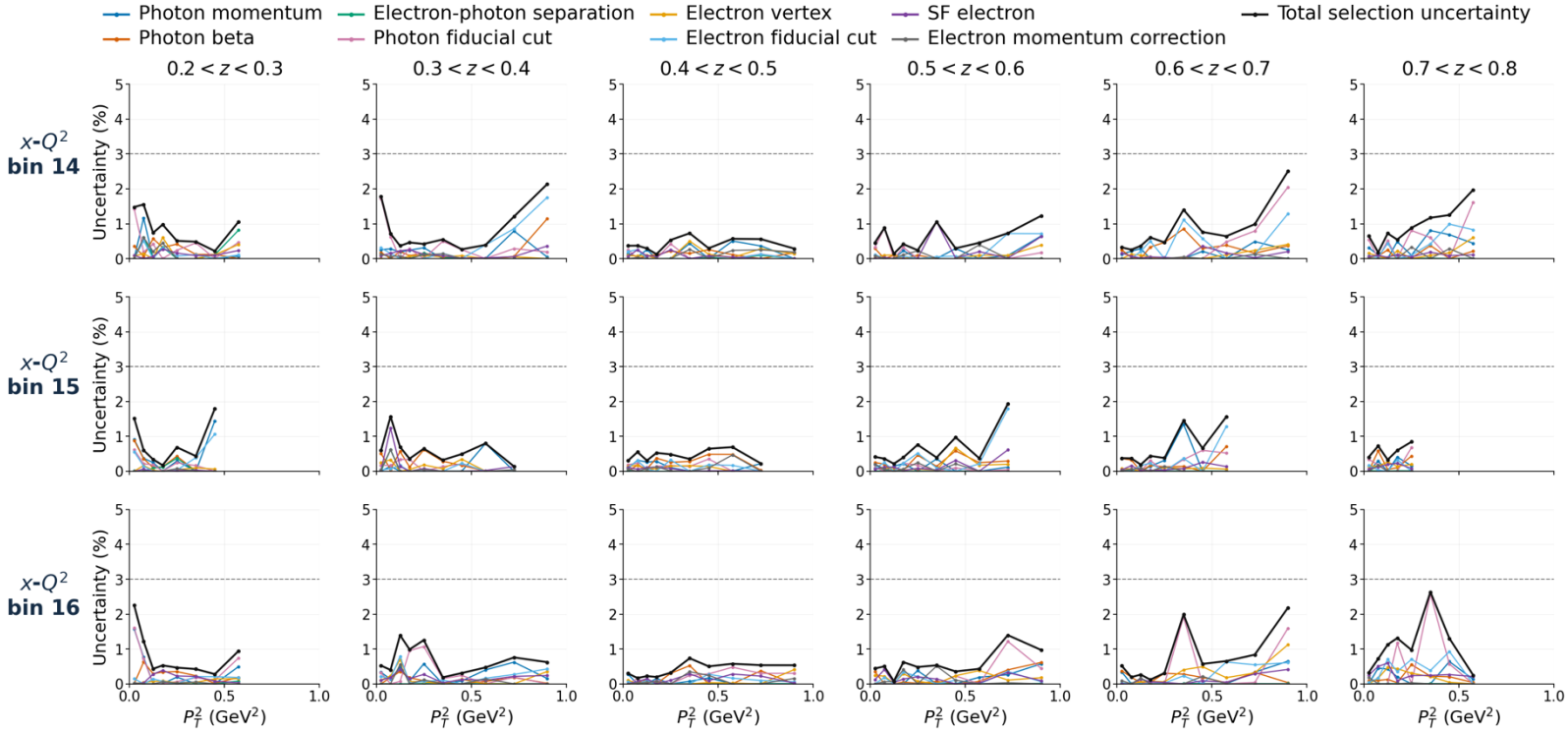
Procedure

- A cut/procedure was varied
- Every acceptance corrected point (x_B, Q^2, z , P_T^2, φ_H) was tested for statical significance:
  - Compute the yield difference: $\mathrm{D} = \mathrm{Y}_{\mathrm{cut\ variation}} - \mathrm{Y}_{\mathrm{nominal}}$
  - Estimate statistic noise via Jackknife (k = 10 splits):
    - $\mathrm{D}_{-\mathrm{k}}$ is D with “k” split removed
    - $\sigma_{\mathrm{jk}}^2 = \frac{9}{10}\sum_{\mathrm{k}=1}^{10}(\mathrm{D}_{-\mathrm{k}} - \overline{\mathrm{D}})$
    - If difference $\mathrm{Z} = \frac{\mathrm{D}}{\sigma_{\mathrm{jk}}}$ is within two standard deviations of zero (abs < 2), the point is replaced with the nominal one
- Integrate over and φ_H
- Uncertainty per source: $\delta_s(\%) = \frac{|M_{\mathrm{low}} - M_{\mathrm{nom}}| + |M_{\mathrm{high}} - M_{\mathrm{nom}}|}{2|M_{\mathrm{nom}}|} \times 100,$
- added in quadrature $\delta_{\mathrm{tot}} = \sqrt{\sum_s \delta_s^2}.$

PARTICLE ID SYSTEMATICS

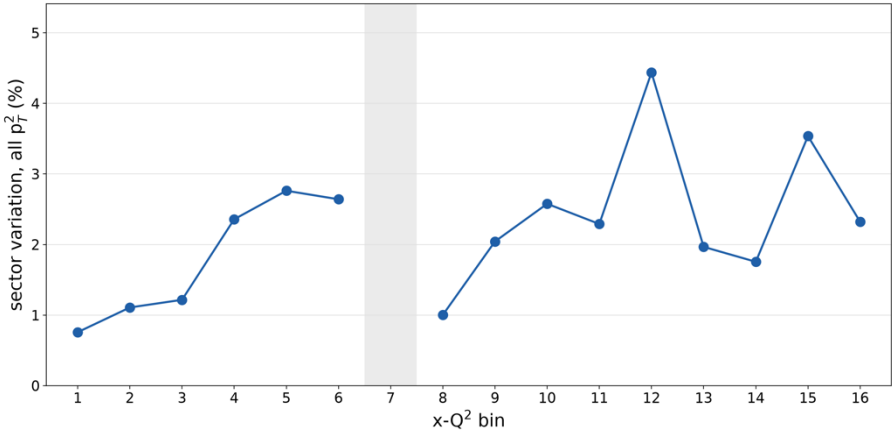
Uncertainty for three x-Q^2 bins





SECTOR DEPENDENCE

- Multiplicities were measured in each sector
- Sector was determined by electron
- Normalization to this sector DIS yield



- The φ_H fit error multiplied by sqrt(chi2/ndf) to match the scatter actually seen
- For (x_BQ^2, z , P_T^2) bin, the variation is sqrt(raw² − statistical²), **if** the chi2 test over the six sectors gives $p < 0.05$
- Raw is the standard deviation of the six values divided by their mean
- Statistical spread: what the six errors alone would produce, sqrt(mean of the squared errors) divided by the mean.



UNFOLDING CLOSURE TESTS AND UNCERTAINTY

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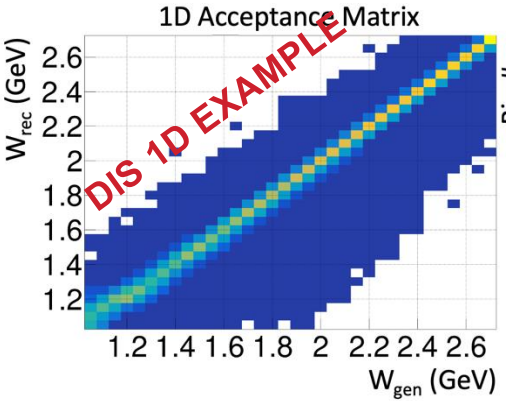
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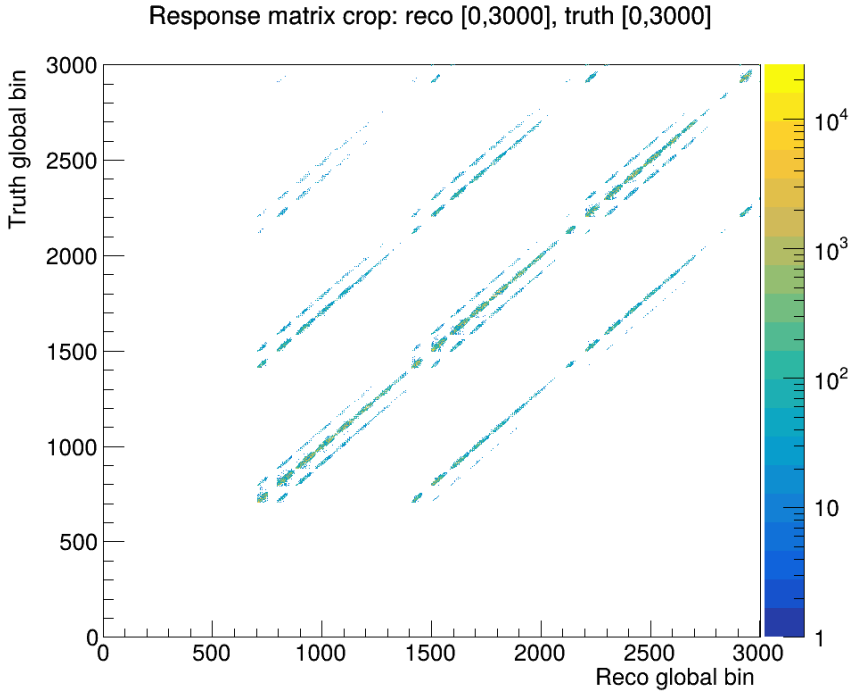
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ACCEPTANCE AND EFFICIENCY CORRECTION

Bayesian Deconvolution

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





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CLOSURE TESTS

Closure Bias

- **Q:** if we feed the unfolding fake data whose true answer we know, how far off is the result, and is that offset real?

  — a 5-fold MC closure. The response is built from 4/5 of the MC and the remaining 1/5 is treated as pseudo-data, repeated for each of the K = 5 folds.

  — Per bin and fold K, compare unfolded yield U with true yield T

$$\mathrm{rel}_K = \frac{\sum_\phi U_K}{\sum_\phi T_K} - 1$$

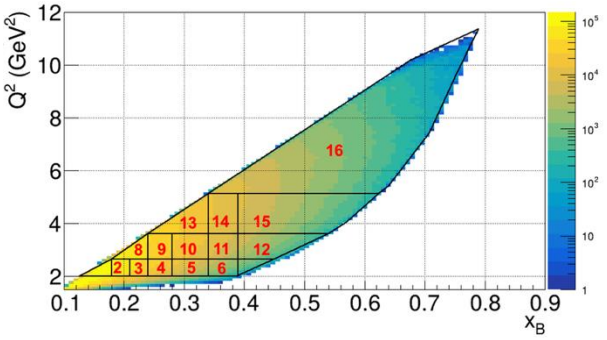
  — Bias b = mean of rel_K over the 5 folds

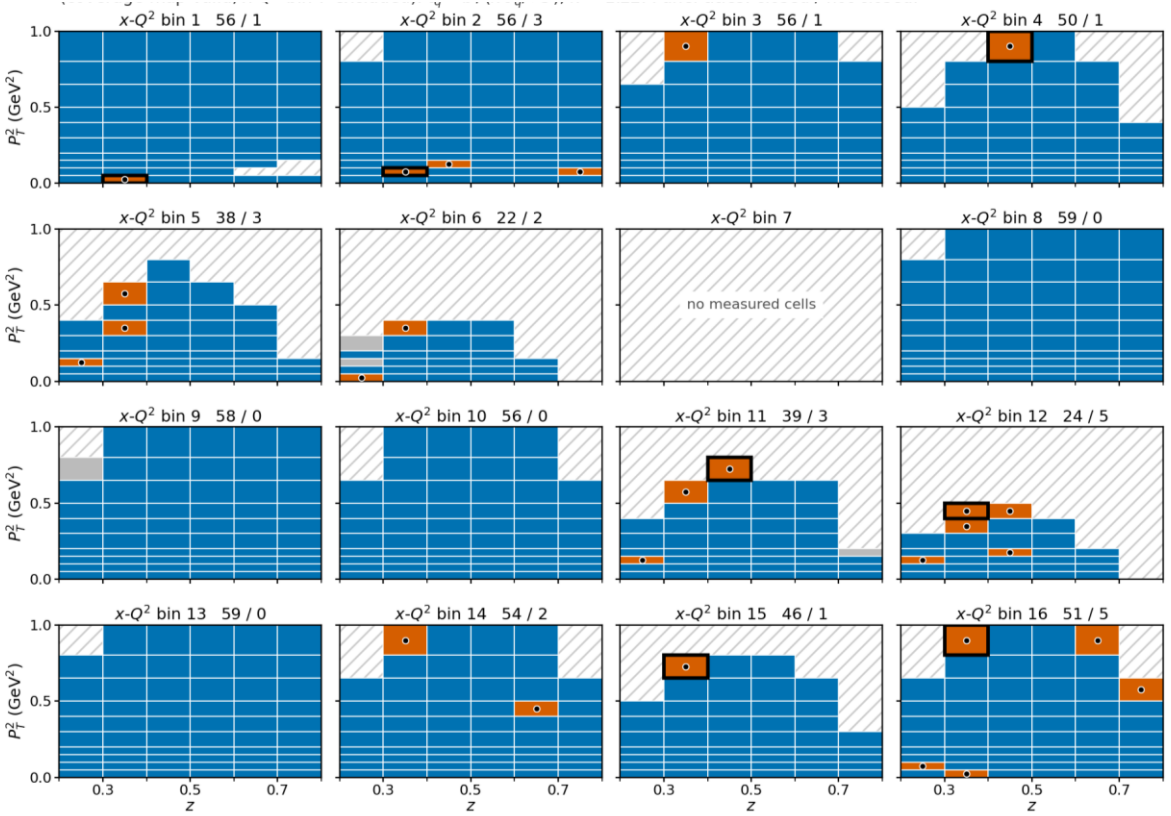
  — Closed: $|b| < 2\sigma$, with σ the statistical error of the fold average, σ from the quoted unfolding errors

CLOSURE TESTS

Closure Bias Results

- A few not closed bins (orange) are mostly at the edge of the phase space





CLOSURE TESTS

Data Driven Prior

- **Q:** the MC truth used as the prior does not look exactly like the data. How much does the answer change if it did?
  - Split MC in 1:8 (pseudo-data (**A**) to response matrix (**B**))
  - Reweight **A** to look like data (unfolded to truth, rec events inherits the w via truth matching)
  - keep a not weighted version of A
  - **B** Response Matrix is not weighted
  - Compute relative error for weighted and non weighted A:

$$\mathrm{rel}^{\mathrm{ind}} = \frac{\sum_\phi U^{\mathrm{ind}}}{\sum_\phi T^{\mathrm{ind}}} - 1 \qquad \mathrm{rel}^{\mathrm{data}} = \frac{\sum_\phi U^{\mathrm{data}}}{\sum_\phi T^{\mathrm{data}}} - 1$$

(U is the unfolded yield, and T is the true yield)

  - Taking the difference **d** = $\mathrm{rel}^{\mathrm{data}}$ – $\mathrm{rel}^{\mathrm{ind}}$ to isolate the effect of the shape mismatch (they share the same statistical fluctuations and the same method bias)
  - 8 splits performed with non-overlapping A selection
  - We get average of **d**, and n_c is the statistical uncertainty of that average
  - Systematic uncertainty $u = \sqrt{\bar{d}^2 - n_c^2}$

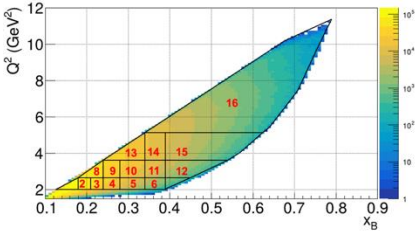
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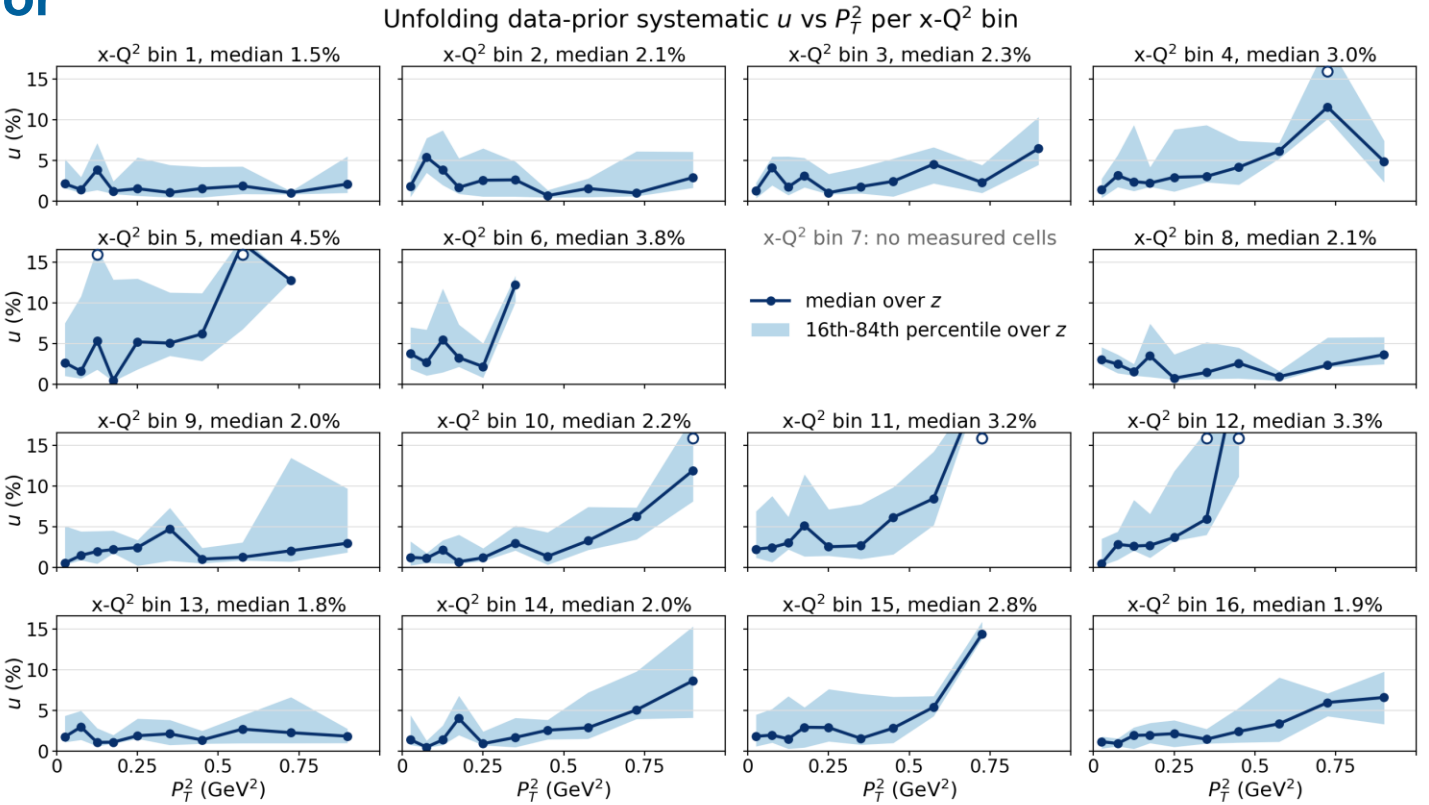
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CLOSURE TESTS

Data Driven Prior

- Median 2.25% over the 755 bins
- 16th-84th percentile 0.7-6.8%
- Grows with P_T^2





STATISTIC UNCERTAINTIES

MC Bootstrap (statistics)

- **Q:** the response matrix comes from a finite MC sample. How much does that limit the result?

  — 50 bootstrap copies of the MC, each event given a Poisson(1) weight

  — Data held fixed

  — The response, unfolding and φ fit are redone for each copy.

  — Uncertainty:

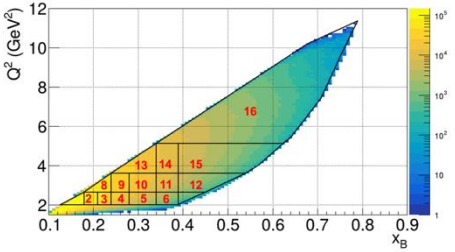
$$u_{\text{respMC}} = \frac{1}{|M_{\text{nom}}|}\sqrt{\frac{\sum_{i=1}^{N}(M_i - \bar{M})^2}{N-1}}$$

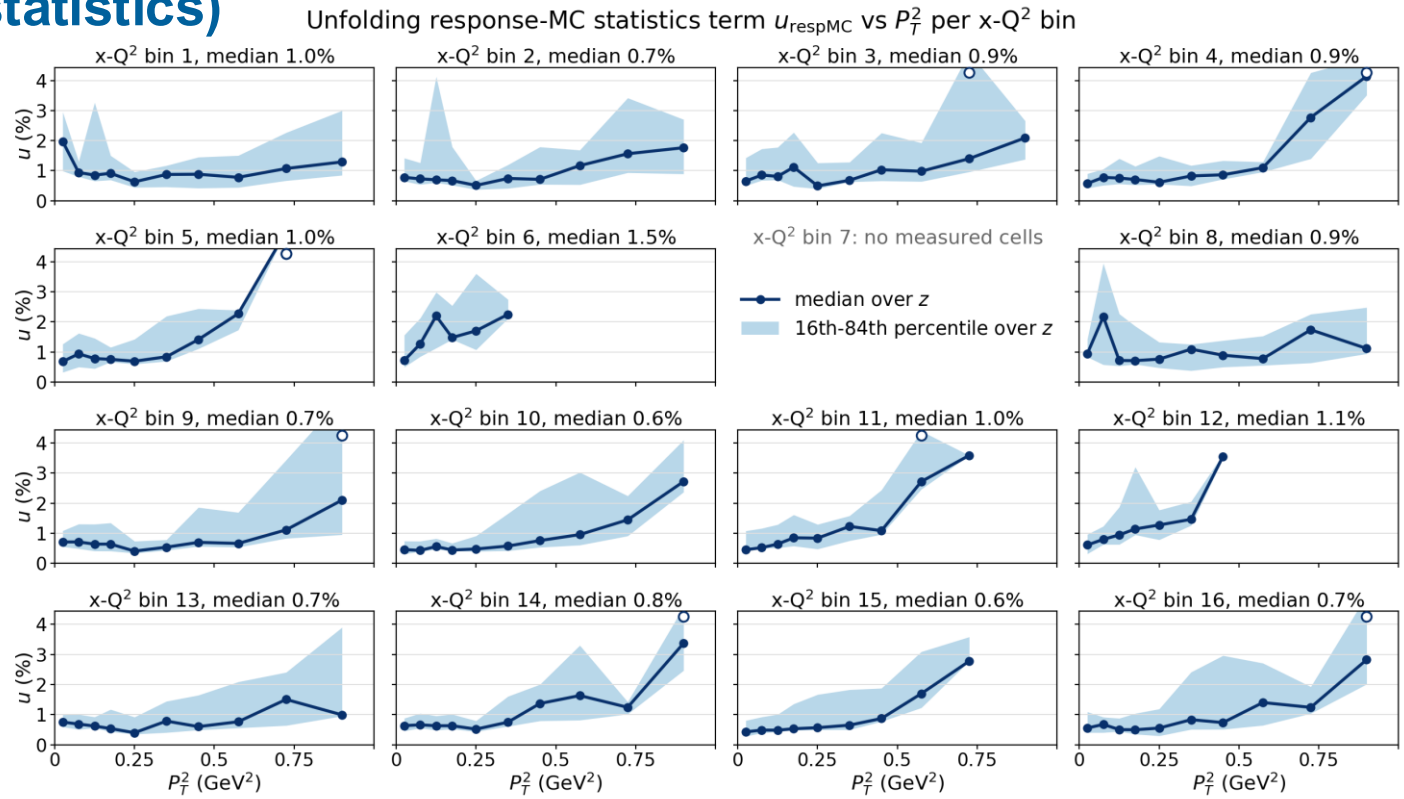
$\mathbf{M_i}$ is the multiplicity from bootstrap copy number i

STATISTIC UNCERTAINTIES

MC Bootstrap (statistics)

- Median 0.84%
- 16th-84th percentile 0.5-2.1%



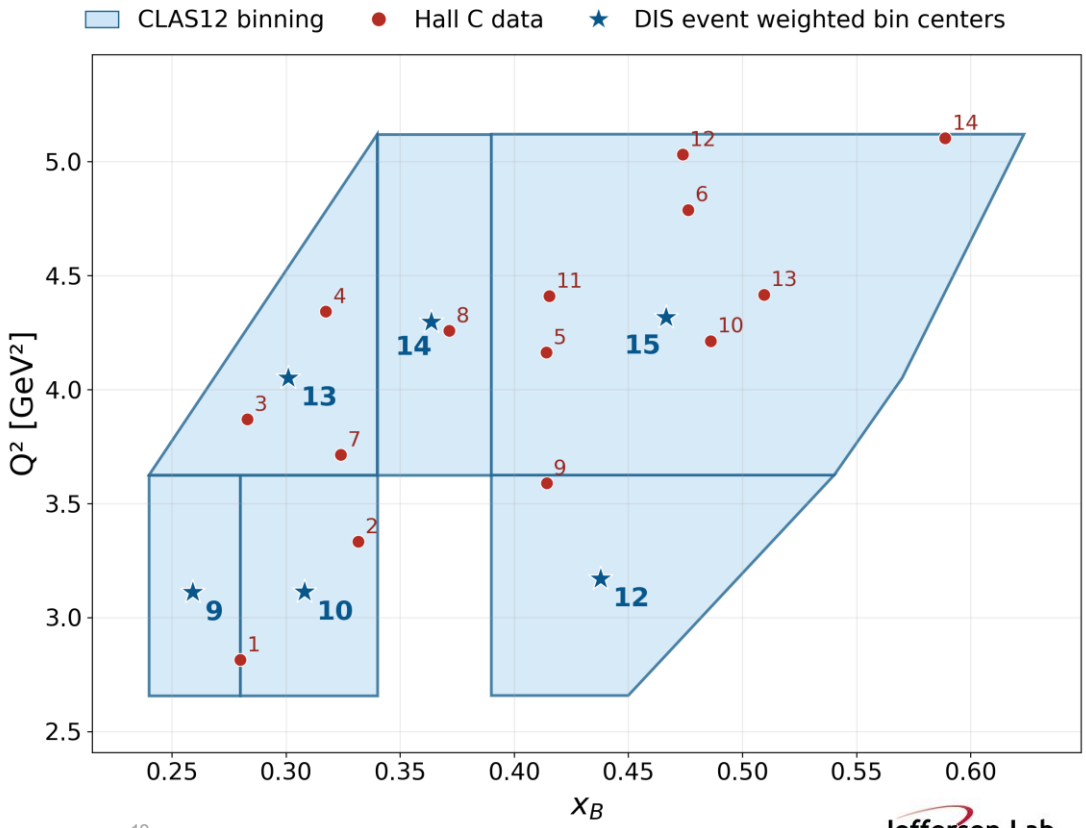




PRELIMINARY HALL C COMPARISON

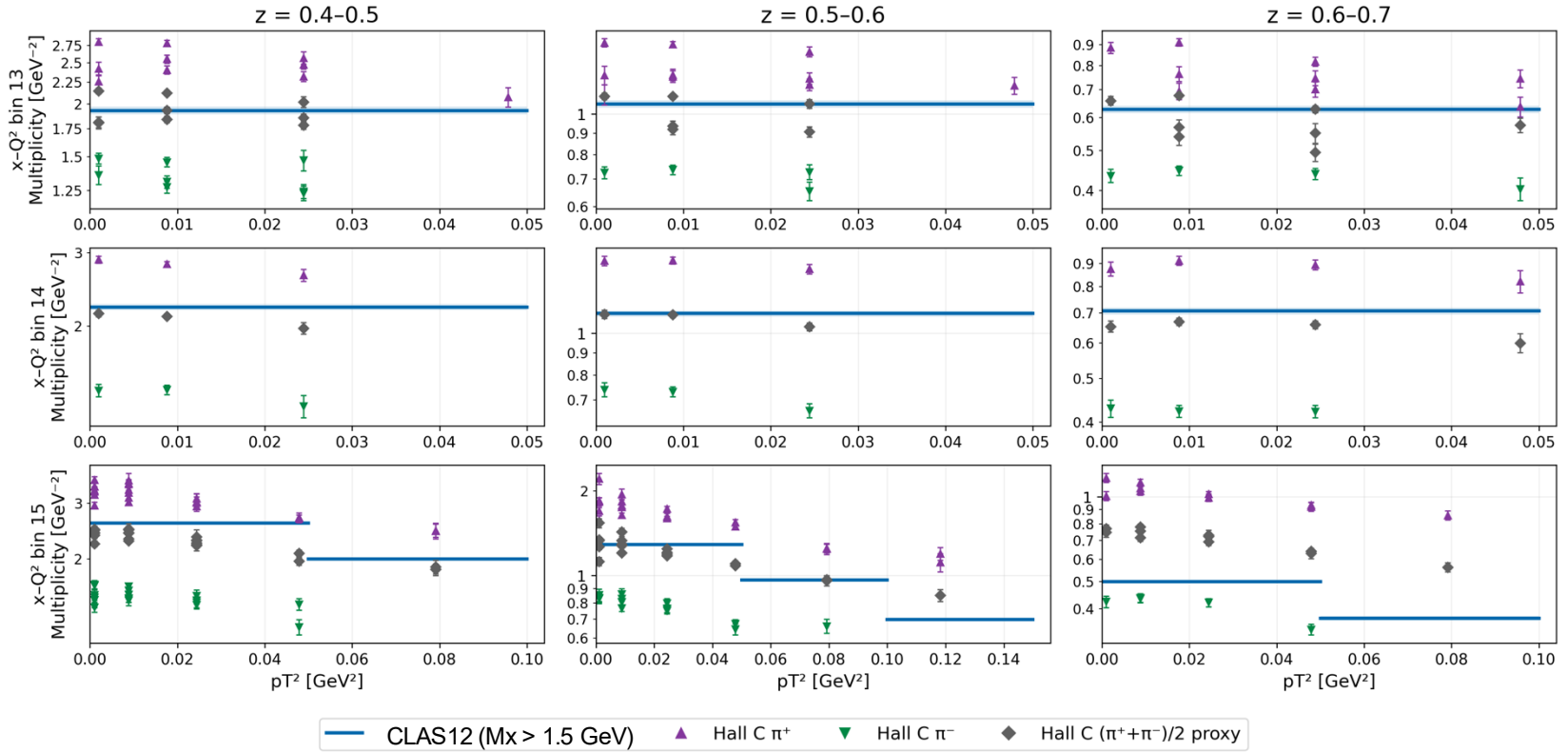
HALL C KINEMATICS OVERLAP

- Hall C - Phys. Rev. C **113**, 035205 – **Published 19 March, 2026**
- Physics Letters B, Volume 865, **2025**, 139485
- Stars mark the DIS event-weighted centers of the CLAS12 bins
- HERMES and COMPASS do not overlap the valid CLAS12 bins

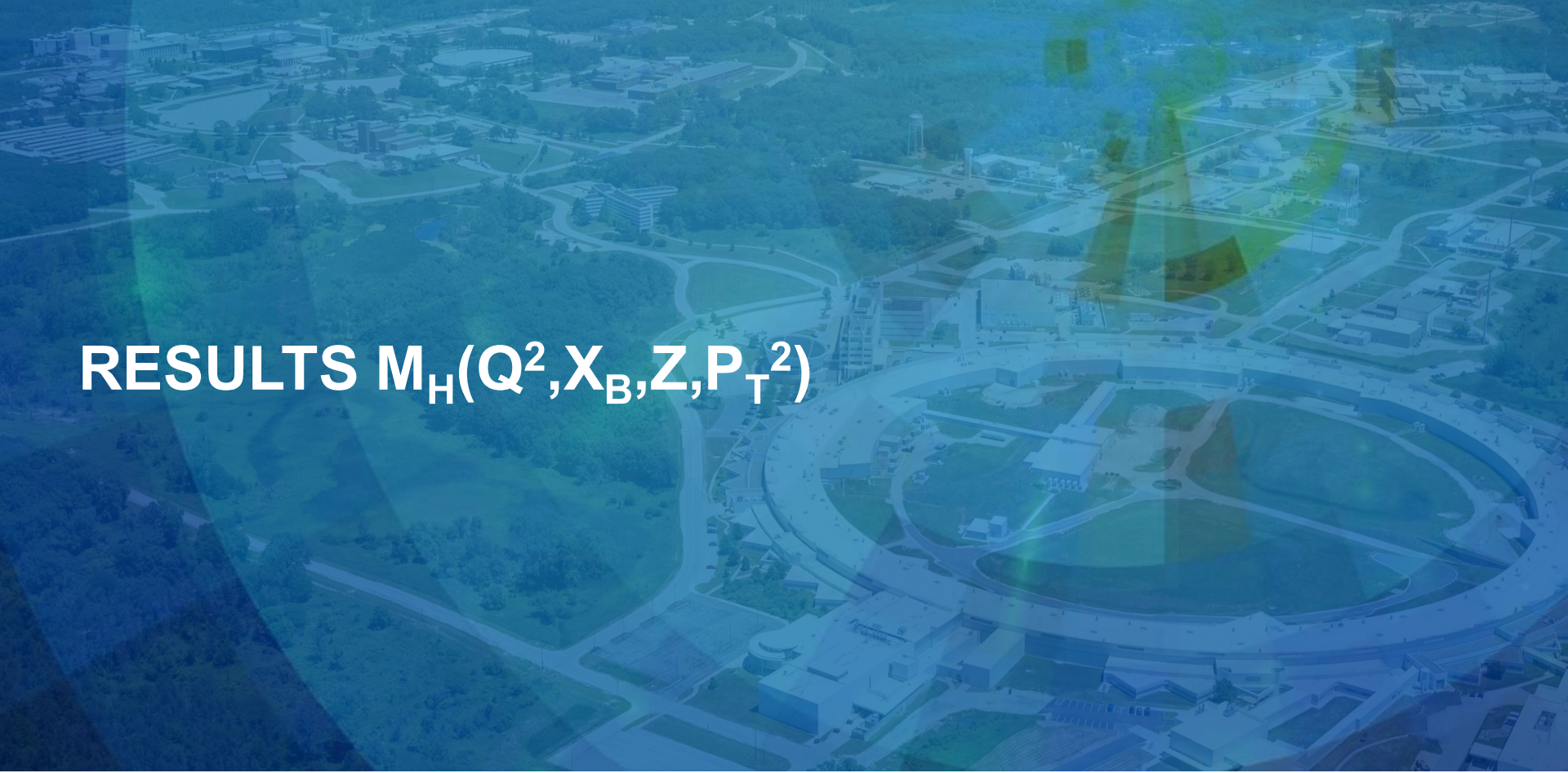


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COMPARISON WITH HALL C



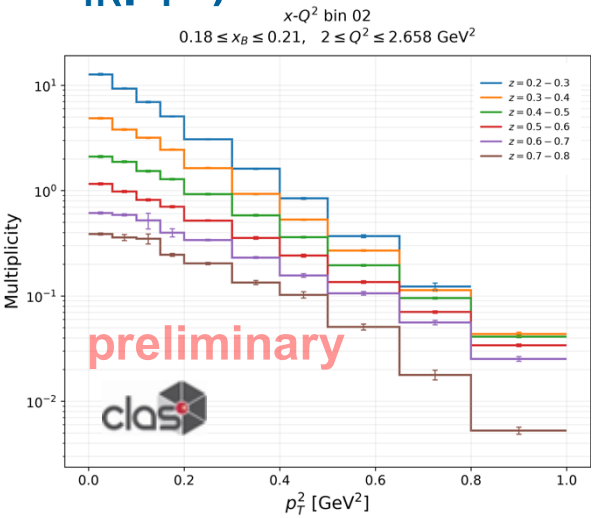
φ-integrated dM/(dz dpT²); statistical errors only. Only pT² bins with Hall C points shown; proxy is not measured π⁰.

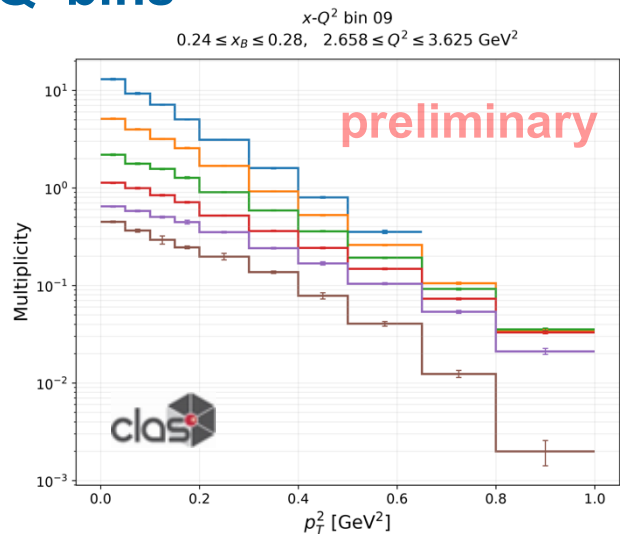


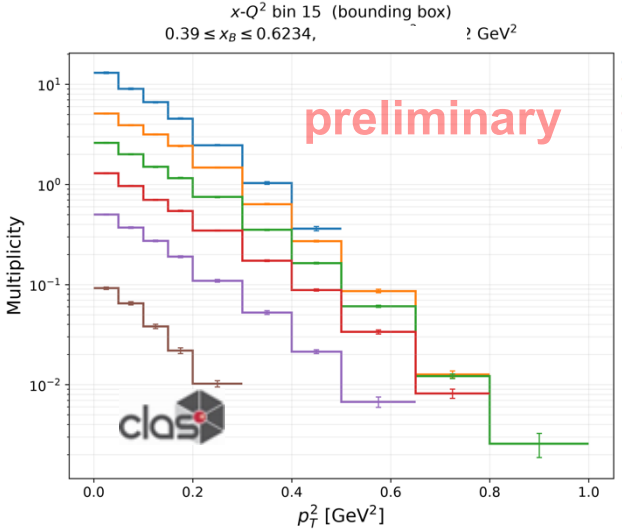
RESULTS $M_H(Q^2,X_B,Z,P_T^2)$

RESULTS

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







- LO, gaussian approximation:

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

- 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

CONCLUSIONS AND OUTLOOK

Updated:

- Systematic uncertainties
- Closure tests
- Preliminary Hall C cross check

In progress:

- Finalizing systematic uncertainties
- Preparing the analysis note

Results:

- 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

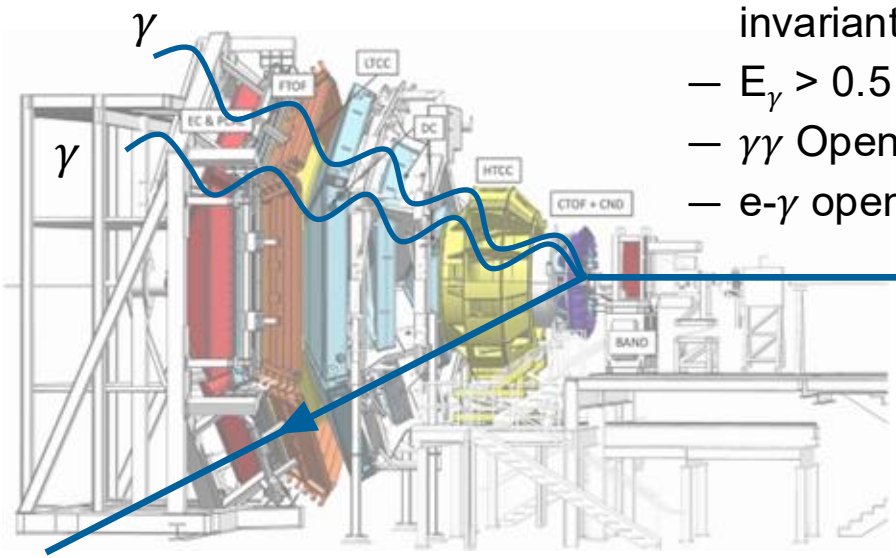


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CLAS12

Selection of the ep → eπ^{0}X reaction with Forward Detector



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

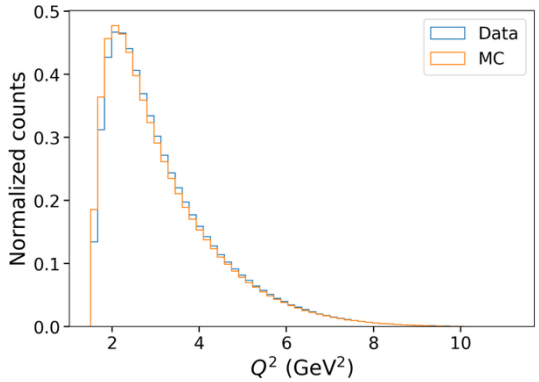
10.6 GeV electron beam, LH_2 5-cm long hydrogen target

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

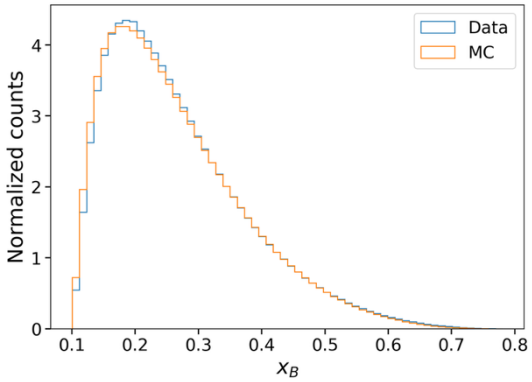
- Drift Chambers (track)
- Calorimeters (EM shower)
- Time of Flight (PID)
- Cherenkov counters (PID)

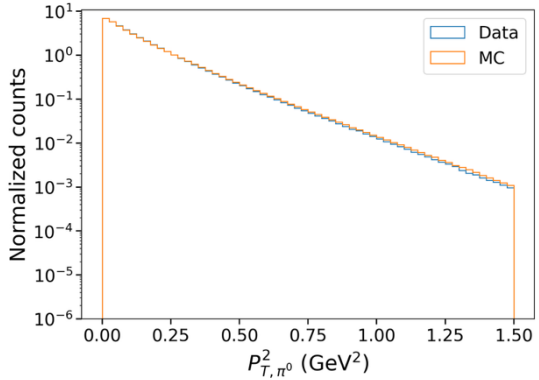
MONTE CARLO

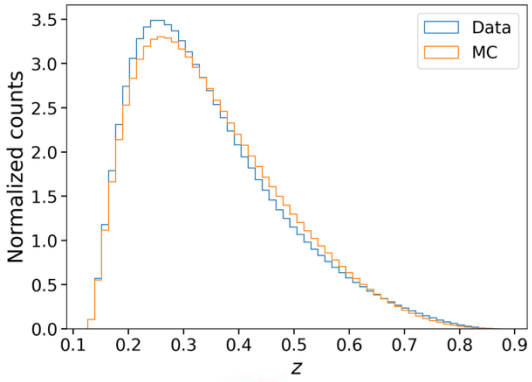
Event Generator used for the Acceptance



- CLASDIS-EG built on LEPTO
- Lund string model as in PYTHIA/JETSET
- LO electroweak DIS (arbitrary lepton polarization); O(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

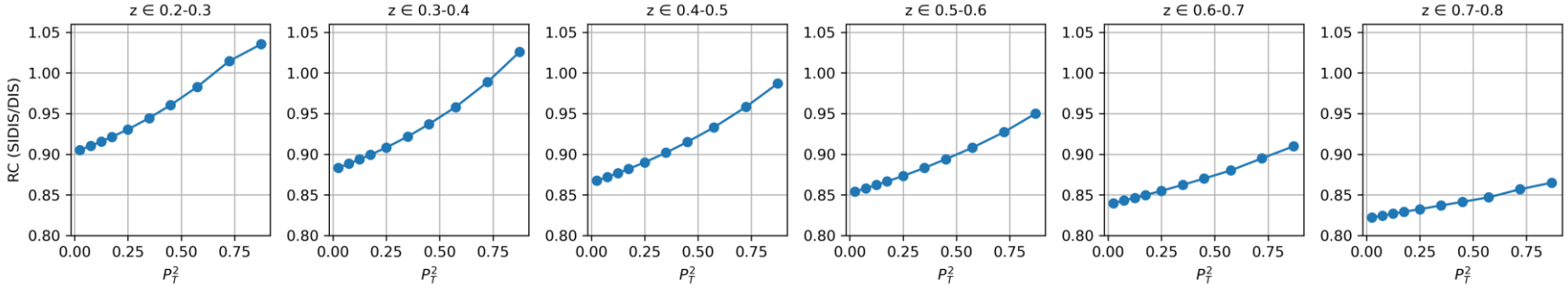
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RADIATIVE CORRECTIONS

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

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



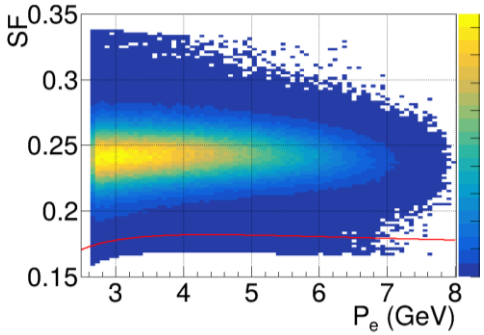
$0.18 < x < 0.21,\ 2.0 < Q^2 < 2.66\ \mathrm{GeV}^2$

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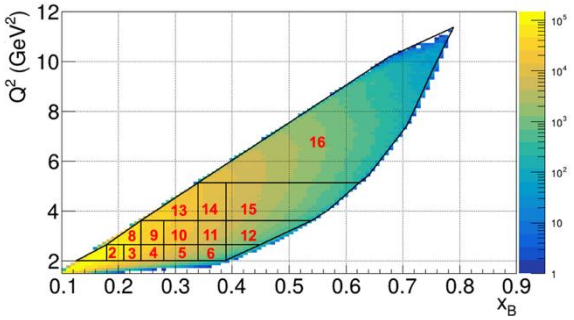
PID AND EVENT SELECTION

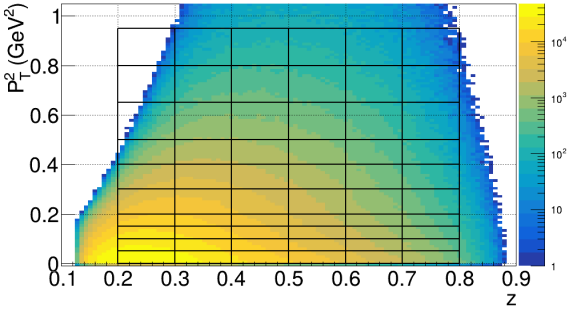
Starts with CLAS12 reconstruction algorithm

- 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



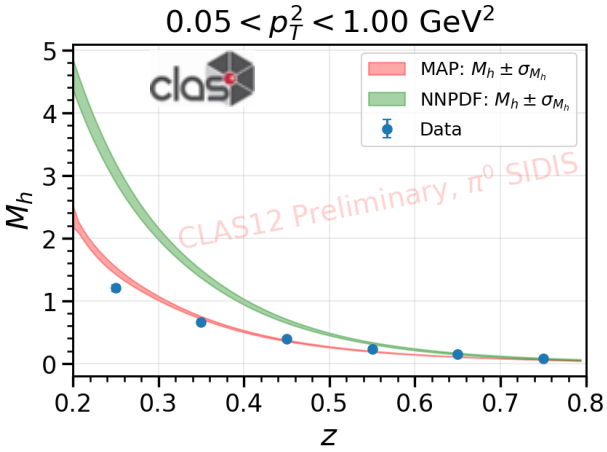


RESULTS

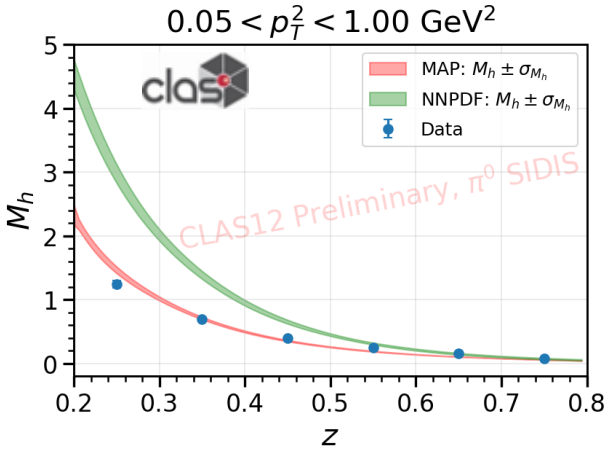
$M_h(z)$ integrated over P_T^2 for selected x-Q^2 bins

P_T^2 integrated multiplicity:

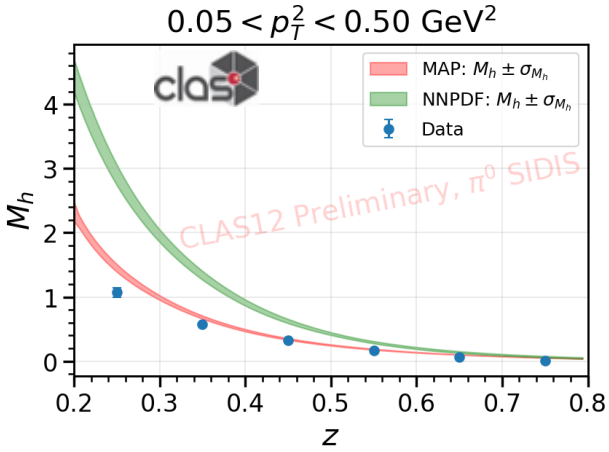
$$M_h = \frac{\sum_q e_q^2 f_q(x) D_q(z)}{\sum_q e_q^2 f_q(x)}$$



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

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