# RG-D Analyses Update

Mariana Tenorio Pita
Mississippi State University
CLAS Collaboration November 2026

# Run Group D

Run Group D is composed of:

## E12-06-106

Color Transparency (CT) in Exclusive Vector Meson Electroproduction off Nuclei

Spokespersons: W. Armstrong[1], L. El Fassi[3], K. Hafidi[1], M. Holtrop[4], B. Mustapha[1]

## E12-06-106A

Nuclear TMDs (nTMDs) in CLAS12

Spokespersons: R. Dupré[2], L. El Fassi[3], Z.-E. Meziani[1], H. Szumila-Vance[5]

## CAA

Studying the In-medium Nuclear Effects on the Nucleon Gluon Distribution with Vector Meson Production

P. Chatagnon[6], R. Tyson[7]

[1] Argonne National Lab
[2] IJCLab, Orsay, France
[3] Mississippi State University
[4] University of New Hampshire
[5] Old Dominion University
[6] Irfu/DPhN, CEA Paris-Saclay, France
[7] University of Glasgow, UK

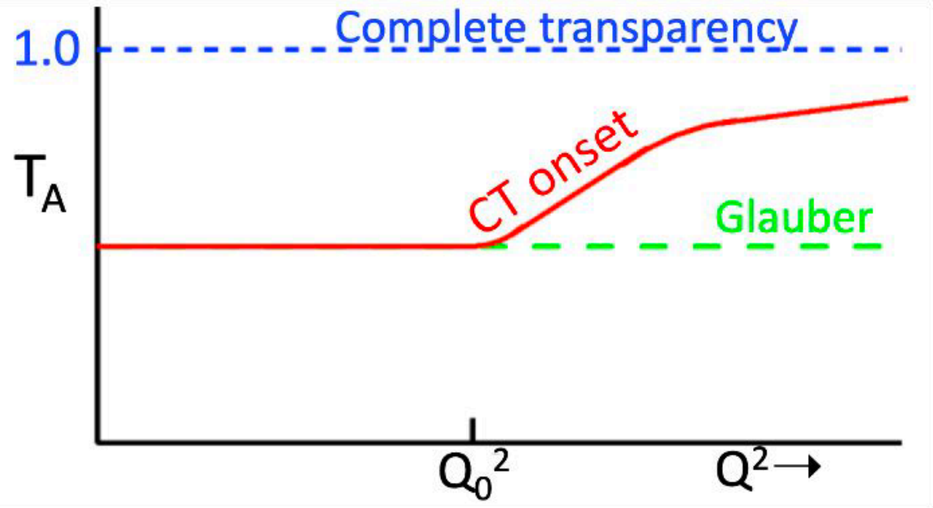
# RG-D: CT Experiment

El Fassi et al., PLB 712, 326 (2012)

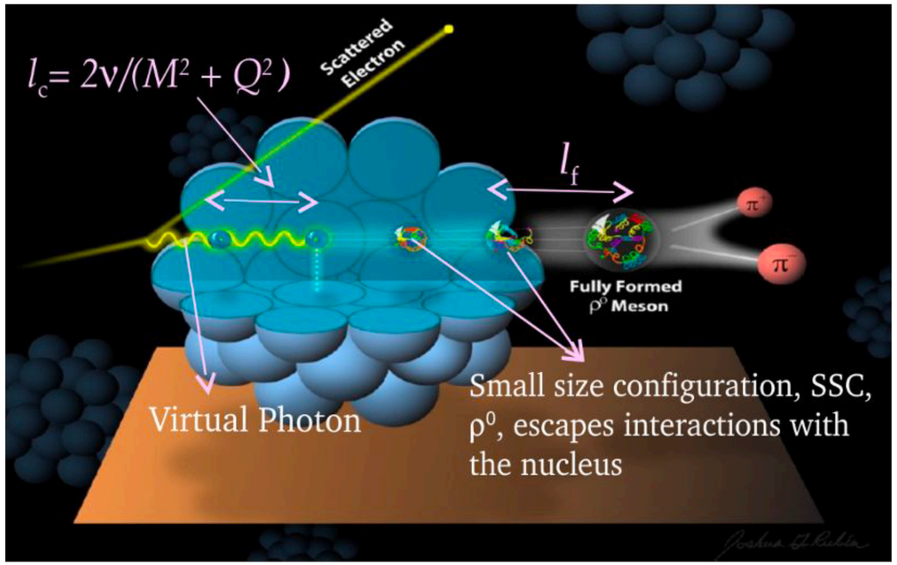
- E12-06-106: Color Transparency, the suppression of interactions of colorless small-size configurations in the nuclear medium.
- Experimental signature: rise of the nuclear transparency $T_A$ with $Q^2$:

$$T_A = \frac{\sigma_A}{A\sigma_N}$$

$\sigma_A$: Nuclei cross-section
$\sigma_N$: Free nucleon cross-section

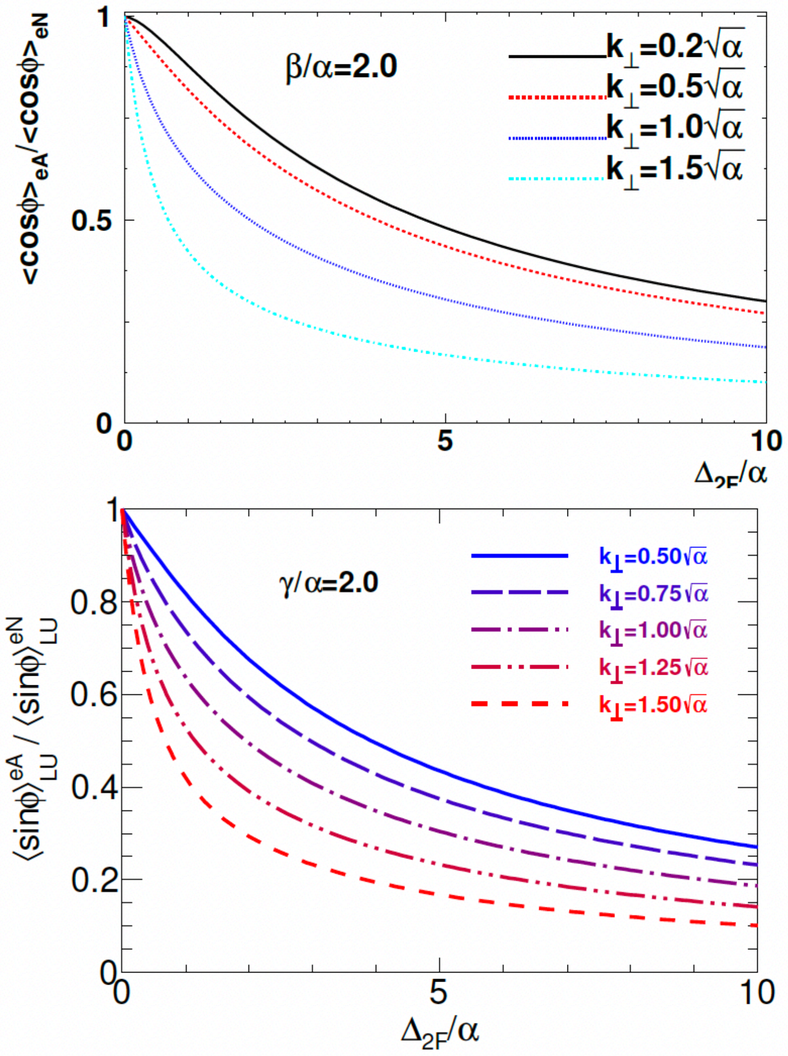



- Probing Color Transparency in meson production provides insight into the evolution of short-lived compact configurations into hadrons and validates the QCD factorization framework needed to access GPDs.



# RG-D: nTMD Experiment

- E12-06-106A: The modification of partonic dynamics and hadron formation in the nuclear medium. Same running conditions as CT, except for the beam polarization.
- Experimental observables: Nuclear multiplicity ratios ($R_A$), transverse-momentum broadening ($\Delta p_T^2$), and beam-spin asymmetries (BSA).
- Probing nuclear TMDs in SIDIS provides insight into the modification of bound nucleon structure and hadron formation in cold nuclear matter.



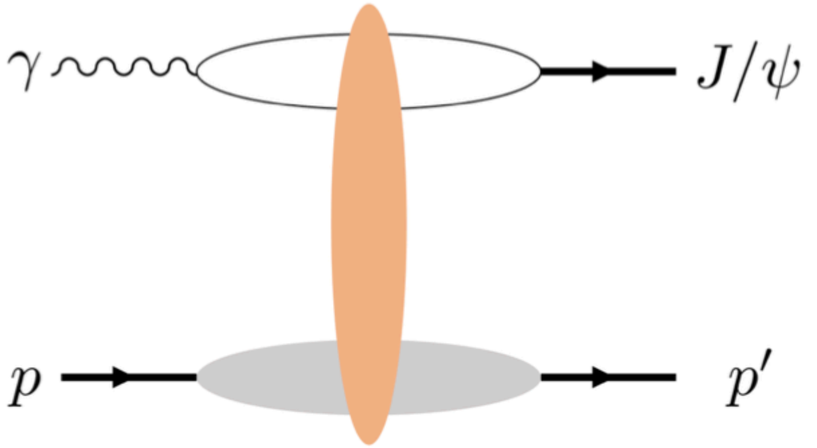

Song, Y. et al. (2014) Physical Review D, 89 014005.

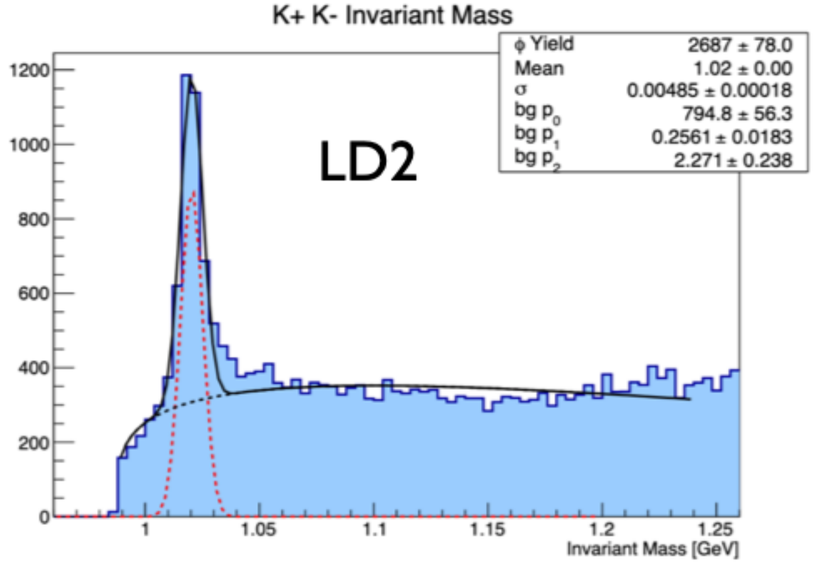
# RG-D: Vector meson production off bound nucleons

- CAA: In-medium modification of the nucleon's gluonic structure, probed through vector meson production off bound nucleons.

- Experimental observables: $J/\psi$ and $\phi$ production cross sections off bound nucleons, compared with free-nucleon measurements.

- Probing near-threshold vector meson production off nuclei provides insight into how the nuclear medium modifies the gluonic mass and pressure distributions of the nucleon, through its gravitational form factors.

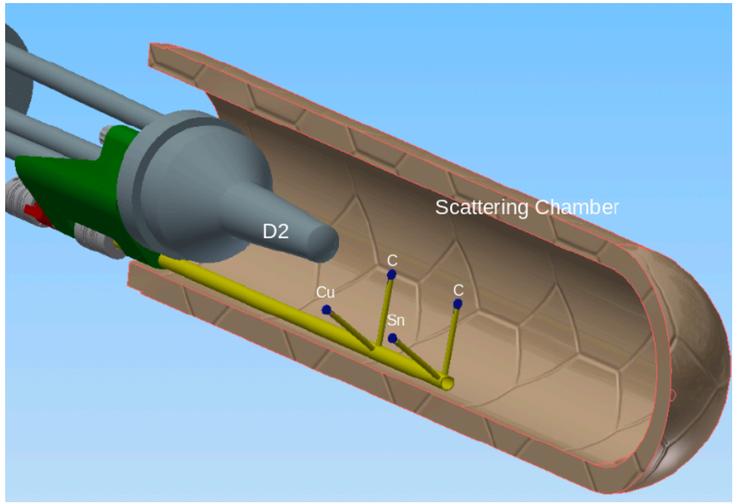


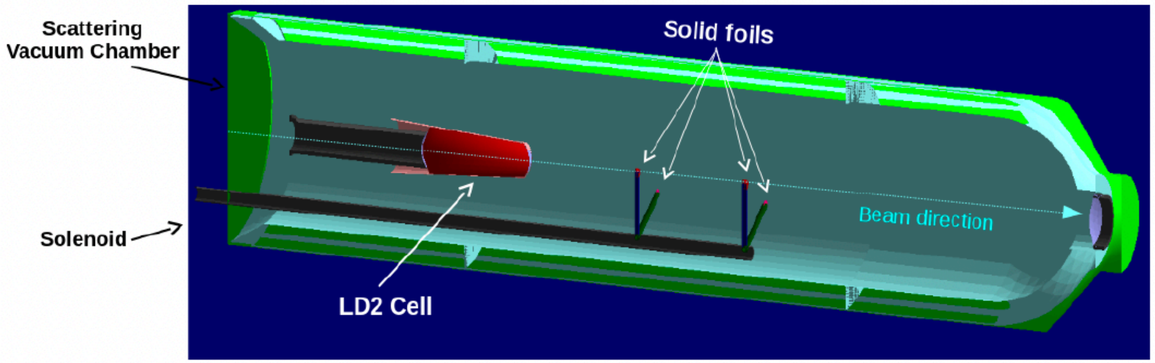




P. Chatagnon, R. Tyson, CLAS Collab. Meeting, Nov. 2025

# RG-D: Run Configuration

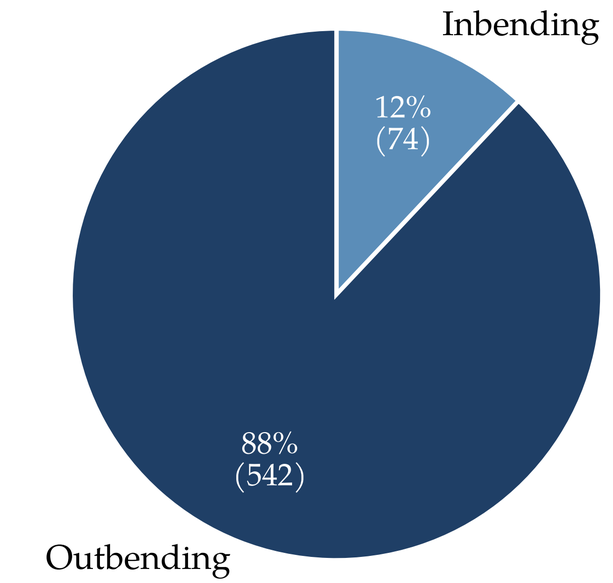
- Data taken in fall 2023:
  - 10.54 GeV polarized electron beam, $I =$ 5 to 175 nA (luminosity scans and production).
  - Standard CLAS12 configuration, FT off, 2 FMT layers.
  - Three target configurations, LD2, CxC and CuSn, each run with inbending and outbending torus polarity.
  - New cryogenic LD2 cell and nuclear-foil flag assembly, centered at $-5$ cm.
- Main run issues: Faraday cup vacuum contamination, Møller cone sagging.

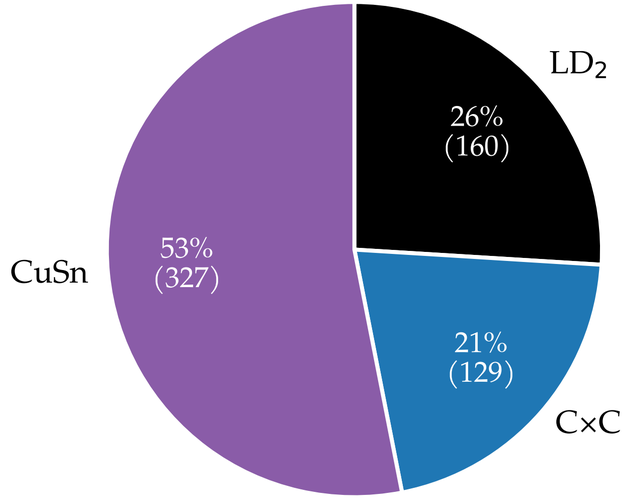


# RG-D Dataset and Analysis Trains

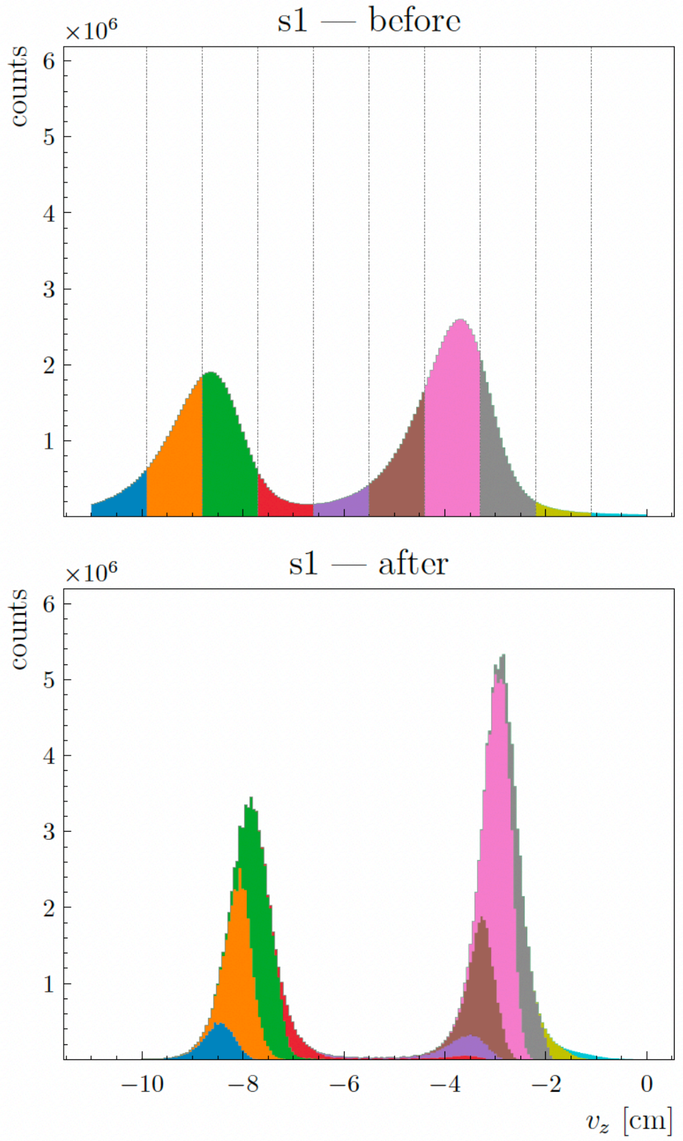
- Pass1 cooking completed in April 2026.
- Data: 616 production runs on three target configurations (LD2, CxC, CuSn), 88% with outbending torus polarity.
- Each RG-D experiment now has a dedicated train:
  - ct train (E12-06-106)
  - sidis train (E12-06-106A)
  - jpsitcs train (CAA)
- The sidis train is prescaled in $Q^2$ to fit in the disk budget: all events with $Q^2 > 2.0$ GeV$^2$ are kept, and 1 in 5 events with $0.8 < Q^2 < 2.0$ GeV$^2$ .
- Trains are on /cache and /mss, with links per torus polarity in /work.



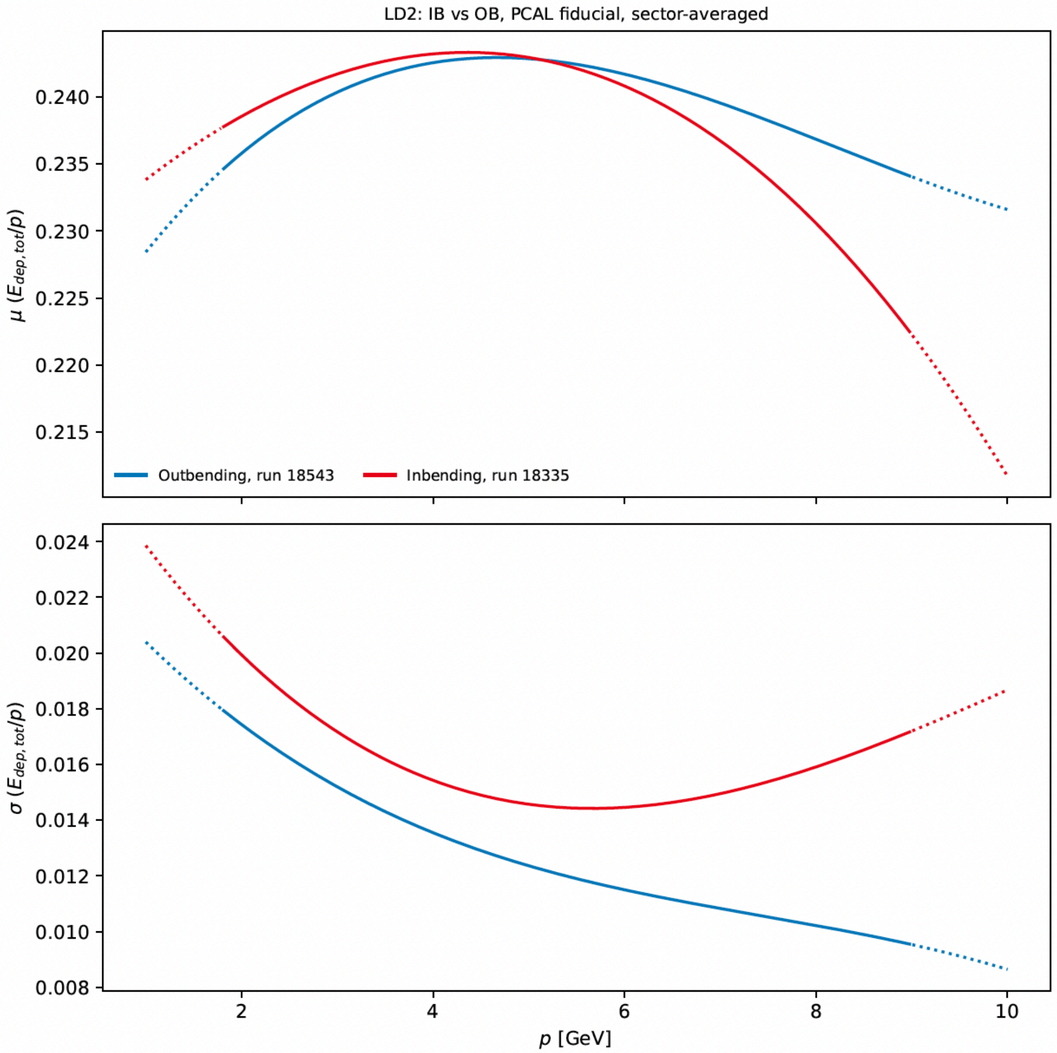
# RG-D Common Aspects Analysis Note

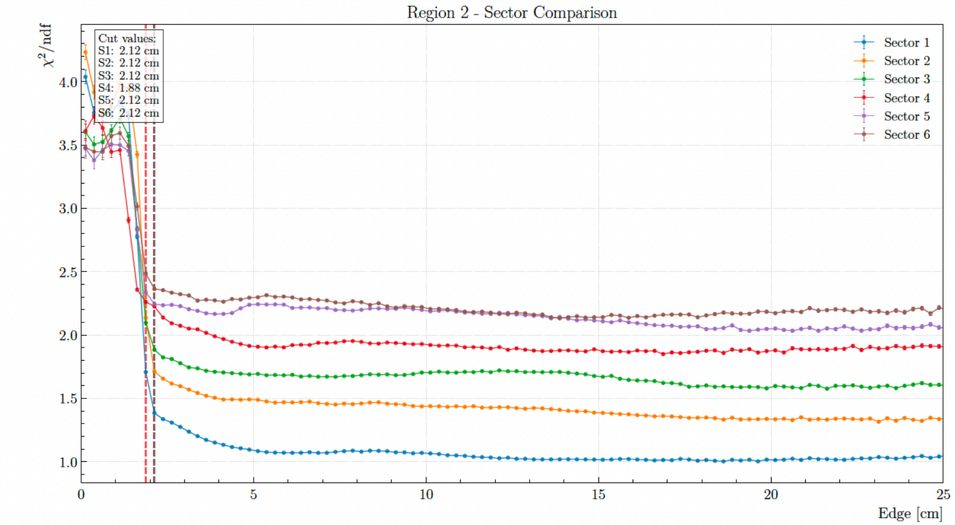
- A shared reference for all RG-D analyses: run conditions, beam charge, and the common electron and charged-pion selection with its corrections.
- Contents:
  - Live-time-corrected beam charge.
  - $e^-$ ID: HTCC, sampling fraction, calorimeter and DC fiducial cuts, vertex correction and target selection.
  - $\pi^{\pm}$ ID: Δt, Vz, ΔVz, DC fiducial cuts, and contamination studies.
- Vertex correction (per sector, momentum and $\phi$) separates the foils; corrected centroids of $e^-$, $\pi^-$ and $\pi^+$ agree within 0.15 cm.

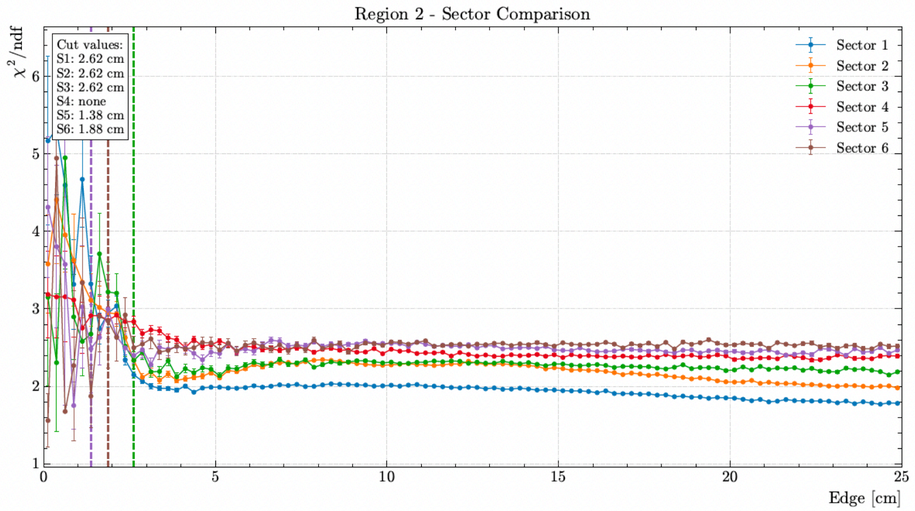


# RG-D Common Aspects Analysis Note

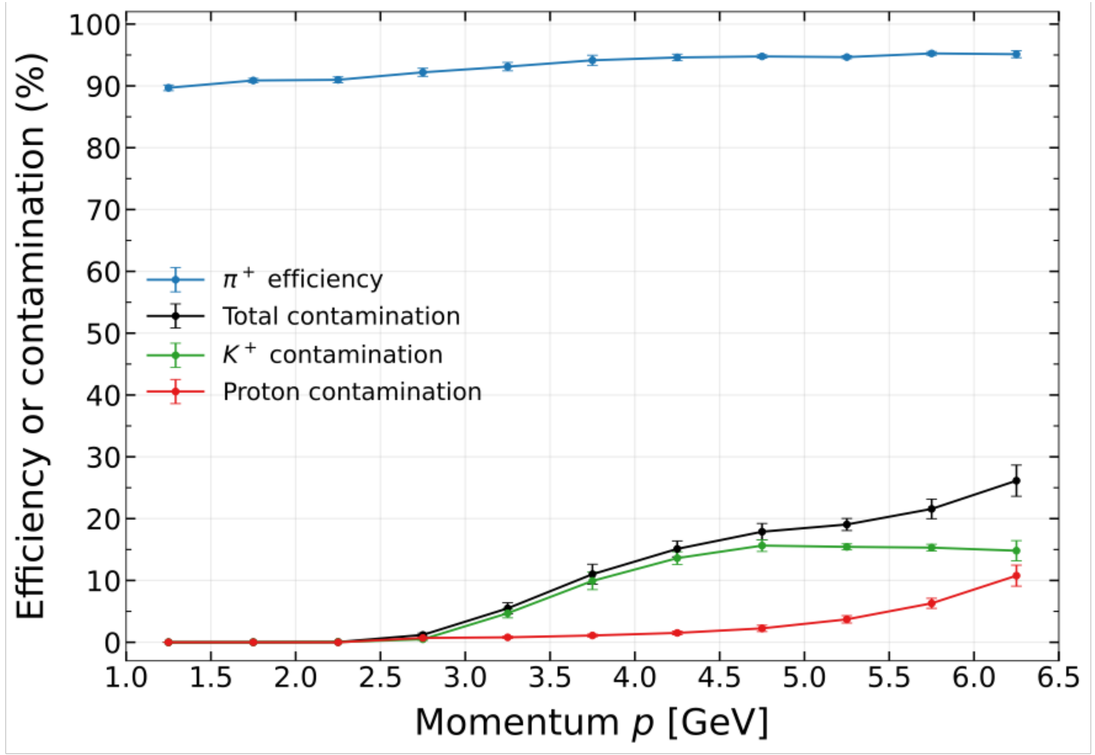
- All $e^-$ and $\pi^\pm$ cuts were derived on OB runs, and verified on IB.

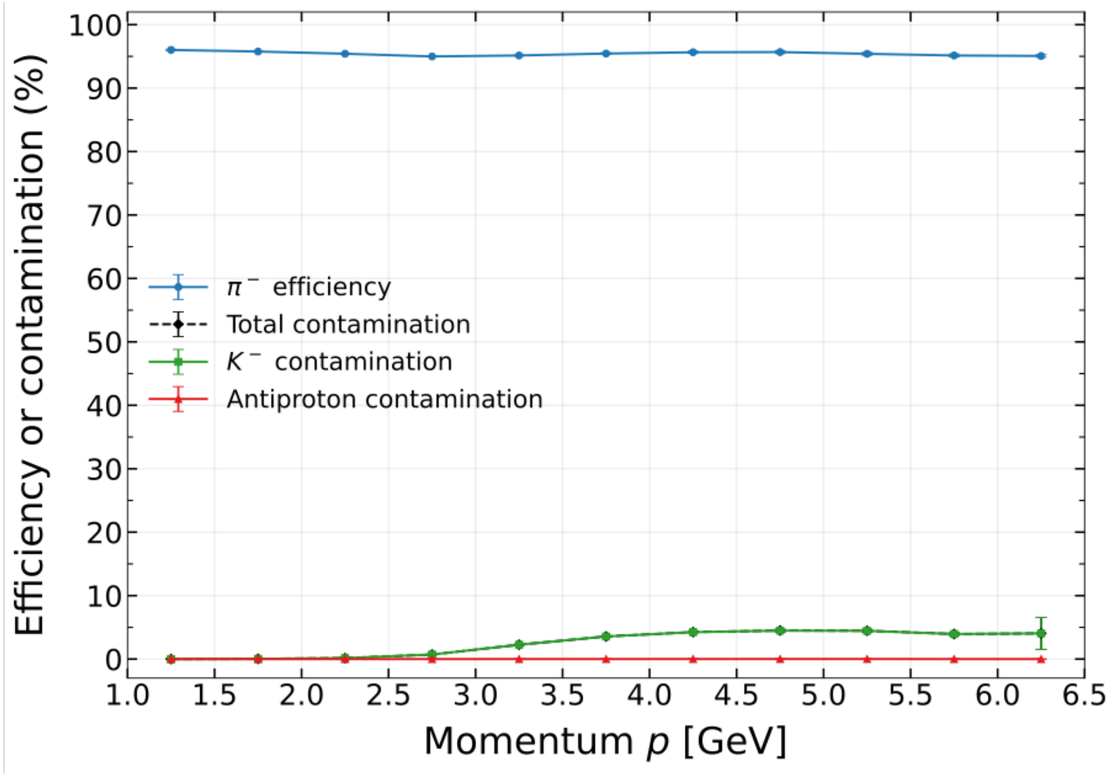


# Data-driven charged-pion PID efficiency and contamination




- $\pi^{\pm}$ selection efficiency remains approximately 90 – 96 %.
- Contamination increases with momentum: $\pi^+$ reaches about 26 %, while $\pi^-$ remains below approximately 5%.

Work by Suman Shrestha

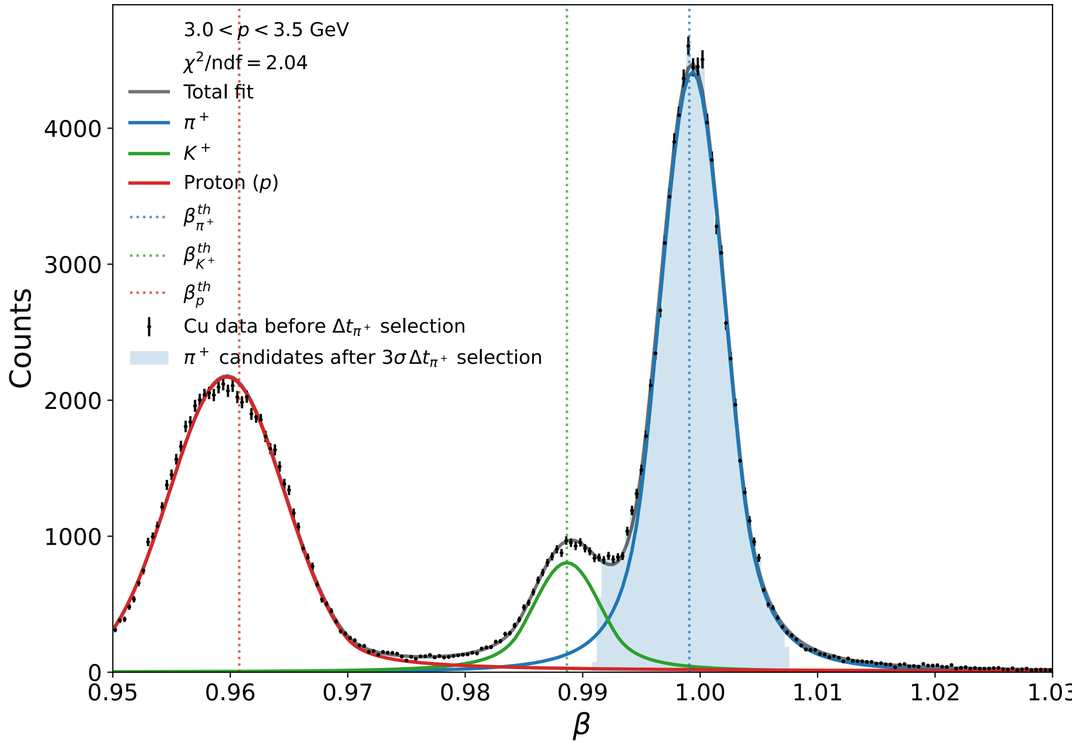
# Methodology for Data-driven charged-pion PID efficiency and contamination study

- The measured $\beta$ distribution is fitted in momentum bins using double-sided Crystal Ball components for pions, kaons, and protons/antiprotons.
- Each candidate is assigned a probability for species:

$$w_{s,i} = \frac{f_s(\beta_i)}{F(\beta_i)} \qquad F(\beta_i) = f_{\pi^\pm}(\beta_i) + f_{K^\pm}(\beta_i) + f_{p/\bar{p}}(\beta_i)$$

where $s \in \{\pi^\pm, K^\pm, p/\bar{p}\}$, and $\beta_i$ is the candidate's measured velocity.

- The yield of each species is obtained by summing its candidate probabilities: $N_s = \sum_i w_{s,i}$
- A $3\sigma$ pion $\Delta t$ selection is applied; the weighted yields before and after the selection determine pion efficiency and contamination.
- Statistical uncertainties combine weighted-counting and fit-parameter contributions in quadrature.

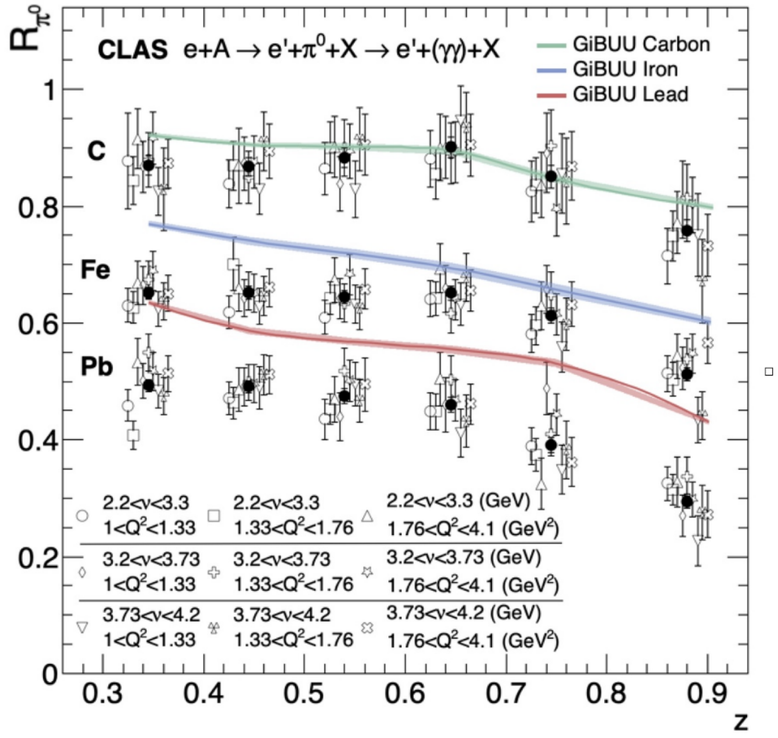


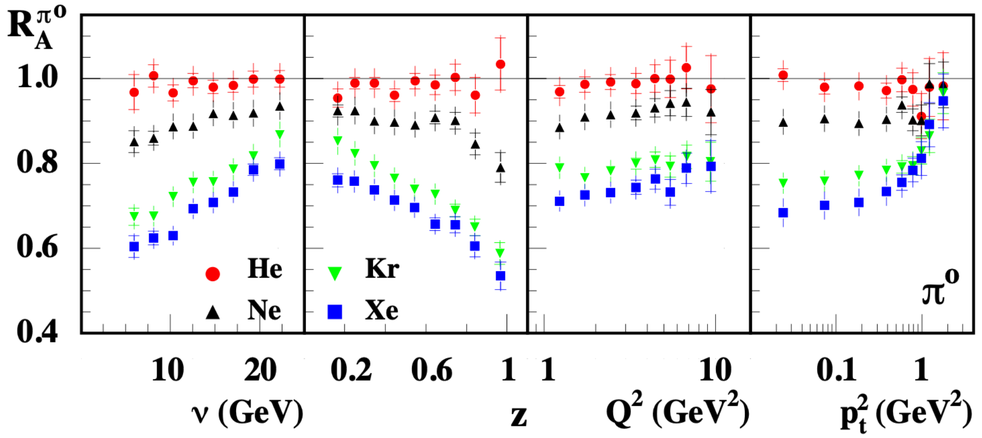

Work by Suman Shrestha

# nTMDs with neutral pions

Figures from T. Mineeva *et al.* (CLAS), Phys. Rev. C **112**, 035203 (2025)
A. Airapetian *et al.* (HERMES), Nucl. Phys. B **780**, 1 (2007)

- SIDIS $\pi^0$ production off LD2, C, Cu and Sn:
  $eA \to e'\pi^0 X,\ \pi^0 \to \gamma\gamma$
- $\pi^0$ completes the pion isospin triplet with $\pi^+$and $\pi^-$
- Observables:
  - Multiplicity ratio $R_A$
  - $p_T$ broadening $\Delta\langle p_T^2 \rangle$
  - Beam spin asymmetry $A_{LU}^{\sin\phi_h}$



# nTMDs with neutral pions

Electron identification follows the RG-D common aspects analysis note:

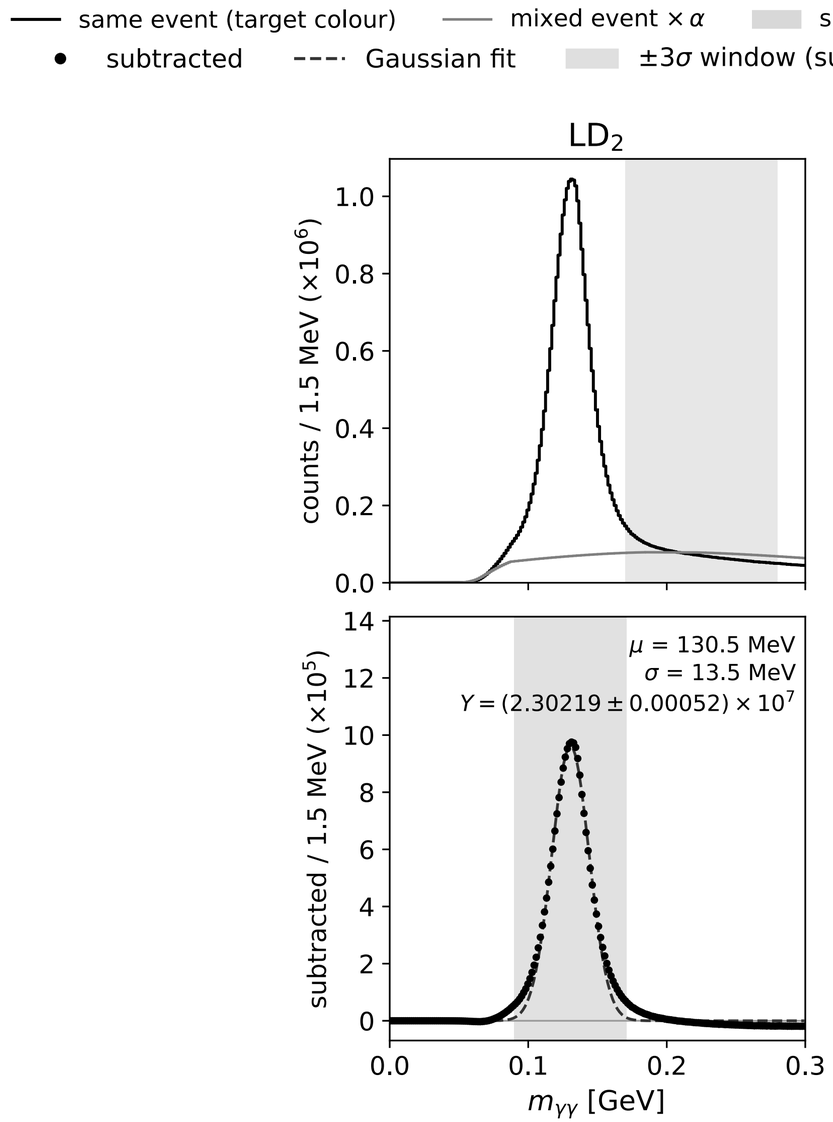
| Cut Type | Observable / Bank Variable | Selection Criterion |
|---|---|---|
| Particle ID | Event Builder assignment | $\texttt{pid} = 11$ (electron) |
| Status | Forward Detector trigger track | $-4000 < \texttt{status} \leq -2000$ |
| $\chi^2_{\mathrm{PID}}$ | Event Builder PID quality | $-5 < \chi^2_{\mathrm{PID}} < 5$ |
| Momentum | Minimum momentum threshold | $p > 1.8$ GeV |
| SF vs Momentum | Momentum-dependent SF cuts | $\mu_{\mathrm{SF}} \pm 3.5\sigma$ vs $p$ |
| Calorimeter Edges | Local coordinates $(v, w)$ | $v > 9$ cm and $w > 9$ cm |
| DC Fiducial | Distance to wire plane boundary | $\texttt{edge} >$ cut(R, S) |
| Vertex Position | Longitudinal vertex position | Target dependent |

DIS cuts: $Q^2 > 1\mathrm{GeV}^2$, $W > 2\mathrm{GeV}$, $y < 0.85$

Photon identification:

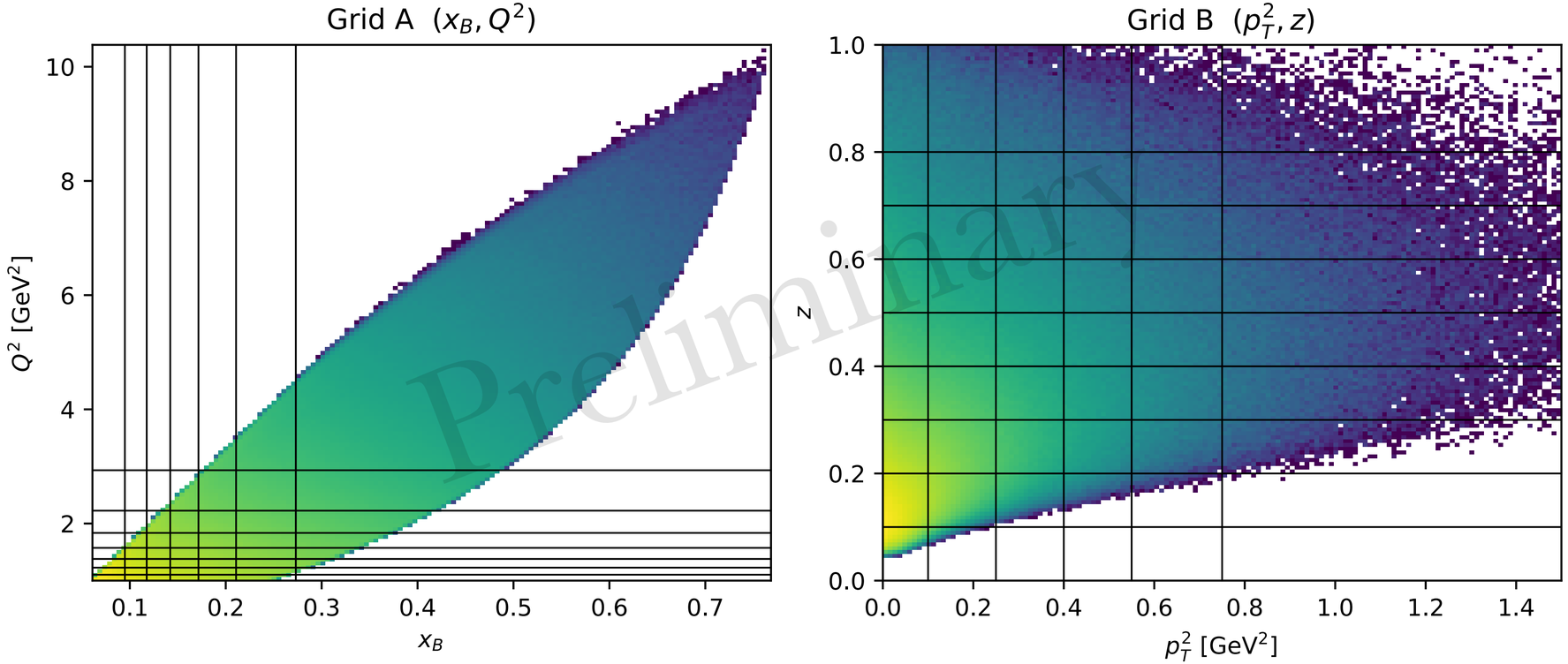
- pid 22
- GBT pre-filter: $E_\gamma \geq 0.2\mathrm{GeV}$, $E_{PCAL} > 0$, and $5^\circ \leq \theta \leq 35^\circ$
- GBT score $> 0.78$ (the RG-A model as fallback)
- PCAL fiducial: $l_v$ and $l_w > 14\mathrm{cm}$
- $0.9 < \beta < 1.1$
- $\theta_{e\gamma} > 8^\circ$
- Photon pairing: $m_{\gamma\gamma} \approx m_{\pi^0}$
- Pair cuts: $m_{\gamma\gamma} > 1\,\mathrm{MeV}, \quad \theta_{\gamma\gamma} > \theta_{\min}(p_{\gamma\gamma}), \quad |m_{\gamma\gamma} - m_{\pi^0}| < 0.2\,\mathrm{GeV}$

Energy fraction: $0 < z < 1$



# nTMDs with neutral pions

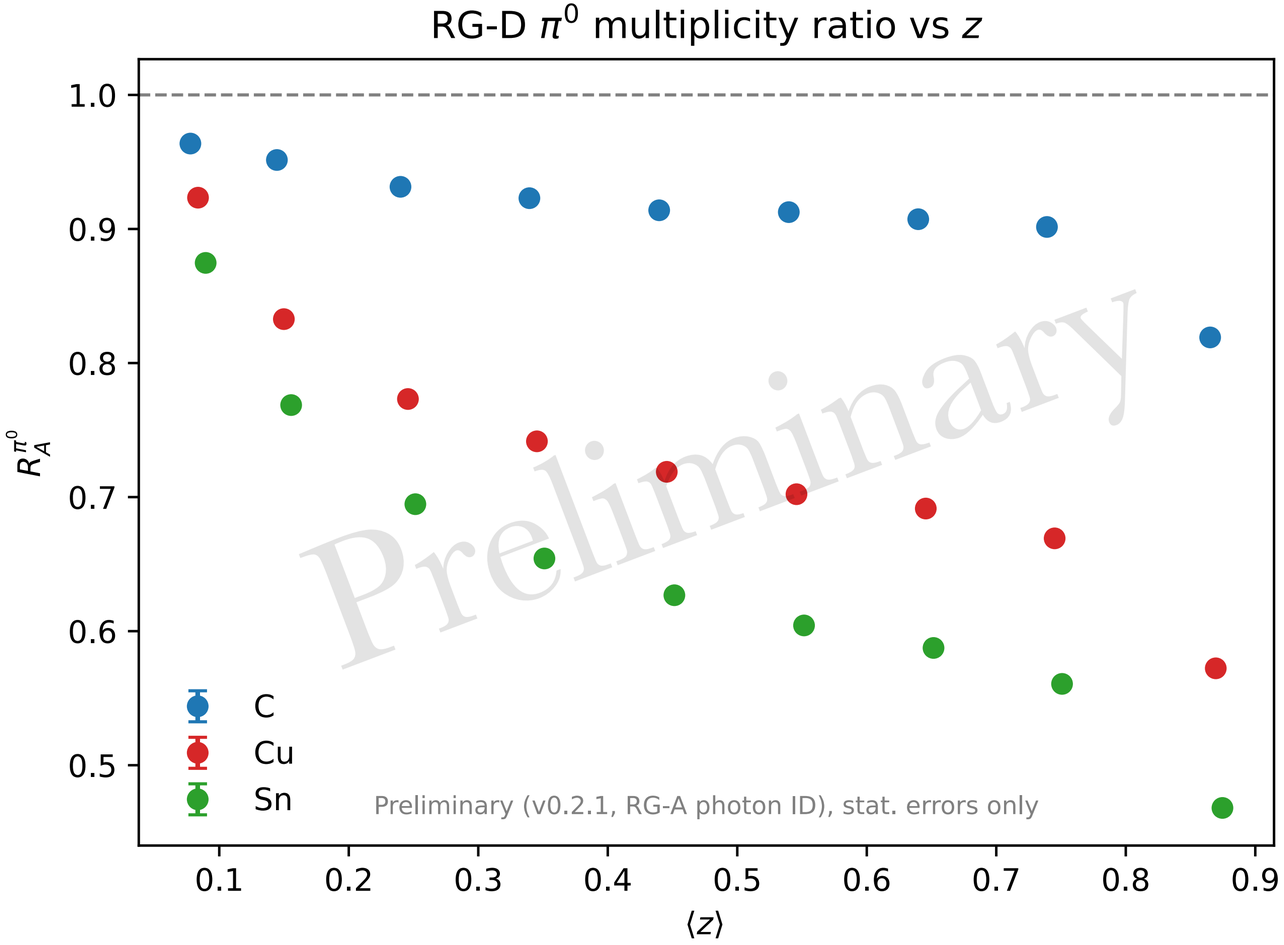
- 4D binning in $(Q^2, x_B, z, p_T^2)$.
- $(Q^2, x_B)$ bins chosen with equal statistics, $(z, p_T^2)$ CLAS6 edges, plus extra bins at low z and high $p_T^2$.
- Same bins for all targets and observables.



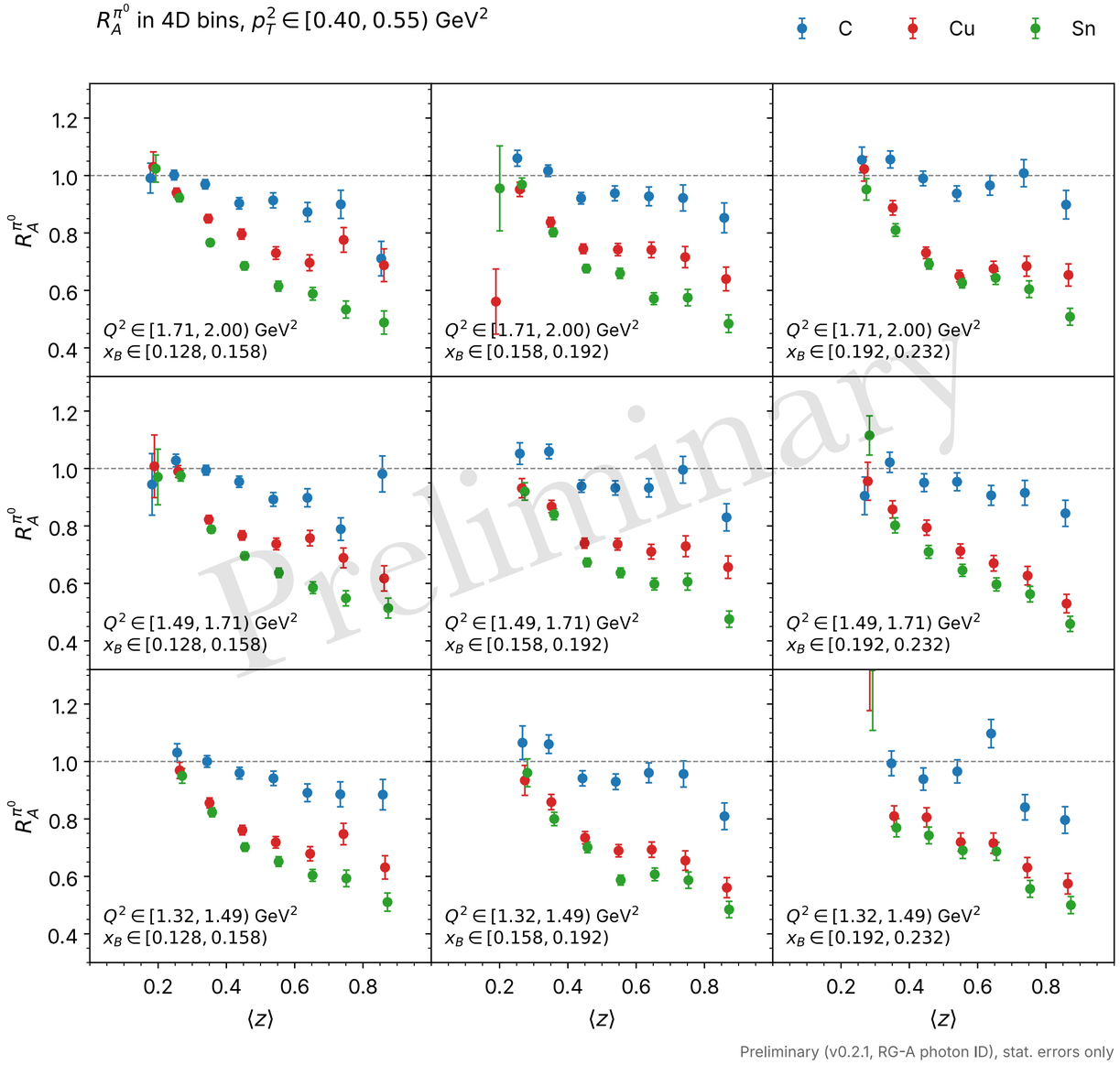
# nTMDs with neutral pions: Raw $R_A$

$$R_A^{\pi^0}(Q^2, x_B, z, p_T^2) = \frac{N_{\pi^0}^A(Q^2, x_B, z, p_T^2) \,/\, N_e^A(Q^2, x_B)}{N_{\pi^0}^D(Q^2, x_B, z, p_T^2) \,/\, N_e^D(Q^2, x_B)}$$

- Raw $\pi^0$ multiplicity ratio relative to LD2, integrated over $Q^2$, $x_B$ and $p_T^2$.
- Target ordering C > Cu > Sn in every z bin.
- $R_A$ decreases with z: stronger attenuation for heavier nuclei.

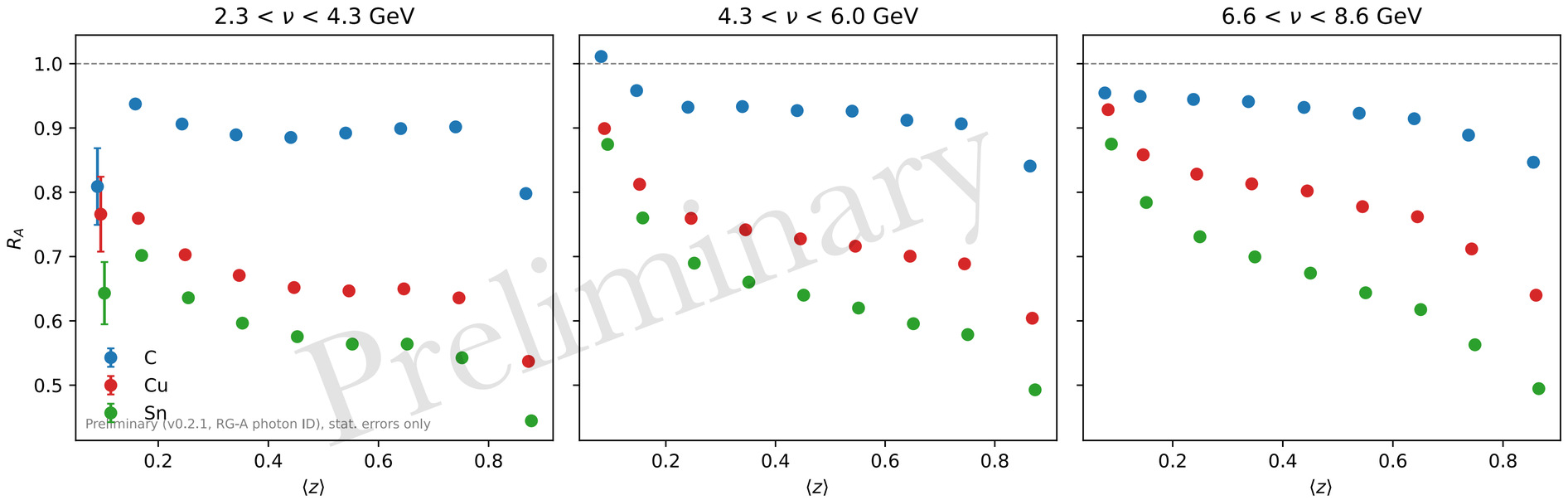


# nTMDs with neutral pions: Raw $R_A$



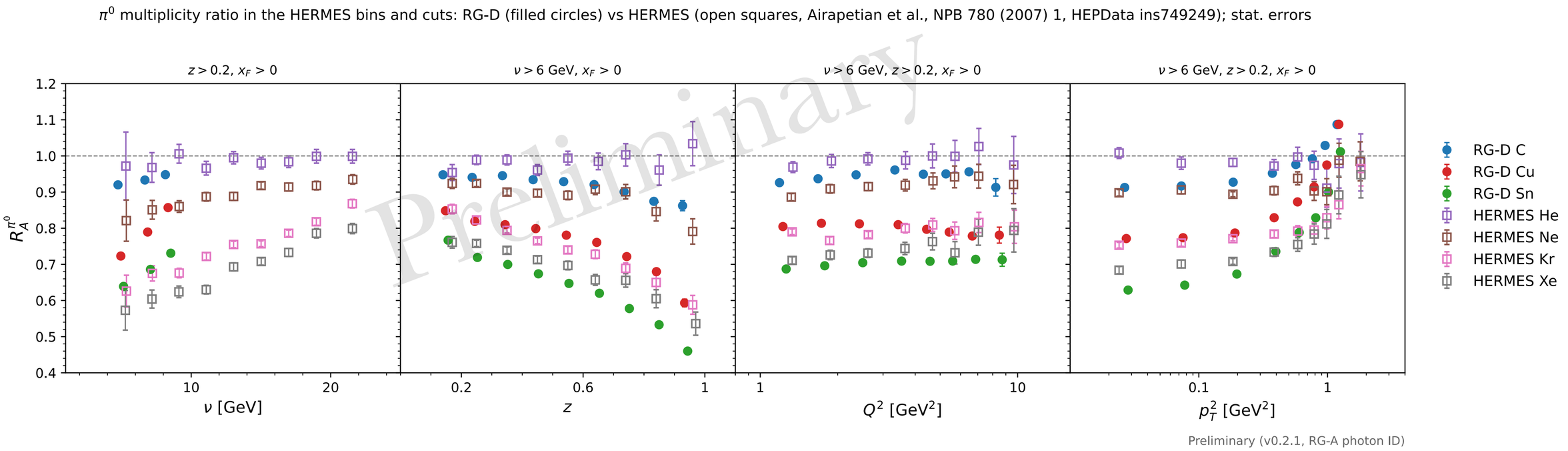

Preliminary (v0.2.1, RG-A photon ID), stat. errors only

# nTMDs with neutral pions: Raw $R_A$



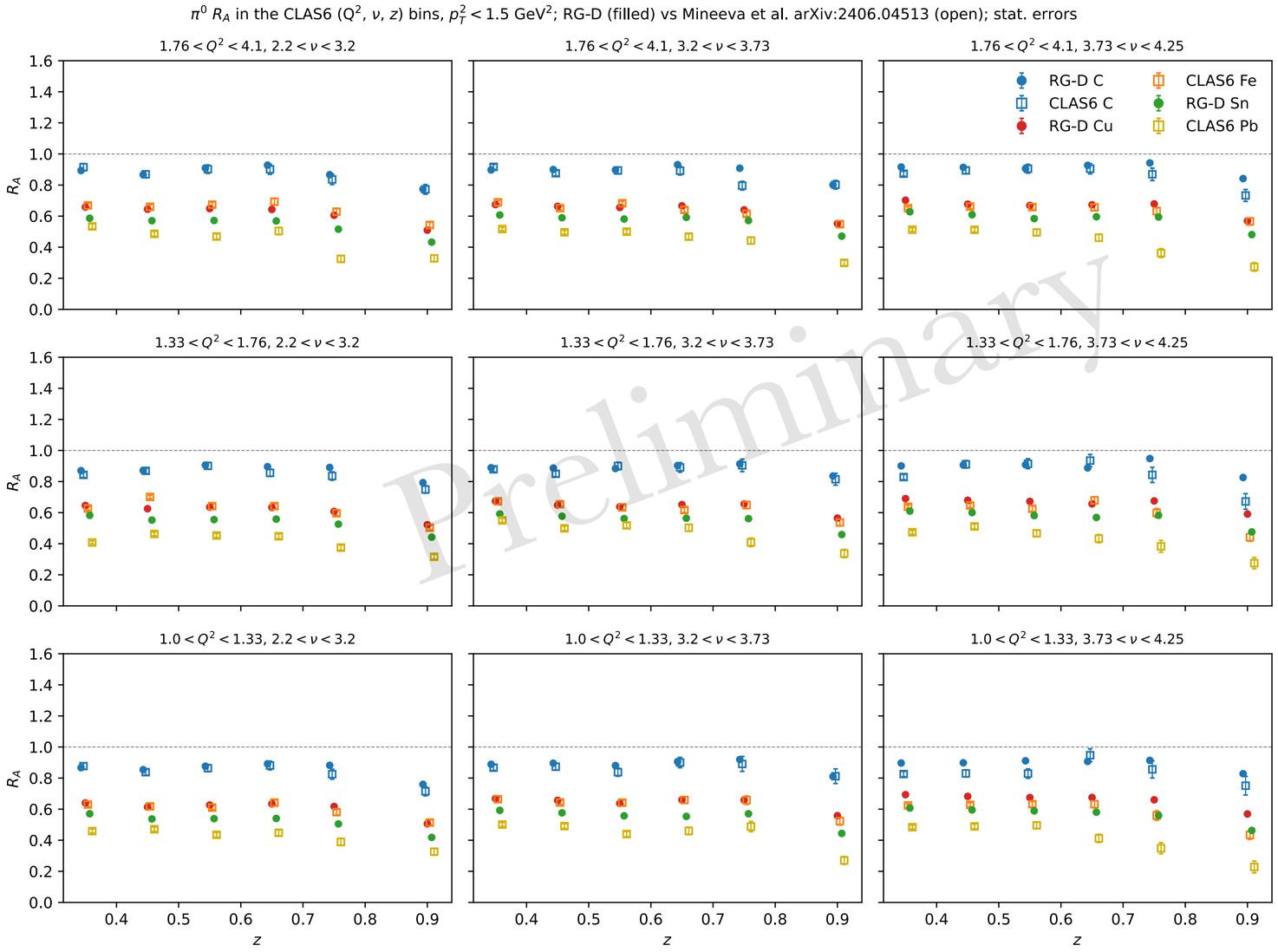
# nTMDs with neutral pions: Raw $R_A$

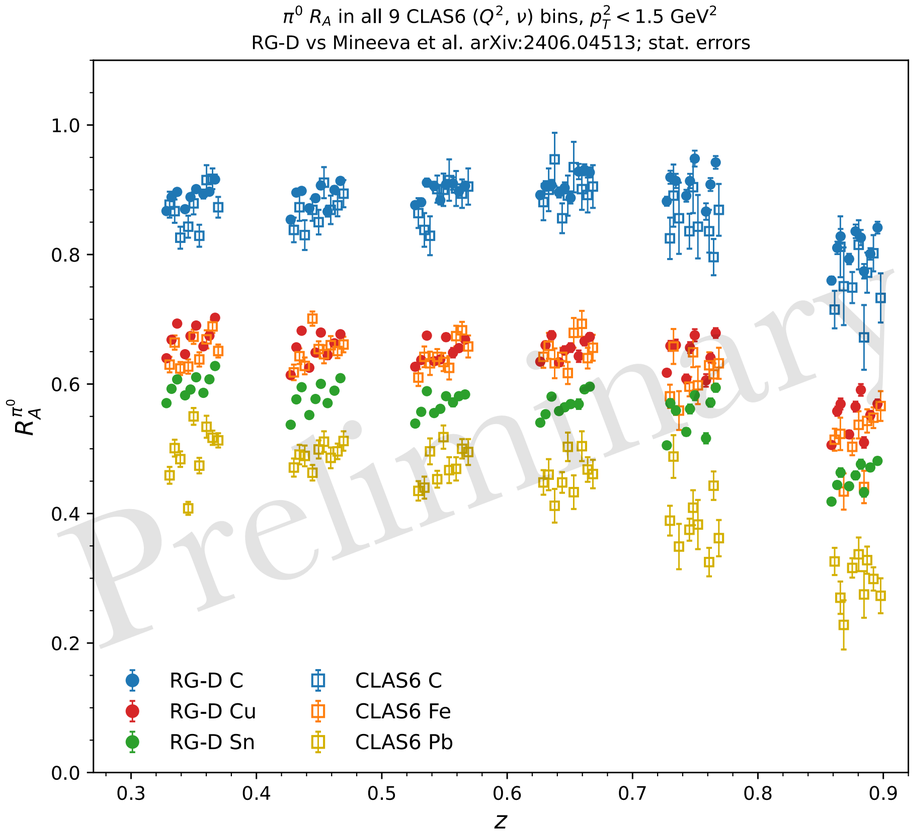
- Comparison with HERMES results



# nTMDs with neutral pions: Raw $R_A$

- Comparison with CLAS6 results

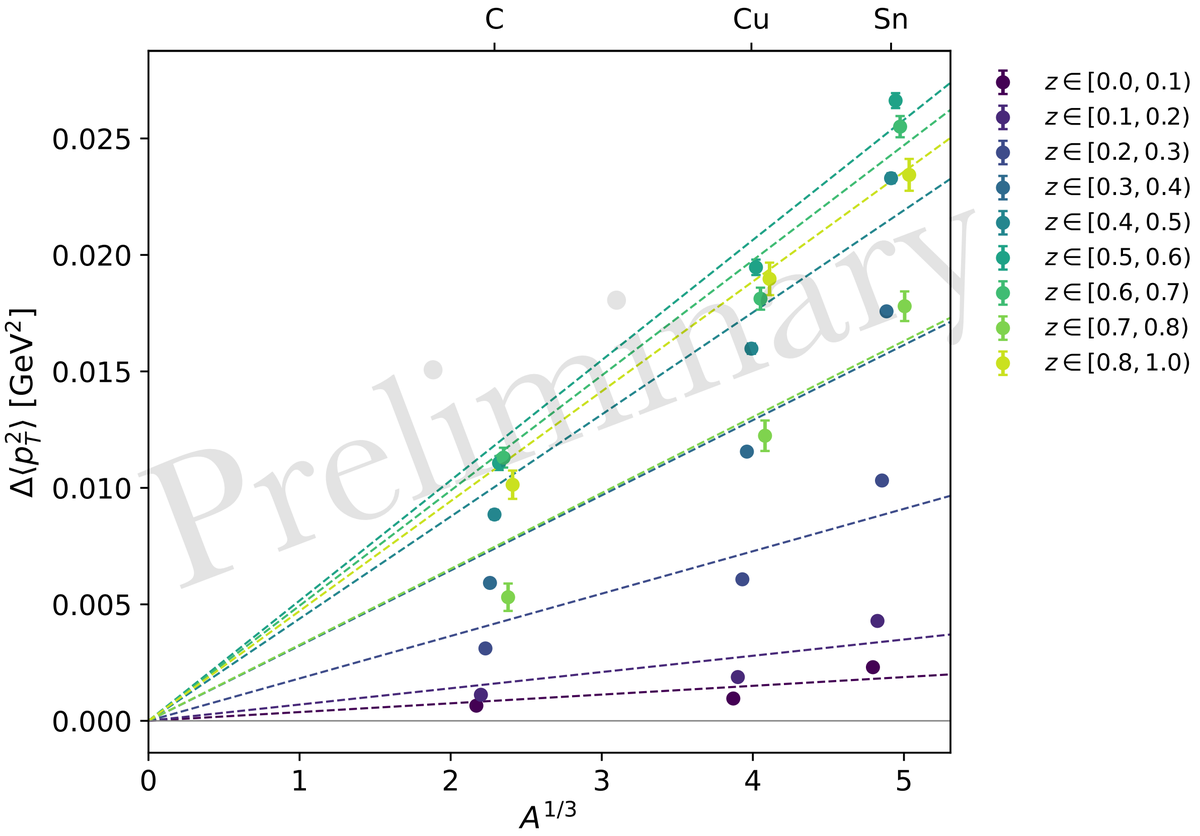


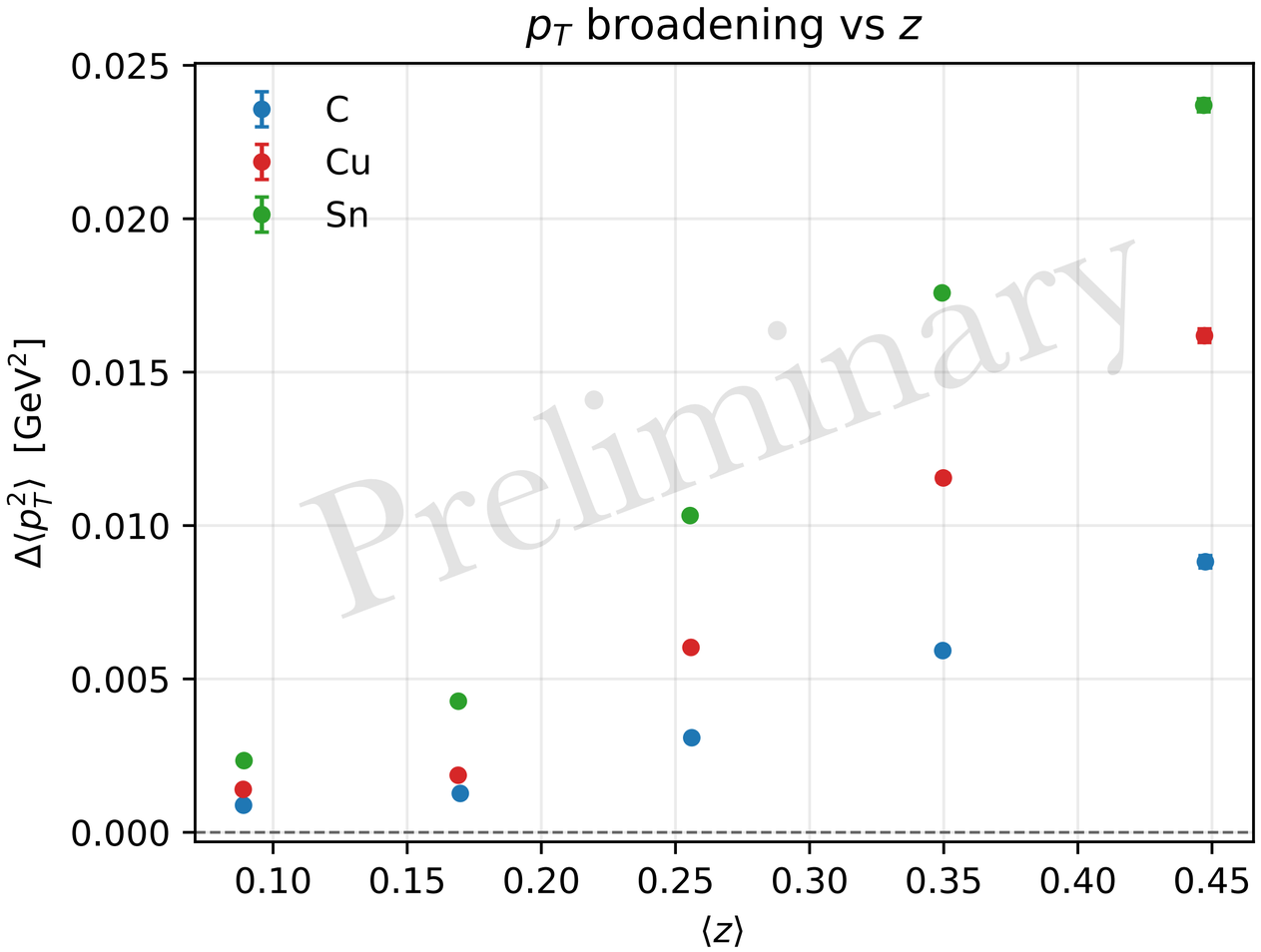
# nTMDs with neutral pions: Raw $\Delta\langle p_T^2 \rangle$

Raw $p_T$ broadening:

$$\Delta\langle p_T^2 \rangle_A(Q^2, x_B, z) = \langle p_T^2 \rangle_A(Q^2, x_B, z) - \langle p_T^2 \rangle_D(Q^2, x_B, z)$$



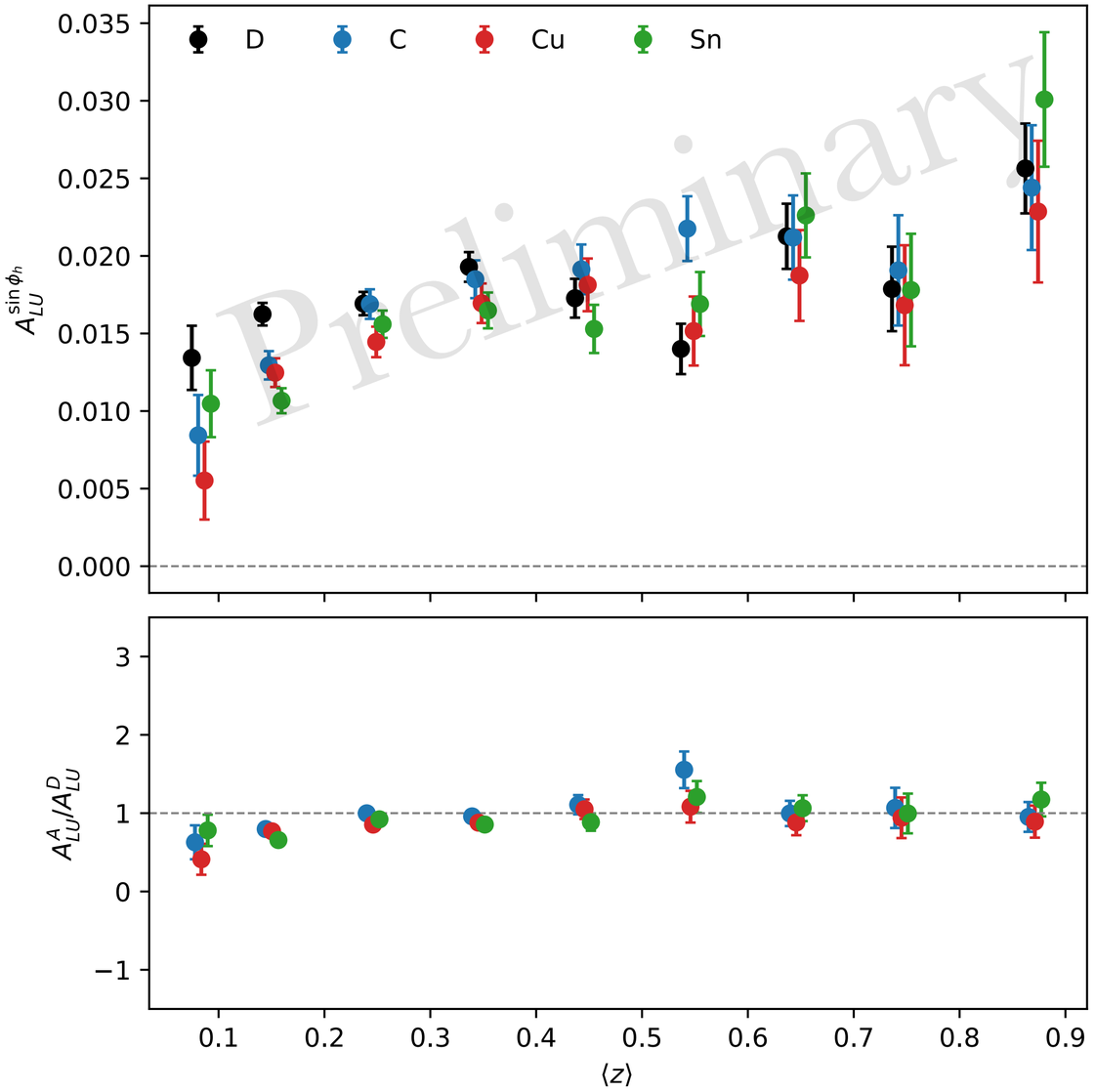

Preliminary (v0.2.1, RG-A photon ID), stat. errors only; dashed: line through the origin



# nTMDs with neutral pions BSA

- First look at $\pi^0$BSA

$$A_{LU}(\phi_h) = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}$$

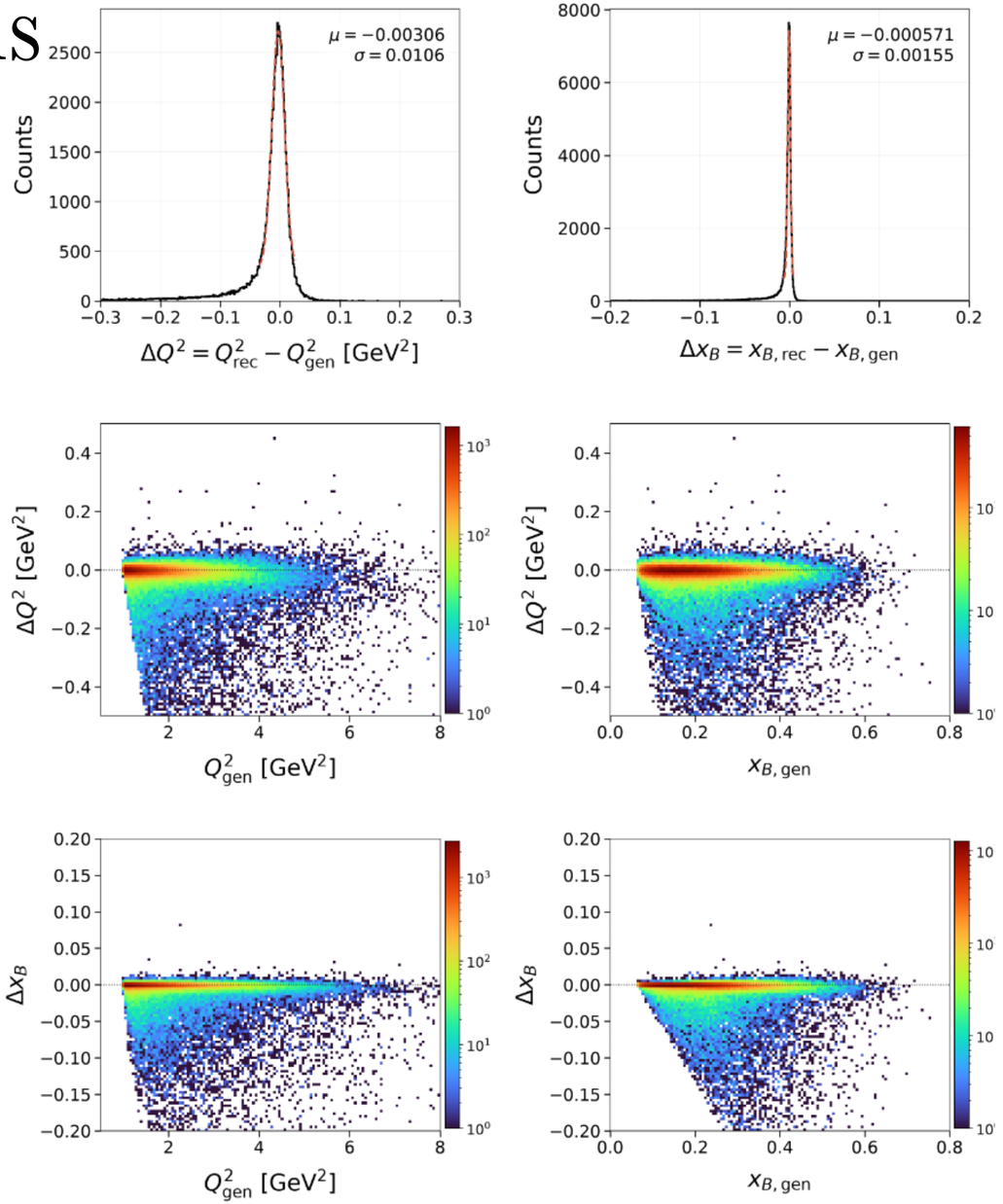



Preliminary (v0.2.1, RG-A photon ID)

# $\pi^+$ nTMDs: Acceptance Corrections

Work by Suman Shrestha

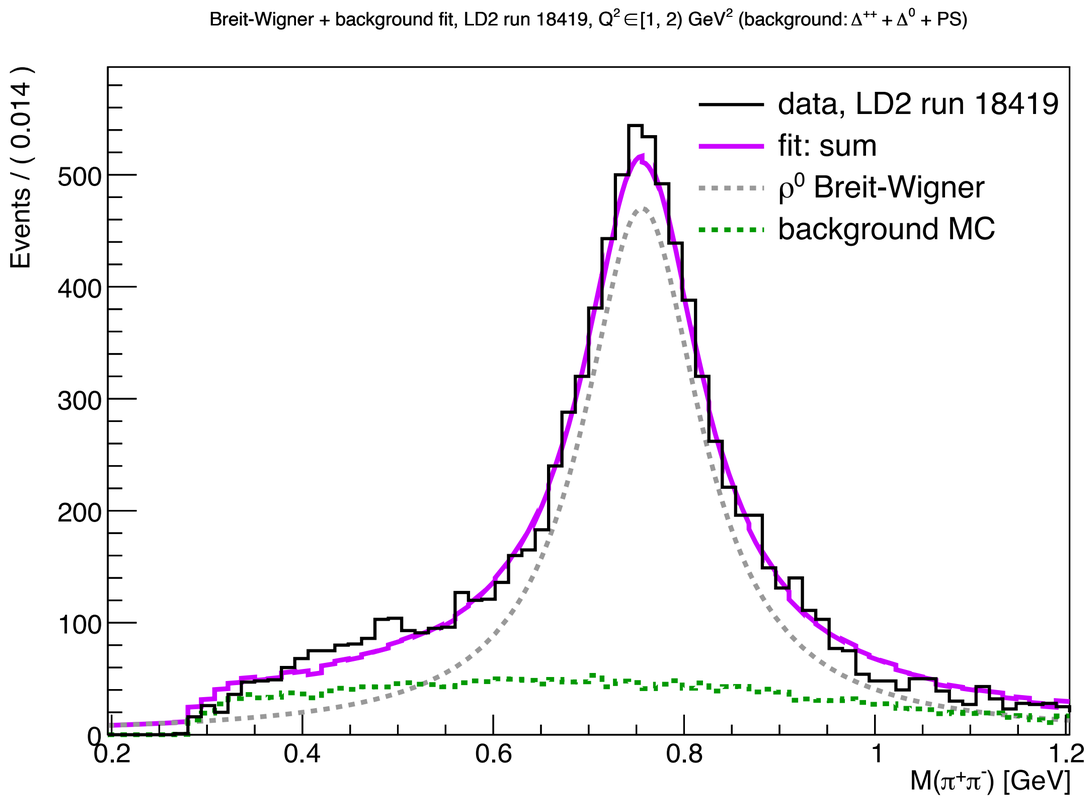
- Detector coverage, reconstruction inefficiencies, and kinematic smearing affect measured event distributions.
- Monte Carlo simulations are used to study these effects by comparing generated and reconstructed events.
- Electron kinematic resolutions are studied using the differences between reconstructed and generated quantities.
- Preliminary Cu MC results show narrow central peaks with negative tails in $\Delta Q^2$ and $\Delta x_B$.
- **Next:** Quantify bin migration and reconstruction efficiency in $(Q^2, x_B)$, followed by a multidimensional acceptance study of $\pi^+$ in $(Q^2, x_B, z, p_T^2, \phi_h)$.

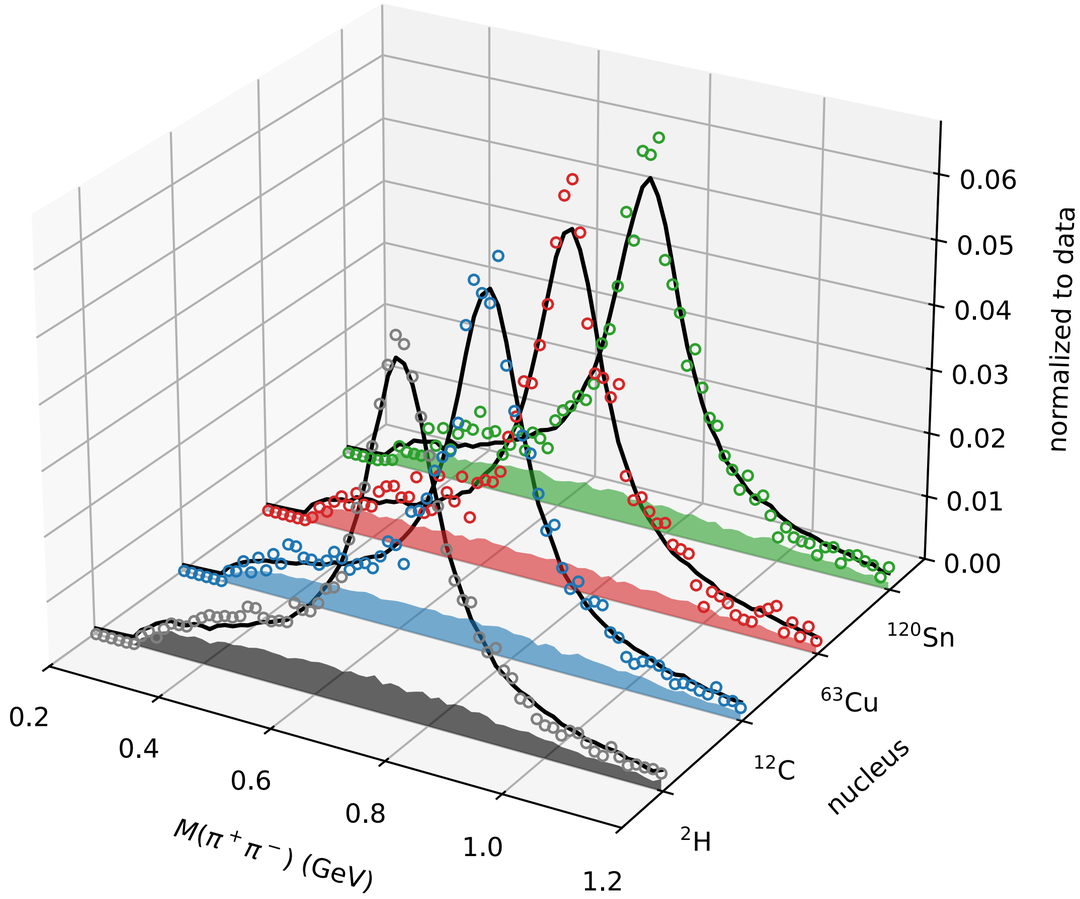


# Color Transparency Update

- $\rho^0$ electroproduction generator ea_vm (L. El Fassi), packaged for OSG submission as EAVM_RGD (code.jlab.org/marianat/EAVM_RGD)

- Also produces the background channels $\Delta^{++}$, $\Delta^0$ and non-resonant $\pi^+\pi^-$




$z_h > 0.85$ , $l_c < 1$ fm, $0.1 < -t < 0.5$ GeV²

# Summary and Outlook

- RG-D pass1 complete (April 2026): dedicated ct, sidis and jpsitcs trains.
- Common Aspects note: shared beam charge, $e^-$ and $\pi^\pm$ selection, and vertex correction for all RG-D analyses.
- $\pi^0$ nTMDs: first preliminary $R_A$, $\Delta\langle p_T^2 \rangle$ and $A_{LU}^{\sin\phi_h}$ for C, Cu, Sn vs LD2 in 4D bins.
- $R_A$ preliminary results show the same trend as HERMES and CLAS6.
- CT: $\rho^0$ generator packaged for OSG; Breit-Wigner + background shape for all targets.
- $\pi^0$ on the full sidis train is currently running, it includes IB and OB polarities.
- Train GBT for RGD datasets for photon identification.
- Implement radiative and acceptance corrections for nuclear transparency and neutral pion nTMD studies.

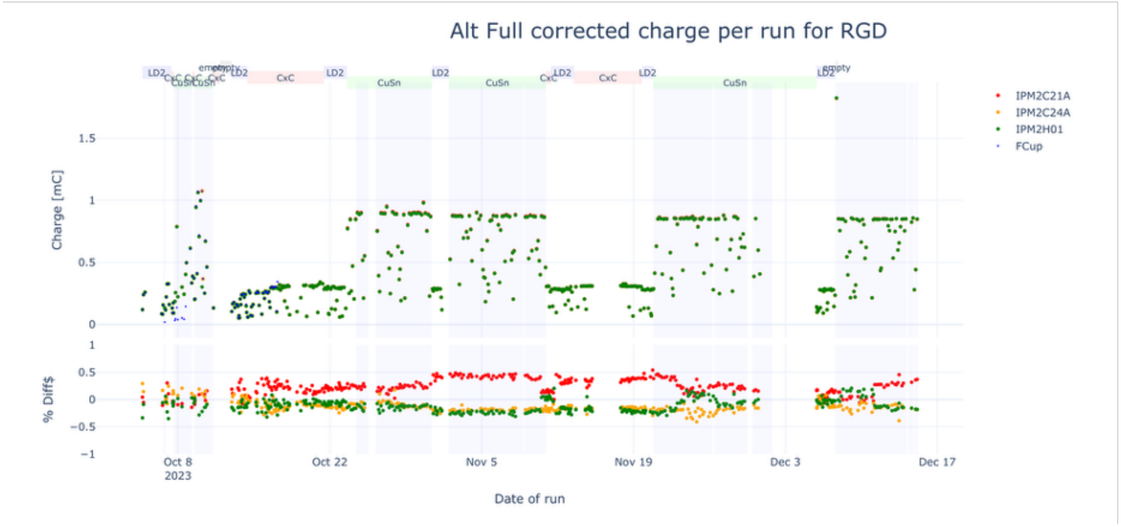
# Backup slides

# Backup: Live-time-corrected Beam Charge

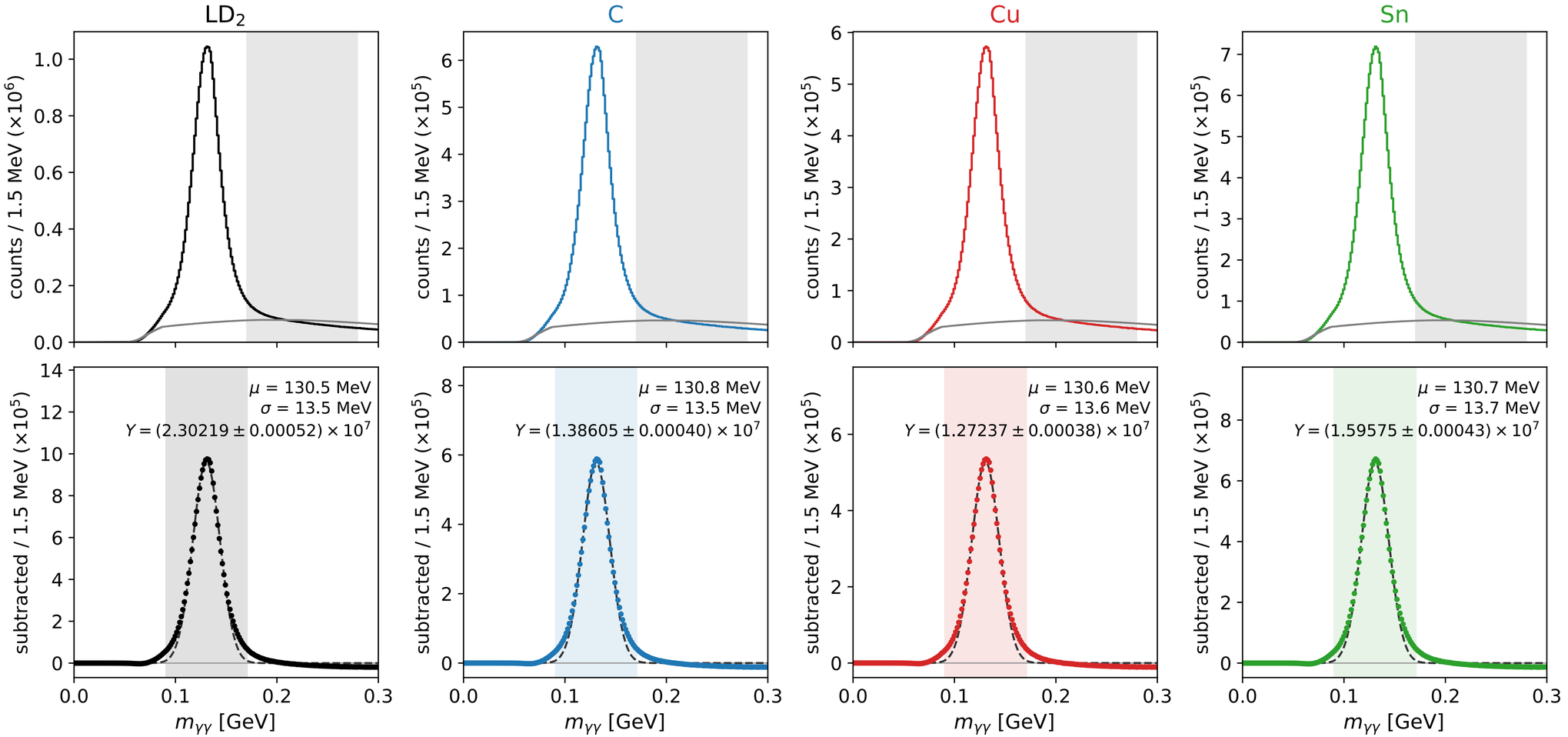
- Faraday cup unusable for RG-D: a vacuum leak made the zero-beam offset drift from ~200 to ~1400 Hz (signal ~4500 Hz at 5 nA), and the beam-blocker attenuation was not reliably recorded
- Charge from 3 BPMs (IPM2C21A, IPM2C24A, IPM2H01), each calibrated to the FCup, $I_{FC} = a\, I_{BPM} + b$, in the Oct 8, 2023 current scan (5 to 200 nA, blocker out, empty target)
- Per run: BPM current integrated with the DAQ live time, averaged over the 3 BPMs; after calibration they agree within ±0.5%
- Common systematic: 0.7% (fit 0.15%, choice of calibration data 0.5%, BPM gain drift 0.5%)

| Target | Runs | Charge [mC] |
|---|---|---|
| LD2 | 165 | 30.69 |
| CxC | 137 | 27.72 |
| CuSn | 349 | 170.79 |
| Empty | 11 | 2.16 |
| **Total** | **662** | **231.36** |



# nTMDs with neutral pions




Preliminary (v0.2.1, RG-A photon ID)

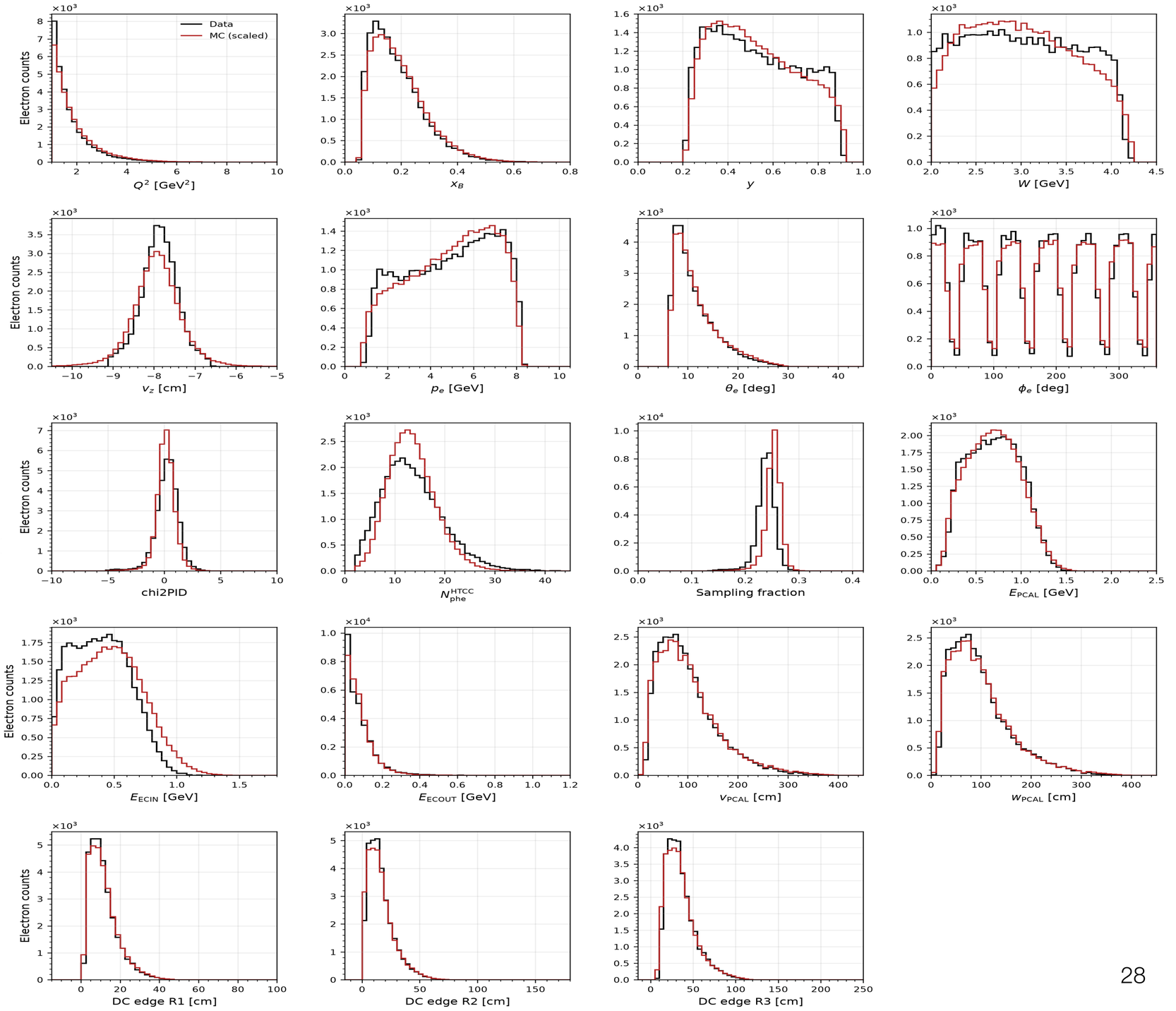
# Backup slide: Data – MC comparison

- Target: Cu.
- Beam energy: 10.54 GeV.
- Configuration: Outbending
- Truth–reconstruction matching : MC::RecMatch quality ≥ 0.98) .

Electron selection

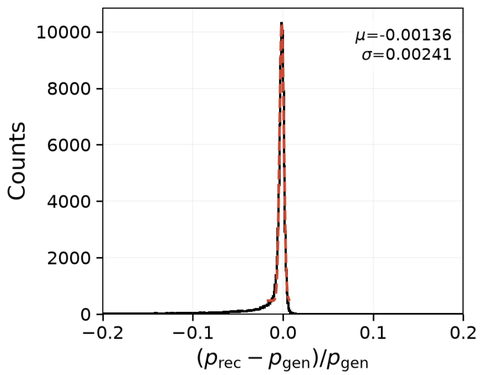
- Forward detector (FD), electron PID = 11.
- $p_e > 1.8$ GeV; HTCC ($N_{phe}$) > 2.
- PCAL energy (>0.06) GeV; (v,w>9) cm.
- Sampling fraction within ($\mu \pm 3.5\ \sigma$); (-5< chi2pid <5).
- DC fiducial edges (R1, R2, R3): 1.88, 2.08, 8.62 cm.
- Z-vertex: [-10.6 < $V_z$< -6.5] cm.

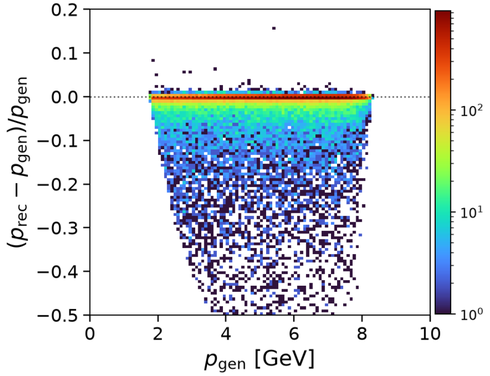
DIS kinematic selection : $Q^2 > 1\ \mathrm{GeV}^2, W > 2\ \mathrm{GeV}, y < 0.85$ to both generated and reconstructed kinematics.

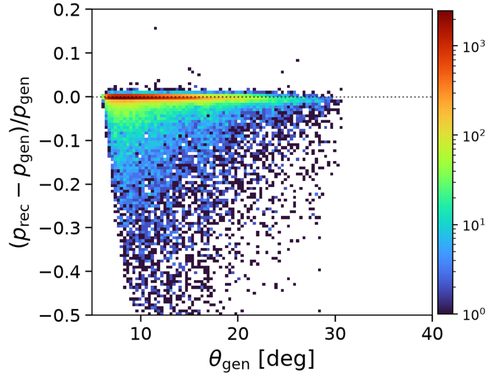


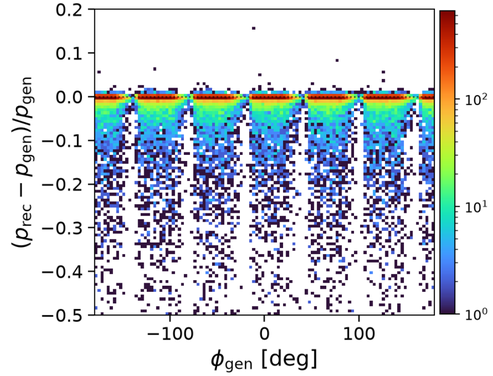
# Backup slide:

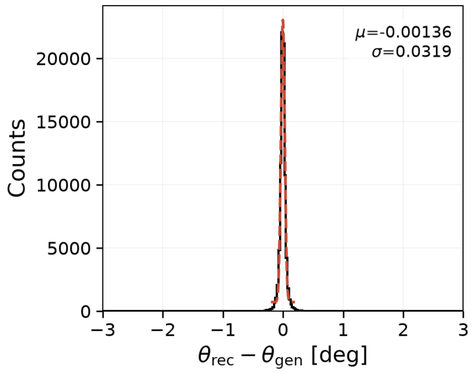
Work by Suman Shrestha

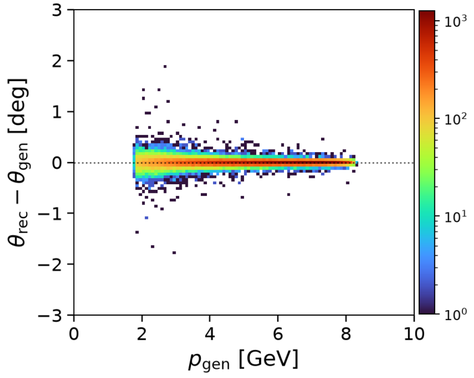


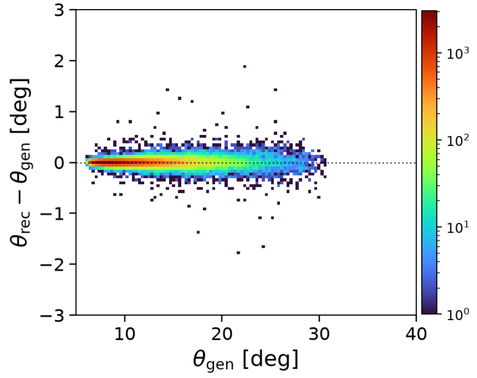



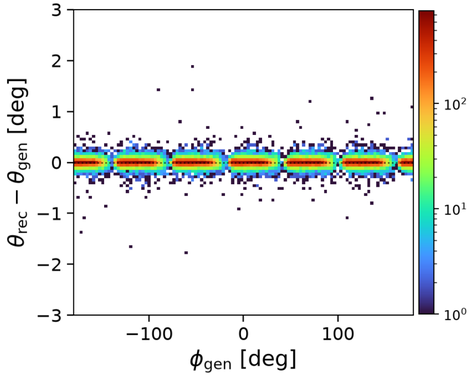



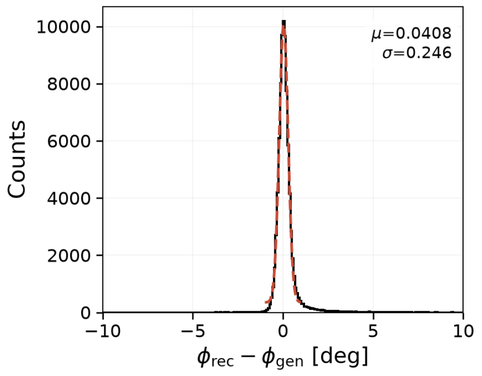



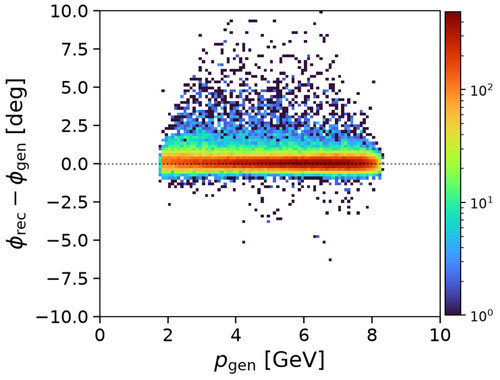



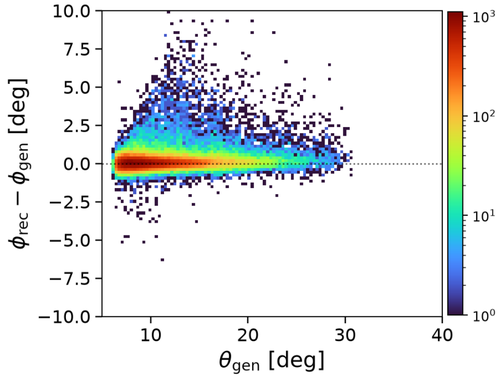



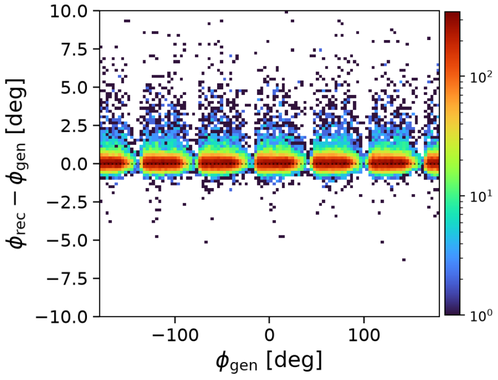



# CT: Background fits for each target

