RG-D Experiments: Status and Analysis Plans

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Run Group D

[1]: Argonne National Lab, [2]: IJCLAB, Orsay, France
[3]: Mississippi State U., [4]: University of New-Hampshire, [5]: Florida International University

Run Group D is composed of two experiments:

Color Transparency (CT)

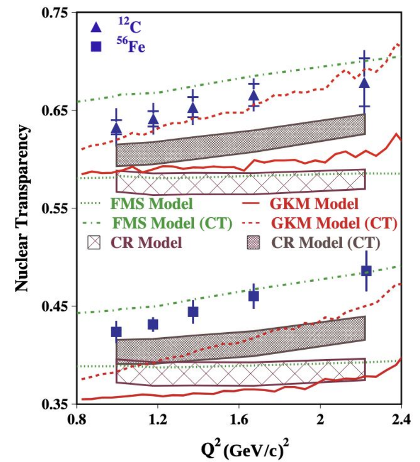
in Exclusive Vector Meson Electro-production off Nuclei E12-06-106

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

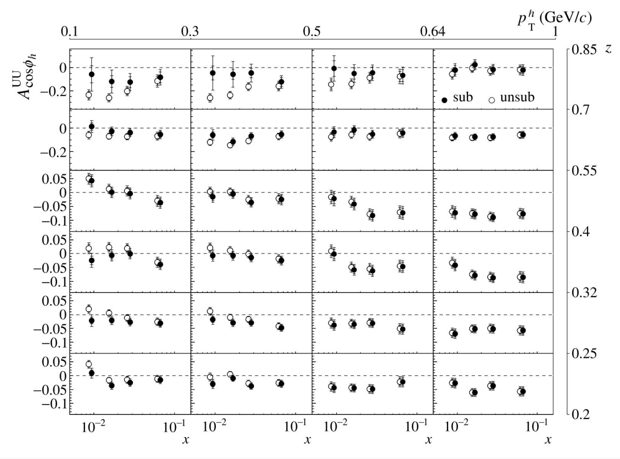
Nuclear TMDs (nTMDs)

in CLAS12 E12-06-106A

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



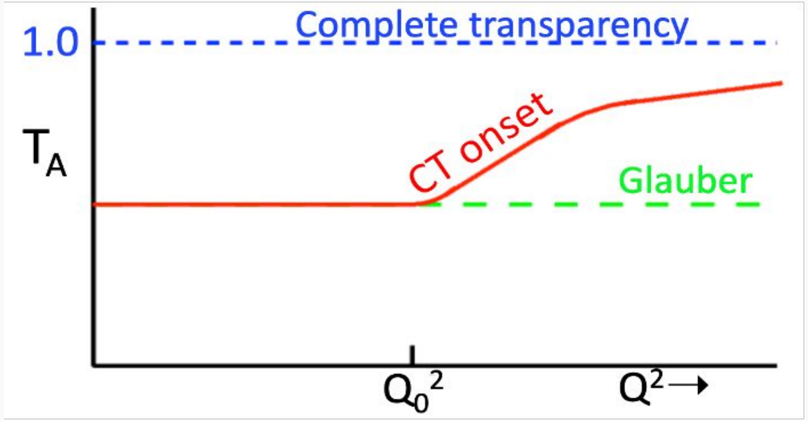
L. El Fassi, Physics 4, no. 3 (2022)



The COMPASS Collaboration arxiv.org:1912.10322

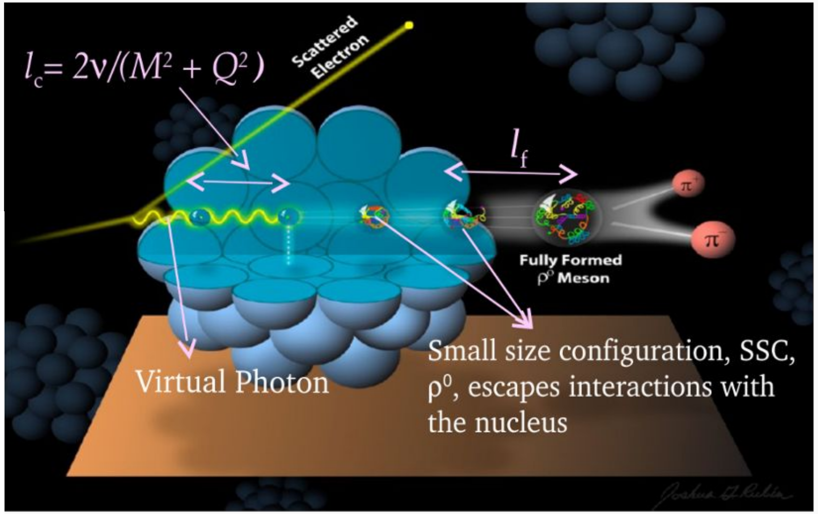
RG-D: CT Experiment

- E12-06-106: Color Transparency: suppression of interactions of colorless small size configuration in nuclear medium
- Experimental signature: rise of the nuclear transparency, T_A as a function of Q^2:
  - T_A: ratio of the cross section per nucleon on a bound nucleon to that on a free nucleon



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

σ_A – nuclei cross section
σ_N – free nucleon cross section



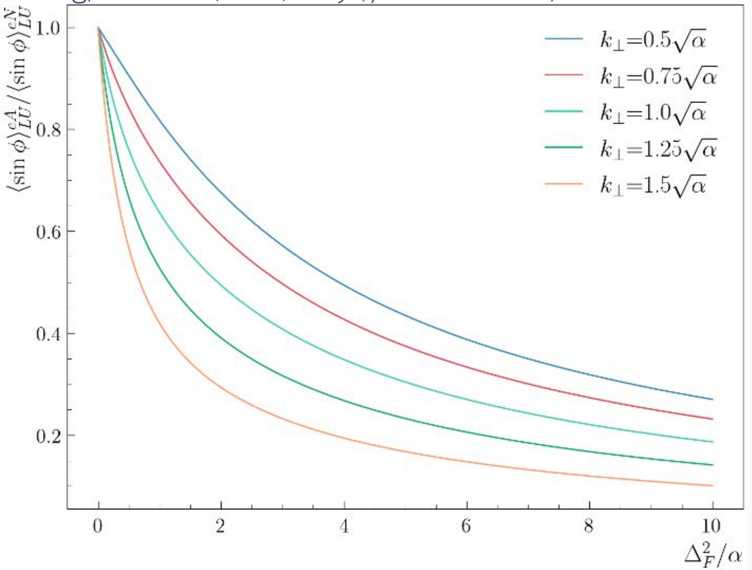
Objective: understanding the dynamical evolution from small-size configurations into ordinary hadrons, and validating the QCD factorization theorem

Coherence length, l_c: the lifetime of the qq-bar pair
Formation time, l_f: the time evolution of SSC to an on-shell ρ^0 meson

RG-D: Nuclear TMDs

- E12-06-106A: nTMDs study uses the same CT running conditions except the beam polarization, and aims to study:
  - Nuclear effect on SIDIS asymmetries
  - Transport coefficient of the nuclear matter
- For that, measure different observables:
  - cos φ, sin φ, cos(2φ)[1] moments for different hadrons (π^+,π^-, and π^0):

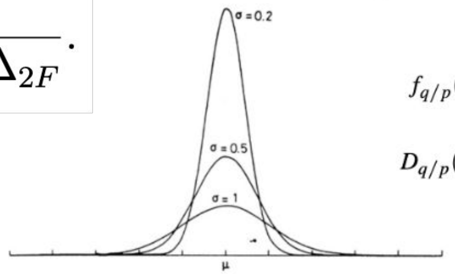
Song, Y. et al. (2014) Physical Review D, 89 014005.



$$\frac{\langle \cos\phi\rangle^{eA}_{UU}}{\langle \cos\phi\rangle^{eN}_{UU}} \approx \frac{\alpha}{\alpha+\Delta_{2F}}, \quad \frac{\langle \sin\phi\rangle^{eA}_{LU}}{\langle \sin\phi\rangle^{eN}_{LU}} \approx \frac{\alpha}{\alpha+\Delta_{2F}}.$$

$$\Delta_{2F} = \int d\xi_N^- \hat{q}_F(\xi_N),$$

$q_F(\xi_N)$: the quark transport parameter



$$f_{q/p}(x,k_T,Q) \simeq \frac{1}{\pi\langle k_T^2\rangle}\exp(-\frac{k_T^2}{\langle k_T^2\rangle})f_{q/p}(x,Q)$$

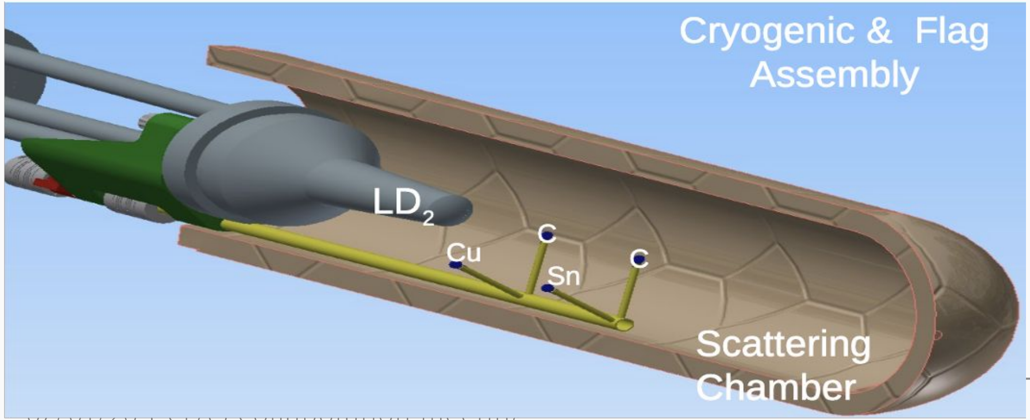
$$D_{q/p}(z,p_T,Q) \simeq \frac{1}{\pi\langle p_T^2\rangle}\exp(-\frac{p_T^2}{\langle p_T^2\rangle})D_{q/p}(x,Q)$$

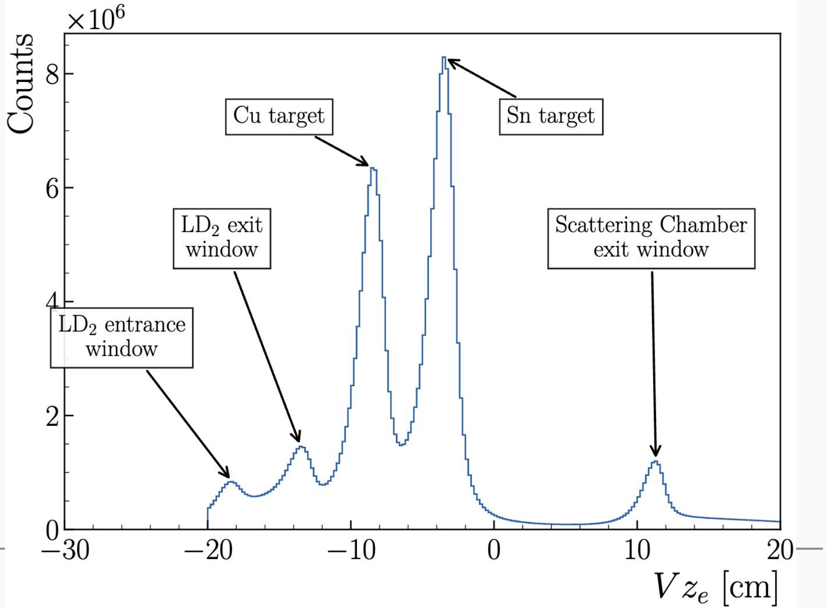
[1] No predictions exist for this observable

The heavier the nucleus, the wider the TMD gaussian width (Nuclear Broadening)

RG-D: Run Configuration

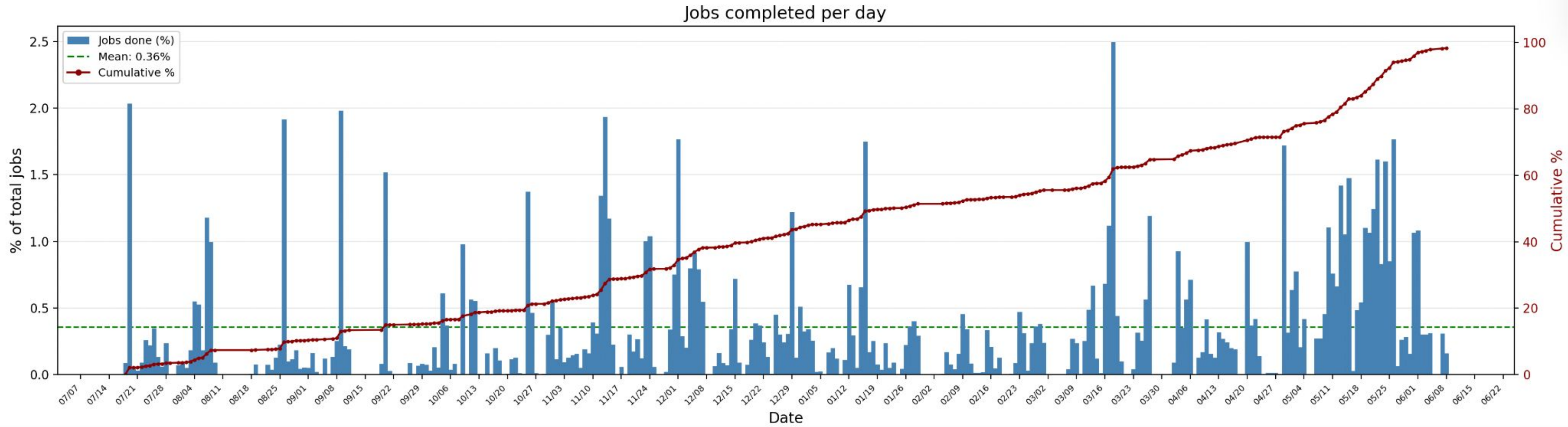
- RG-D experiments collected data in the fall of 2023 with
  - 10.54 GeV polarized beam energy and I=5–175 nA for luminosity scans and production
  - Standard CLAS12 configuration with FT-OFF and three layers of FMT
  - Three target configurations, LD2, CxC, and CuSn, deployed with InBending and OutBending
  - New cryogenic LD2 and the nuclear-foil flag assembly centered at -5 cm for each configuration
- Main run hiccups:
  - Faraday Cup vacuum contamination
  - Moller cone sagging





RG-D Status: Cooking Summary

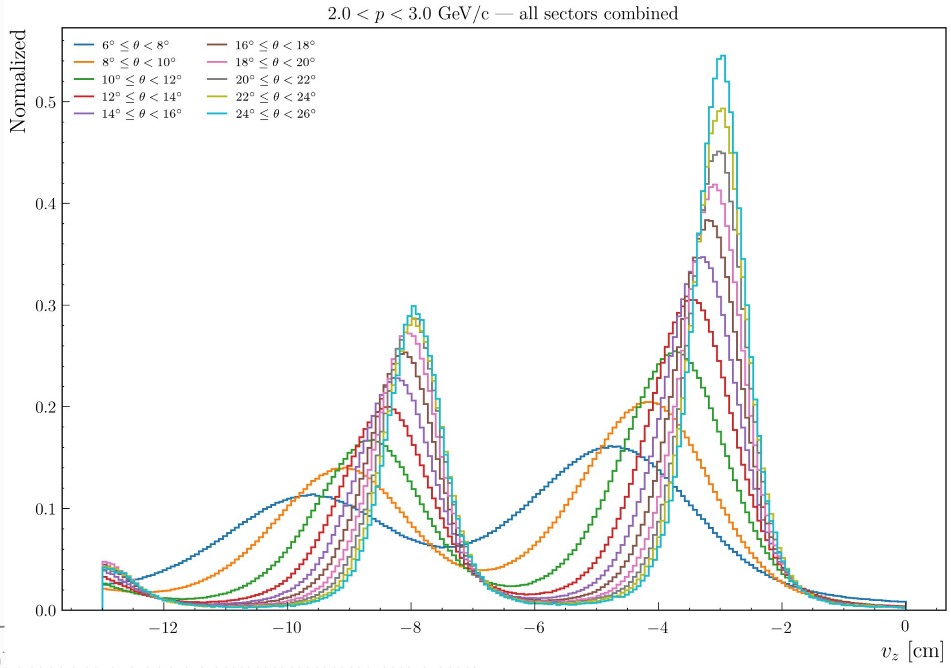
- RG-D successfully passed Pass1 review on May 27th 2025
- Pass1 cooking initiated on June 13th 2025 using COATJAVA 13.0.0
- The cooking finished beginning of April:
  - Took 11M CPU-hours, for a total of 177,259 jobs

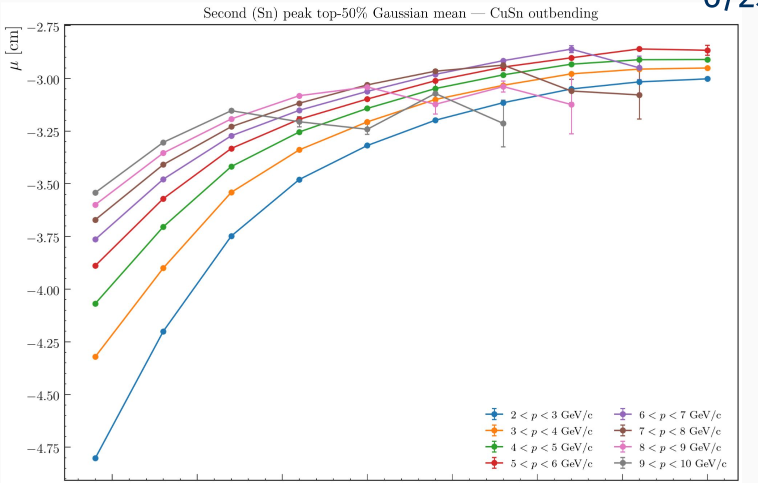


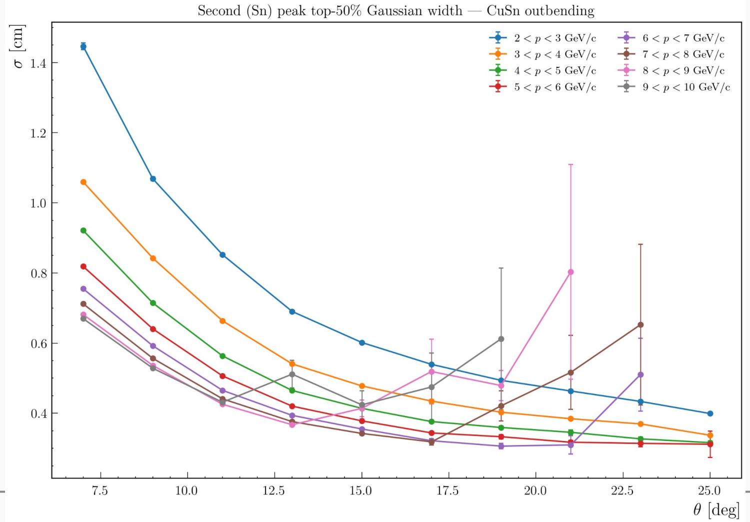
Thanks to CalCom Experts for their support for calibration and cooking

Electron Vertex Study

- With double foil targets: found that the electron Z vertex is shifted and wider as function of momentum, θ, φ, and sector.







Electron Vertex Study

- Found that the electron V_z peaks are shifted and broadened, and the effect depends on p, θ, φ, and sector.
- Goal: derive a correction so that a single pair of V_z cut values works across all kinematics.
- Binning: 6 sectors, $p \Rightarrow 16$ bins $\in [2, 10]$ GeV/c, $\theta \Rightarrow 24$ bins $\in [6, 30]°$, local-φ $\Rightarrow$ 6 bins $\Rightarrow$ 13,824 (s, p, θ, φ) bins
- The distribution is stable across bins when $\theta > 15°$ and $p > 5$ GeV/C → reference region
- Fit the distribution with a double Gaussian and extract μ_0 and σ_0

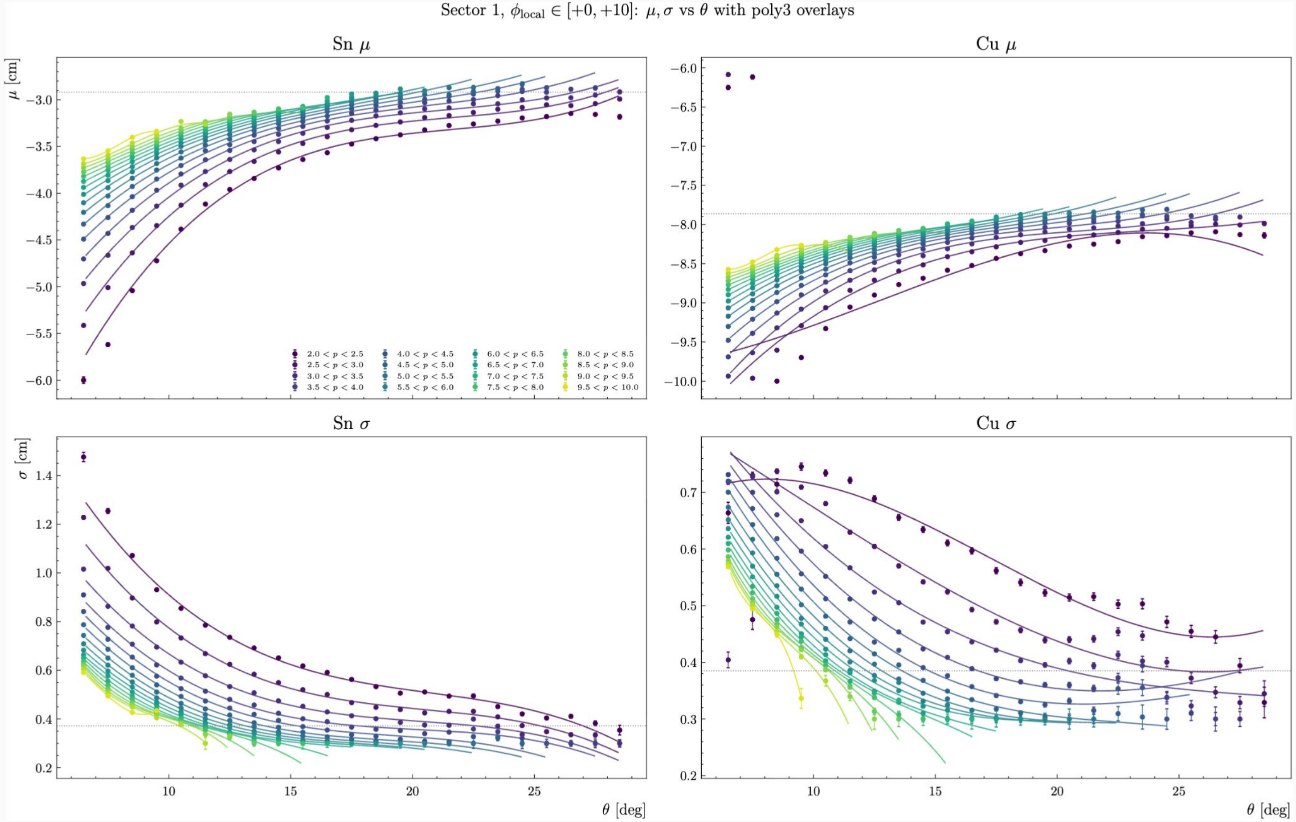
Tin: μ_0 = -2.92 cm
σ_0 = 0.37 cm

Copper: μ_0 = -7.86 cm
σ_0 = 0.38 cm

Electron Vertex Study

- For every (s, p, φ, θ) bin: Fit two peaks with Gaussians.
- Give μ, σ with errors for both targets, per (sector, p, φ, θ).

- Fit with third-order polynomial function the 24 θ-points of: $\mu_{Sn}(\theta)$, $\sigma_{Sn}(\theta)$, $\mu_{Cu}(\theta)$, $\sigma_{Cu}(\theta)$.



Electron Vertex Study

- The correction is:

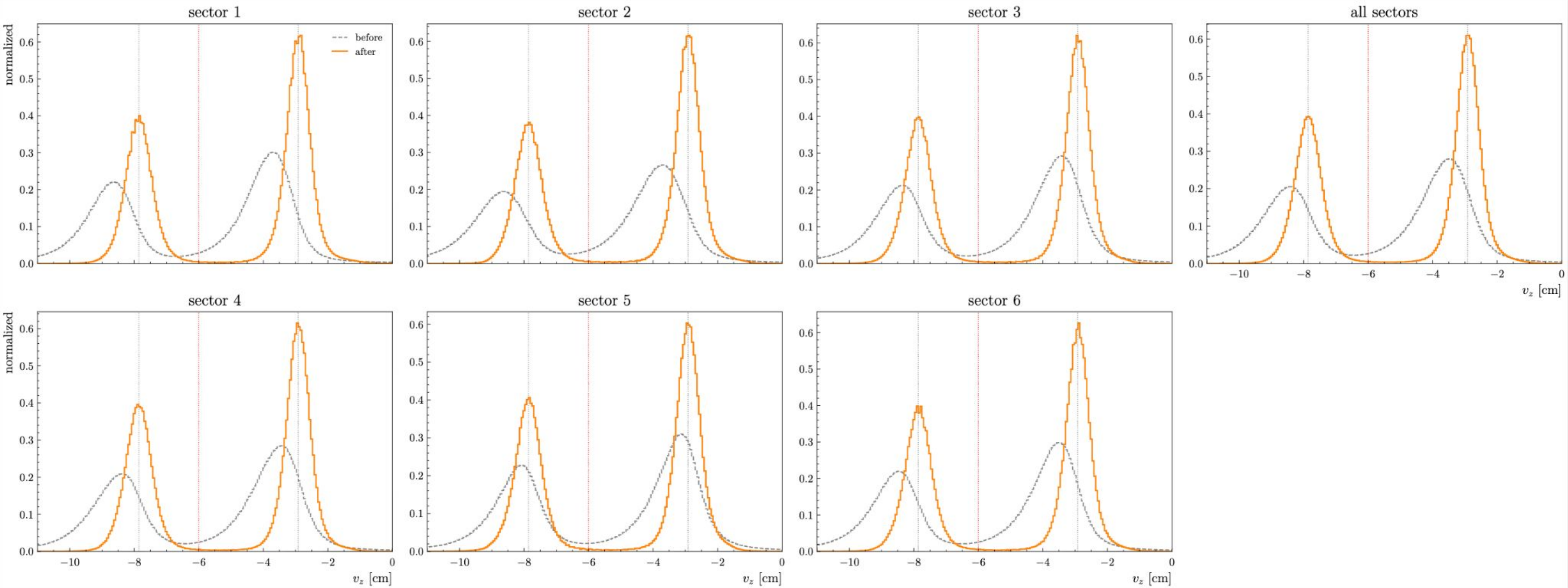
$$v_z^{\mathrm{Sn}} = \mu_0^{\mathrm{Sn}} + \left(\sigma_0^{\mathrm{Sn}}/\sigma_p^{\mathrm{Sn}}(\theta)\right)\left(v_z - \mu_p^{\mathrm{Sn}}(\theta)\right), v_z^{\mathrm{Cu}} = \mu_0^{\mathrm{Cu}} + \left(\sigma_0^{\mathrm{Cu}}/\sigma_p^{\mathrm{Cu}}(\theta)\right)\left(v_z - \mu_p^{\mathrm{Cu}}(\theta)\right)$$

$$w_{\mathrm{Sn}} = \frac{1}{1 + e^{-(v_z - v_{\mathrm{mid}})/\tau}}, \qquad v_z^{\mathrm{corr}} = w_{\mathrm{Sn}} v_z^{\mathrm{Sn}} + \left(1 - w_{\mathrm{Sn}}\right) v_z^{\mathrm{Cu}}$$

- Per-bin transform that shifts and rescales V_z to align each peak with the reference μ_0 and σ_0.
- Each event shifts toward its nearest target; smooth handover.
- μ_p, σ_p come from the third order polynomial function evaluated at the event's (s, p, φ, θ)

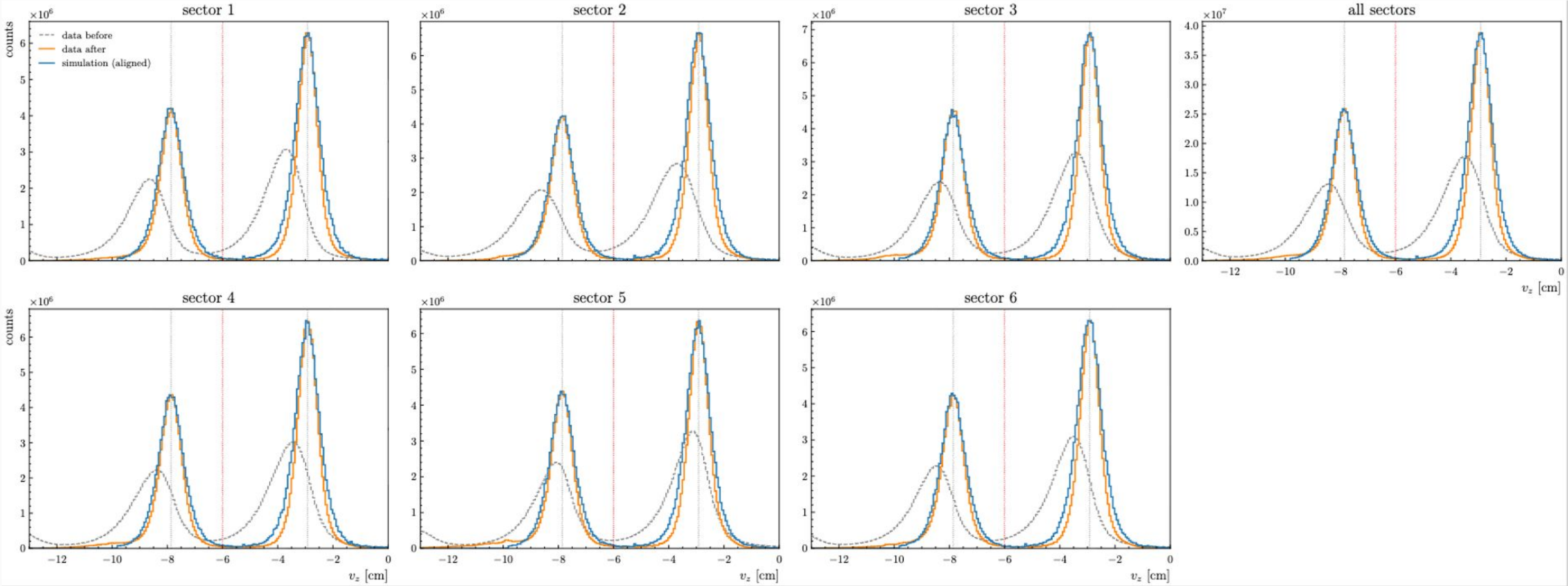
Electron Vertex Study

- Effect of the correction on outbending electron:



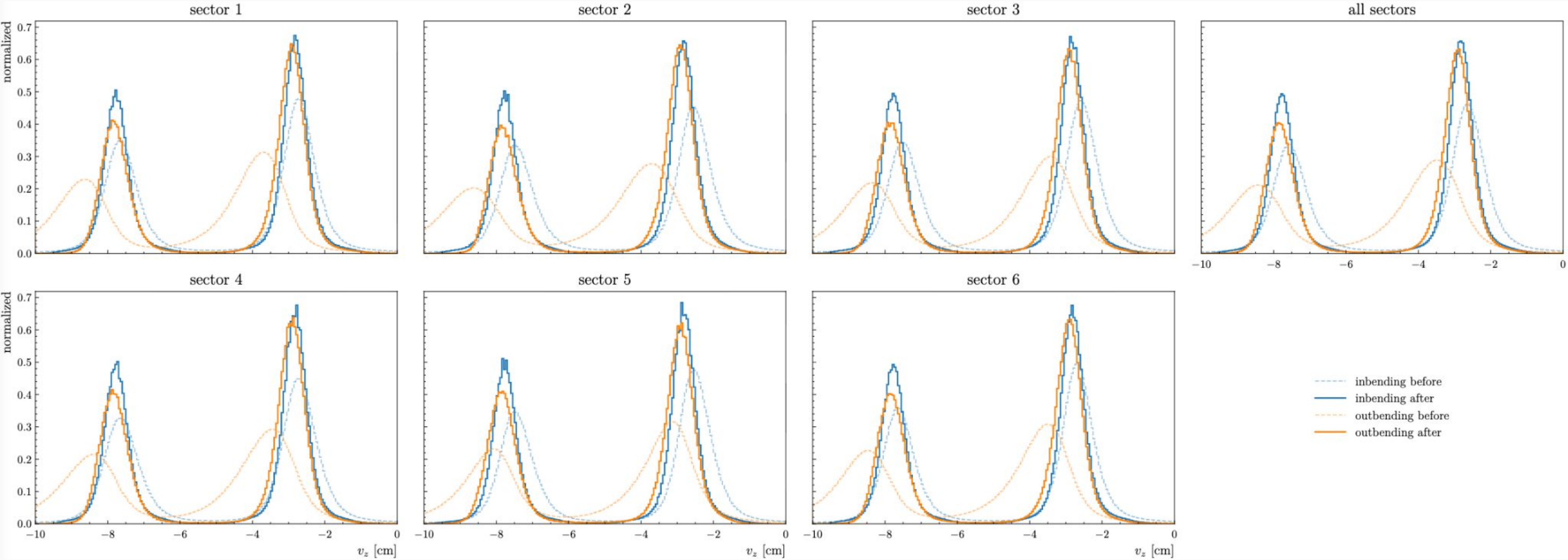
Electron Vertex Study

- Comparison of MC and data:



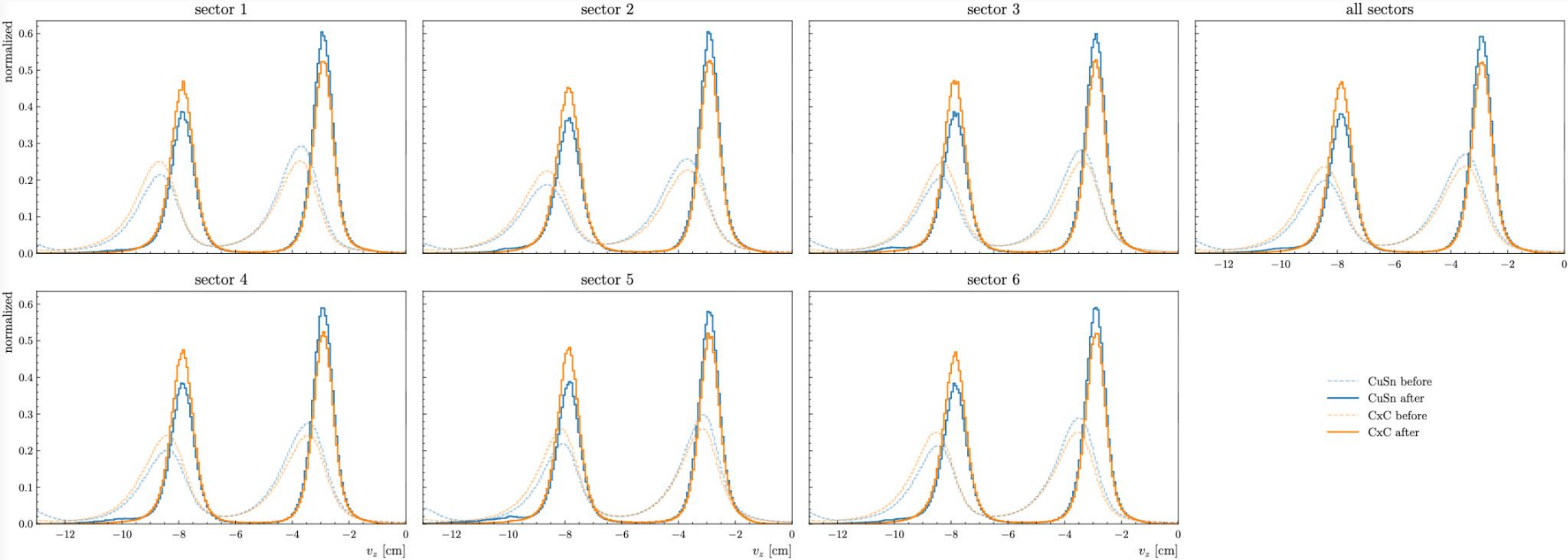
Electron Vertex Study

- Comparison of Inbending vs Outbending CuSn:



Electron Vertex Study

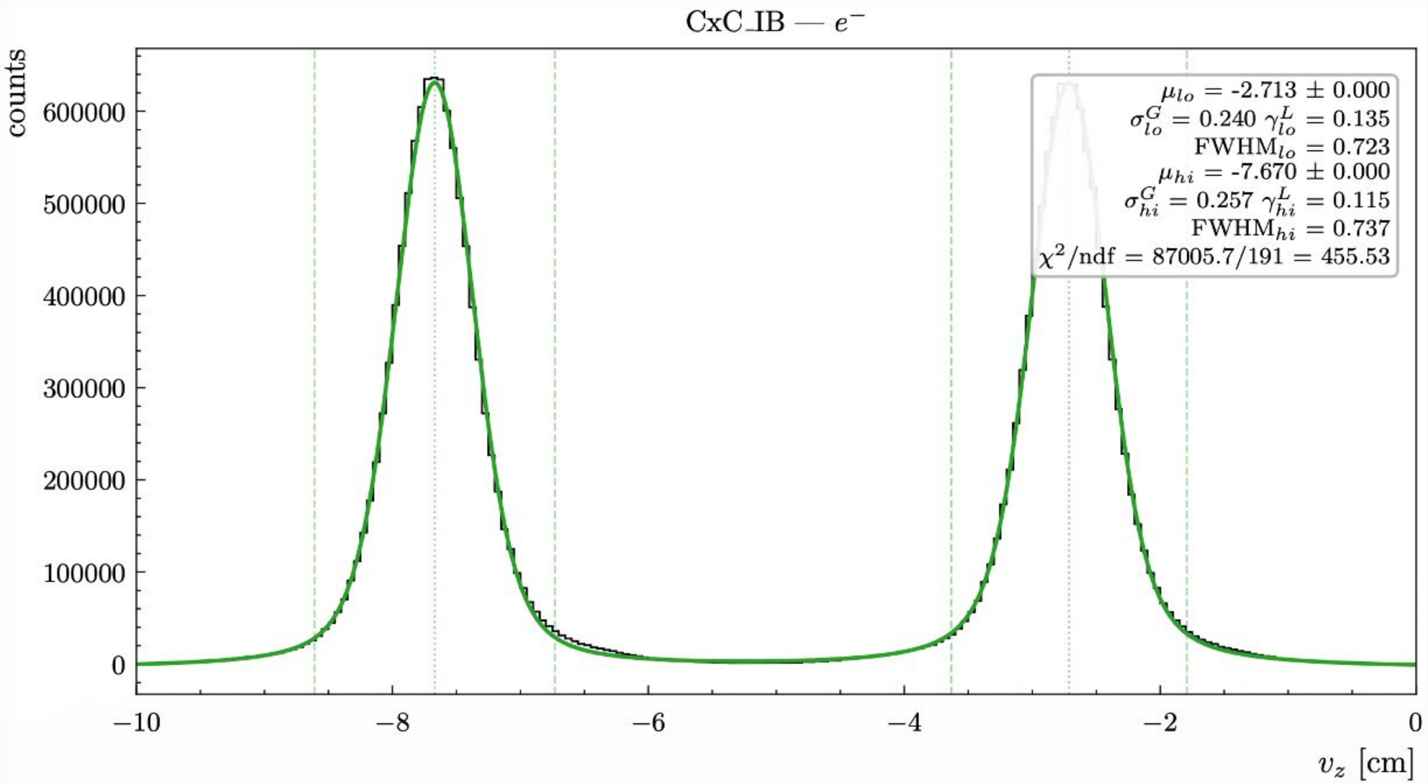
- Comparison of Carbon vs CuSn Outbending:



Electron Vertex Study

- After correction: fit the Vz distribution with simpler function (same for electron and pions):

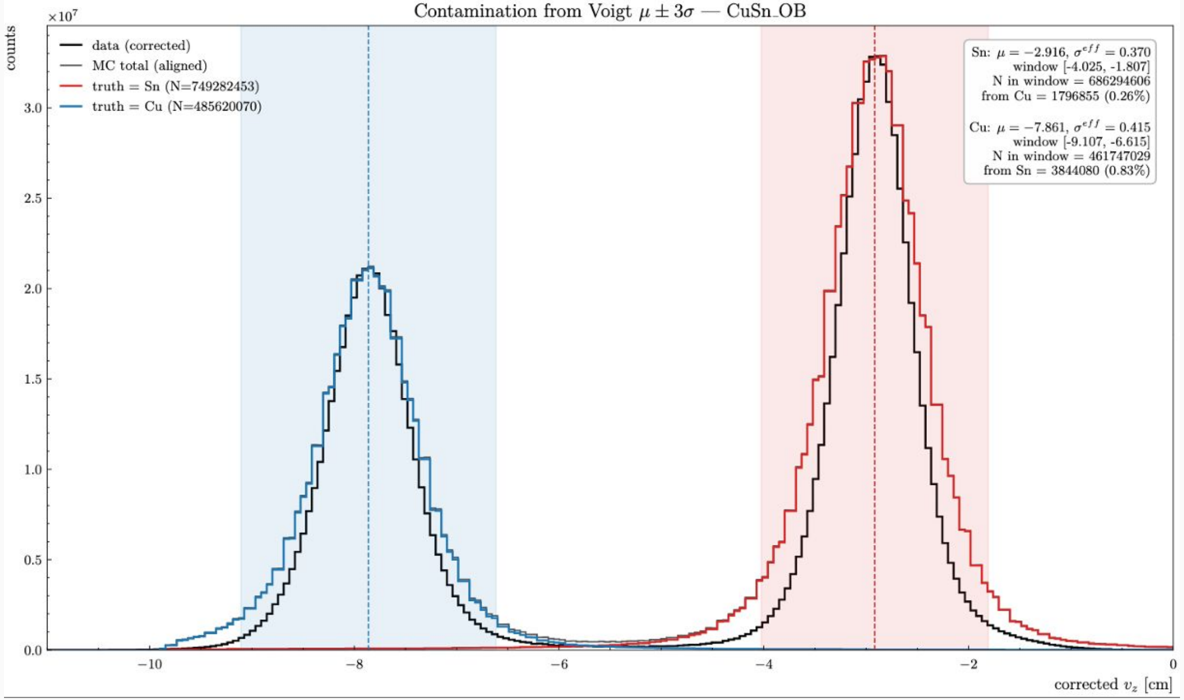
Use 2 Voigt distributions as fit function



Electron Vertex Study

We can use simulation to estimate the Cu contamination in the Sn target and Sn contamination in Cu target:

For each target peak we define a ±3σ window from its Voigt fit. Contamination is the fraction of counts in that window coming from the other target, estimated from truth-labelled MC integrated in the same window.

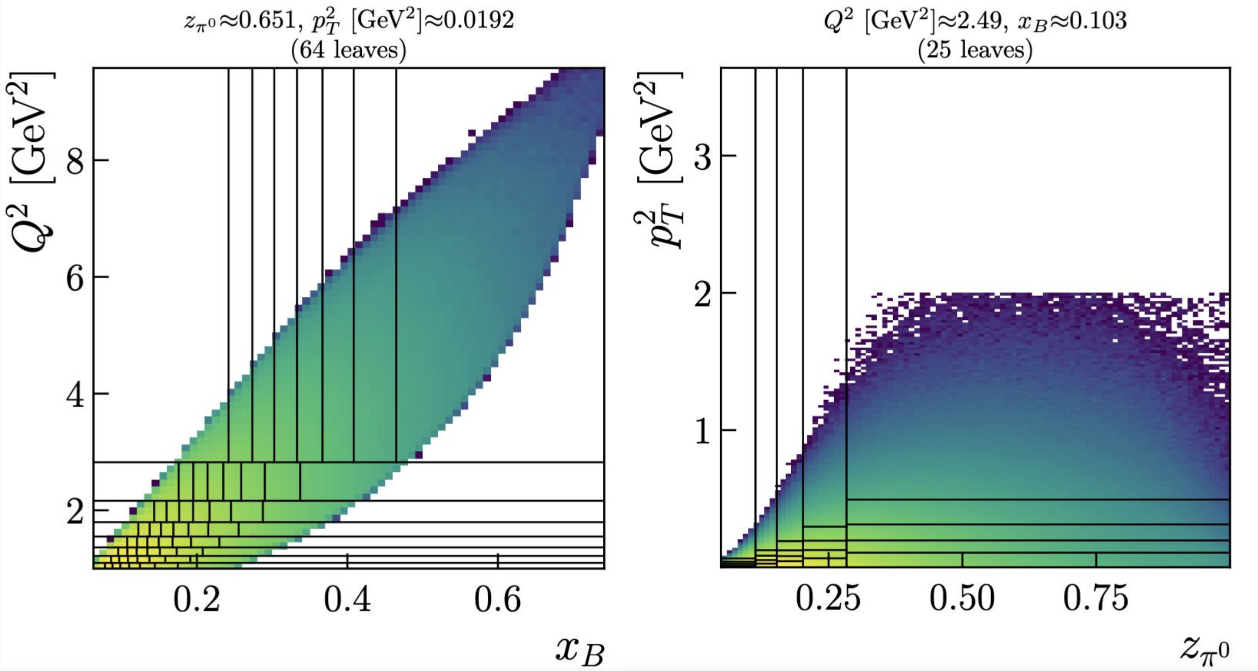


$$C_{\mathrm{Cu}} = \frac{N^{\mathrm{MC}}\text{Sn-truth in Cu window}}{N^{\mathrm{MC}}\text{total in Cu-window}}, \qquad C_{\mathrm{Sn}} = \frac{N^{\mathrm{MC}}\text{Cu-truth in Sn window}}{N^{\mathrm{MC}}\text{total in Sn window}}$$

RG-D TMDs Studies: π^0 analysis

First look at the π^0 channel to extract multiplicity ratios and azimuthal asymmetries:

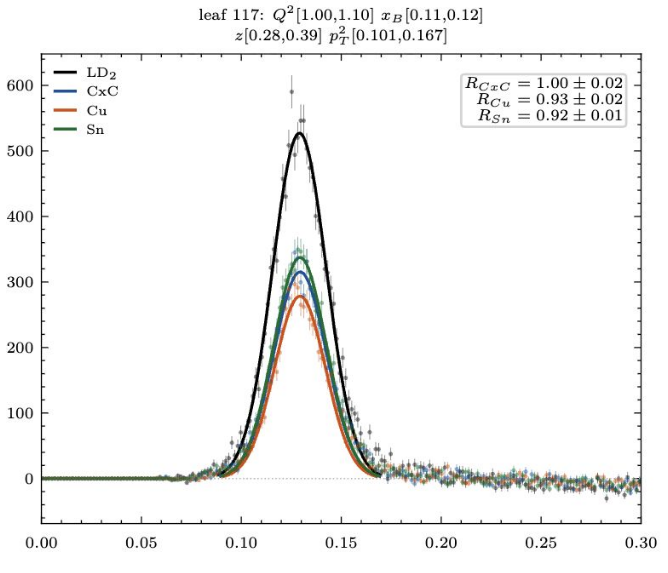
Use 4D binning, with equal statistic (KD-Tree): 8 Q^2, 8 x_B, 5 z_h and 5 p_T^2 bins: 1600 bins
Different z_h and p_T^2 bins for each Q^2 and x_B bins

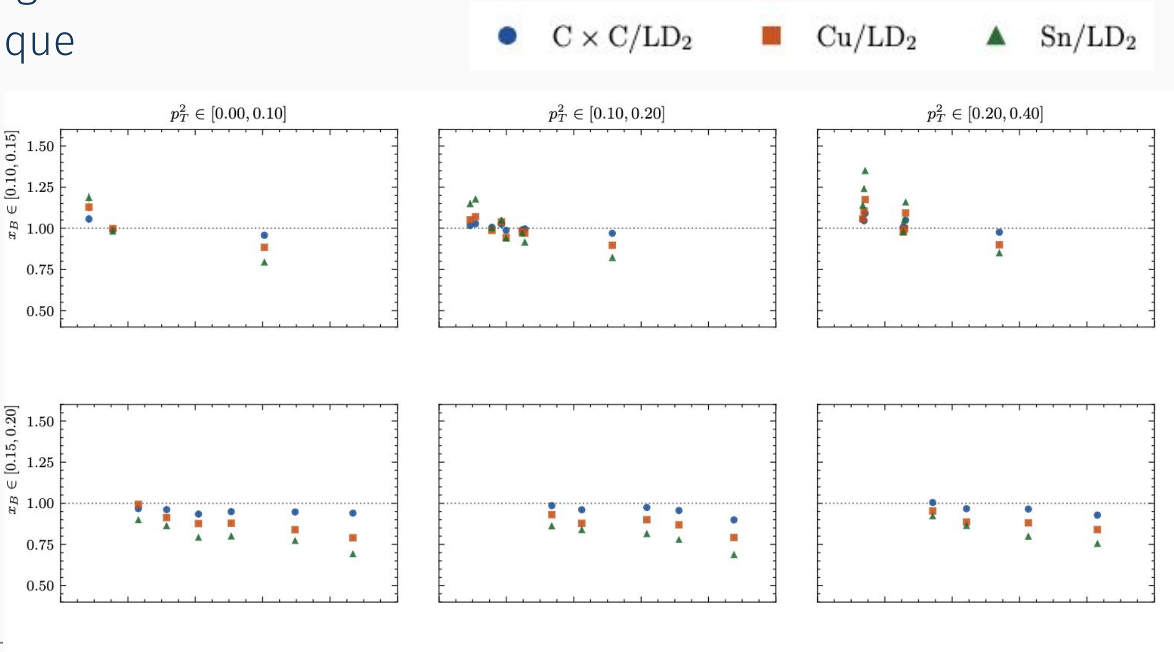


RG-D TMDs Studies: π^0 analysis

First look at the π^0 channel to extract multiplicity ratios and azimuthal asymmetries:

Extract multiplicity ratio after the background subtraction using event mixing technique

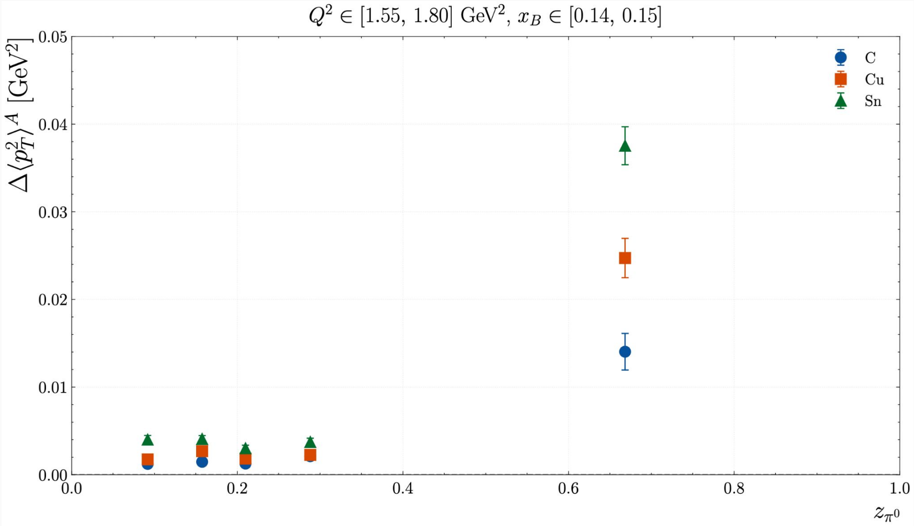


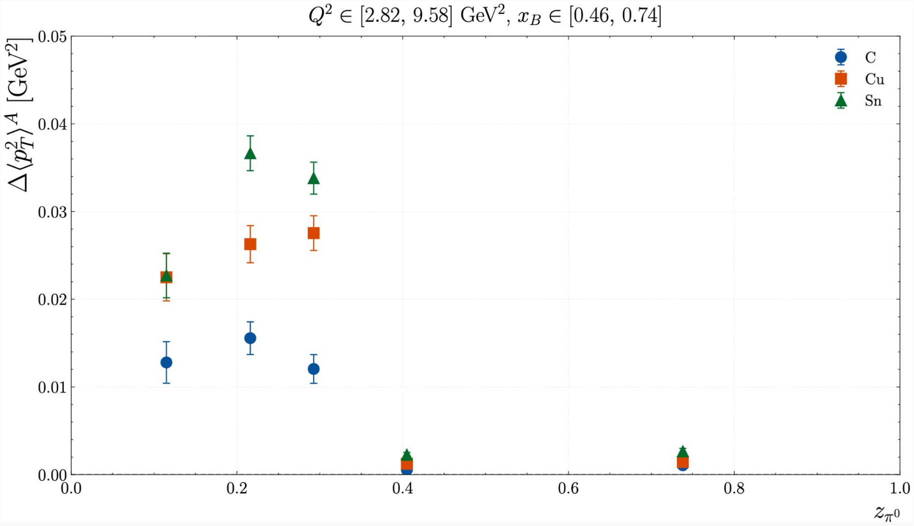


RG-D TMDs Studies: π^0 analysis

First look at the π^0 channel to extract multiplicity ratios and azimuthal asymmetries:

Extract p_T broadening for 8 Q^2, 8 x_B, 5 z_h

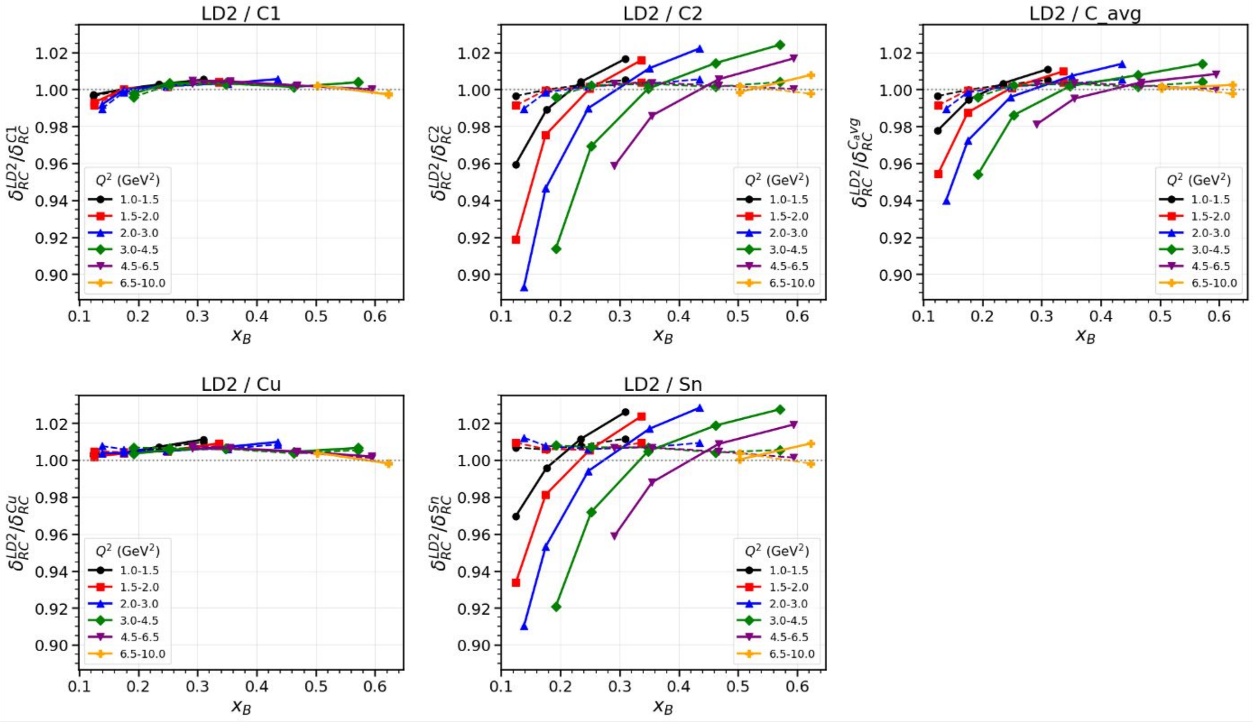




RG-D TMDs Studies: pions analysis

Study multiplicity ratio, transverse momentum broadening and azimuthal moments for both negatively and positively charged pions:

- Ratio of radiative-correction factors, $\delta_{RC}^{LD2} / \delta_{RC}^{A}$.
- Dashed lines show internal-only corrections and solid lines show internal+external corrections.

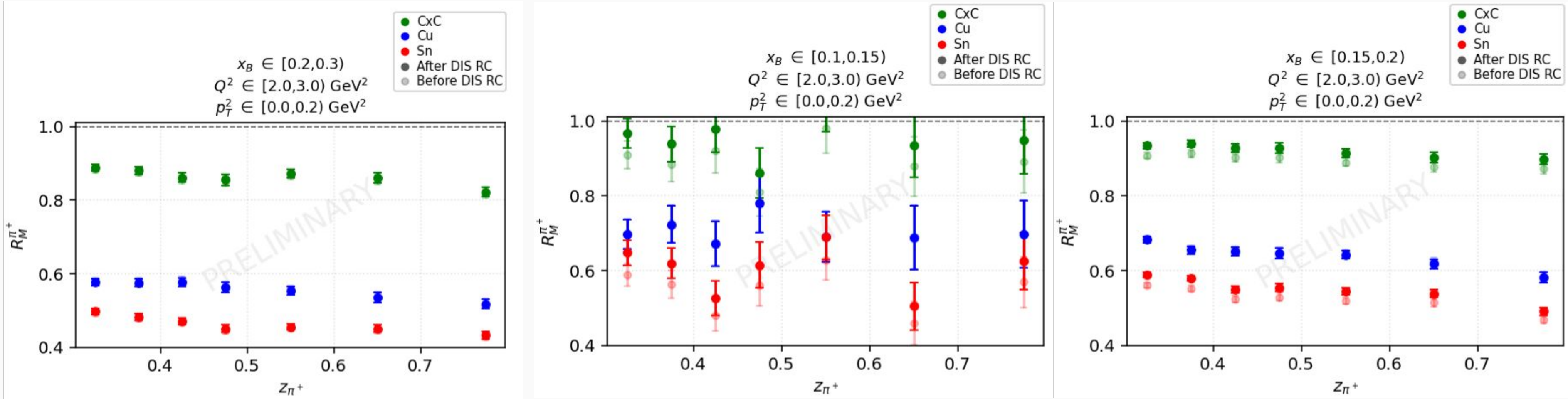


Ongoing analysis by S. Shrestha

RG-D TMDs Studies: pions analysis

Study multiplicity ratio, transverse momentum broadening and azimuthal moments for both negatively and positively charged pions:

- π^+ multiplicity ratio $R_M^{\pi^+}$) versus z_{π^+} before and after applying the DIS radiative correction. Three x_B bins are shown at fixed Q^2 and p_T^2.

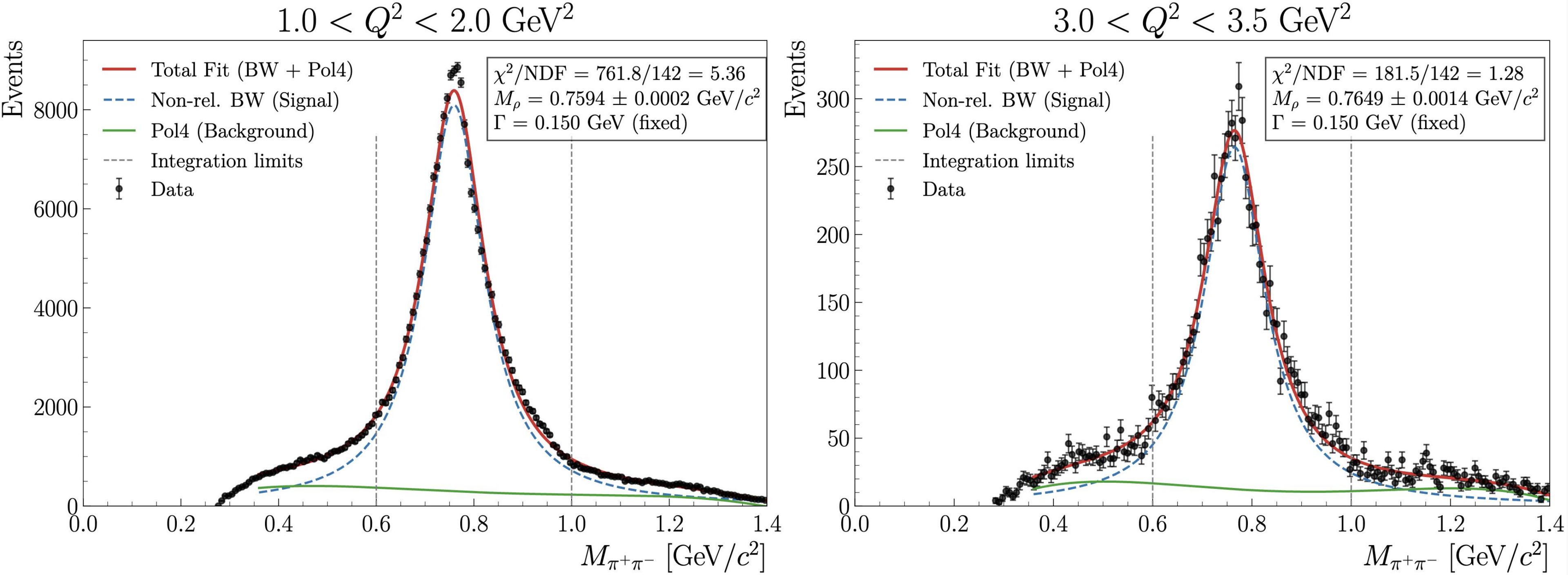


Ongoing analysis by S. Shrestha

RG-D CT Study: Very Preliminary Nuclear Transparency

Fit oppositely charged pions invariant mass with a Breit-Wigner and 3rd-order polynomial

- Extract ρ^0 yield by integrating the background-subtracted BW within a 3σ range using 10% of the Pass1 reconstruction data

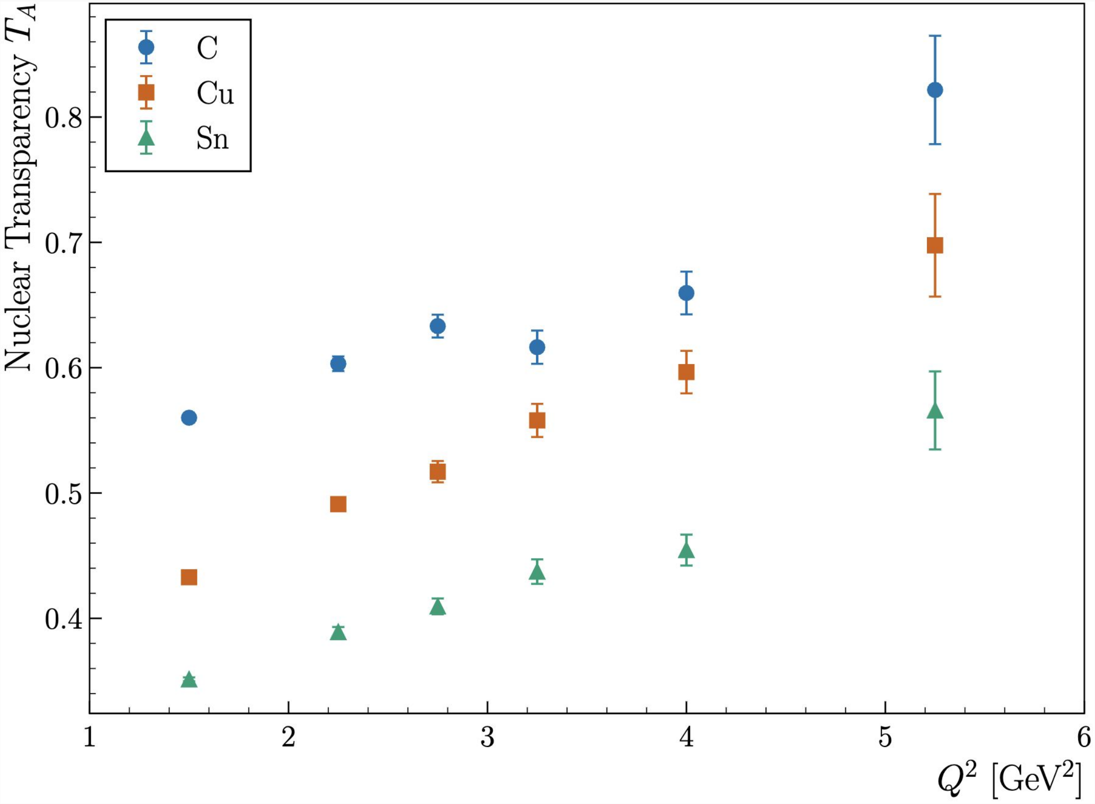


RG-D CT Study: Very Preliminary Nuclear Transparency

Extract (raw) nuclear transparency as currently available Pass1 reconstructed data (around 10% of total)

$$T_A = \frac{N^A_{\rho^0}}{N^{LD2}_{\rho^0}} \frac{r_{LD2}\rho_{LD2}}{r_A\rho_A} \frac{Q_{LD2}}{Q_A}$$

- r_{LD2} = 5 cm: LD2 thickness
- r_C = 0.4 cm: CxC thickness
- r_{Cu} = 93 μm: Copper thickness
- r_{Sn} = 171 μm: Tin thickness
- ρ_{LD2} = 0.164 g/cm^3: LD2 density
- ρ_C = 2.2 g/cm^3: Carbon density
- ρ_{Cu} = 8.96 g/cm^3: Copper density
- ρ_{Sn} = 7.31 g/cm^3: Tin density



Summary and Outlook

- **RG-D has passed the Pass1 review, and the cooking is done**
  - Thanks to everyone who help us

- **Optimizing analysis tools for CT and nTMDs studies to**
  - Study the hadron/electron contamination in pion sample
  - Continue to develop the correction contamination with the CuSn target
  - Deploy the ρ^0 event generator for the two-pion invariant mass background subtraction and apply necessary corrections for the extraction of the preliminary CT results
  - Implement radiative and acceptance correction for the nuclear transparency
  - Extract azithumal asymmetry, multiplicity ratio and pT broadening results for π^0
  - Obtain the preliminary asymmetry results for charged pions nTMDs studies

Backup slides

RG-D Particle IDentification: Pions Fiducial

The goal is to remove tracks near the drift chamber edges where tracking quality degrades

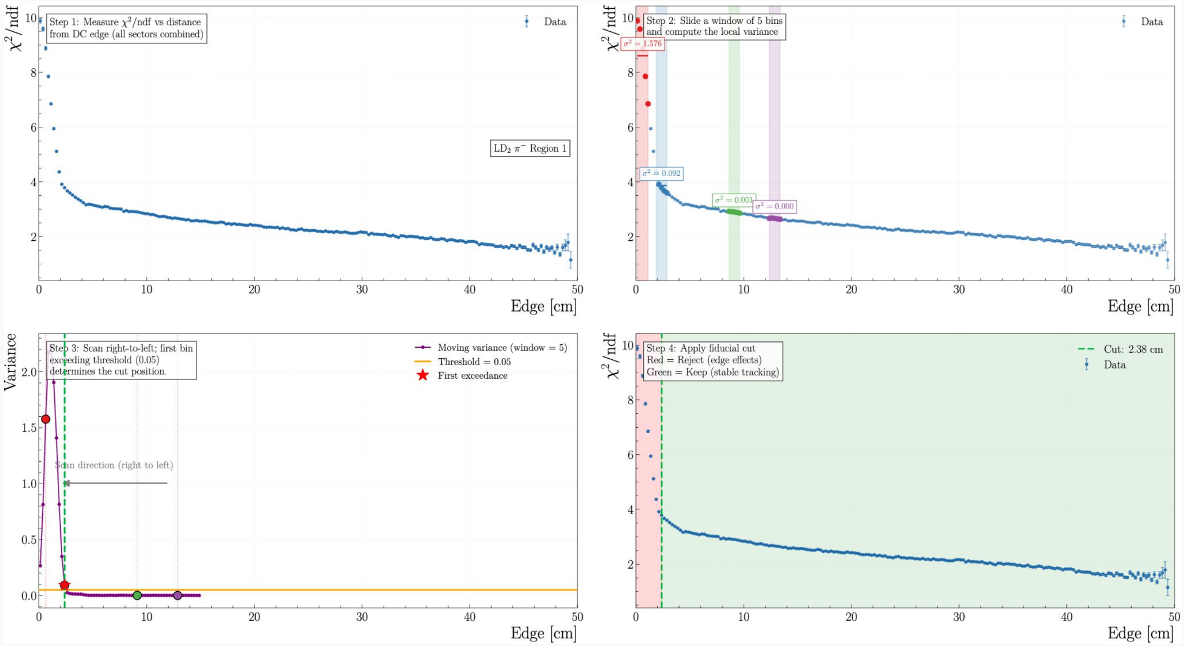
- profile the chi2/ndf of the track fit as a function of distance from the DC edge
- Near the edge: chi2/ndf fluctuates due to poor tracking resolution
- Far from the edge: chi2/ndf is stable (good tracking)

To find the transition between these two regimes automatically:

- Compute a moving variance of the chi2/ndf profile using a sliding window of 5 bins
- Scan from right to left (from the stable region toward the edge)
- The first bin where the variance exceeds a threshold (0.05) marks the boundary — this is the cut position

Tracks closer to the edge than the cut position are rejected; tracks beyond are kept

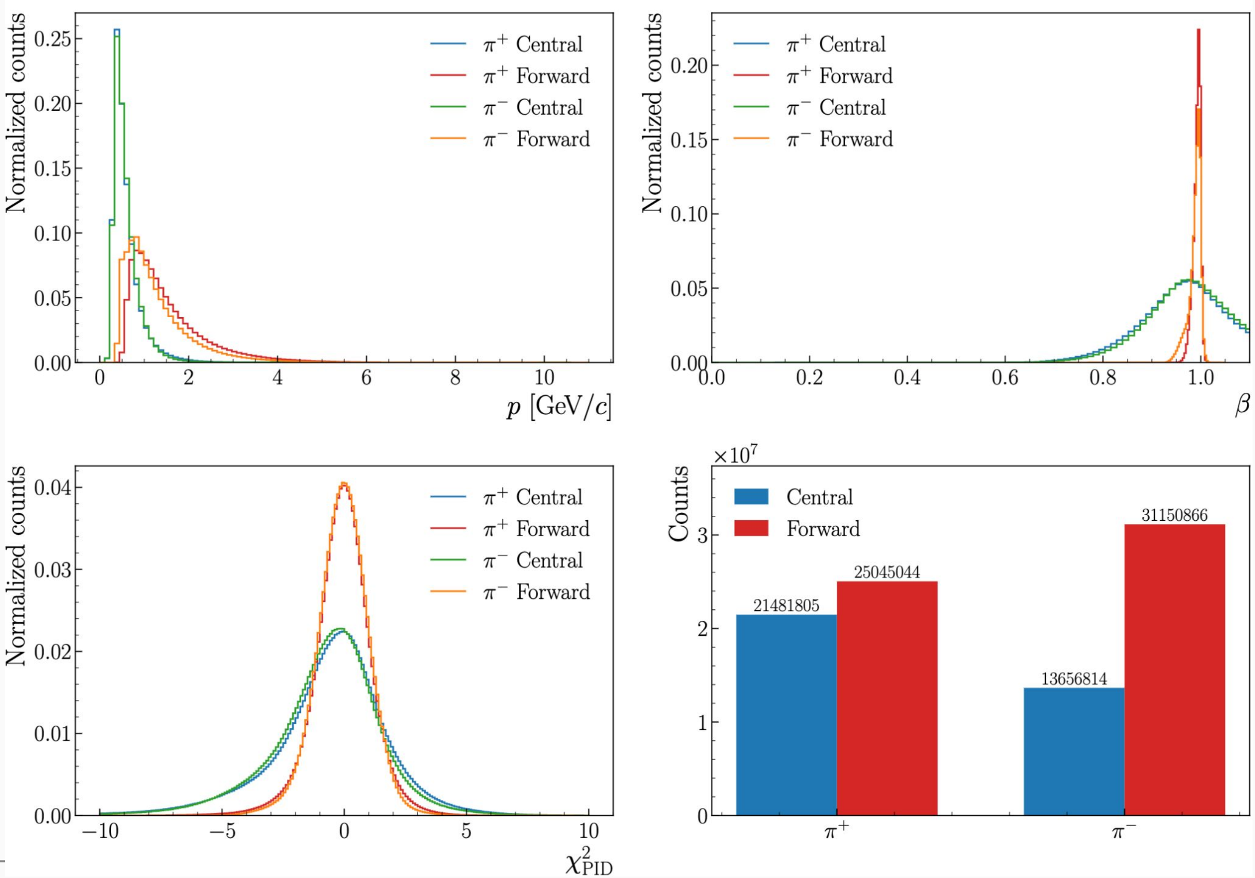
The method is applied independently for each target, pion charge, and DC region (R1, R2, R3)



RG-D Particle IDentification: Pions

The pion identification is very important for RG-D analyses (both CT and TMDs)

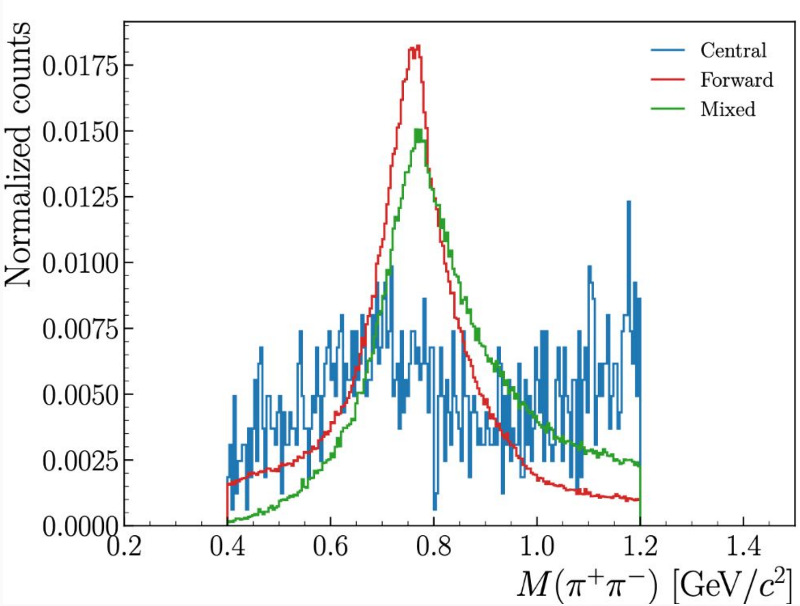
- Also look into the pions detected in the central detector (CD)
- π^+: Central 46.2%, Forward 53.8%
- π^-: Central 30.5%, Forward 69.5%
- **Between a third and half of the statistic is in the central**
- Worse β and chi2pid in the central
- The central pions don't have any cuts

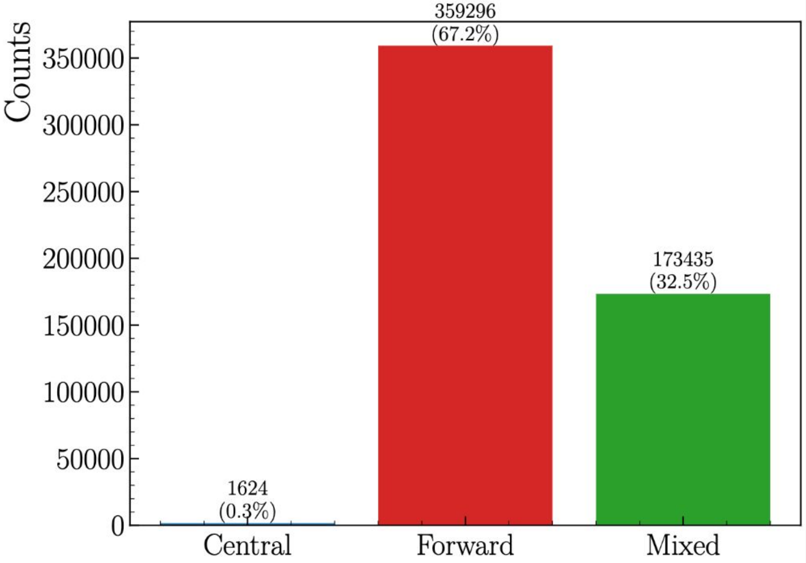


RG-D Particle IDentification: Pions

The pion identification is very important for RG-D analyses (both CT and TMDs)

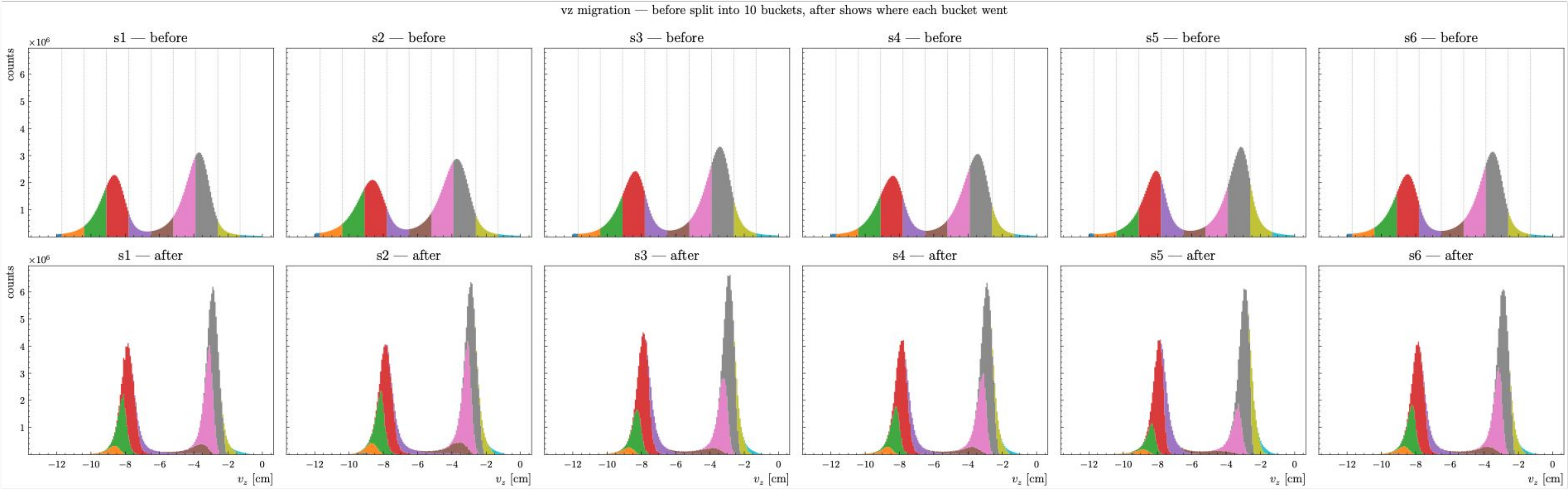
- Also look into invariant mass for the pions detected in the central detector (CD)
- After applying cuts: $z_h > 0.9$, $0.1 < -t < 0.5$ GeV^2, $l_c < 1$ fm





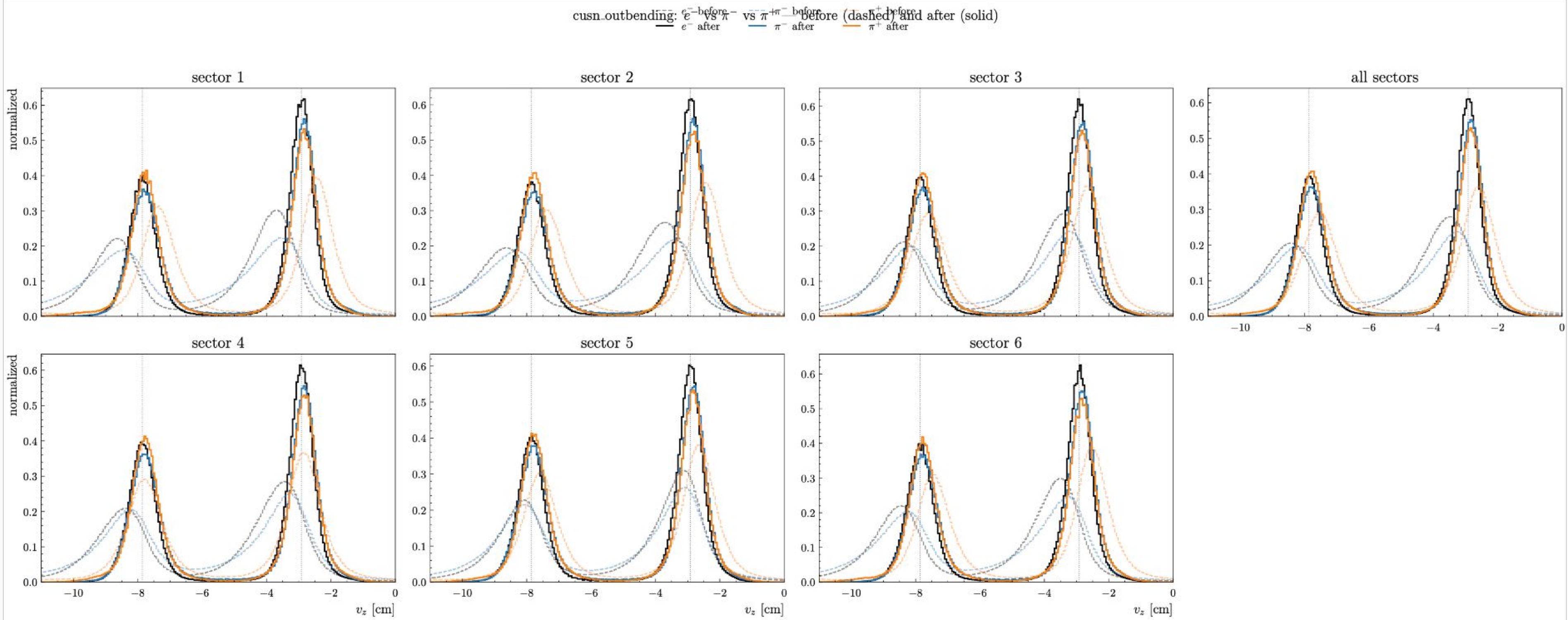
Electron Vertex Study

Effect of the correction:



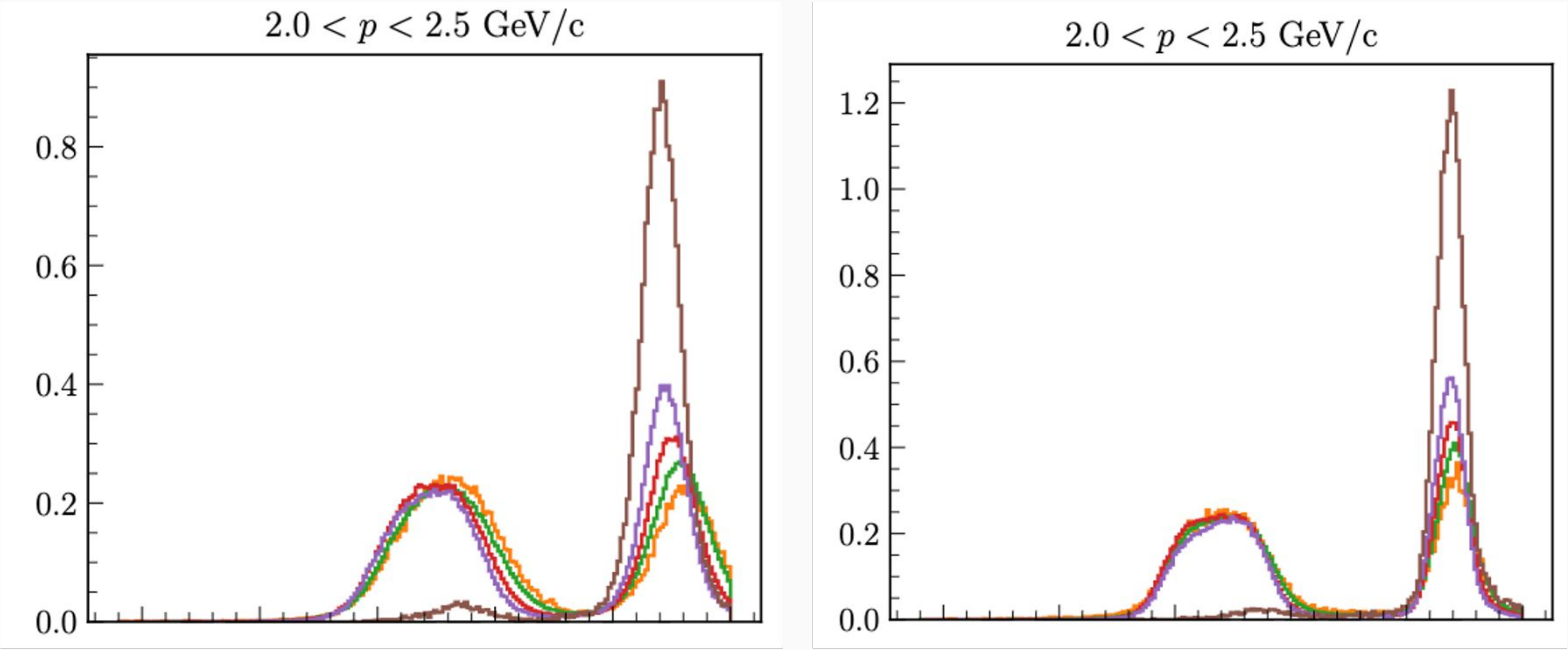
Electron Vertex Study

- Develop a similar correction for pions (CuSn Outbending):



Electron Vertex Study

Effect of the FMT on RG-E inbending dataset:



CT Study: Two-pion Invariant Mass

- Our event generator incorporates the measured cross sections by Cassel et al. for the electroproduction of ρ0 and the three main background processes