

RG-D Experiments: Status and Analysis Plans

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Run Group D

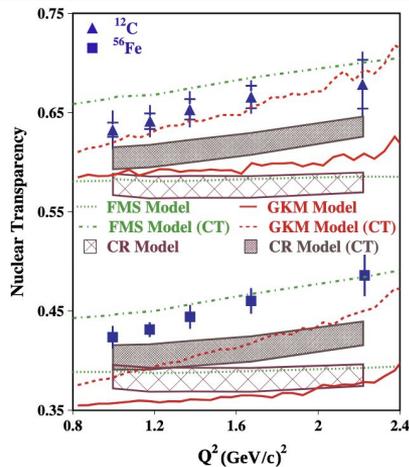
1: Argonne National Lab, 2: IJCLAB, Orsay, France
 3: Mississippi State U., 4: University of
 New-Hampshire, 5: Florida International University

Run Group D is composed of two experiments:

Color Transparency (CT)

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

Spokespersons: W. Armstrong¹, L. El Fassi³,
 K. Hafidi¹, M. Holtrop⁴, B. Mustapha¹

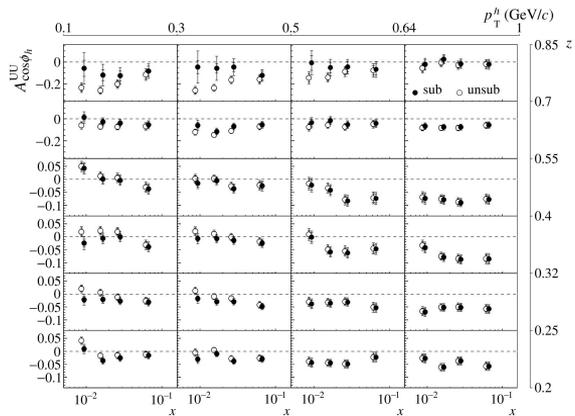


L. El Fassi, Physics 4,
 no. 3 (2022)

Nuclear TMDs (nTMDs)

in CLAS12 E12-06-106A

Spokespersons: R. Dupré², L. El Fassi³,
 Z.-E. Meziani¹, H. Szumila-Vance⁵



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

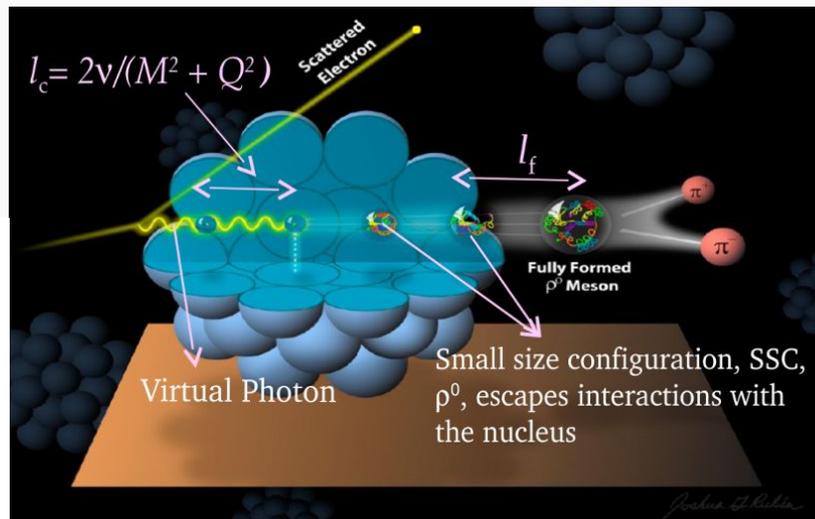
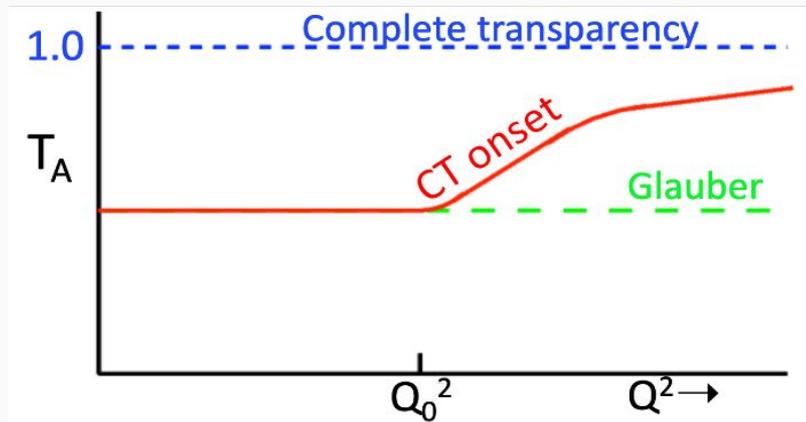
$$T_A = \frac{\sigma_A}{A\sigma_N}$$

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:
 - $\cos \varphi$, $\sin \varphi$, $\cos(2\varphi)$ ¹ moments for different hadrons (π^+ , π^- , and π^0):

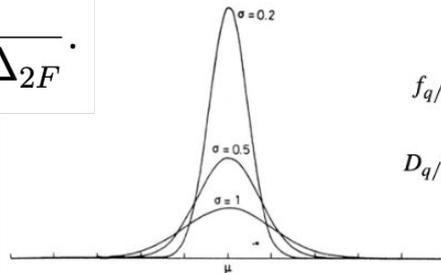
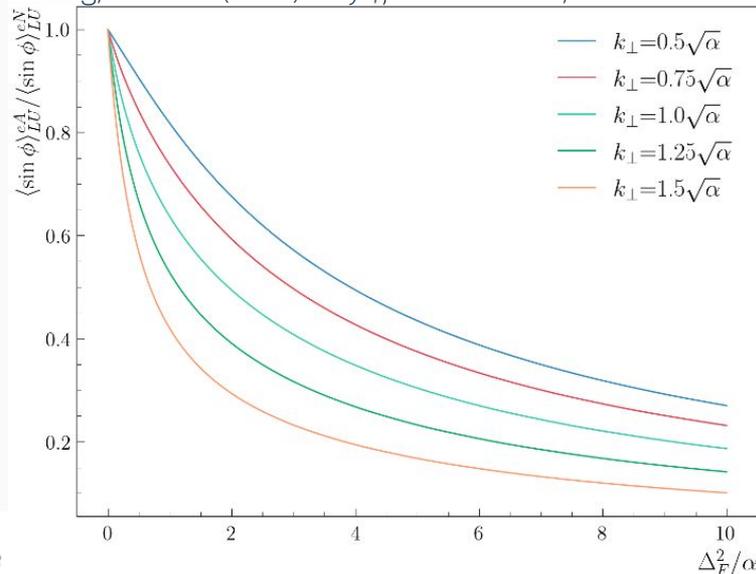
$$\frac{\langle \cos \phi \rangle_{UU}^{eA}}{\langle \cos \phi \rangle_{UU}^{eN}} \approx \frac{\alpha}{\alpha + \Delta_{2F}}, \quad \frac{\langle \sin \phi \rangle_{LU}^{eA}}{\langle \sin \phi \rangle_{LU}^{eN}} \approx \frac{\alpha}{\alpha + \Delta_{2F}}.$$

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

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

¹ No predictions exist for this observable The heavier the nucleus, the wider the TMD gaussian width (Nuclear Broadening)

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

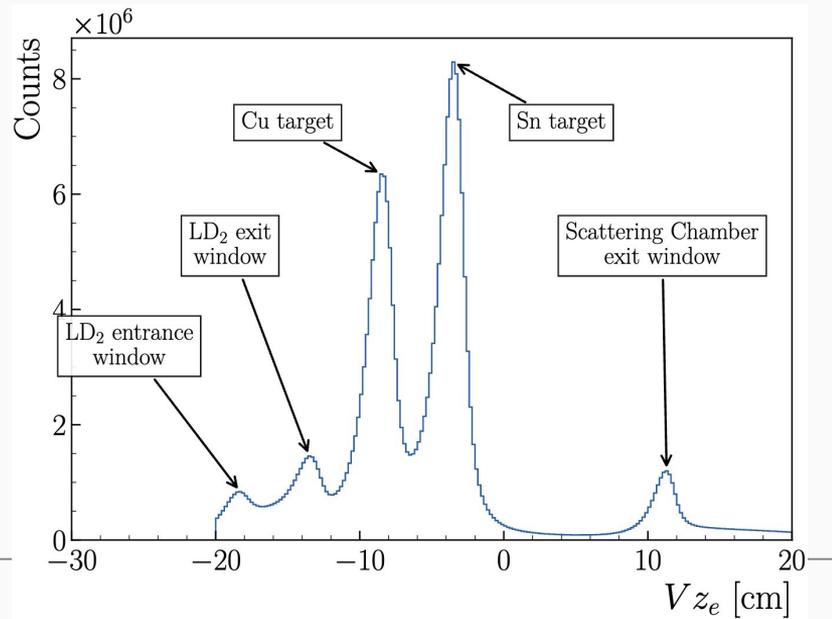
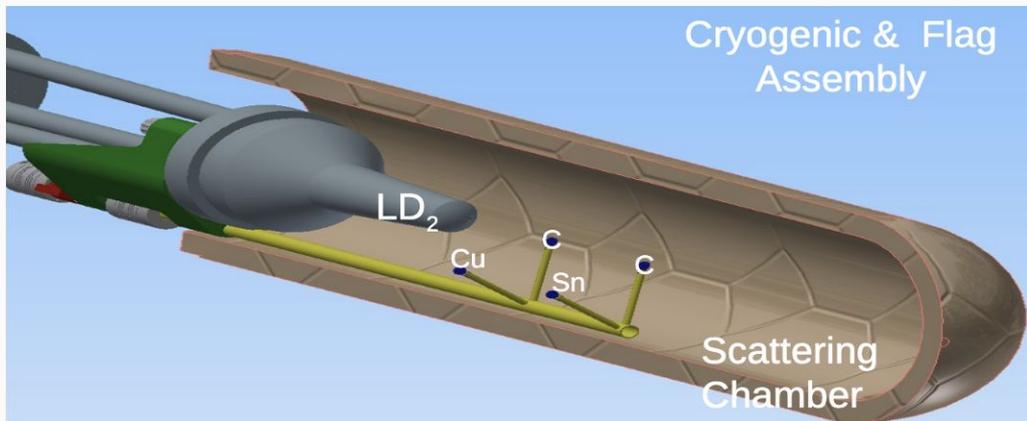


$$f_{q/p}(x, k_T, Q) \simeq \frac{1}{\pi \langle k_T^2 \rangle} \exp\left(-\frac{k_T^2}{\langle k_T^2 \rangle}\right) f_{q/p}(x, Q)$$

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

RG-D: Run Configuration

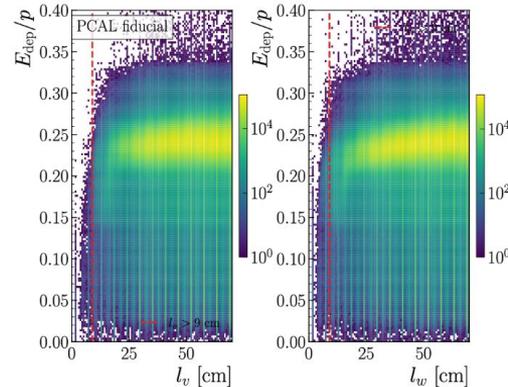
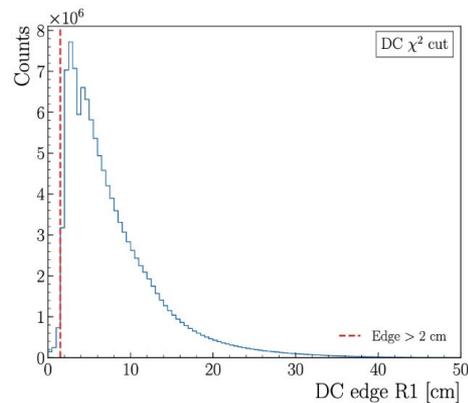
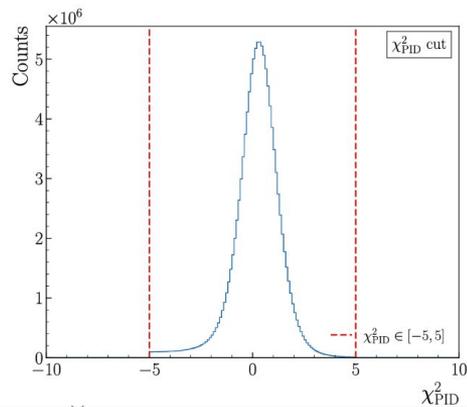
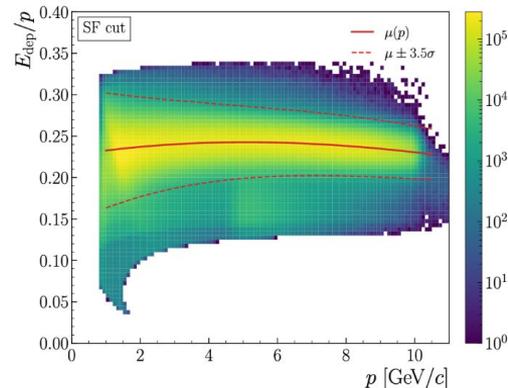
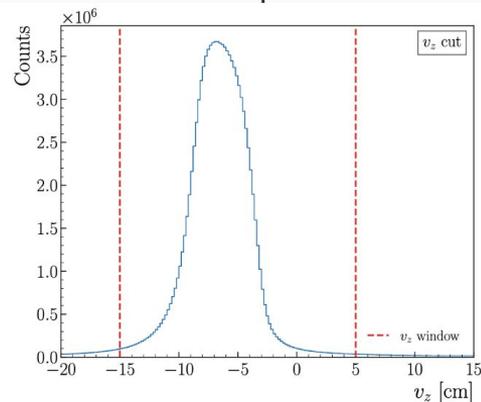
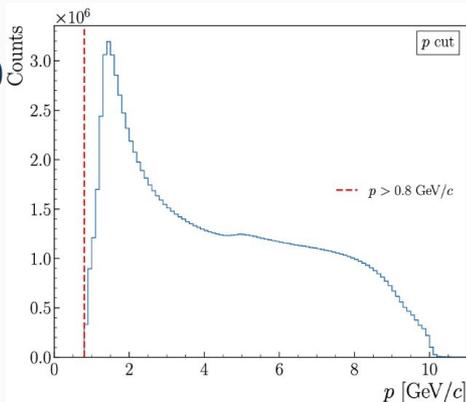
- RG-D experiments collected data in the fall of 2023 with
 - 10.54 GeV polarized beam energy and $I=5\text{--}175$ nA for luminosity scans and production
 - Standard CLAS12 configuration with FT-OFF and three layers of FMT
 - Three target configurations, LD2, CxC, and CuSn, deployed with InBending and 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 Particle Identification: Electron

Both refinement and fiducial cuts have been developed and optimized for RG-D:

- $\text{pid} = 11$, $\text{status} < 0$
- $2000 \leq |\text{status}| < 4000$
- $|\text{chi2pid}| < 5$



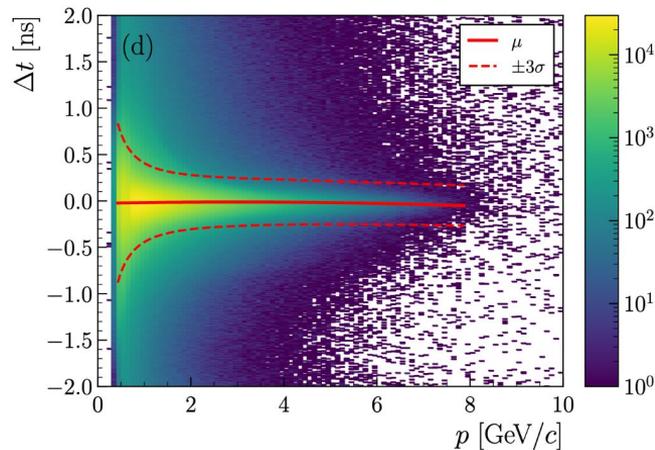
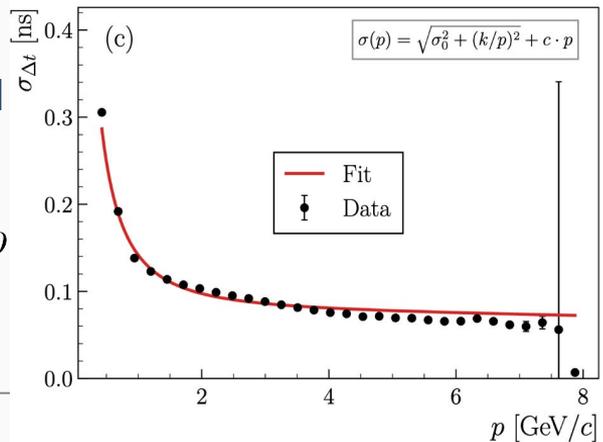
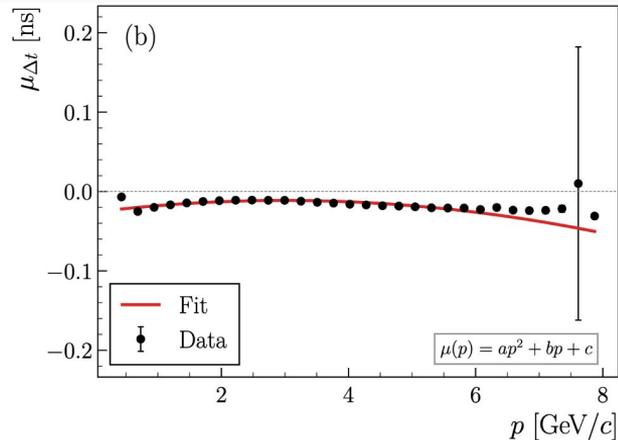
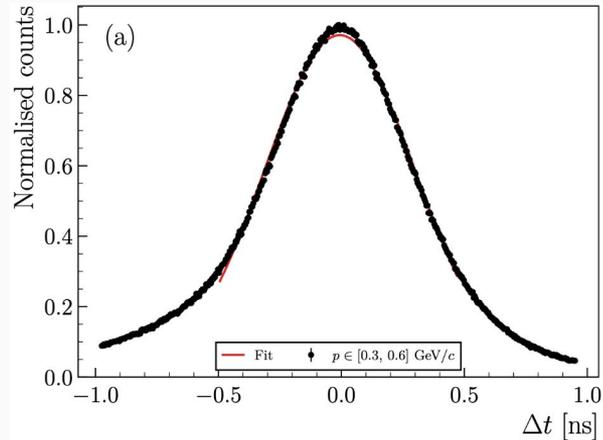
RG-D Particle Identification: Pions

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

- Develop refinement cuts: Δt vs p , and V_z
- Slice Δt vs p in slices, fit each with Gaussian
- Fit the mean of the Gaussian with 2rd order polynomial and σ with:

$$\sigma(p) = \sqrt{\sigma_0^2 + (k/p)^2 + c \cdot p}$$

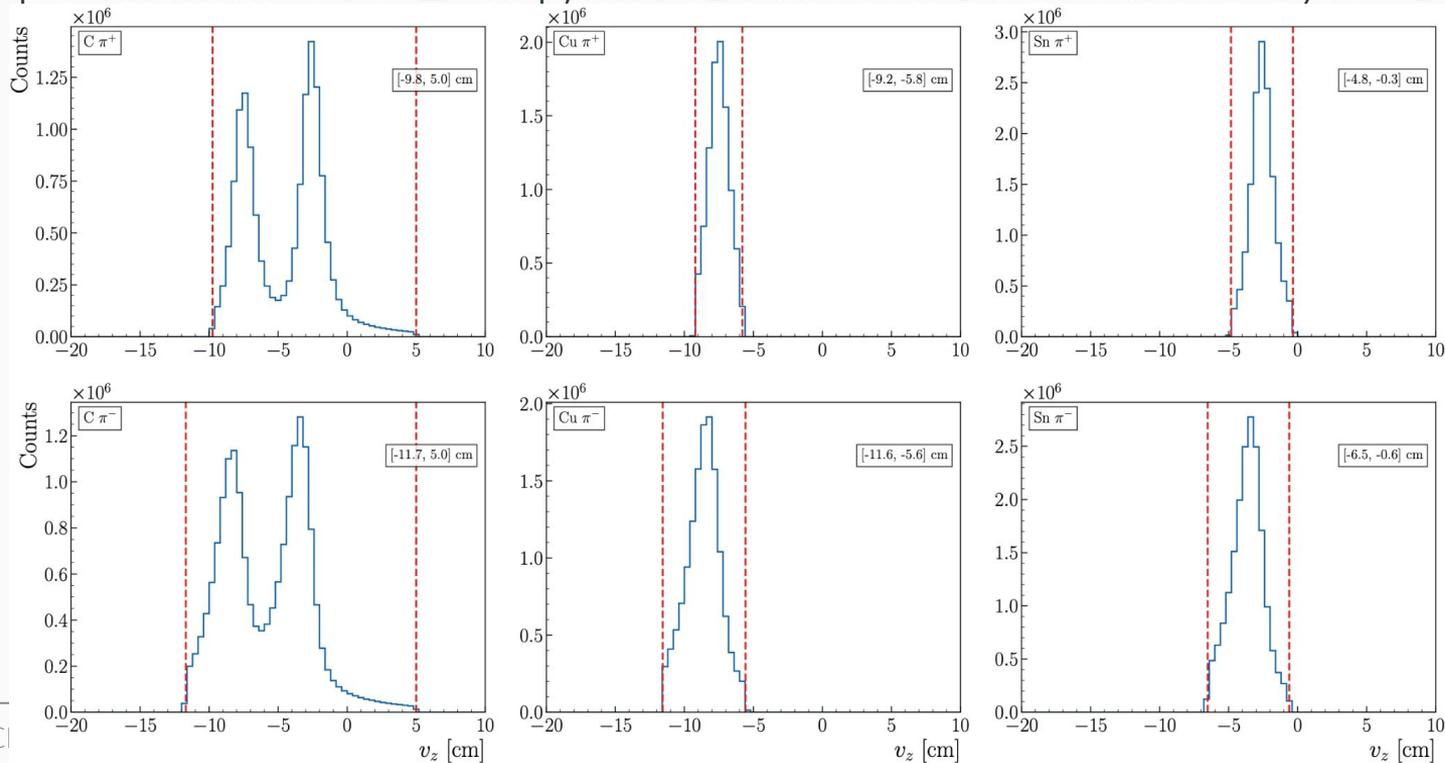
- Use $\mu \pm 3\sigma$ for the cut



RG-D Particle Identification: Pions

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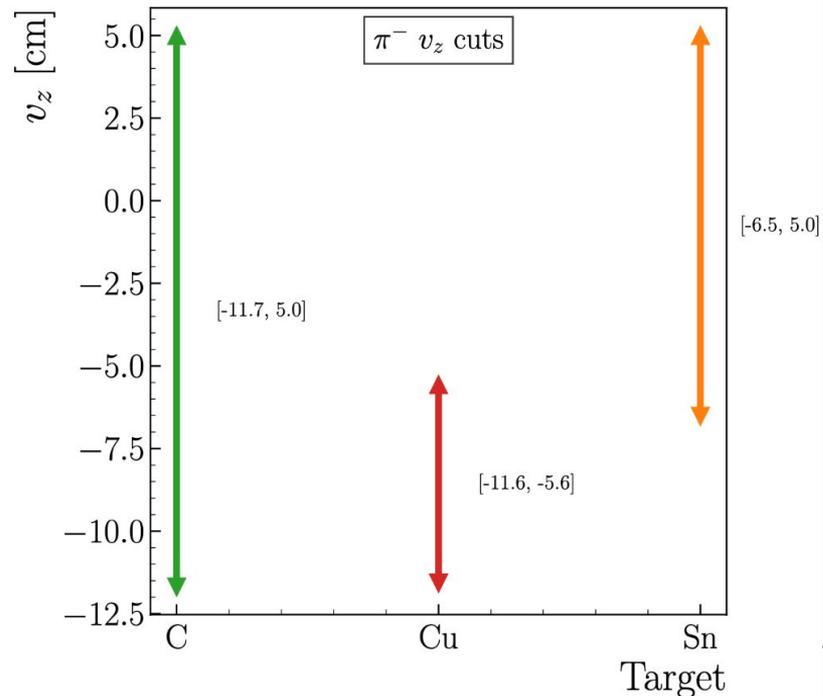
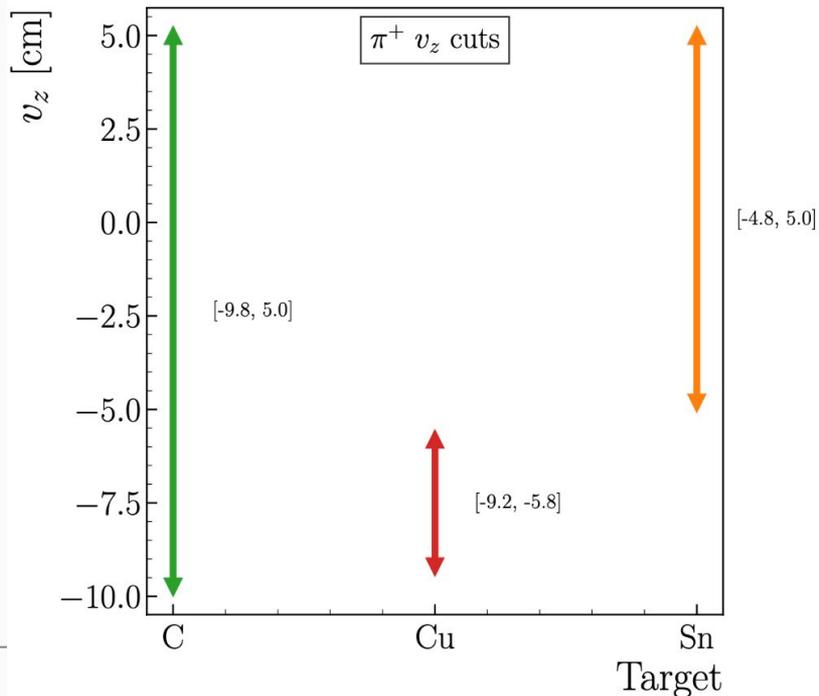
- Develop refinement cuts: Δt vs p , and V_z based on Double sided Crystal Ball function



RG-D Particle Identification: Pions

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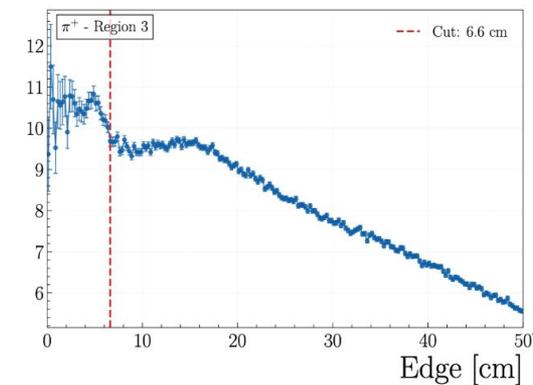
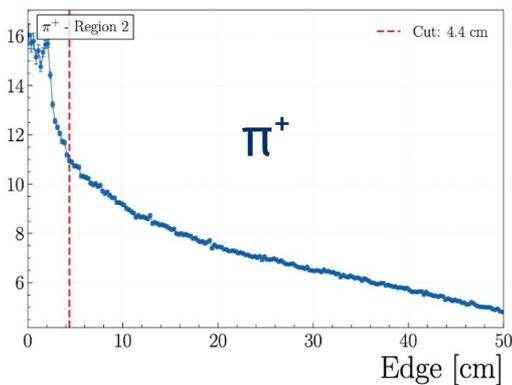
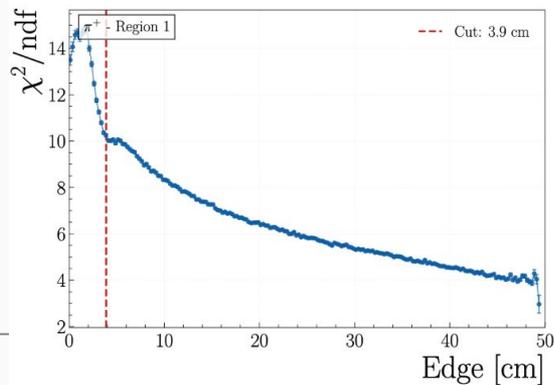
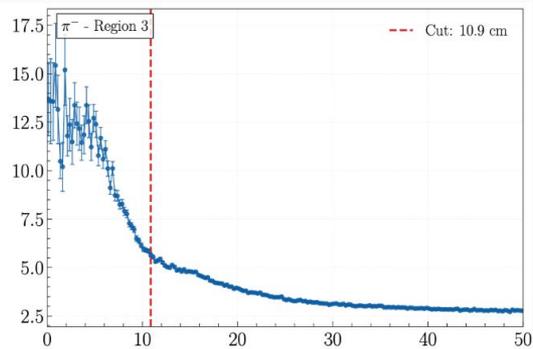
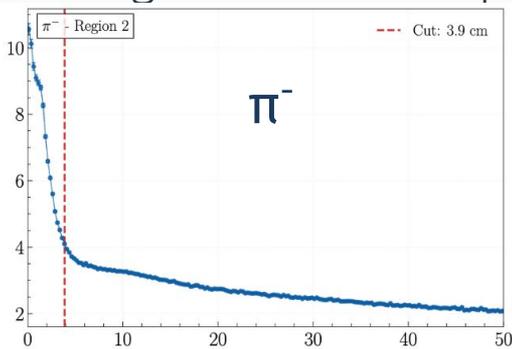
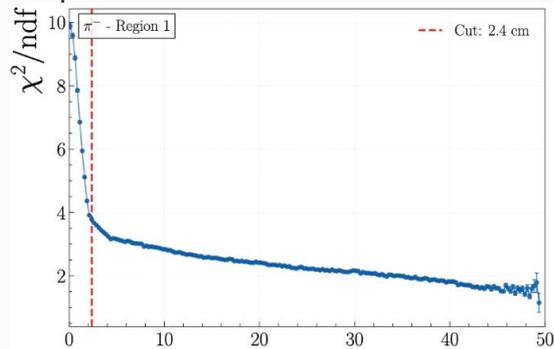
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RG-D Particle Identification: Pions

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

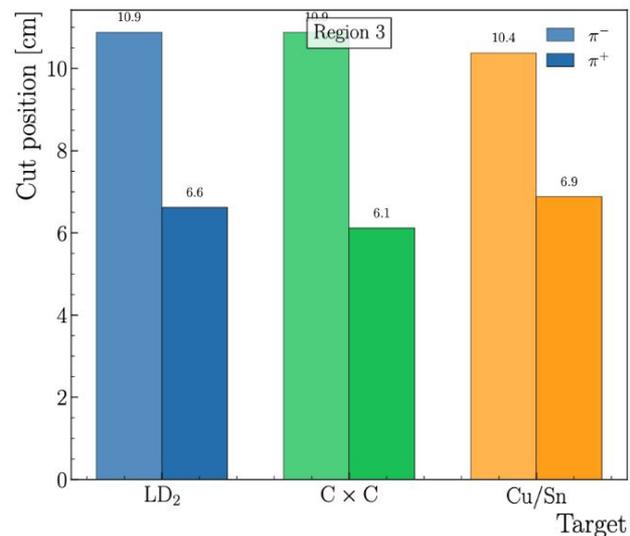
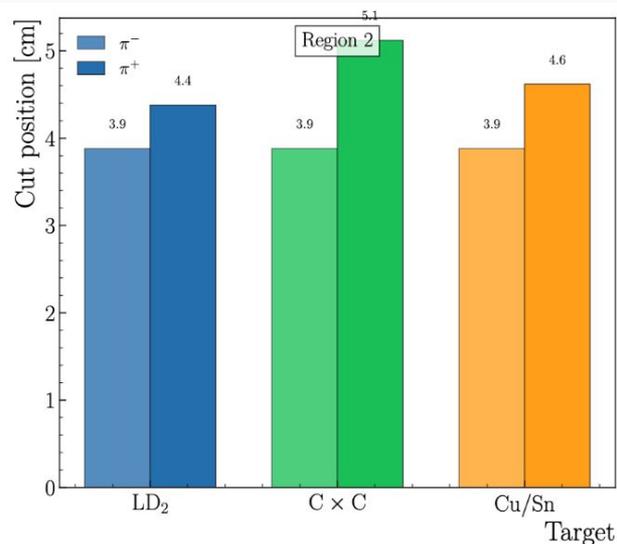
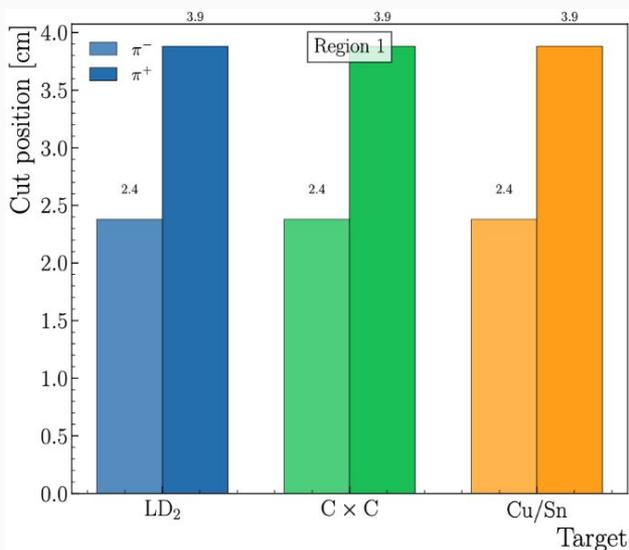
- Develop also DC fiducial cuts following similar technique as for electrons



RG-D Particle Identification: Pions

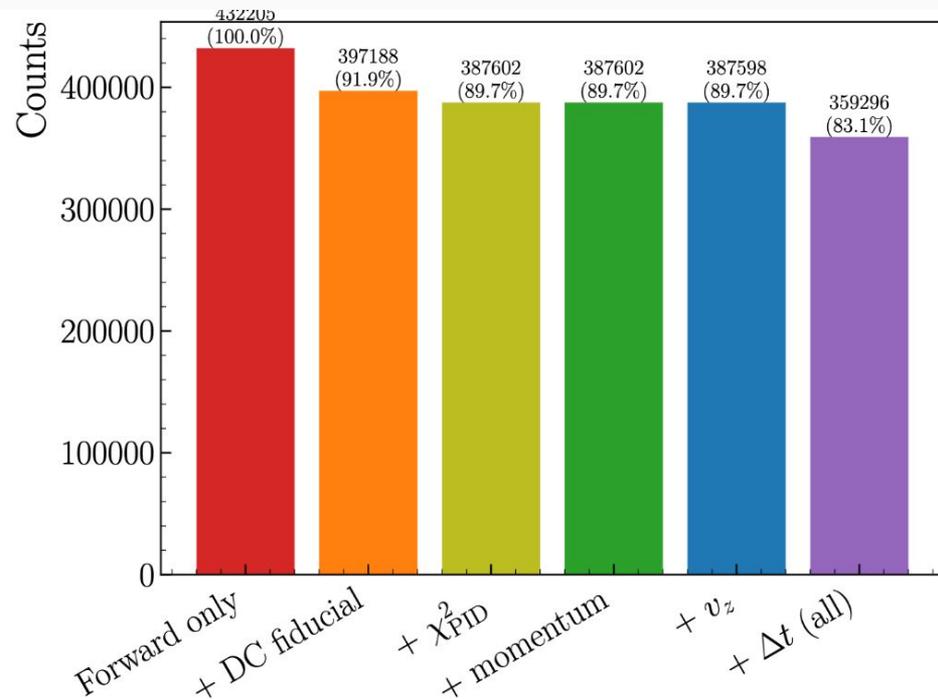
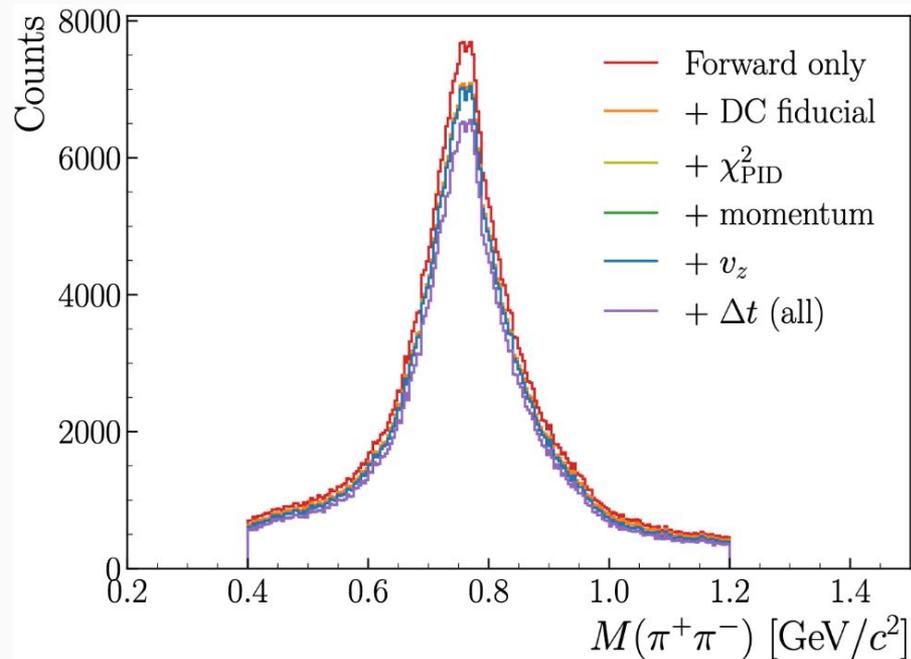
The pion identification is very important for RG-D analyses (both CT and TMDs)

- Develop also DC fiducial cuts following similar technique as for electrons



RG-D Particle Identification: Pions

The pion identification is very important for RG-D analyses (both CT and TMDs)
 - Look into the impact of the pions cuts on the invariant mass of the two pions



RG-D TMDs Studies: π^0 analysis

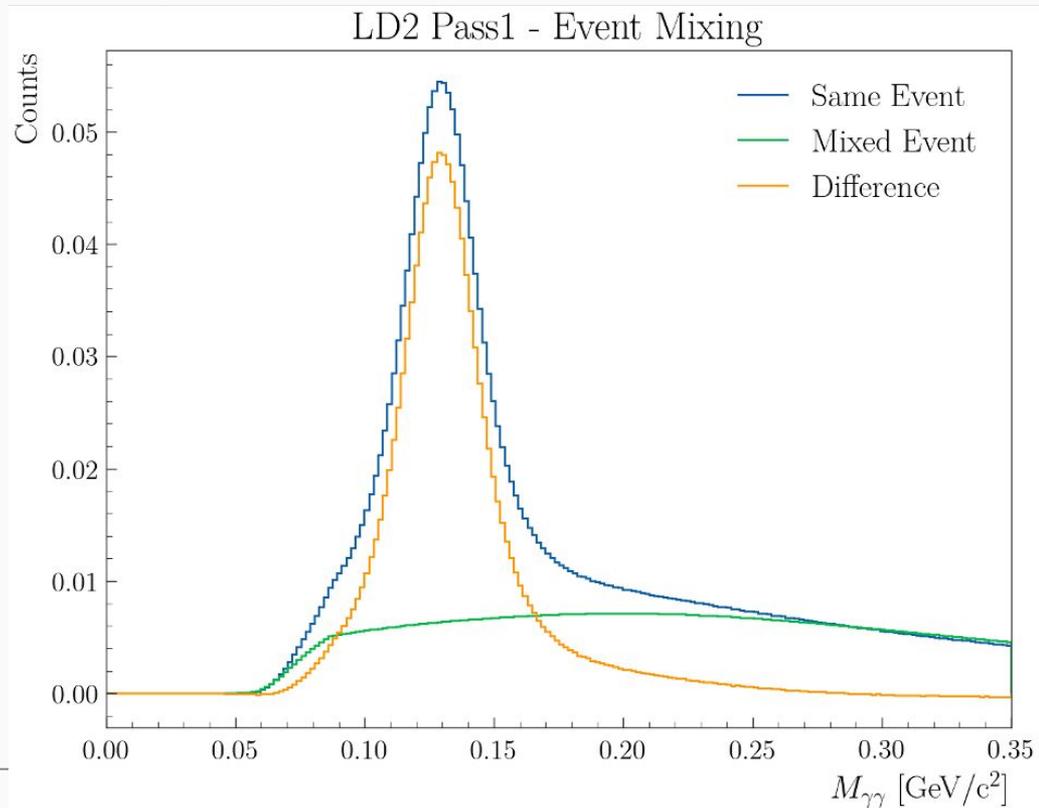
First look at the π^0 channel to extract multiplicity ratios and azimuthal asymmetries:

In-progress efforts to employ the event mixing technique to subtract the background underneath the two-photon mass peak

Electron cuts: Standard RG-D cuts

Photon cuts: pid = 22 and $E > 0.2$ GeV

+ AI develop by Gregory Matousek



RG-D TMDs Studies: π^0 analysis

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

Multidimensional binning:

$$R_{\pi^0}^A(Q^2, x_B, z, p_T) = \frac{\frac{N_A^{\pi^0}(Q^2, x_B, z, p_T)}{N_A^{e^-}(Q^2, x_B)}}{\frac{N_{LD2}^{\pi^0}(Q^2, x_B, z, p_T)}{N_{LD2}^{e^-}(Q^2, x_B)}}$$

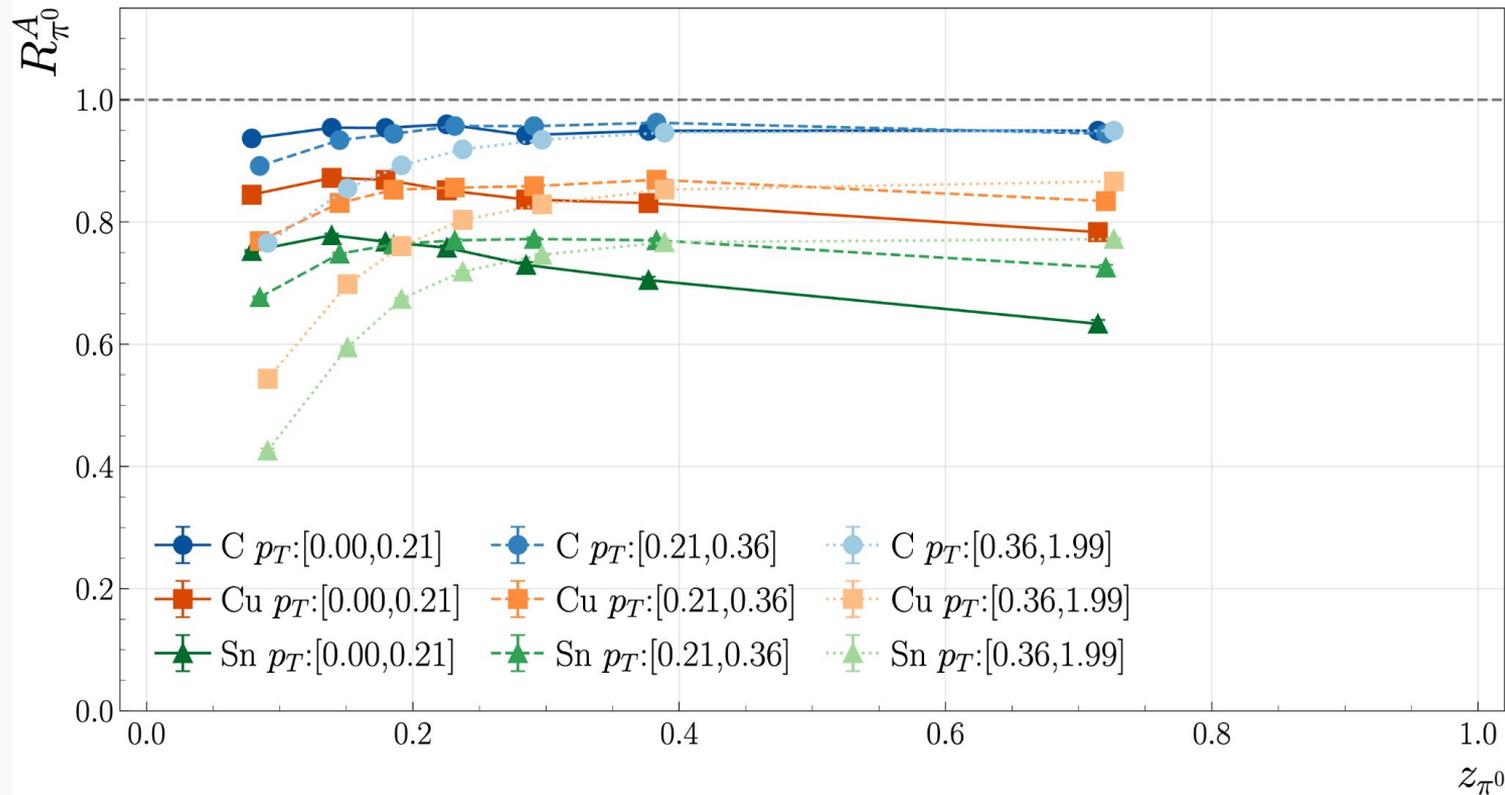
Variable	Bins	Edges
Q^2	3	[1.0, 1.33, 1.96, 10.98]
x_B	3	[0.06, 0.13, 0.21, 2.21]
z_h	7	[0.04, 0.13, 0.17, 0.21, 0.26, 0.33, 0.44, 1.0]
p_T	3	[0.00, 0.21, 0.36, 1.99]

SIDIS cut:

- $Q^2 > 1 \text{ GeV}^2$, $W > 2 \text{ GeV}$, $y < 0.85$

RG-D TMDs Studies: π^0 analysis

$Q^2 \in [1.00, 1.33] \text{ GeV}^2, x_B \in [0.06, 0.13]$



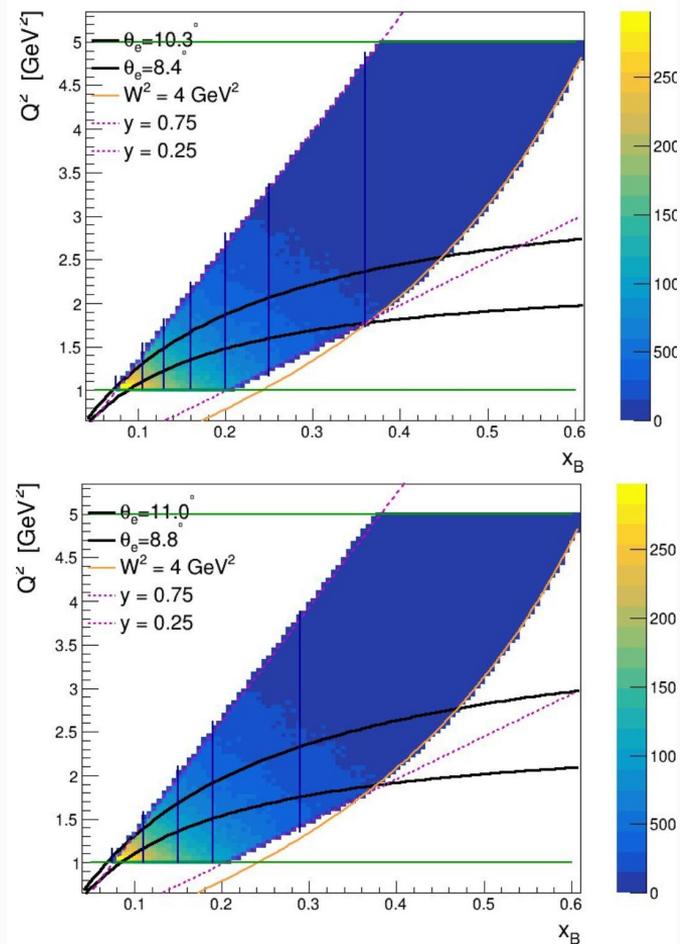
RG-D TMDs Studies: π^+ analysis

• Motivation

- SIDIS: Electron scattering off a target nucleus producing hadrons through virtual photon exchange. Nuclear effects influence SIDIS behavior in nuclear targets
- Goal: compare nuclear targets to deuterium reference to study medium induced modifications

• Main observables

- Hadron multiplicity ratio
- Transverse momentum broadening $\Delta\langle p_T^2 \rangle$
- Azimuthal modulations over hadronic angle ϕ_h
- Study in multi-dimensional bins (Q^2 , x_B , p_T^2 , z) covering different kinematic ranges
- 21 two-dimensional bins in x_B and Q^2 kinematics
- 5x5 binning in hadron kinematics
- Total bins: 525 across SIDIS kinematics



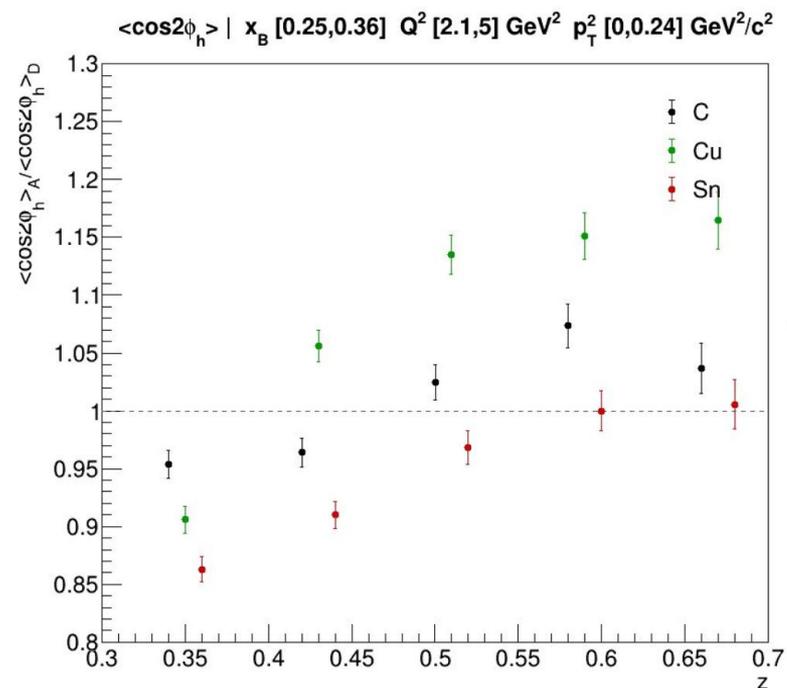
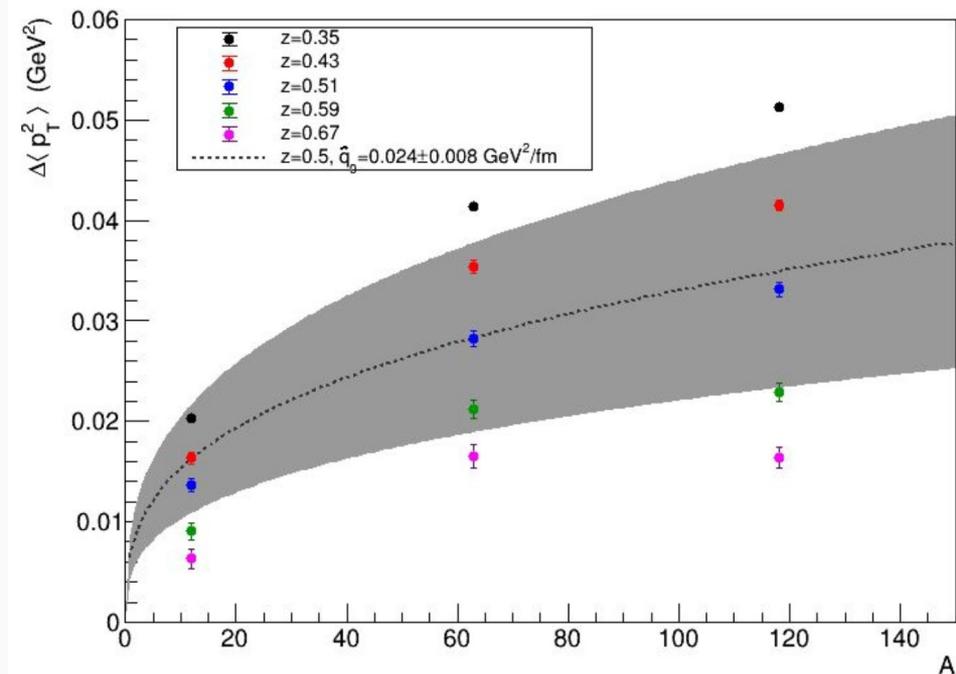
RG-D TMDs Studies: π^+ analysis

Ongoing analysis by D. Matamoros

- Extract:

- Nuclear Dependence of Transverse momentum Broadening
- Azimuthal Modulation Ratio

$$\frac{\langle \cos 2\phi_h(x_B, Q^2, p_t^2, z) \rangle_A}{\langle \cos 2\phi_h(x_B, Q^2, p_t^2, z) \rangle_{LD_2}}$$



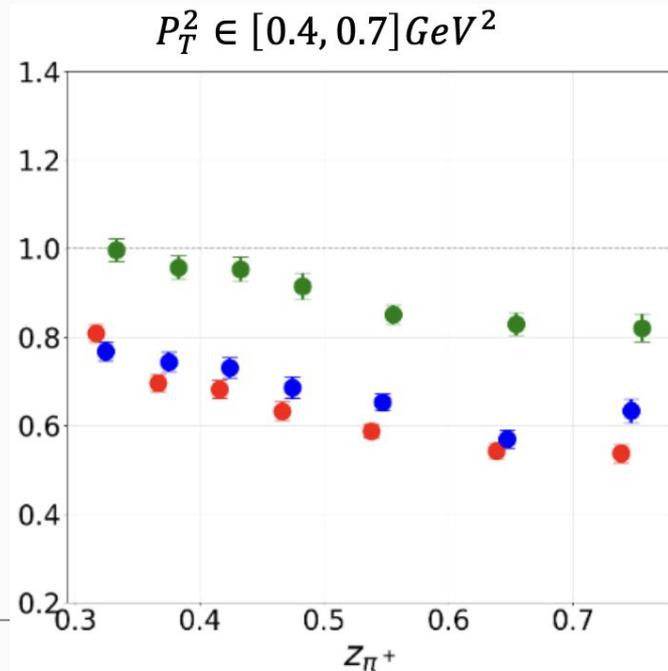
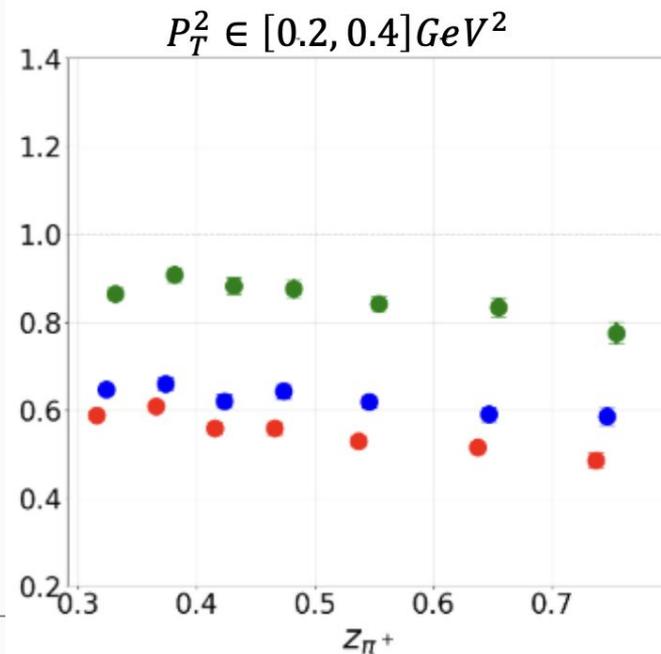
RG-D TMDs Studies: pions analysis

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

- Multidimensional binning in Q^2 , x_B , z_h and p_T^2

$$R_M^h(Q^2, x_B, z, P_T^2) = \frac{\frac{N_A^h(Q^2, x_B, z, P_T^2)}{N_A^e(Q^2, x_B)}}{\frac{N_D^h(Q^2, x_B, z, P_T^2)}{N_D^e(Q^2, x_B)}}$$

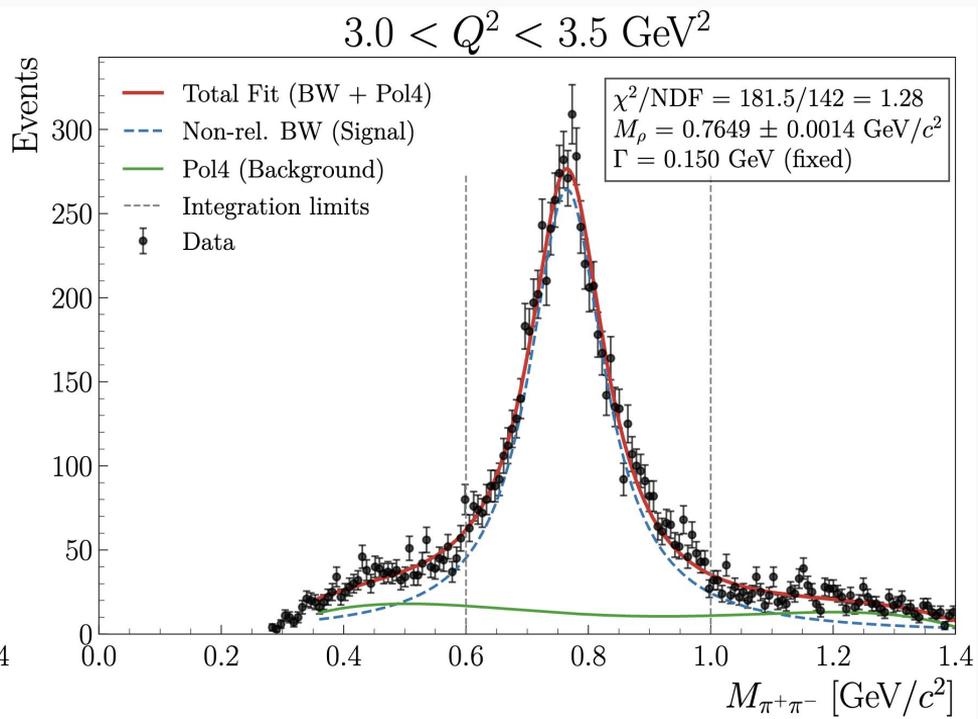
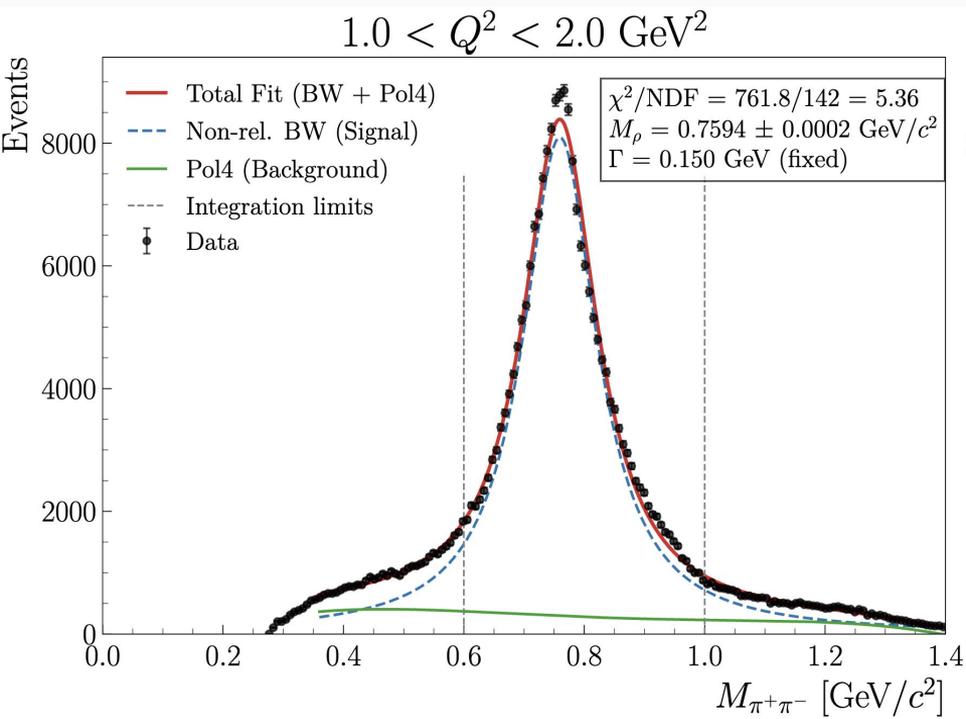
Ongoing analysis by S. Shrestha



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

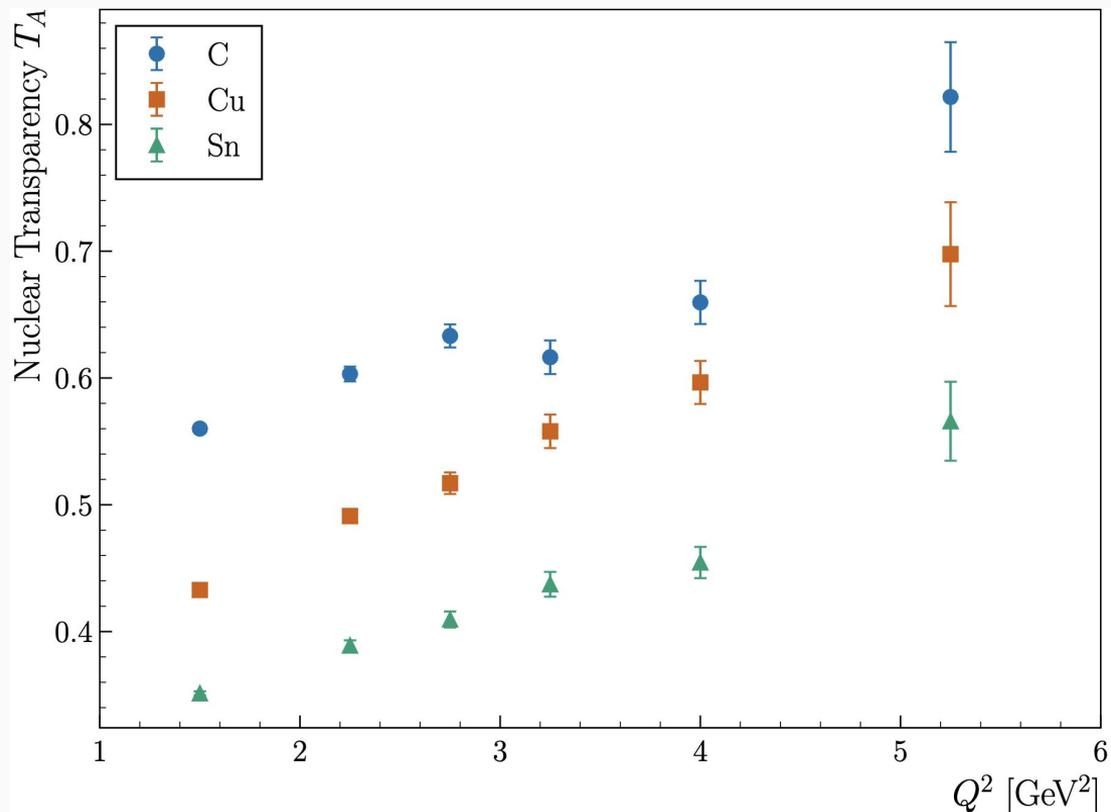


RG-D CT Study: Very Preliminary Nuclear Transparency

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

$$T_A = \frac{N_{\rho^0}^A}{N_{\rho^0}^{LD2}} \frac{r_{LD2} \rho_{LD2}}{r_A \rho_A} \frac{Q_{LD2}}{Q_A}$$

- $r_{LD2} = 5$ cm: LD2 thickness
- $r_C = 0.4$ cm: CxC thickness
- $r_{Cu} = 93$ μm : Copper thickness
- $r_{Sn} = 171$ μm : Tin thickness
- $\rho_{LD2} = 0.164$ g/cm³: LD2 density
- $\rho_C = 2.2$ g/cm³: Carbon density
- $\rho_{Cu} = 8.96$ g/cm³: Copper density
- $\rho_{Sn} = 7.31$ g/cm³: Tin density



Summary and Outlook

- **RG-D has passed the Pass1 review, and the cooking continue**
 - Cooking will take three/four more months
- **Optimizing analysis tools for CT and nTMDs studies to**
 - Study the hadron/electron contamination in pion sample
 - Correct for 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
 - Finalize the π^0 event mixing background-subtraction and extract its preliminary asymmetry results
 - Obtain the preliminary asymmetry results for charged pions nTMDs studies



THANKS

Backup slides

RG-D Particle Identification: Pions Fiducial

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

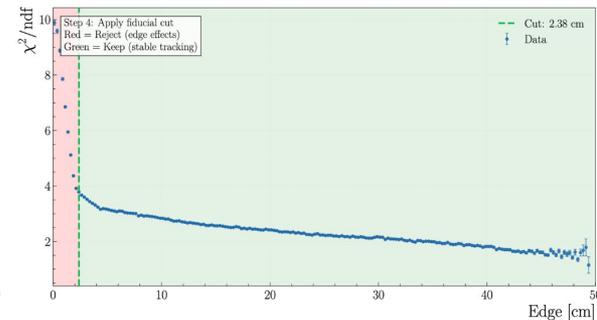
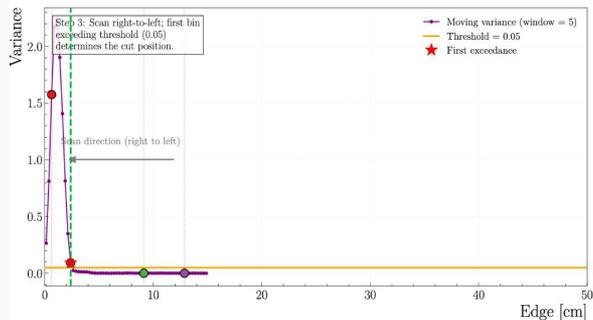
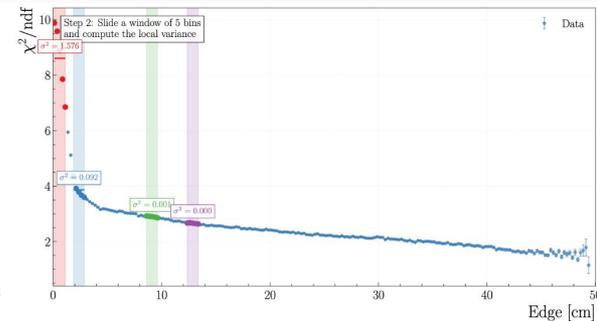
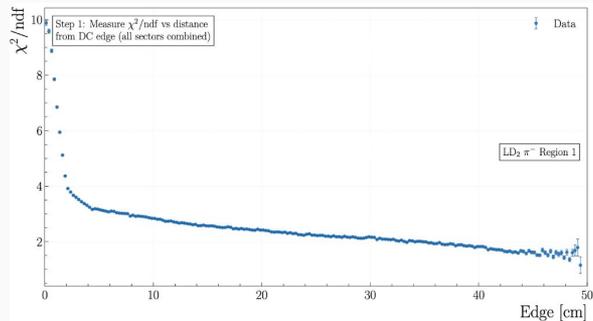
- profile the χ^2/ndf of the track fit as a function of distance from the DC edge
- Near the edge: χ^2/ndf fluctuates due to poor tracking resolution
- Far from the edge: χ^2/ndf is stable (good tracking)

To find the transition between these two regimes automatically:

- Compute a moving variance of the χ^2/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

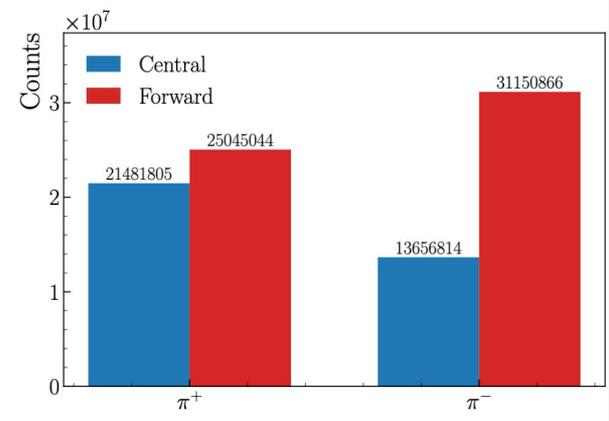
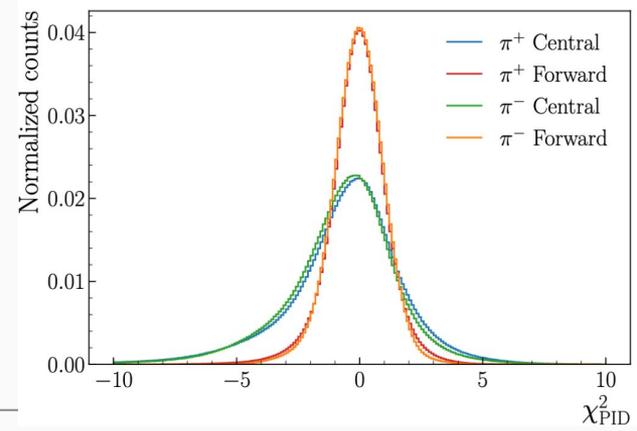
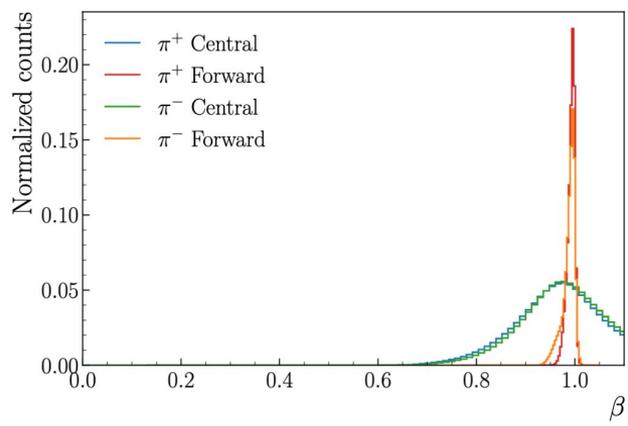
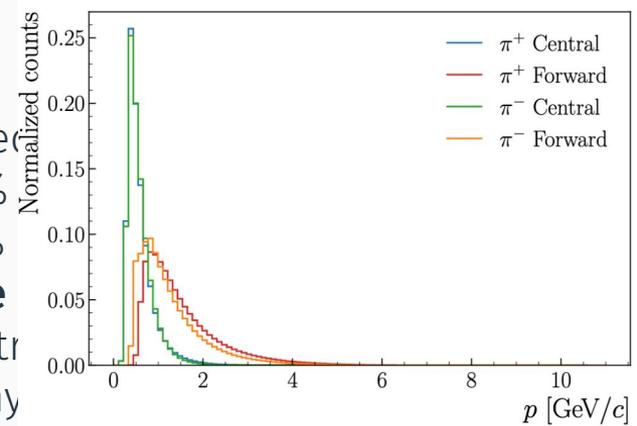
The method is applied independently for each target, pion charge, and DC region (R1, R2, R3)



RG-D Particle Identification: Pions

The pion identification is very

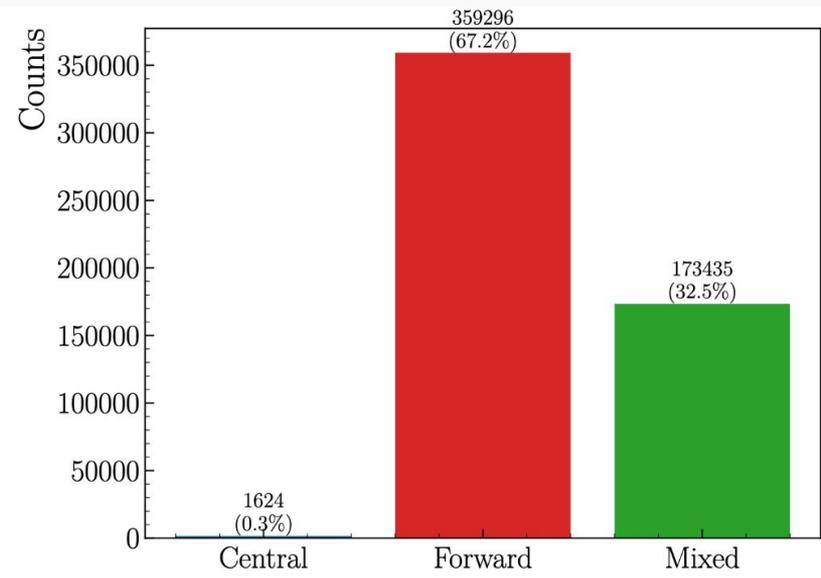
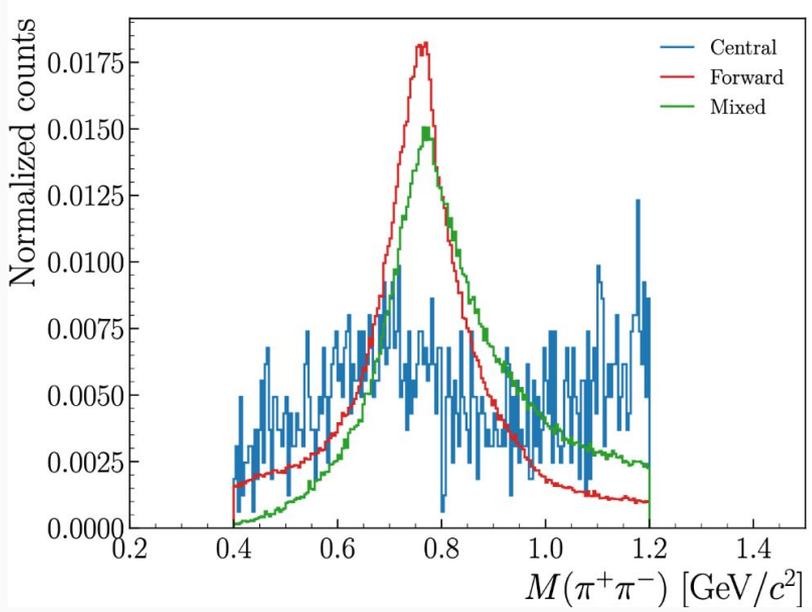
- Also look into the pions detected
- π^+ : Central 46.2%, Forward 53.8%
- π^- : Central 30.5%, Forward 69.5%
- **Between a third and half of the**
- Worse β and χ^2_{PID} in the centr
- The central pions don't have any



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: $z_h > 0.9$, $0.1 < -t < 0.5 \text{ GeV}^2$, $l_c < 1 \text{ fm}$



CT Study: Two-pion Invariant Mass

- Our event generator incorporates the measured cross sections by Cassel et al. for the electroproduction of ρ^0 and the three main background processes

D. G. Cassel *et al.*, Phys. Rev. D 24, 2787 (1981)

Simple Breit-Wigner
 $e + p \rightarrow e + p + \rho^0$

Simulated Background's Shapes

$e + p \rightarrow e + p + \pi^+ + \pi^-$

$e + p \rightarrow e + \Delta^{++} + \pi^-$

$e + p \rightarrow e + \Delta^0 + \pi^+$

