Update on RG-D Experiments: Calibration and Analysis Status

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CLAS Collaboration (5 March, 2025)

MISSISSIPPI STATE UNIVERSITY™

Run Group D

RG-D is composed of two experiments:

- Study of Color Transparency (CT) in Exclusive Vector Meson Electroproduction off Nuclei (E12-06-106):
  - Spokespeople: W. Armstrong[1] , L. El Fassi[3] , K. Hafidi[1] , M. Holtrop[4], and B. Mustapha[1]
- Nuclear Transverse Momentum Distributions (nTMDs) in CLAS12 (E12-06-106A):
  - Spokespeople: R. Dupré[2] , L. El Fassi[3] , Zein-Eddine Meziani[1] , and Holly Szumila-Vance[5]

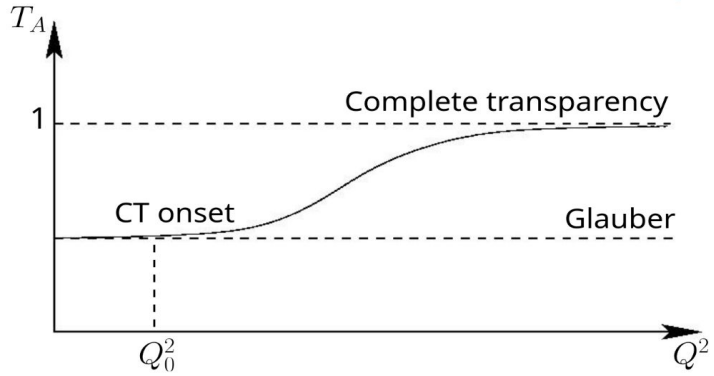
[1]: Argonne National Lab, [2]: IJCLAB, Orsay, France [3]: Mississippi State U., [4]: University of New-Hampshire, [5]: Jefferson Lab

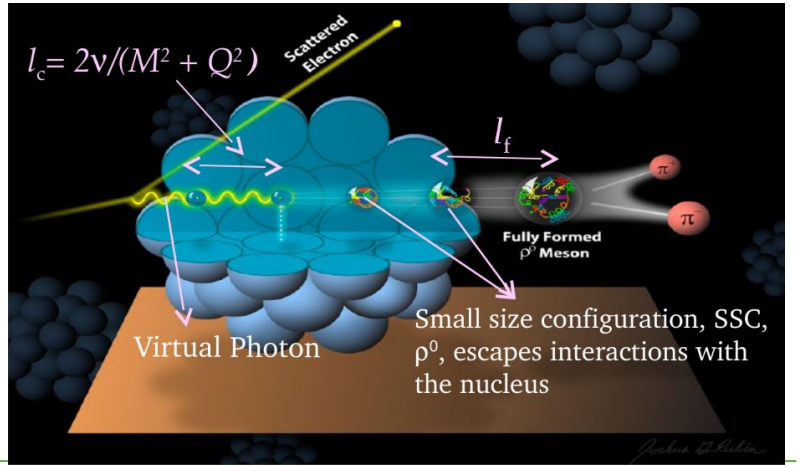
RG-D: CT Experiment

- E12-06-106, CT - the experimental signature of CT is the rise of the nuclear transparency, T_A as a function of Q^2:
  - T_A is defined as the 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

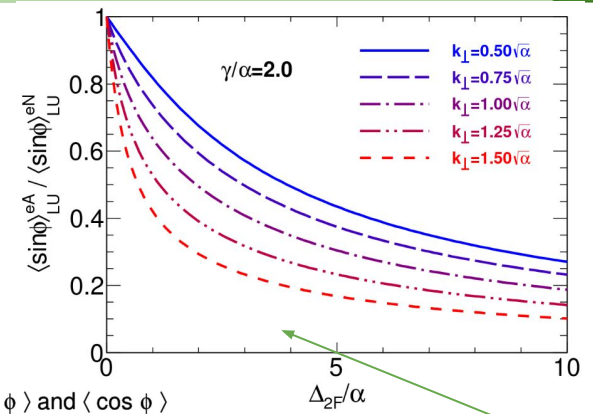




Coherence length, l_c: the lifetime of the qq-bar pair
Formation time, l_f: the time evolution of small size configurations (SSC) to an on-shell ρ^0 meson

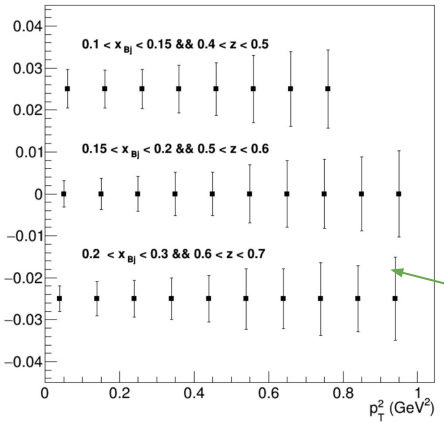
RG-D: Nuclear TMDs

- E12-06-106A: nTMDs study uses the same CT running conditions except the beam polarization, and aims to explore:
  - Fragmentation functions in nuclei
  - Nuclear asymmetries at the partonic level
  - Missing part of nuclear effects description
- Goal:
  - Measure the cos and sin modulations for p^2_T
  - Mesure multiplicity ratios
  - For both charged pions and kaons
  - Accesses transport coefficient at parton level



Ratio of sin asymmetries nuclei to nucleon

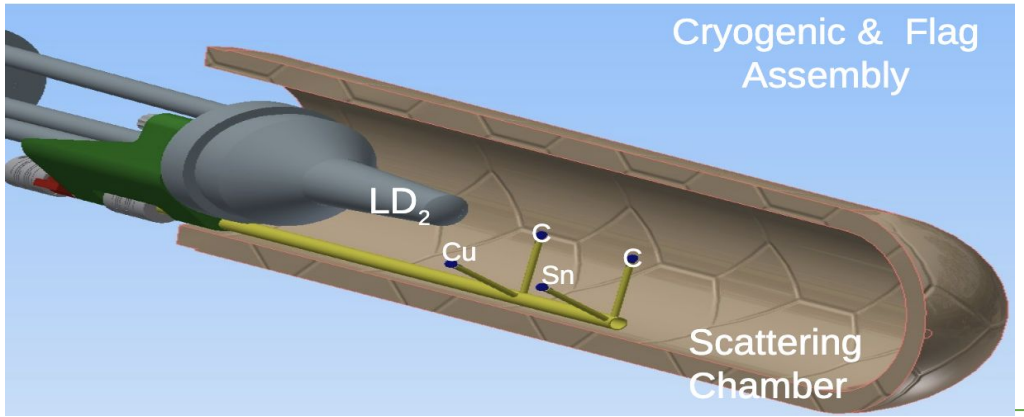
⟨ sin ϕ ⟩ and ⟨ cos ϕ ⟩

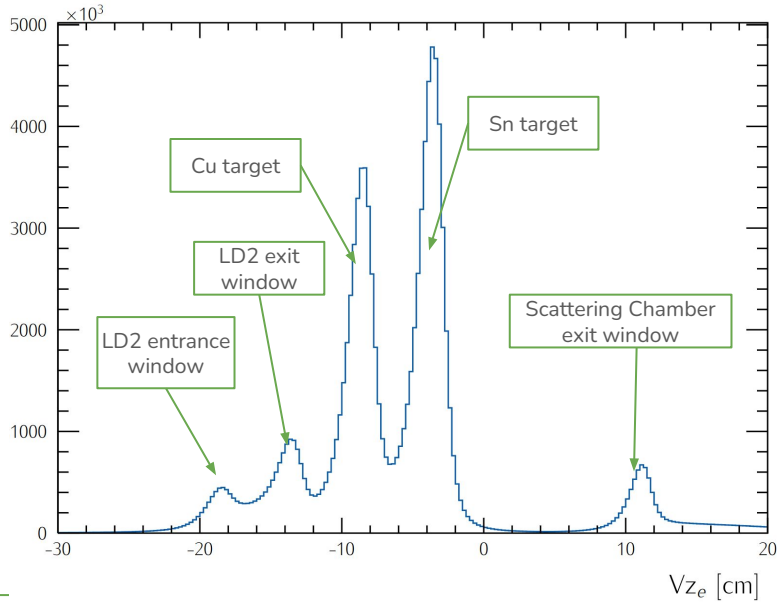


Projected statistical error bars for sin and cos moments

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 torus polarity
  - 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





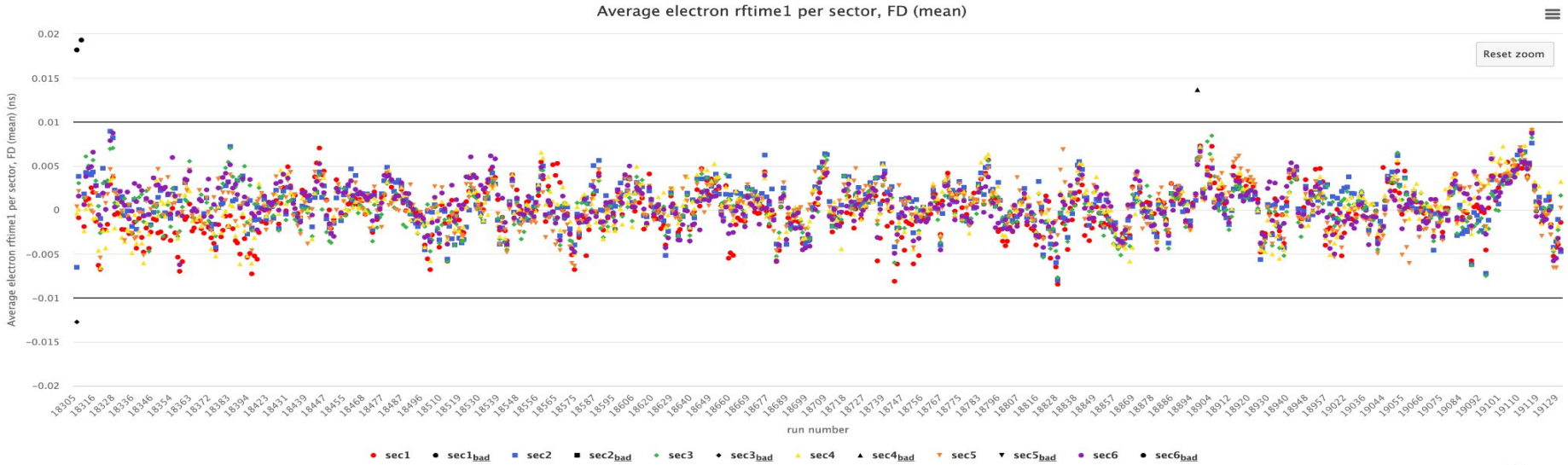
RG-D Status: Calibration Summary

- The calibration of most subsystems LTCC, FTOF, ECal, HTCC, RICH, and CND is done
  - DC: T0 and T2D calibrations are in an advanced stage and expected to converge soon, depending on the to-be-produced timelines after the latest iteration
- Minor fine-tuning occurred since November's report for
  - CTOF: Some parameters such as attenuation length, effective velocity, gain balance, and time offsets were re-calibrated for unstable run ranges
  - HTCC: Performed a 4 ns time adjustment for a few unstable runs and sectors
  - ECal: Performed a second iteration for the time resolution and time-walk correction to reduce the observed gain offsets for IB and OB datasets

Thanks to CalCom Experts for their support

Data Processing Summary

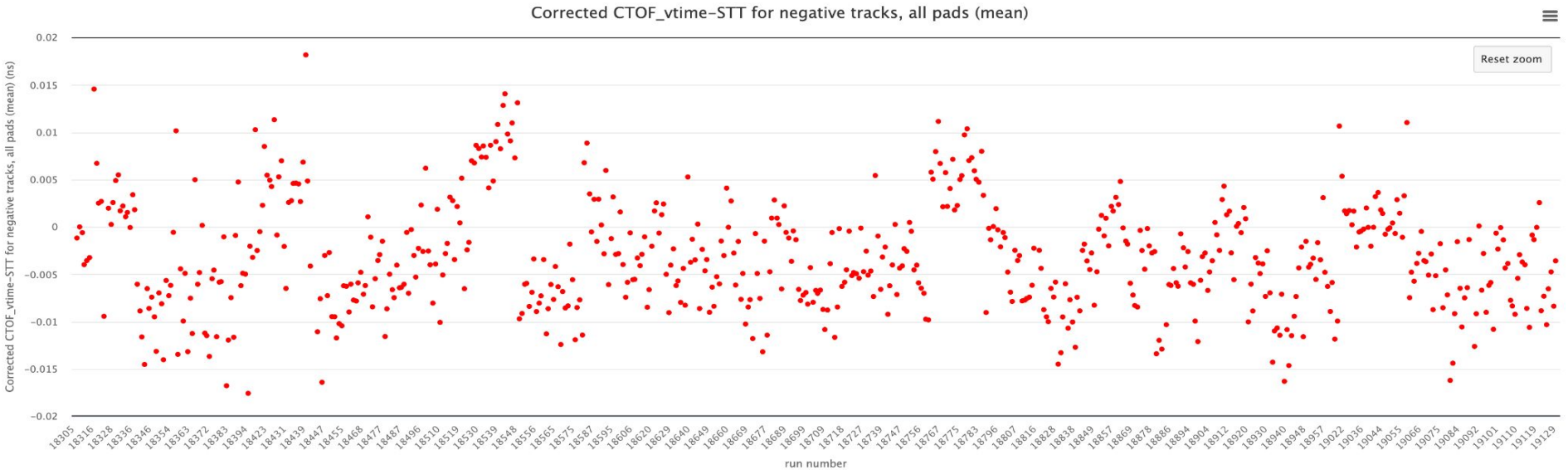
- Timelines monitoring:
  - November 18th, 2024: Pass0v7 was processed after a new iteration of RF, FTOF, ECal, LTCC, CTOF, CND, and HTCC calibration
    - Timelines are available here



- For more details, please visit the RG-D analysis wikipage

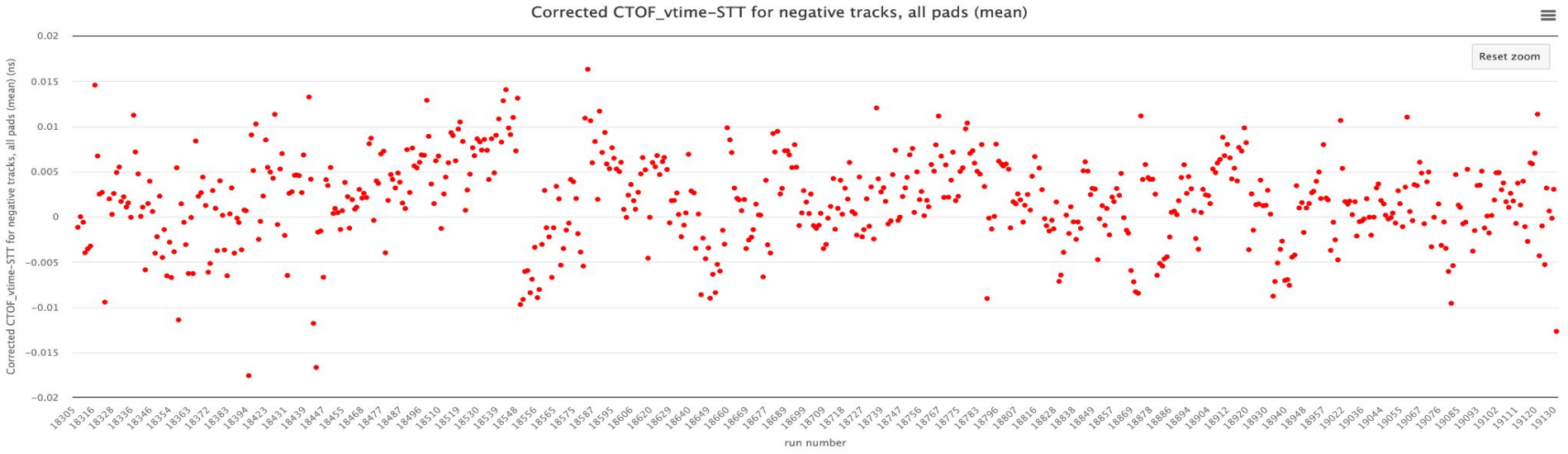
Data Processing Summary

- Timelines monitoring:
  - January 24th, 2025; Pass0v8: Processed with same Pass0v7 conditions + cross-check of reconstructed CND and CVT vertex difference (zdiff), second iteration of the ECal time resolution and time walk correction, fine-tuning of CTOF parameters along with HTCC 4 ns time adjustment for some unstable runs.
    - Timelines are available here



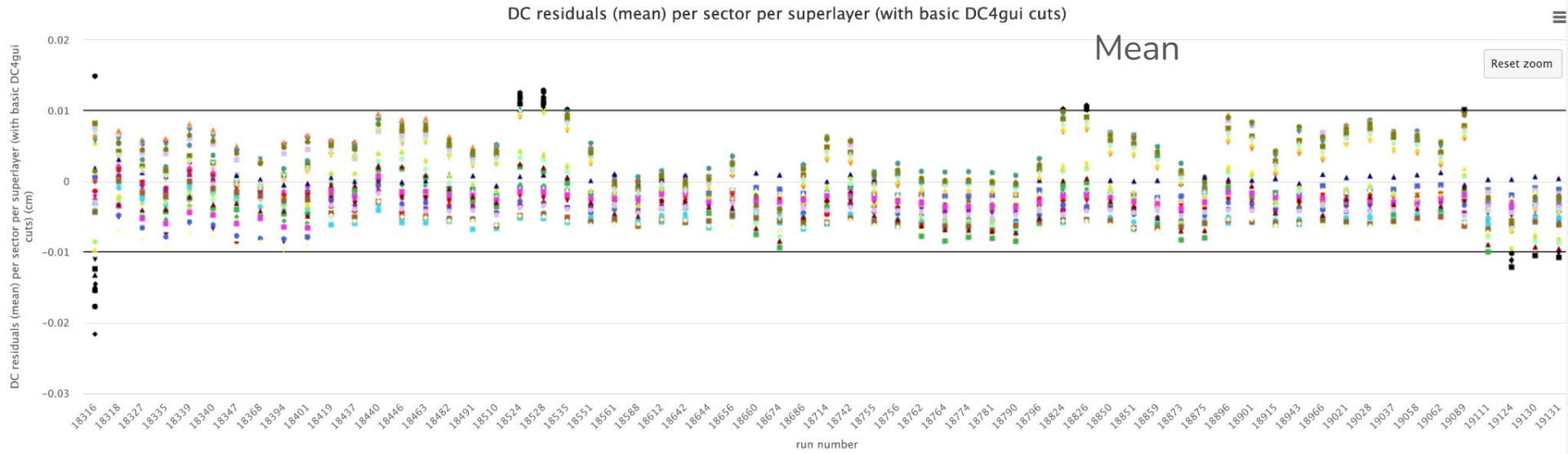
Data Processing Summary

- Timelines monitoring:
  - February 01st, 2025; Pass0v9: Processed with same Pass0v8 conditions + CD vertex cut to restore the selection zone of good tracks that was affected after updating the CCDB with the actual RG-D solid target material/geometry (*ongoing work to find a robust solution for this issue*)
    - Timelines are available here



Data Processing Summary

- Timelines monitoring:
  - February 14th, 2025; Pass0v9_dc: DC mini-timelines produced with same Pass0v9 conditions to check the quality of the newly extracted T2D and pressure calibration constants
    - Timelines are available here



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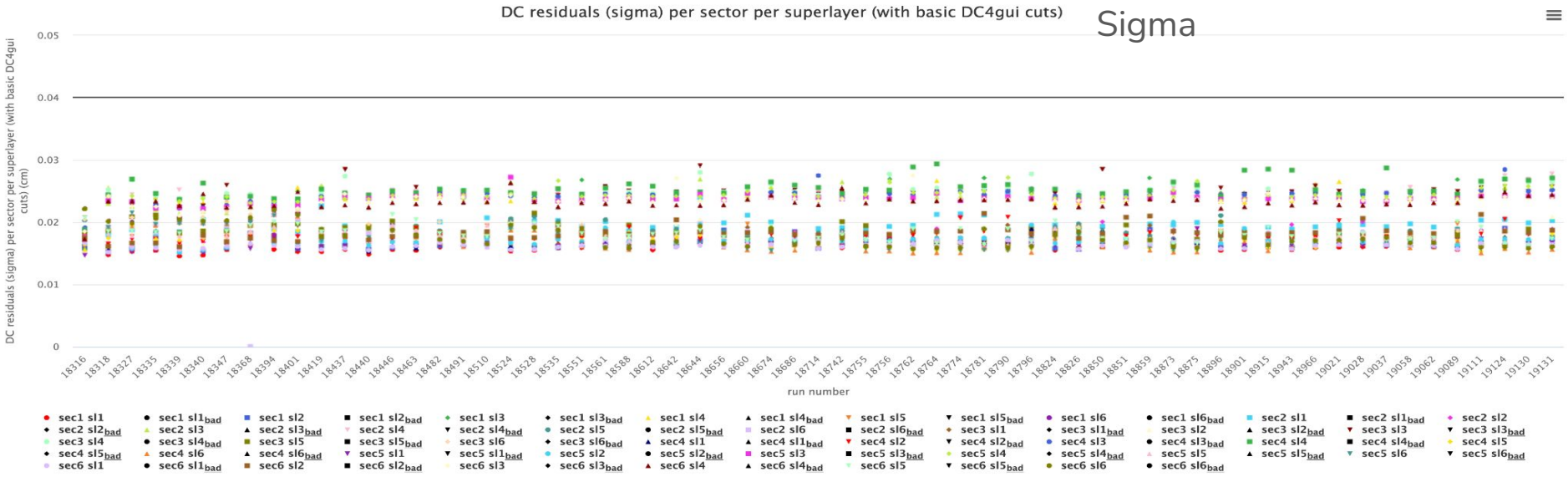
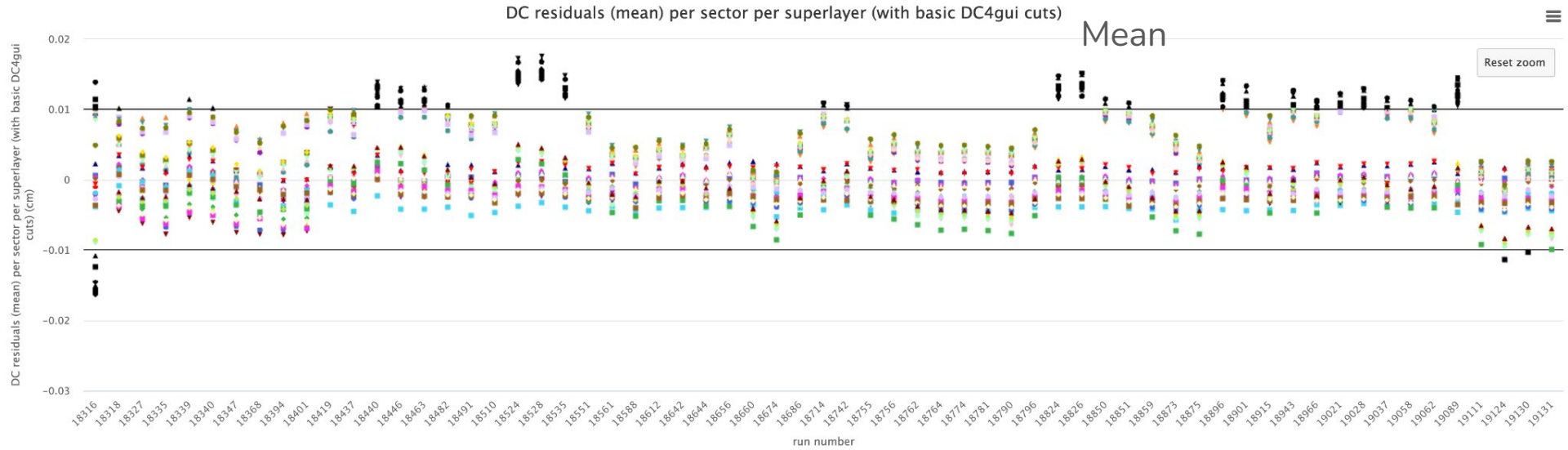


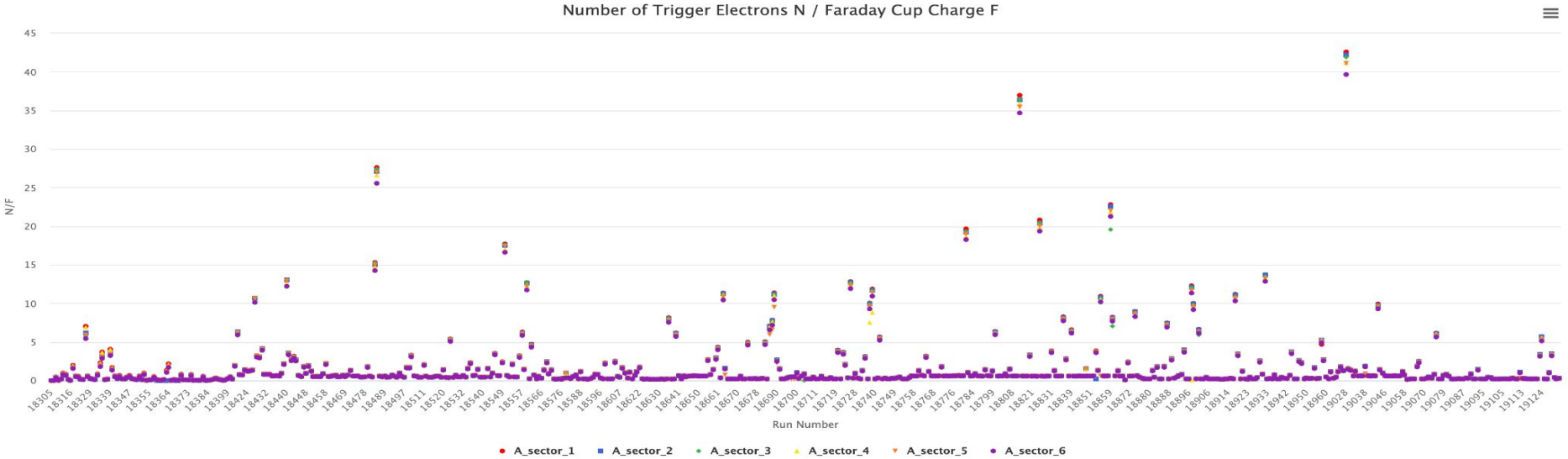
Data Processing Summary

- Timelines monitoring:
  - February 25th, 2025; Pass0v9_dcv2: DC mini-timelines produced with same Pass0v9 conditions to check the quality of the T0/T00 correction adjustment
    - Timelines are available here



Data Processing Summary

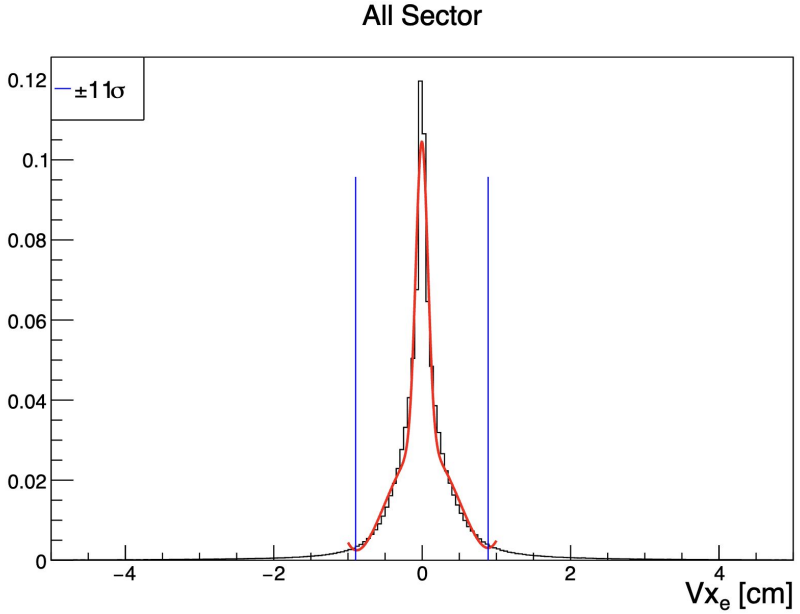
- Ongoing cross-check of the high-level physics QA timeline
  - More changes are needed to accommodate RG-D data suffering from the FCup vacuum contamination issue

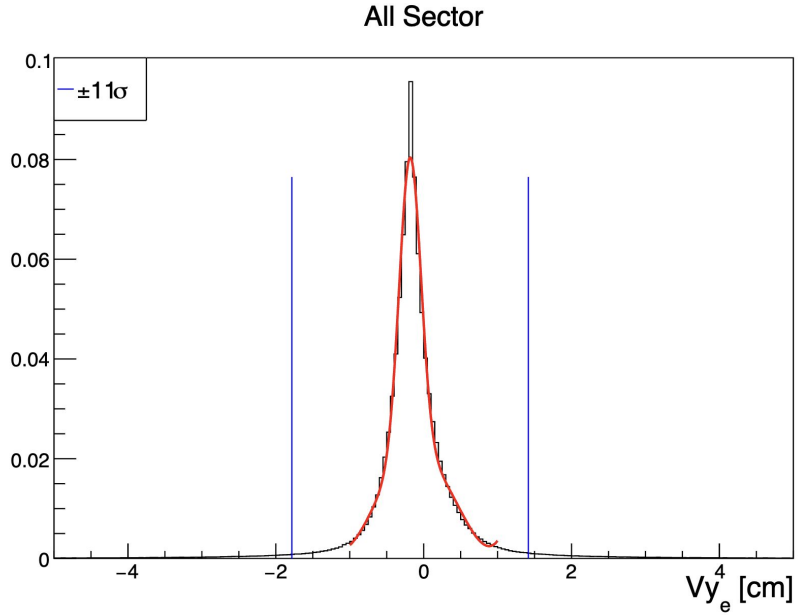


Outliers are expected to diminish once full runs are processed since the normalization is done with the accumulated gated per-run beam-charge (current timelines has only 20 files per run)

RG-D Vertex Studies

- The study aimed to
  - Separate solid-foil peaks from the empty LD2 cell and scattering chamber exit windows
  - Reduce the contamination for the target configuration with two different foils, Cu and Sn
  - Check the effect of Vx and Vy cuts on Vz distributions:
    - Fit sector-independent Vx and Vy with a Gaussian and a 4^{th}-order polynomial function





RG-D Vertex Studies

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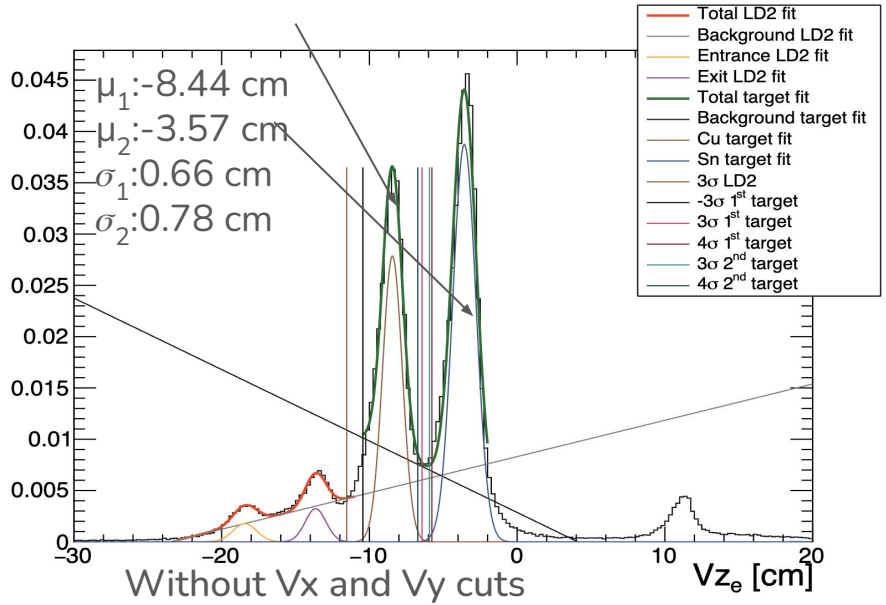
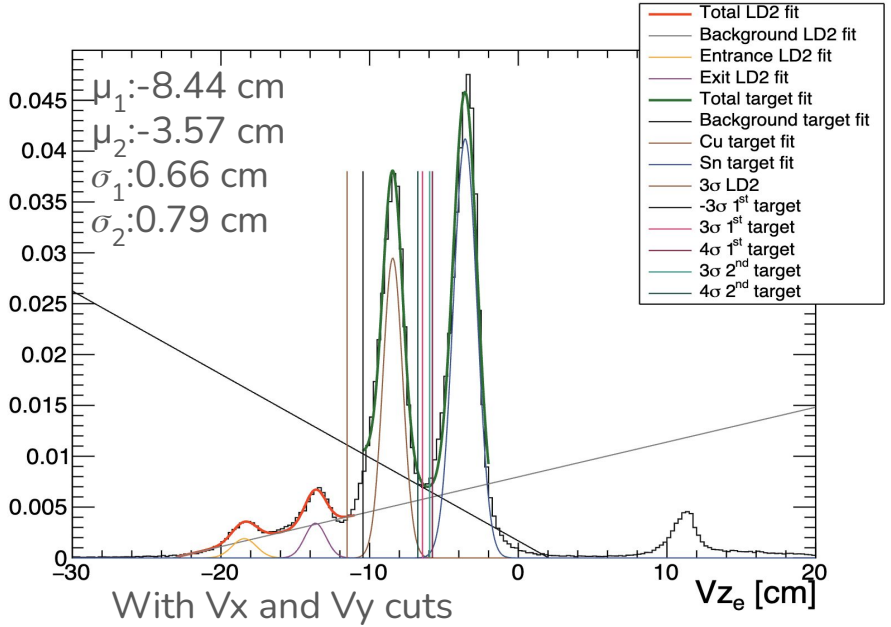
  - Separate solid-foil peaks from the empty LD2 cell and scattering chamber exit windows
  - Reduce the contamination for the target configuration with two different foils, Cu and Sn
  - Check the effect of Vx and Vy cuts on Vz distributions:
    - No noticeable effects of Vx and Vy cuts on Vz fit parameters; thus, eliminated!

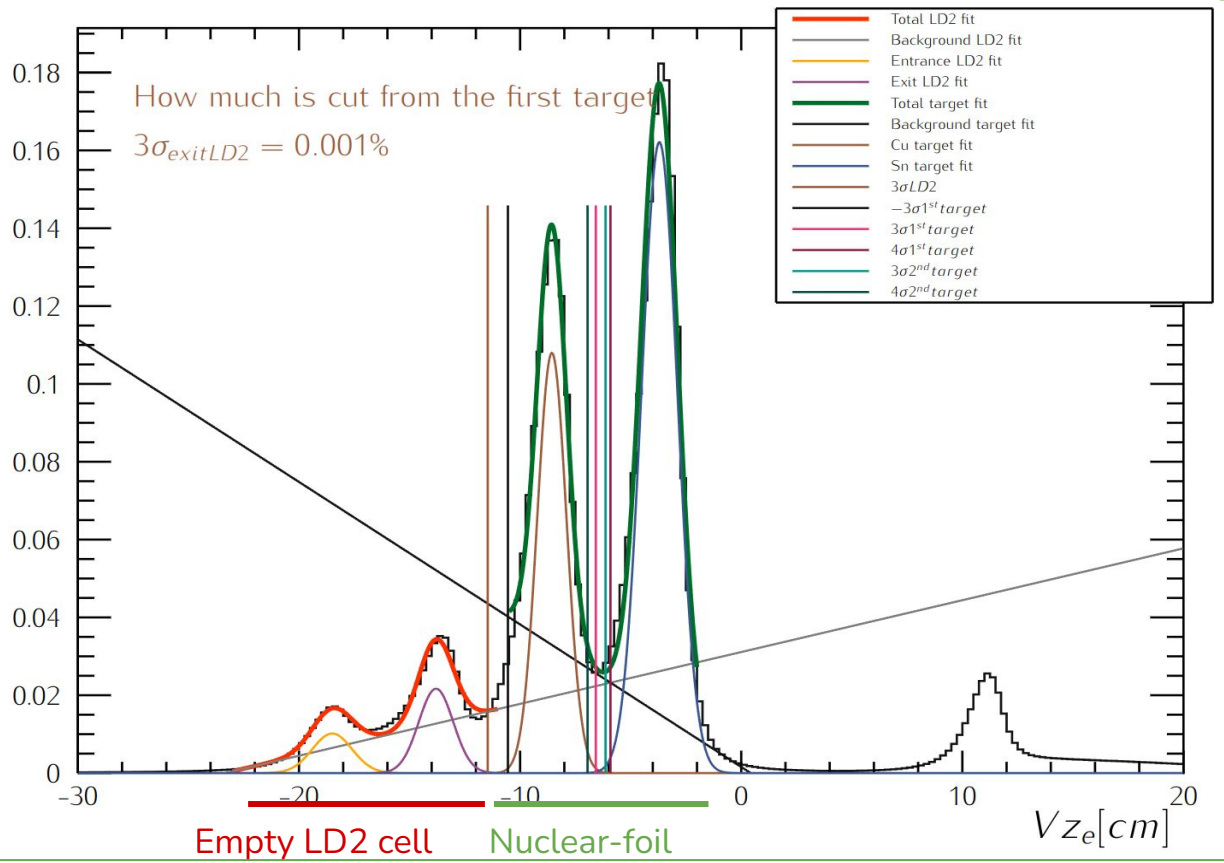


Without Vx and Vy cuts



With Vx and Vy cuts

RG-D Vertex Studies



RG-D Vertex Studies

- Established Vz cuts for electrons and charged pions and various solid foils

Upstream (Cu) and Downstream (Sn) foils

Electron	Vz	
	μ [cm]	σ [cm]
Entrance of the empty LD2 cell	-18.437182	0.840693
Exit of the empty LD2 cell	-13.688906	0.738610
first foil	-8.477611	0.674902
second foil	-3.620864	0.795920

π^+	Vz	
	μ [cm]	σ [cm]
first foil	-7.463966	0.765427
second foil	-2.645098	0.594126

π^+	Vz	
	μ [cm]	σ [cm]
first foil	-5.897985	0.642928
second foil	-2.589883	0.683810

π^-	Vz	
	μ [cm]	σ [cm]
first foil	-8.394546	0.853582
second foil	-3.325793	0.630868

π^-	Vz	
	μ [cm]	σ [cm]
first foil	-4.251155	1.409331
second foil	-3.311006	0.717284

Carbon

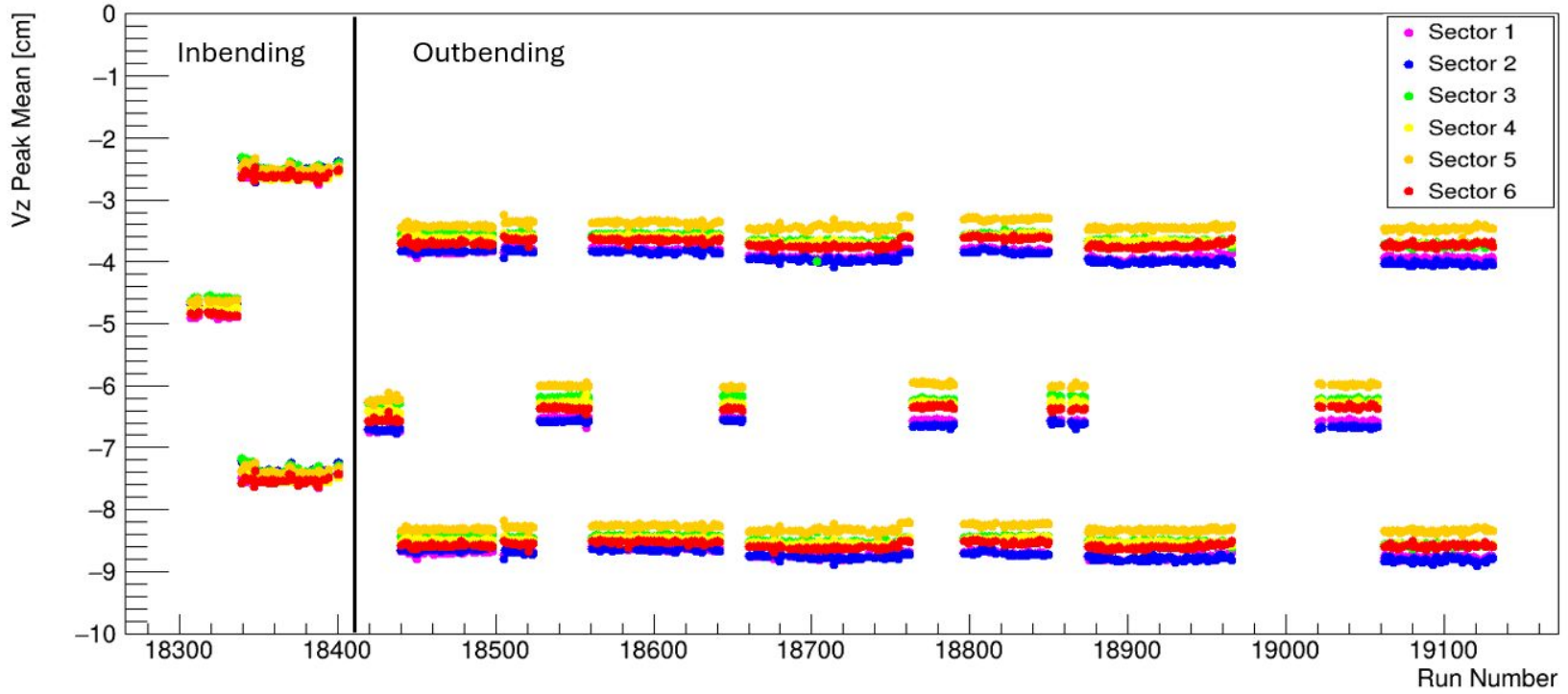
Electron	Vz	
	μ [cm]	σ [cm]
Entrance of the empty LD2 cell	-18.997963	0.018457
Exit of the empty LD2 cell	-13.996970	-0.017141
first foil	-8.516623	0.671765
second foil	-3.651899	0.812204

π^+	Vz	
	μ [cm]	σ [cm]
first foil	-7.524694	0.724985
second foil	-2.604698	0.634244

π^-	Vz	
	μ [cm]	σ [cm]
first foil	-8.367294	0.731321
second foil	-3.519357	0.850363

RG-D Vertex Studies

- Extracted Vz timeline in which a global 1 cm shift is observed between IB and OB datasets!?

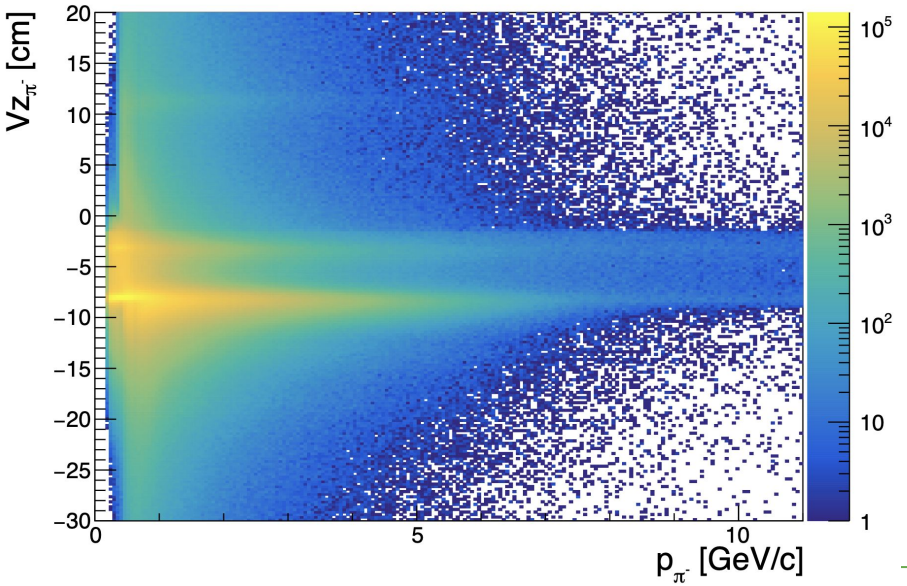


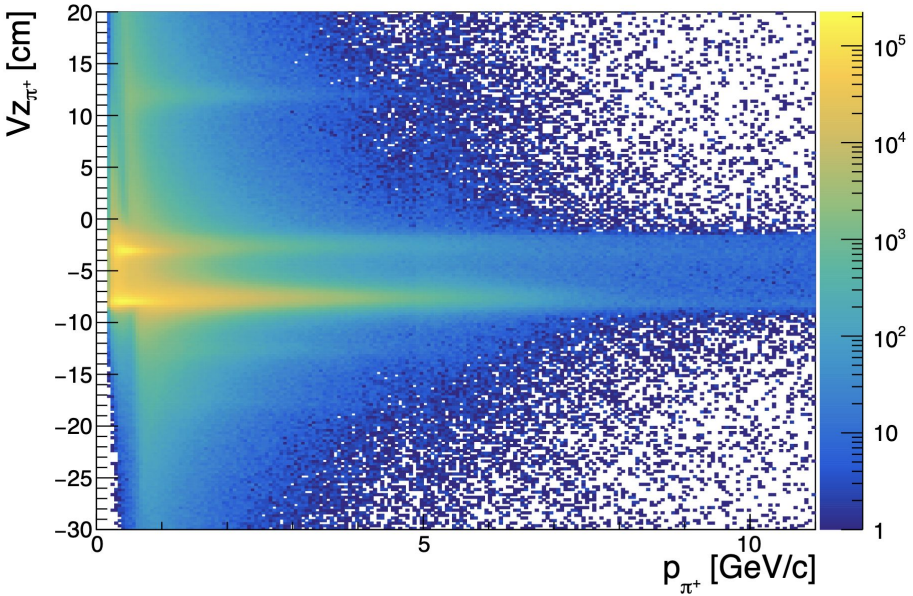
Plot credit of M. Maynes

RG-D Analysis Study: Particle IDentification

- Electron:
  - PID = 11
  - Status < 0
  - -5 < chi2pid < 5
  - Vz cuts depending on the target

- Charged pions, $\pi^{\pm}$:
  - PID (+/-) = (+/-) 211
  - -10 < chi2pid < 10
  - Vz cuts depending on the target

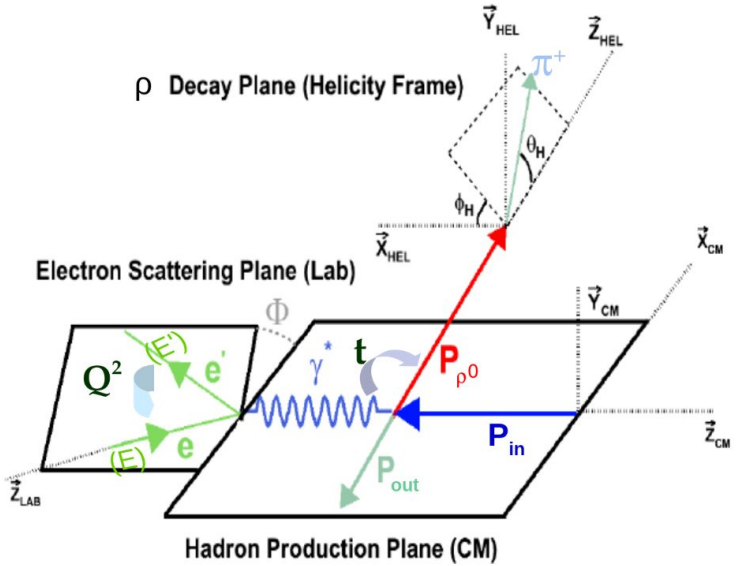




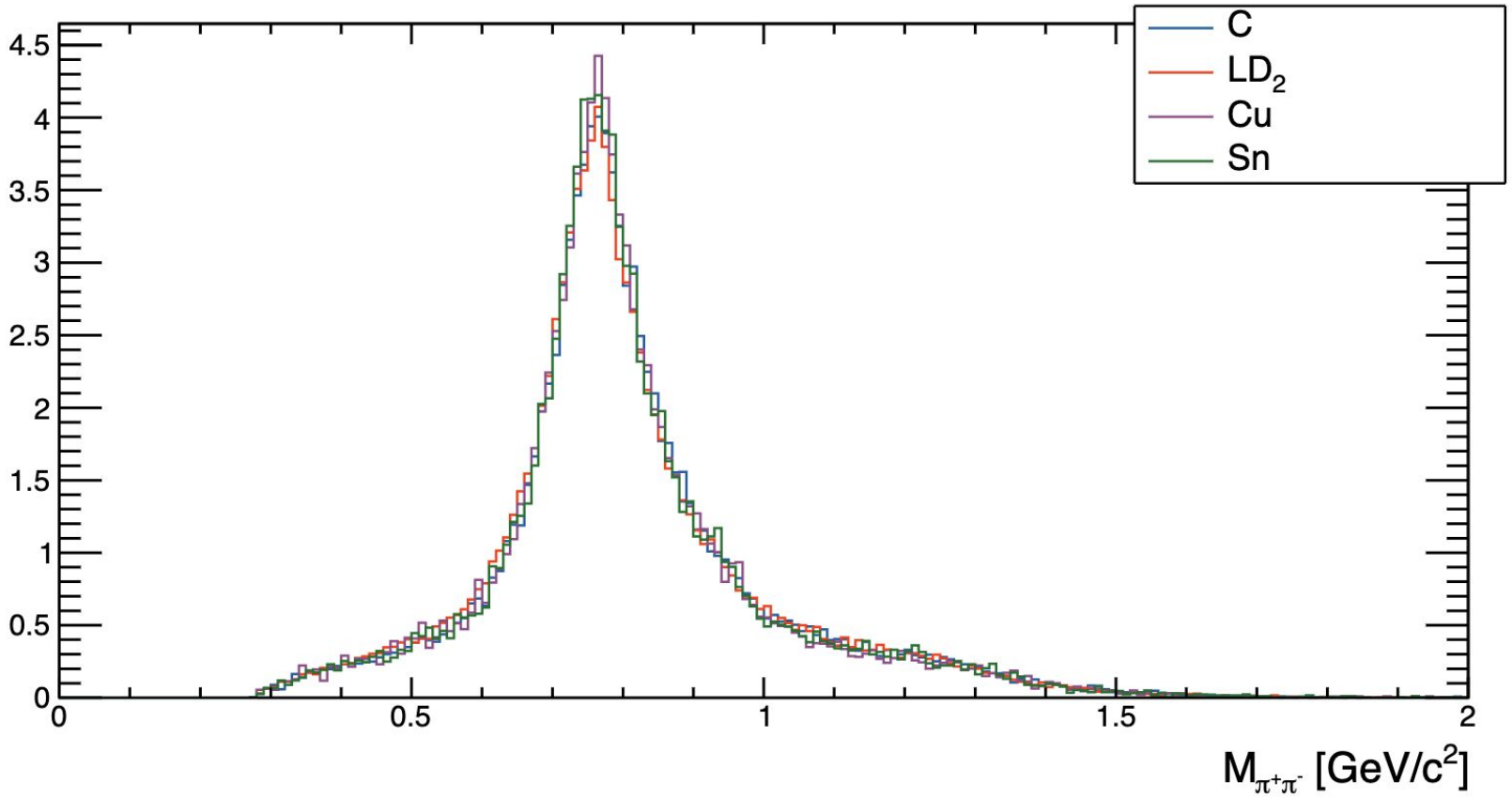
RG-D CT Study: Kinematical Cuts

- $\nu = E - E'$: virtual photon(γ^*) energy in the Lab frame,
- $Q^2 = -(P_e - P_{e'})^2 = 4EE'\sin^2(\theta/2)$: photon virtuality,
- $t = (P_{\gamma^*} - P_\gamma)^2$: momentum transfer square,
- $W^2 = (P_{in} + P_{\gamma^*})^2 = -Q^2 + M_p^2 + 2M_p\nu$: invariant mass squared in (γ^*, p) center of mass (CM)

- Kinematical cuts:
  - W> 2 GeV ↦ avoid resonance region
  - $z_h = E_h/\nu > 0.9$ ↦ select elastic channel
  - $-t > 0.1$ GeV^2 ↦ exclude coherent production
  - $-t < 0.5$ GeV^2 ↦ select diffractive process

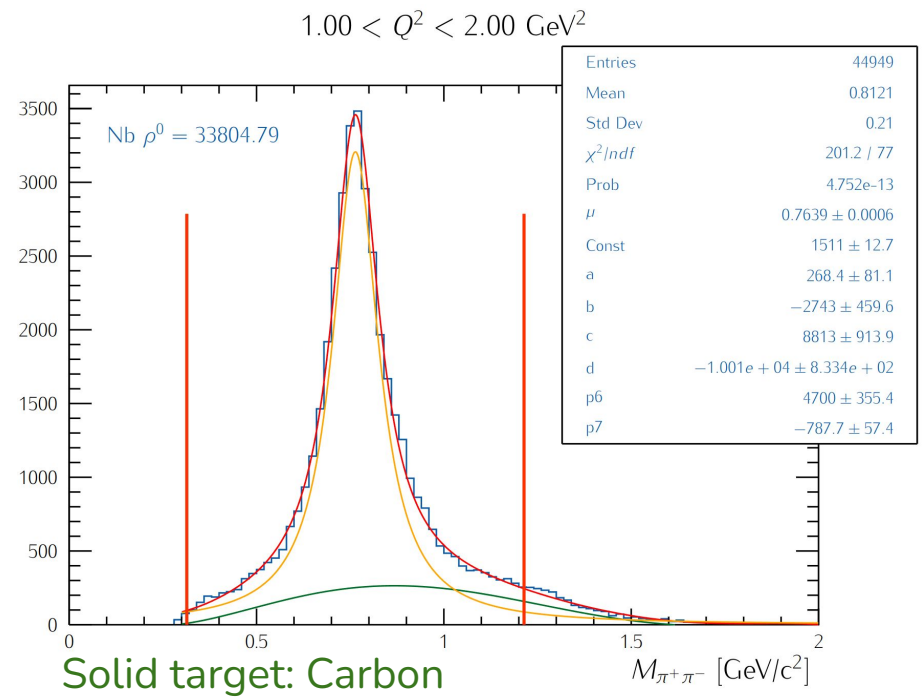


CT Study: Two-pion Invariant Mass

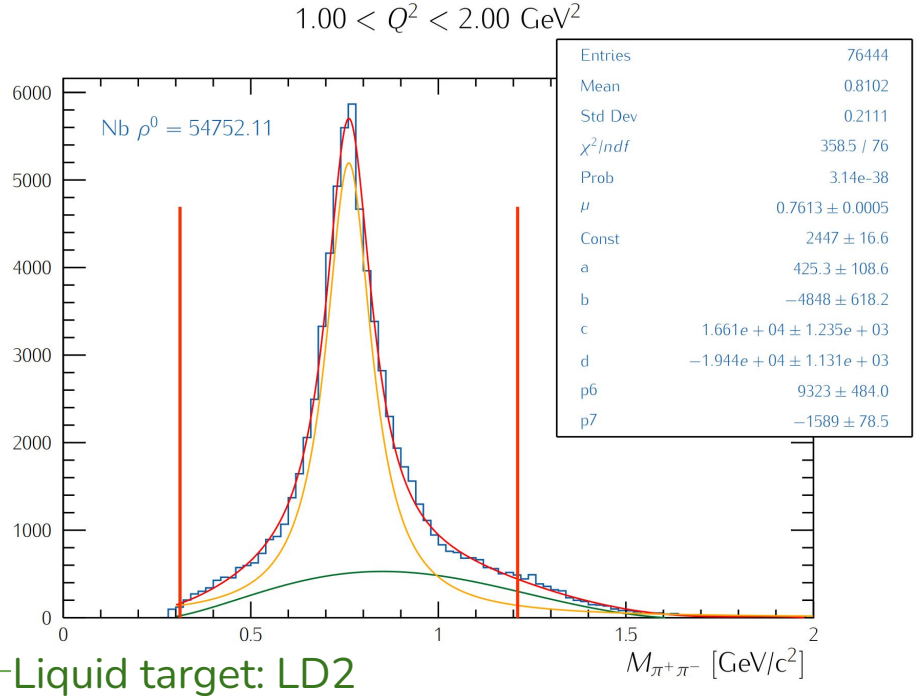


CT Study: Yield Extraction

- Fit oppositely charged pions invariant mass with a Breit-Wigner and 3rd-order polynomial function (*the latter will be replaced with the simulated background shape*)
- Extract ρ^0 yield by integrating the background-subtracted BW within a 3σ range



Solid target: Carbon



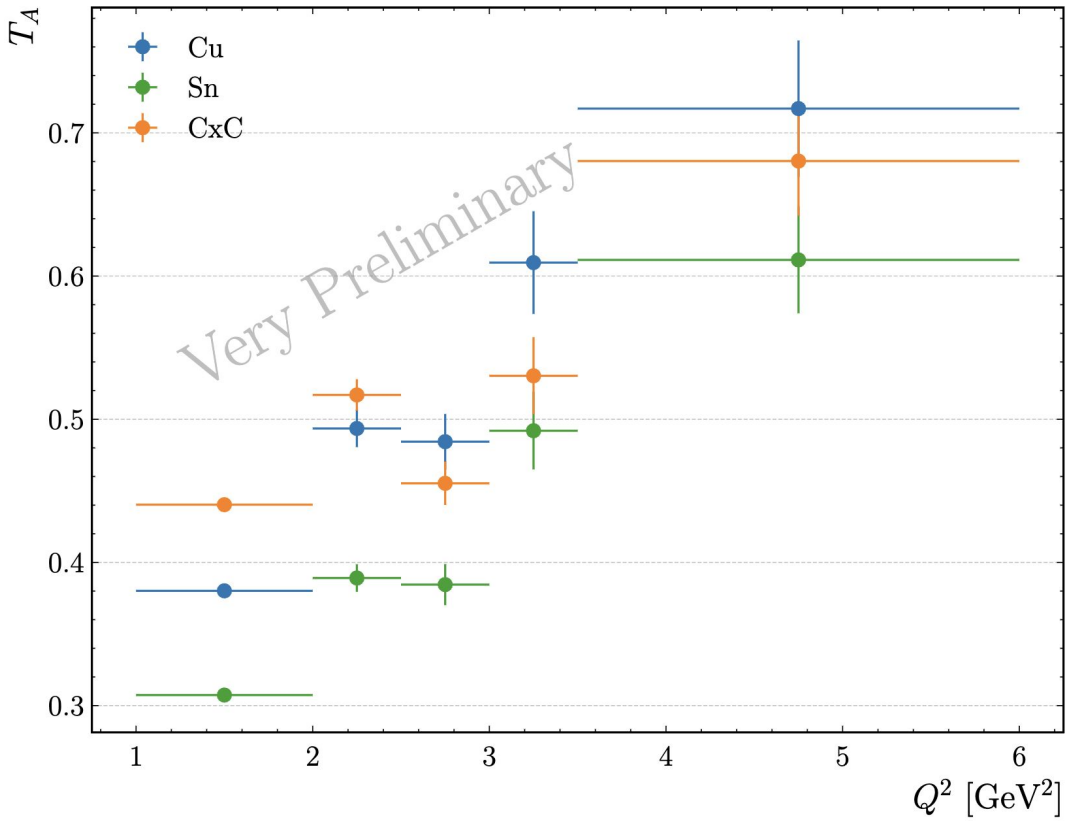
Liquid target: LD2

CT Study: Very Preliminary Nuclear Transparency

- Extract (raw) nuclear transparency as

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

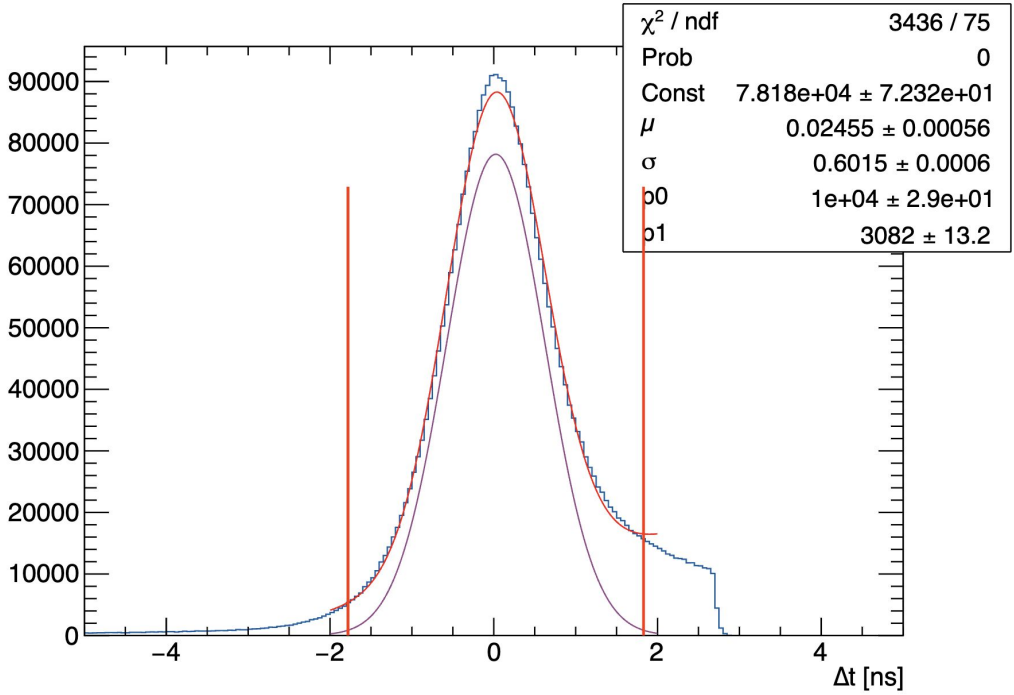
  - r_{LD2}= 5 cm: LD2 thickness
  - r_{CxC} = 0.4 cm: CxC thickness
  - r_{Cu}= 93 μm: Copper thickness
  - r_{Sn} = 171 μm: Tin thickness
  - ρ_{LD2}= 0.164 g/cm^3: LD2 density
  - ρ_C= 2.2g/cm^3 : Carbon density
  - ρ_{Cu}= 8.96 g/cm^3: Copper density
  - ρ_{Sn}= 7.31g/cm^3 : Tin density



Ongoing analysis by M. Maynes

RG-D nTMDs 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:
  - pid = 11
  - status < 0
  - -11 < Vz < 5 cm (for LD2)
- Photon cuts:
  - pid = 22
  - E > 0.2 GeV
  - $-1.67 < \Delta t = (t_{EC} - t_{start} - l_{EC}/30) < 1.55$ ns
  - $\theta_{e\gamma} > 8$ deg → reduce radiative photon



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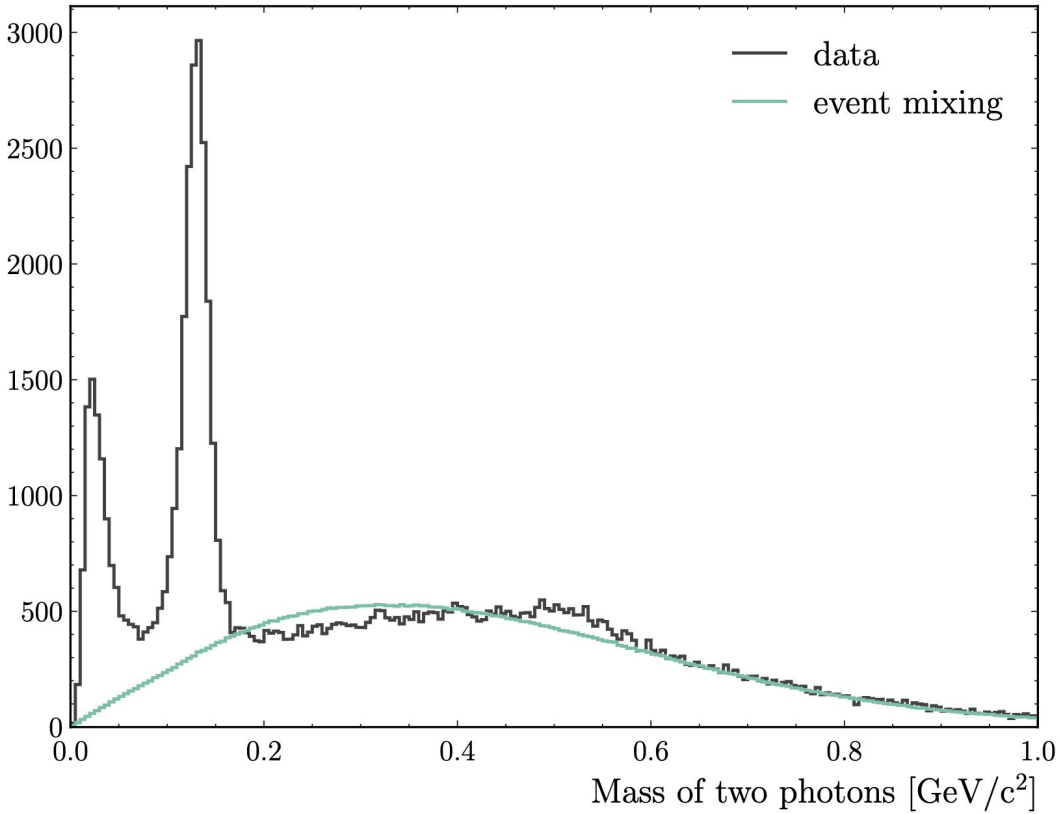
- Kinematical cuts:
  - W > 2 GeV ↦ avoid resonance region
  - Q^2 >1 GeV^2 and 0.3< z_h< 0.7 ↦ region in which the TMDs factorization holds



Summary and Outlook

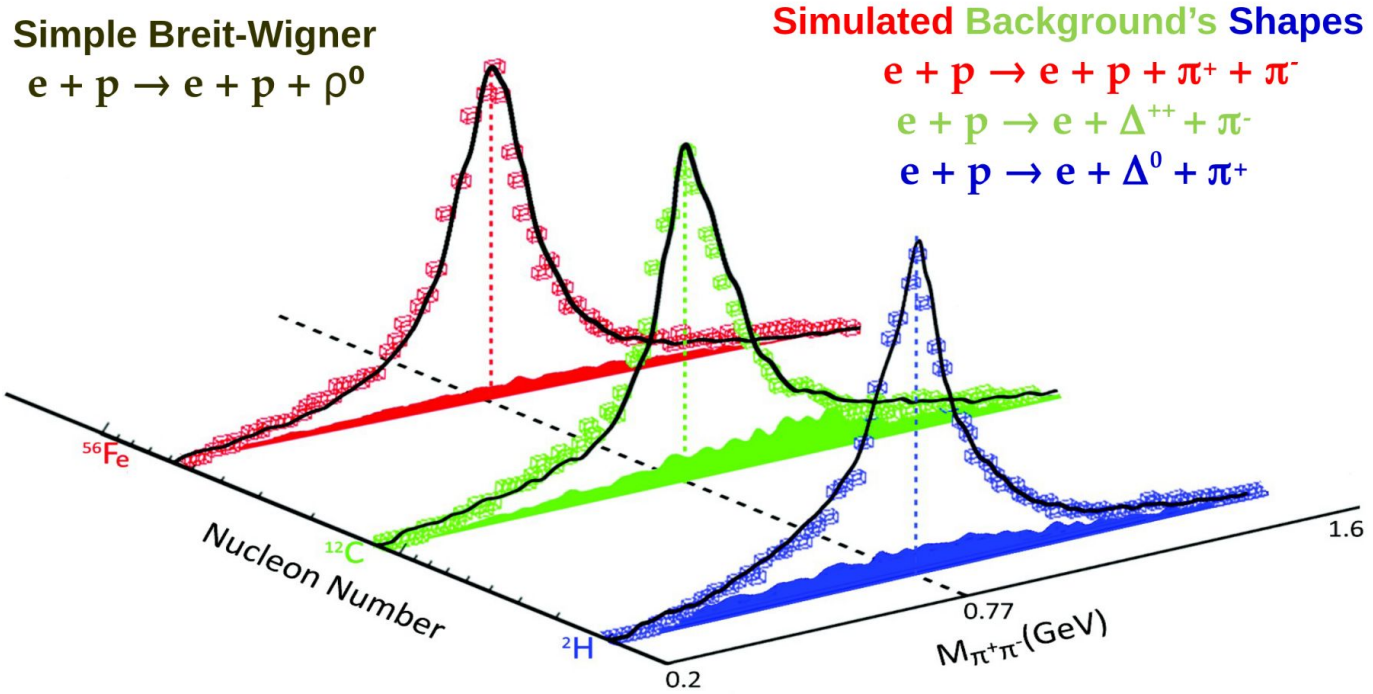
- RG-D preparation for the Pass1 cooking review entails
  - Finalizing the DC calibration and checking its quality with Pass0 timelines, while all other subsystems calibration is done
  - Retrain the RG-D AI network after completing the DC calibration
  - Complete adapting the high-level physics QA timeline to RG-D run conditions
  - Perform background merging for data and Monte-Carlo tracking efficiency comparison
- Optimizing analysis tools for CT and nTMDs studies to
  - Improve Particle IDentification for all final-state particles
  - Fine-tune the vertex cuts and corrections once the full calibration is completed
  - Implement fiducial cuts
  - Deploy the ρ^0 event generator for its two-pion invariant mass background subtraction and apply necessary corrections for the extraction of the preliminary CT results
  - Finalize the π^0 event mixing background-subtraction and extract its preliminary asymmetry results
  - Obtain the preliminary asymmetry results for charged pions nTMDs studies

Backup

CT Study: Two-pion Invariant Mass

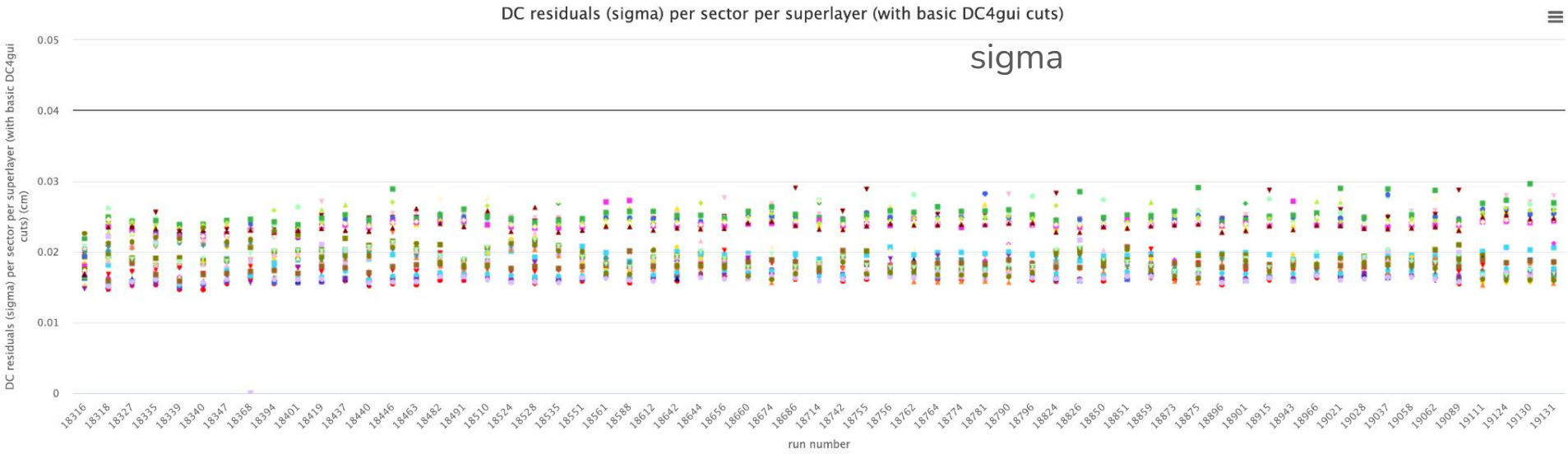
- Our event generator incorporates the measured cross sections by Cassel et *al*. for the electroproduction of ρ^0 and the three main background processes

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



Data Processing Summary

- Timelines monitoring:
  - February 25th, 2025: Pass0v9_dcv2: DC mini-timelines produced with same Pass0v9 conditions to check the quality of the T0 correction
    - Timelines are available here



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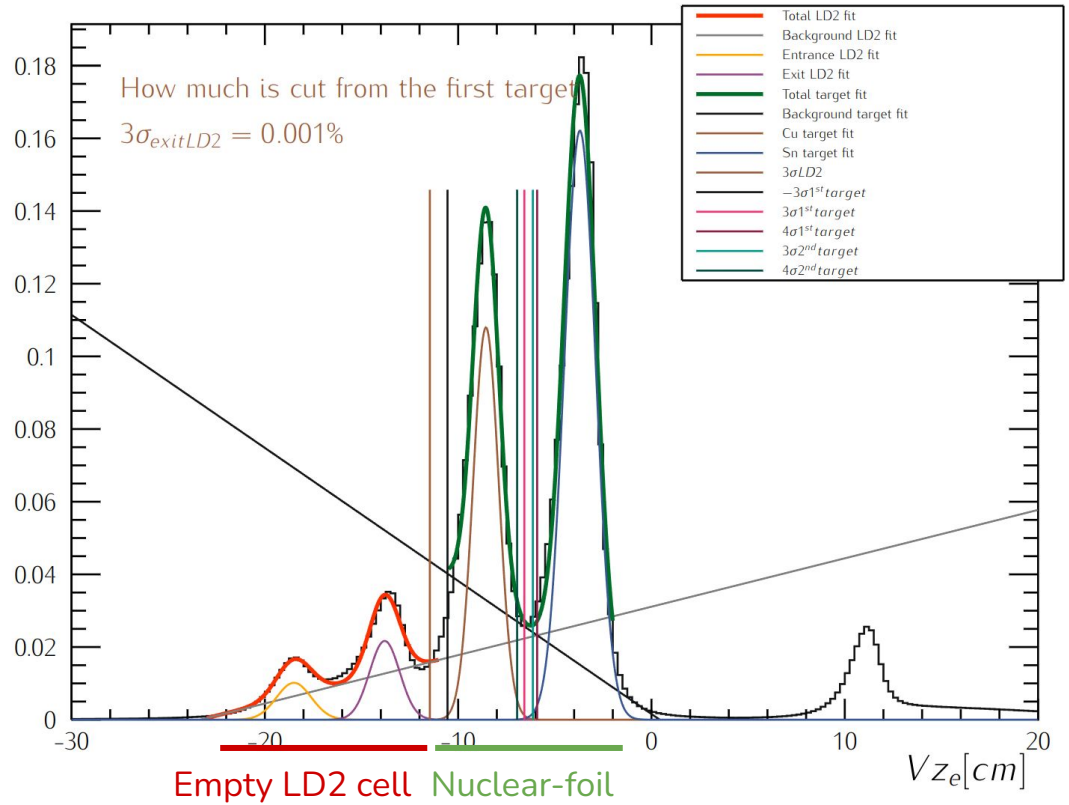
RG-D Vertex Studies



- Fits:
  - Fit the empty LD2 cell and solid-foil regions, CxC and CuSn. Use double gaussians and first-order polynomial function for both LD2 cell and solid foils
  - Separate the two different foils Cu and Sn peaks from each other
  - Same study is performed for hadrons, but the fit is performed with only one double gaussians and first order polynomial function since the empty LD2 cell had been already removed with the electron vertex cut

RG-D nTMDs Studies: Charged Pions

- Two parallel nTMDs analysis for charged pions by D. Matamoros and S. Shrestha
  - D. Matamoros will give a talk about his analysis about nTMDs on positively charged pion
  - S. Shrestha is currently working to understand the EB PID and compare it to offline PIDs based on \delta_T cuts