RG-E Lambda Analysis

CLAS Collaboration Meeting

June 30th, 2026

Uditha Weerasinghe

Mississippi State University

Jefferson Lab

Outline

- Introduction
  - Physics Motivation
  - Kinematic Cuts
  - RG-E Experimental Setup
- Fiducial Cuts
- Refining Particle Identification
  - Electron
  - π^-
  - Proton
- Vertex Cuts
- Λ Production Channel
- Event Mixing for Background Subtraction

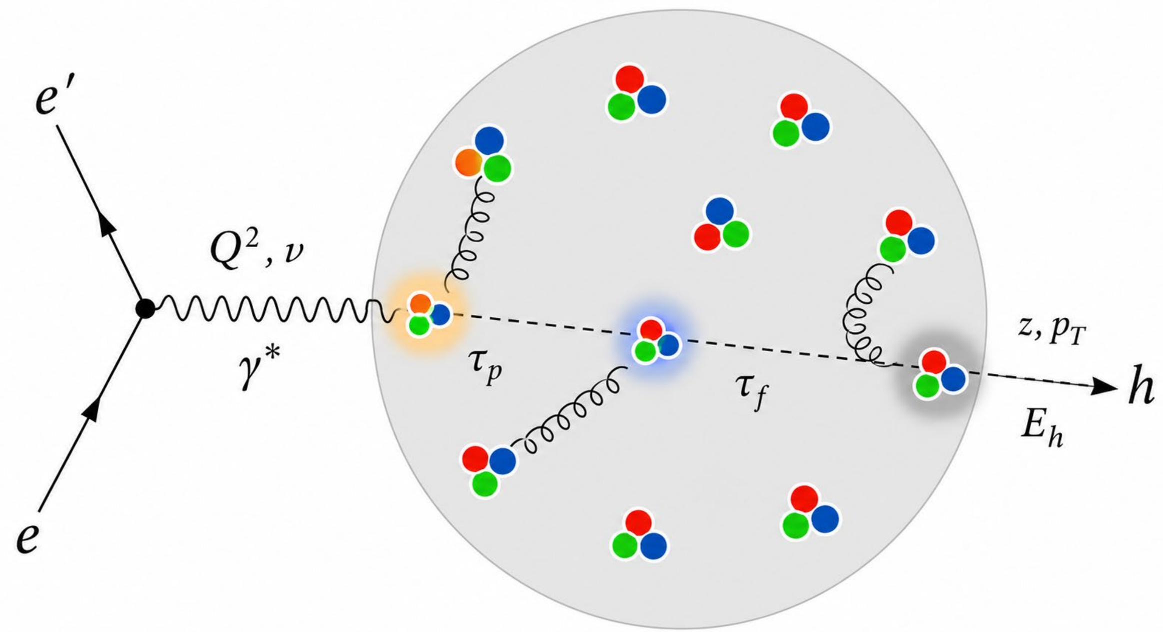
Introduction

Physics Motivation

- Studying hadronization processes in Semi Inclusive Deep Inelastic Scattering (SIDIS) production helps improve our understanding of the confinement dynamics, a fascinating feature of Quantum Chromodynamics, the fundamental theory of strong interactions between quarks and gluons

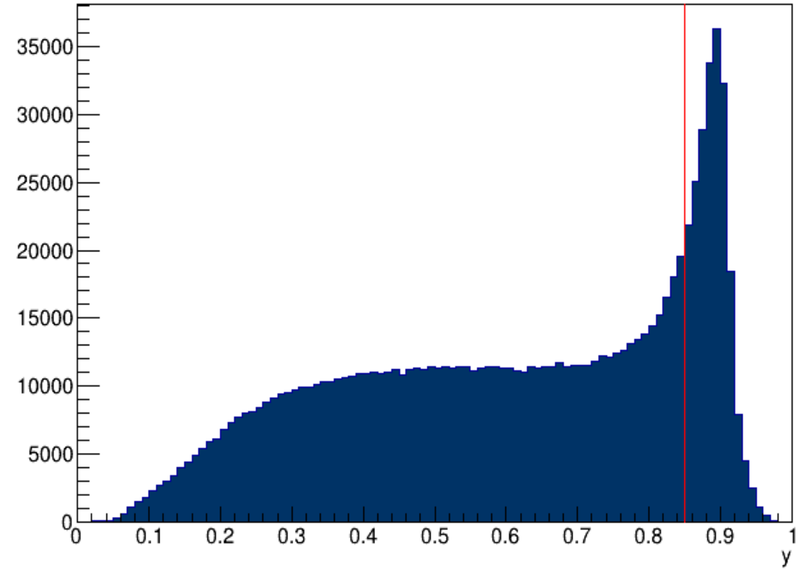
- Hadronization process is characterized by two time-distance scales:
  - **Production time (τ_p):** Struck quark propagates as a colored object during the color-neutralization stage
  - **Formation time (τ_f):** Time needed for the color-neutral prehadron to evolve into a fully dressed hadron with its gluonic field

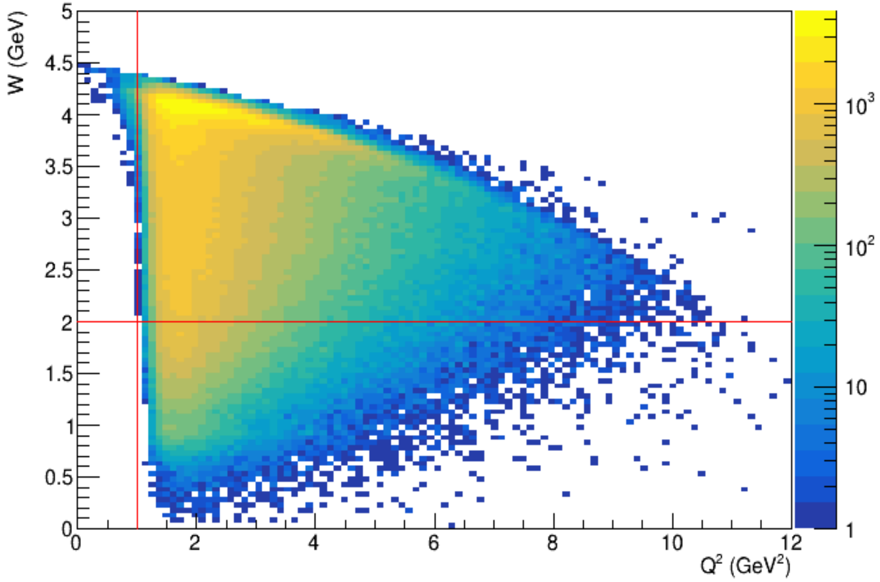
$$e + p \to e' + h + X$$



Kinematic Cuts

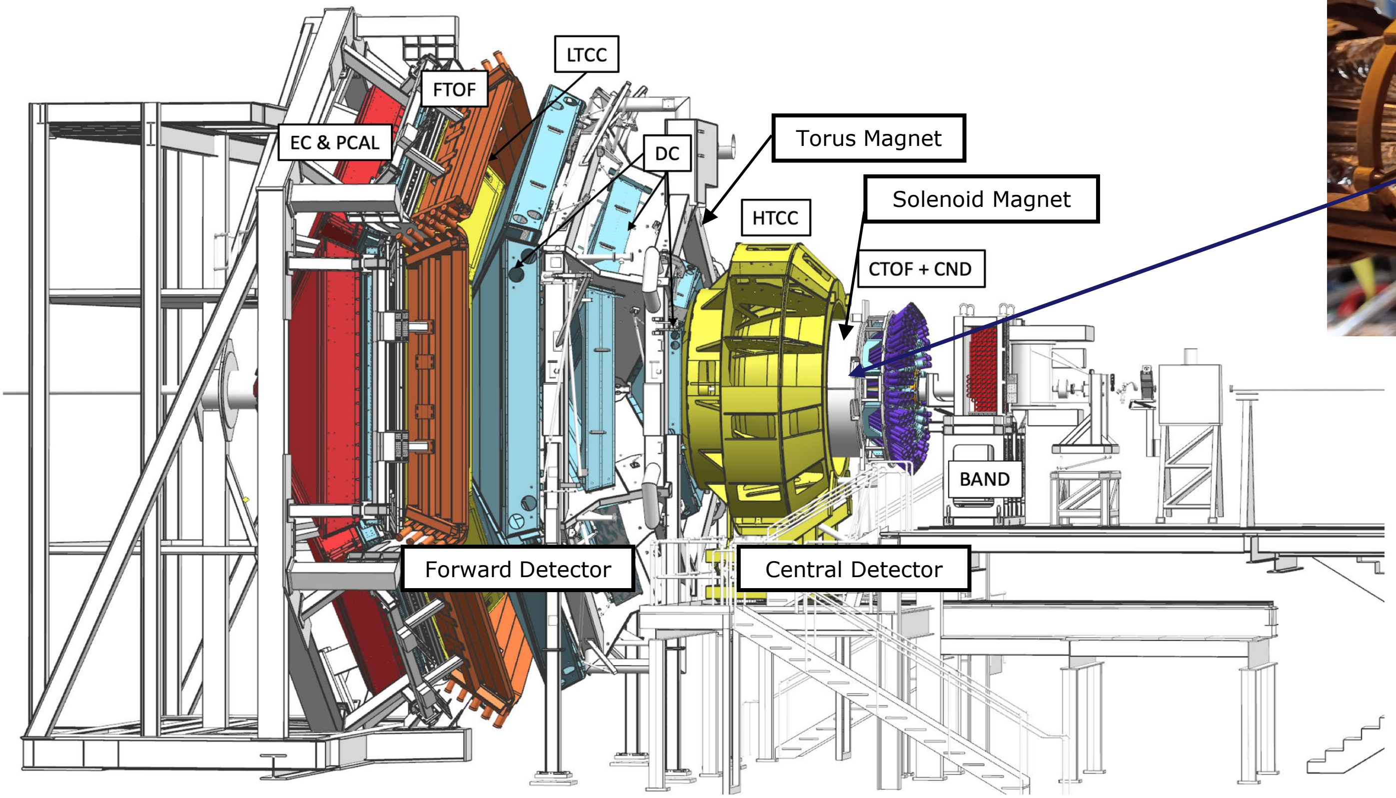
- The study of hadronization dynamics is probed in the SIDIS regime using this set of kinematics and cuts:
  - ν: electron energy loss or struck quark's initial energy
  - Q^2: four-momentum transferred squared
    - $\mathrm{Q}^2 > 1\ \mathrm{GeV}^2$: to probe the intrinsic structure of nucleons
  - $y = {}^{\nu}/_{E_{beam}}$: electron energy fraction transferred to a struck quark
    - $\mathrm{y} < 0.85$: to reduce radiative effects based on former HERMES studies
  - $W = \sqrt{M^2 + 2\nu M - Q^2}$: total mass of the hadronic final state, where M is the nucleon mass
    - $W > 2\ \mathrm{GeV}$: to avoid contamination from the resonance region
  - $z_h = {}^{E_h}/_{\nu}$: struck quark's initial energy fraction carried by the formed hadron
  - p_T: hadron transverse momentum measured relative to the virtual photon direction





RG-E Experiment Setup

- RG-E experiments collected data during the spring of 2024 using the standard CLAS12 detectors with FT-OFF
- A double target assembly consisting of liquid deuterium (LD2) and solid foil targets placed inside the solenoid magnet



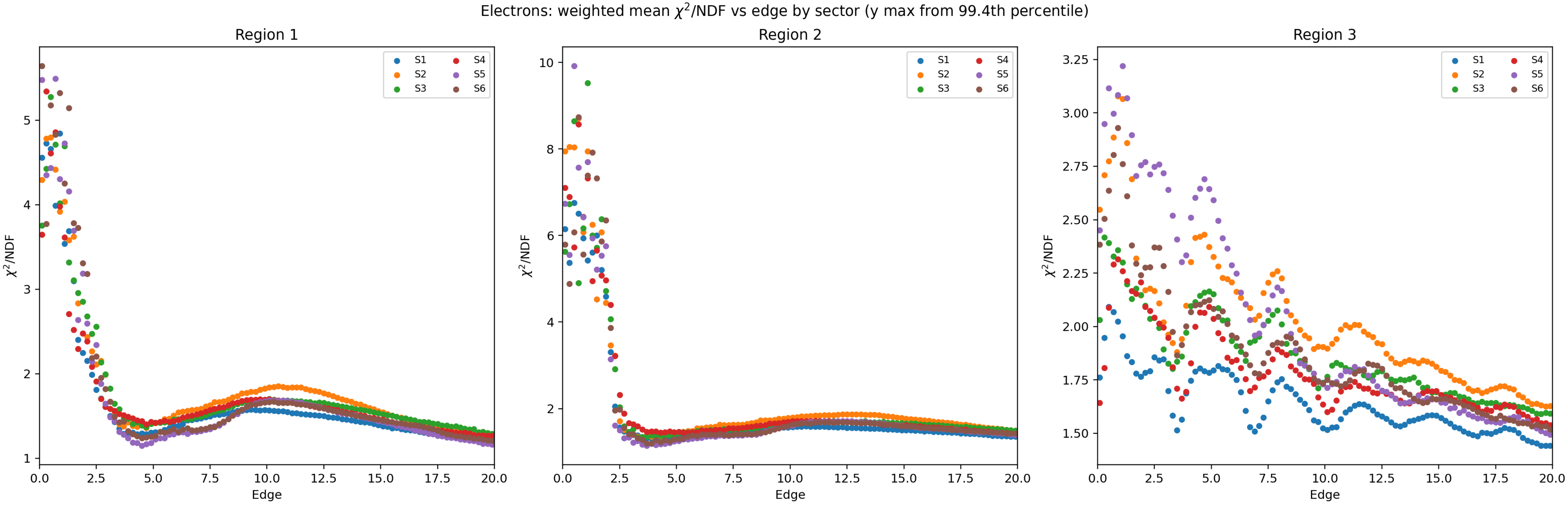
Solid foils:
- C
- Al
- Cu
- Sn
- Pb

Electron Beam

Fiducial Cuts

Forward Detector Fiducial Cuts – Drift Chamber

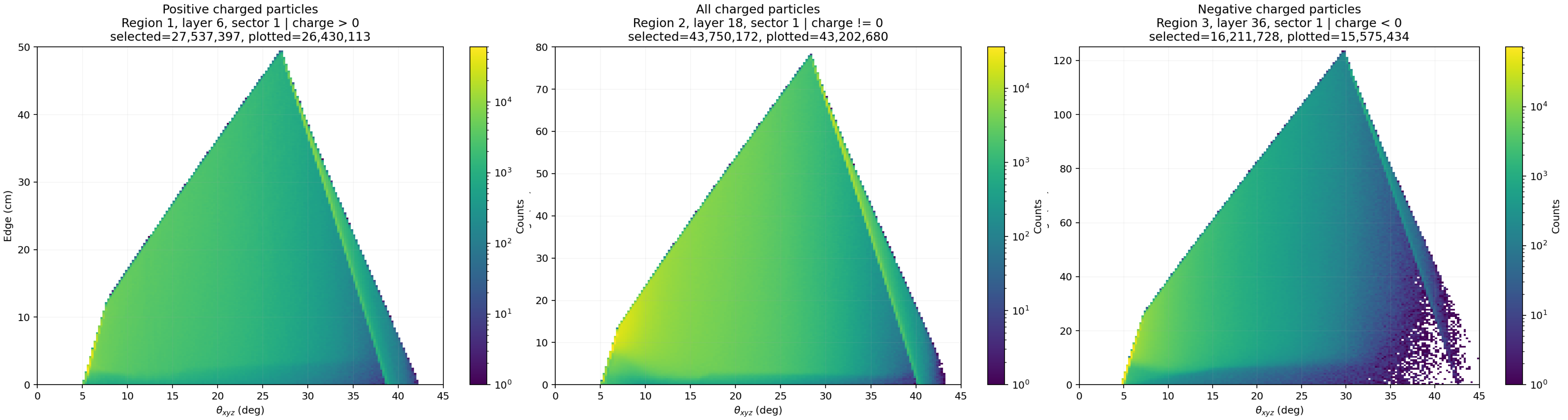
- The chi2/ndf vs edge method found in several analysis notes was trialled
- Region 3 showed a strong dependence on the PCAL acceptance



Forward Detector Fiducial Cuts – Drift Chamber

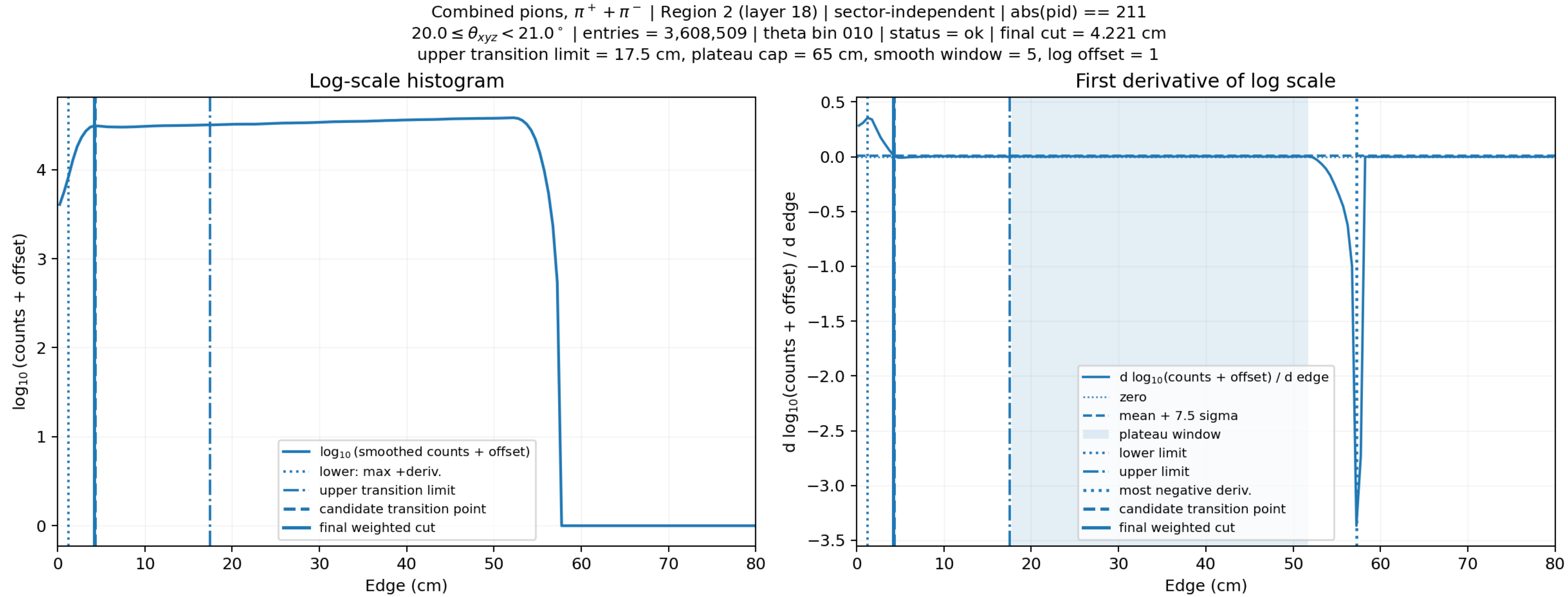
- The chi2/ndf vs edge method found in several analysis notes was trialled
- Region 3 showed a strong dependence on the PCAL acceptance
- A better method was to take the yield vs edge in theta bins
- The choice of particles used in each region was based on the magnetic field configuration

(ref: CLAS12 software office hours discussion with Raffaella)



Determining the Edge Cut Value

- The 1D edge histograms for each theta bin were plotted and smoothed
- Then the log of the counts were plotted
- Used several methods to find the transition point between low and high efficiency
  - Highest first derivative: too loose
  - Lowest second derivative (before a fixed limit): too strict & unstable
  - Followed a complex procedure: close to where we need to be



Determining the Edge Cut Value

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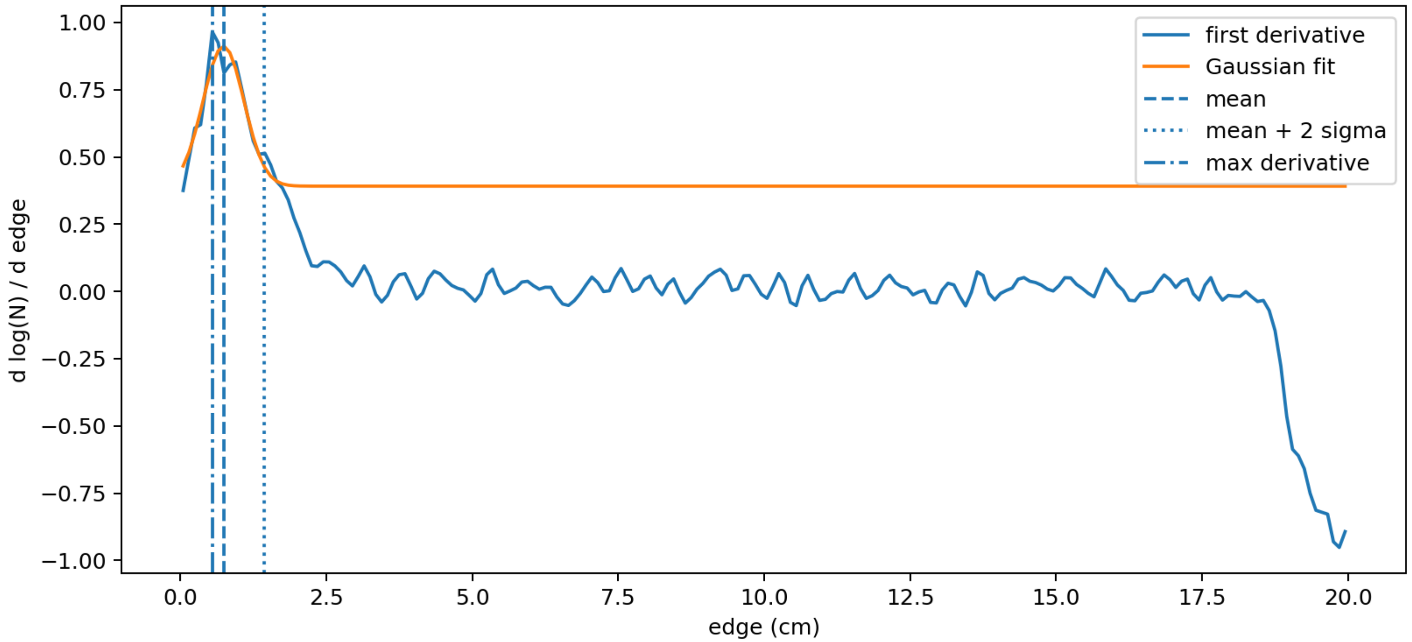
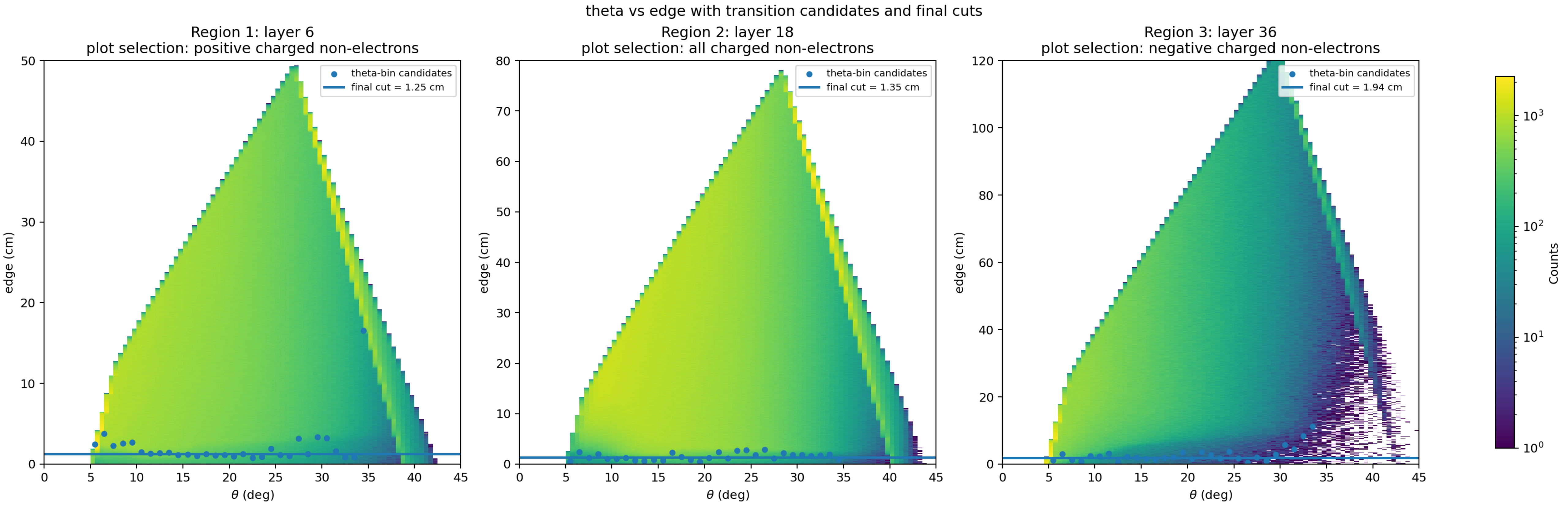
- Then the log of the counts were plotted
- Used several methods to find the transition point between low and high efficiency
  - Highest first derivative: too loose
  - Lowest second derivative (before a fixed limit): too strict & unstable
  - ~~Followed a complex procedure: close to where we need to be~~ (later discarded)
  - Fitted the initial peak of the first derivative with a Gaussian and took the 3 σ limits

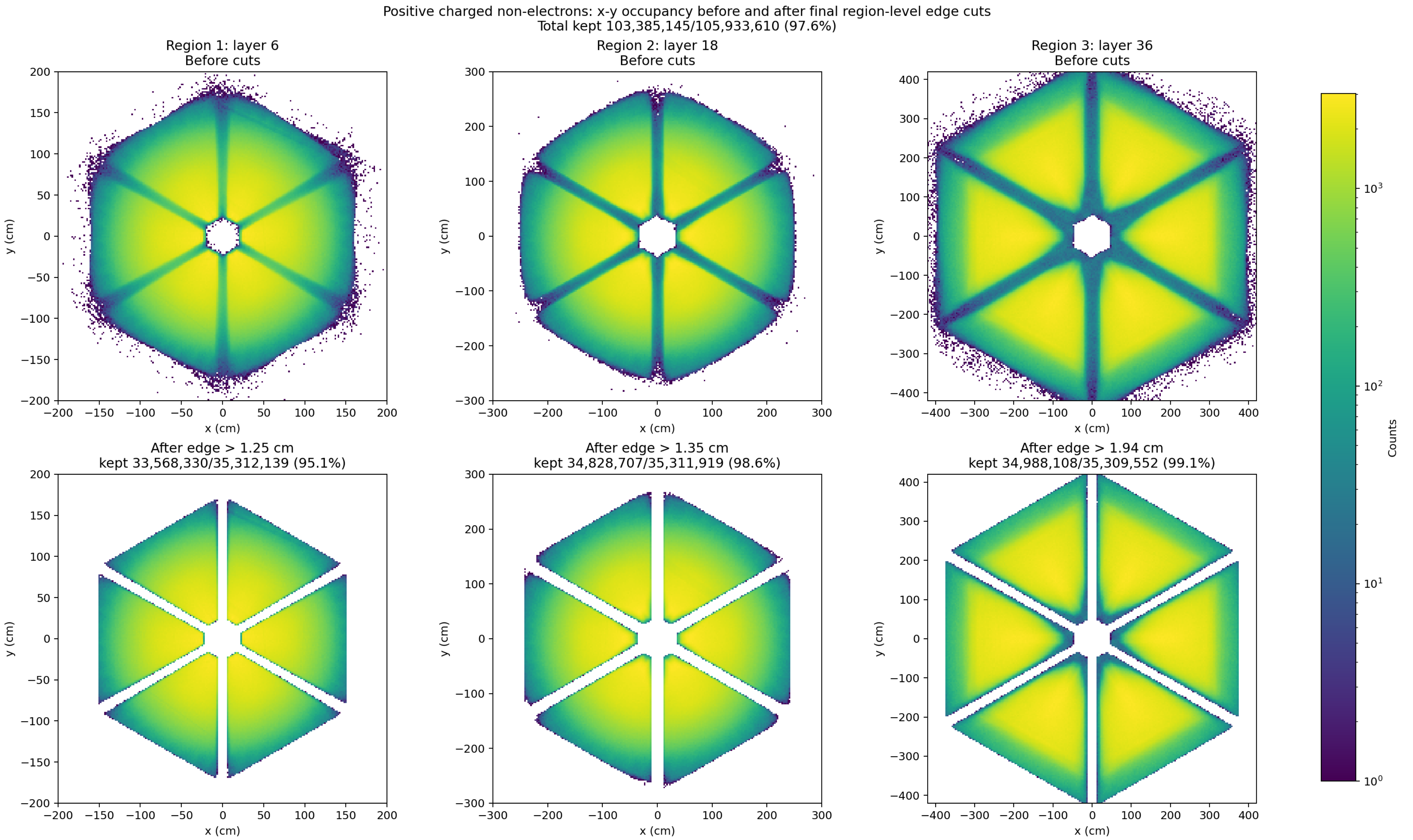


Determining the Edge Cut Value

- The transition point between high and low efficiency was found for each theta bin
- These points were fitted with a constant function to determine the region-dependent DC fiducial cuts



Effect of Applying Drift Chamber Fiducial Cuts



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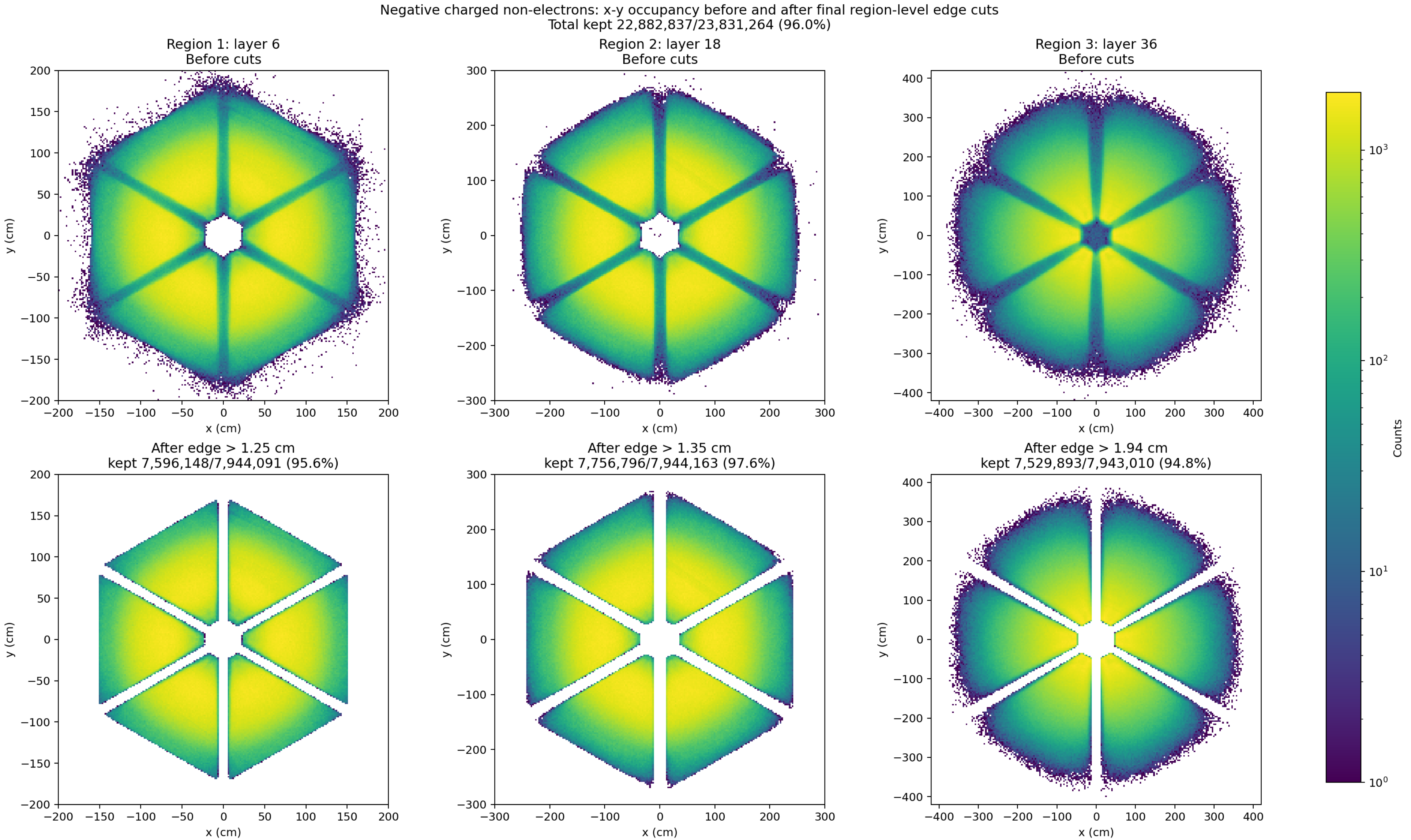
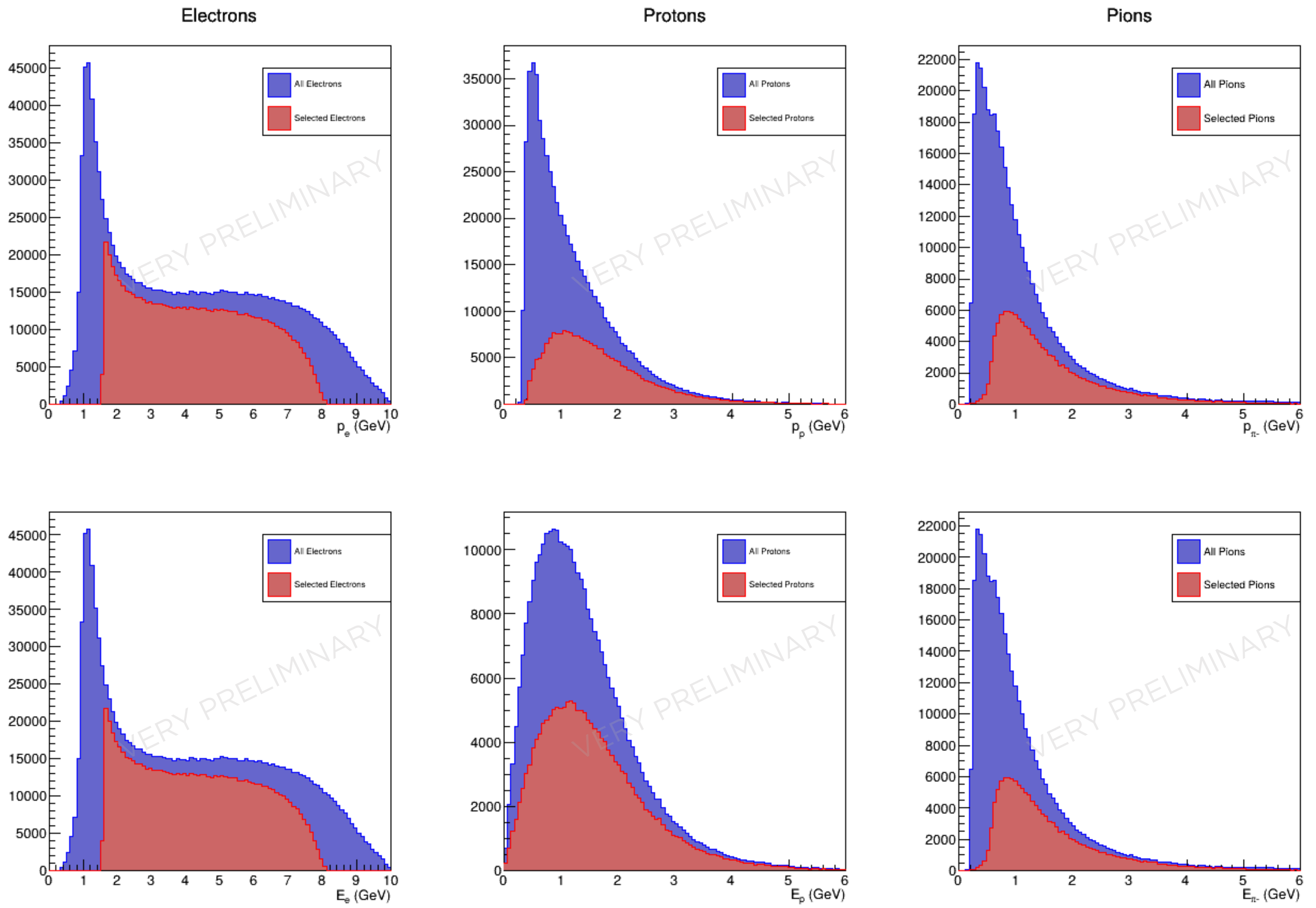


Refining Particle Identification

Refining Particle Identification

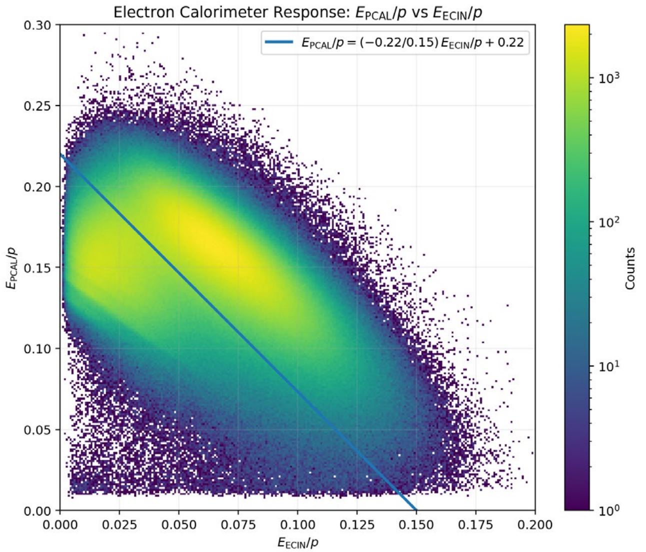
- Particle ID:
  - Electron: +11
  - (+/-) pions: (+/-) 211
  - Proton: +2212
- Detectors cuts:
  - Electron should be in the forward region
  - Pions and protons are either in the forward or central region
- Reconstruction quality cut:
  - 5 σ cuts on `chi2pid`

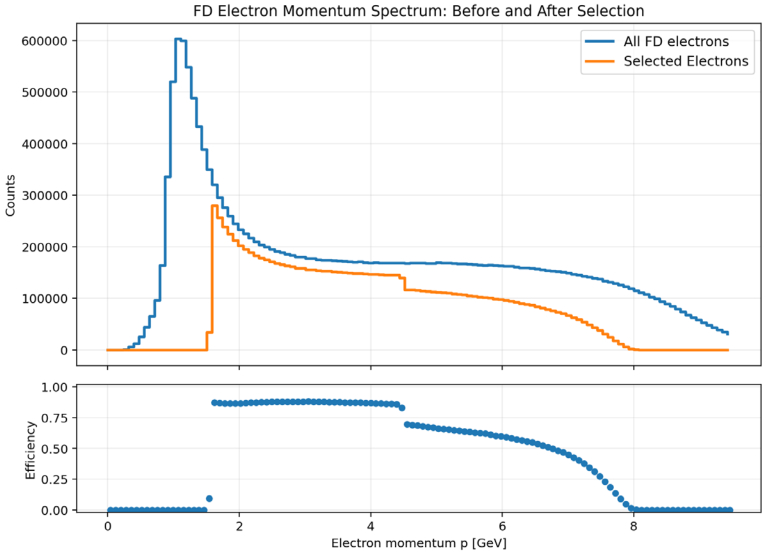


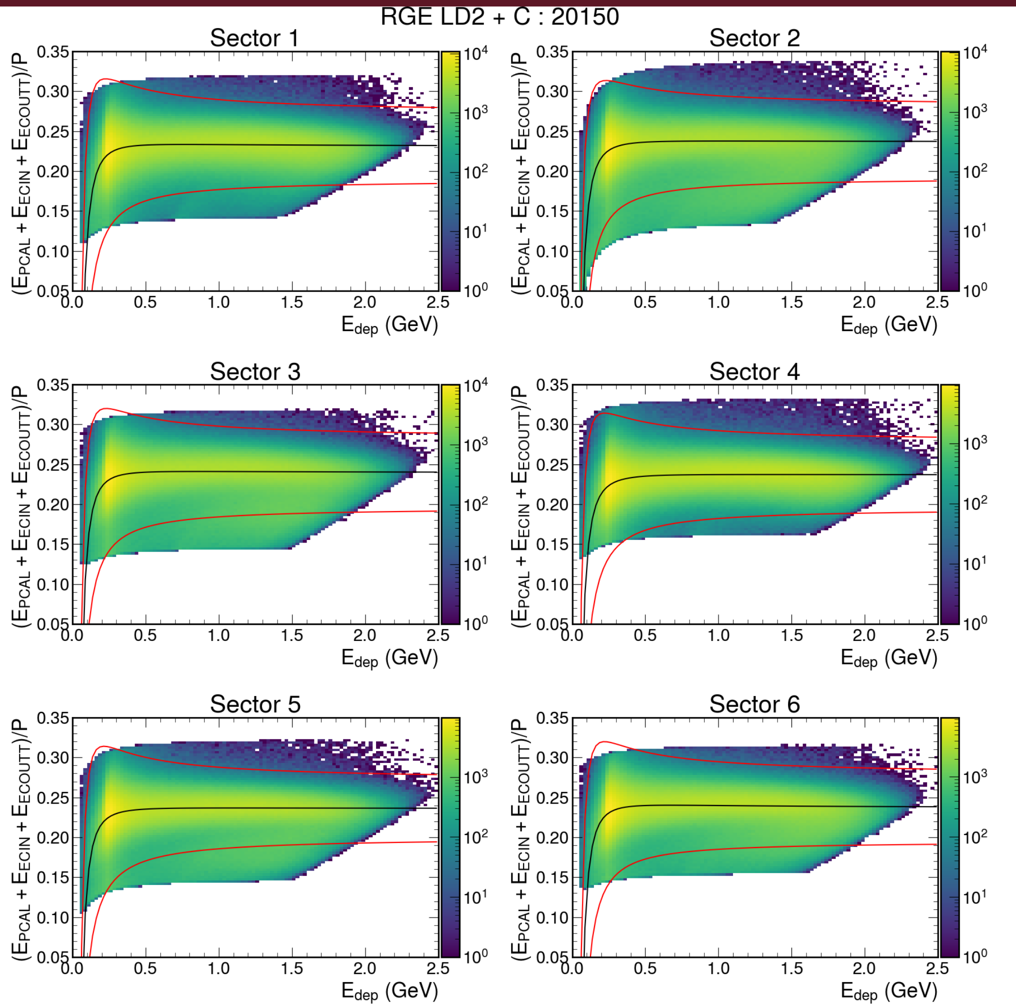
Refining Particle Identification: Electron

- **Sampling fraction vs Energy deposition** was used to get the initial refinement
- Additional **partial sampling fraction cut** was used to remove pion contamination:
  - For electrons with $p > 4.5\ GeV$ (electrons with $p < 4.5\ GeV$ are vetoed by the Cherenkov)
  - Electrons were selected if they were above the line defined by

$$E_{PCAL}/p = \left(-\frac{0.22}{0.15}\right) * E_{PCAL}/p + 0.22$$



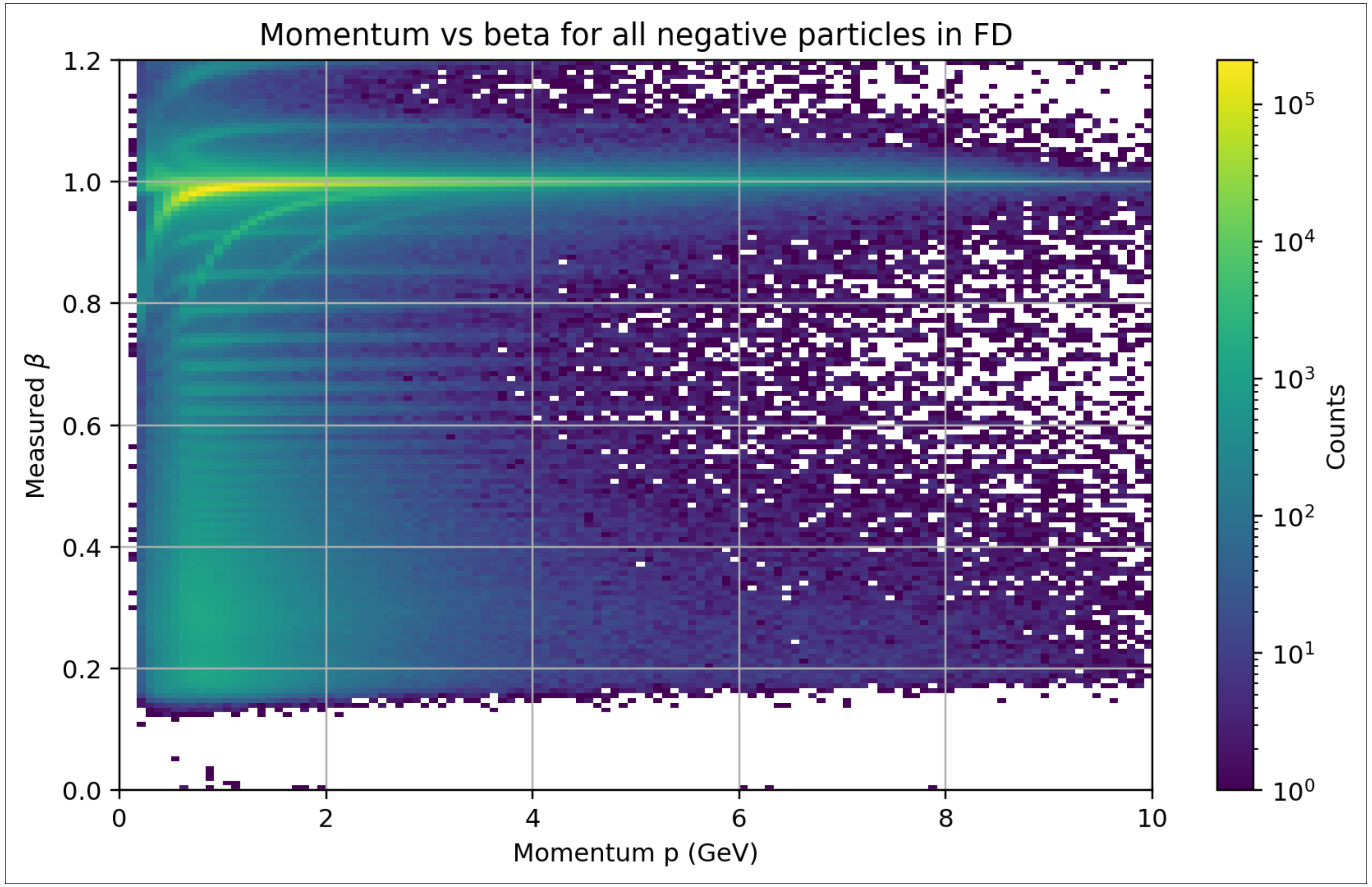




Refer to Ryan's talk for more details

Event Builder Hadron PID

- Charged particles with a TOF hit that are not identified as $e^{\pm}$ and are not the start-time particle are assigned hadron PID.
- Possible hypotheses include d, p, K, π (both charge states for p/K/π).
- PID is determined by minimizing the difference between vertex time and event start time.
- The timing comparison is based on the expected vertex time for each particle hypothesis.



Ref: CoatJava Event Builder Documentation

Contamination Affecting π^- PID

- ΔT was calculated as follows:

$$\Delta T = (T_{FTOF} - T_{start}) - \frac{l_{path}}{c \cdot \beta_{exp}}$$

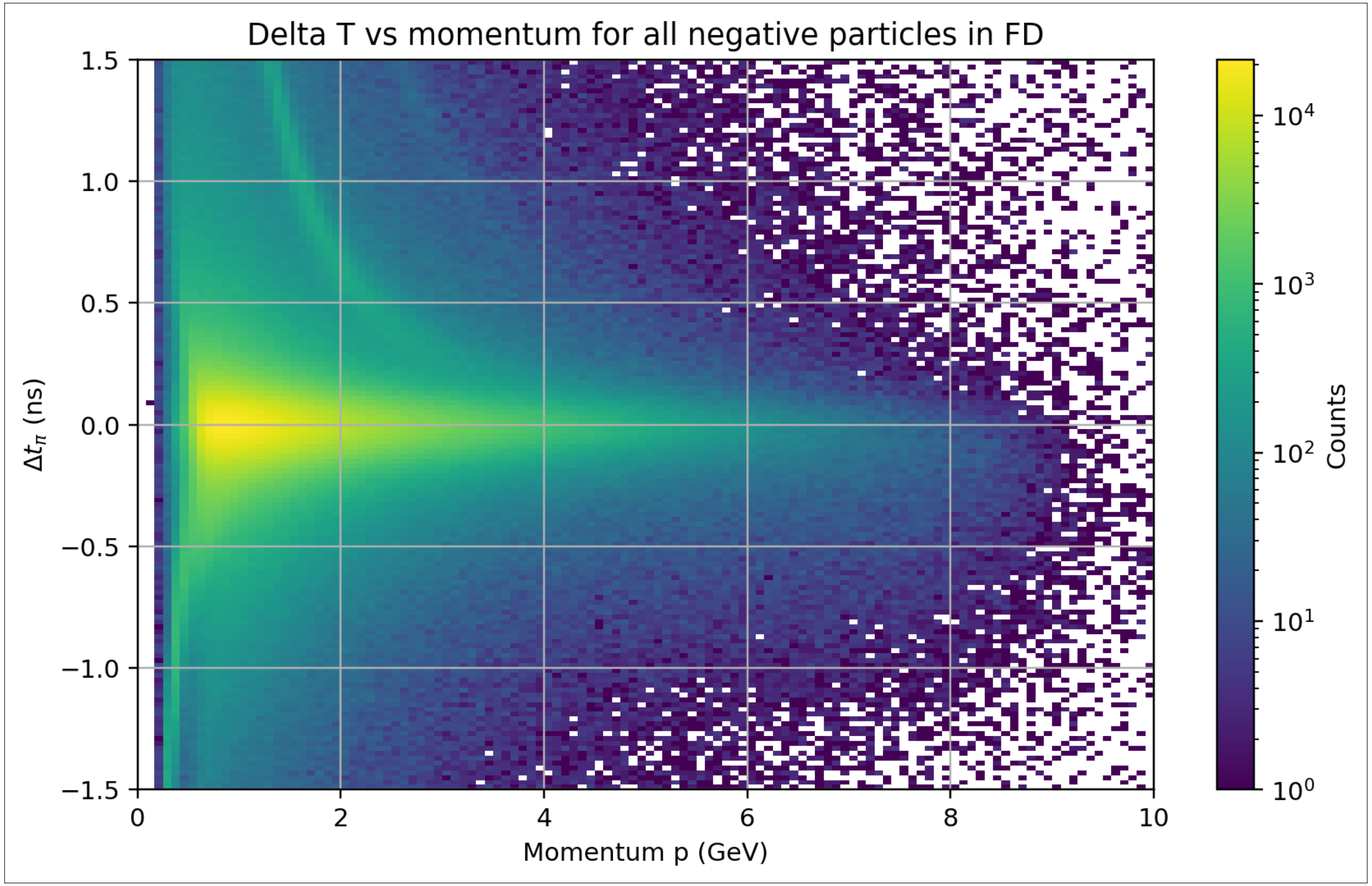
where $\beta_{exp} = \frac{p}{\sqrt{p^2+m_\pi^2}}$

- FTOF priority order was selected according to CLAS12 convention:

`FTOF1B > FTOF1A > FTOF2`

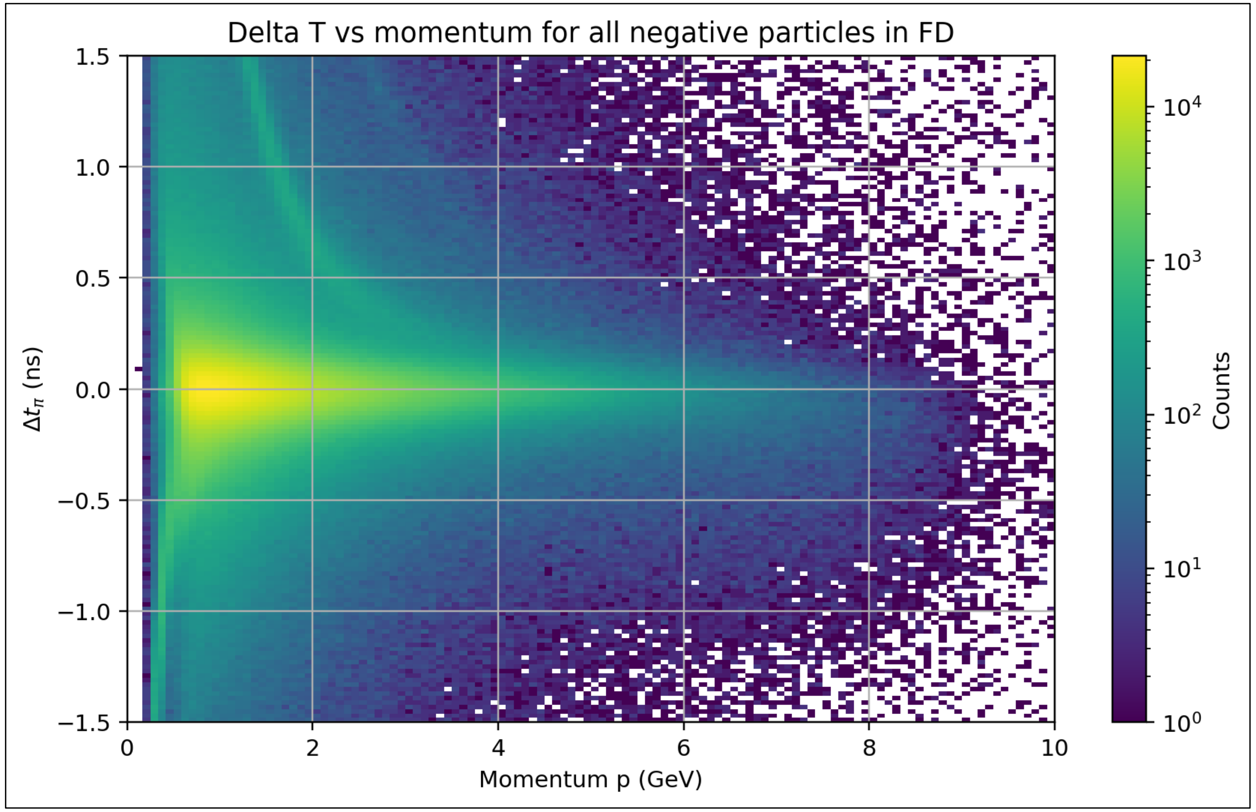
- Alternatively, we could also look at $\Delta\beta$ defined as:

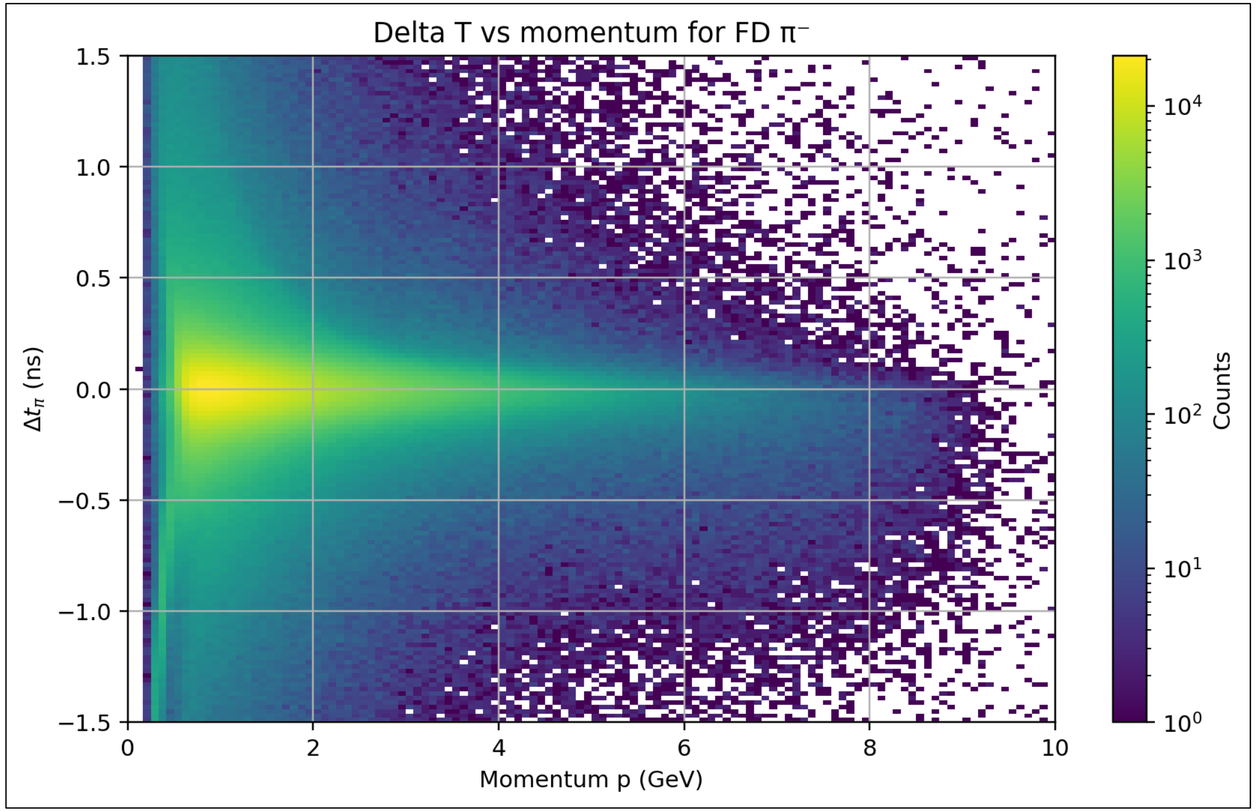
$$\Delta\beta_\pi = \beta_{meas} - \beta_{exp}^{(\pi)}$$



Contamination cleared by Event builder PID

- Most of the contamination is cleared by the event builder as shown by the ΔT and Δβ plots





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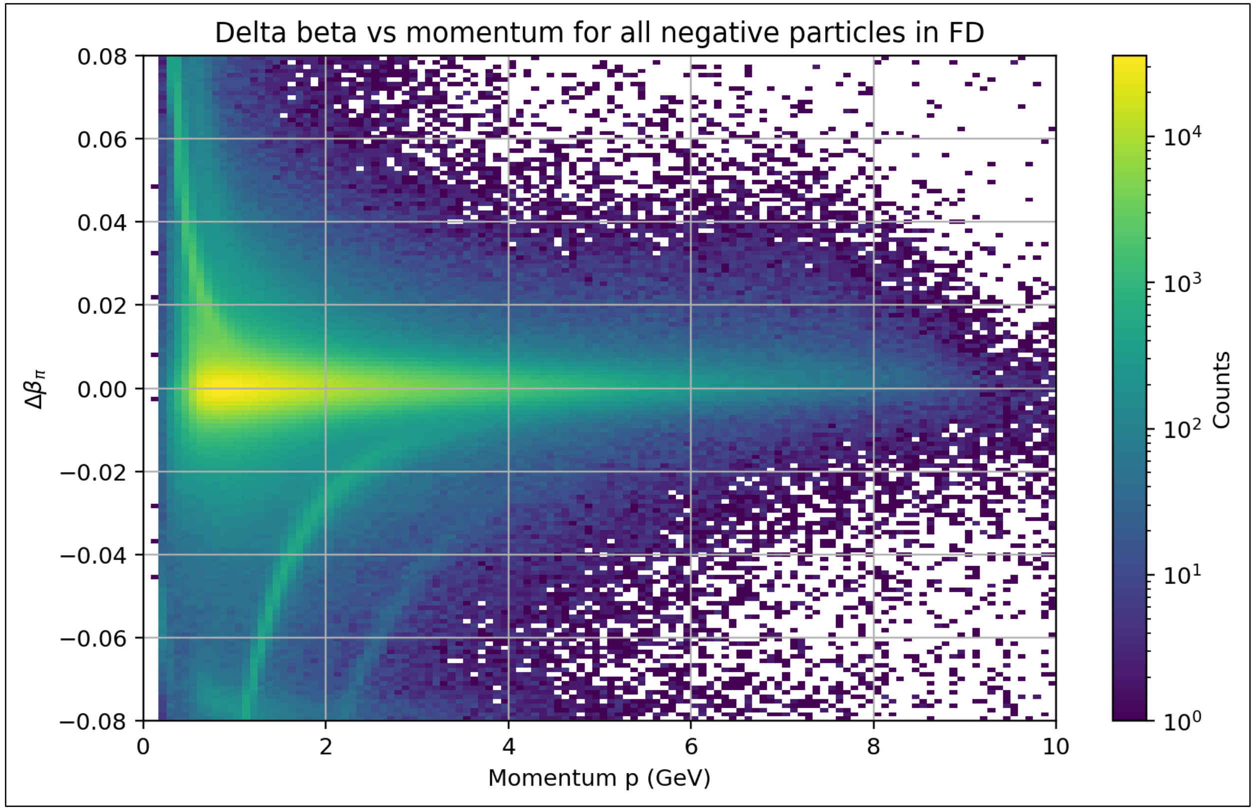
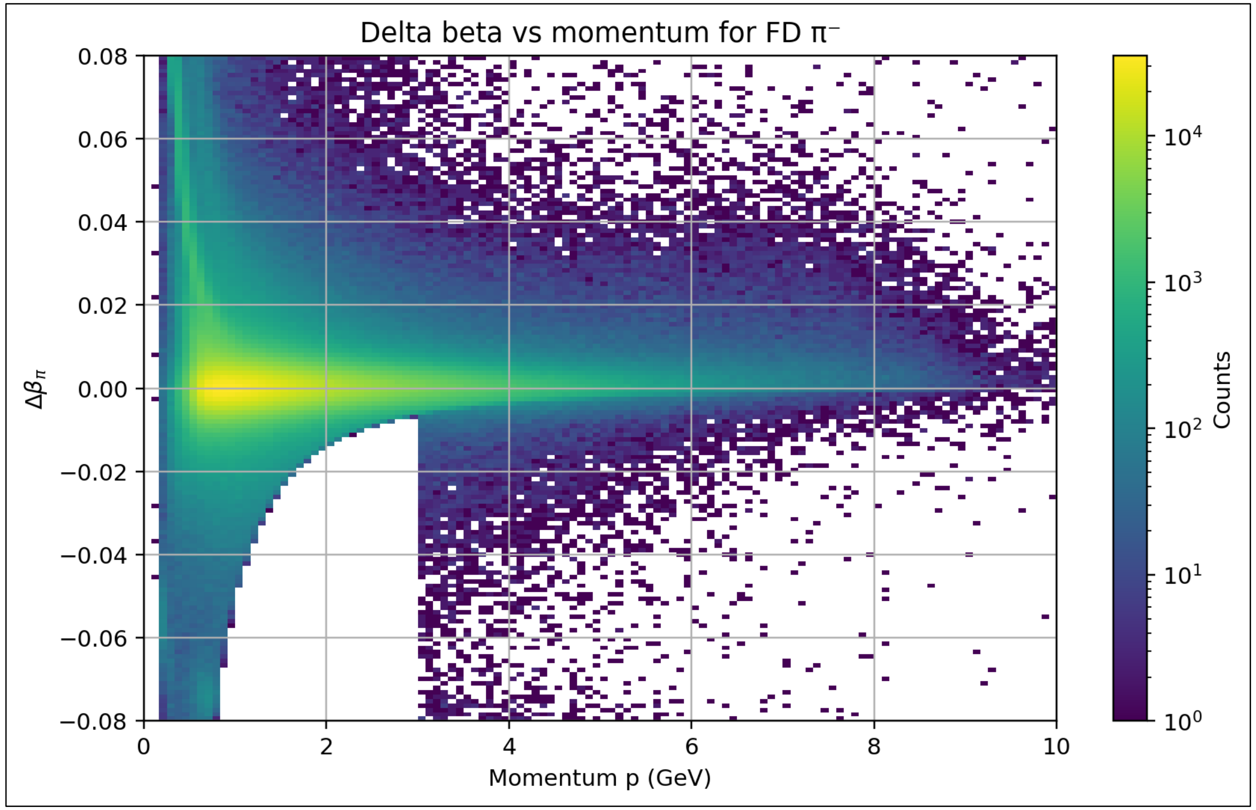
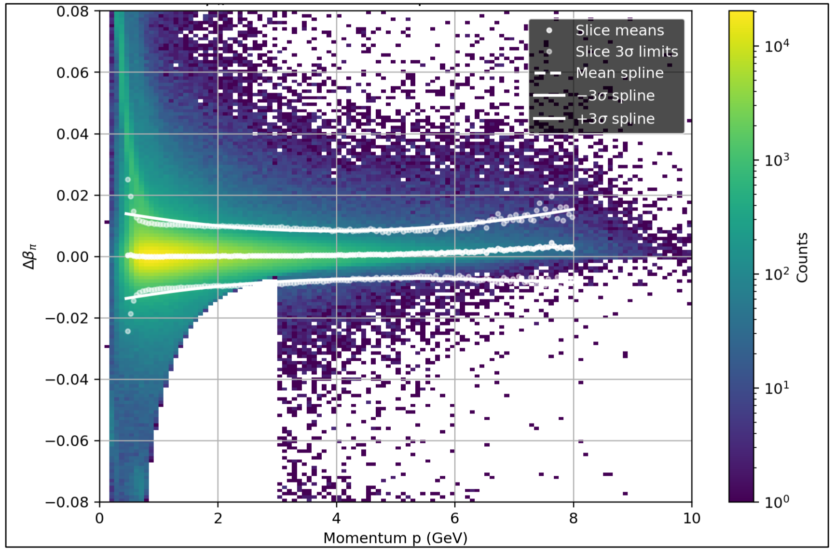


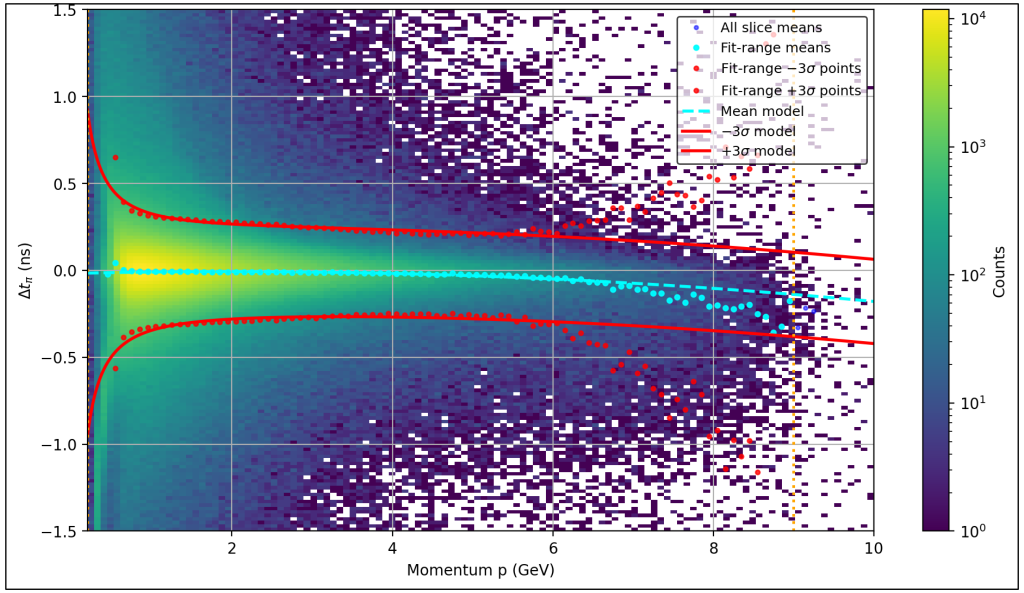


Cut Extraction Strategy

Cut Extraction Procedure

- The ΔT (or Δβ) vs momentum distribution was divided into 50 MeV momentum slices from 0–10 GeV.
- In each slice, a Gaussian fit was performed to extract the π^- peak.
- The resulting peak parameters and their errors were used to determine momentum-dependent PID cuts.
- Several functions were trialed to get a meaningful cut
  - Spline fit on ΔT and Δβ
  - **Resolution function with polynomial on ΔT**





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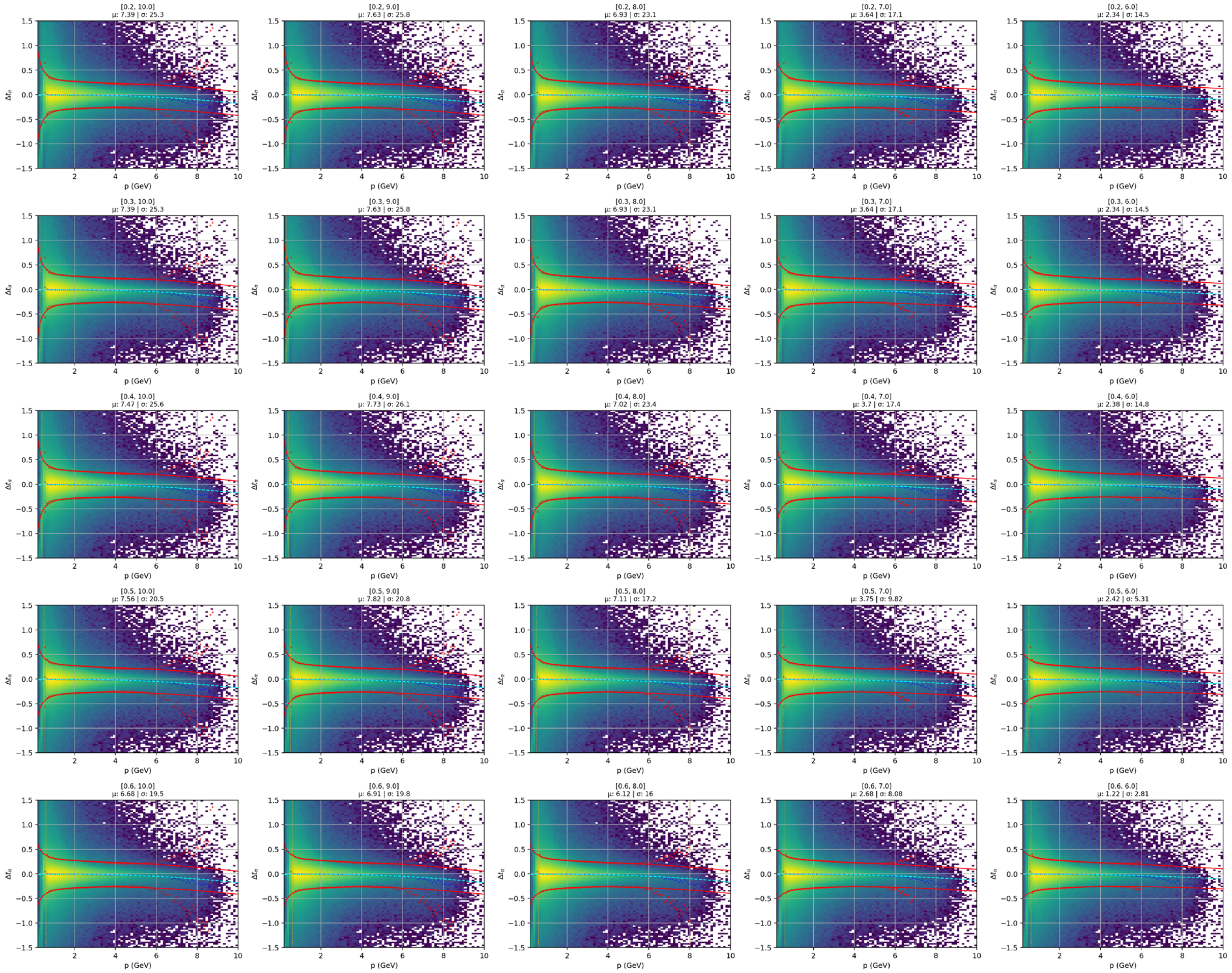


Momentum Range Selection

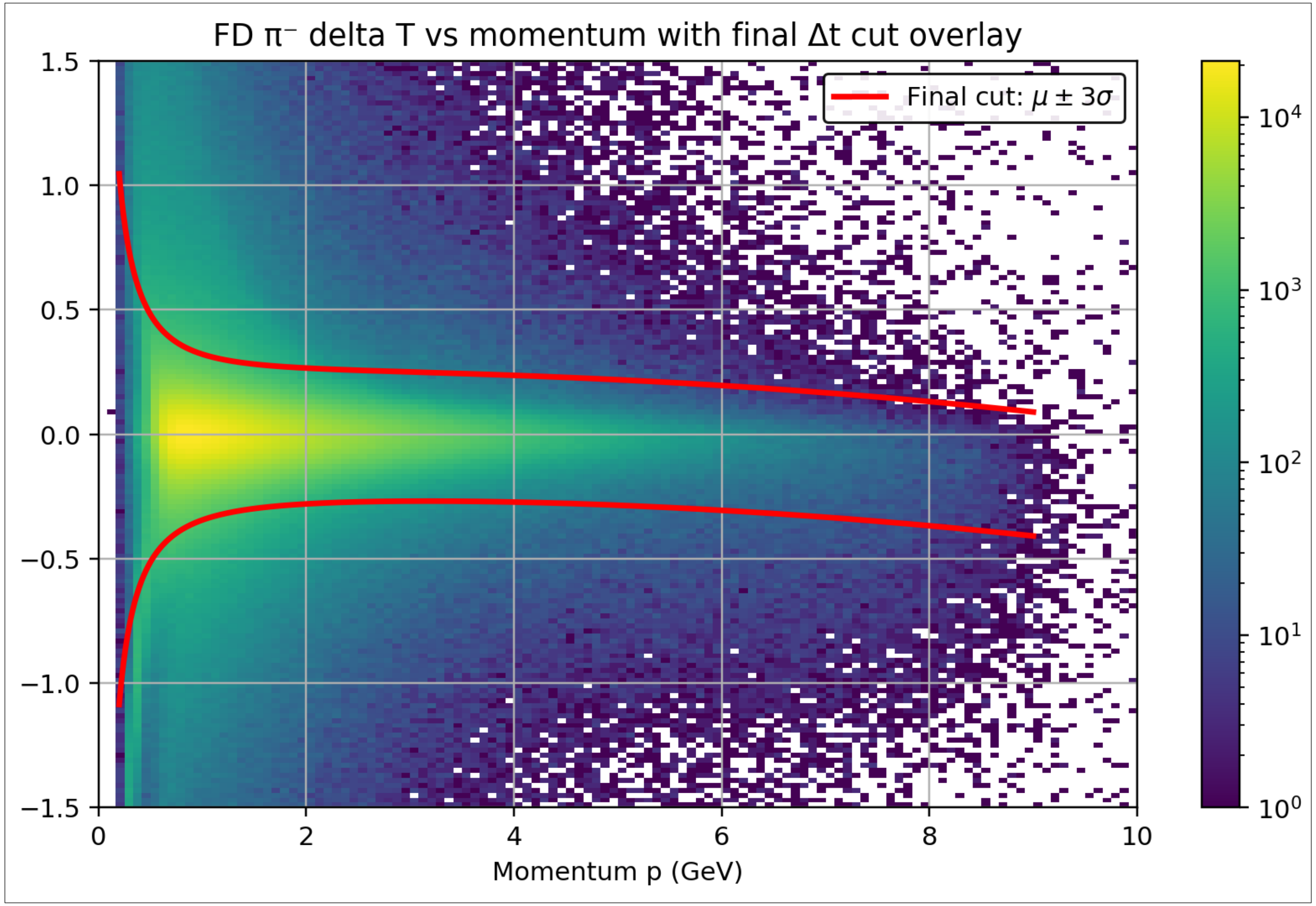
- **p < 0.2 GeV:** excluded due to noisy data
- **p > 9 GeV:** excluded due to lack of statistics

Final Cuts for π^- PID Refinement

- Initial PID window defined as $\mu_{\pi-} \pm 3\sigma_{\pi-}$
- Since the spline function didn't fit properly, a resolution function was fitted to the $3\sigma_{\pi-}$ points and a 2^{nd} order polynomial was fitted to the $\mu_{\pi-}$ points
- The resolution function is given by:

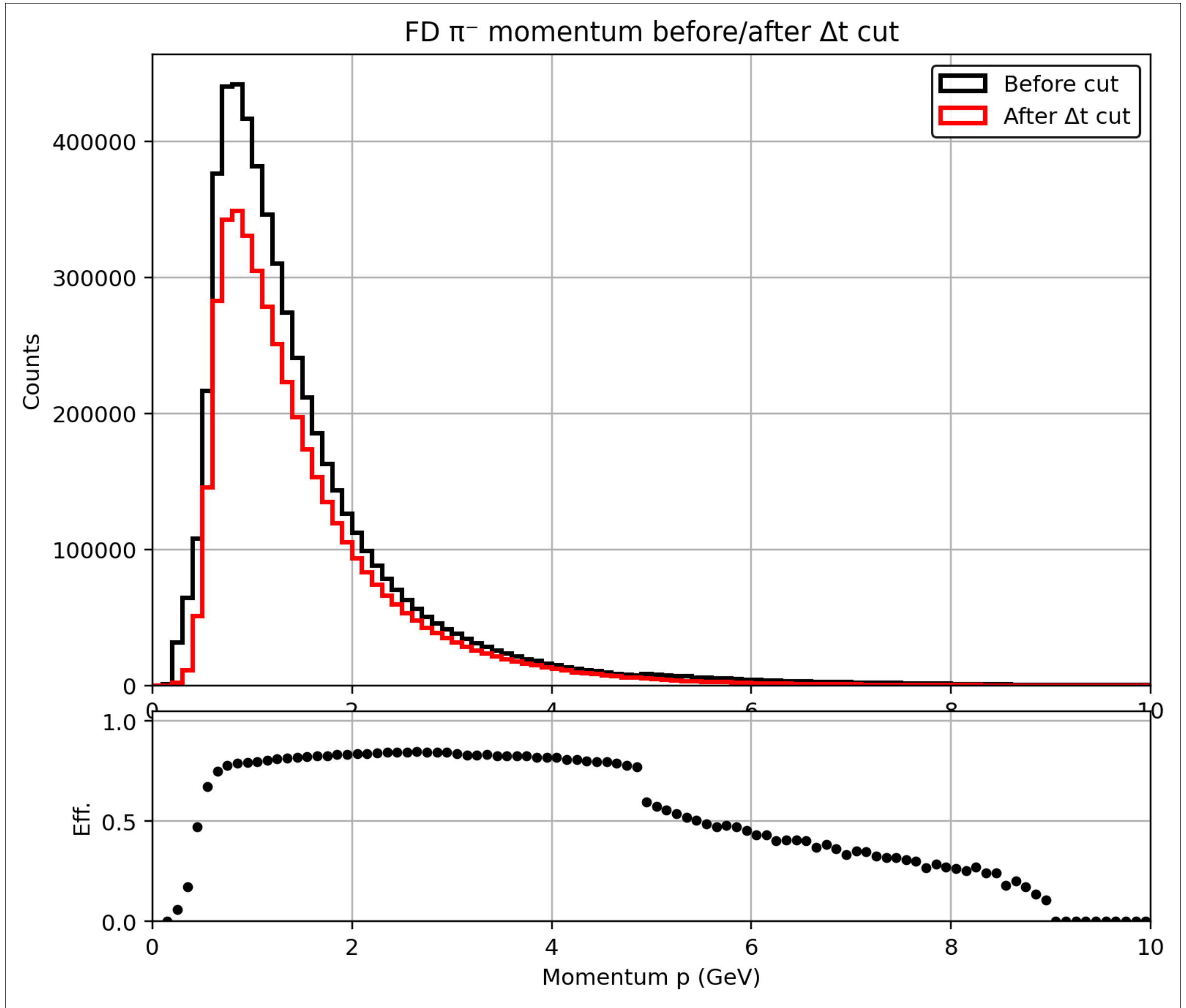
$$\sigma(p) = \sqrt{a^2 + \left(\frac{b}{p^\alpha}\right)^2}$$

- This function is more stable across the higher momentum region despite the low statistics



Impact of π^- PID Refinement

- These adaptive cuts were implemented in the analysis framework and validated by comparing π^- momentum distributions before and after the refinement



Contamination Affecting Proton PID

- ΔT was calculated as follows:

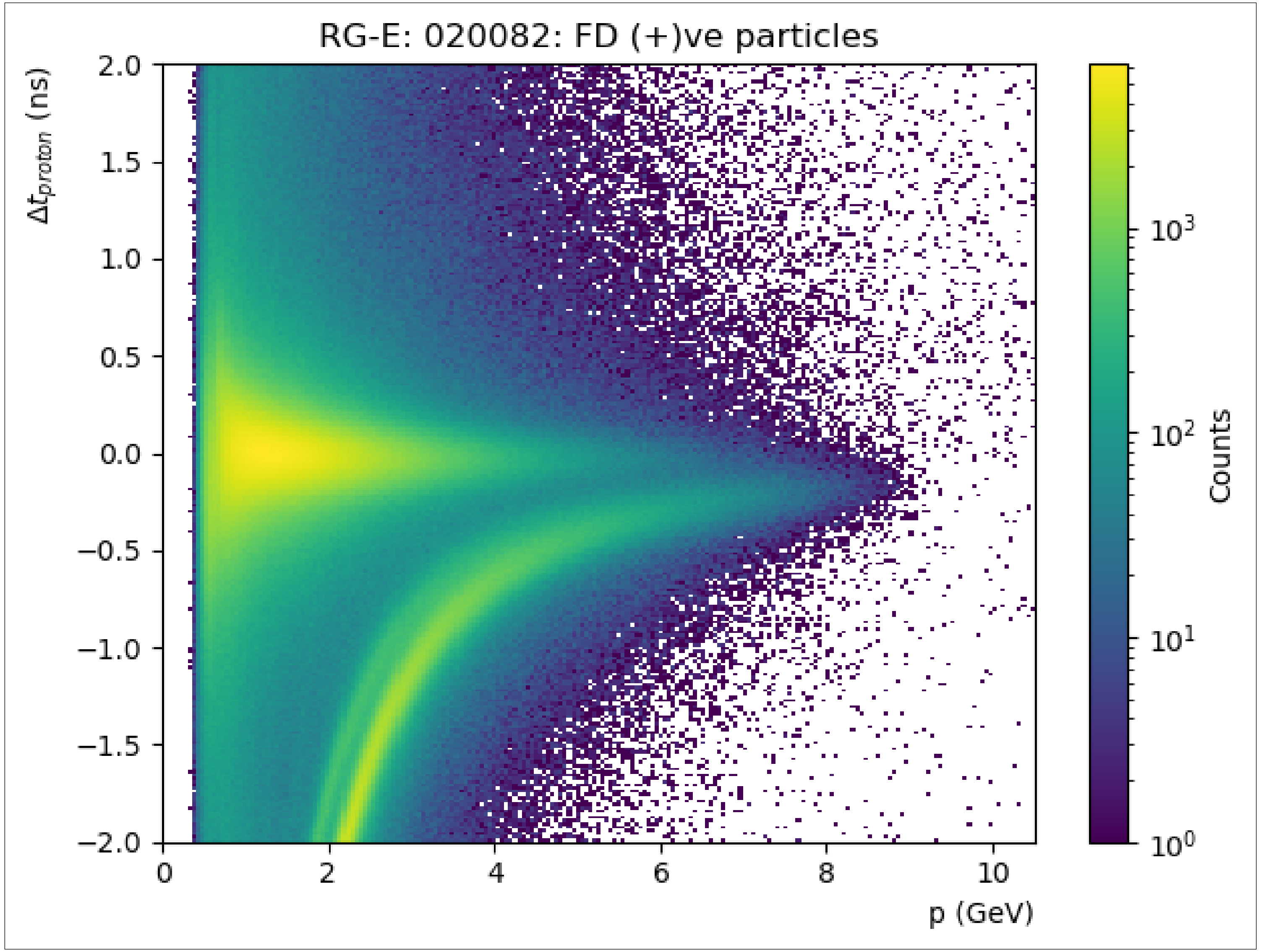
$$\Delta T = (t_{FTOF} - t_{start}) - \frac{l_{path}}{c \cdot \beta_{exp}}$$

where $\beta_{exp} = \frac{p}{\sqrt{p^2+m_p^2}}$

- FTOF priority order was selected according to CLAS12 convention:

`FTOF1B > FTOF1A > FTOF2`

- Higher momentum regions show increasing π and K contamination



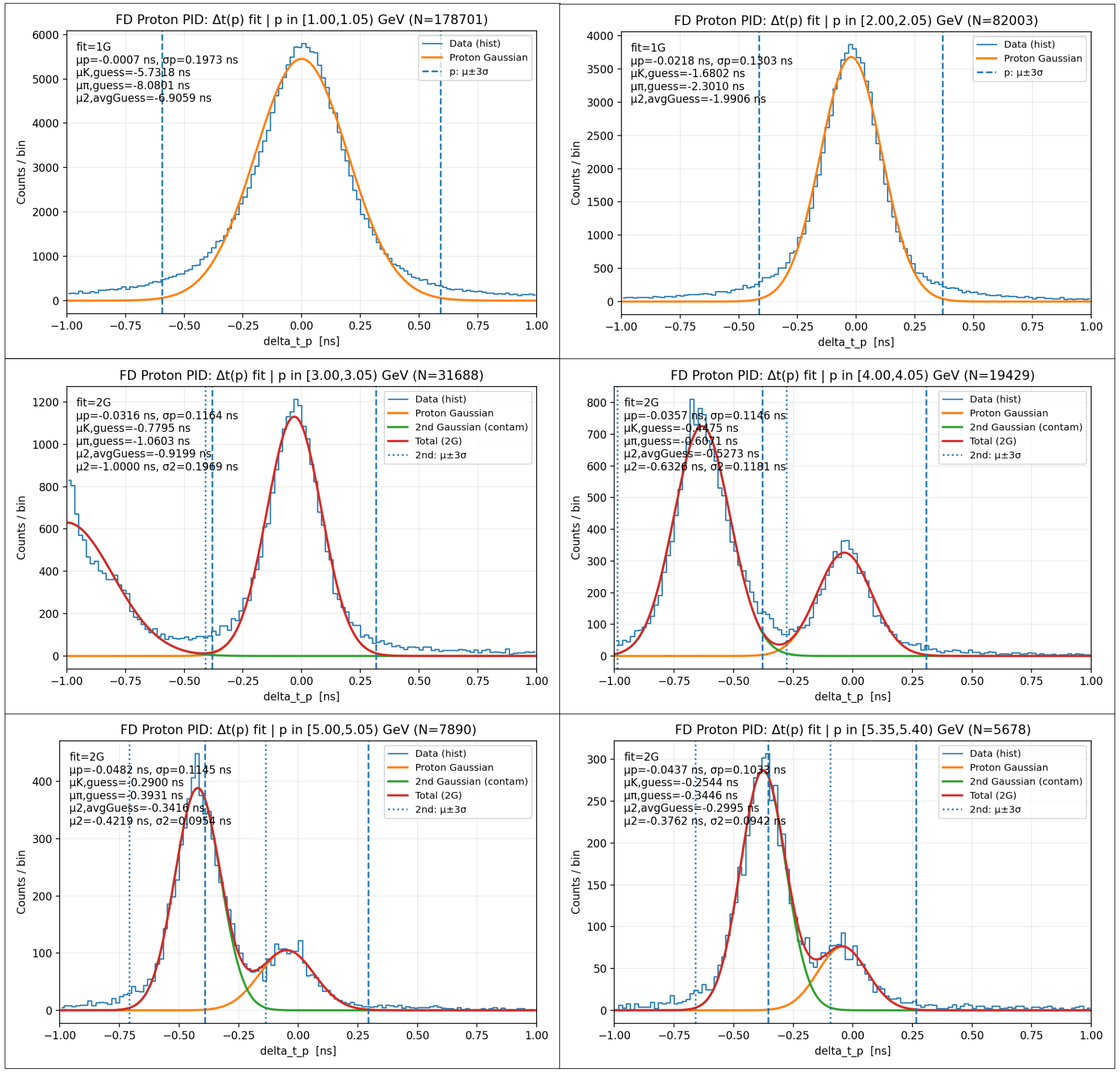
Cut Extraction Strategy

Cut Extraction Procedure

- ❖ The ΔT vs momentum distribution was divided into 50 MeV momentum slices from 0–6 GeV.
- ❖ In each slice, Gaussian fits were performed to extract the proton peak and the contamination peak.
- ❖ The resulting peak parameters were used to determine momentum-dependent PID cuts.

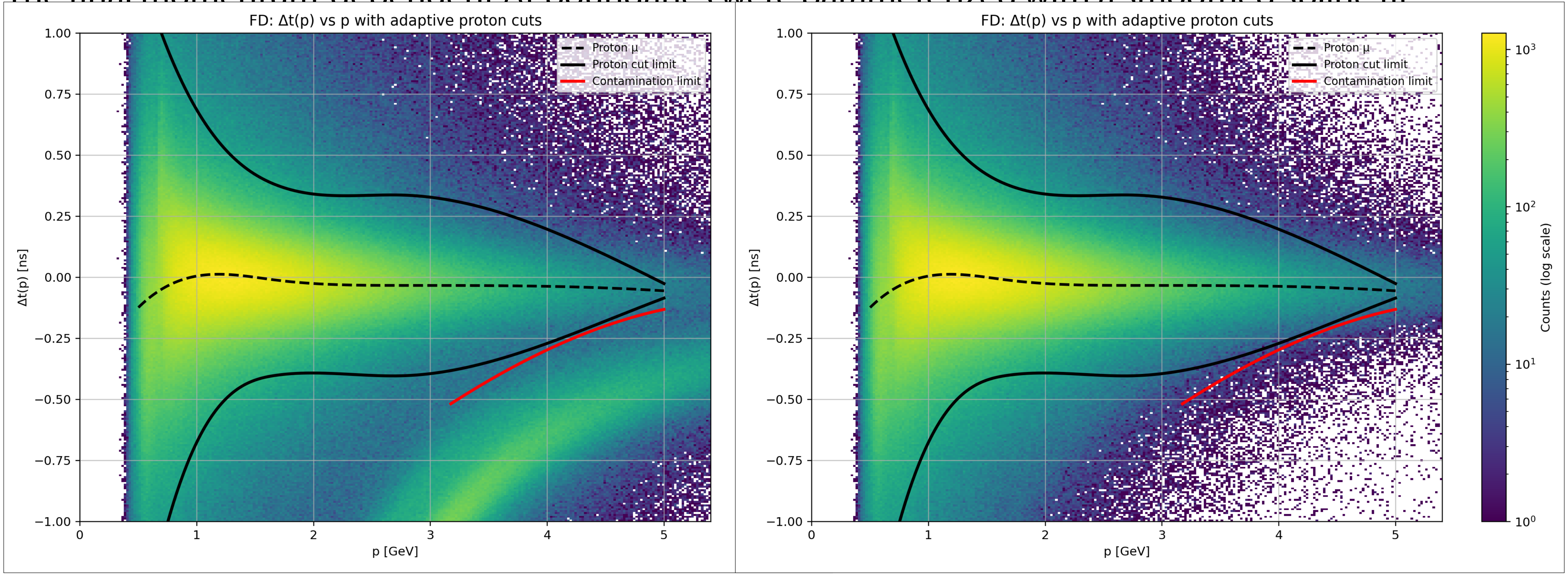
Momentum range selection

- ❖ **p < 0.5 GeV:** excluded due to noisy data
- ❖ **p > 5 GeV:** excluded due to significant pion/kaon contamination



Final Cuts for Proton PID Refinement

- Initial PID window defined as $\mu_p \pm 3\sigma_p$
- Once the K/π band overlaps the proton region, the lower bound was progressively tightened to suppress contamination
- The final momentum-dependent Δt boundaries were parameterized with a smoothed spline fit



Impact of Proton PID Refinement

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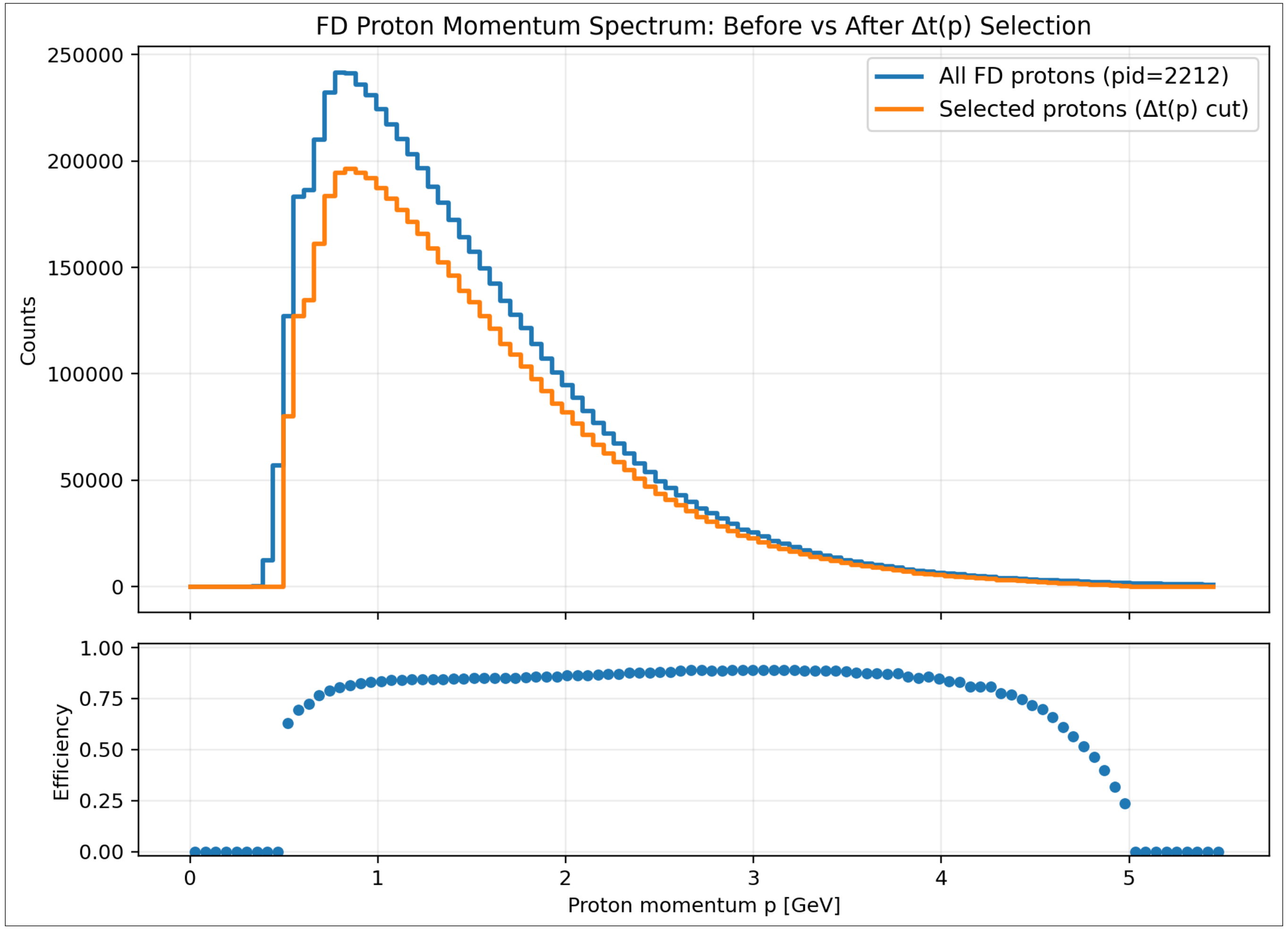
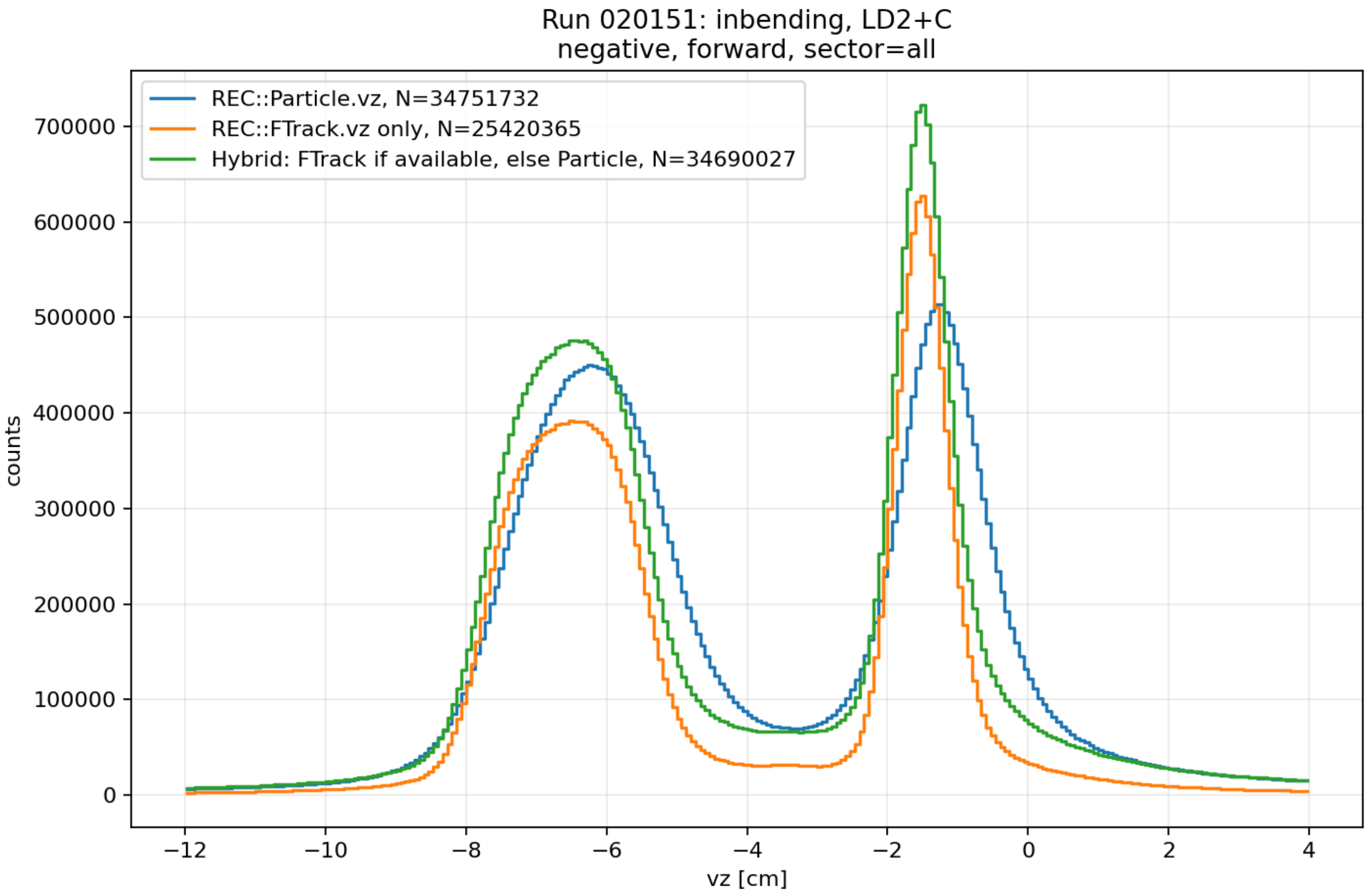


Vertex Cuts

Resolving the Reference Foil

- Information from the FMT was used to improve the vertex resolution
  - Without the FMT, the Aluminum reference foil between the liquid target and the solid target could not be resolved



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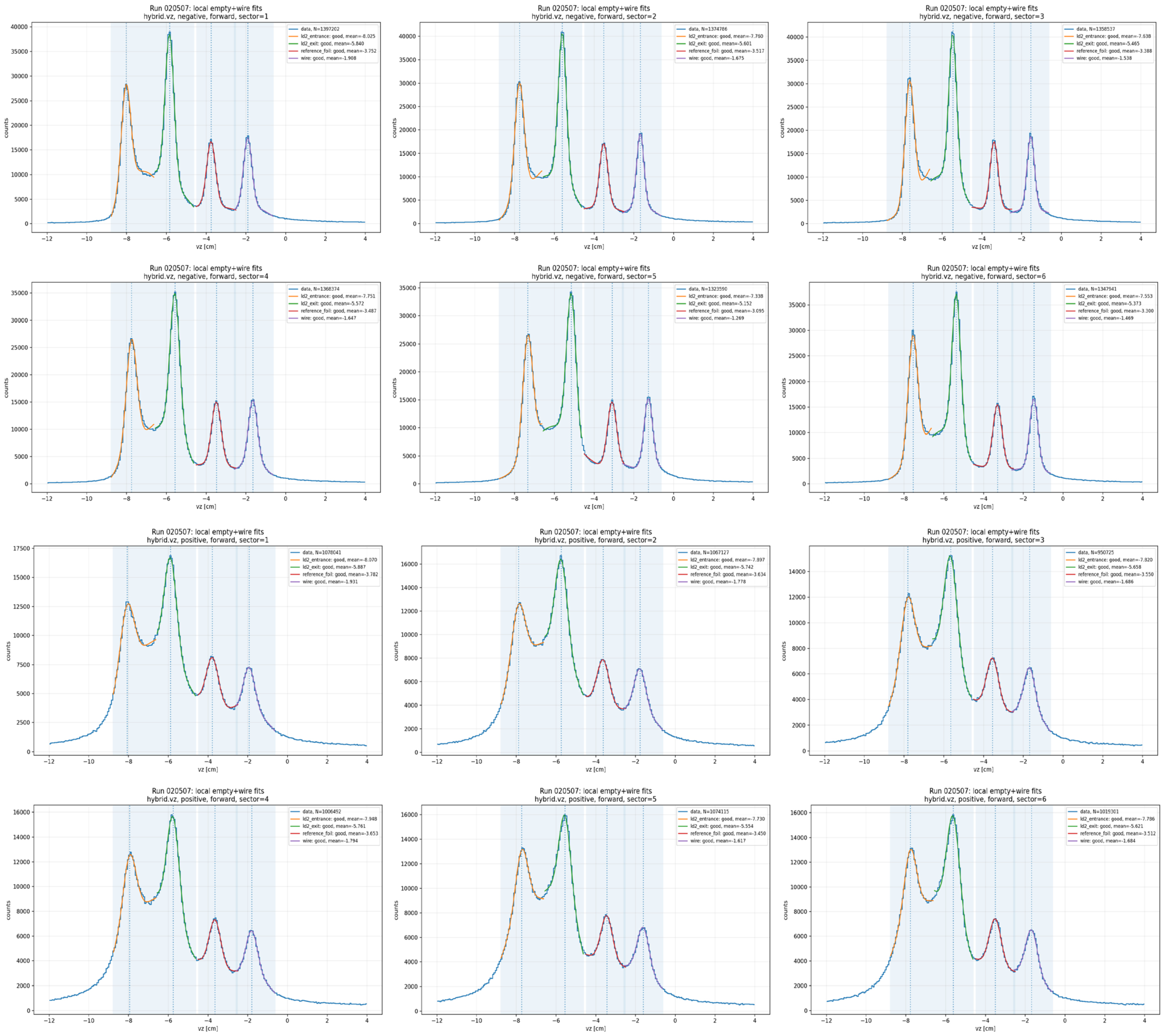
- The empty+wire target configuration was used to obtain the limits of the reference foil
- These limits were then used to set the upper limit of the LD2 target and the lower limit of the solid target



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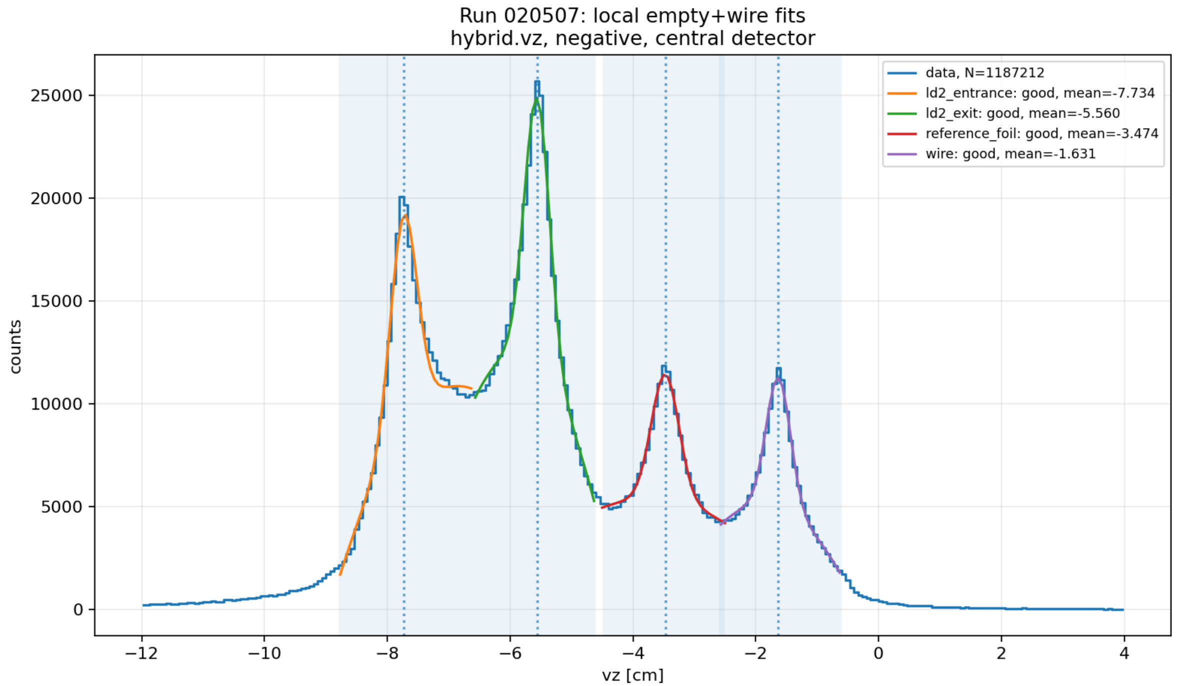
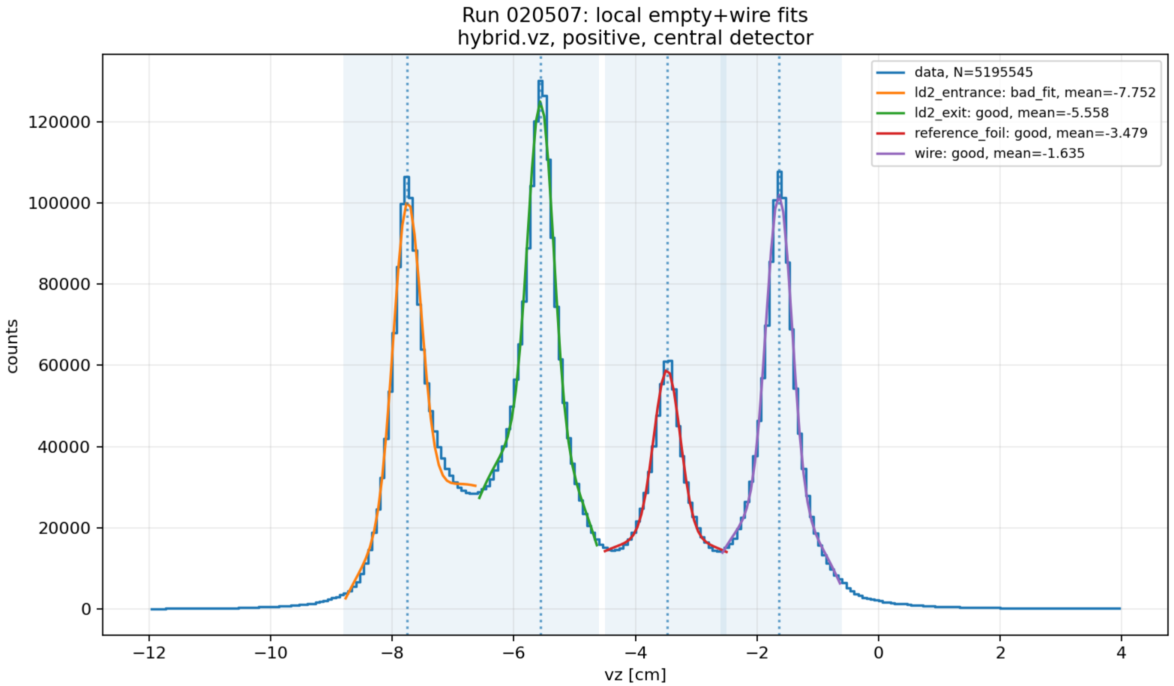
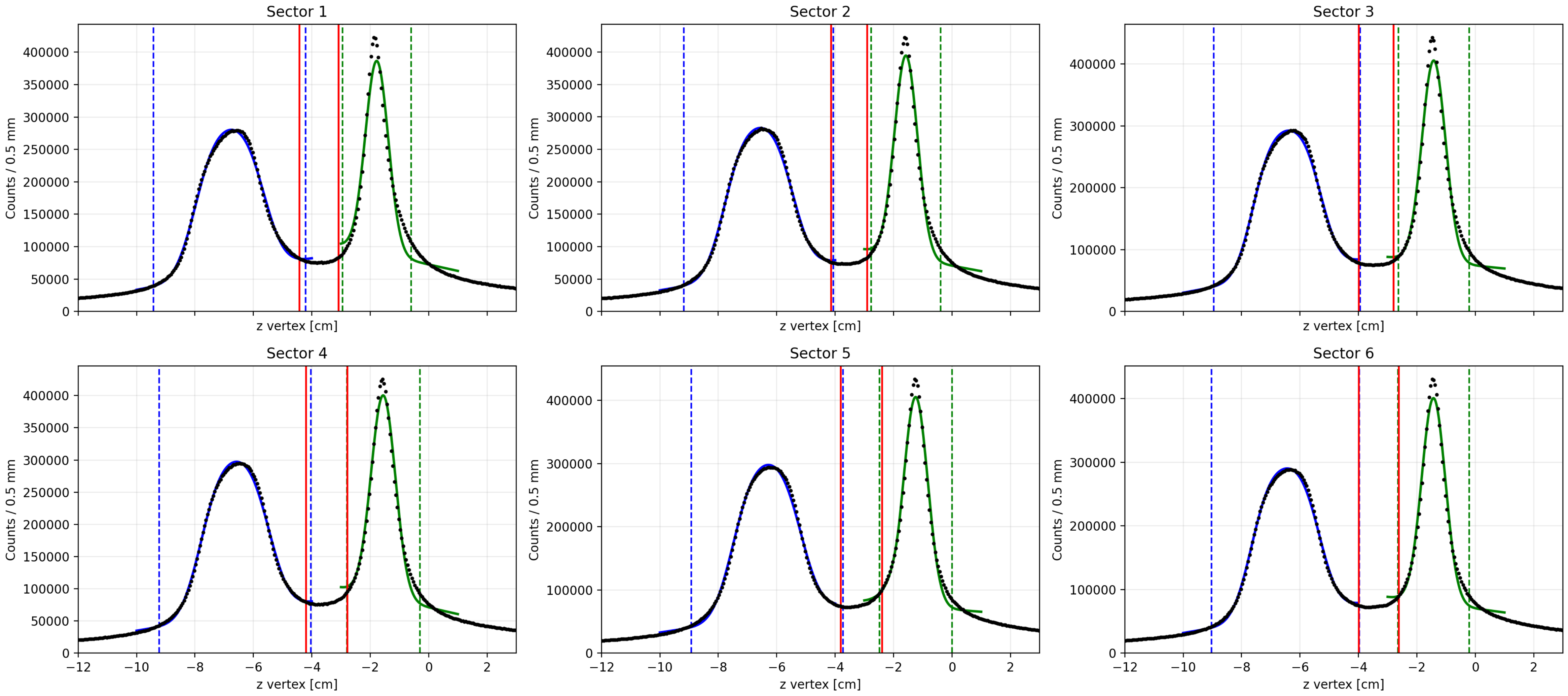




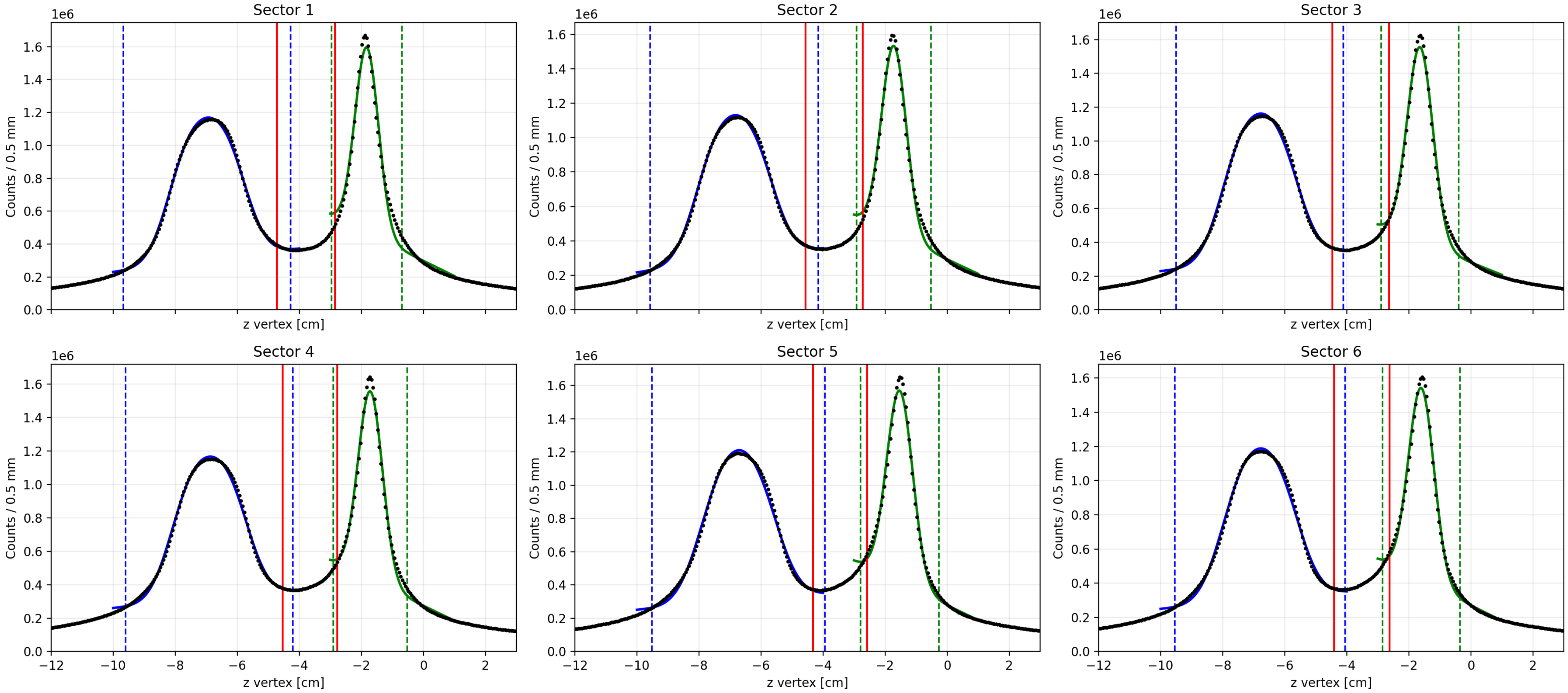
Vertex Cuts Excluding the Reference Foil

- Forward Detector Negative Particles:



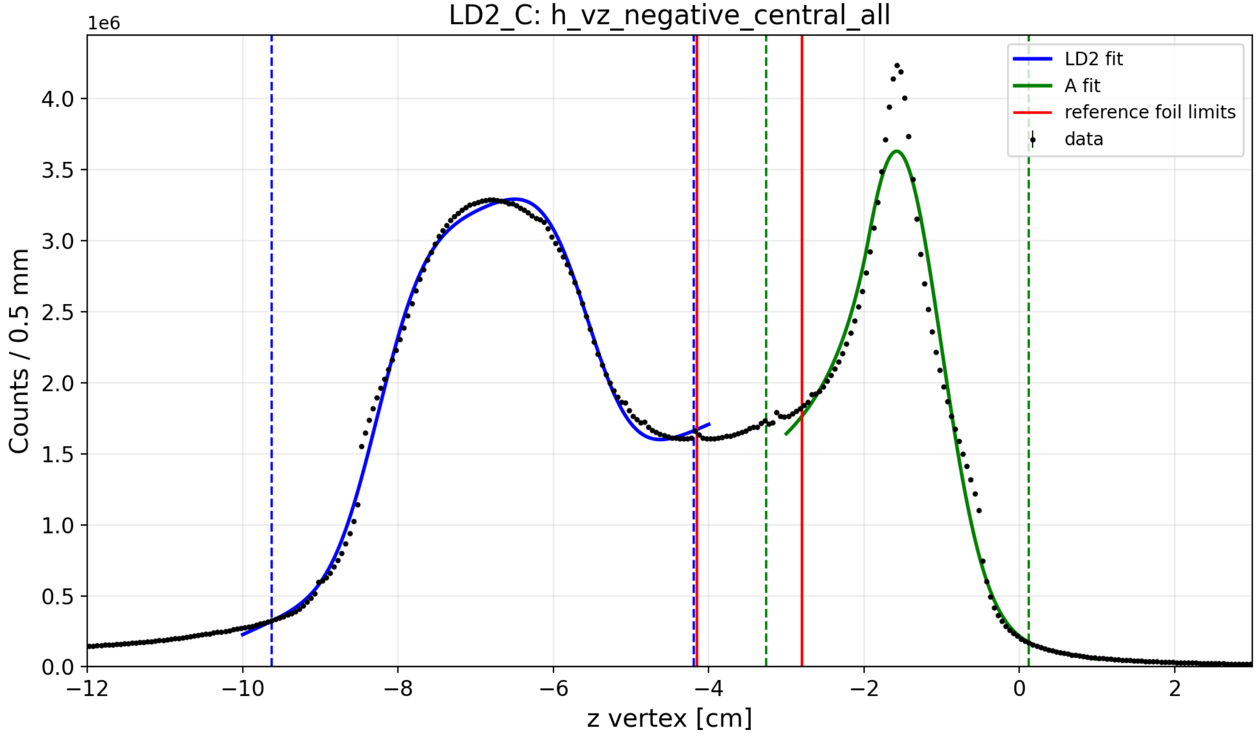
Vertex Cuts Excluding the Reference Foil

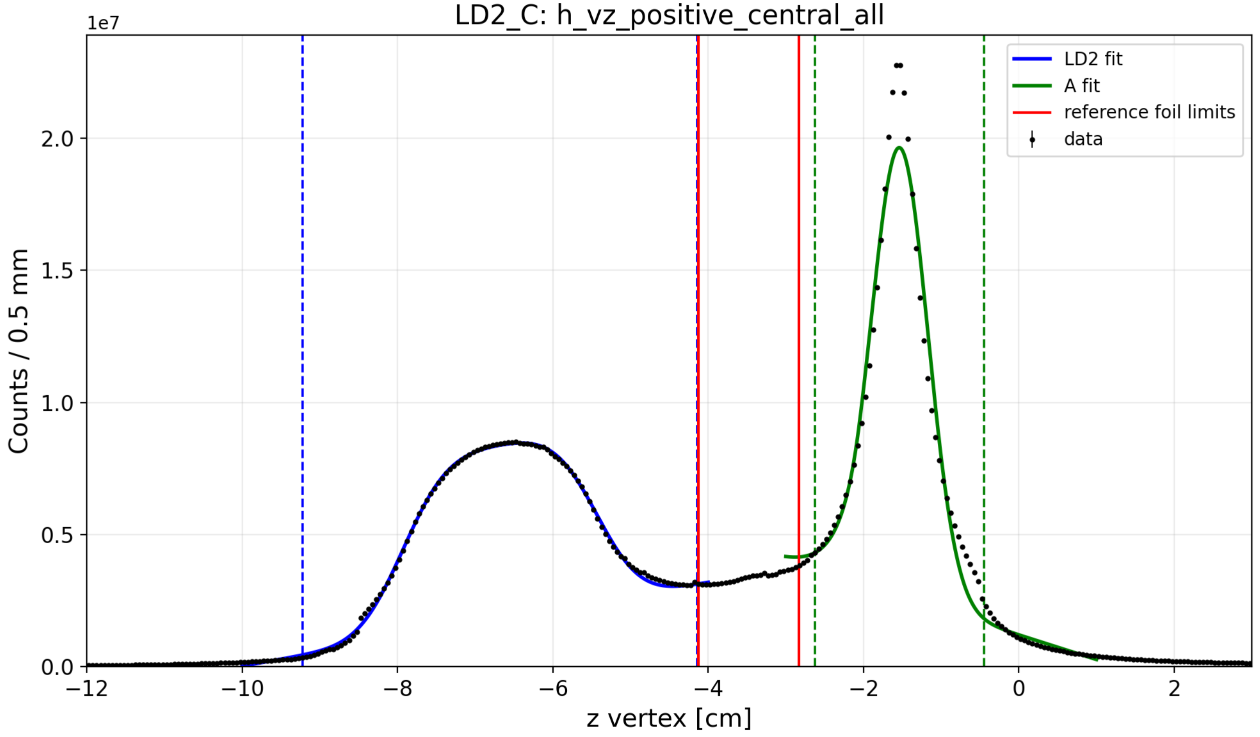
❖ Forward Detector Positive Particles:



Vertex Cuts Excluding the Reference Foil

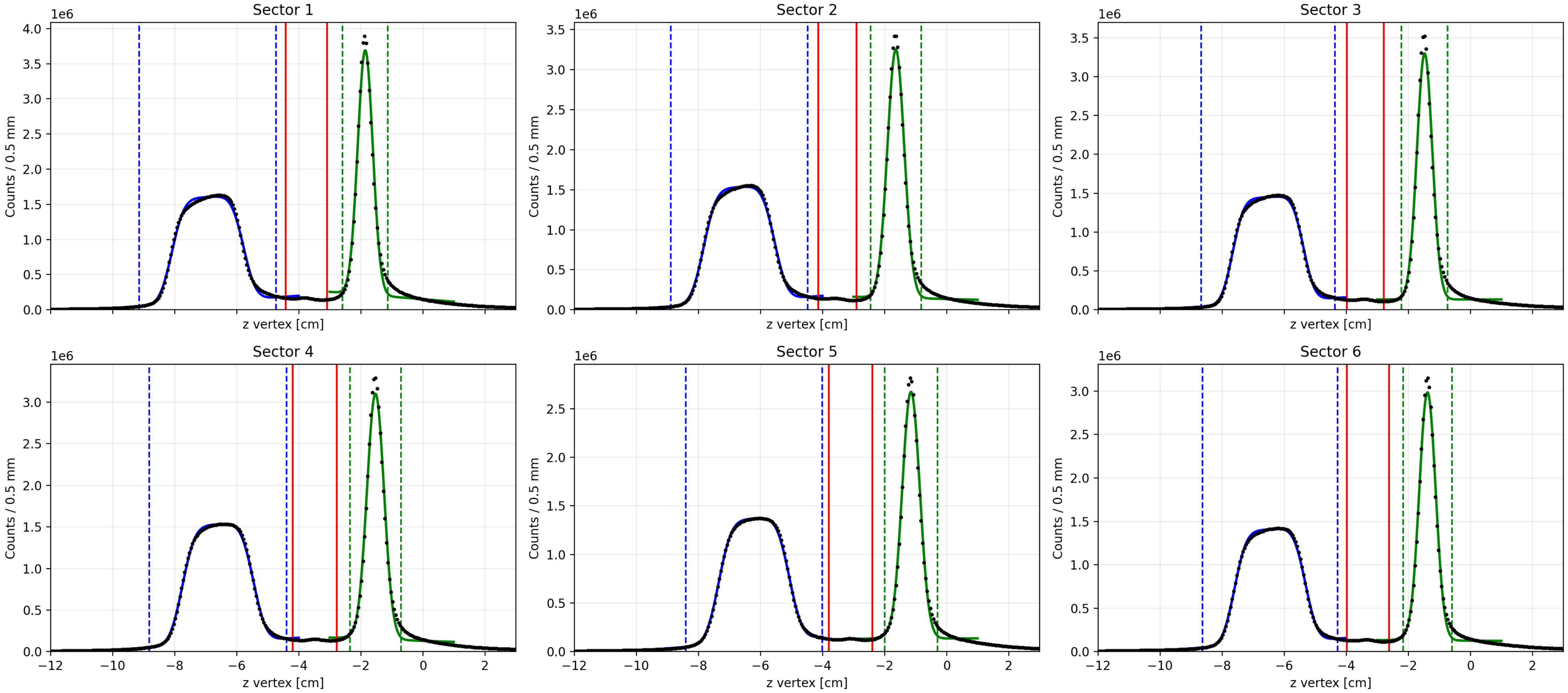
- Central Detector negative and positive particles:





Vertex Cuts Excluding the Reference Foil

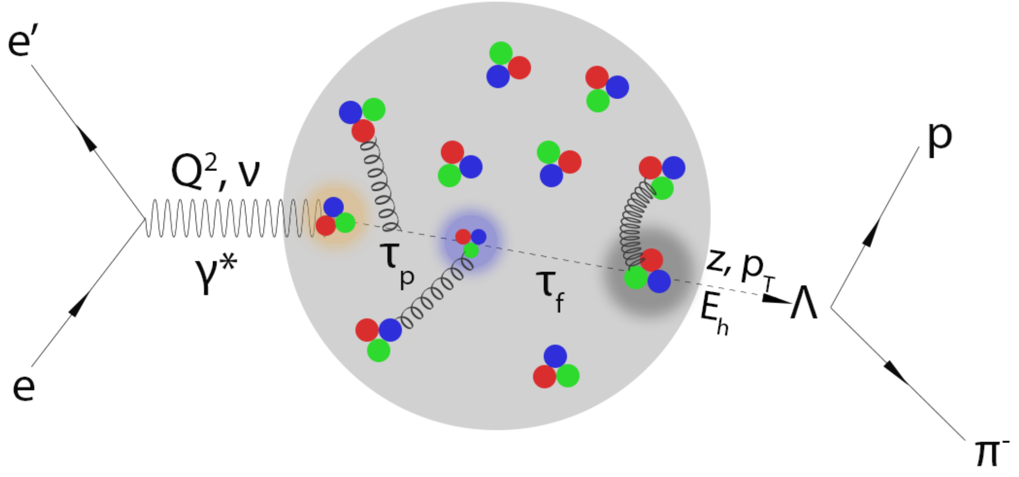
❖ For the Lambda analysis, only the electron vertex is used as a primary vertex

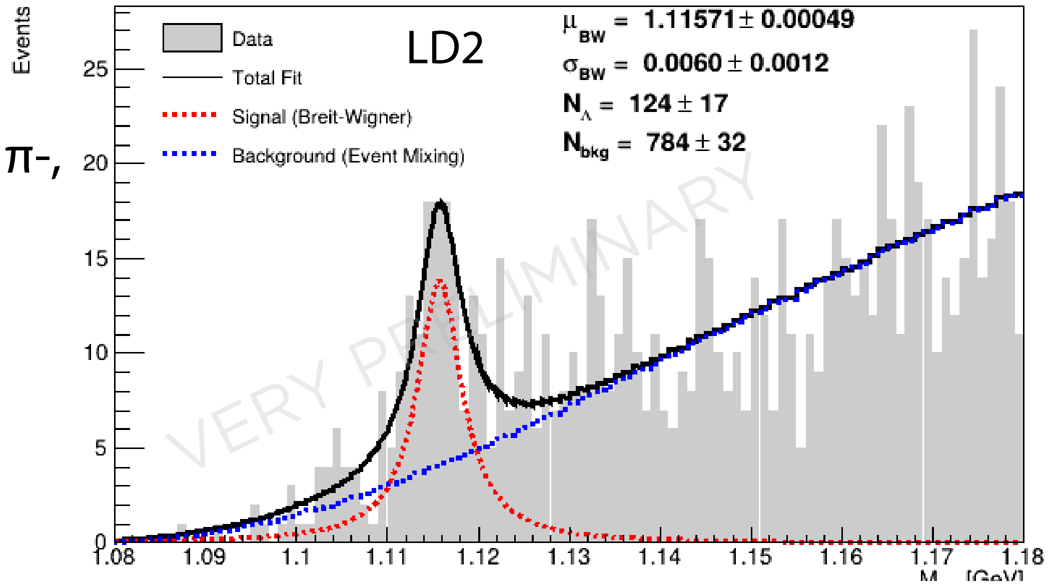


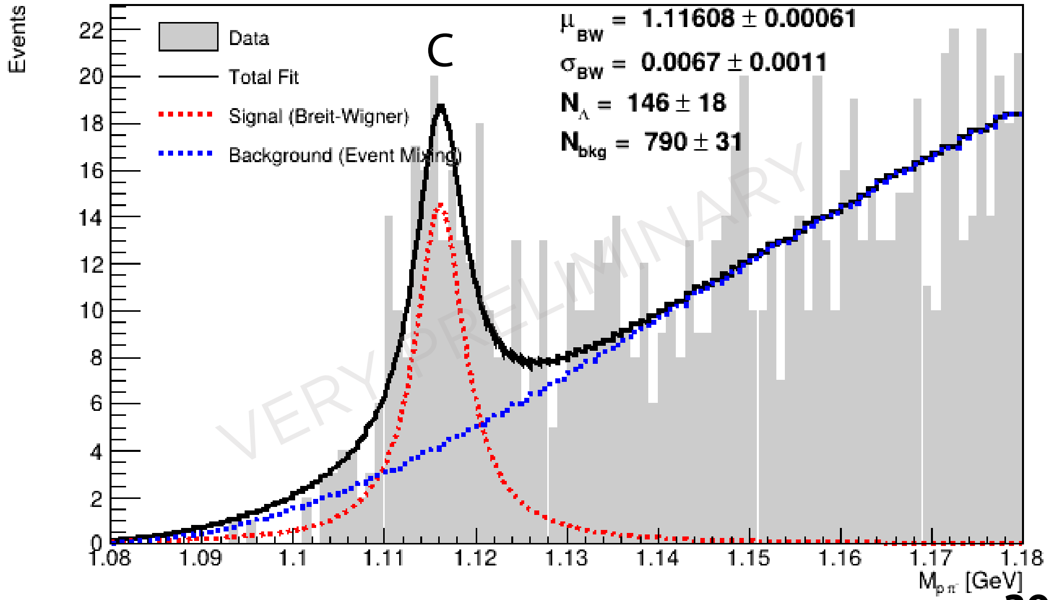
Λ Production Channel

Λ Production Channel

- Our channel of interest is Λ SIDIS production off nuclei
- Λ is identified through its decay daughter particles, proton and π-, detected in coincidence with the scattered electron
- Cuts applied on secondary vertex to refine the Λ signal
  - Distance between the electron and secondary Λ vertex
  - Opening angle between protons and π-s

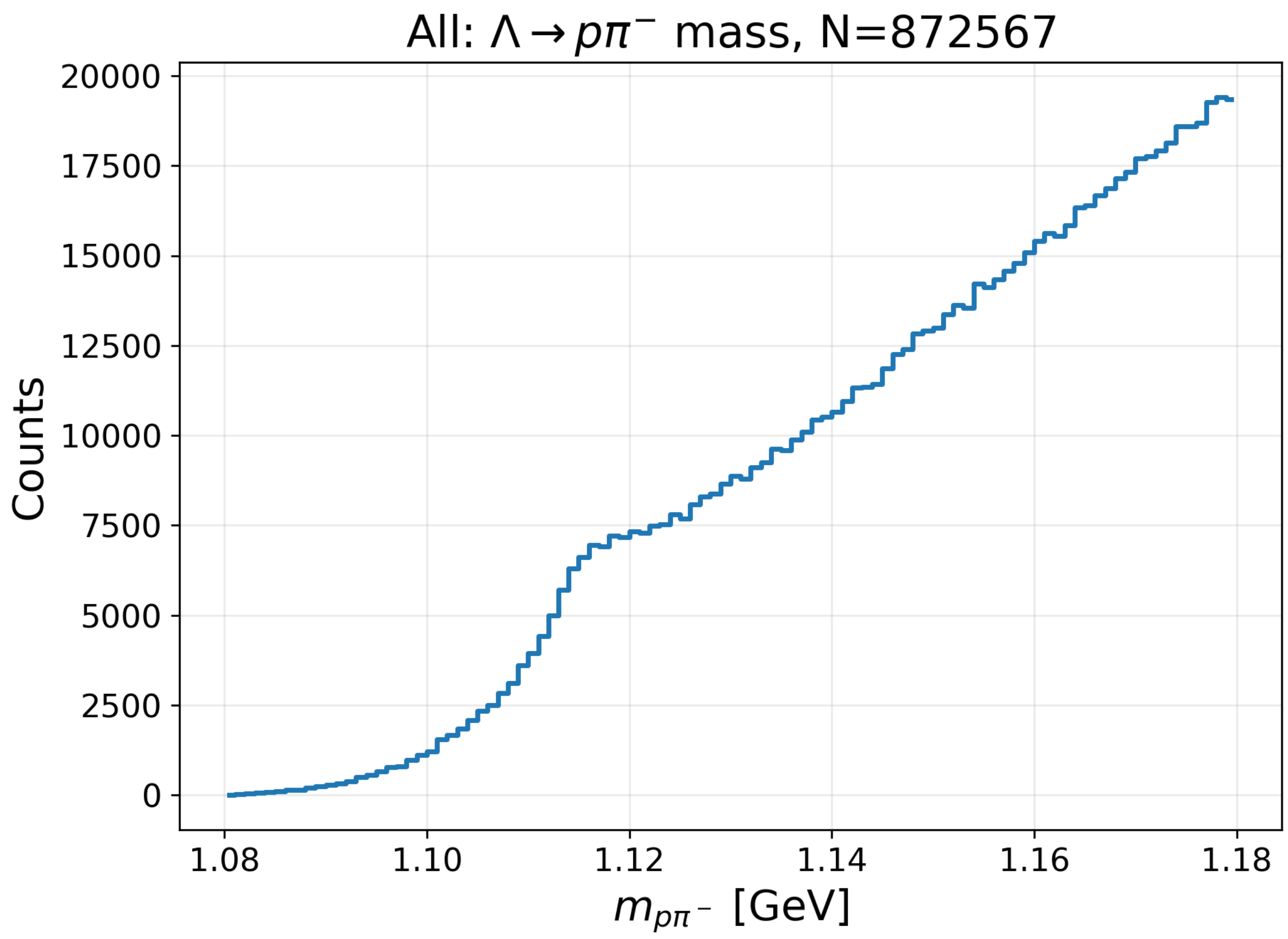






Λ Invariant Mass Distributions

- A plot of Lambda invariant mass distributions shows a large background that subdues the Lambda peak



Λ Invariant Mass Distributions

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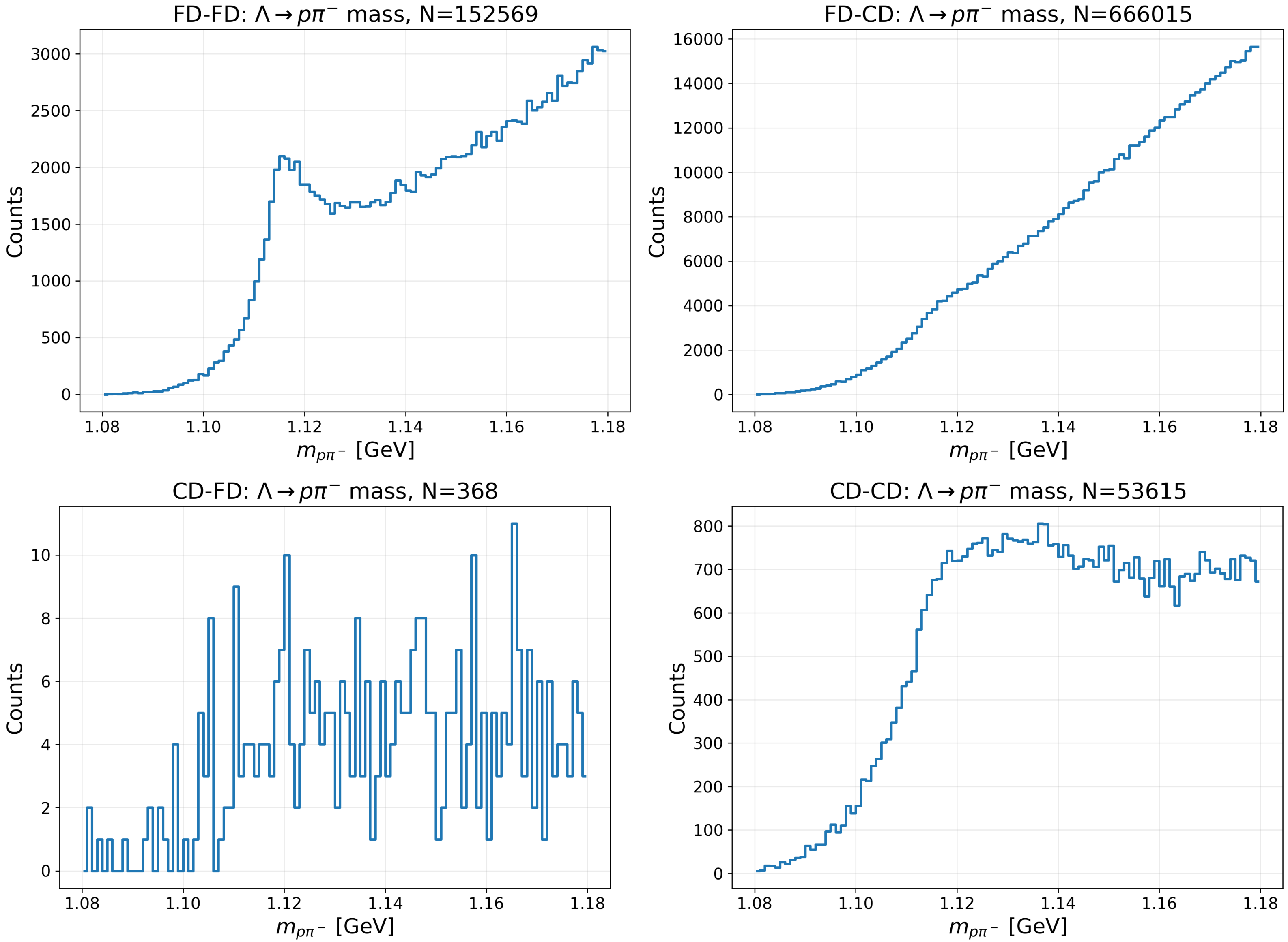
- However, our decay products could be found in four topologies:
  - Both proton and pion in the forward detector (FD-FD)
  - Proton in forward, pion in central (FD-CD)
  - Proton in central, pion an forwards (CD-FD)
  - Both proton and pion in central detector (CD-CD)



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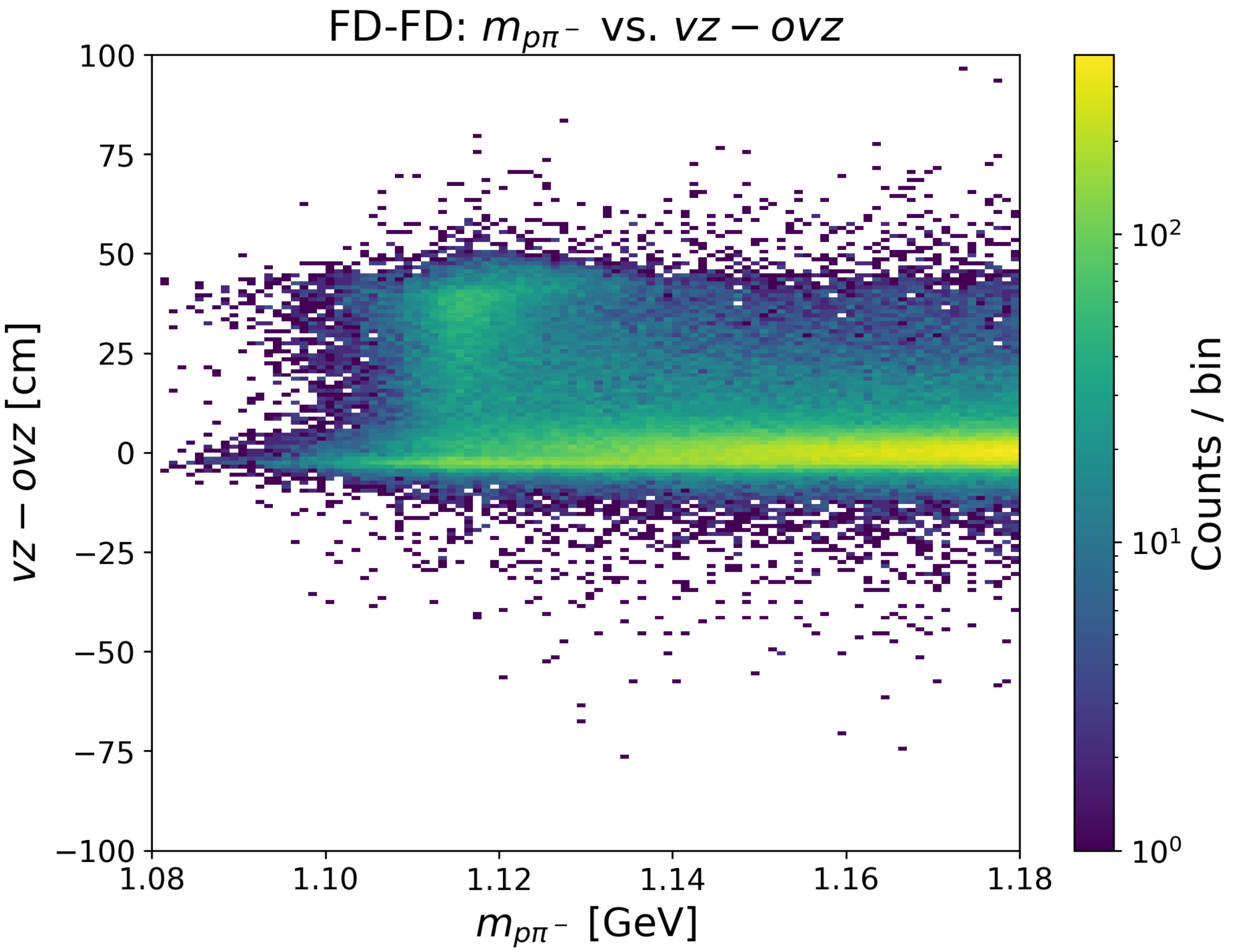
  - Proton in forward, pion in central (FD-CD)
  - Proton in central, pion an forwards (CD-FD)
  - Both proton and pion in central detector (CD-CD)
- Looking at secondary vertex distributions could help clean our invariant mass distributions



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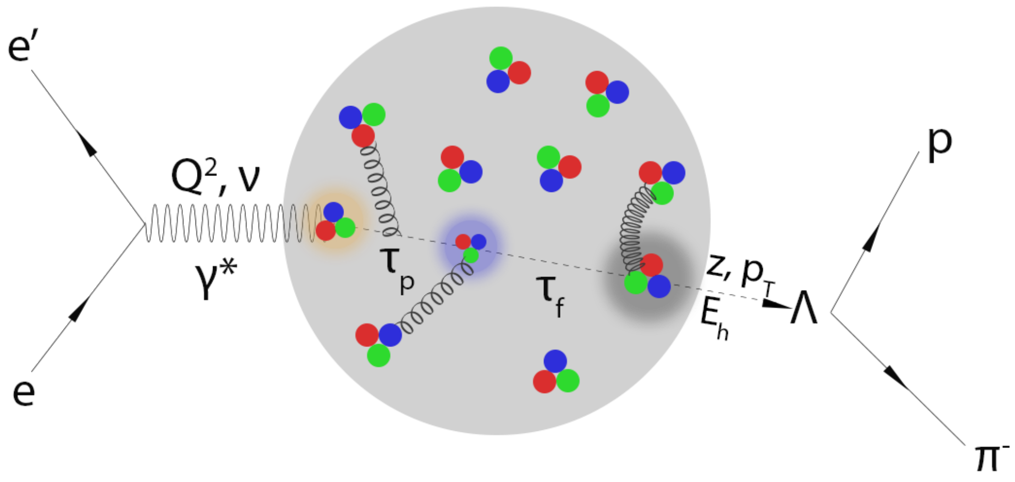
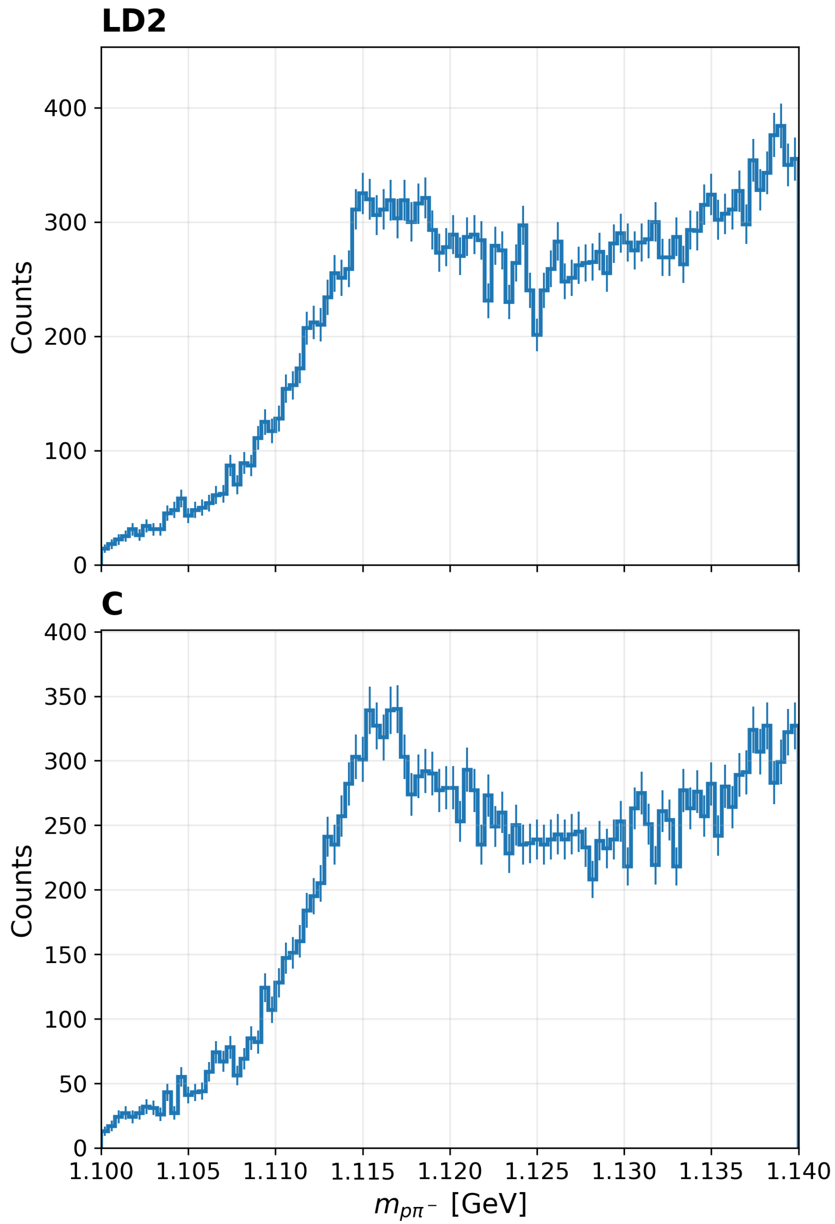
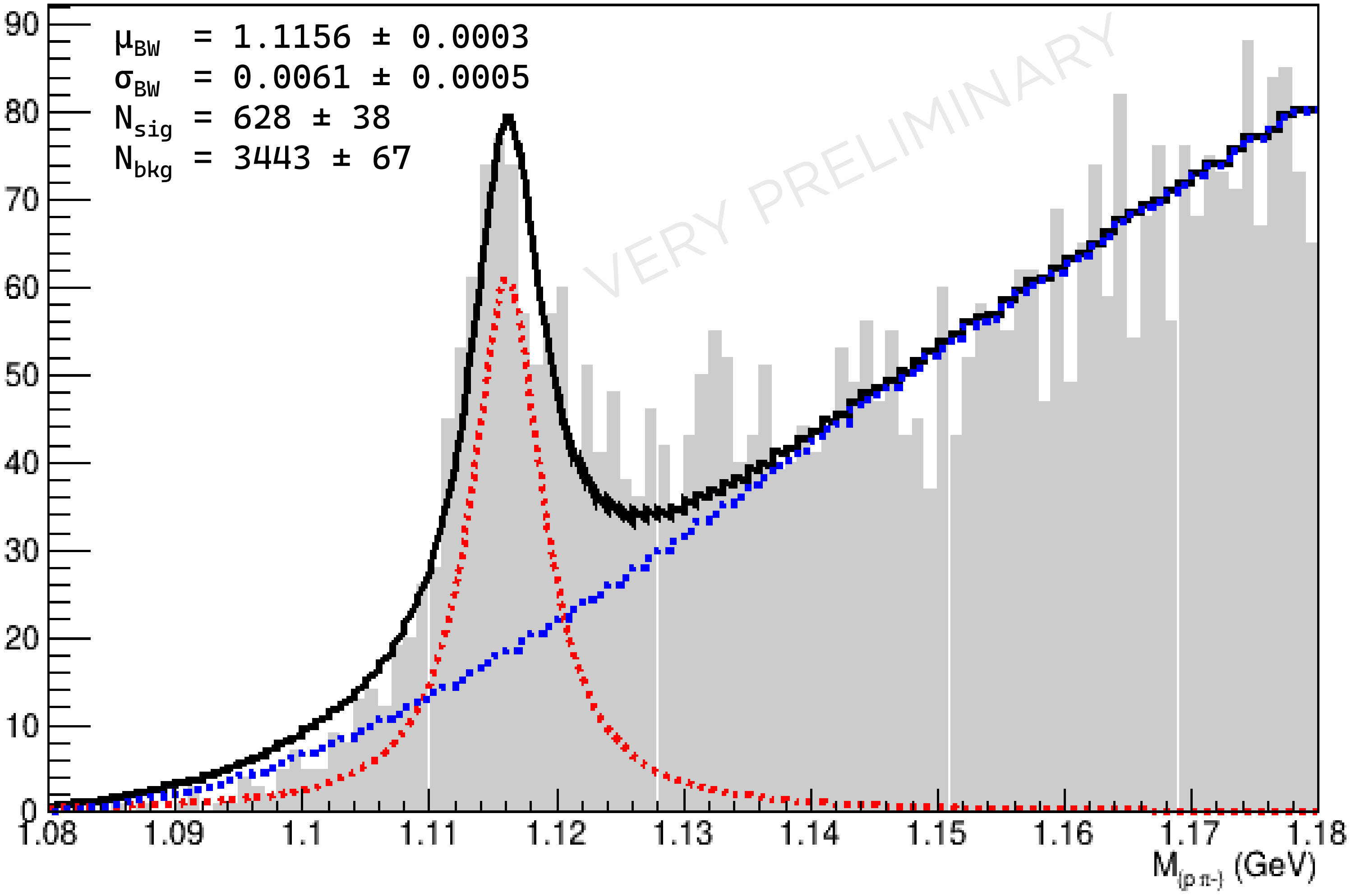




Event Mixing for Background Subtraction

- Event mixing technique proved to be effective in modeling the background in the Λ invariant mass for CLAS6 EG2 data
- Each correlated event protons and pions pairs are mixed, respectively, with pions and protons from uncorrelated events to model the combinatorial background underneath the Λ peak
- The RooFit library was used to assign probability distribution functions- Breit-Wigner for the signal and the mixed events sample for the background, to fit the invariant mass distribution and obtain the Λ yield



Summary and Outlook

- The pass-1 cooking of the CLAS12 RG-E dataset is complete
- Studies to determine fiducial, vertex and particle ID cuts are nearing completion
- Analysis codes are under development to
  - polish the Lambda signal using secondary vertex cuts
  - improve the event mixing algorithm for the background subtraction underneath the Lambda peak
  - extract the Lambda preliminary results for multiplicity ratios and transverse momentum broadening

Thank You!

Backup Slides

Physics Observables

Multiplicity Ratio

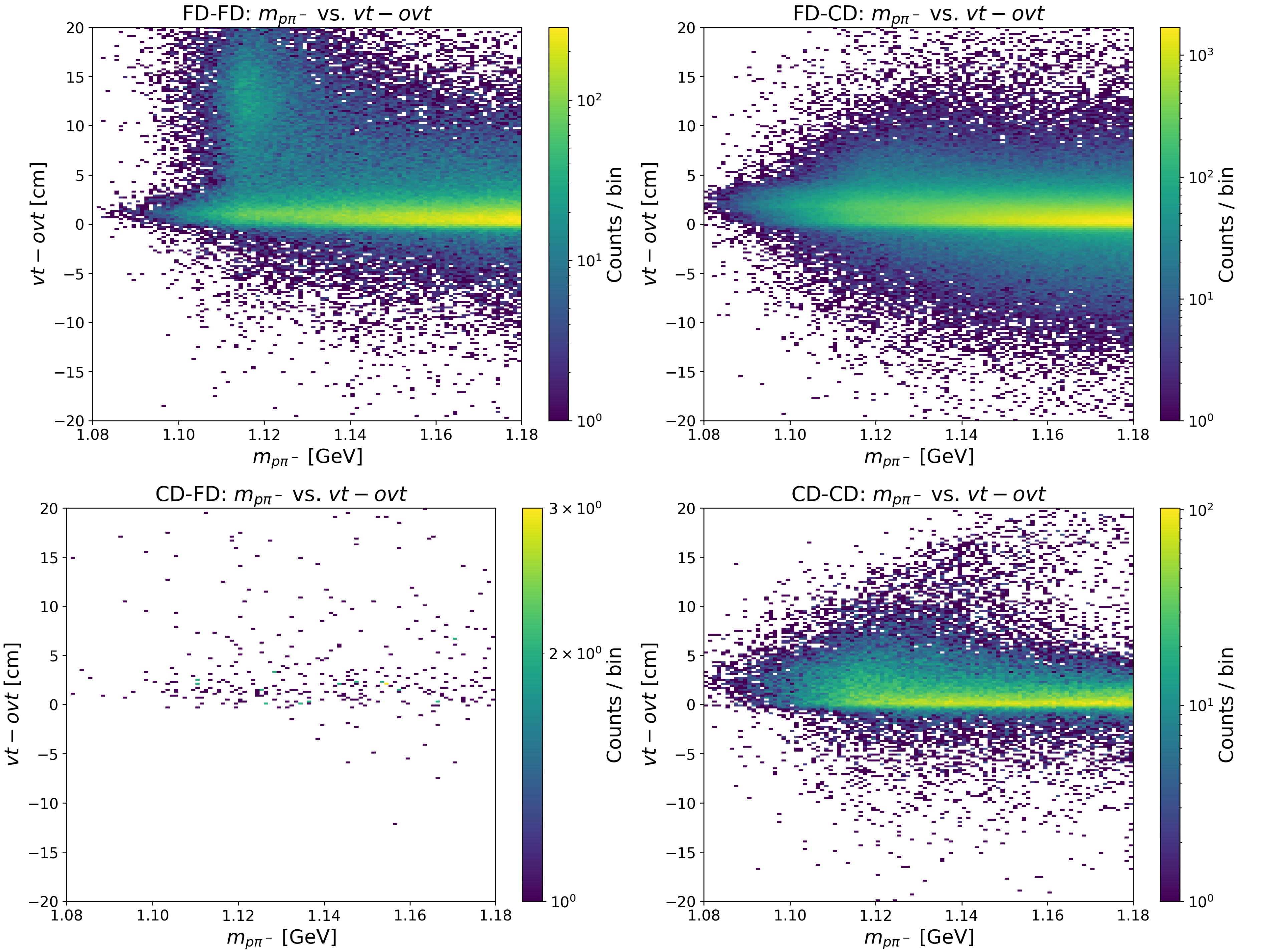
$$R_A^h = \frac{N_{SIDIS}^{h\,(A)} \Big/ N_{DIS}^{e\,(A)}}{N_{SIDIS}^{h\,(LD_2)} \Big/ N_{DIS}^{e\,(LD_2)}}$$

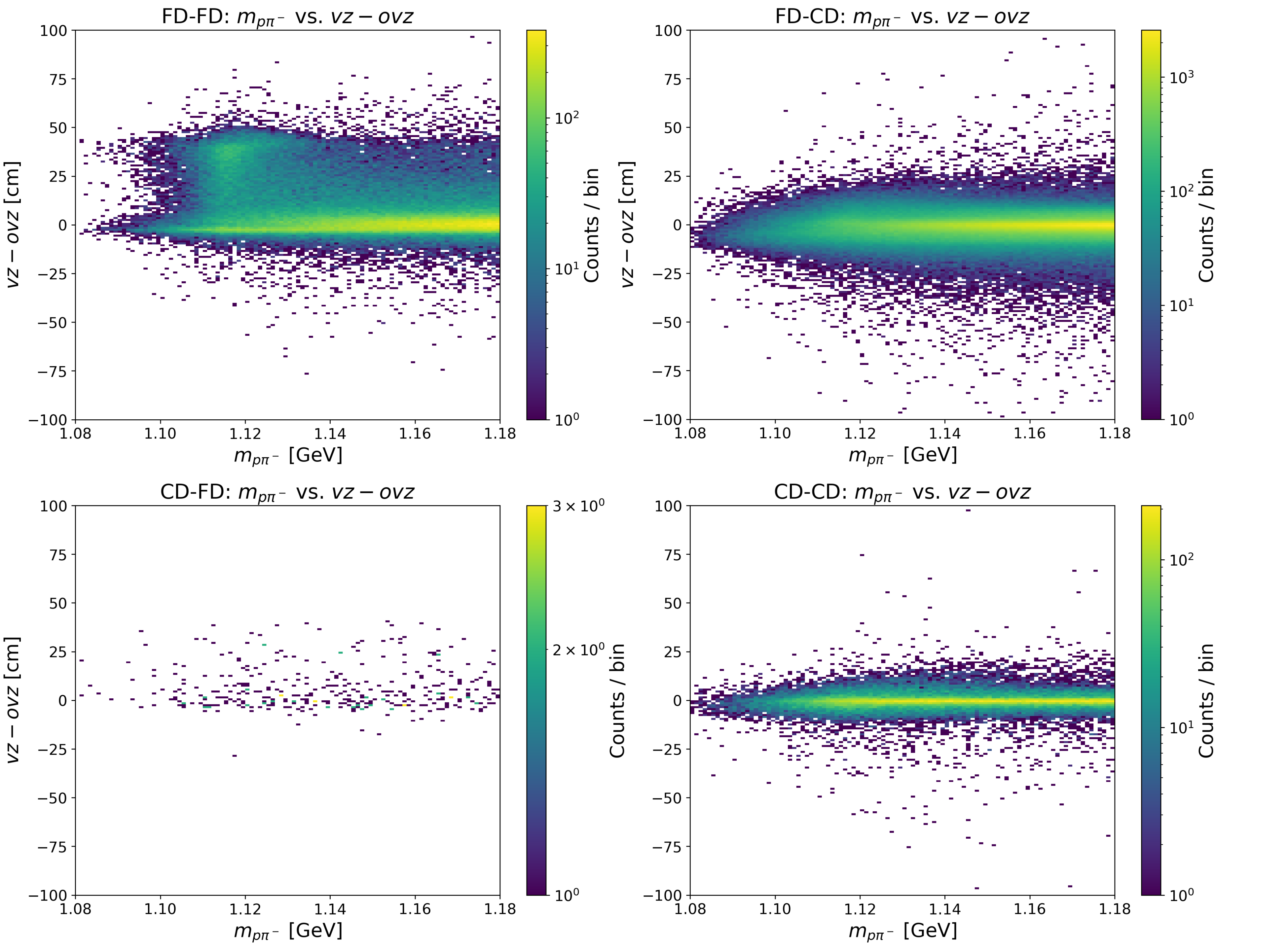
R_A^h describes the attenuation of formed hadrons, h, in the medium

Transverse Momentum Broadening

$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_{LD_2}$$

Δp_T^2 is due to the energy loss of the propagating struck quark(s) and/or the elastic and inelastic scattering of prehadrons and hadrons


FD-FD: $m_{p\pi^-}$ vs. $vt - ovt$
FD-CD: $m_{p\pi^-}$ vs. $vt - ovt$
CD-FD: $m_{p\pi^-}$ vs. $vt - ovt$
CD-CD: $m_{p\pi^-}$ vs. $vt - ovt$
$vt - ovt$ [cm]
$m_{p\pi^-}$ [GeV]
Counts / bin



FD-FD: $m_{p\pi^-}$ vs. $vz - ovz$
FD-CD: $m_{p\pi^-}$ vs. $vz - ovz$
CD-FD: $m_{p\pi^-}$ vs. $vz - ovz$
CD-CD: $m_{p\pi^-}$ vs. $vz - ovz$
$vz - ovz$ [cm]
$m_{p\pi^-}$ [GeV]
Counts / bin
100
75
50
25
0
−25
−50
−75
−100
1.08
1.10
1.12
1.14
1.16
1.18
10^0
10^1
10^2
10^3
2×10^0
3×10^0