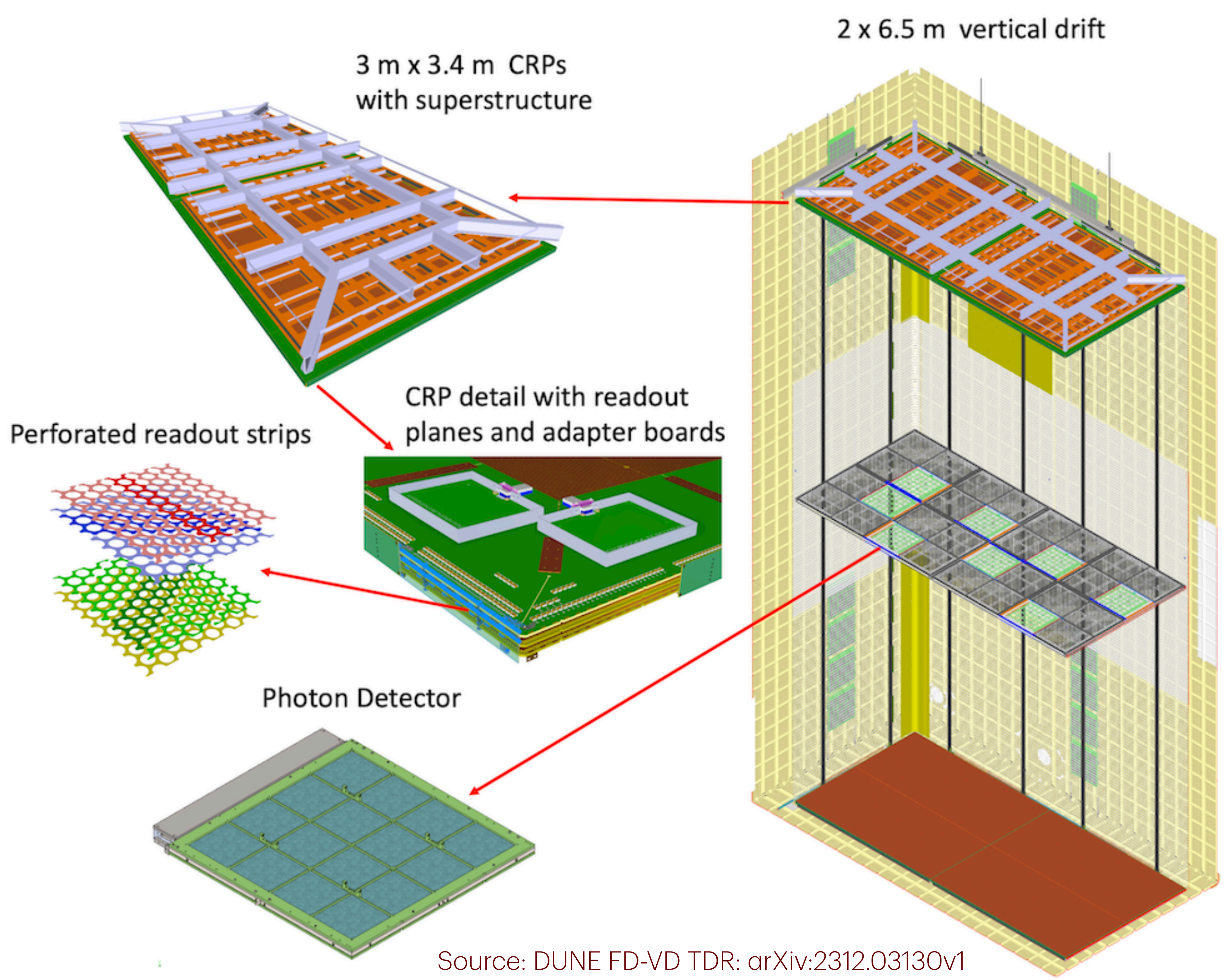
Energy resolution in DUNE Far Detector Vertical Drift

Daria Borodulina under supervision of Anselmo Meregaglia

02.06.2026, IRN

The DUNE FD-VD. Motivation



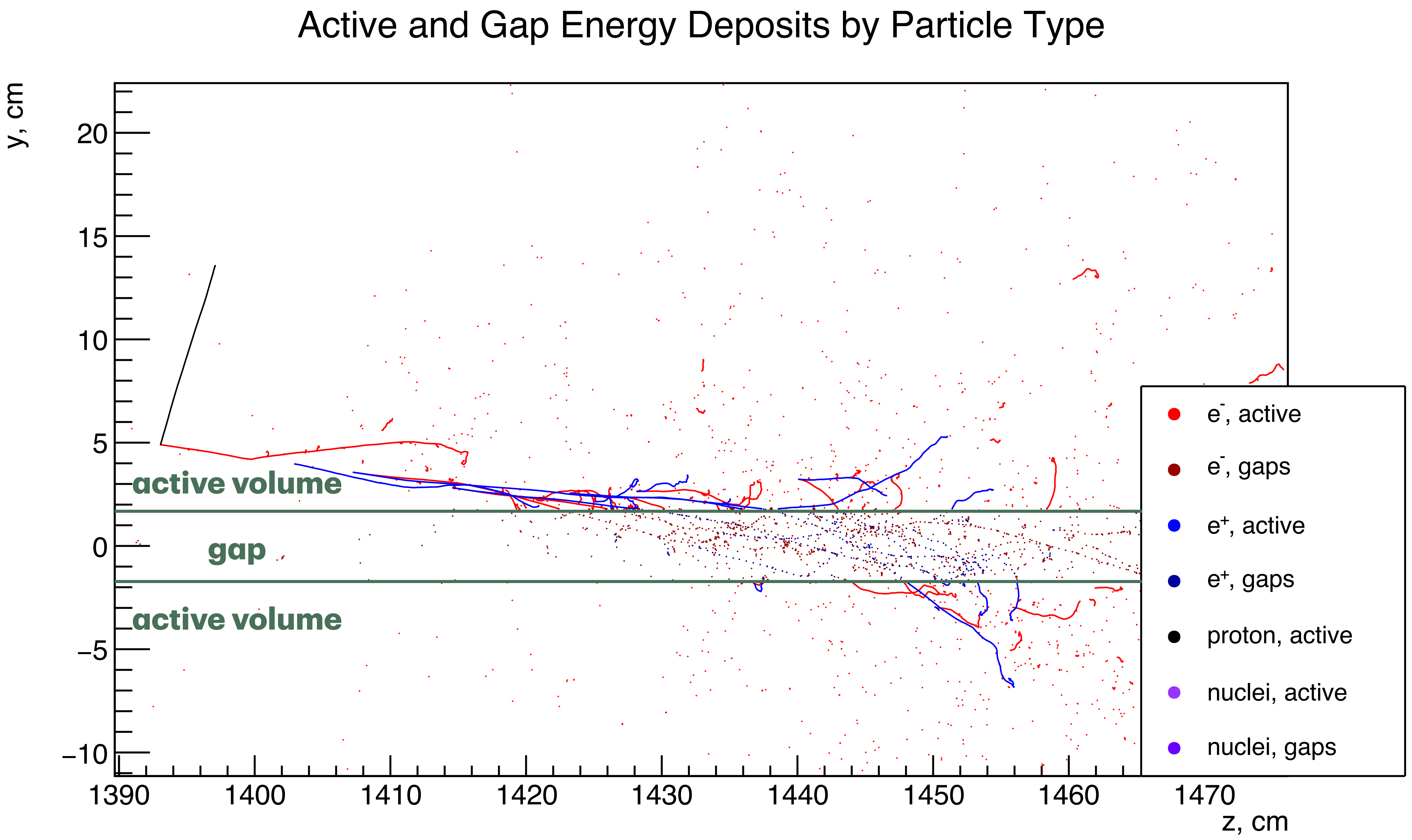
Source: DUNE FD-VD TDR: arXiv:2312.03130v1

- Neutrino energy in the Far Detector must be well known in order to perform neutrino oscillation analysis
- Energy resolution of electromagnetic showers contributes significantly to the neutrino energy resolution
- The value claimed in DUNE papers (e.g. $15\%/\sqrt{E[GeV]}$ in *DUNE CDR*) is based on simulations only and is worse than the standard values achievable in LArTPC detectors (e.g. $3\%/\sqrt{E[GeV]}$ in ICARUS)

A prototype of the Vertical Drift technology - ProtoDUNE-VD started data taking in 2025 at CERN Neutrino Platform. This is a smaller version of the detector with 2 top and 2 bottom CRPs

Introduction. CRP gaps

Even for very clean CCQE neutrino events inside the detector the resolution is not perfect, even before the full reconstruction



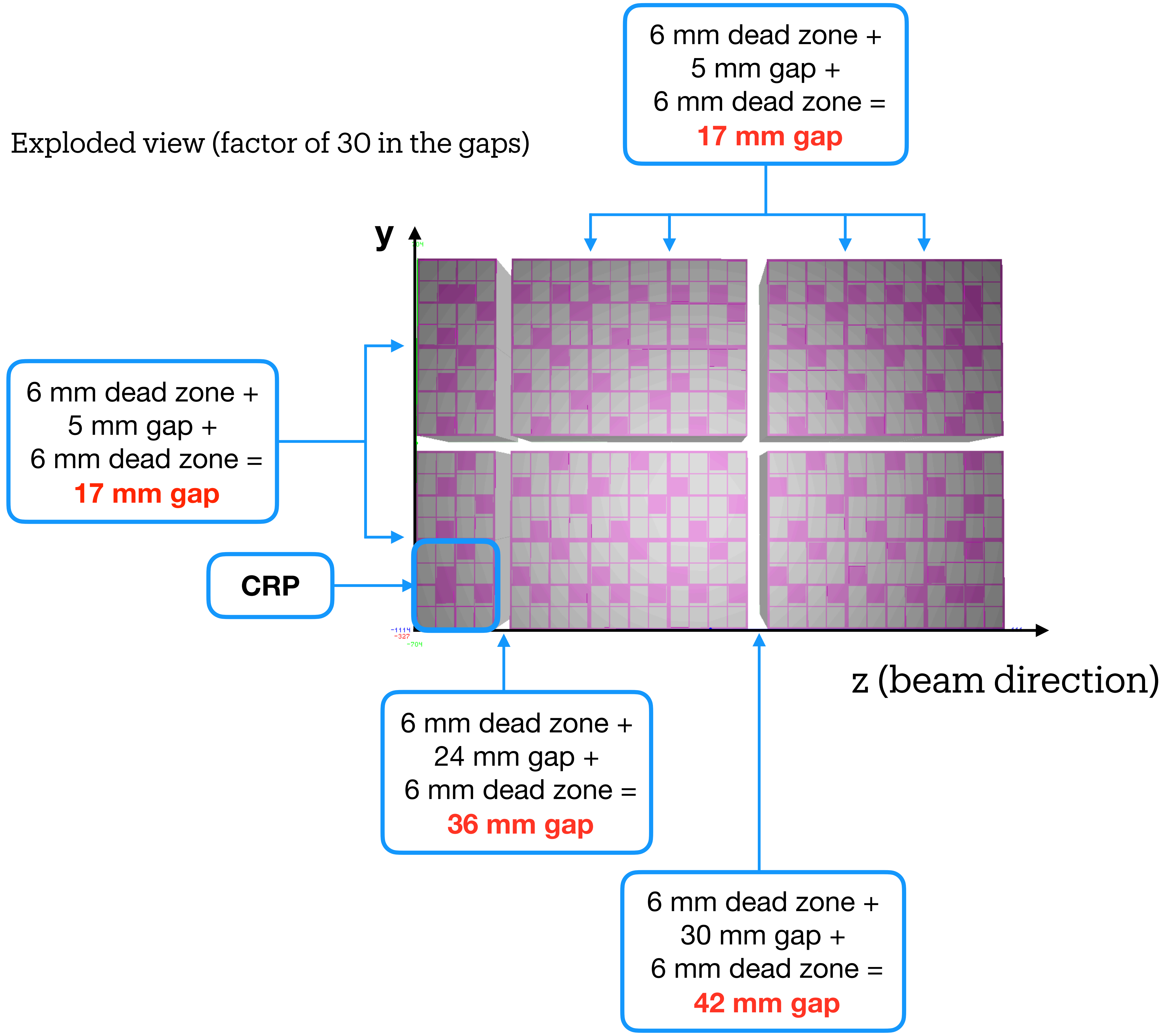
EM showers and CRP gaps - we study those

- This work has started with improving the FD-VD simulation by implementing the realistic dimensions of the gaps between CRPs and understanding the behaviour of the charge deposited in such gaps
- A charge recovery tool was developed to model the fraction of charge deposited in CRP gaps that is recovered in neighbouring CRPs
- The fact that the CRP gap in ProtoDUNE is of similar size (16 mm) to some of the gaps in the realistic FD-VD simulation (17 mm) allowed us to use the real data to tune the charge recovery tool in the simulation, i.e. understand what fraction of the charge deposited in the gap gets recovered in the CRPs

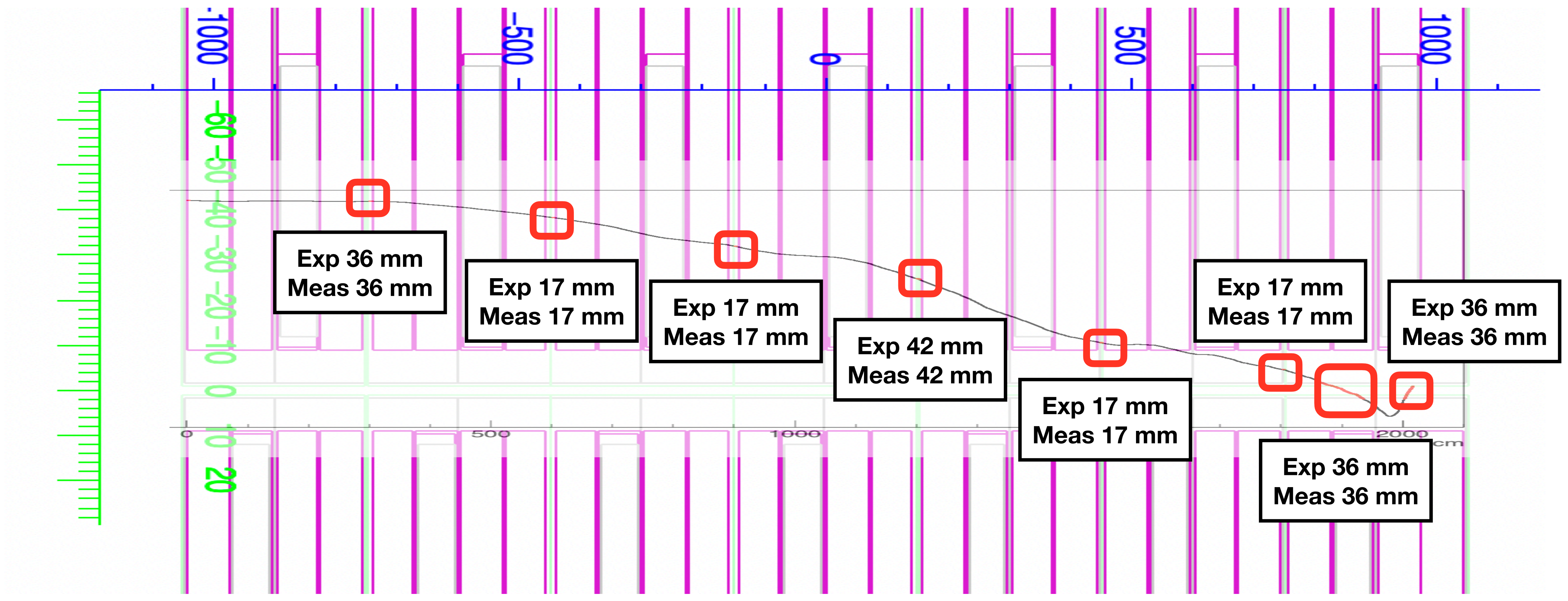
GDML output and tests

We created a new realistic geometry for DUNE FD-VD and tested the gaps size by simulating a single muon going through the detector

Exploded view (factor of 30 in the gaps)

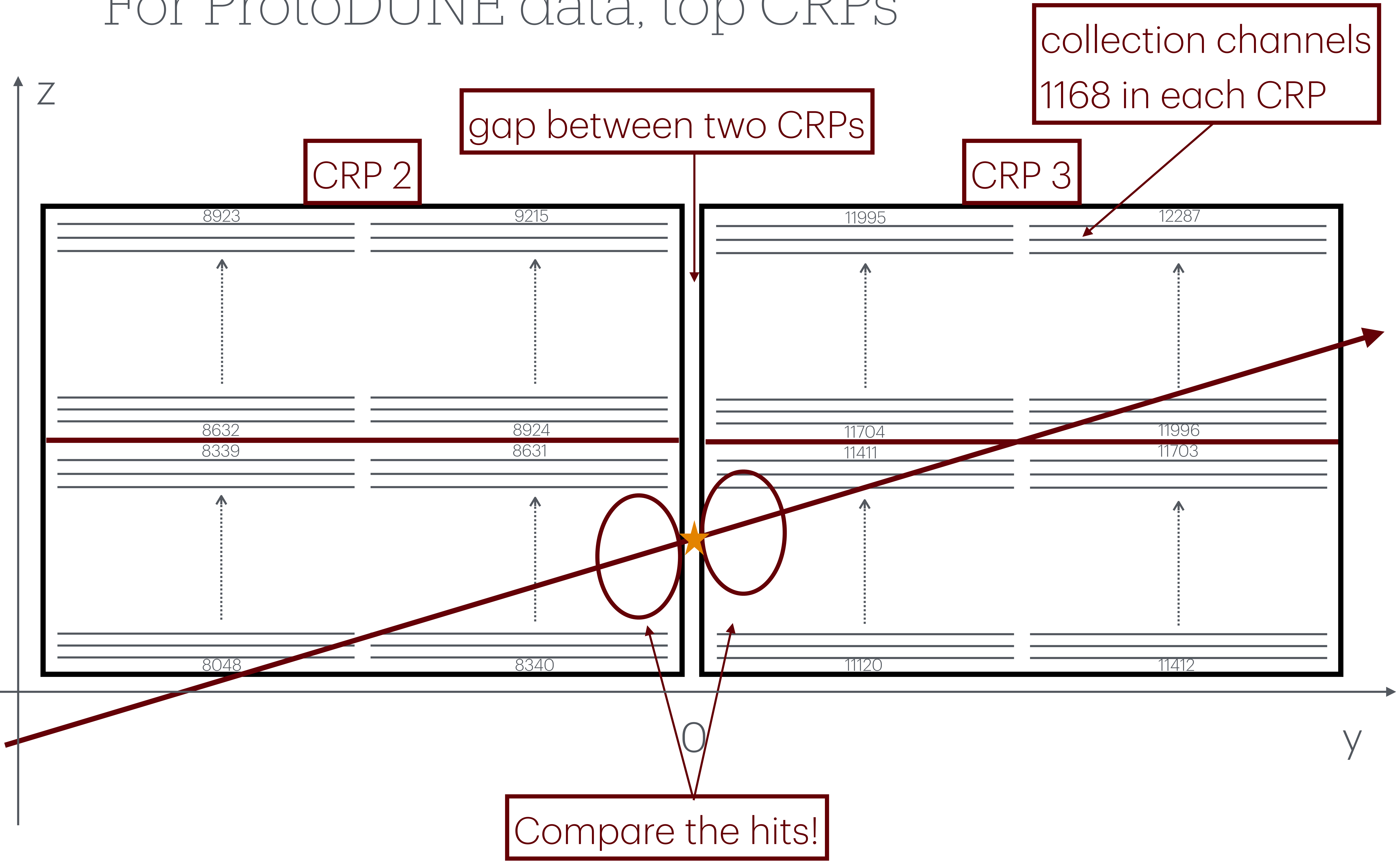


For test purposes the dimensions of the gaps are measured by looking at the charge deposited in the active and passive volumes and is in agreement with the expectations



CRP gap in Y direction

For ProtoDUNE data, top CRPs

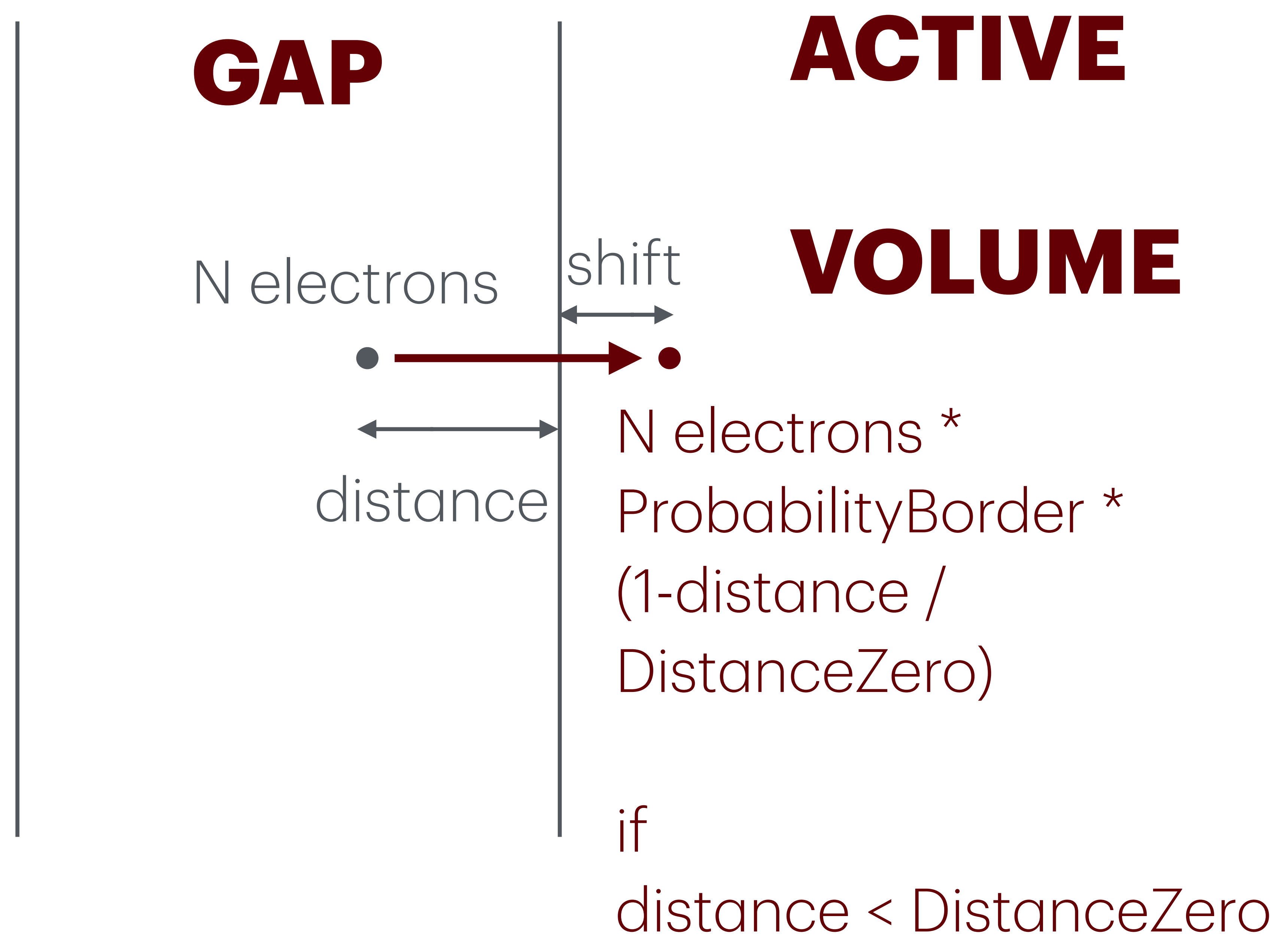


1. Calculate the z-coordinate (z_ref) at which the gap was crossed based on reconstruction information
2. Retrieve the nearest channels to the z_ref in each CRP. Get the hits values at them
3. Calculate the Δchannel: distance from the channel to the crossing point
4. Fill the histogram with Δ channel and hit (in adc units) as weight

The simulation

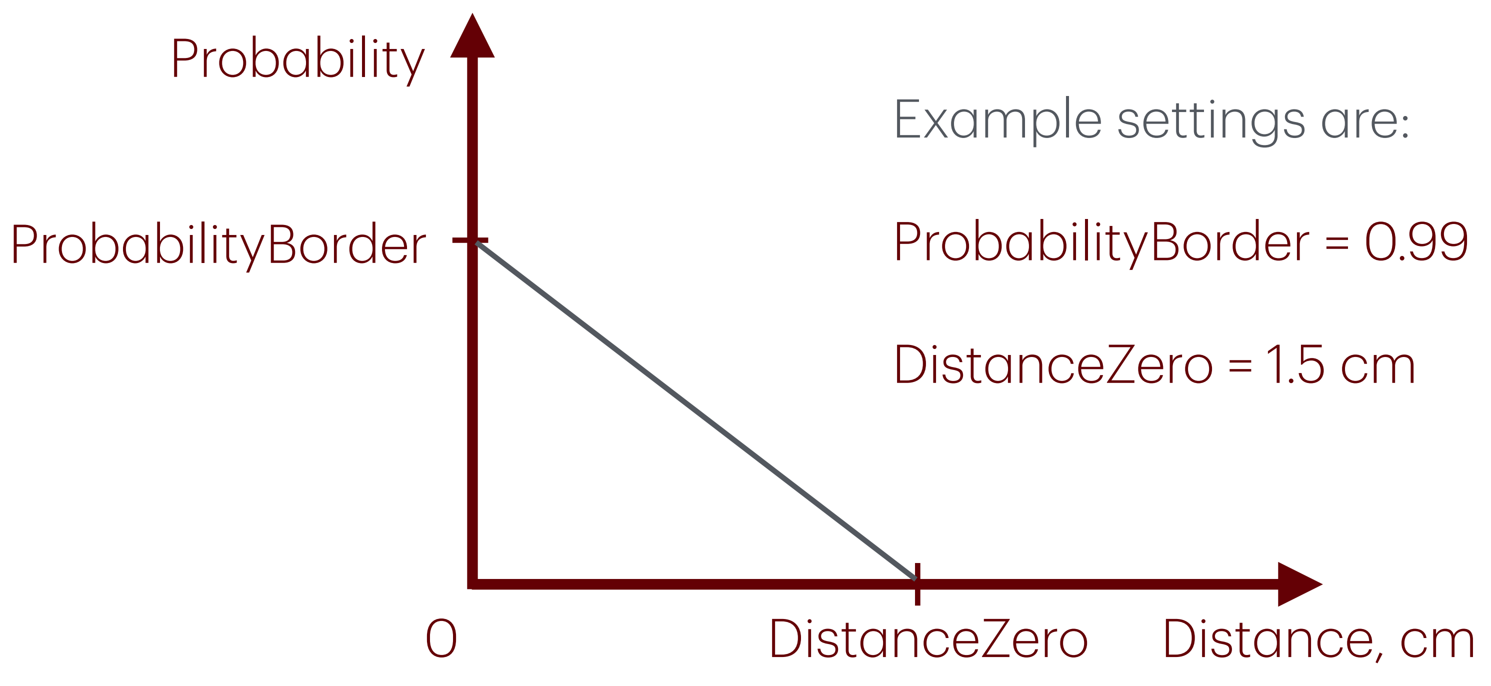
Developing a way to recover the charge

- The goal is to recover more charge the closer the deposition occurs to the active volume. For the time being, a linear function is used
- An important requirement is flexibility of the parameters of the function, calculating the fraction of the charge to be moved. This is needed to tune the function with ProtoDUNE data

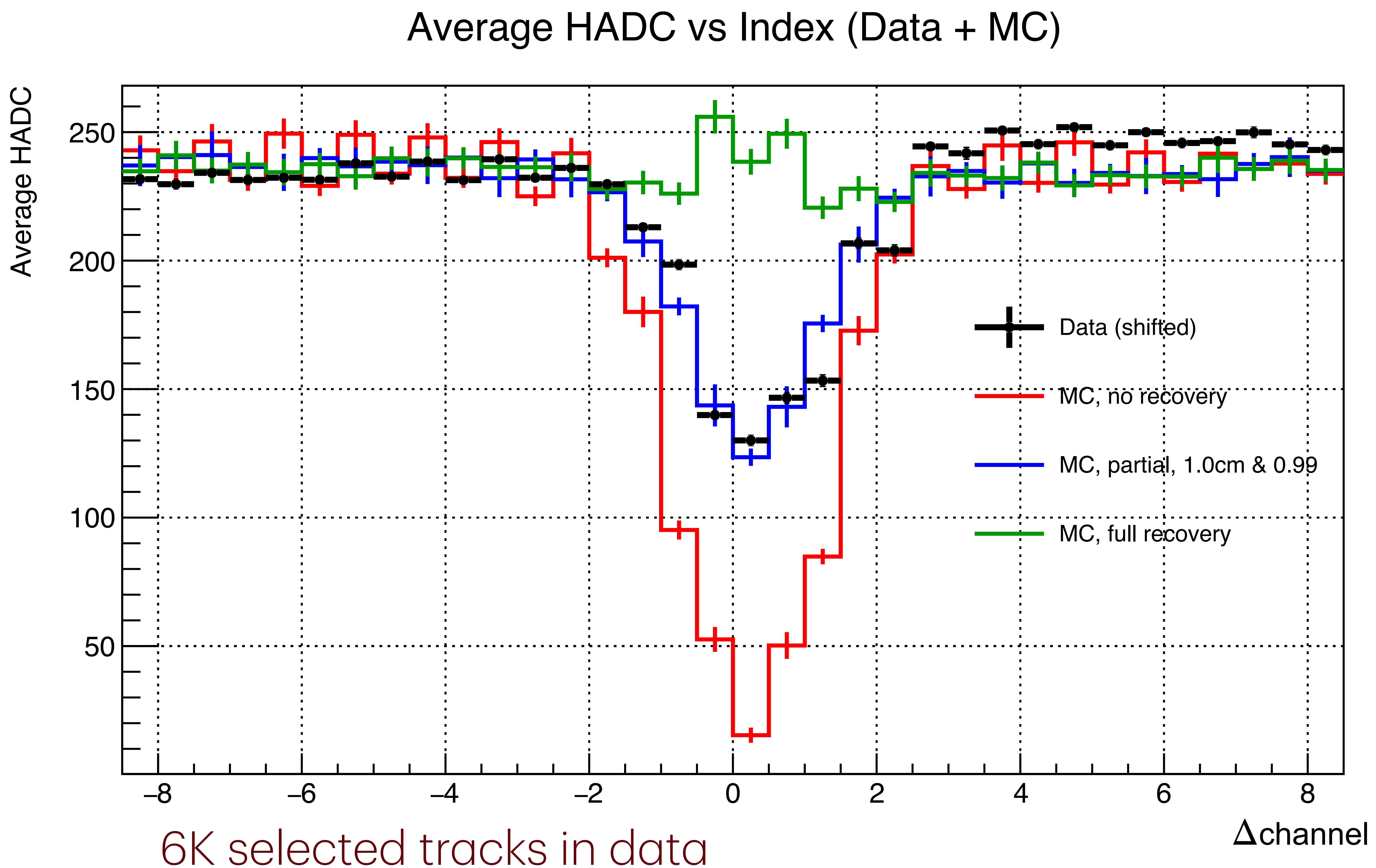


How we produce MC

- The simulated particle is a MIP muon
- The vertex and direction for each track are taken from the ProtoDUNE data so that the muon crosses a 17 mm Y-gap in the simulation at the same point and at the same angle it did in data



Comparison between data and MC



6K selected tracks in data

1K simulated muons in each MC sample

The actual charge recovery seems to be close to partial recovery with parameters (1.0 cm, 99%). It is impossible to tune both the parameters independently with only one CRP gap in data.

The average hits values in the flat parts of the histogram are higher on the right-hand side. This can be explained by the higher mean ADC values in CRP3 (on the right)

EM showers energy resolution in DUNE FD-VD simulation

Energy, GeV	Resolution, % no recovery	Resolution, % realistic recovery	Resolution, % full recovery
0.5	**5.02**	**2.93**	**0.54**
1.5	**4.09**	**2.27**	**0.30**
3	**5.05**	**2.54**	**0.22**

How is the energy resolution defined

We compare the resolution at the level of the Geant4 simulation before the reconstruction algorithms

The number of electrons after the Ionization and Scintillation step of the simulation is used

Events with photo-nuclei interaction are discarded

Res = std dev / mean x 100%

What is simulated

Electrons are uniformly distributed on a plane, including 1 CRP and the gaps near it
with energies, generated in the beam direction:
- 0.5 GeV
- 1.5 GeV
- 3.0 GeV

WORK IN PROGRESS

Estimating energy resolution of EM showers using pi-zero mass in ProtoDUNE-VD

- Unfortunately, it is impossible to get a monoenergetic electron beam that would develop a shower in the active volume of ProtoDUNE-VD

- What we can do though, is studying the $\pi_o -> \gamma\gamma$ process and estimating the energy resolution of the π_o invariant mass

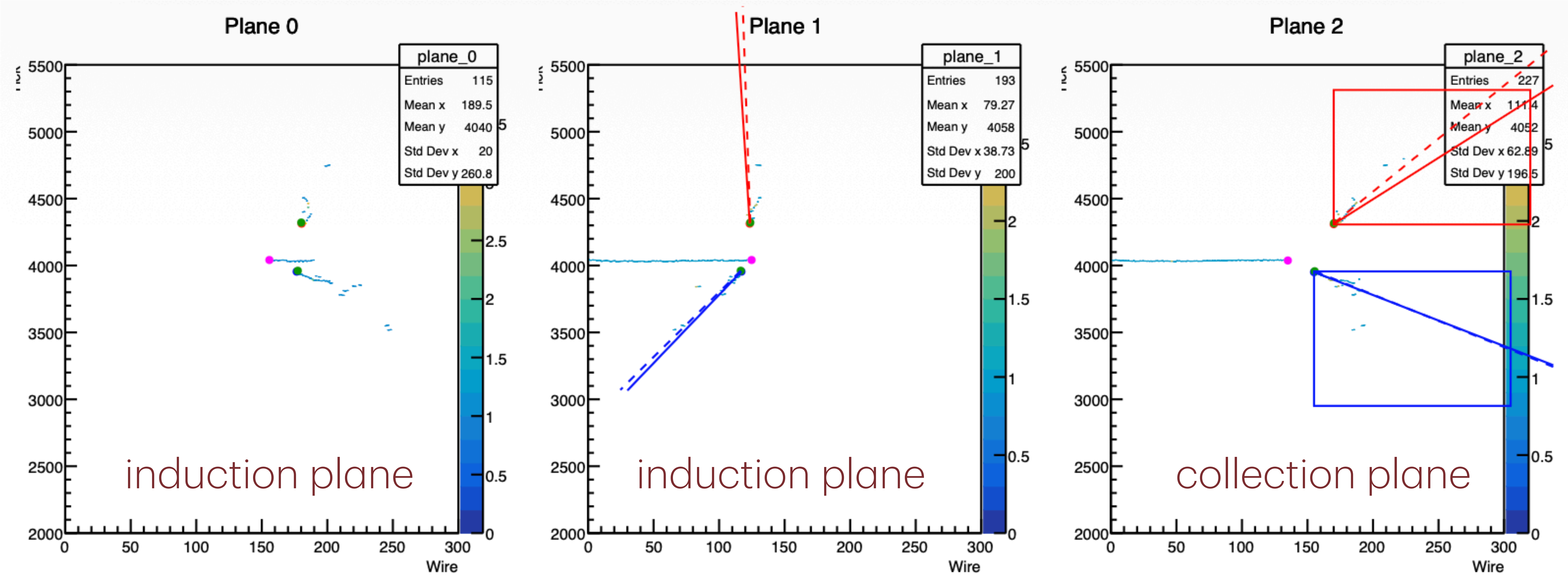
- $m(\pi_0) = \sqrt{2E_1E_2(1 - cos\theta)}$, where θ is the angle between showers, E_1 and E_2 - energies of the two showers

- We are interested in this study because it provides a way to estimate the energy resolution of EM showers in the FD-VD and we want to know how precise in terms of this resolution the detector is

- Currently we have a simulation of a pi-zero and several analysed real ProtoDUNE data events

MC

We simulate 1 pi-zero and a muon from the same vertex



2 methods to calculate the angle between the showers:

- determine the vertex and the starting points of the two showers
- fit the shower with a straight line to get its direction

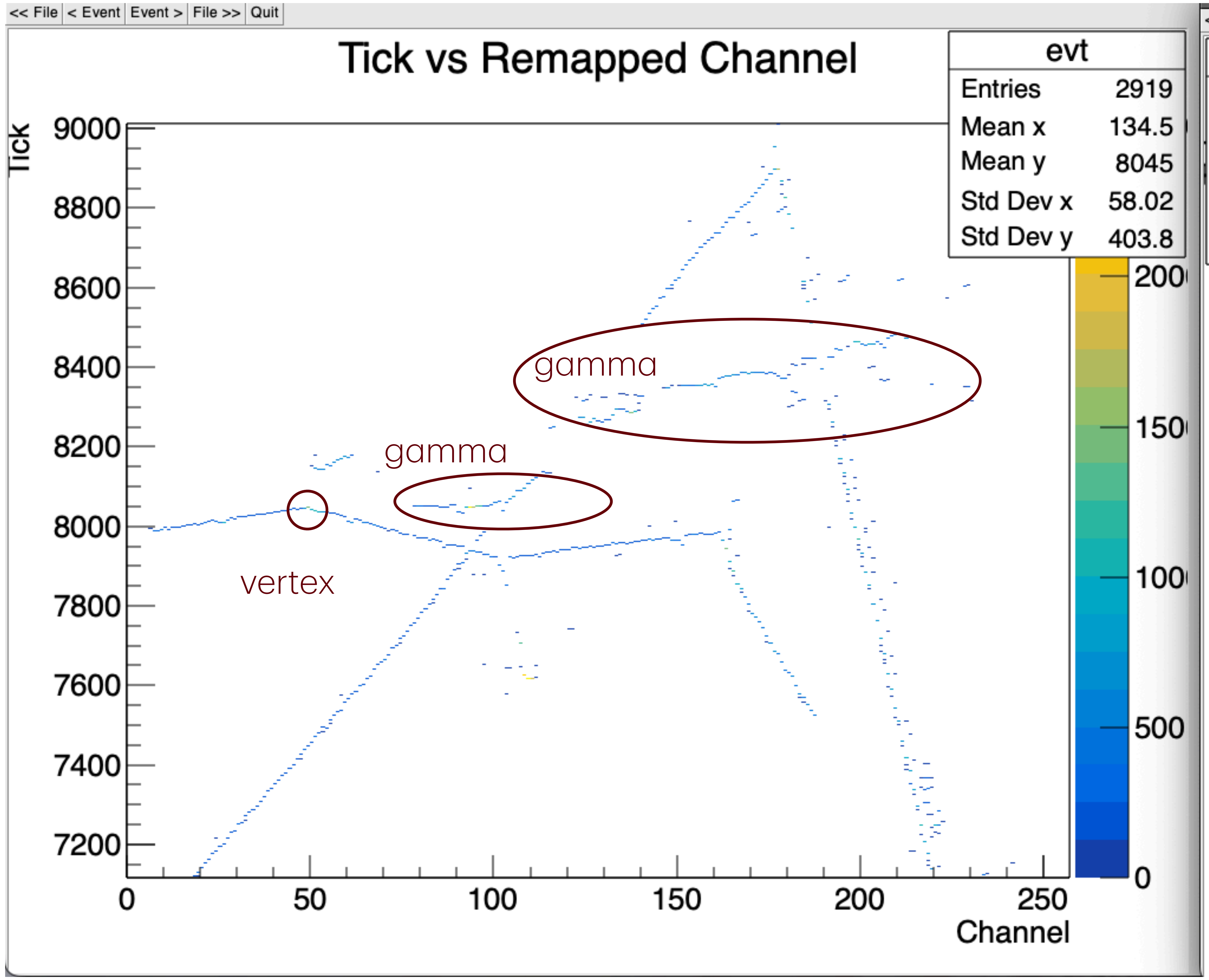
dashed - true direction

solid - reconstructed

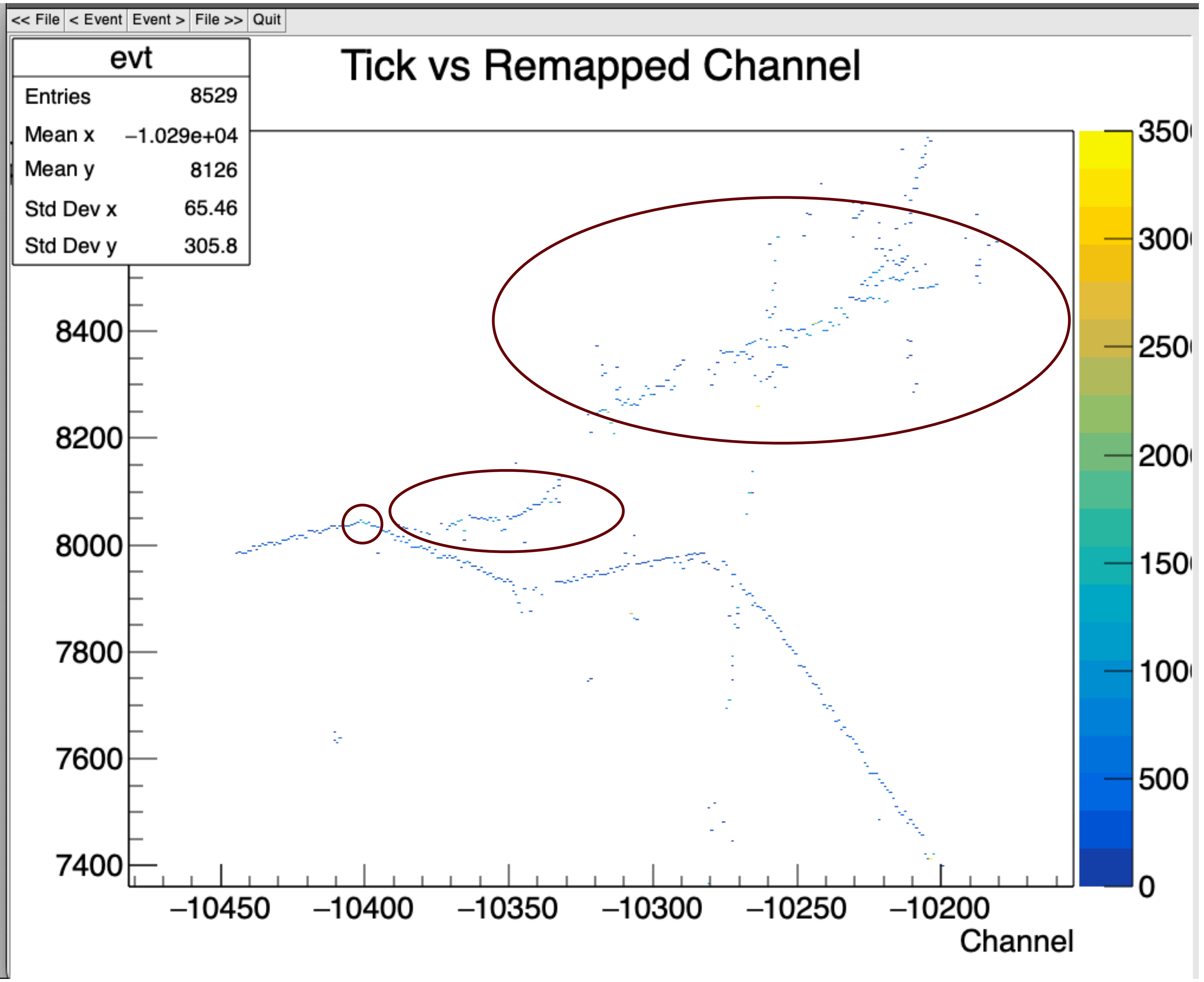
Pi-zero event in ProtoDUNE-VD

Example, 3 GeV beam

WORK IN PROGRESS



collection plane



induction plane

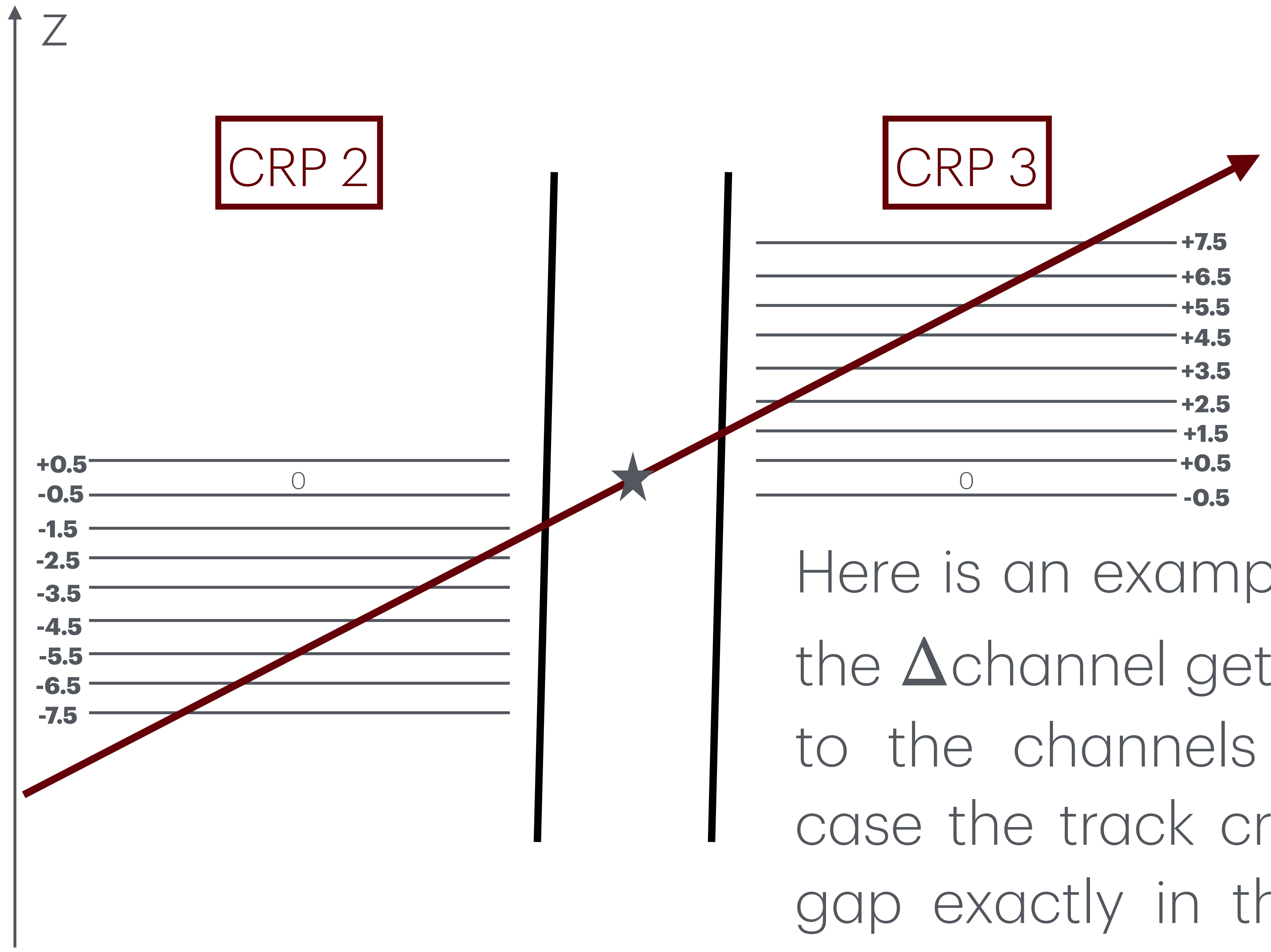
Conclusions

- The realistic CRP gaps and the charge recovery tool have now been fully implemented, validated, and committed for the FD-VD simulation
- Good agreement between MC and experimental data from ProtoDUNE-VD was achieved for the tuned recovery configuration. This configuration is now used as default parameters of the tool
- The impact of realistic CRP gaps and charge recovery on EM shower energy resolution in FD-VD was quantified and found to be significant
- One cannot further tune the simulation now, because there is only one CRP gap size available in ProtoDUNE-VD. However, it will be possible with the data from FD-VD once it starts the data-taking process in several years
- The work on estimating the energy resolution of EM showers in ProtoDUNE-VD using pi-zero rest mass is ongoing
- We hope that despite the uncertainty of the angle between the two showers it would be possible to precisely estimate the electromagnetic energy resolution once we analyse enough ProtoDUNE-VD events

BACKUP SLIDES

CRP gap in Y direction - algorithm

Details



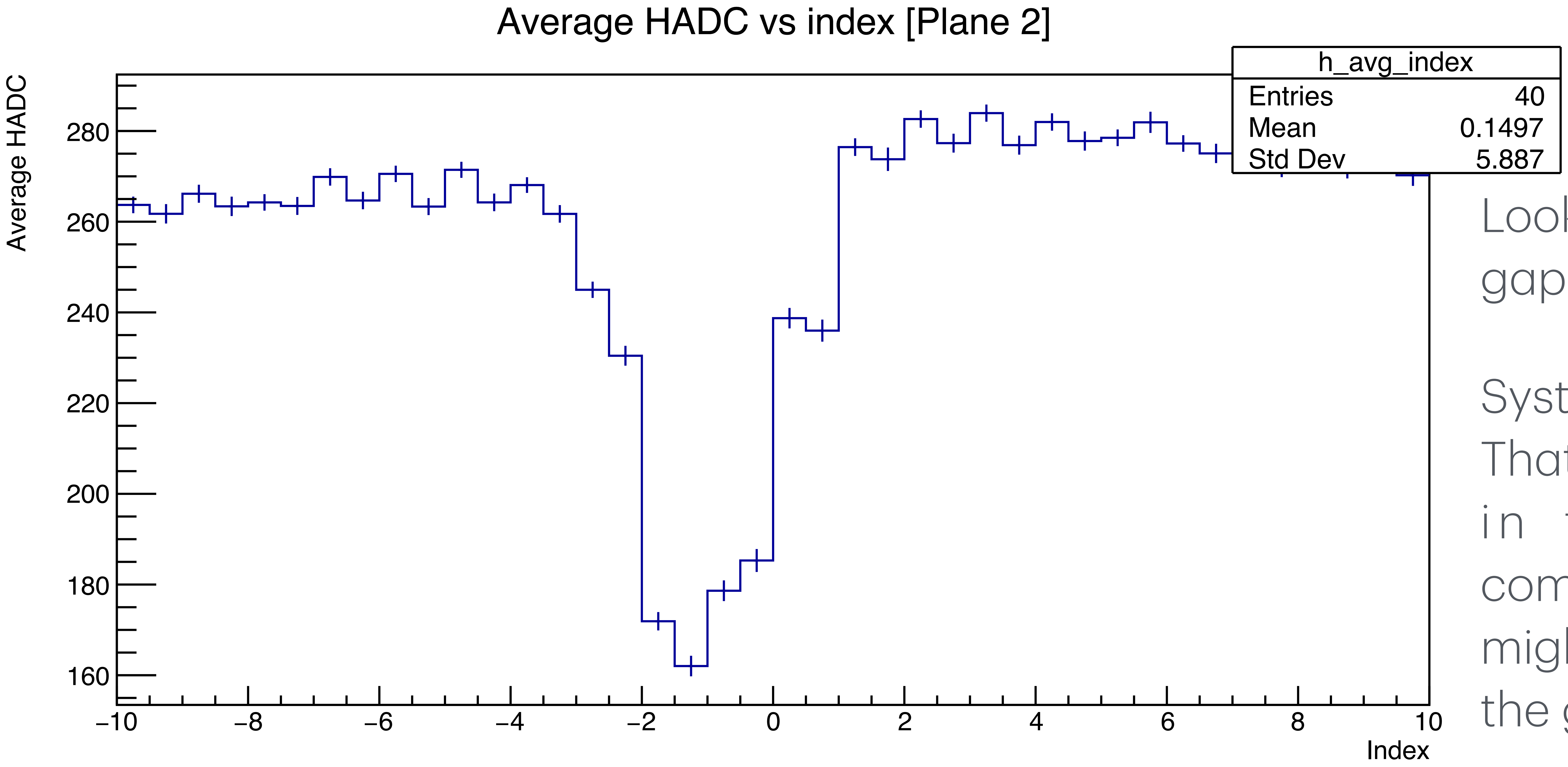
Here is an example of how the Δchannel get assigned to the channels - in this case the track crosses the gap exactly in the middle between two channels on the same z-level

What else we account for?

- Disconnected channels: the tracks that cross the gap near the disconnection are discarded
- The overlap between the channels on the left and right at the same z-level (no more than 3): we only select tracks for which it is clear where it crossed the gap and have at least 10 hits in both the CRPs
- Average noise is calculated for the channels not touched by the track and this value is subtracted from the histogram

Y-gap: data

The final histogram



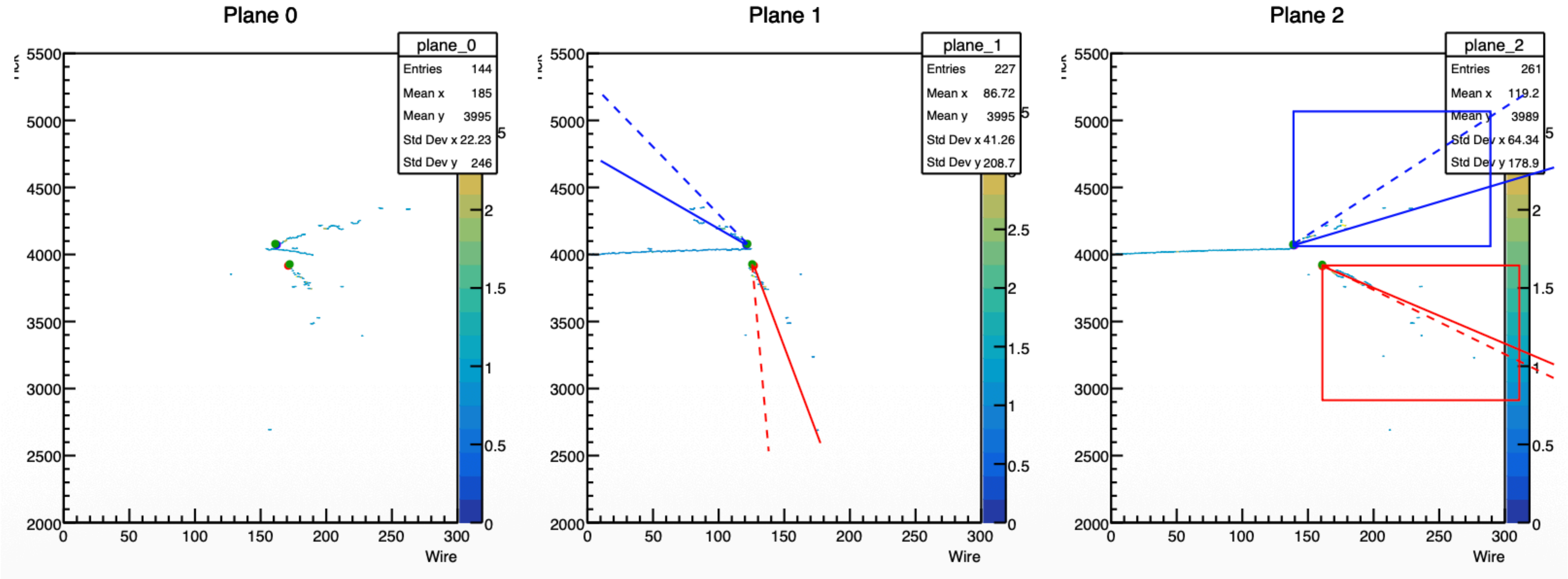
Looks good and has a visible gap!

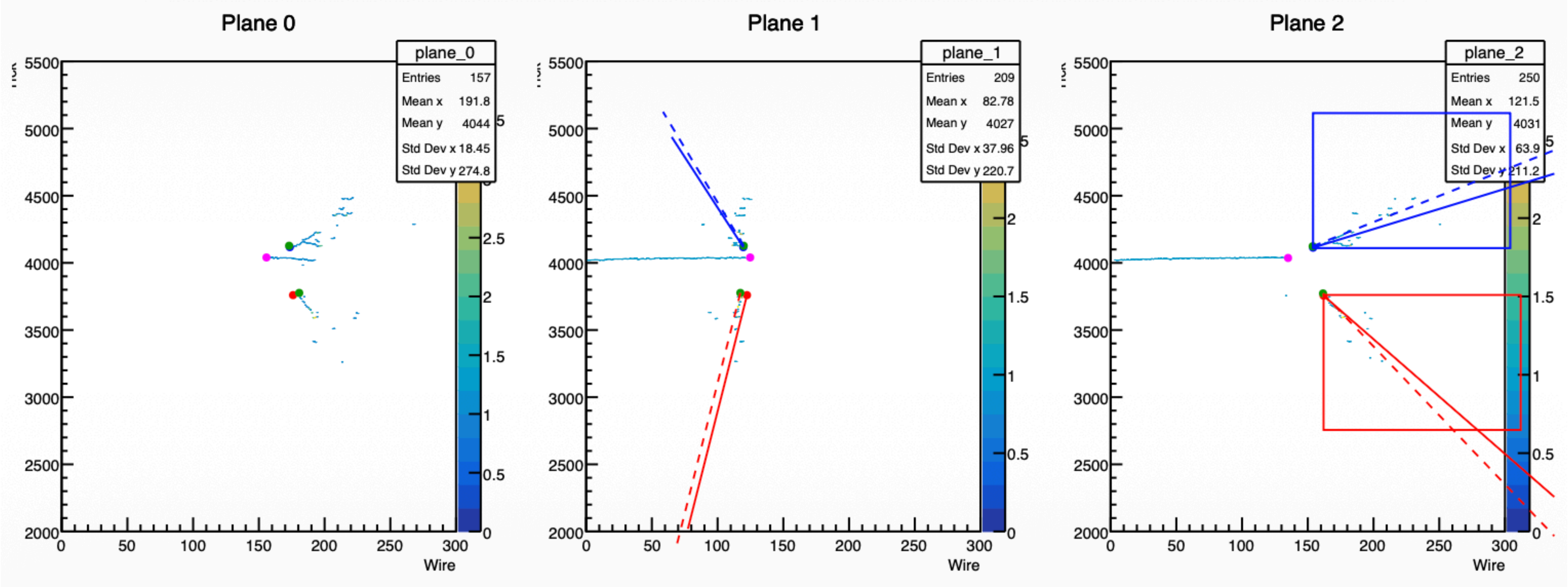
Systematic shift to the left? That could be due to a shift in the z_ref, that was computed at y = 0 which might not be the centre of the gap

We take the vertexes and directions of the selected tracks for MC!

MC

Problematic events





MC

Resolutions for 200MeV pions

	energy true	energy reco (60% cut)	energy reco (no cut)
true angle	0.0	4.5	3.5
points method	1.6	7.2	6.8
lines method	6.4	11.3	8.9

this MC sample is not suitable for pandora reconstruction

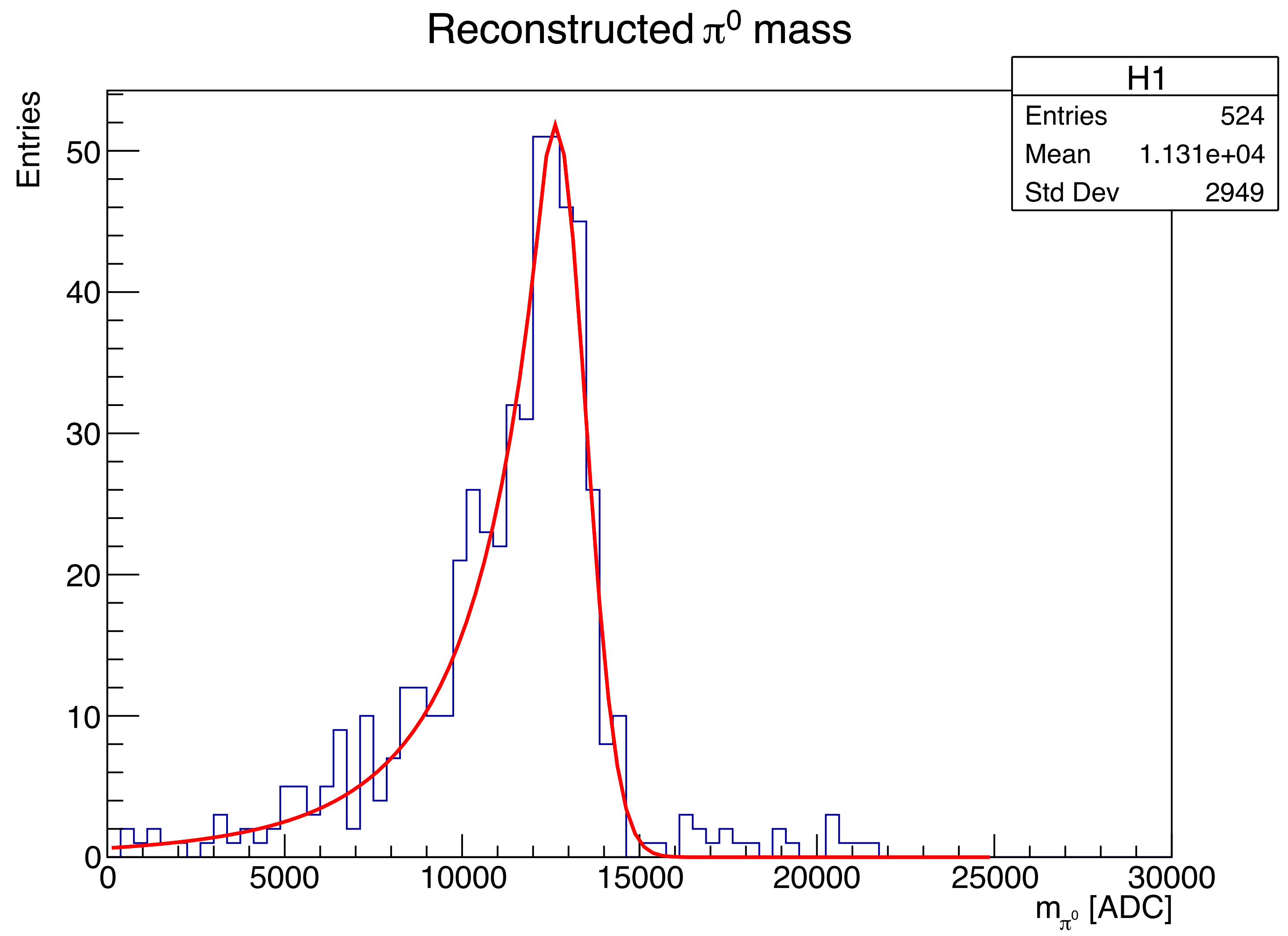
MC

Resolutions for 500 MeV pions

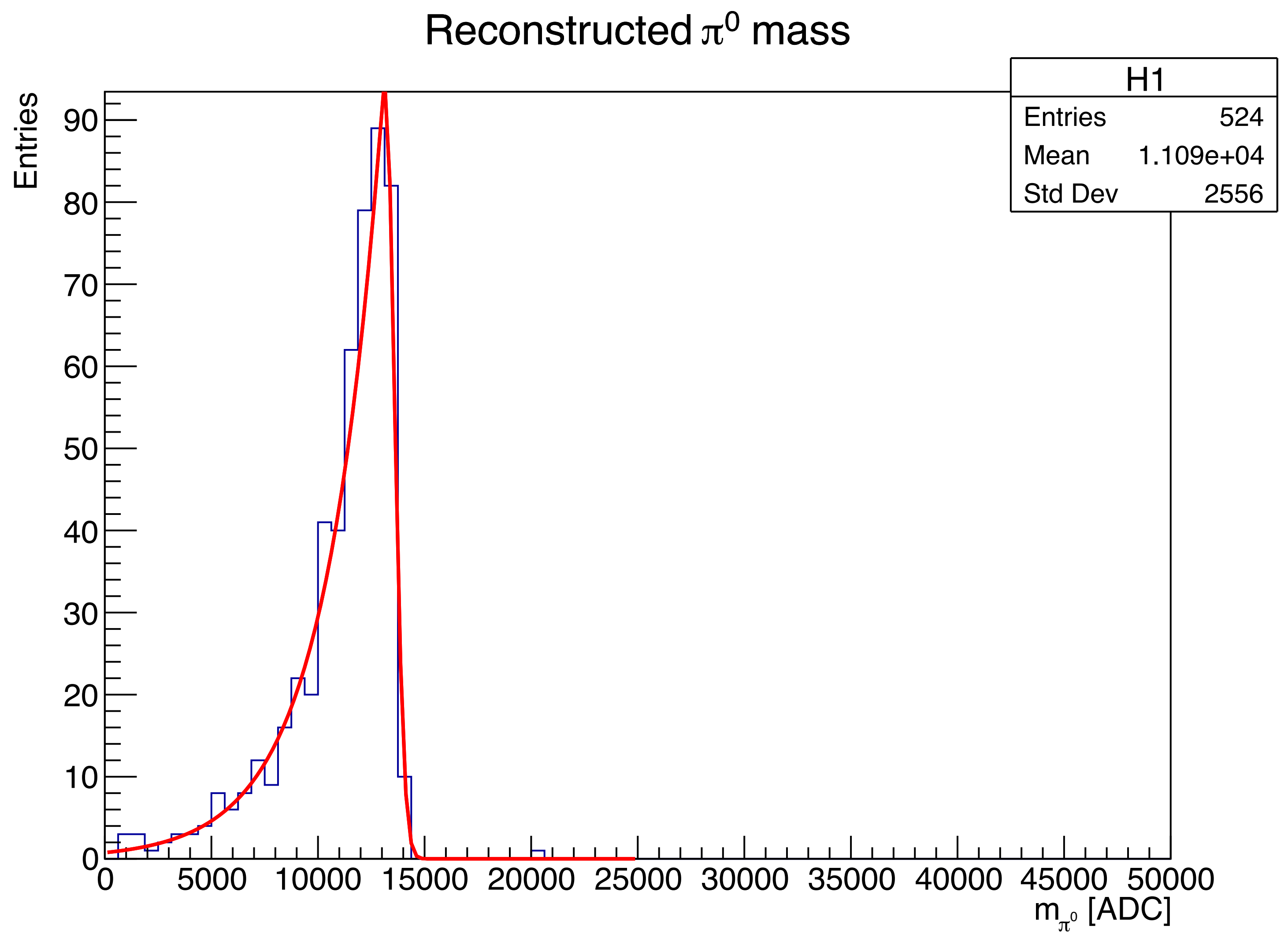
	energy true	energy reco (60% cut)	energy reco (no cut)
true angle	0.0	7.3	4.12
points method	2.5	11.4	11.5
lines method	7.7	14.1	18.2

MC

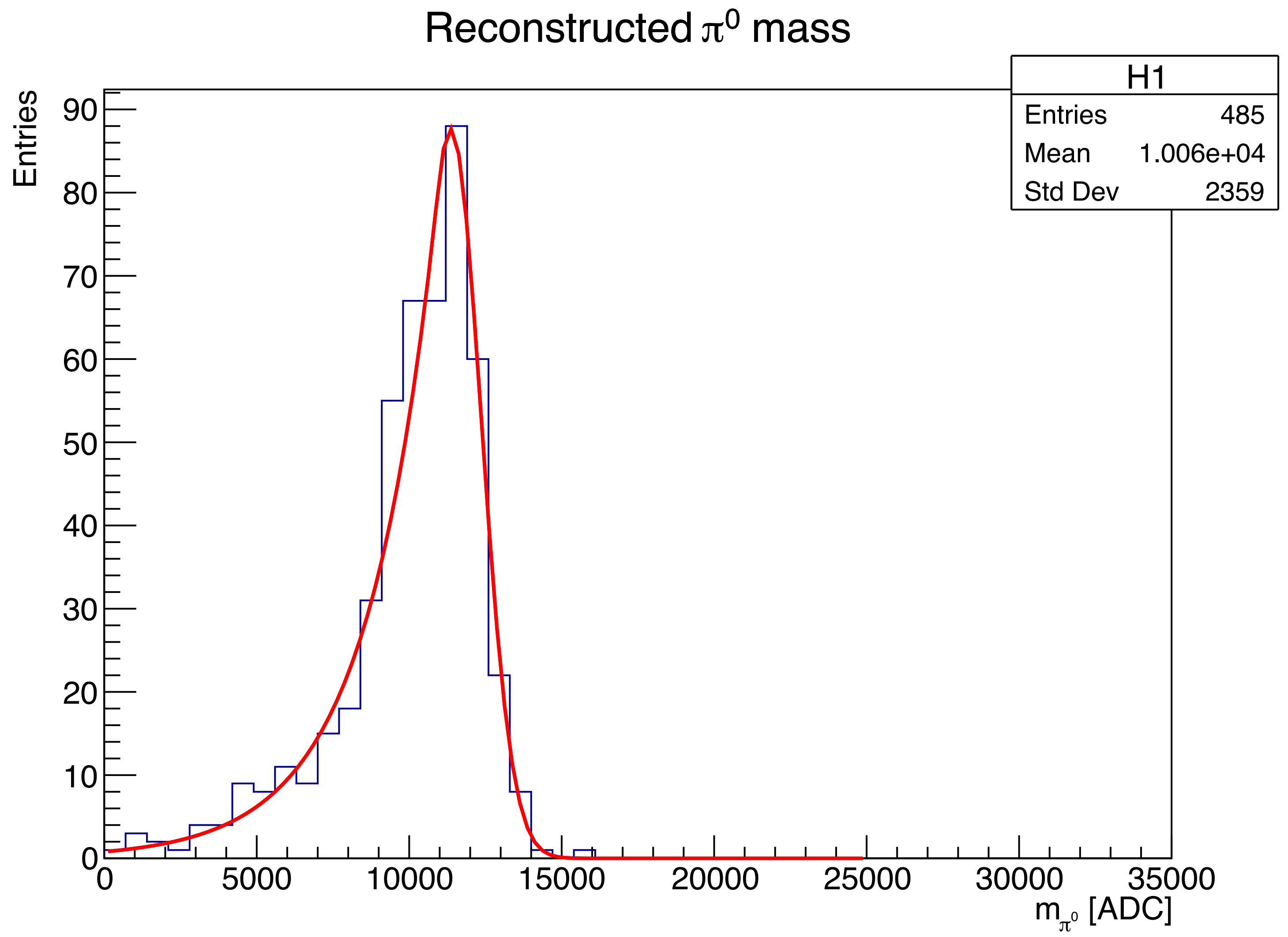
Histograms, no energy cut, 0.2 GeV



angle reconstructed with points



true angle



results are very sensitive to the fit, here crystal ball was used

angle reconstructed with lines