FLArE Simulation and Physics

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FPF6, CERN
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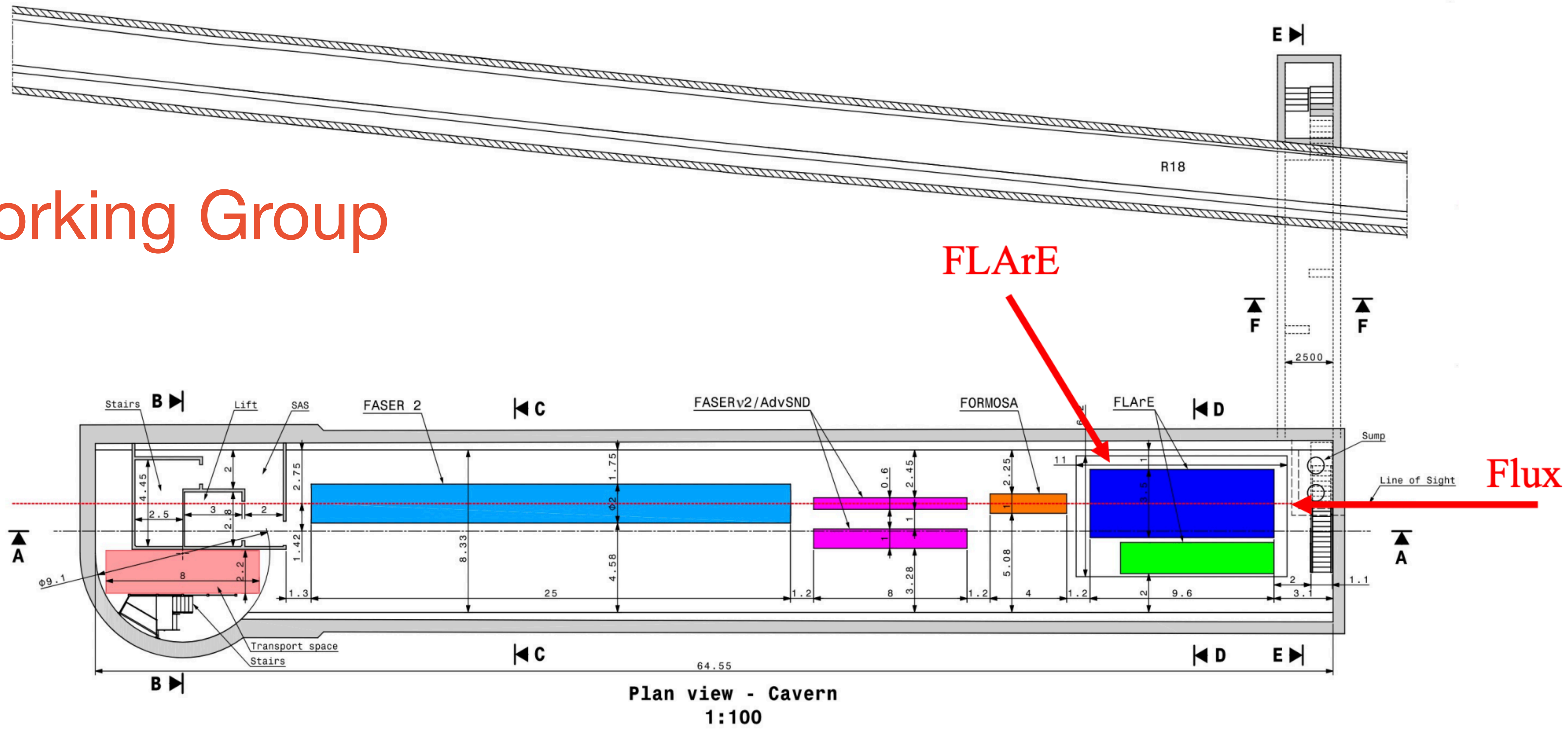
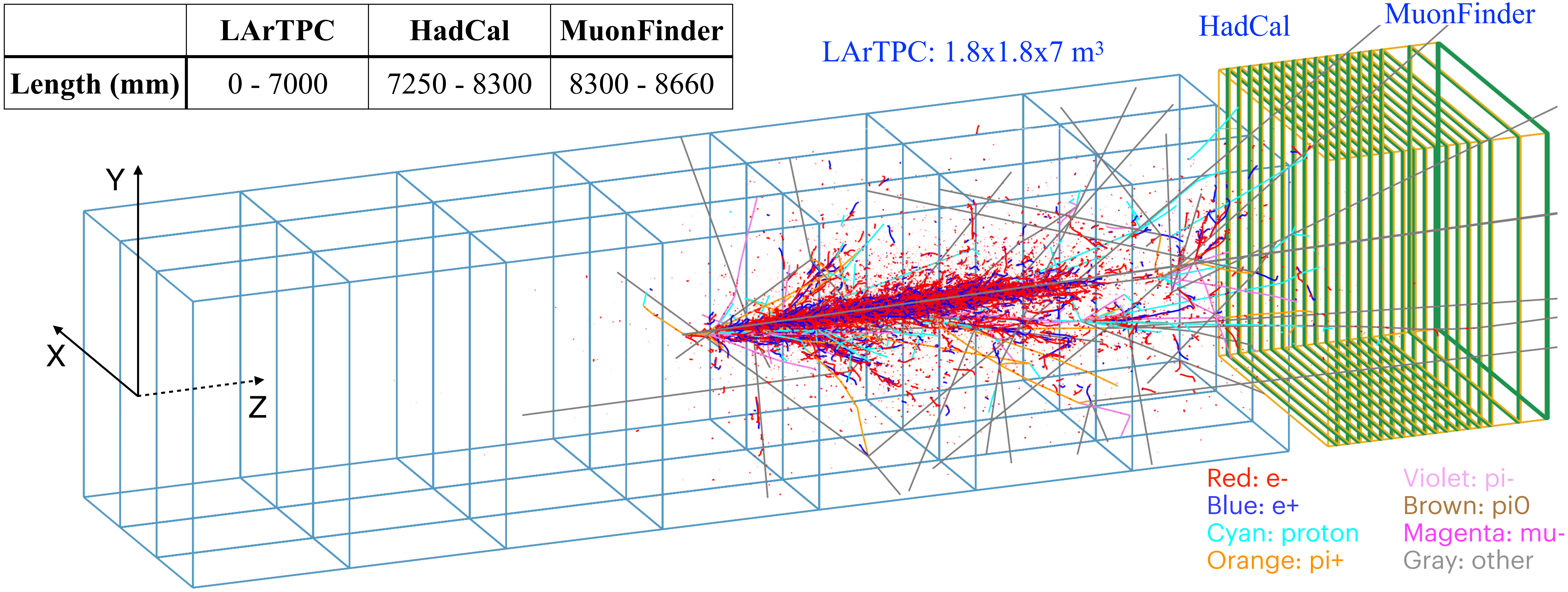


Introduction

- FLArE: a liquid argon time projection chamber (LArTPC) detector in FPF to detect neutrinos and dark matter from LHC
  - Fiducial mass of 10 tons (1x1x7 m^3) is needed for good statistics and sensitivity to dark matter
  - Detector needs to have good energy containment and resolution for neutrino physics
  - Muon and electron ID. Very good spatial resolution (~1 mm) for tau neutrino detection

	LArTPC	**HadCal**	**MuonFinder**
Length (mm)	0 - 7000	7250 - 8300	8300 - 8660

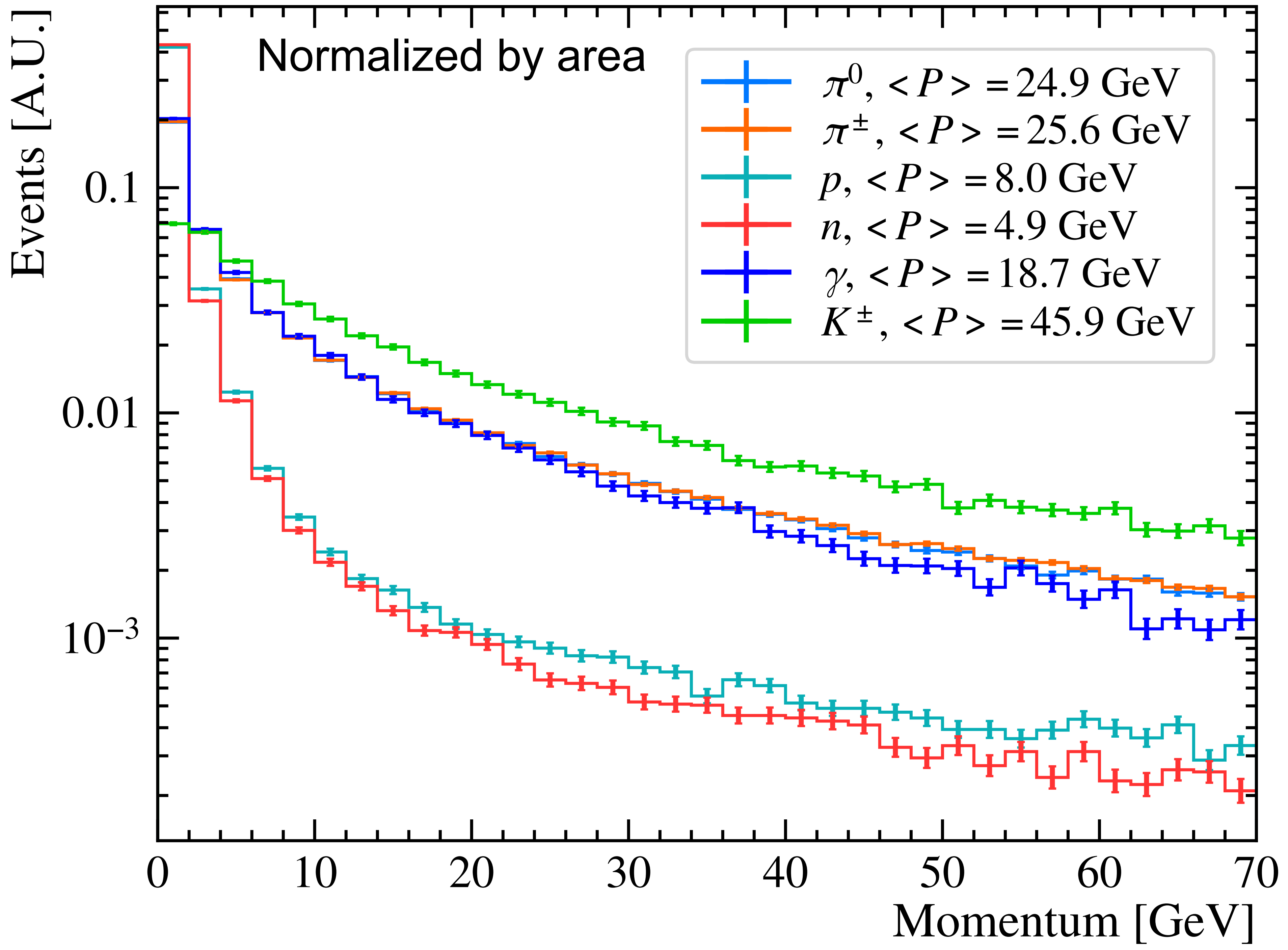


Introduction

- We're developing simulation and reconstruction for
  - Detector design optimization: geometry, pixel size, trigger …
  - Detector performance: spatial/energy resolution, containment, thresholds …
  - Physics sensitivity: tau neutrino, light dark matter scattering …
- Previous studies (FPF5, FLArE Far Forward Physics working group meeting, FLArE Technical group meeting)
  - The detector size is optimized for energy containment
  - The event classifiers trained on pseudo-reconstructed variables for ν_τ identification look promising
  - Preliminary phase space coverage studies have been carried out: energy and angle acceptance of muons
- Work in progress
  A. Study the effects of pixel size on particle identification
  B. Muon acceptance and momentum reconstruction with magnets at HadCal+MuonFinder, and FASER2
  C. Initial studies of a hardware-based trigger system

Pixel size studies

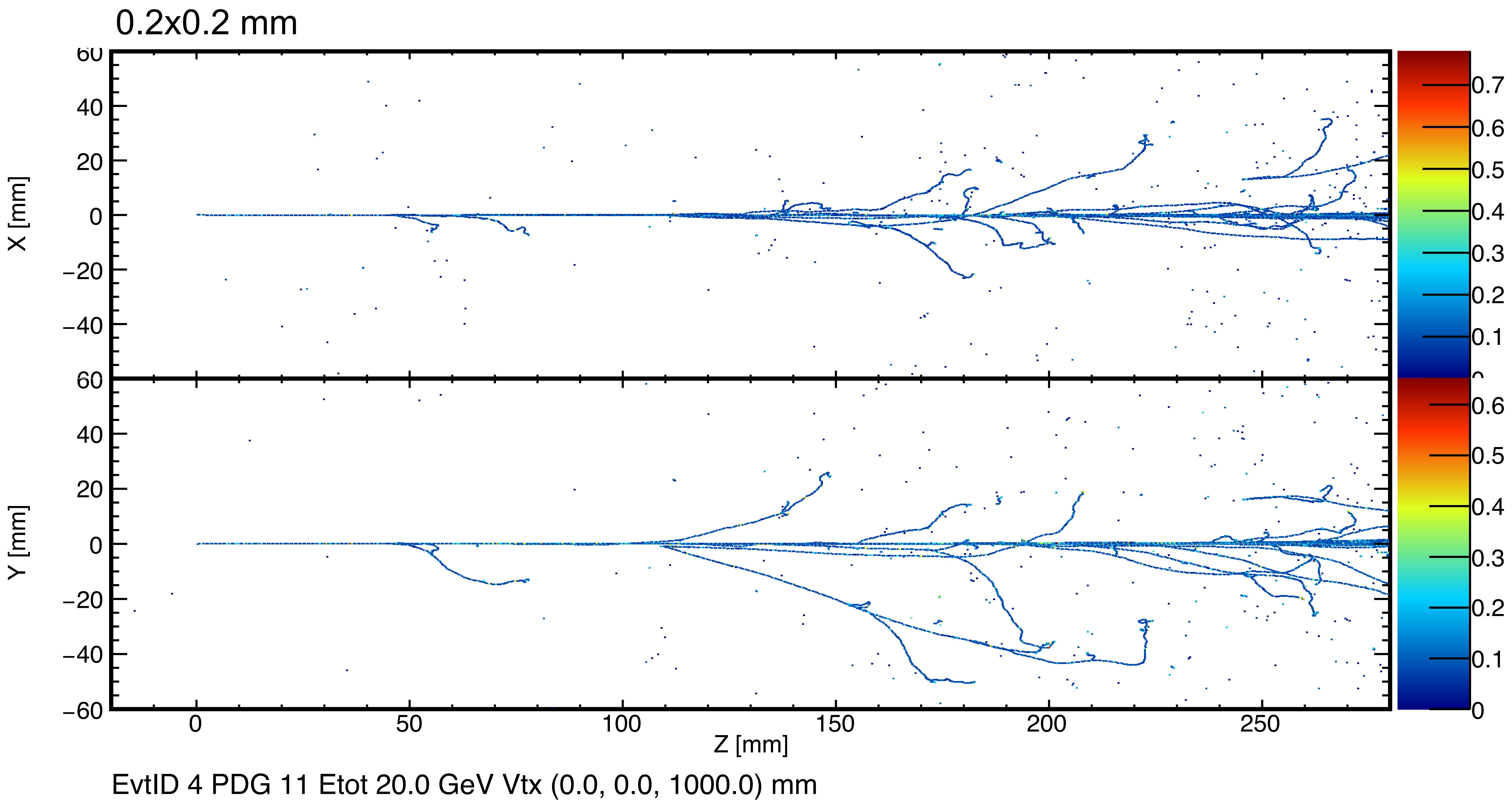
- The distribution of collected electrons depends on the diffusion effect and the pixel size
- For simplicity, the detector performance (particle ID capability) with different pixel sizes is studied with single particle events
- Single particle events are generated based on the population of the final state particles for all neutrino flavors



Single particle sample

	Momentum (GeV)
Electron	20
Muon	20
Tau	20
Gamma	20
Pizero	25
Piminus	25
Kminus	50
Proton	8
Neutron	5

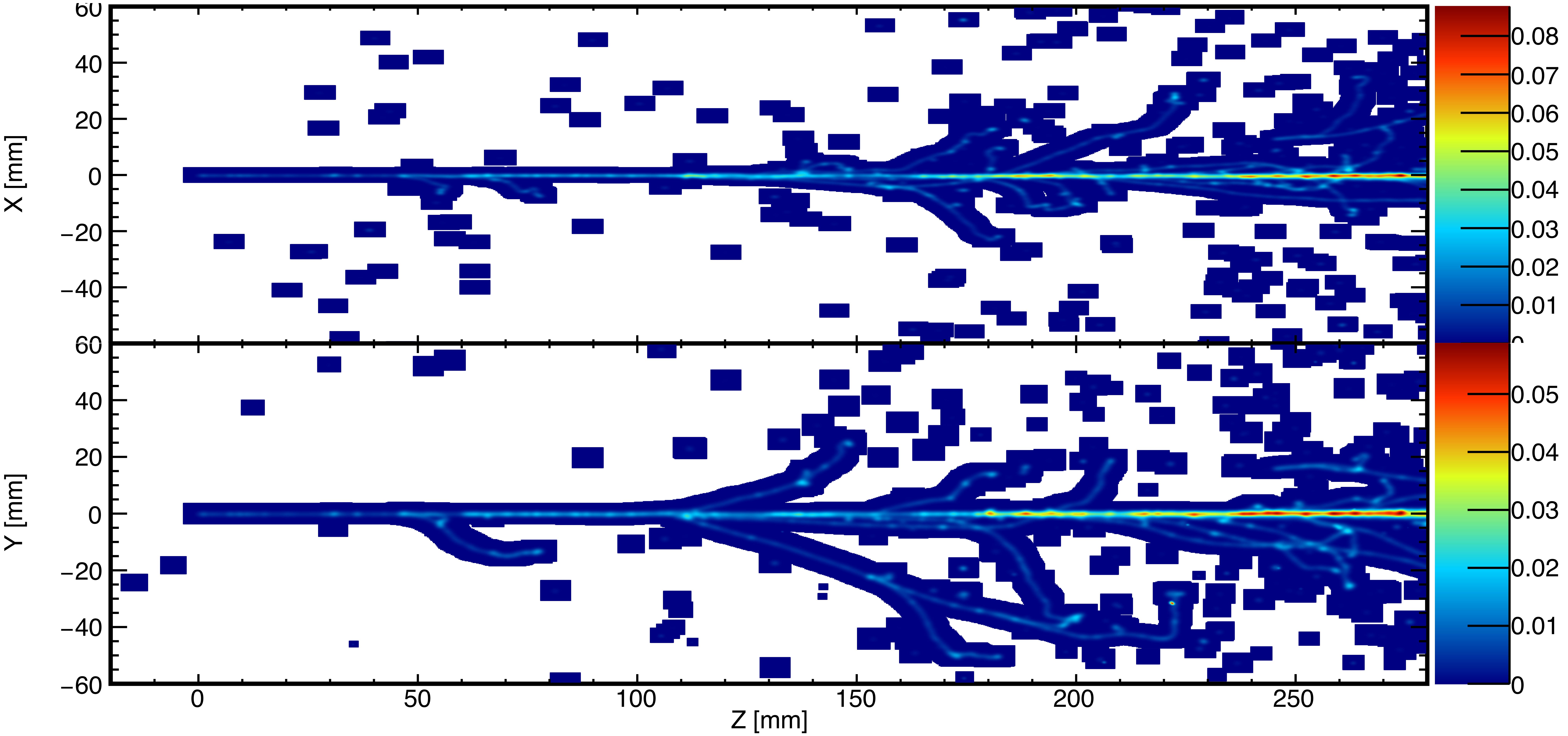
Electron



0.2x0.2 mm
X [mm]
Y [mm]
60
40
20
0
−20
−40
−60
0
50
100
150
200
250
Z [mm]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
EvtID 4 PDG 11 Etot 20.0 GeV Vtx (0.0, 0.0, 1000.0) mm

Electron with diffusion

0.2x0.2 mm

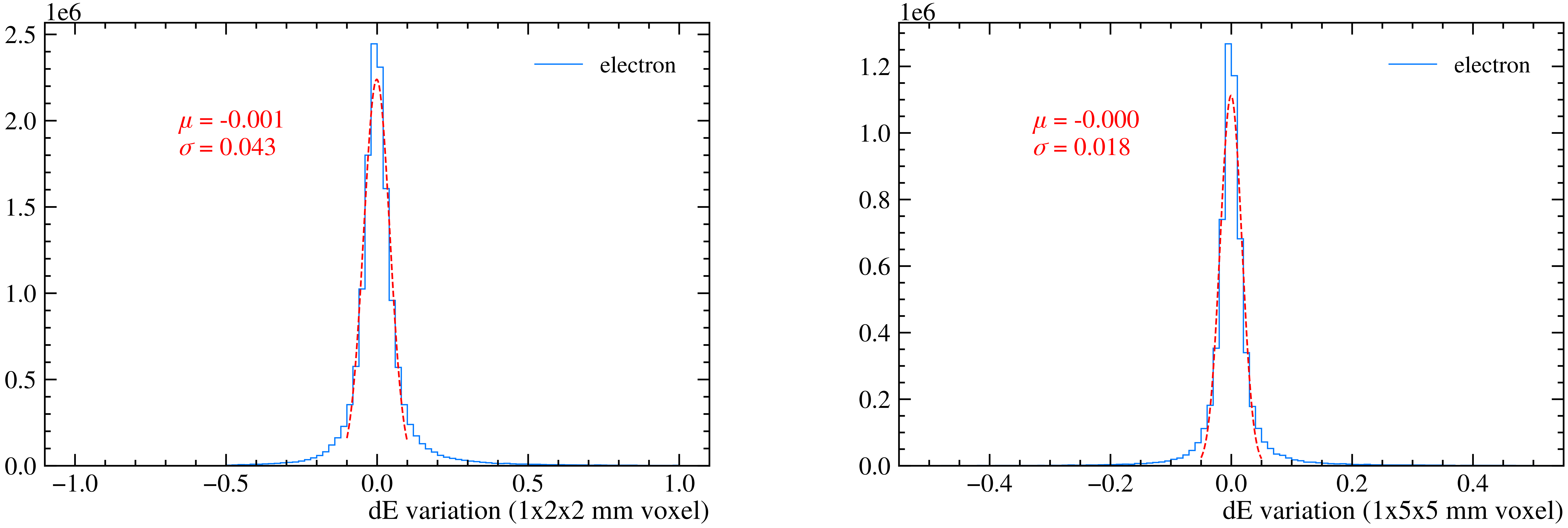


EvtID 4 PDG 11 Etot 20.0 GeV Vtx (0.0, 0.0, 1000.0) mm

dE variation of each voxel

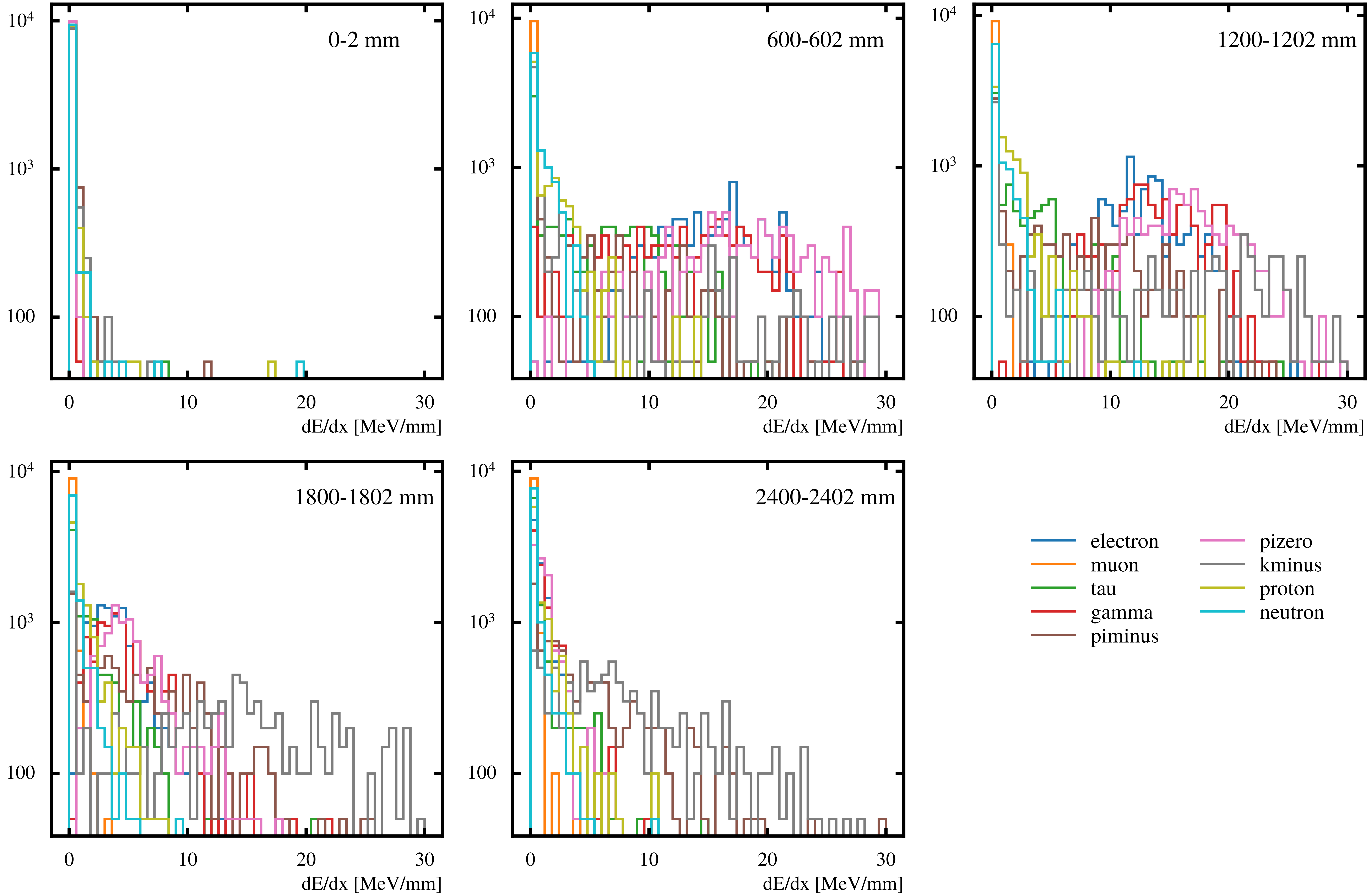
- Mimic difference pixel sizes by using different binning of the Y-Z plane (2x2 mm^2 and 5x5 mm^2)
- The distribution of the number of collected electrons on pixels can be empirically obtained

$$\frac{dQ}{dX} = \frac{\ln[\beta \frac{dE}{dX} + \alpha]}{\beta W_{\text{ion}}}$$



dE/dx start from the vertex

- Distance to the vertex: 0 - 3000 mm, with 2 mm step



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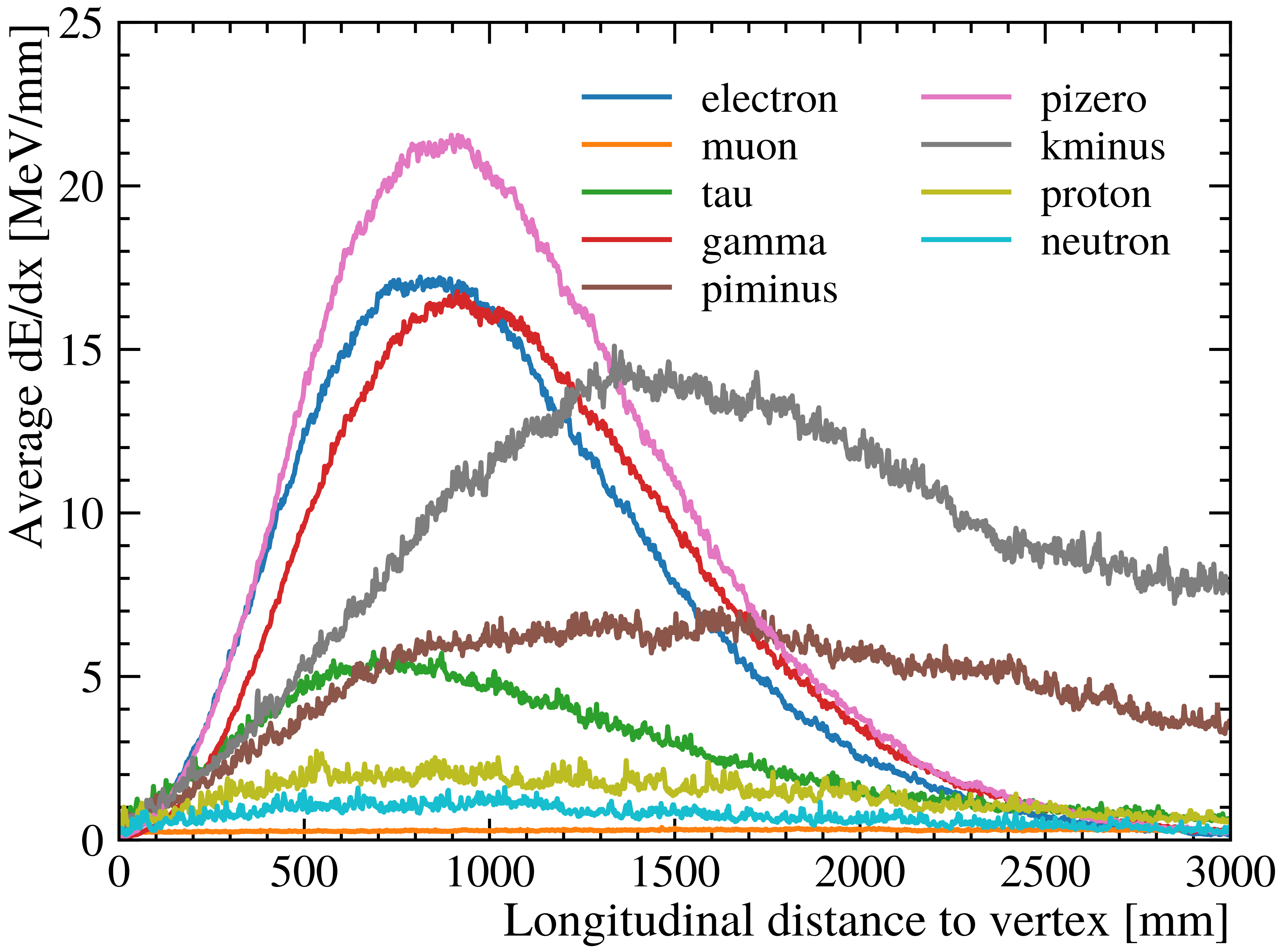
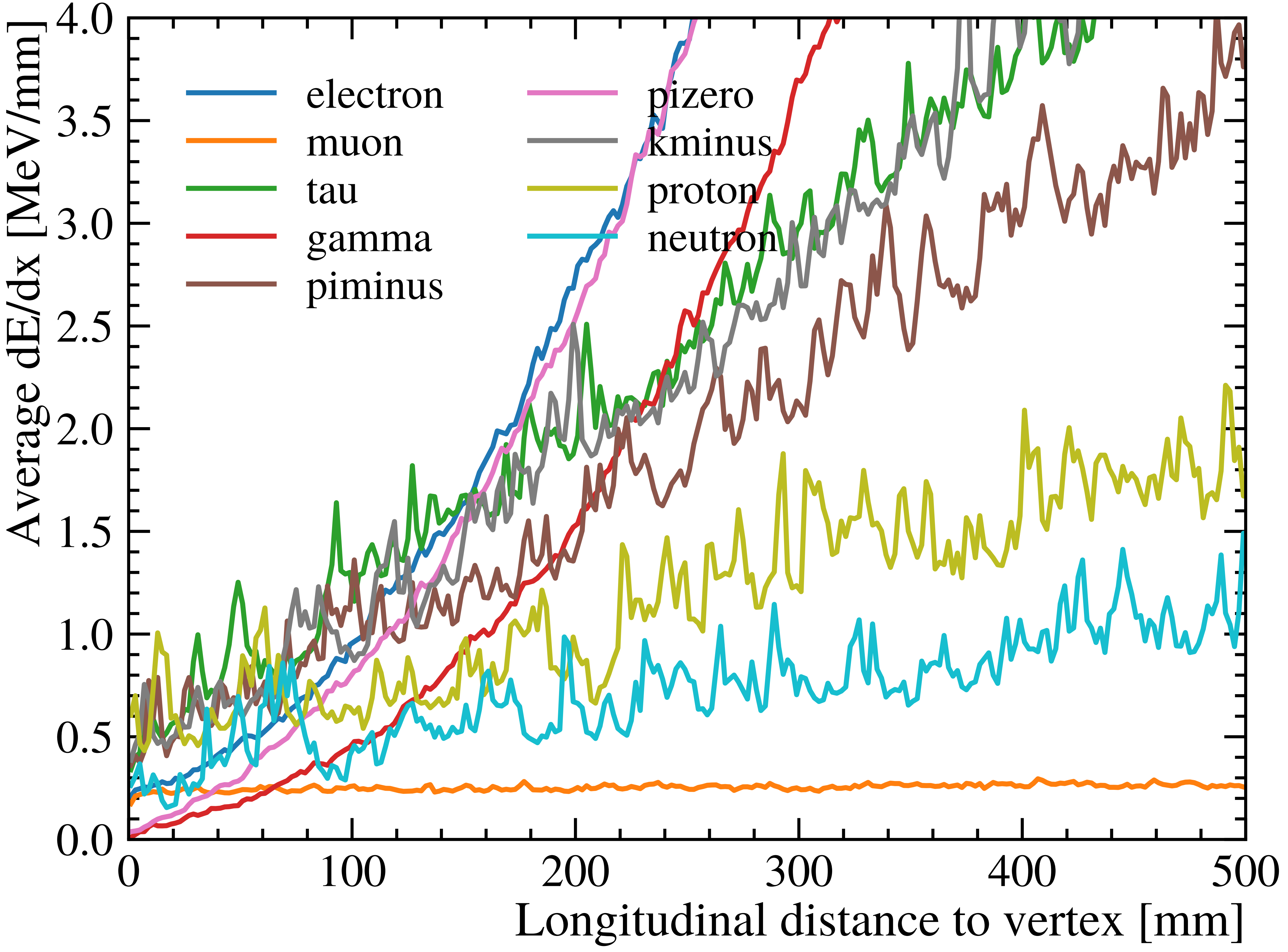


Zoom in to (0, 50) cm

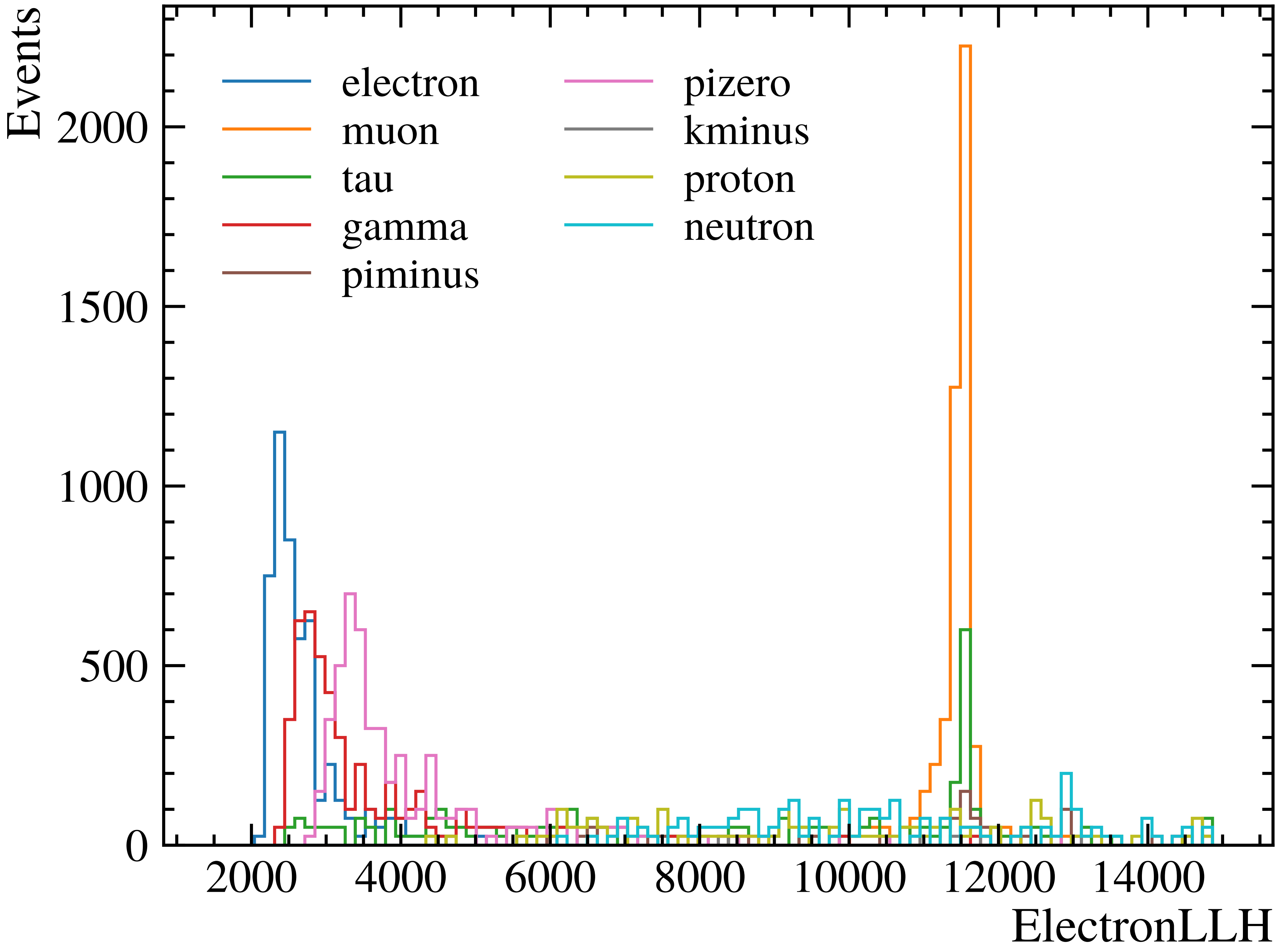


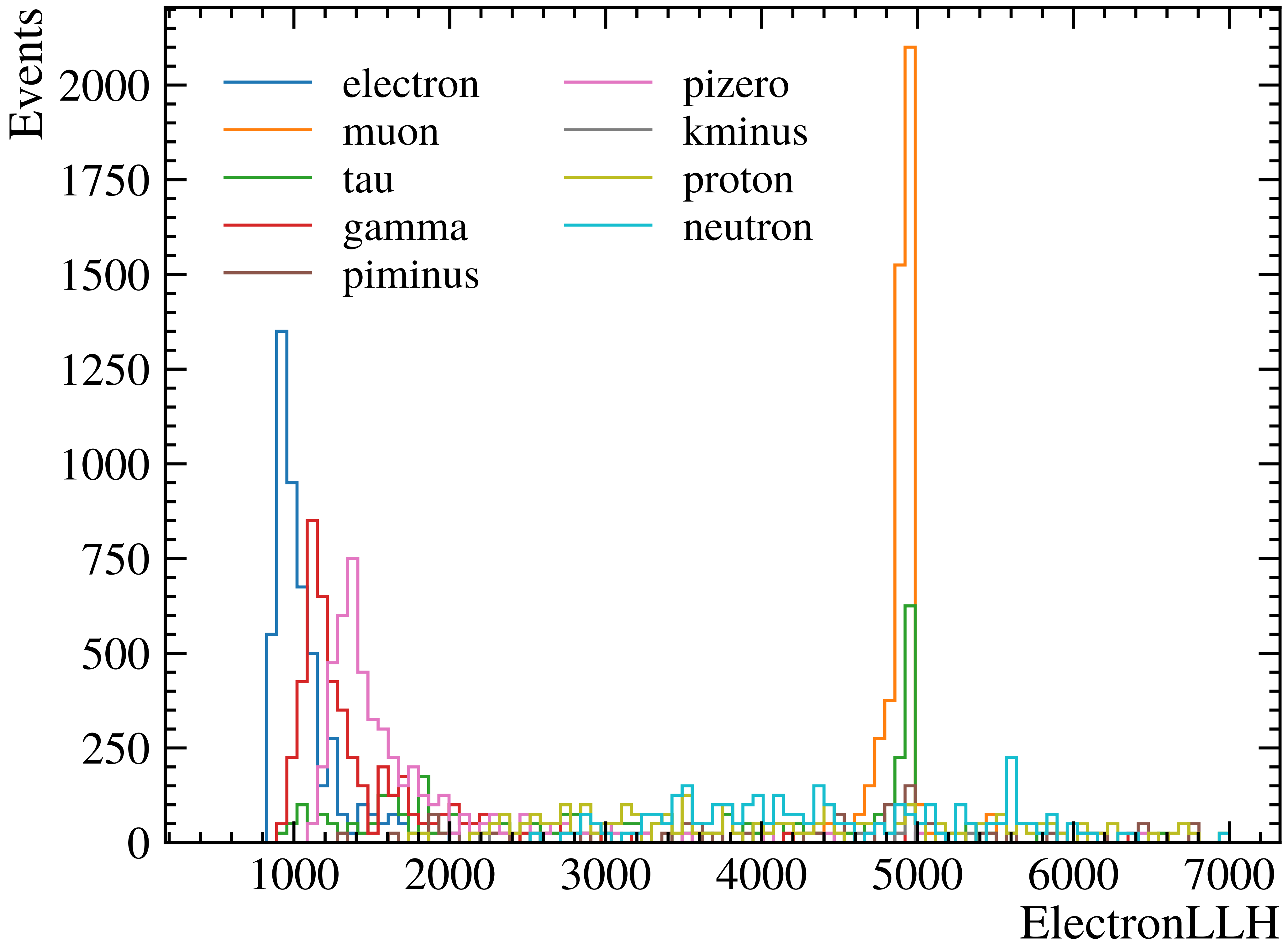
dE/dx start from the vertex

- Construct a log-likelihood based on the dE/dx distribution in the longitudinal direction of each type of particle
- Use these 9 log-likelihood functions as the input of a boosted decision tree for particle identification

$$-\mathrm{LLH} = \sum_{i=1}^{1500} \ln(P_i(\mathrm{dE/dx}\,|\,\mathrm{type}, \mathrm{step\ in\ 2\ mm})$$

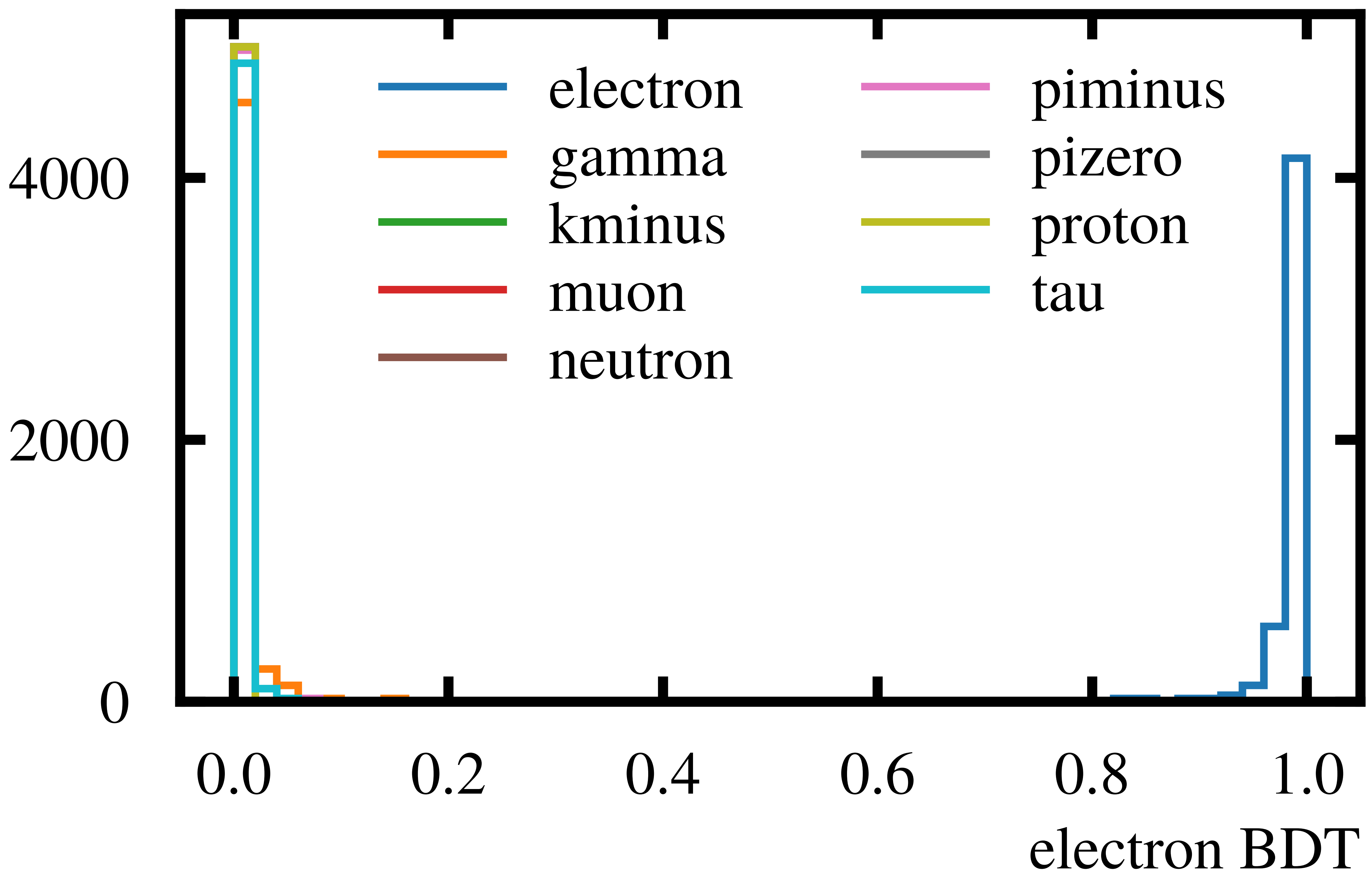
$$-\mathrm{LLH} = \sum_{i=1}^{600} \ln(P_i(\mathrm{dE/dx}\,|\,\mathrm{type}, \mathrm{step\ in\ 5\ mm})$$

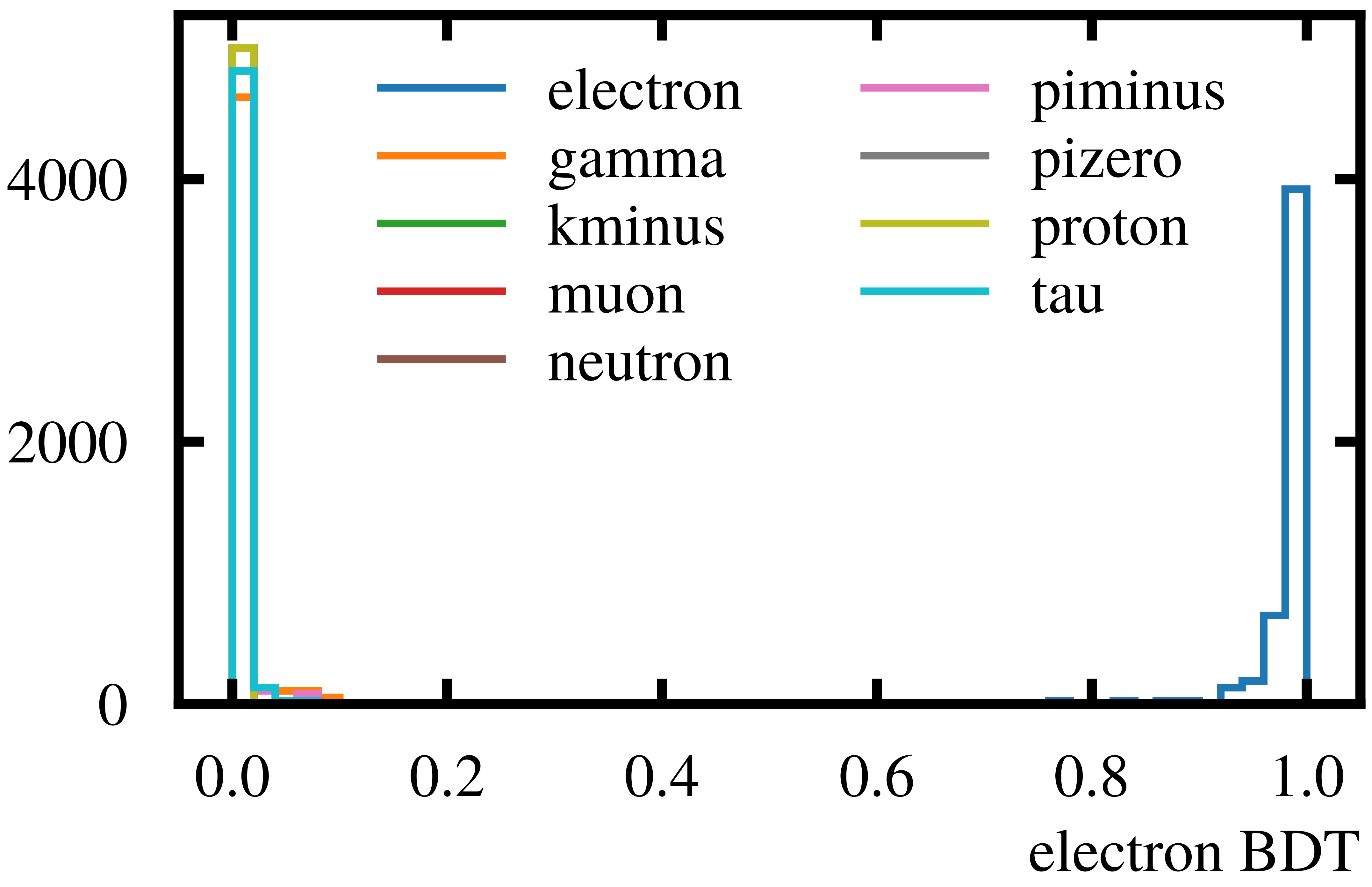




BDT Score

- The BDT output the scores for 9 classes, here are the examples for the probability of predicting the particle to be an electron
  - Will quantity the identification capability
  - Will extend this method for neutrino identification


$1 \times 2 \times 2$ mm

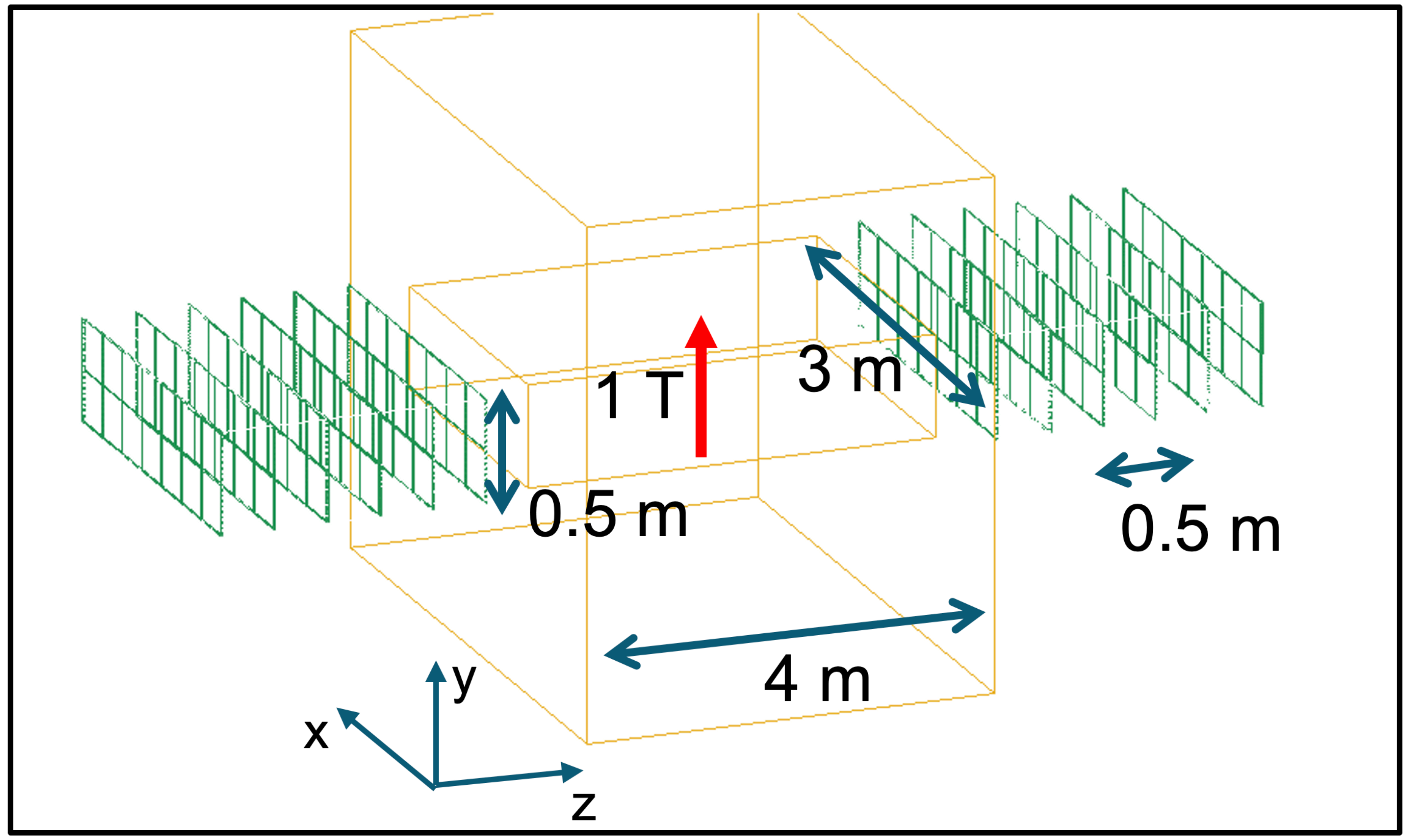

$1 \times 5 \times 5$ mm

Muon momentum reconstruction

Matteo (BNL)

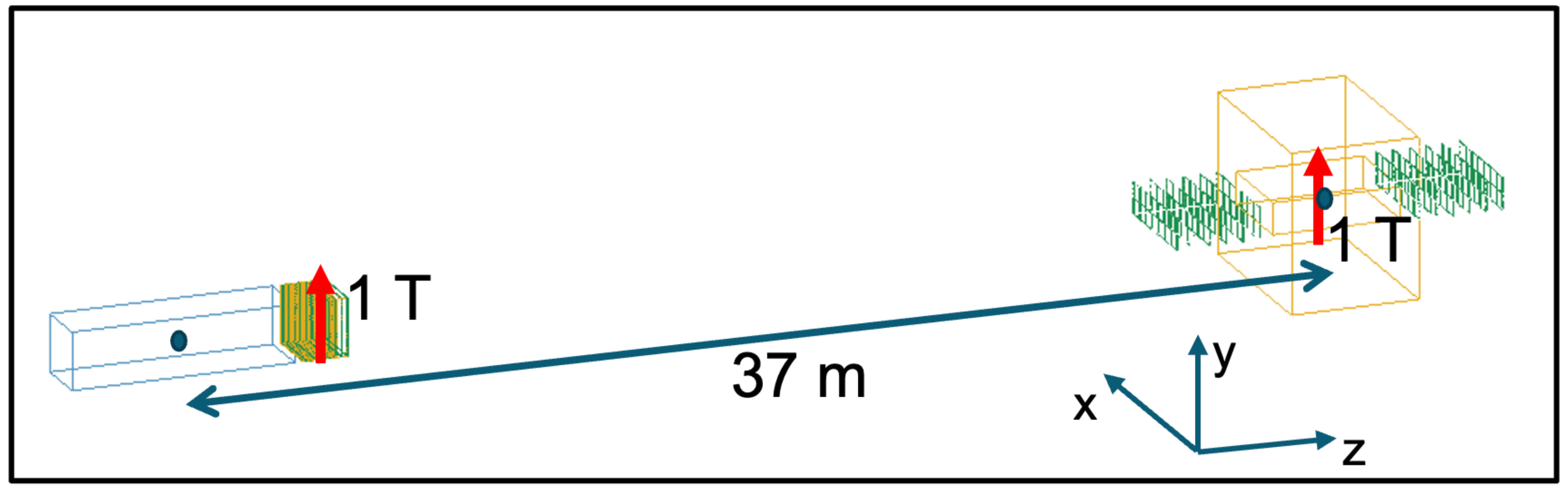
- Muons can easily pass through the detector, with a small portion of the energy deposited in the detector
- Propose to cooperate with FASER2's magnet, along with the magnetized HadCal and MuonFinder, in order to precisely reconstruct the muon momentum

[FASER2 magnet geometry]

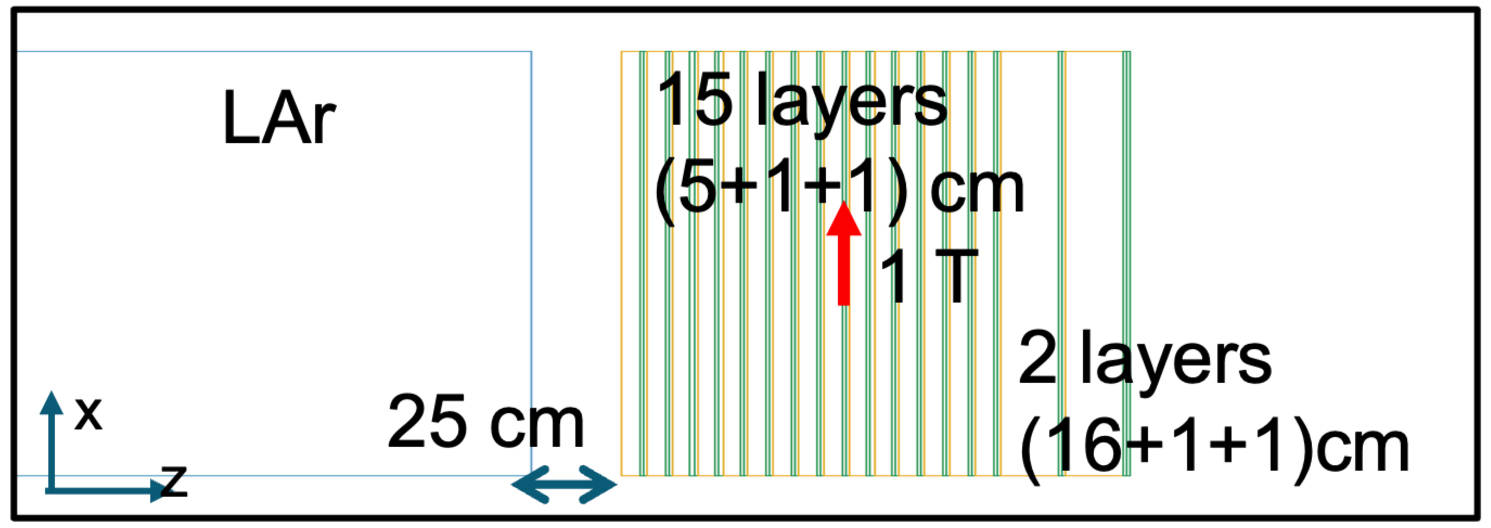


Rectangular window: 3 m x 0.5 m (4 Tm)
6 tracking stations, 50 cm apart
B = 1 T (fixed)

Complete geometry in the simulation:

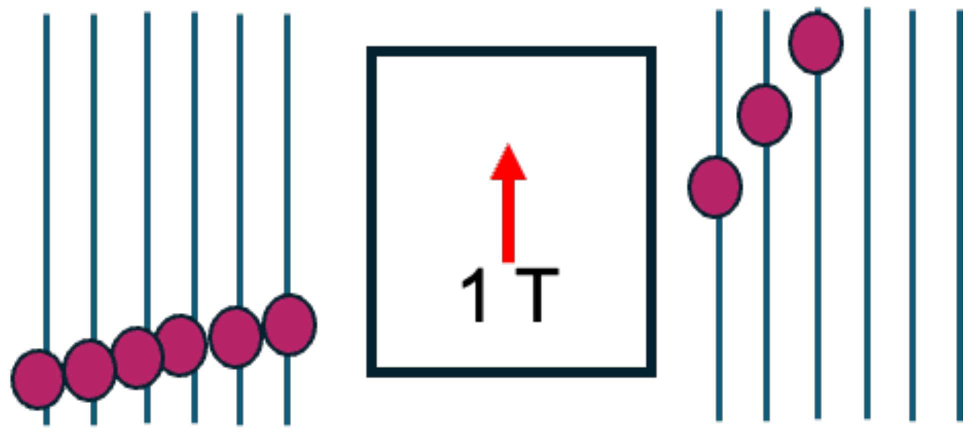


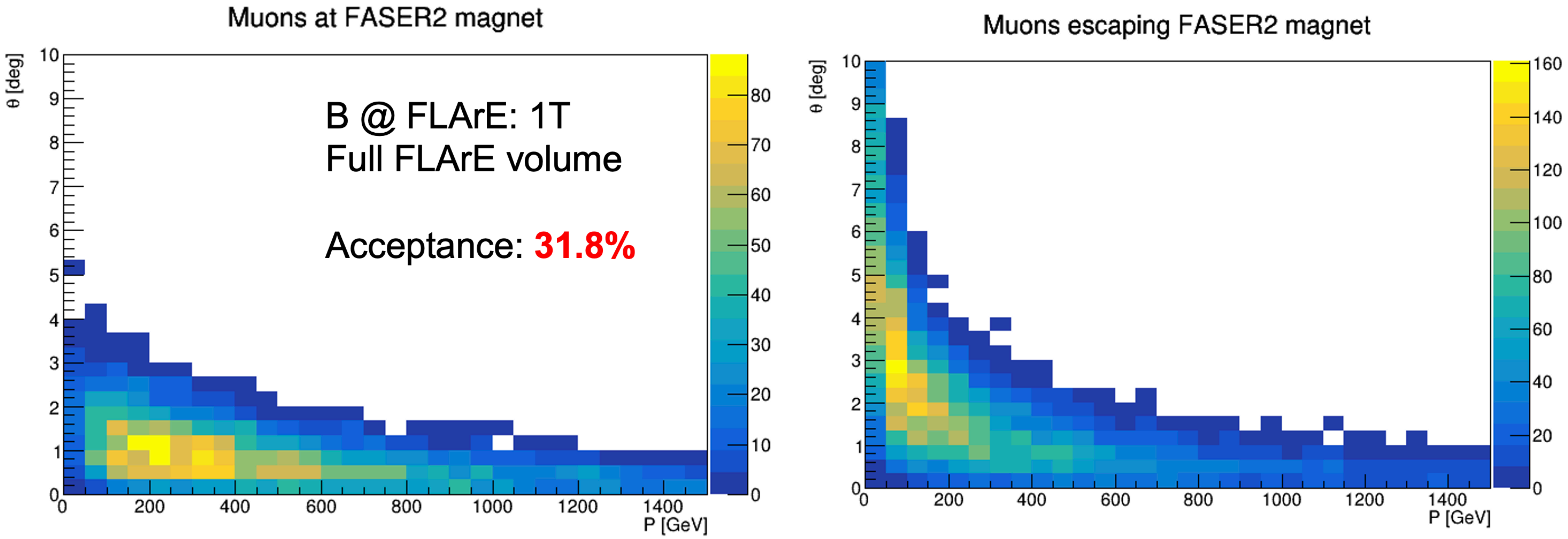
FLArE center to magnet center: 36.9 m
Magnetized HadCatcher and MuonFinder
B = 1 T (default, but still open to optimization)



Muon acceptance to the FASER2 magnet

Requirement: > 0 hit before magnet && > 2 hits after magnet





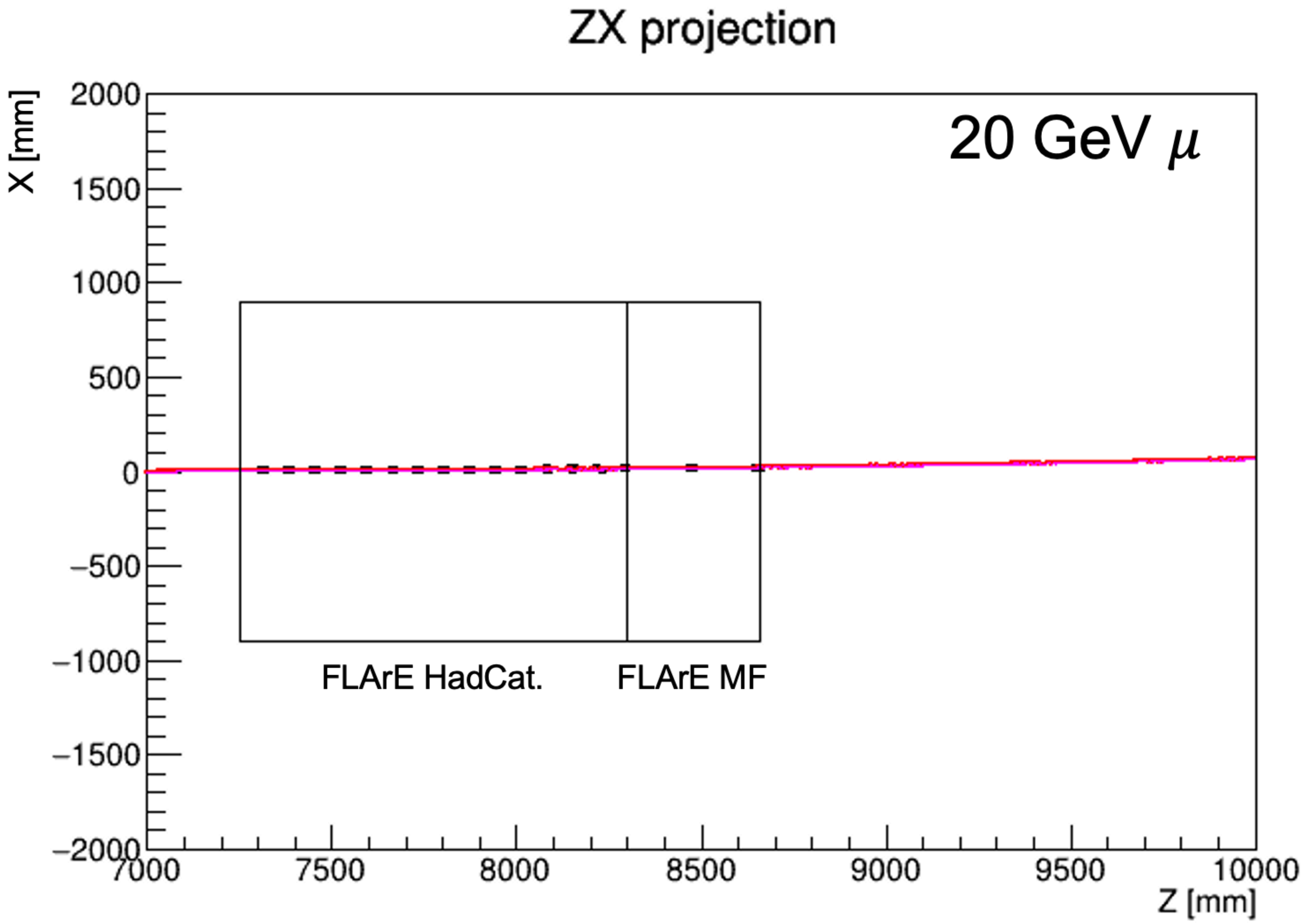
B @ FLArE: 1T
Full FLArE volume

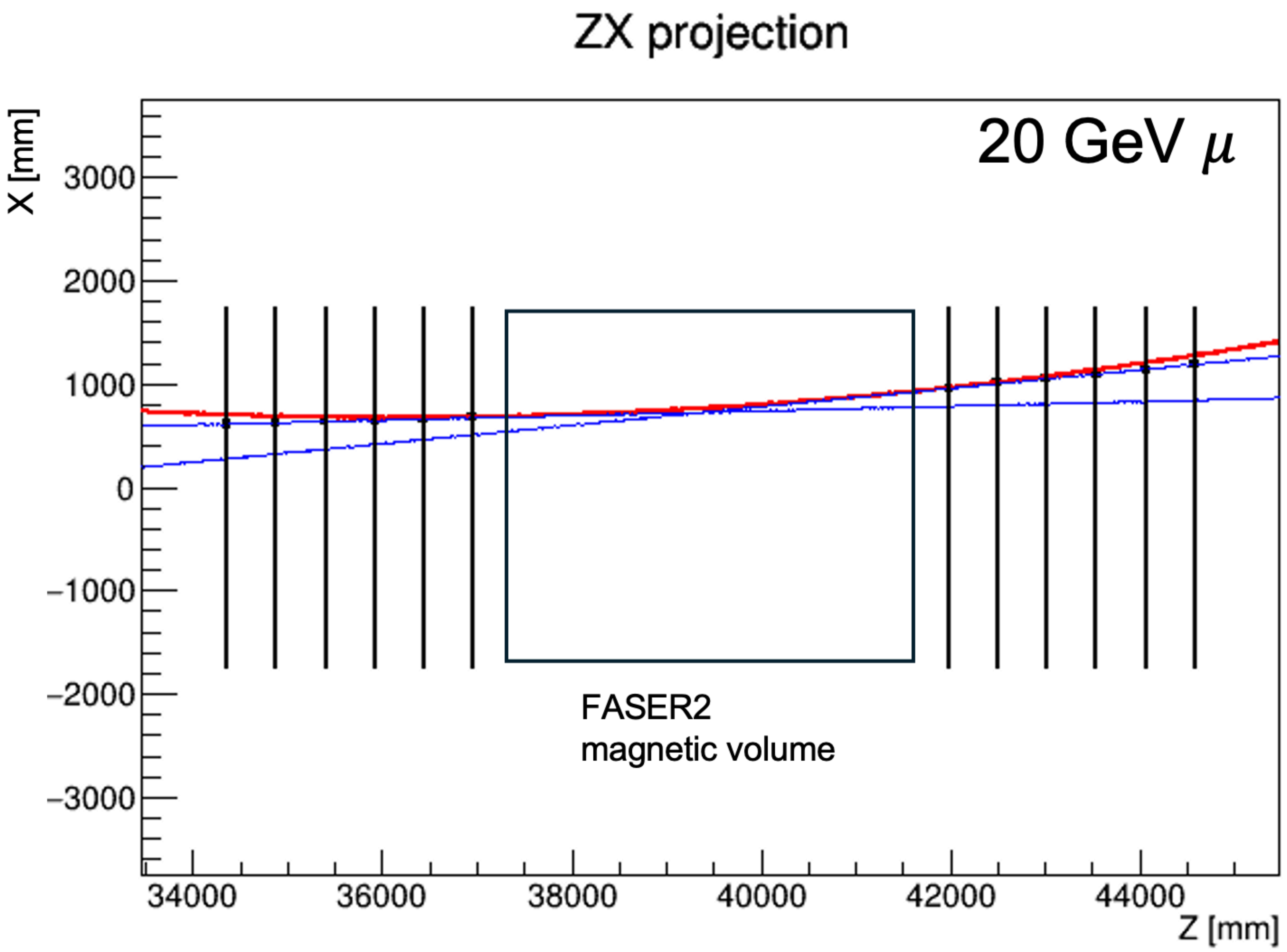
Acceptance: **31.8%**

* Different B-field values @ FLArE have negligible effect on acceptance to the FASER2 magnet

Transverse momentum reconstruction

- First attempts at p_T reconstruction, using MC hits (no smearing!)
- Two different strategies: analytical circular fitting @ FLArE [ref], analytical circle extraction from track bending before and after the magnetic volume @ FASER2.

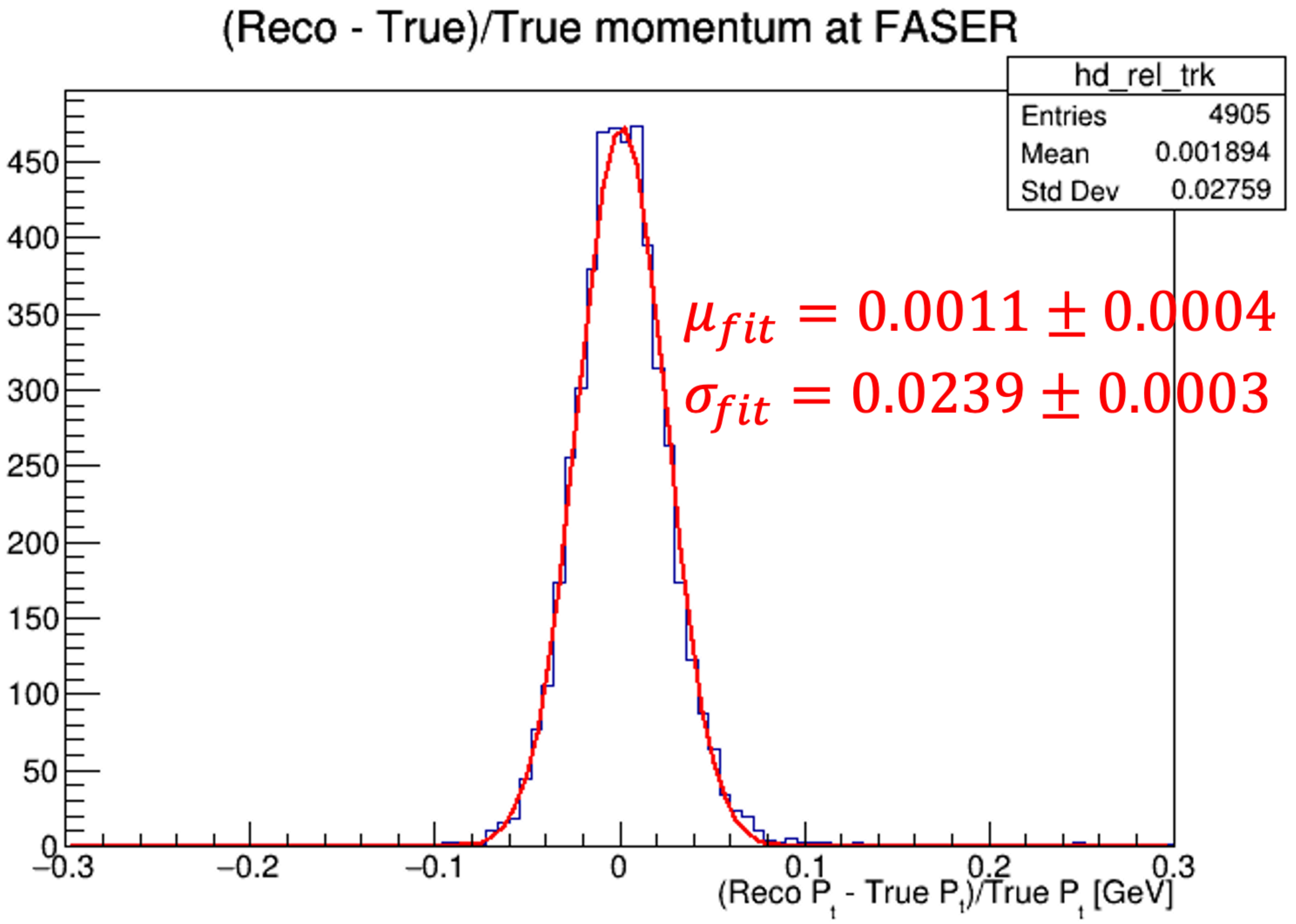




Transverse momentum reconstruction

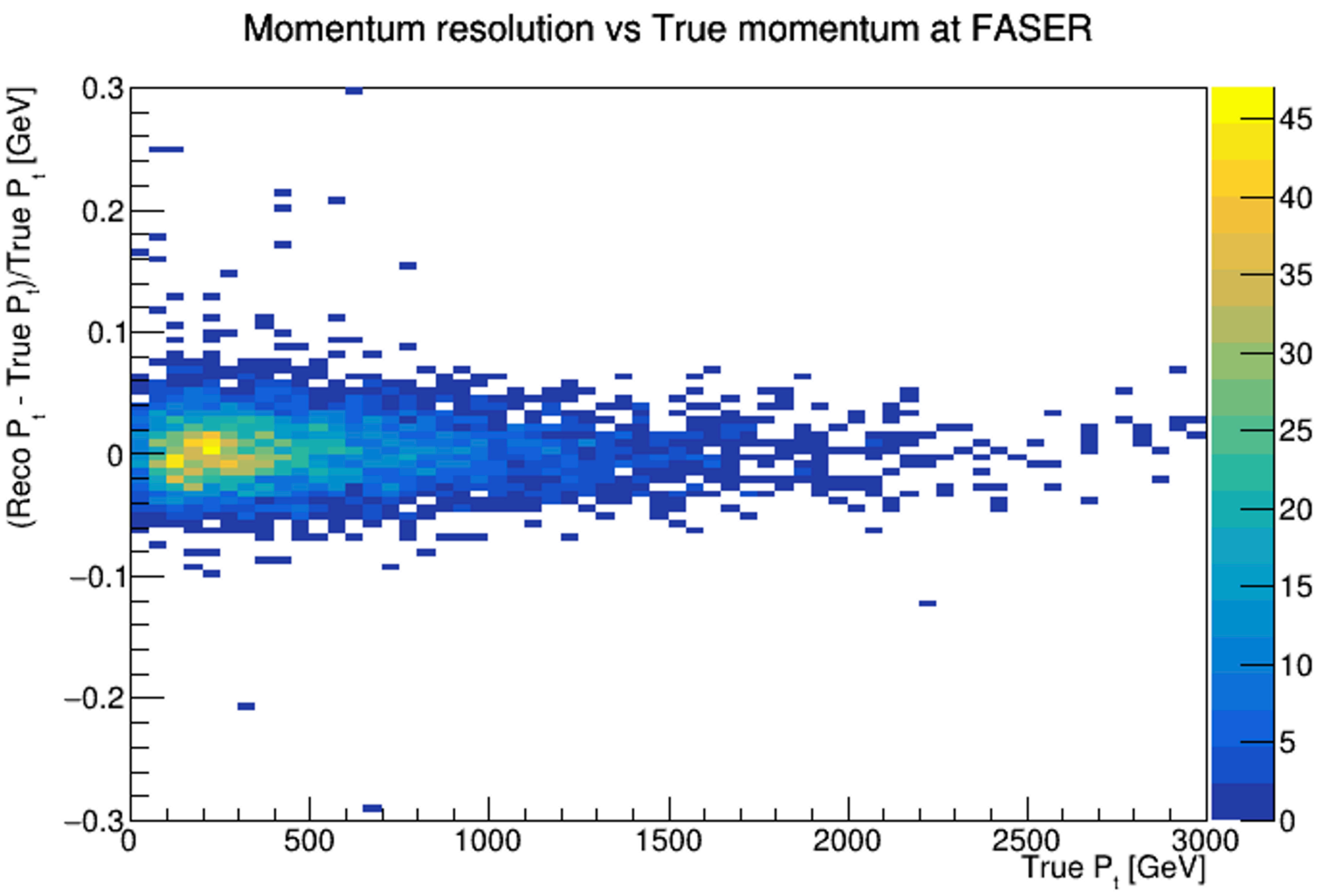
- Muon transverse momentum reconstructed at FASER2 vs MC truth momentum.
- Performance independent of B-field @ FLArE.

B @ FLArE: 1T
Full FLArE volume



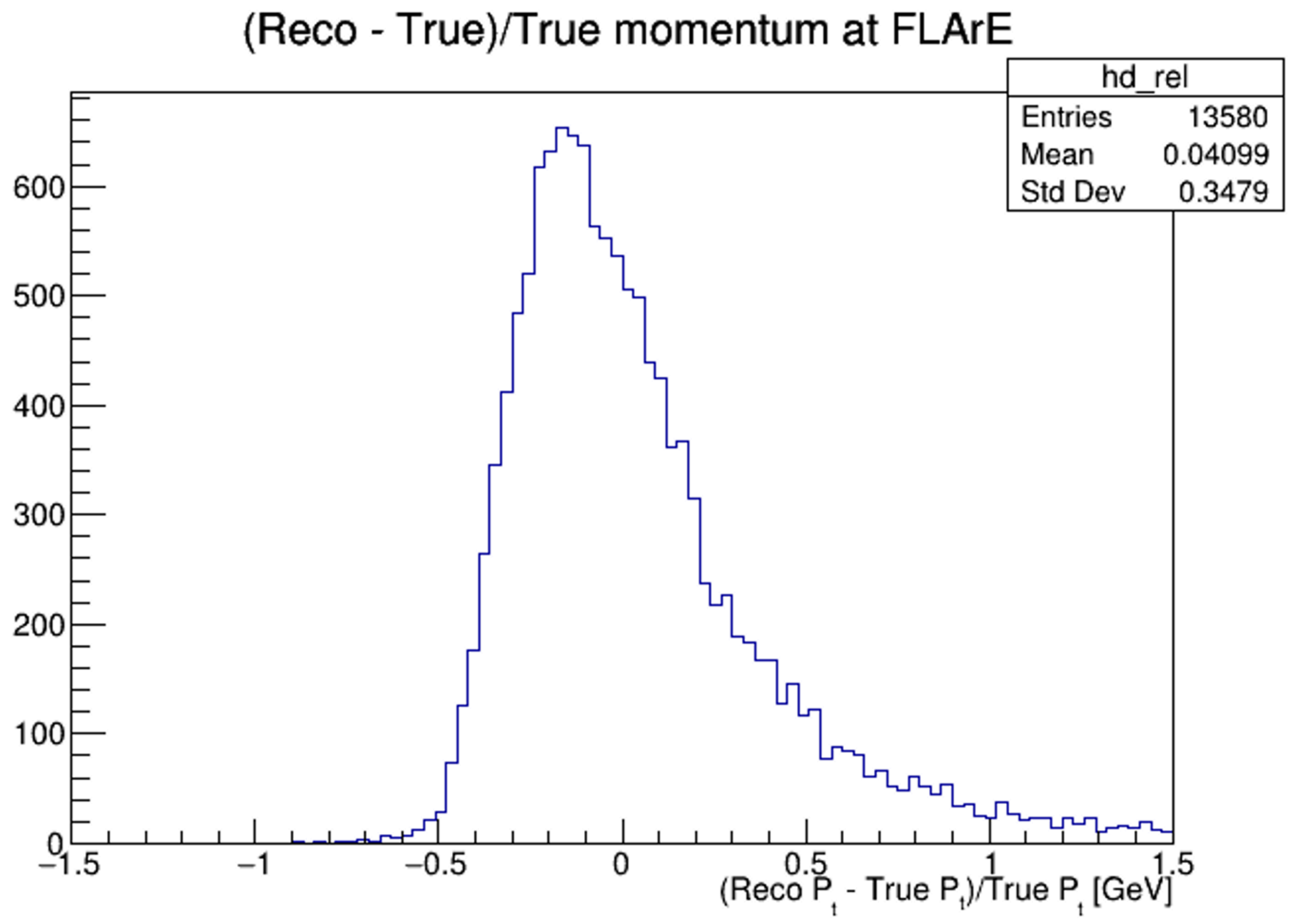
$\mu_{fit} = 0.0011 \pm 0.0004$

$\sigma_{fit} = 0.0239 \pm 0.0003$

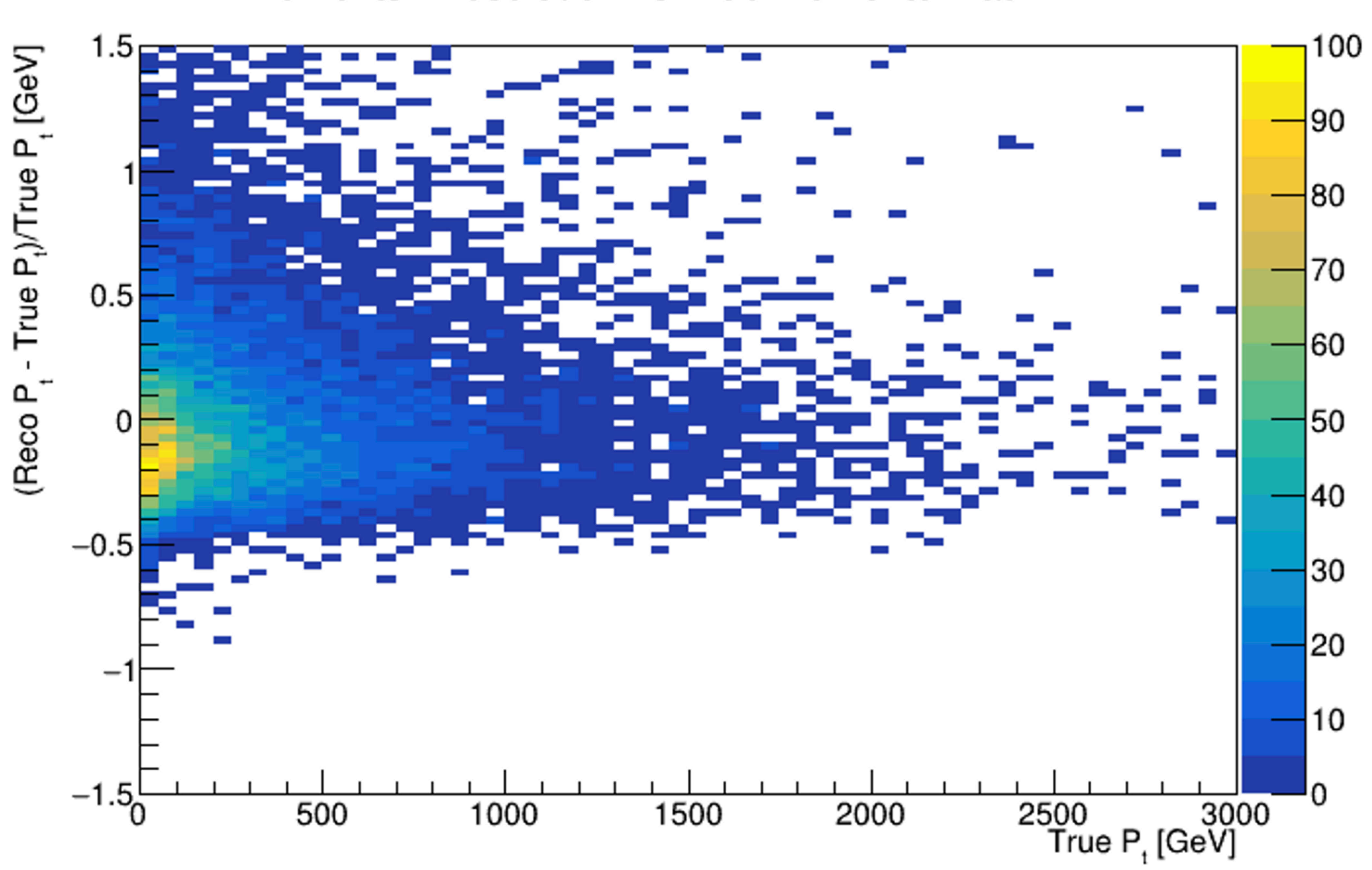


Transverse momentum reconstruction

- Muon transverse momentum reconstructed at FLArE vs MC truth momentum.
- Curvature is hardly visible → requires optimization of B-field and sensitive layers.



B @ FLArE: 1T
Full FLArE volume



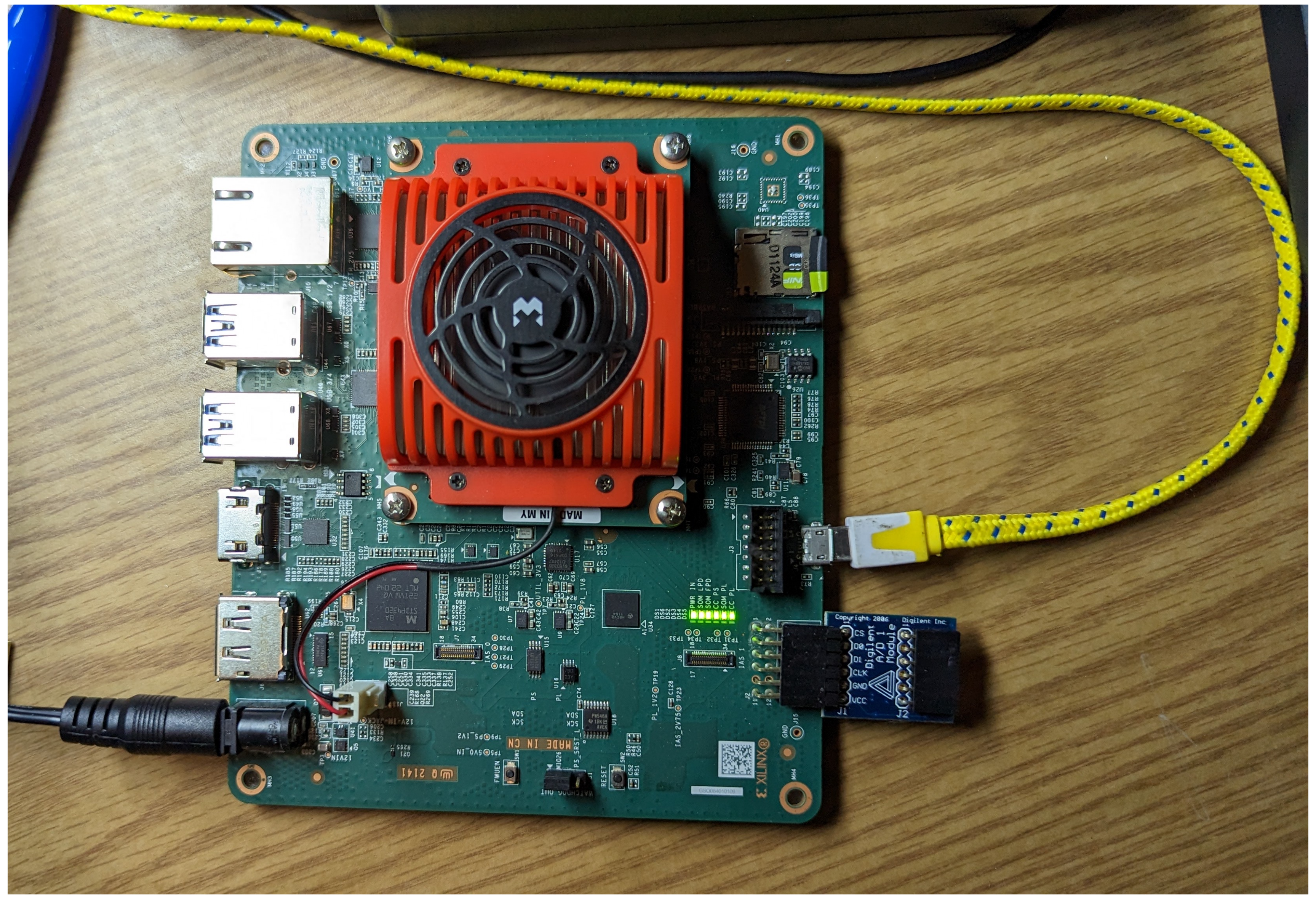
Hardware-based trigger studies

Alejandro (UCI)

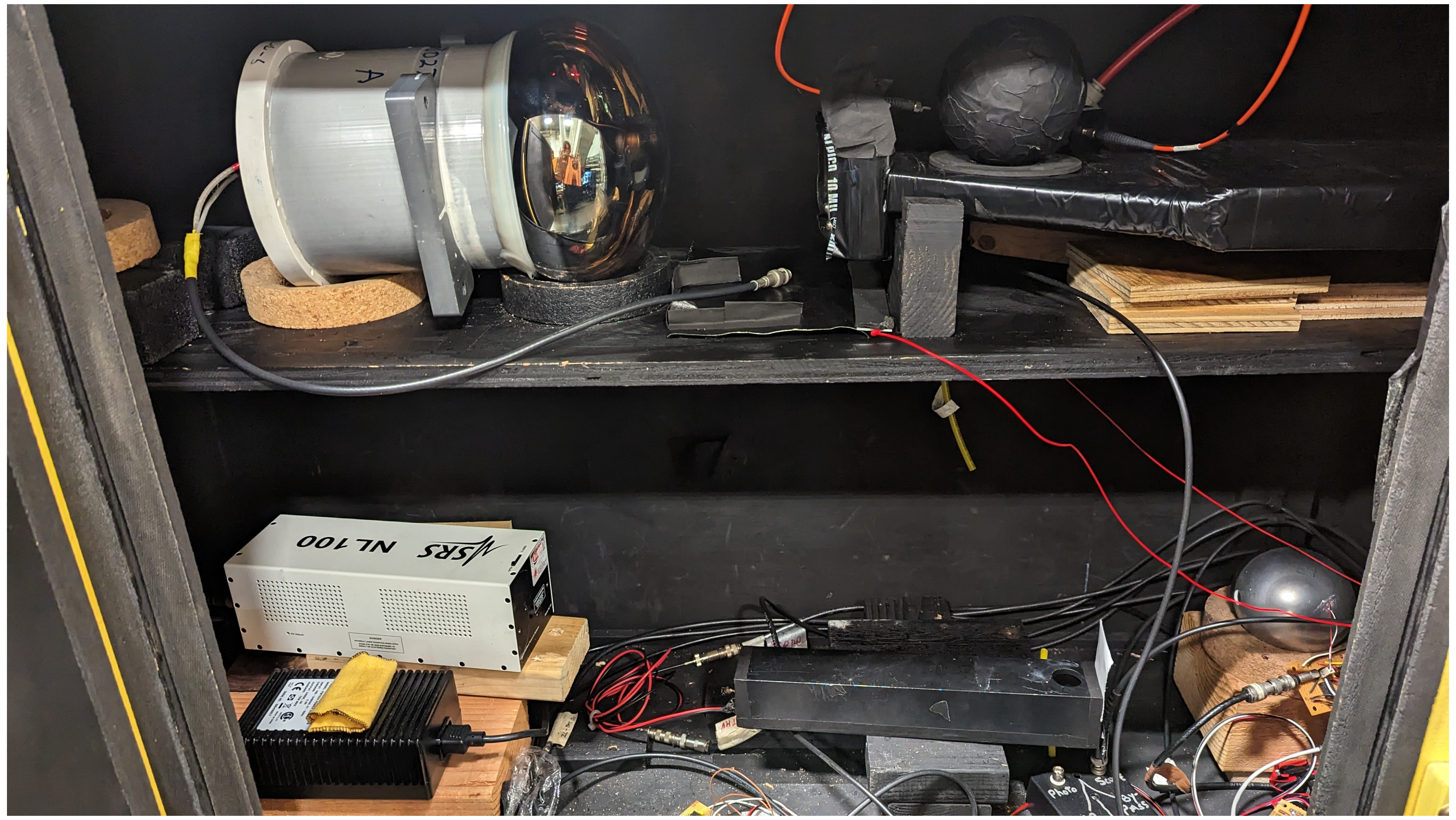
- FLArE trigger system will need to identify signal events from muon background.
  - 0.5 Hz/cm^2 muon flux from ATLAS collisions gives 5 kHz rate in the 1m x 1m x 7m fiducial region
- Want to match signal events to ATLAS bunch crossings
  - Need fast trigger decisions to meet HL-LHC ATLAS 6 μs (30 μs) L0 (L1) trigger latency requirements
- Will try combination of traditional/ML methods for SiPM/event-level trigger decisions on GPU/FPGA.

Hardware setup

Connected Xilinx Kria KV260 FPGA development board to GPU group server

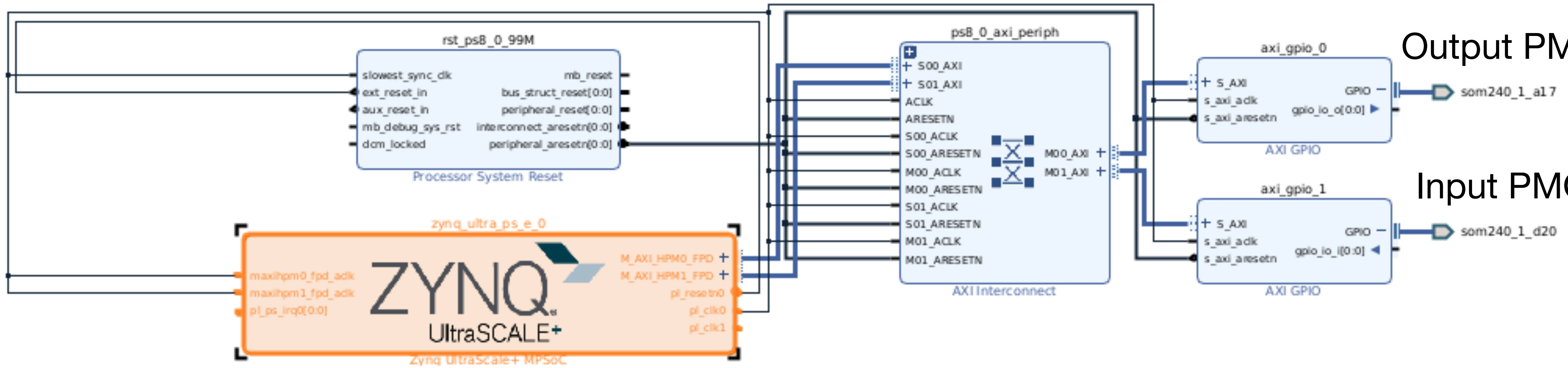


- Nitrogen laser and 1” PMT in a dark box for realistic signal and dark noise pulses.
- Will replace PMT with Hamamatsu S13360PE 3 mm SiPM.



Trigger program

- Feed analog function generator signal to PMOD pin
- Basic program for 1 ch voltage level trigger with/without processor
  - I/O latency with processor and GPIO: 0.3 - 1.0 µs
  - I/O latency with hardware alone: 25 ns



Output PMOD Pin

Input PMOD Pin

- Next steps
  - Replace PMT with SiPM
  - Digitize SiPM pulses (GHz digitizer), and feed digitized signal to board
  - Implement more complex trigger algorithms based on single channel waveforms and multiple channel coincident hits
  - Consider detector simulation of signal and background to guide trigger algorithms.

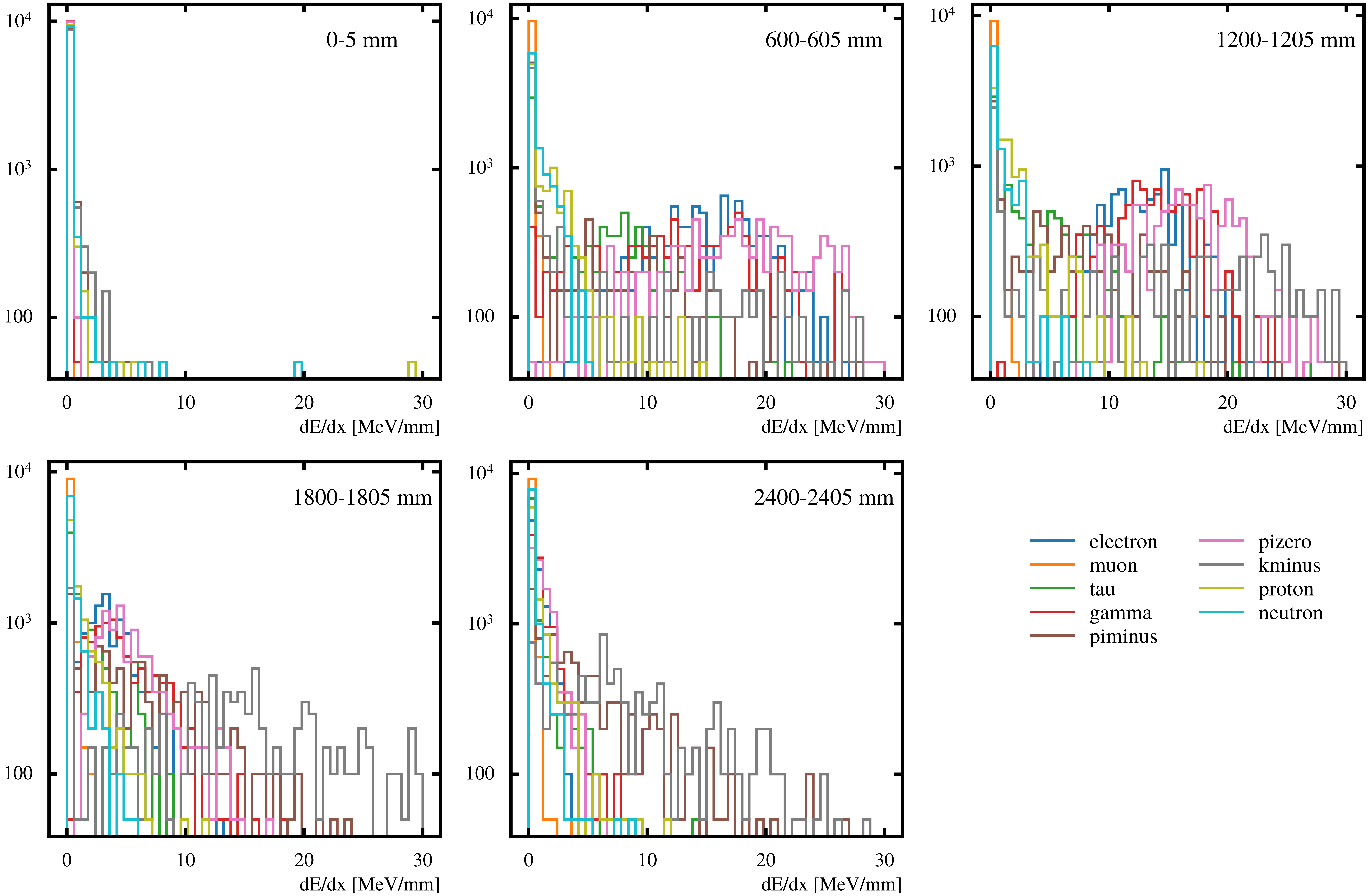
Summary

- Work towards a CDR is underway
  - Detector design and parameters (geometry, pixel size, trigger requirement)
  - Performance requirements (containment, thresholds, spatial/energy resolution)
  - Physics reach (neutrino, light dark matter search, etc)
- More to be done
  - Muon background study
  - Allocate computing resource and develop tools for electronic simulation (electron transportation, electronic response, etc)
  - ……

Backup Materials

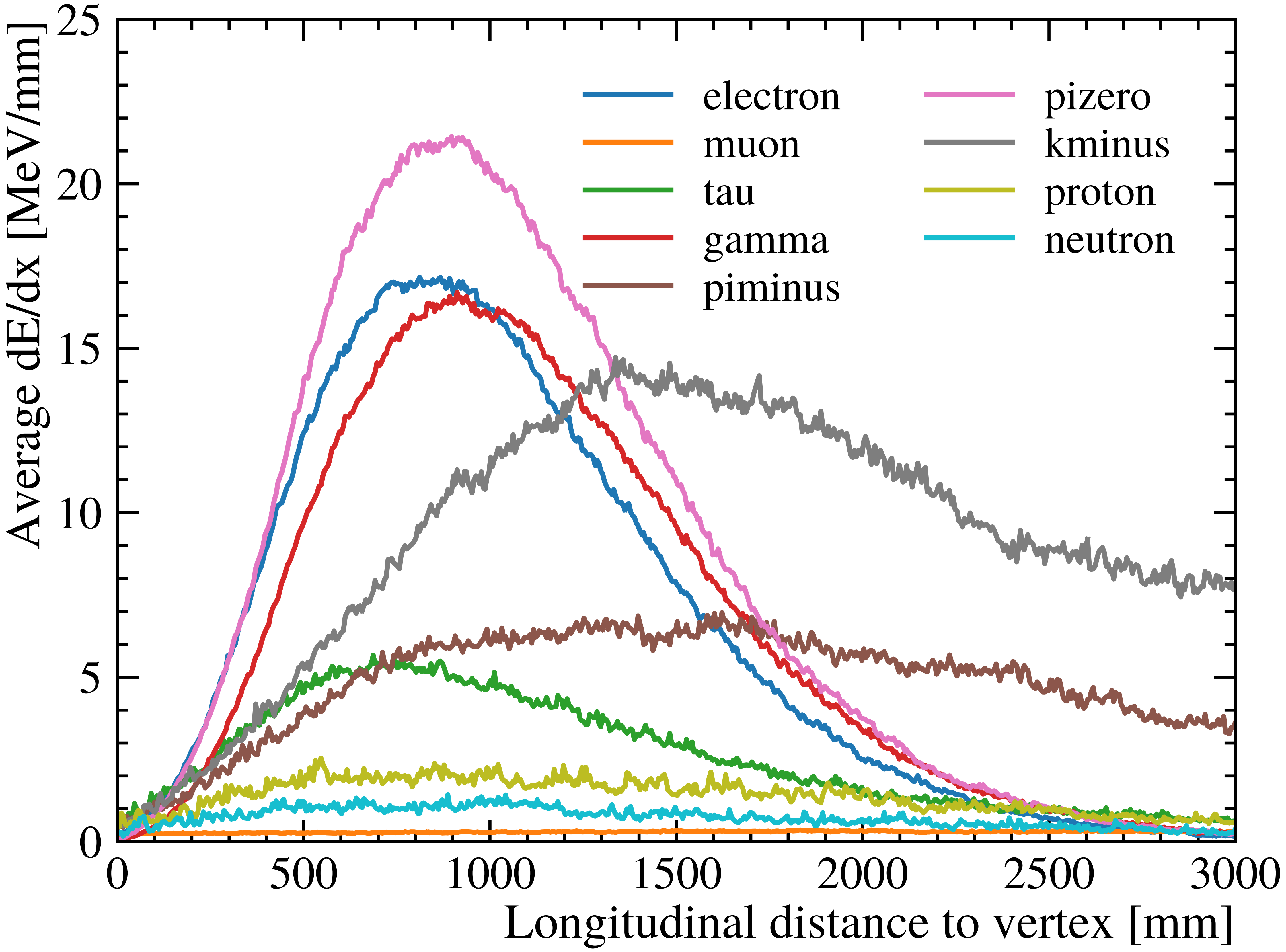
dE/dx start from the vertex

- Distance to the vertex: 0 - 3000 mm, with 5 mm step

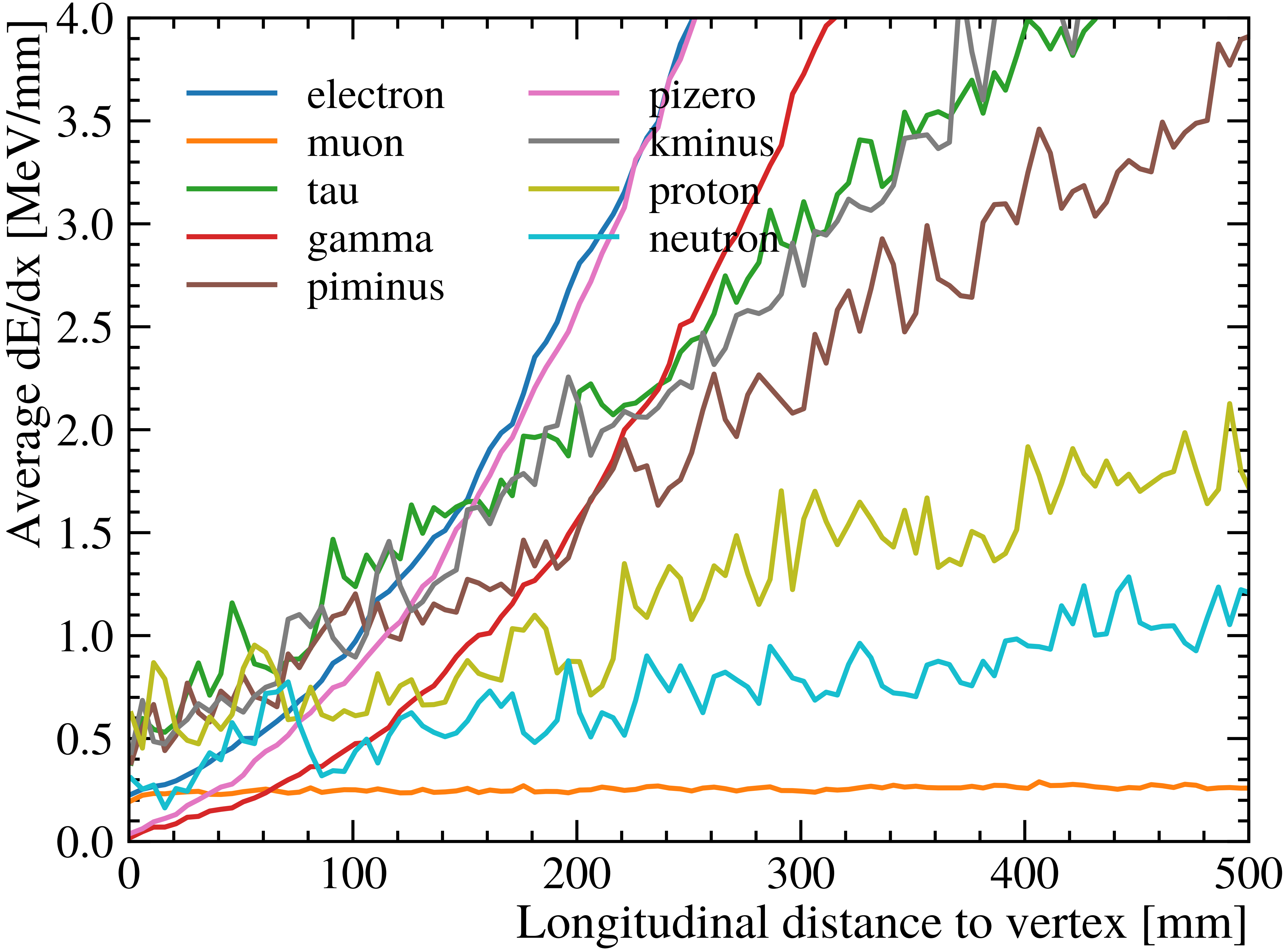


dE/dx start from the vertex

- Distance to the vertex: 0 - 3000 mm, with 5 mm step

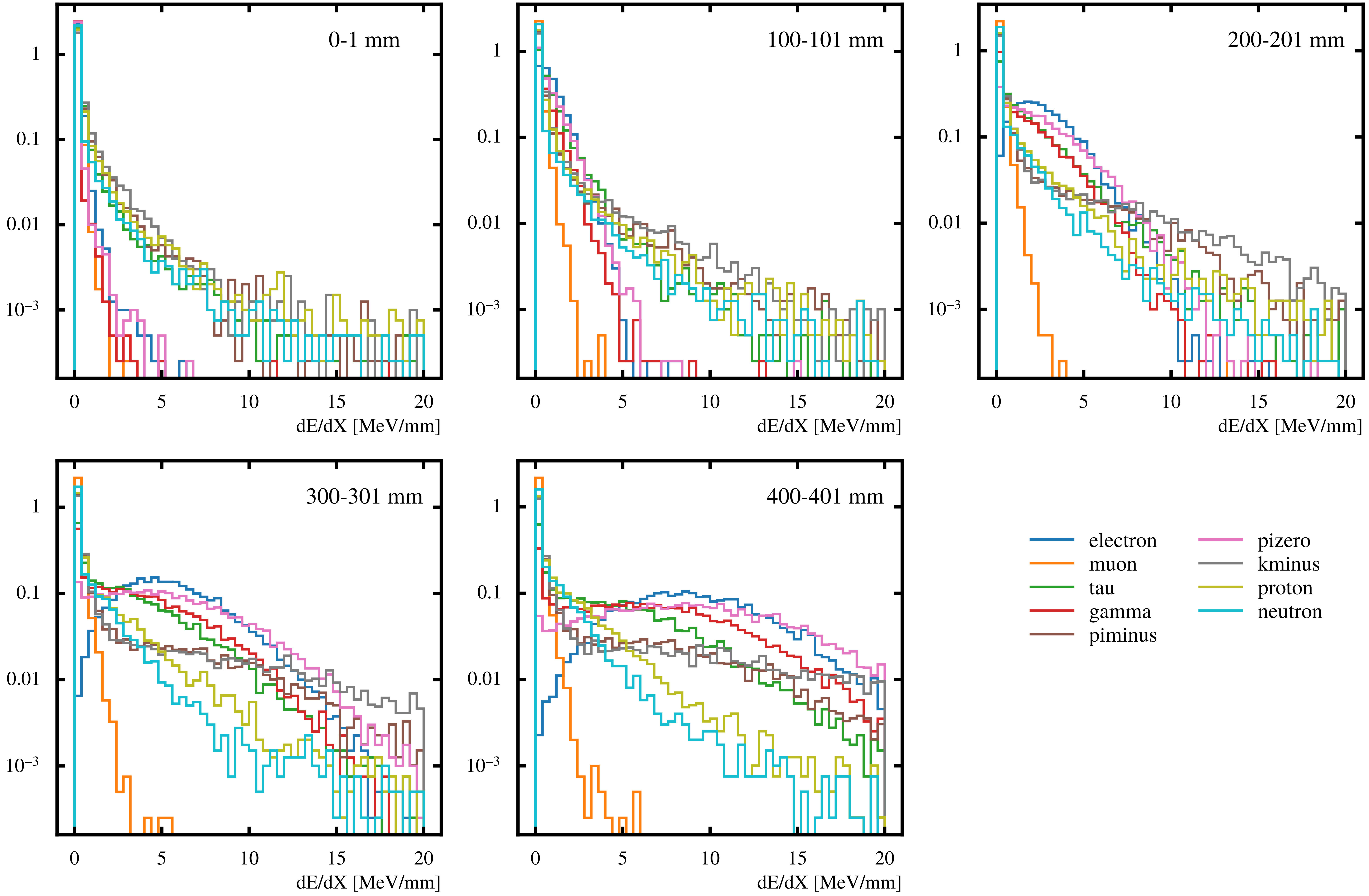


Zoom in to (0, 50) cm

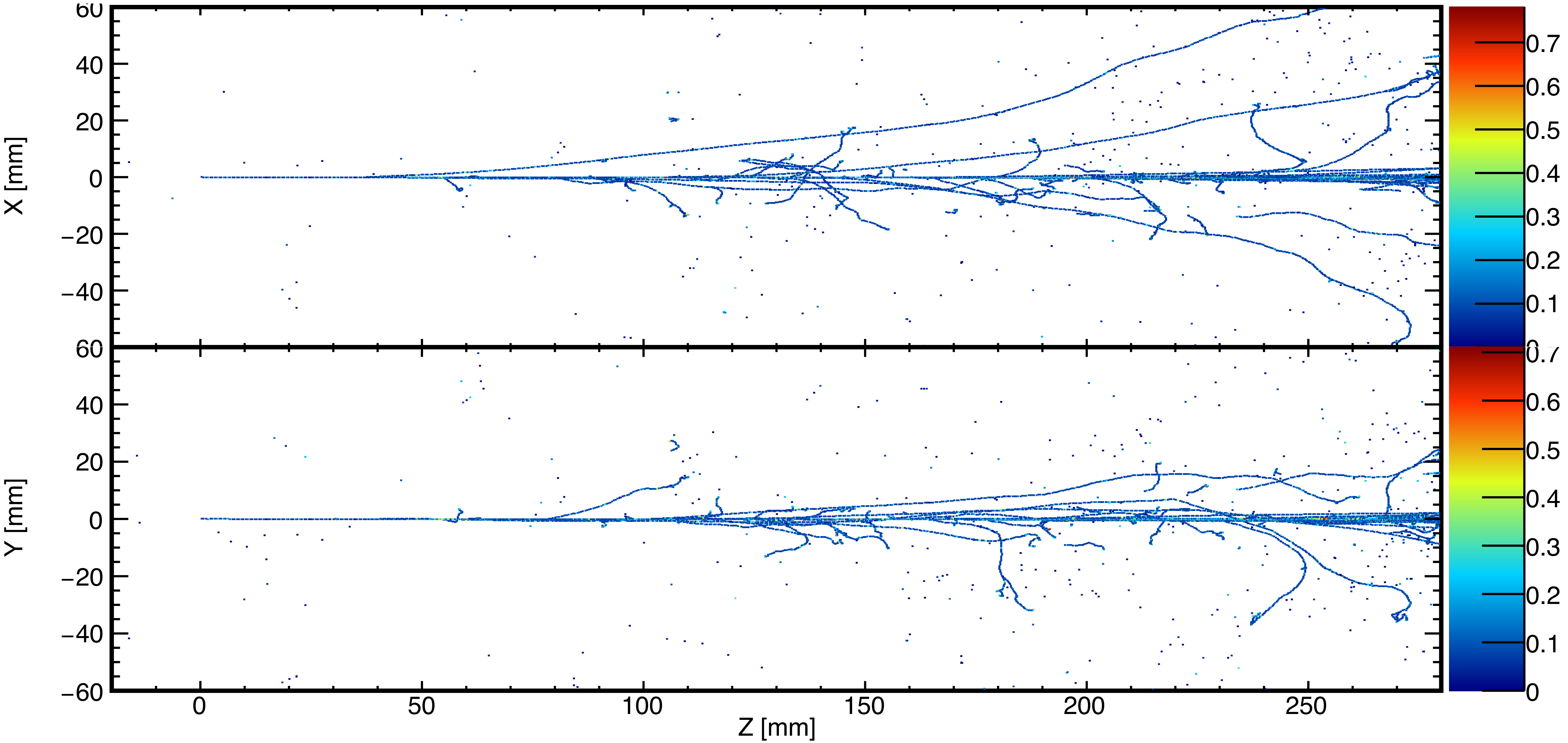


dE/dx start from the vertex

- Distance to the vertex: 0 - 500 mm, with 1 mm step
- Without diffusion

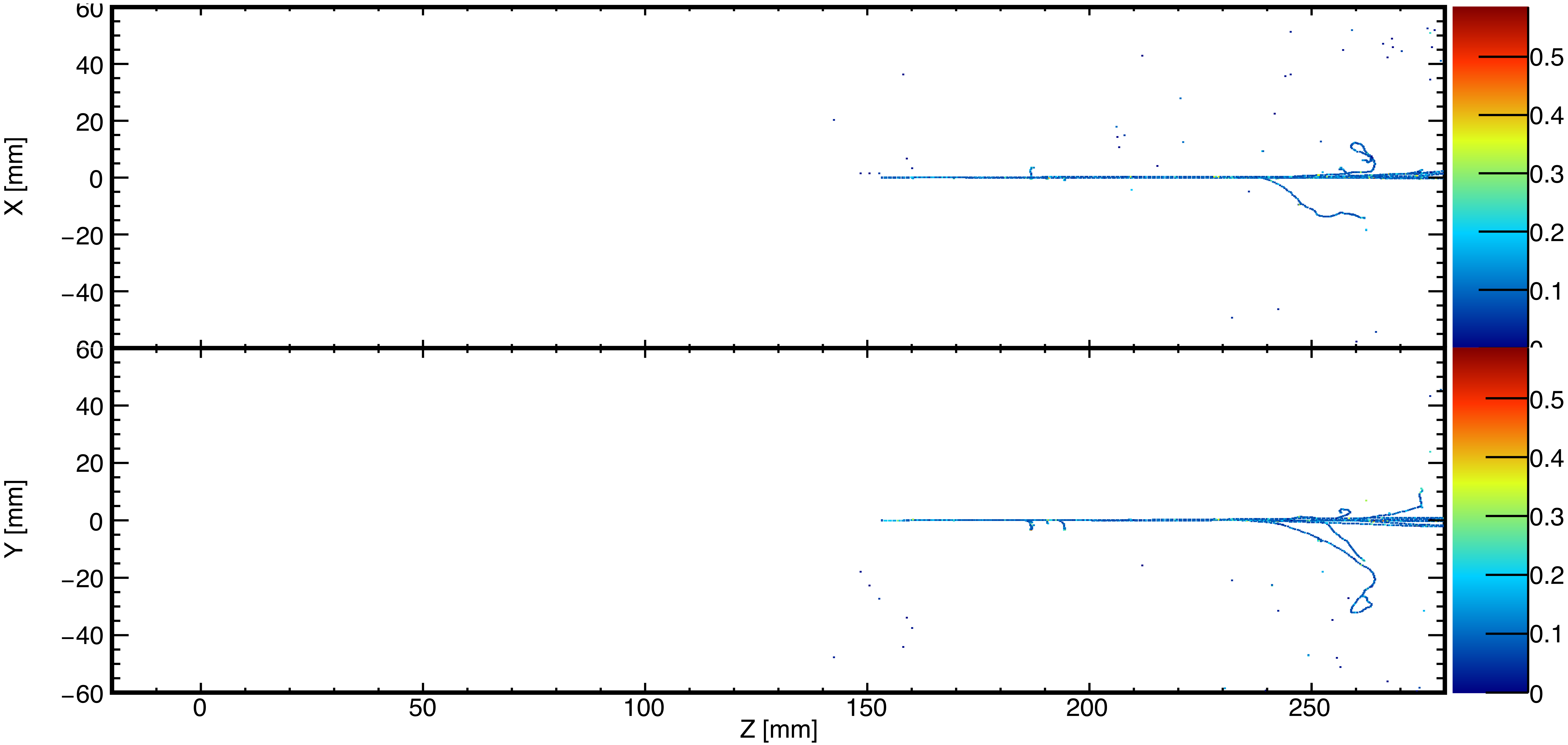


Electron



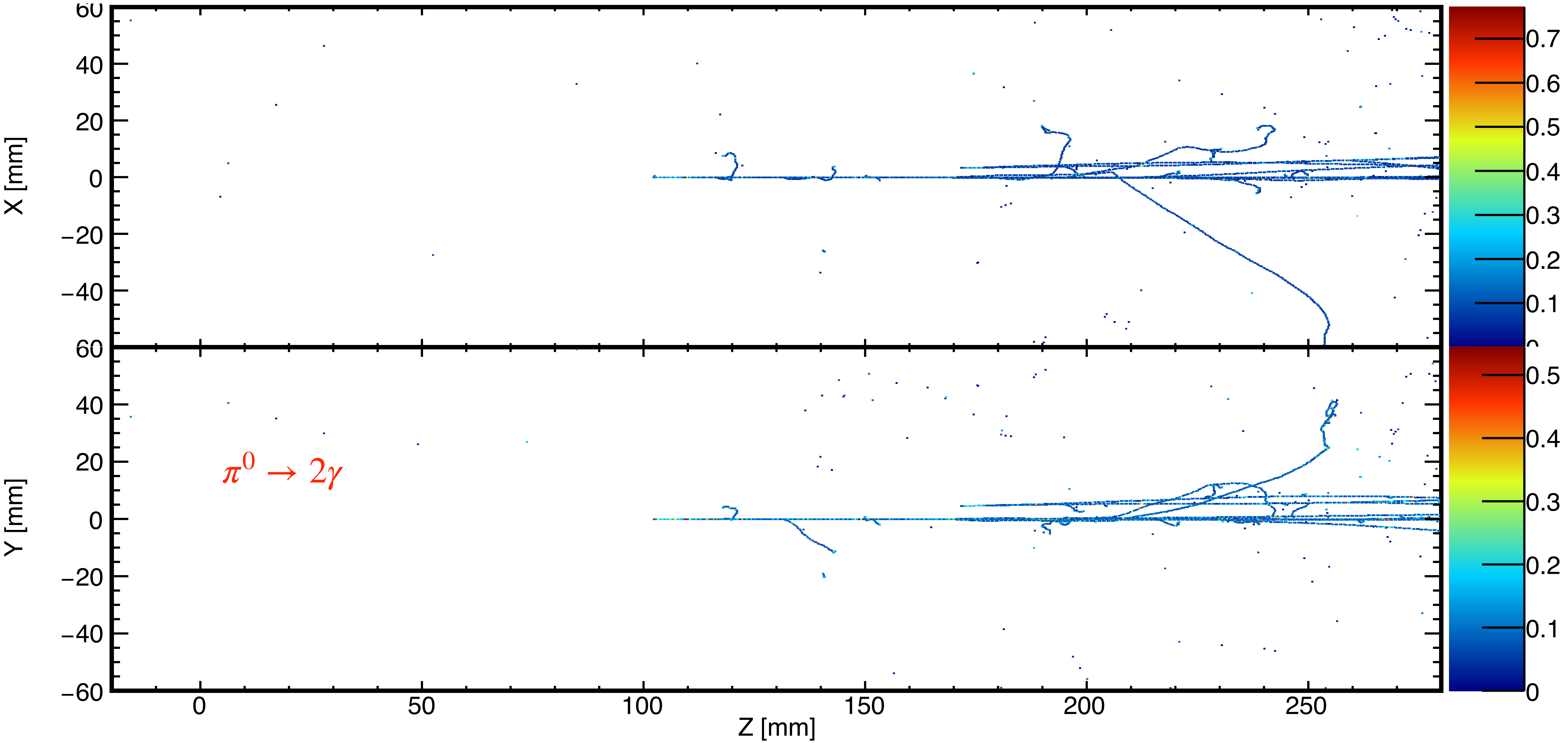
EvtID 0 PDG 11 Etot 20.0 GeV Vtx (0.0, 0.0, 1000.0) mm

Gamma



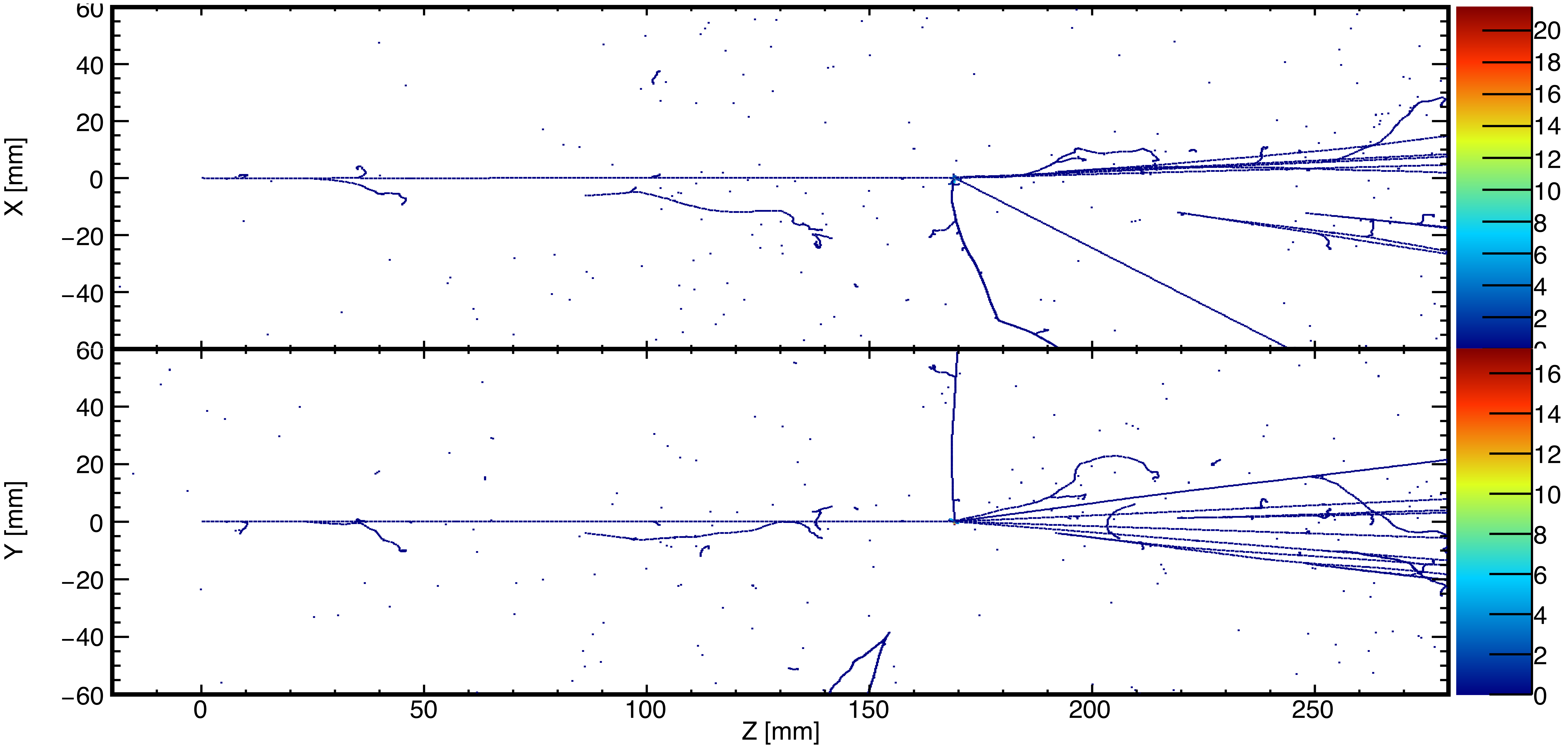
EvtID 1 PDG 22 Etot 20.0 GeV Vtx (0.0, 0.0, 1000.0) mm

Pi0



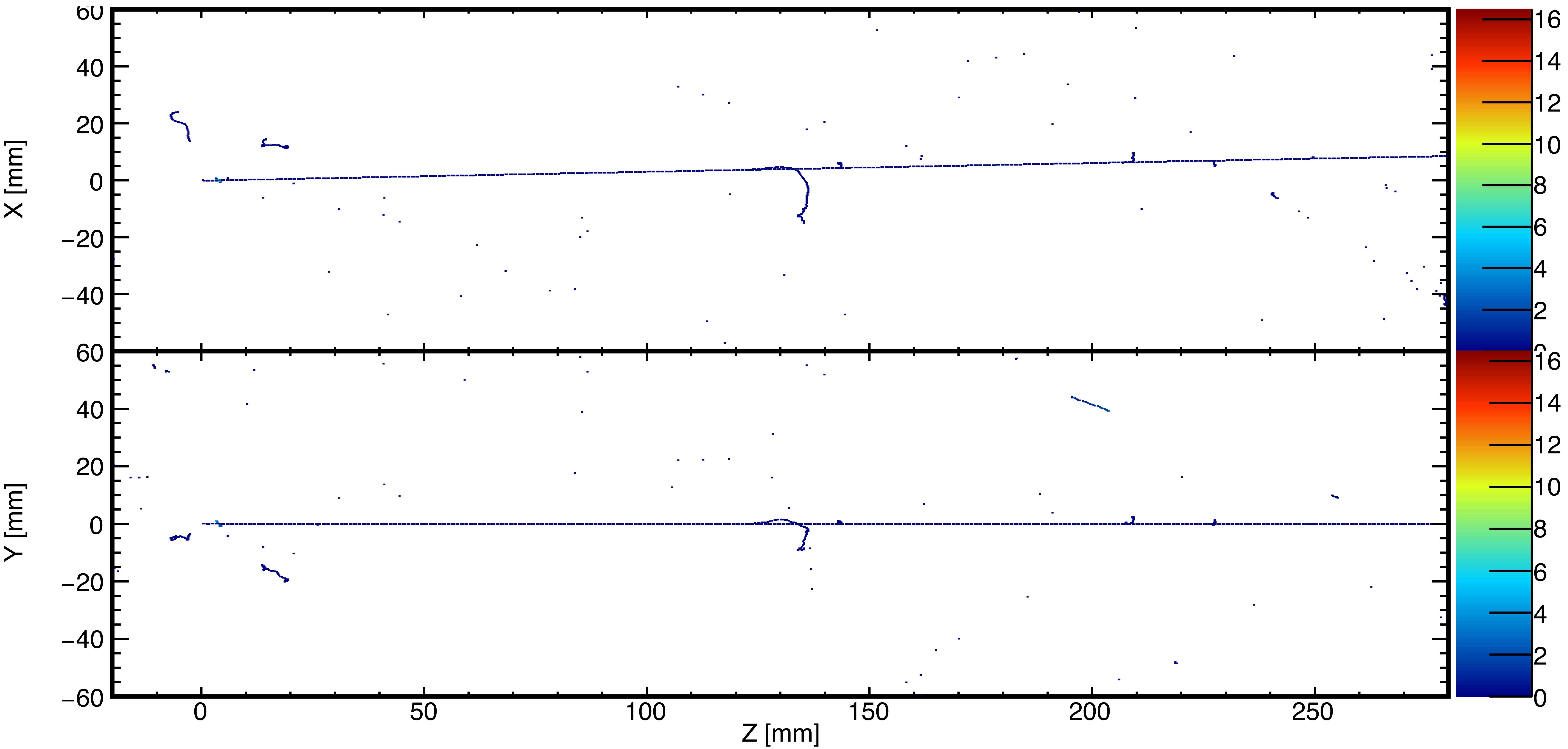
EvtID 4 PDG 111 Etot 25.0 GeV Vtx (0.0, 0.0, 1000.0) mm

Pi-



EvtID 3 PDG -211 Etot 25.0 GeV Vtx (0.0, 0.0, 1000.0) mm

Proton



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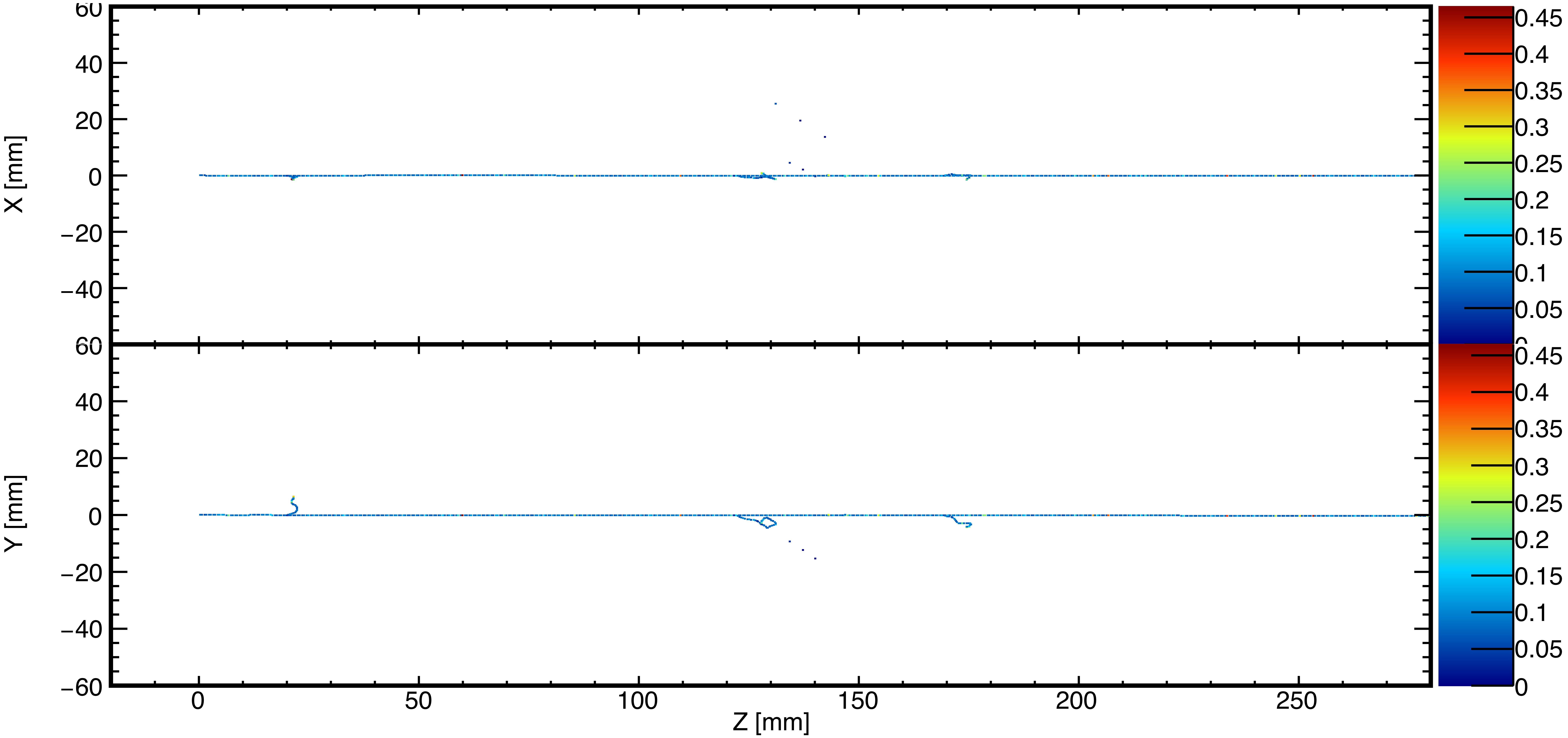
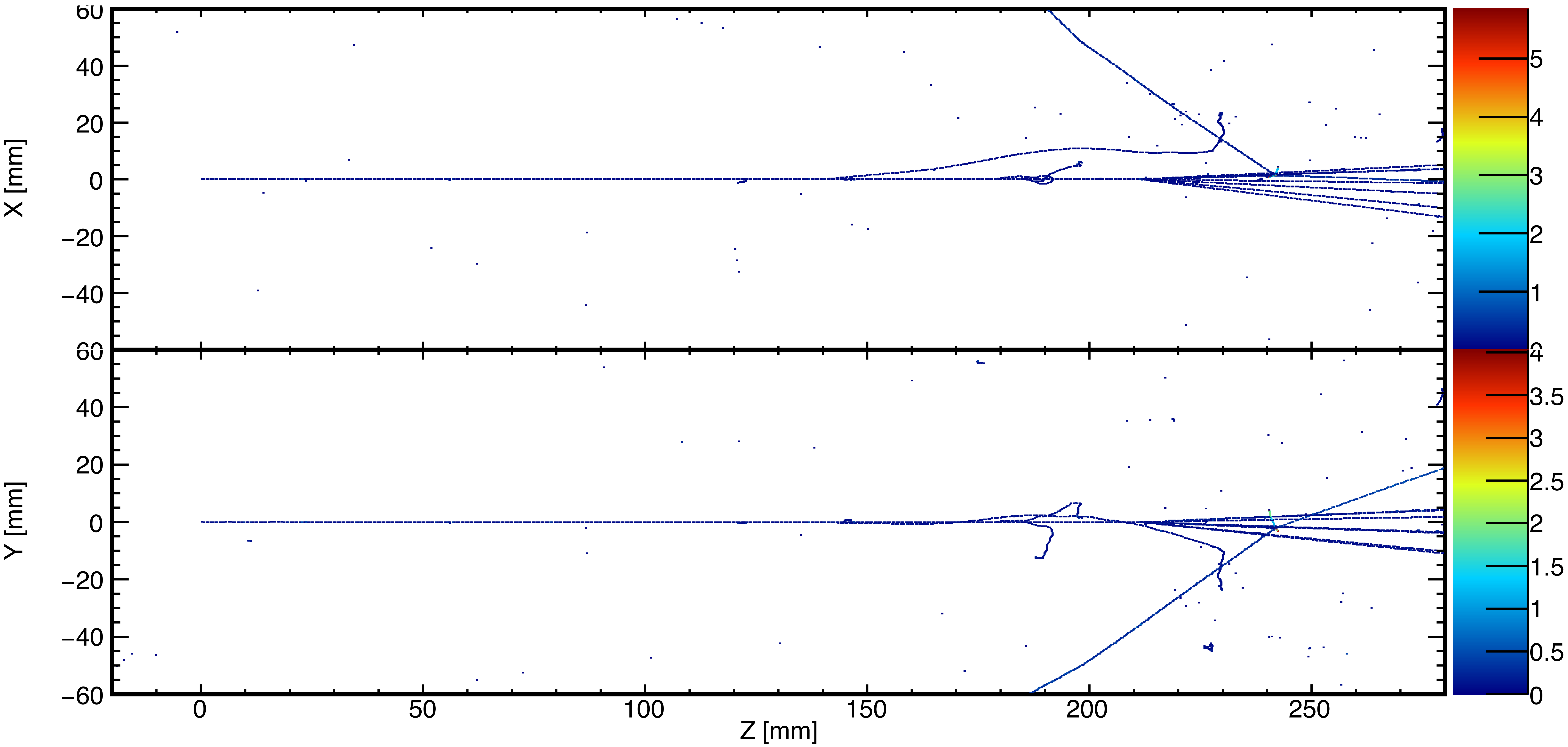
Muon



EvtID 0 PDG 13 Etot 20.0 GeV Vtx (0.0, 0.0, 1000.0) mm

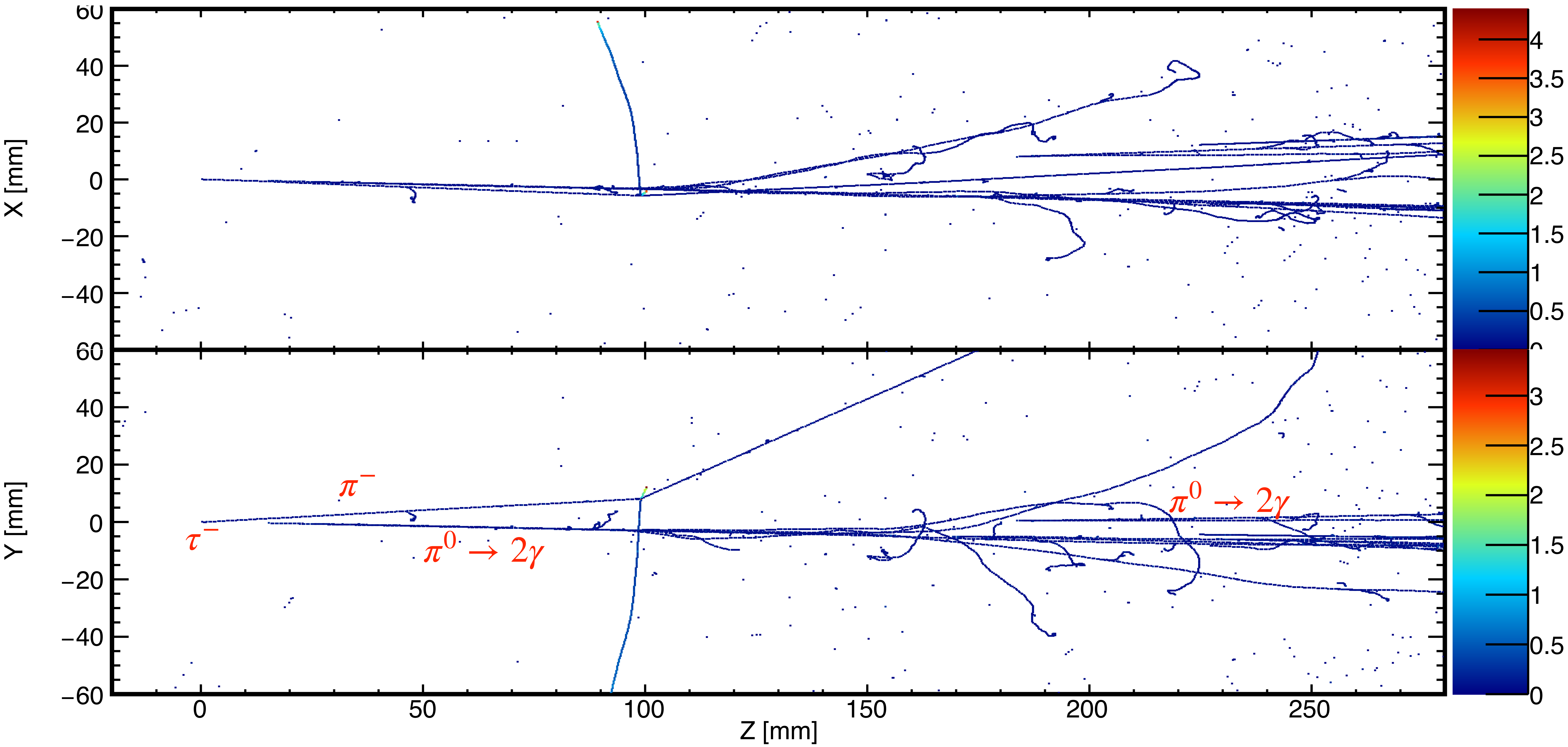
K-



EvtID 3 PDG -321 Etot 50.0 GeV Vtx (0.0, 0.0, 1000.0) mm

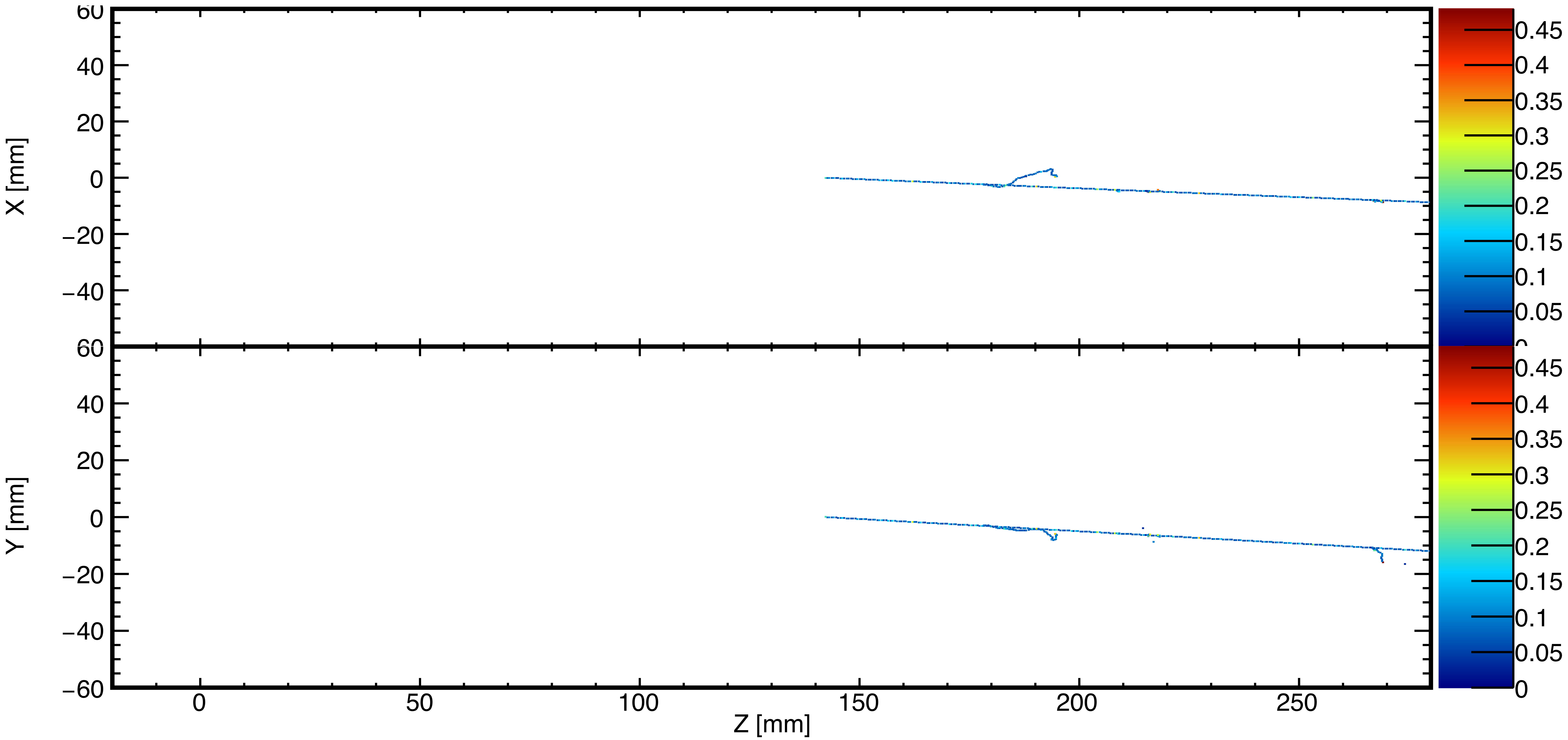
Tau-

$\tau^- \to \pi^-\pi^0\pi^0$



EvtID 1 PDG 15 Etot 20.1 GeV Vtx (0.0, 0.0, 1000.0) mm

Neutron

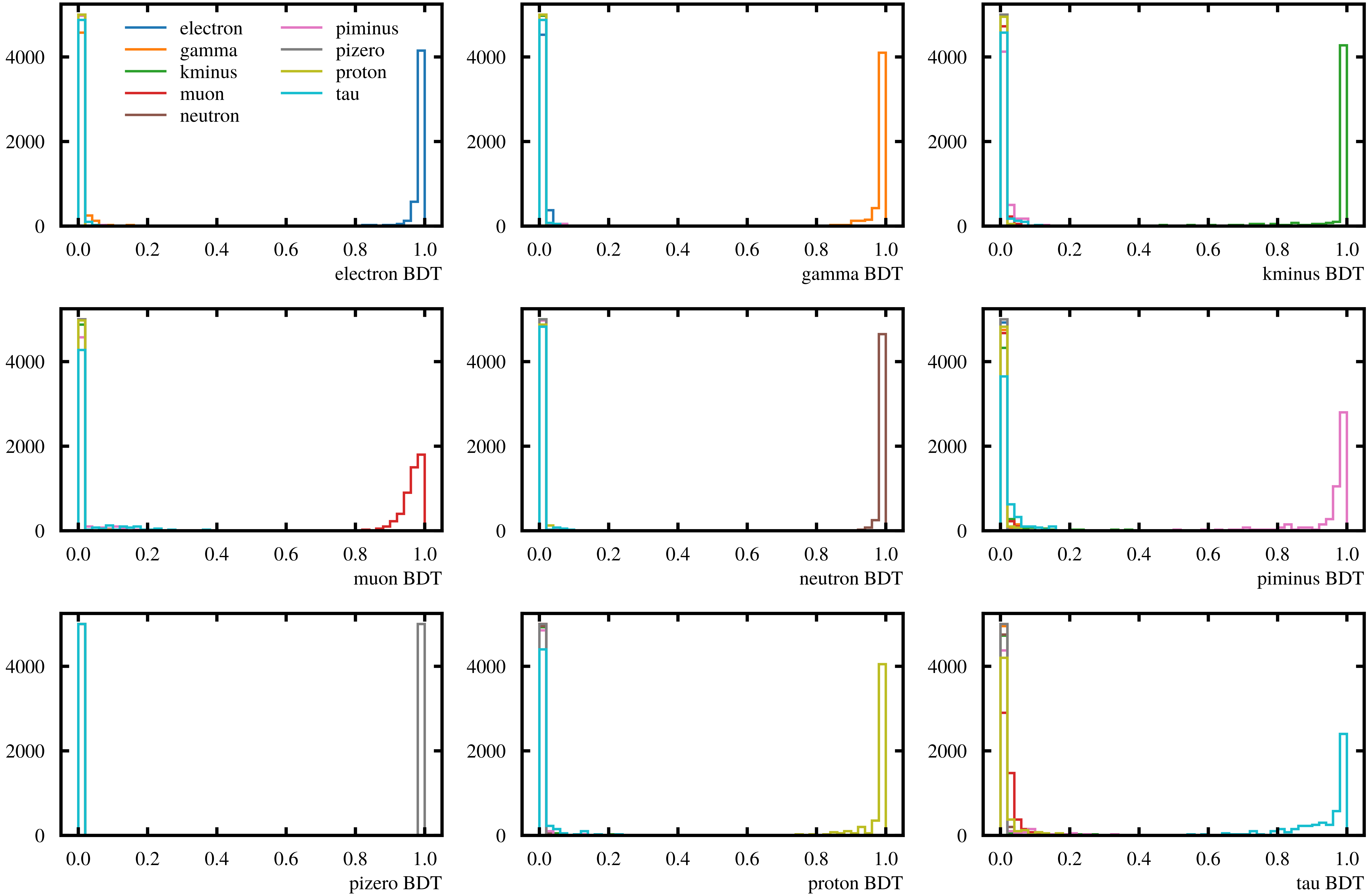


EvtID 3 PDG 2112 Etot 5.1 GeV Vtx (0.0, 0.0, 1000.0) mm

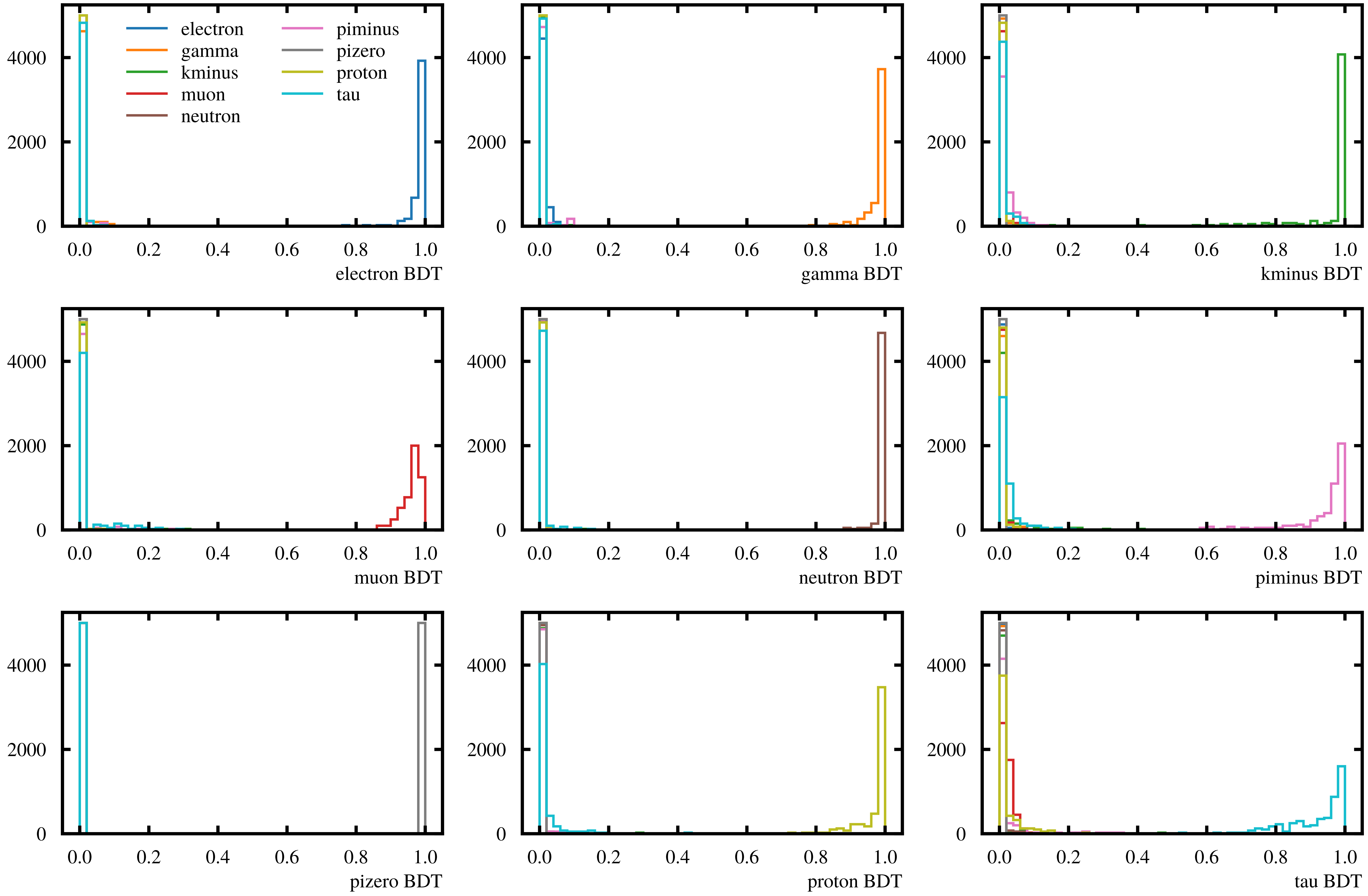
Final state particle population

	Nue CC		Nue NC		Numu CC		Numu NC		Nutau CC		Nutau NC	
	pi+	19.68%	pi0	19.35%	pi+	19.5%	pi0	19.13%	pi0	18.22%	pi0	19.11%
	pi0	18.9%	pi-	17.91%	pi0	18.76%	pi-	17.69%	pi+	16.83%	pi-	17.48%
	pi-	15.73%	pi+	17.27%	pi-	15.48%	pi+	17.14%	pi-	16.82%	pi+	16.82%
	p	13.99%	n	14.15%	p	14.2%	n	14.54%	p	11.61%	n	14.54%
	n	12.93%	p	13.53%	n	13.13%	p	13.64%	n	10.84%	p	13.91%
	e-	6.46%	nu_e	6.61%	mu-	6.58%	nu_mu	6.77%	nu_tau	5.57%	nu_tau	6.91%
	gamma	3.91%	gamma	2.71%	gamma	3.9%	gamma	2.62%	tau-	5.57%	gamma	2.67%
	K+	1.79%	K+	1.7%	K+	1.82%	K+	1.71%	gamma	3.32%	K+	1.76%
	K-	1.44%	K0	1.64%	K-	1.45%	K0	1.62%	K+	1.48%	K0	1.68%
	K0	1.39%	K-	1.42%	K	1.4%	K-	1.41%	K-	1.2%	K-	1.43%
Other		3.78%		3.71%		3.78%		3.73%		8.54%		3.69%

BDT Score of each type (1x2x2)



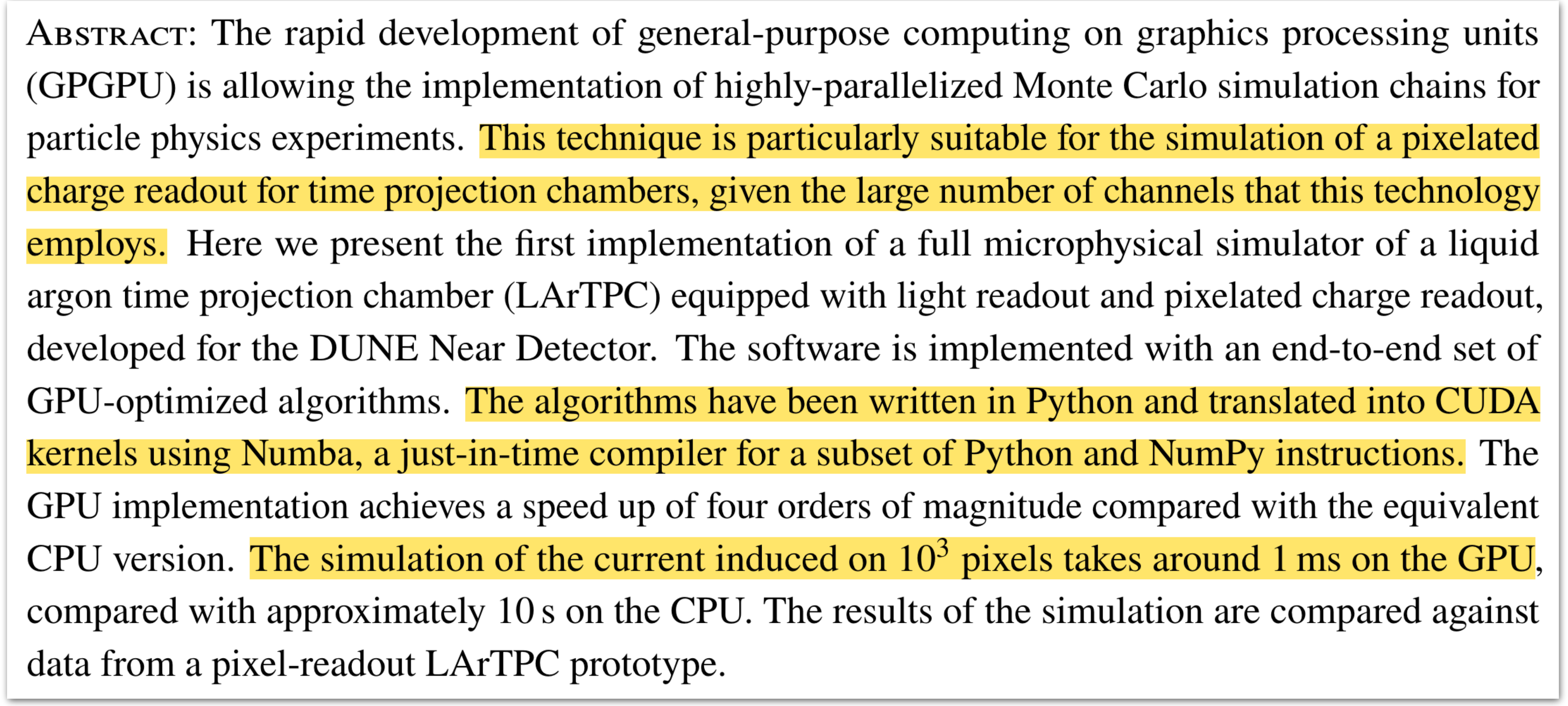
BDT Score of each type (1x5x5)



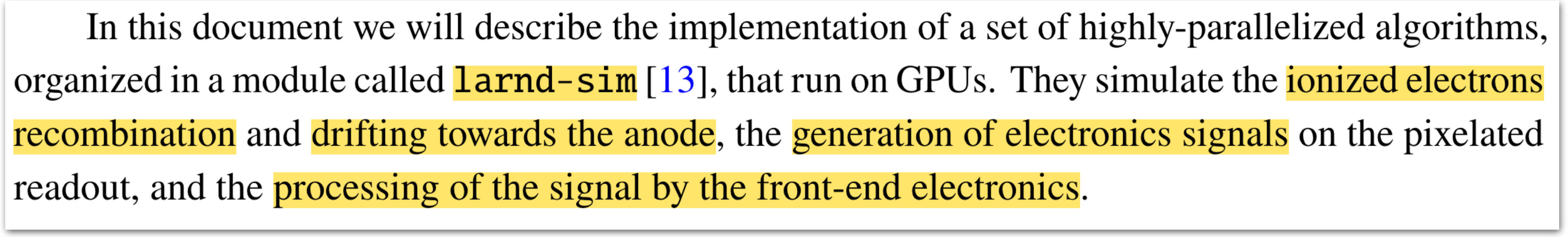
ND-LAr simulation

Highly-parallelized simulation of a pixelated LArTPC on a GPU

J. Inst. 18, P04034 (2023)



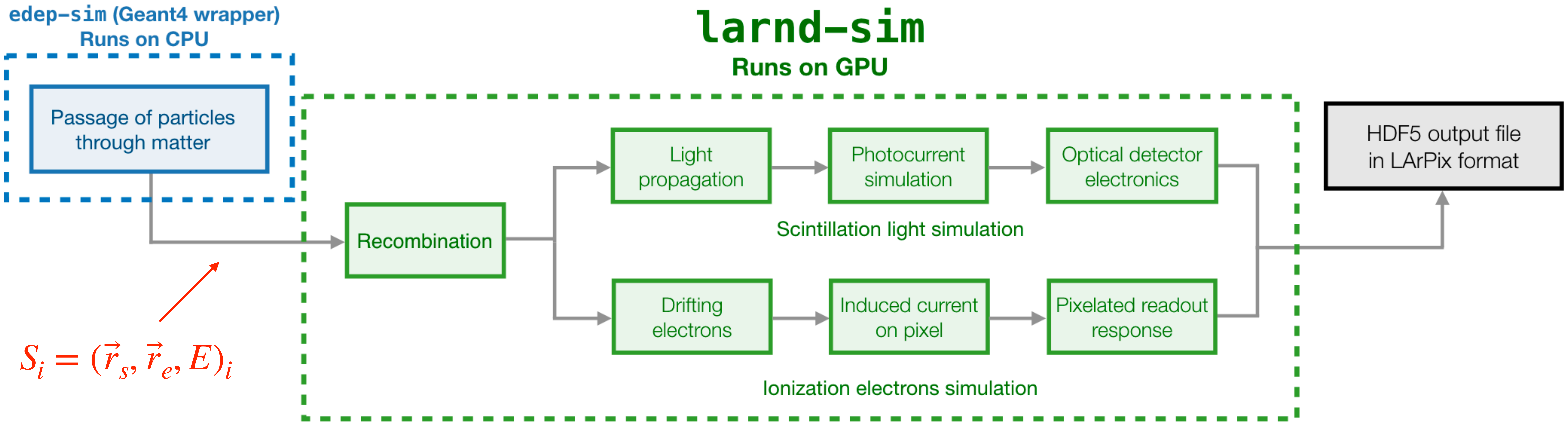
ABSTRACT: The rapid development of general-purpose computing on graphics processing units (GPGPU) is allowing the implementation of highly-parallelized Monte Carlo simulation chains for particle physics experiments. This technique is particularly suitable for the simulation of a pixelated charge readout for time projection chambers, given the large number of channels that this technology employs. Here we present the first implementation of a full microphysical simulator of a liquid argon time projection chamber (LArTPC) equipped with light readout and pixelated charge readout, developed for the DUNE Near Detector. The software is implemented with an end-to-end set of GPU-optimized algorithms. The algorithms have been written in Python and translated into CUDA kernels using Numba, a just-in-time compiler for a subset of Python and NumPy instructions. The GPU implementation achieves a speed up of four orders of magnitude compared with the equivalent CPU version. The simulation of the current induced on 10^3 pixels takes around 1 ms on the GPU, compared with approximately 10 s on the CPU. The results of the simulation are compared against data from a pixel-readout LArTPC prototype.



In this document we will describe the implementation of a set of highly-parallelized algorithms, organized in a module called `larnd-sim` [13], that run on GPUs. They simulate the ionized electrons recombination and drifting towards the anode, the generation of electronics signals on the pixelated readout, and the processing of the signal by the front-end electronics.

https://github.com/DUNE/larnd-sim

ND-LAr simulation



$S_i = (\vec{r}_s, \vec{r}_e, E)_i$

Figure 1. Diagram showing the full simulation workflow. The passage of the particle through matter is simulated by `edep-sim` on the CPU. The output is fed to `larnd-sim`, which runs entirely on GPU. Its output is finally saved in a HDF5 file.