Status update on FLArE Simulation

Jianming Bian, Wenjie Wu

University of California, Irvine

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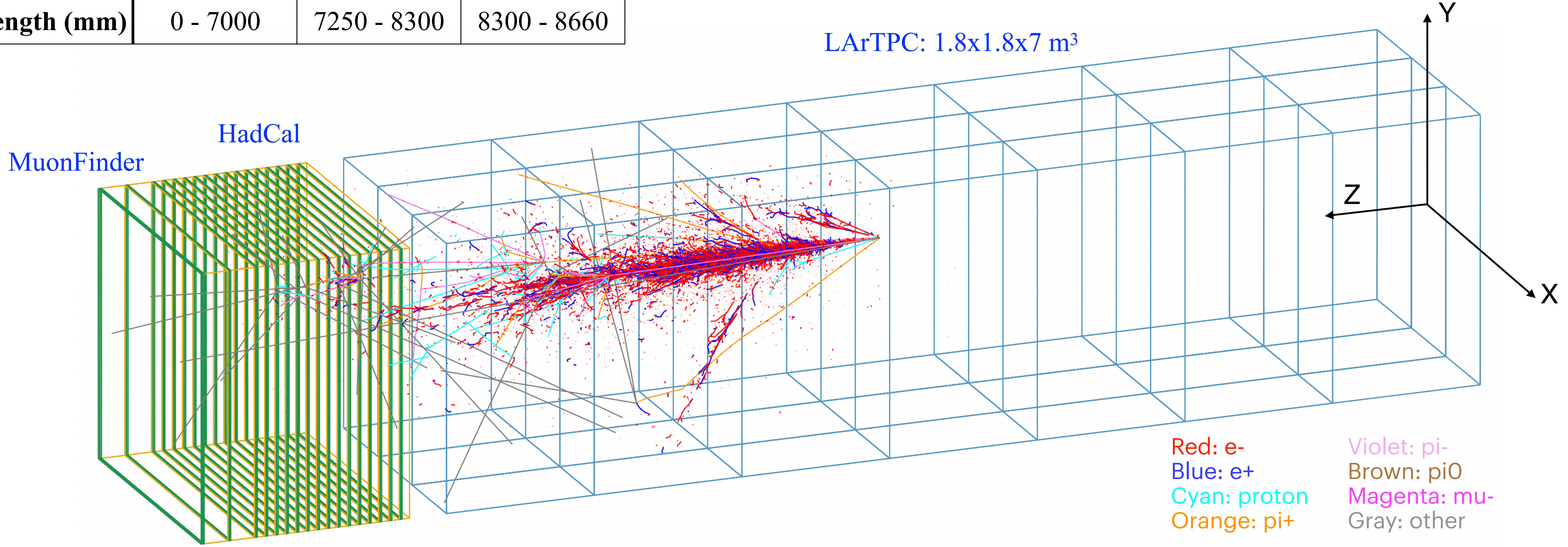
Status recap

- 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 (https://indico.cern.ch/event/1160758/#2-progress-and-status-of-flare)
  - The detector size is optimized for energy containment.
  - The event classifiers trained based on pseudo-reconstructed variables for tau's hadron decay look promising.
- Work in progress
  - Phase space coverage (muon neutrino): energy and angle acceptance.
  - More on tau neutrino identification.
  - Study the effects of pixel size on event identification.

Detector configuration in simulation

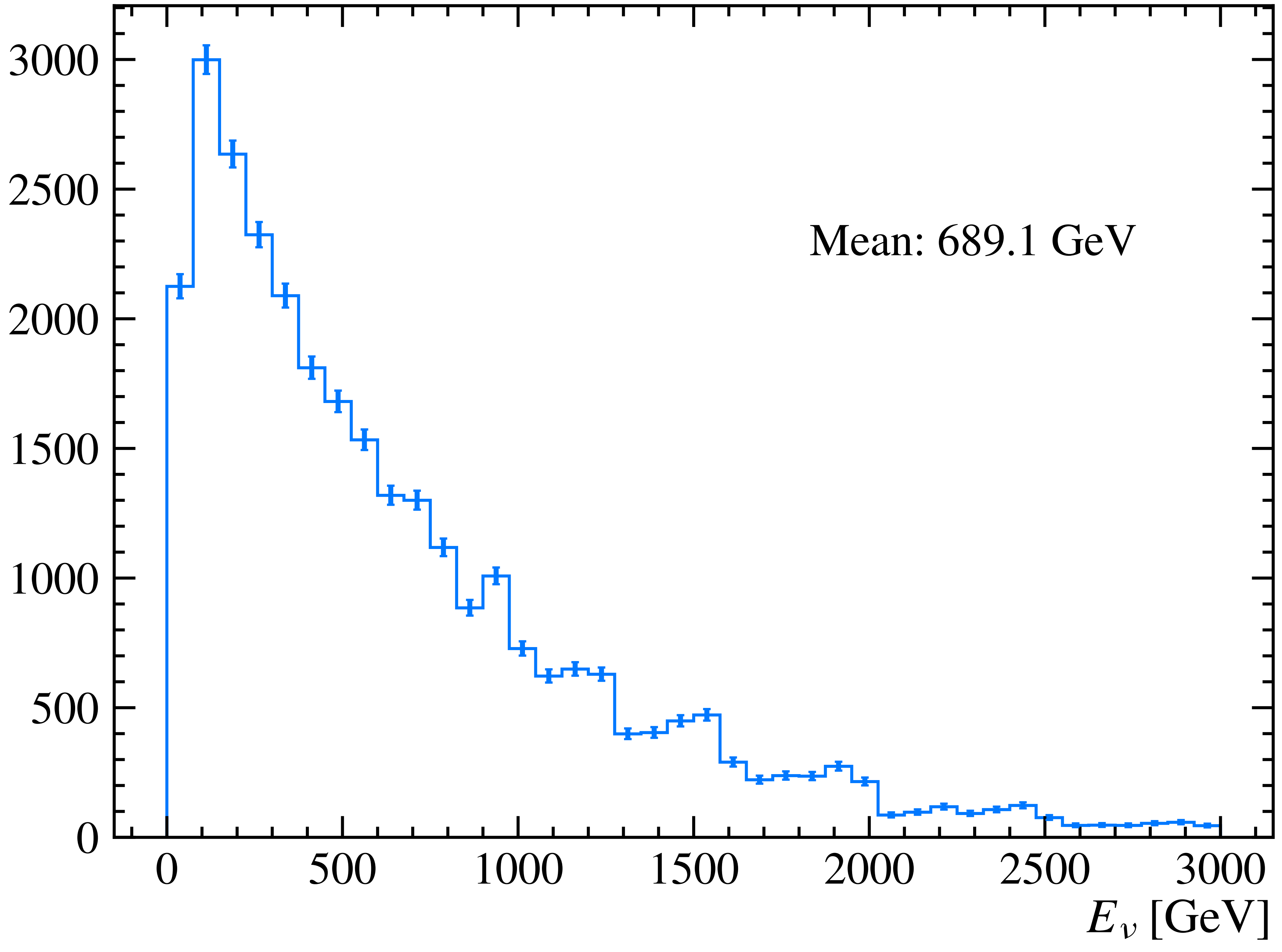
- Fiducial mass of 10 tons (1x1x7 m^3) is needed for good statistics and sensitivity to dark matter.
- Detector needs to have good energy containment and resolution for neutrino physics.
- Muon and electron ID. Very good spatial resolution (~1 mm) for tau neutrino detection.

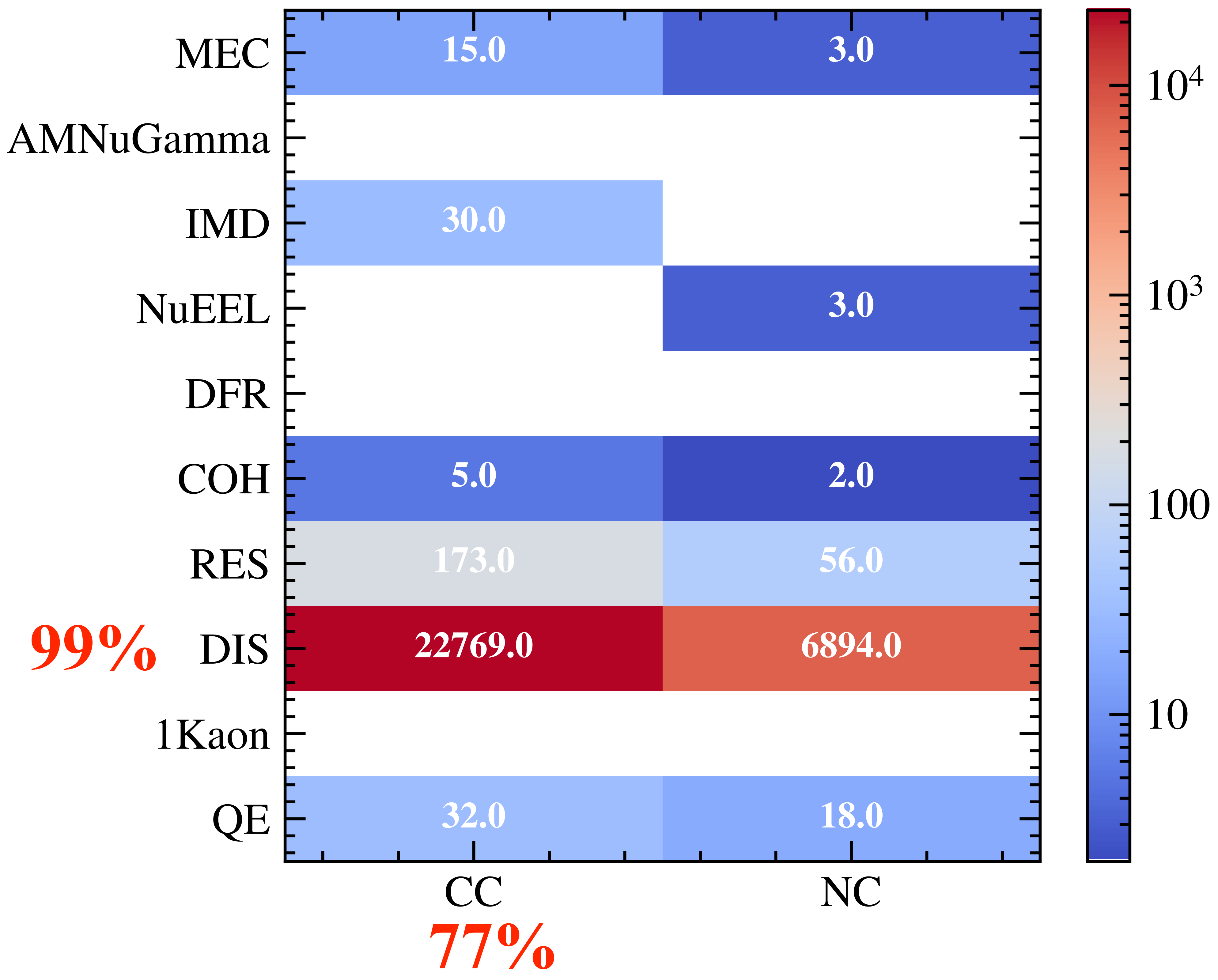
	LArTPC	HadCal	MuonFinder
Length (mm)	0 - 7000	7250 - 8300	8300 - 8660



Muon neutrino

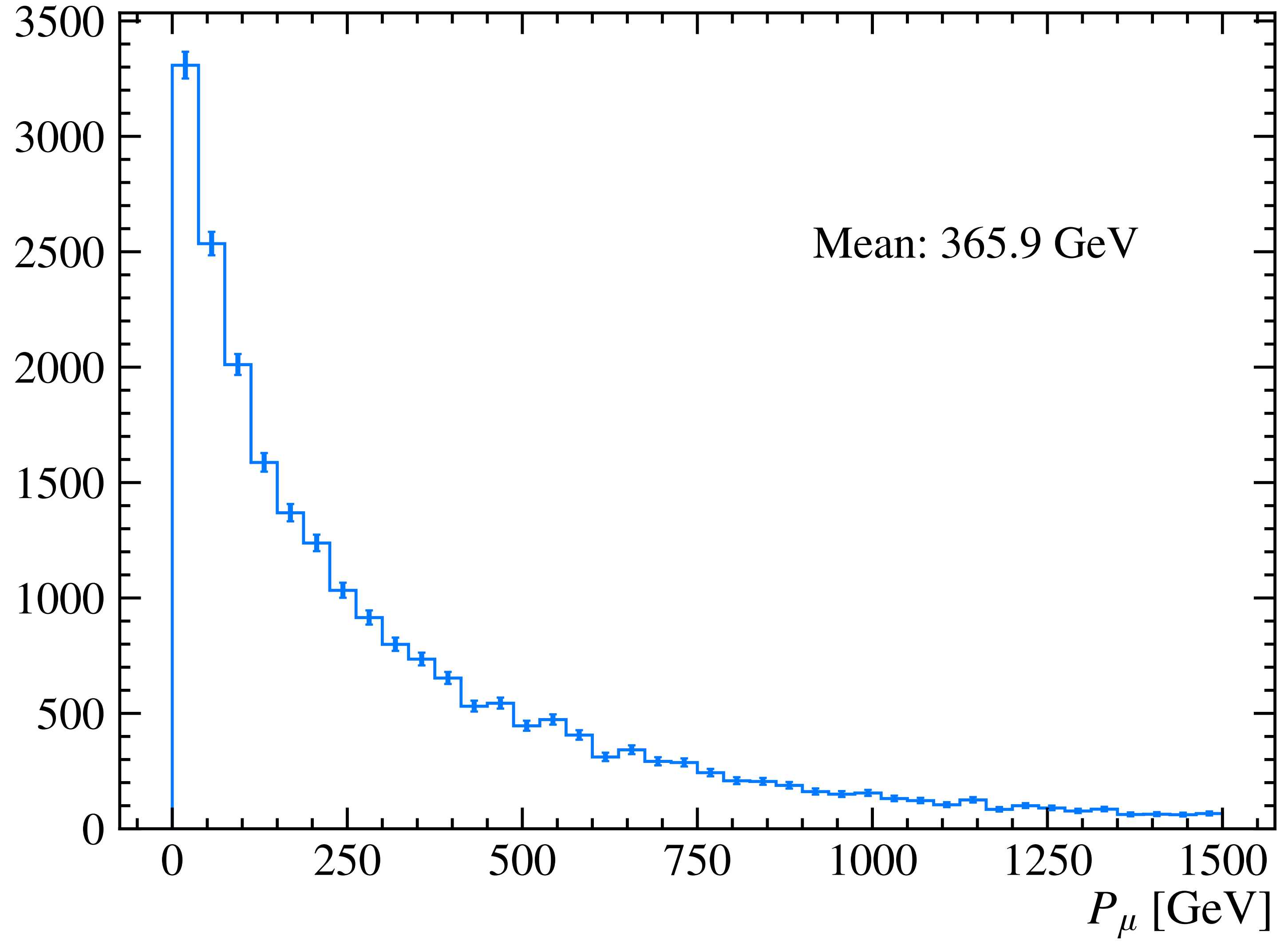
- Neutrino vertices are uniformly distributed in the fiducial volume (1x1x7 m^3).
- Neutrino interaction simulated by GENIE v3_00_06k.

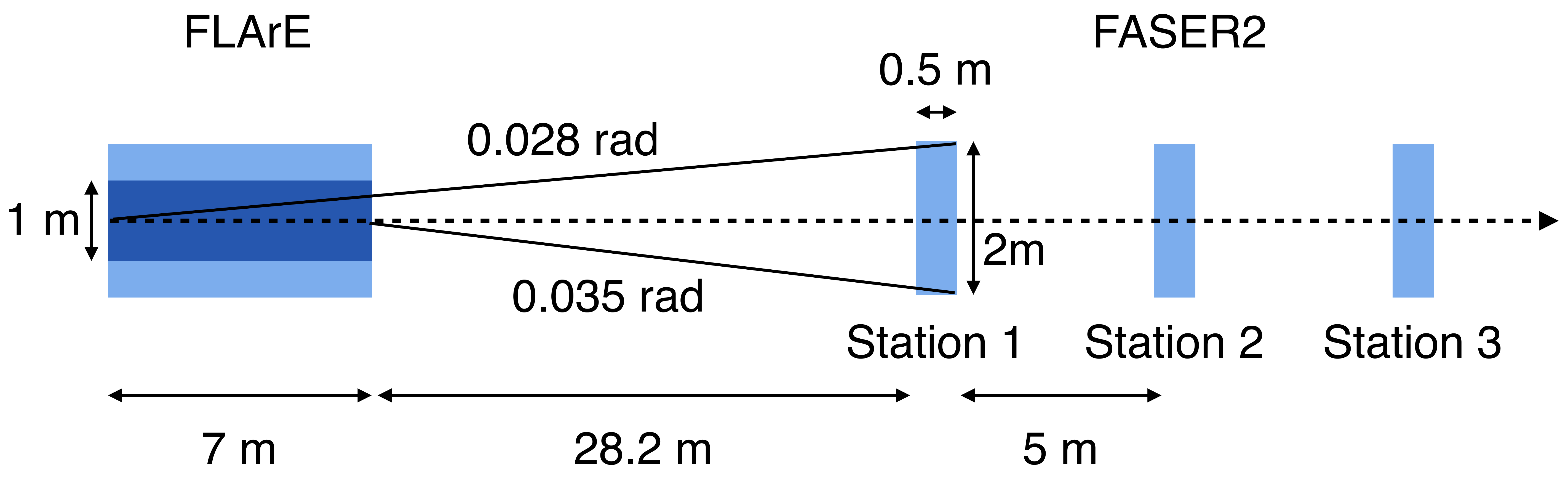


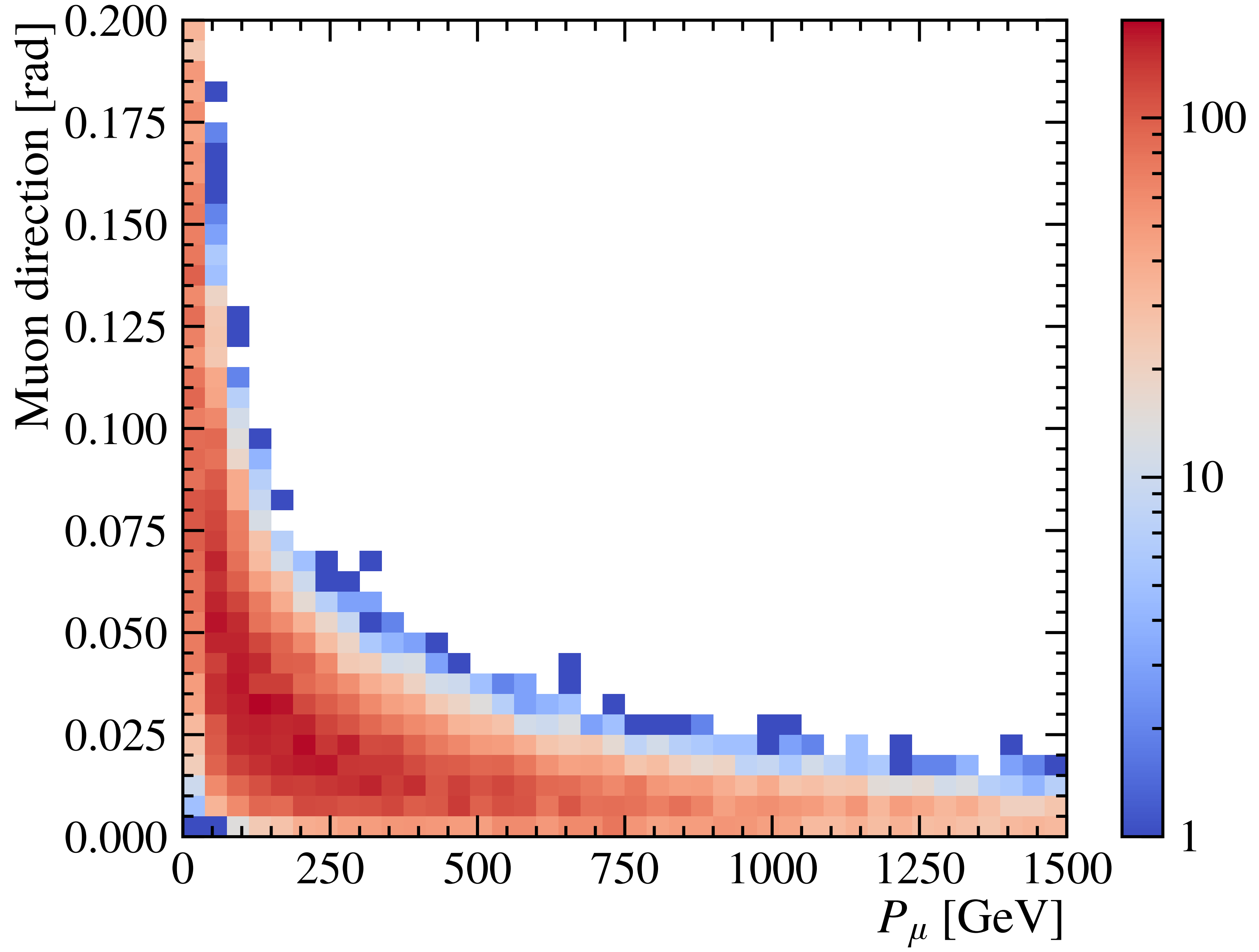


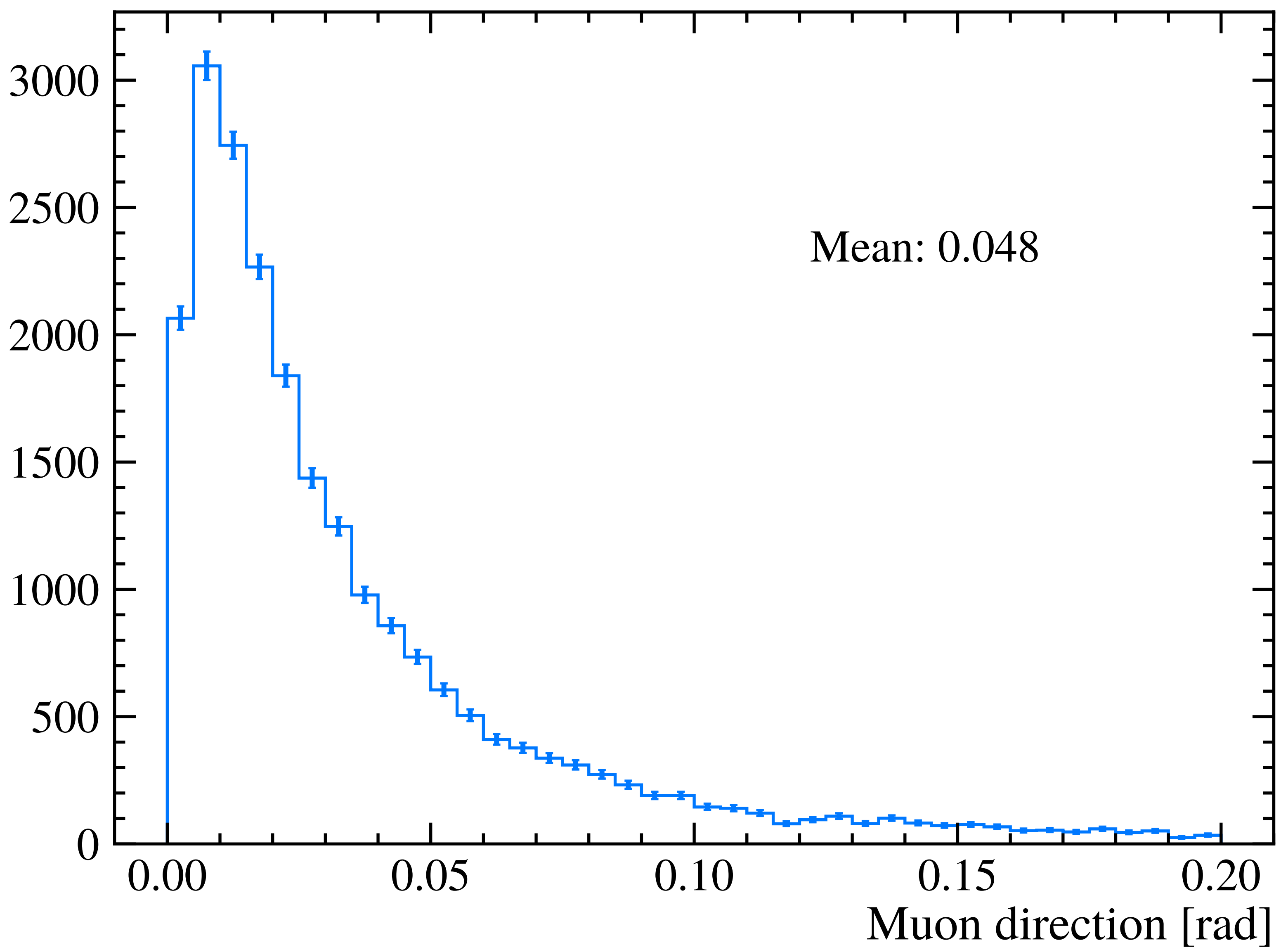
- We're considering magnetizing HadCal and MuonFinder, and possibly utilizing FASER2 magnet, in order to better measure the muon momentum.

Muon neutrino



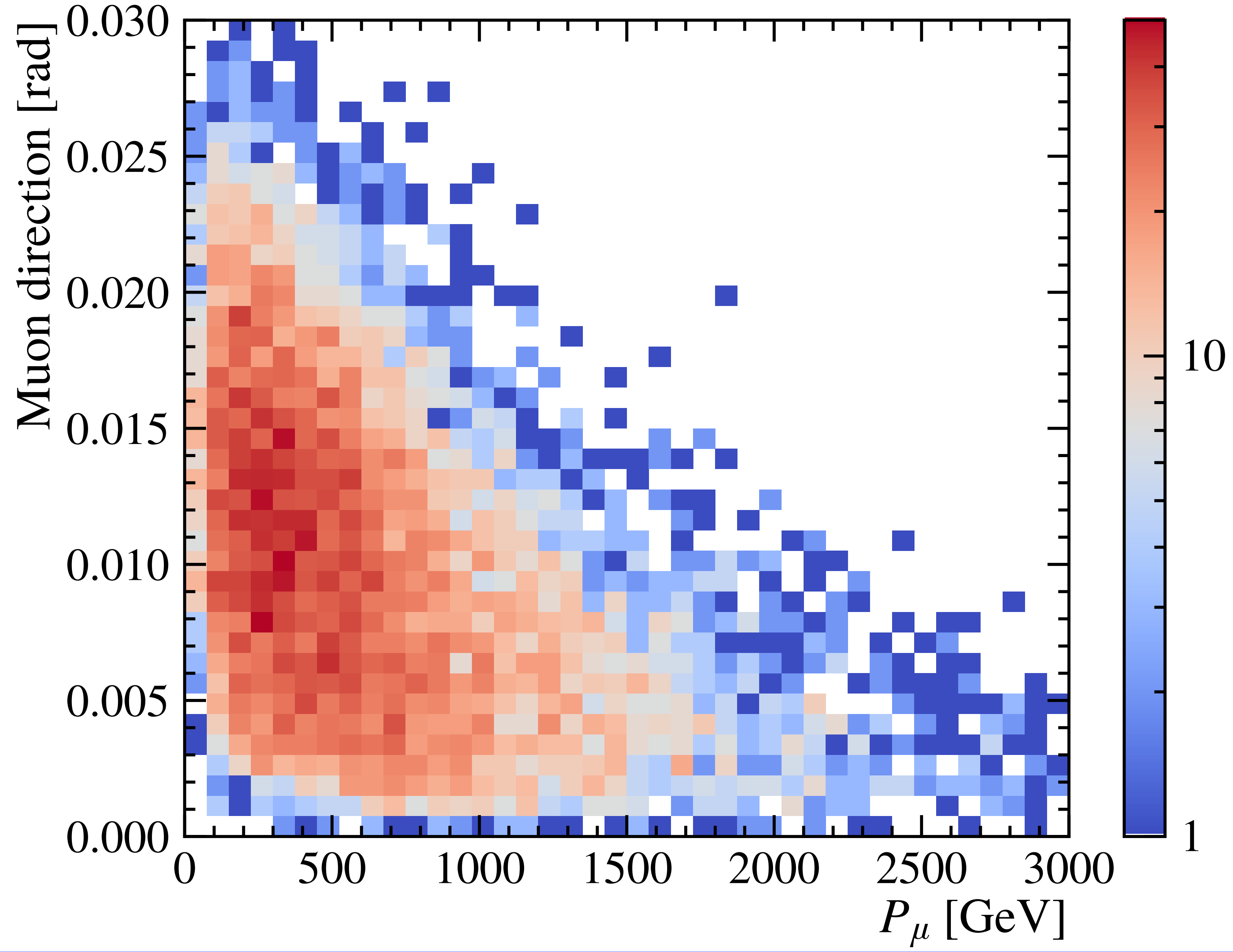






Uniformly distributed ν_μ CC in the FV

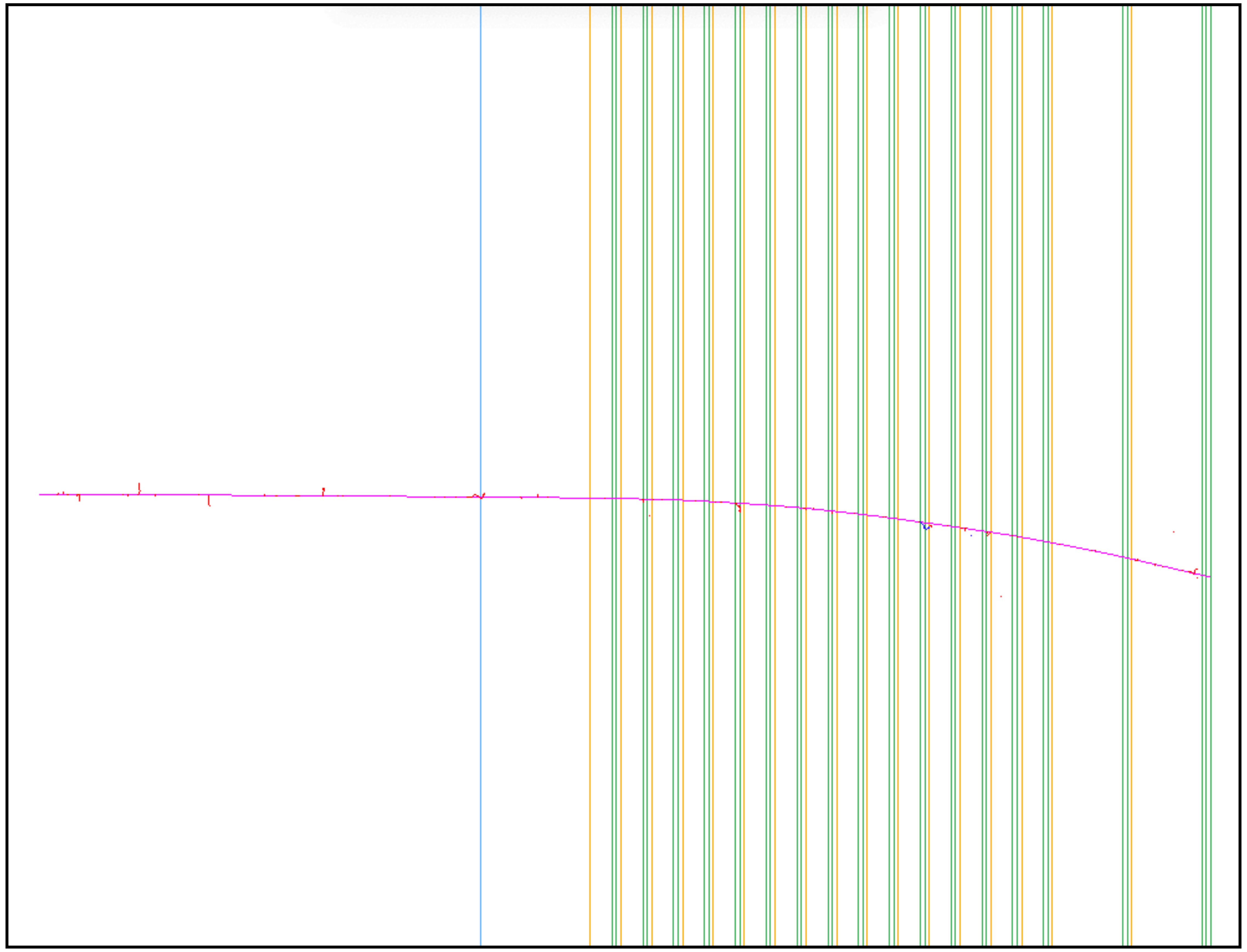
acceptance ratio (to the magnet): 41.7%



Muon neutrino

Muon neutrino

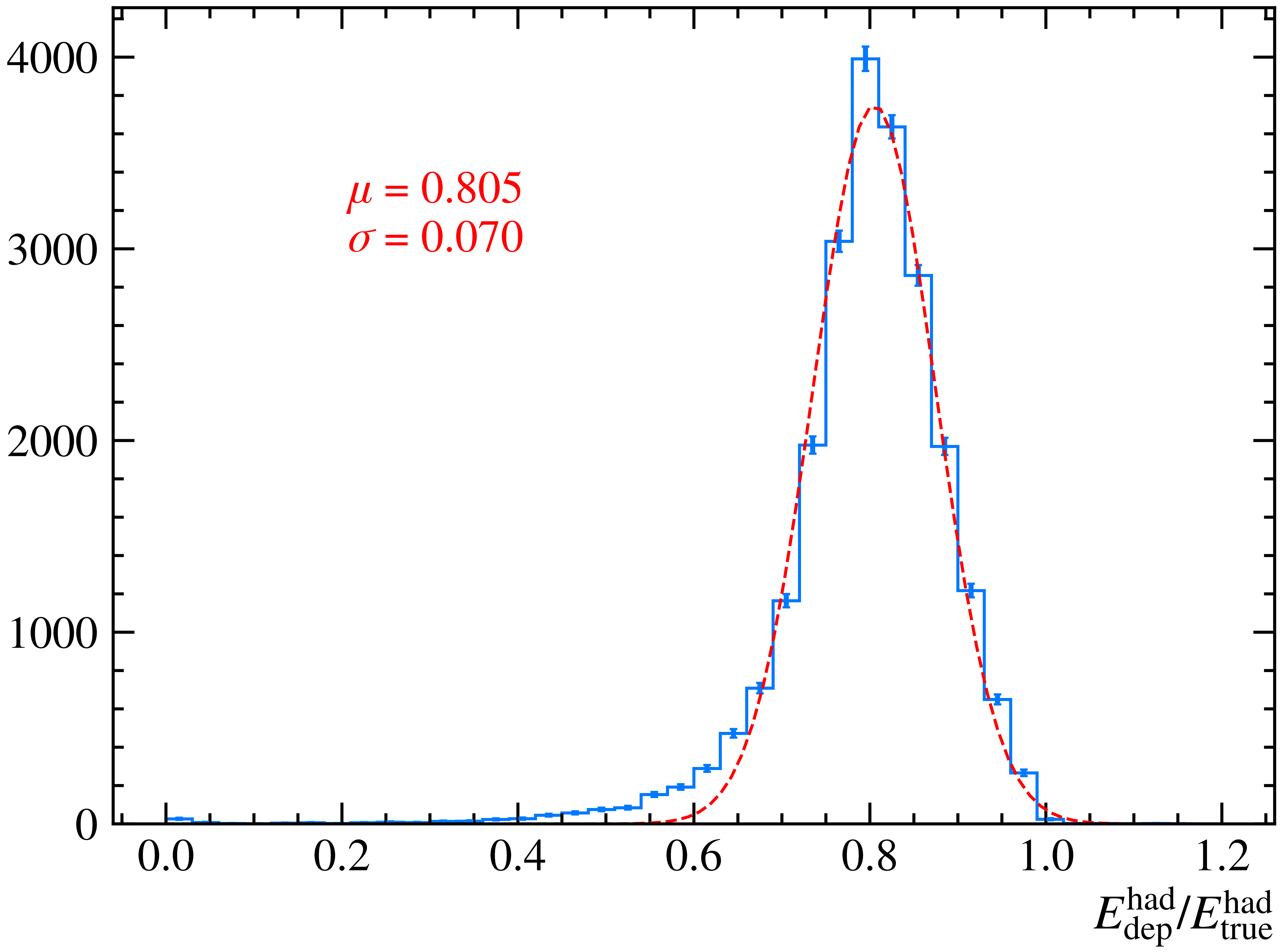
- To take into account of the geometry of the magnet, we'll simulate the magnetic field in Geant4 (on going).

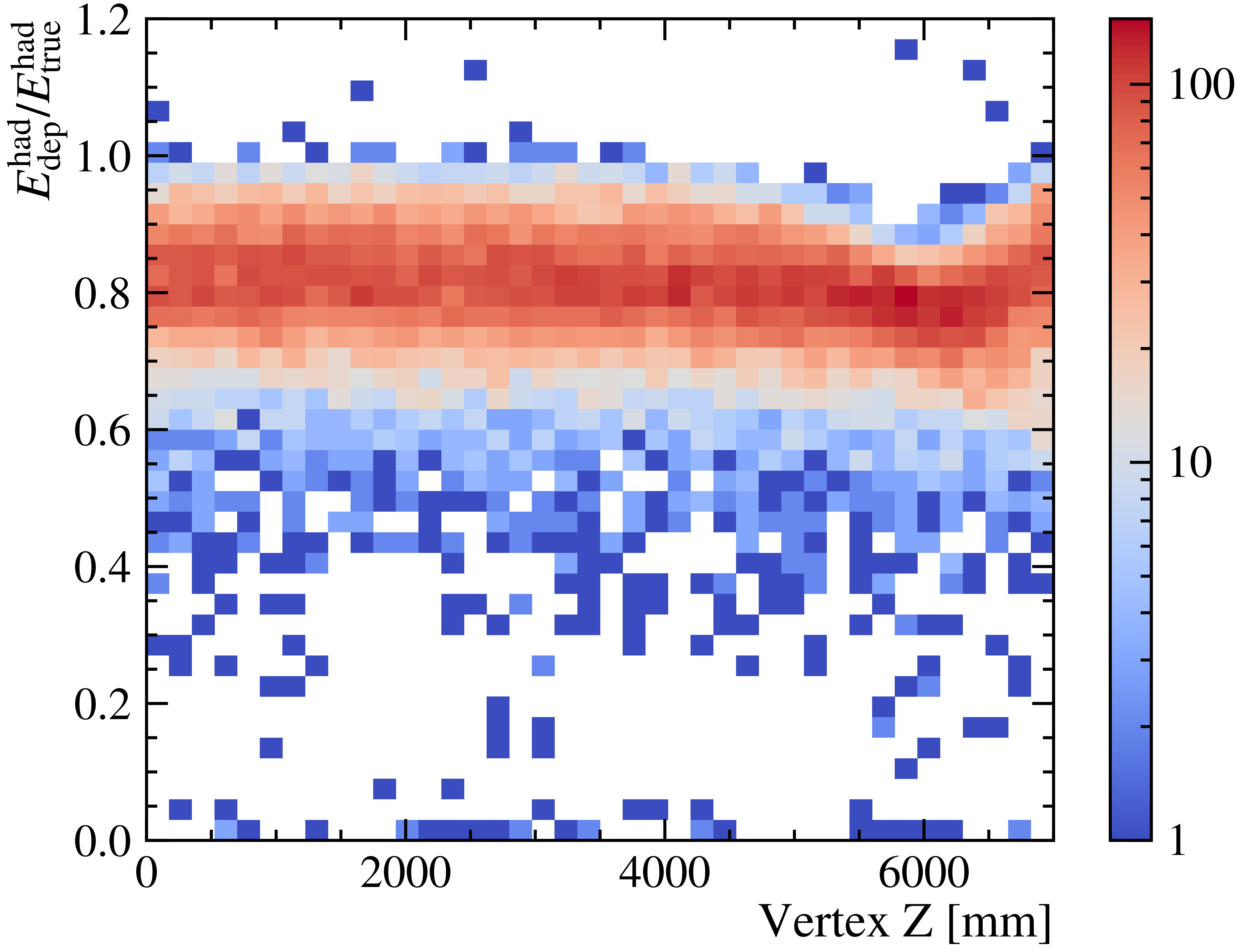


Muon neutrino: hadronic energy containment

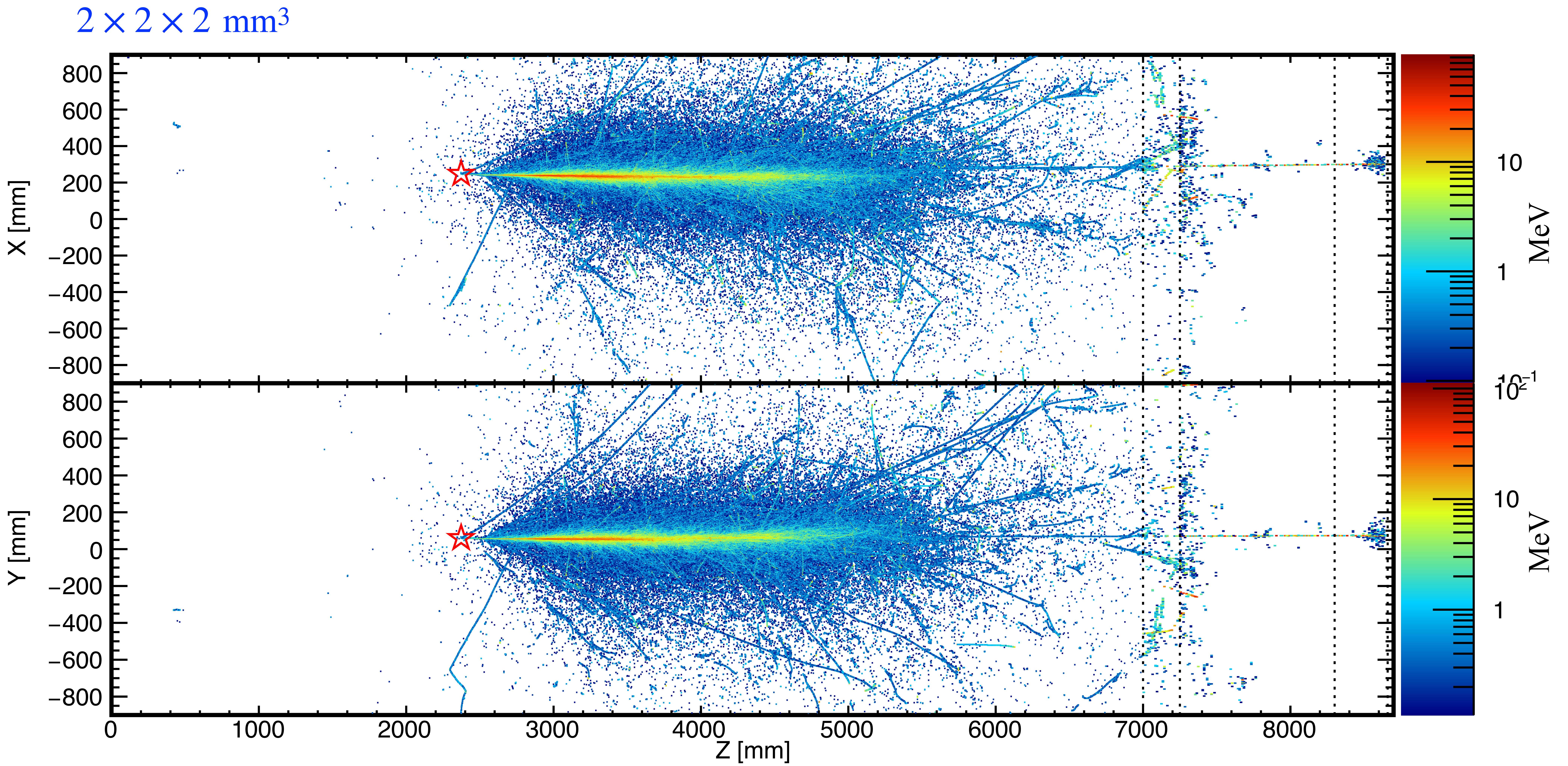
$E^{\mathrm{had}}_{\mathrm{dep}} = E^{\mathrm{total}}_{\mathrm{dep}} - E^{\mathrm{lep}}_{\mathrm{dep}}$ (E_{dep}: deposited energy in LAr and HadCal)

$E^{\mathrm{had}}_{\mathrm{true}} = E^{\nu}_{\mathrm{true}} - E^{\mathrm{lep}}_{\mathrm{true}}$





Muon neutrino



EvtID 2 nuPDG 14 nuE 907.49 GeV nuVtx (247.7, 59.9, 2372.7) mm

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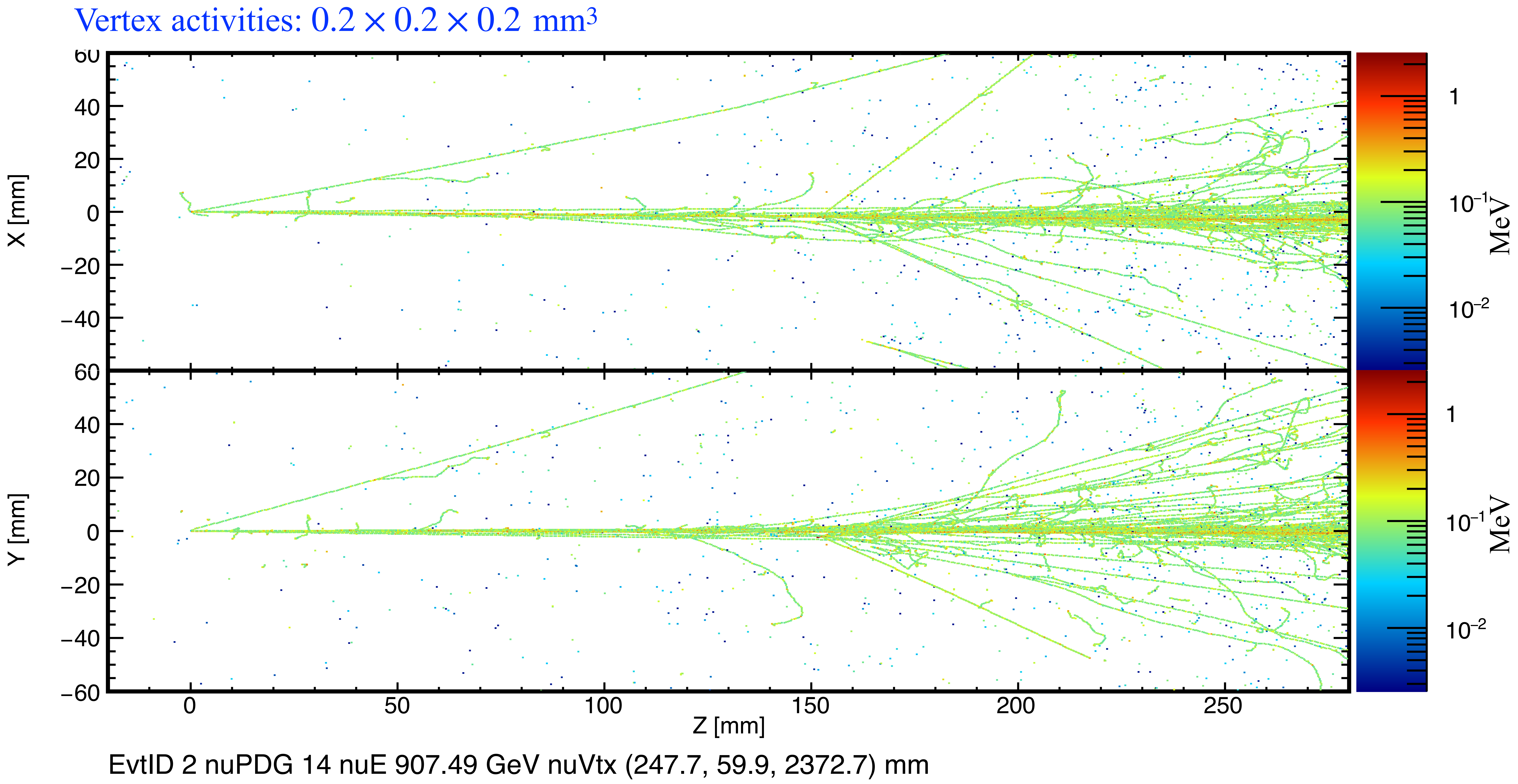
Muon neutrino



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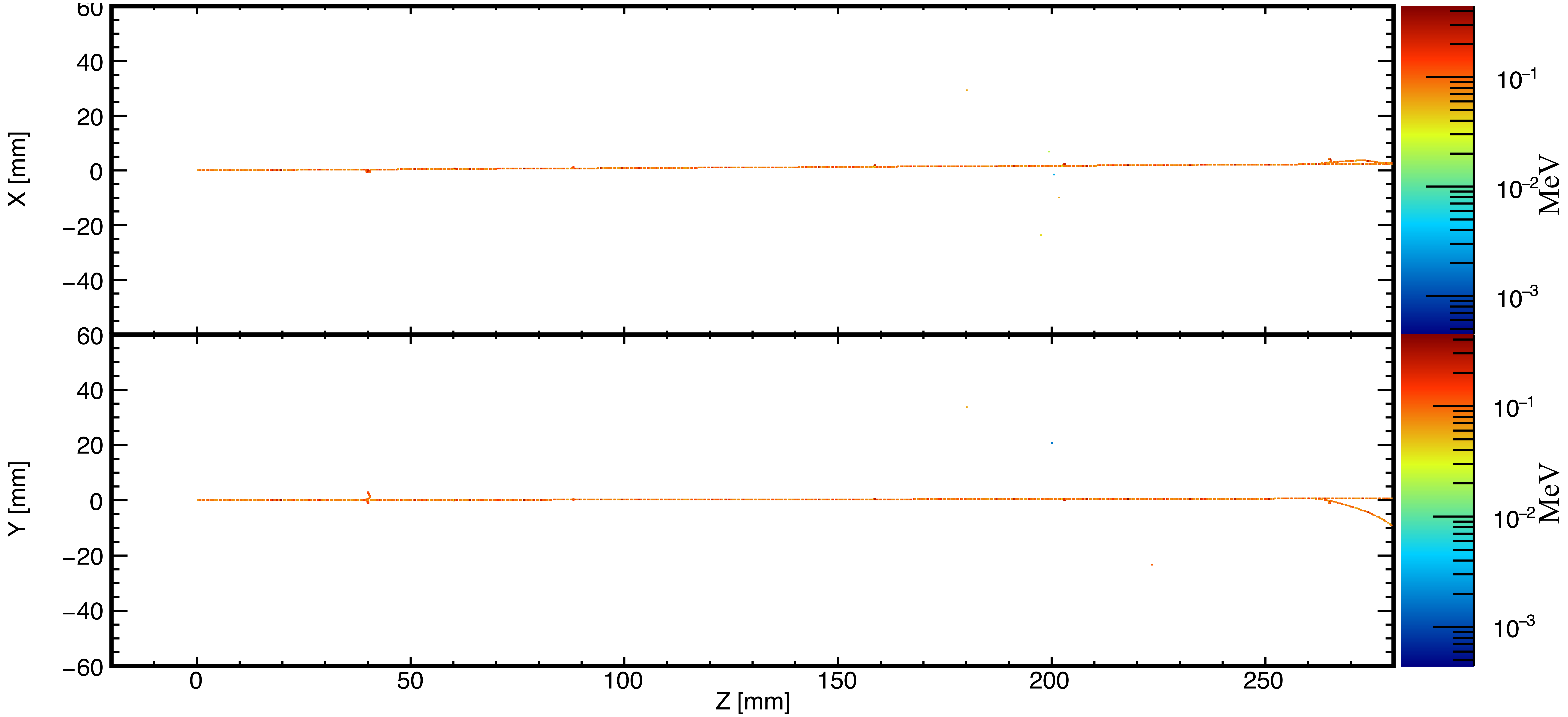
Muon neutrino

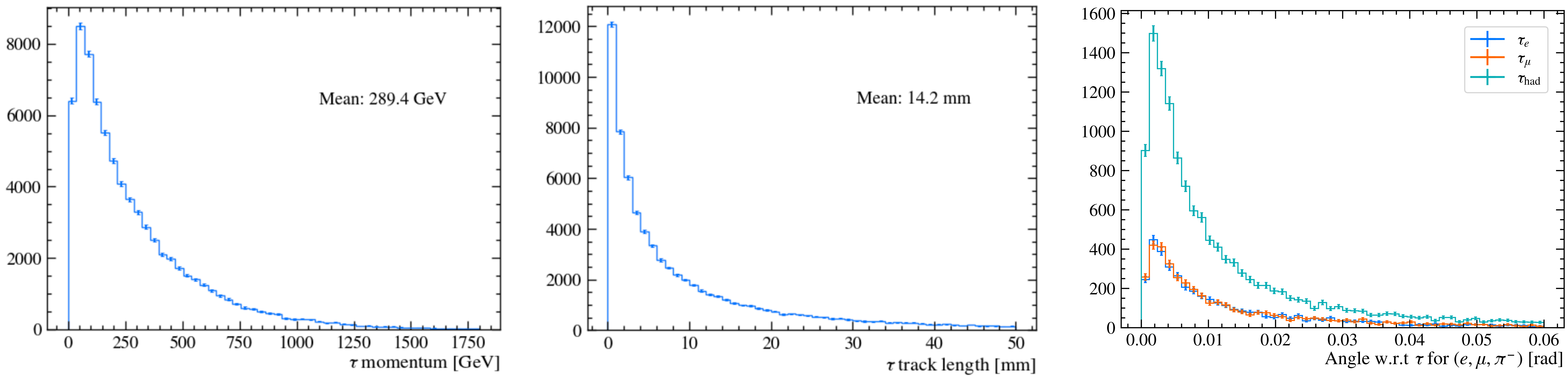
Vertex activities: $0.2 \times 0.2 \times 0.2\ \mathrm{mm}^3$



EvtID 2 PDG 13 Etot 519.7 GeV (247.7, 59.9, 2372.7) mm

Tau neutrino

- A key motivation of the detector is the detection and measurement of TeV-scale neutrino events from a laboratory-generated source, including the tau neutrinos.
- The identification of tau neutrinos presents a particular challenge, requiring both high spatial and kinematic resolution.
  - τ decays very fast in the detector, leaves very short track in the detector.
  - The decay products follow the tau direction with small deviation (~ mrad).



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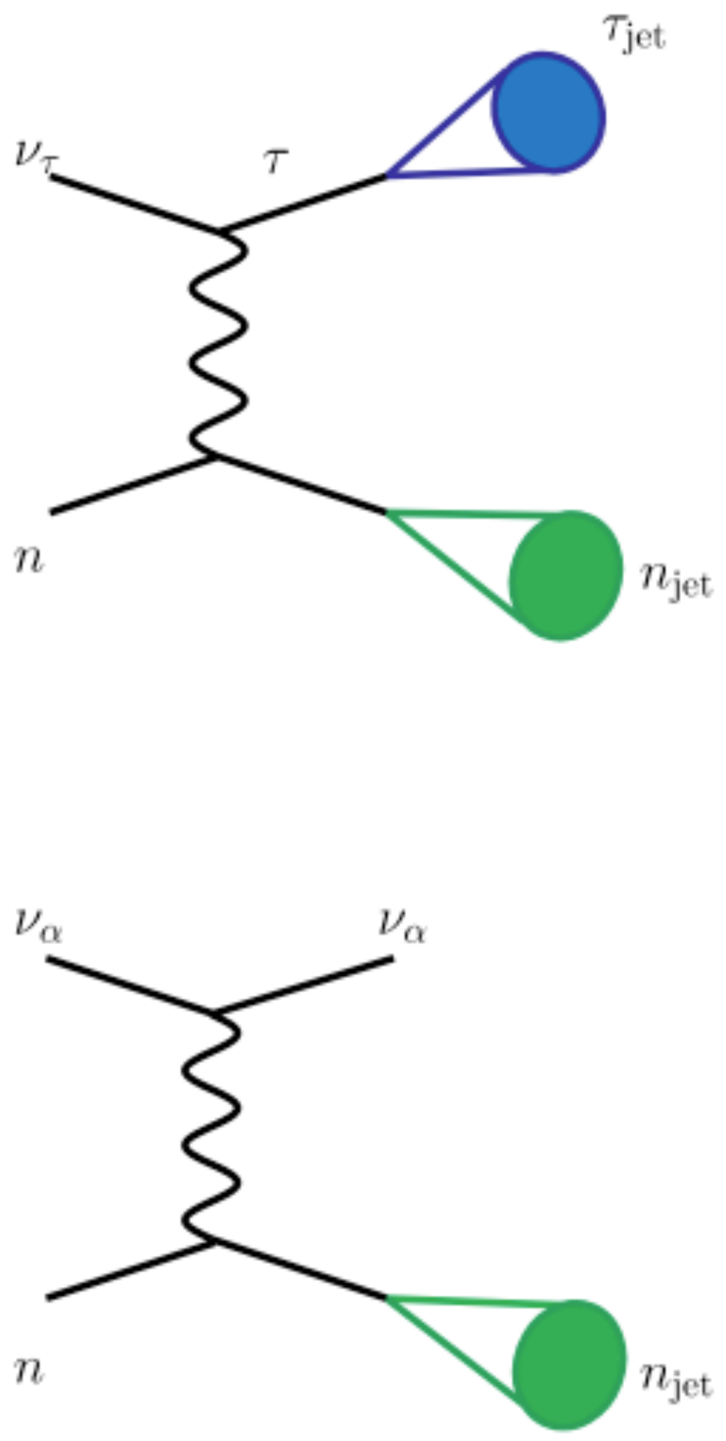
Hadronic decay

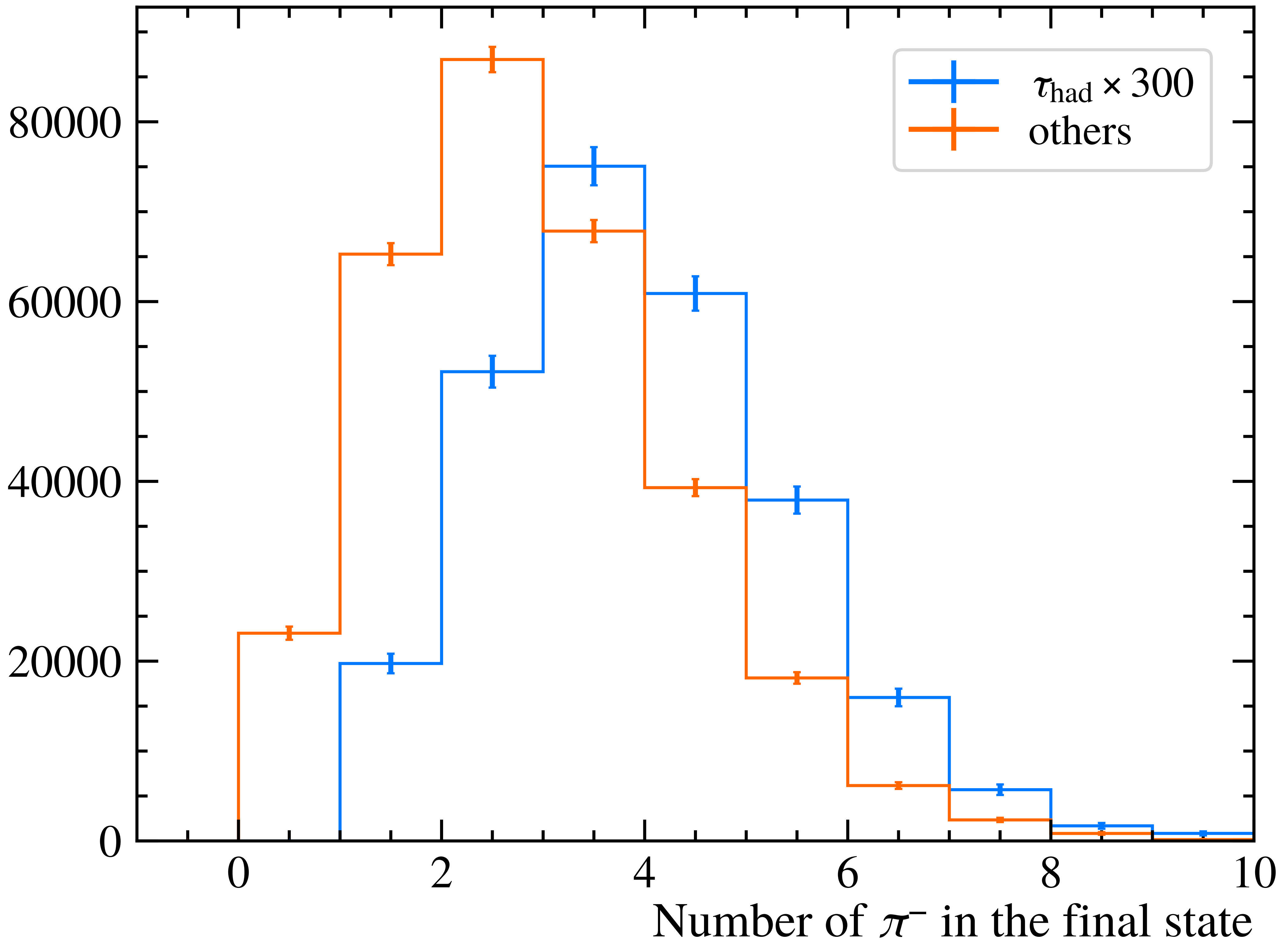
- We build a BDT with pseudo-reconstructed variables to identify tau's hadronic decay channel.
    - Missing transverse momentum, leading pion energy, angle between showers and the leading pion…
- It's also possible to identify $\tau^- \rightarrow 3\pi^\pm$ using the dE distribution along the track.

TABLE I. Dominant decay modes of τ^-. All decays involving kaons, as well as other subdominant decays, are in the "Other" category.

Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
Other	5.7%



10.1103/PhysRevD.102.053010



$\tau^- \rightarrow 3\pi^\pm$

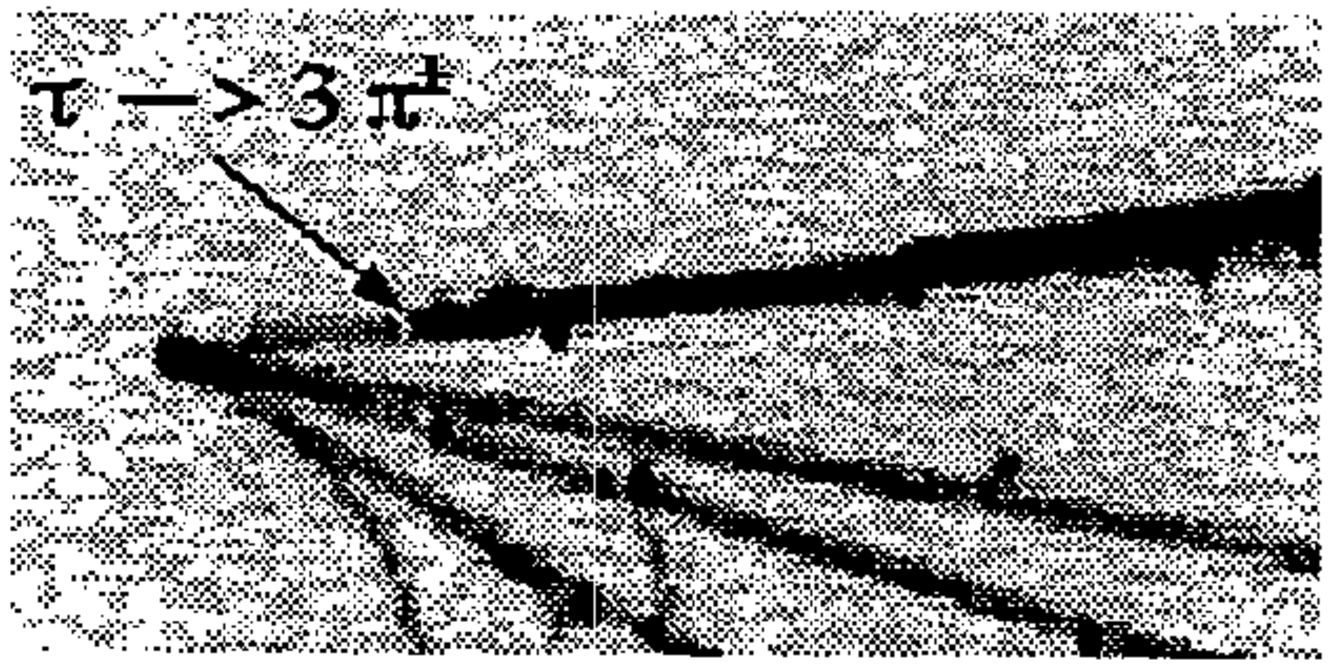


Fig.3 Simulation of a ν_τ CC interaction followed by τ decaying in $3\pi^\pm$.

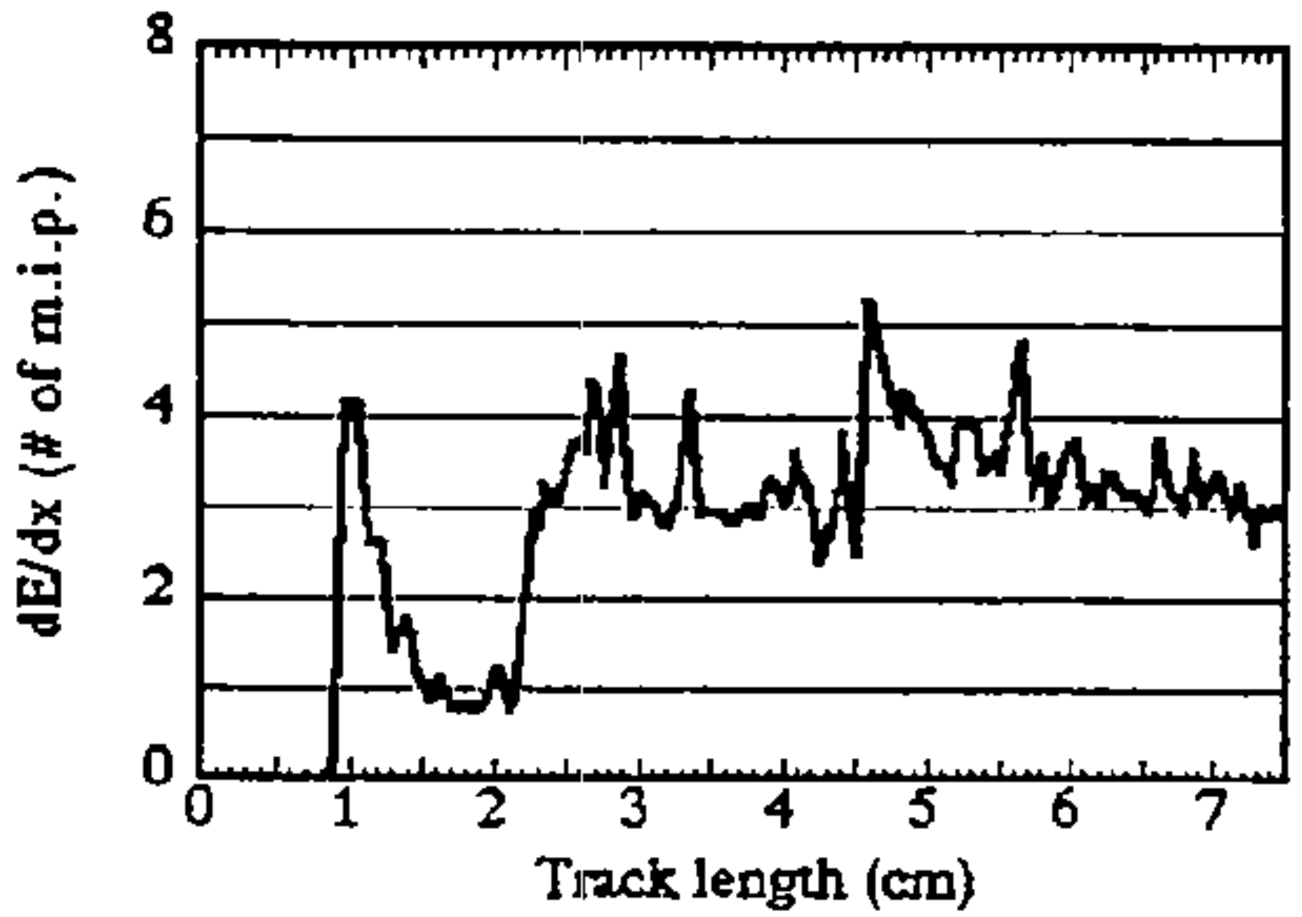
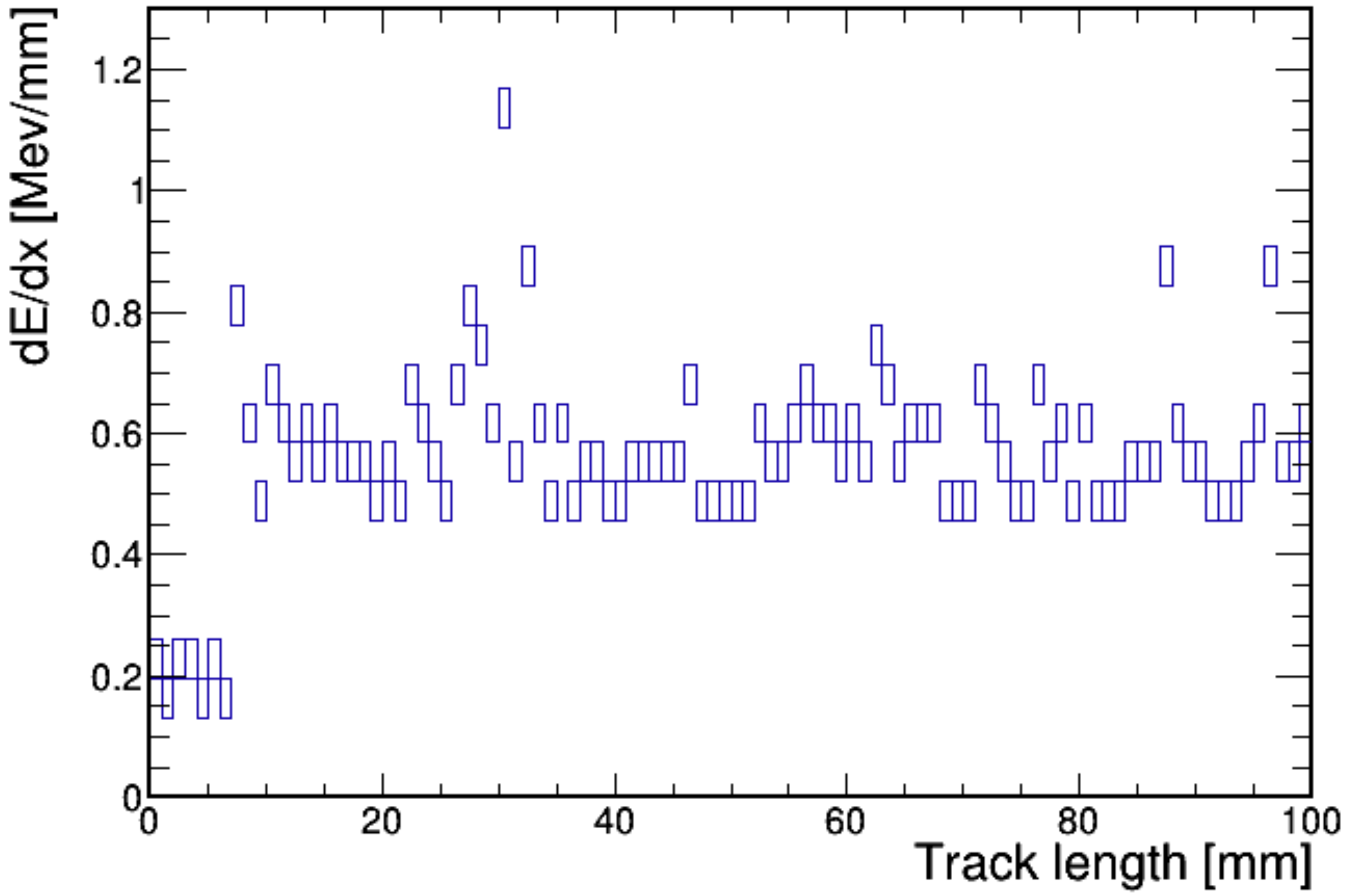


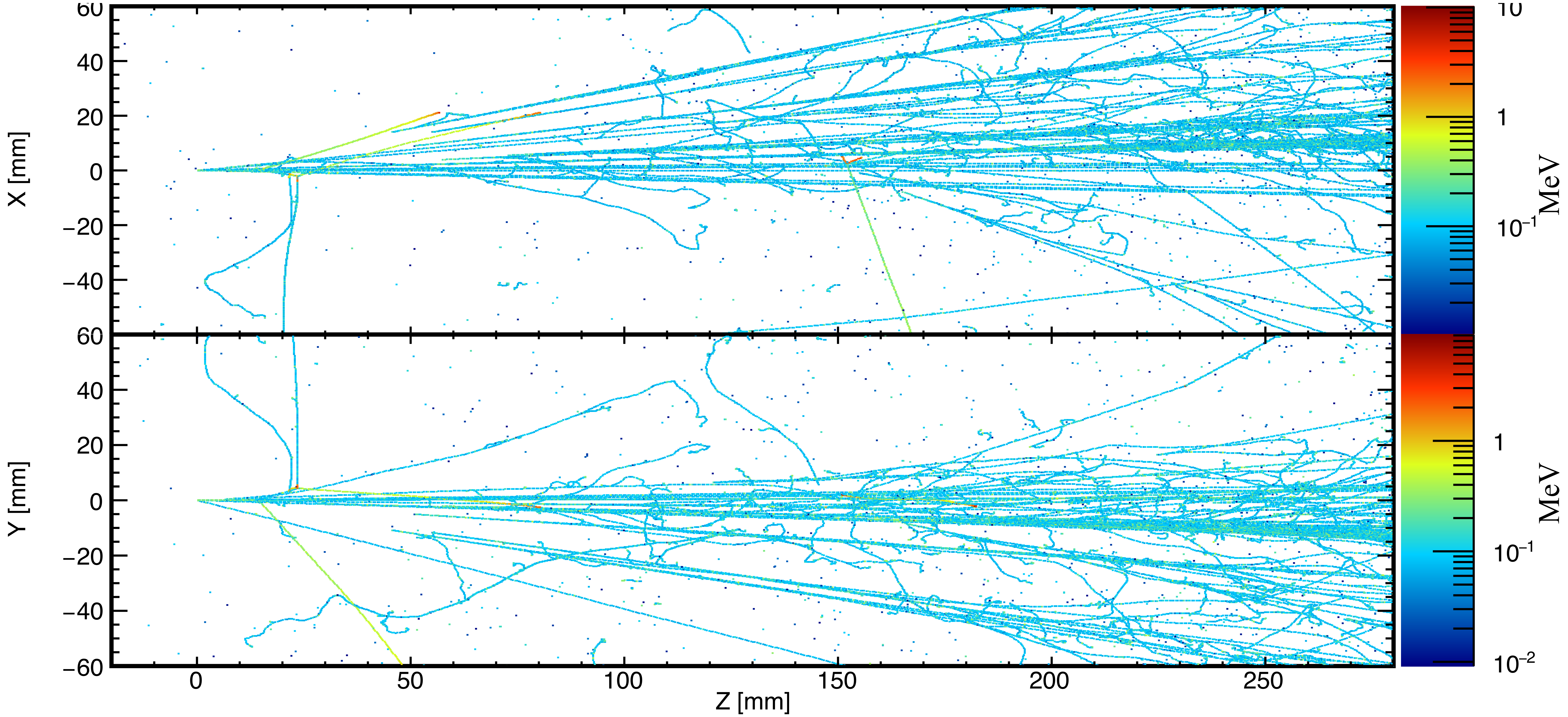
Fig.4 Detection technique consists in identifying the secondary vertex by the sudden increase in the dE/dx (+2 minimum ionizing particles) exiting the main vertex.

"The ICARUS liquid argon TPC: A New detector for tau-neutrino search", LNGS-92-20.



$\tau^- \rightarrow 3\pi^\pm$

Vertex activities: $0.2 \times 0.2 \times 0.2\ \mathrm{mm}^3$



EvtID 0 nuPDG 16 nuE 407.12 GeV nuVtx (-30.1, 387.3, 3637.0) mm

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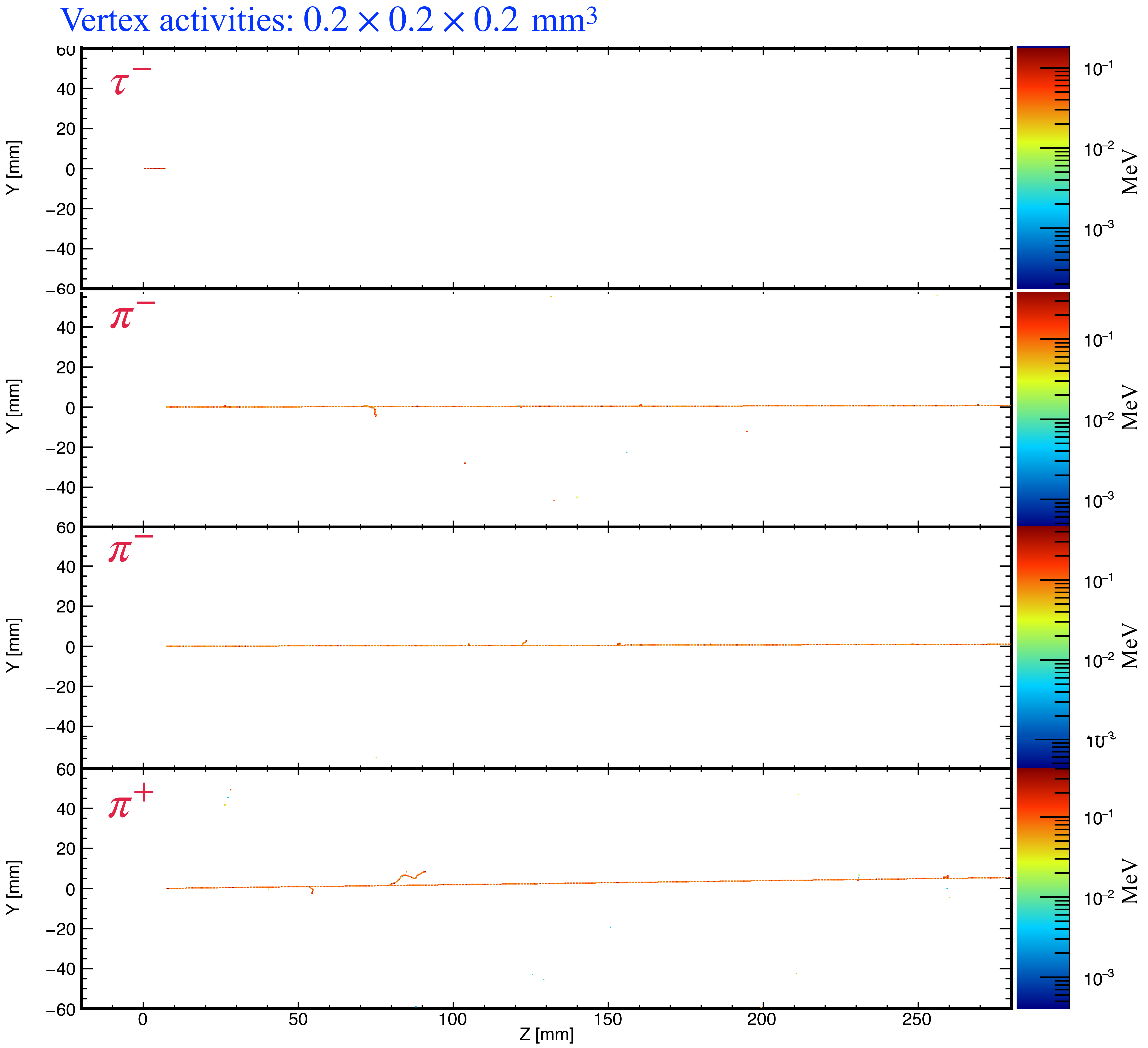
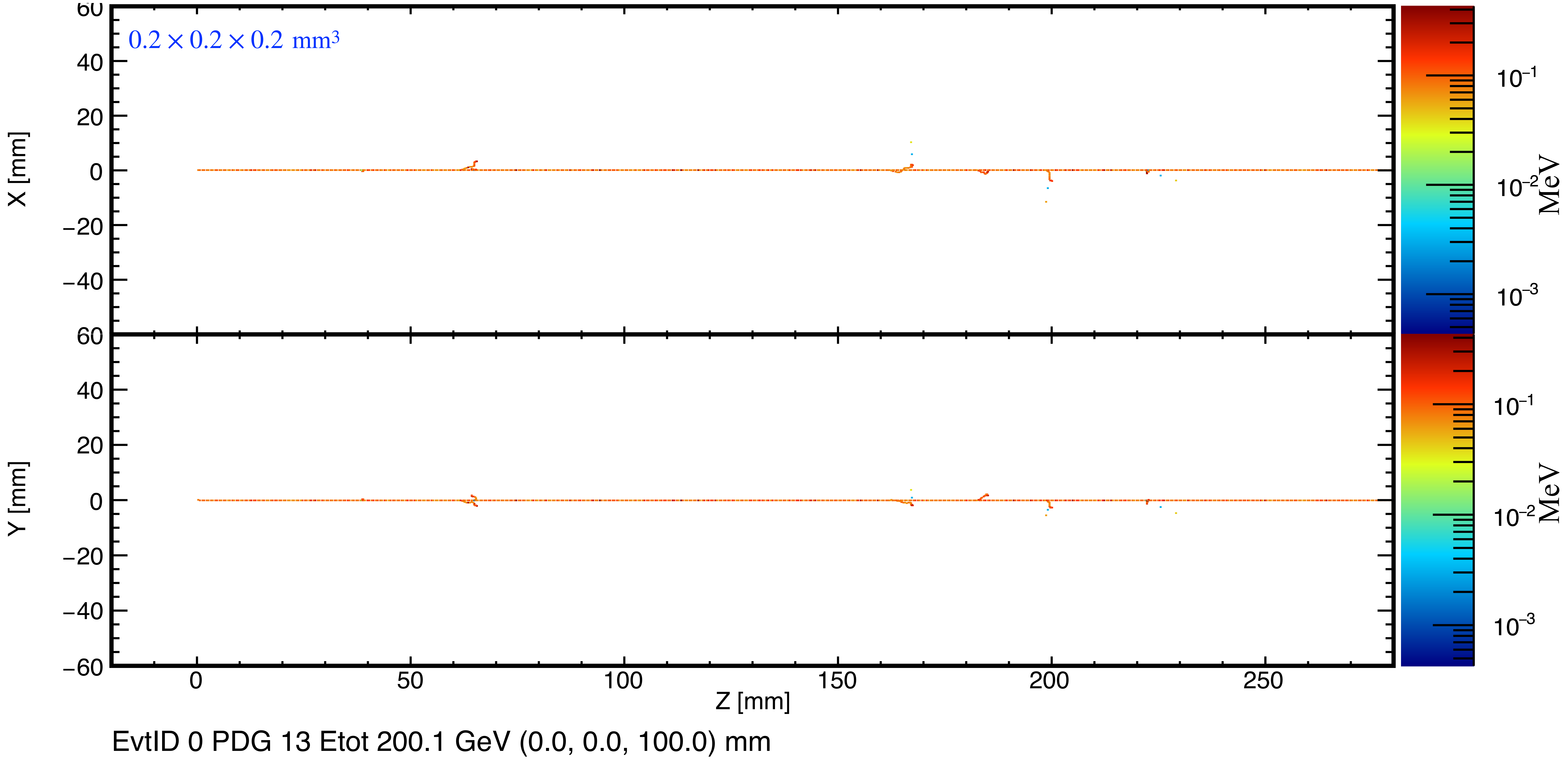
$\tau^- \to 3\pi^\pm$



Diffusion and pitch size

Without diffusion effect



Electron diffusion and the pitch size can affect how the charge expected to be detected.

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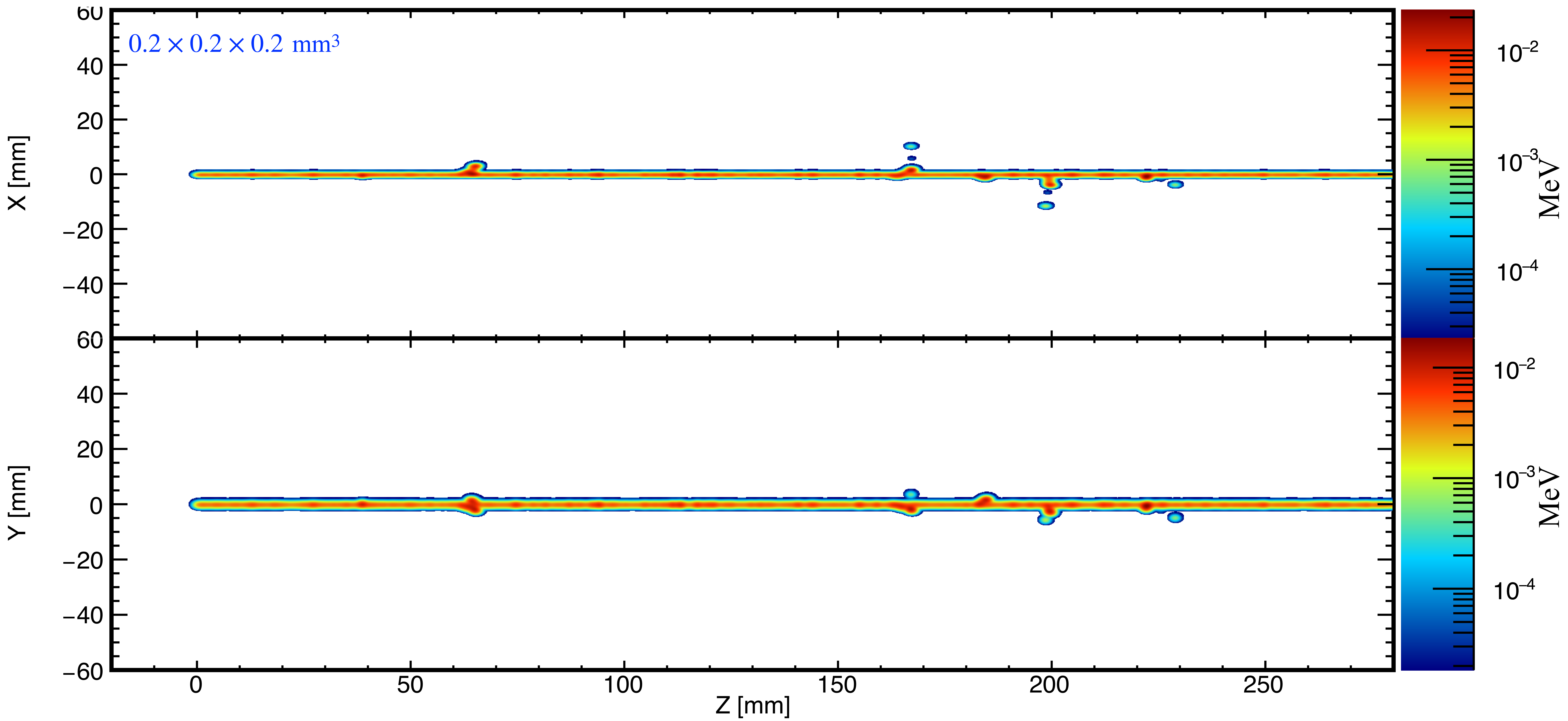
Diffusion and pitch size

https://lar.bnl.gov/properties/

Electron transverse diffusion coefficient @ 500 V/cm: D_T = 13.2 cm²/s

Electron longitudinal diffusion coefficient @ 500 V/cm: D_L = 6.6 cm²/s

With diffusion effect



EvtID 0 PDG 13 Etot 200.1 GeV (0.0, 0.0, 100.0) mm

Summary

Possible magnet components from both FLArE and FASER2 could enhance the ability to measure the muon momentum

Geant4 configuration of the magnetic field will be added to have a better estimation of the muon acceptance

Another possible method to identify tau neutrinos using the dEdx signature of $\tau^- \rightarrow 3\pi^\pm$

It requires good clustering of final state tracks in order to separate $3\pi^\pm$ from the other particles

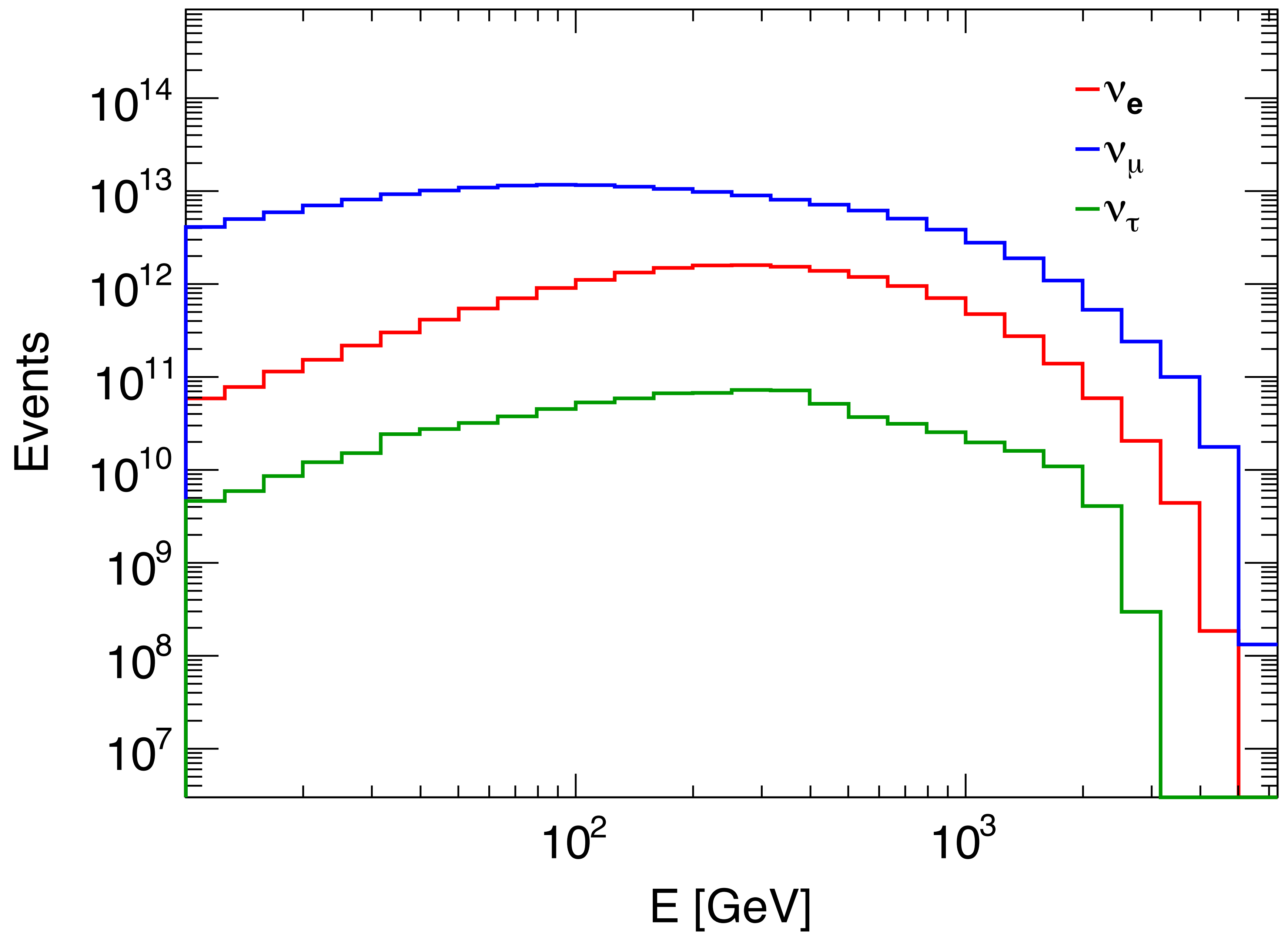
Electron diffusion and the pitch size can affect how the charge expected to be detected

Quantitatively measure how large the effects are on dE/dx distributions and Particle ID

Backup

Neutrino

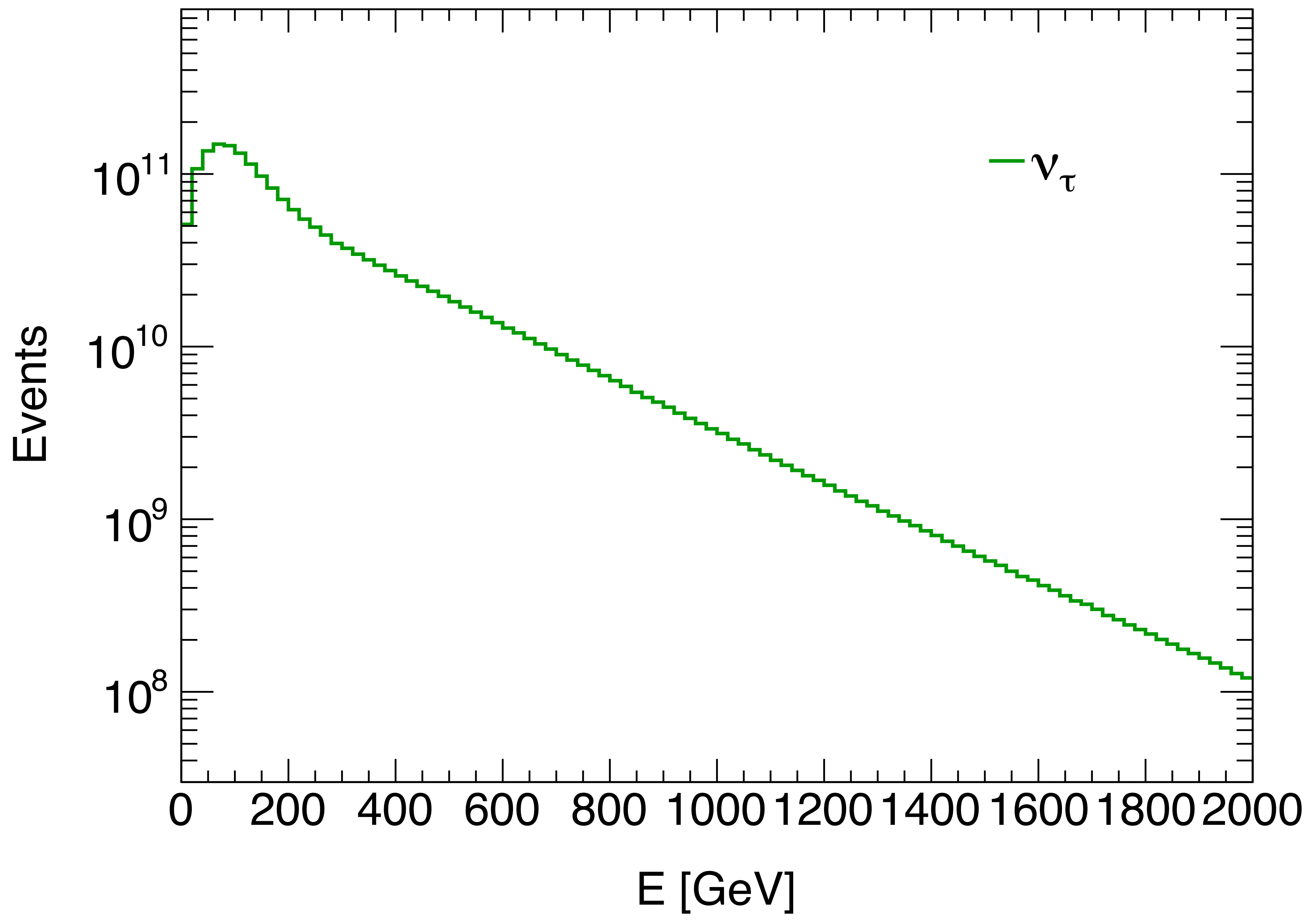
- Neutrino flux prediction have large uncertainties.
- Muon and electron neutrino spectra require detailed simulation of the beam line, including HL-LHC geometry.
- ν_τ is predominantly produced by the charm decay $D_s \rightarrow \tau\nu_\tau$ and the subsequent tau decay, which need deeper understanding of the production mechanism in the pp collision.



Felix Kling, et. al. 2105.08270

Github, Using Sibyll 2.3d

FLArE10, 620m downstream from IP, 3000/fb



Weidong Bai, et. al. 2112.11605

NLO perturbative evaluations of charm production using PROSA PDFs

eta > 6.9 (radius 1 m at a distance of 480 m from IP)

ν_τ

Felix Kling, et. al.
Mean: 329.2 GeV
RMS: 372.4 GeV

Weidong Bai, et. al.
Mean: 256.6 GeV
RMS: 261.8 GeV

Neutrino

Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Table 7.1: Detectors and neutrino event rates: The left side of the table summarizes the detector specifications in terms of the target mass, pseudorapidity coverage and assumed integrated luminosity for both the LHC neutrino experiments operating during Run 3 of the LHC as well as the proposed FPF neutrino experiments. On the right, we show the number of charged current neutrino interactions occurring the detector volume for all three neutrino flavors as obtained using two different event generators, `Sibyll 2.3d` and `DPMJet 3.2017`.

Neutrino

Physics topic	Event rate/3000/ fb-1/10 ton	Event containment for	Electron detection	Muon Detection	Tau Detectio	Hadronic shower	Muon momentum	visible Energy	Energy resolution	Lepton kinematics	vertex kinematics
Muon neutrino cross section	1.00E+06	Yes except muon		Yes		Yes	May be	10 GeV	30%	yes	
Electron Neutrino Cross section	1.00E+05	Yes	Yes			Yes		10 GeV	30%	yes	
Tau neutrino cross section	5.00E+03	yes	yes	yes	yes	yes	yes	10 GeV	30%	yes	yes
Charm and QCD measurements	Electron/tau rates	yes	yes	yes	yes	yes	yes	100 GeV	30%	yes	
Sterile Neutrino oscillations with tau neutrinos	5.00E+03	yes	yes	yes	yes	yes	yes	10 GeV	10-20%	yes	
Neutrino electron elastic scattering	200	yes	yes					1 GeV	10%	yes	yes
Inverse muon decay	1000			yes			May be	11 GeV	20%	yes	yes
Neutrino tridents	25		yes	yes	may be		Yes	100 GeV	30%	yes	yes
Light Dark matter scattering on electrons	BSM physics	yes	yes					< 1 GeV	10%	yes	yes
Light dark matter scattering nucleons	BSM physics	yes				yes		< 1 GeV	10%		

Final state particles

	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%