FLArE Simulation and Physics Reach

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Introduction

- FLArE: a liquid argon time projection chamber (LArTPC) detector in FPF to detect neutrinos and dark matter from LHC.
- High spatial and time resolution, good background rejection, large containment, precise particle identification and kinematic measurements, large dynamic range from ~MeV to ~TeV

Develop simulation and reconstruction for

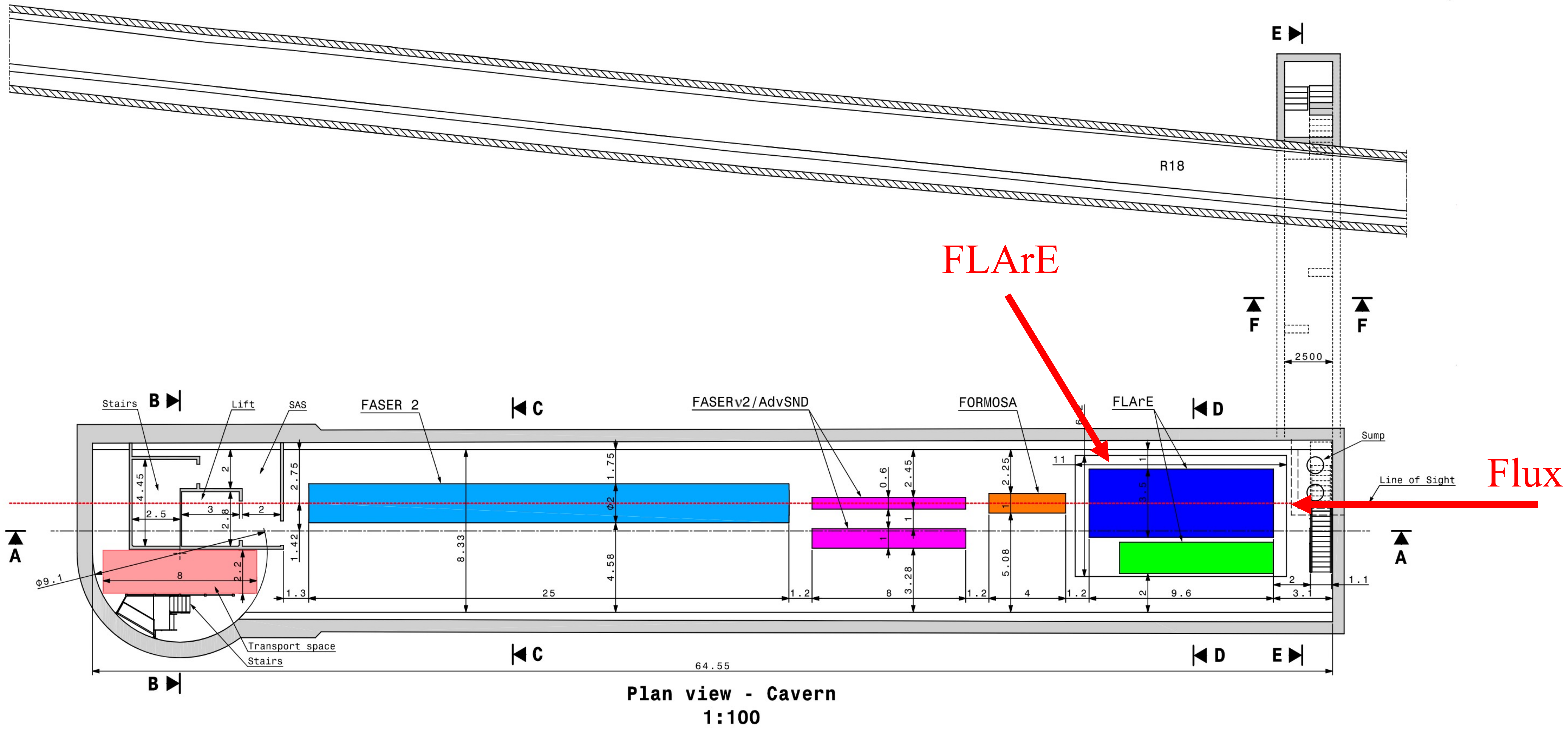
- Detector Design Optimization
- Detector performance
- Physics sensitivity

For CDR (next year)

- Simple geometry and simulation
- Pseudo reconstruction

For TDR

- Full geometry and simulation
- Full reconstruction chain



Physics Requirements

Physics topic	Events/ 3000/fb-1/10 ton	Fiducial Event ontainmen	Electron ID	Muon ID	Tau ID	Hadronic shower	Muon momentum	Practical Energy threshold	Energy resolution	Lepton kinematics	vertex kinematics atial resoluti
Muon neutrino cross section	1E+06	Partial		Yes		Yes	may be	10 GeV	30%	yes	
Electron Neutrino Cross section	1E+05	yes	Yes			Yes		10 GeV	30%	yes	
Tau neutrino cross section	5E+03	yes	yes	yes	yes	yes	yes	10 GeV	30%	yes	yes
Charm and QCD measurements	rates >100 GeV	yes	yes	yes	yes	yes	yes	100 GeV	30%	yes	yes
Sterile Neutrino oscillations tau neutrinos	5E+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 (on Ar)		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%		
Tagged neutrinos with ATLAS for charm/QCD studies	rates > 100 GeV	may be	yes	yes	yes	yes	yes	>100 GeV	Requires timing and DAQ coordination		

Goal: Optimize detector design to address these requirements and estimate physics reach

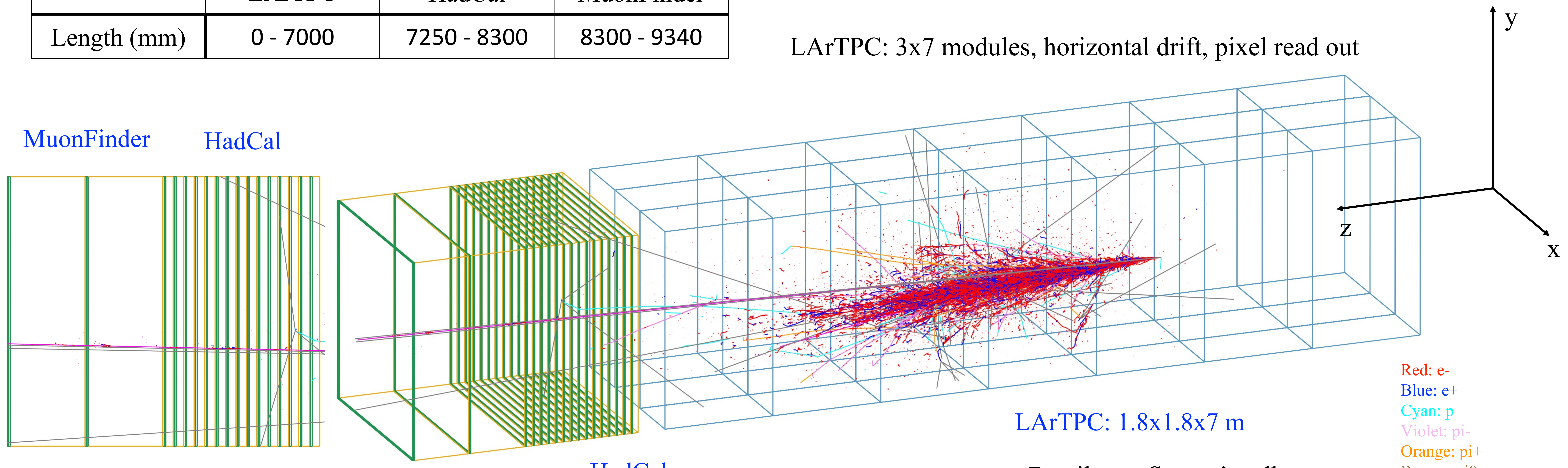
From Milind's overall talk

Detector Configuration

- Fiducial mass of 10 tons (1x1x7 m) 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 - 9340

LArTPC: 3x7 modules, horizontal drift, pixel read out



Red: e-
Blue: e+
Cyan: p
Violet: pi-
Orange: pi+
Brown: pi0
Magenta: mu-
Gray: other

Details see Steven's talk

MuonFinder: *16 cm Fe, 1 + 1 cm scint planes. 2 layers*

HadCal: *5 cm Fe, 1 + 1 cm scint planes. 15 layers*

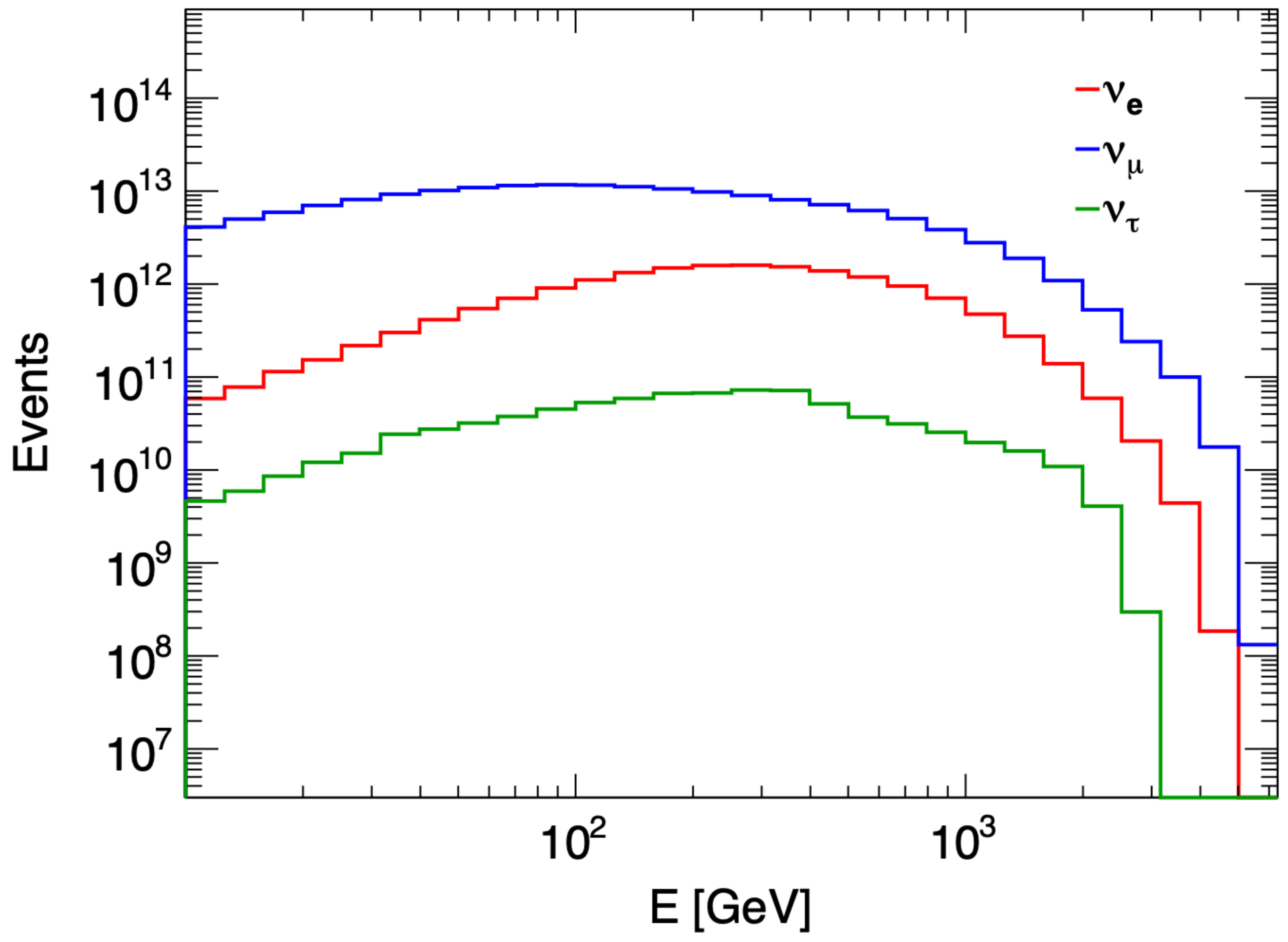
Detector Design Optimization Strategy

- Detector size: Energy containment
- Required pixel size, time ticks: Needed angular special and energy resolution for ν_τ identification and electron from light dark matter scattering
- Trigger requirement: Muon background rejection

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

Neutrino flux

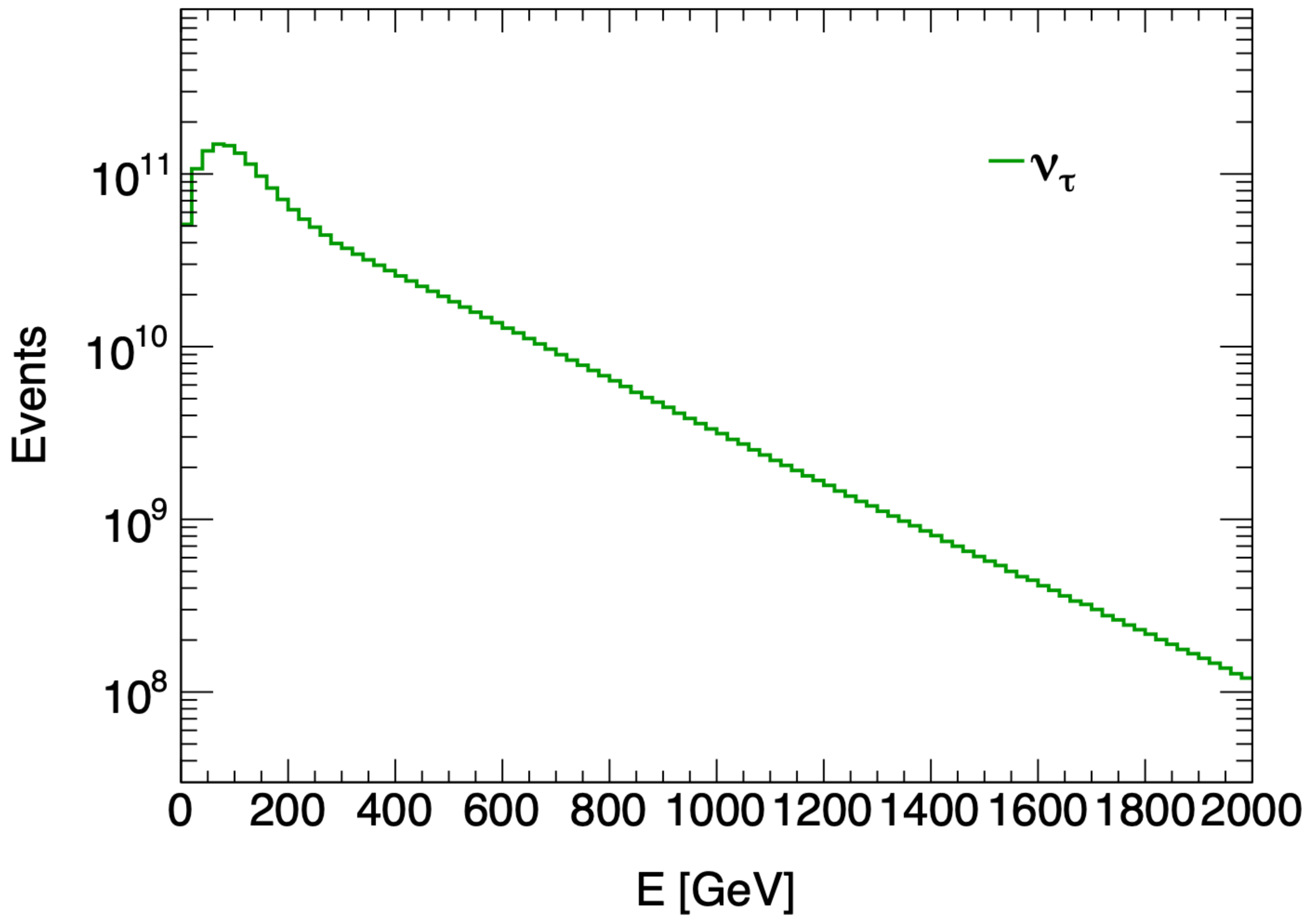
- Neutrino flux prediction have large uncertainties.
- Muon and electron neutrino spectra require detailed simulation of the beam line, including HL-LHC geometry.
- ν_τ is predominantly produced by the charm decay $D_s \to \tau\nu_\tau$ and the subsequent tau decay, which need deeper understanding of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

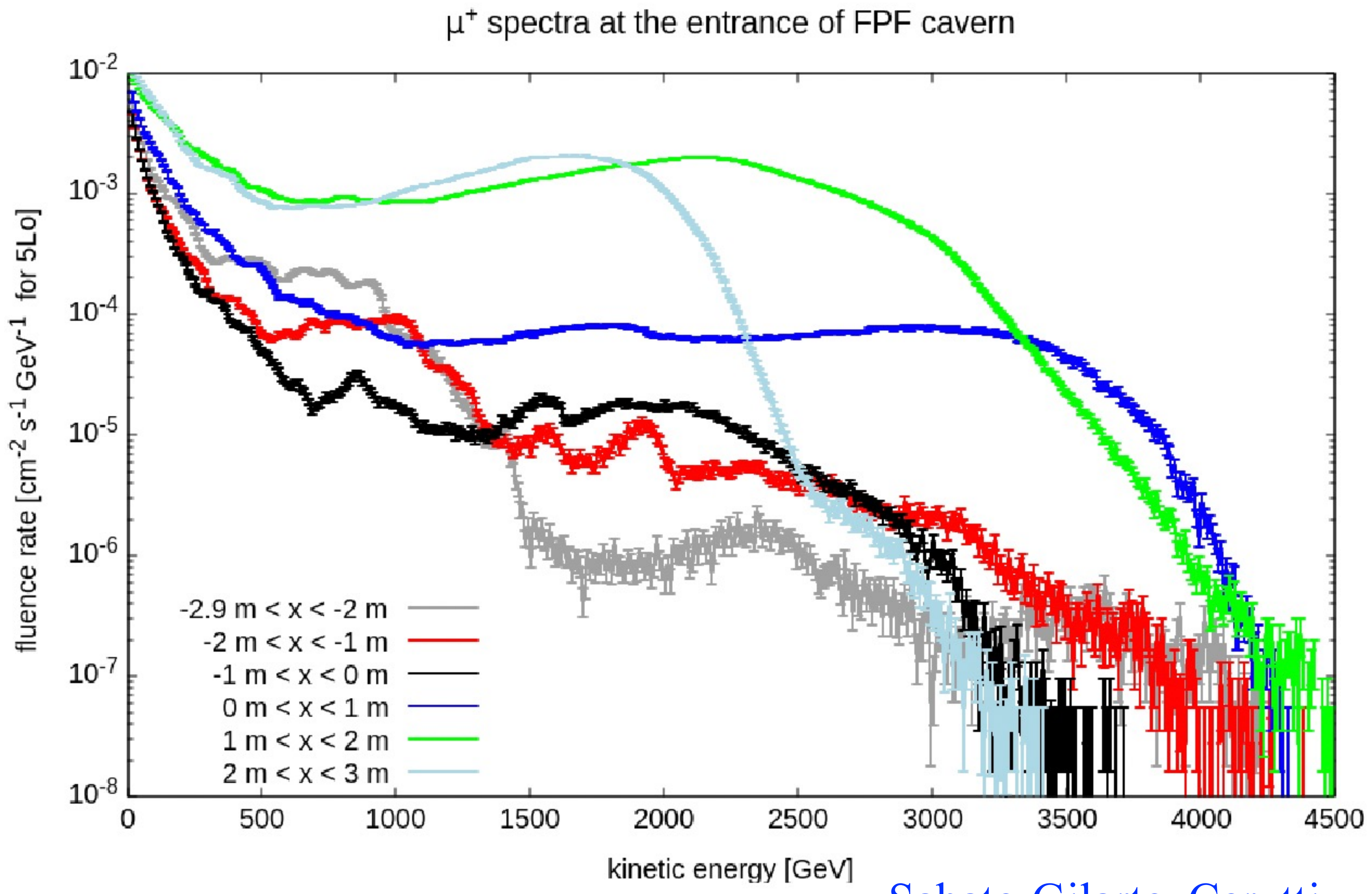
Neutrino rates

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`.

Beam Muons

- Muon flux about 0.5 Hz/cm^2 , ~5kHz in the 1x1 m region, ~10kHz in the peripheral region → trigger rate
- Drift distance ~30 cm, drift time ~0.15 ms , 1 m x1 m fiducial → ~ 1 muon bkg event in a signal trigger window
- Can be removed by containment cut and timing-space clustering



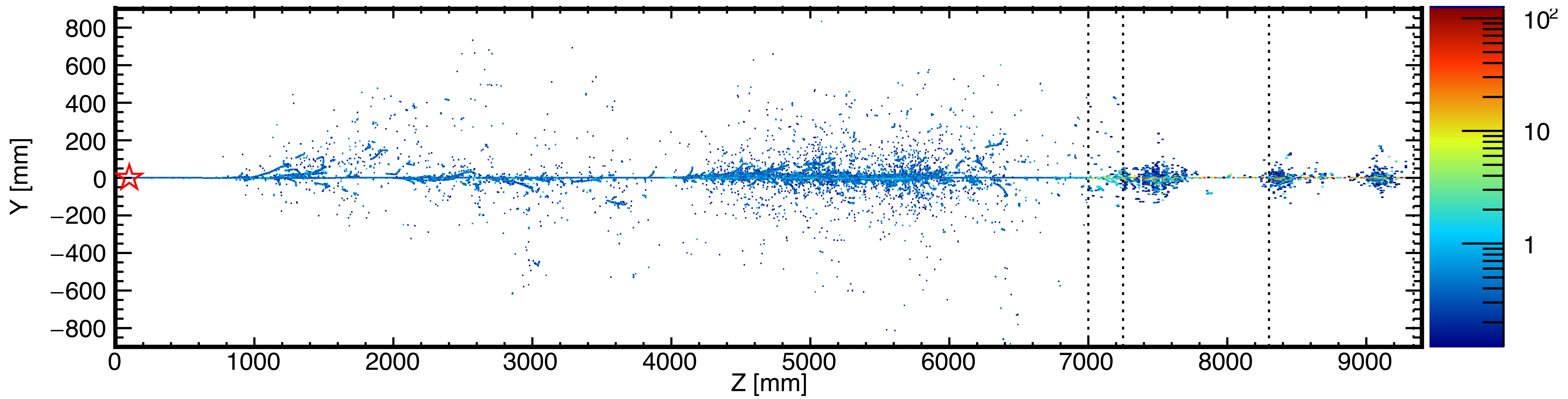
Sabate-Gilarte, Cerutti

Looking in slices 0.5m wide, 1m high, covering region +/-2m away from the LOS in horizontal plane
Muon flux from FLUKA simulation in Hz/cm^2

Slice	-2 - -1.5m	-1.5 - -1m	-1 - -0.5m	-0.5 – 0m	0 – 0.5m	0.5 – 1m	1 – 1.5m	1.5 – 2m
Mu+ flux	0.29	0.23	0.17	0.15	0.21	0.41	0.71	1.24
Mu- flux	0.44	0.34	0.28	0.29	0.40	0.62	0.78	0.84
Total flux	0.72	0.57	0.45	0.44	0.61	1.03	1.49	2.08

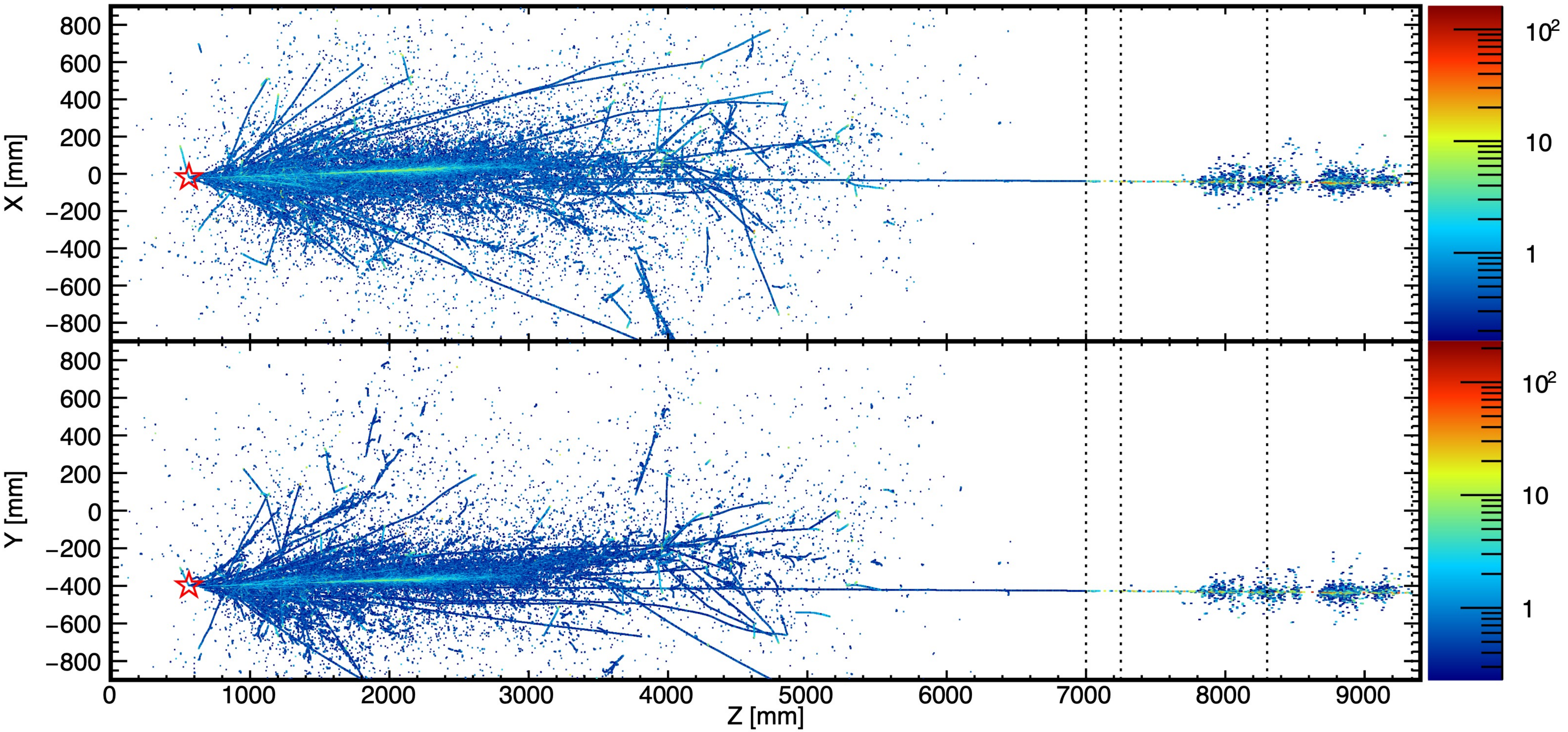
From Jamie Boyd

Over 1m x 1m square the rate is ~0.5Hz/cm^2



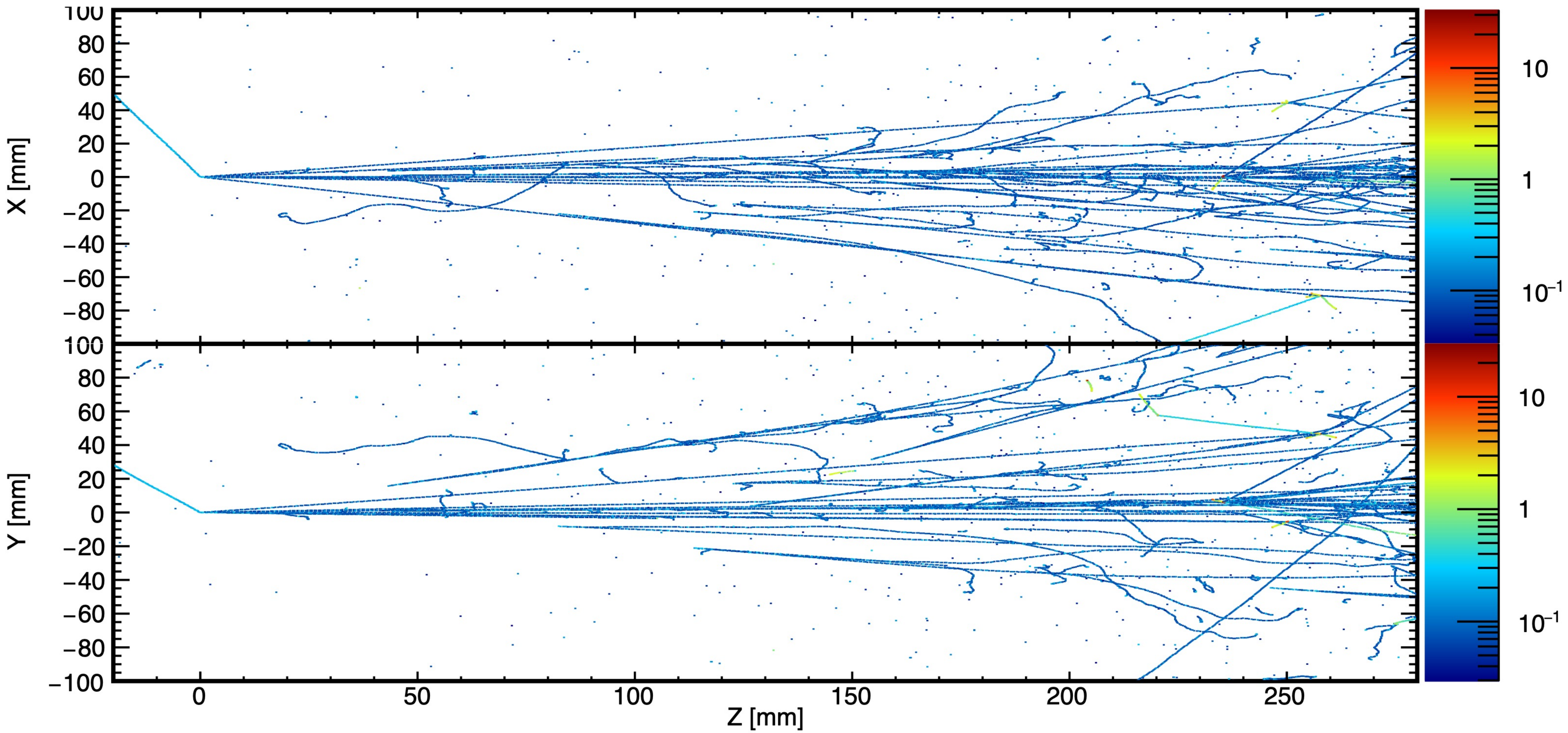
EvtID 9 PDG 13 Etot 500.1 GeV (0.0, 0.0, 100.0) mm

ν_τ CC



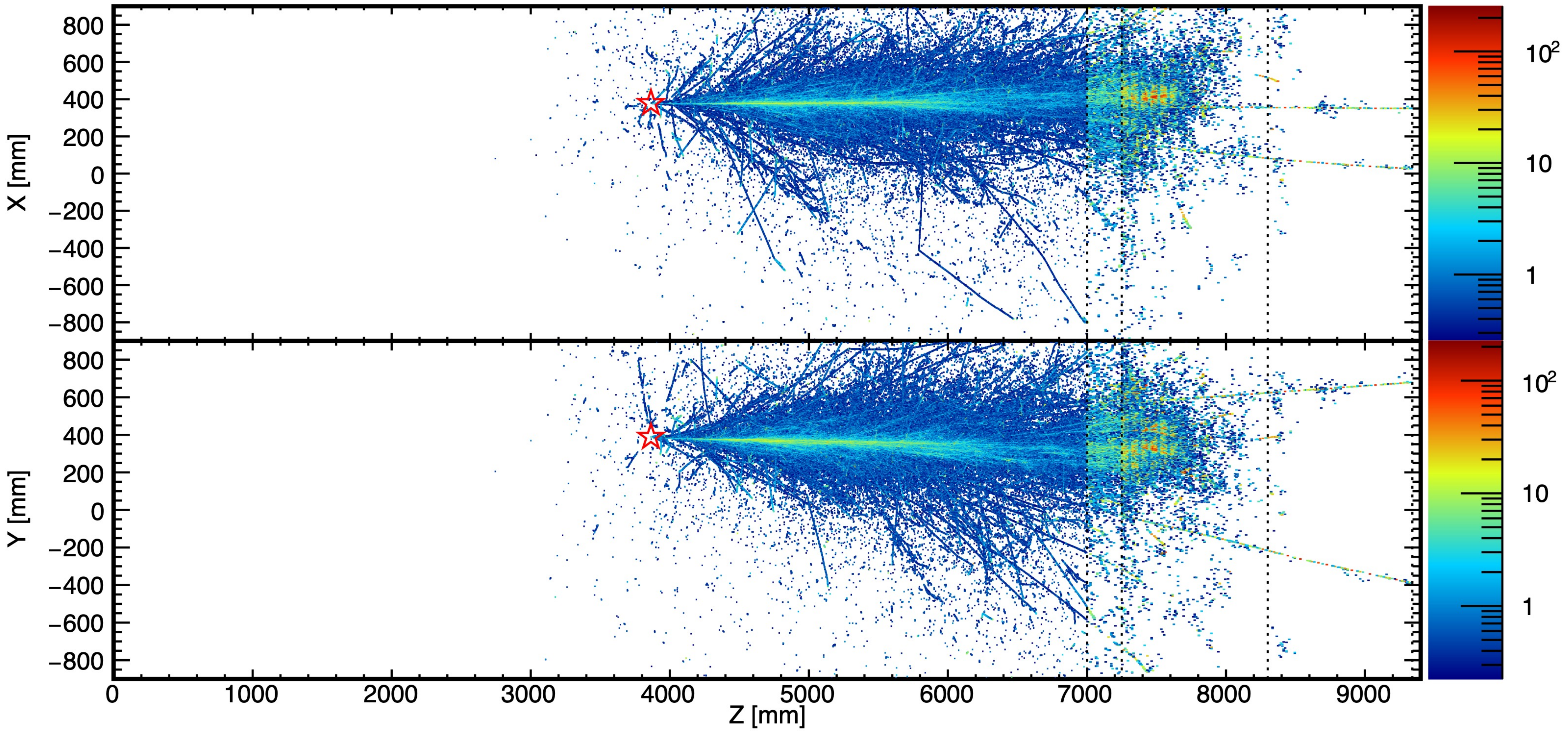
EvtID 0 nuPDG 16 nuE 1097.80 GeV nuVtx (-19.0, -398.4, 561.3) mm

Tau neutrino



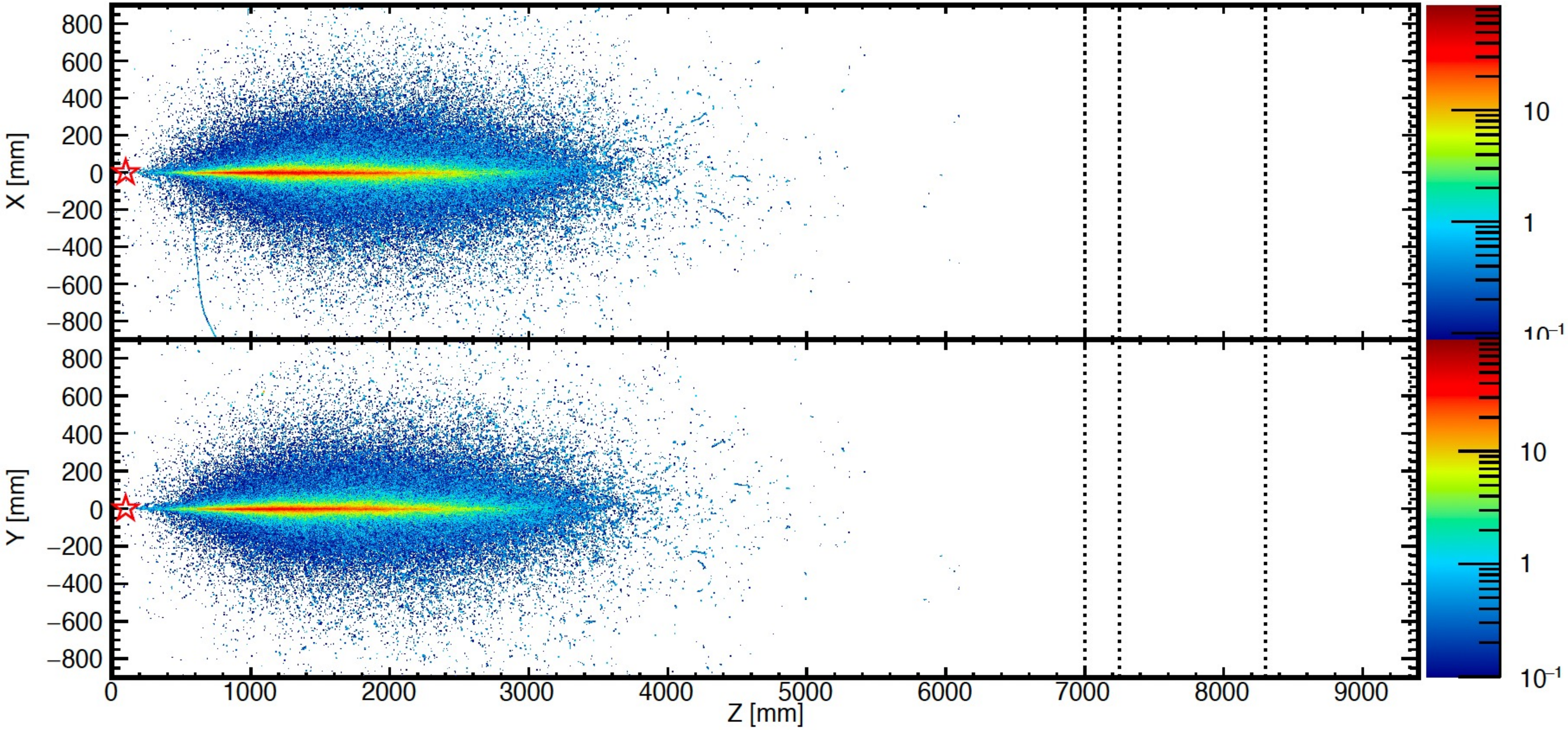
EvtID 0 nuPDG 16 nuE 1097.80 GeV nuVtx (-19.0, -398.4, 561.3) mm

ν_μ CC



EvtID 0 nuPDG 14 nuE 706.96 GeV nuVtx (378.7, 389.0, 3864.4) mm

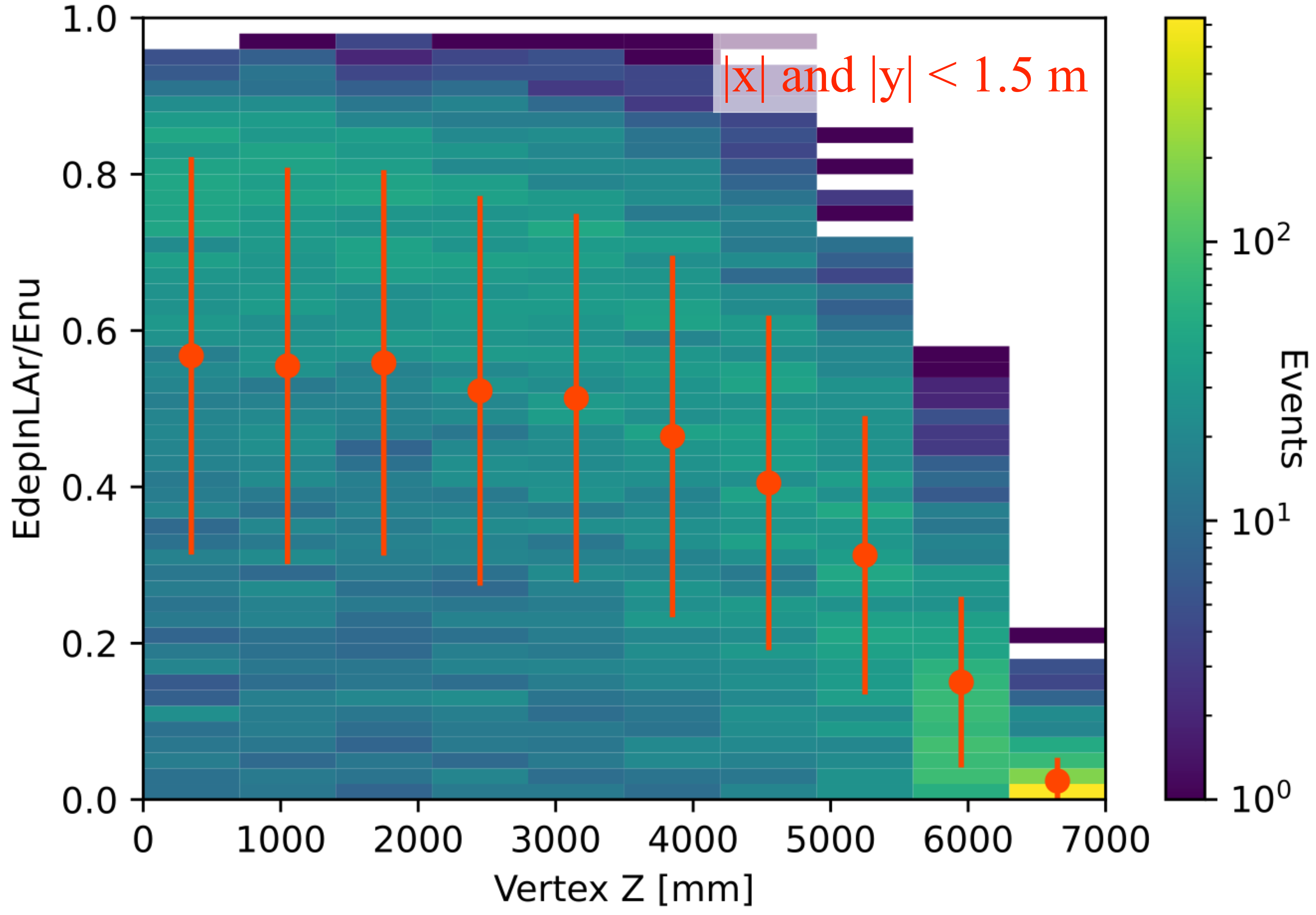
Electron

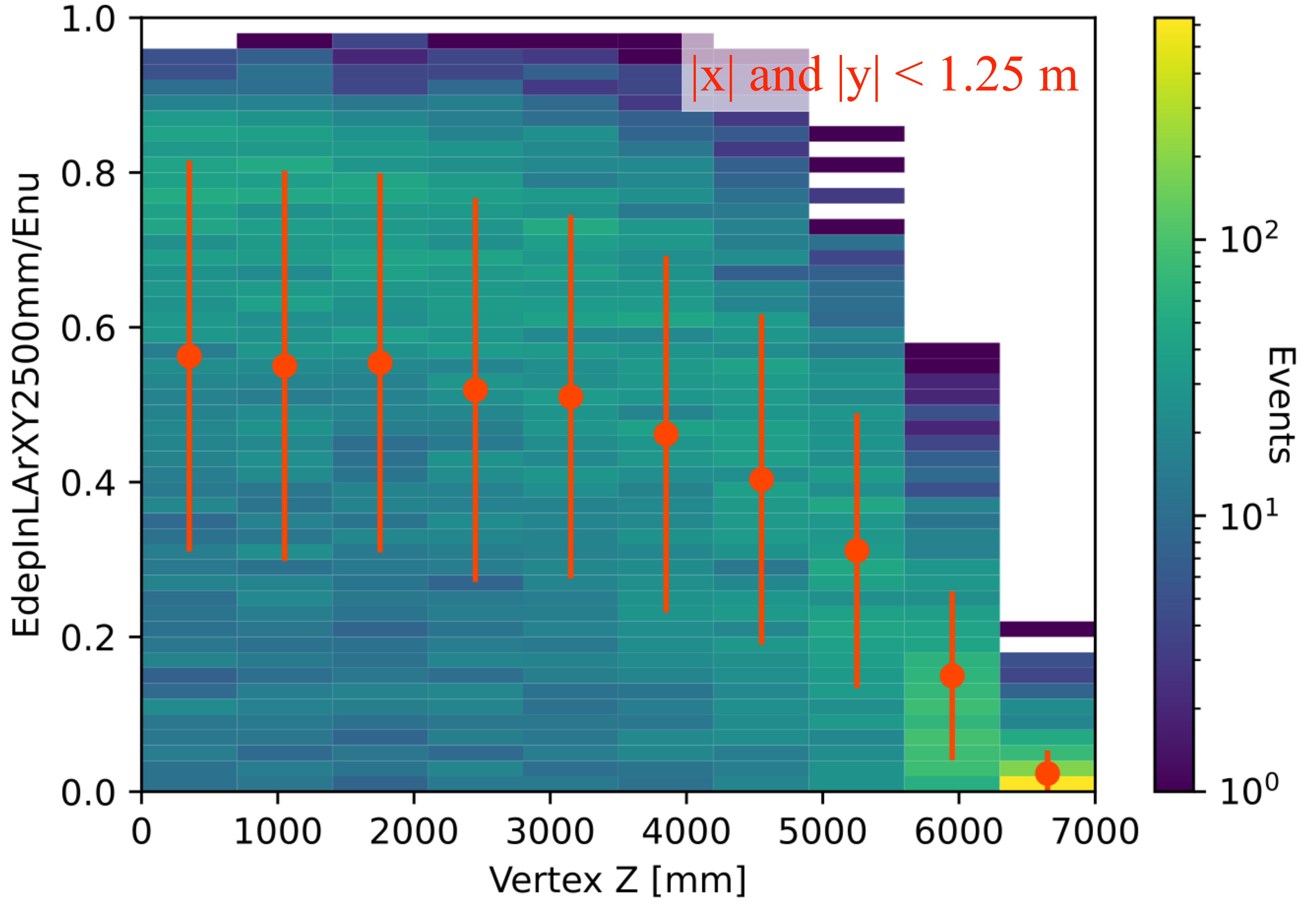


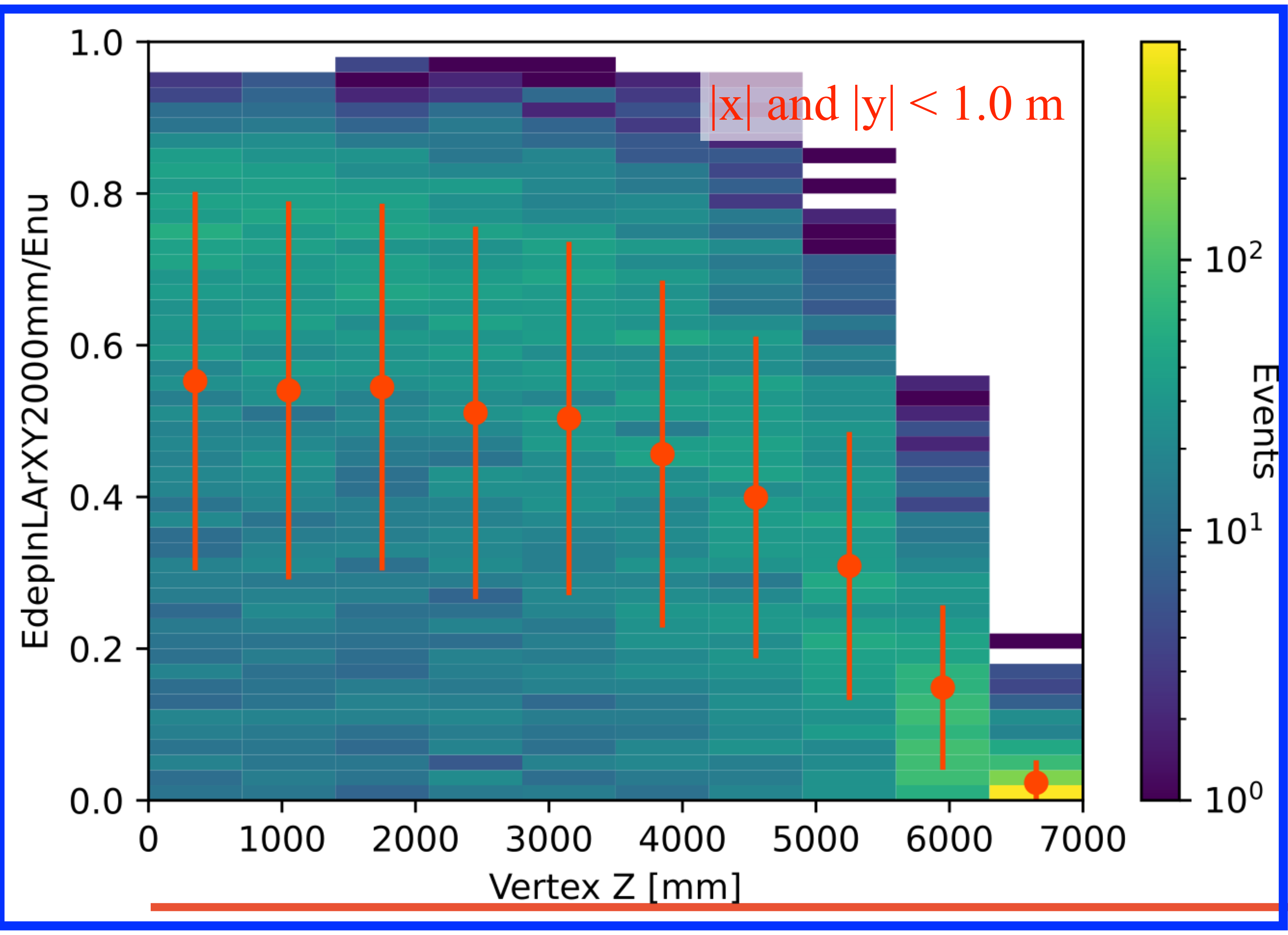
EvtID 0 PDG 11 Etot 500.0 GeV (0.0, 0.0, 100.0) mm

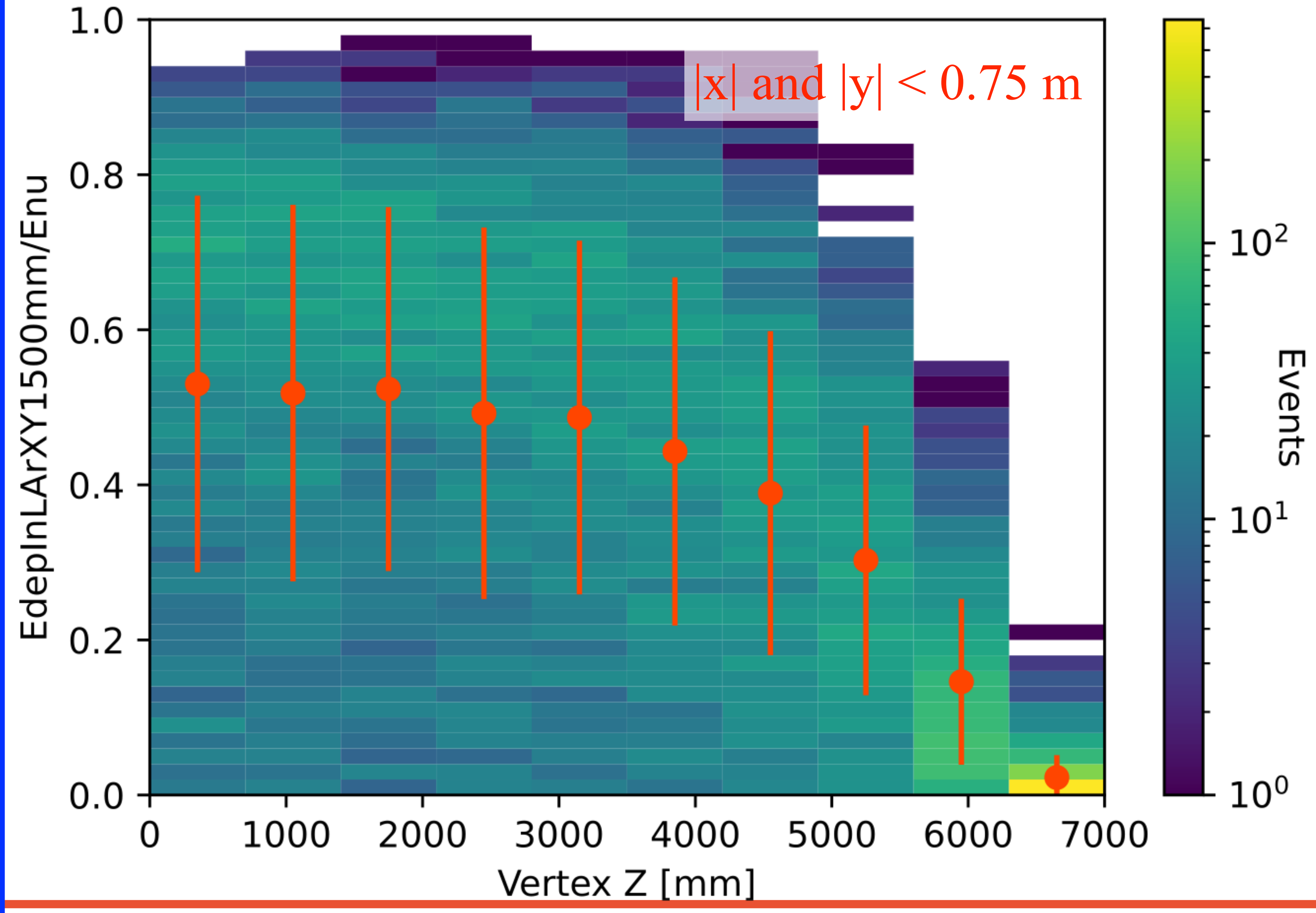
LArTPC Detector Fiducial Optimization with ν_τ

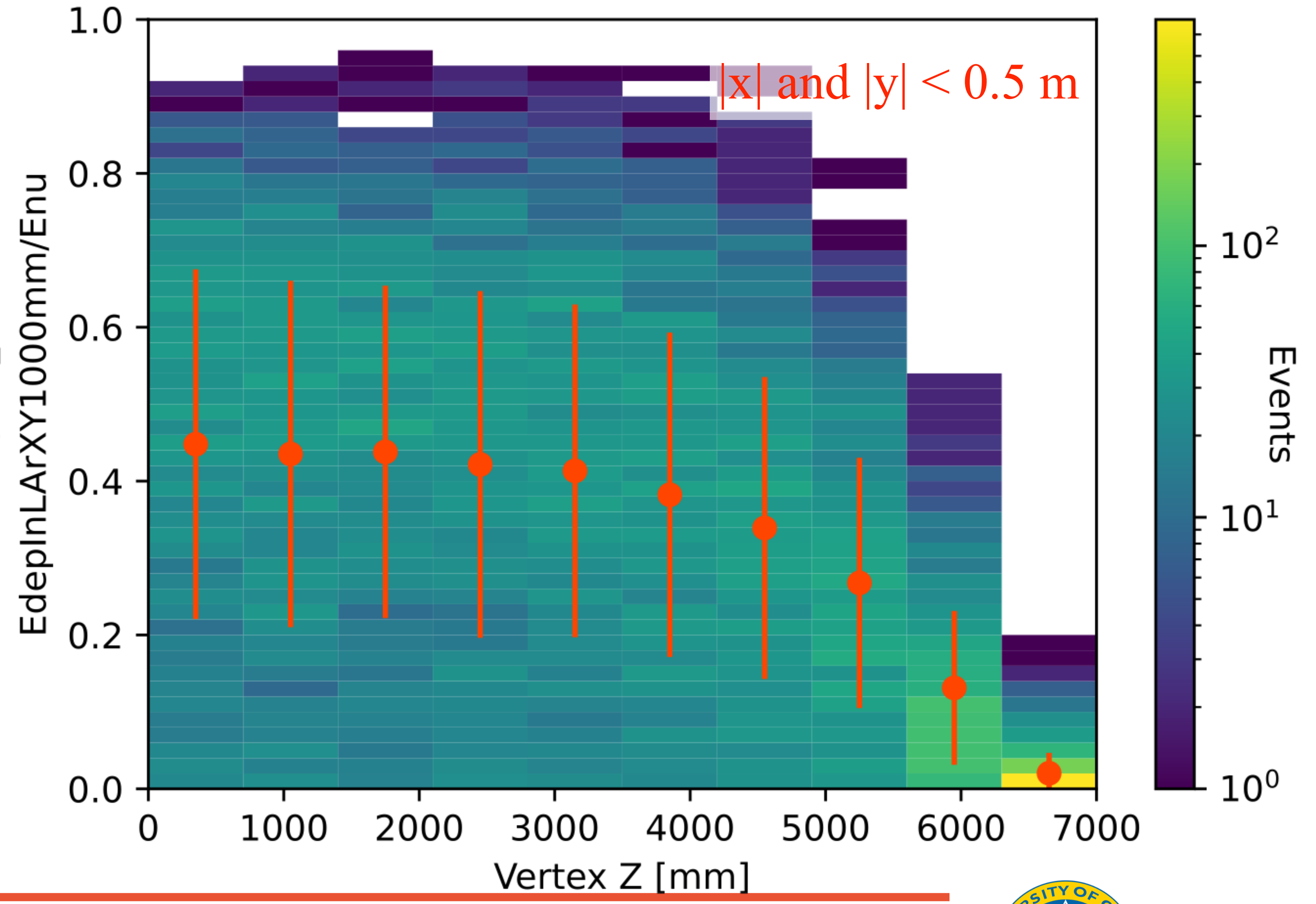
- The ratio of the energy deposited in the LArTPC to the neutrino energy
  - The orange markers are the mean values and standard deviation as error bars
- Make transverse cuts for energy containment in different detector fiducial volumes
- 1.0x1.0 m fiducial is determined





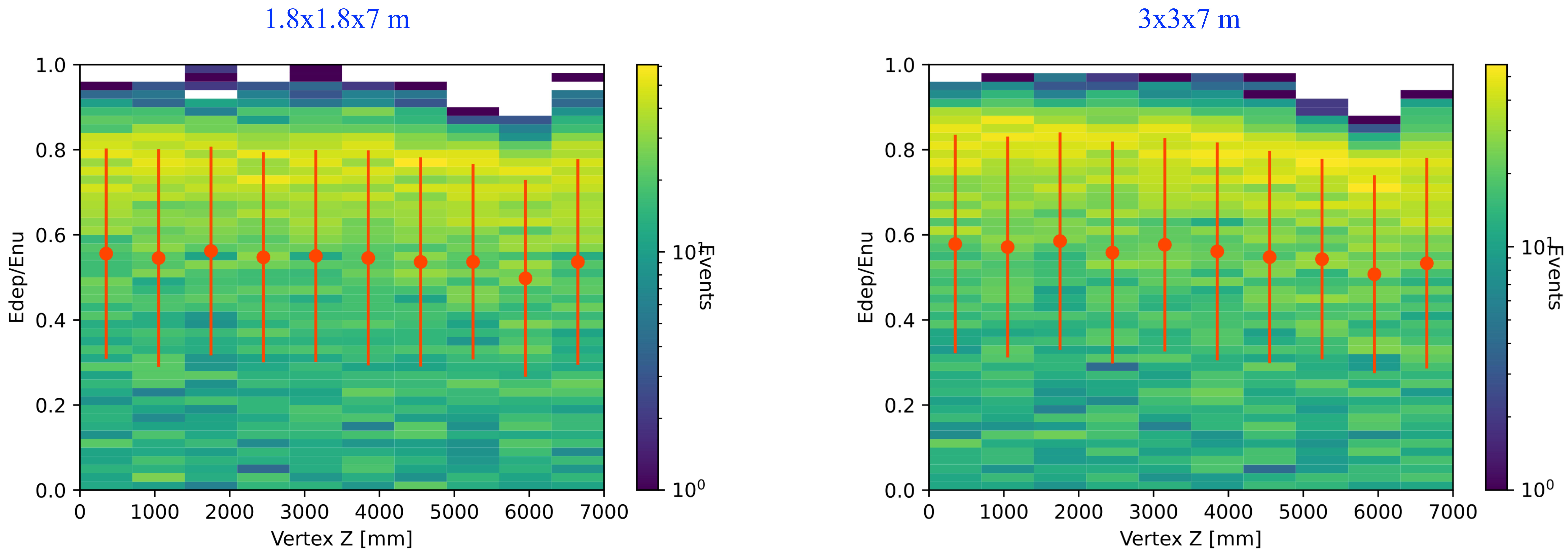






Energy containment w/ HadCal

- Verified the energy containment in the geometry 1.8x1.8x7
- The ratio of the energy deposited in the (LArTPC+HadCal) to the neutrino energy
  - The orange markers are the mean values and standard deviation as error bars
- The Hadron Calorimeter (hadCal) can save loss energies for events happened in the downstream of the detector



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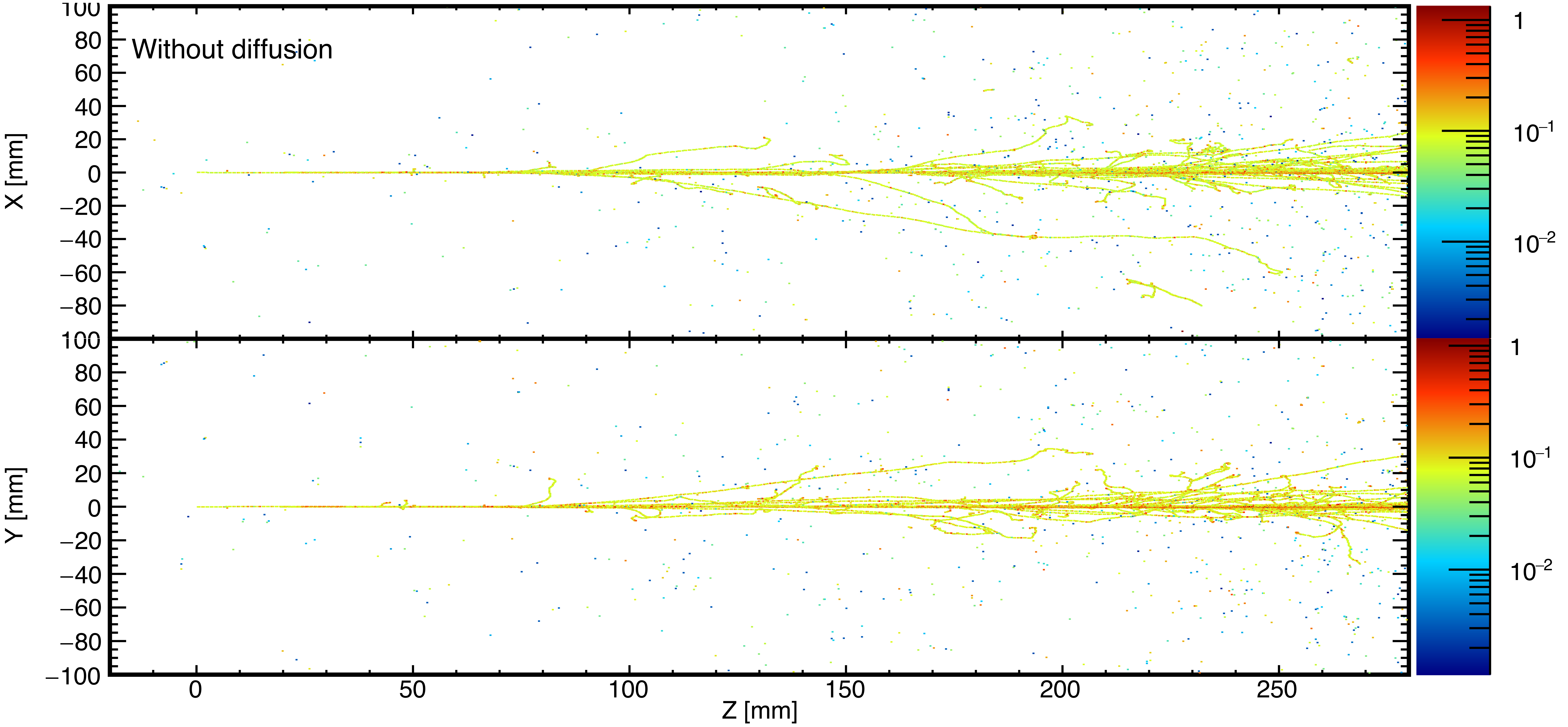
Electron diffusion

Electron transverse diffusion coefficient @ 500 V/cm: $D_T = 13.2\ \mathrm{cm^2/s}$

Electron longitudinal diffusion coefficient @ 500 V/cm: $D_L = 6.6\ \mathrm{cm^2/s}$



EvtID 0 PDG 11 Etot 500.0 GeV (0.0, 0.0, 100.0) mm

Electron diffusion

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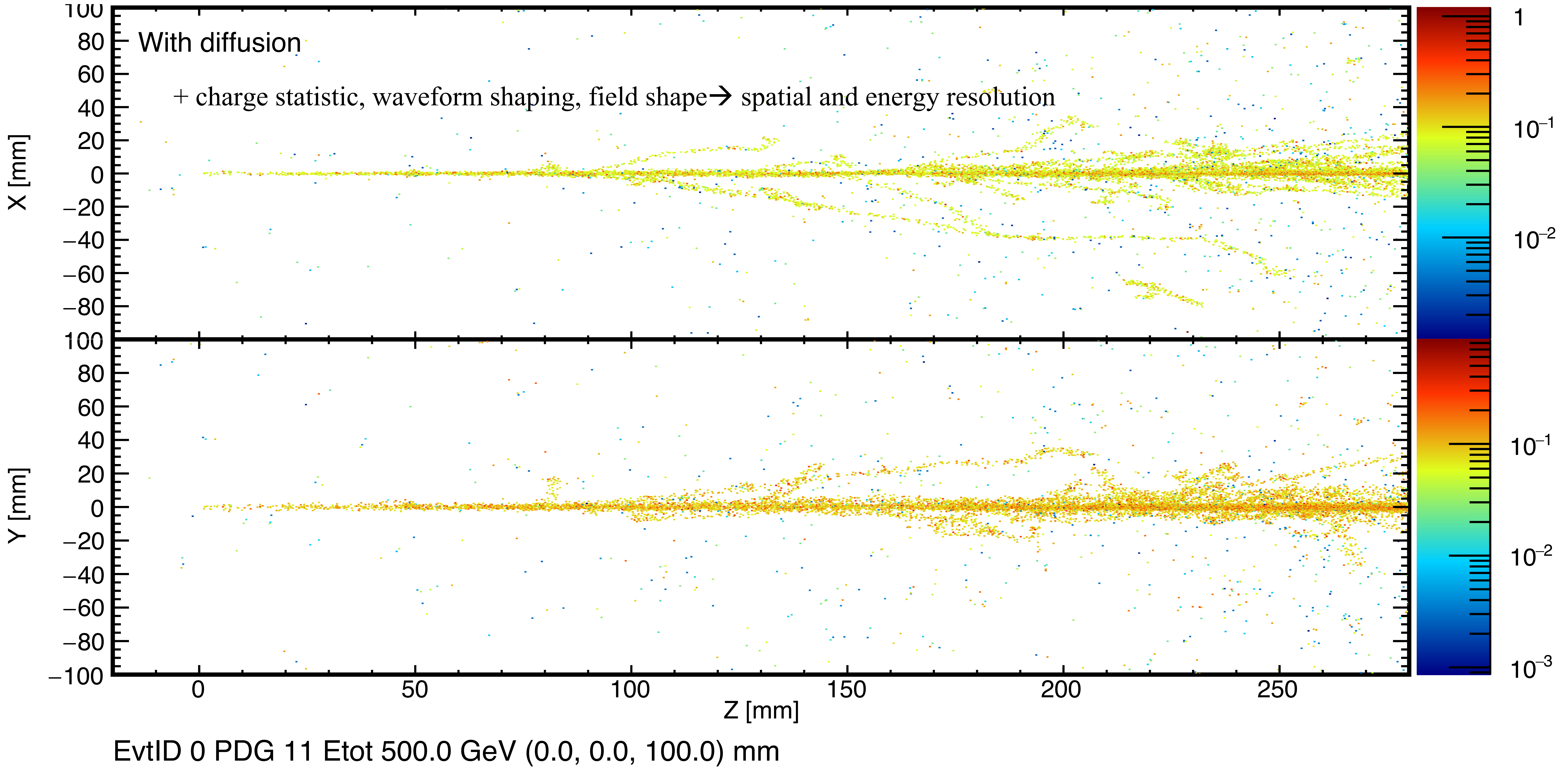
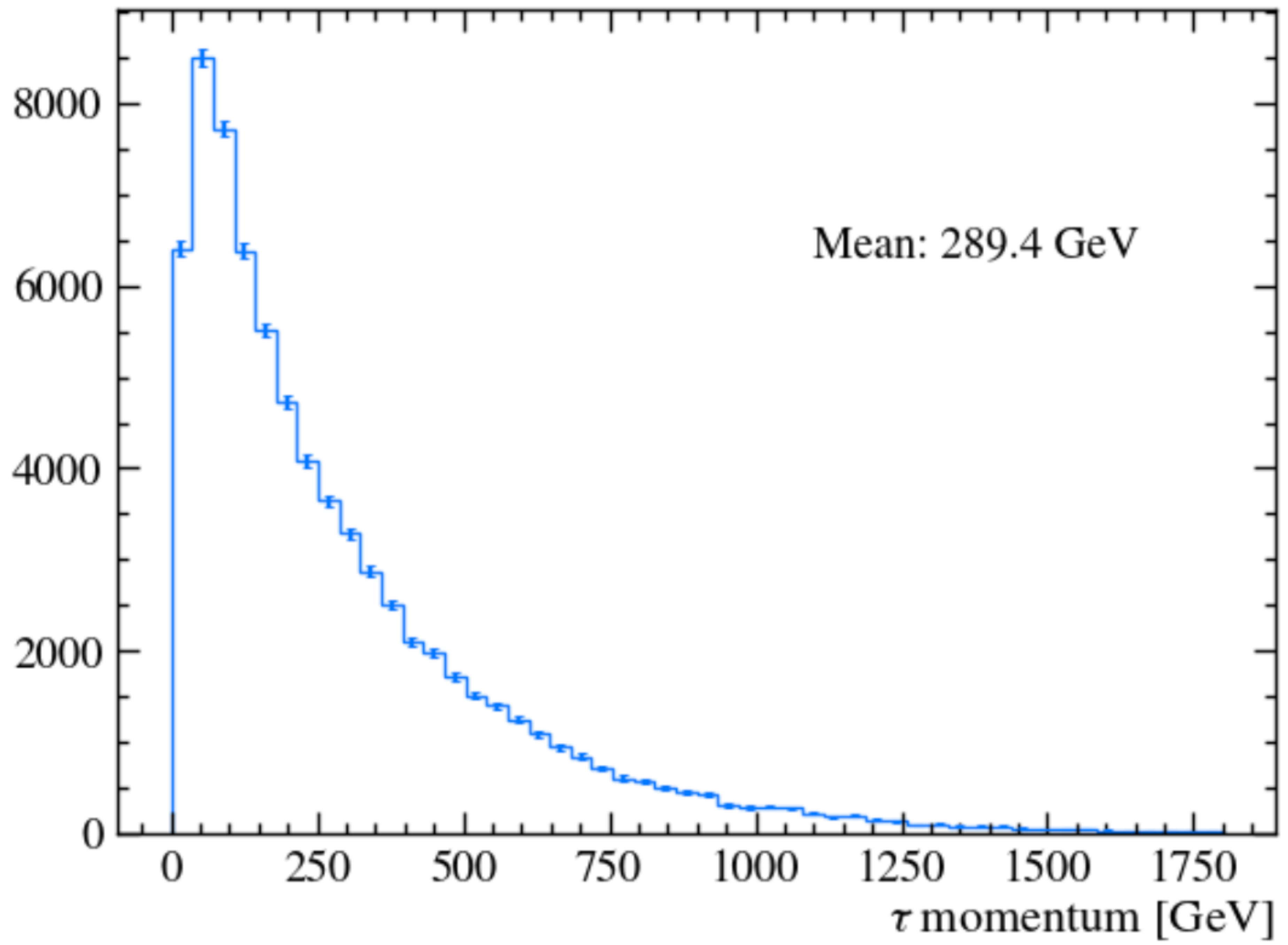
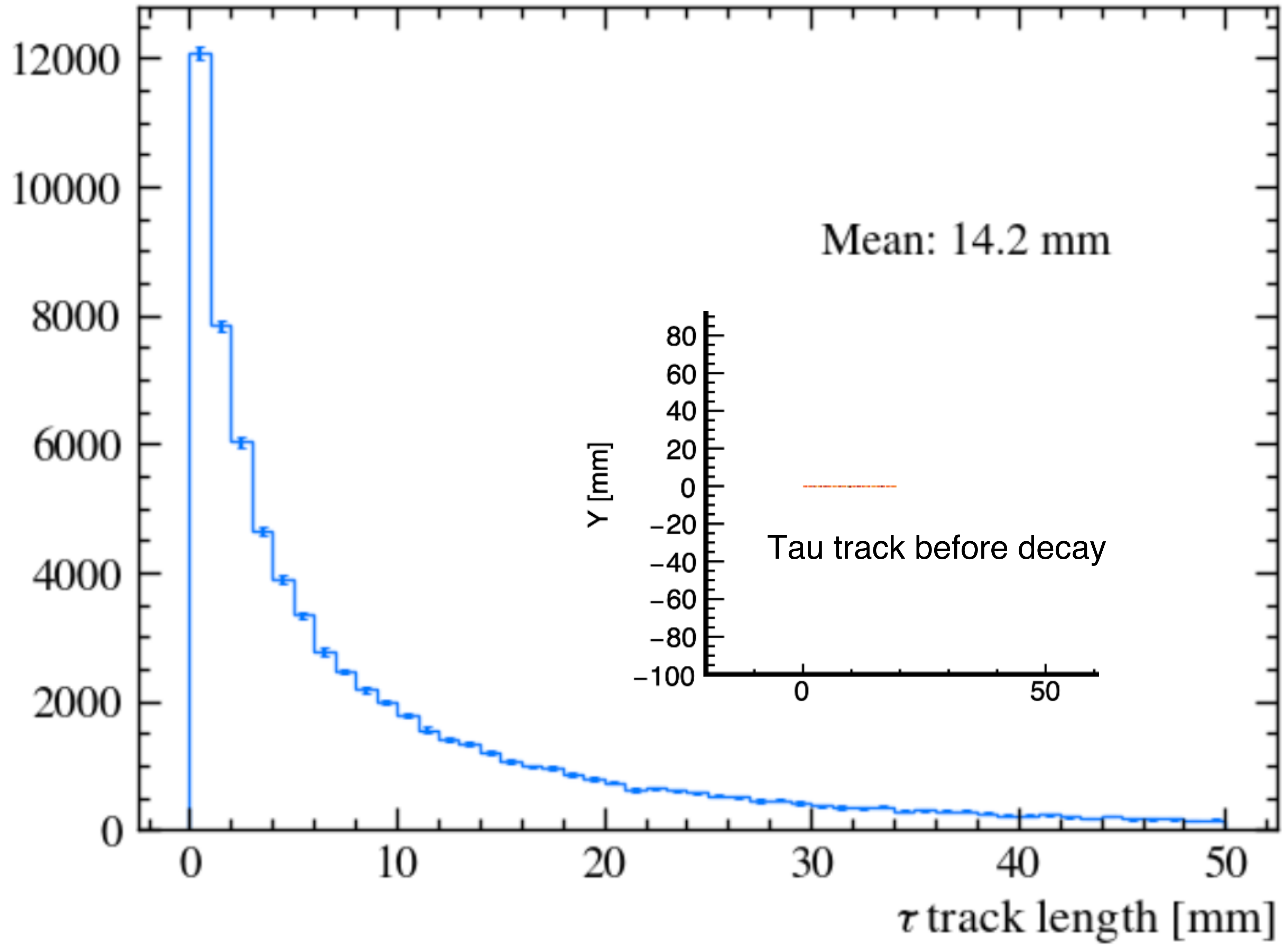


+ charge statistic, waveform shaping, field shape → spatial and energy resolution

ν_τ Measurements

- A key motivation of the detector is the detection and measurement of TeV-scale neutrino events from a laboratory-generated source, including the intense tau neutrinos
- The identification of tau neutrinos presents a particular challenge, requiring both high spatial and kinematic resolution
  - $\tau's$ decay very fast in the detector, leave very short track in the detector





ν_τ Signal and Backgrounds

- Signal: tau decays into
  - Muon or Electron
  - Hadrons
- Backgrounds: $\boldsymbol{\nu_\mu}$, $\boldsymbol{\nu_e}$, beam muons

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%

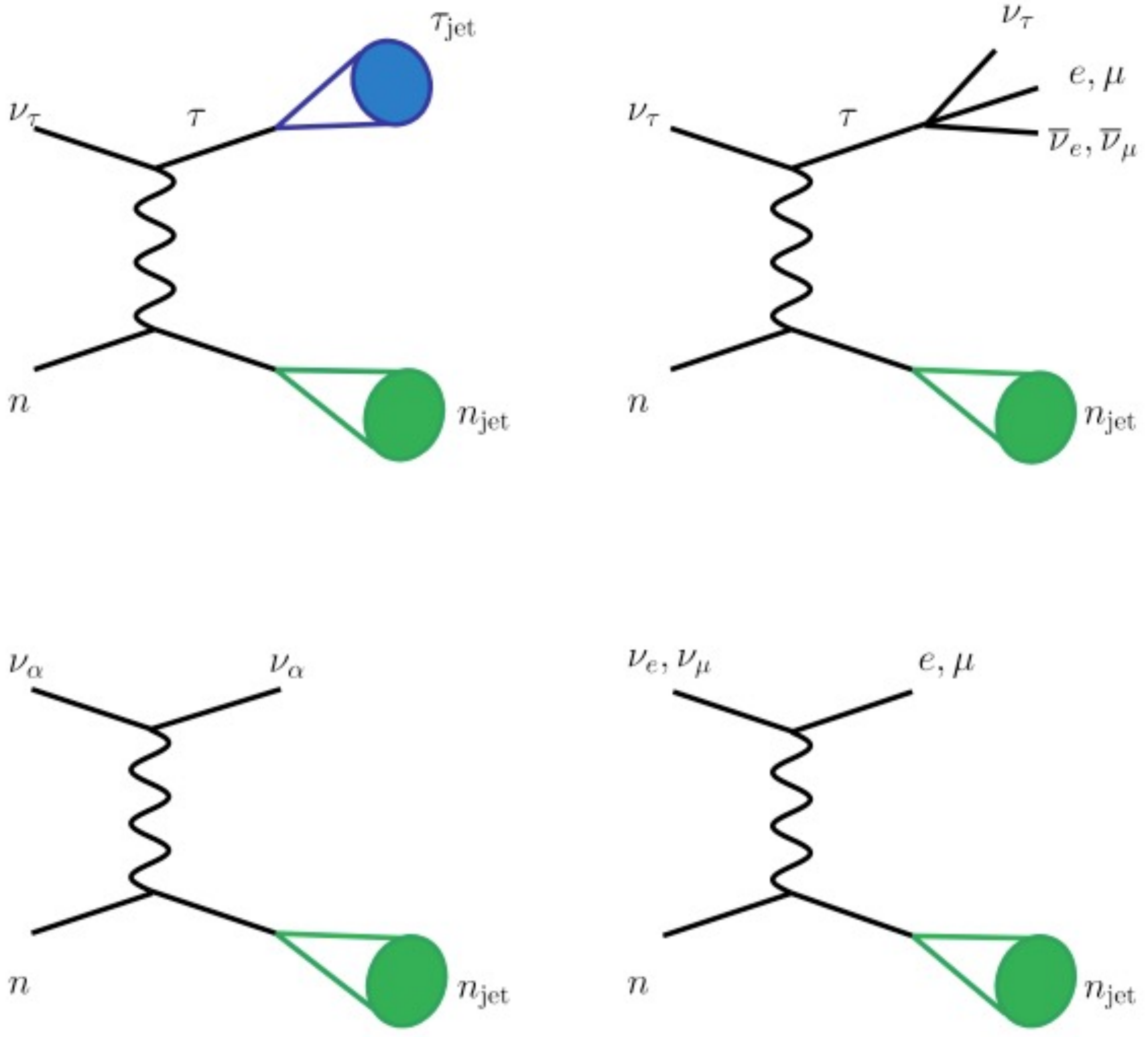
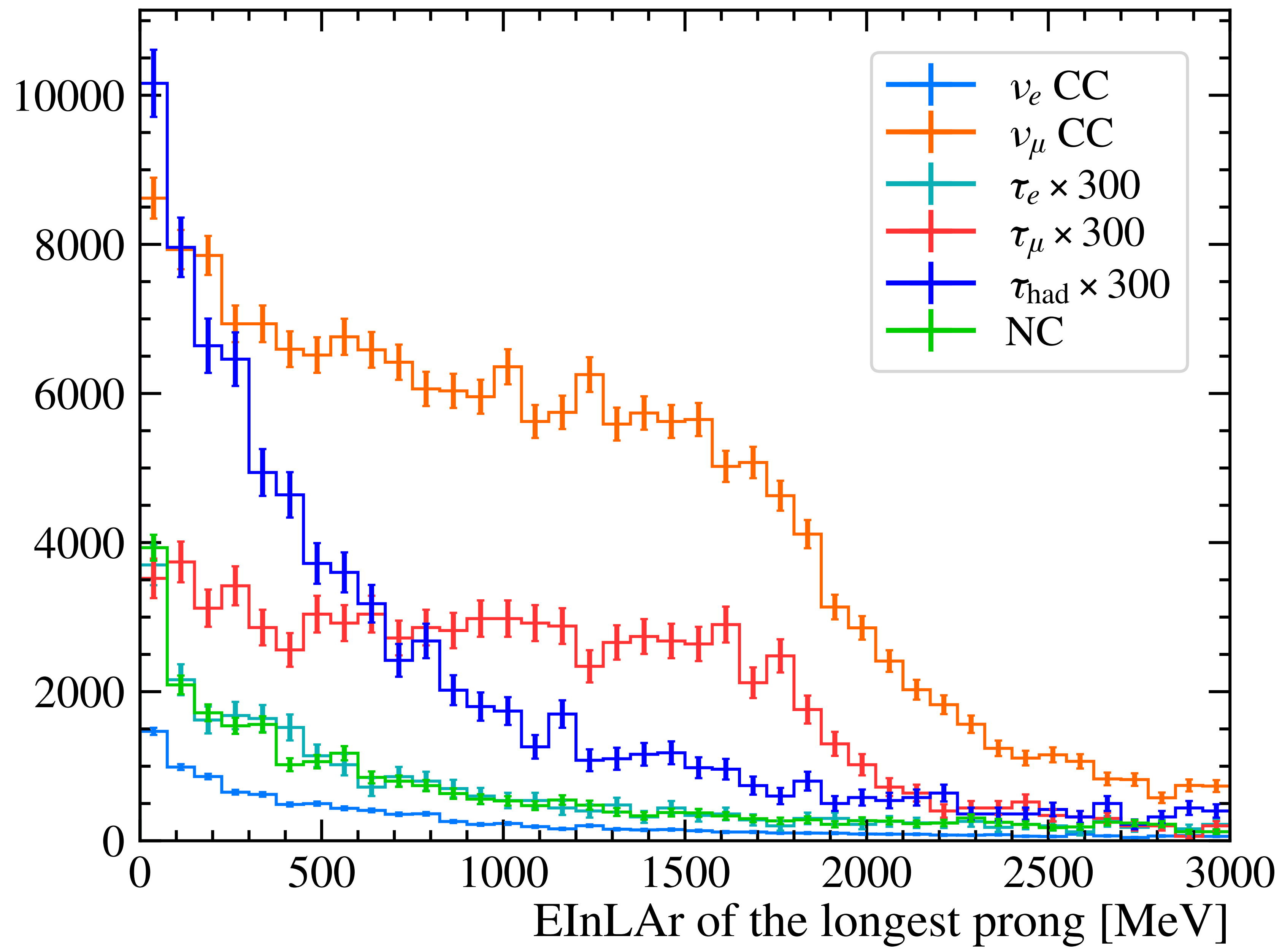
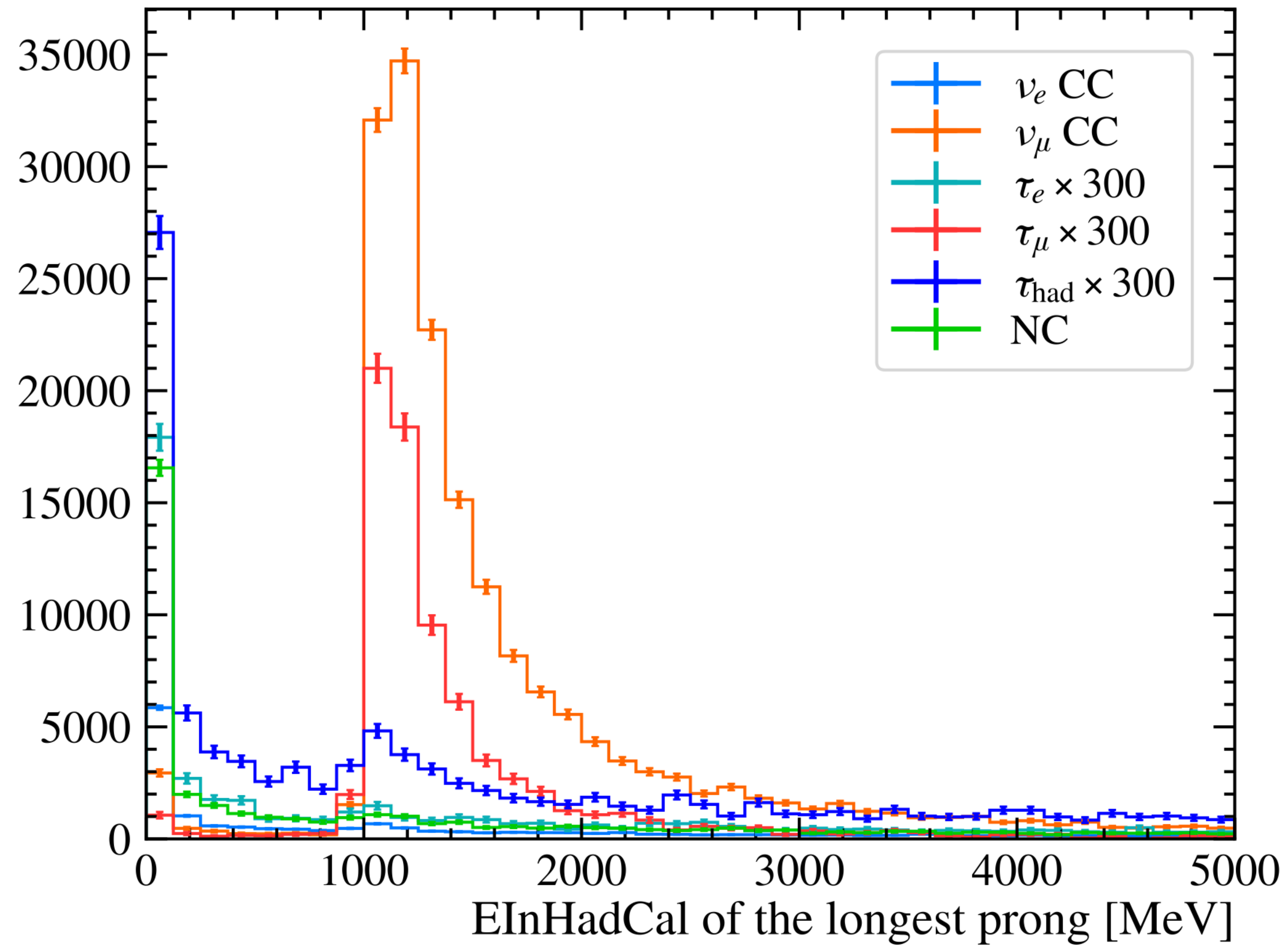


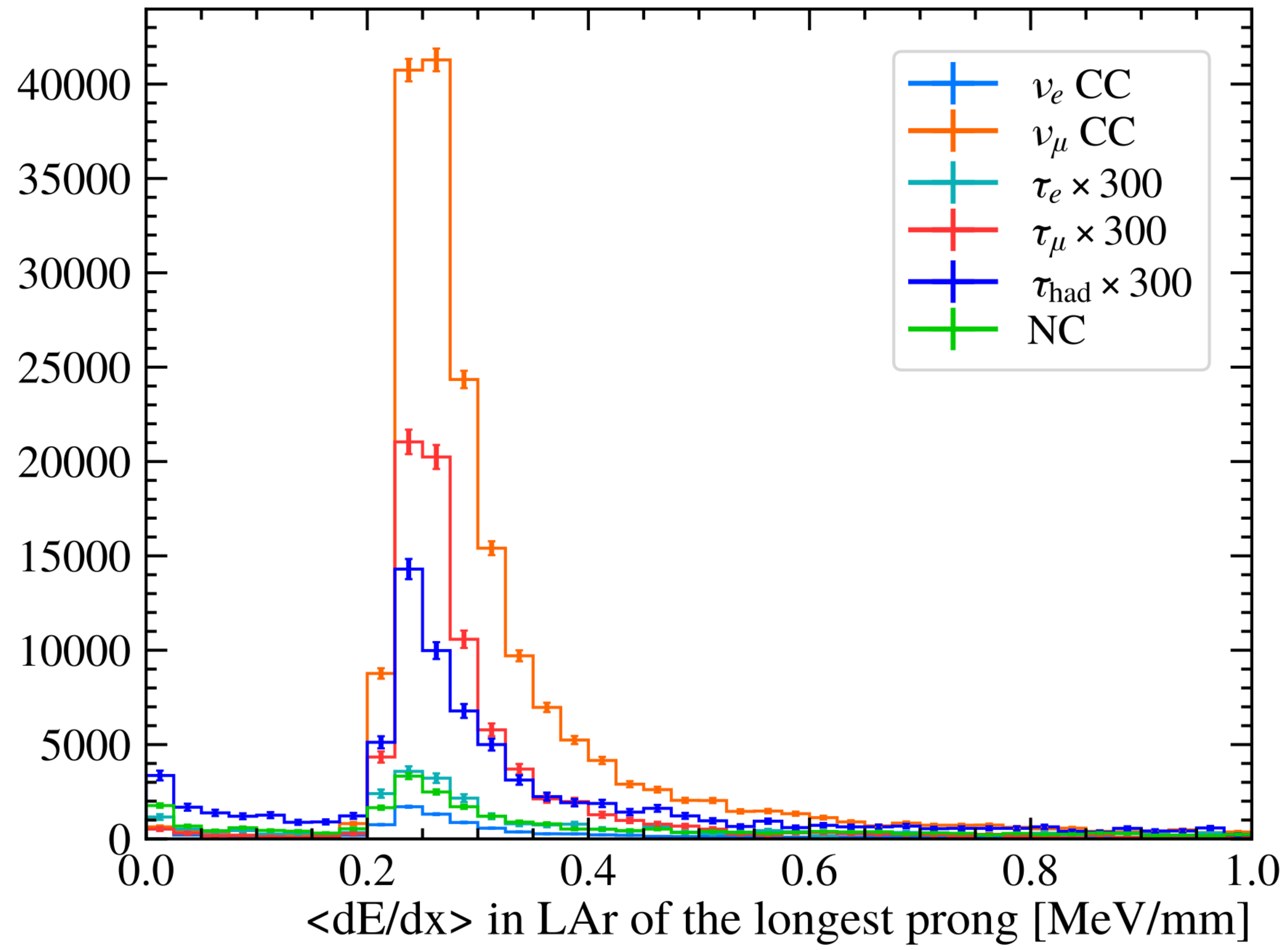
FIG. 2. Pictorial representation of hadronic tau (upper left) and leptonic tau (upper right) signals, and their corresponding backgrounds (lower).

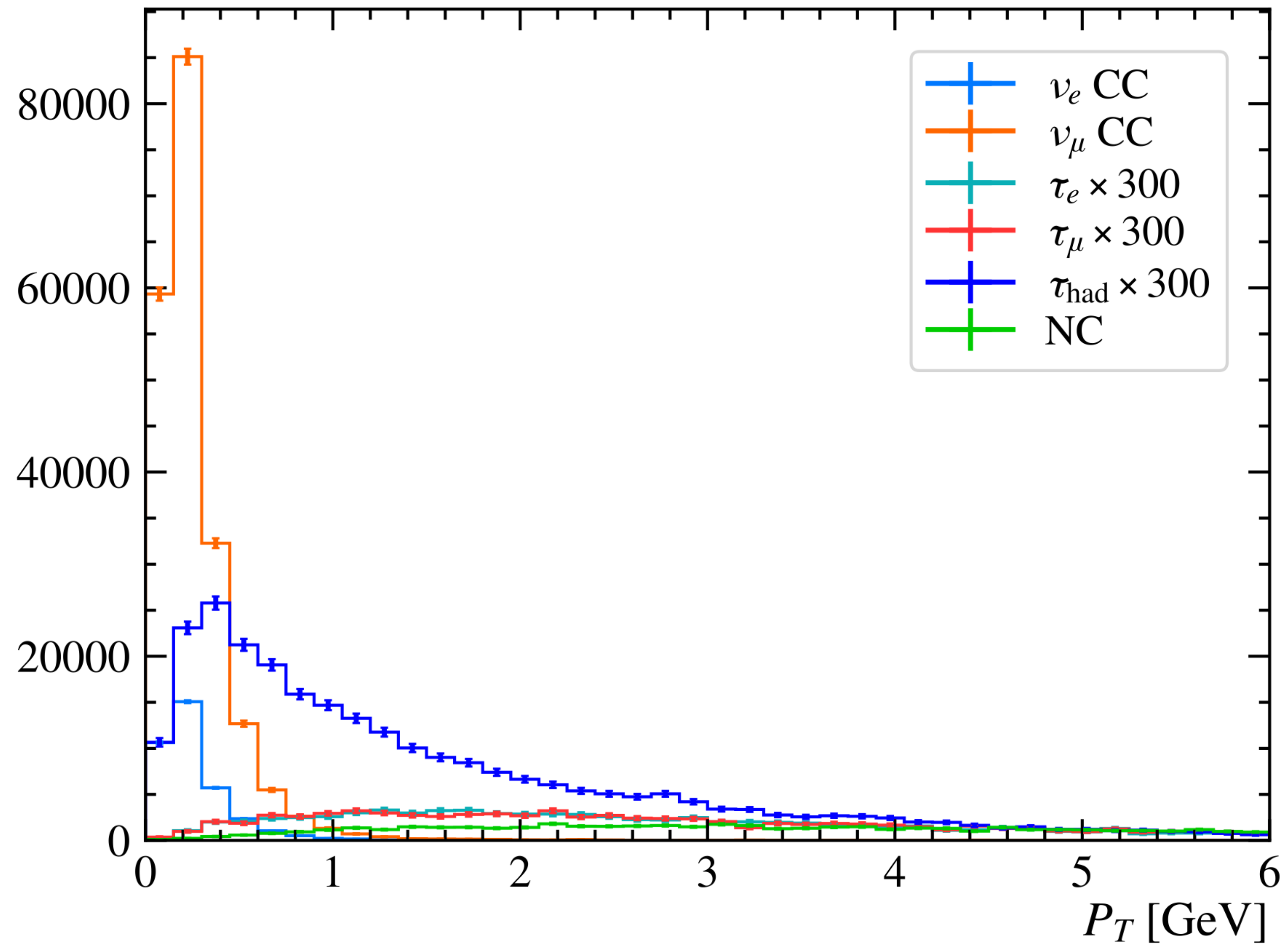
10.1103/PhysRevD.102.053010

Energy deposition









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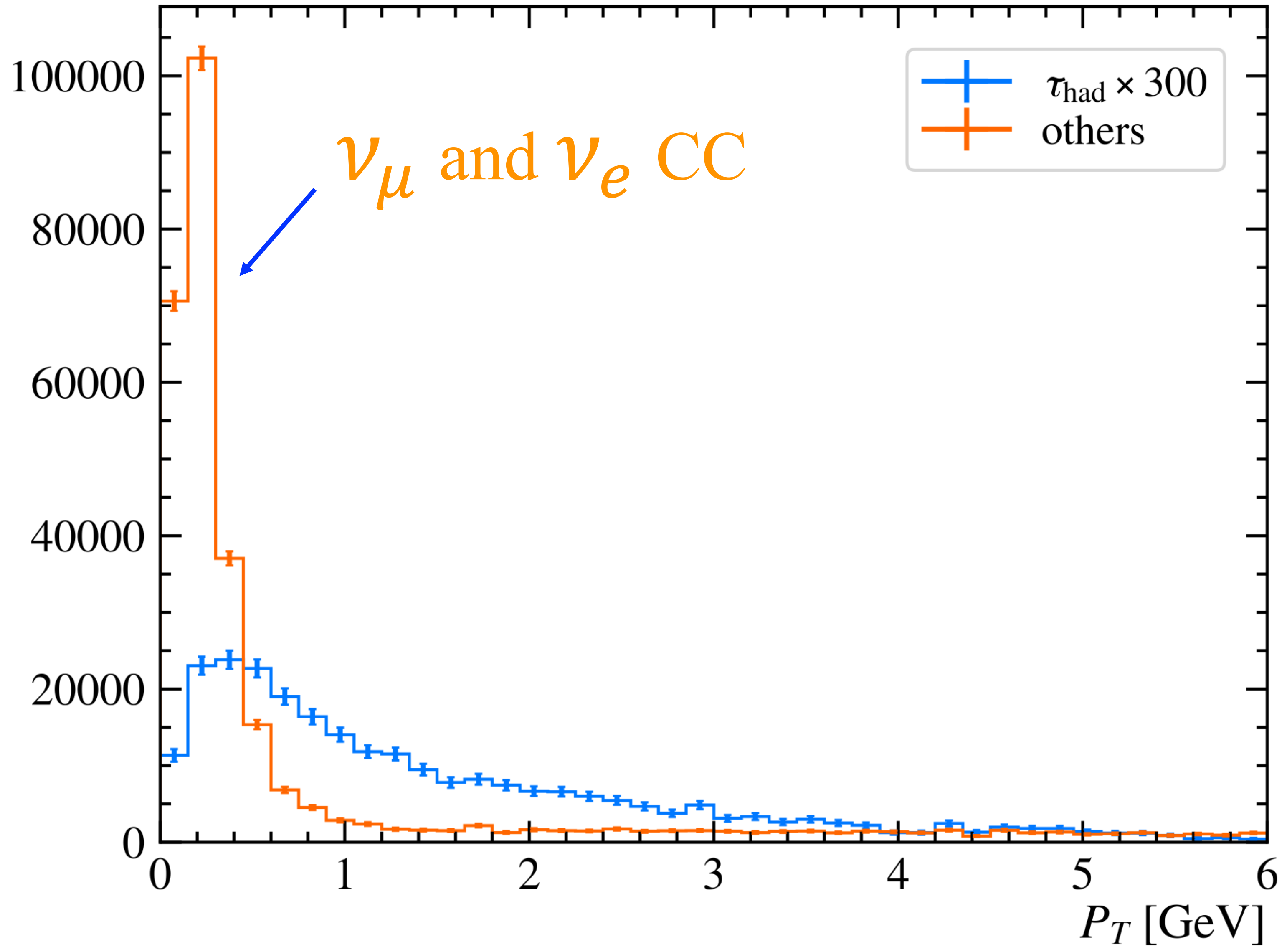
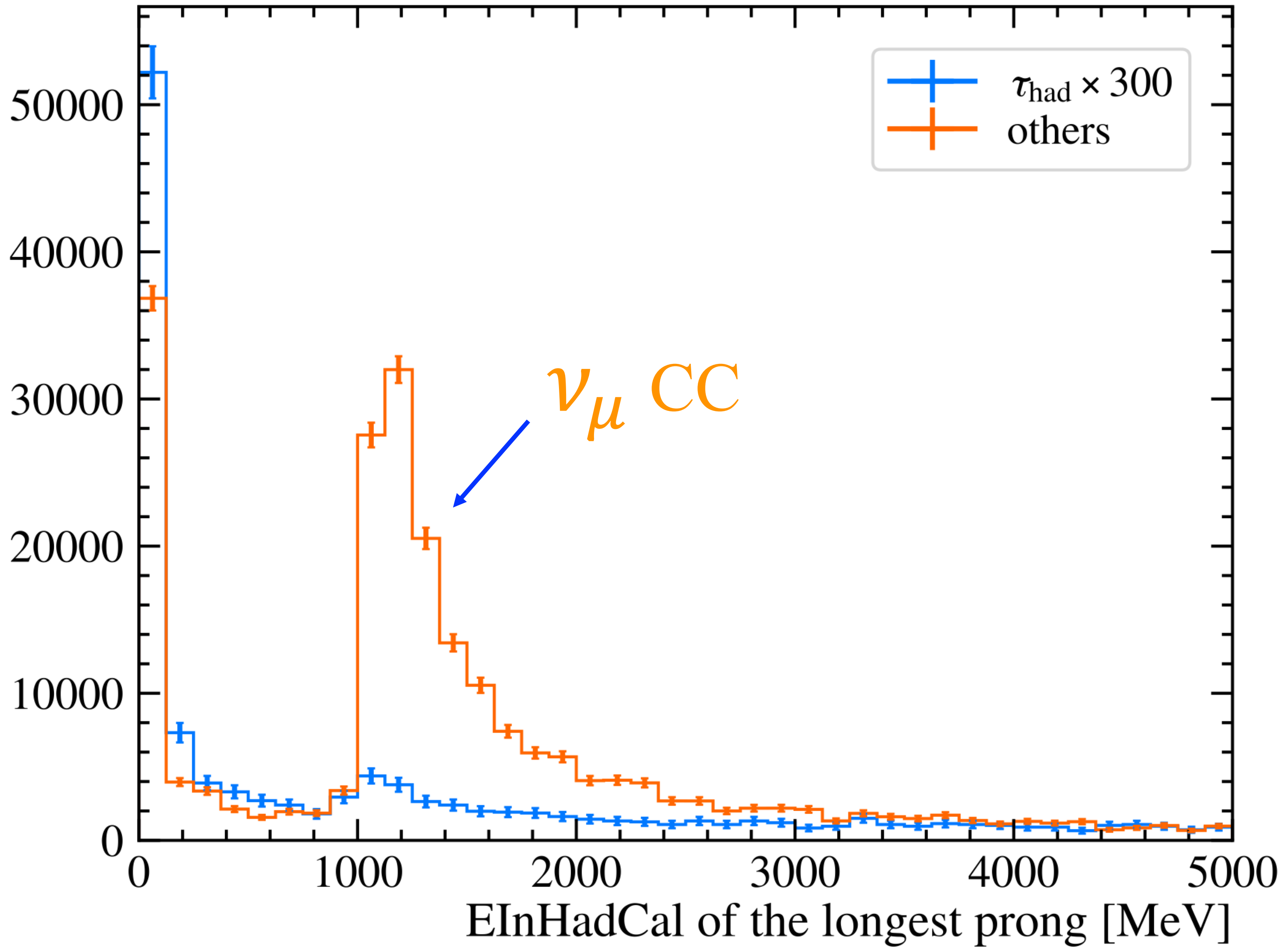
Identify ν_τ CC via τ hadronic decay

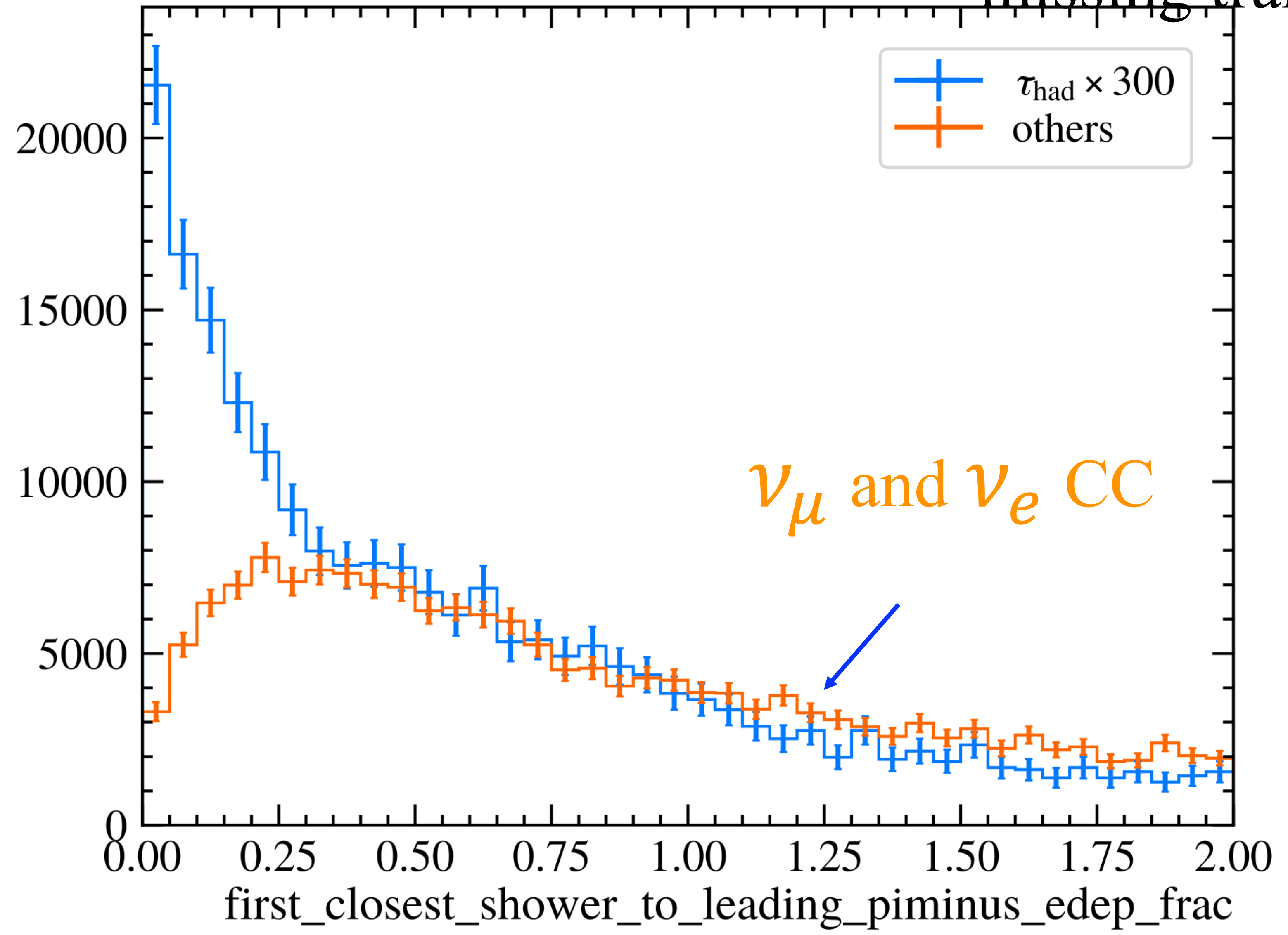
ν_τ hadronic decays vs. ν_μ and ν_e

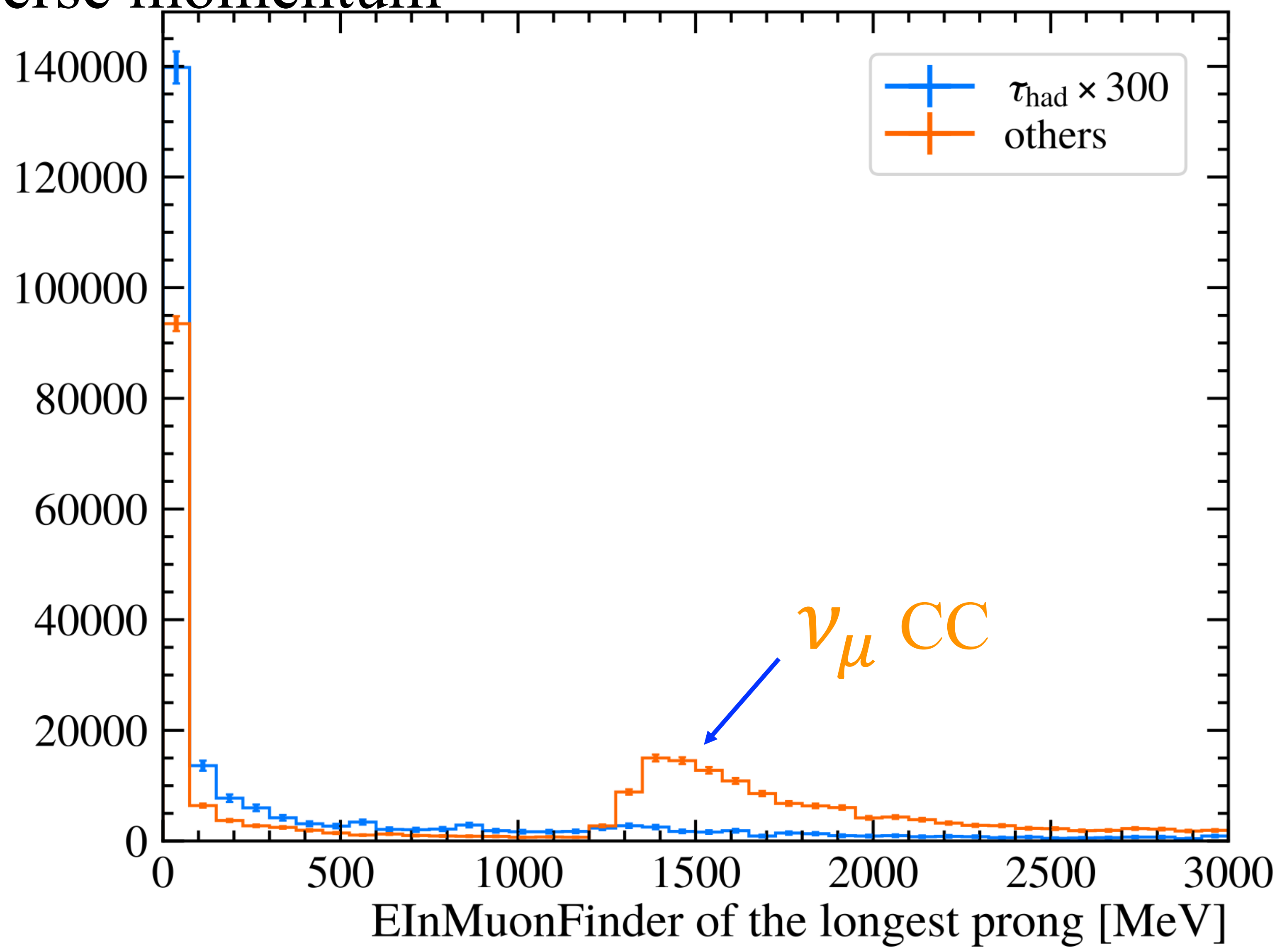
- Larger missing transverse momentum
- Smaller energy deposit in HadCal and Muon
- Tracks and Showers closet to leading pion

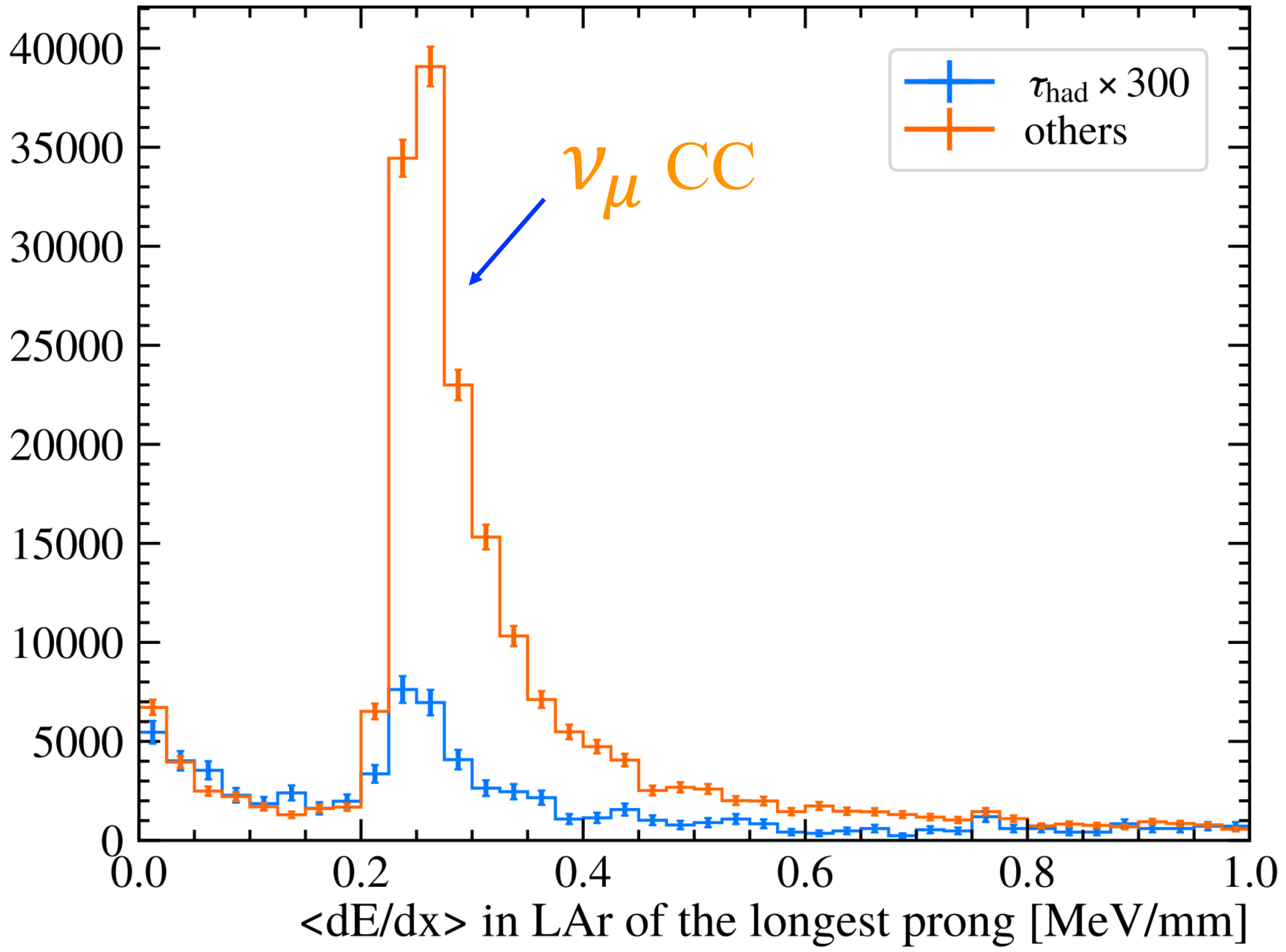




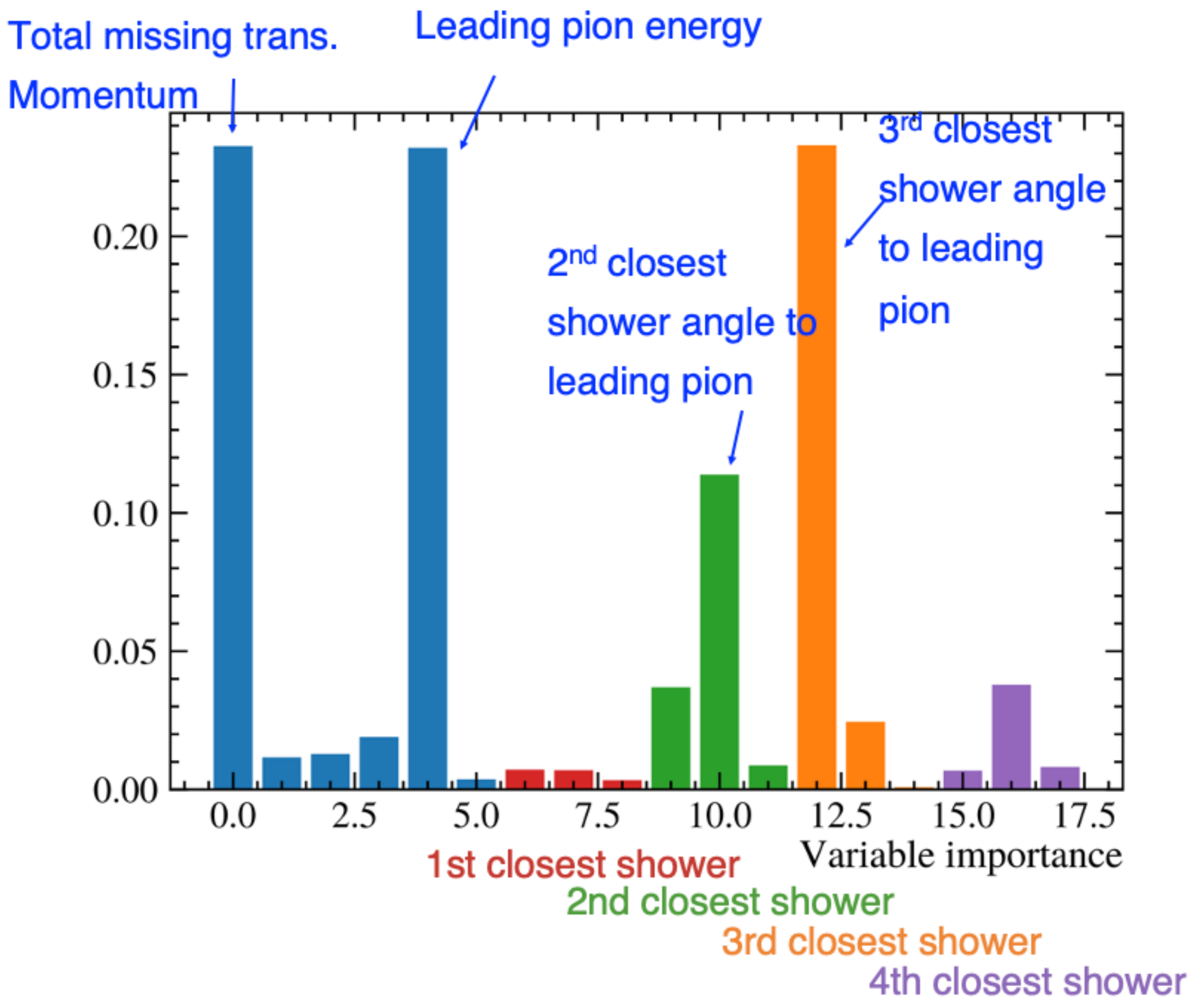
missing transverse momentum



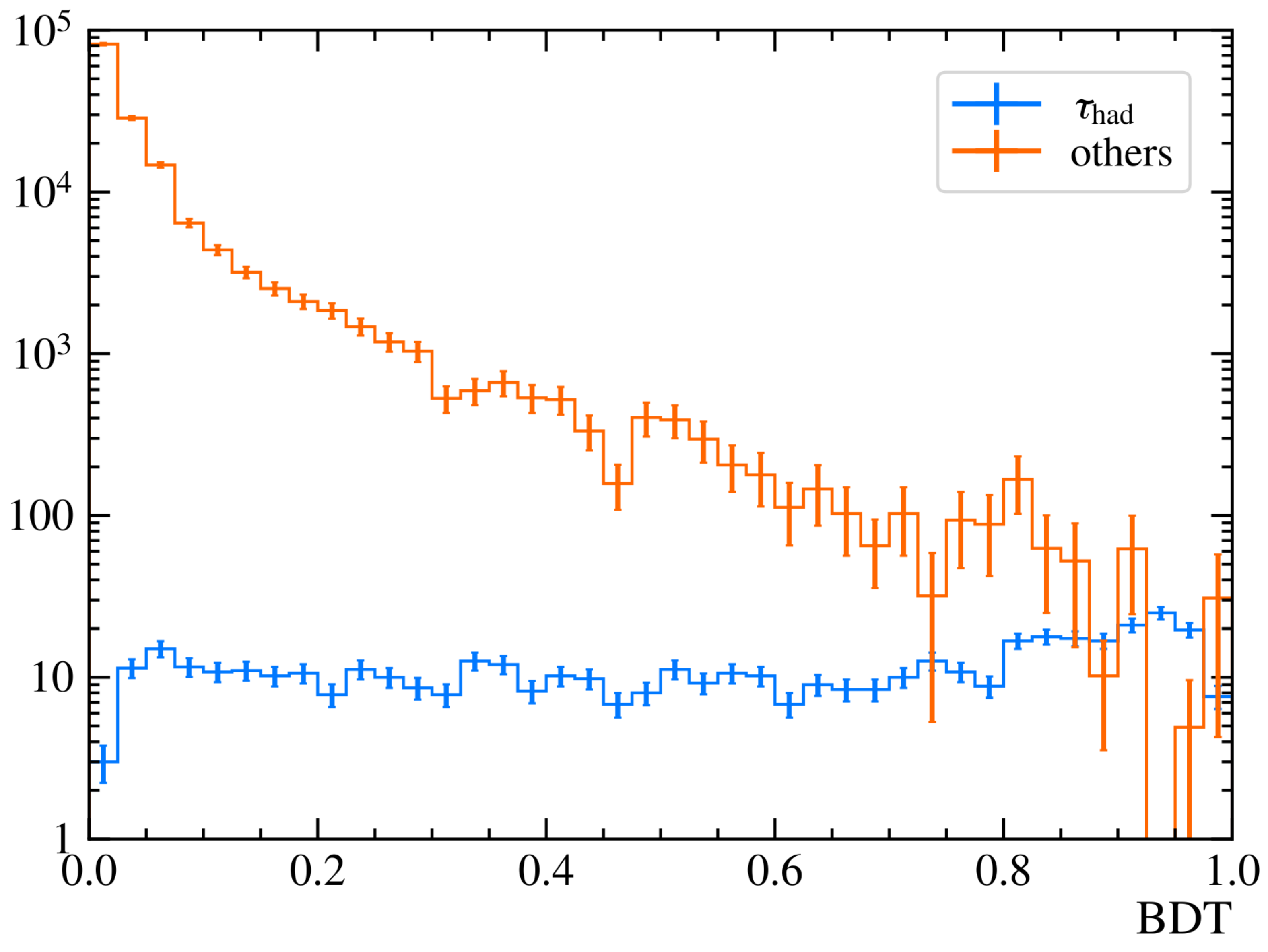


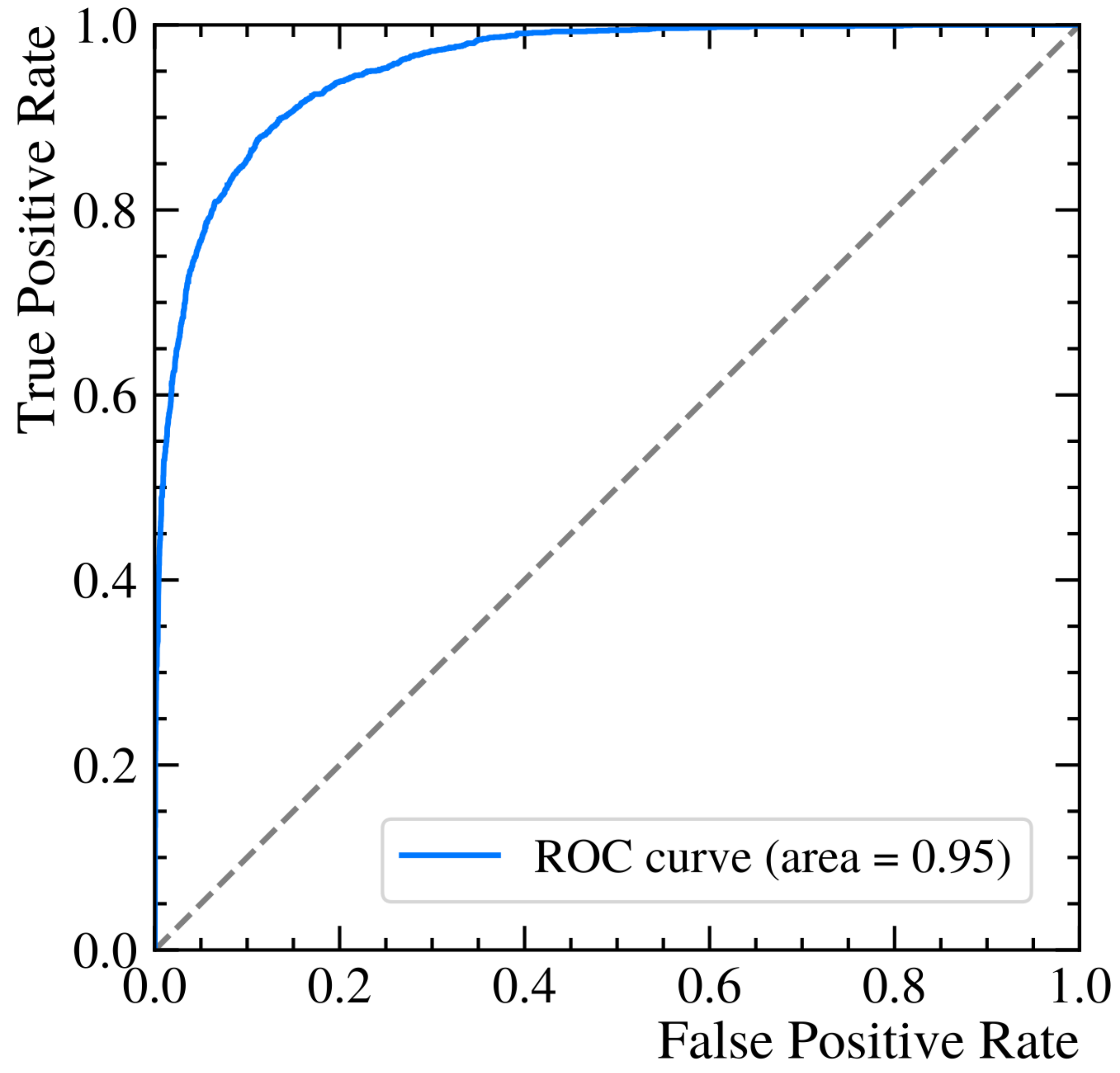


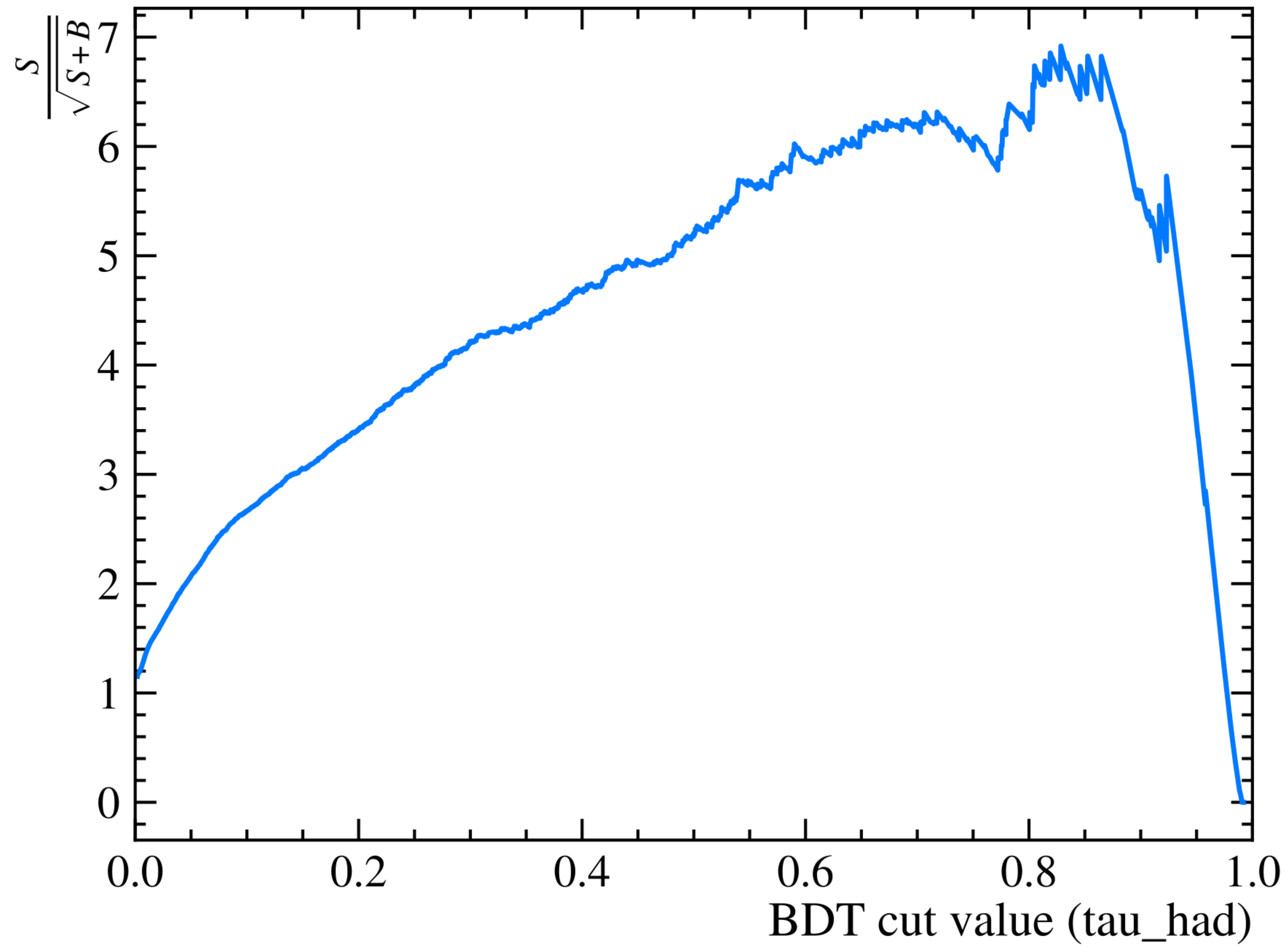
Identify ν_τ CC via τ hadronic decay



- BDT with 17 variables
- Promising results
- τ decay vertex not used yet
- τ lepton decays study underway







Summary

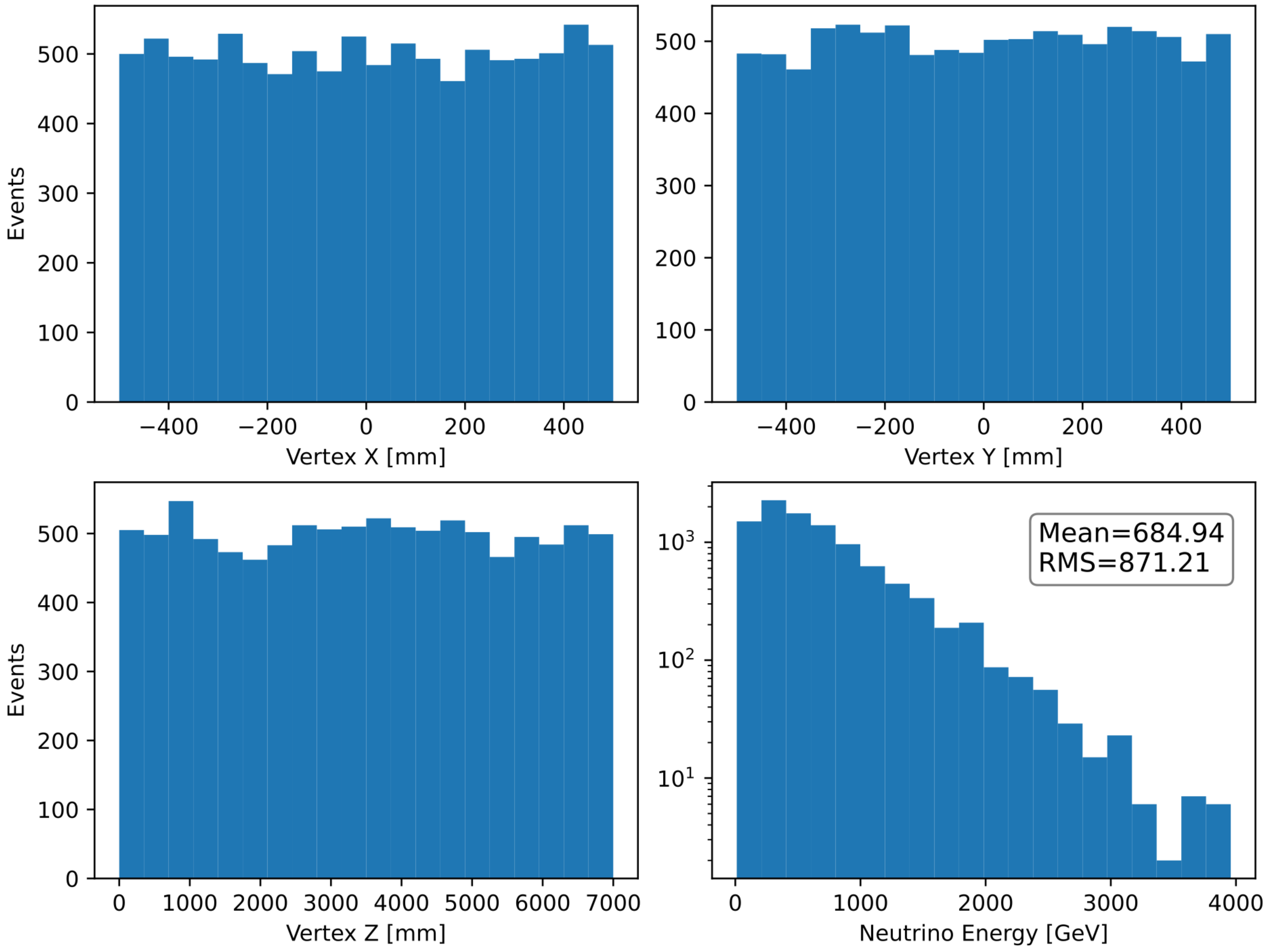
- CDR goals:
  - Detector design and parameters (geometry, pixel size, trigger rate/window…)
  - Performance requirements (spatial/energy resolution, containment, thresholds …)
  - Physics reach (tau neutrino, light dark matter scattering, etc)
- Simulation and "reconstruction" ready for these tasks
- Beam muon background handleable
- The event classifiers trained based on the pseudo-reconstructed variables for tau's hadron decay look promising
- TO DO: vertex, energy/spatial resolutions, tau leptonic decays, electrons from light dark matter scattering …

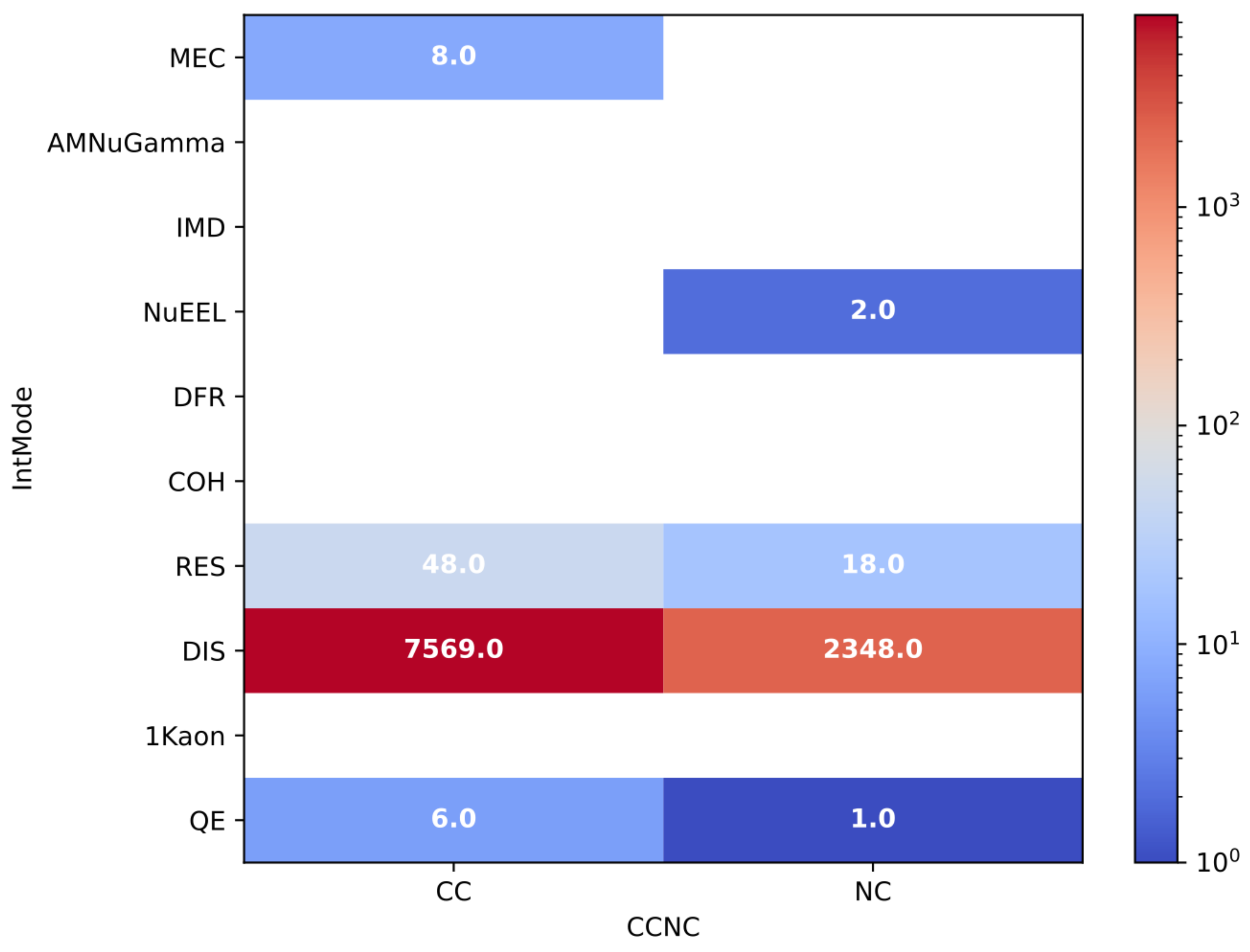
Backup

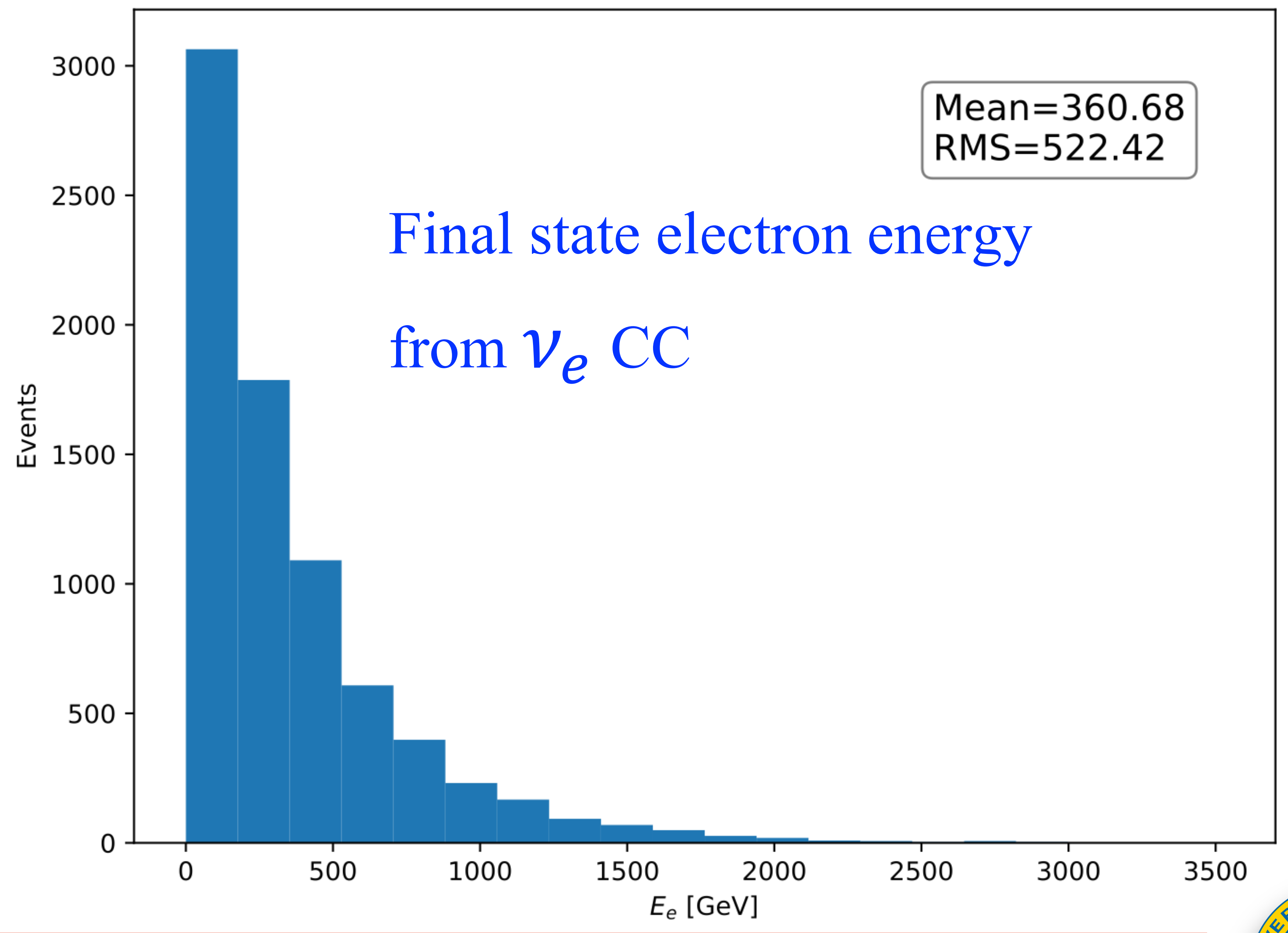
Containment studies

ν_e in the detector

- Neutrino vertices are uniformly distributed in a 1x1x7 meter FV
- Neutrino energy/Interaction mode/FSL come from GENIE v3_00_06k
  - Flux comes from Felix Kling, et. al. [2105.08270]







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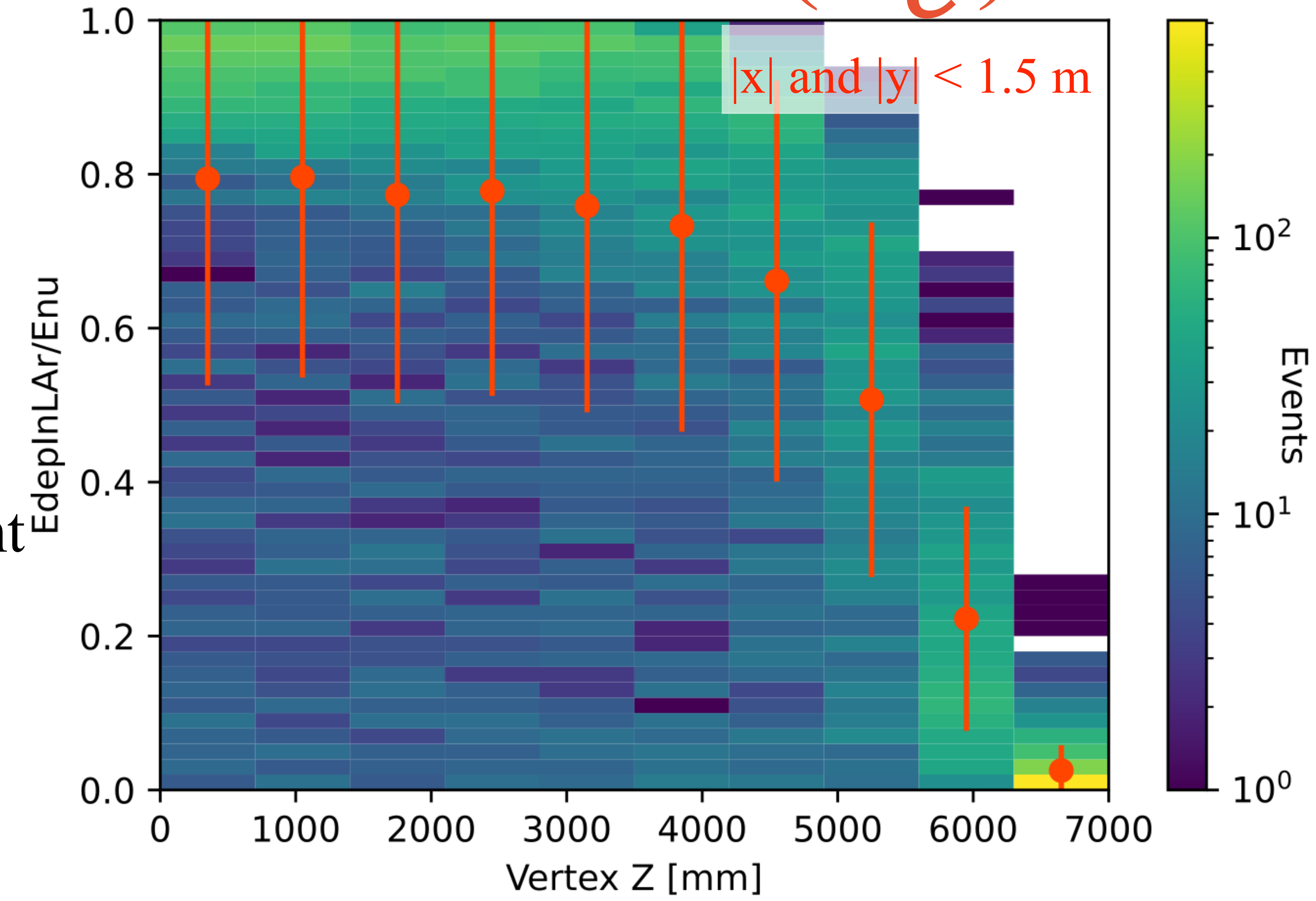
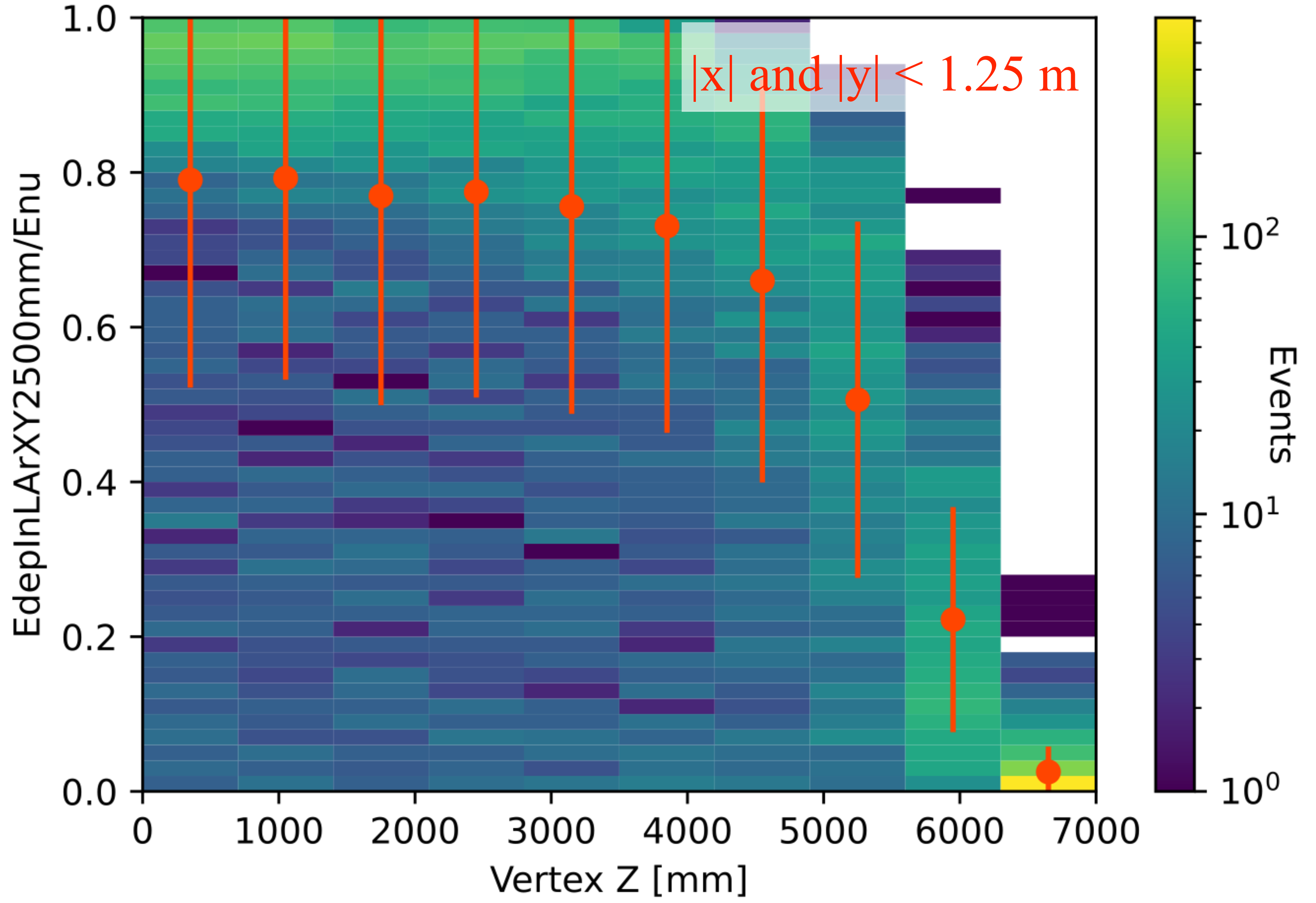
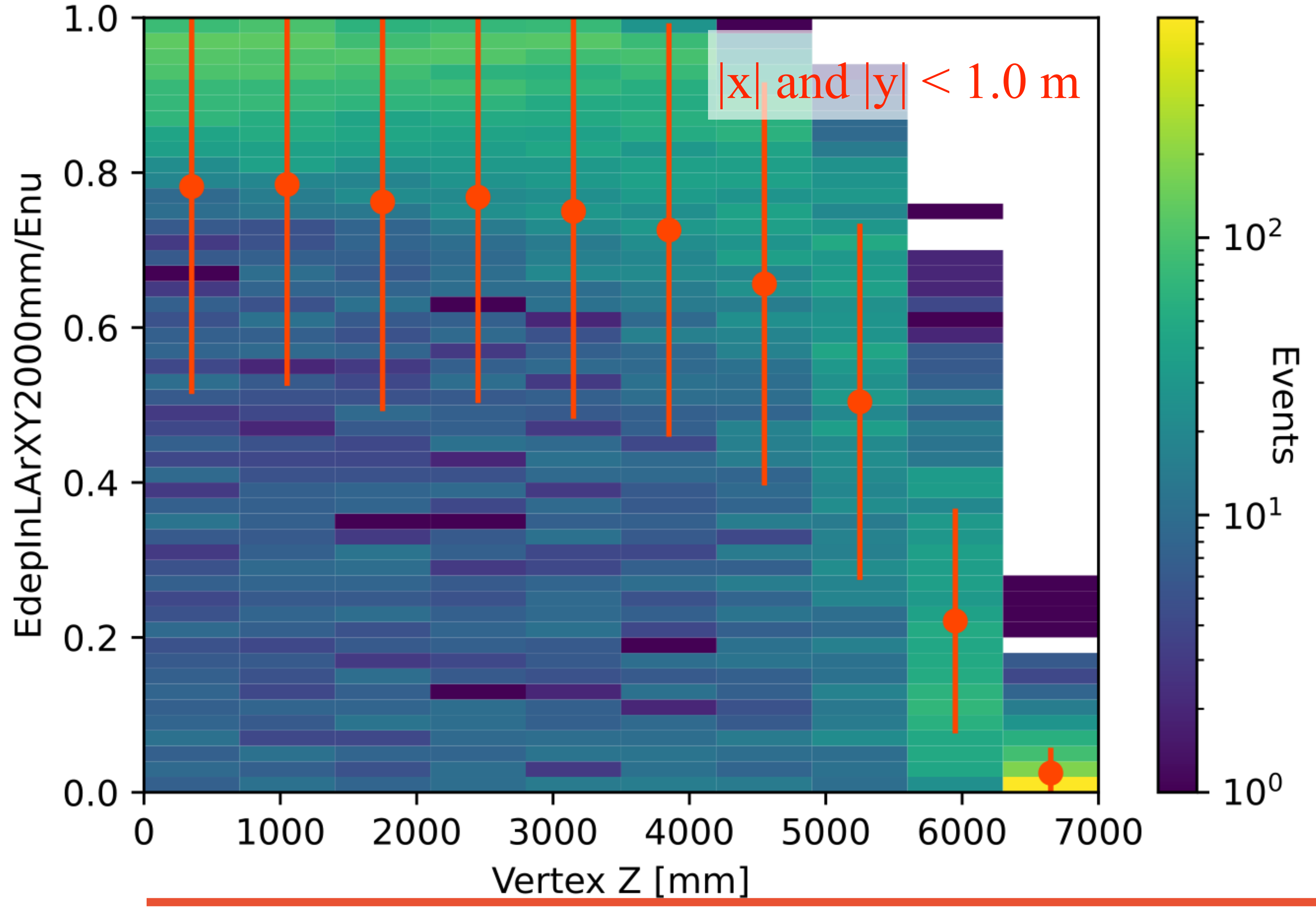
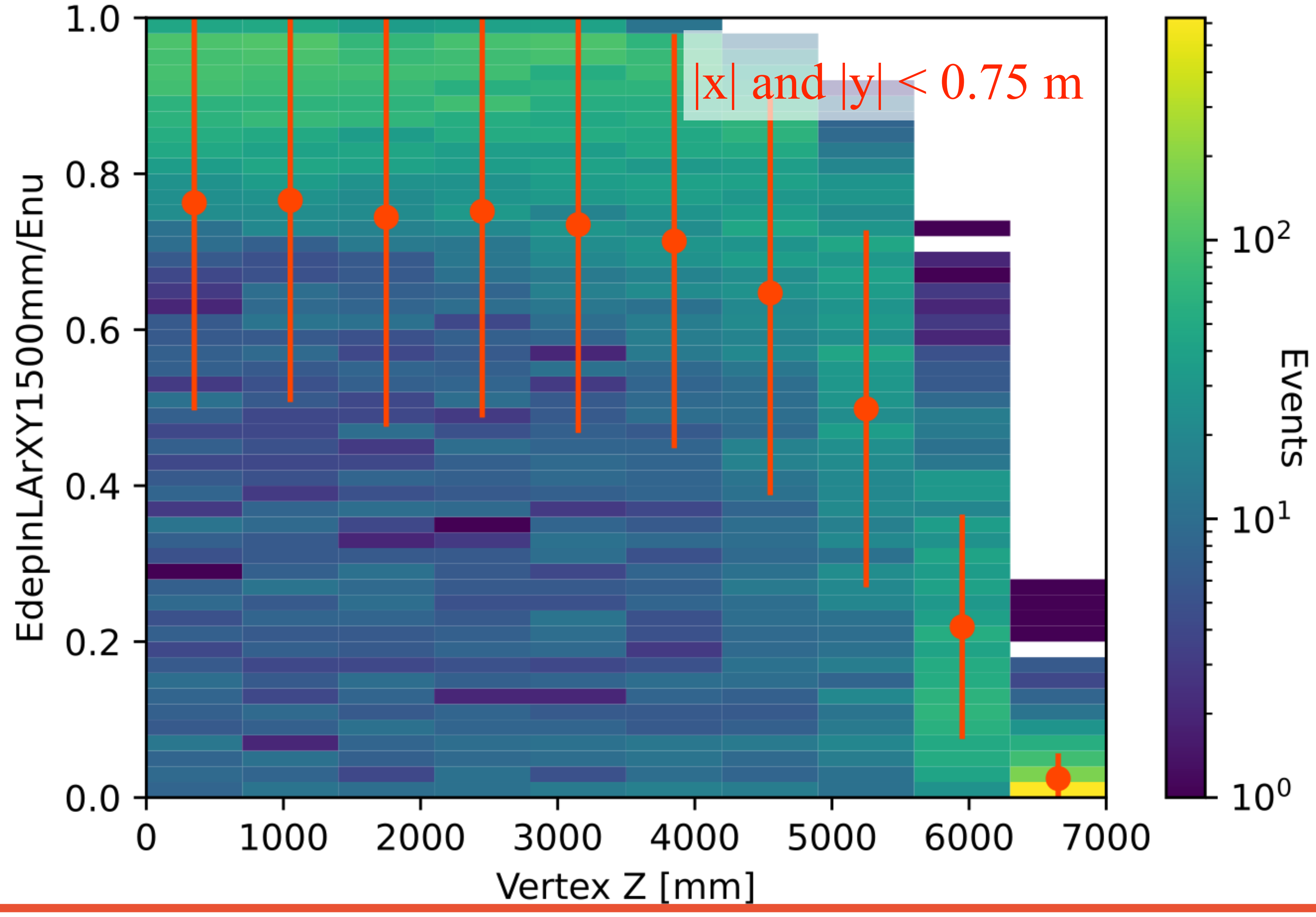
Energy containment in the LArTPC (ν_e)

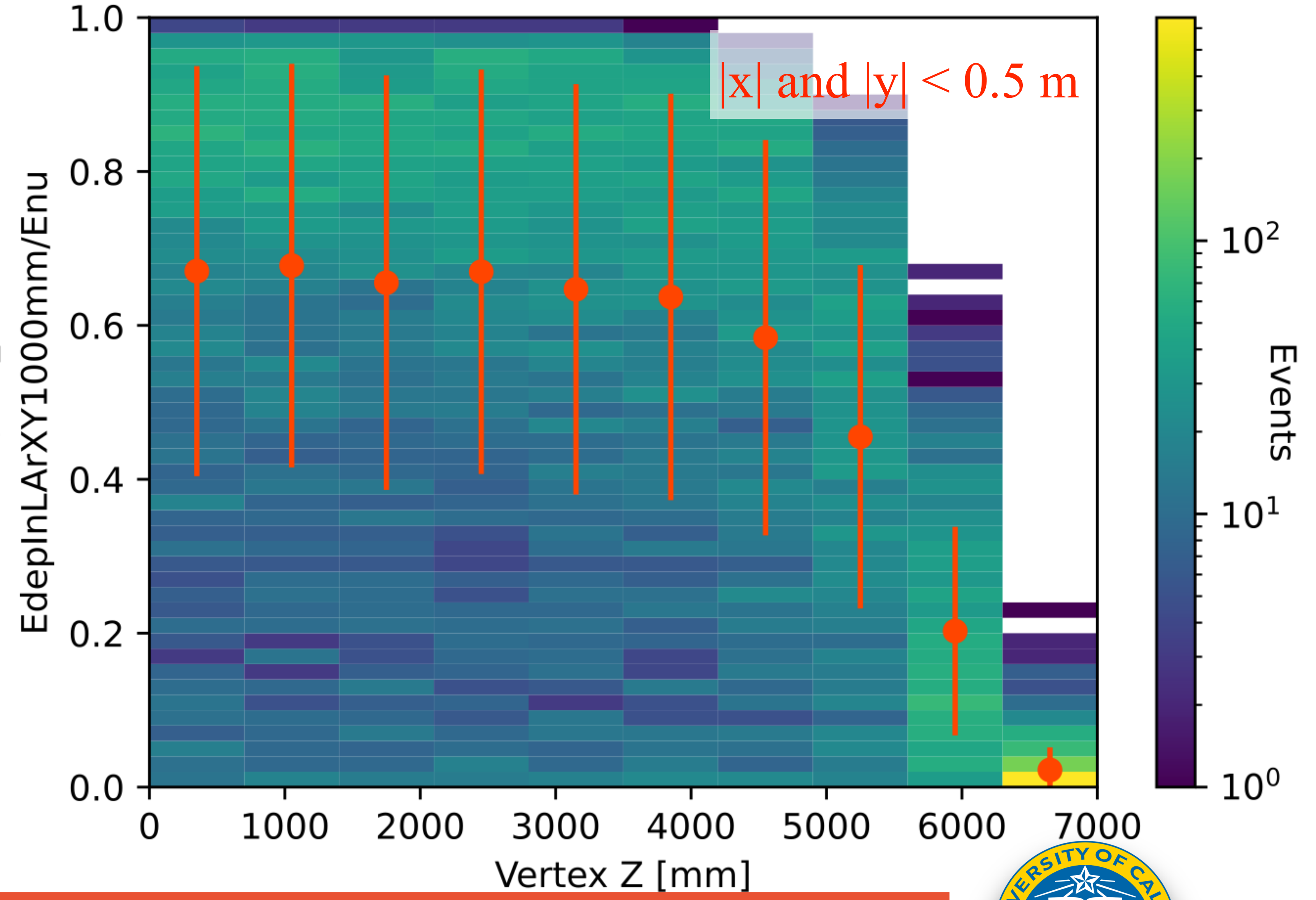
- The ratio of the energy deposited in the LArTPC to the neutrino energy
  - The orange markers are the mean values and standard deviation as error bars
- Make transverse cuts for energy containment in different detector sizes
  - |x| and |y| < 1.5, 1.25, 1.0, 0.75, 0.5 m





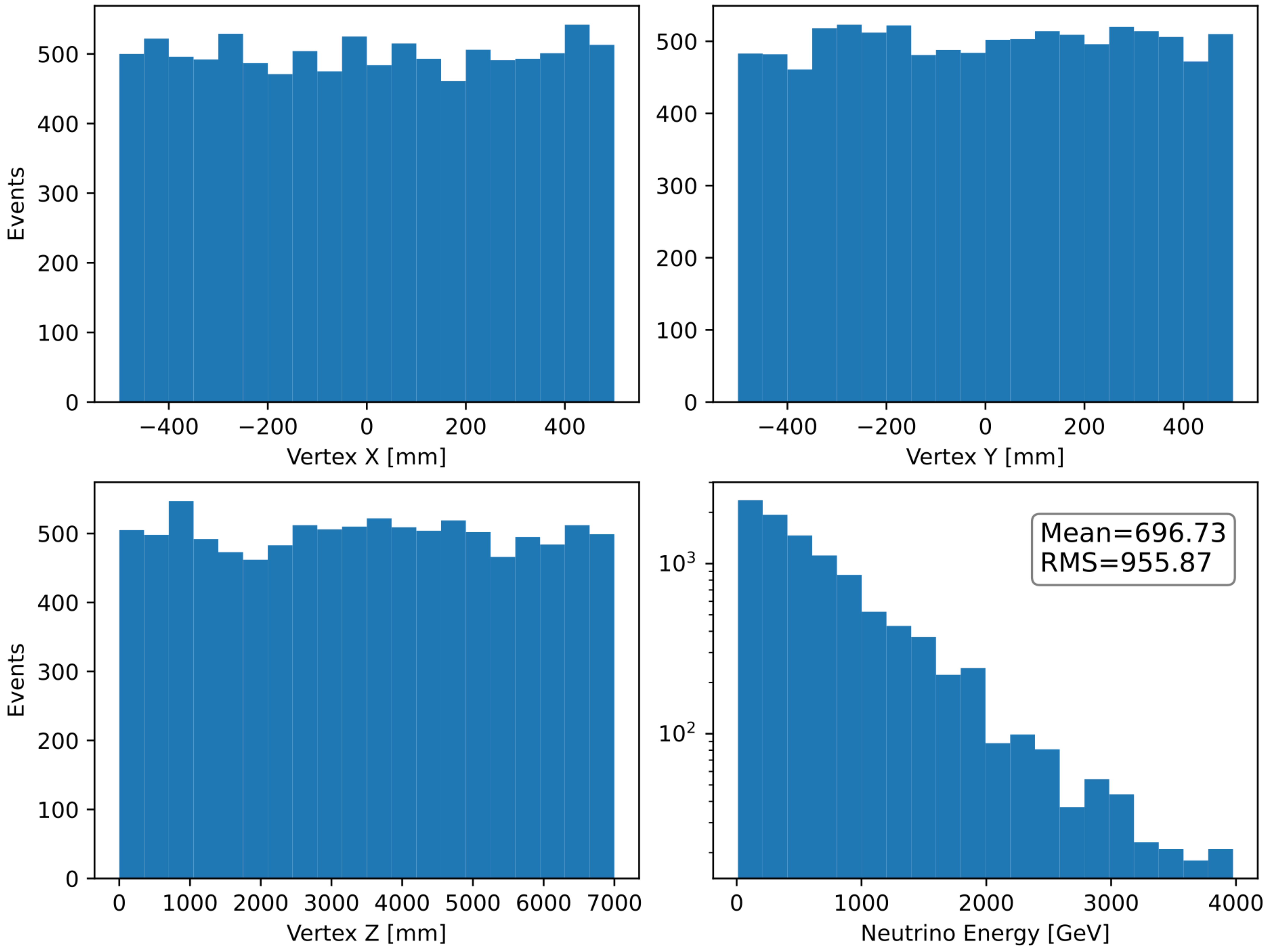


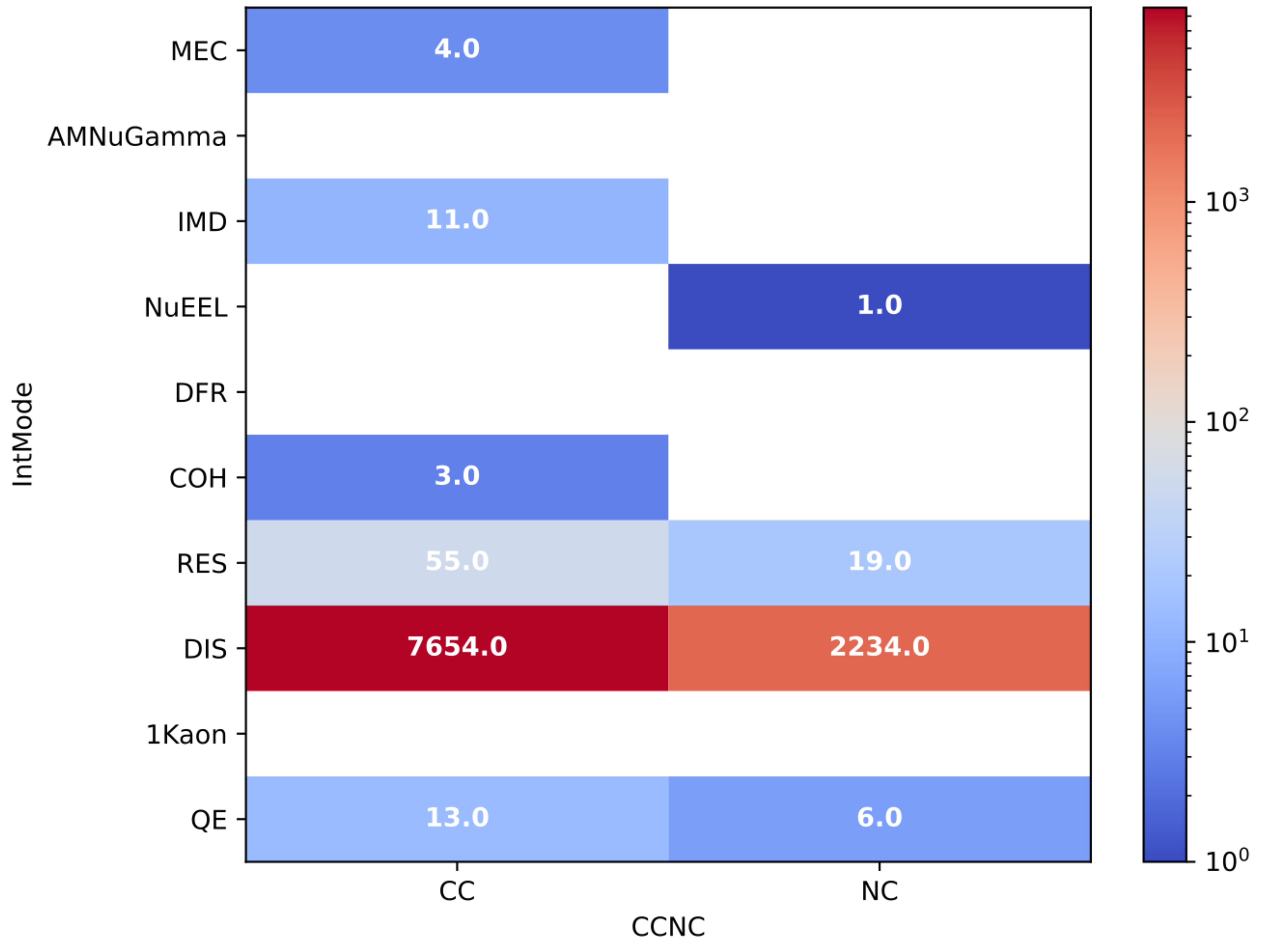


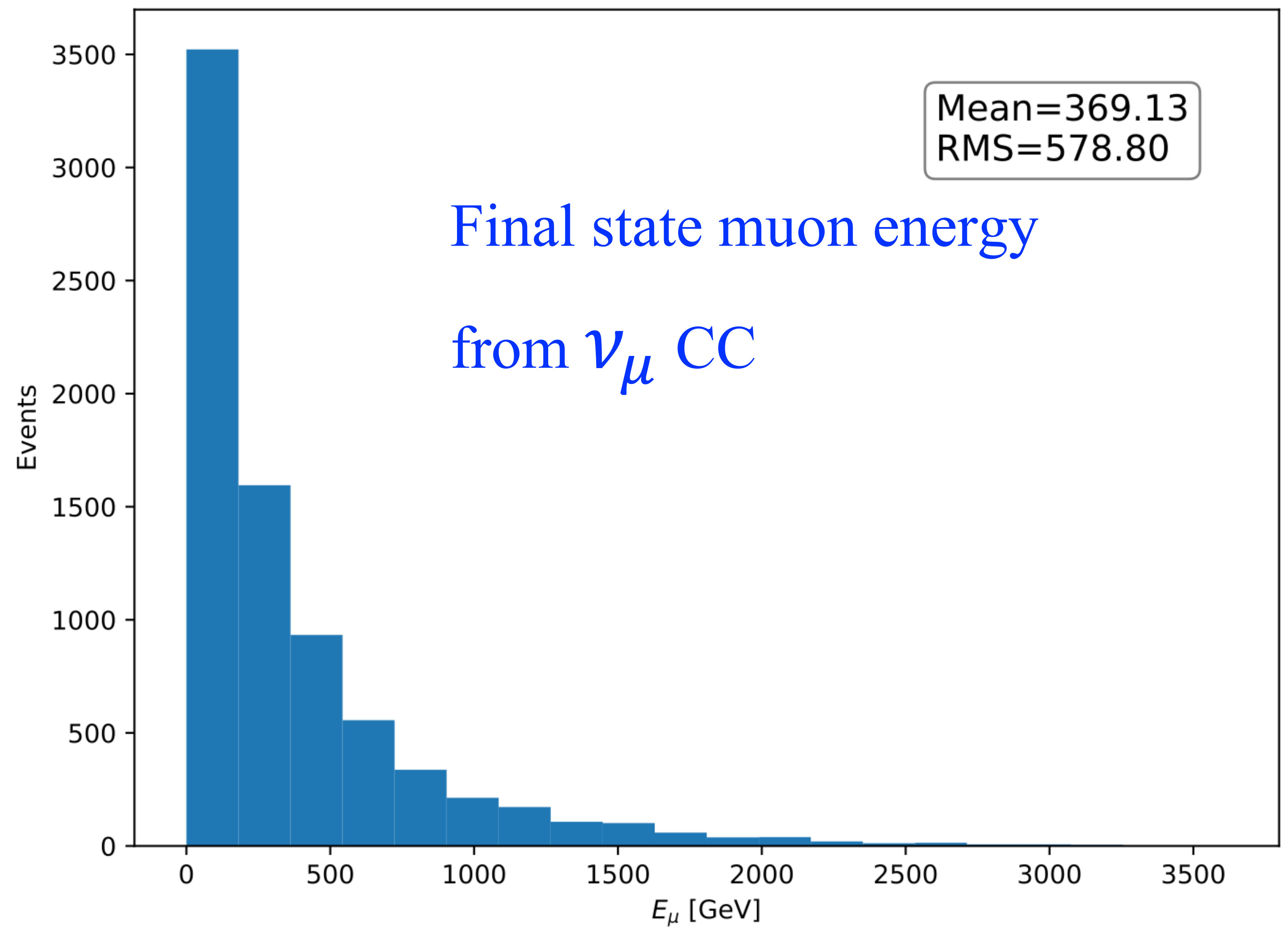


ν_μ in the detector

- Neutrino vertices are uniformly distributed in a 1x1x7 meter volume
- Neutrino energy/Interaction mode/FSL come from GENIE v3_00_06k
  - Flux comes from Felix Kling, et. al. 2105.08270

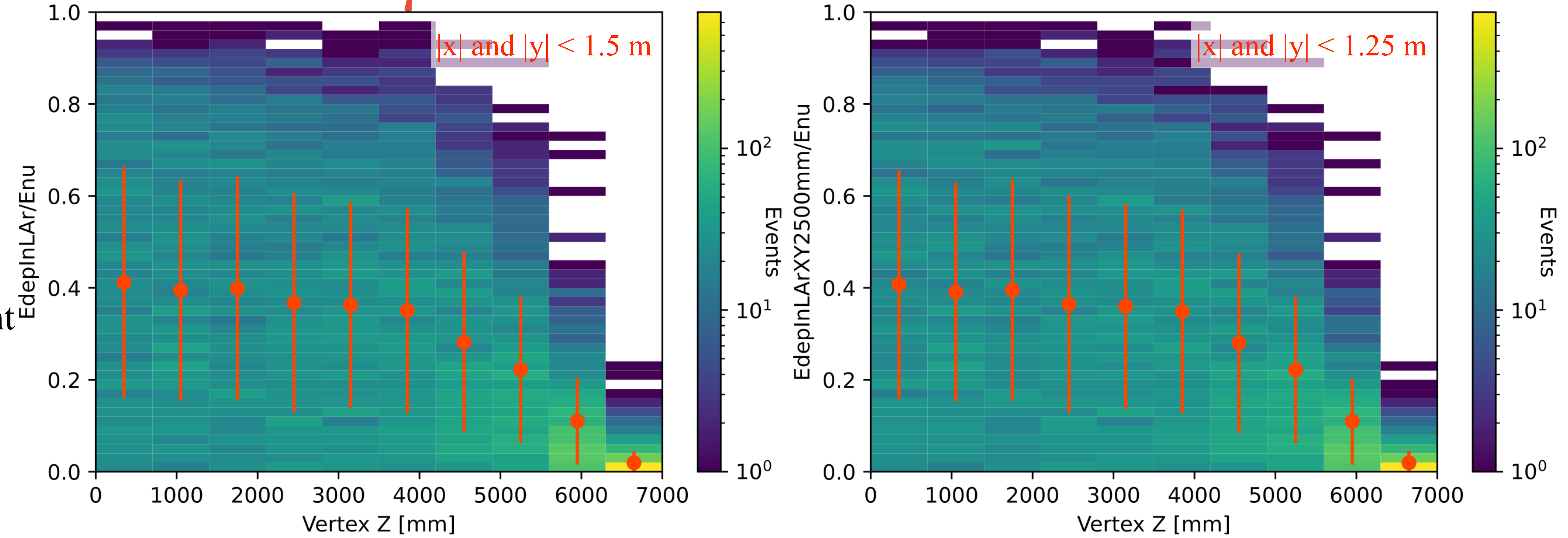






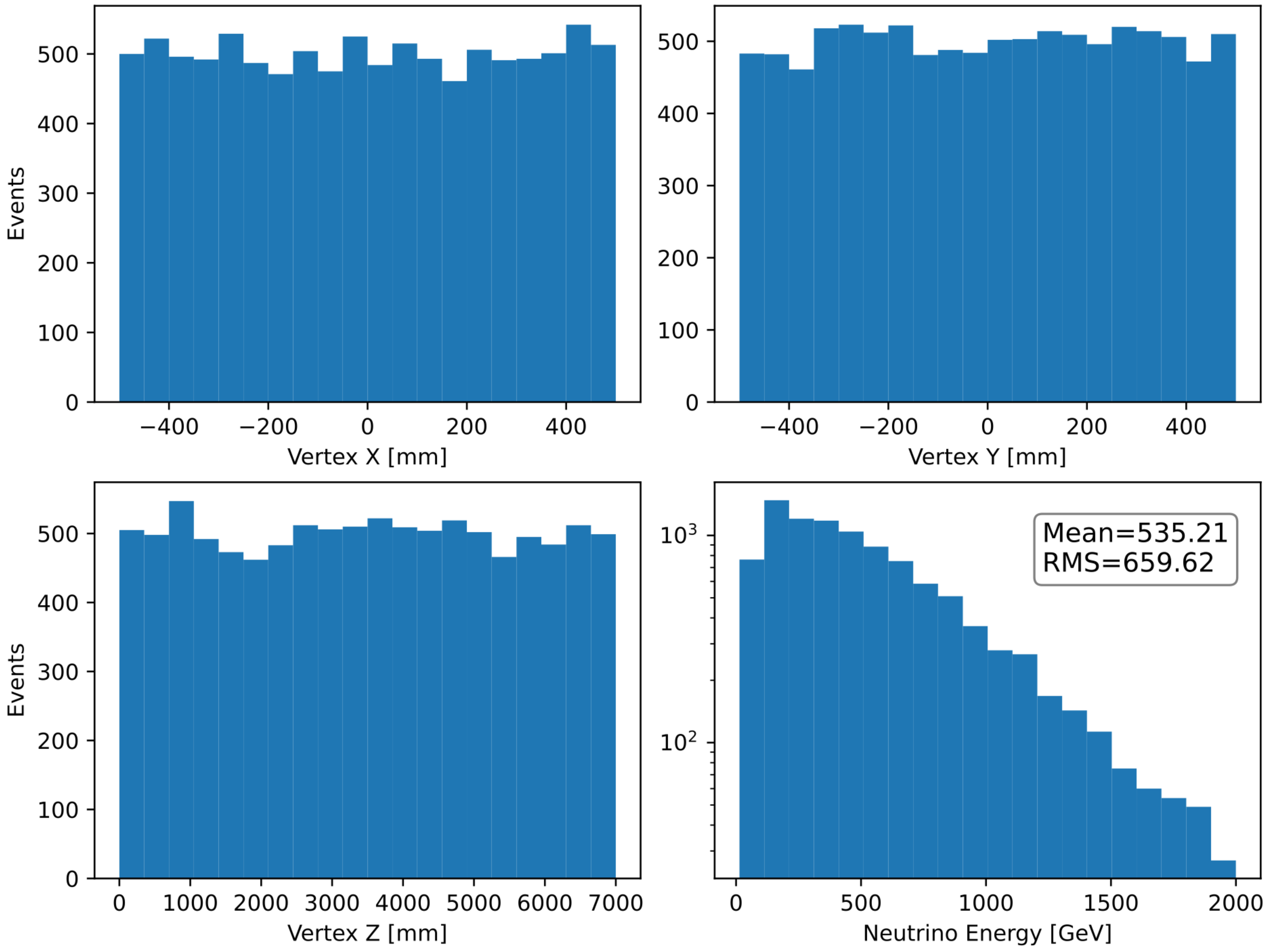
Energy containment in the LArTPC (ν_μ)

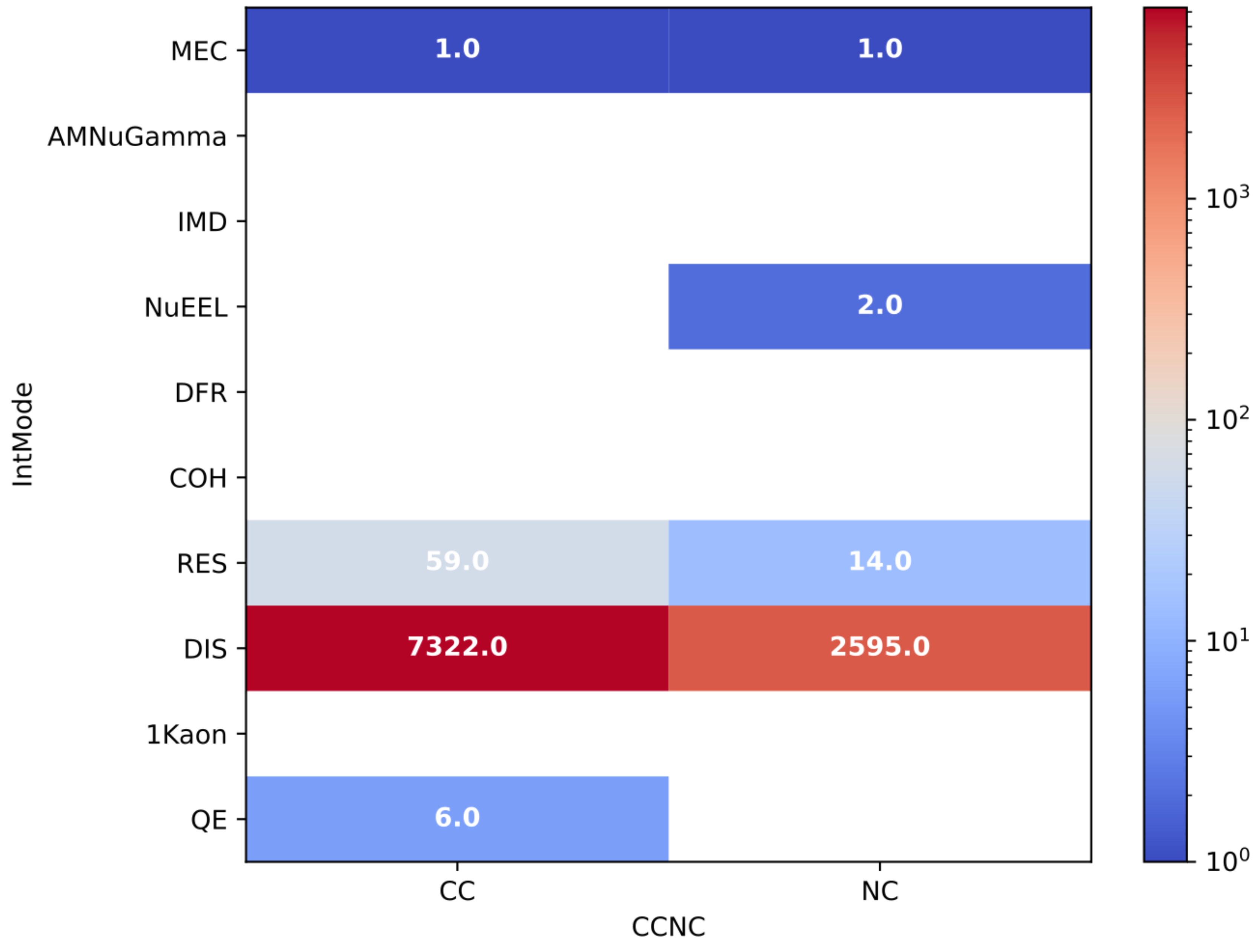
- The ratio of the energy deposited in the LArTPC to the neutrino energy
  - The orange markers are the mean values and standard deviation as error bars
- Make transverse cuts for energy containment in different detector sizes
  - |x| and |y| < 1.5, 1.25, 1.0, 0.75, 0.5 m

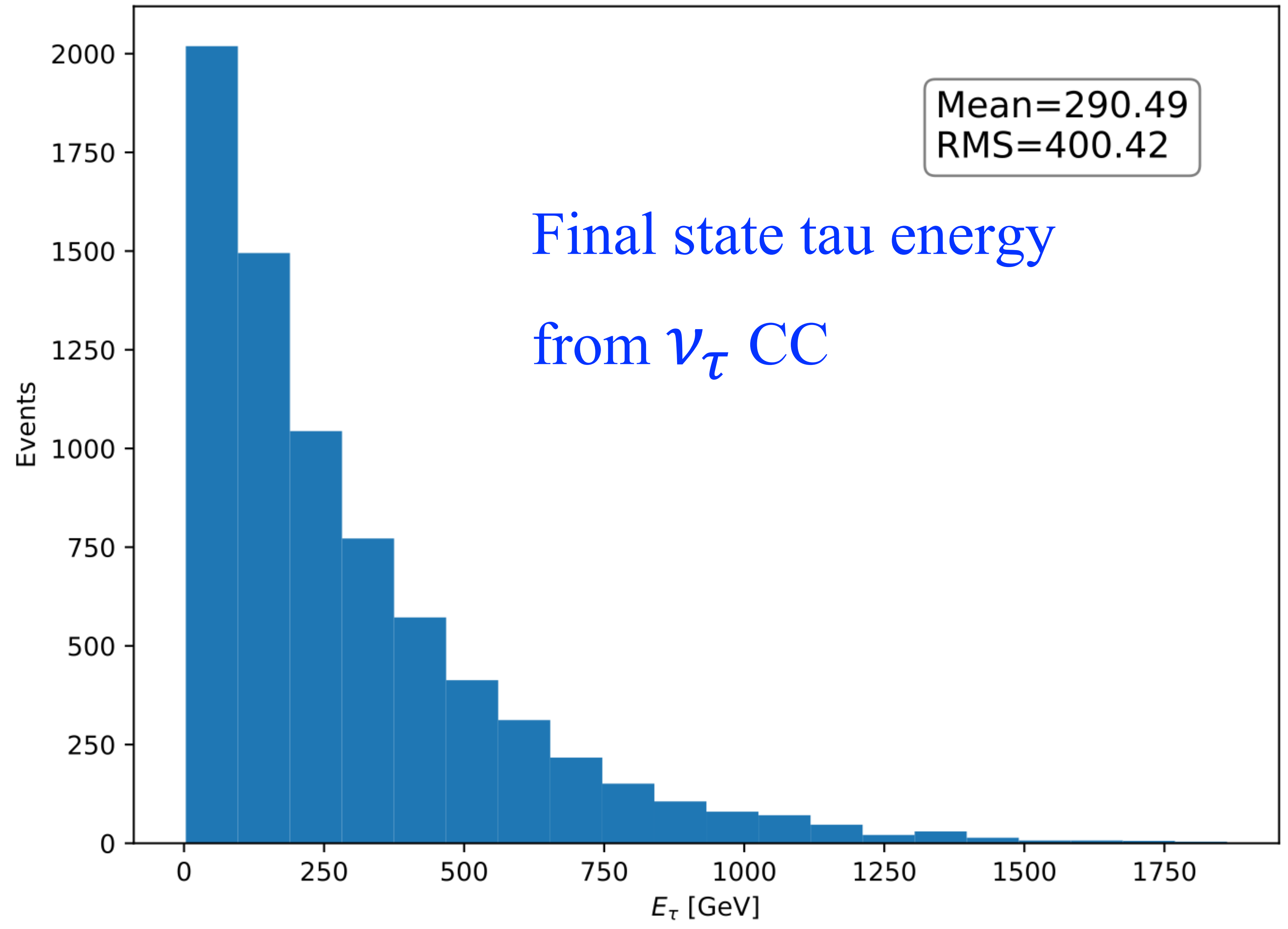


ν_τ in the detector

- Neutrino vertices are uniformly distributed in a 1x1x7 meter volume
- Neutrino energy/Interaction mode/FSL come from GENIE v3_00_06k
  - Flux comes from Weidong Bai, et. al. 2112.11605







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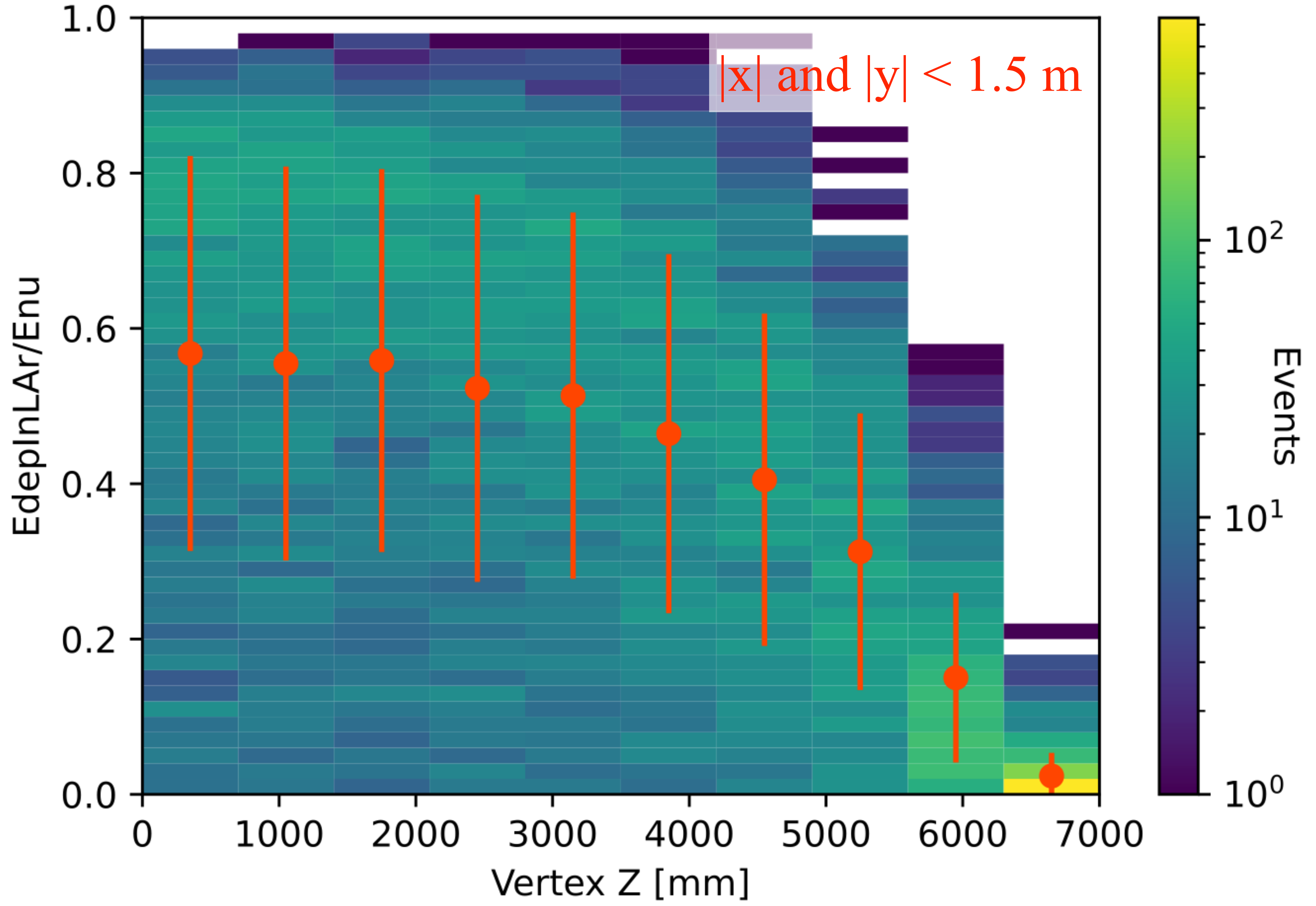
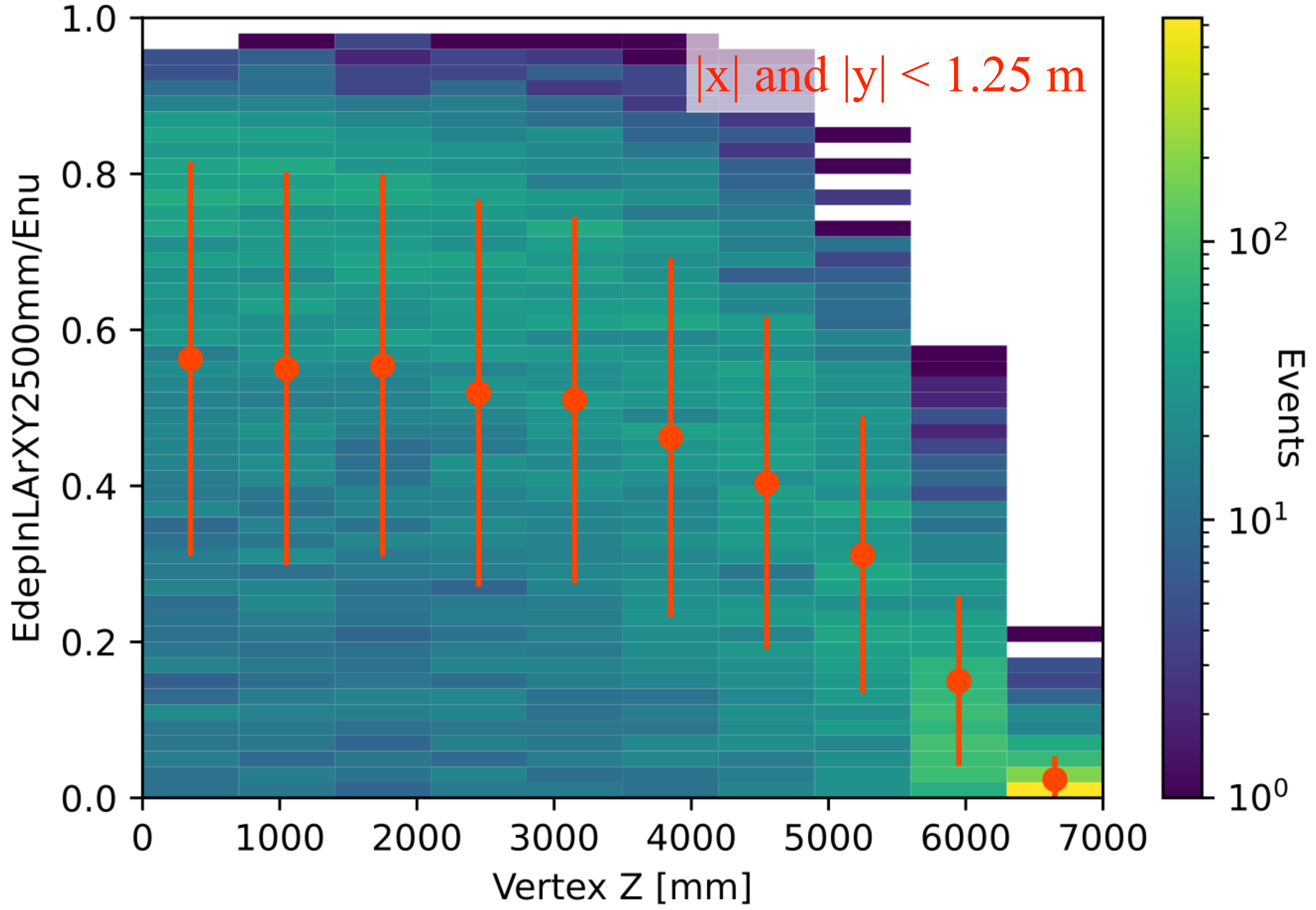
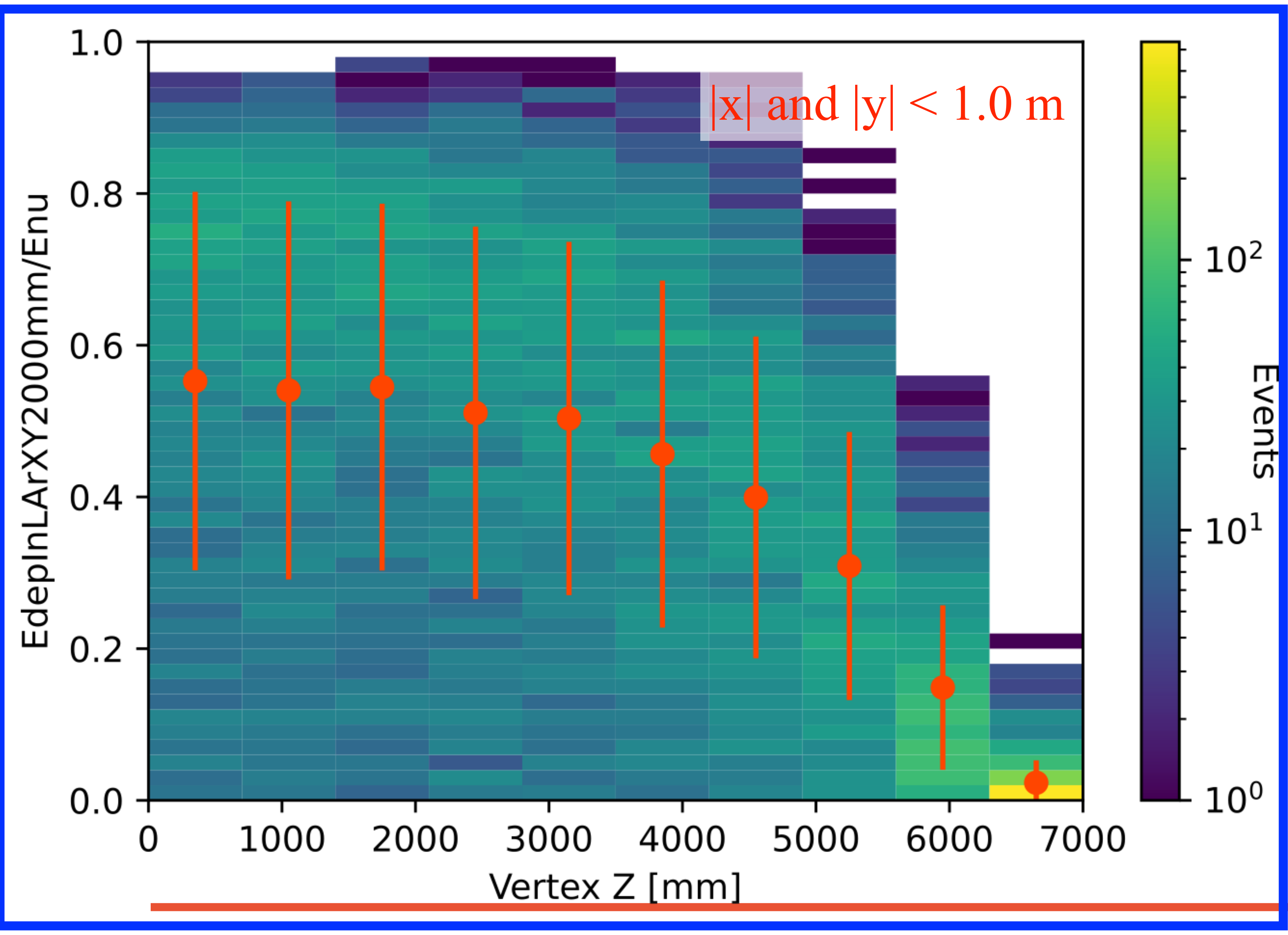
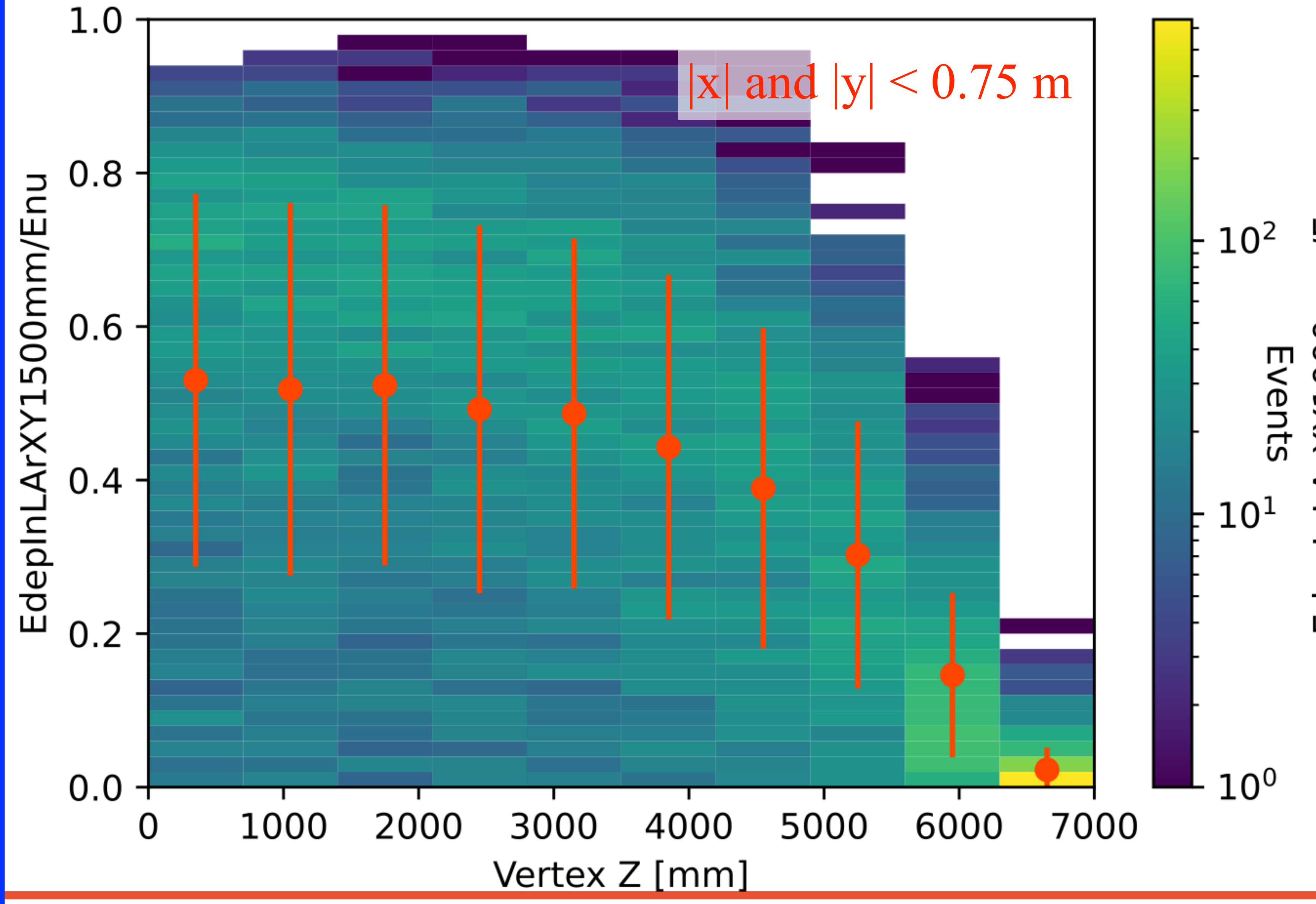
LArTPC Detector Fiducial Optimization with ν_τ

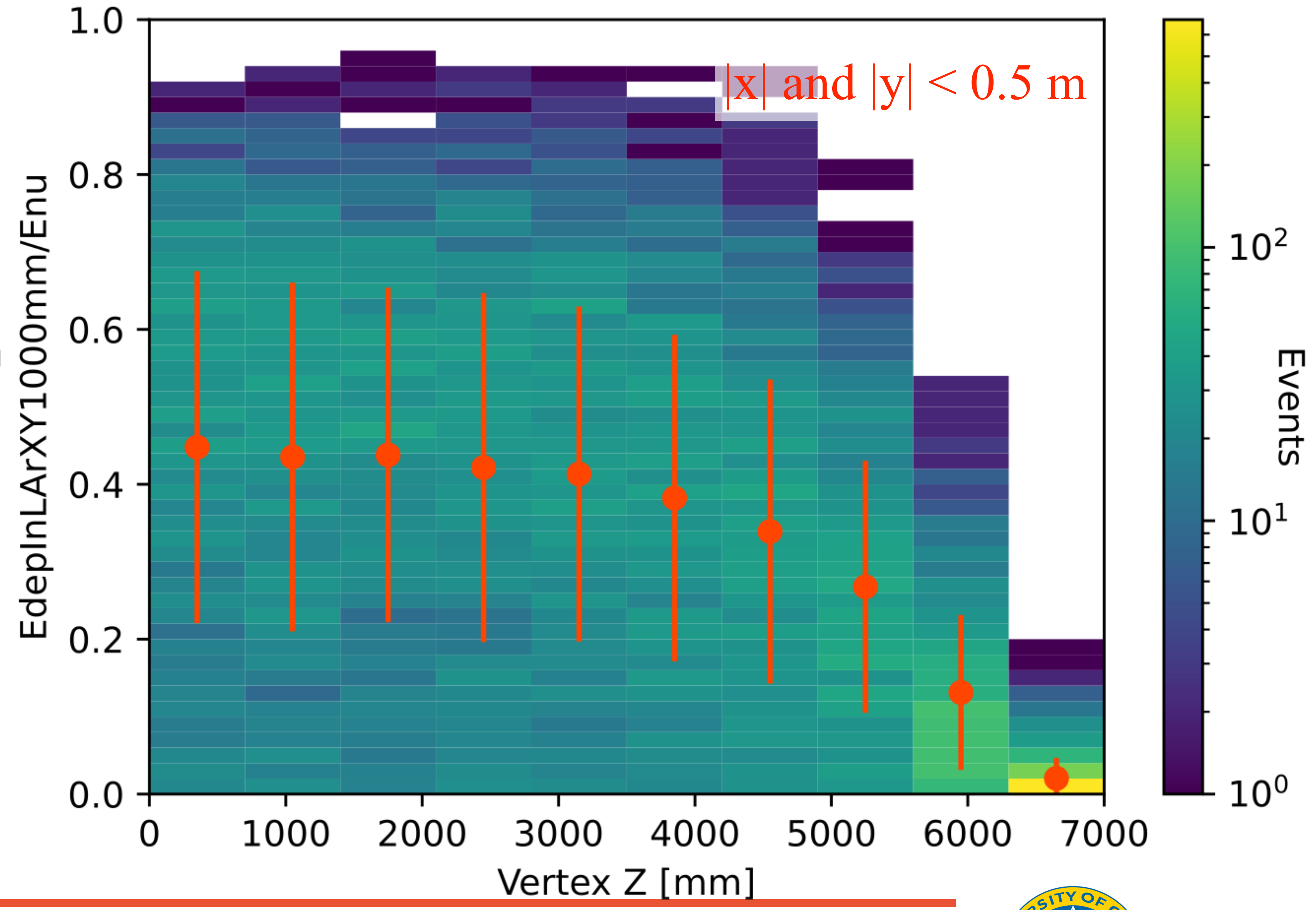
- The ratio of the energy deposited in the LArTPC to the neutrino energy
  - The orange markers are the mean values and standard deviation as error bars
- Make transverse cuts for energy containment in different detector fiducial volumes
- 1.0x1.0 m fiducial is determined





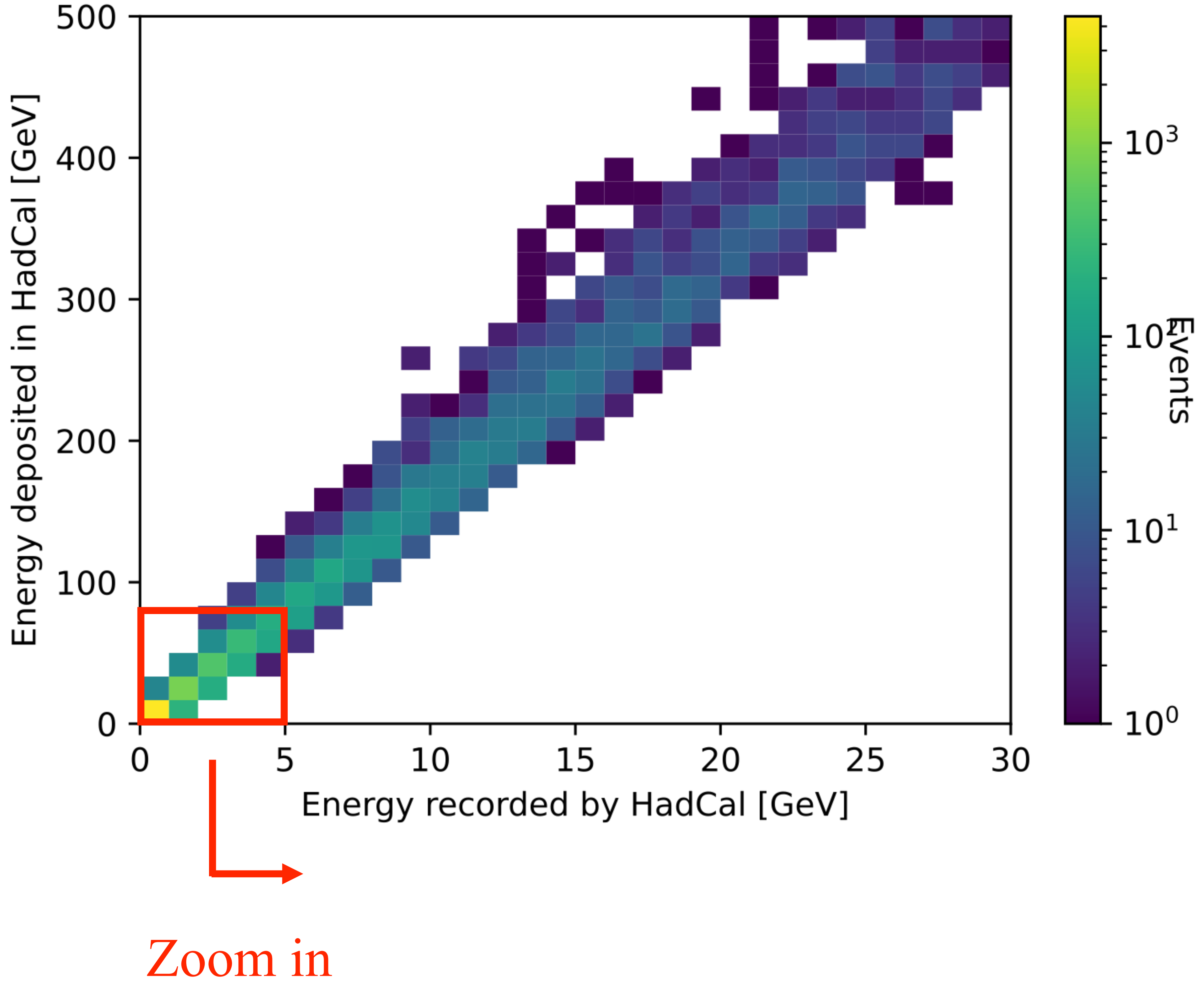


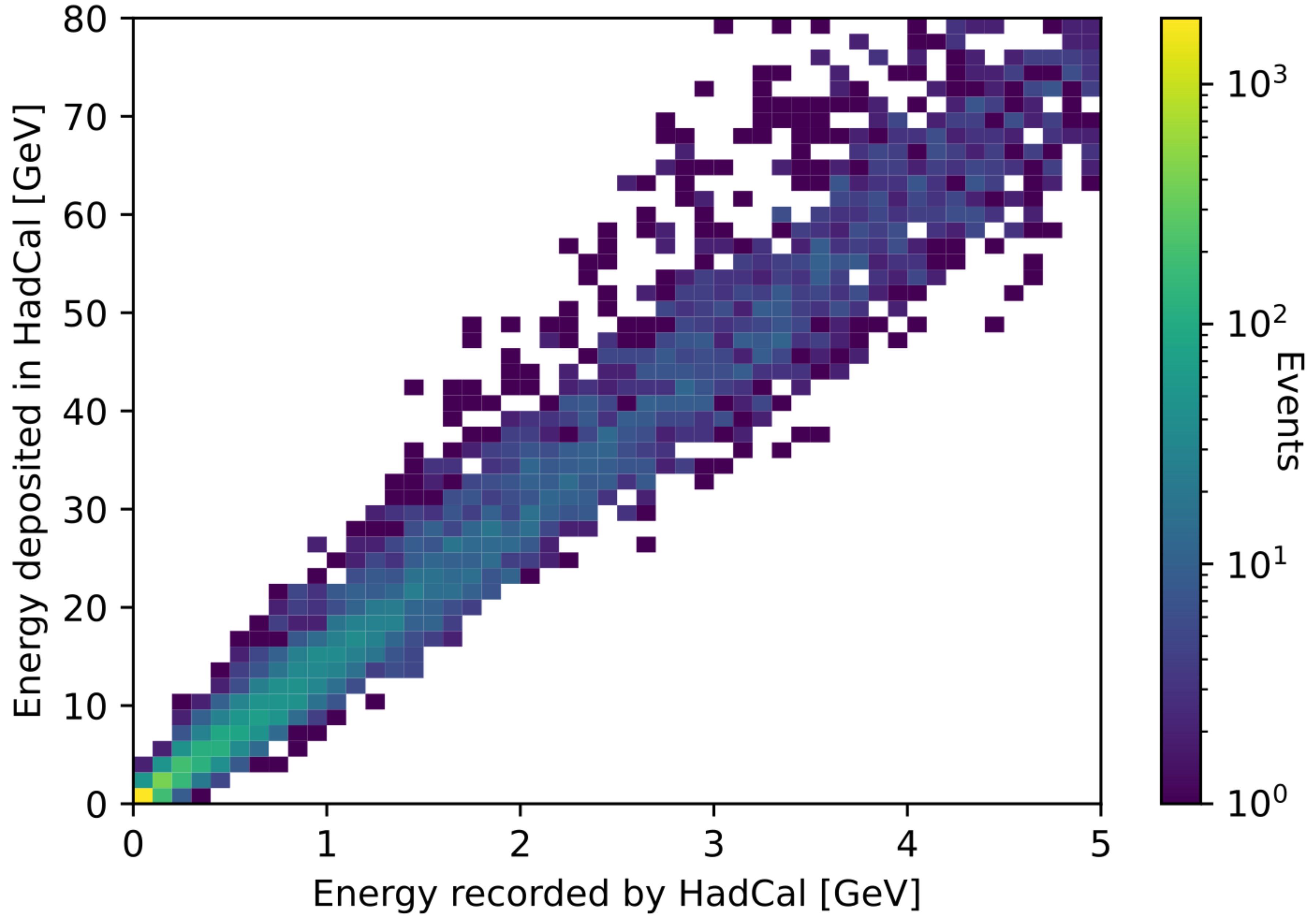




HadCal Calibration

- In order to reconstruct the energy deposited in the HadCal, we'll need to calibrate it
  - The energy deposited in HadCal is proportional to the energy recorded by HadCal (the scintillator)
  - Good linearity





Studies of event selection with MC truth-based pseudo-reconstruction

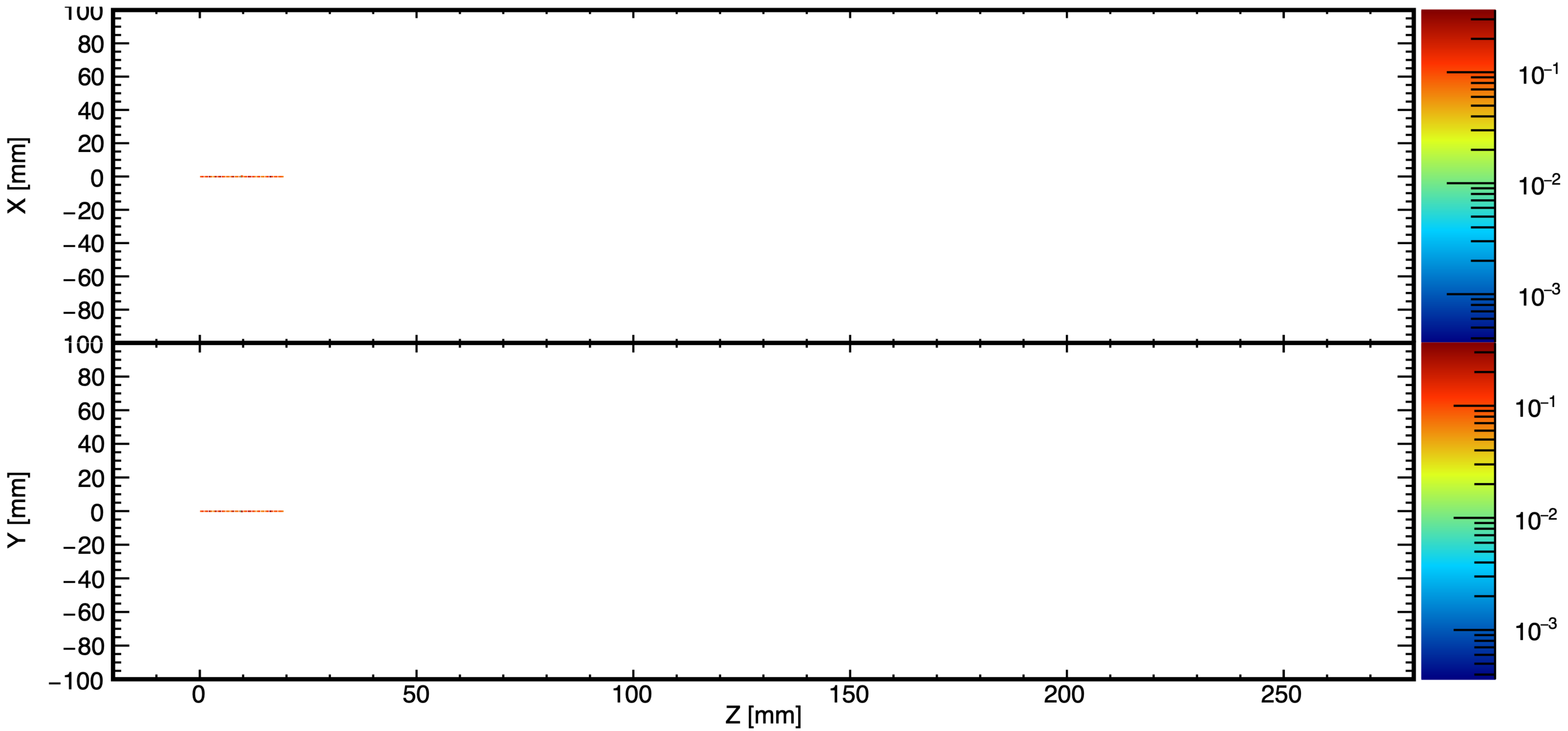
Signal and background

- Same amount of neutrino interactions were simulated for ν_e, ν_μ, and ν_τ (10000 for each)
- To have proper percentages of the 3 flavor neutrinos, weights were applied based on the numbers below
  - 10 tons (1x1x7 m FV), 3000/fb luminosity of HL-LHC

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

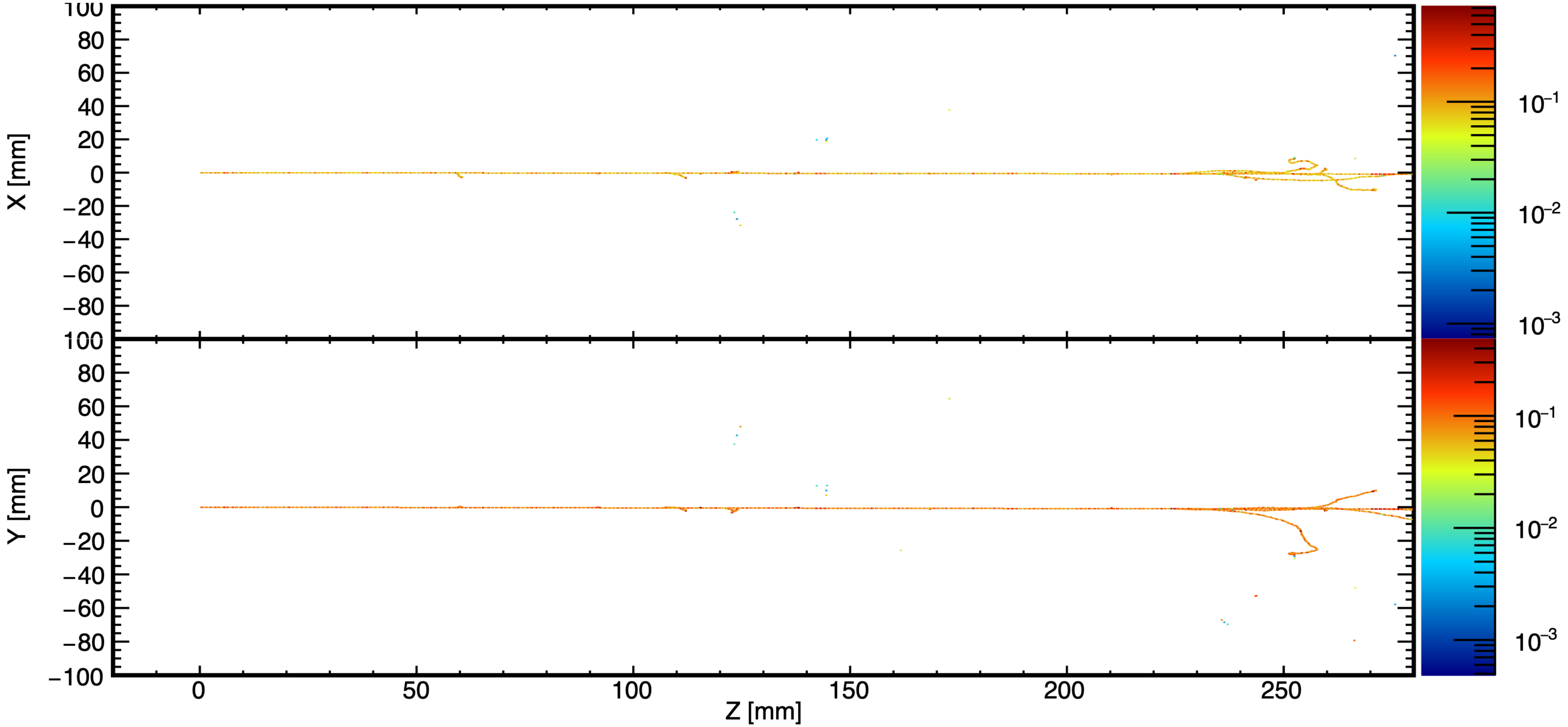
Table 7.1: Detectors and neutrino event rates: The left side of the table summarizes the detector specifications in terms of the target mass, pseudorapidity coverage and assumed integrated luminosity for both the LHC neutrino experiments operating during Run 3 of the LHC as well as the proposed FPF neutrino 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`.

Tau before decay



EvtID 0 PDG 15 Etot 963.8 GeV (-19.0, -398.4, 561.3) mm

Tau after decay



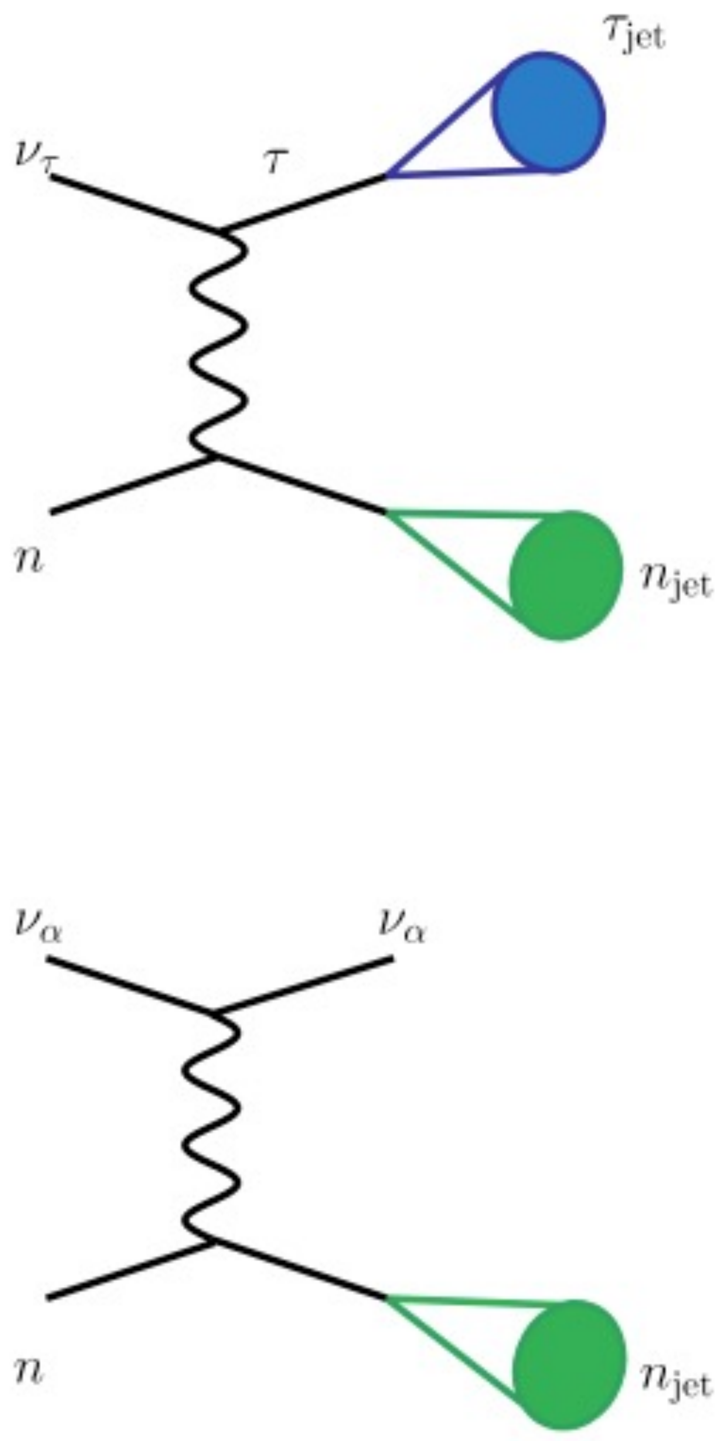
EvtID 0 PDG 13 Etot 672.1 GeV (-19.0, -398.5, 580.6) mm

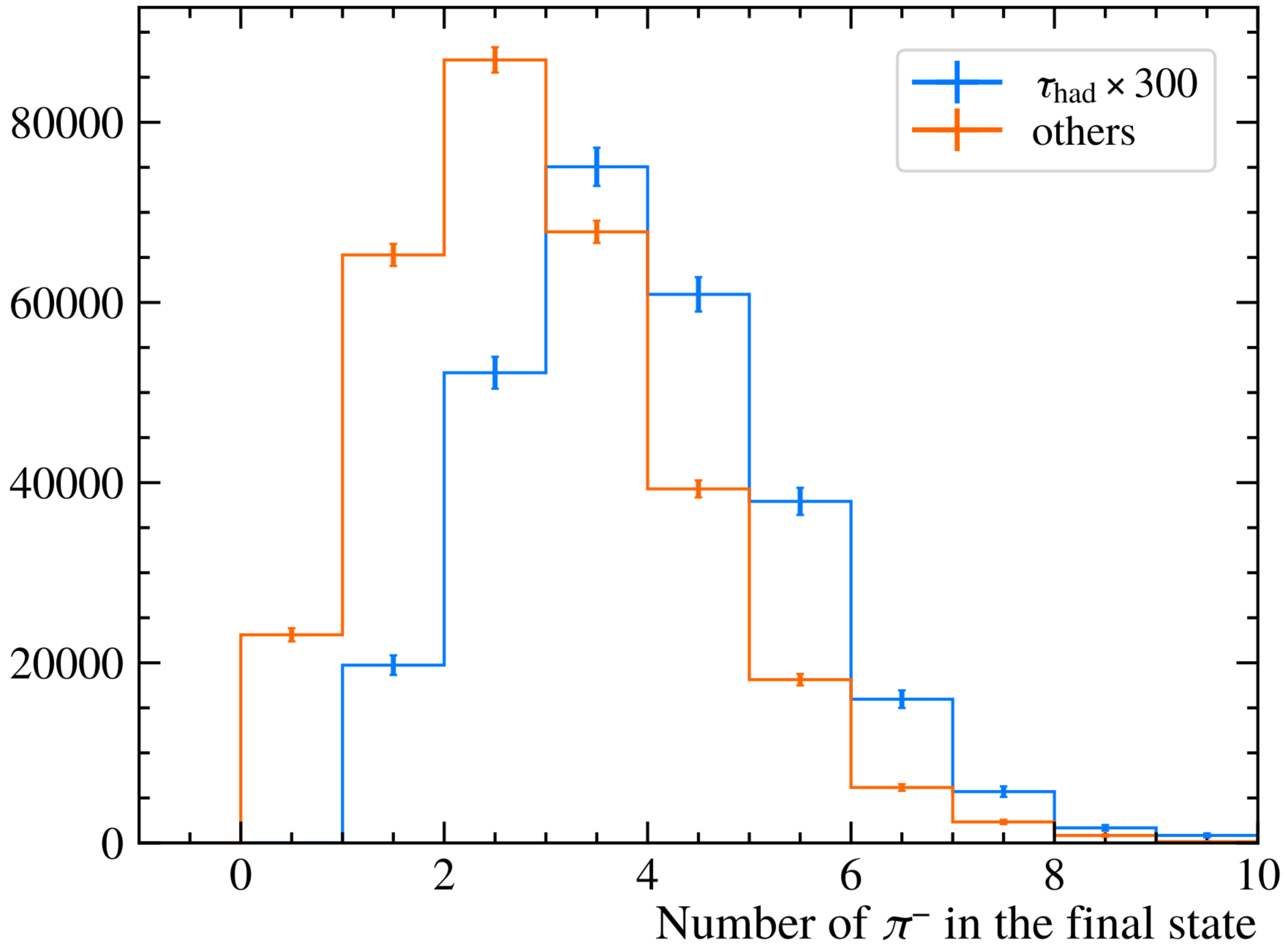
Hadronic decay

- Signal: τ_{had} (taus decay to hadrons)
  - τ_{had} has larger branch ratio than τ_μ and τ_e, there is potential to be a good channel to select ν_τ
  - τ_{had} has at least one π^- in the final state

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%

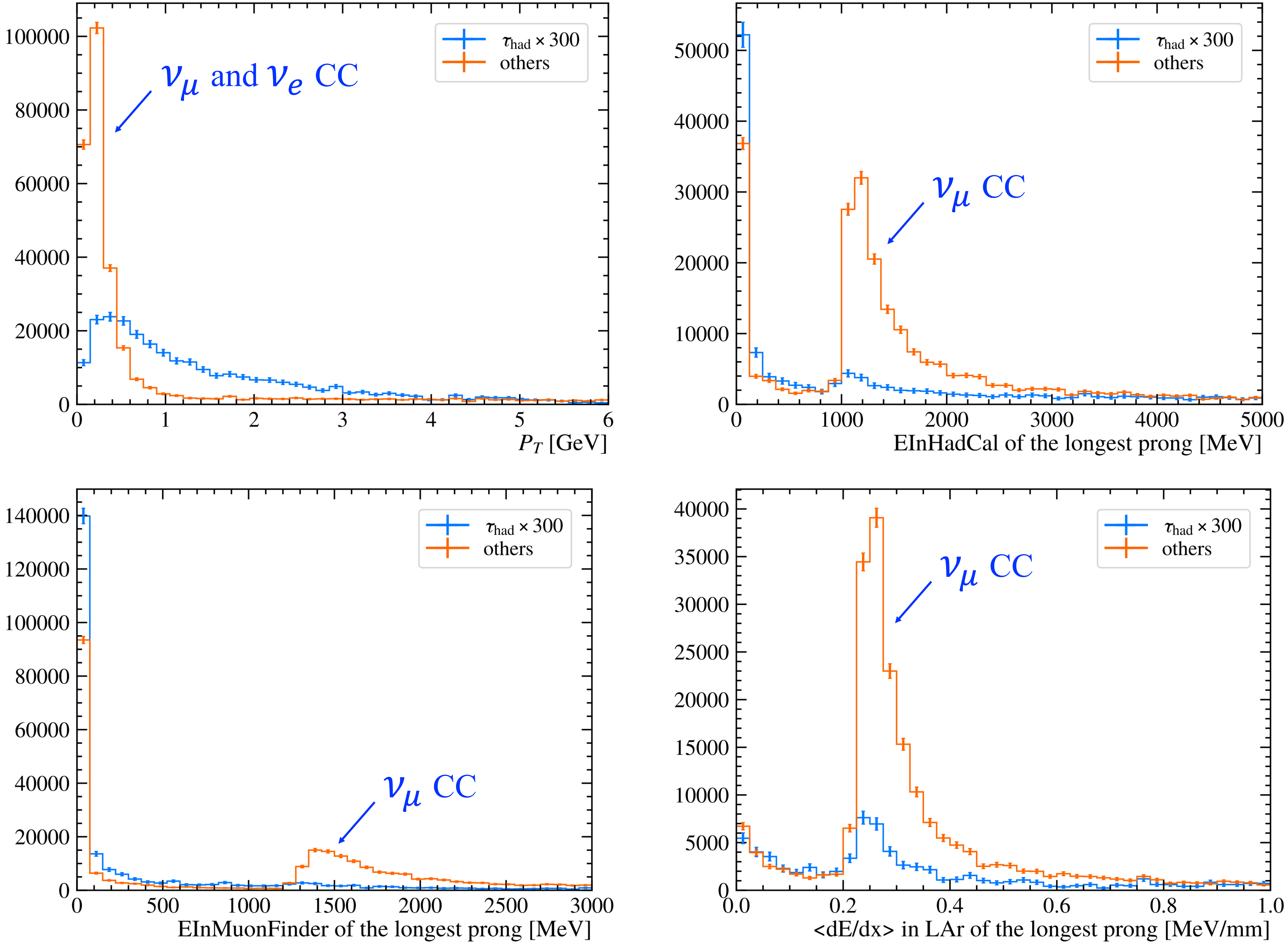




10.1103/PhysRevD.102.053010

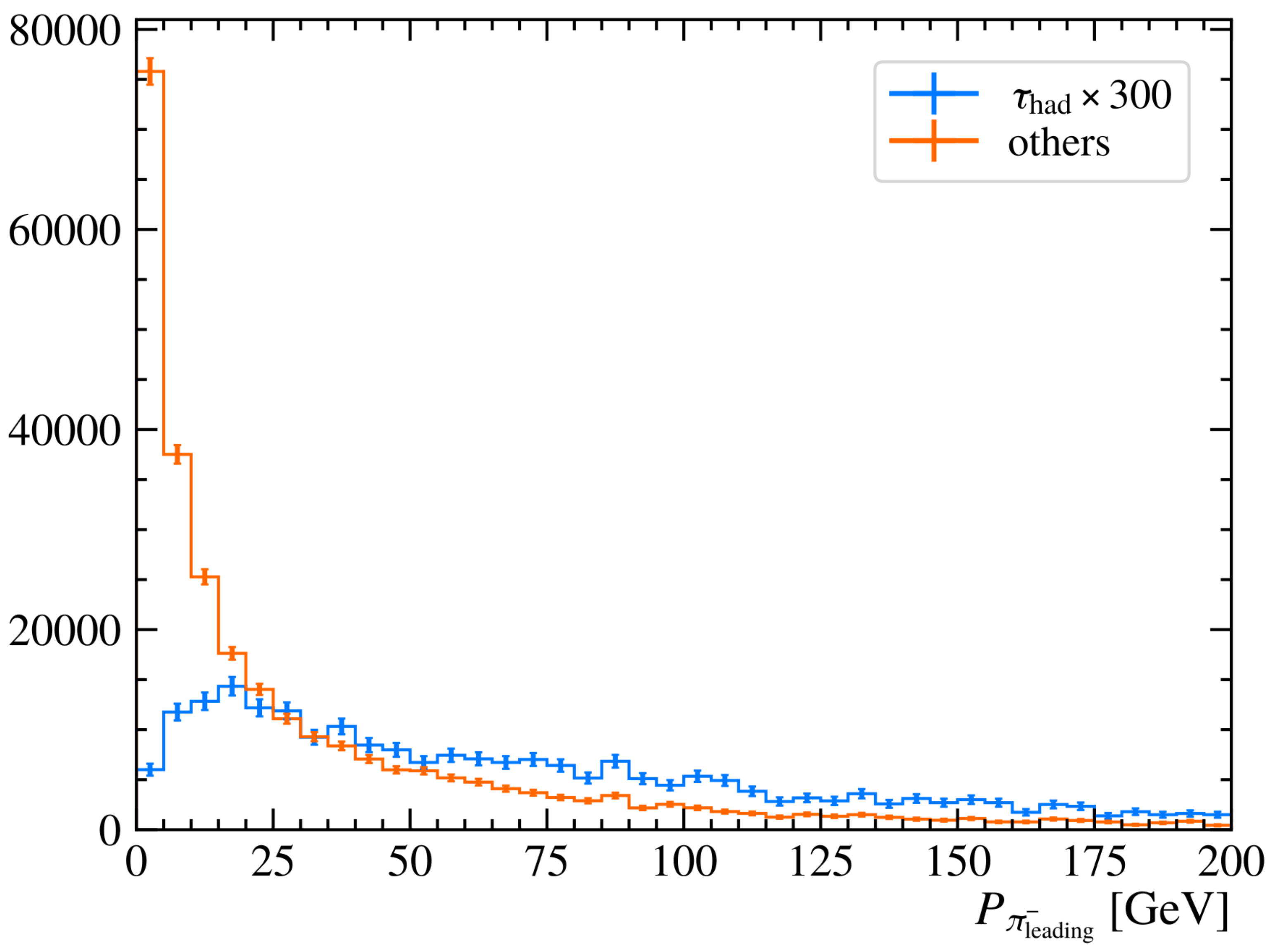
Hadronic decay

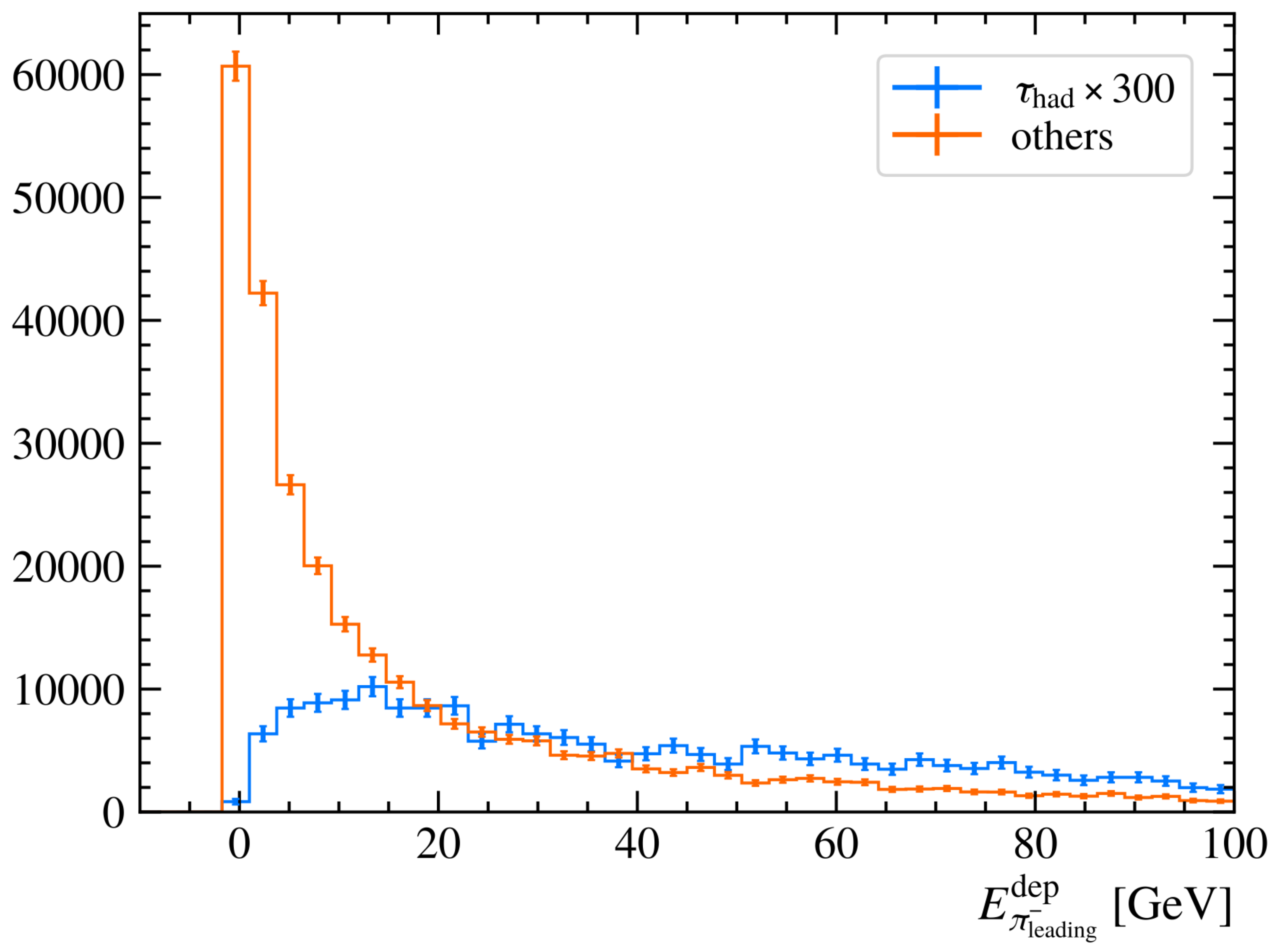
- Neutrinos in the final state are invisible to the detector, contributing to the missing transverse momentum
  - Almost all ν_μCC, ν_eCC have zero neutrino in the final state
  - NC events and τ_{had} have 1 neutrino, τ_μ and τ_e have 2 neutrinos

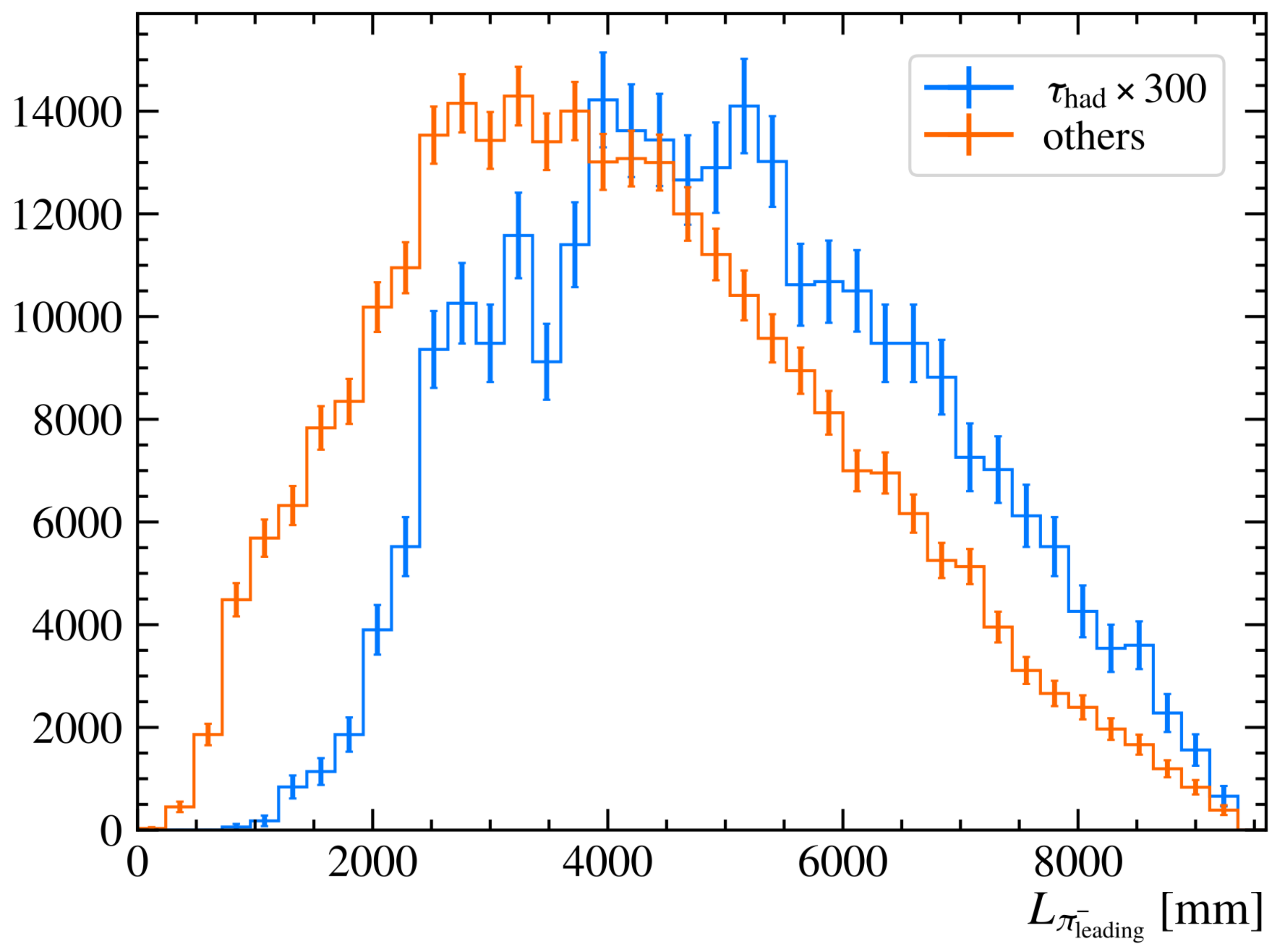


Hadronic decay

- Find the most energetic π^- shower of each event
  - τ_{had} generally has a more energetic π^- in the final state

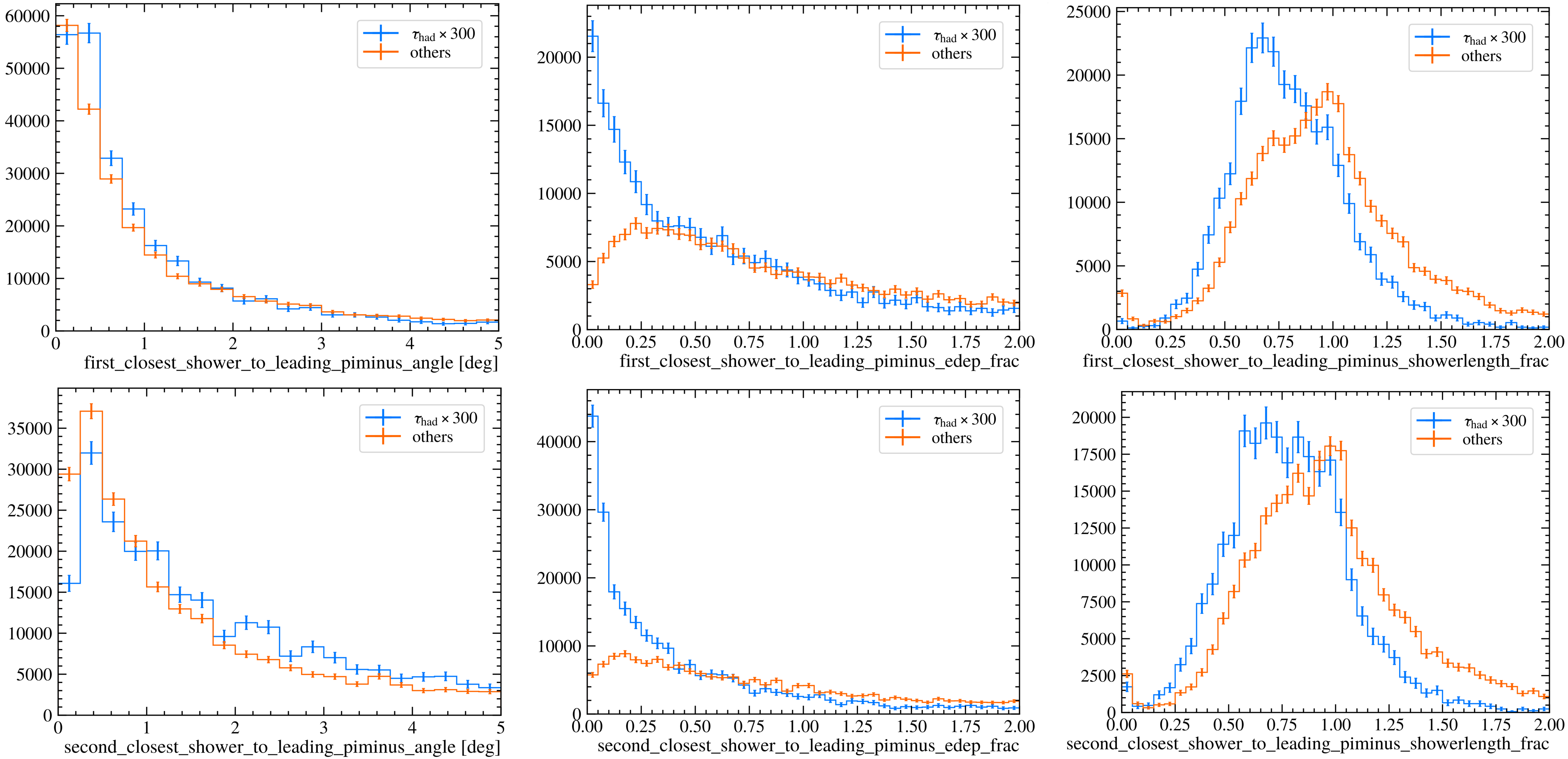






Hadronic decay

- Find the most energetic π^- shower of each event



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Hadronic decay

- Find the most energetic π^- shower of each event