Simulations of the FLArE Detector

Jianming Bian, Wenjie Wu

University of California, Irvine

September 1, 2022

UCIRVINE

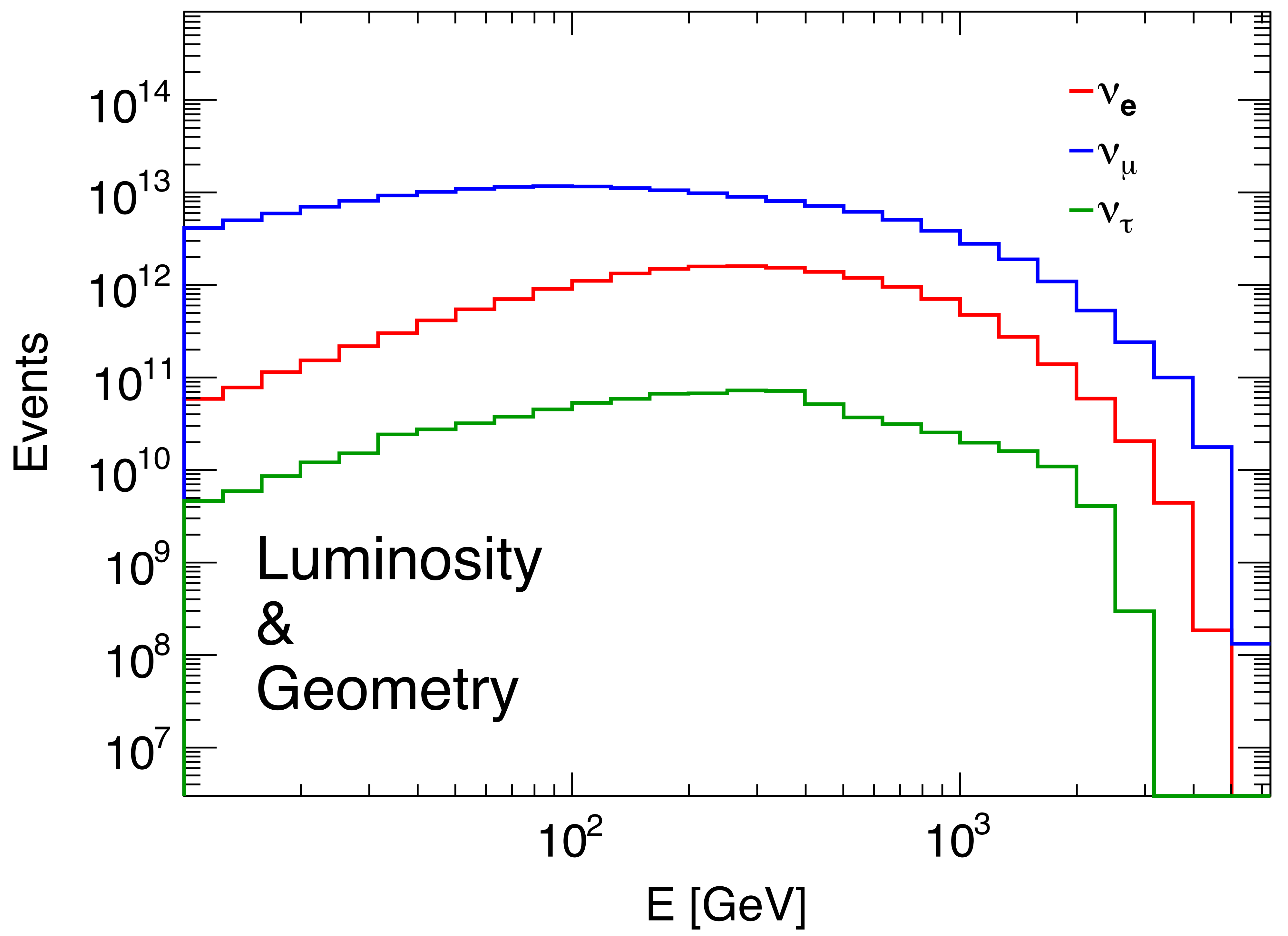
Content

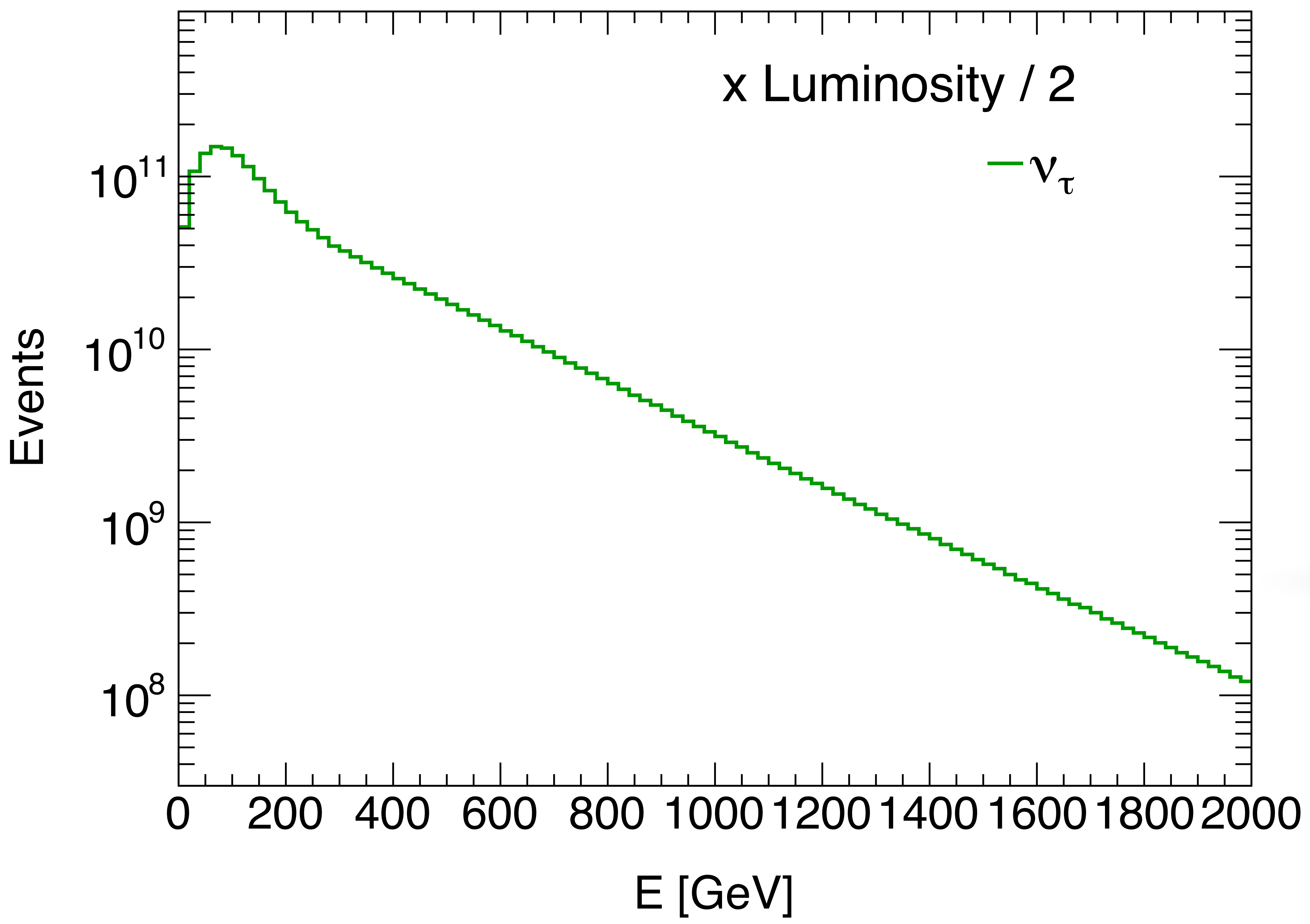
- Simulation of neutrino events: Genie to Geant4
- Containment studies of neutrino interactions
- Studies of event selection with MC truth-based pseudo-reconstruction

Simulation of neutrino events: Genie to Geant4

Neutrino flux

- ν_τ is predominantly produced by the charm decay $D_s \to \tau\nu_\tau$ and the subsequent tau decay
- NLO perturbative evaluations of charm production using the PROSA PDFs





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

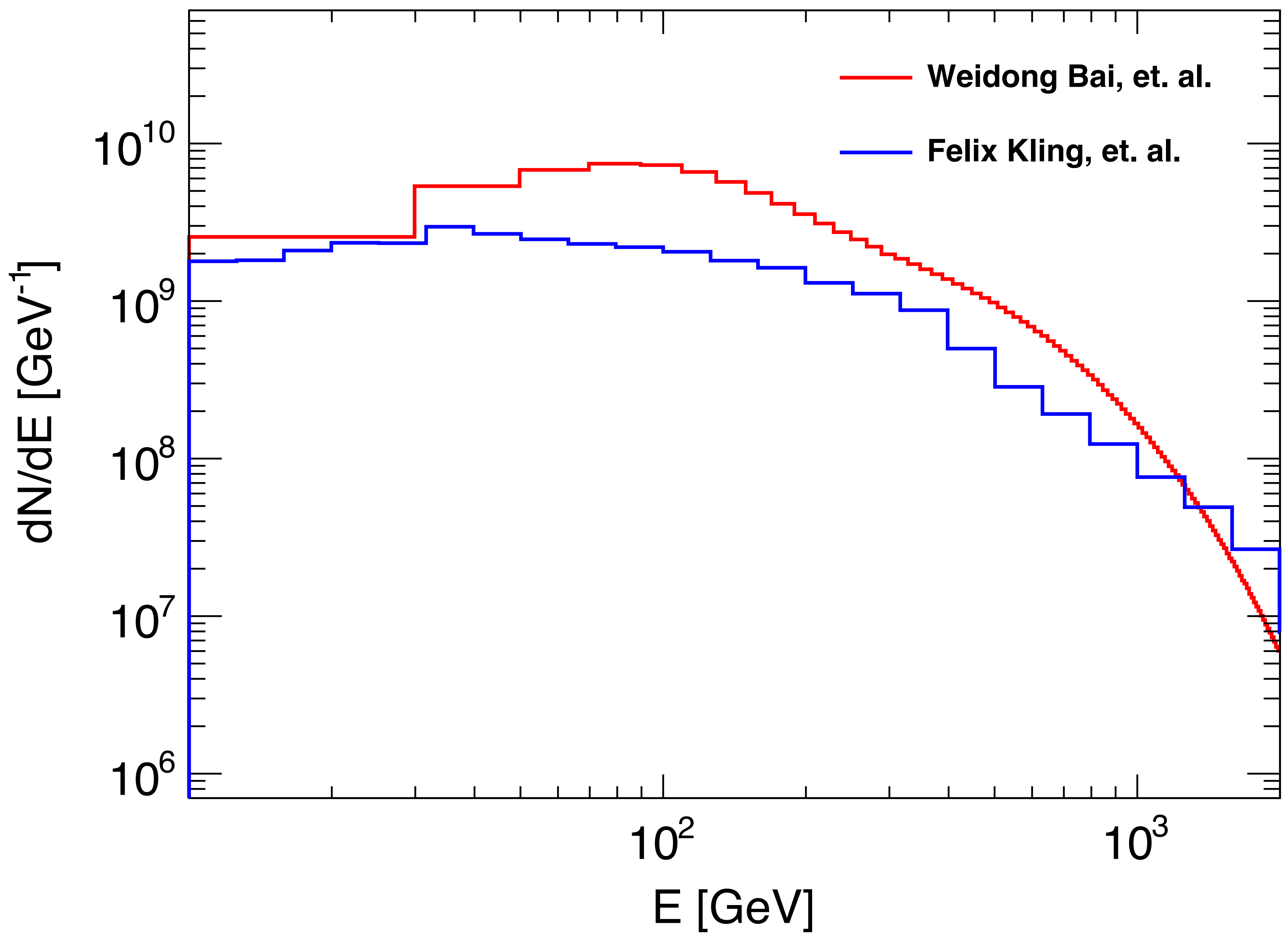
Felix Kling, et. al. 2105.08270
Github, Using Sibyll 2.3d

FLArE10, 620m downstream from IP, 3000/fb

Weidong Bai, et. al. 2112.11605
Figure 12, Table 5

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

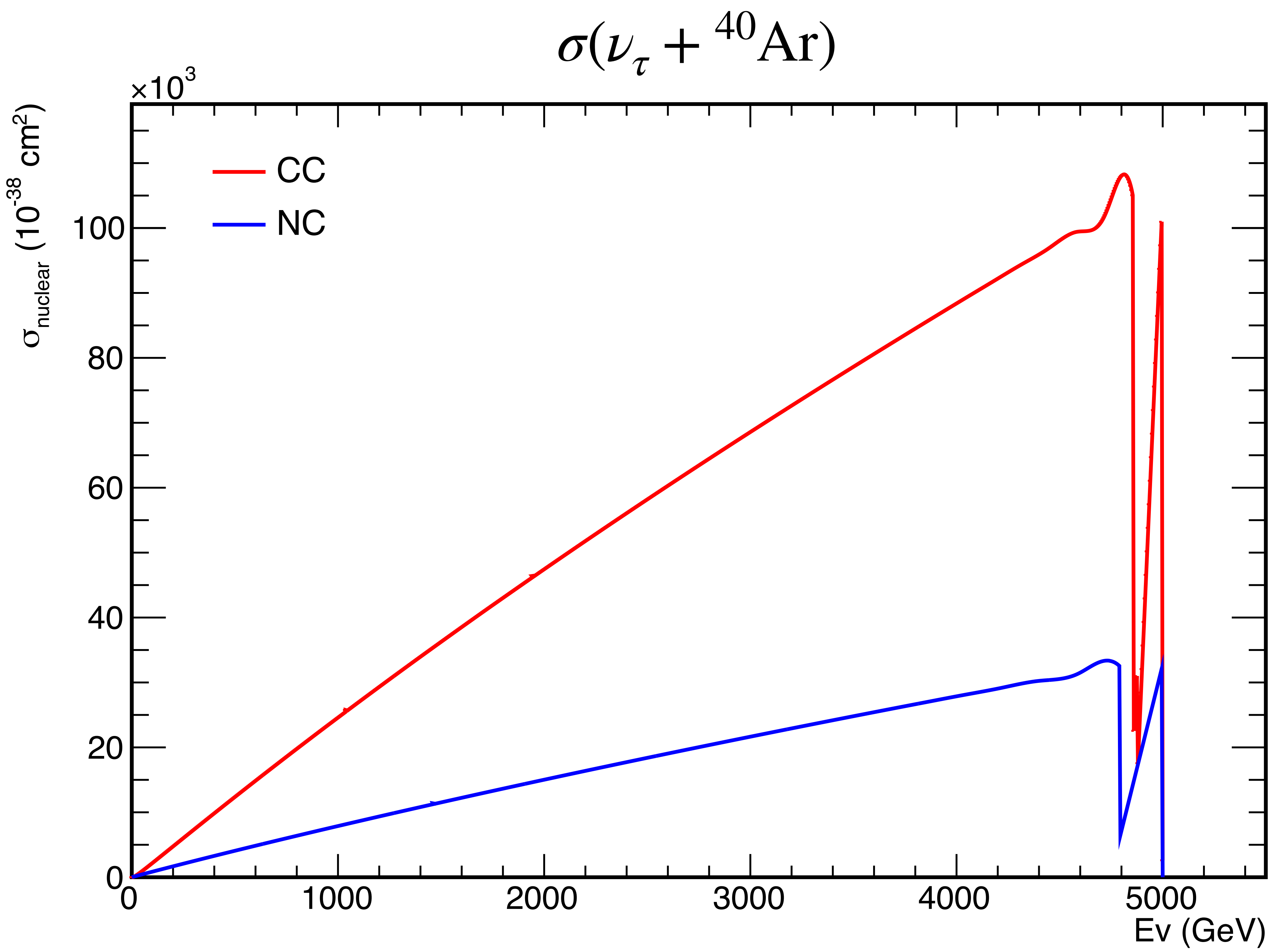
Neutrino flux



- ν_τ flux from two studies are very different
- Large uncertainties exist for the neutrino flux in the far-forward region at the LHC

Cross section (up to 5 TeV) in GENIE

https://scisoft.fnal.gov/scisoft/packages/genie_xsec/v3_00_06/
genie_xsec-3.00.06-noarch-G1802a00000-k250-e5000-resfixfix.tar.bz2



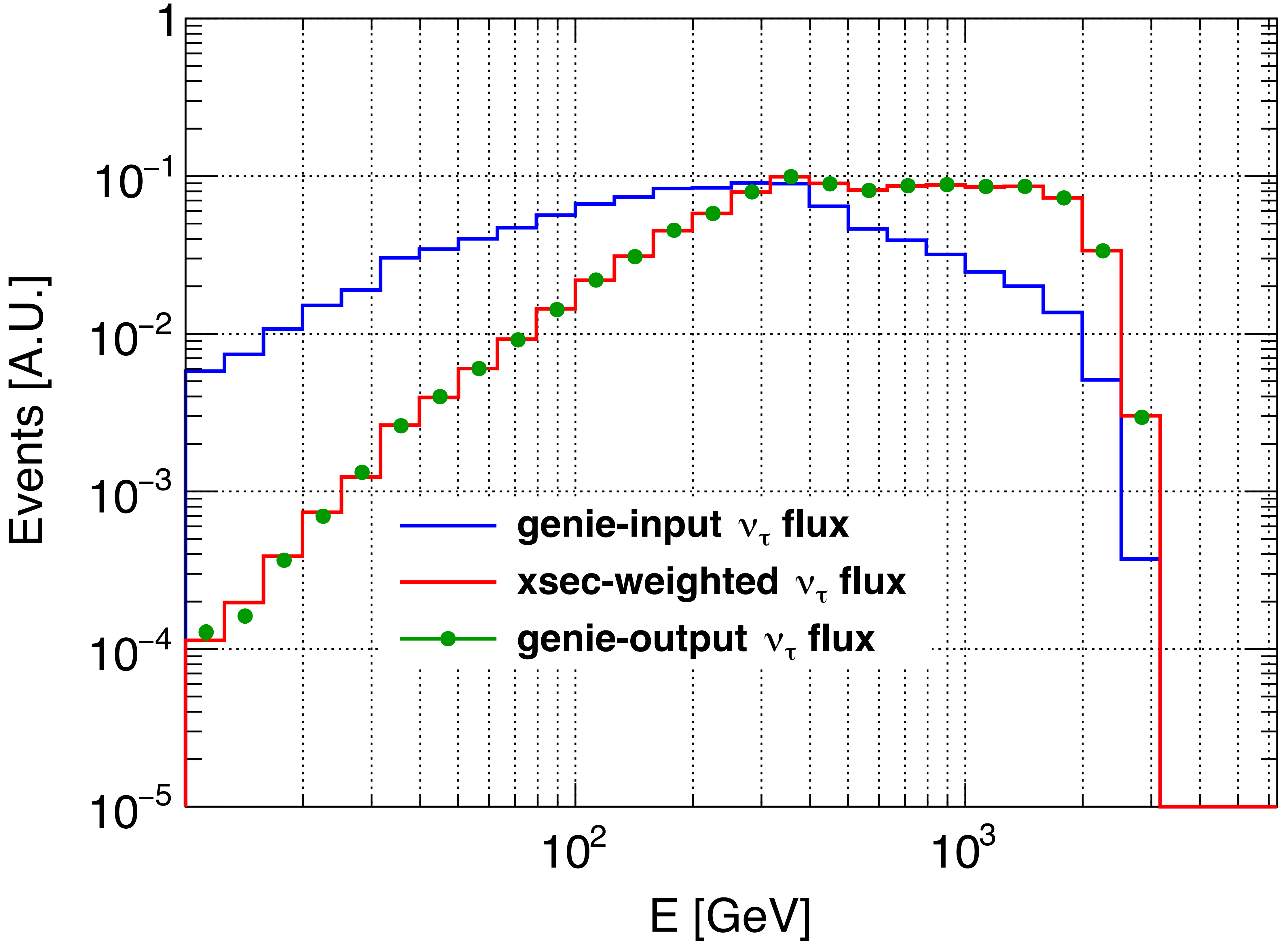
This cross section is not promising when energy goes too high

Flux drops quickly after 4.8 TeV, but it's not a big issue for energies lower than that for now

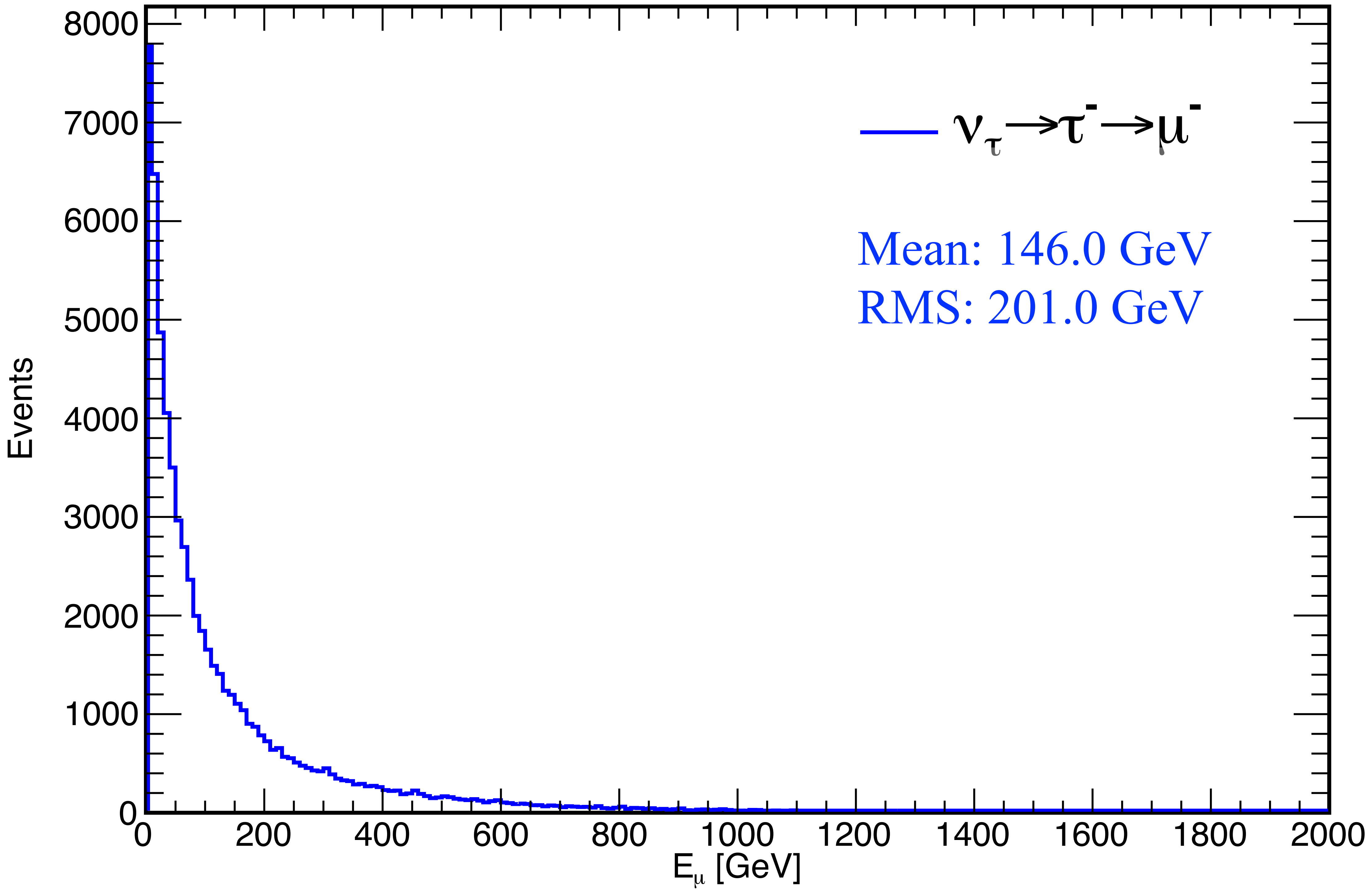
Recently GENIE updated a new package HEDIS, implementing high-energy cross section calculation and event generation modules (https://arxiv.org/pdf/2106.09381.pdf), which we can probably give it a try

UCIrvine

GENIE simulation: ν_τ

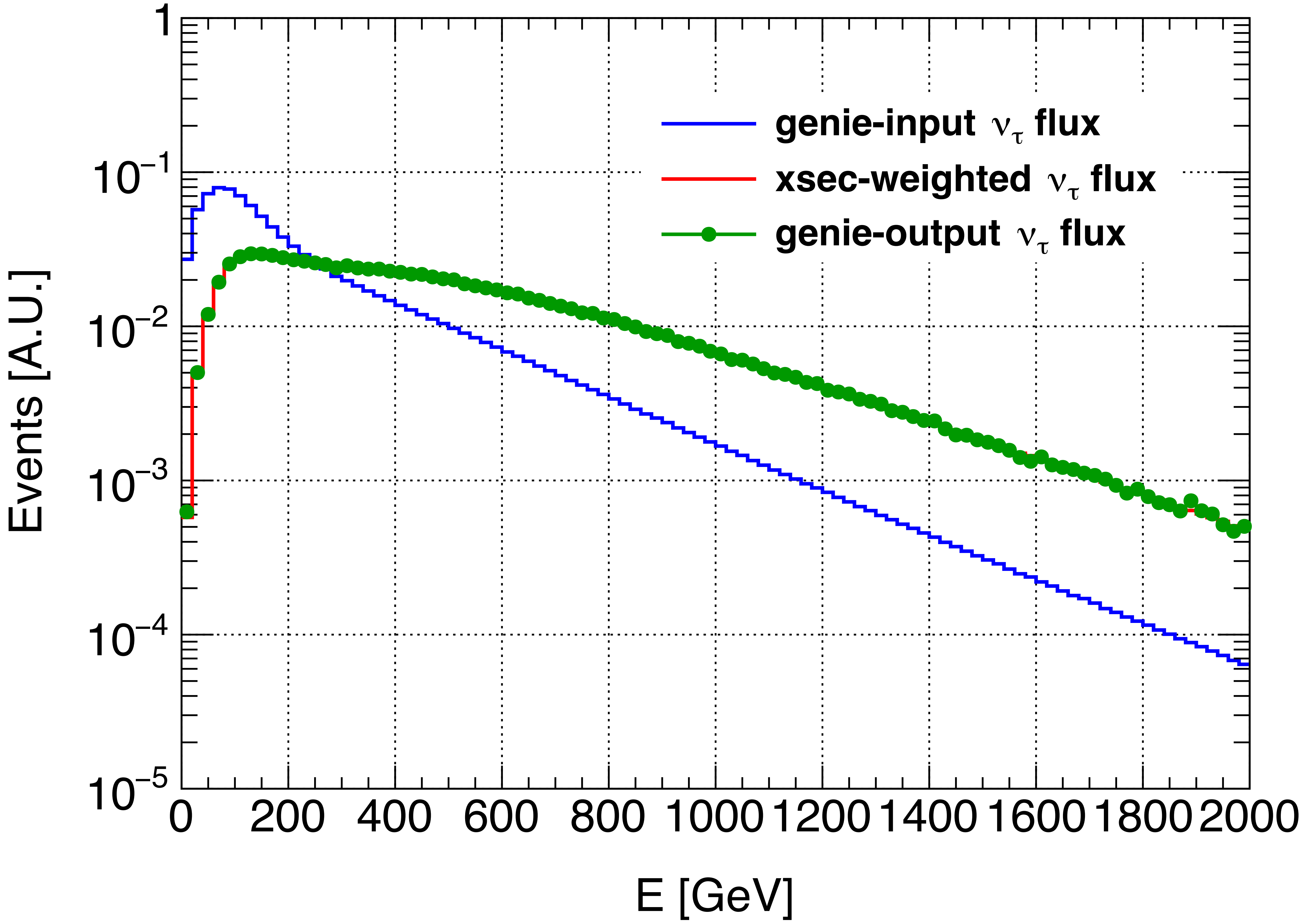


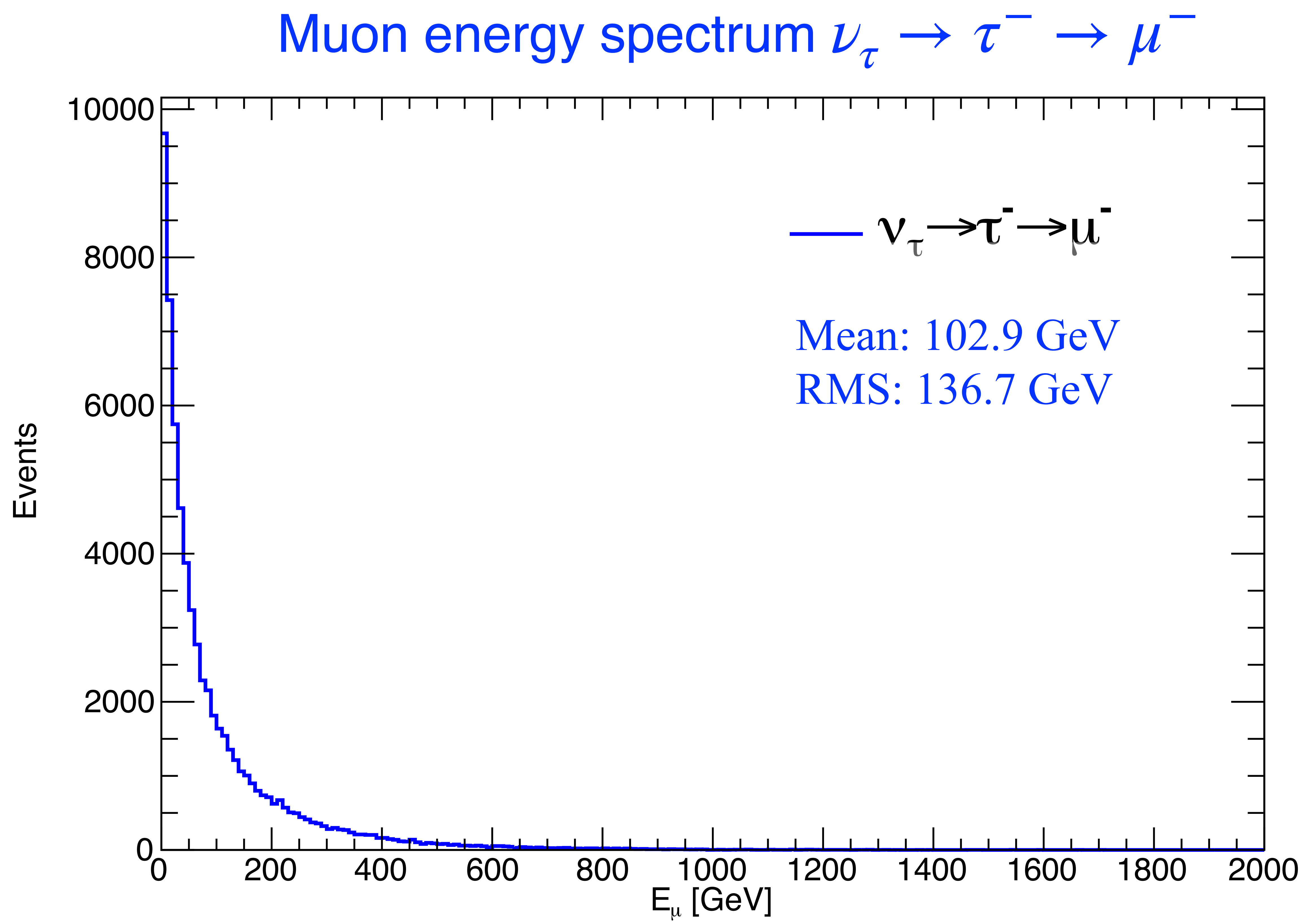
Muon energy spectrum $\nu_\tau \rightarrow \tau^- \rightarrow \mu^-$



Felix Kling, et. al. 2105.08270

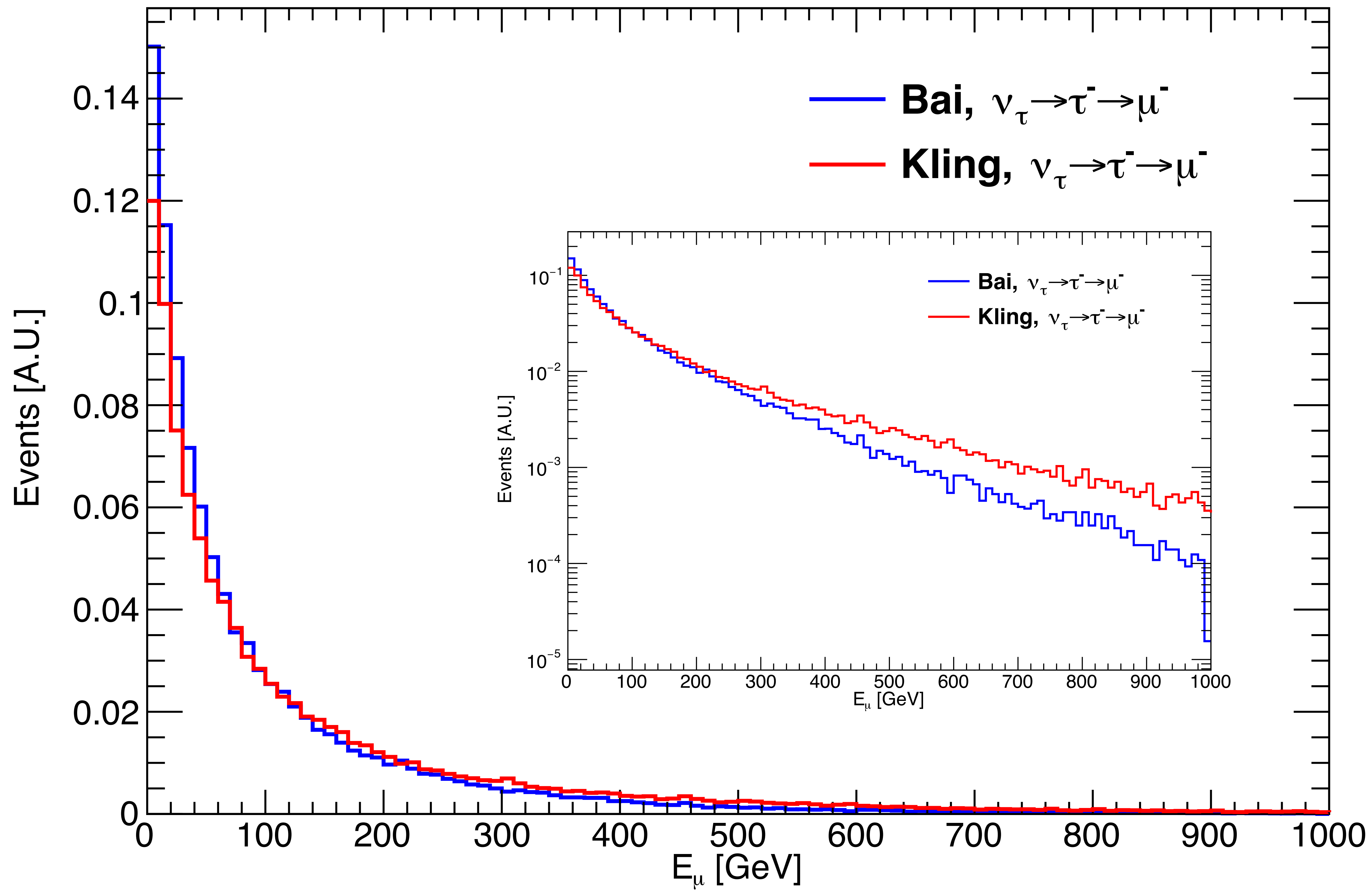
GENIE simulation: ν_τ





Weidong Bai, et. al. 2112.11605

GENIE simulation: muon spectrum from tau decay



Bai, $\nu_\tau \to \tau^- \to \mu^-$
Mean: 102.9 GeV
RMS: 136.7 GeV

Kling, $\nu_\tau \to \tau^- \to \mu^-$
Mean: 146.0 GeV
RMS: 201.0 GeV

Muon energy spectrum, area normalized

Importing GENIE events to Geant4

- Gean4 doesn't know anything about GENIE formats (.ghep.root). What we're doing now is
  - to link to GENIE libraries, so we can have a dictionary for the ROOT file format
  - read in the event record and then loop over the particles in the event record

```
|-----------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                       |
|-----------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |      m  |
|-----------------------------------------------------------------------------------------------------------------|
|   0 |        nu_tau |   0 |         16 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 | 999.000 | 999.000 |   0.000 |
|   1 |          Ar40 |   0 | 1000180400 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  37.216 |  37.216 |
|   2 |       neutron |  11 |       2112 |   1 |  -1 |   5 |   5 |   0.143 |   0.034 |  -0.048 |   0.929 | **0.940 | M = 0.916
|   3 |          Ar39 |   2 | 1000180390 |   1 |  -1 |  23 |  23 |  -0.143 |  -0.034 |   0.048 |  36.286 |  36.286 |
|   4 |          tau- |   3 |         15 |   0 |  -1 |  24 |  26 |   4.942 |  -0.842 | 614.564 | 614.587 |   1.777 | P = (-0.008,0.001,-1.000)
|   5 |      HadrSyst |  12 | 2000000001 |   2 |  -1 |   6 |   7 |  -4.800 |   0.876 | 384.388 | 385.342 | **0.000 | M = 26.660
|   6 |             u |  12 |          2 |   5 |  -1 |   8 |   8 |  -4.801 |   0.876 | 384.527 | 384.558 |   0.330 |
|   7 |          ud_1 |  12 |       2103 |   5 |  -1 |   8 |   8 |   0.002 |  -0.000 |  -0.139 |   0.784 |   0.771 |
|   8 |        string |  12 |         92 |   6 |  -1 |   9 |  13 |  -4.800 |   0.876 | 384.388 | 385.342 | **0.000 | M = 26.660
|   9 |           pi0 |  14 |        111 |   8 |  -1 |  16 |  16 |  -2.716 |   0.496 | 257.866 | 257.880 |   0.135 | FSI = 1
|  10 |           pi+ |  14 |        211 |   8 |  -1 |  17 |  17 |  -0.980 |   0.207 |  38.737 |  38.751 |   0.140 | FSI = 1
|  11 |           pi- |  14 |       -211 |   8 |  -1 |  18 |  18 |  -1.522 |   0.658 |  85.730 |  85.747 |   0.140 | FSI = 1
|  12 |       neutron |  14 |       2112 |   8 |  -1 |  19 |  19 |   0.654 |  -0.624 |   1.056 |   1.678 |   0.940 | FSI = 1
|  13 |          rho+ |  12 |        213 |   8 |  -1 |  14 |  15 |  -0.235 |   0.140 |   0.998 |   1.286 | **0.767 | M = 0.764
|  14 |           pi+ |  14 |        211 |  13 |  -1 |  20 |  21 |   0.210 |  -0.069 |   0.162 |   0.307 |   0.140 | FSI = 2
|  15 |           pi0 |  14 |        111 |  13 |  -1 |  22 |  22 |  -0.445 |   0.209 |   0.836 |   0.979 |   0.135 | FSI = 1
|  16 |           pi0 |   1 |        111 |   9 |  -1 |  -1 |  -1 |  -2.716 |   0.496 | 257.866 | 257.880 |   0.135 |
|  17 |           pi+ |   1 |        211 |  10 |  -1 |  -1 |  -1 |  -0.980 |   0.207 |  38.737 |  38.751 |   0.140 |
|  18 |           pi- |   1 |       -211 |  11 |  -1 |  -1 |  -1 |  -1.522 |   0.658 |  85.730 |  85.747 |   0.140 |
|  19 |       neutron |   1 |       2112 |  12 |  -1 |  -1 |  -1 |   0.654 |  -0.624 |   1.056 |   1.678 |   0.940 |
|  20 |           pi0 |   1 |        111 |  14 |  -1 |  -1 |  -1 |  -0.007 |   0.124 |   0.014 |   0.184 |   0.135 |
|  21 |        proton |   1 |       2212 |  14 |  -1 |  -1 |  -1 |   0.334 |  -0.354 |   0.088 |   1.061 |   0.938 |
|  22 |           pi0 |   1 |        111 |  15 |  -1 |  -1 |  -1 |  -0.445 |   0.209 |   0.836 |   0.979 |   0.135 |
|  23 |      HadrBlob |  15 | 2000000002 |   3 |  -1 |  -1 |  -1 |  -0.261 |   0.127 |   0.108 |  35.349 | **0.000 | M = 35.347
|  24 |     nu_mu_bar |   1 |        -14 |   4 |  -1 |  -1 |  -1 |   3.601 |  -0.718 | 355.999 | 356.018 | **0.000 | M = 0.106
|  25 |           mu- |   1 |         13 |   4 |  -1 |  -1 |  -1 |   0.586 |   0.193 | 125.415 | 125.417 | **0.106 | M = 0.101
|  26 |        nu_tau |   1 |         16 |   4 |  -1 |  -1 |  -1 |   0.756 |  -0.317 | 133.150 | 133.152 | **0.000 | M = -0.038
|-----------------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                                |   0.000 |  -0.000 |  -0.000 |  -0.000 |         |
|-----------------------------------------------------------------------------------------------------------------|
|       Vertex:         nu_tau @ (x =      0.00000 m, y =      0.00000 m, z =      0.00000 m, t =    0.000000e+00 s) |
|-----------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                                   none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:    YES                         |
|-----------------------------------------------------------------------------------------------------------------|
| sig(Ev) =       1.19811e-34 cm^2  | d2sig(x,y;E)/dxdy =       2.76522e-34 cm^2       | Weight =          1.00000 |
|-----------------------------------------------------------------------------------------------------------------|
```


UCIRVINE

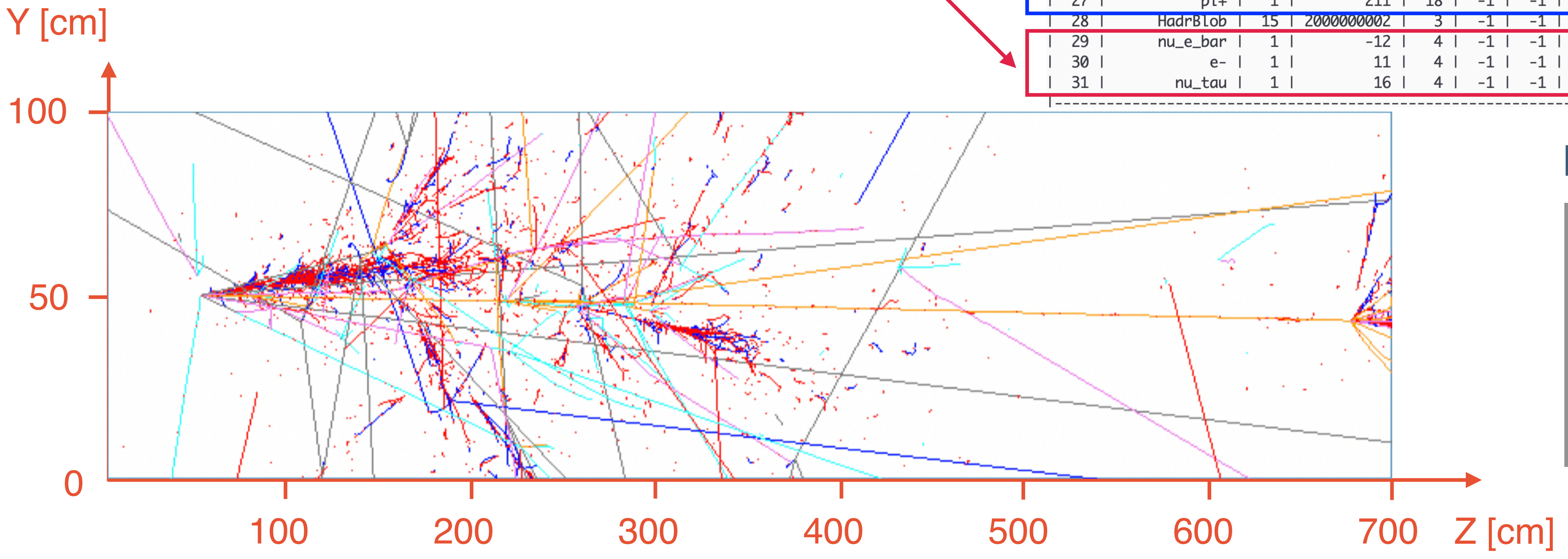
100 GeV ν_τ

- DIS CC
- ν_τ + Ar40 $\rightarrow \tau^-$ + Ar39 + hadrSyst

  $\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^-$

GENIE GHEP Event Record [print level: 3]

Idx	Name	Ist	PDG	Mother		Daughter		Px	Py	Pz	E	m
0	nu_tau	0	16	-1	-1	4	4	0.000	0.000	100.000	100.000	0.000
1	Ar40	0	1000180400	-1	-1	2	3	0.000	0.000	0.000	37.216	37.216
2	neutron	11	2112	1	-1	5	5	-0.068	0.054	0.167	0.929	**0.940
3	Ar39	2	1000180390	1	-1	28	28	0.068	-0.054	-0.167	36.286	36.286
4	tau-	3	15	0	-1	29	31	1.562	0.484	25.817	25.929	1.777
5	HadrSyst	12	2000000001	2	-1	6	7	-1.630	-0.430	74.350	75.000	**0.000
6	u	12	2	5	-1	8	8	-1.627	-0.429	74.193	74.213	0.330
7	ud_1	12	2103	5	-1	8	8	-0.003	-0.001	0.157	0.787	0.771
8	string	12	92	6	-1	9	14	-1.630	-0.430	74.350	75.000	**0.000
9	rho0	12	113	8	-1	15	16	-0.654	-0.116	33.267	33.282	**0.768
10	Delta++	12	2224	8	-1	17	18	-0.465	-0.306	31.178	31.202	**1.231
11	pi-	14	-211	8	-1	19	19	-0.282	-0.224	2.723	2.750	0.140
12	Lambda0_bar	14	-3122	8	-1	20	20	-0.157	0.659	5.247	5.407	1.116
13	Lambda0	14	3122	8	-1	21	21	-0.136	-0.396	1.732	2.102	1.116
14	pi0	14	111	8	-1	22	23	0.064	-0.048	0.203	0.257	0.135
15	pi-	14	-211	9	-1	24	24	0.052	0.119	10.504	10.506	0.140
16	pi+	14	211	9	-1	25	25	-0.705	-0.236	22.763	22.776	0.140
17	proton	14	2212	10	-1	26	26	-0.462	-0.332	27.597	27.619	0.938
18	pi+	14	211	10	-1	27	27	-0.003	0.026	3.581	3.584	0.140
19	pi-	1	-211	11	-1	-1	-1	-0.282	-0.224	2.723	2.750	0.140
20	Lambda0_bar	1	-3122	12	-1	-1	-1	-0.157	0.659	5.247	5.407	1.116
21	Lambda0	1	3122	13	-1	-1	-1	-0.136	-0.396	1.732	2.102	1.116
22	neutron	1	2112	14	-1	-1	-1	-0.441	0.263	-0.101	1.076	0.940
23	proton	1	2212	14	-1	-1	-1	0.417	-0.270	-0.038	1.062	0.938
24	pi-	1	-211	15	-1	-1	-1	0.052	0.119	10.504	10.506	0.140
25	pi+	1	211	16	-1	-1	-1	-0.705	-0.236	22.763	22.776	0.140
26	proton	1	2212	17	-1	-1	-1	-0.462	-0.332	27.597	27.619	0.938
27	pi+	1	211	18	-1	-1	-1	-0.003	0.026	3.581	3.584	0.140
28	HadrBlob	15	2000000002	3	-1	-1	-1	0.156	-0.095	0.176	34.405	**0.000
29	nu_e_bar	1	-12	4	-1	-1	-1	0.227	0.285	7.080	7.089	0.000
30	e-	1	11	4	-1	-1	-1	0.373	0.736	10.029	10.063	**0.001
31	nu_tau	1	16	4	-1	-1	-1	0.962	-0.537	8.708	8.777	**0.000



Exclude gamma/neutron

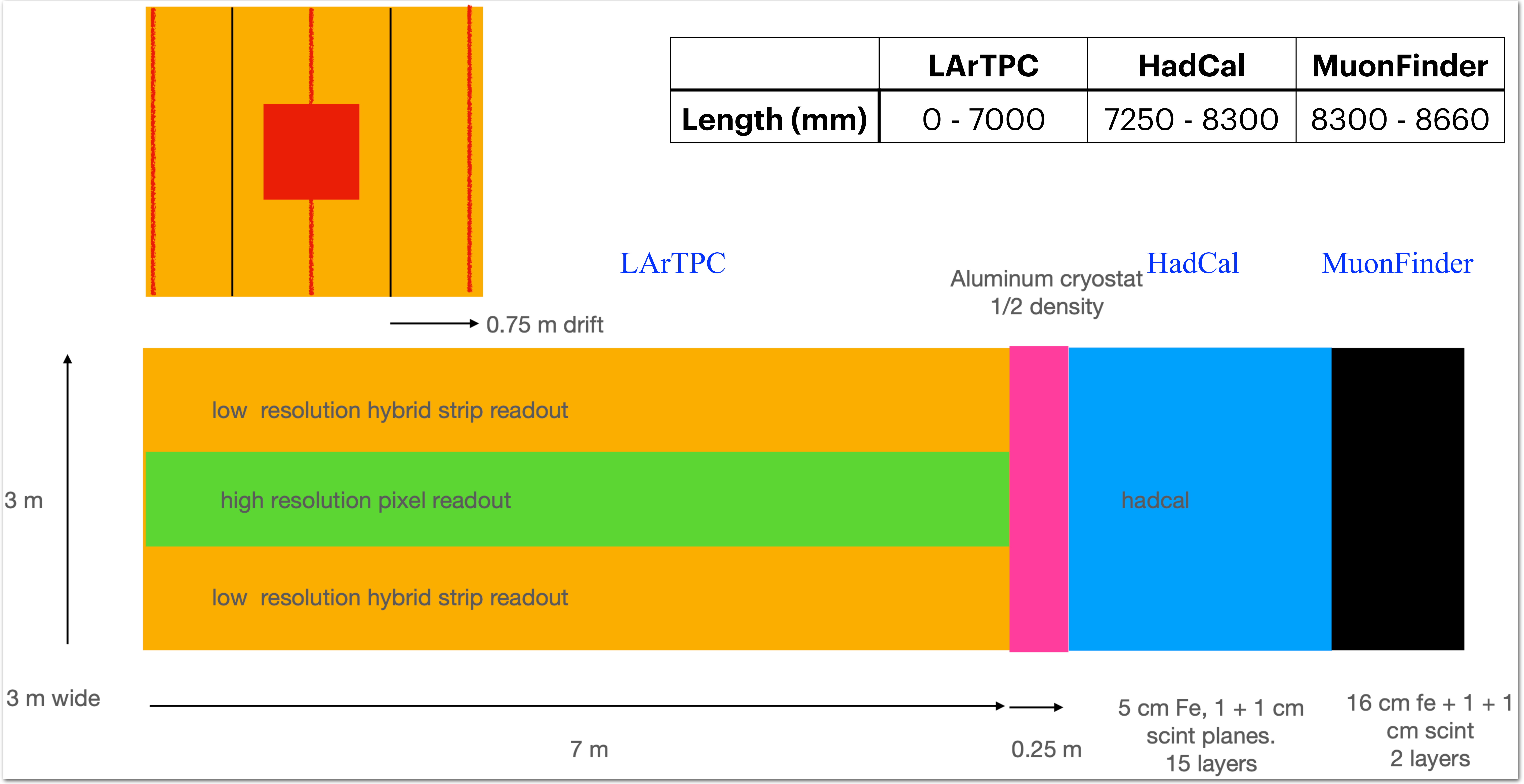
red: e-
blue: e+
cyan: proton
orange: pi+
violet: pi-

UCIRVINE

Containment studies

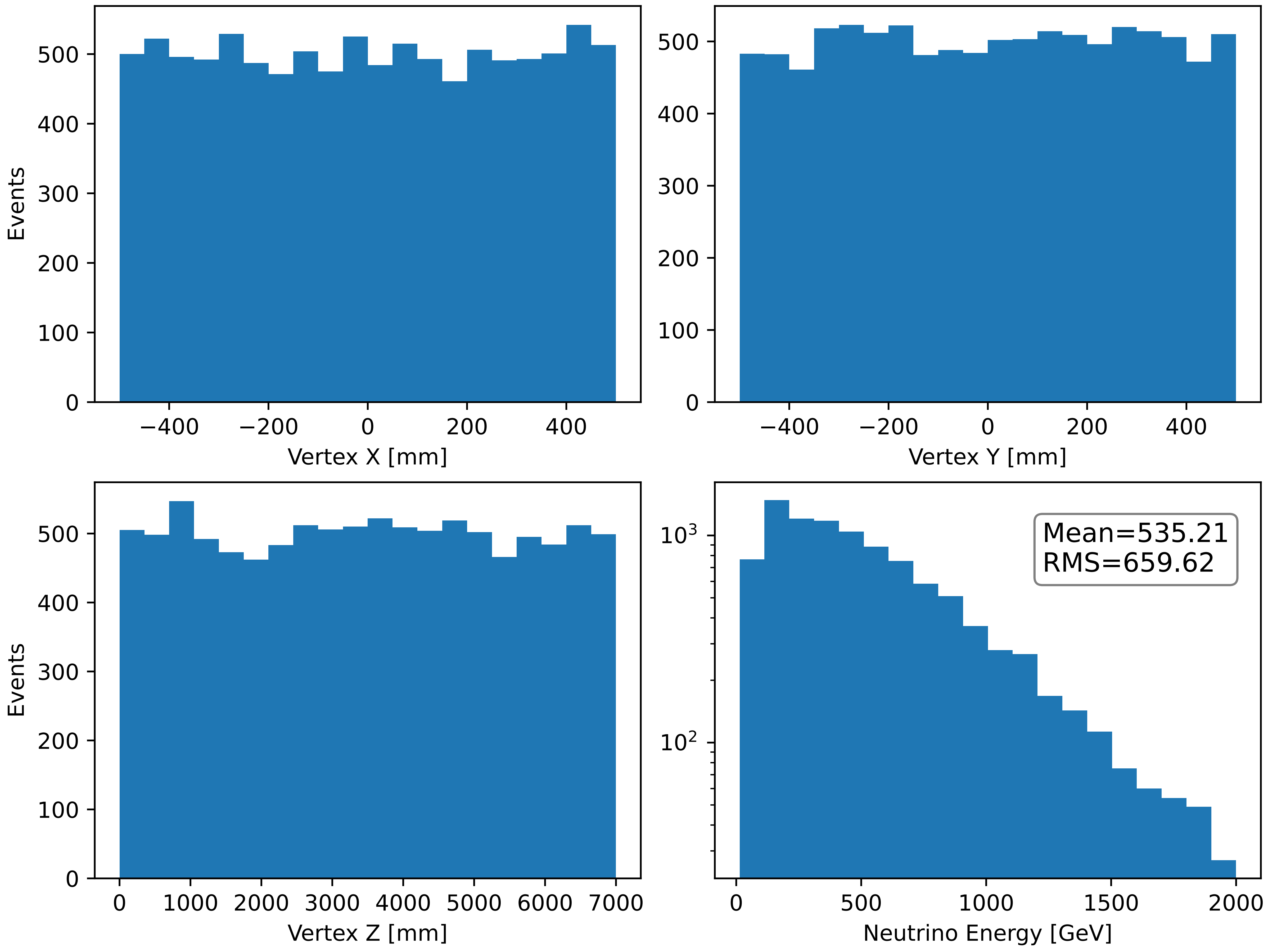
Preliminary detector configuration

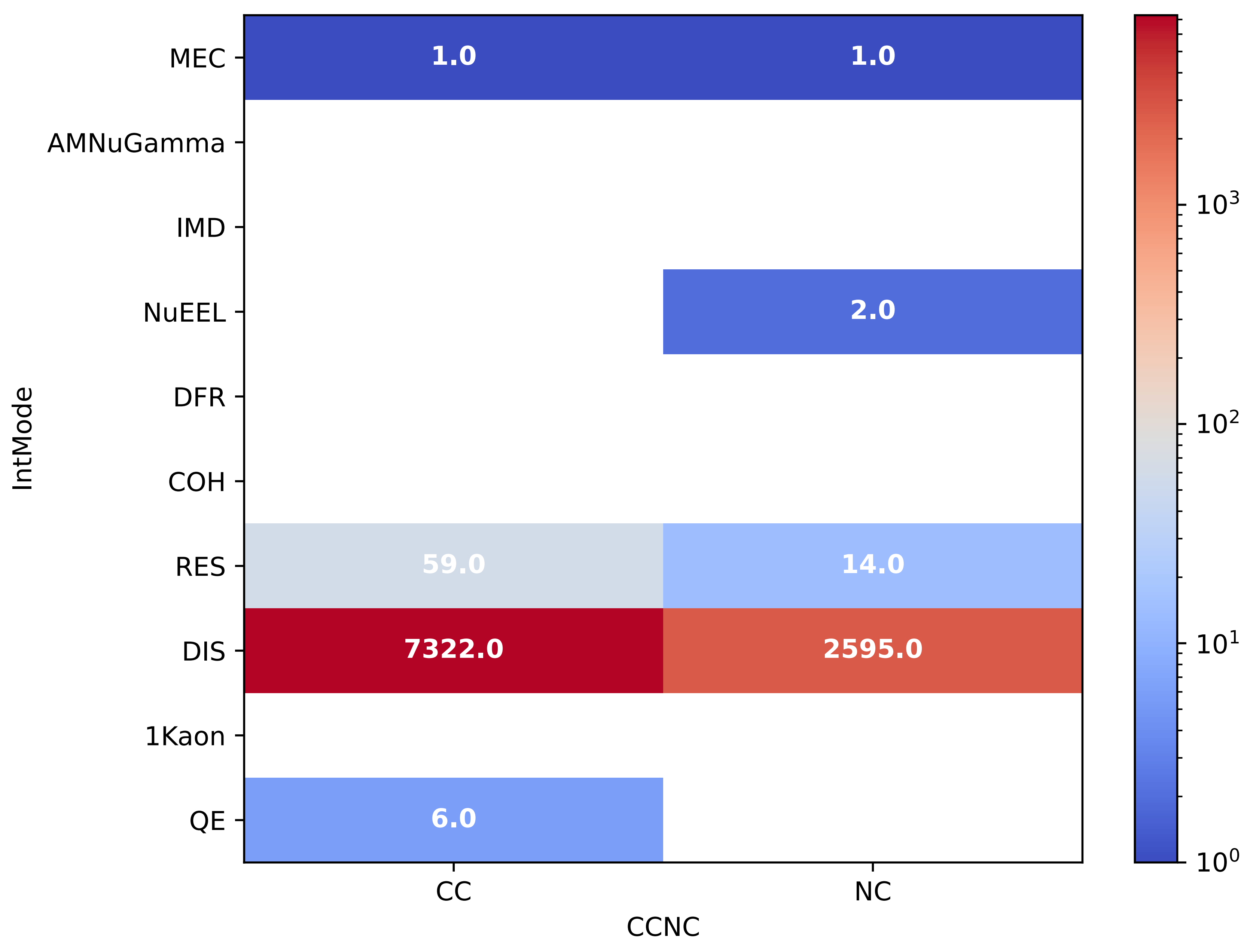
	LArTPC	HadCal	MuonFinder
Length (mm)	0 - 7000	7250 - 8300	8300 - 8660

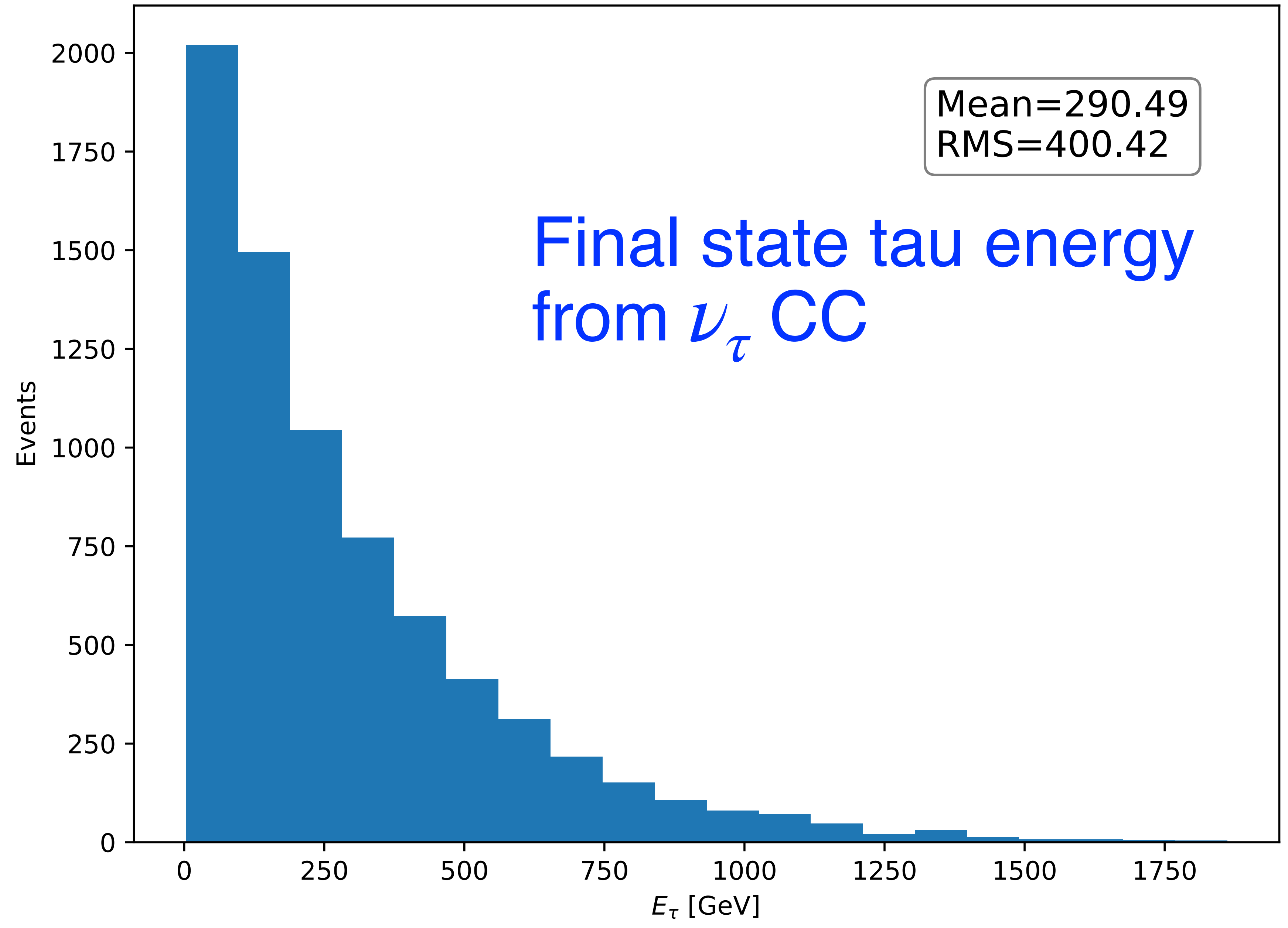


ν_τ in the detector

- 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]

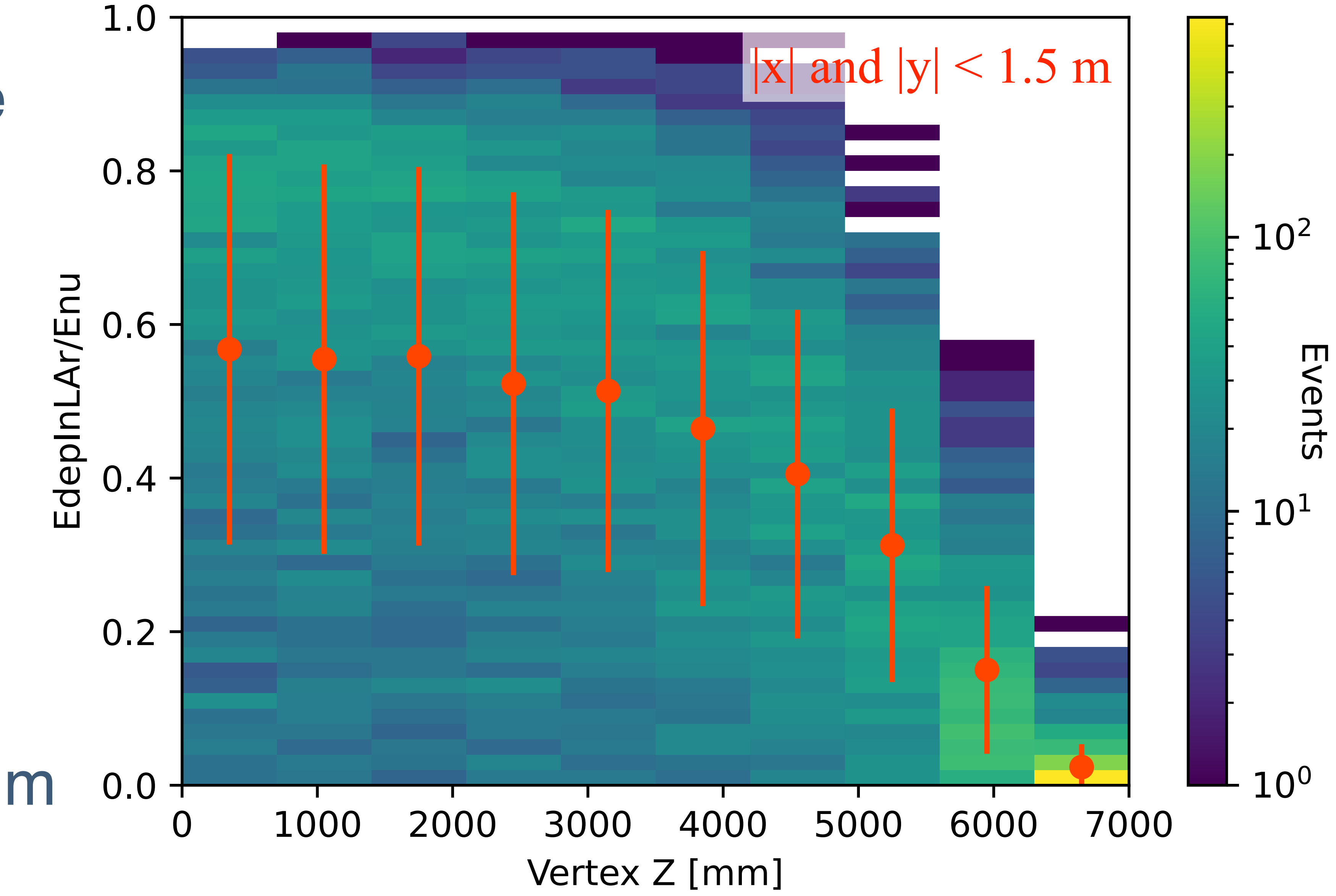


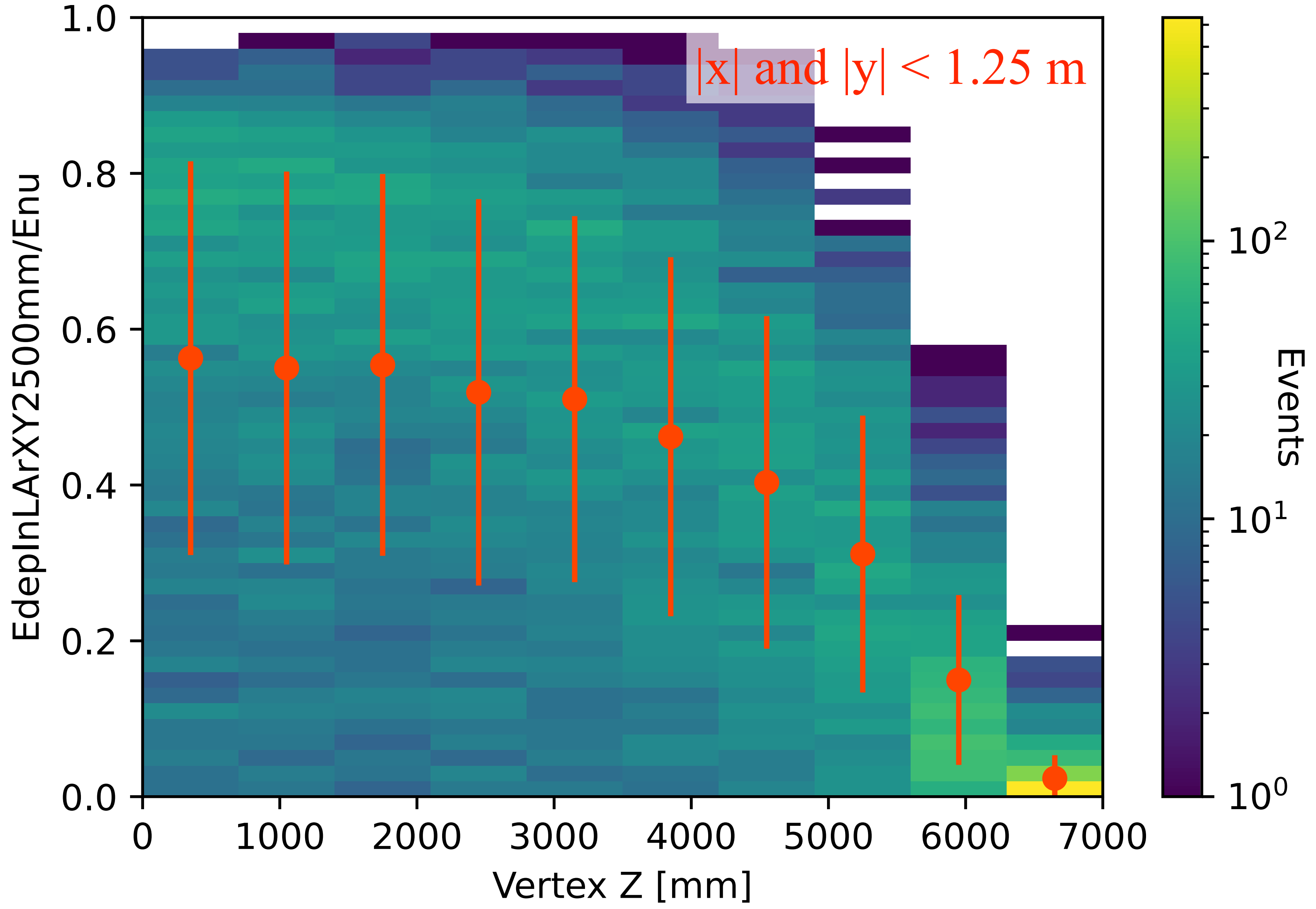


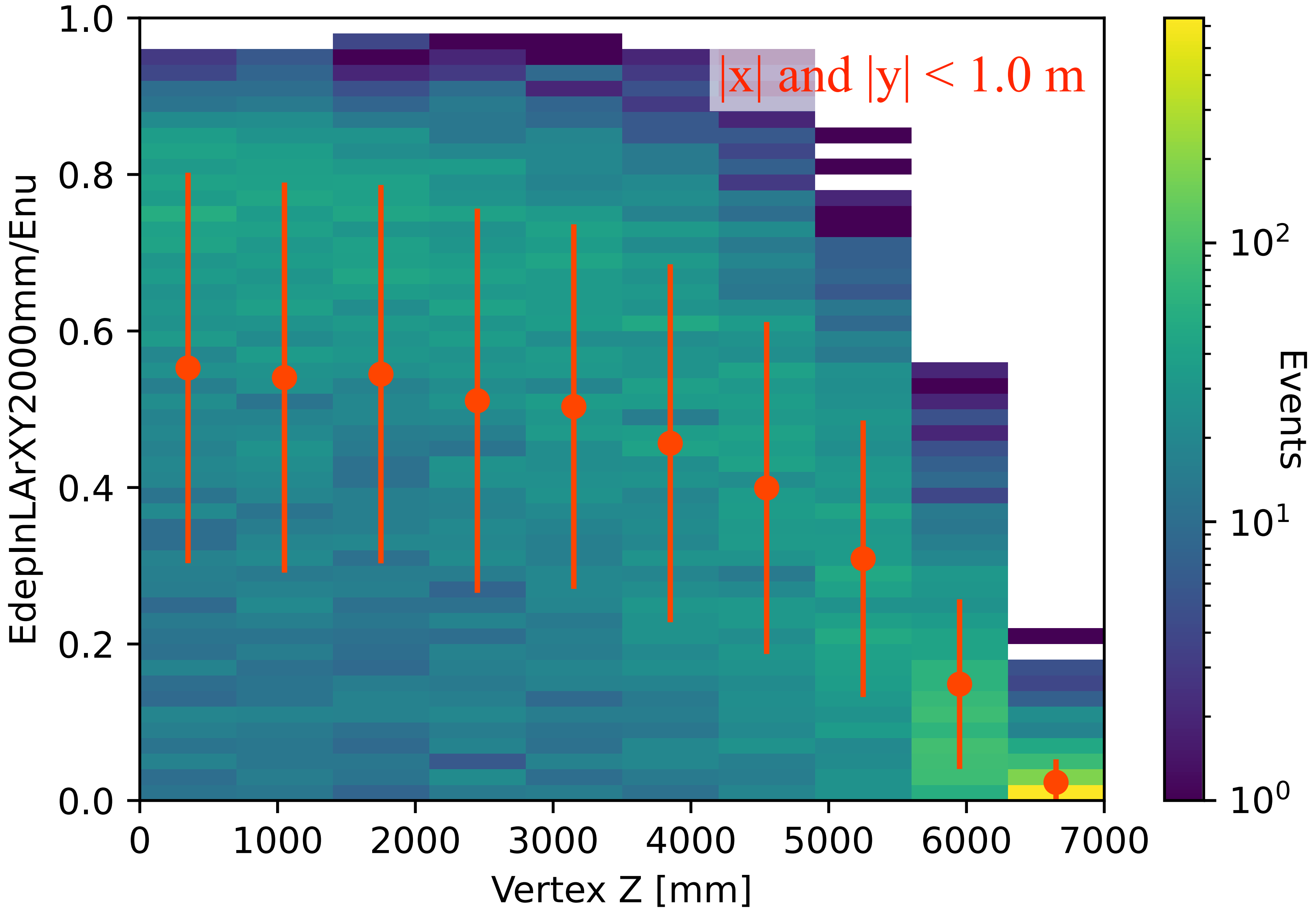


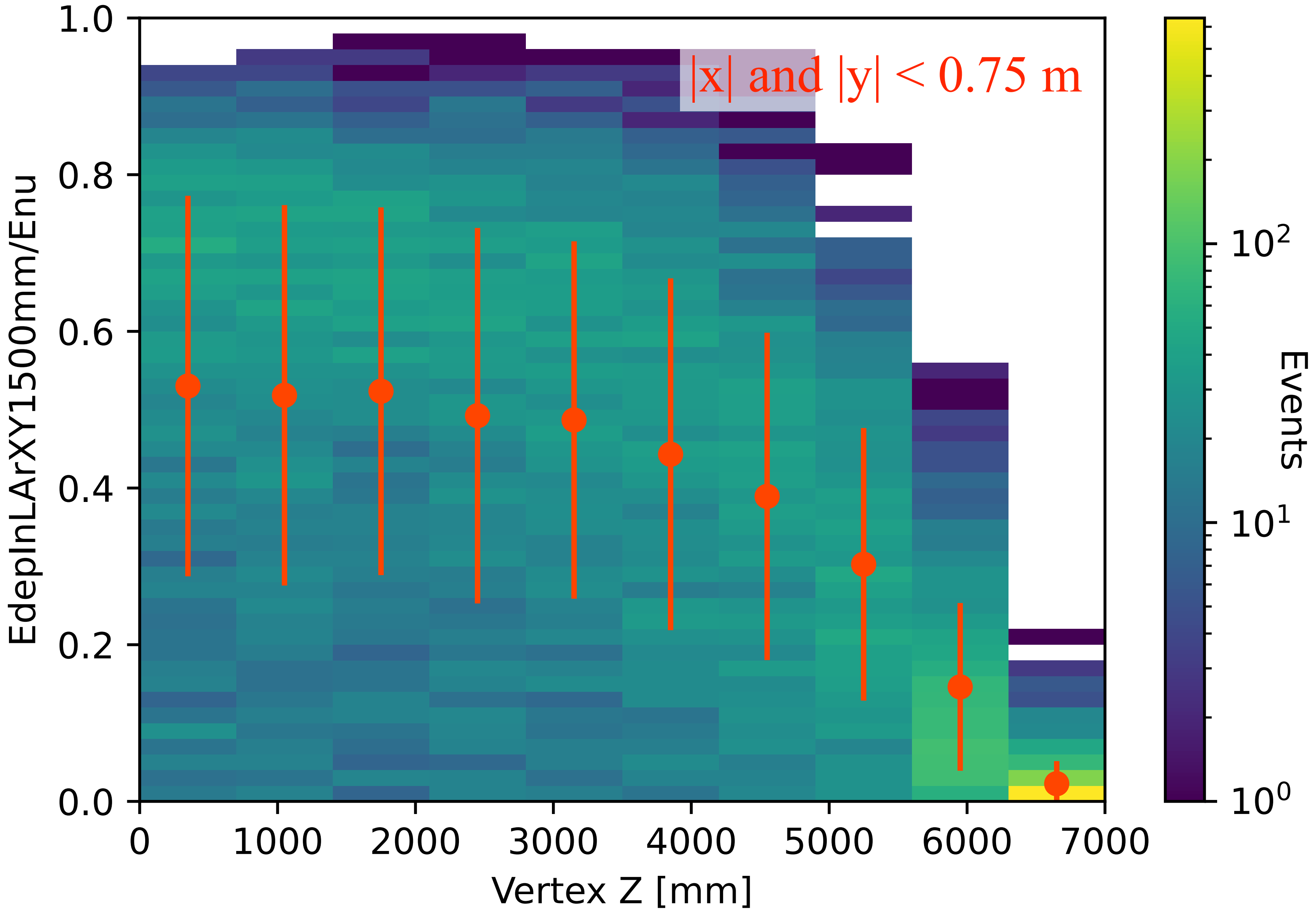
Energy containment in the LArTPC

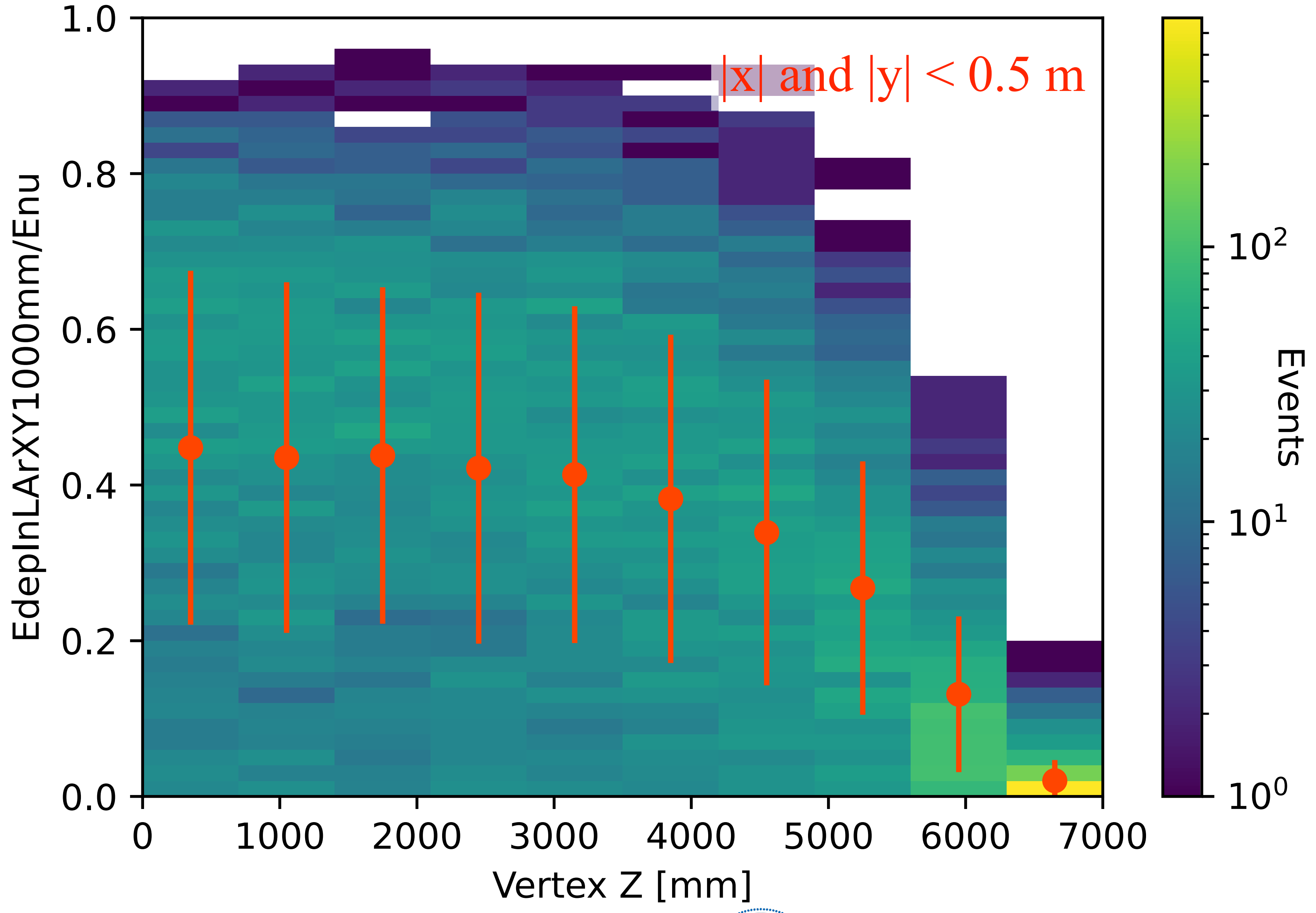
- The ratio of the energy deposited in the LArTPC to the neutrino energy
  - The orange markers are the mean values and standard deviation as error bars
- Make transverse cuts for energy containment in different detector sizes
  - lxl and lyl < 1.5, 1.25, 1.0, 0.75, 0.5 m







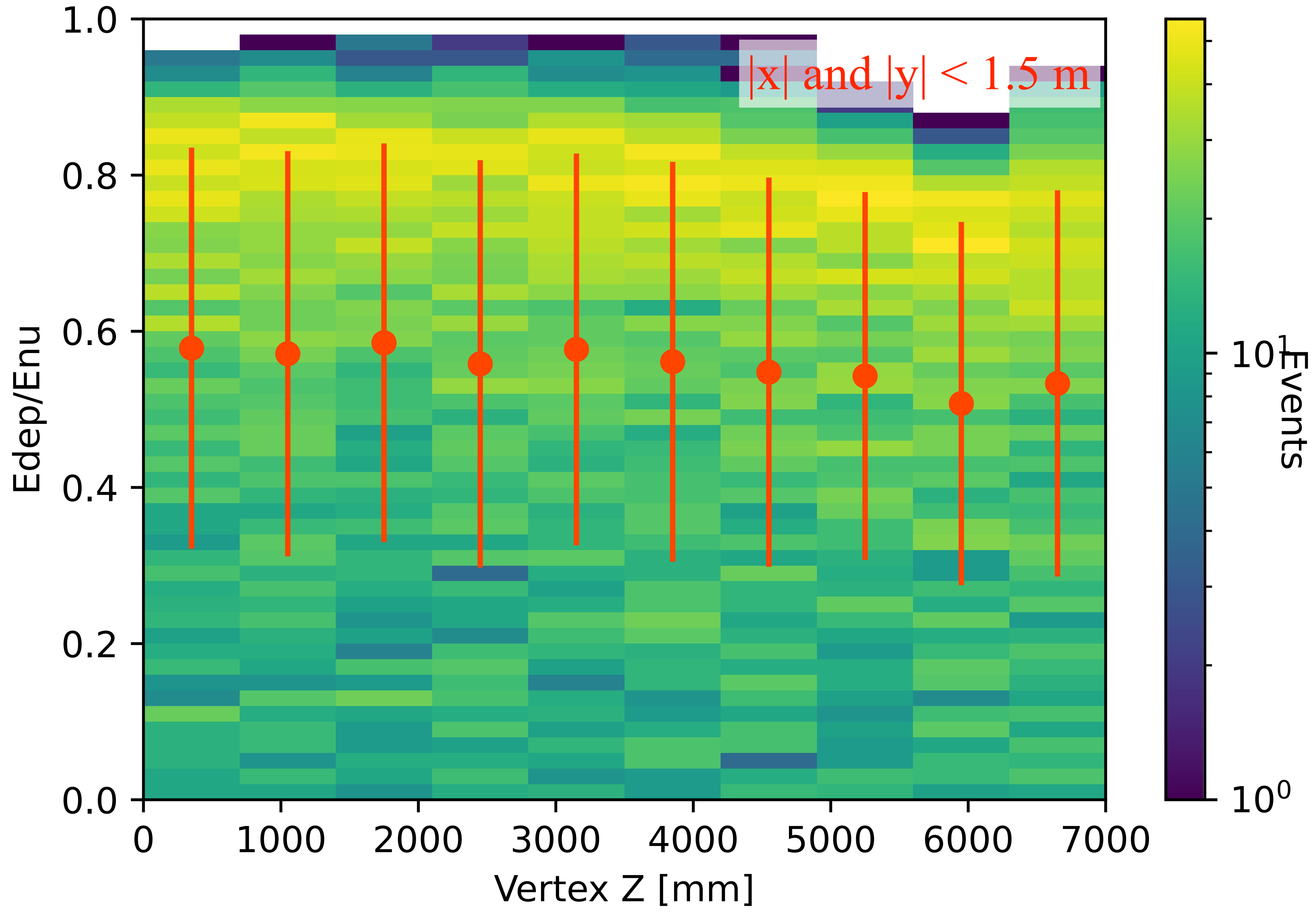


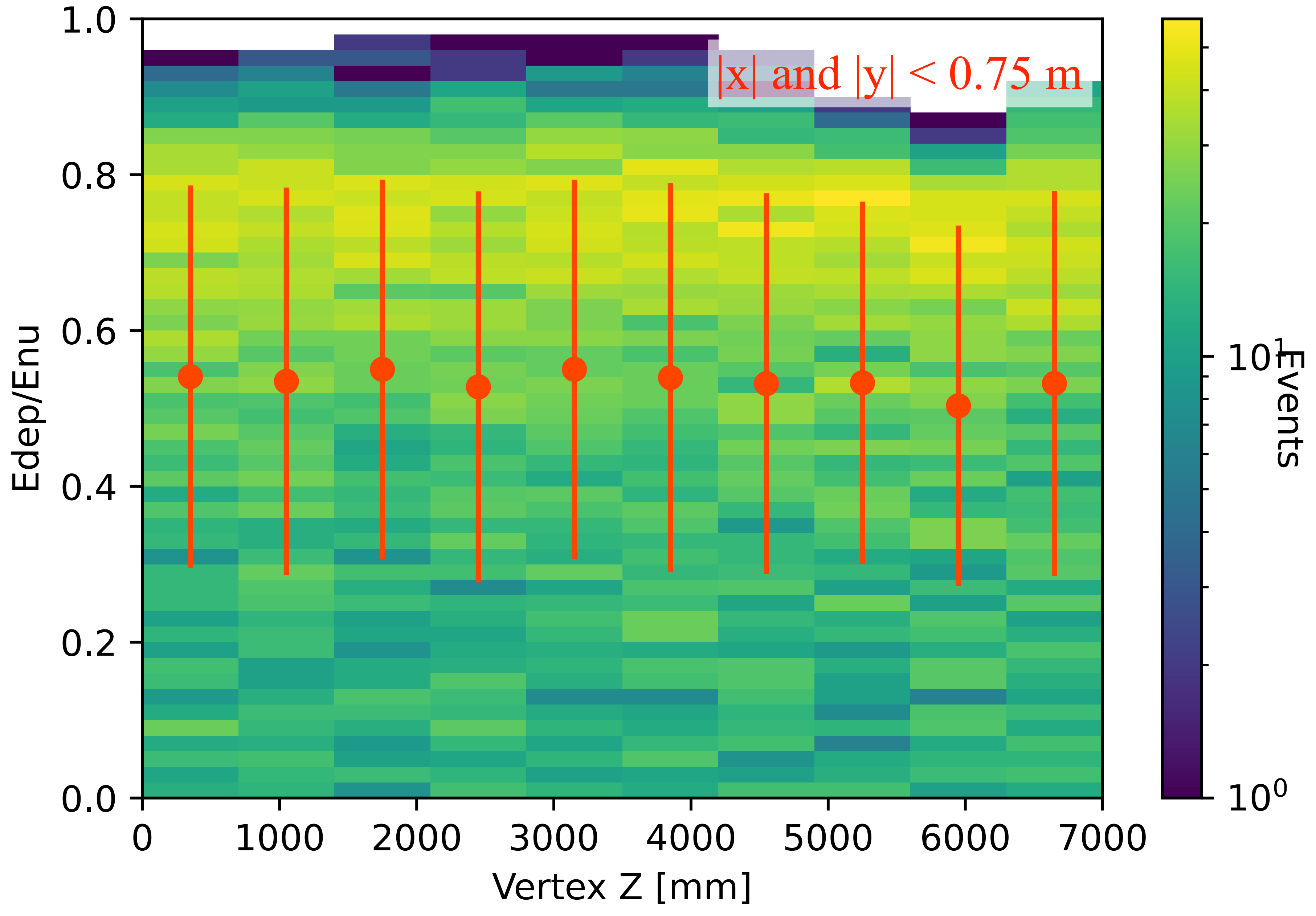


UCIRVINE

Energy containment w/ the HadCal

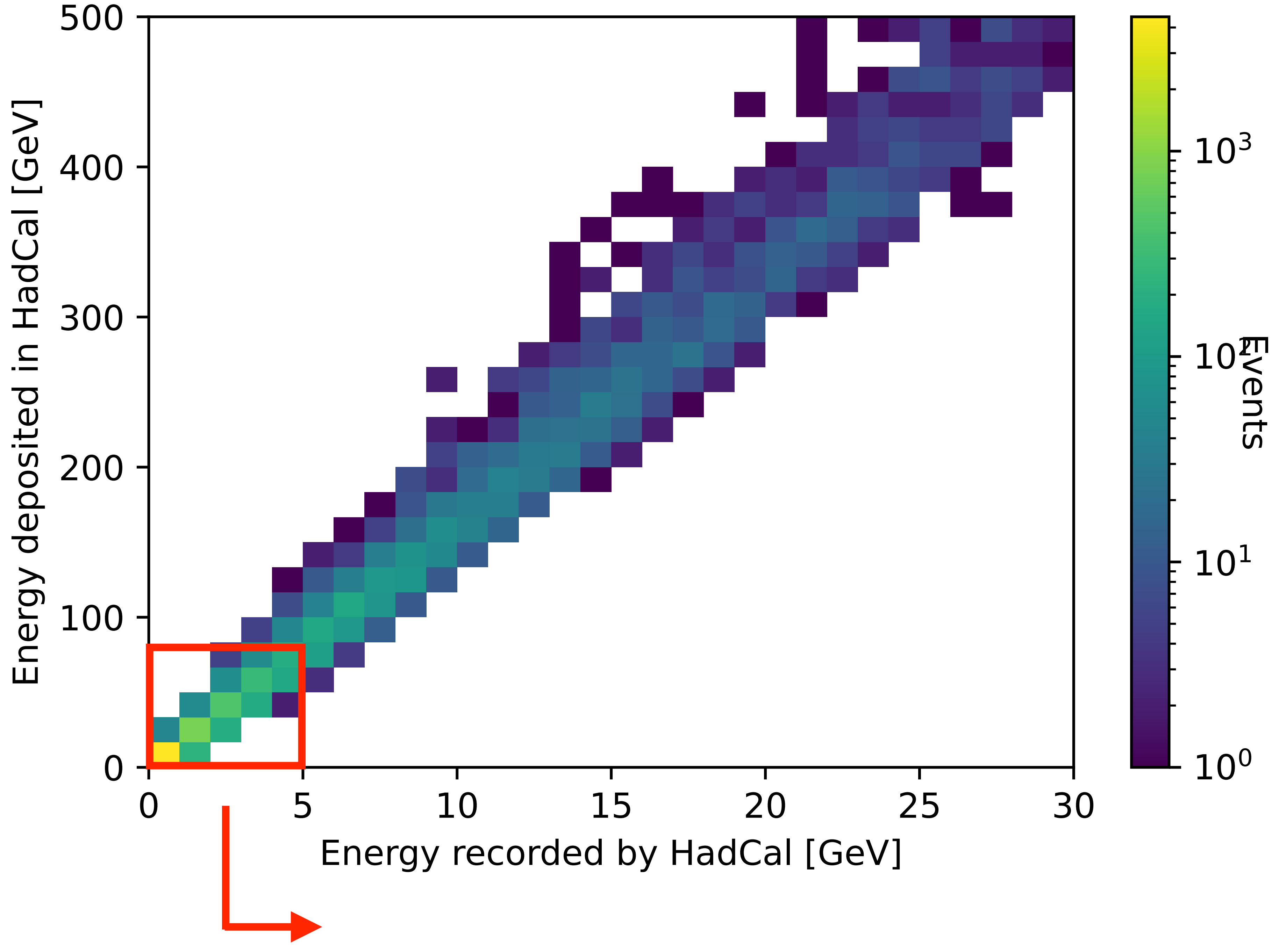
- The ratio of the energy deposited in the (LArTPC+HadCal) to the neutrino energy
  - The orange markers are the mean values and standard deviation as error bars
- The hadCal can save loss energies for events happened in the downstream of the detector
  - The containment becomes flat for both transverse cuts



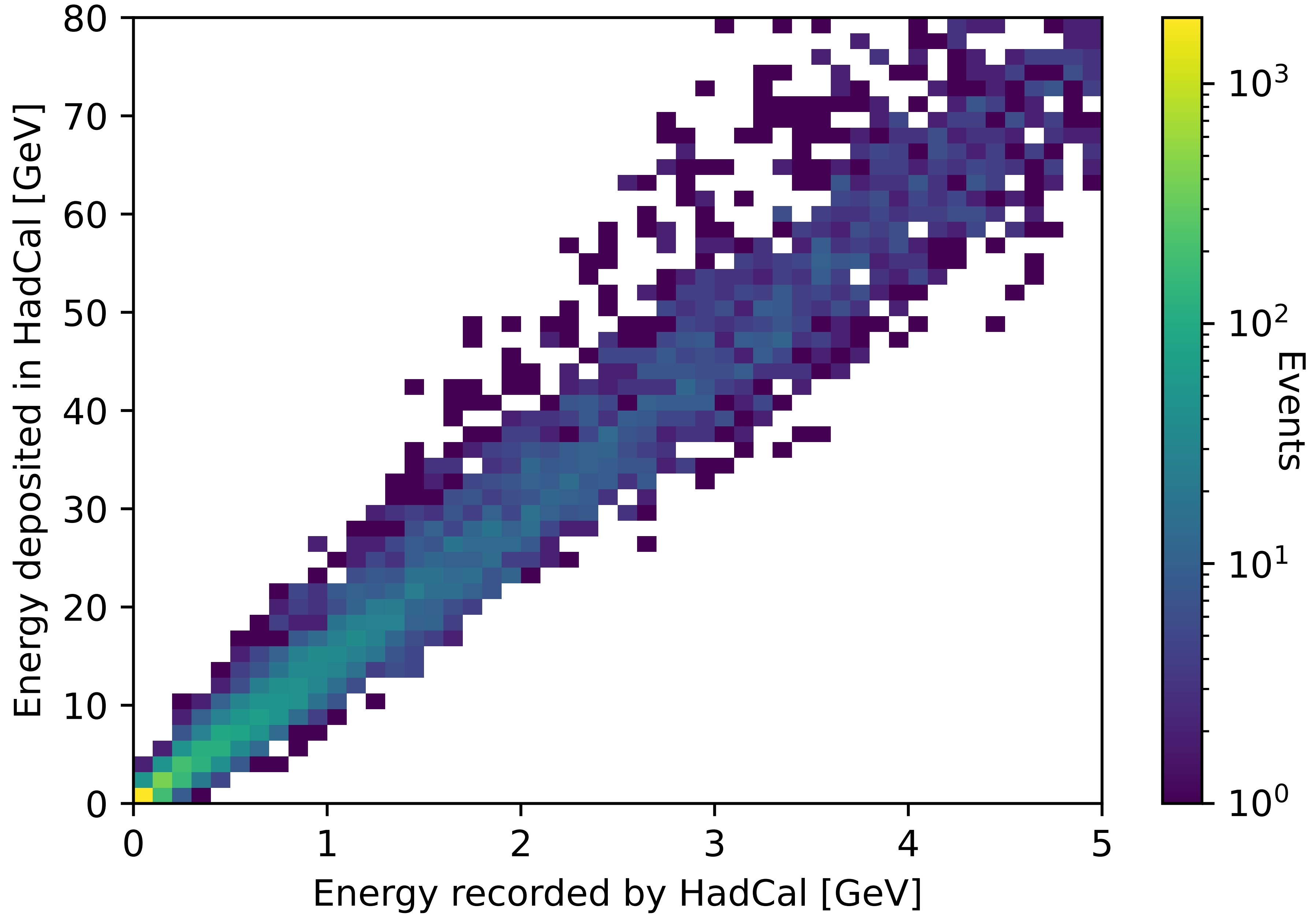


HadCal Calibration

- 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

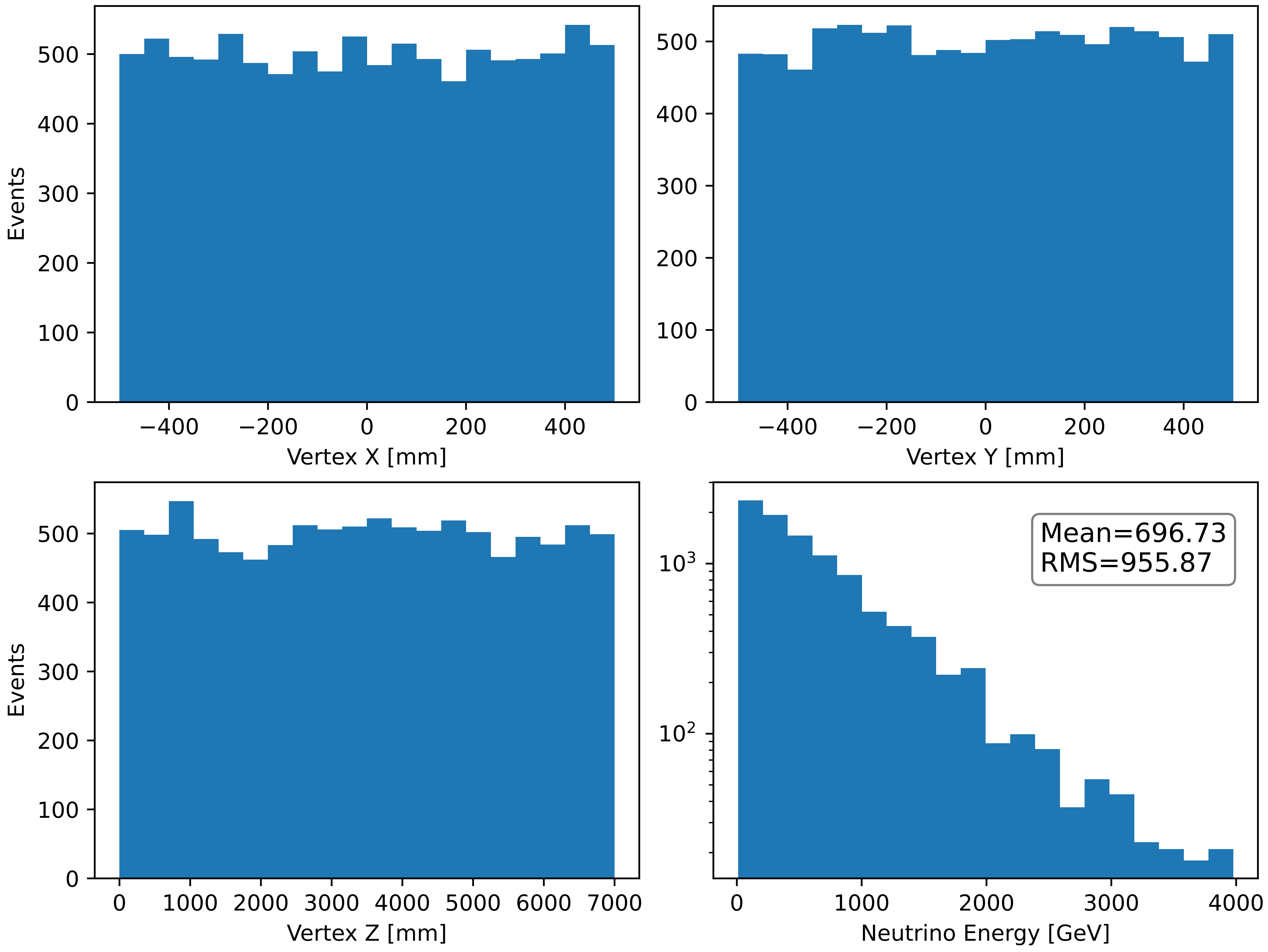


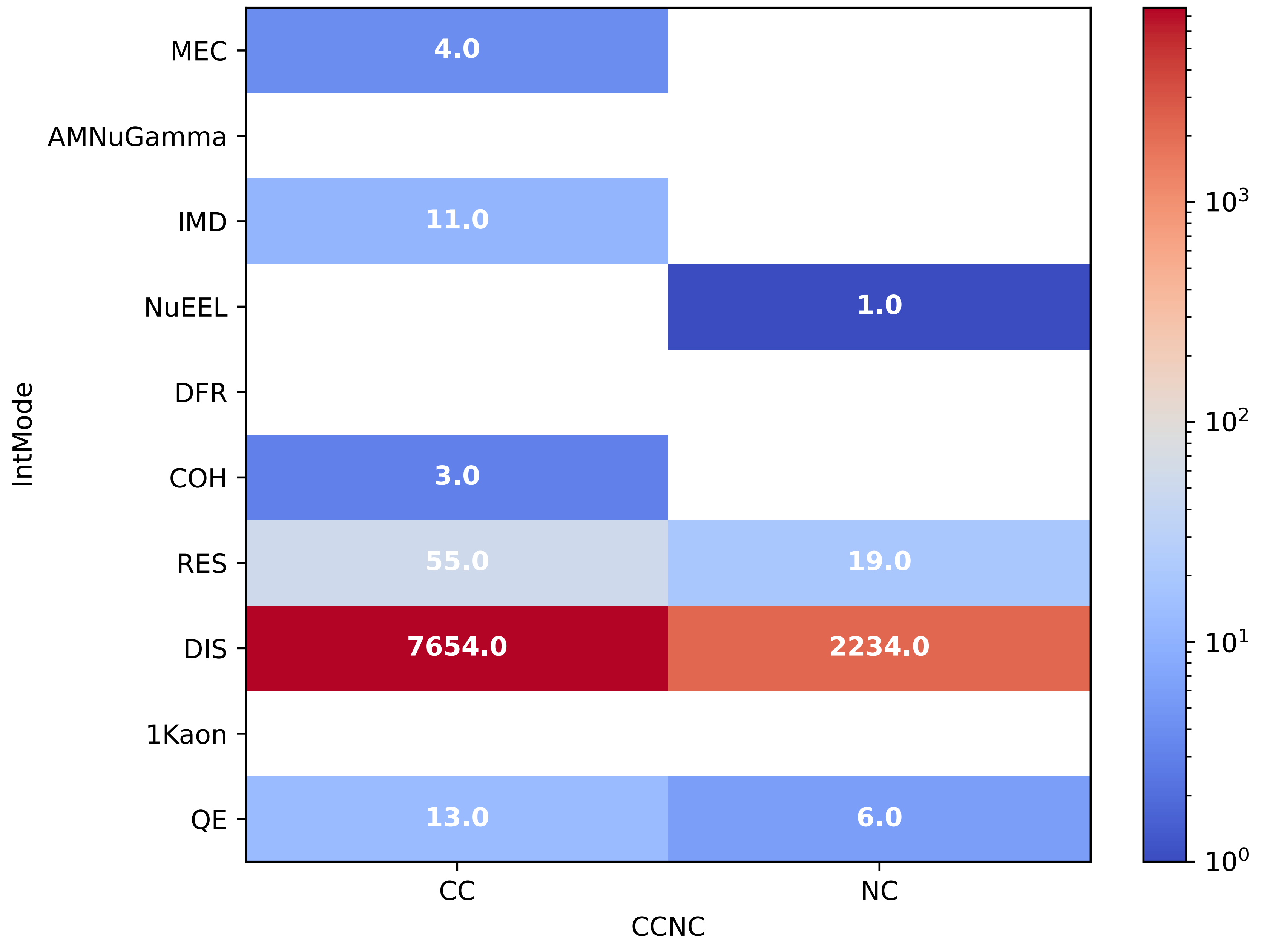
Zoom in

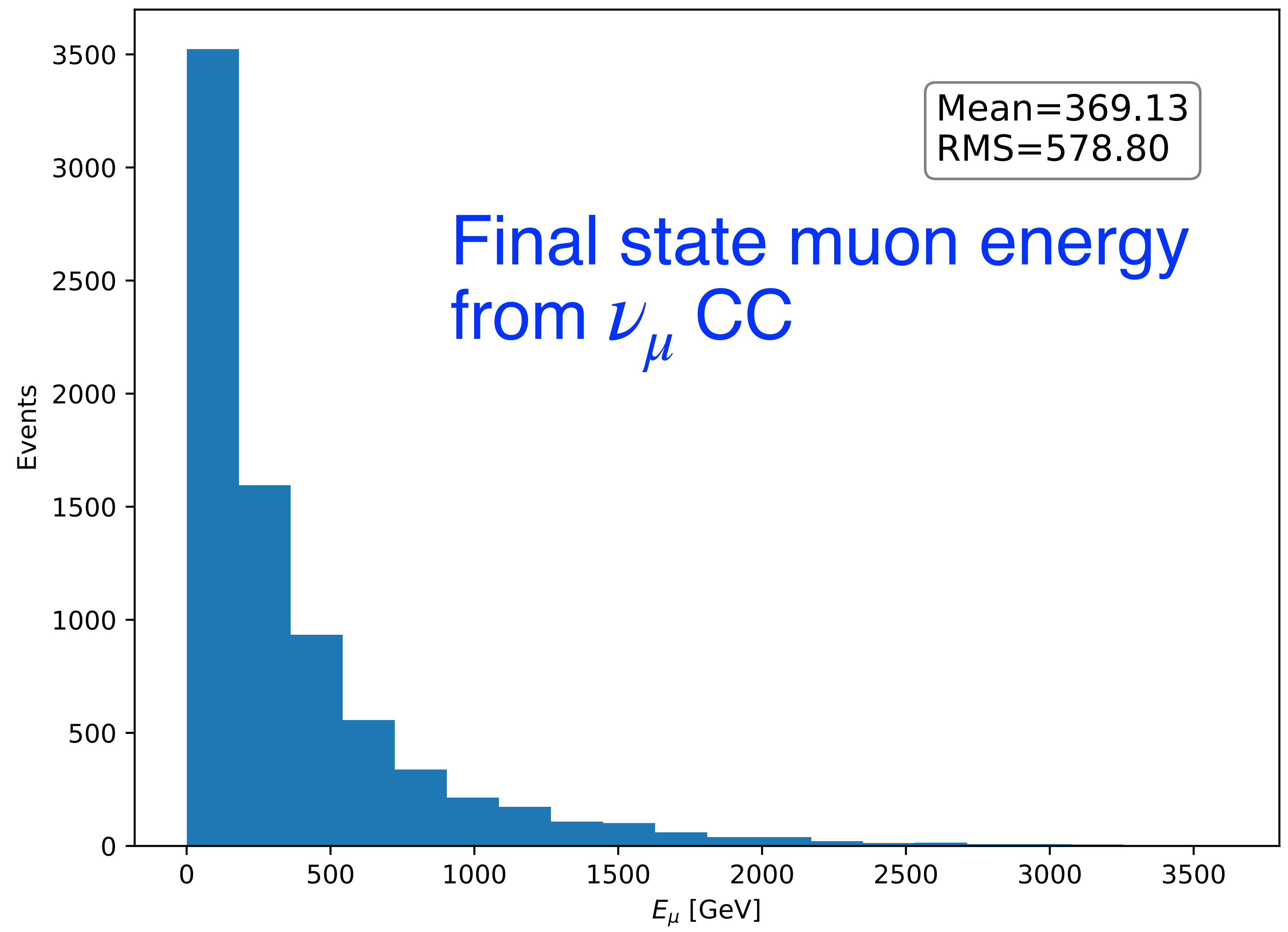


ν_μ in the detector

- 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*



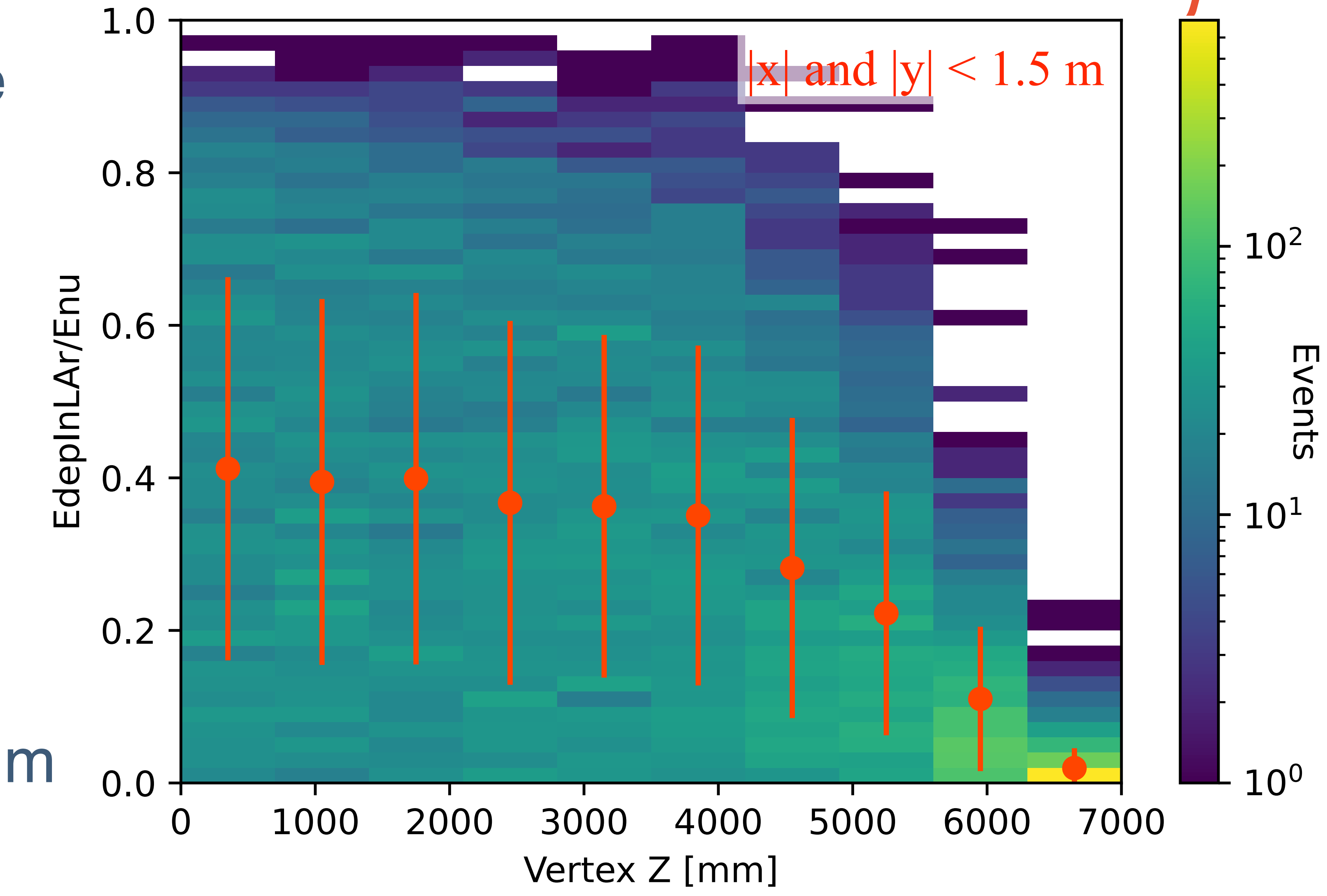


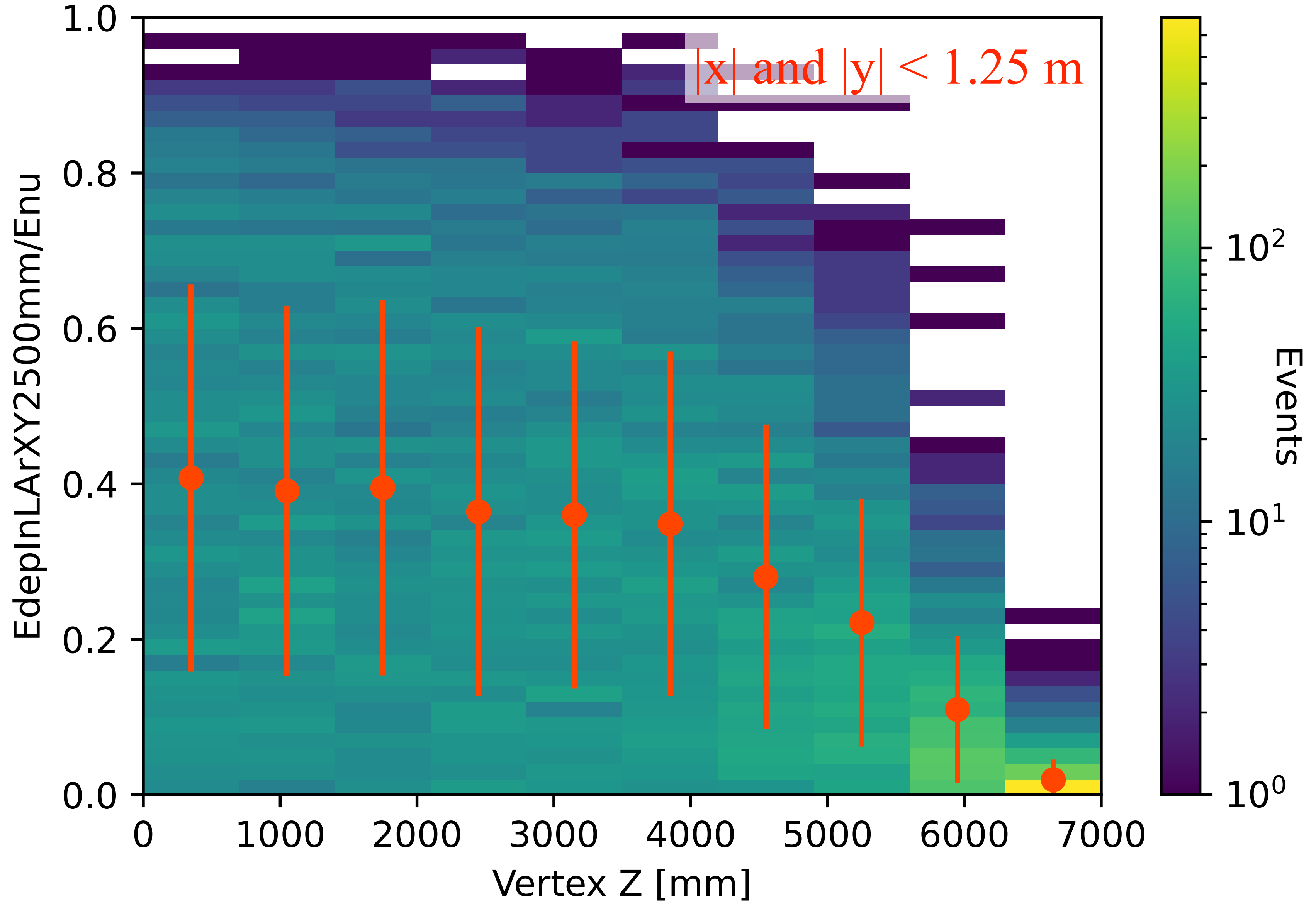


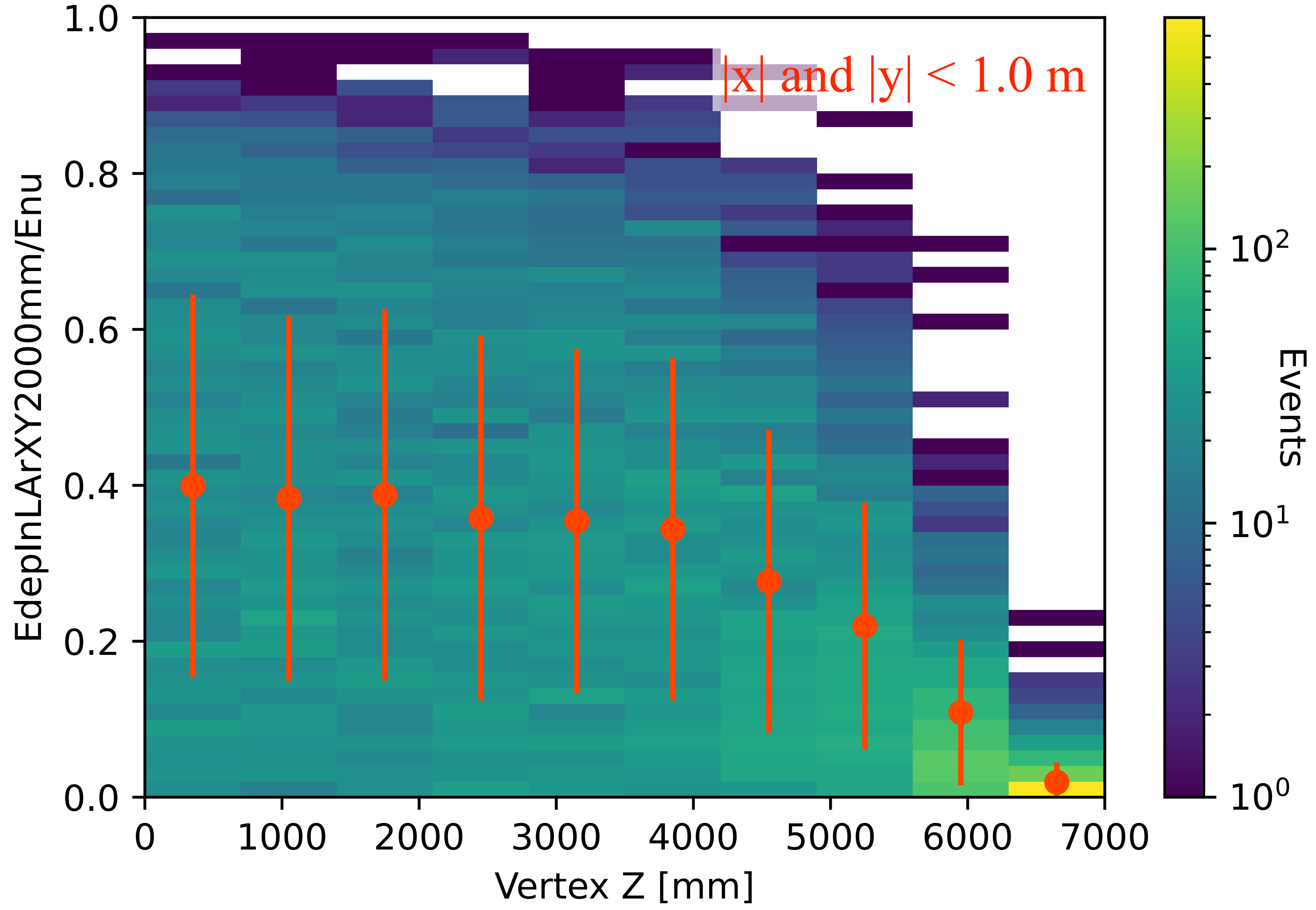
UCIRVINE

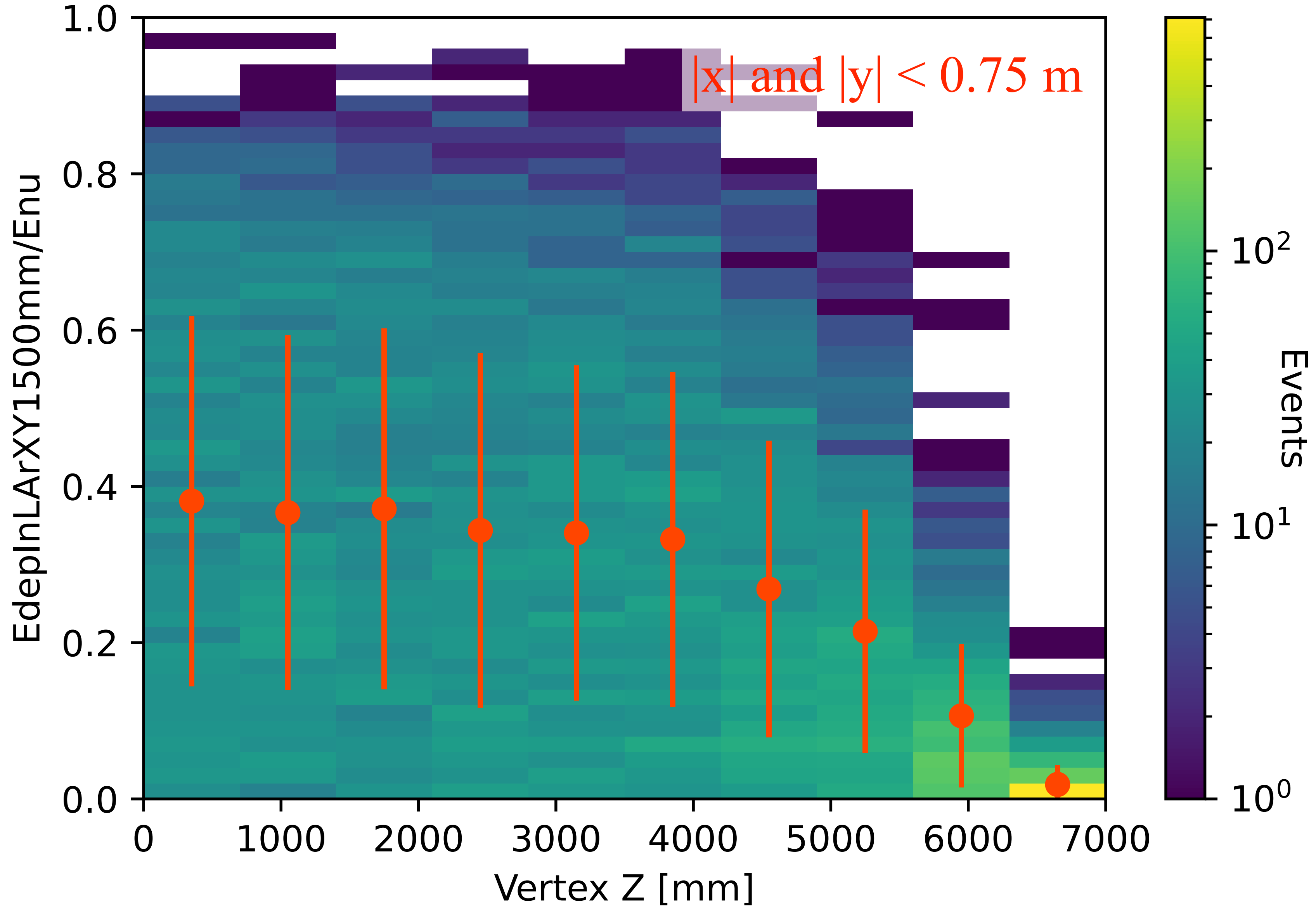
Energy containment in the LArTPC (ν_μ)

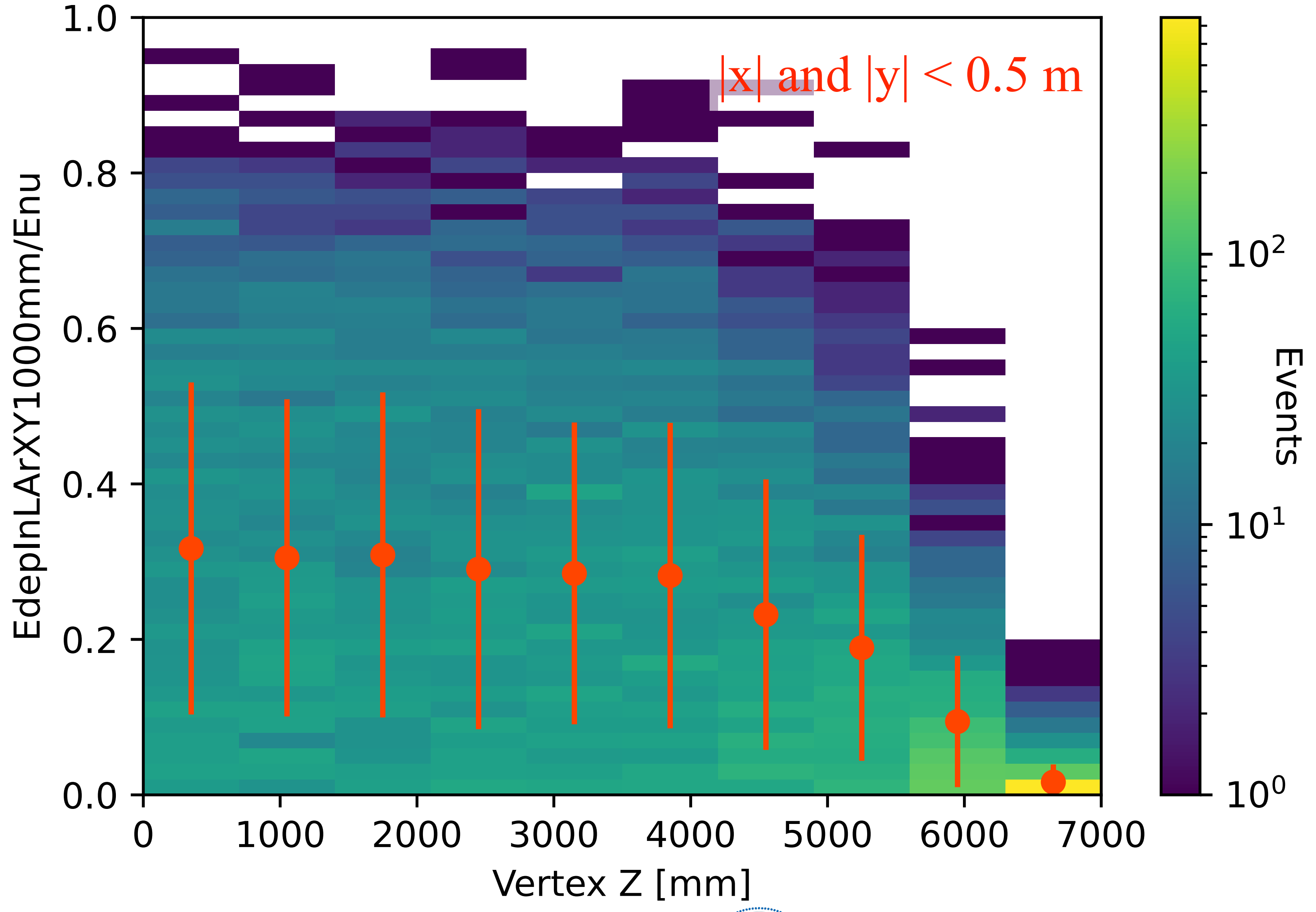
- The ratio of the energy deposited in the LArTPC to the neutrino energy
  - The orange markers are the mean values and standard deviation as error bars
- Make transverse cuts for energy containment in different detector sizes
  - |x| and |y| < 1.5, 1.25, 1.0, 0.75, 0.5 m





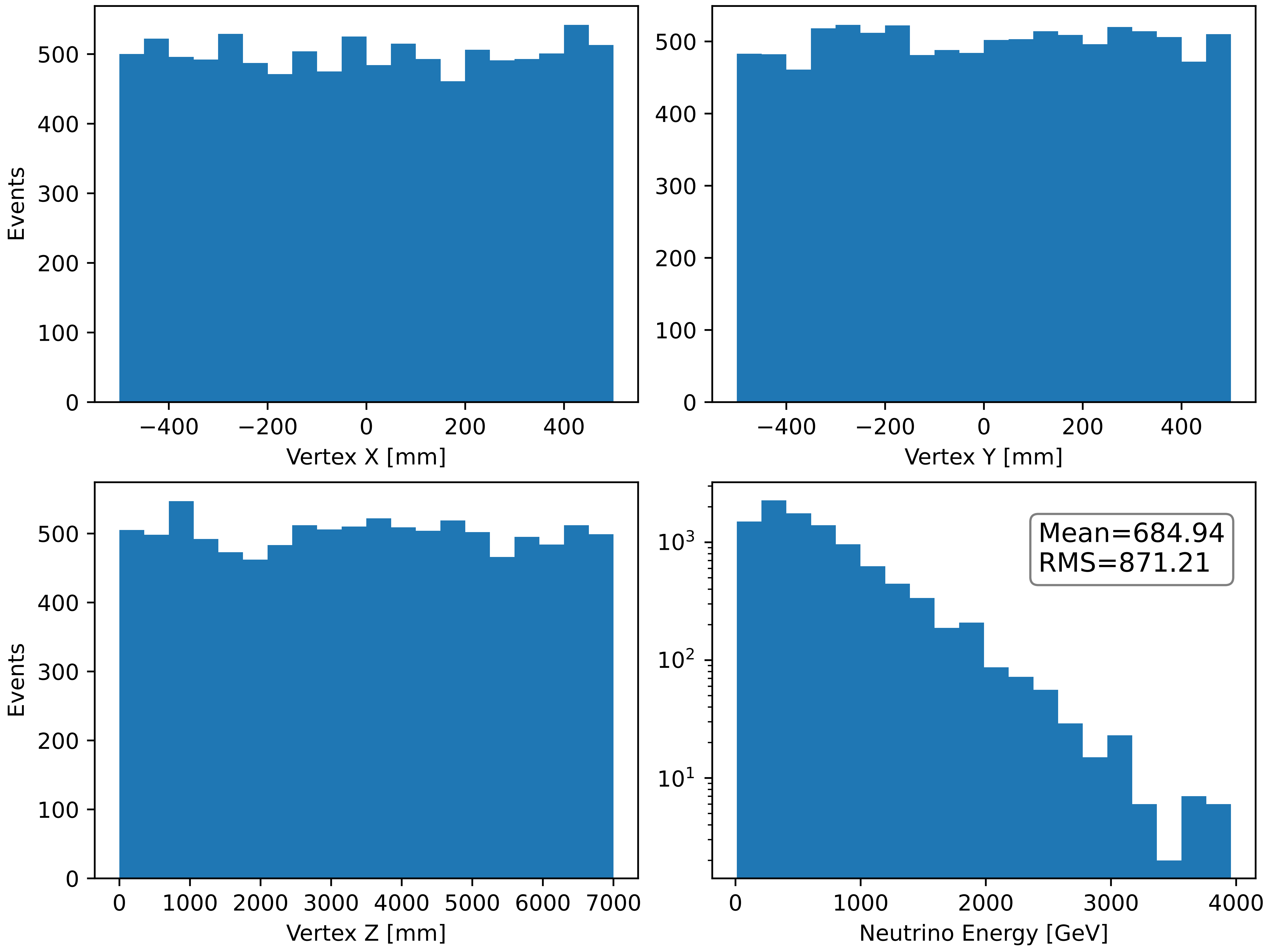


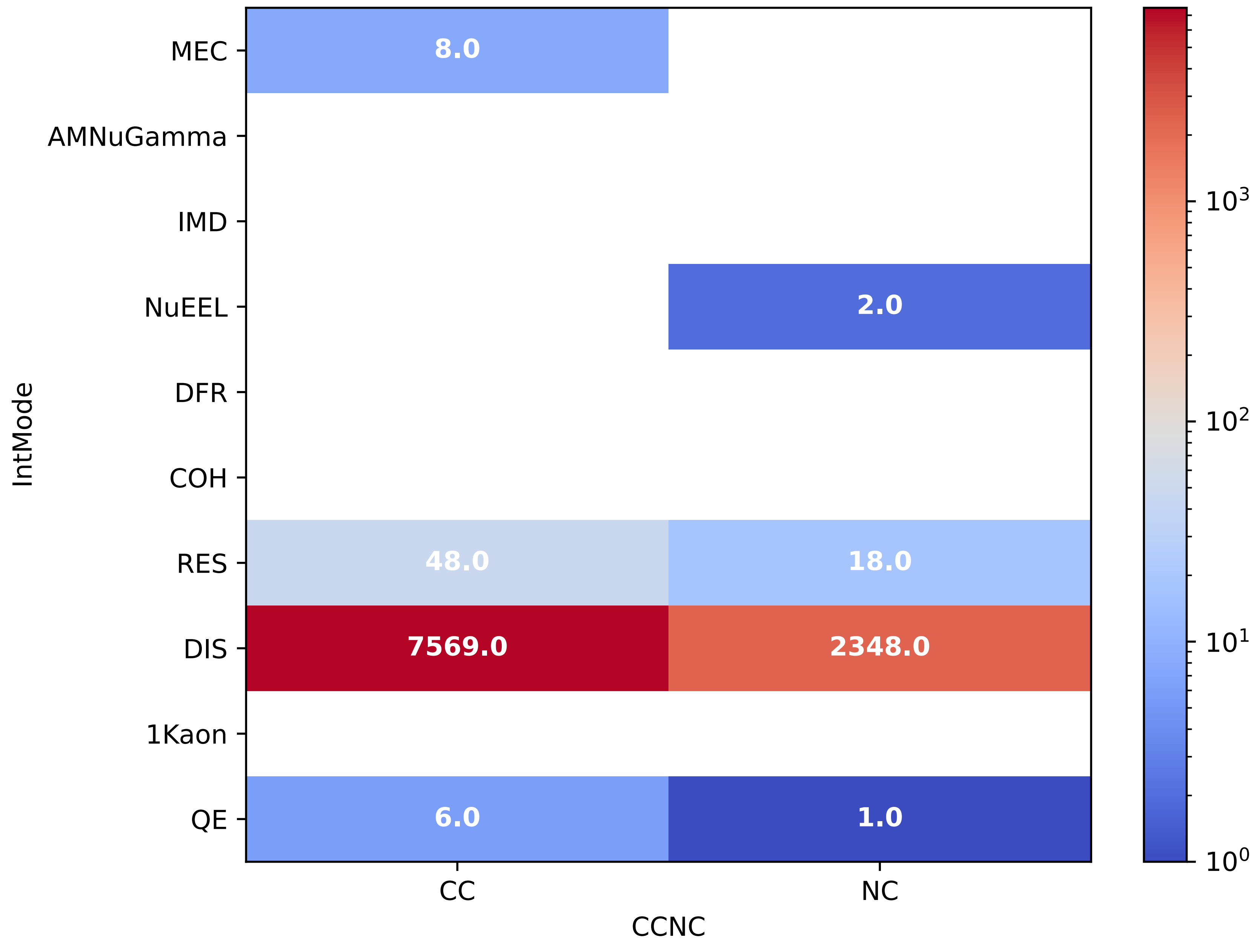


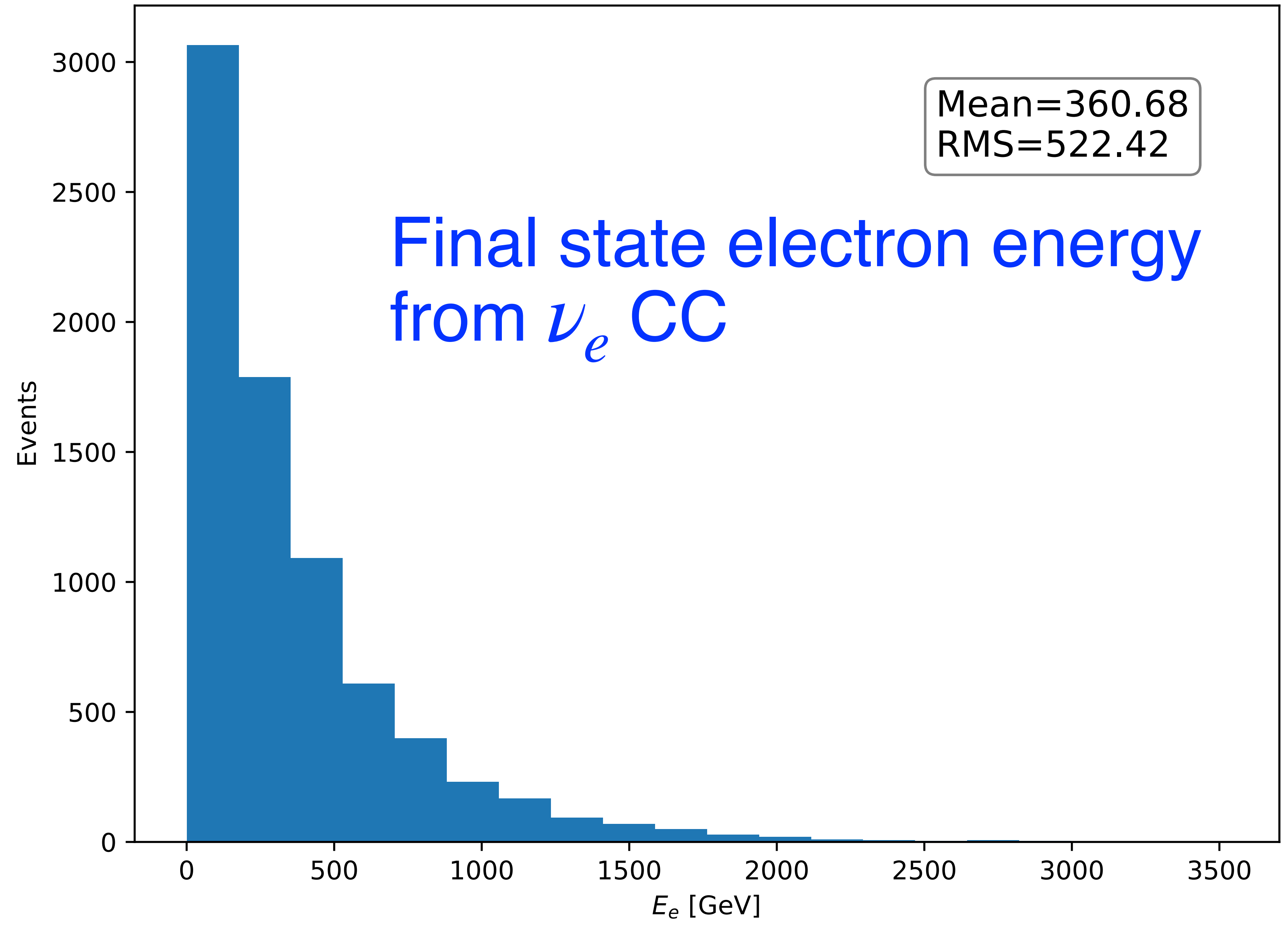


ν_e in the detector

- 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*

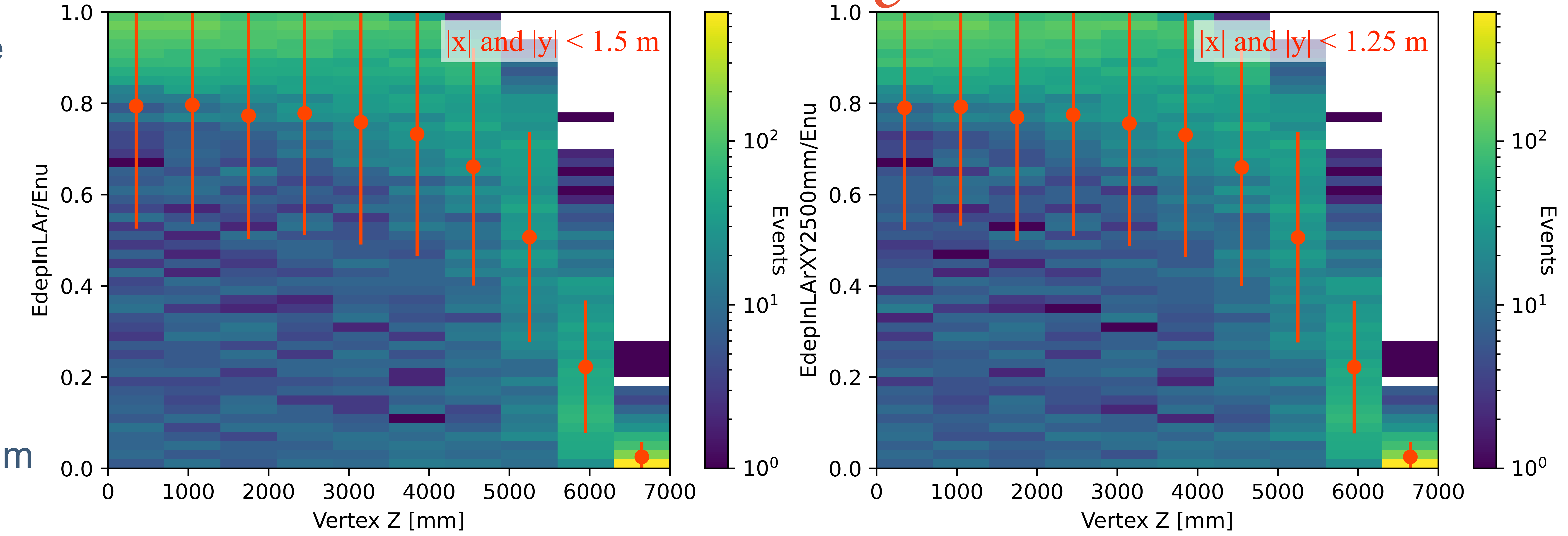






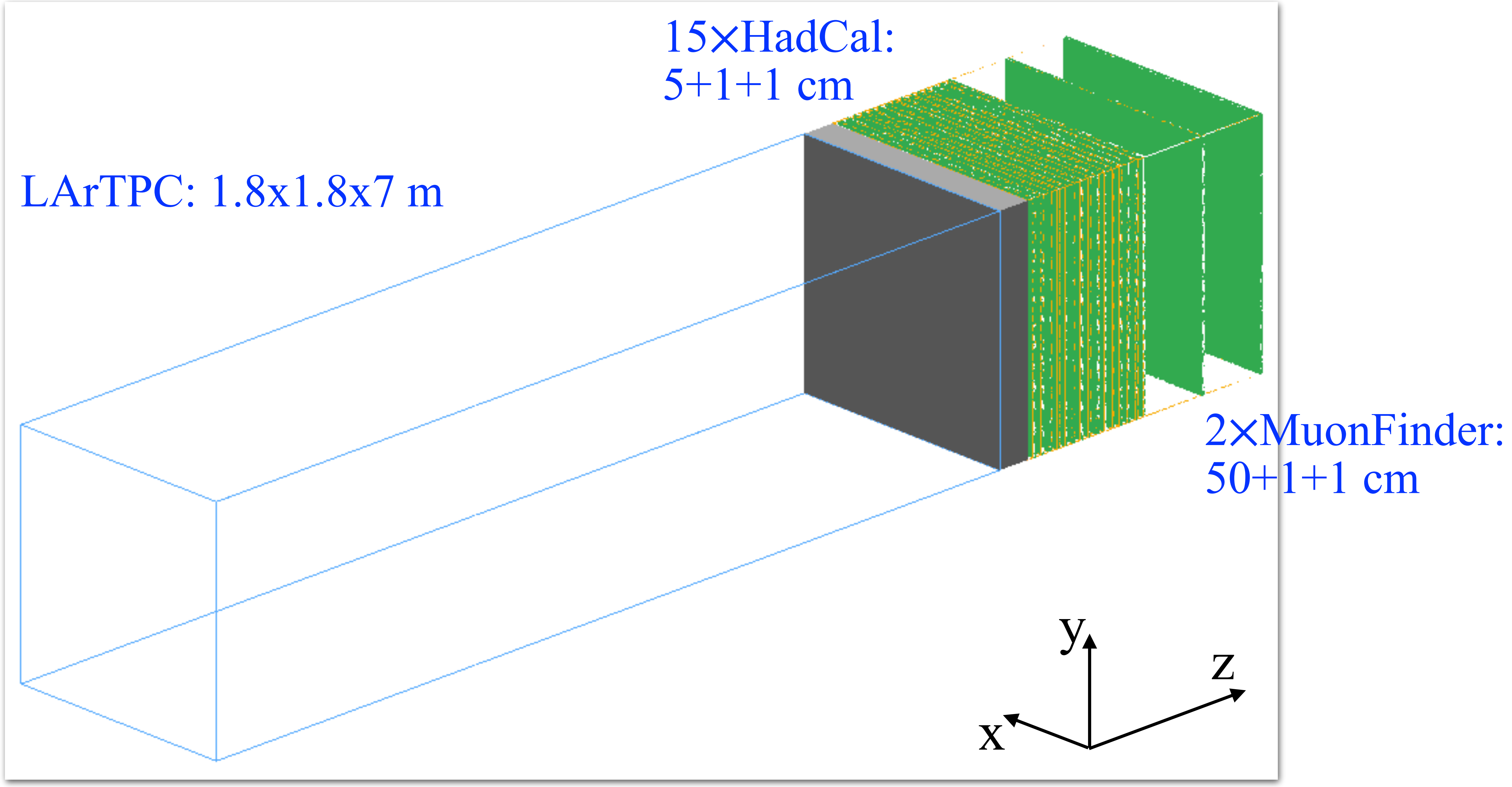
Energy containment in the LArTPC (ν_e)

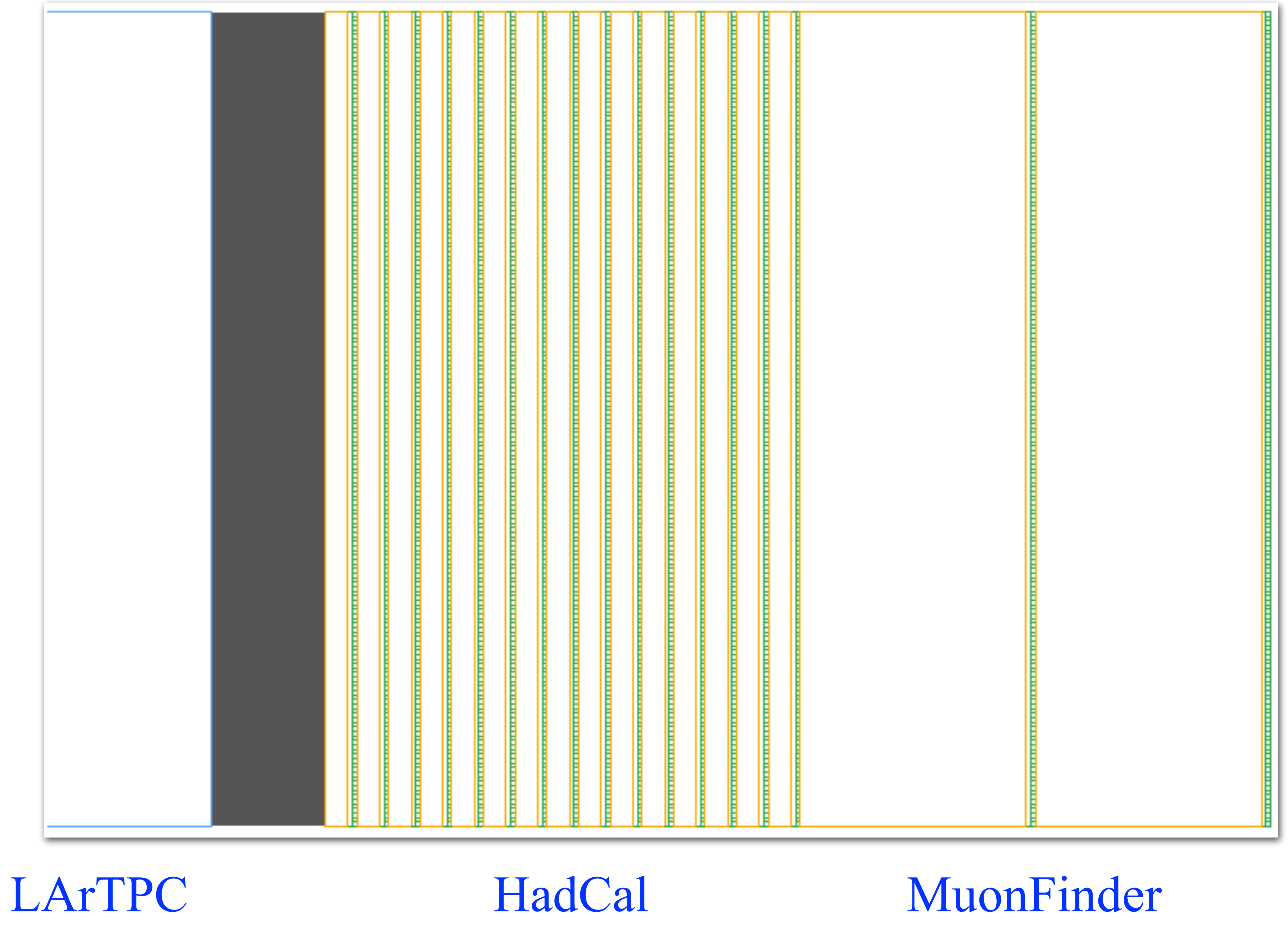
- The ratio of the energy deposited in the LArTPC to the neutrino energy
  - The orange markers are the mean values and standard deviation as error bars
- Make transverse cuts for energy containment in different detector sizes
  - |x| and |y| < 1.5, 1.25, 1.0, 0.75, 0.5 m



Current detector configuration in Geant4

	LArTPC	HadCal	MuonFinder
Length (mm)	0 - 7000	7250 - 8300	8300 - 9340

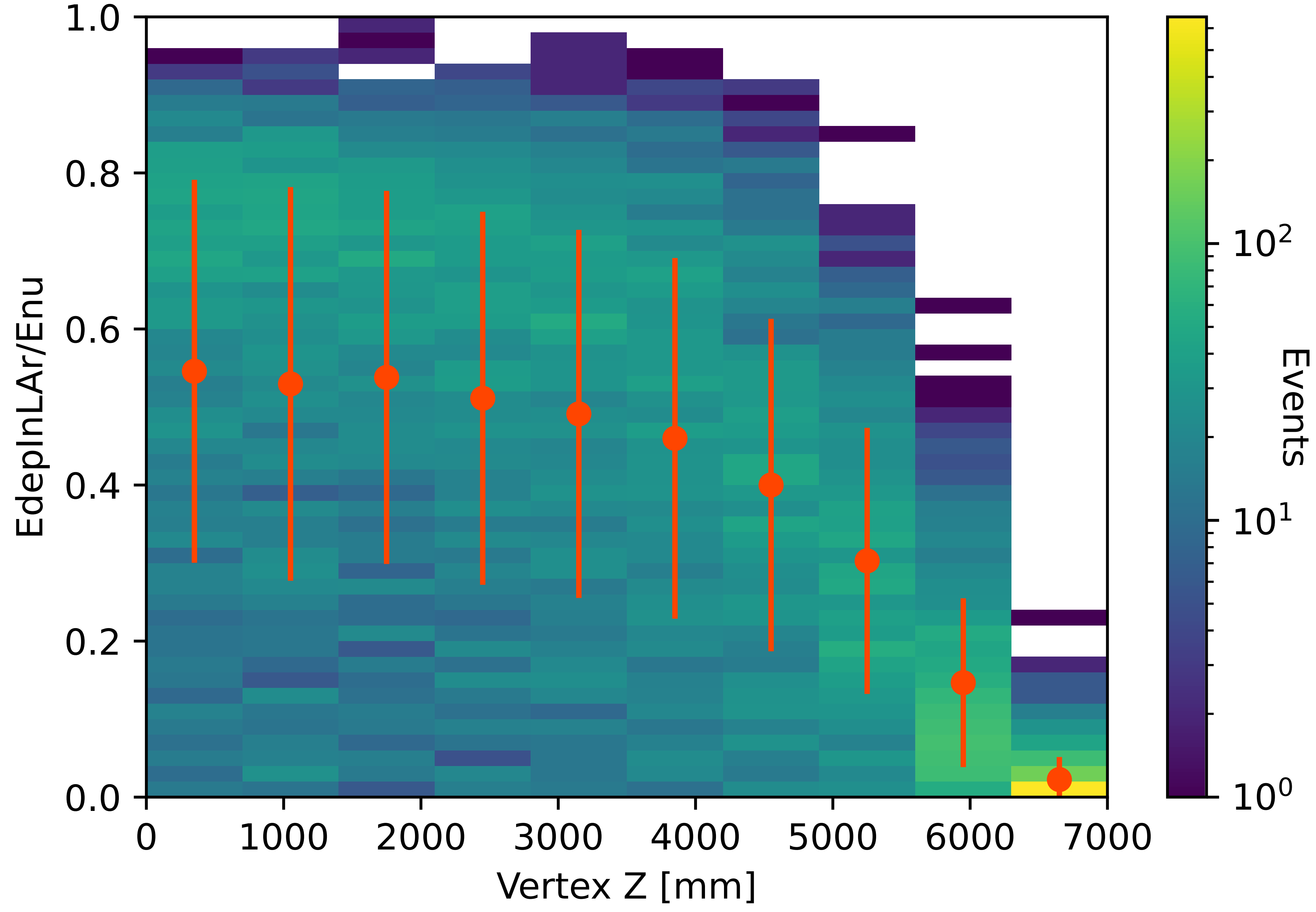




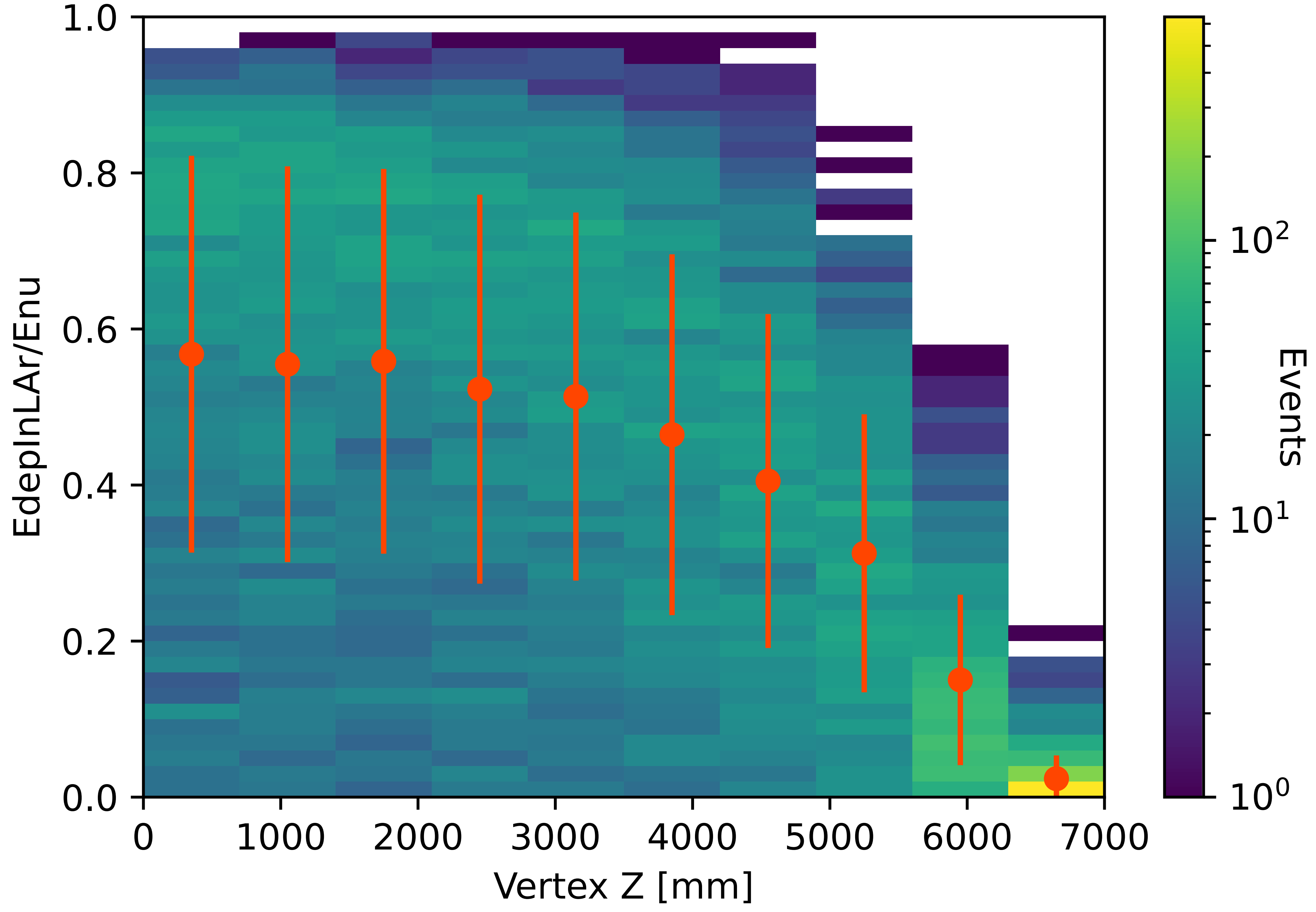
Energy containment in the LArTPC

- To verify the energy containment in the geometry 1.8x1.8x7
- 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

1.8x1.8x7 m



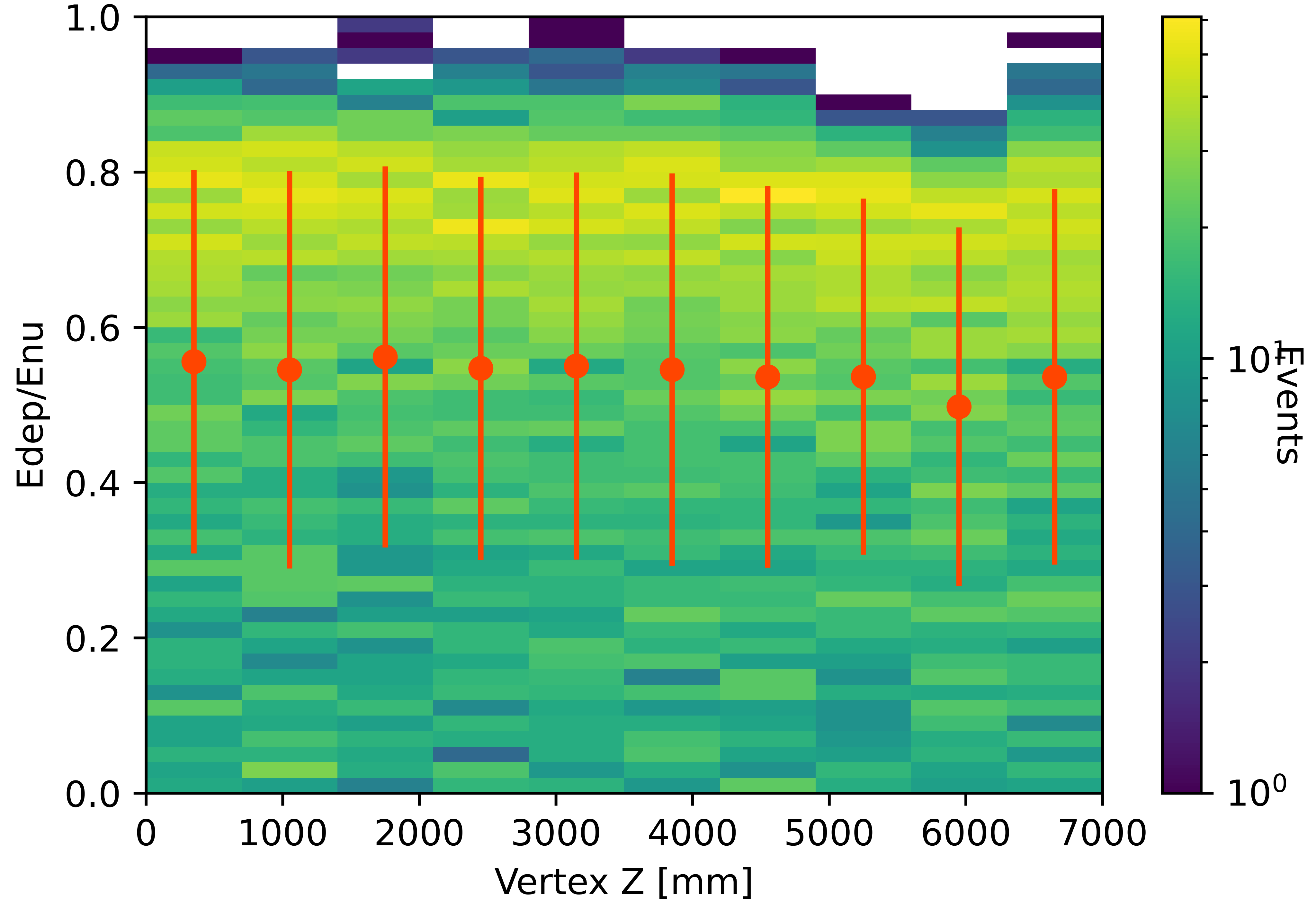
3x3x7 m



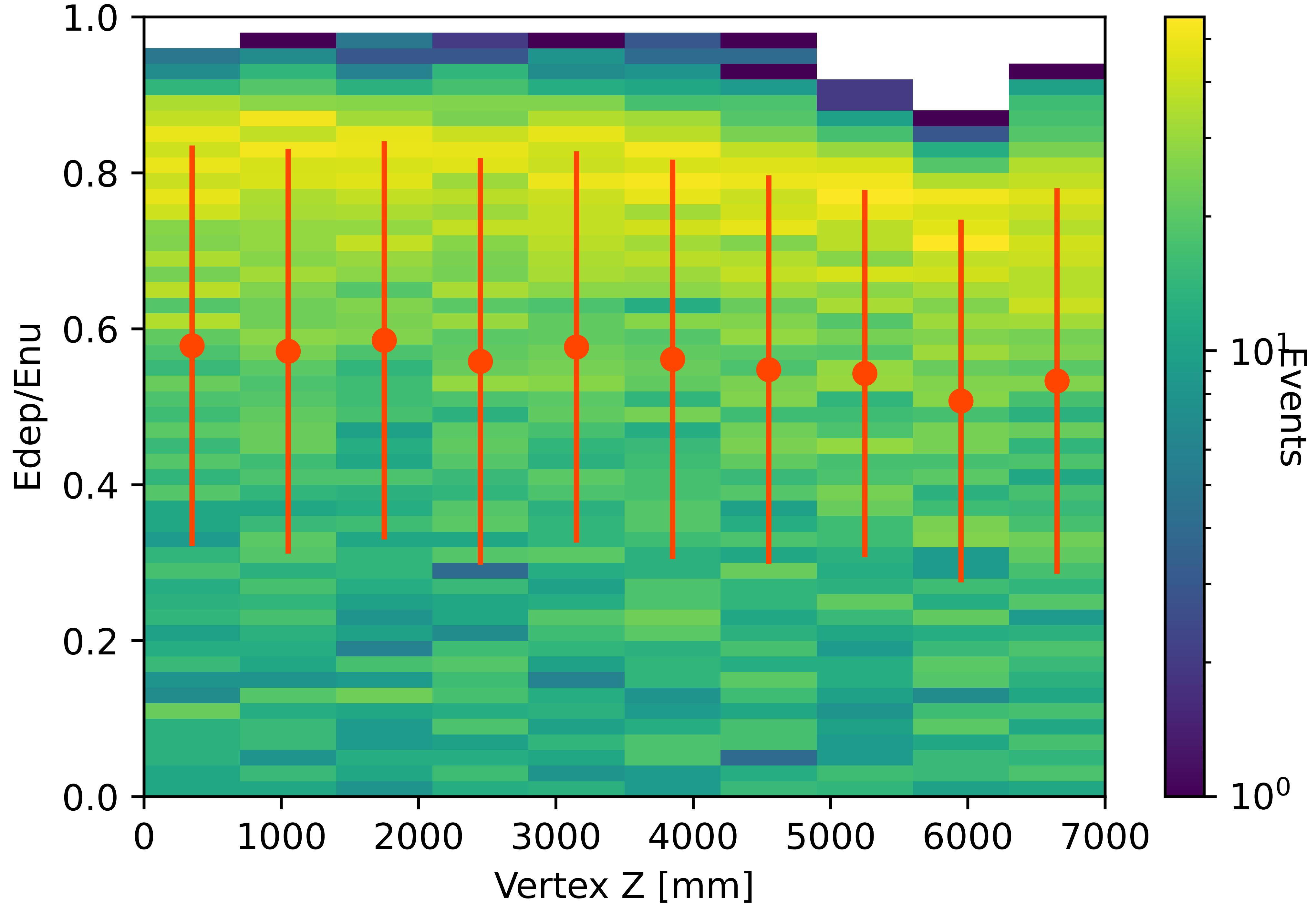
Energy containment w/ HadCal

- To verify 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 hadCal can save loss energies for events happened in the downstream of the detector

1.8x1.8x7 m



3x3x7 m



UCIRVINE

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

Signal and background

- Only considered beam neutrino background here
- Decay modes of the tau lepton
  - τ_e: taus decay to electrons
  - τ_μ: taus decay to muons
  - τ_{had}: taus decay to hadrons

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%

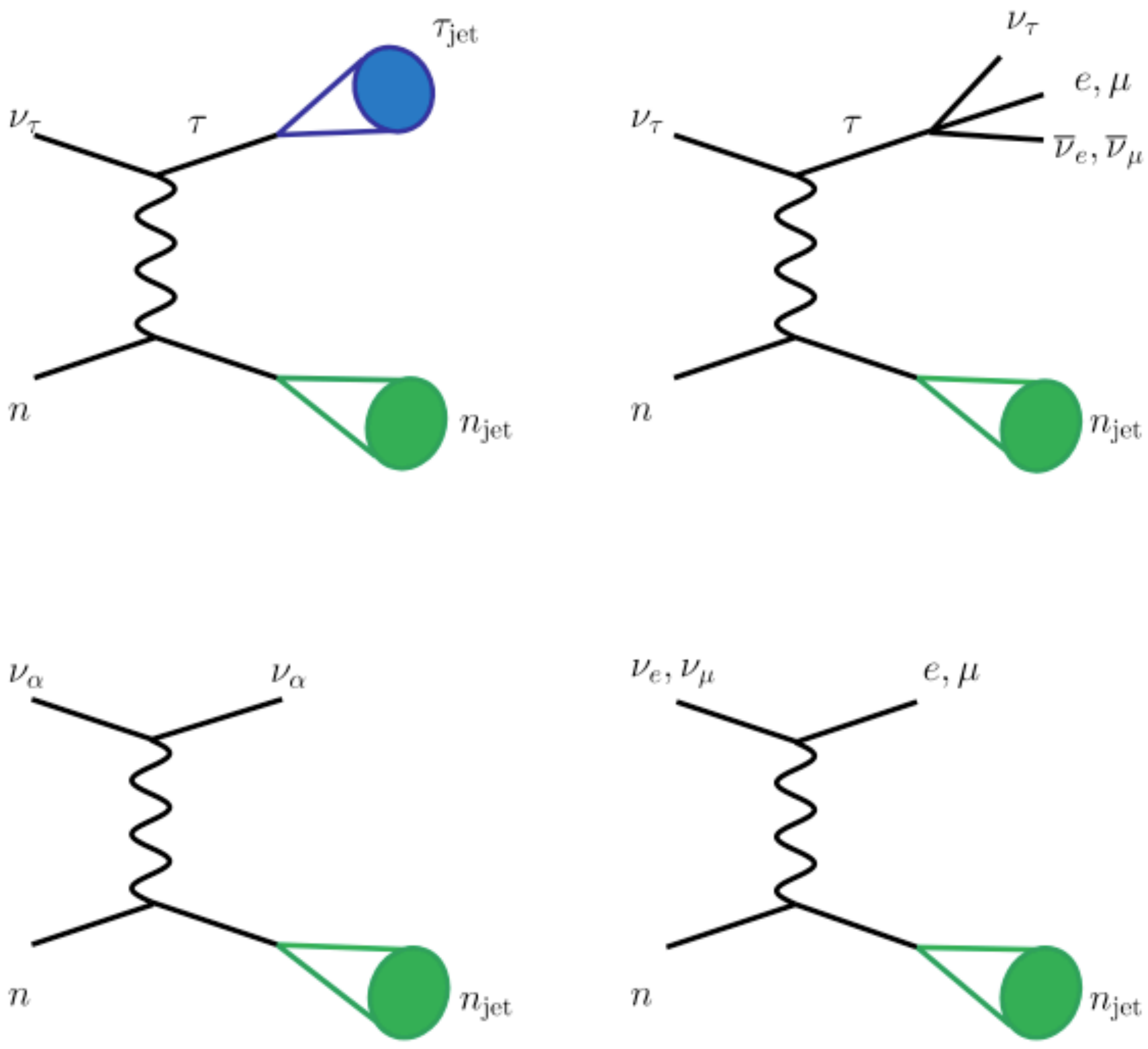


FIG. 2. Pictorial representation of hadronic tau (upper left) and leptonic tau (upper right) signals, and their corresponding backgrounds (lower).

10.1103/PhysRevD.102.053010

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

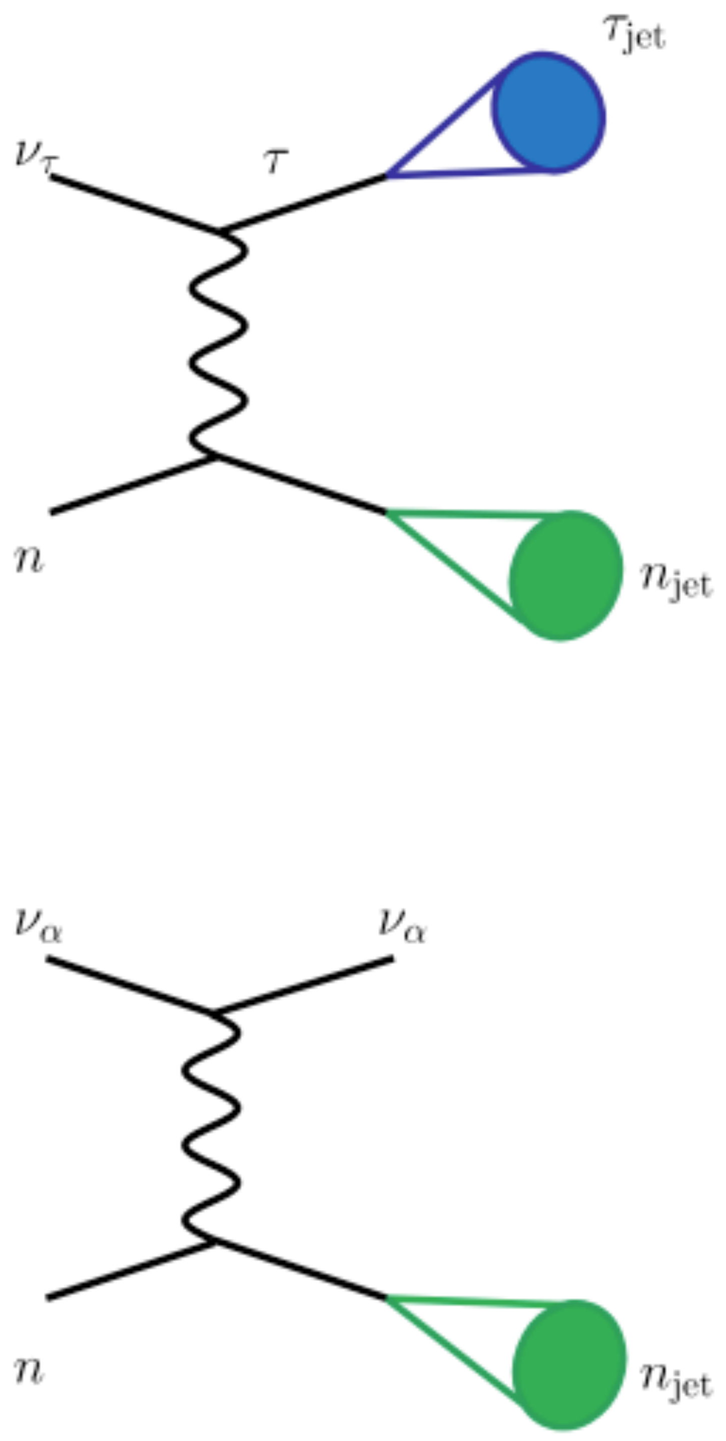
Table 7.1: Detectors and neutrino event rates: The left side of the table summarizes the detector specifications in terms of the target mass, pseudorapidity coverage and assumed integrated luminosity for both the LHC neutrino experiments operating during Run 3 of the LHC as well as the proposed FPF neutrino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

Hadronic decay

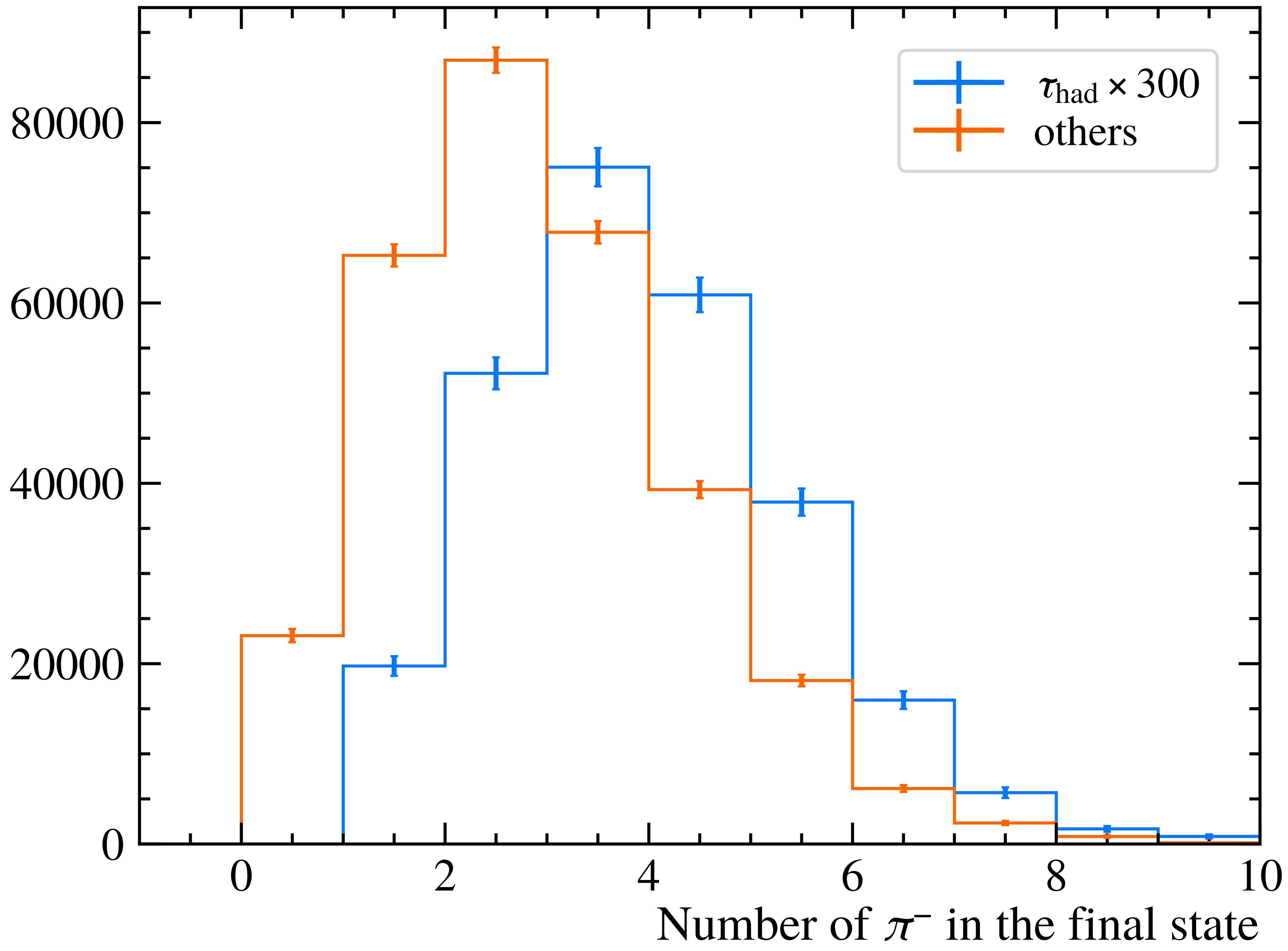
- Signal: τ_{had} (taus decay to hadrons)
  - τ_{had} has larger branch ratio than τ_{μ} and τ_{e}, there is potential to be a good channel to select ν_{τ}
  - τ_{had} has at least one π^{-} in the final state

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%

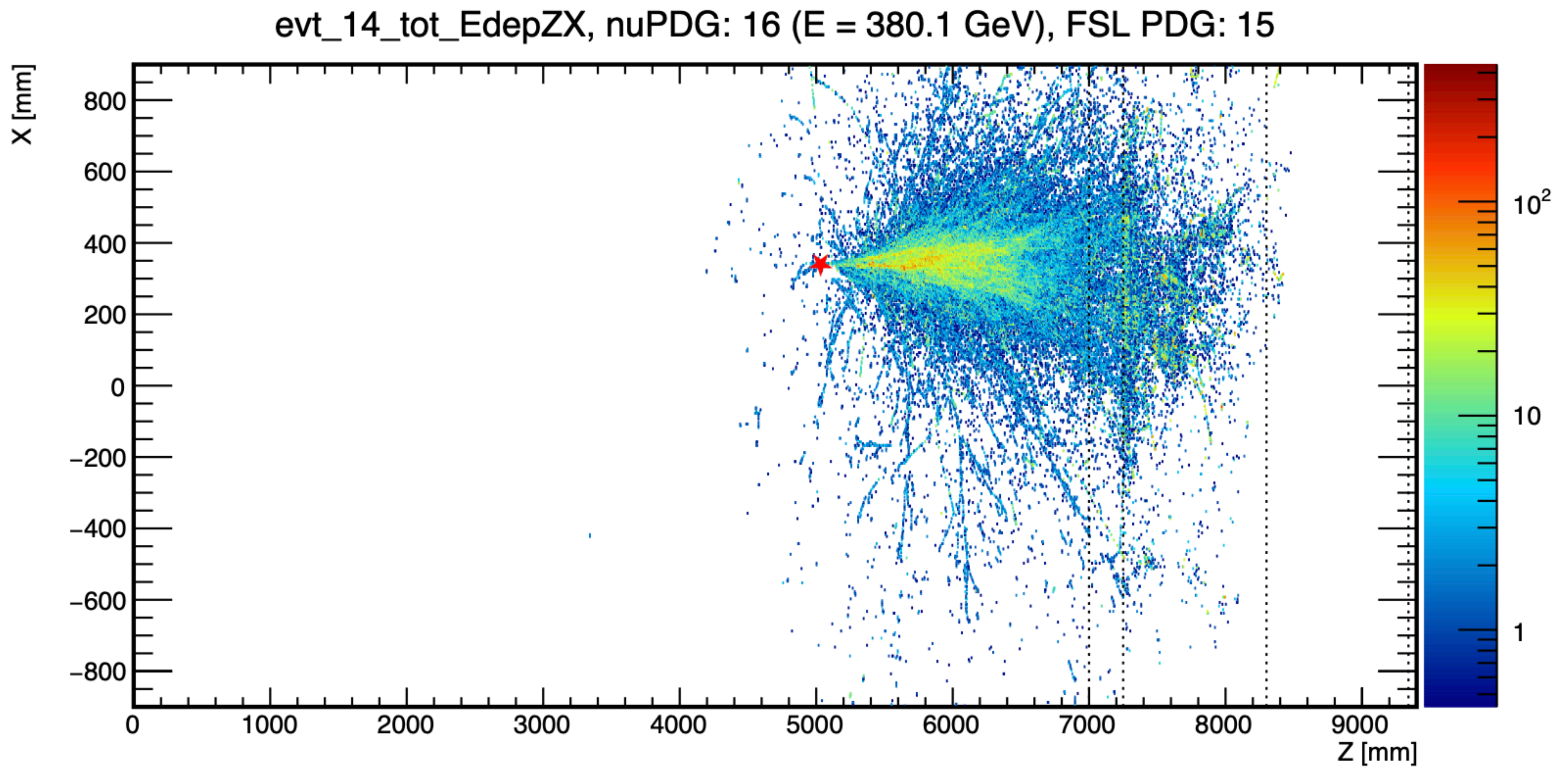


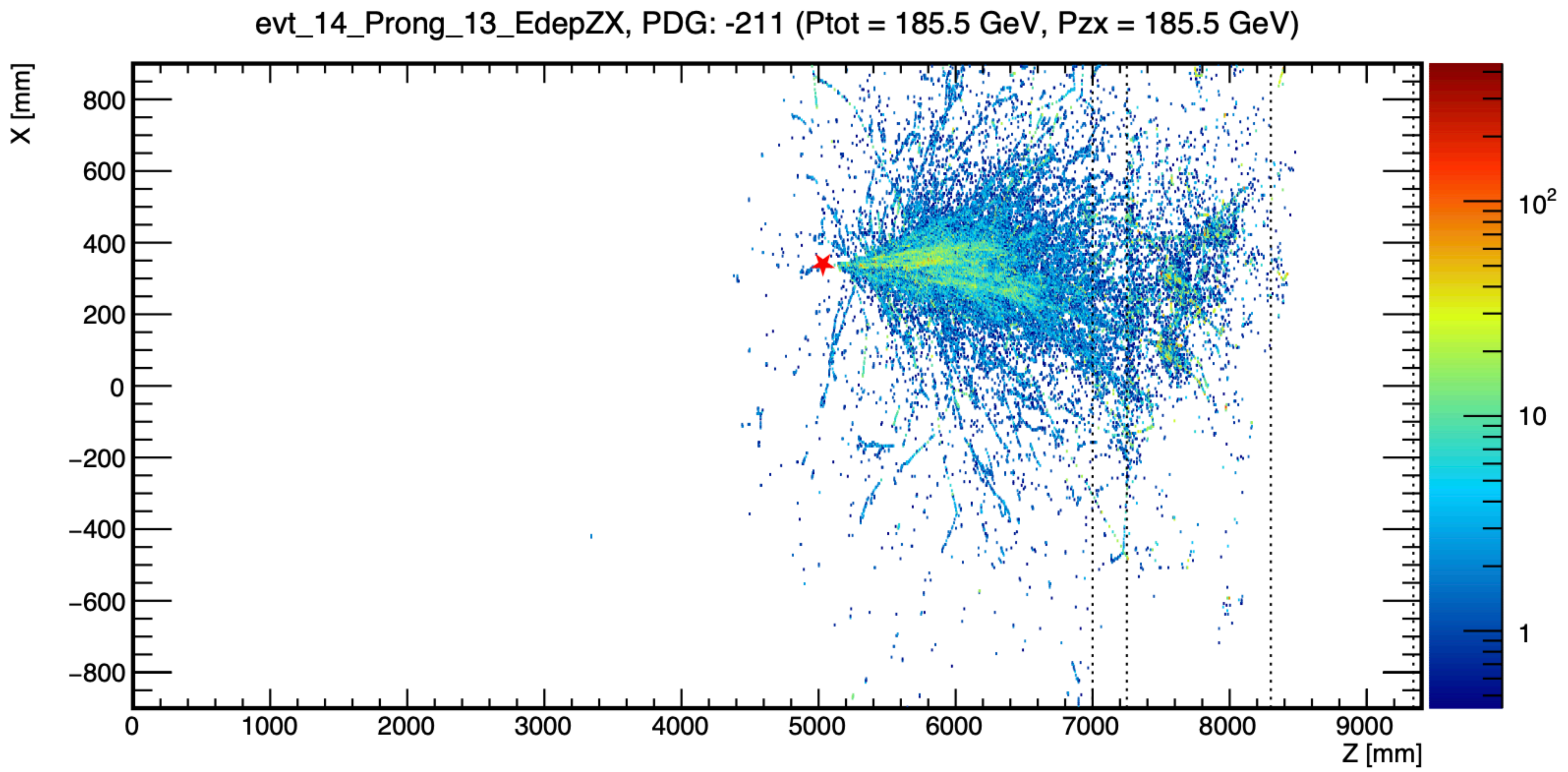
10.1103/PhysRevD.102.053010

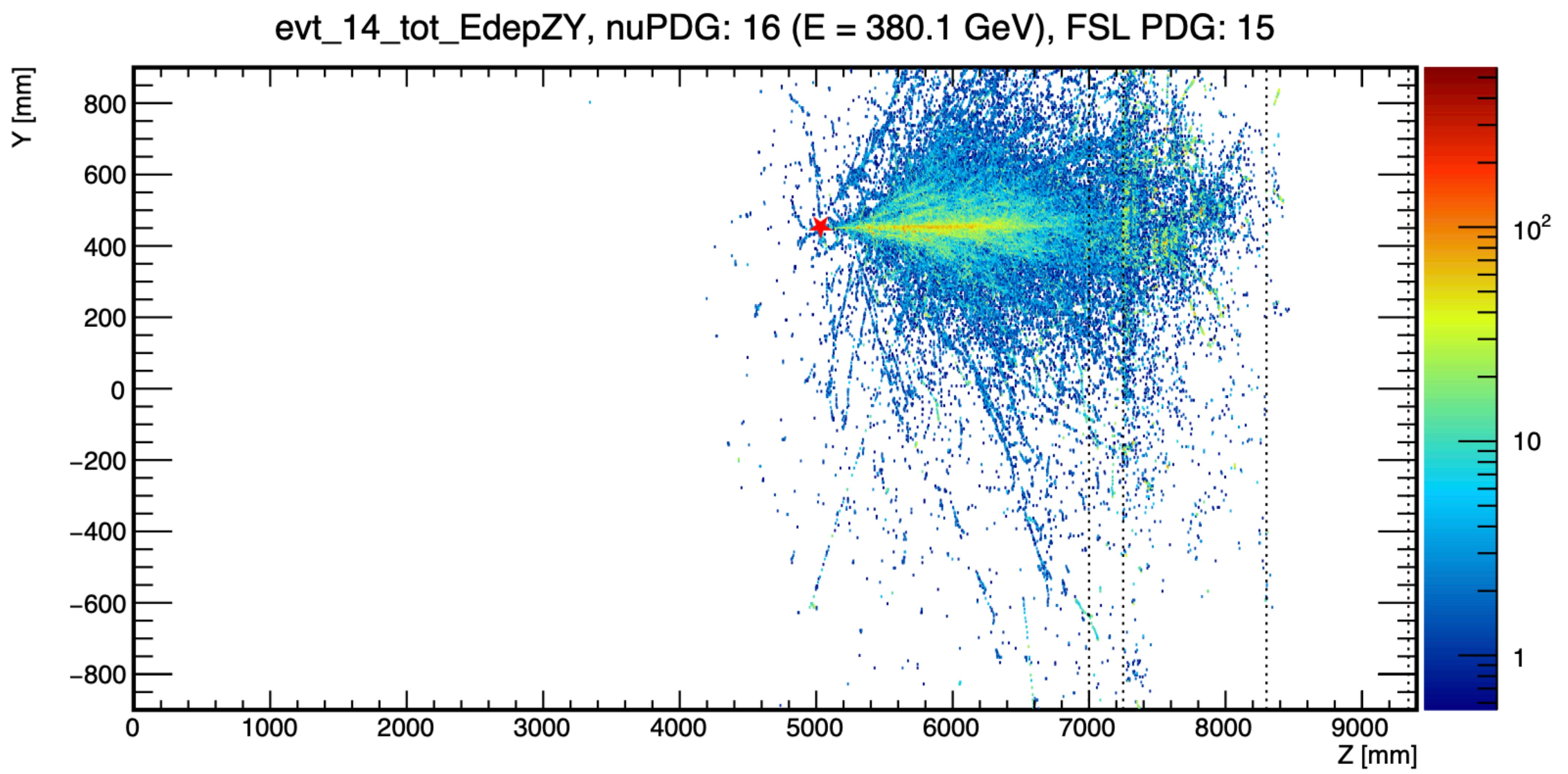


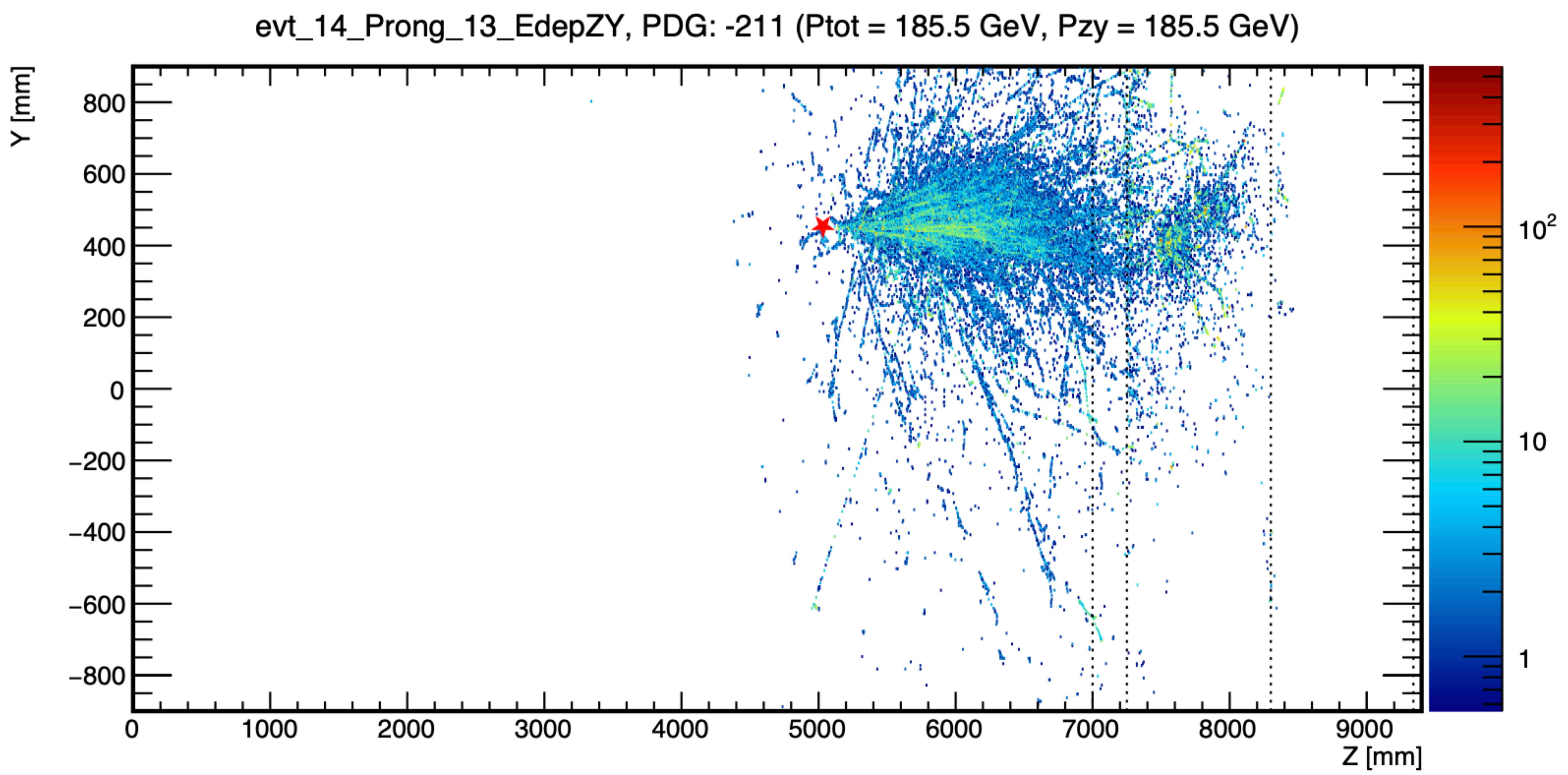
Hadronic decay

ν_τ CC, $\tau^- \rightarrow \pi^- \nu_\tau$





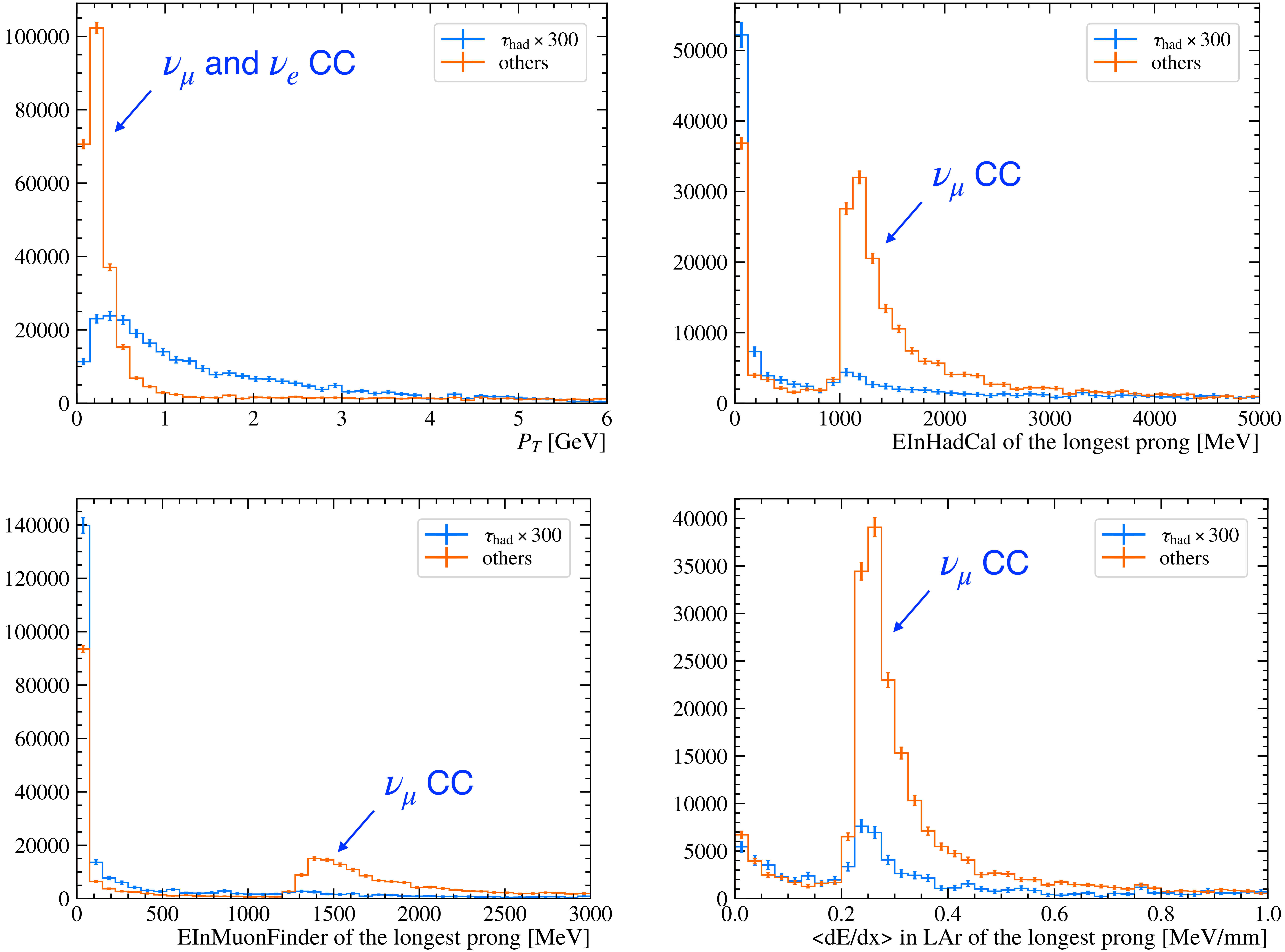




UCIRVINE

Hadronic decay

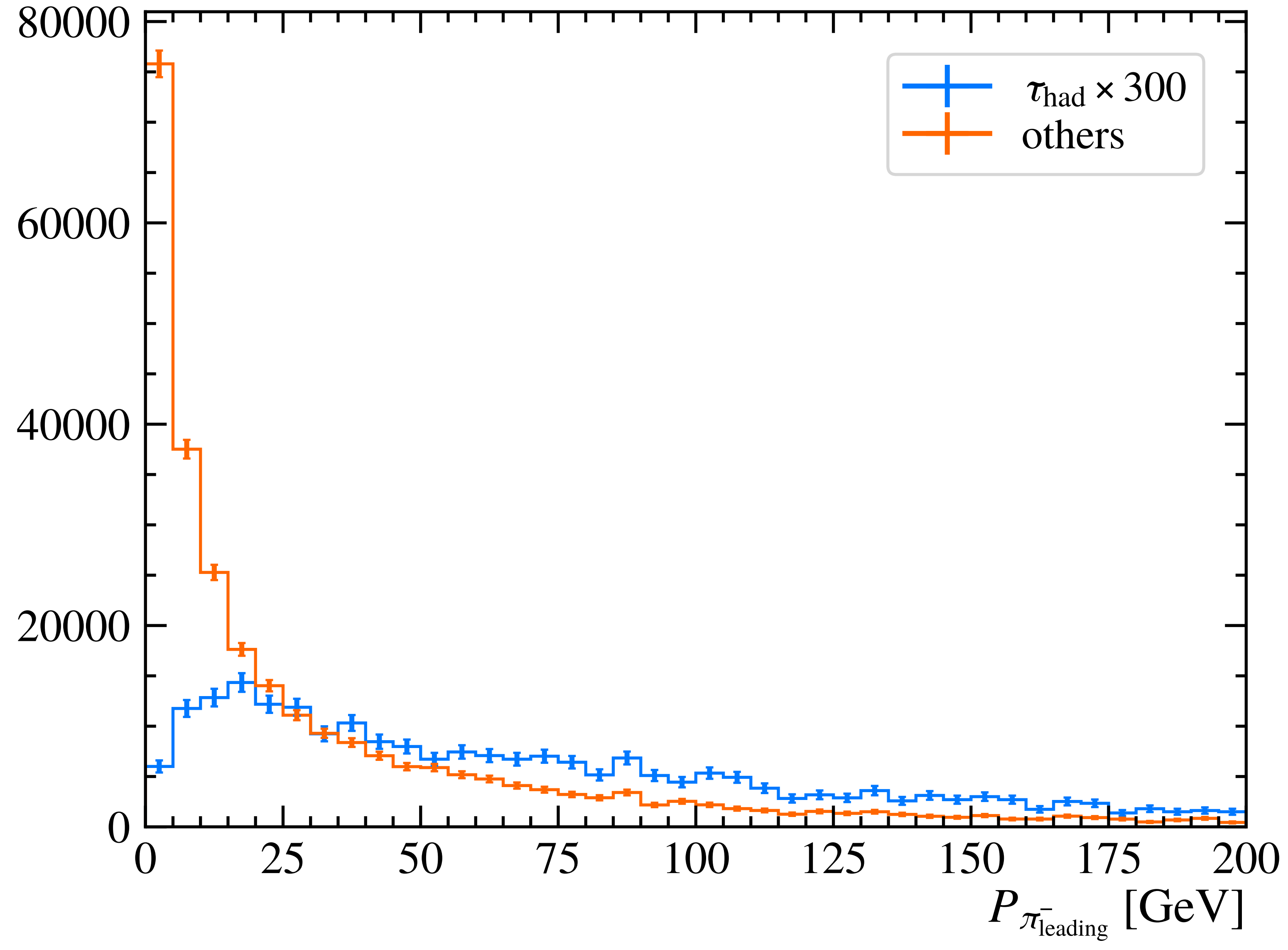
- Neutrinos in the final state are invisible to the detector, contributing to the missing transverse momentum
  - Almost all ν_μCC, ν_eCC have zero neutrino in the final state
  - NC events and τ_{had} have 1 neutrino, τ_μ and τ_e have 2 neutrinos

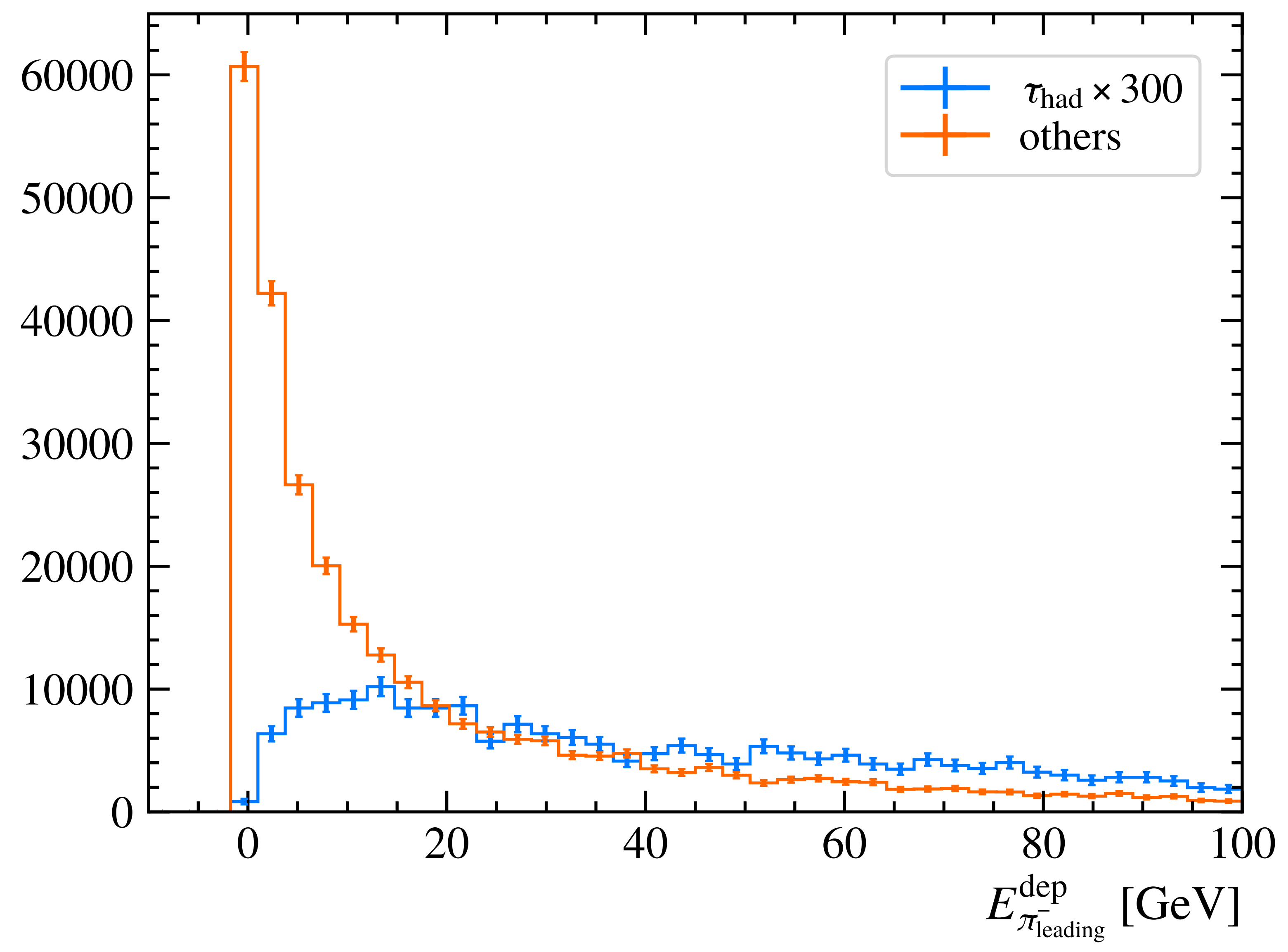


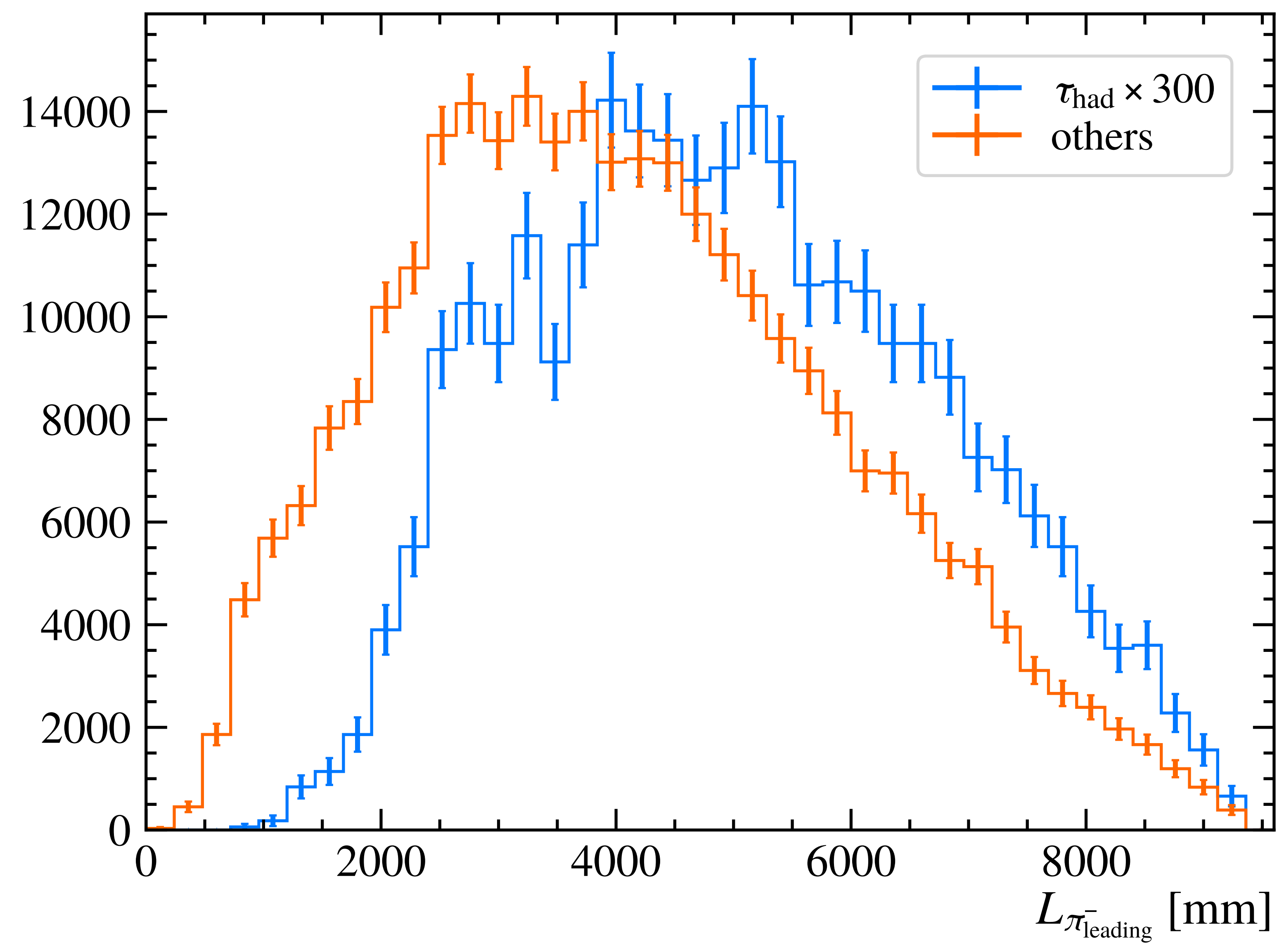
UCIRVINE

Hadronic decay

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



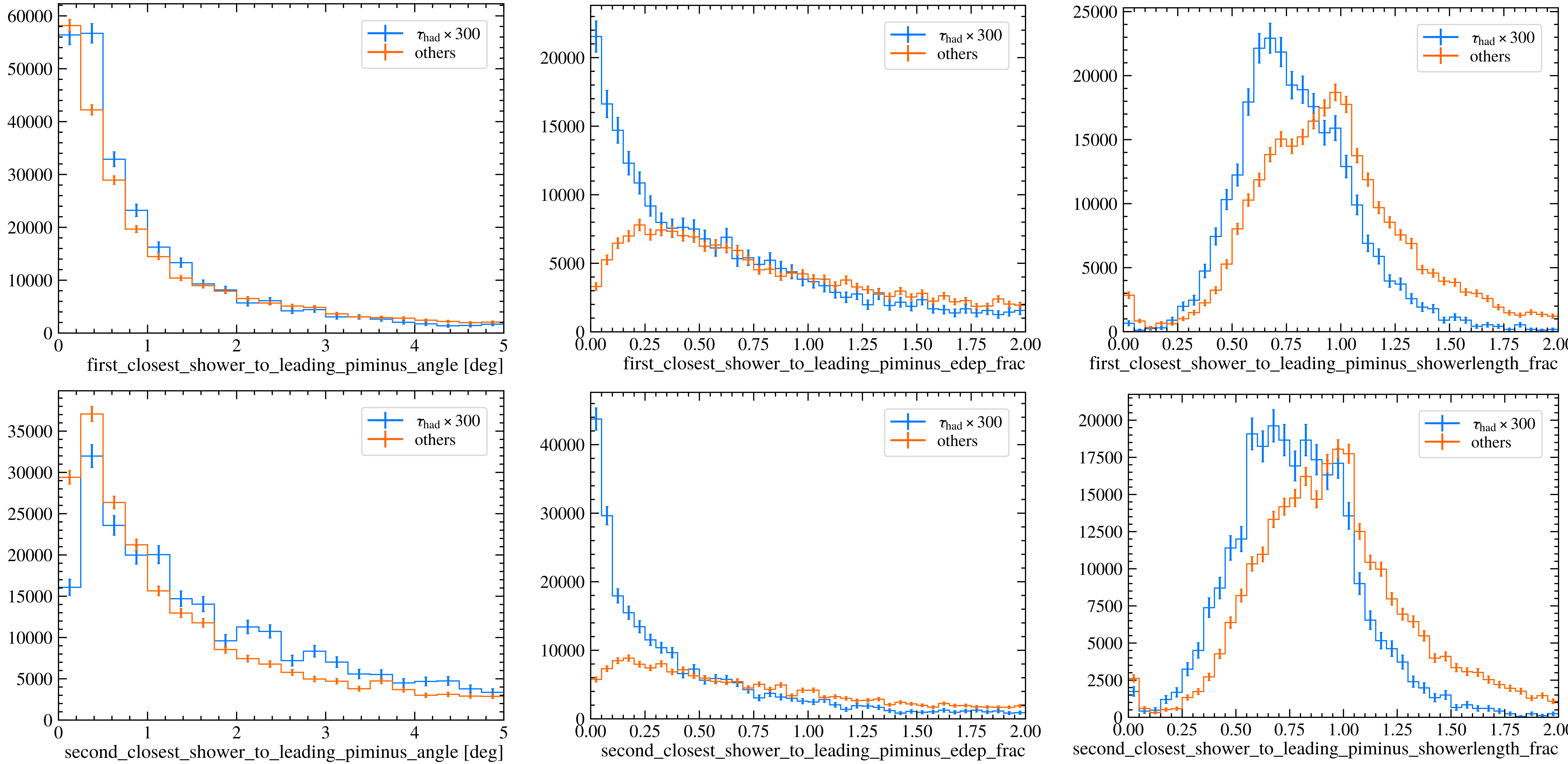




UCIRVINE

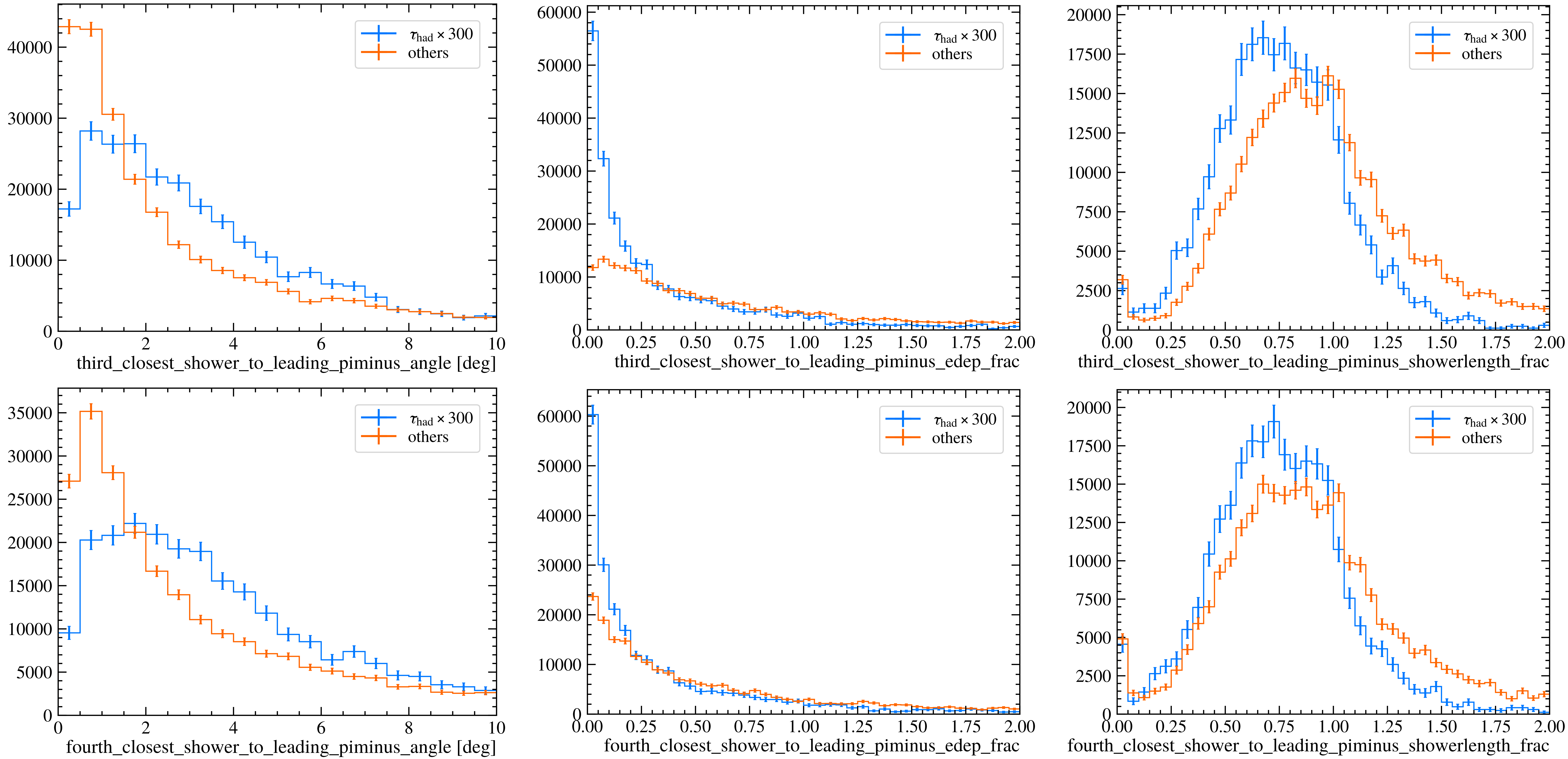
Hadronic decay

- Find the most energetic π^- shower of each event
  - Search for showers around the leading π^-



Hadronic decay

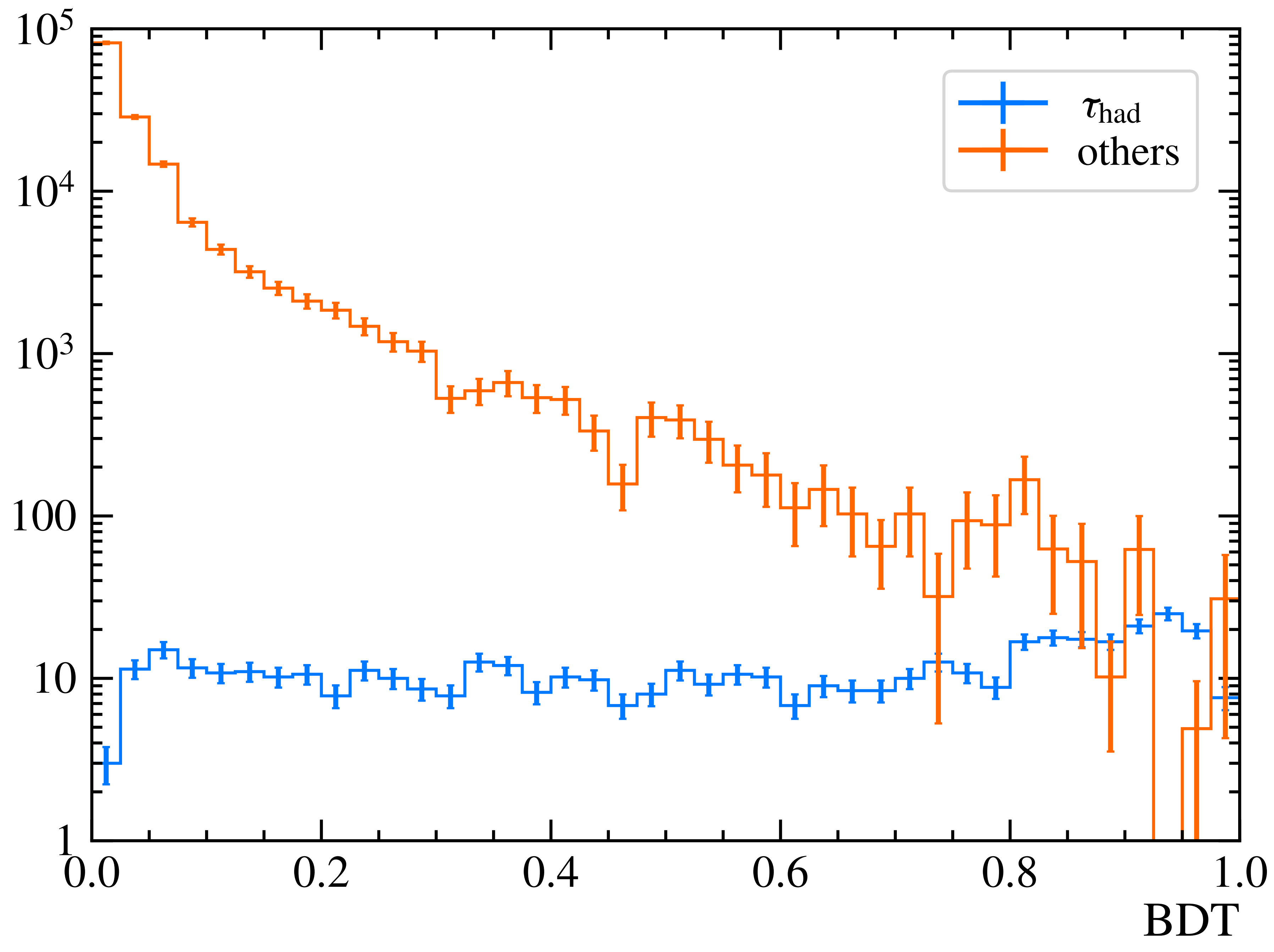
- Find the most energetic π^- shower of each event
  - Search for showers around the leading π^-

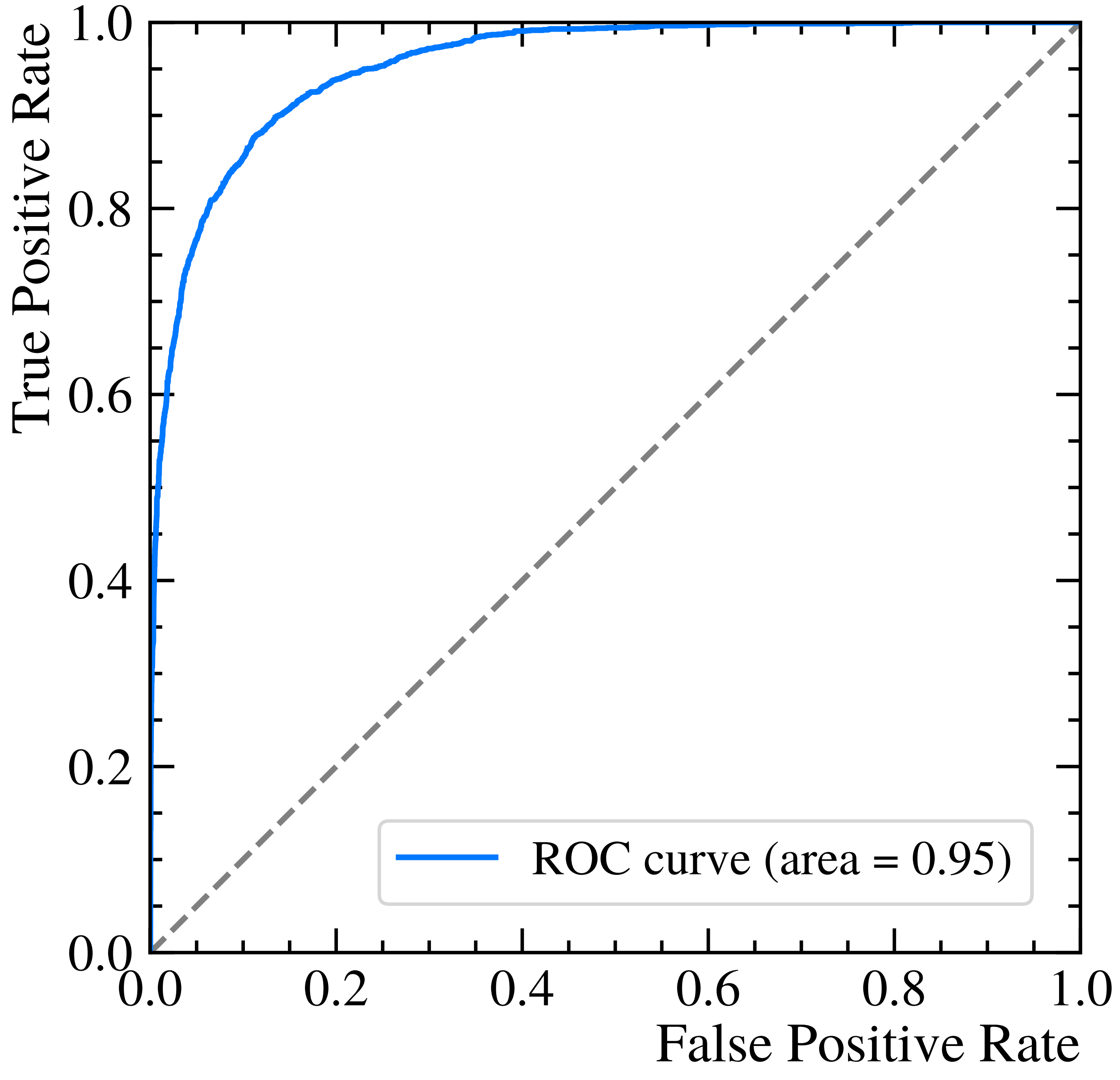


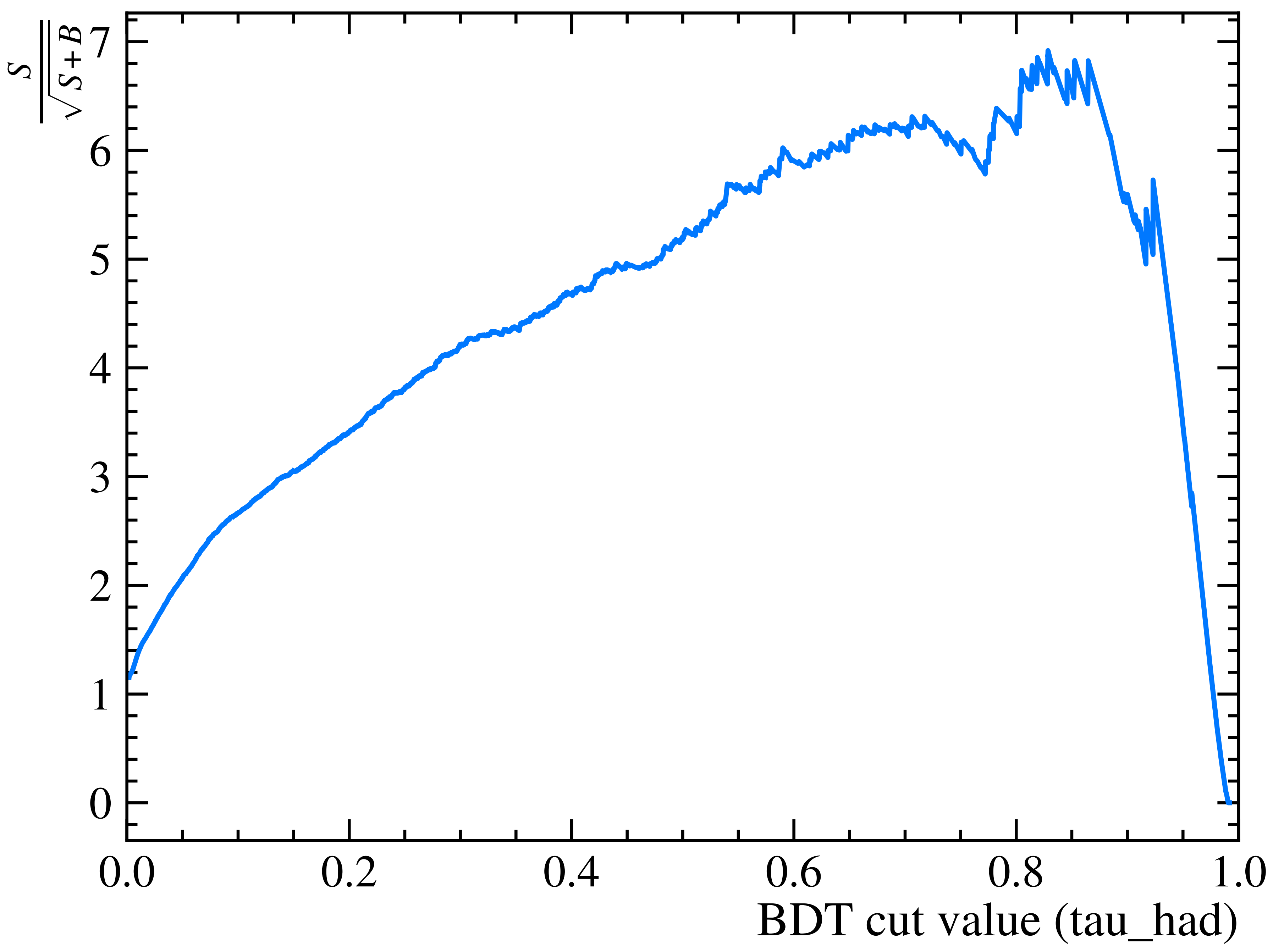
UCIRVINE

GradientBoostingClassifier

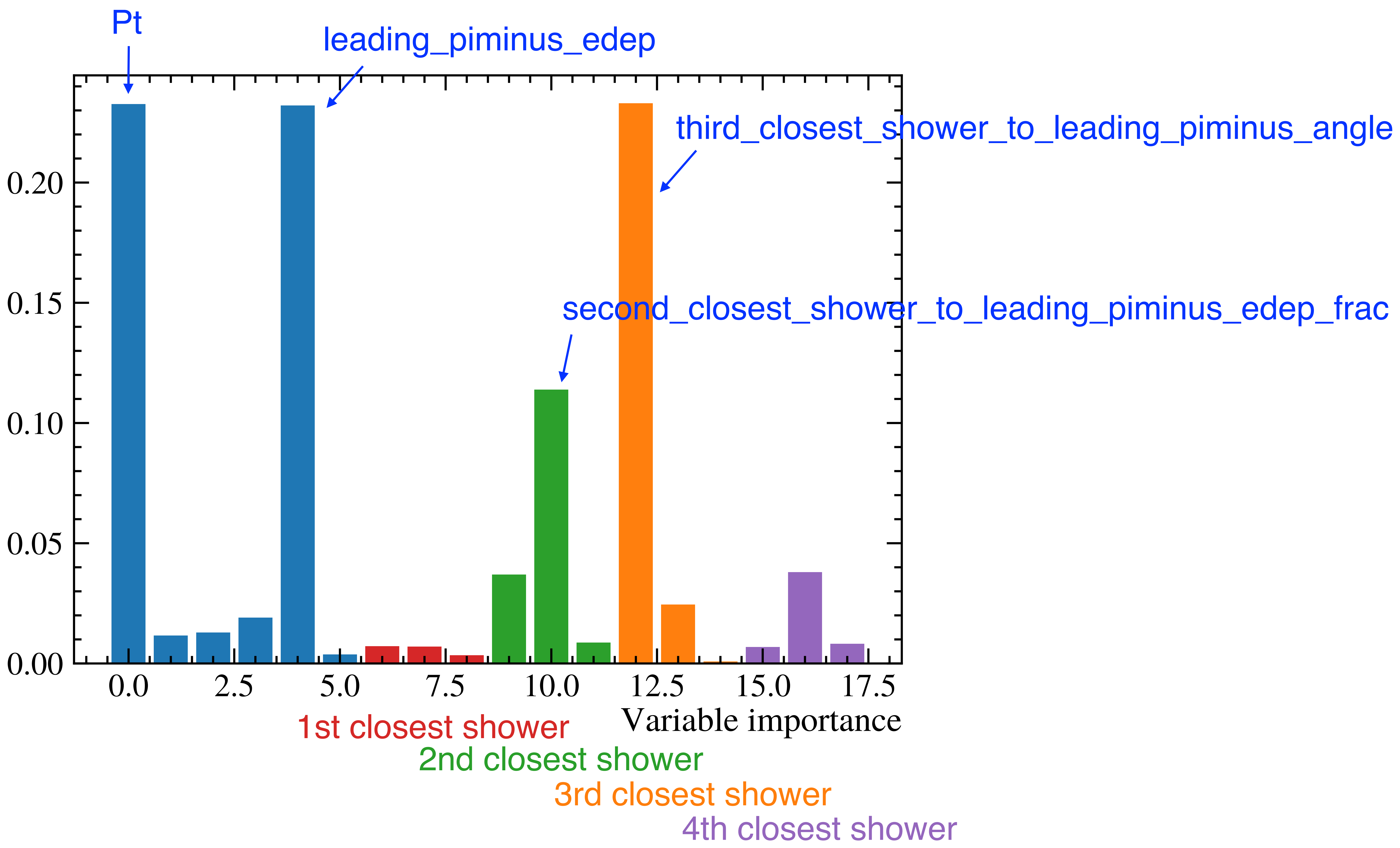
- τ_{had}/others
- Training:Testing = 1:1
- Testing sample (scaled): 454.6 signal, 155,345.9 background
- Define FOM, find the optimum cut value is 0.83, with N_{sig}=122.8, N_{bkg}=192.3, FOM=6.92





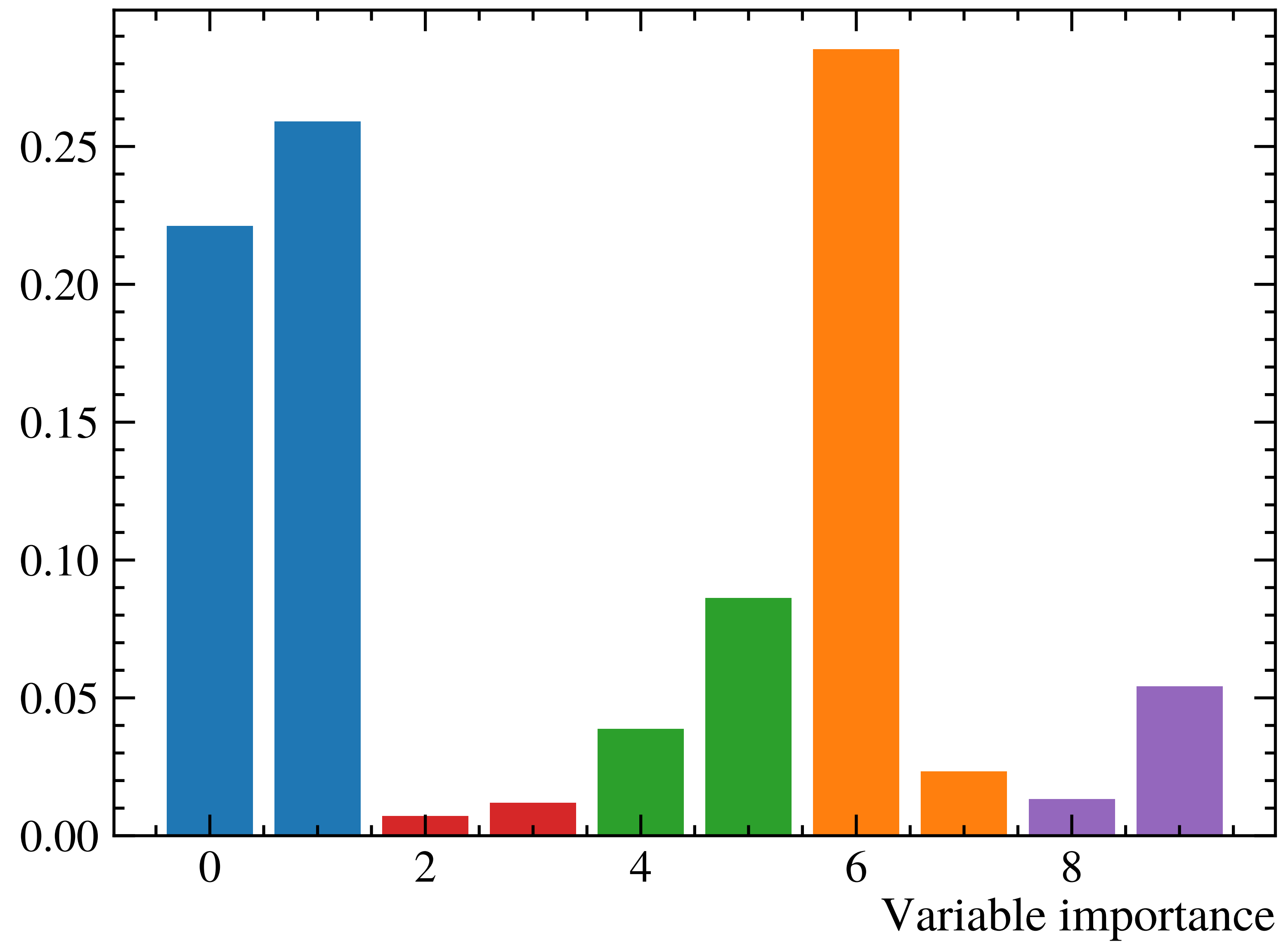


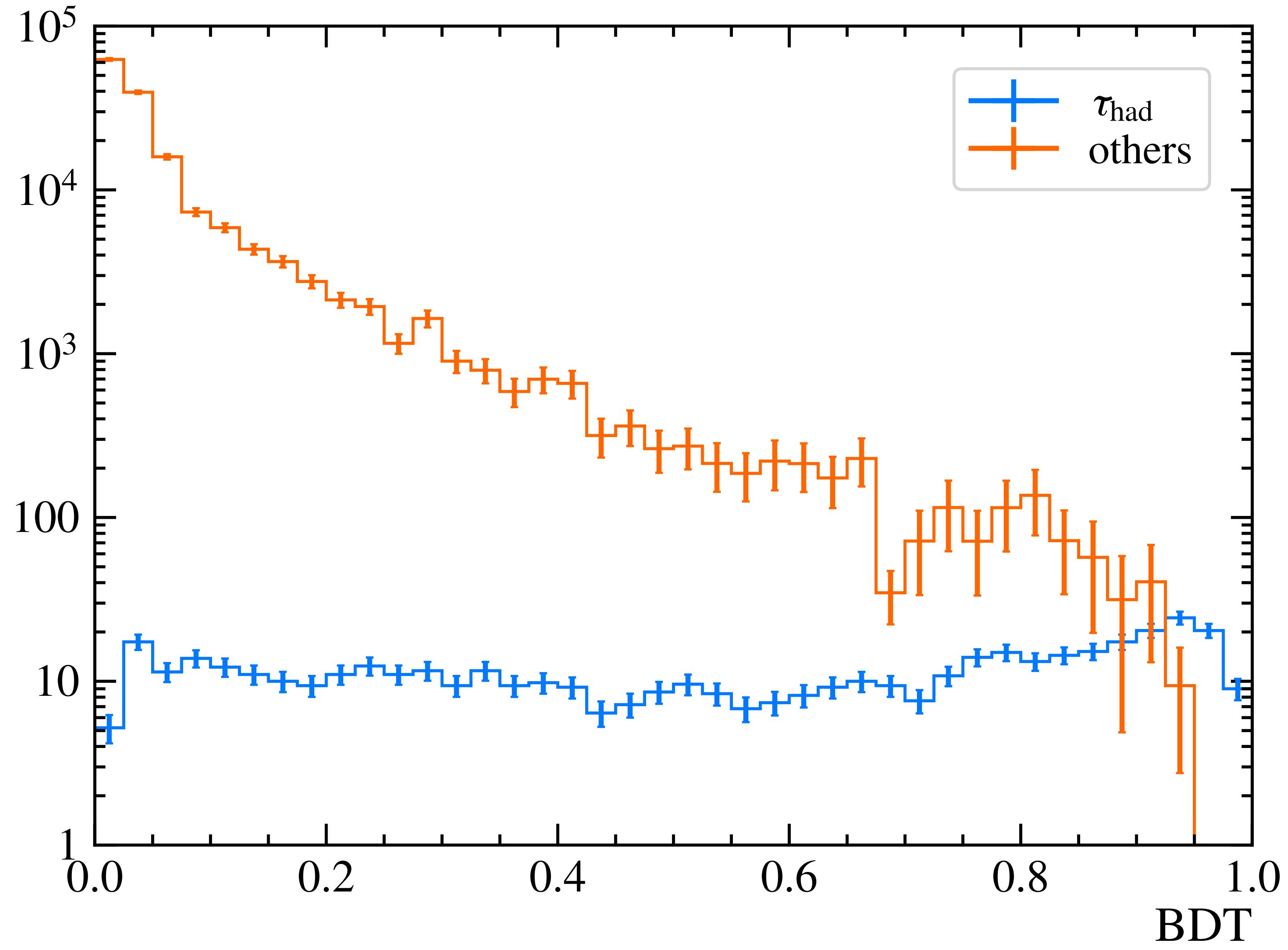
GradientBoostingClassifier

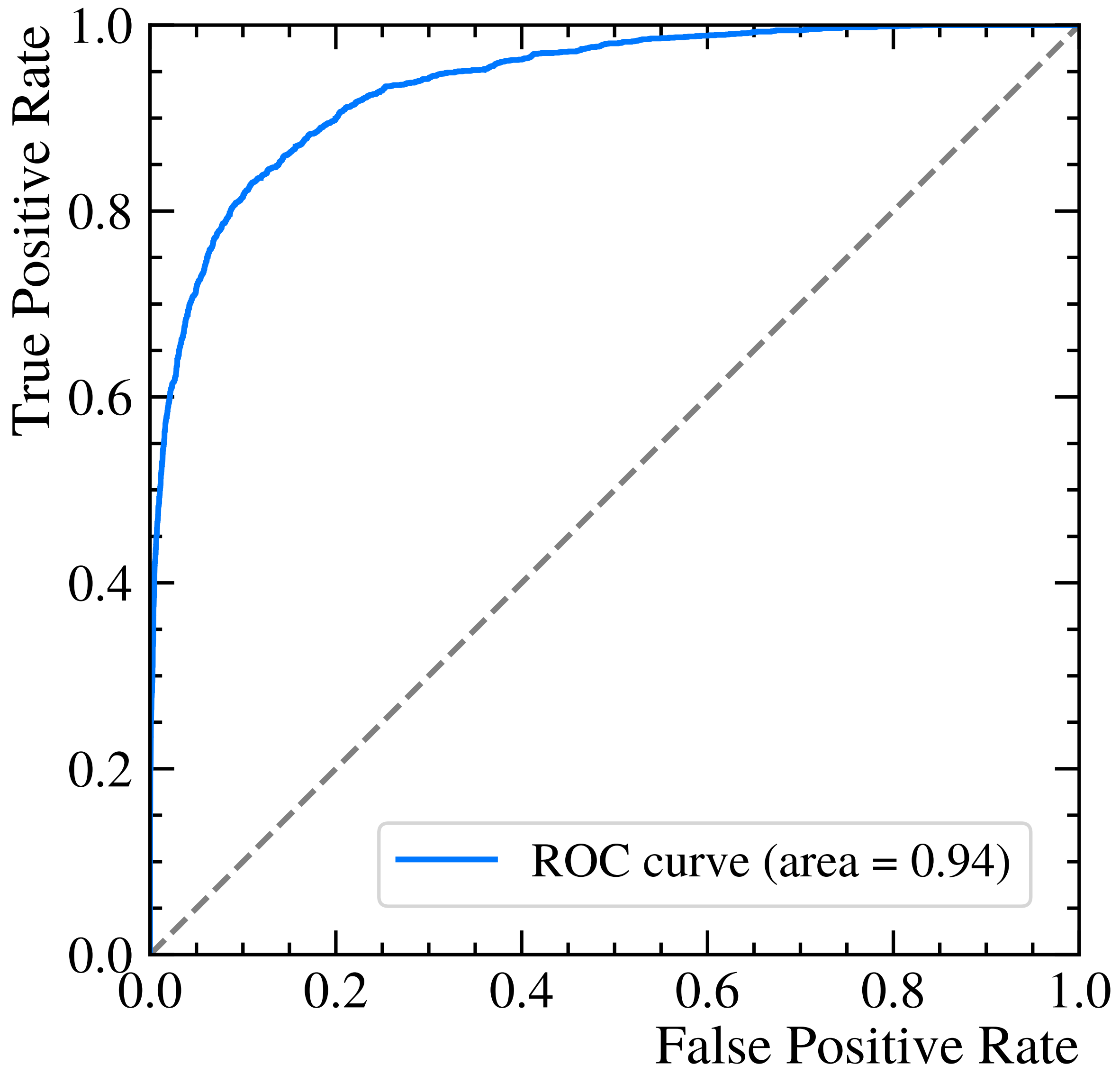


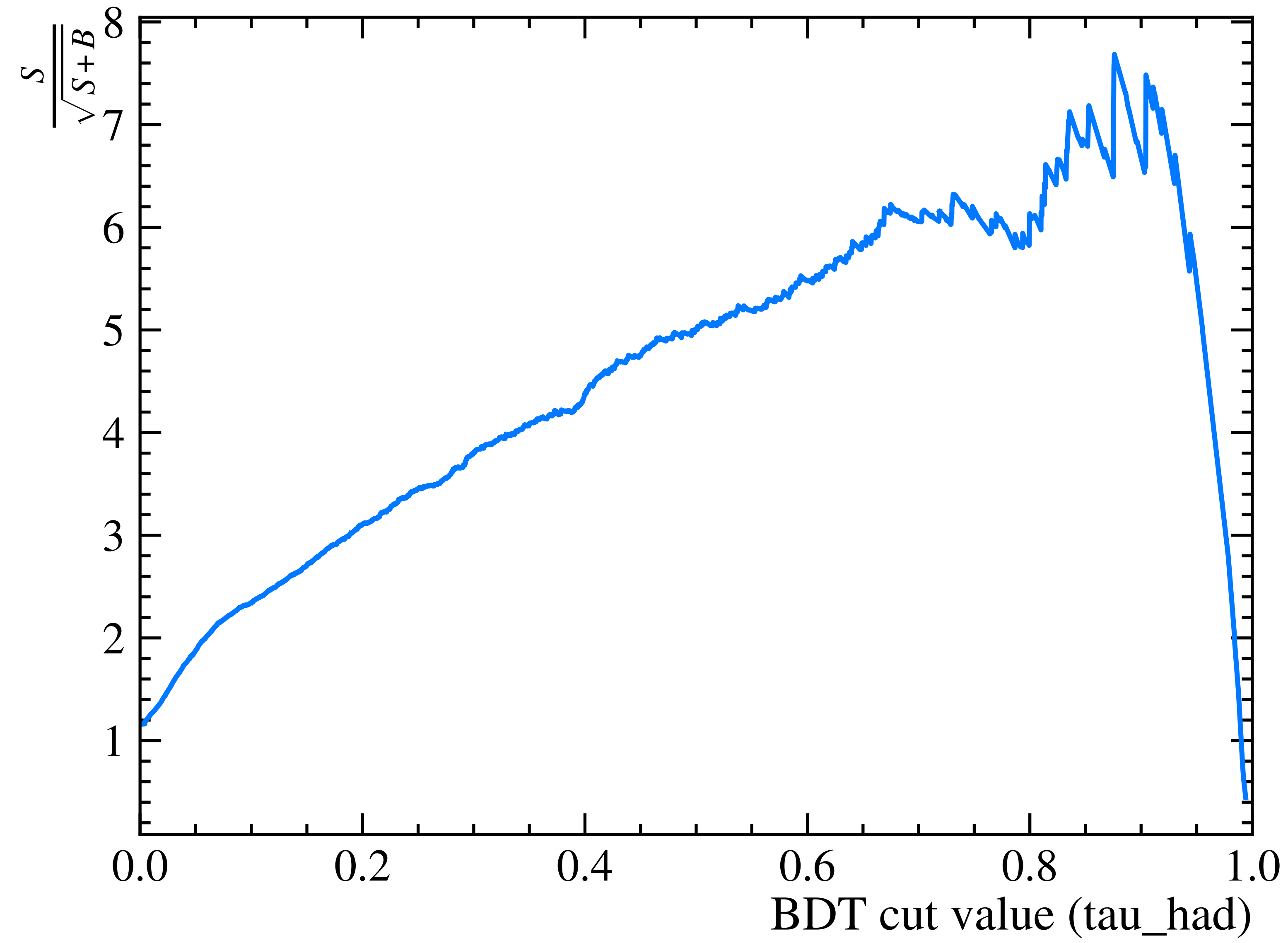
GradientBoostingClassifier

- Pt, leading_piminus_edep, angle and edep_frac of 4 showers
- Testing sample: 458.8 signal, 155,599.7 background
- The optimum cut value is 0.88, with N_{sig}=91.6, N_{bkg}=50.5, FOM=7.68









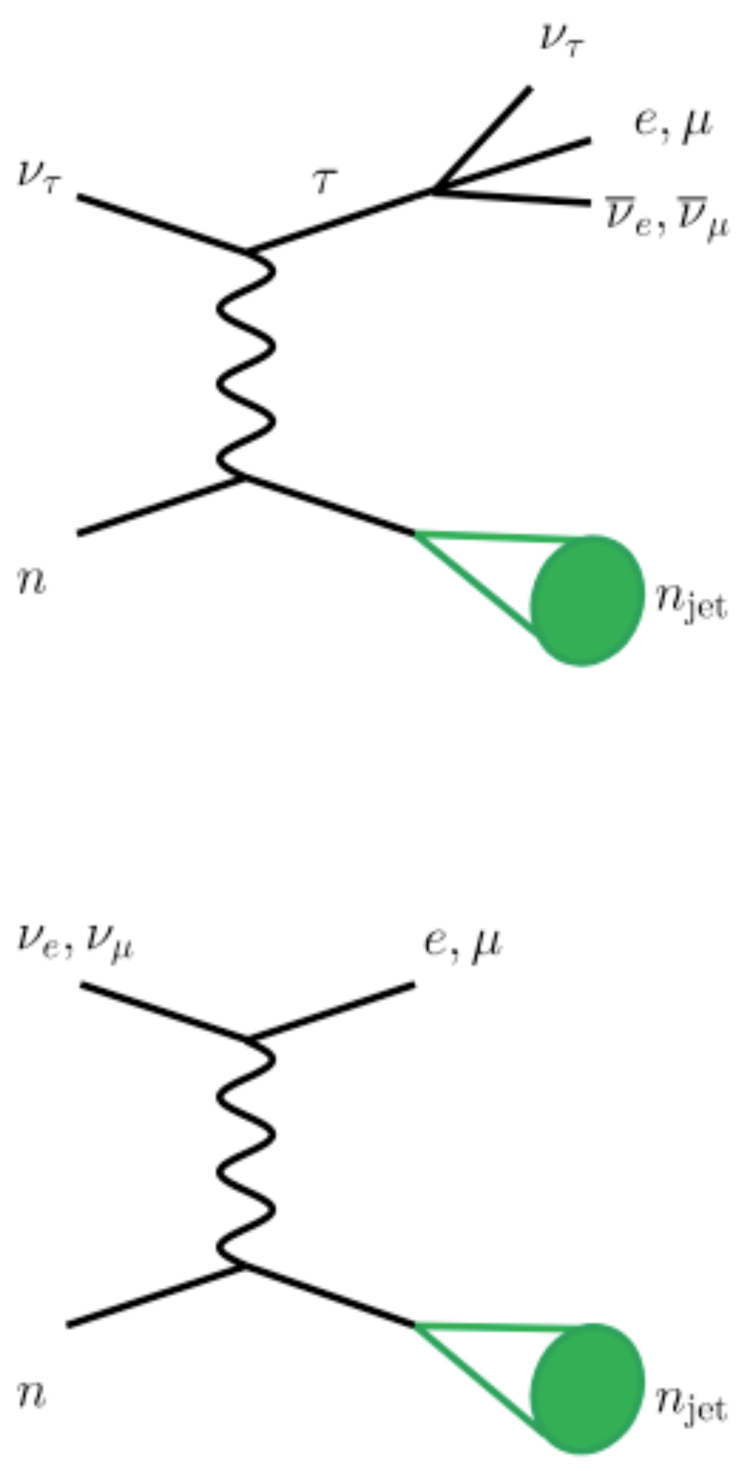
UCIRVINE

Leptonic decay

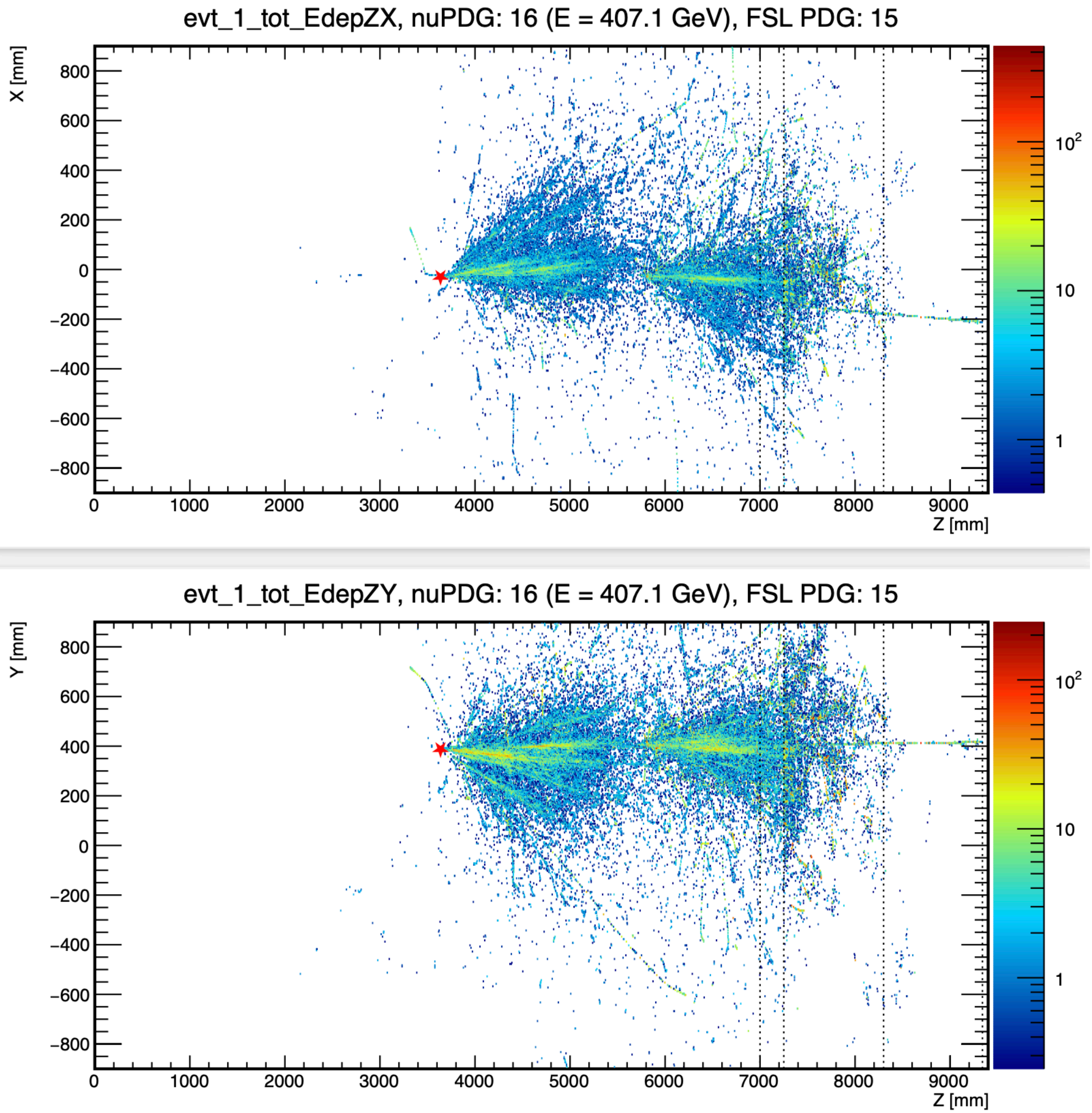
- Signal: τ_μ (tau decays to muon)
  - τ_μ will leave a muon track in the detector, like ν_μ CC

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

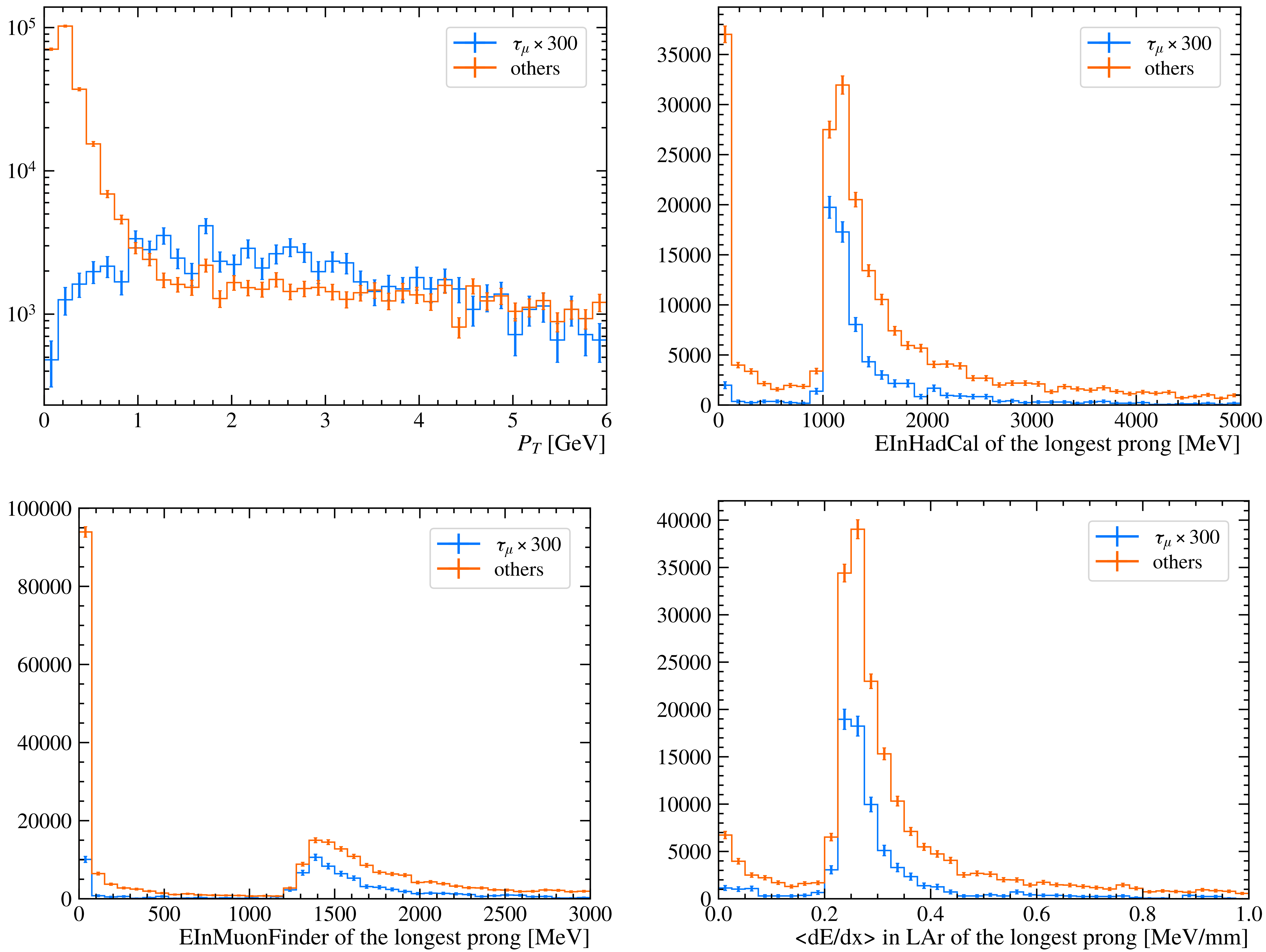
Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
Other	5.7%



10.1103/PhysRevD.102.053010

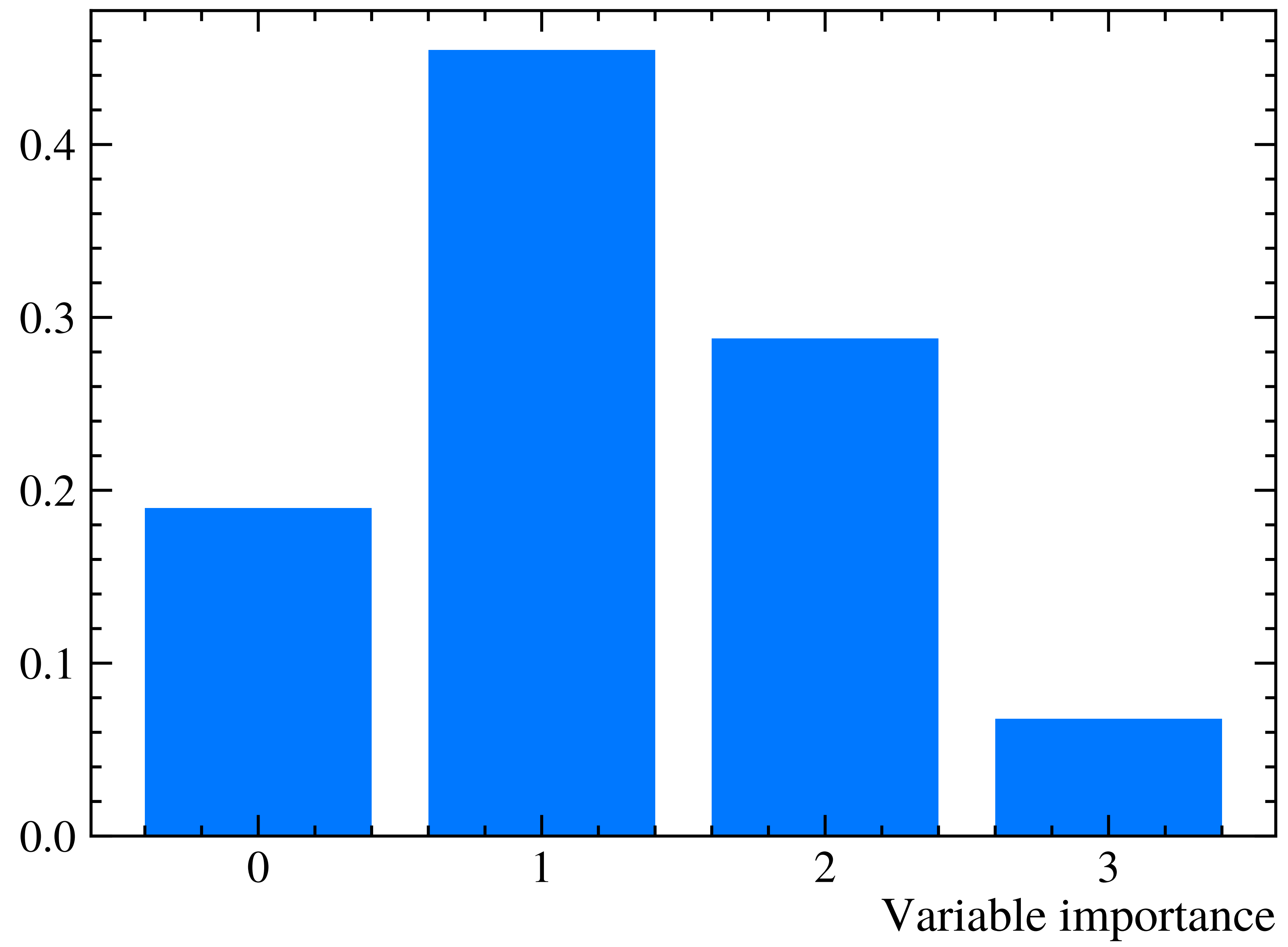


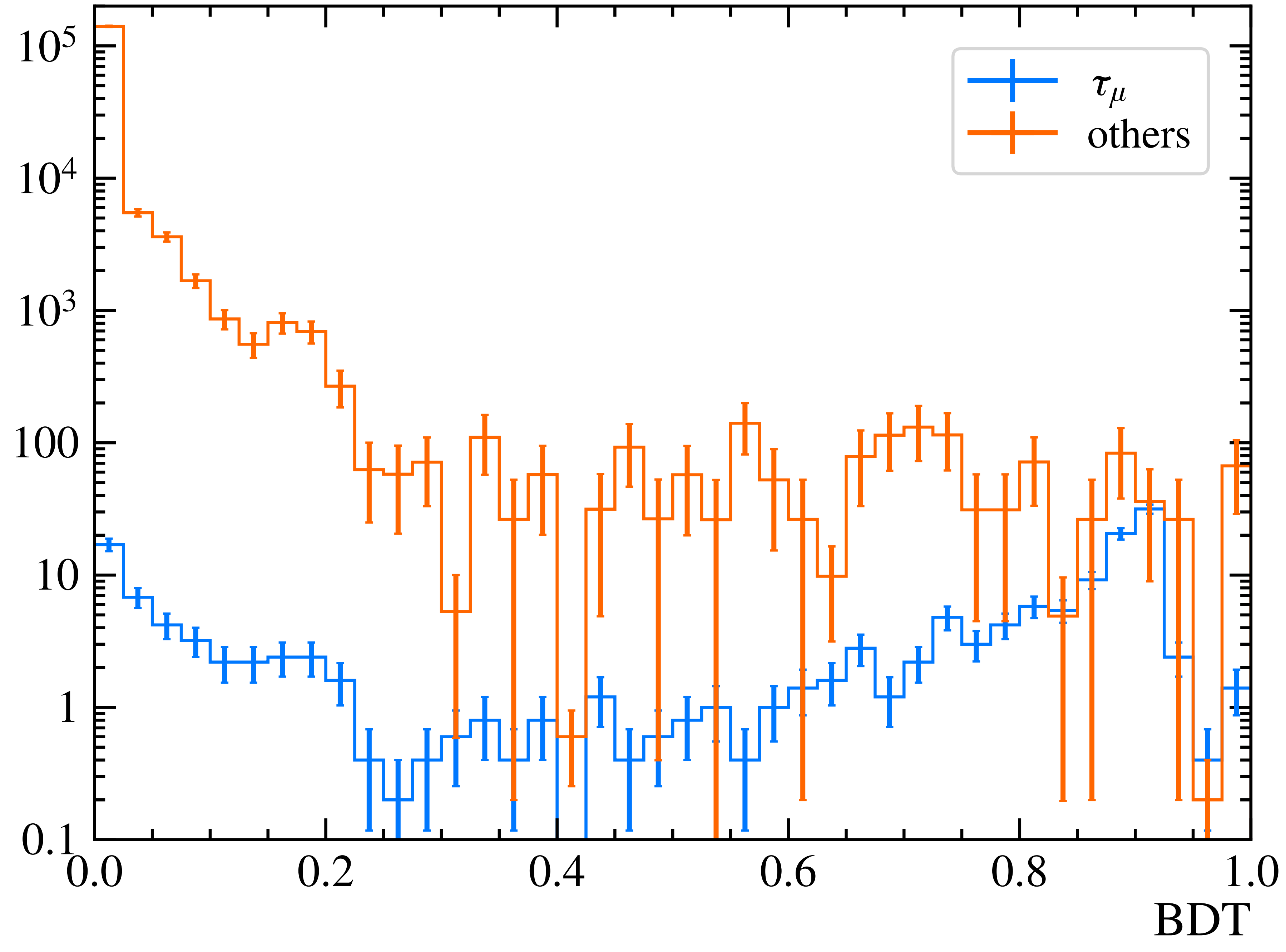
Leptonic decay

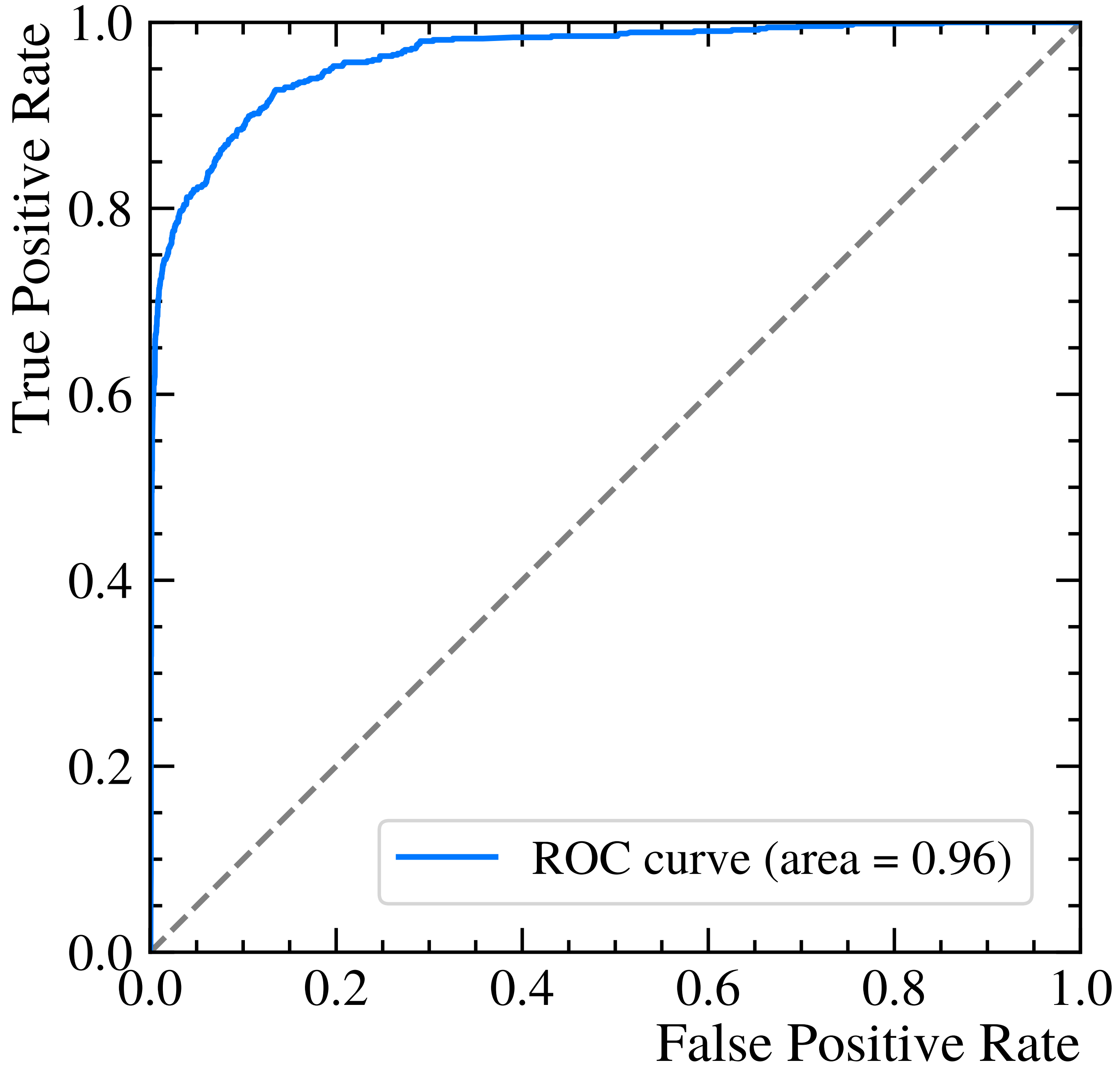


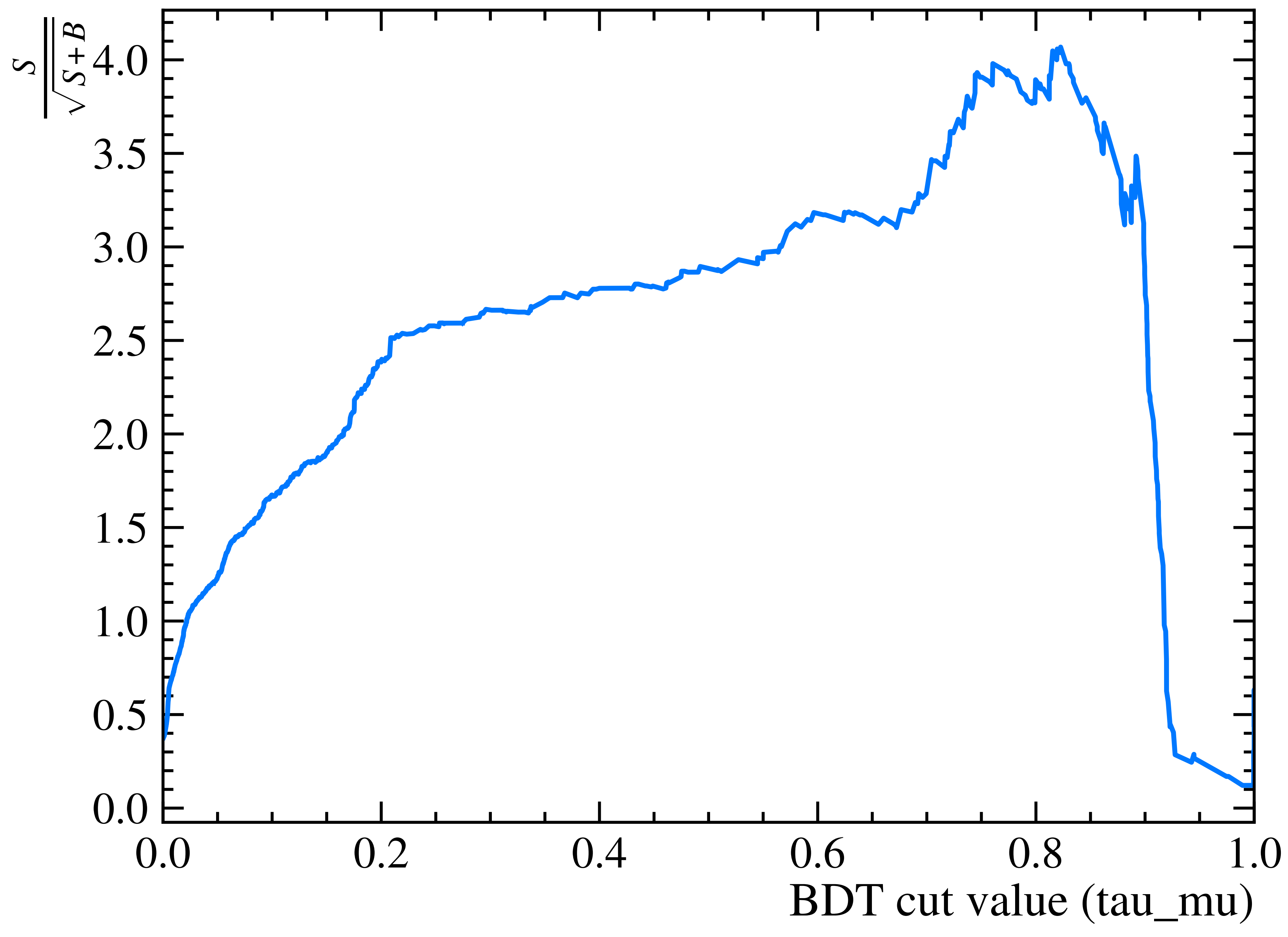
Leptonic decay

- τ_μ/others
- Training:Testing = 1:1
- Testing sample: 149 signal, 156,033.5 background
- Define FOM, find the optimum cut value is 0.82, with N_{sig}=72.4, N_{bkg}=244.3, FOM=4.07



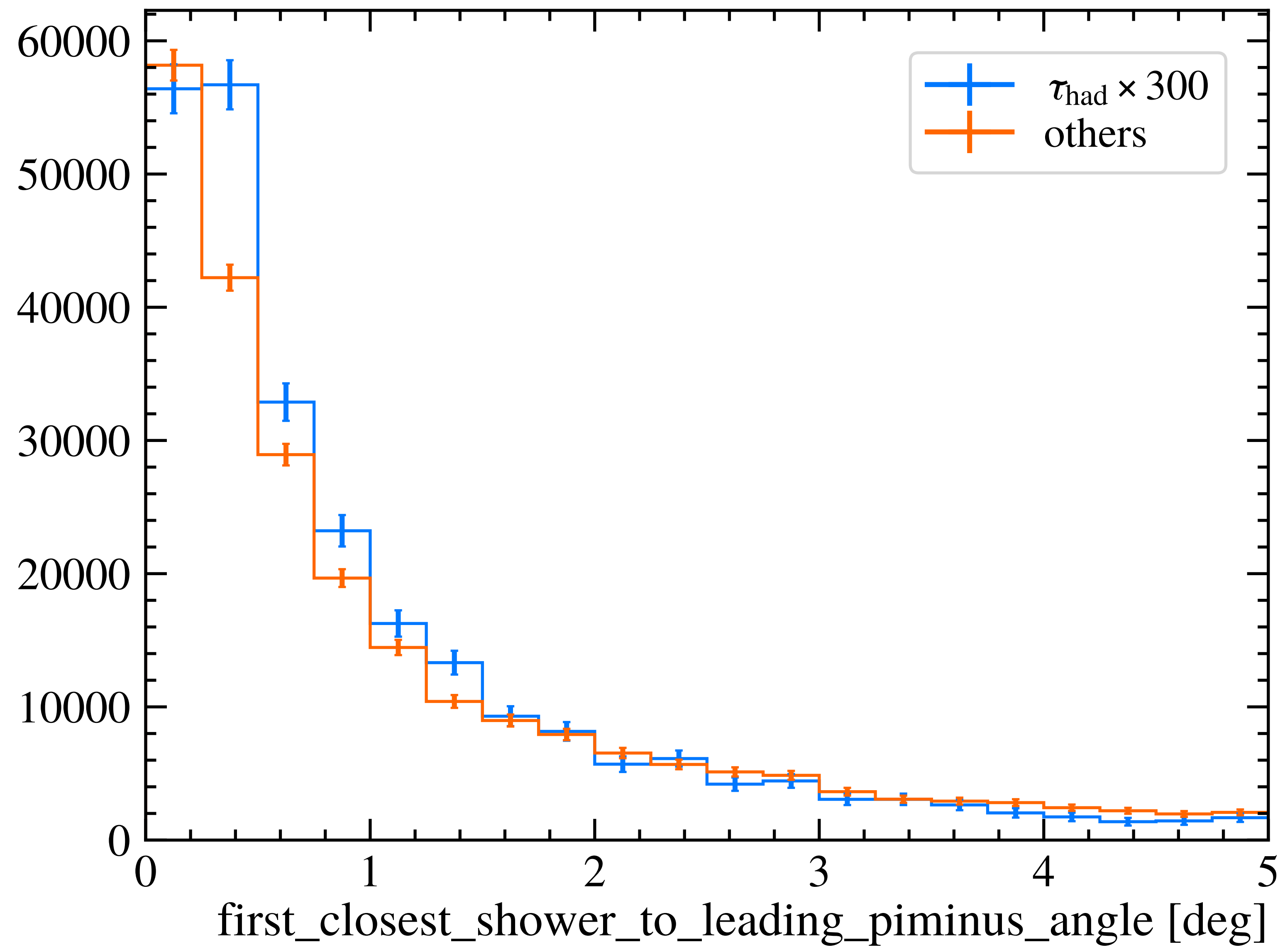


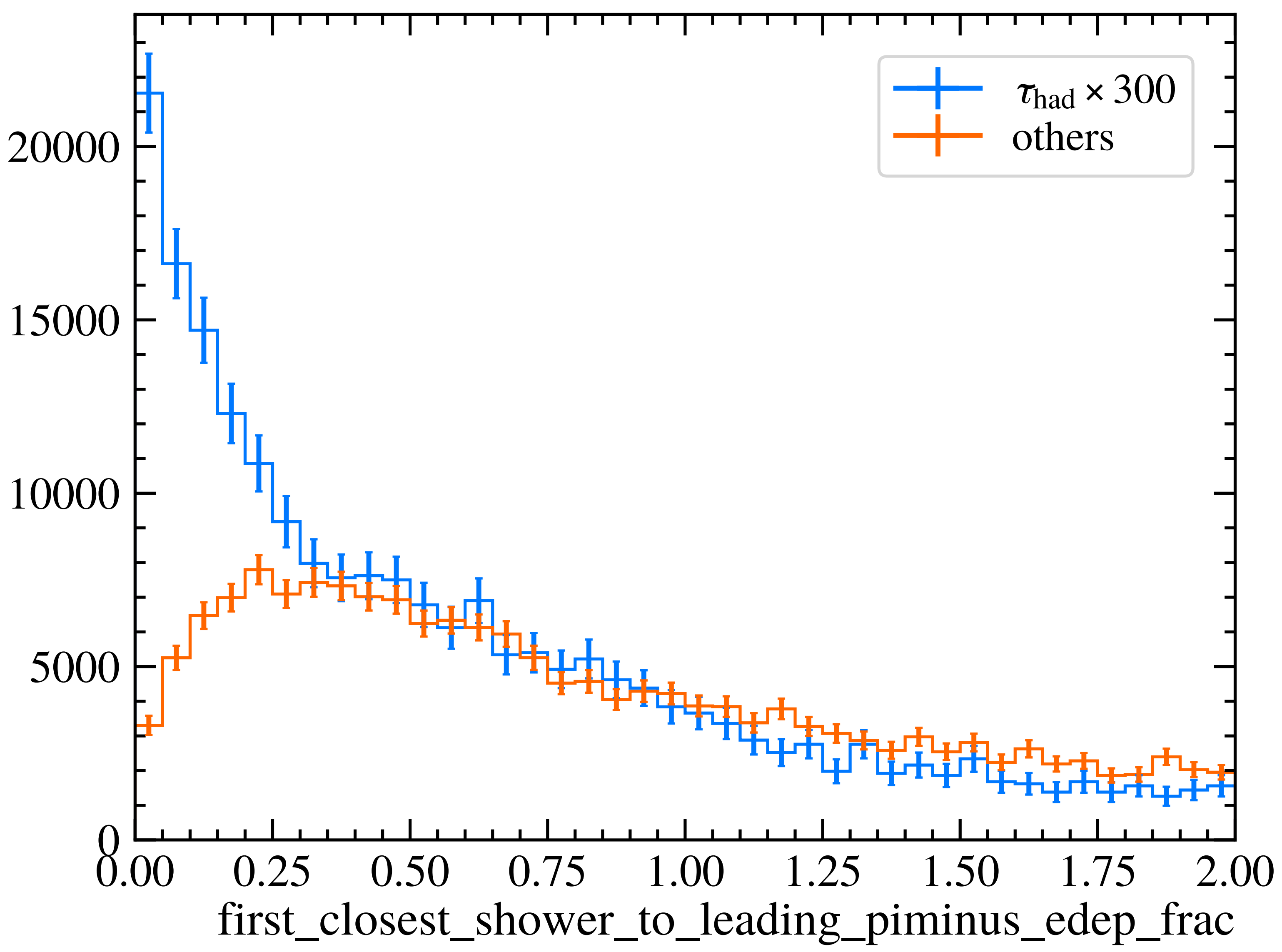




Detector requirement

- The event classifiers are trained based on MC truth information
- We can add smearing to the angle, deposited energy et.al, and then check how do they affect the classification capability. It should be able to provide some insight on the requirement of the detector





UCIRVINE

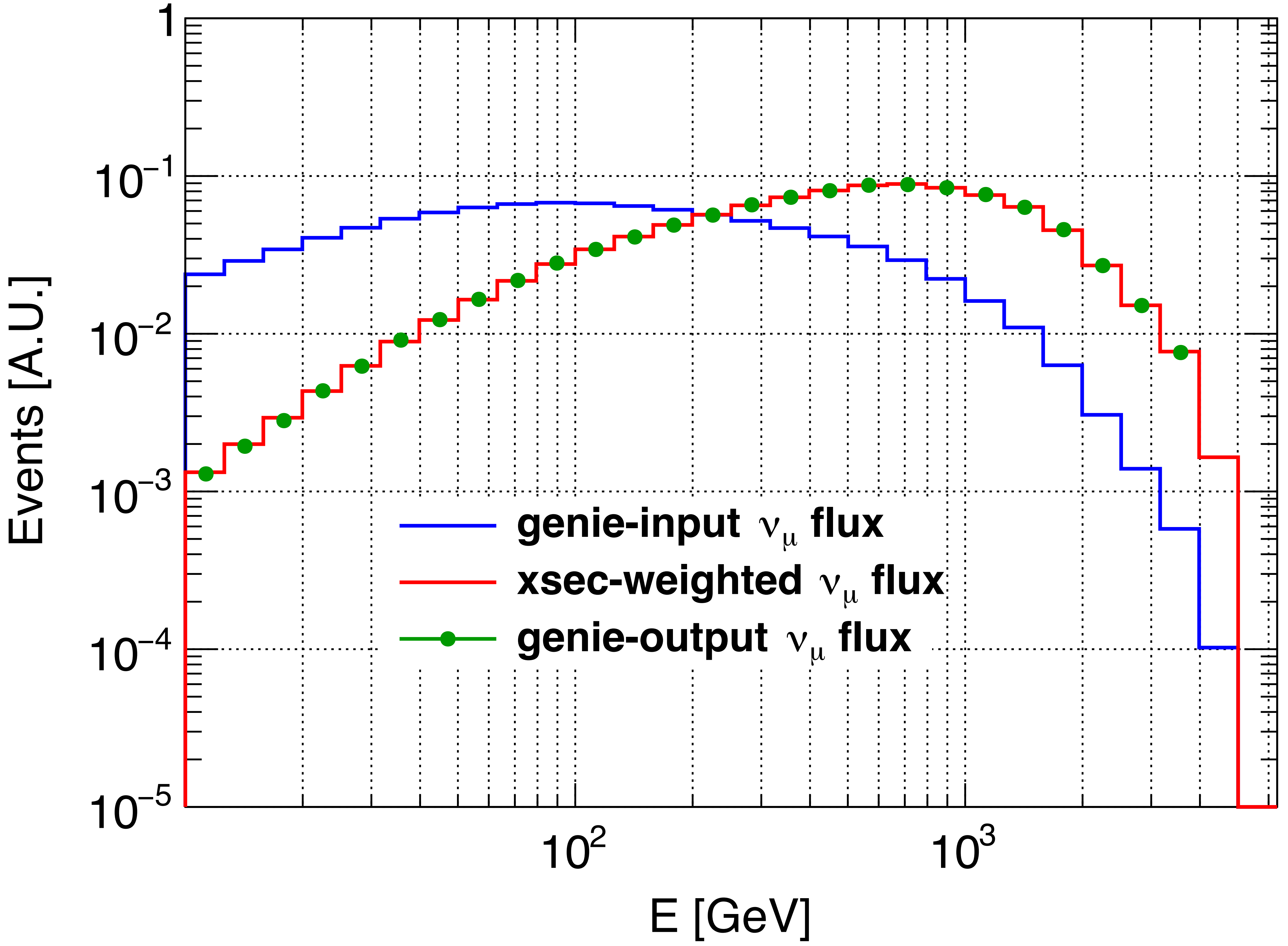
Summary and next steps

- With different transverse cuts, detector sizes with 3m - 2m width/height don't show noticeable difference
  - Currently use 1.8x1.8x7 m geometry
- With HadCal, energy loss for events happened at the downstream of the detector can be effectively recorded
  - The energy deposited in HadCal can be reconstructed by the energy recorded in the scintillator layers
- MuonFinder can be used to effectively tag the muons
  - We can tune the thickness of steel layers or the number of layers to have a better muon acceptance
- The event classifiers trained based on the pseudo-reconstructed variables for τ_{had} and τ_{μ} look promising, while for τ_e it will be more challenging which is still under investigation

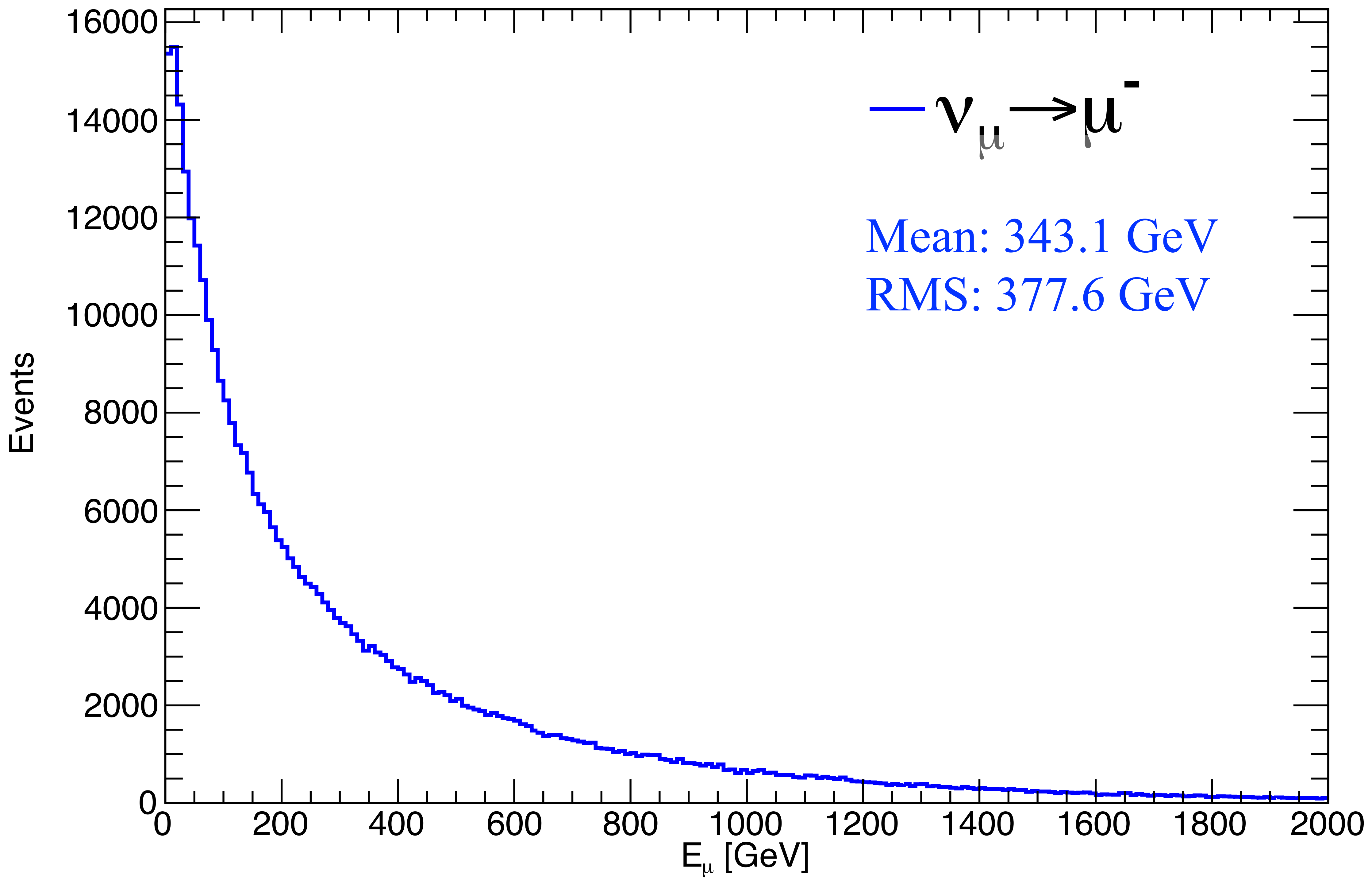
- Large statistical fluctuation, will generate a larger sample
- Will keep looking into other possibilities for event classification
- Including muon background as well

Backup

GENIE simulation: ν_μ

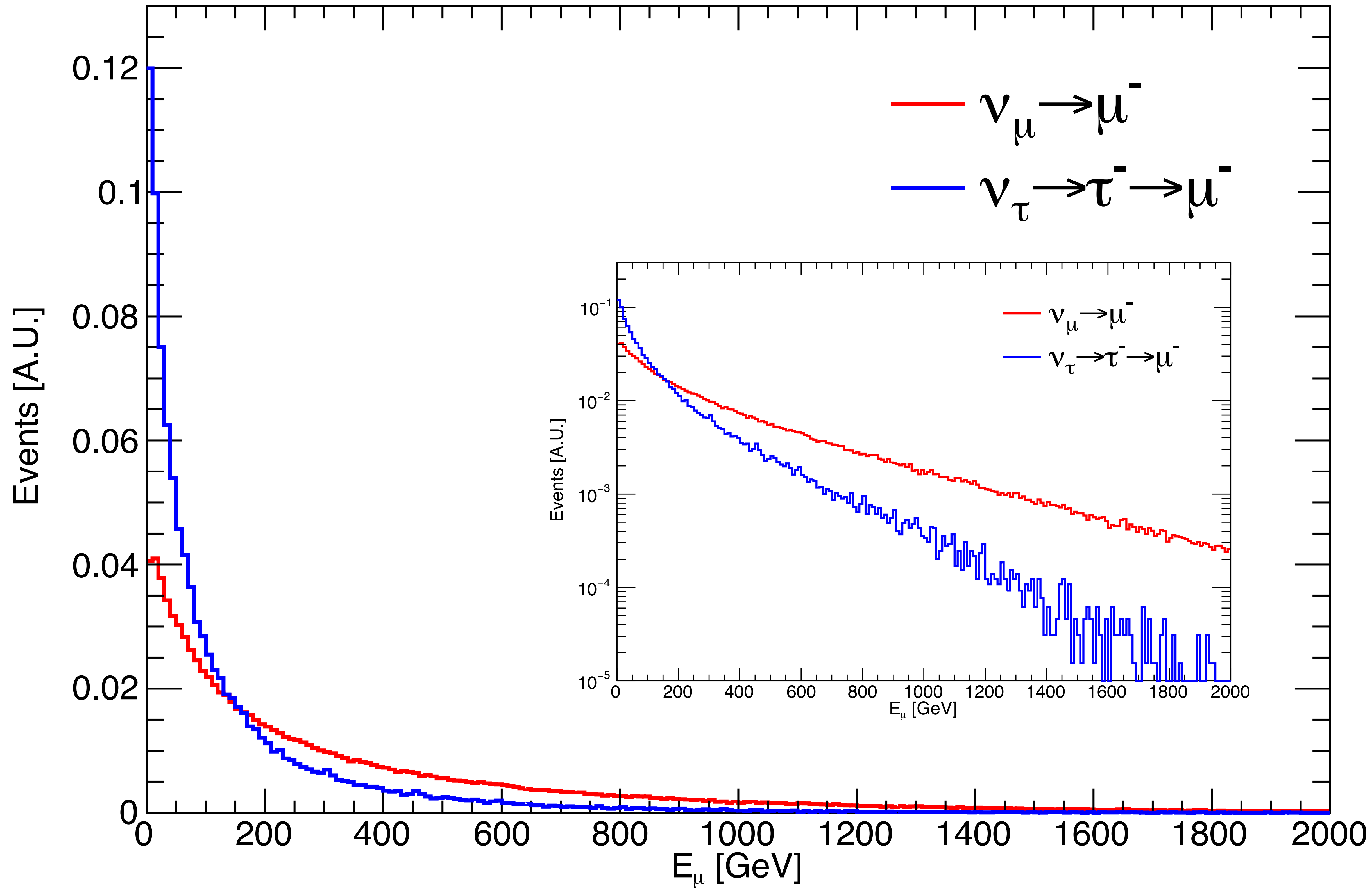


Muon energy spectrum $\nu_\mu \to \mu^-$



Felix Kling, et. al. 2105.08270

GENIE simulation



$\nu_\mu \to \mu^-$
Mean: 343.1 GeV
RMS: 377.6 GeV

$\nu_\tau \to \tau^- \to \mu^-$
Mean: 146.0 GeV
RMS: 201.0 GeV

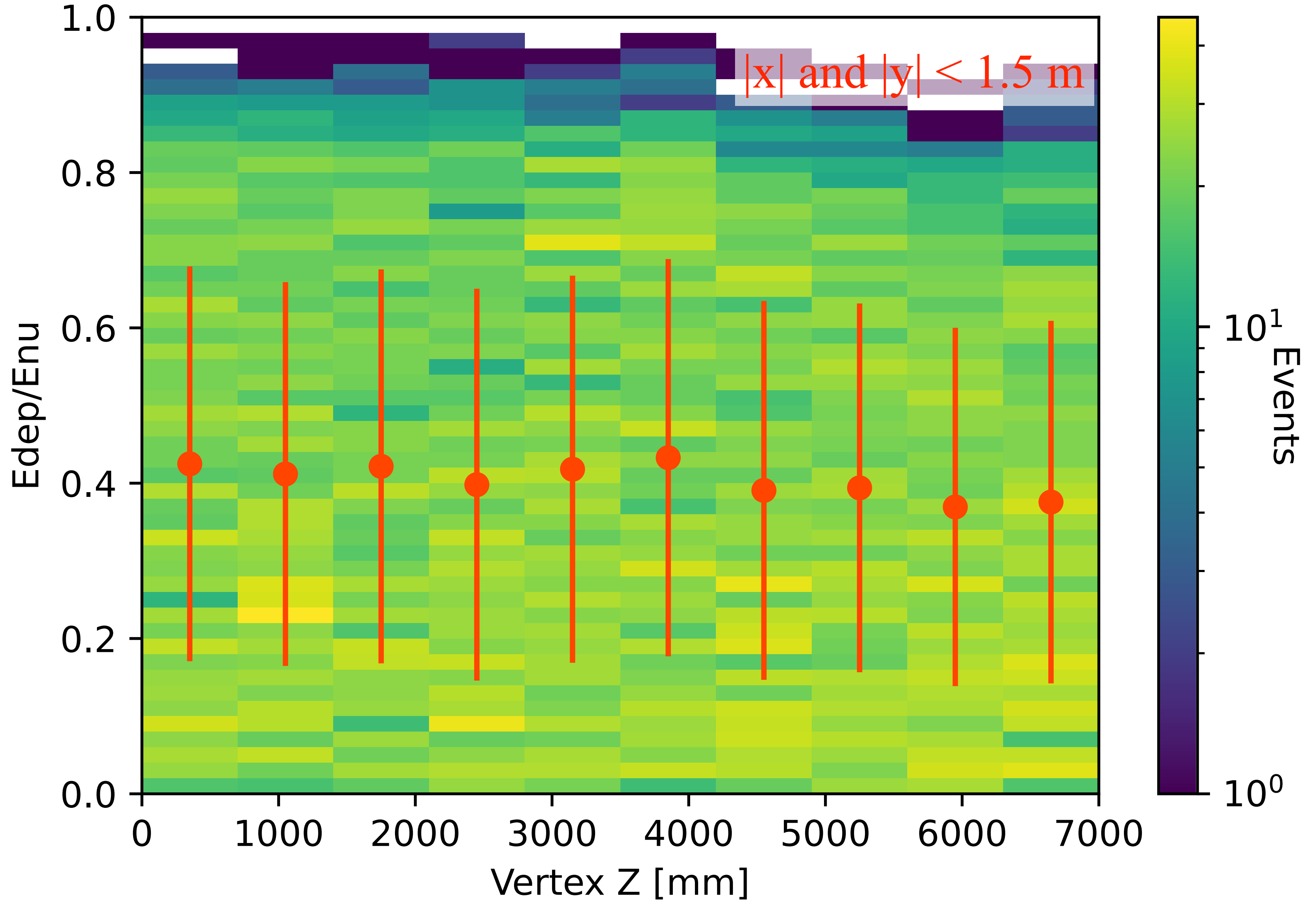
Felix Kling, et. al. 2105.08270

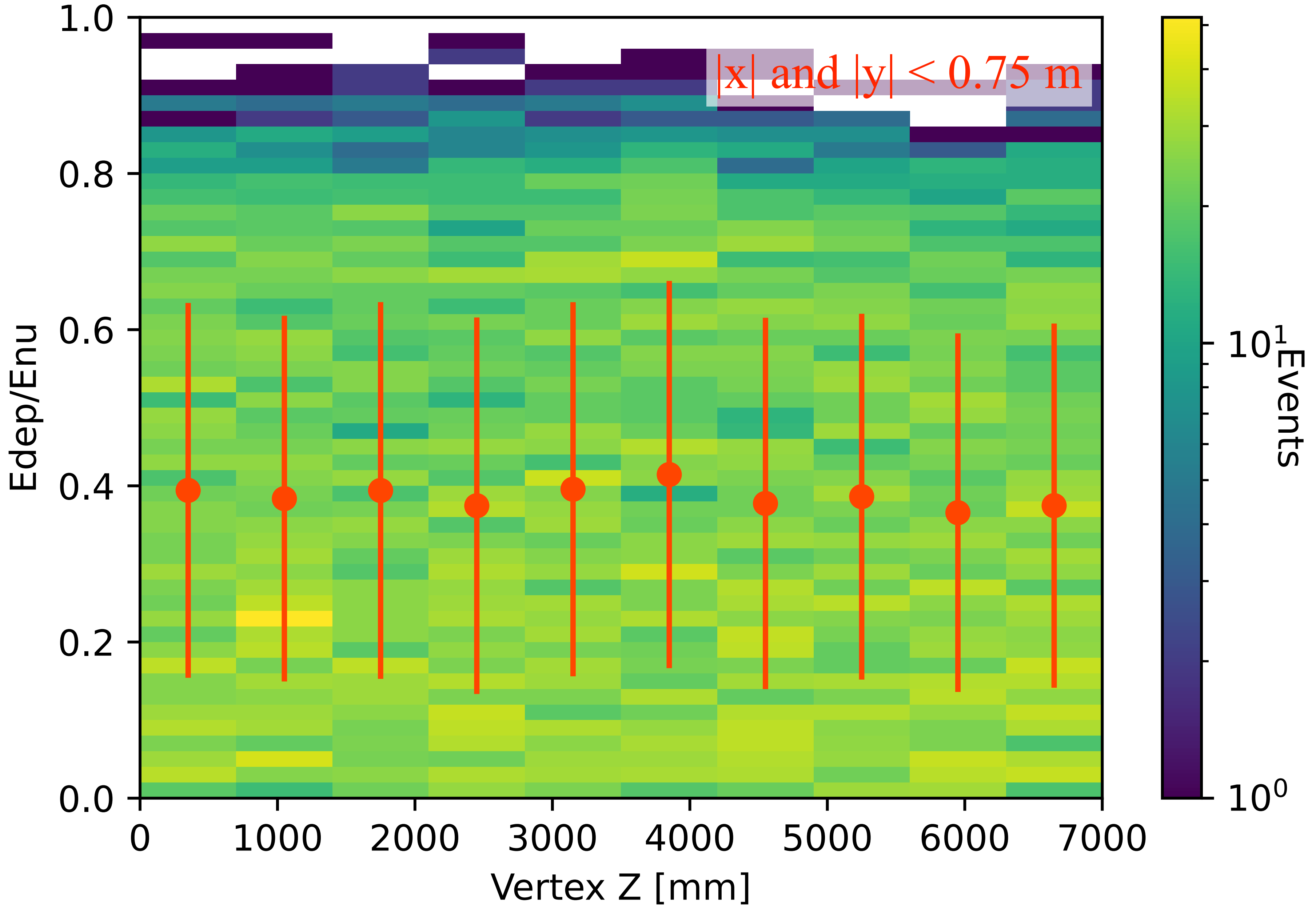
Muon energy spectrum, area normalized

Muon from tau decay is softer

Energy containment w/ the HadCal (ν_μ)

- 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 hadCal can save loss energies for events happened in the downstream of the detector
  - The containment becomes flat for both transverse cuts





Energy containment w/ HadCal (ν_e)

- 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 hadCal can save loss energies for events happened in the downstream of the detector
  - The containment becomes flat for both transverse cuts