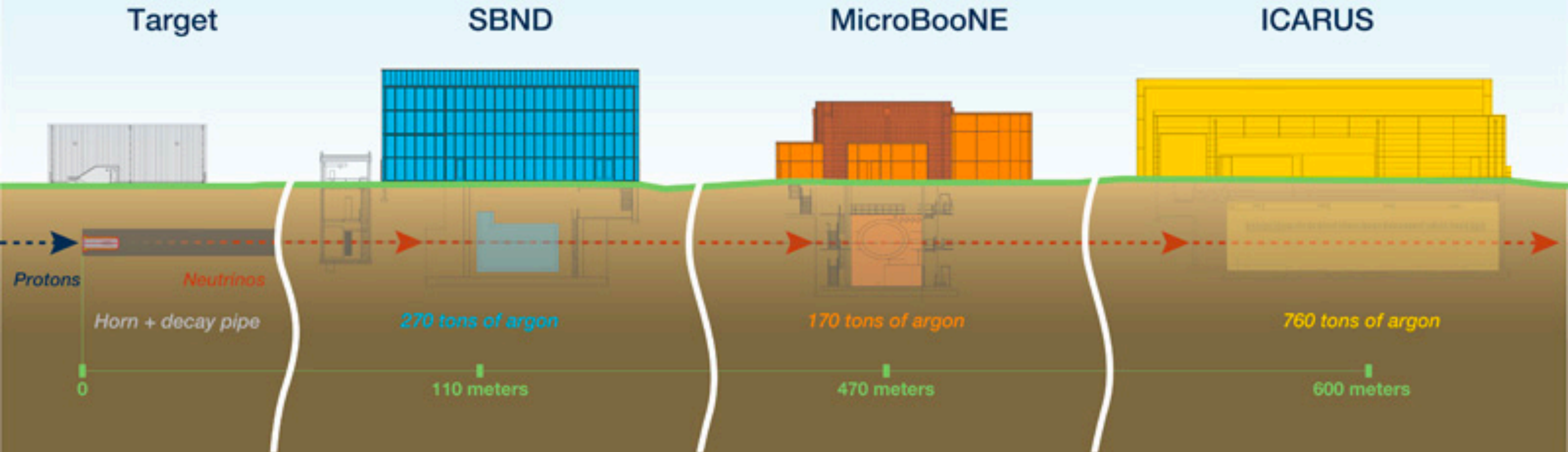# Cosmogenic Background Suppression at ICARUS

Biswaranjan Behera
Colorado State University
for the ICARUS Collaboration

NuFACT 2022
August 05, 2022

# Short-Baseline Neutrino Program at Fermilab

Target — Horn + decay pipe — 0

SBND — 270 tons of argon — 110 meters

MicroBooNE — 170 tons of argon — 470 meters

ICARUS — 760 tons of argon — 600 meters

Protons — Neutrinos

Three Liquid Argon Time Projection Chamber (LArTPC) detectors located along the Booster Neutrino Beamline (BNB) at Fermilab

Short Baseline Neutrino

ICARUS : Imaging Cosmic And Rare Underground Signals

- First large LArTPC: still one of the largest in operation

- Two cryostat: each 19.6 x 3.6 x 3.9 m^3

  760t total LAr mass / 476t active

- Two TPCs per cryostat, with a common central cathode:
  1.5 m drift length, E_{Drift}= 500V/cm, V_{Drift}~1.6 mm/µs,
  3 mm wire pitch

- Three readout wire planes per TPC, ≈54000 wires at
  0°, ±60° w.r.t. horizontal

- Ionization charge continuously read (400 ns sampling
  time) by three readout wire planes per TPC

- Each TPC has 90 8" PMTs, 15 phe/MeV deposited
  energy

- ~4π coverage of Cosmic Ray Tagger (CRT)

Wire planes (anode)

Cathode   Field cage   PMTs

Short Baseline Neutrino
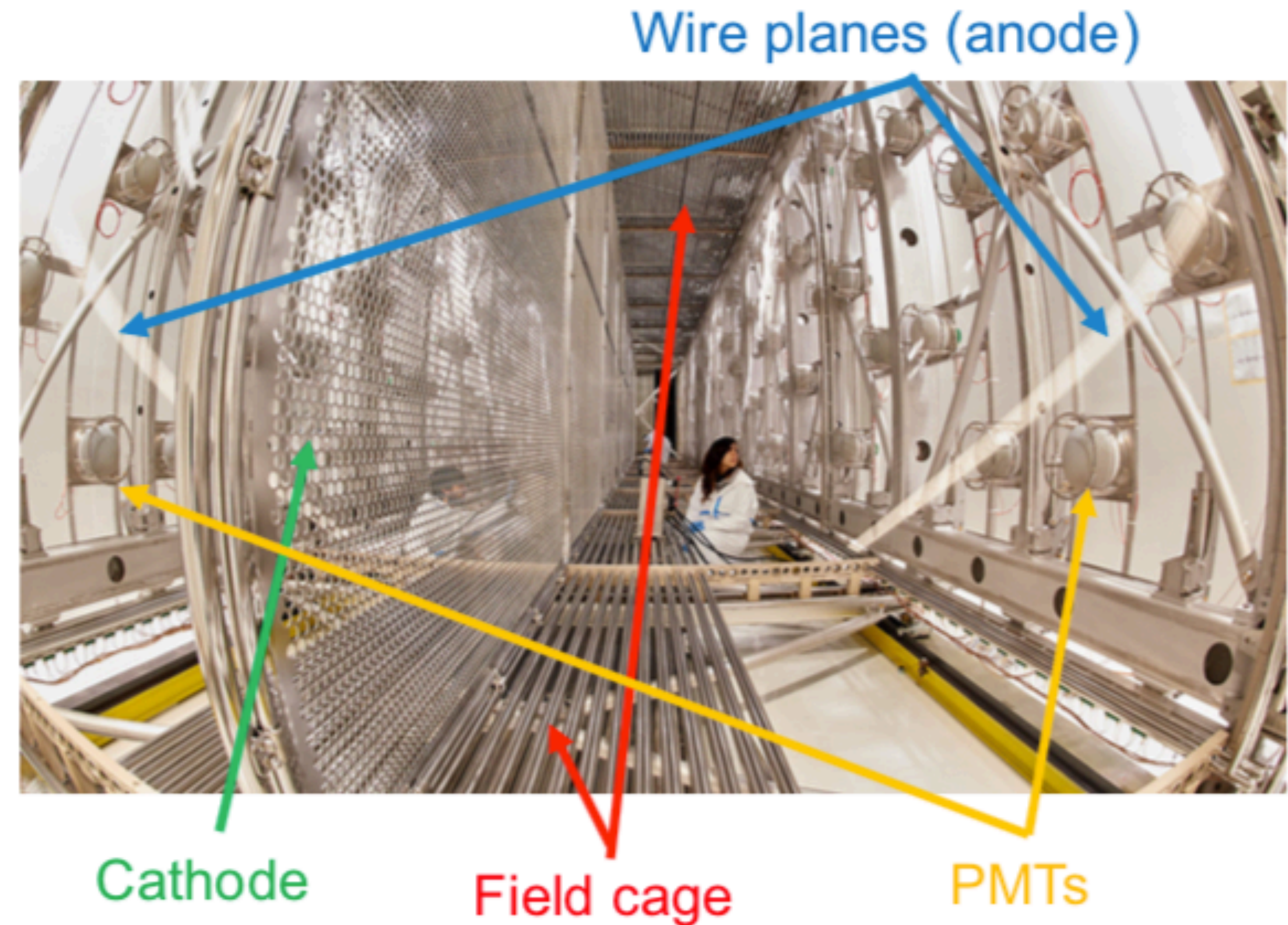
SBN expected sensitivities

The combined analysis of near and far detector data will allow to cover the currently allowed parameter region with 5σ sensitivity both in appearance and disappearance channels in 3 years of data taking
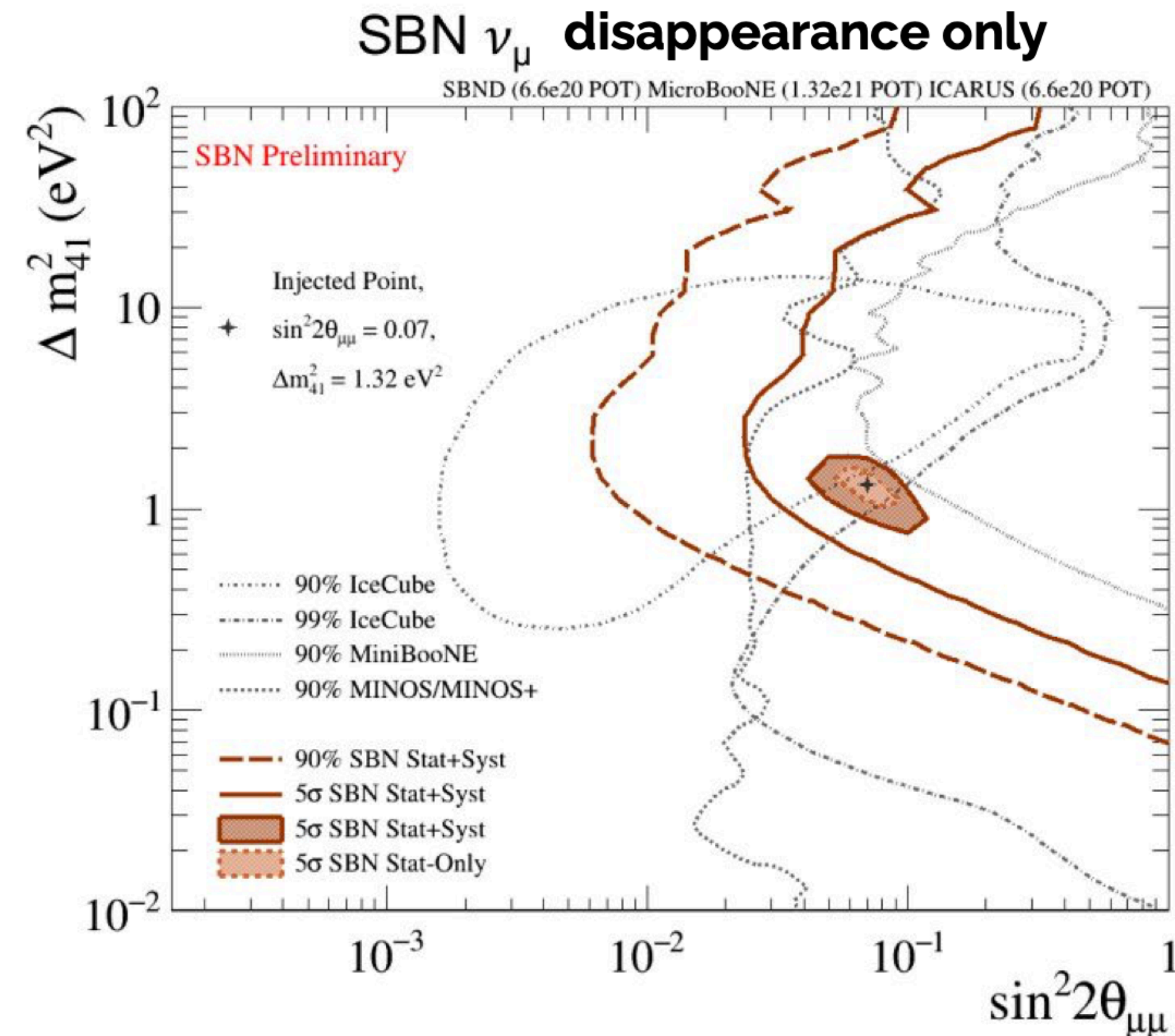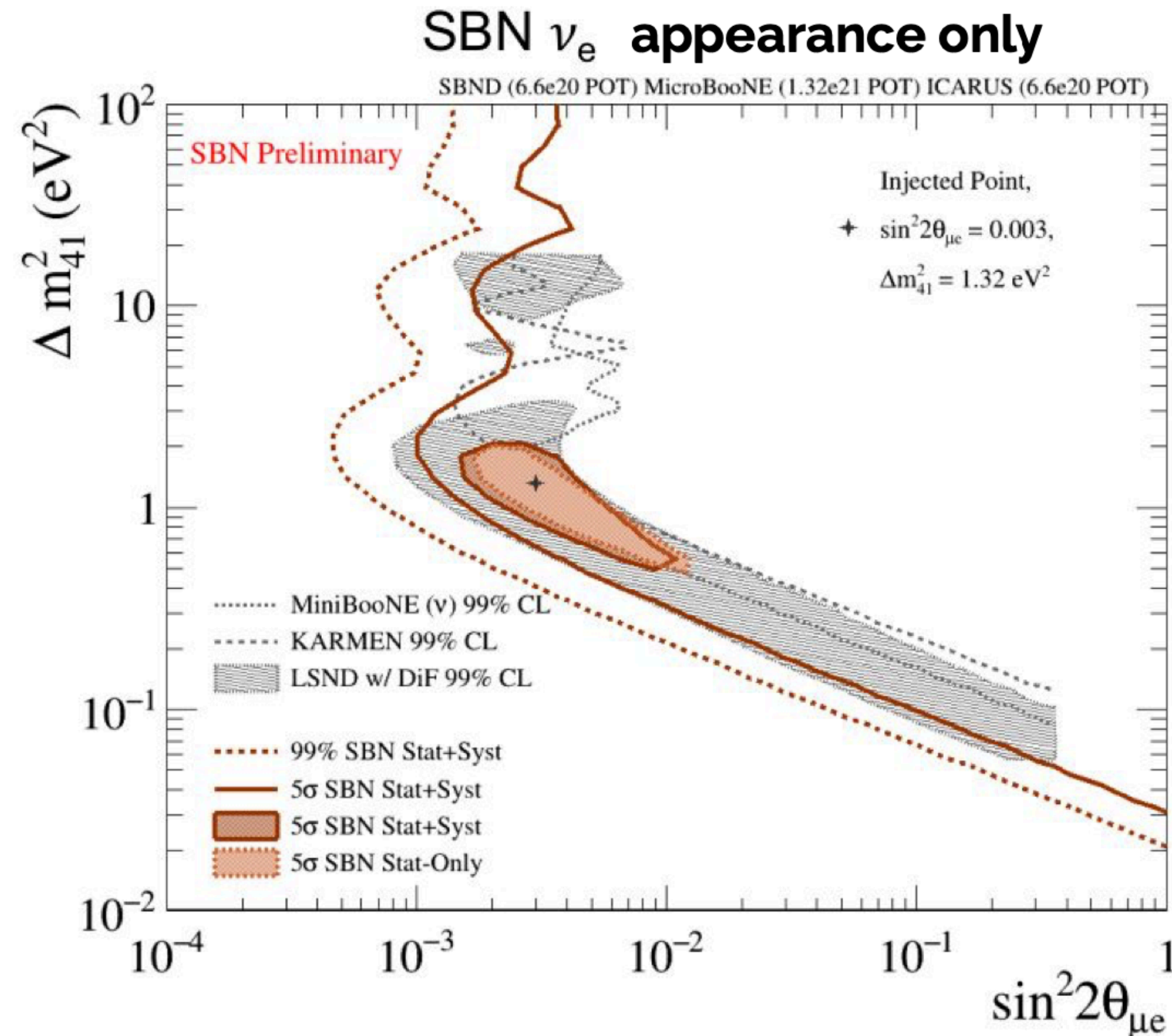
Systematic errors will reduce using the same detector technology. Near detector helps in providing the initial beam composition and the spectrum. The clear electron neutrino identification capability will help on reducing backgrounds
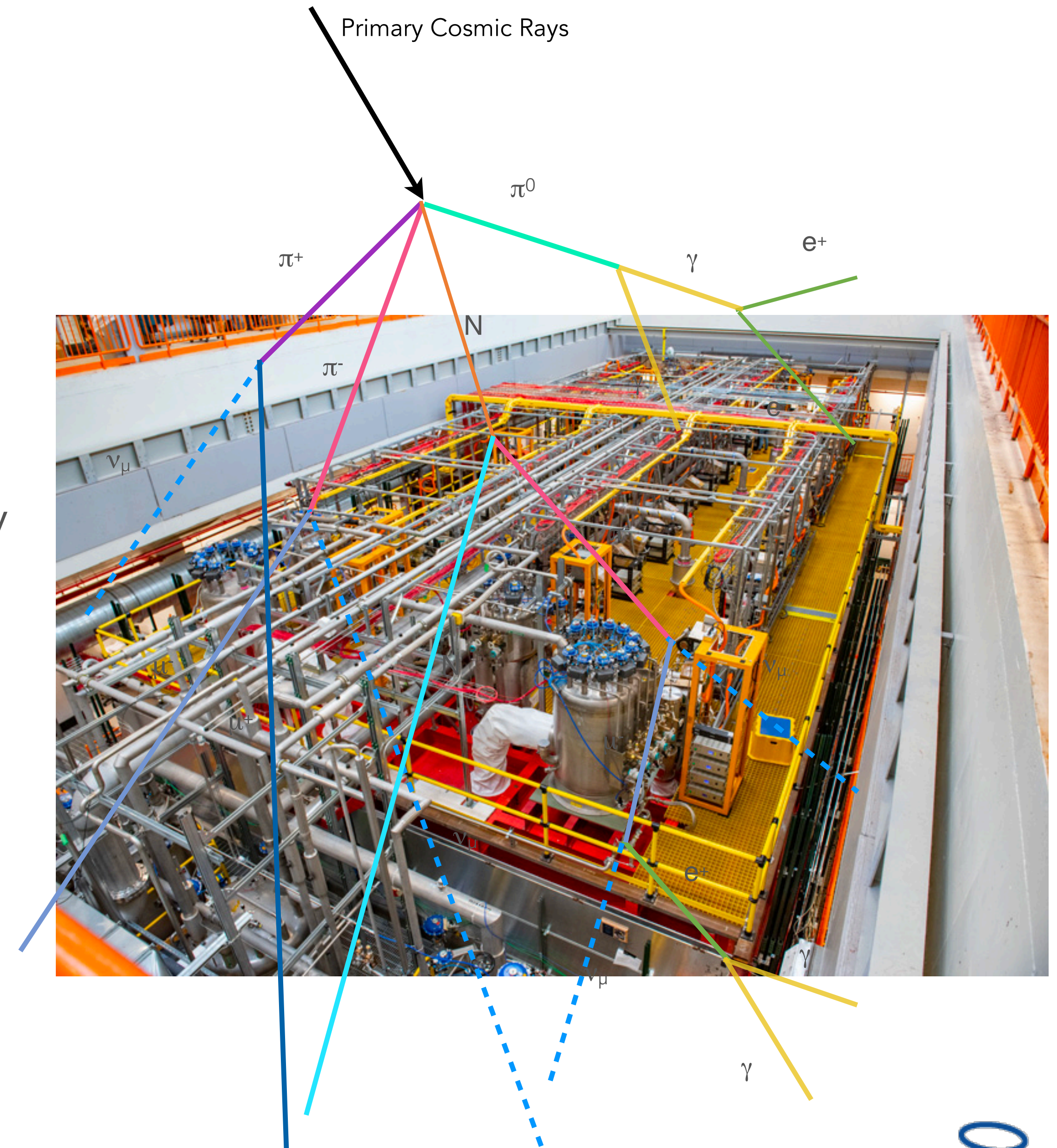
Cosmogenic Particle

- **ICARUS is on the surface** and exposed to huge cosmic activity, is the primary background for several physics analysis.


1arxiv: 1503.01520

Short Baseline Neutrino

Cosmogenic Particle

- **ICARUS is on the surface** and exposed to huge cosmic activity, is the primary background for several physics analysis.

- The electromagnetic showers generated by cosmic particles crossing the detector in time with the beam spill have to be reduced as much as possible a priori since they may introduce a background for the ν_e CC analysis.

Primary Cosmic Rays

π^0

π^+

γ

e^+

π^-

N

ν_μ

[1]

Short Baseline Neutrino

Cosmogenic Particle

- ICARUS is on the surface and exposed to huge cosmic activity, is the primary background for several physics analysis.

- The electromagnetic showers generated by cosmic particles crossing the detector in time with the beam spill have to be reduced as much as possible a priori since they may introduce a background for the ν_e CC analysis.

- In the approved Fermilab SBN[1] experiment the impact of cosmic rays is mitigated by placing ~ 3 m concrete overburden placed on top of the ICARUS detector and ~4π coverage of Cosmic Ray Tagger (CRT) were introduced.

[1]arxiv: 1503.01520

Short Baseline Neutrino
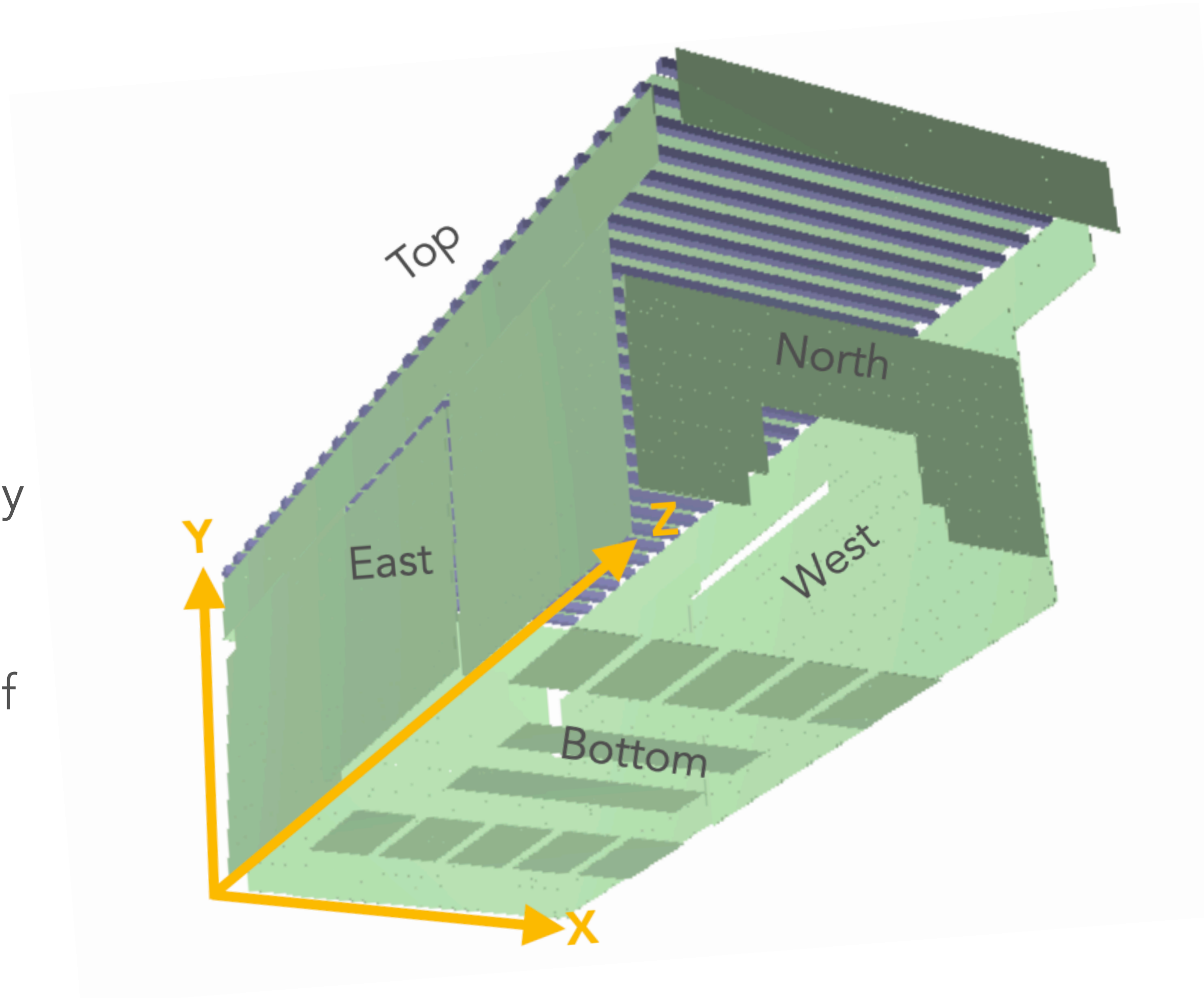
Cosmic Background Rejection

- **In-time** : Cosmic particle entering anywhere in the detector during the beam spill (1.6 us for BNB and 9.5 us for NuMI)

- **Out-of-time** : Cosmic particle crossing anywhere in the detector during the drift time

1.6 us

0.96 ms

- **In ICARUS with Overburden [BNB (NUMI)]:**
    1 ν interaction in active LAr in every **180 (15)** spills
    1 in-time cosmic ray in active LAr in every **44 (10)** spills
    14 out of- time cosmic rays in active LAr during each TPC drift time (**0.96 ms**)
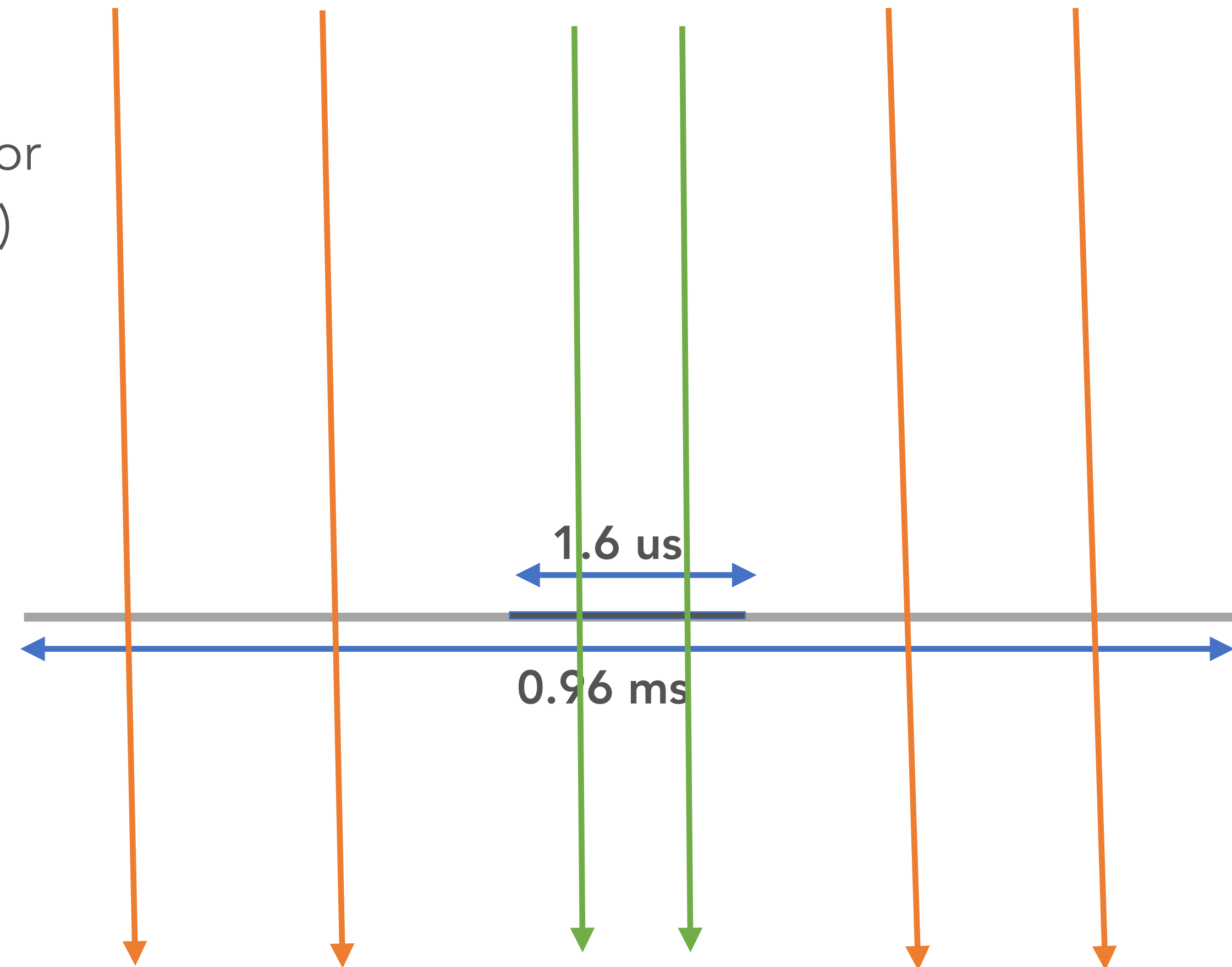
In the case of NuMI, a factor of 4 more cosmic present within the beam gate

Short Baseline Neutrino

PART I: Installing ~3 m concrete overburden

Cosmic rays simulation in ICARUS setups

no overburden

with overburden

Building Roof

Building Walls

Overburden

Ground Floor
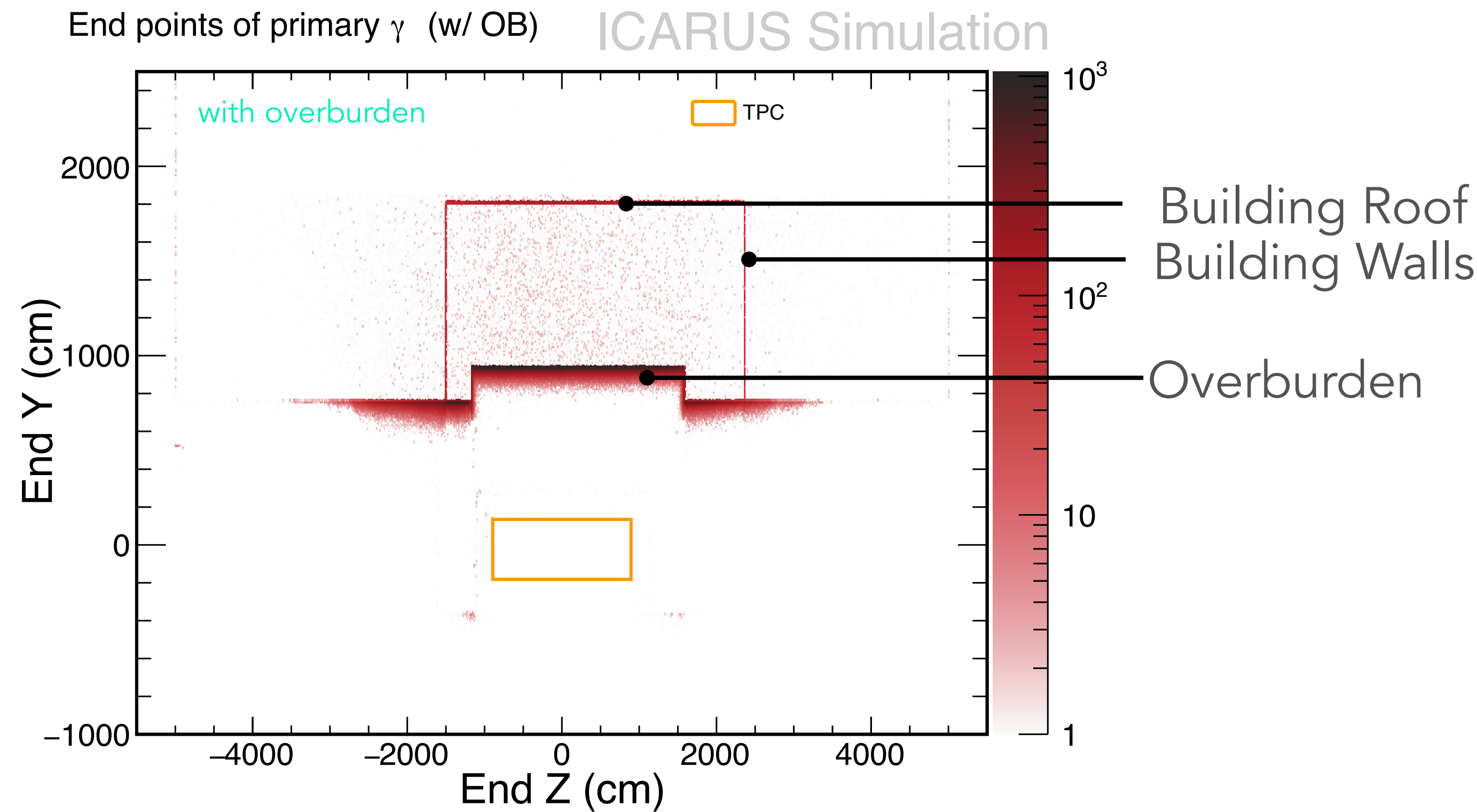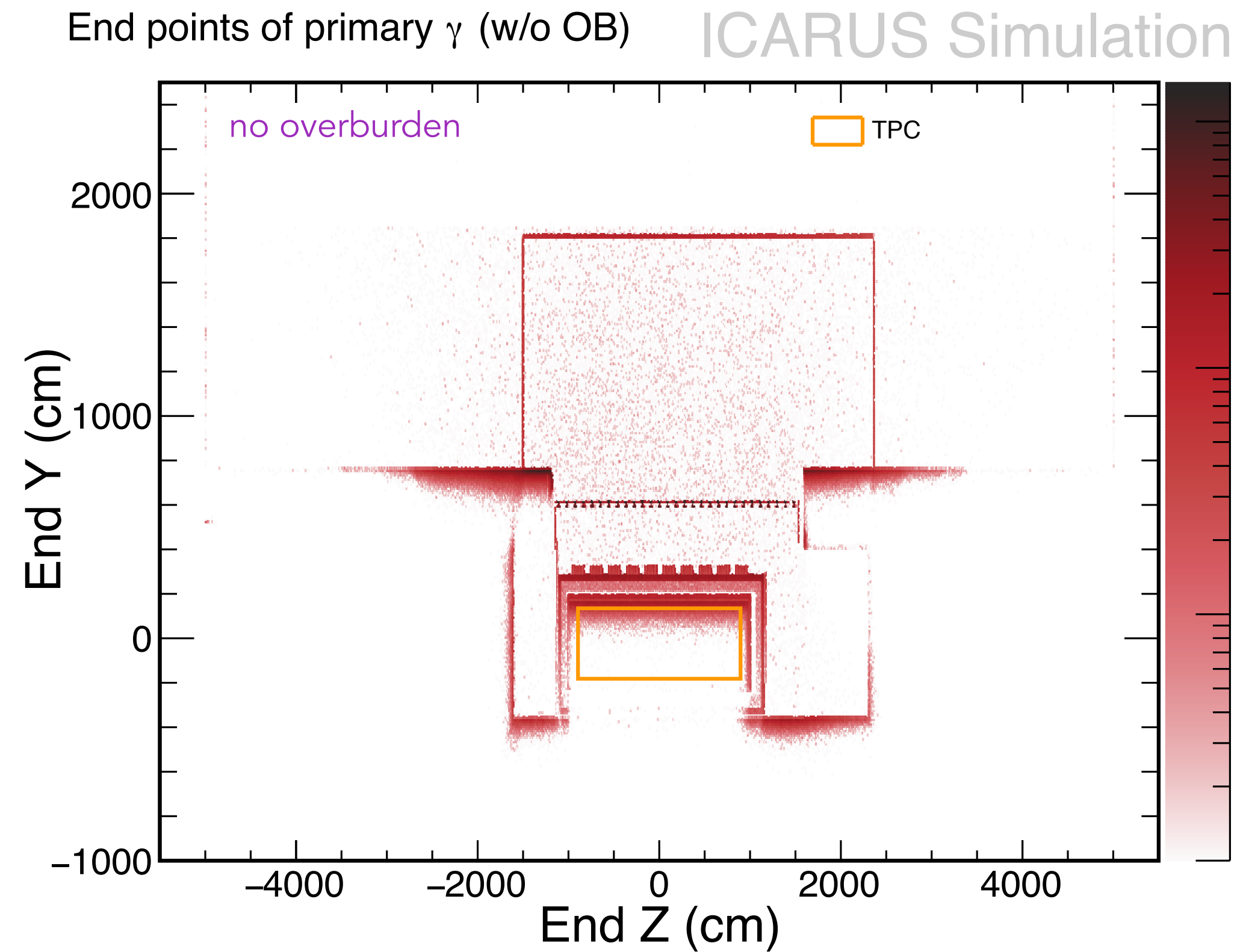Chimneys
Warm Vessel
Cryostat
TPC
CRT
Pit Walls
Pit Floor
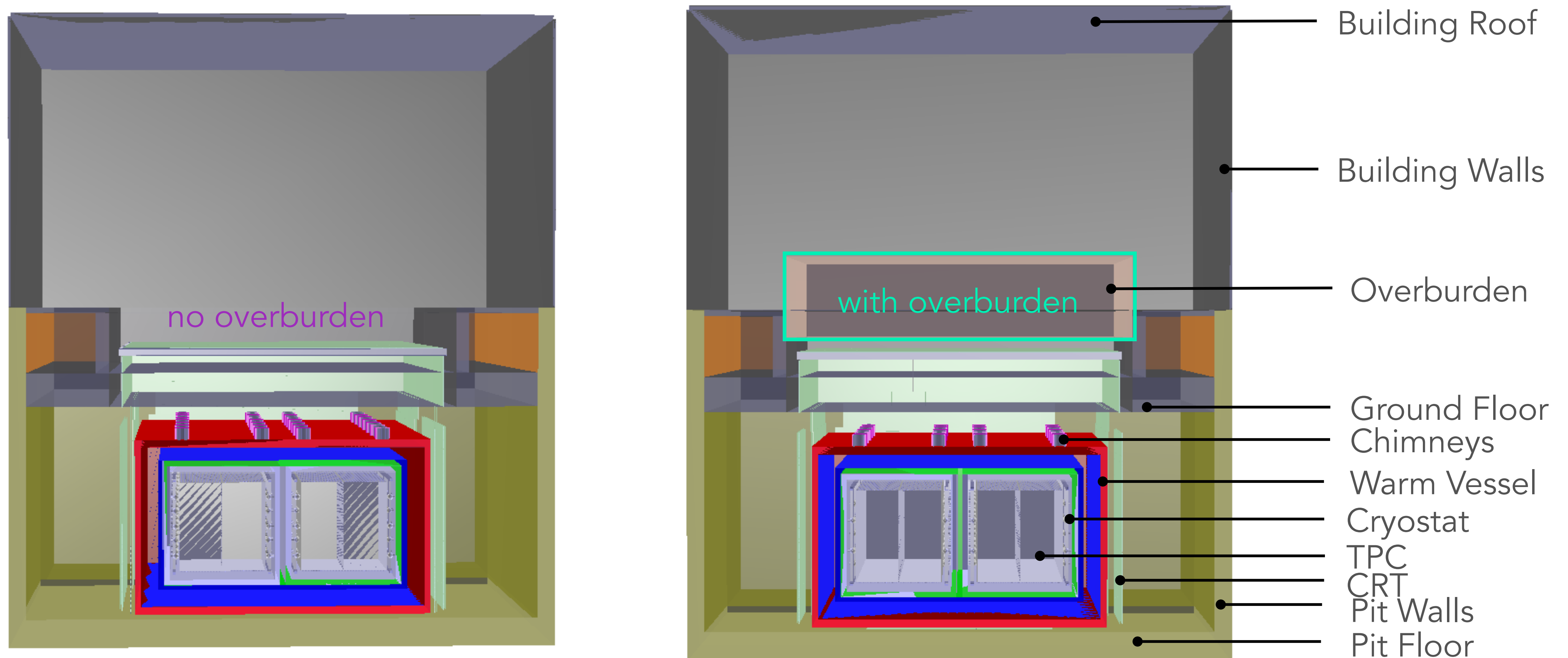
Understanding the role of overburden in the reduction of the cosmics.
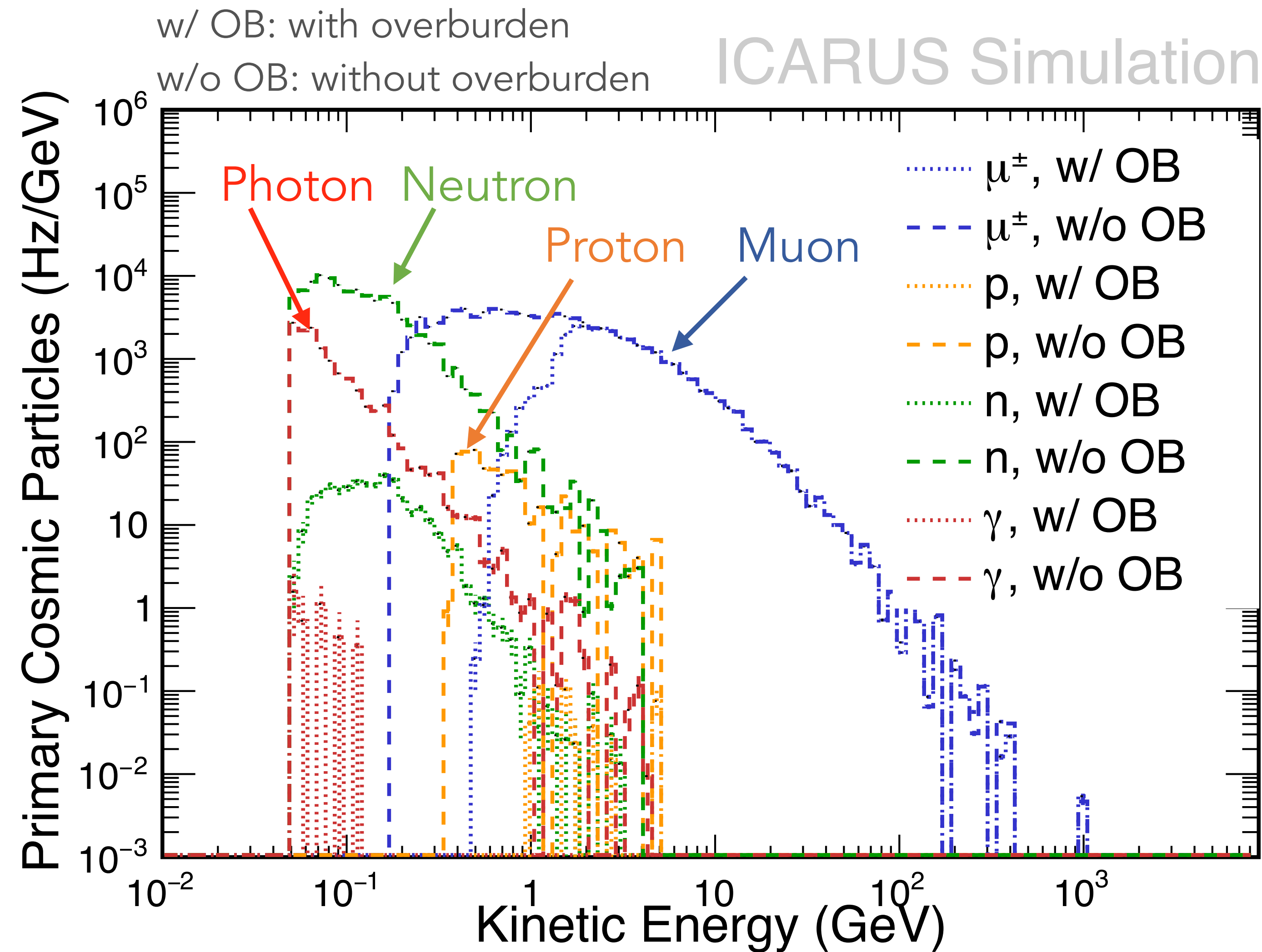For each configuration an event statistics for the 3 years data taking (6.6e20 POT).

Short Baseline Neutrino

Primary Cosmic Particles Reaching to the Active Liquid Argon

Primary Cosmic Particles Reaching to the Active Liquid Argon

End points of primary γ (w/o OB)   ICARUS Simulation

End points of primary γ (w/ OB)   ICARUS Simulation

Short Baseline Neutrino

Primary Cosmic Particles Reaching to the Active Liquid Argon

w/ OB: with overburden
w/o OB: without overburden

ICARUS Simulation

Full suppression of primary photons

More effective for the hadrons, by a factor ~150 of primary neutrons
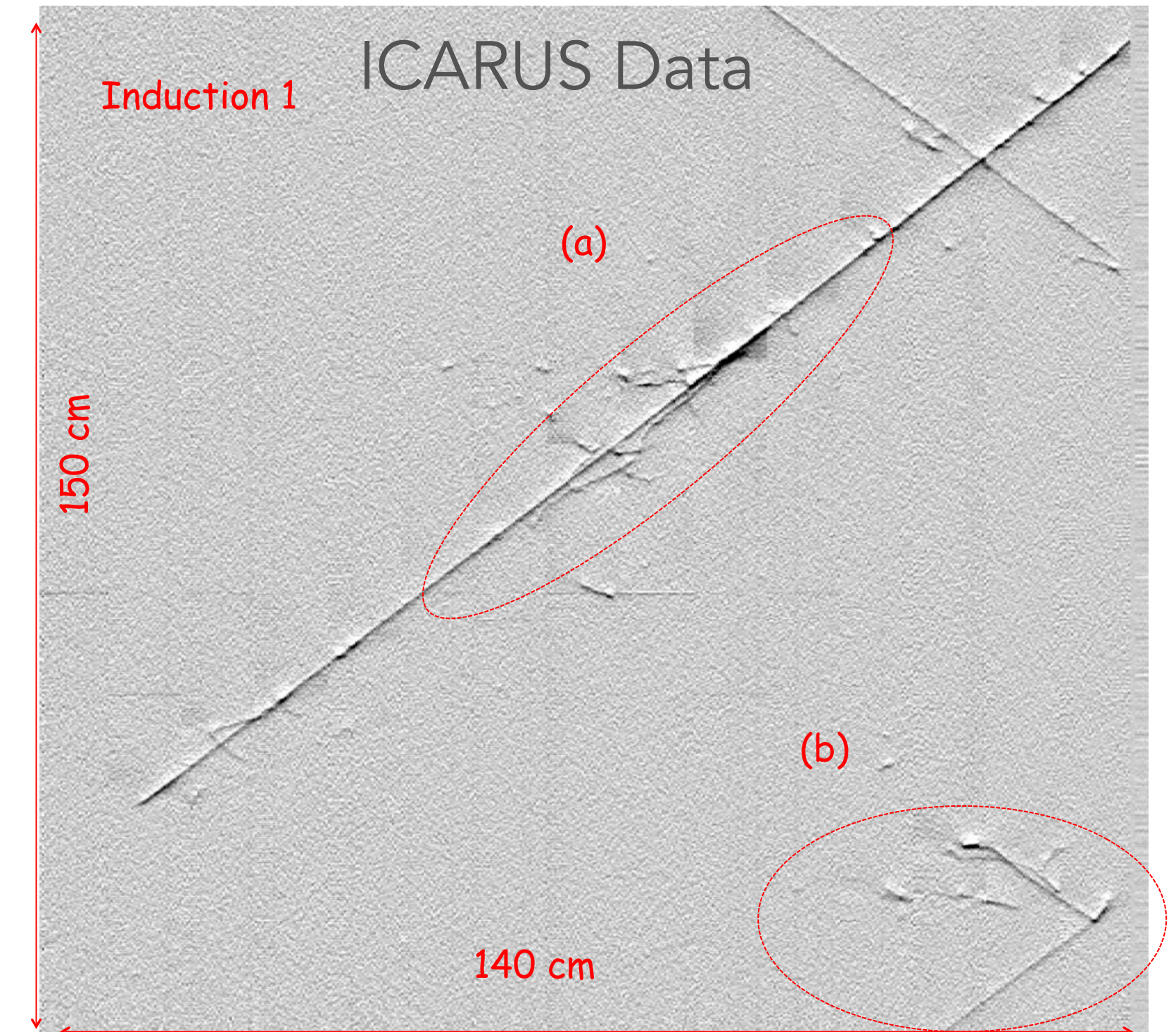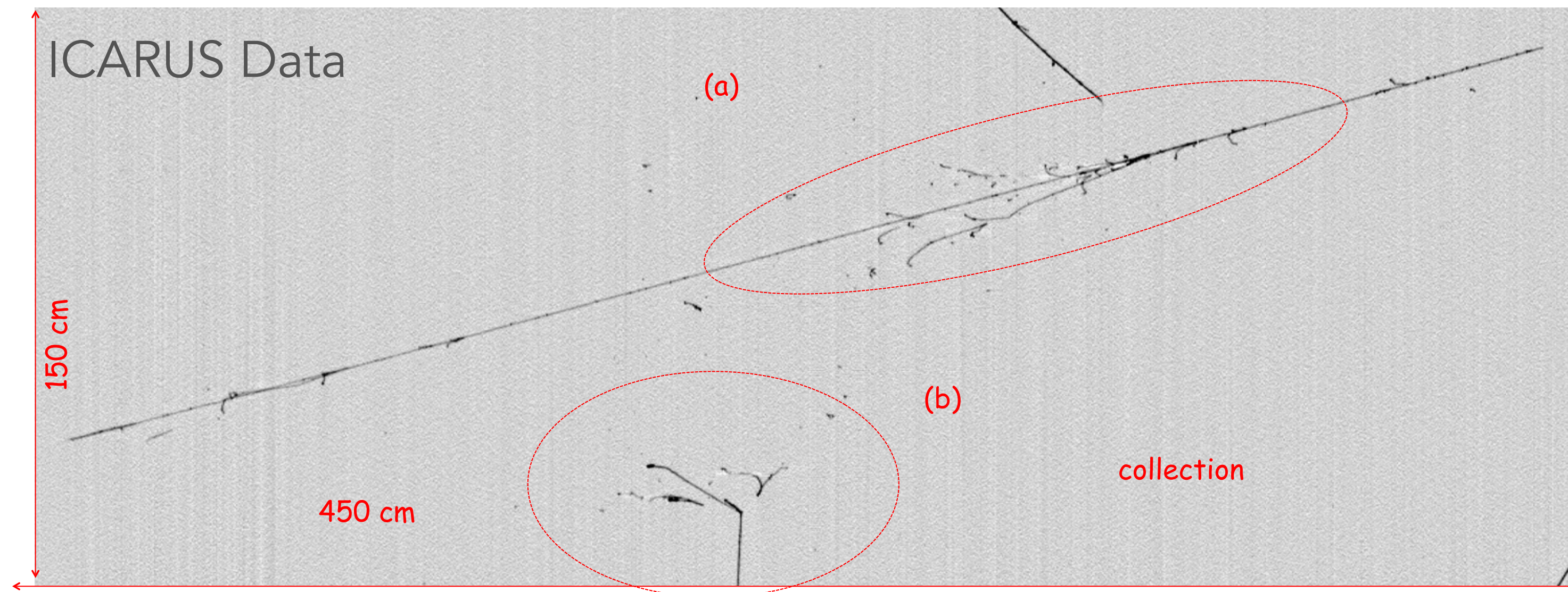
The overburden reduces the dominant muon flux by ~ 25%

Cosmogenic Electromagnetic Activity in the ICARUS
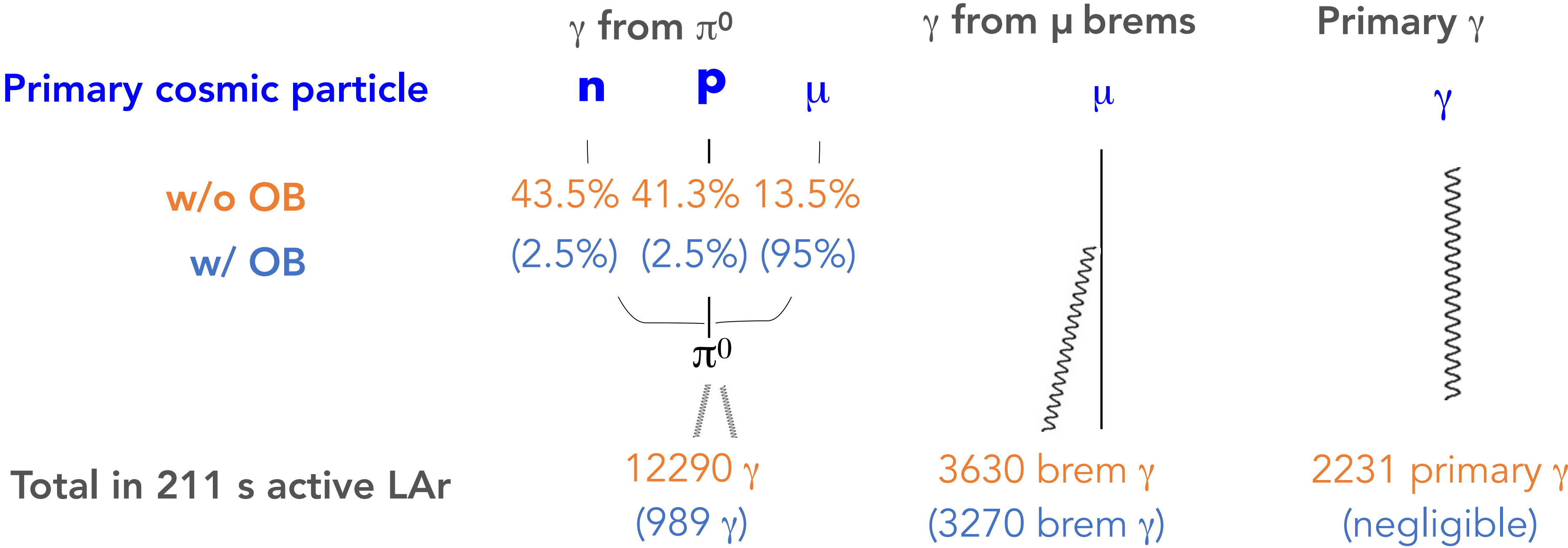
Cosmogenic Electromagnetic Activity in the ICARUS

(a) Electron initiated shower
(b) Photon initiated shower

(a) An example of a muon emitting an high energy delta ray developing a shower
(b) Cosmic neutron interacting in the active argon producing a π^0 decaying into two photons

Cosmogenic Electromagnetic Activity in the ICARUS

Three main categories of events are involved in the production of γ showers (E>200 MeV) inside the liquid argon

	γ from π⁰			γ from μ brems	Primary γ
Primary cosmic particle	**n**	**p**	μ	μ	γ
w/o OB	43.5%	41.3%	13.5%		
w/ OB	(2.5%)	(2.5%)	(95%)		

$$\pi^0$$

Total in 211 s active LAr

	12290 γ	3630 brem γ	2231 primary γ
	(989 γ)	(3270 brem γ)	(negligible)

In absence of overburden the dominant contribution is from the π⁰, which is predominantly produced by incoming cosmic hadrons

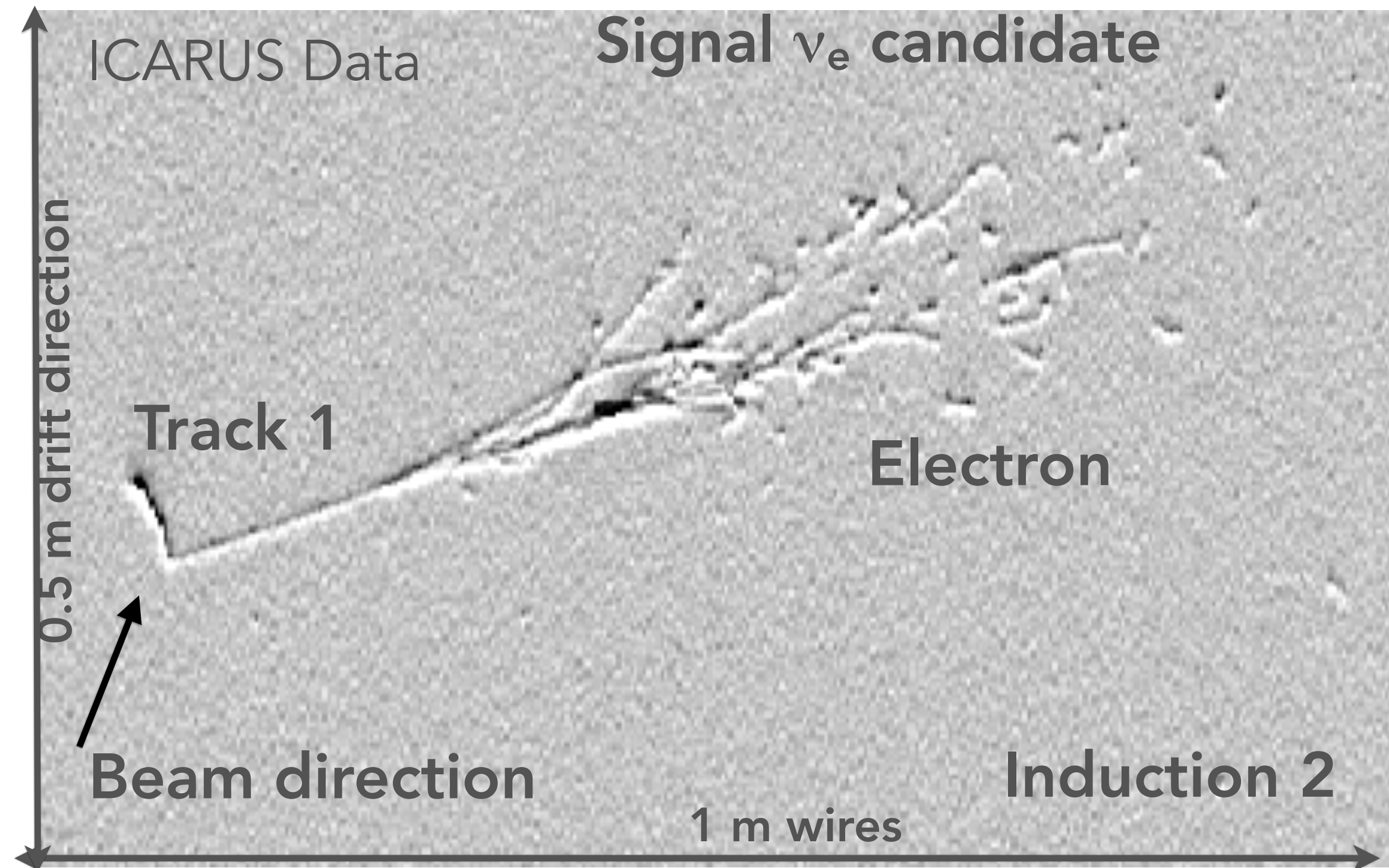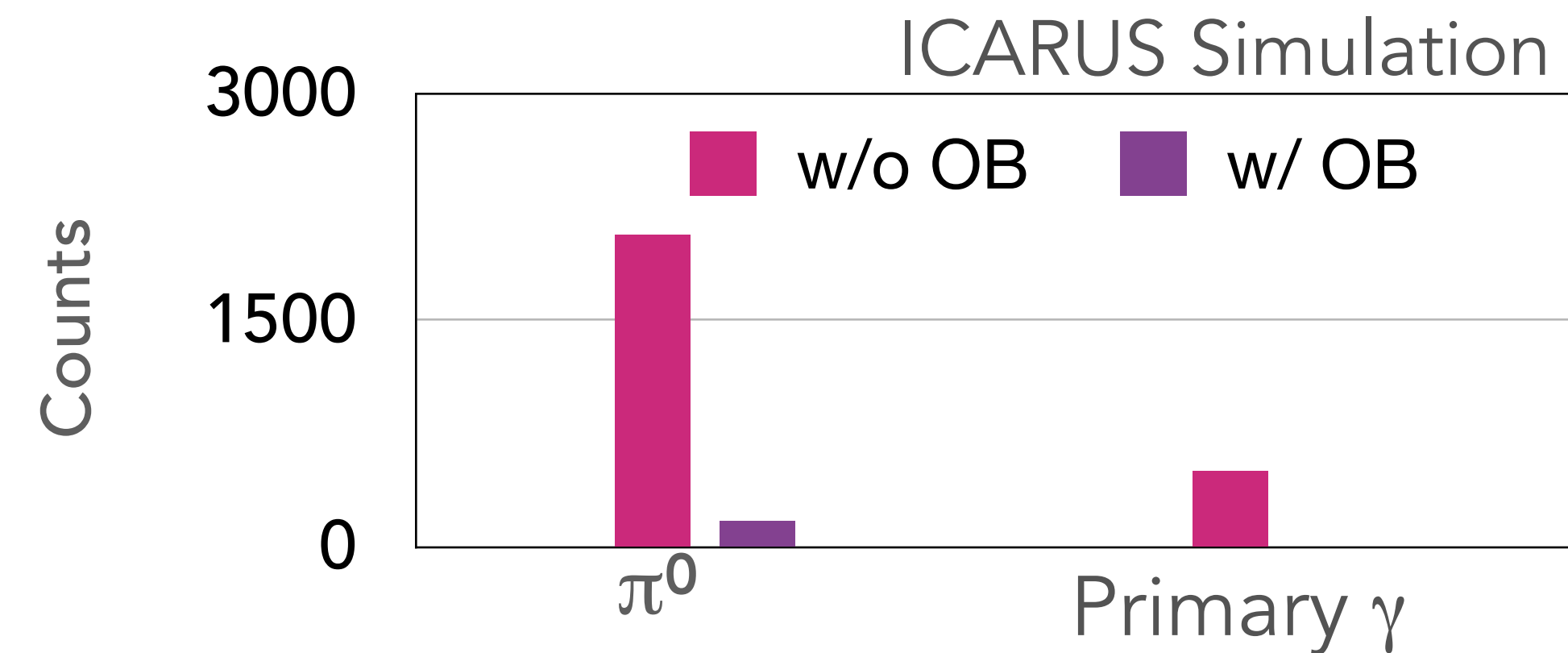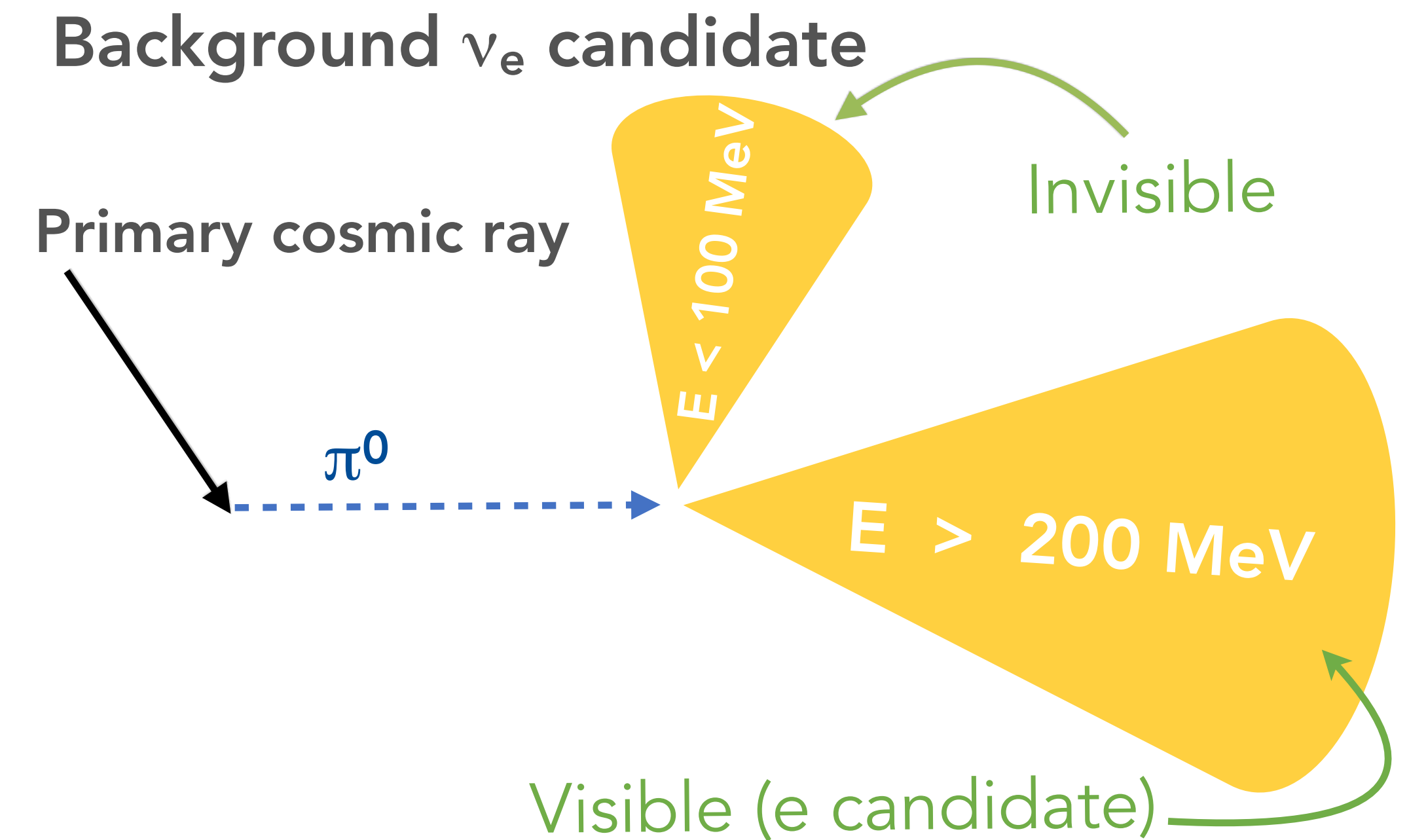Overburden strongly suppress hadrons and removes primary γ and associated showers

Short Baseline Neutrino

π^0 Selected as Background ν_e Candidate

Short Baseline Neutrino

π^0 Selected as Background ν_e Candidate

ICARUS Data

Signal ν_e candidate

0.5 m drift direction

Track 1

Electron

Beam direction

Induction 2

1 m wires

Background ν_e candidate

Primary cosmic ray

π^0

E < 100 MeV

E > 200 MeV

Invisible

Visible (e candidate)

If a cosmic event produces one π^0 which produces a leading showers E>200 MeV (electron candidate) and an another sub leading shower with E <100 MeV (undetected), this event is selected as background ν_e candidate.

ICARUS Simulation

Counts

3000

1500

0

w/o OB   w/ OB

π^0 Primary γ

Short Baseline Neutrino

The Effect of Overburden on Cosmic Rate (Data)
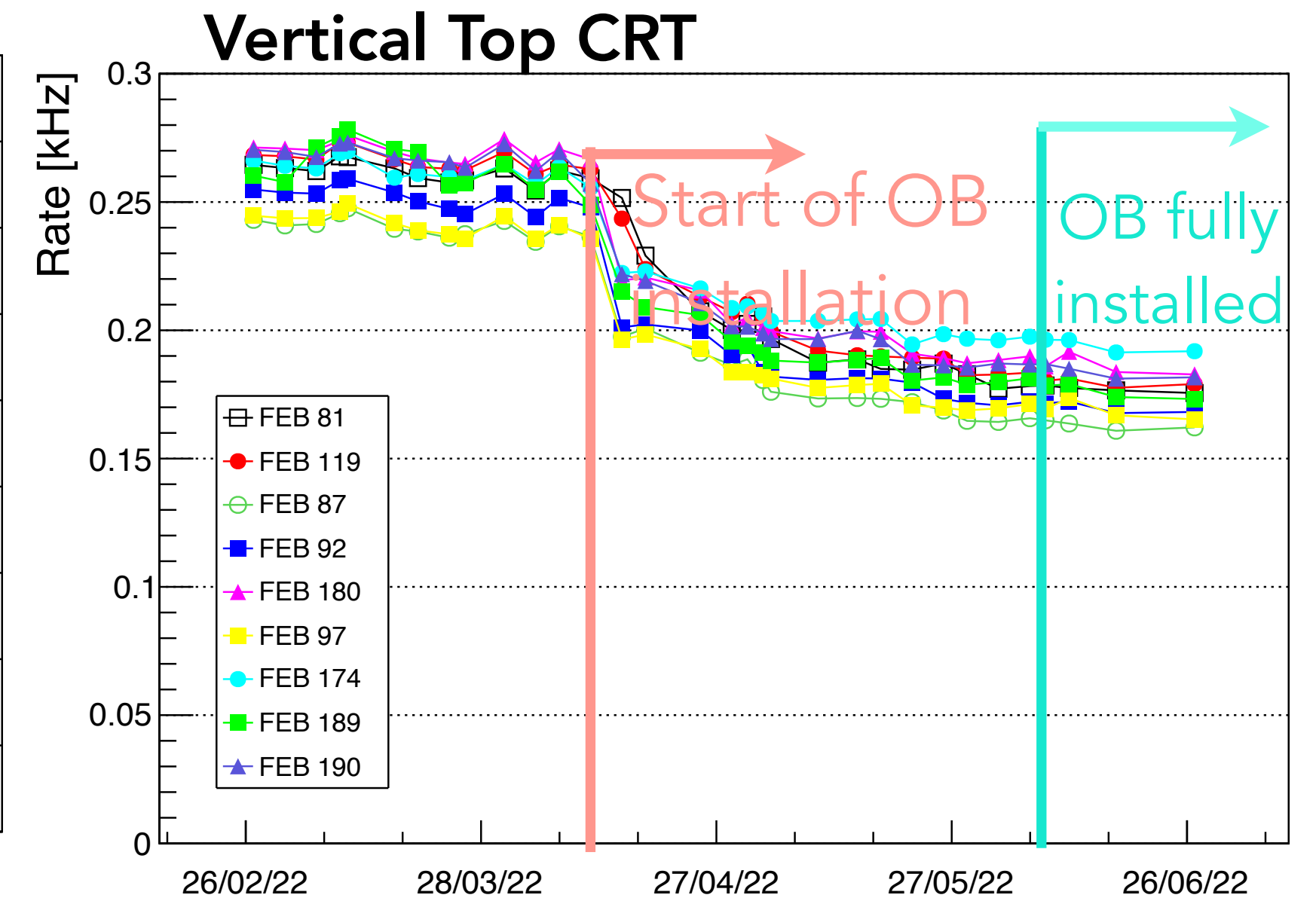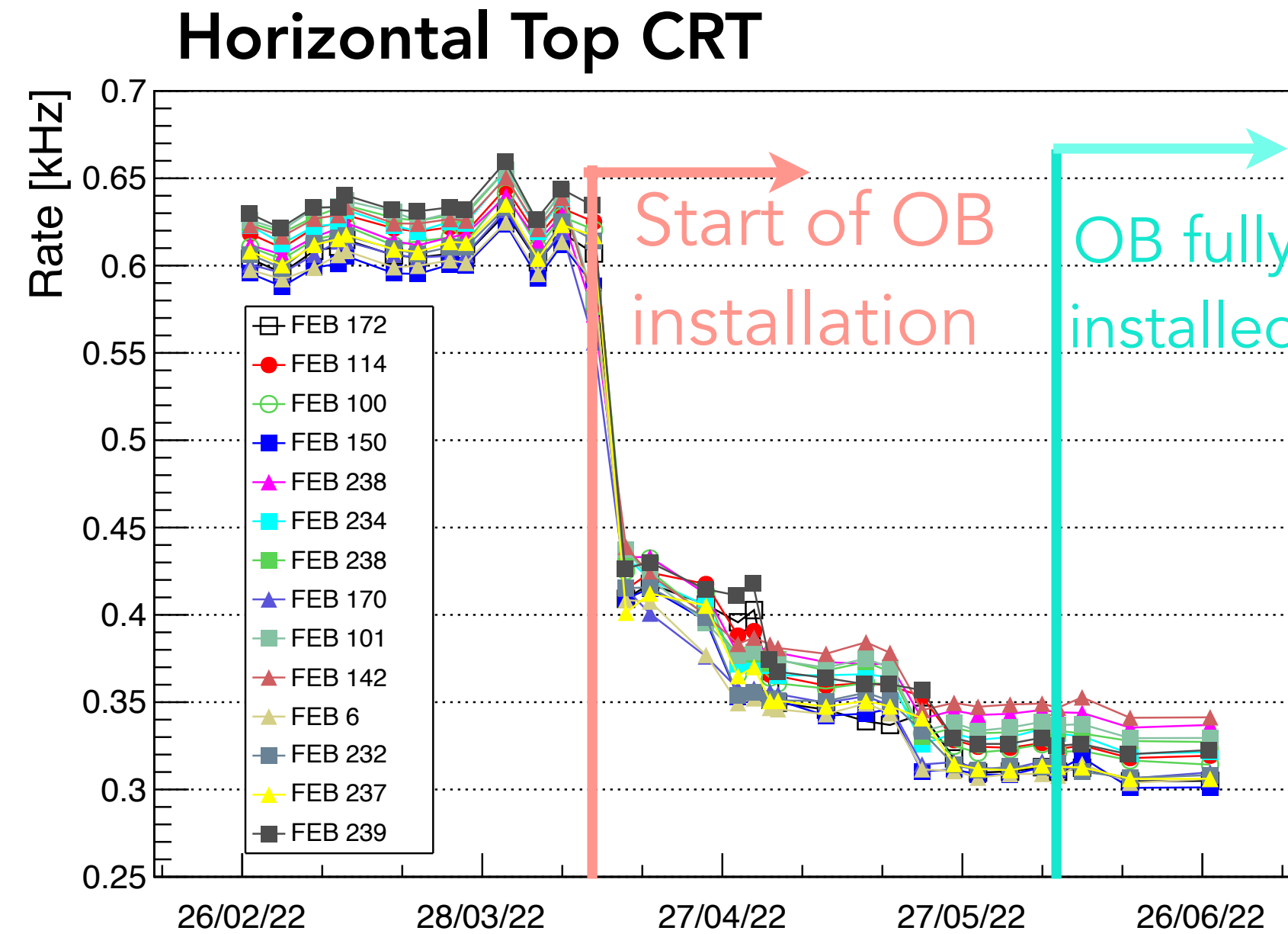
The overburden is composed of three layer of concrete blocks of 1m height each. The total mass of the three layer is 5 million pounds.

The reduction of the cosmic rate is sensible: horizontal (vertical) Top CRT modules rate decreased from 600 (250) Hz to 330 (180) Hz.
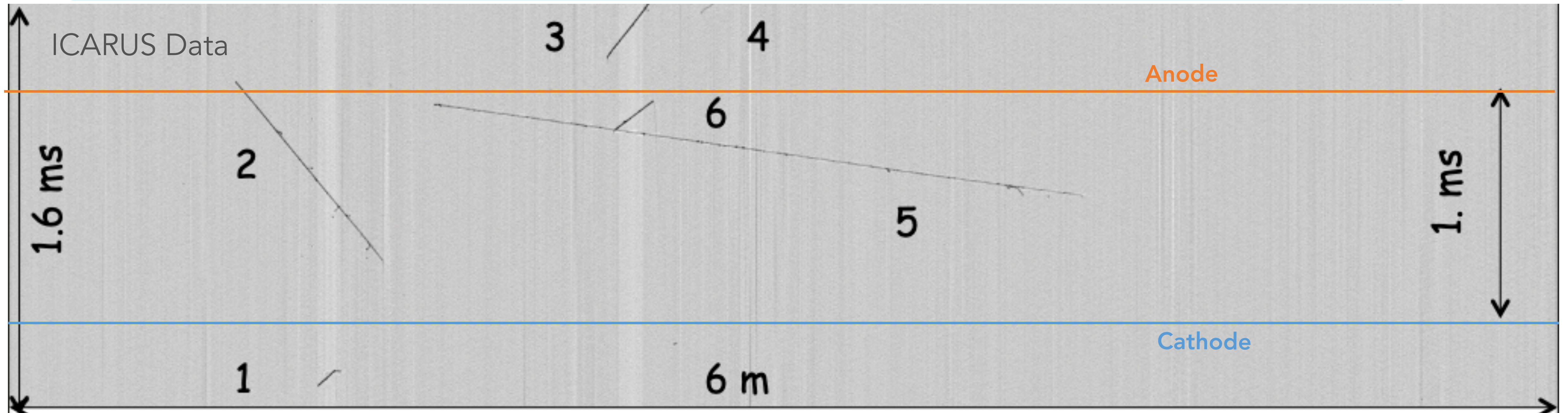
PART II: Exploiting the information from TPC, PMT and CRT

Tools for rejecting In-time/Out-of-time Cosmic Using TPC Alone (real event example)

TPC alone will be helpful on rejecting this track quite effectively

Out of time tracks reconstructed outside the physical drift window (Track 1,2, 3, 4)
Cosmic crossing crossing from top to bottom (Track 5)
Entering from the top and exiting from the wire planes (Track 6)

Tools for rejecting In-time/Out-of-time Cosmic Using TPC Alone (real event example)

TPC alone will be helpful on rejecting this track quite effectively

ICARUS Data

$\Delta t_{tk-Anode} = 51\ \mu s$

Ghost track from ionization behind the wires
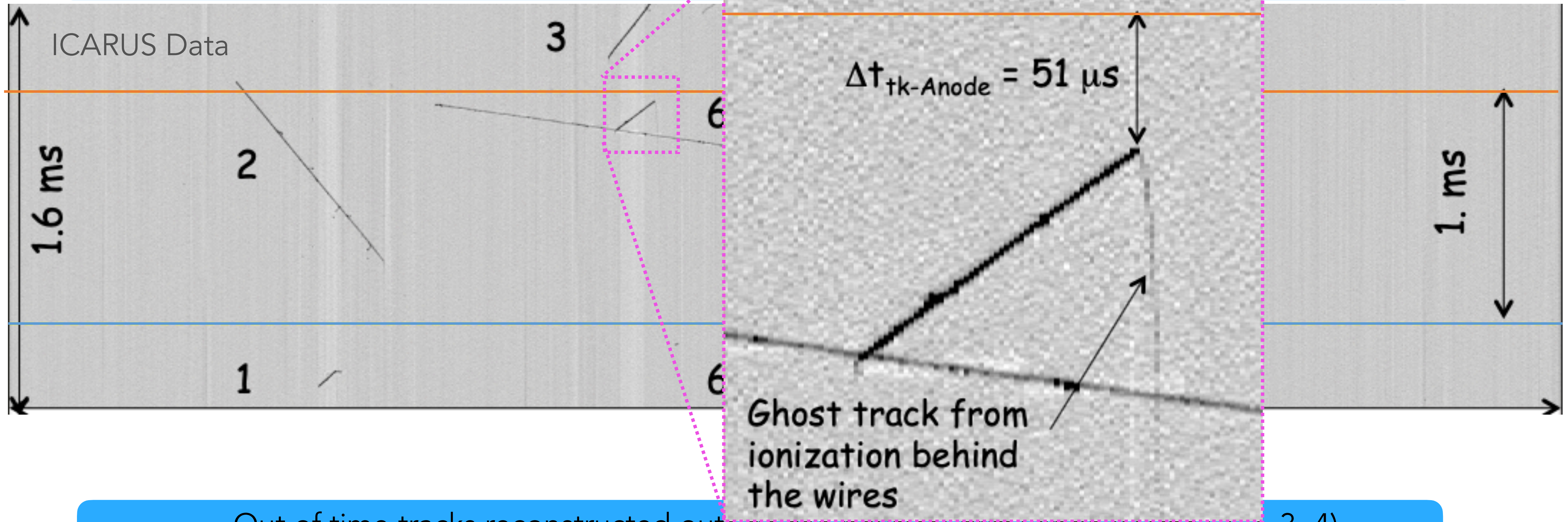
Out of time tracks reconstructed outside the physical drift window (Track 1, 2, 3, 4)
Cosmic crossing crossing from top to bottom (Track 5)
Entering from the top and exiting from the wire planes (Track 6)

Tools for rejecting In-time/Out-of-time Cosmic

Stopping muons [in-time/out-of-time]:

The tracks are entering from outside (background) or from neutrino interaction (signal) and stopping inside

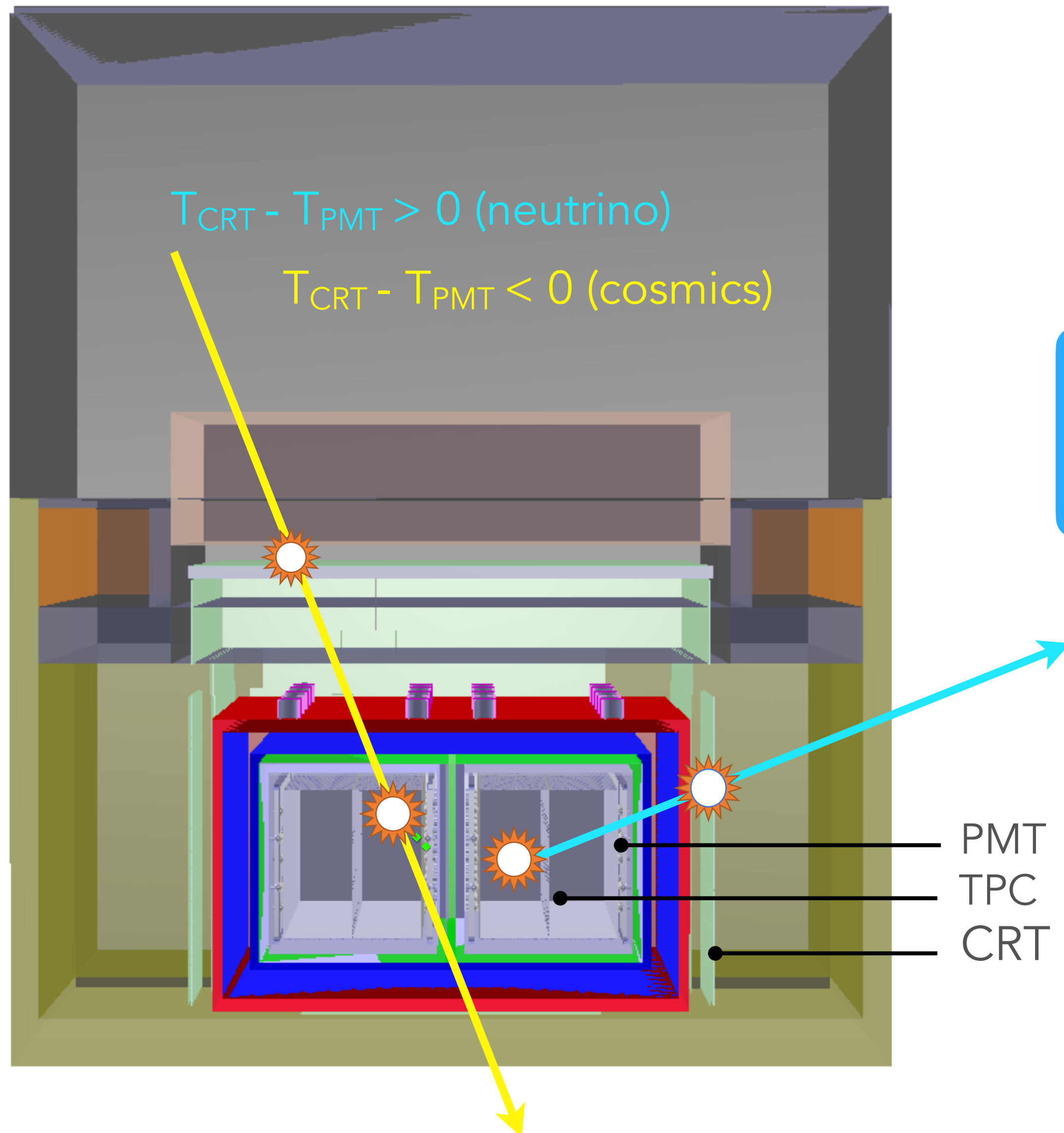The **CRT , TPC reconstruction and light information** can be used

Clear neutrino vertex can inform us the direction of stopping muons

From the Bragg peak we could identify the direction of flight

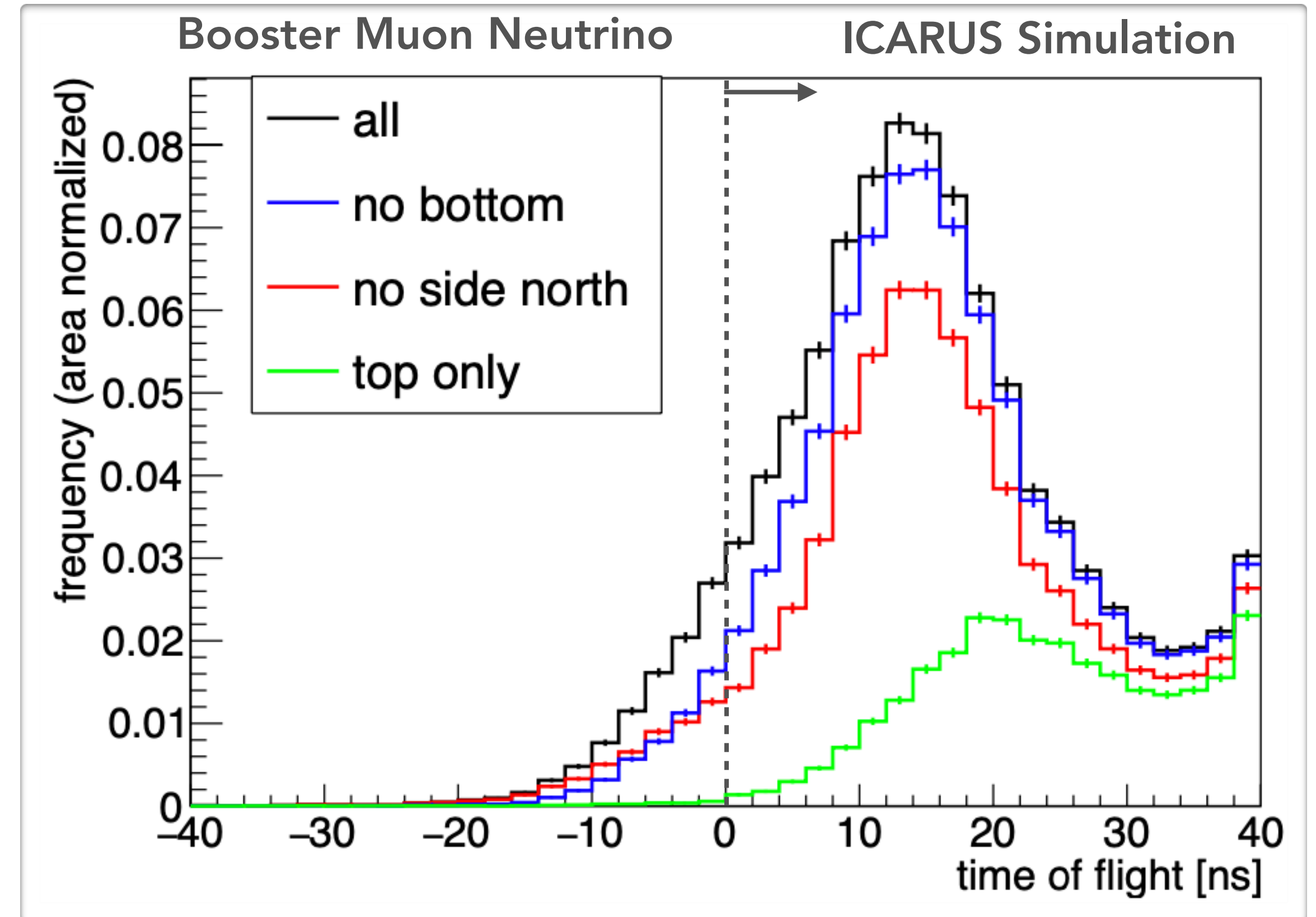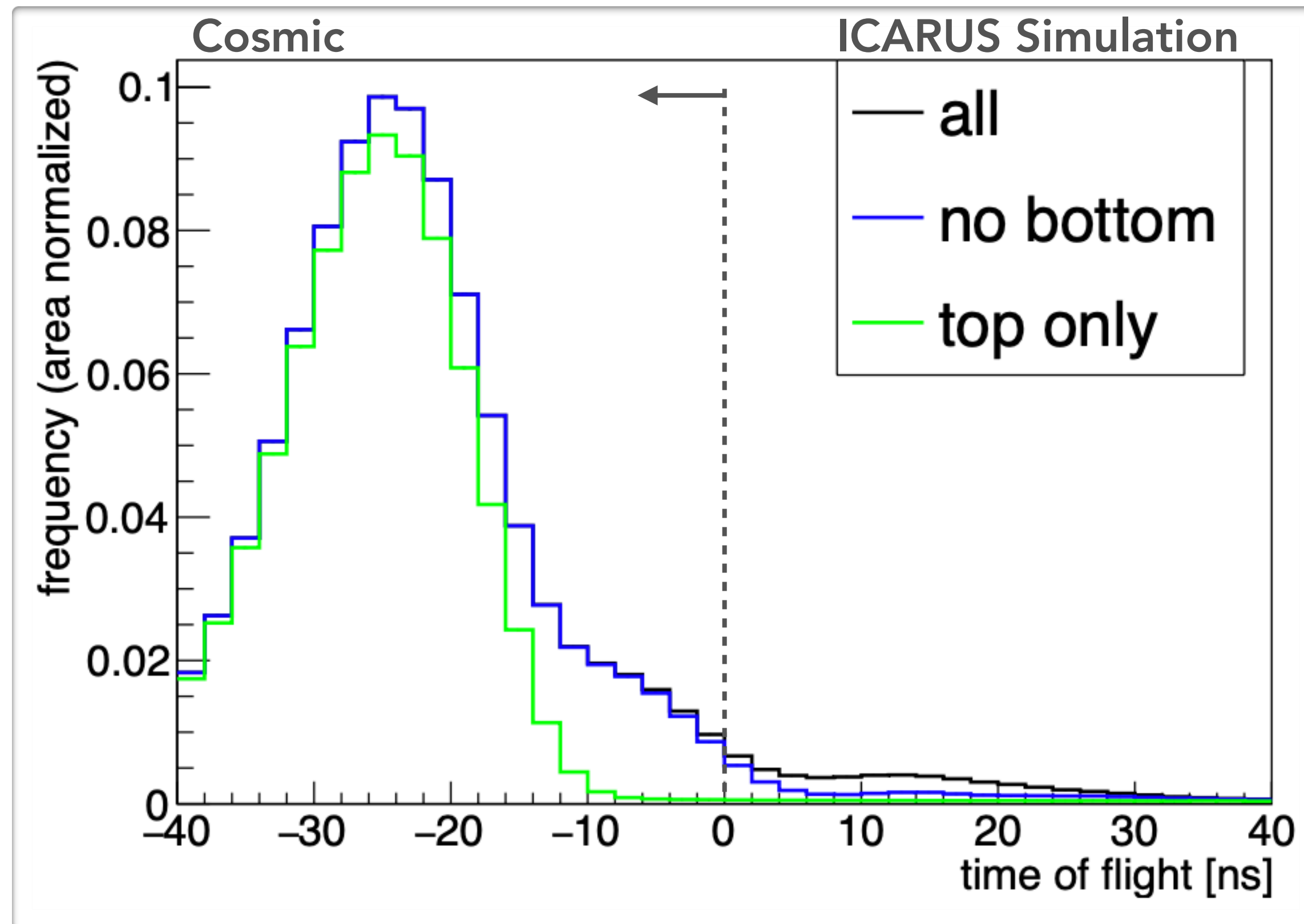The stopping muons are mostly vertical while a neutrino interaction with muon is more horizontal

# Time of Flight using CRT and PMT

$T_{CRT} - T_{PMT} > 0$ (neutrino)

$T_{CRT} - T_{PMT} < 0$ (cosmics)
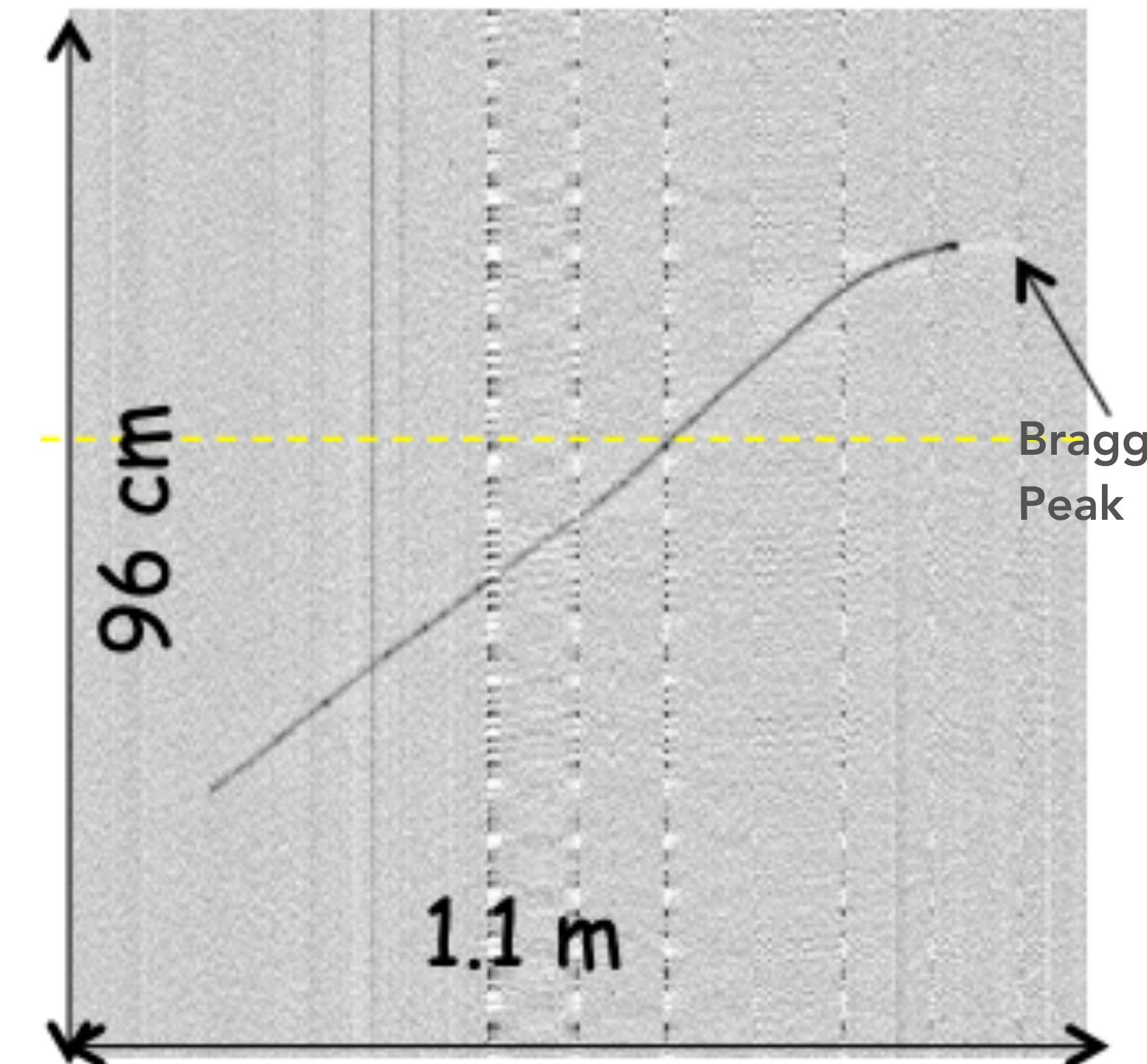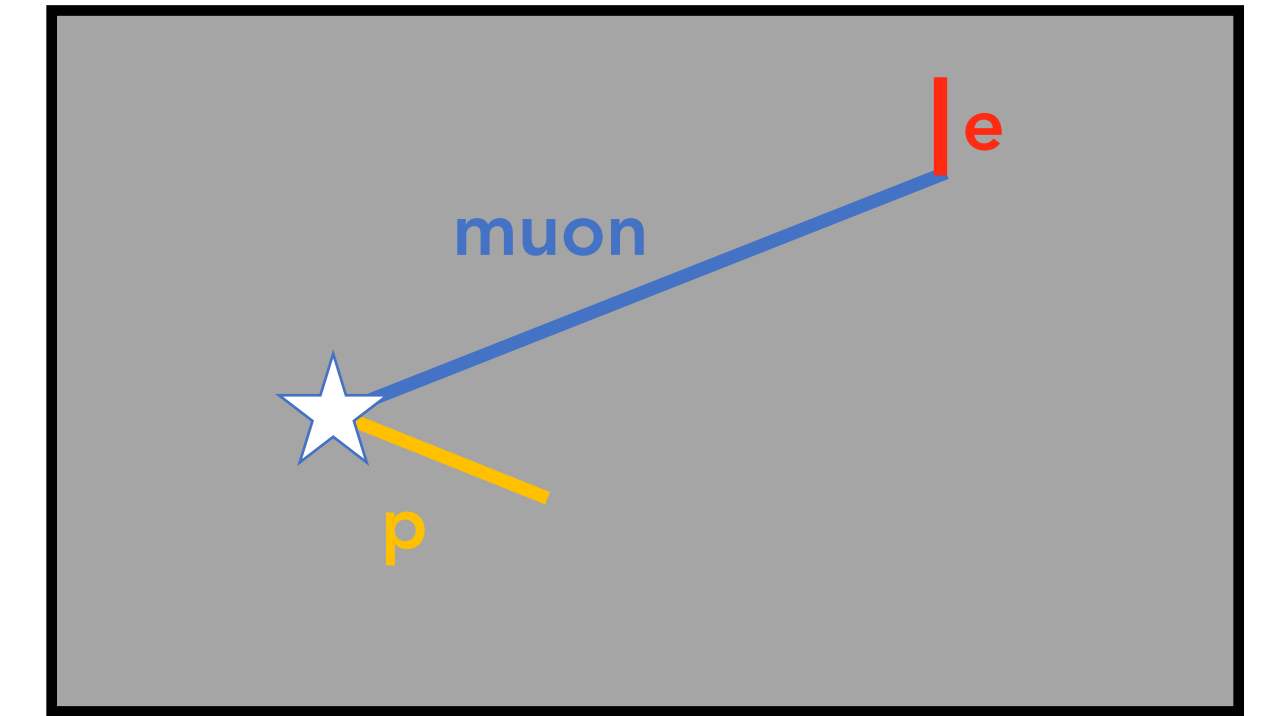
We can discriminate in-going cosmic tracks and from exiting neutrino tracks using the time of the CRT and PMT information

PMT

TPC

CRT

Short Baseline Neutrino

Time of Flight using CRT and PMT

Cosmogenic matches have time of flight (TOF) values < 0 ns, while the opposite is true for the Booster muon neutrino samples

CRT Hit - TPC Track Association

CRT hit

Drift Direction

reconstructed track

displaced track with the CRT time

$-v_d t_{crt}$
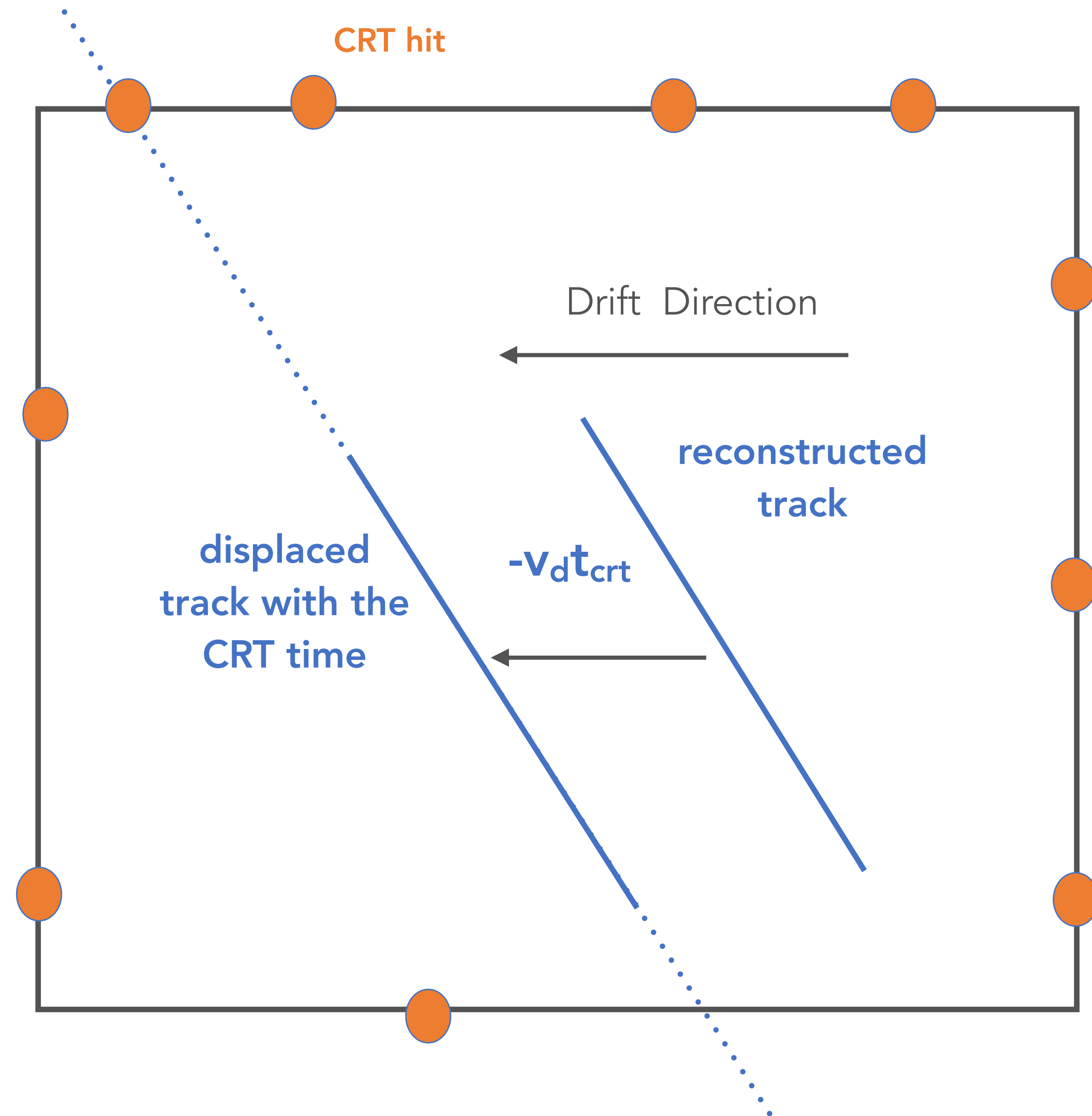
The reconstructed TPC track once we drift it according to the time at CRT, we will see a pointing track matching to a CRT hit. Assign this time to the TPC track.
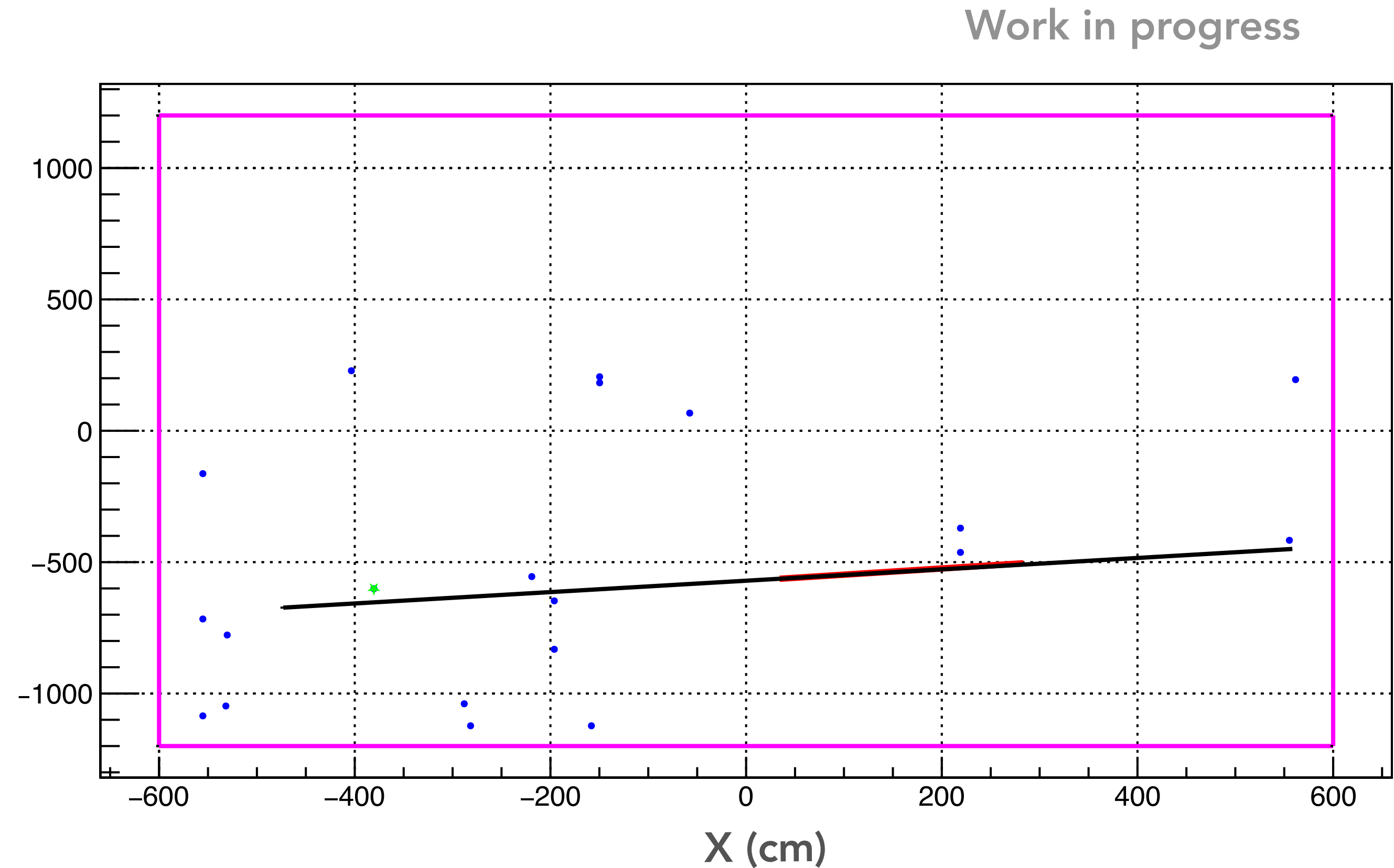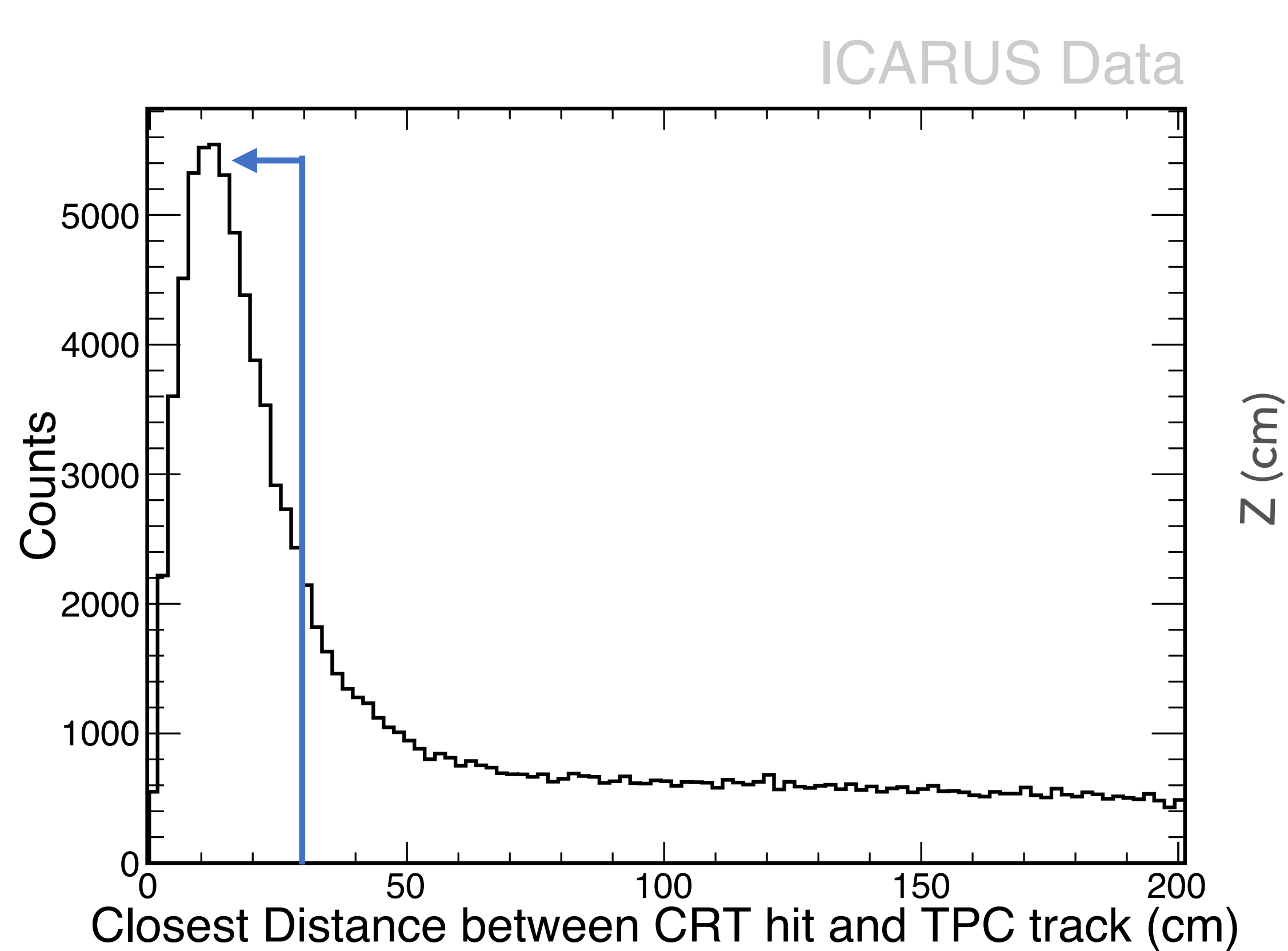
Short Baseline Neutrino

CRT Hit - TPC Track Association

Summary and Outlook

The overburden is very effective in reducing the hadrons while fully eliminating the electromagnetic cosmic ray components

The overburden will significantly reduce the amount of data collected (~25% less cosmic muons in time with the beam) and the subsequent effort and time required for the analysis

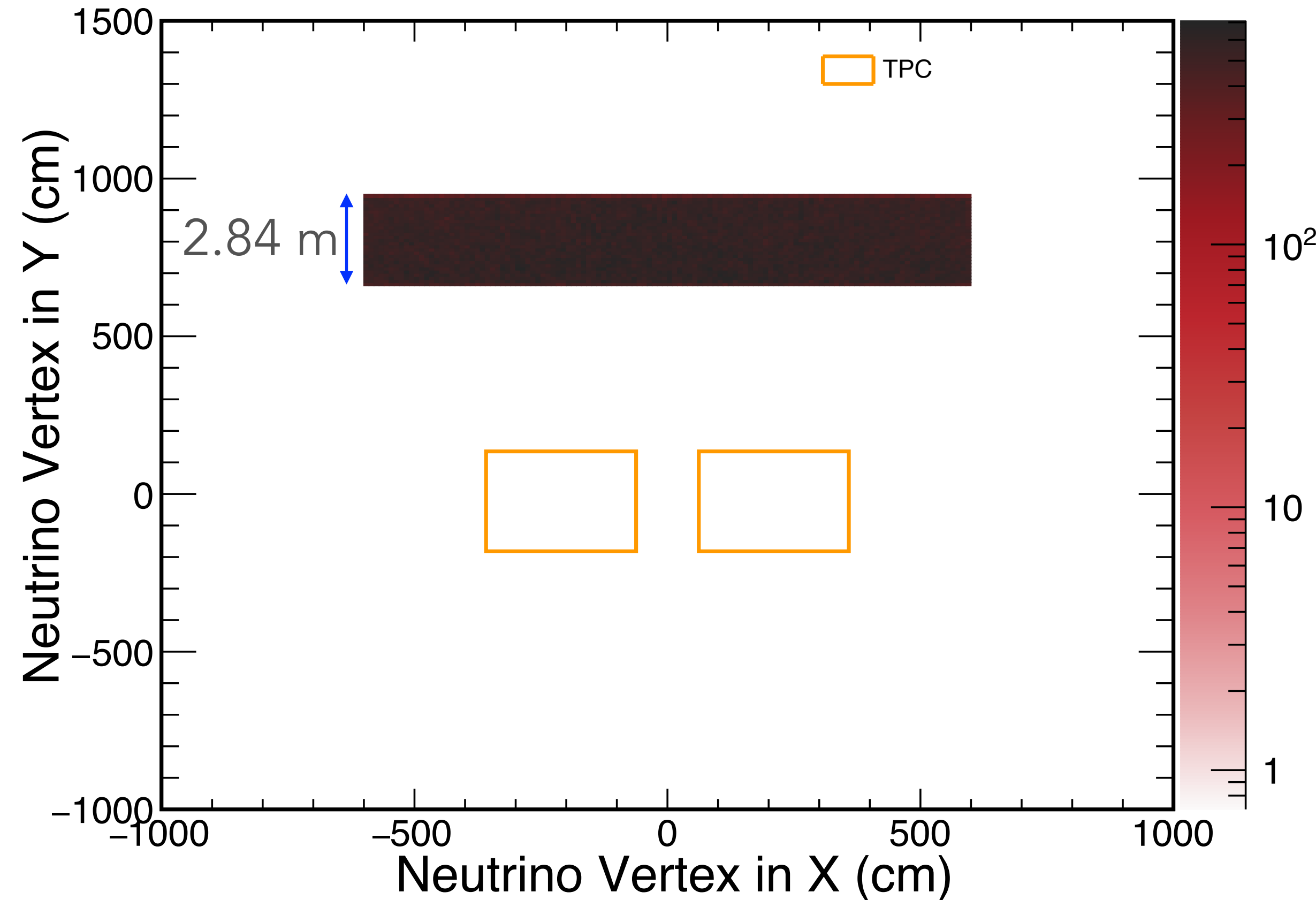Potential of TPC, CRT and PMT matching with data has been studied, using it in the event selection process is on going
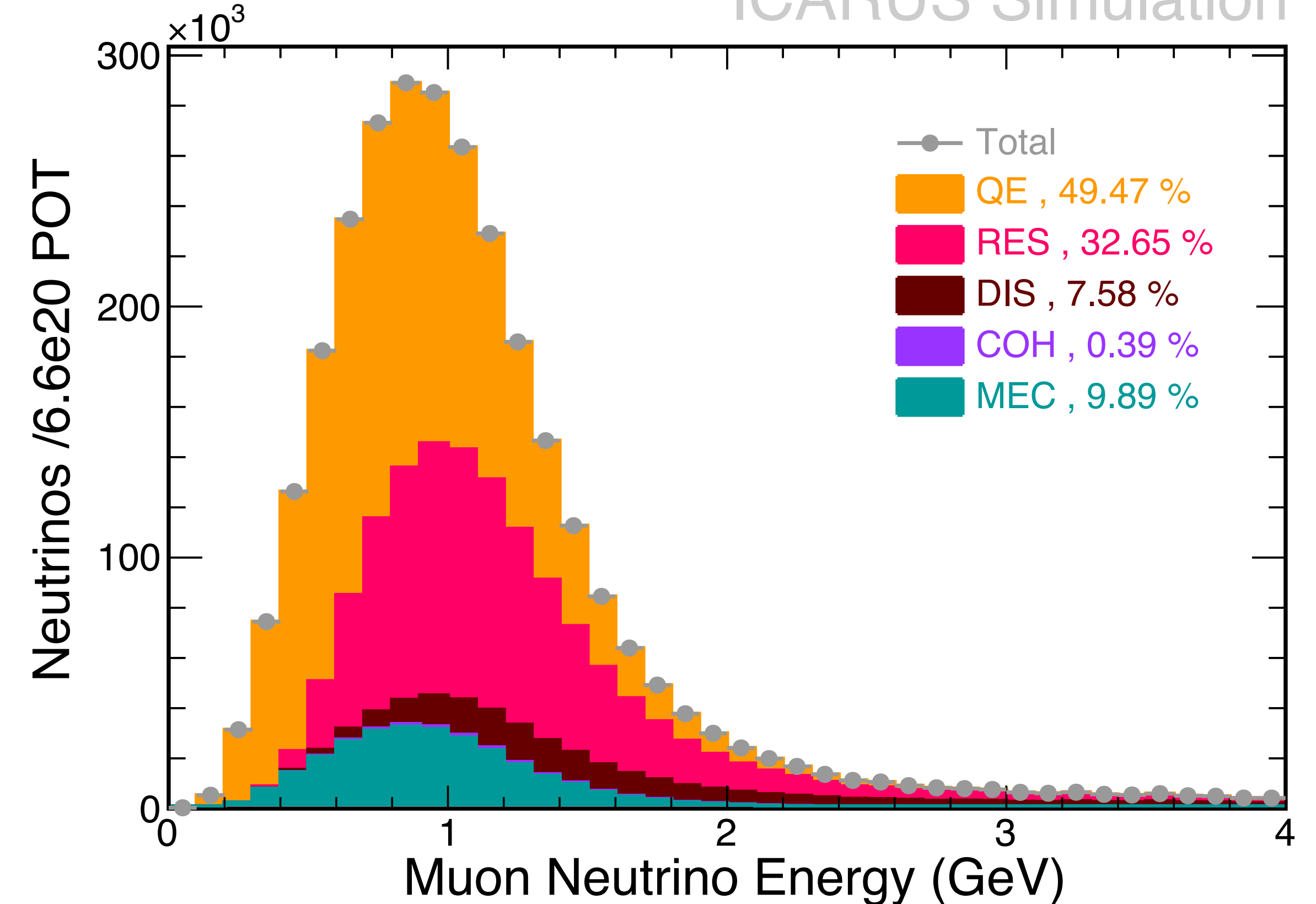
Thank you for your attention!

Back up

Neutrino Interactions in the Overburden

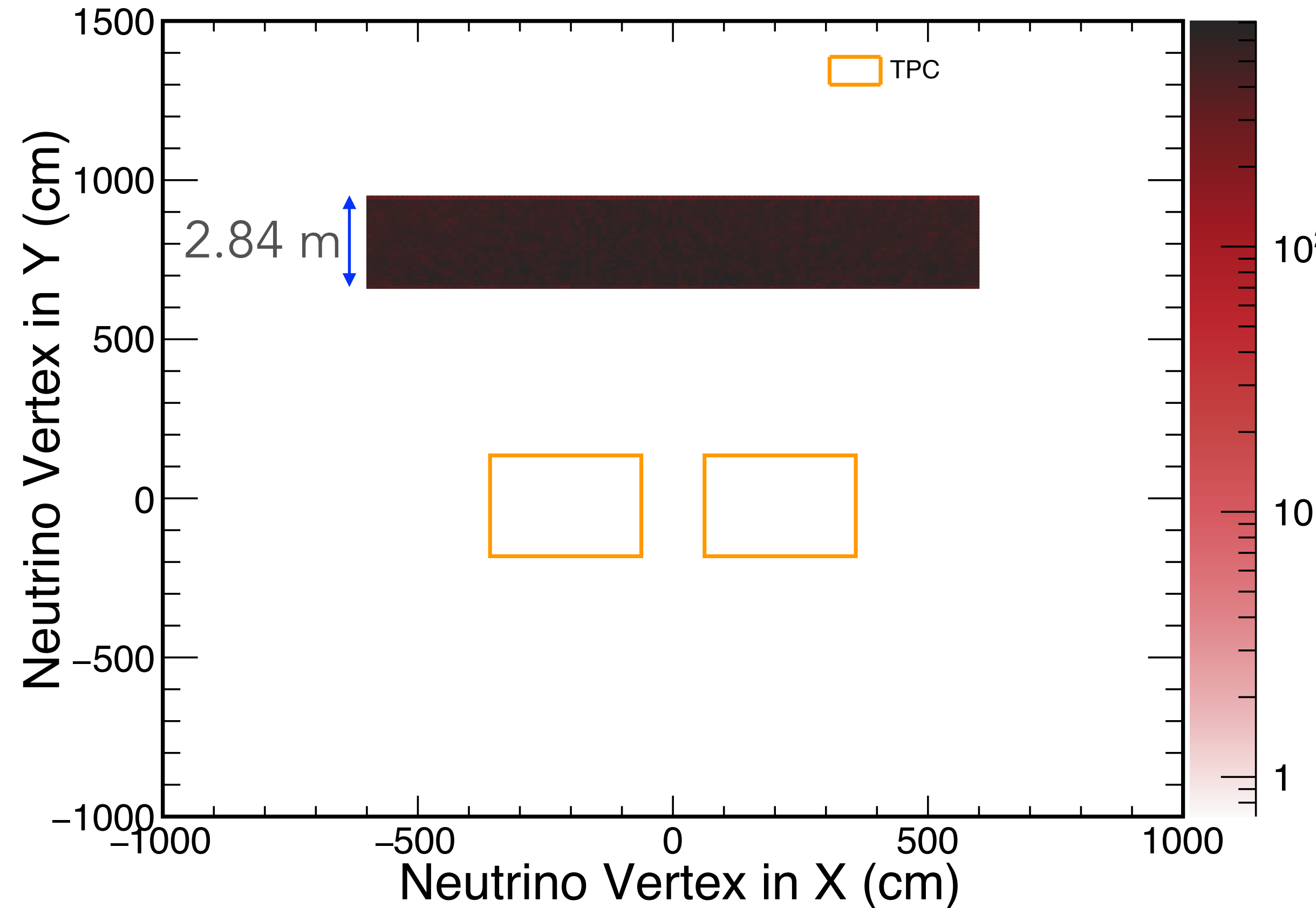Studying neutrinos that interact with the 2.845 m overburden material

Energy spectra of neutrinos interacting in the overburden

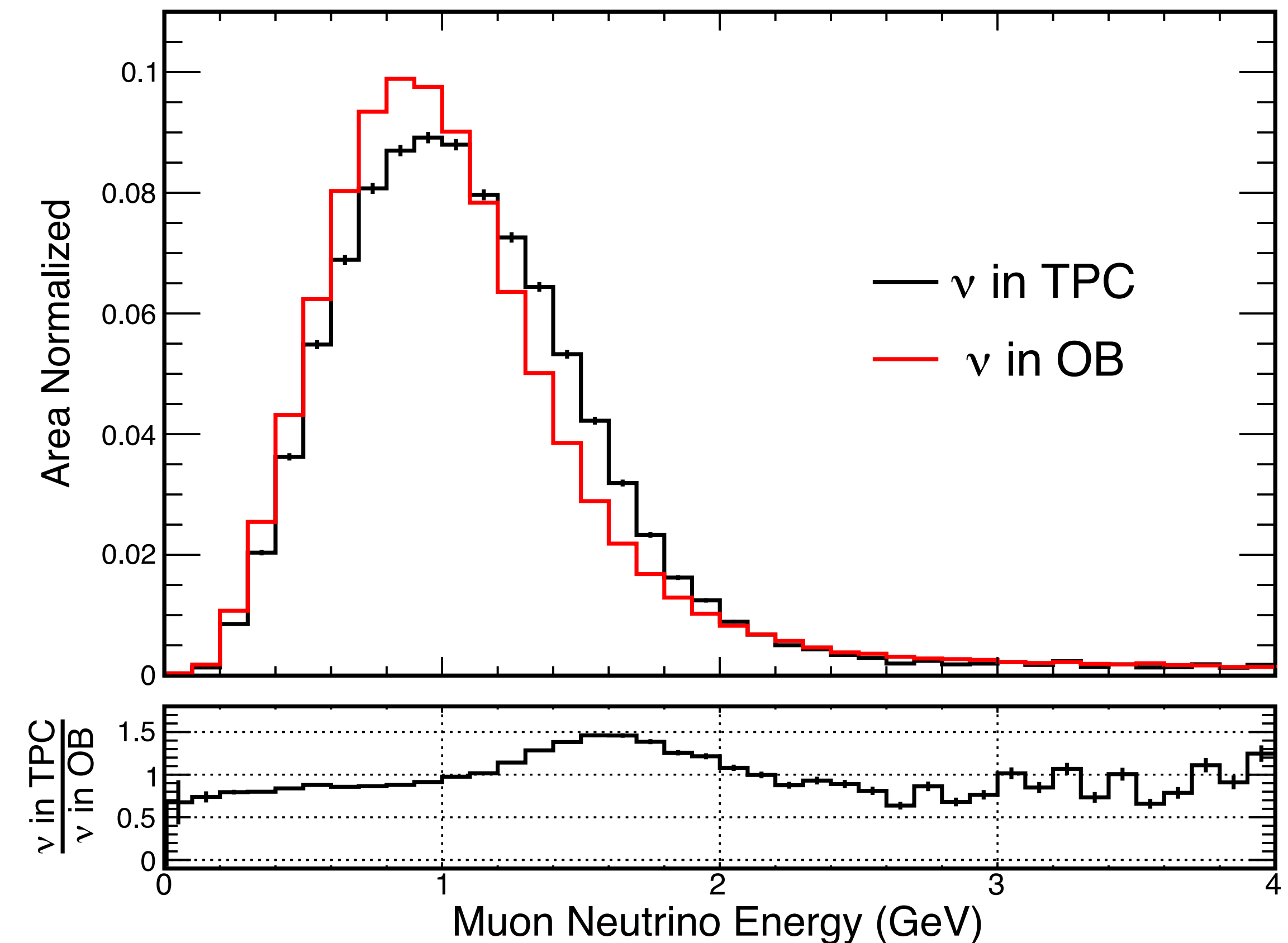# Neutrino Interactions in the Overburden

Studying neutrinos that interact with the 2.845 m overburden material

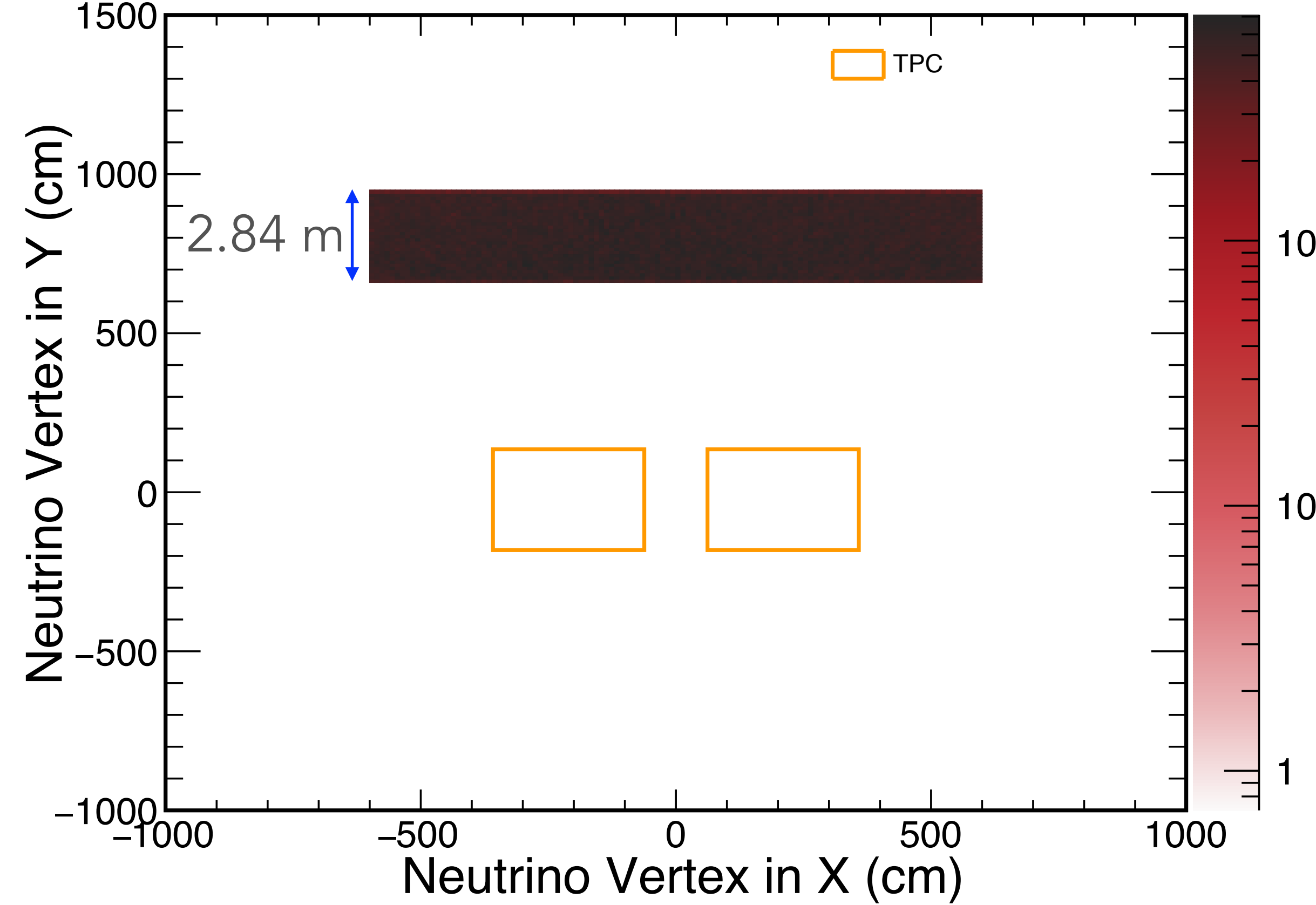Energy spectra of neutrinos interacting in the overburden compared to active volume

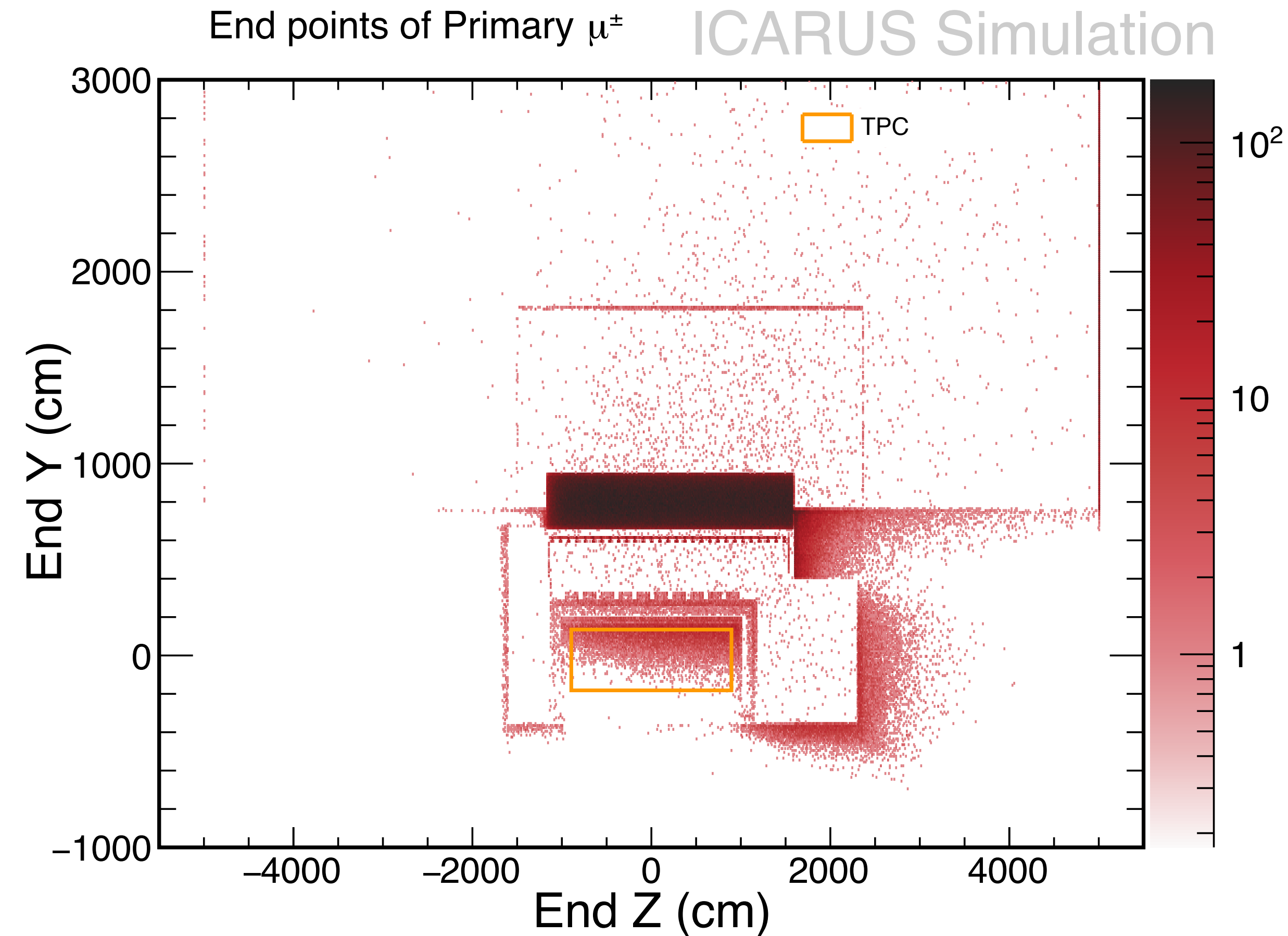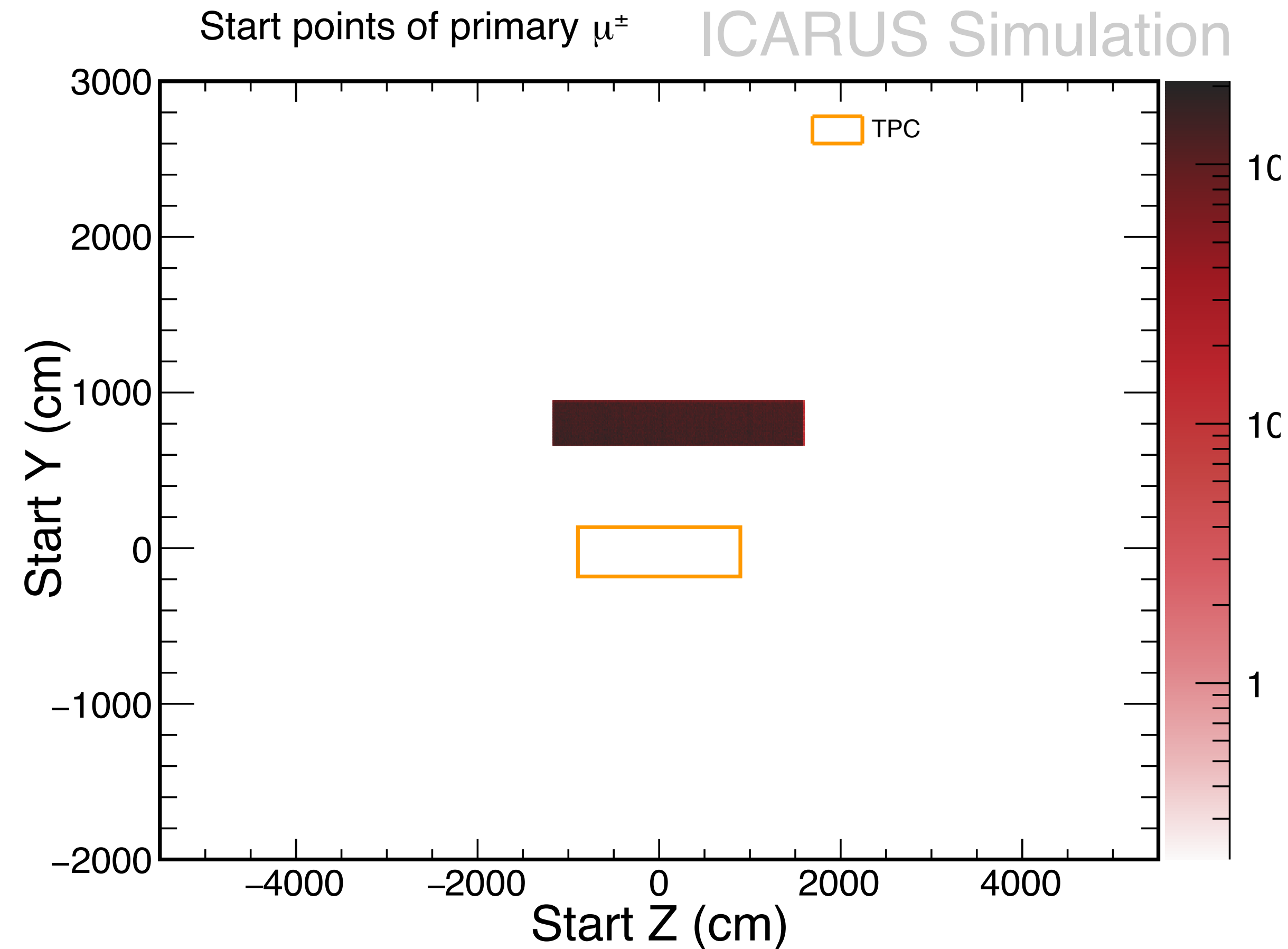# Neutrino Interactions in the Overburden

ICARUS Simulation

	Volume [m³]	Mass (t)	Interactions in 6.6e20 POT
Overburden	992.15	2282	3 M
Active Volume	336.2	476	0.77 M

Studying neutrinos that interact with the 2.845 m overburden material

Volume, mass and event counts in overburden compared to active volume

Short Baseline Neutrino
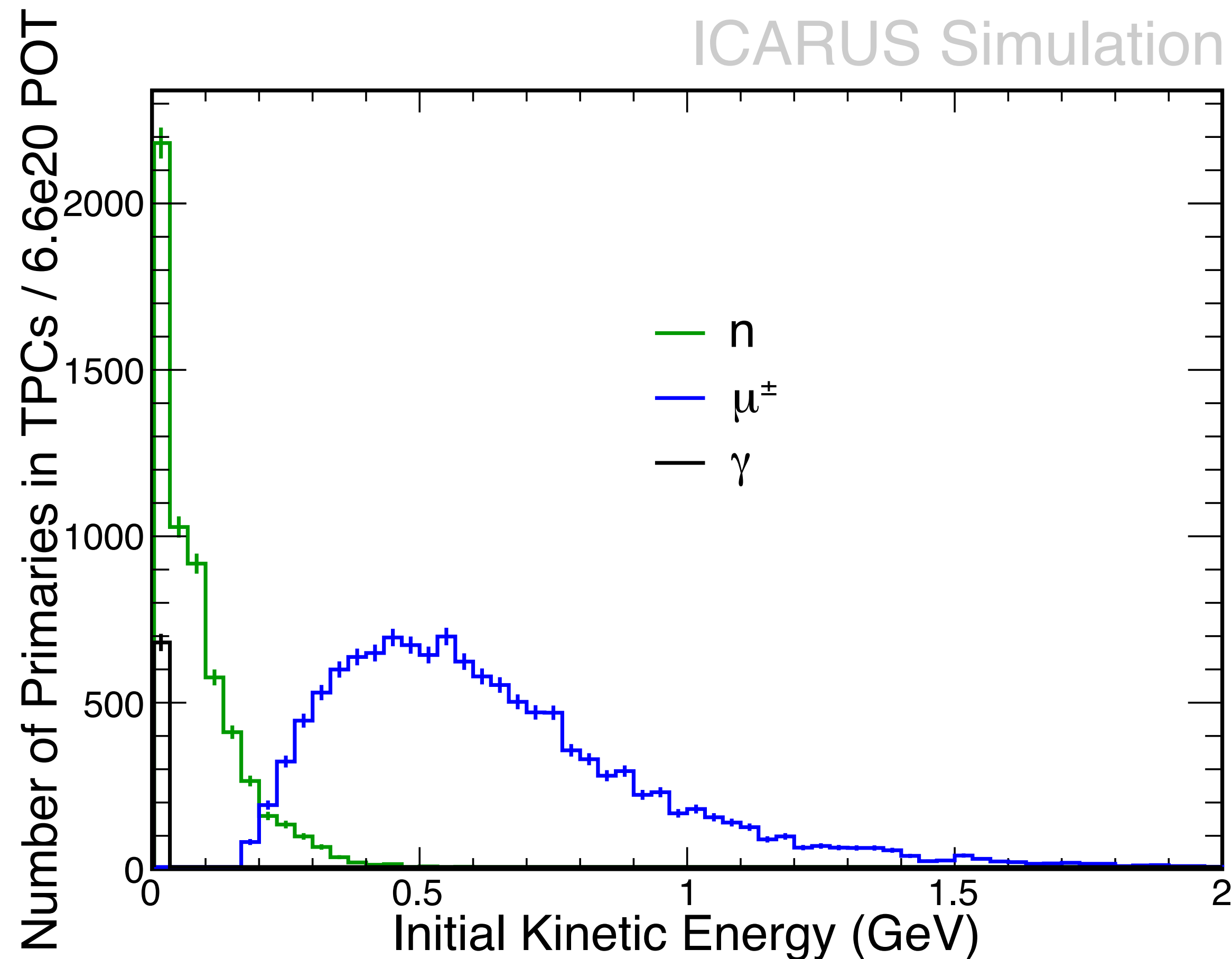
Neutrino in Overburden - Final State Muons

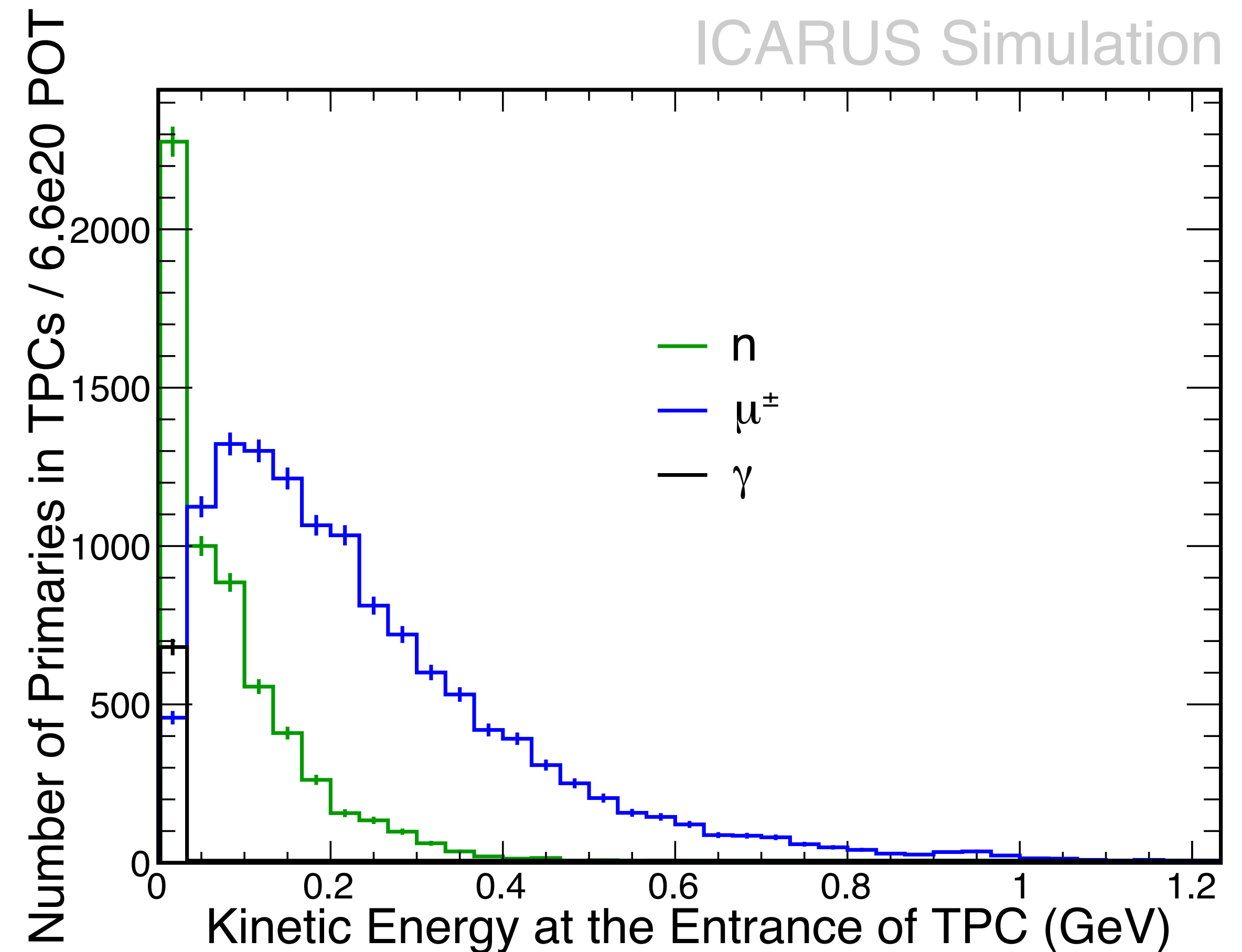Muon start points as neutrinos that interact with the 2.845 m overburden material

Muon end points in the TPC as well as in the surroundings

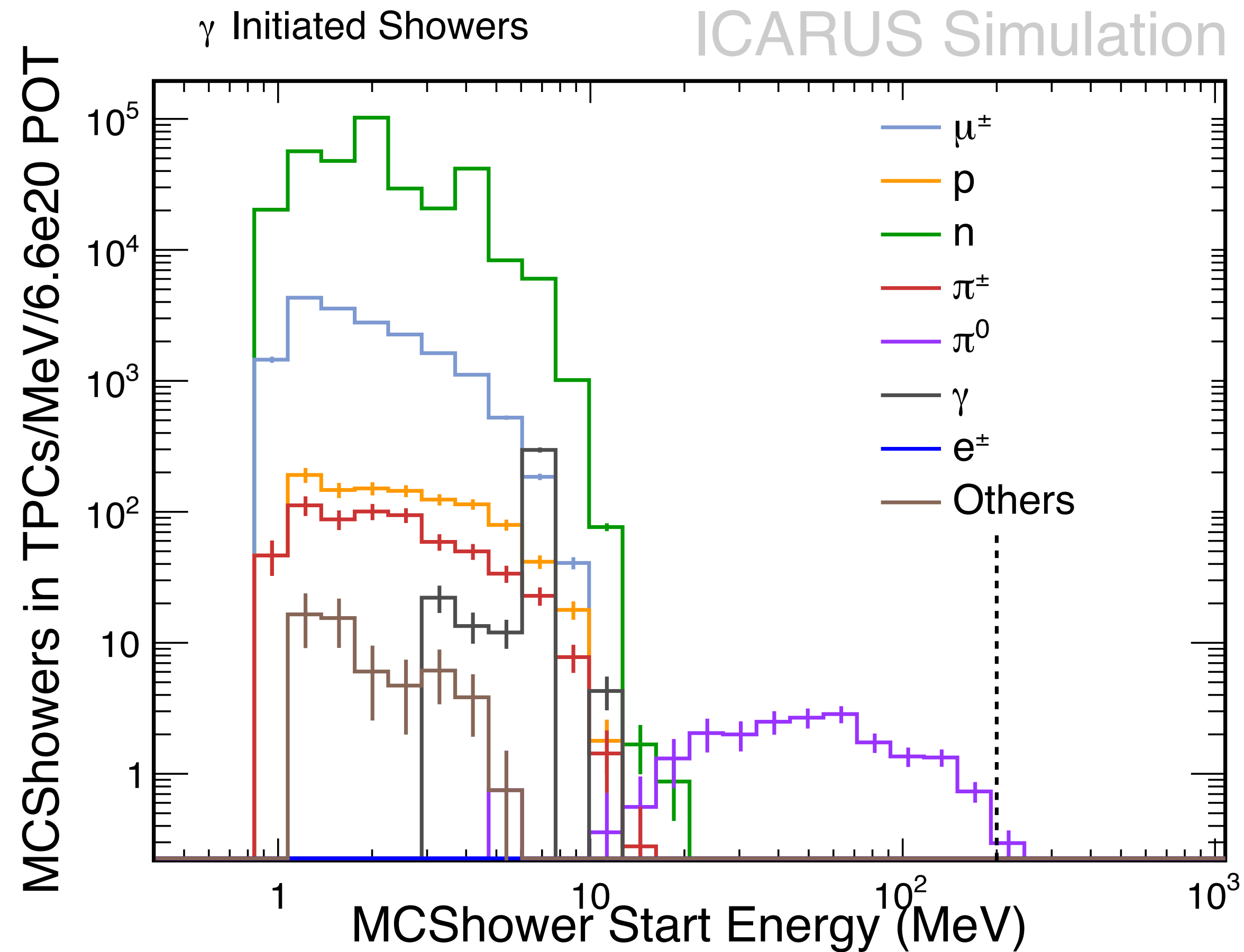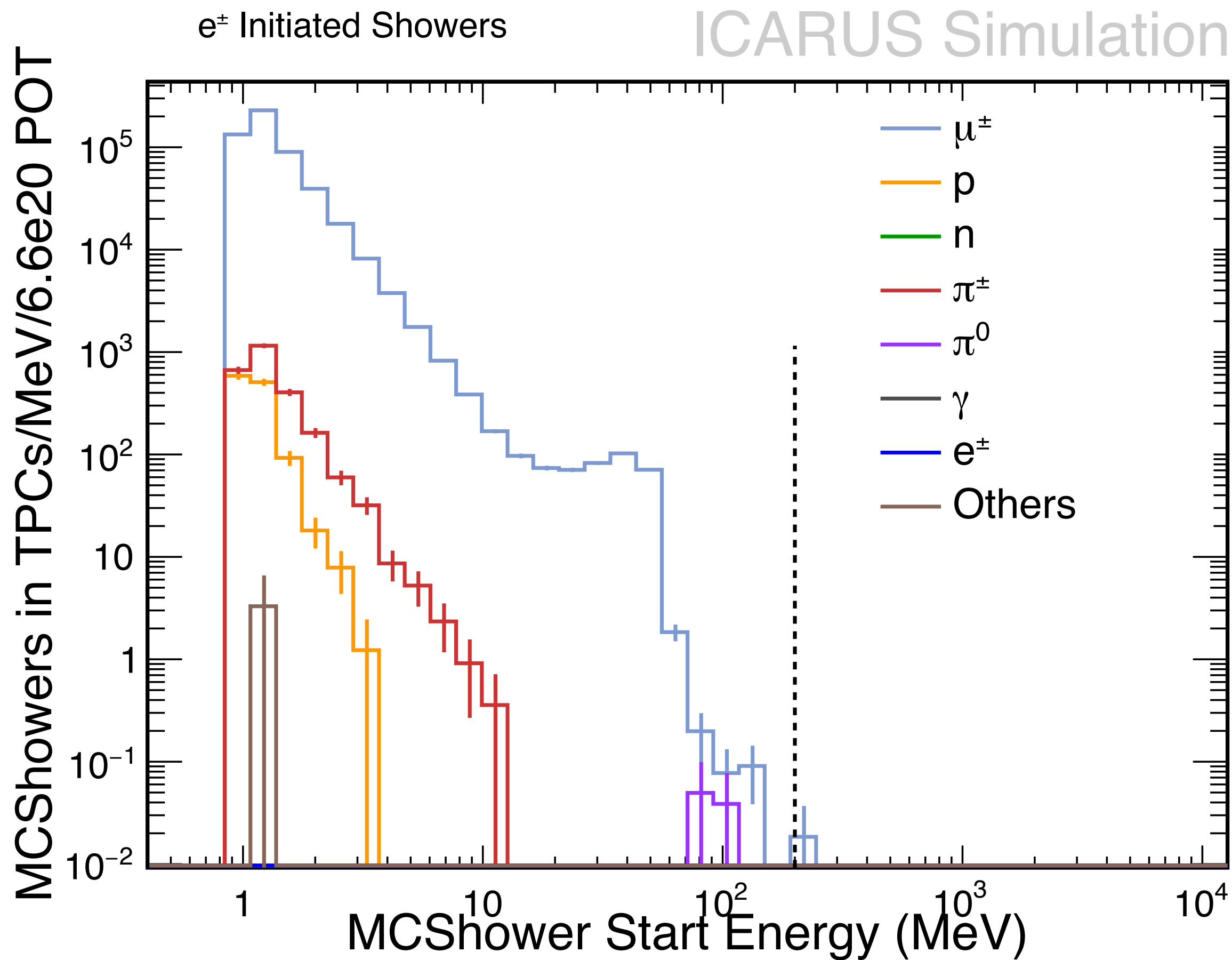# Particles Reaching TPCs from Neutrino interaction in the Overburden

Particles entering to TPCs, kinetic energy at the production

Particles entering to TPCs, kinetic energy at the entrance of the TPC

Cosmogenic Activity: Neutrino Interactions in the Overburden

e± Initiated Showers — ICARUS Simulation

γ Initiated Showers — ICARUS Simulation

No photons in active (fiducial) volume E > 200 MeV

π⁰	All	Selected
Active	46	9
Fiducial	13	0

Cosmic Ray Tagger (CRT)

CRT system detects charge particles entering the detector from outside, whose tracks may interfere with the reconstruction of beam neutrino events
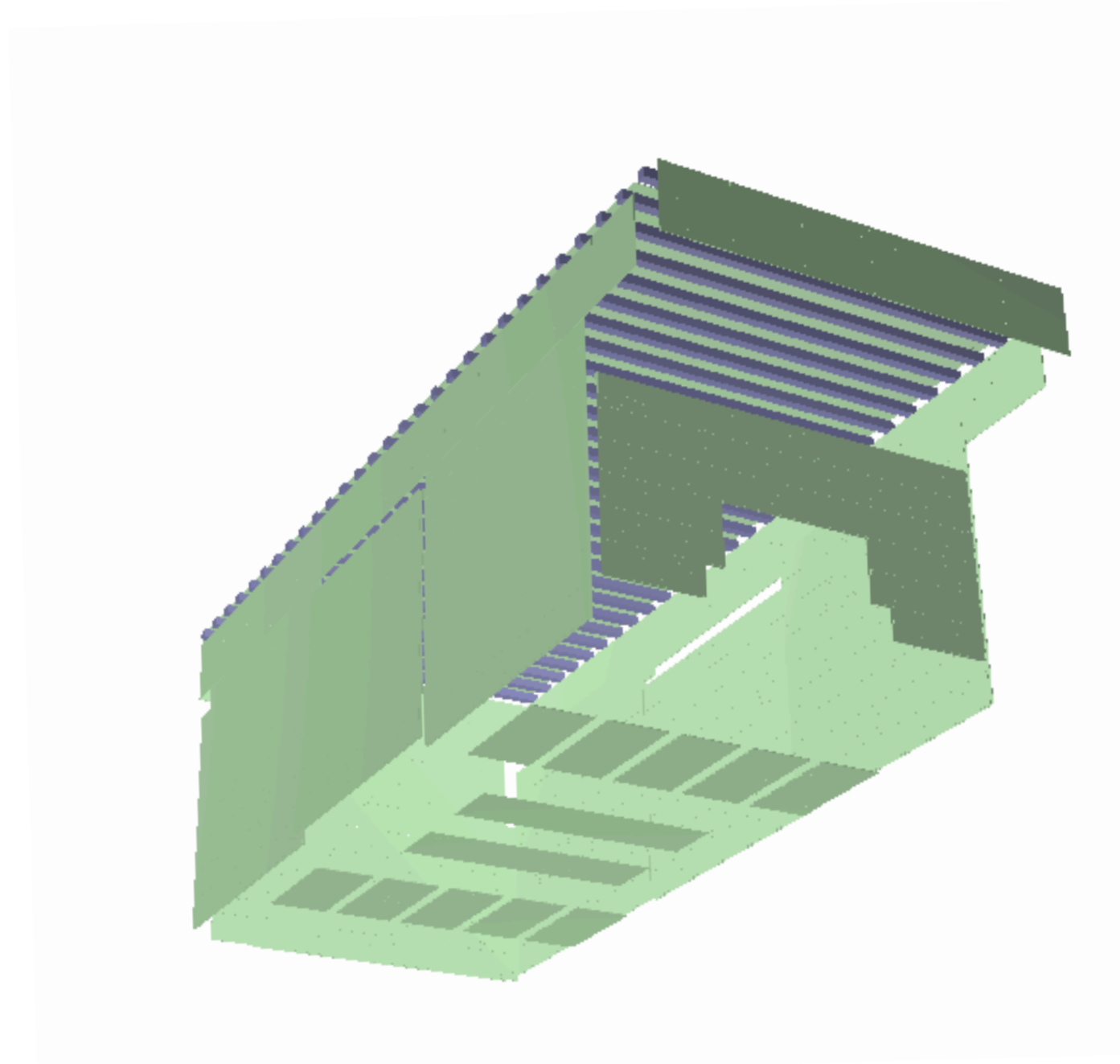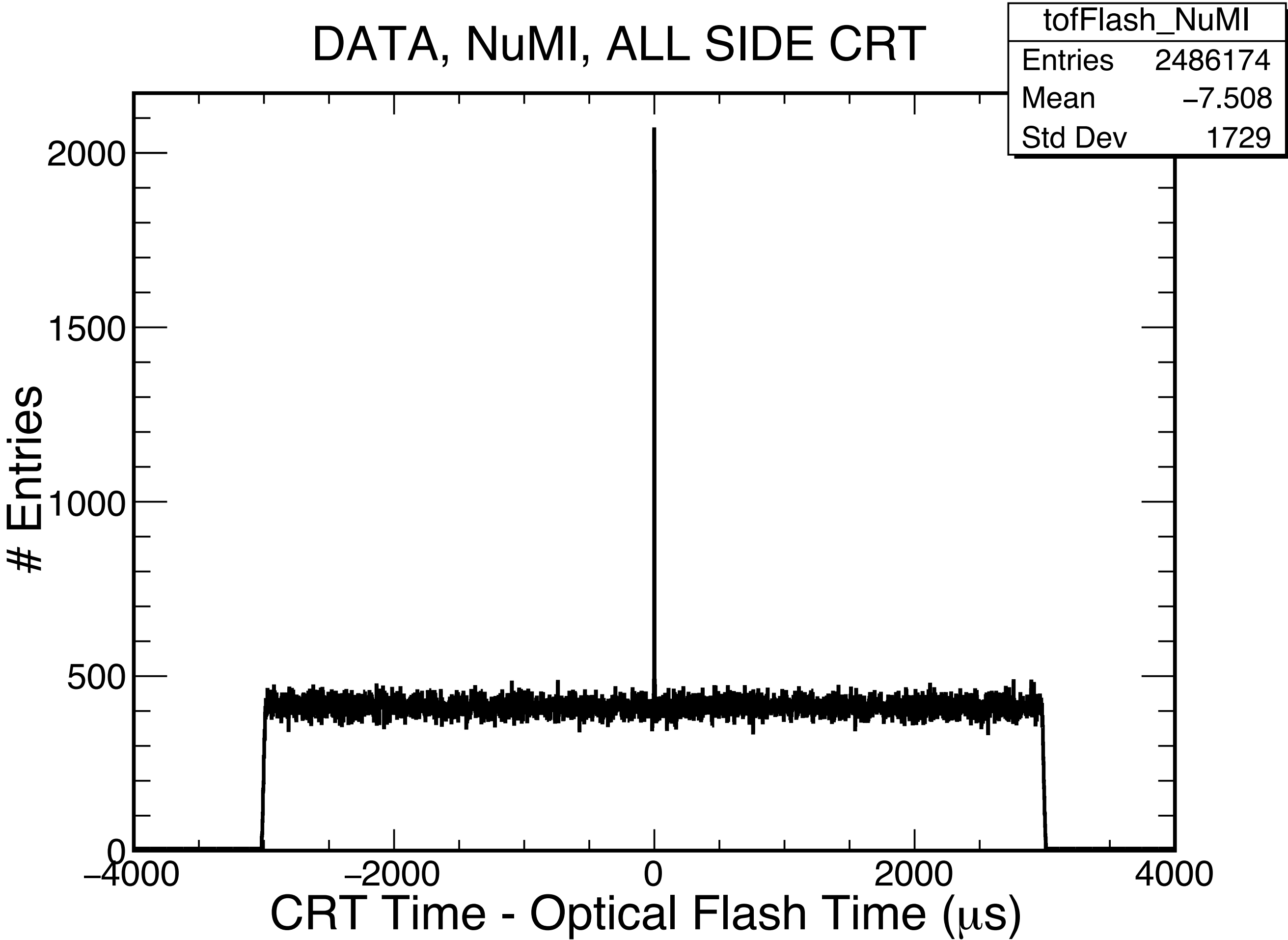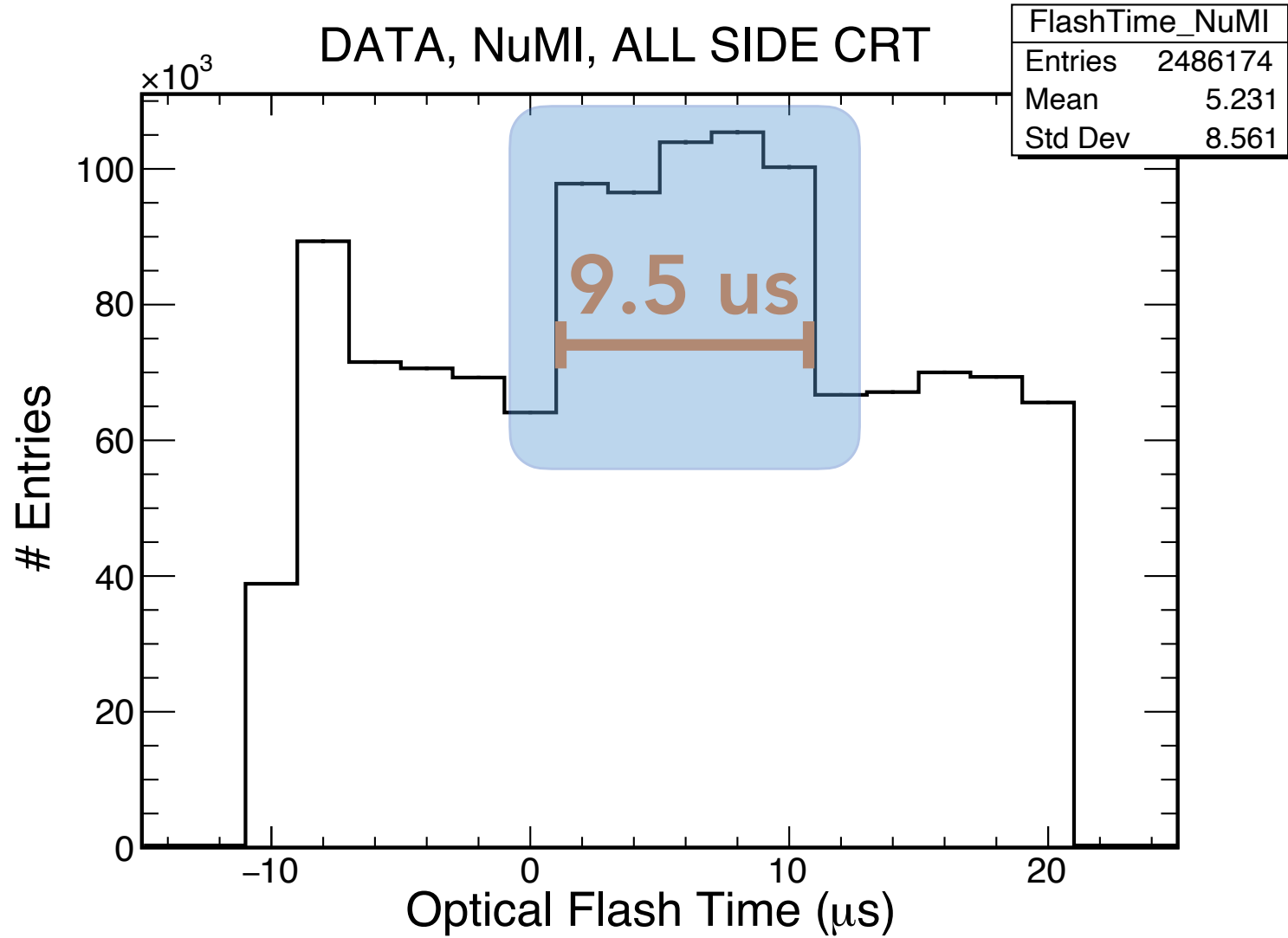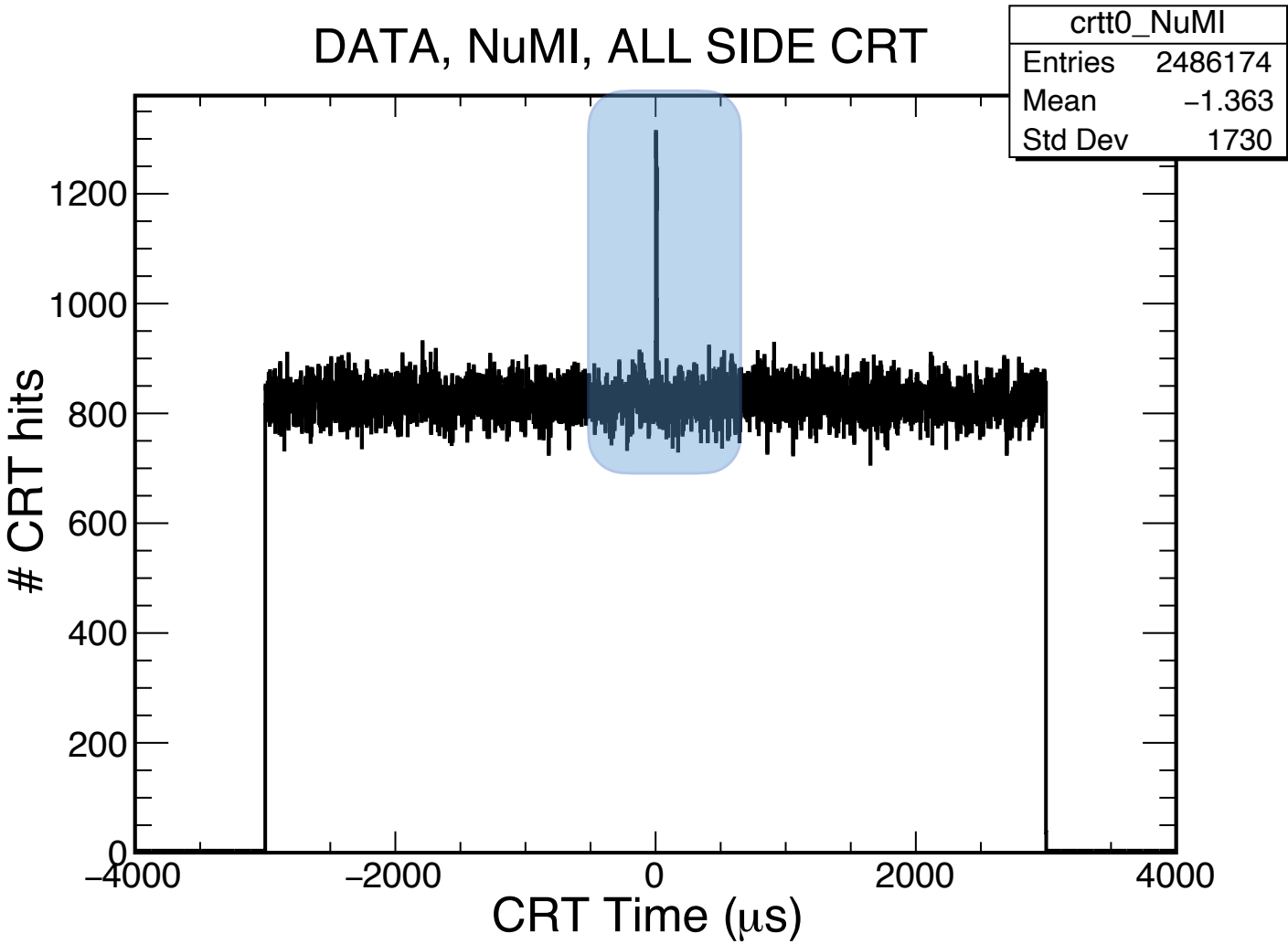
CRT system surrounds the exterior of the warm vessel as much as reasonably possible

It has three sub-systems with different modules and different readout electronics

Beam
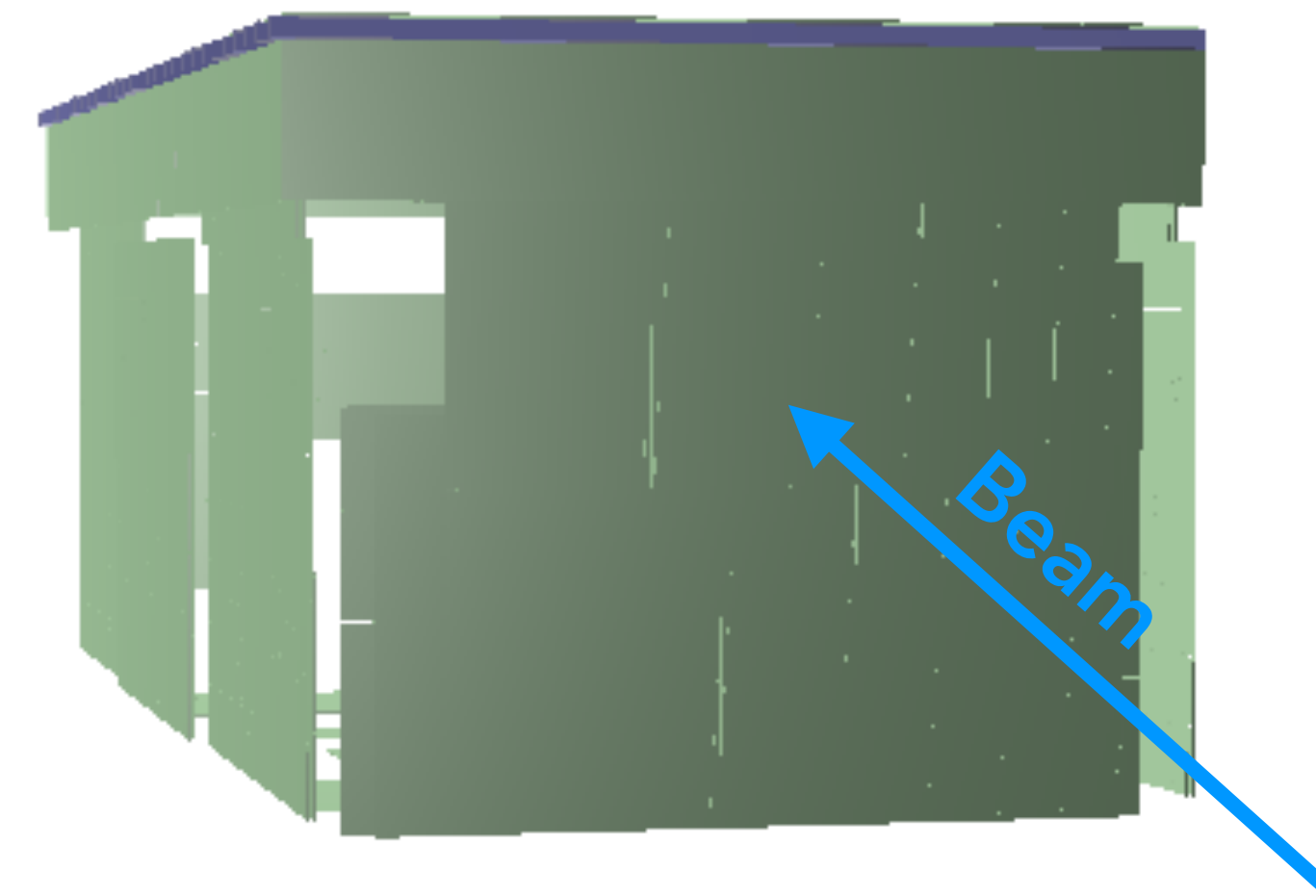
Time of Flight (NuMI, ICARUS DATA)

Tools for rejecting In-time/Out-of-time Cosmic using TPC Alone

Crossing Tracks :

Track is crossing the LAr volume with a clear entering/ existing point

Track that has signals on the wires in the unphysical drift window

Cathode Crossing Tracks :

Cosmic crossing the cathode before the trigger (Track 1,2)
Cosmic crossing the cathode after the trigger (Track 4)

TPC alone will be helpful on rejecting this track quite effectively and requires a good 3D reconstruction track

3 : in-time
1,2 : out-of-time (before the trigger)
4 : out-of-time (after the trigger)
5,6 : entering from top
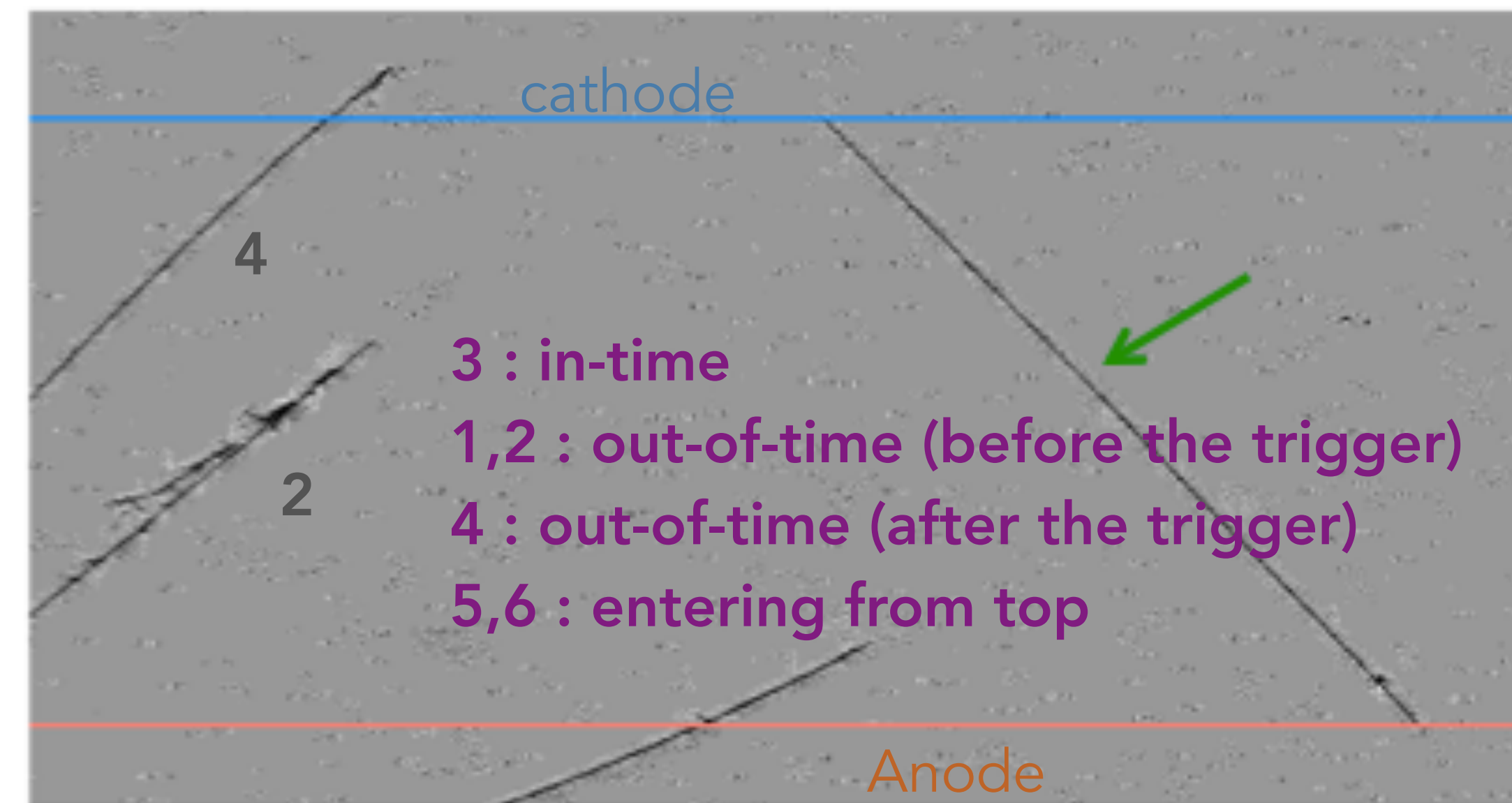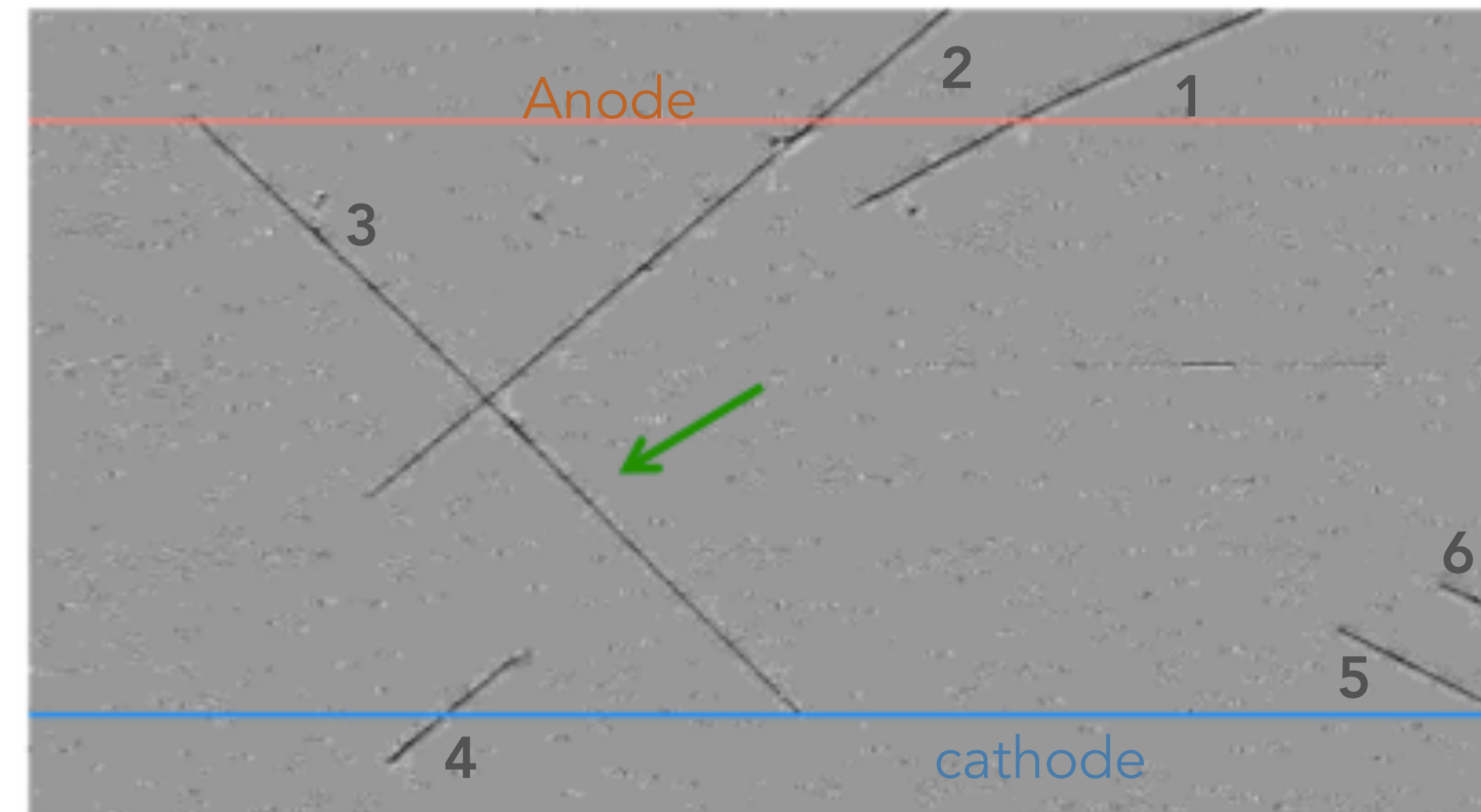
Coordinates of ICARUS Detector
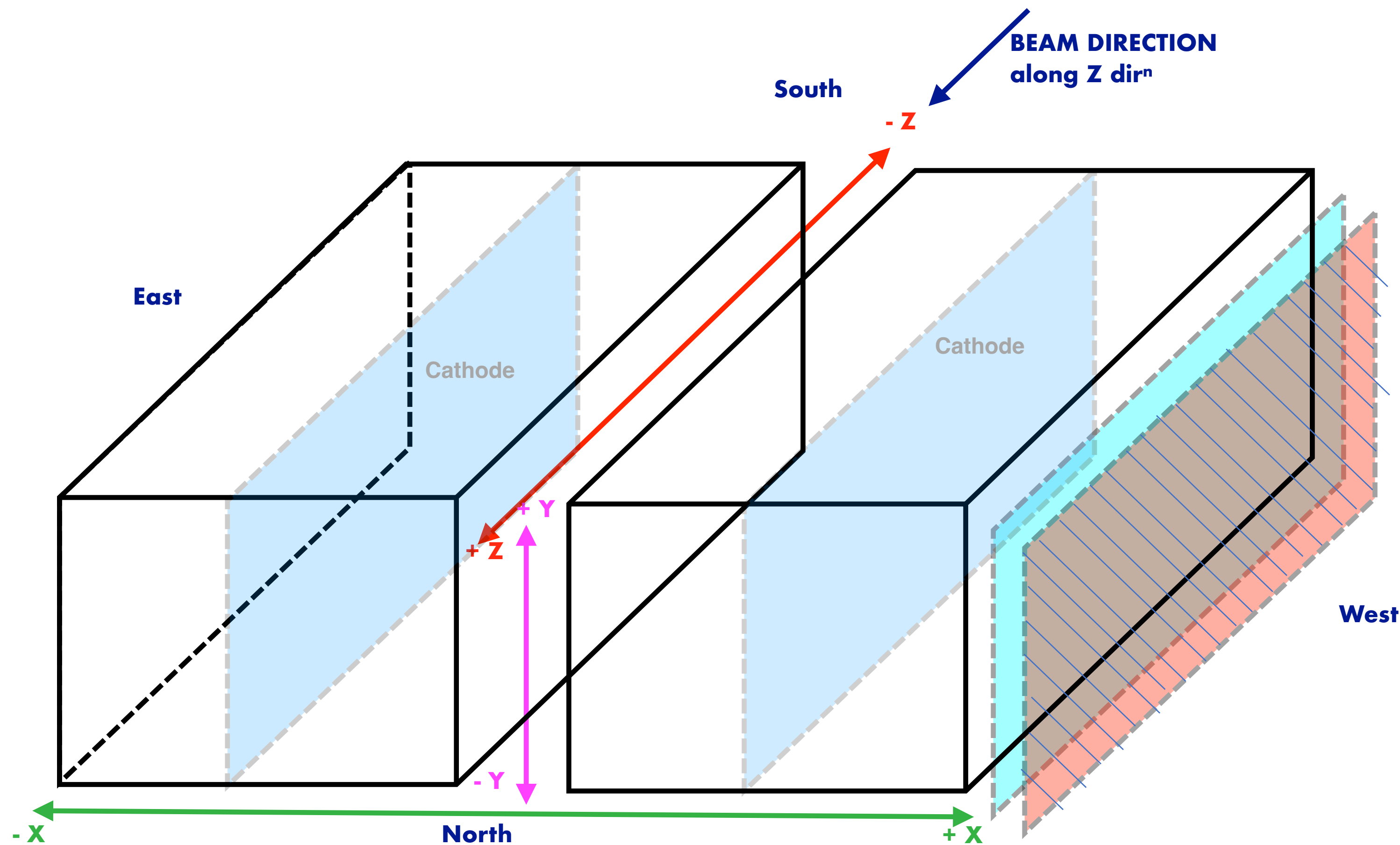
Signal for Analysis

ν_e CC events :
 - Signal is characterized by primary electron initiated showers

ν_μ CC Events :
 - Signal is characterized by a muon from the neutrino interaction

Backgrounds for Analysis

ν_e Events :

- **Event Topology (I) :** Secondary cosmogenic photon interacts in the fiducial volume, and the parent muon enters the active volume.
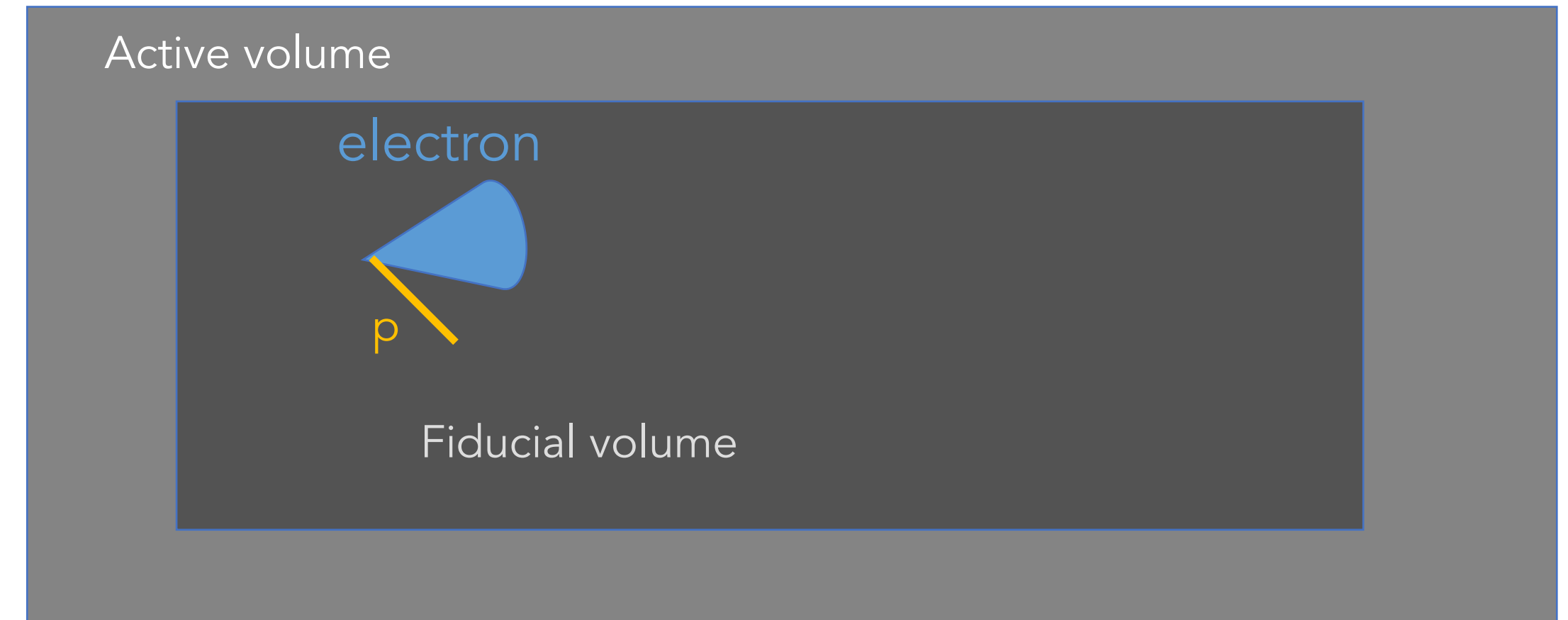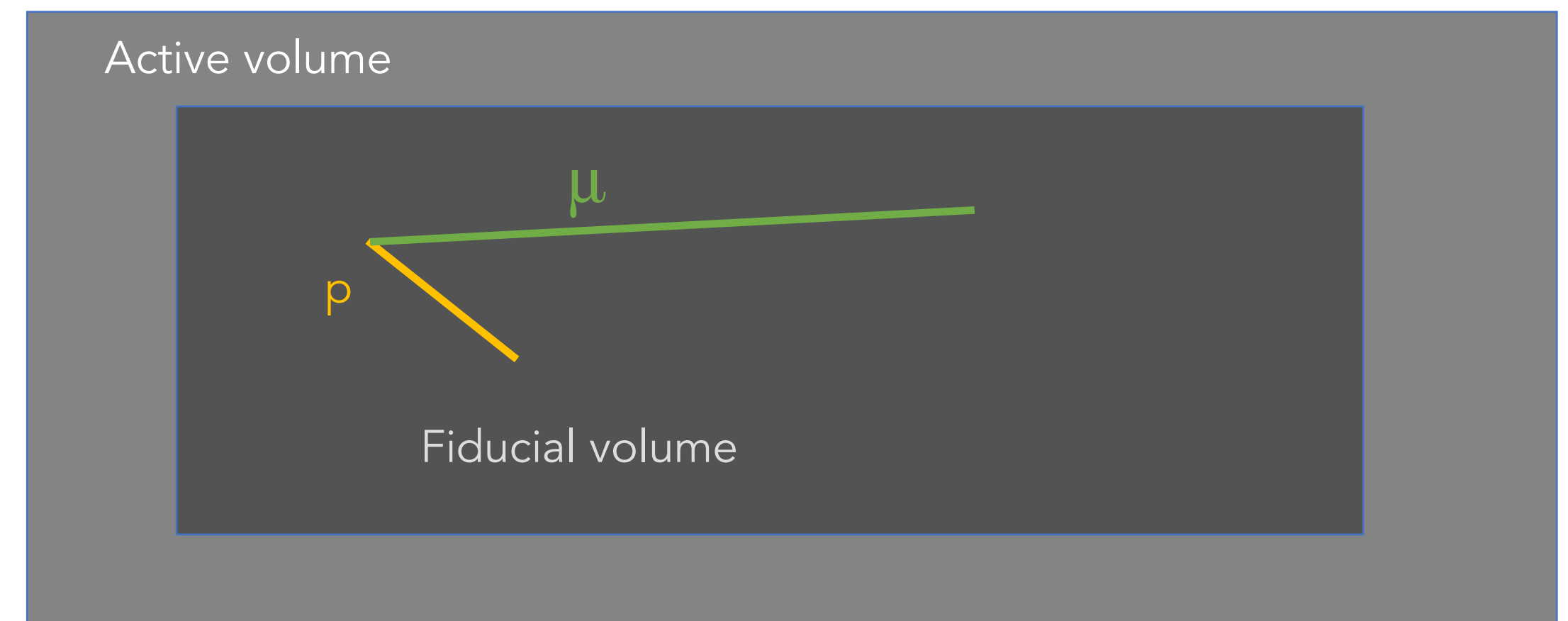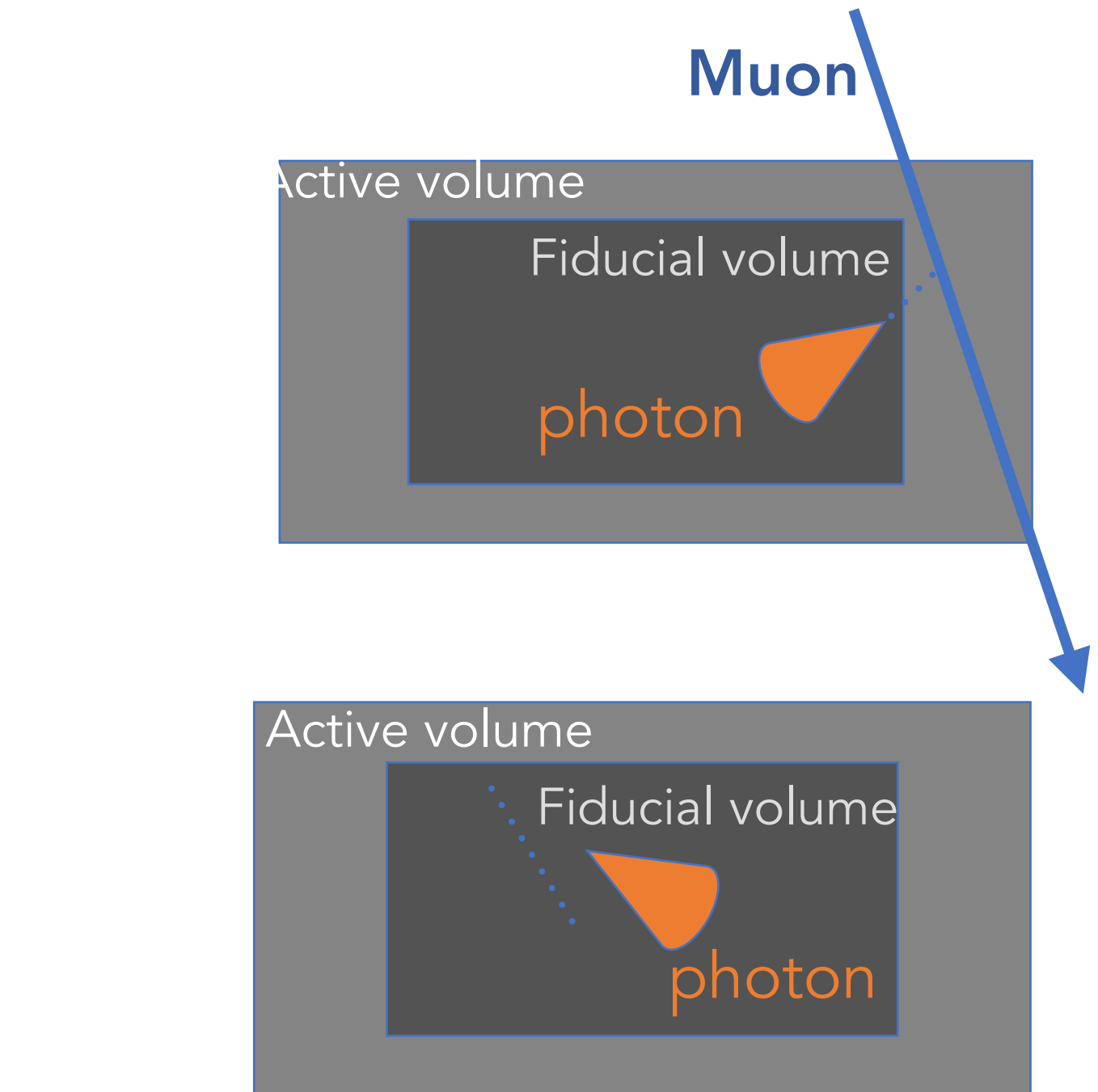
- **Event Topology (II) :** Cosmogenic photon interacts in the fiducial volume and is a primary, the parent is not visible (e.g. a neutron), or the parent does not enter the active volume.

ν_μ Events :

- **Charged pion from cosmic neutron :** Cosmic neutron interactions in LAr producing one charged π and at least 1 proton are a possible source of background events, since pions in the TPC can be misidentified as muons and mimic contained QE ν_μ CC.
  - Total number of events in 3yr of data taking will 1165 (20) in without overburden (with overburden). This is minor contribution with overburden.
  - see more in Prof. Carlo Rubbia's talk at June 2021 PAC meeting.
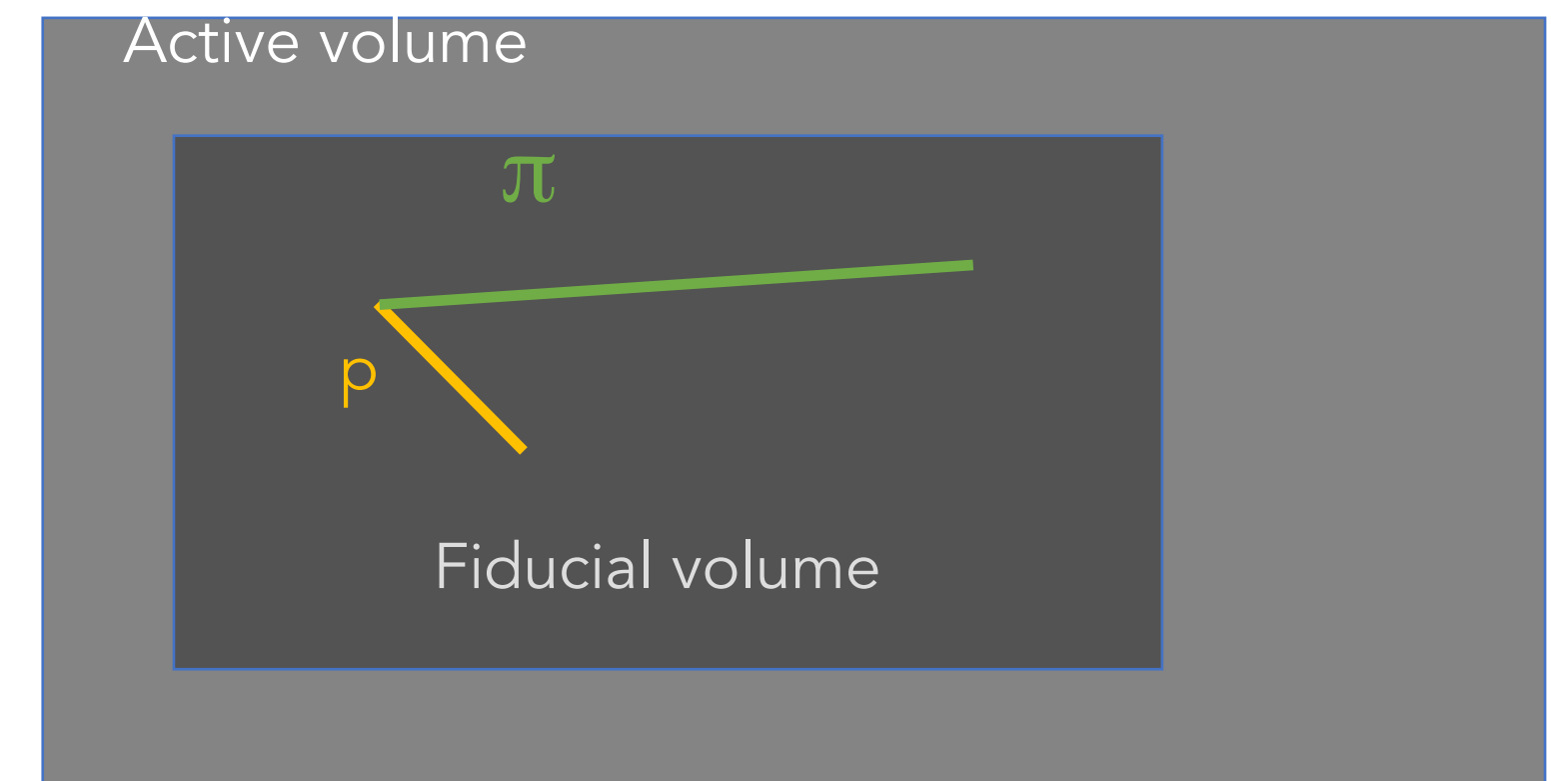
Common Backgrounds for both ν_e and ν_μ CC Analysis

- In this talk, I will mostly focused on dominant backgrounds coming from cosmic.

- Both for in-time and out-of-time **cosmic muons are the main source of background.**

- Following slides describe strategy and various handles for rejecting cosmic.

- **How to reject :**

  - To strongly reject the main component of cosmic a combination of TPC, PMT and CRT information be exploited.

  - Appropriate tools have to be developed can be used also in the event selection.

  - Explained in later slides how CRT, PMT and TPC can be used for different cases.

Reconstruction Tools for background removal for ν_e/ν_μ events with TPC/PMT/CRT [out-of-time]

- **Track entering/exiting through the wires [out-of-time]:**
  - This category we can explored the CRT to track association to reject them.

  - **Additional Handle (**In the case of inefficiency in the CRT track) : PMT signal in the proximity of the track at a time Δt_{PMT} after the trigger equal to the drift time between the closest endpoint of the track and the anode $\Delta t_{tk\text{-}Anode}$

  - Also PMT - CRT time association will help on rejecting this out-going tracks.

Drift Direction

Anode

$\Delta t_{Tk\text{-}Anode}$

Reconstructed Track

Original track

Short Baseline Neutrino
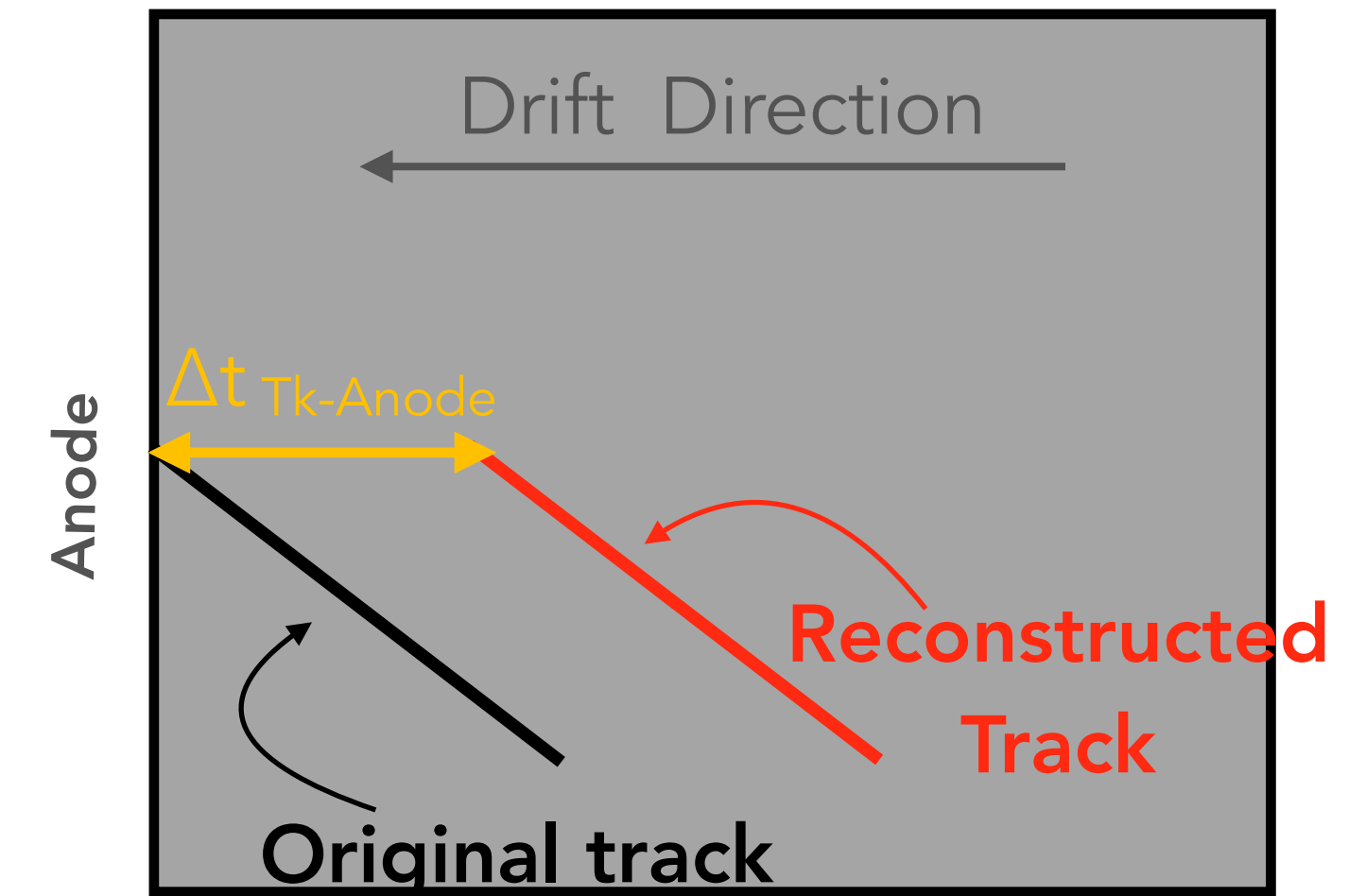
Cosmogenic Electromagnetic Activity in the ICARUS

> 200 MeV shower energy, cosmic muons are larger contributor and primary e± are tiny fraction on producing e± initiated showers

> 200 MeV they are mostly produced by π⁰ with minor contributions from primary γ and brems by muons
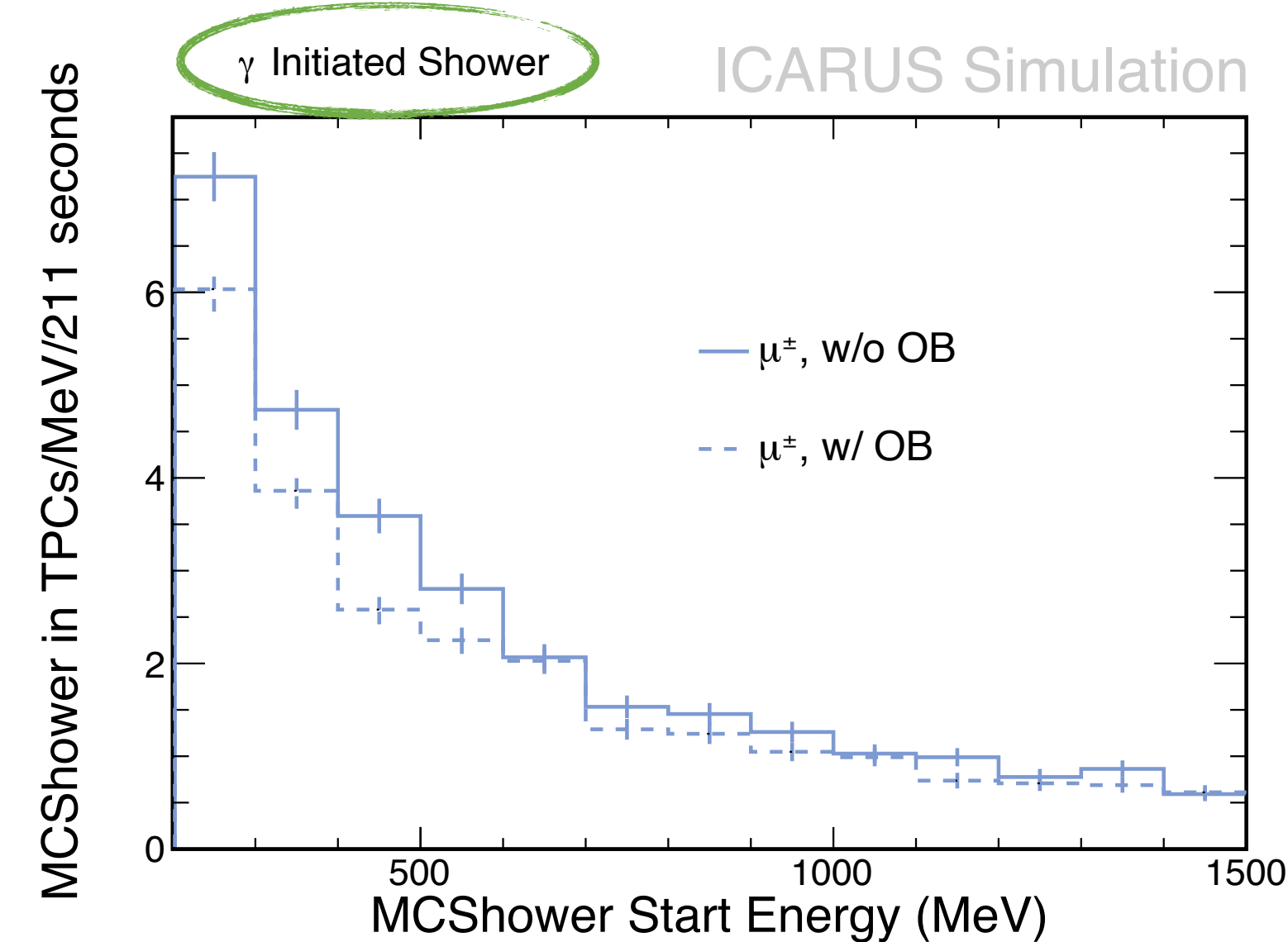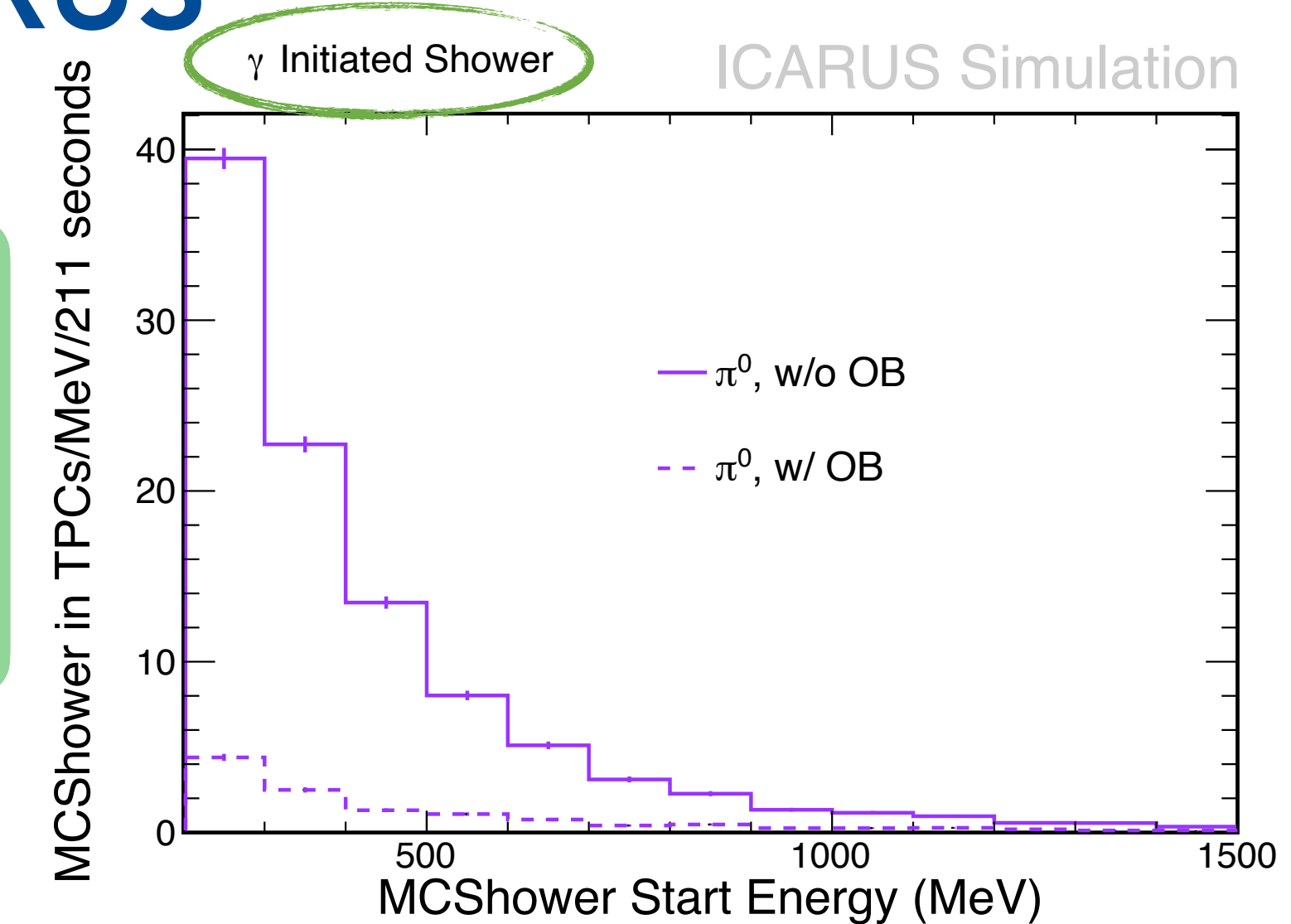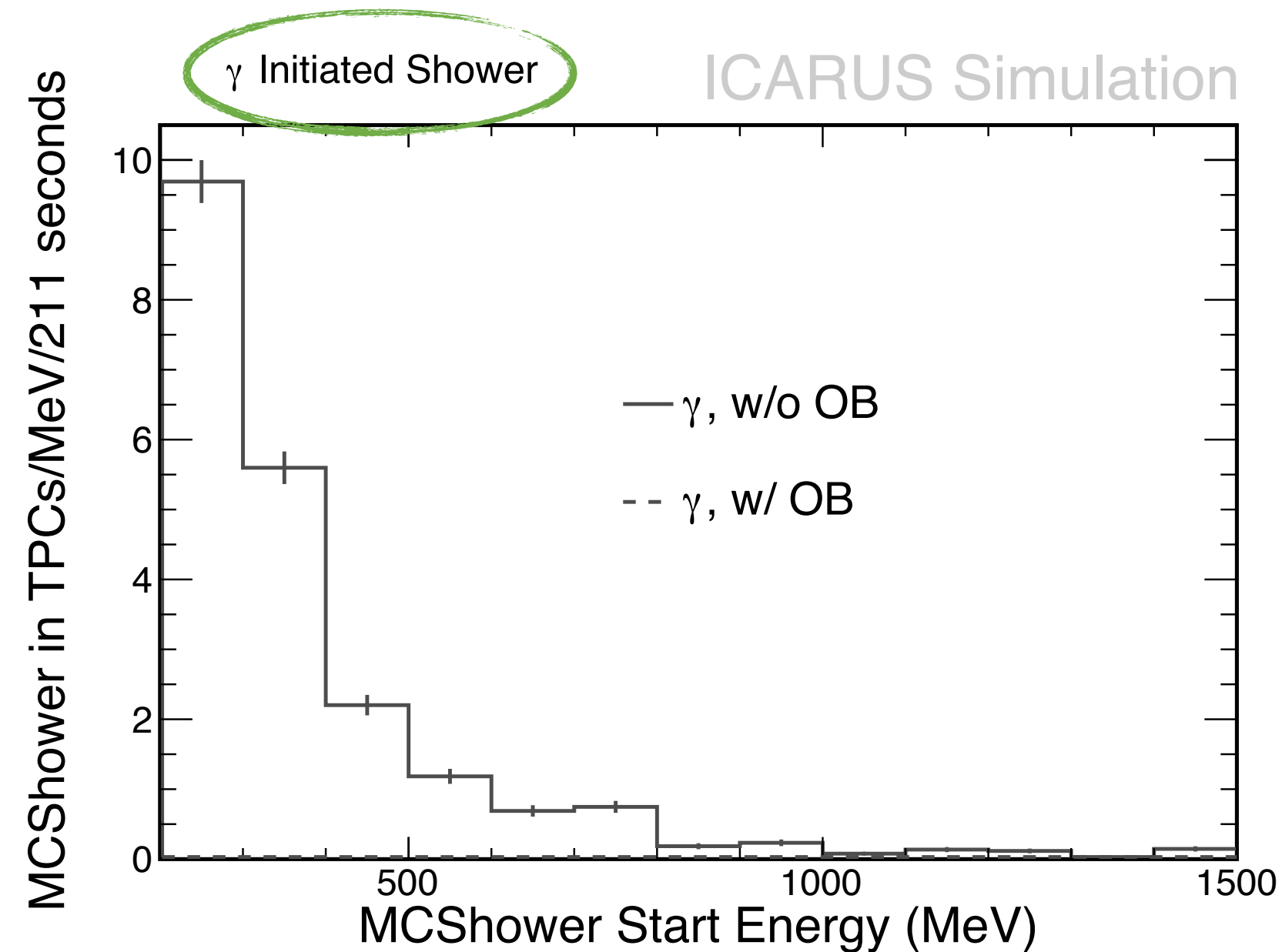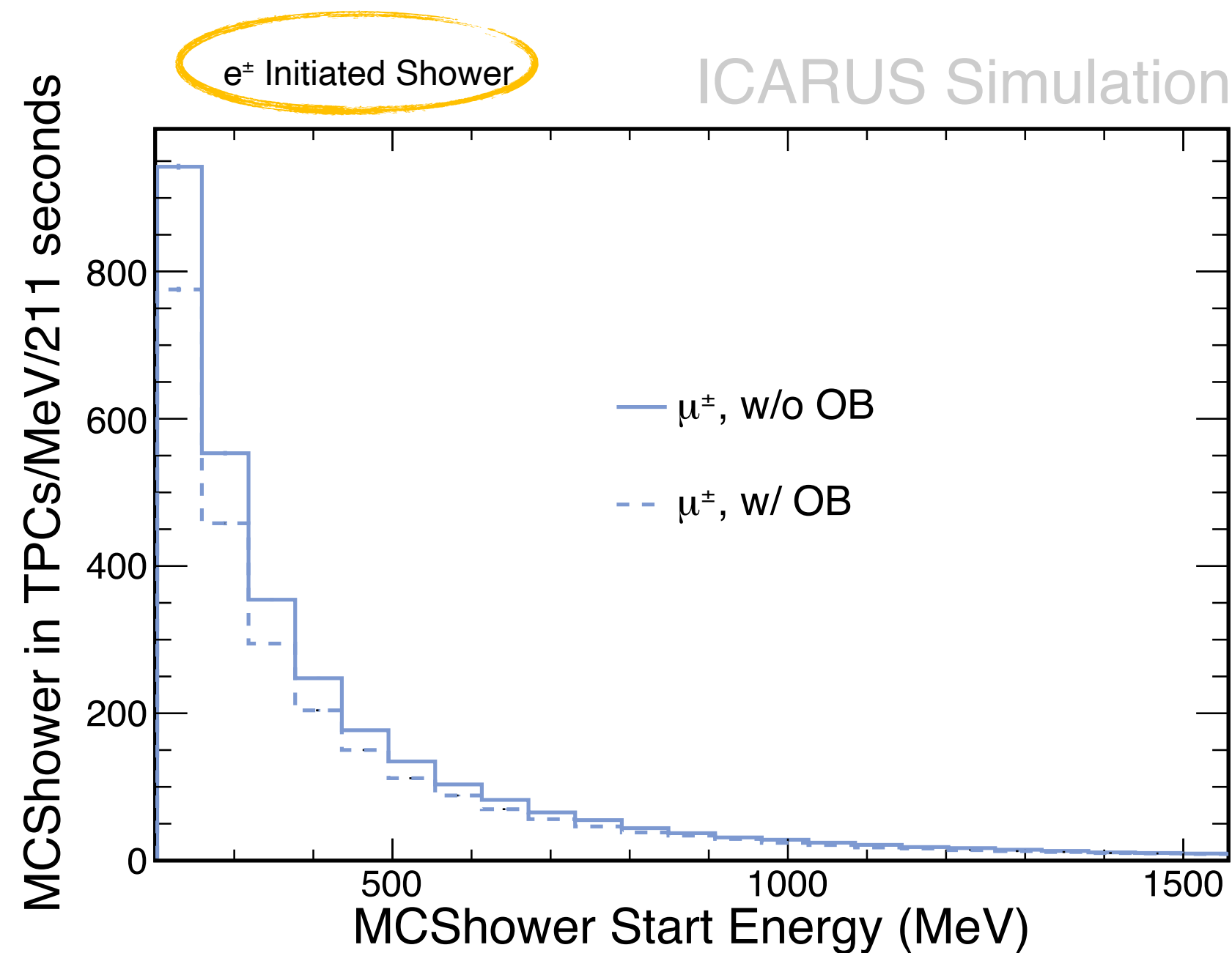
Introduction

Beam	Mean Energy [GeV]	Spill Rate [Hz]	Spill Width [µs]	Bunch Width [ns]	Bunches/Spill
BNB	0.7	5.00	1.6	2	81
NuMI	2.0	0.75	9.5	2	486

BNB

- 5×10^{12} protons per spill to the beryllium target

- 6.6×10^{20} POT (1.32×10^{8} spills) in 3 years.

NuMI

- 6×10^{13} protons per spill

Introduction

Beam			
BNB			
NuMI			

- 5x10^{12} protons p
- 6.6 x 10^{20} POT (1
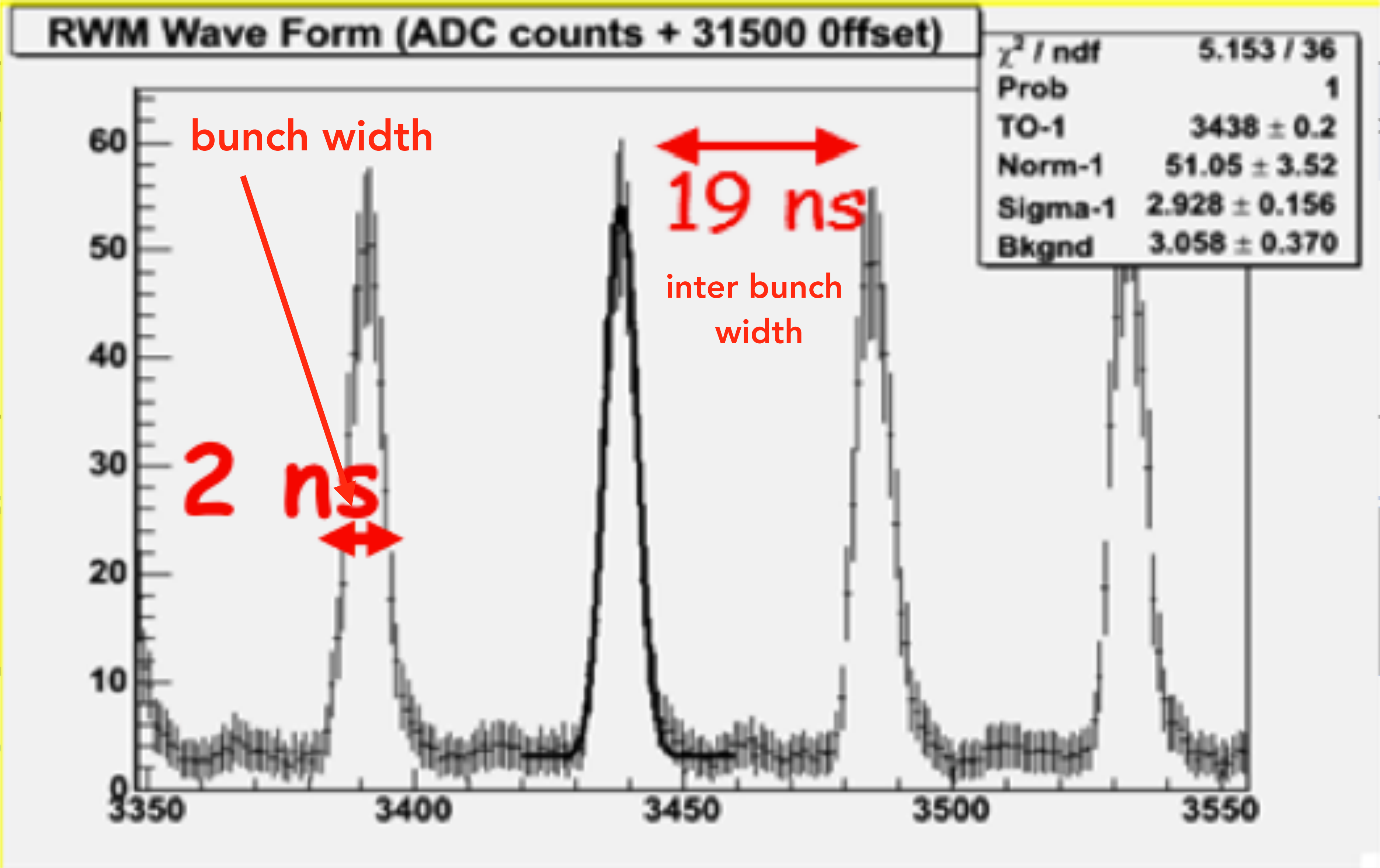
Reconstruction Tools for background removal for ν_e events [Both in-time and out-of-time]
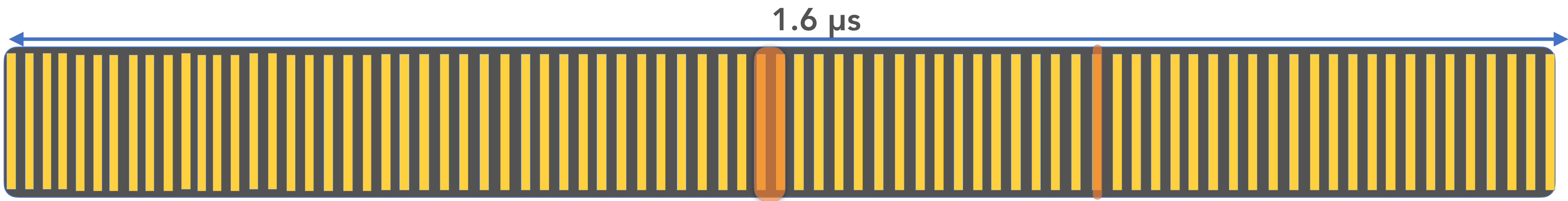
CRT will help on killing photon from muons.
PMT will help us distinguishing in-time and out-of time

- **Gap cut with hadronic activity at the vertex :** If hadronic activity is visible at the neutrino vertex, the mm-level spatial resolution can be exploited to check for a gap between the vertex and the beginning of the candidate EM shower. This is highly effective in rejecting gammas as they usually propagate a few cm before interacting while electrons begin to ionize the LAr immediately.

- **dE/dx :** Using precise spatial and calorimetric information, photon and electrons induced EM showers can be distinguished. About 94% of pair-producing photons are rejected.

- **Distance from the muon track :** In cases where a muon track is present in the active LAr volume, simulation studies from proposal show that 99.2% of all photons produced by the muon convert within 15 cm of the track. This motivates a strategy where a cylinder with a 15-cm radius centered on the muon track is used to exclude a portion of the active volume.

single e+/- → 2 MeV/cm
γ→e-e+ → 4 MeV/cm