Tens-of-MeV ν_e-Ar CC Events: Potential of Better Reconstruction with PDS

FD3 APEX Biweekly Meeting
Jan 11, 2024

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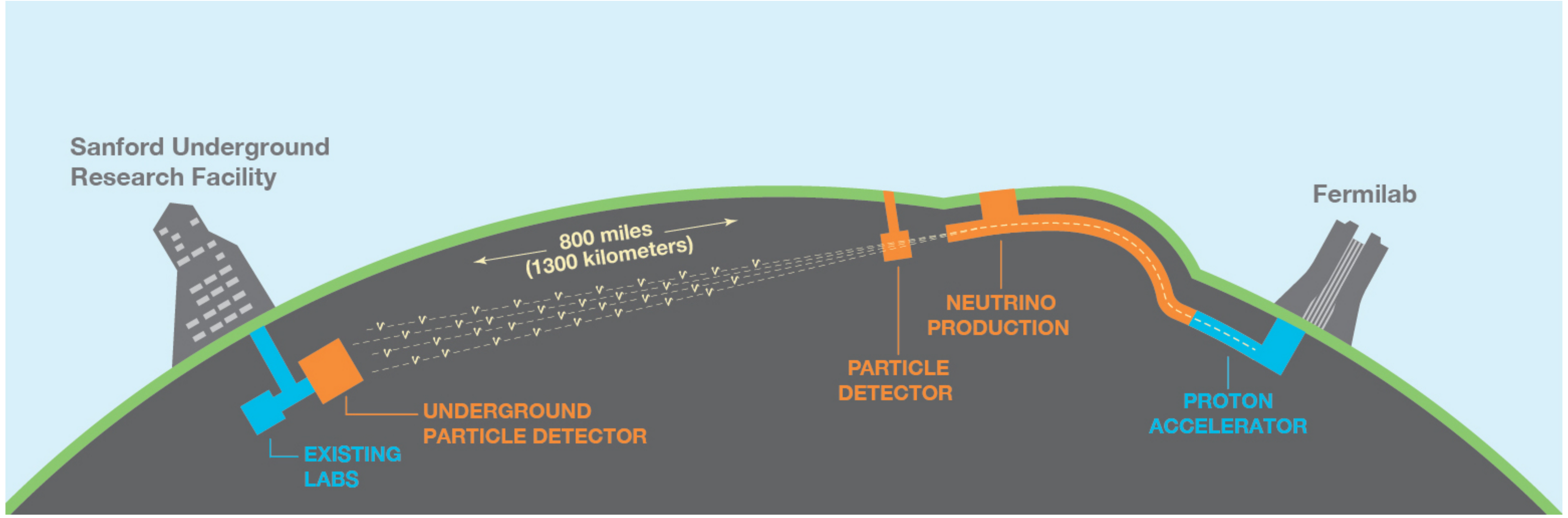
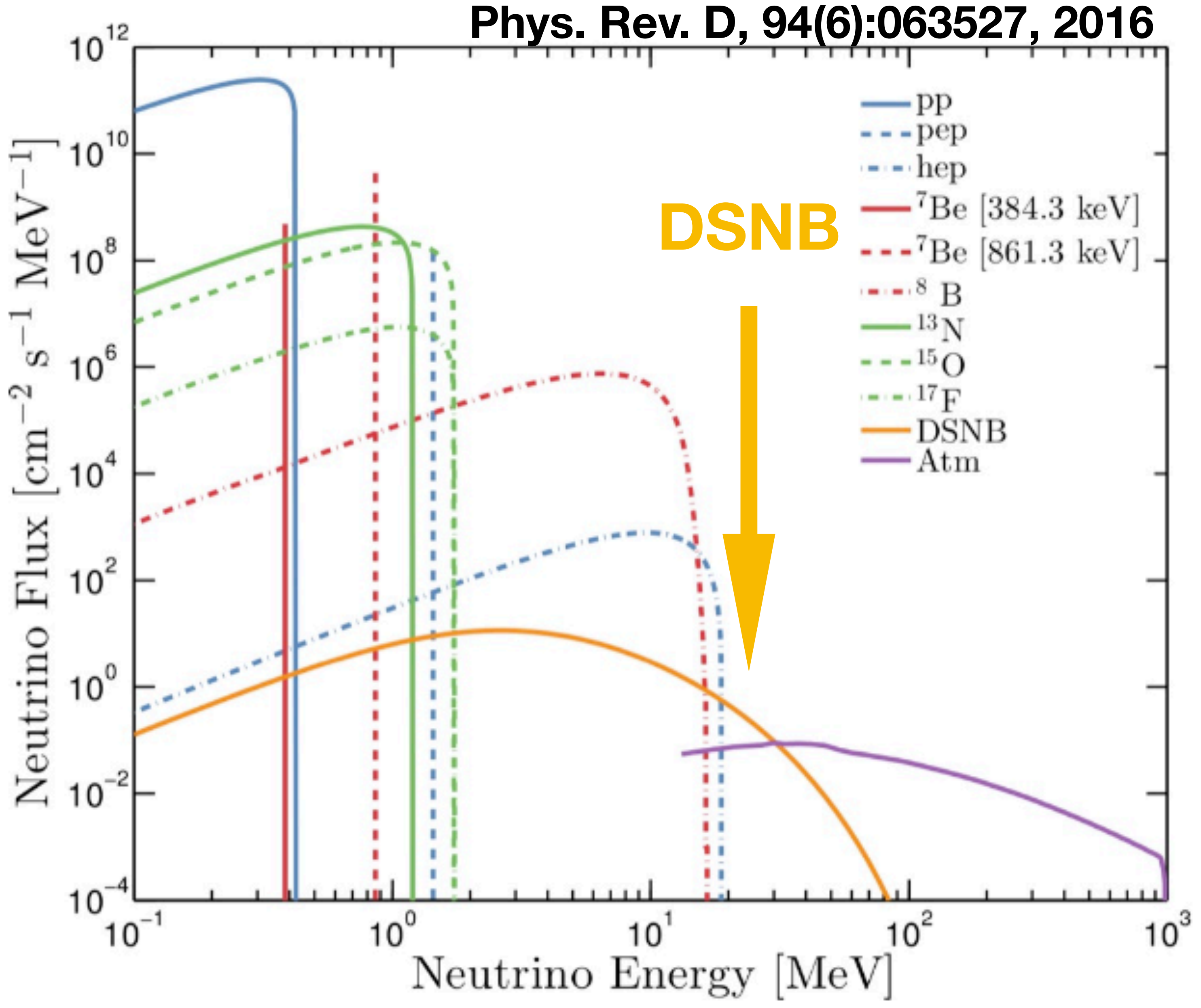
DEEP UNDERGROUND NEUTRINO EXPERIMENT

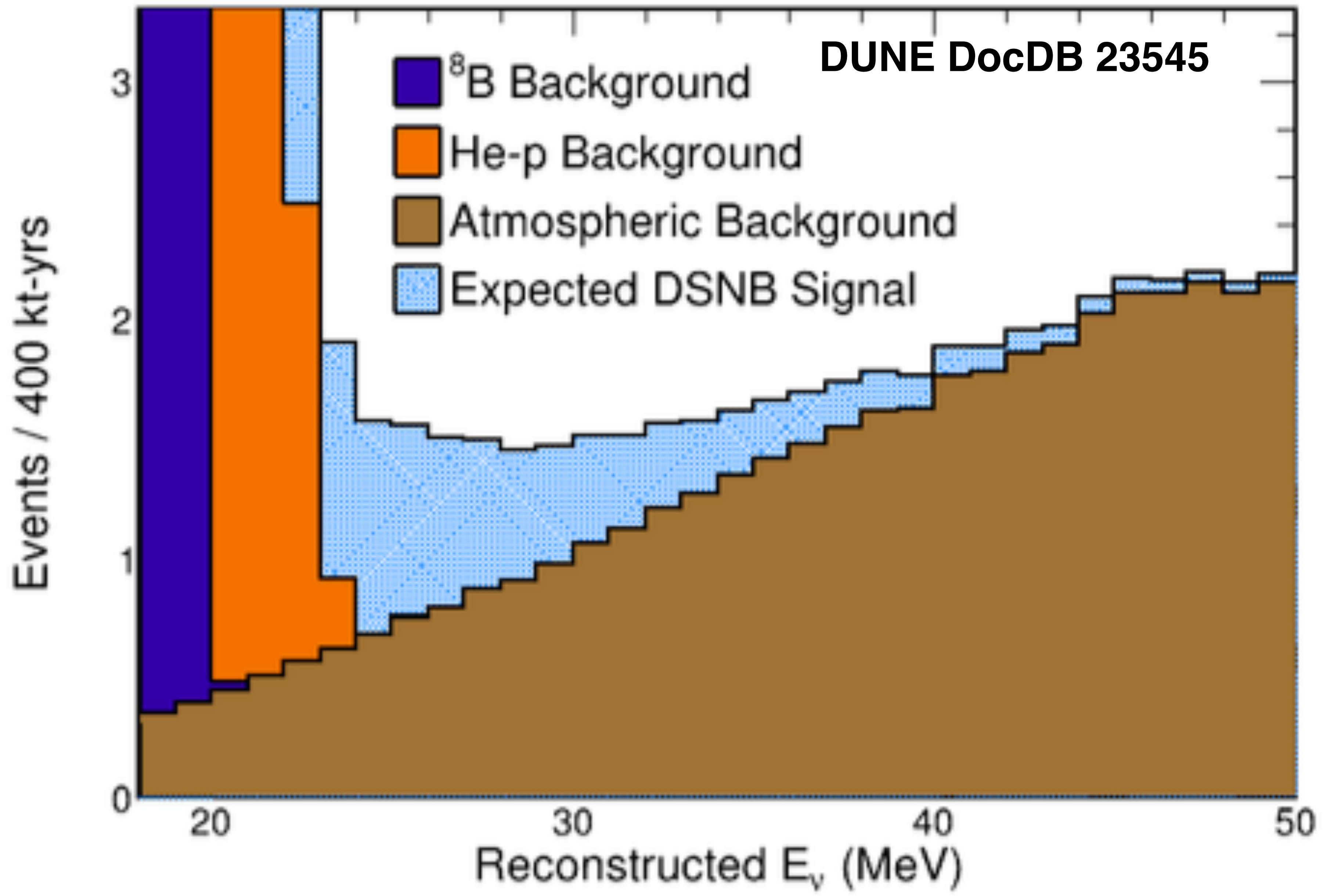


Stony Brook University

Motivation

- Diffused Supernova Neutrino Background (DSNB)
  - Neutrino fluxes from all core-collapse supernovae in the observable universe that arrive at Earth
- A potential major discovery channel for DUNE Phase II program
  - DUNE uniquely constrains ν_e via ν_e-Ar CC (<1 event/yr)
    - ν_e-e ES xsec 2 orders of magnitude smaller and energy resolution is poor as the scattering angle is unknown
  - JUNO and HK have better sensitivity to the $\bar{\nu}_e$ component via IBD
- Challenging: ~2.2σ evidence of excess with an expectation of 6 DSNB events at 400 kt-yrs using Phase I FD and reconstruction (σ_E/E: ~8%)

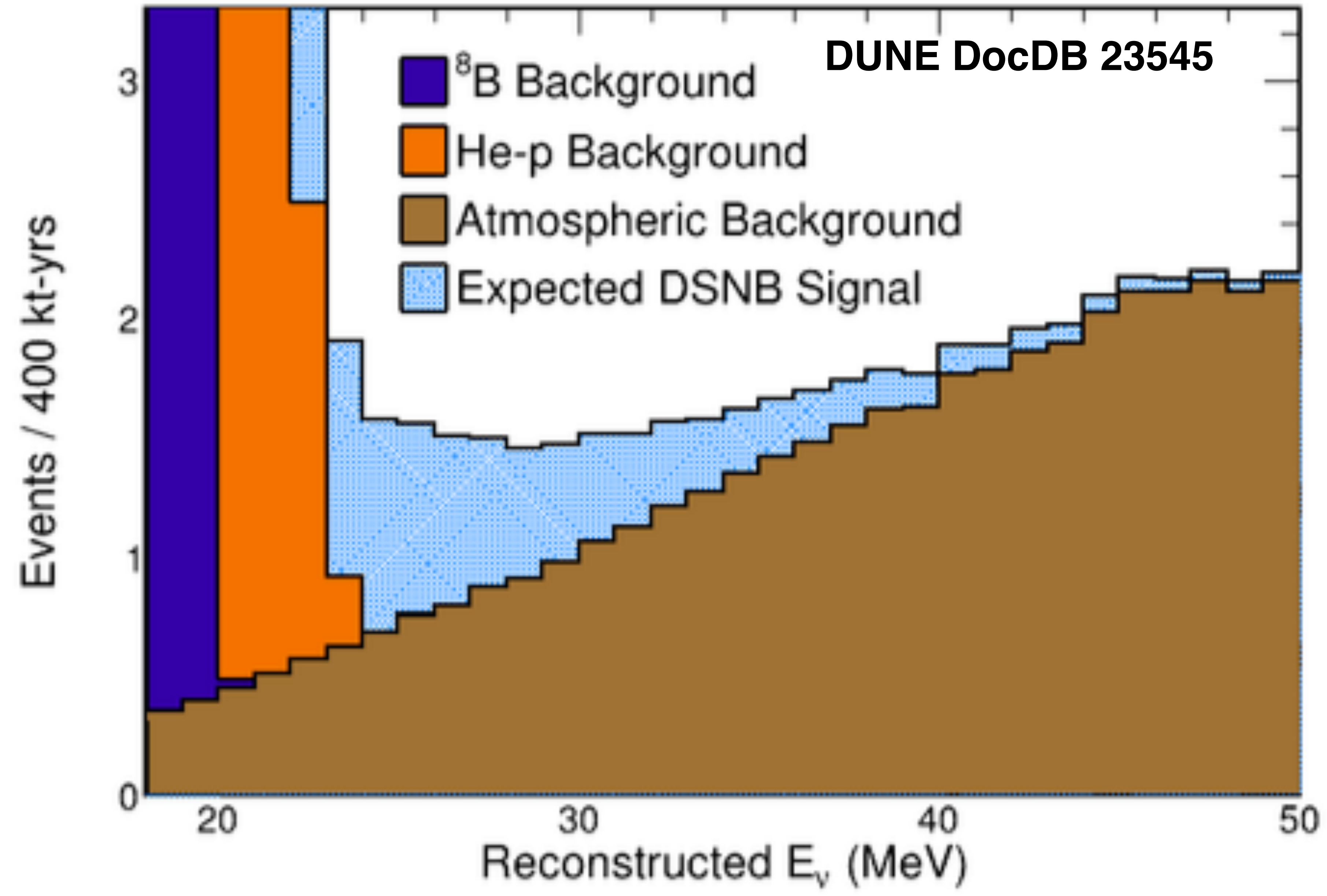




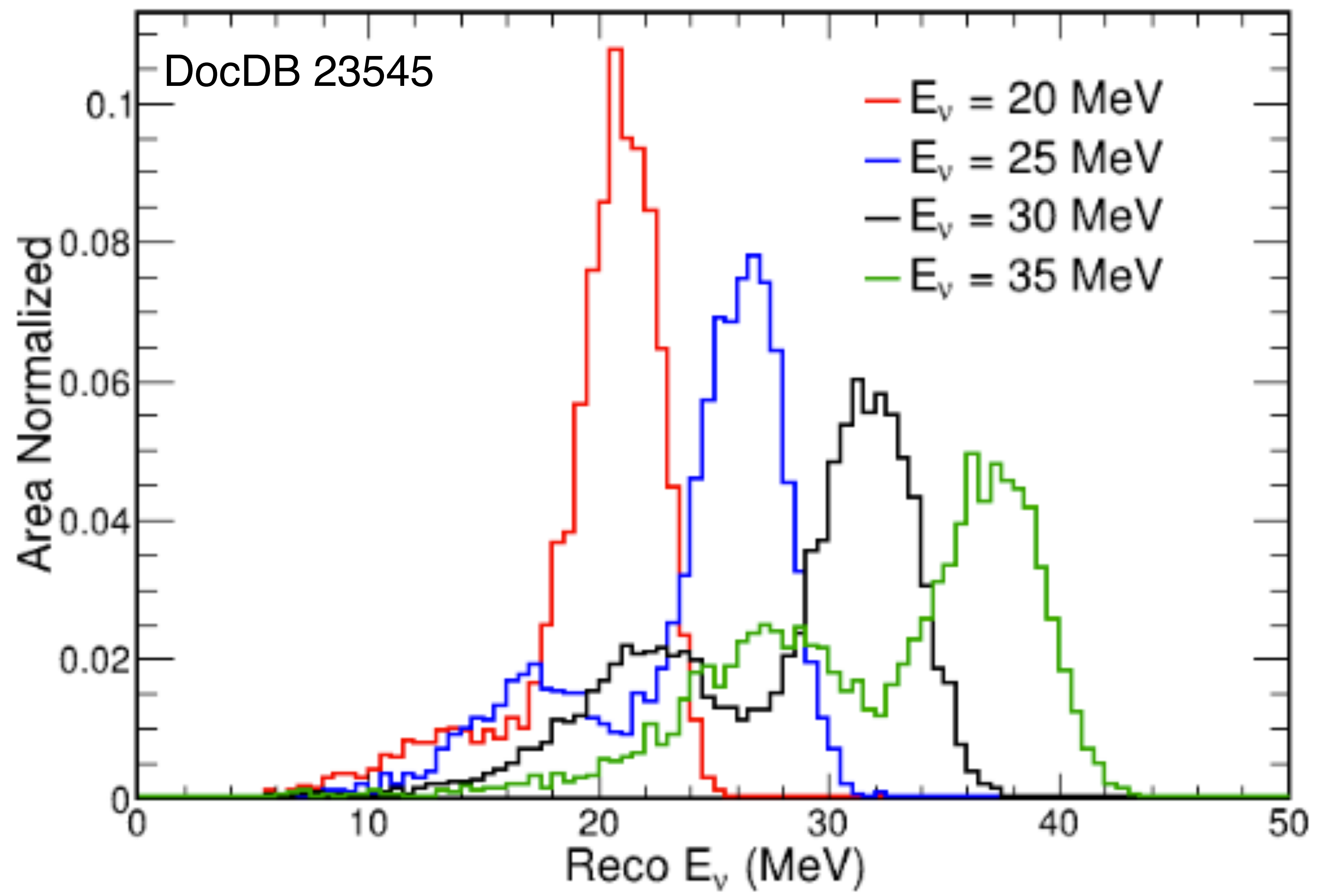
Motivation

- Previous studies by D. Pershey at reconstruction level (DocDB 23545)
  - Huge feed down from higher energies in Phase I FD reconstruction
  - Many visible charge are lost, especially at higher energy
    - A large lost fraction from clustering completeness in reconstruction
    - Invisible energy like neutron emission

- Excellent energy resolution (<8%) at 10s of MeV will increase DSNB discovery potential
  - Resolve DSNB signal and three main backgrounds
  - Also helps many low energy physics programs: SNB measurement, solar neutrino



Full reconstruction at SinglePhase



Simulation

$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

- Marley + edep-sim: mono-E from 5 MeV to 50 MeV, 1k events per 5 MeV
  - Same event display tools Chao used for GeV events
- Geometry: large LAr bath (200 meters long each dimension)
- Record true + G4simulation info (dE/dx, timing)
  - Detector/reconstruction effects not considered yet

- Possible contributors to ν_e energy resolution (⊗ : not apply to MeV ν_e CC)

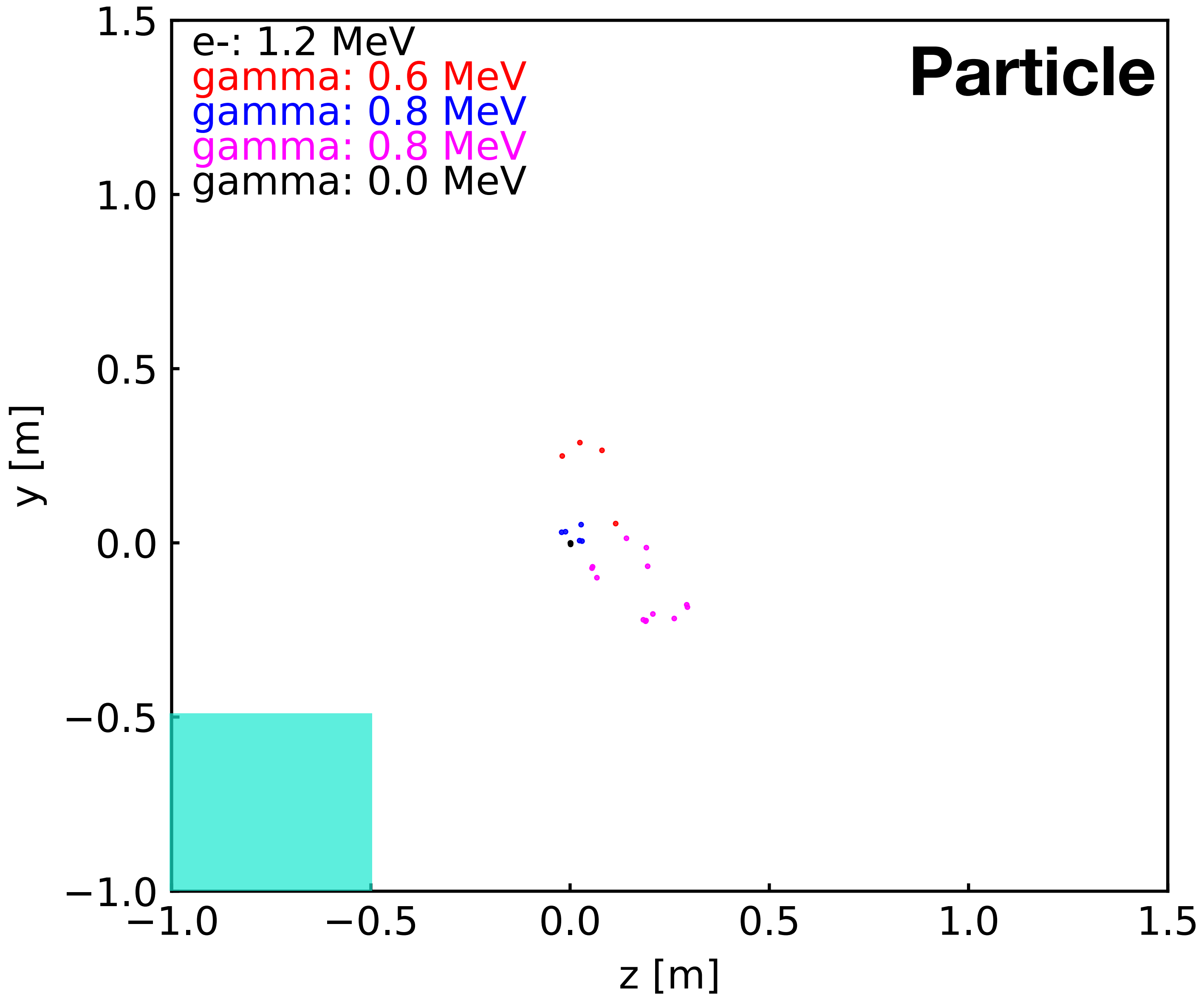
❑ Generator models
❑ "Missing energy"
❑ Nuclear scatter
❑ Muon/pion decay ⊗
❑ muon capture ⊗

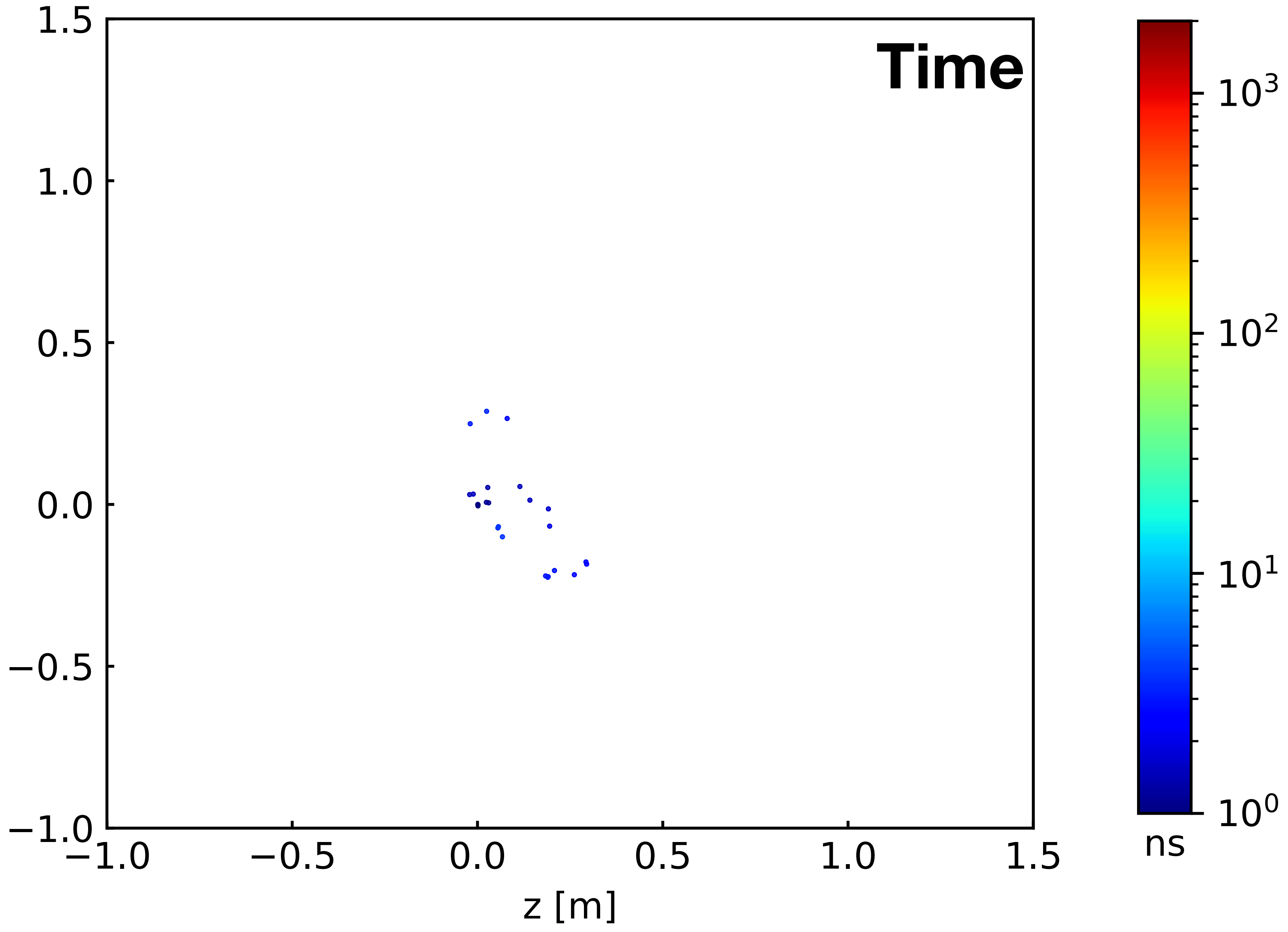
This presentation

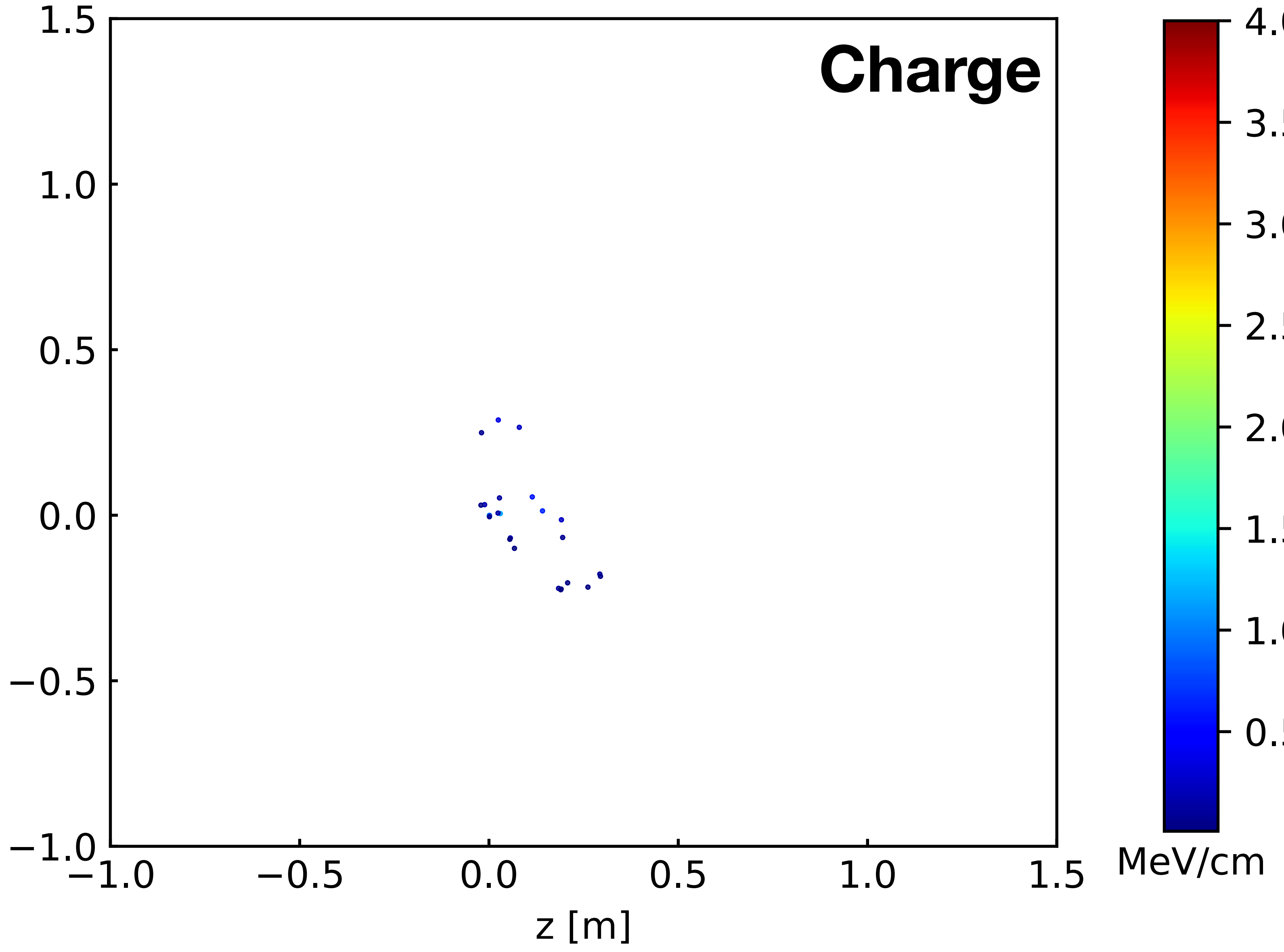
❑ Detection threshold
❑ dE/dx -> dQ/dx
❑ Reconstruction and PID
❑ Others

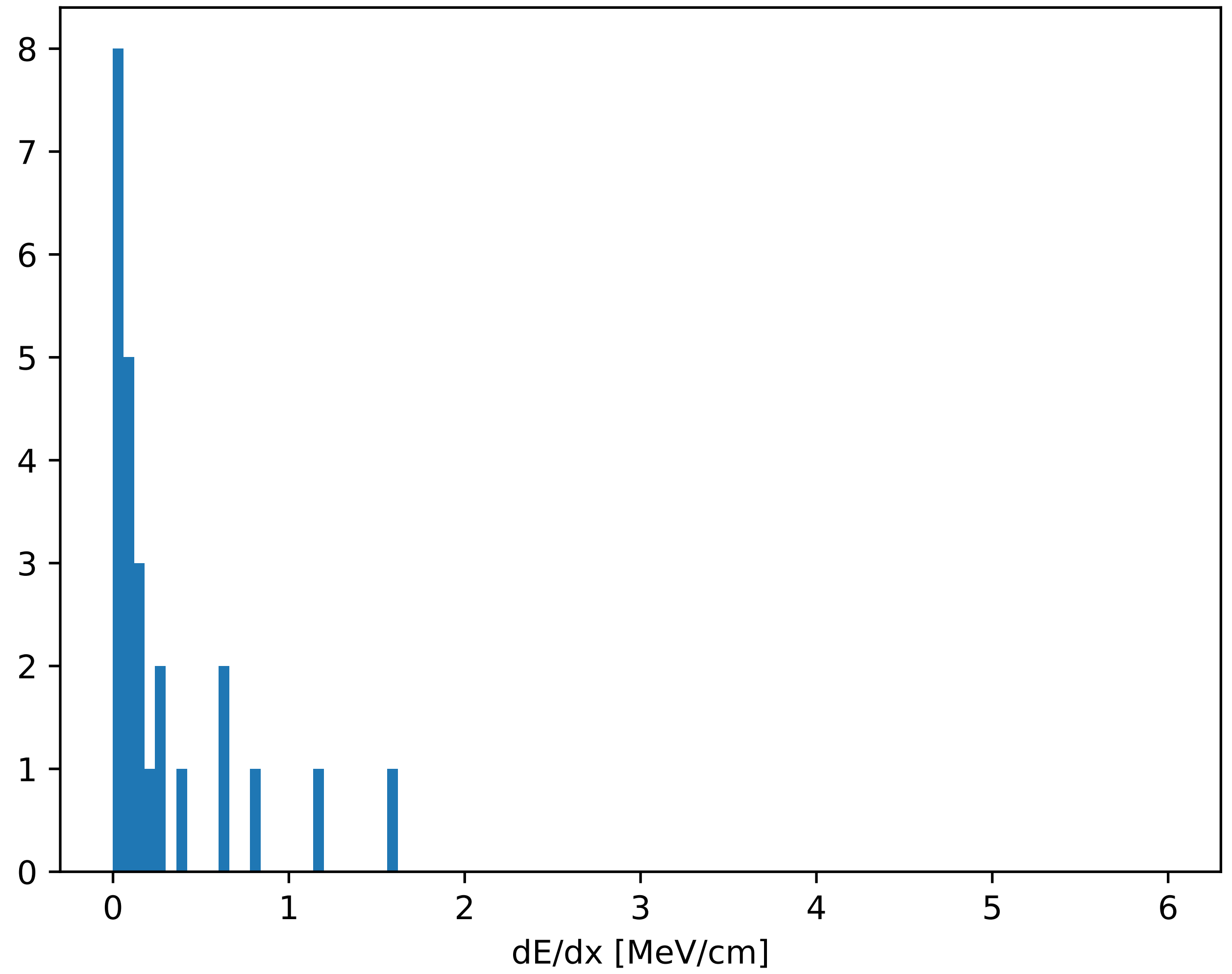
5 MeV nue-Ar CC: evt 2

50x50cm PD module in current APEX design



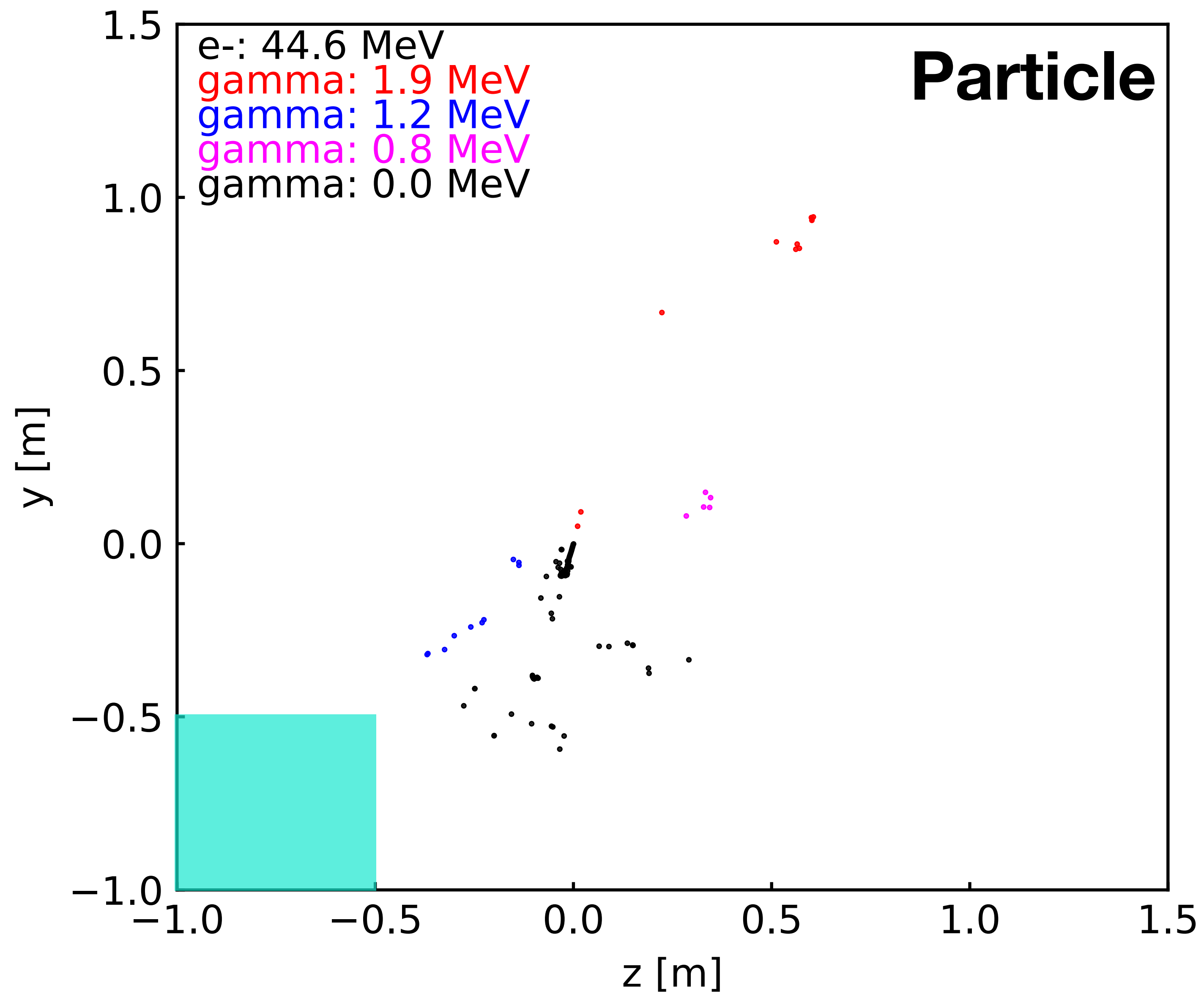


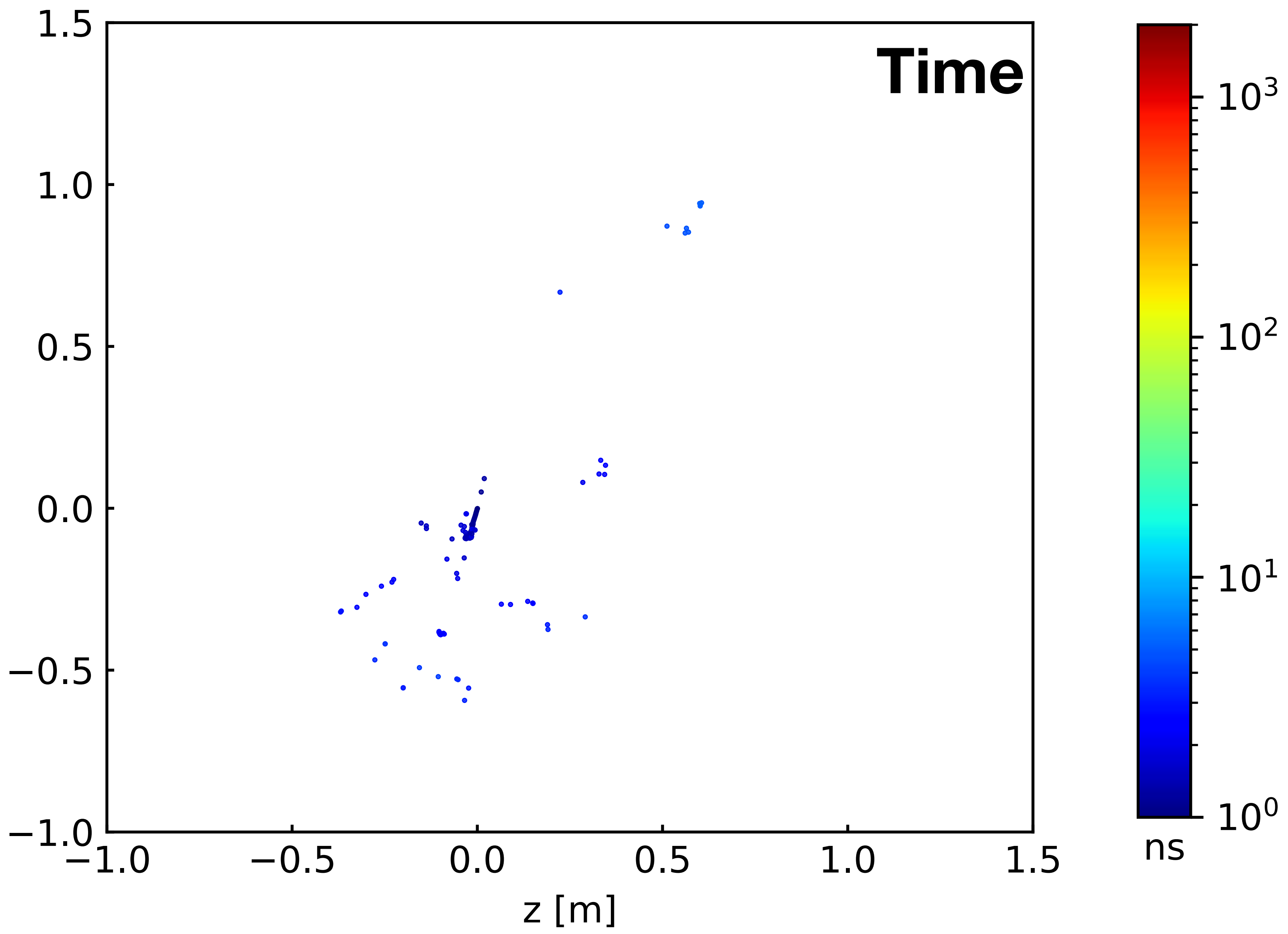


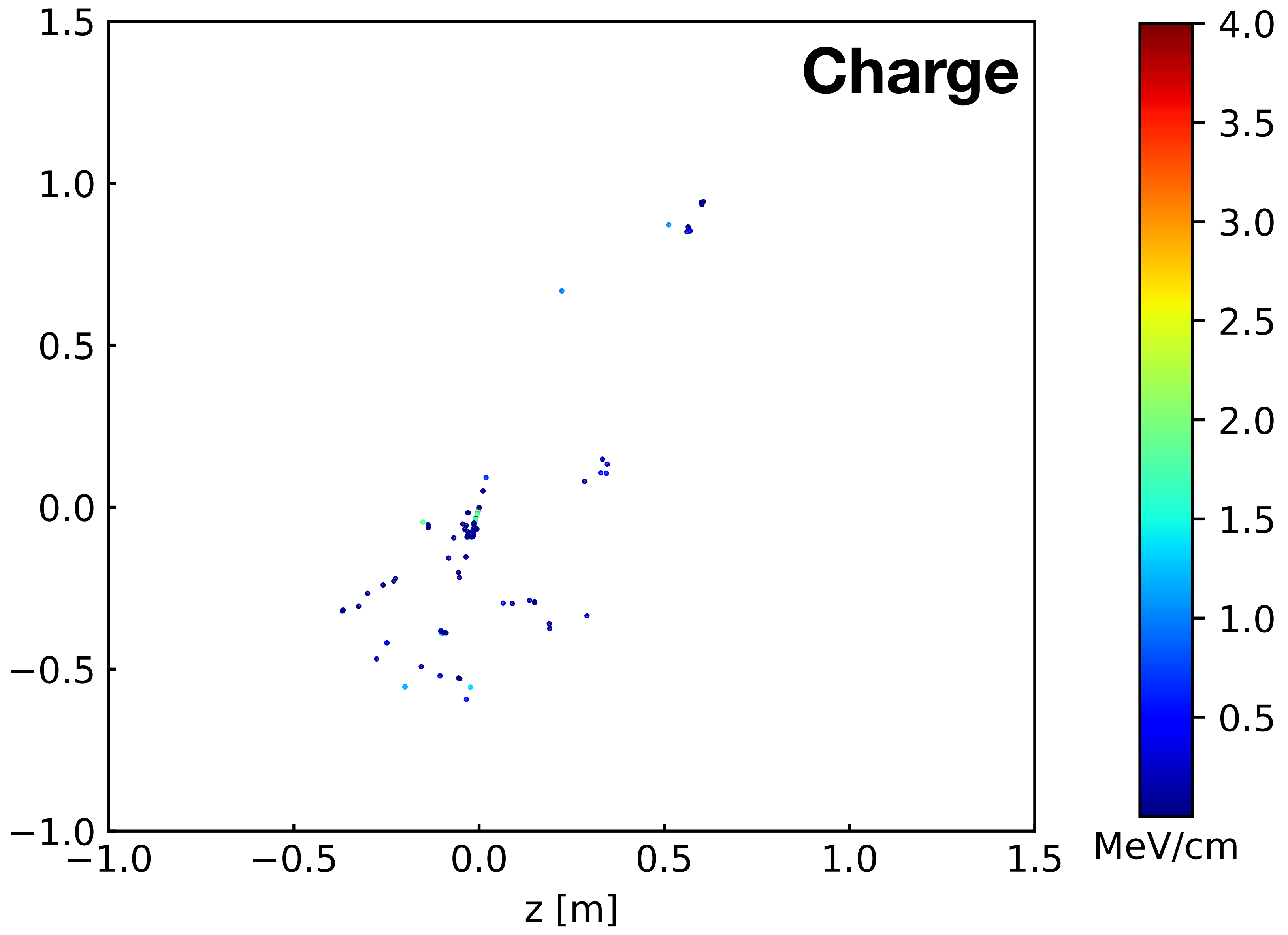


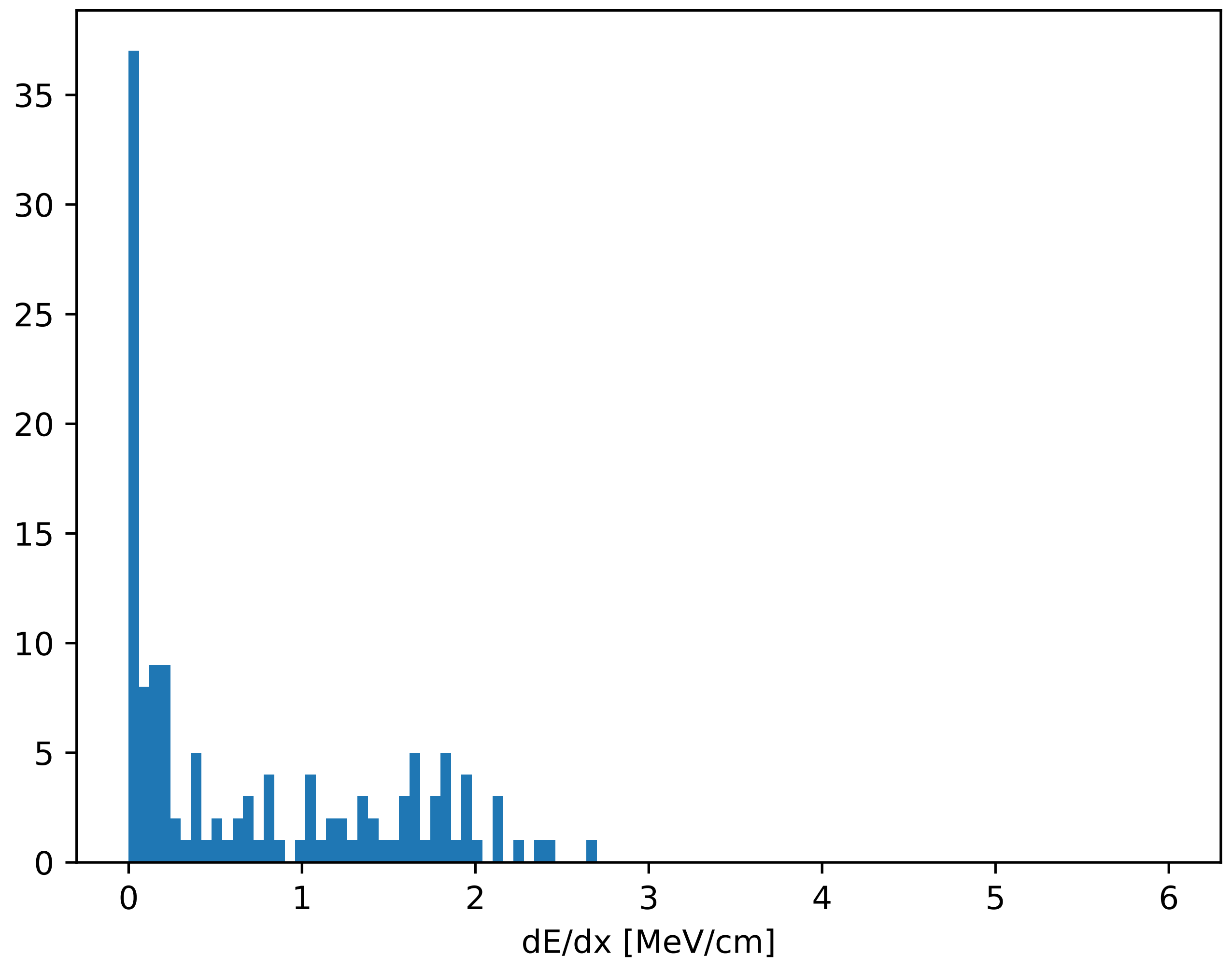
50 MeV nue-Ar CC: evt 1

50x50cm PD module in current APEX design



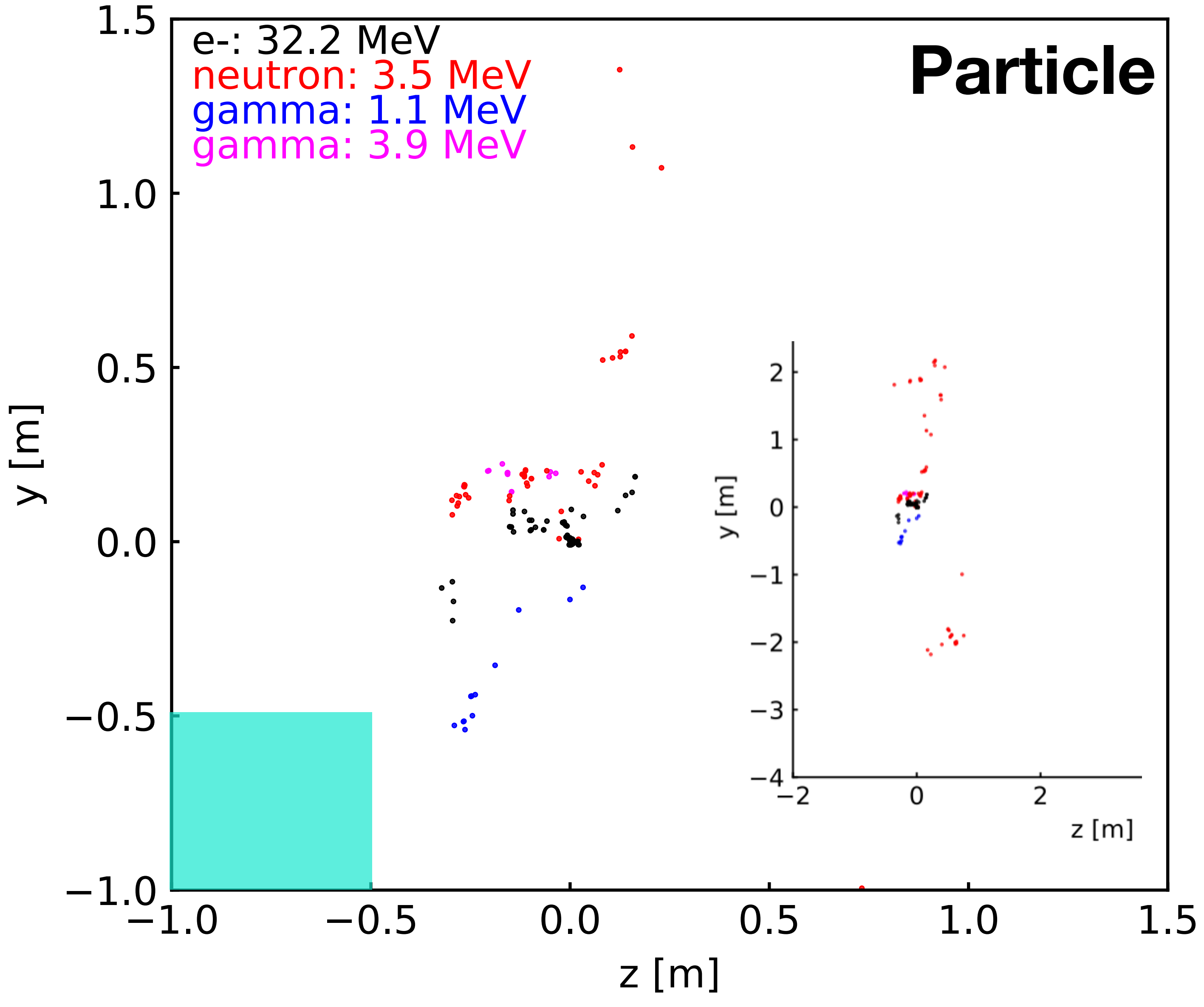


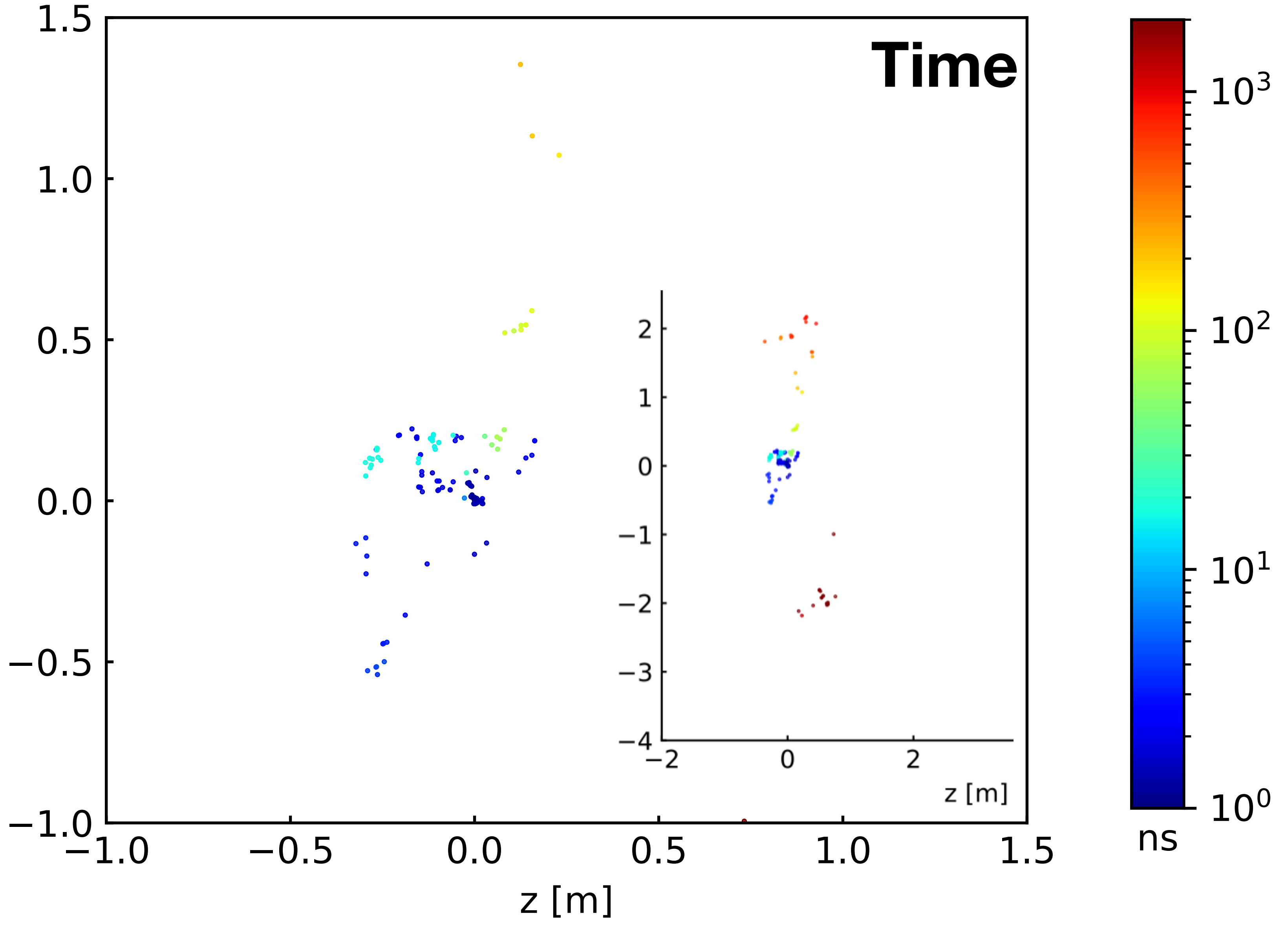


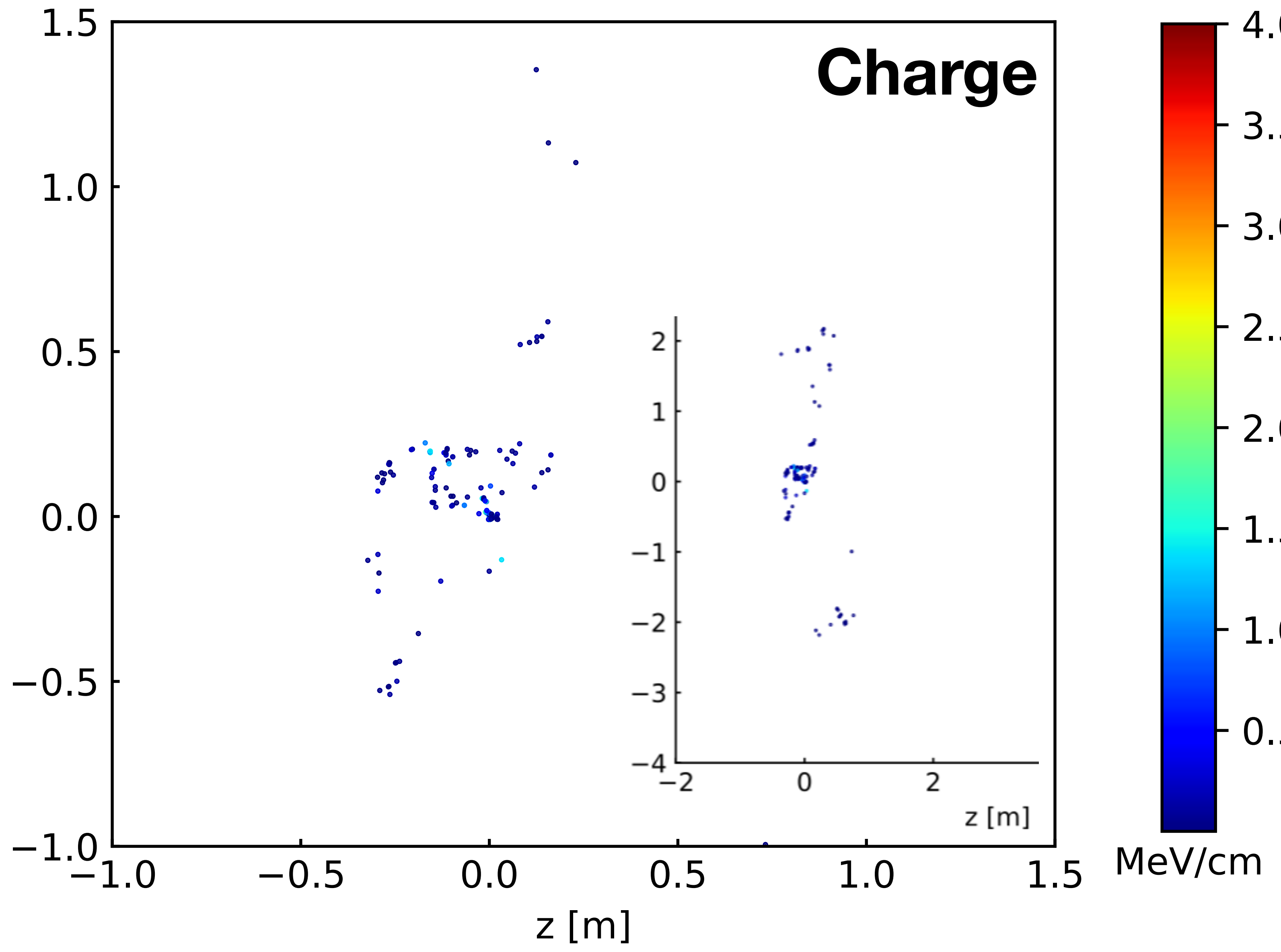


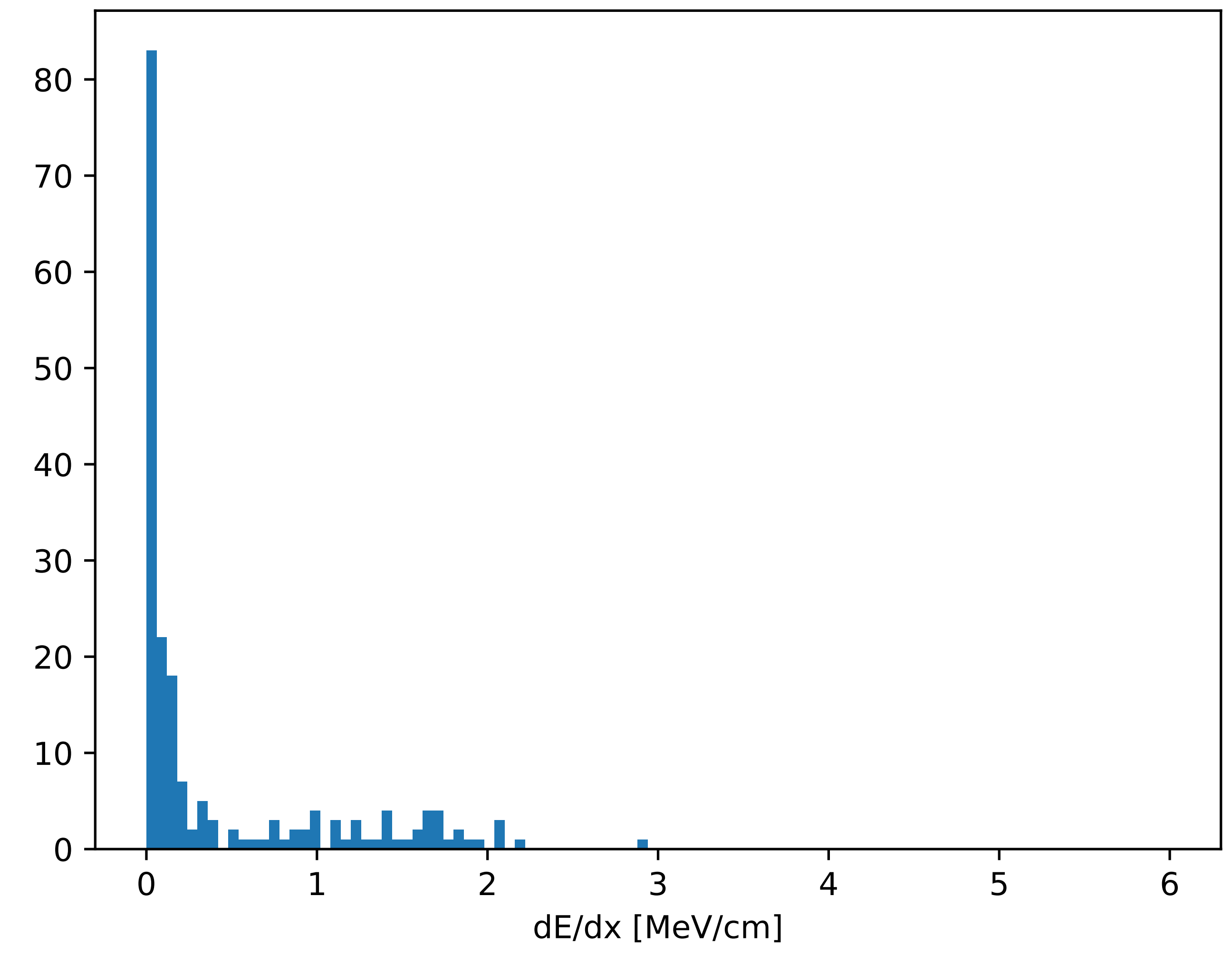
50 MeV nue-Ar CC: evt 2

50x50cm PD module in current APEX design



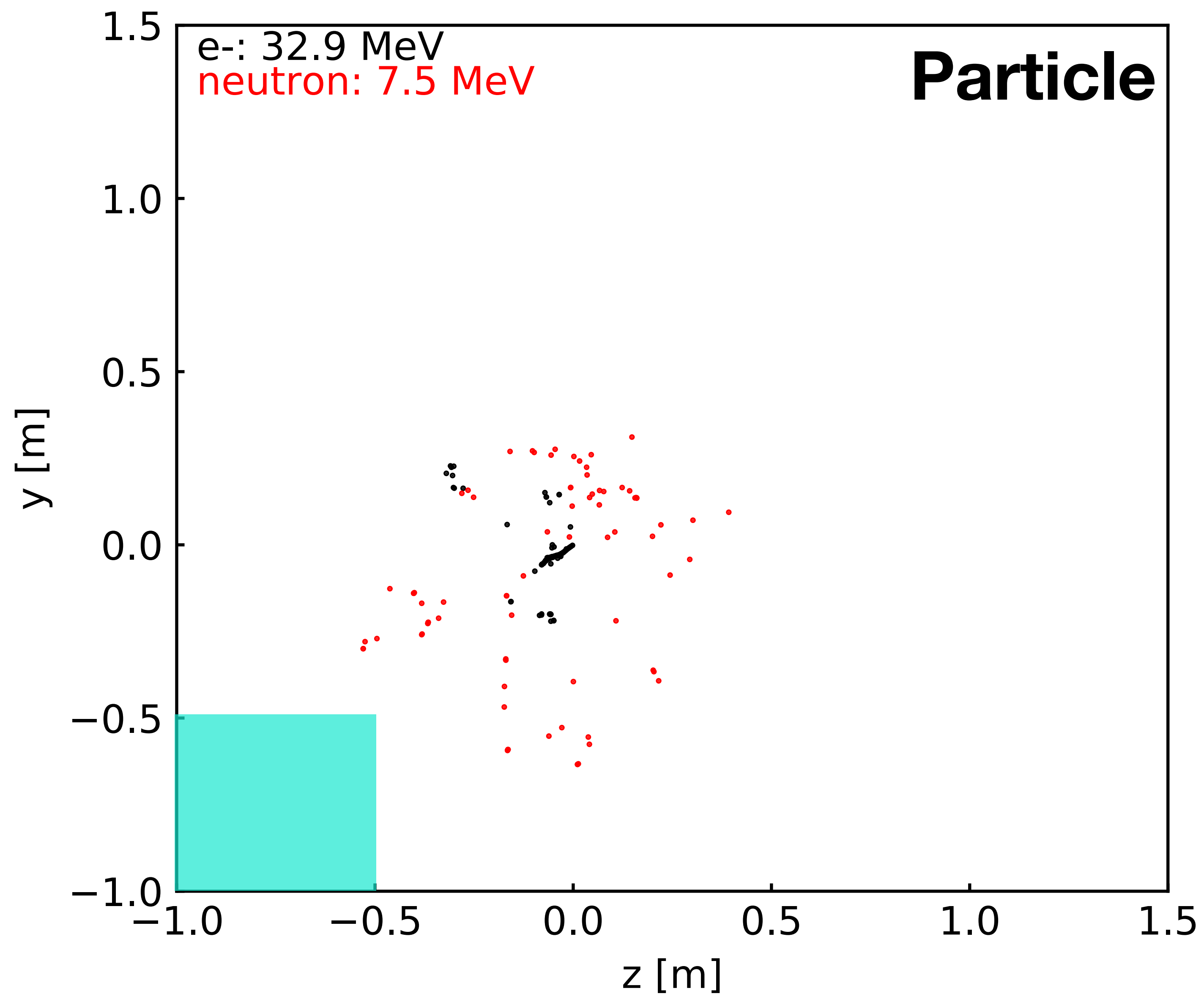


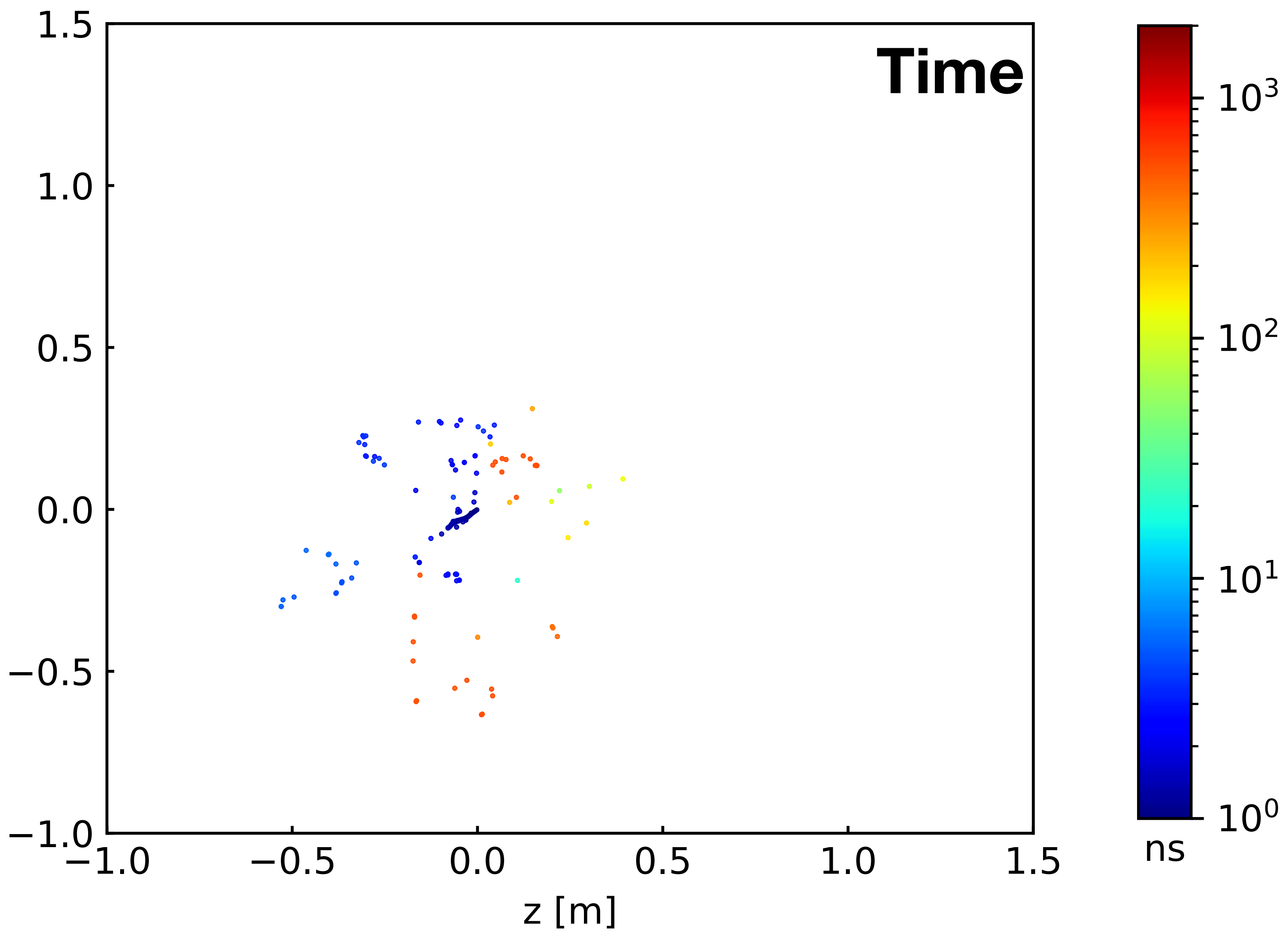


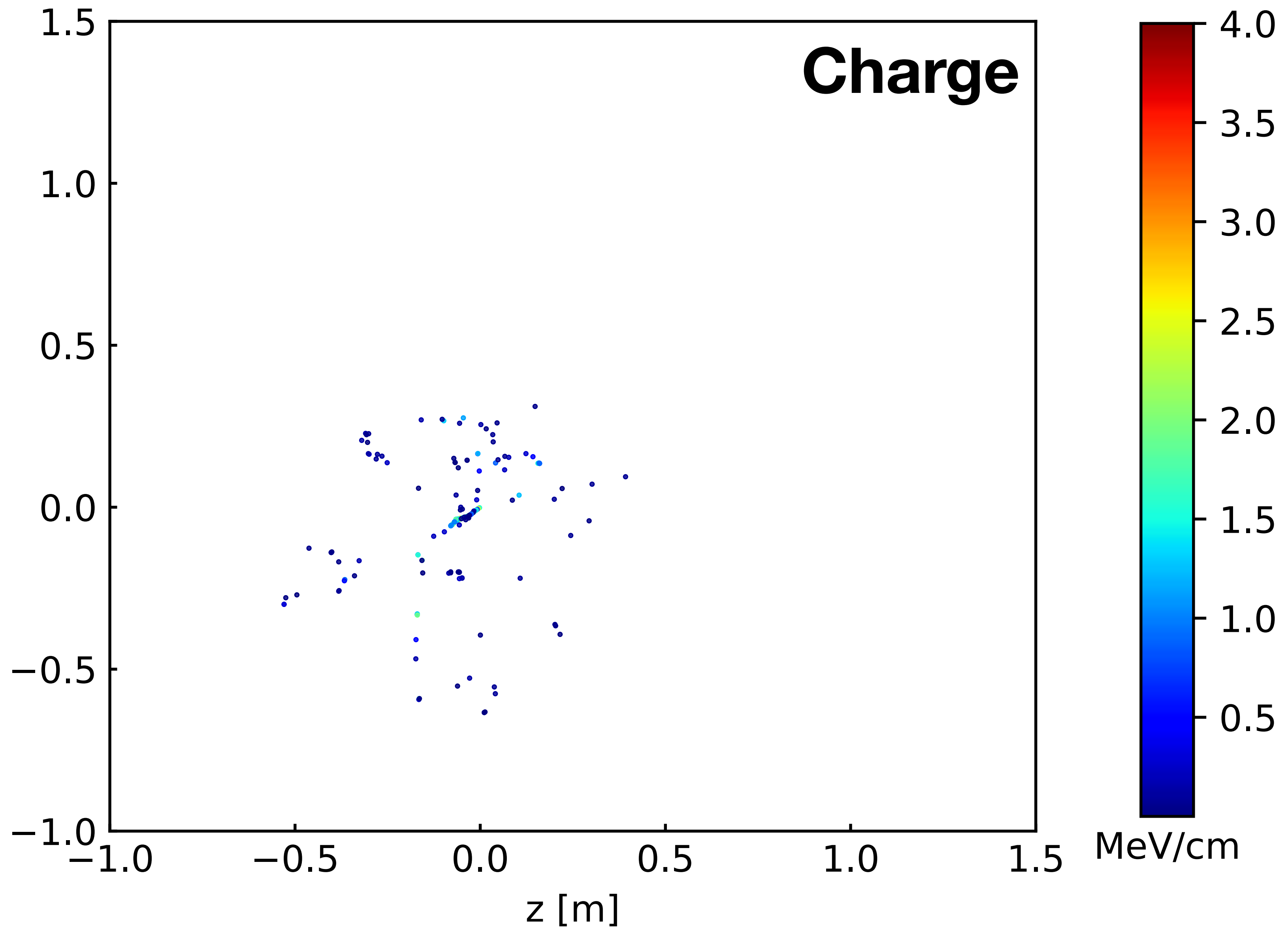


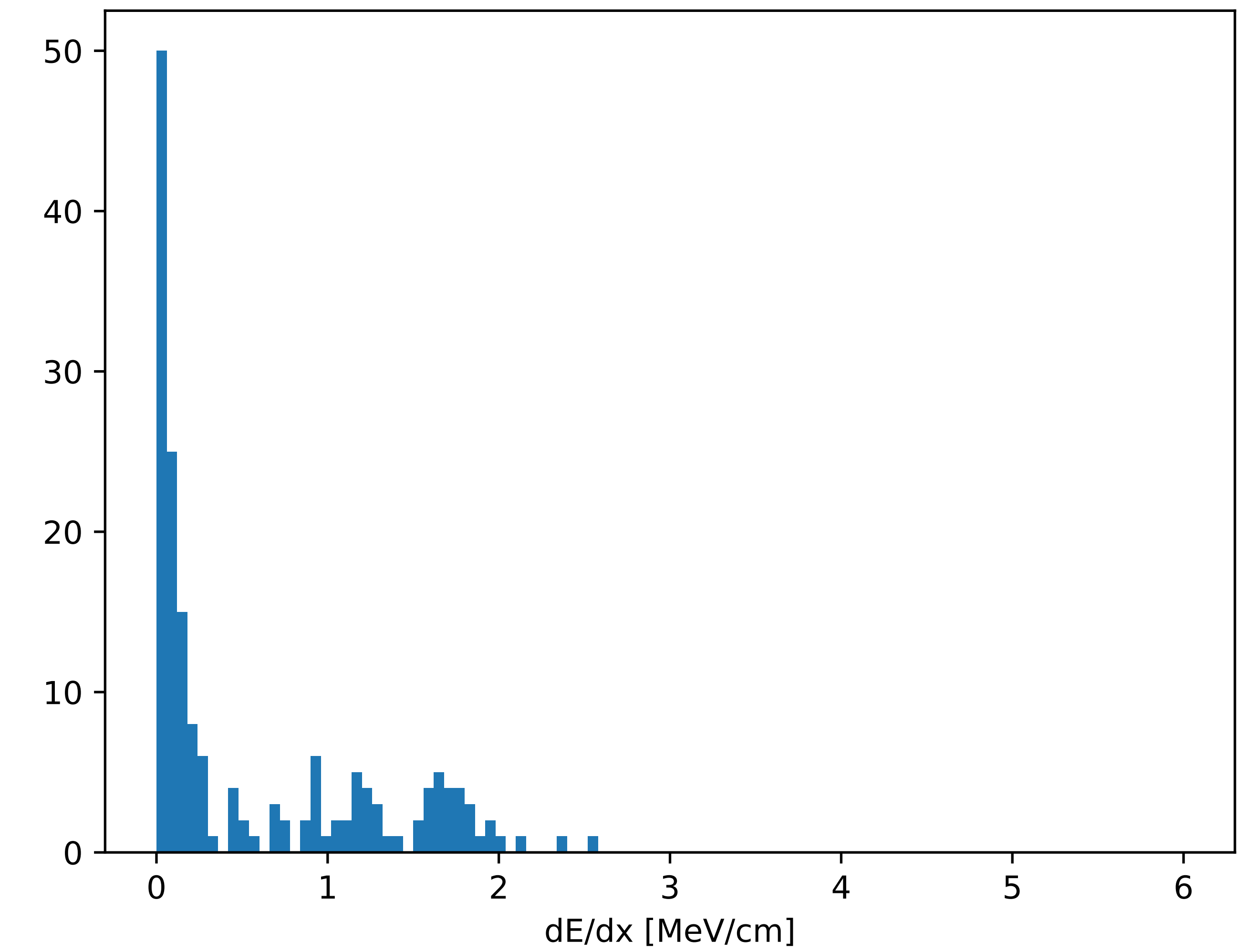
50 MeV nue-Ar CC: evt 3

50x50cm PD module in current APEX design



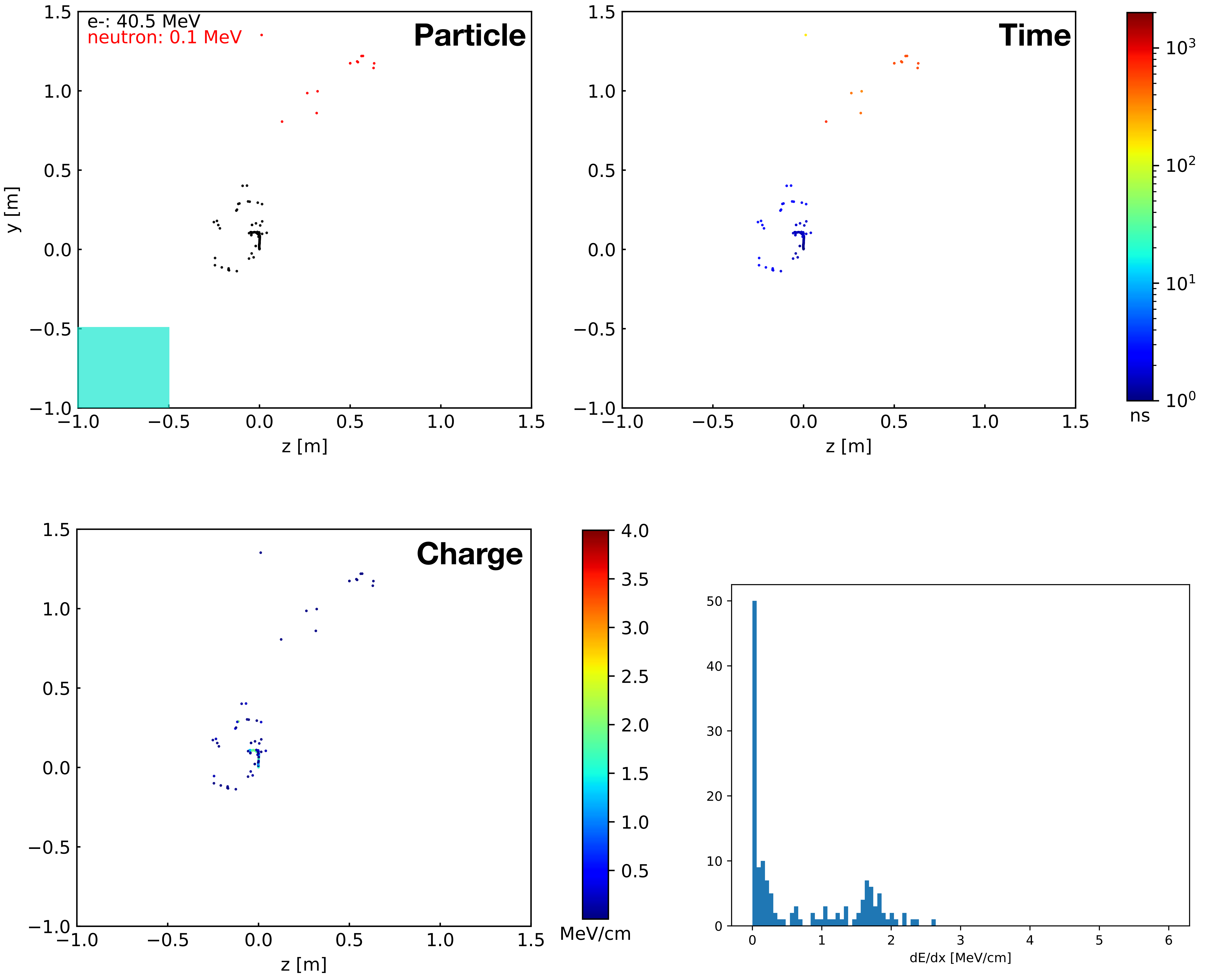






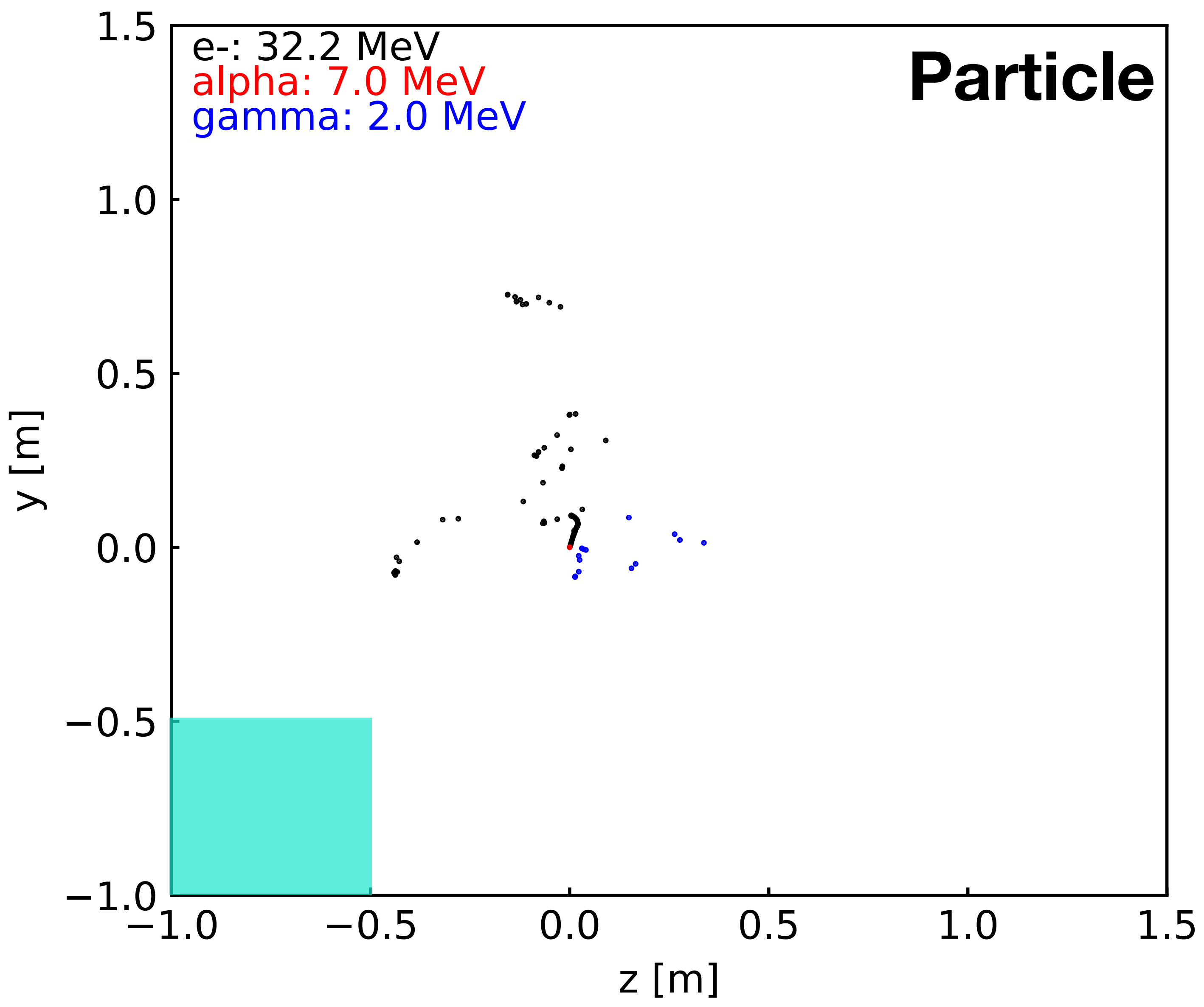
50 MeV nue-Ar CC: evt 8

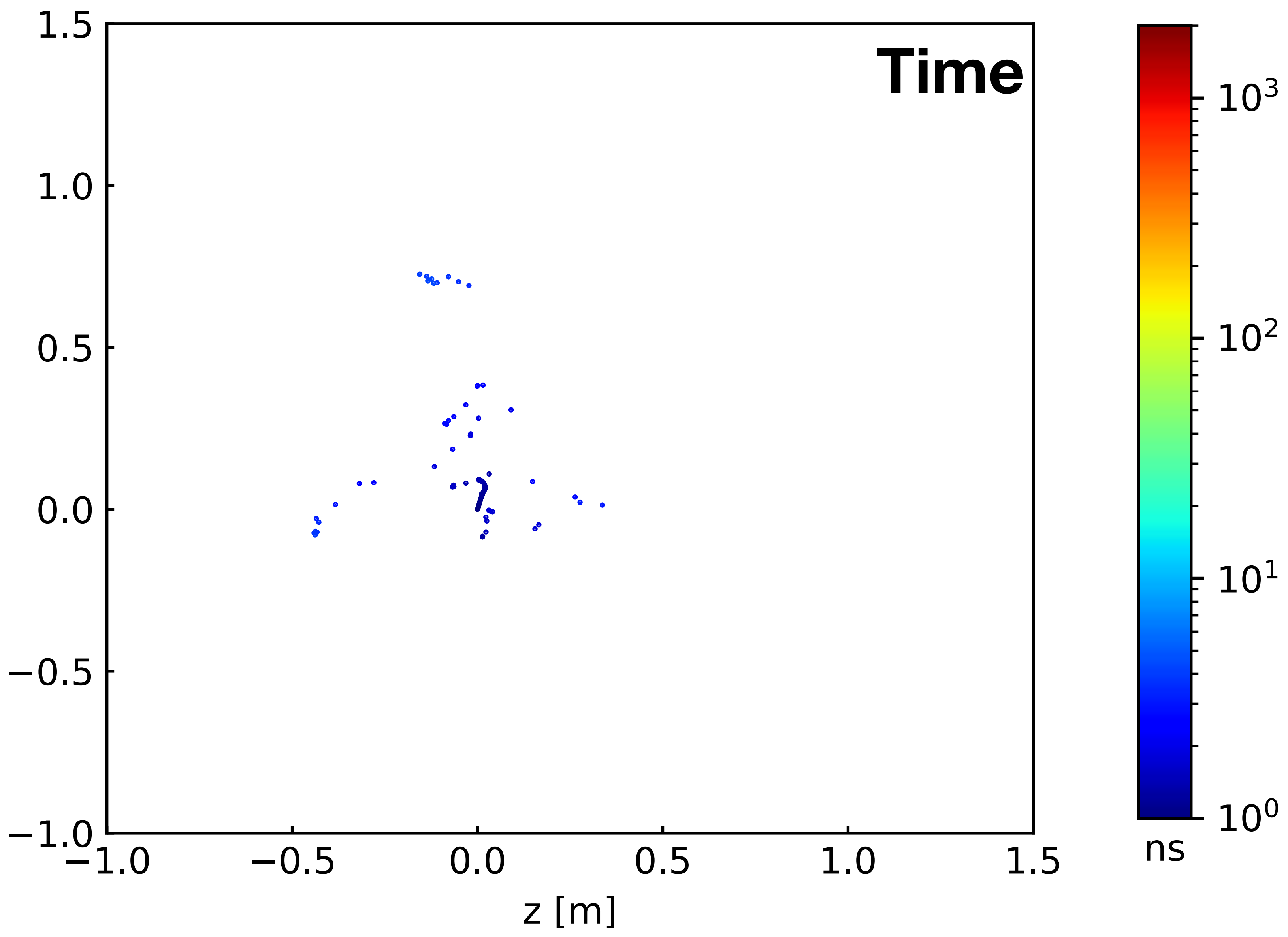
50x50cm PD module in current APEX design

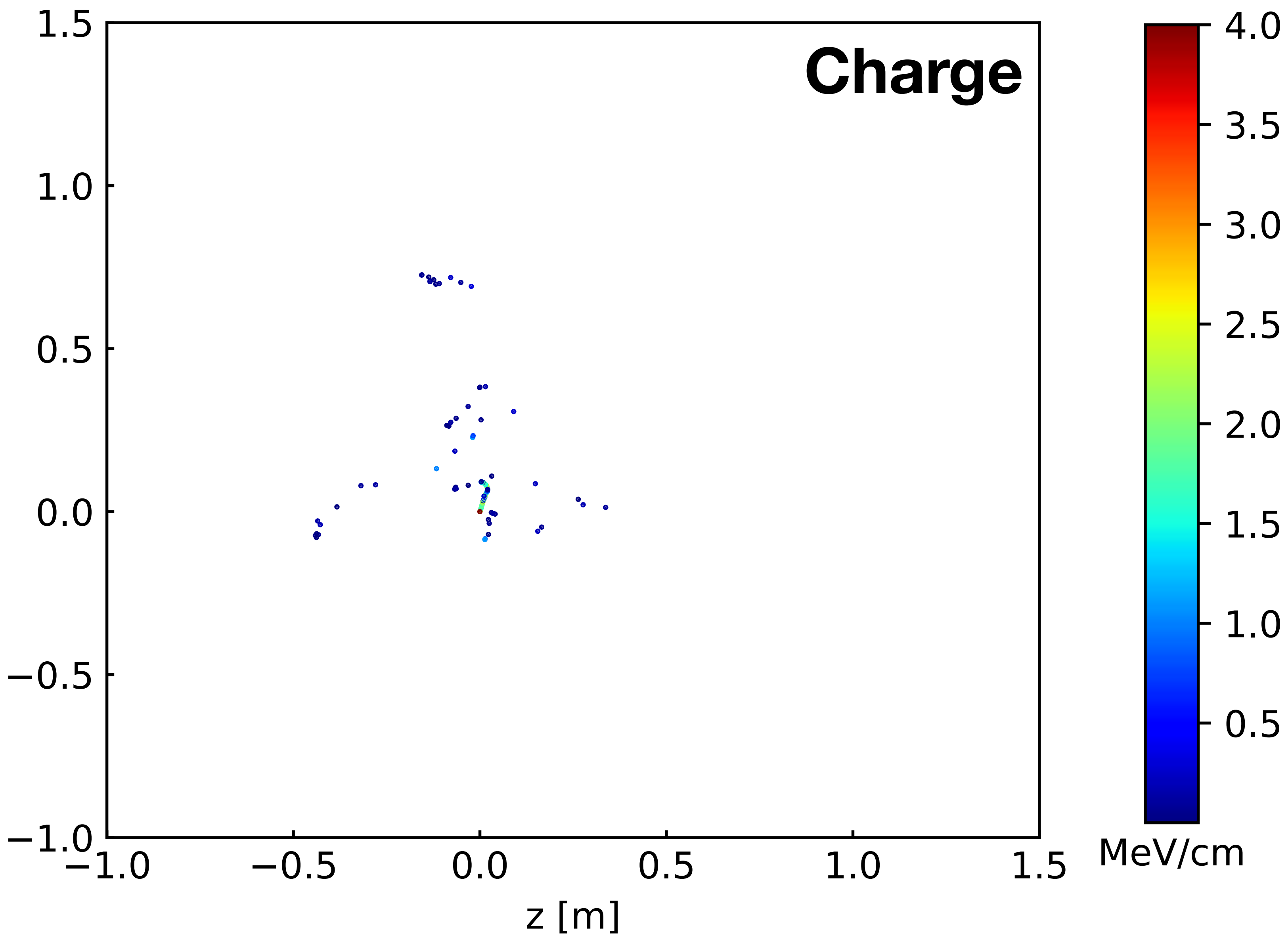


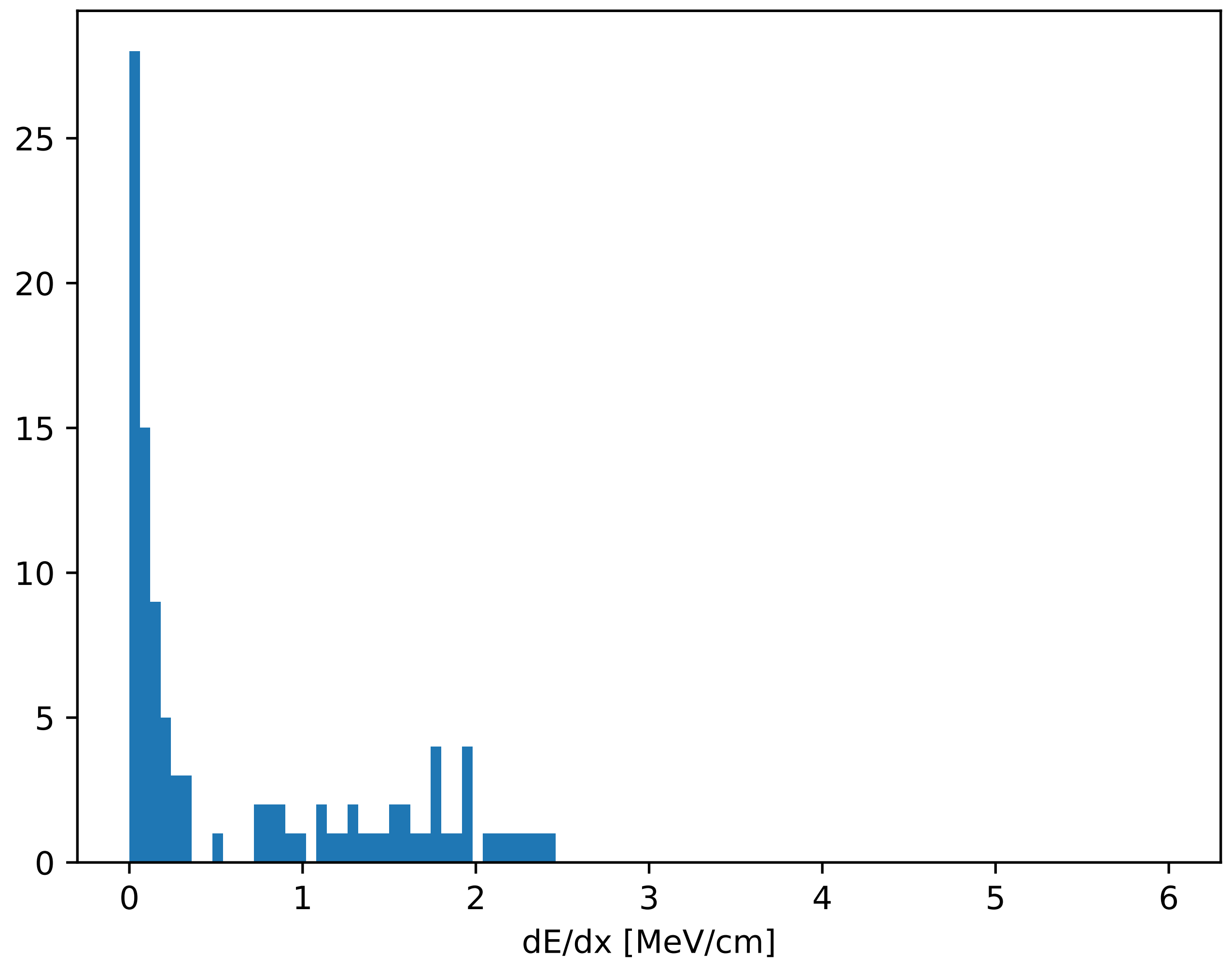
50 MeV nue-Ar CC: evt 4

50x50cm PD module in current APEX design

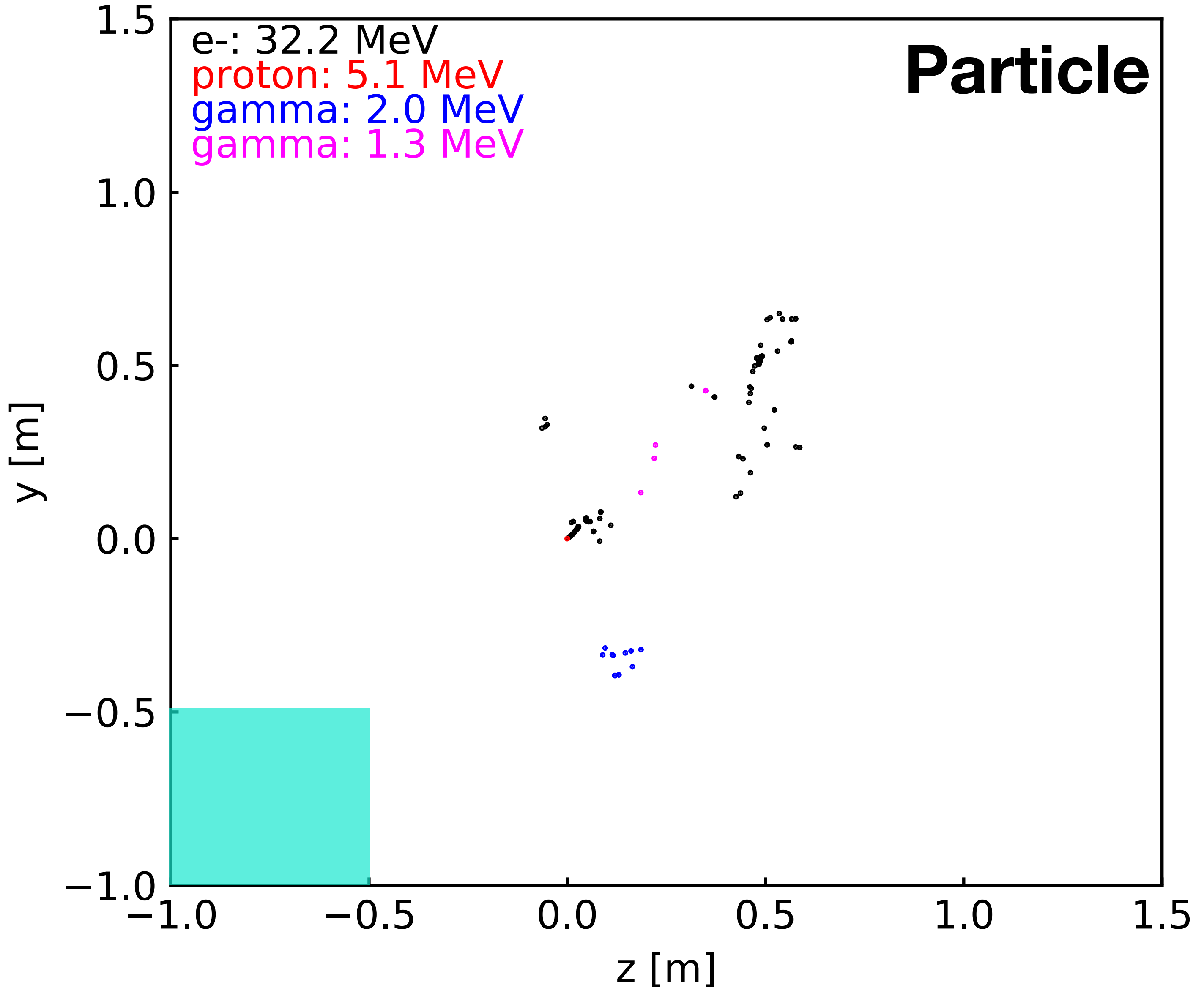


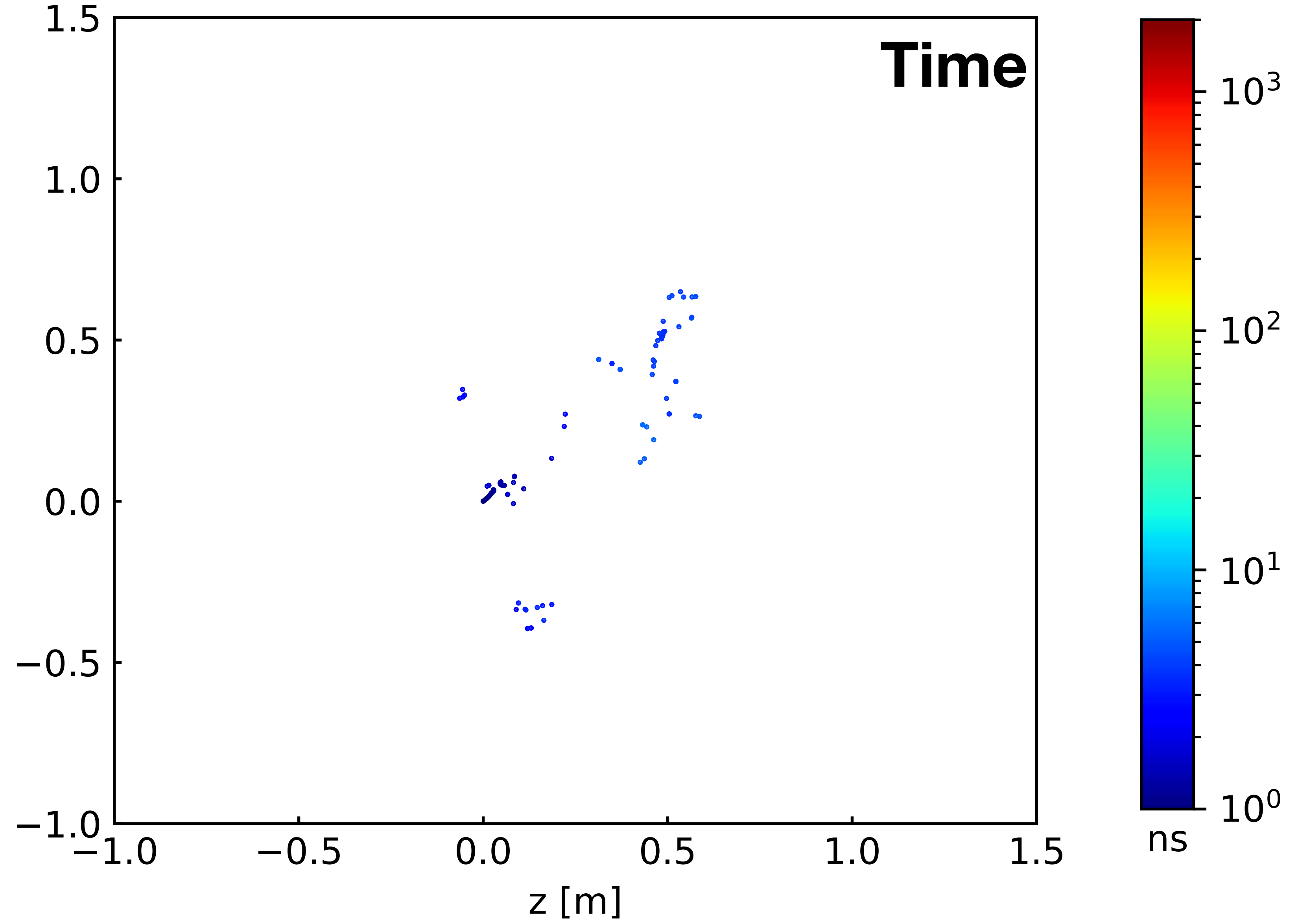




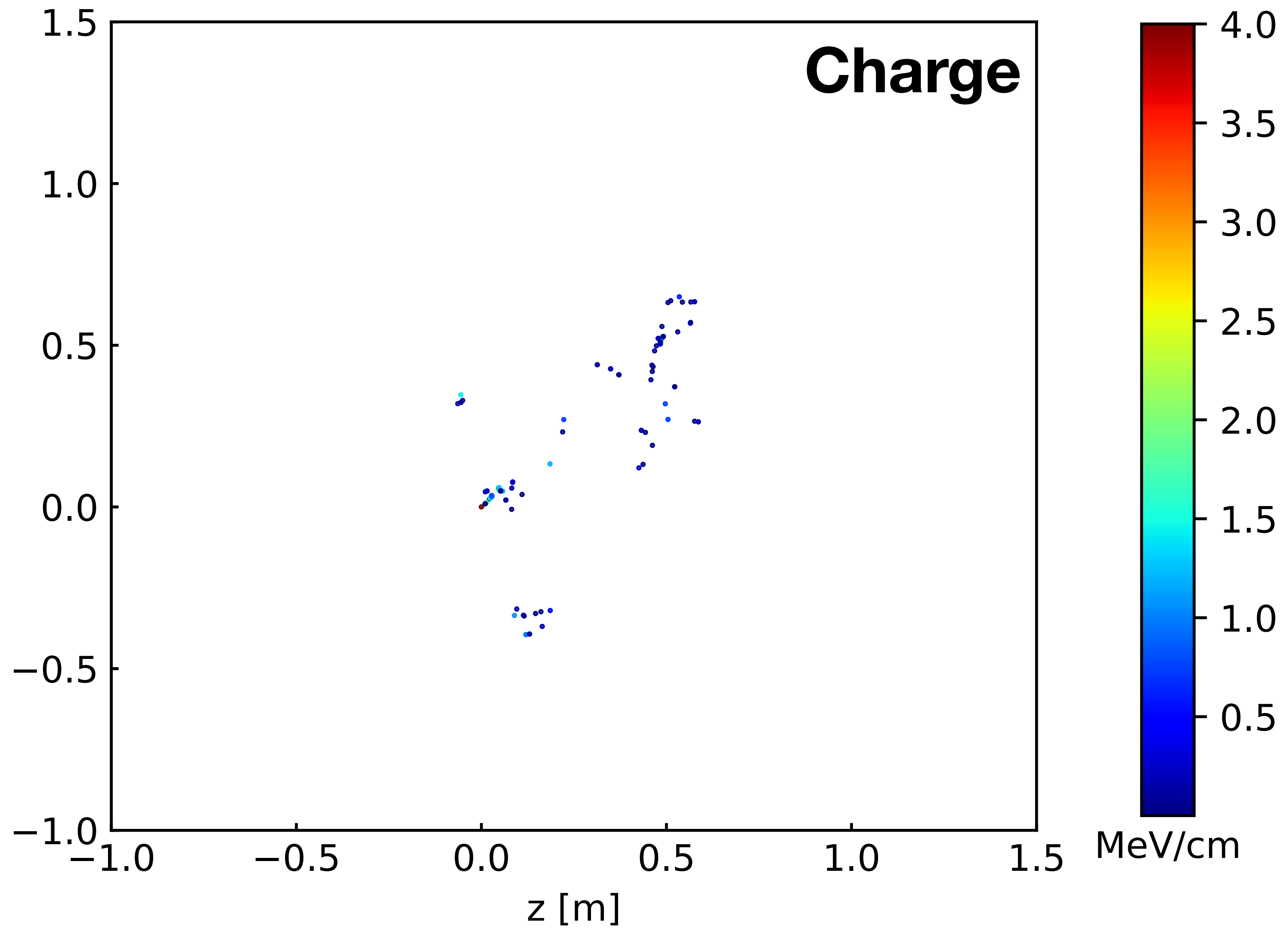


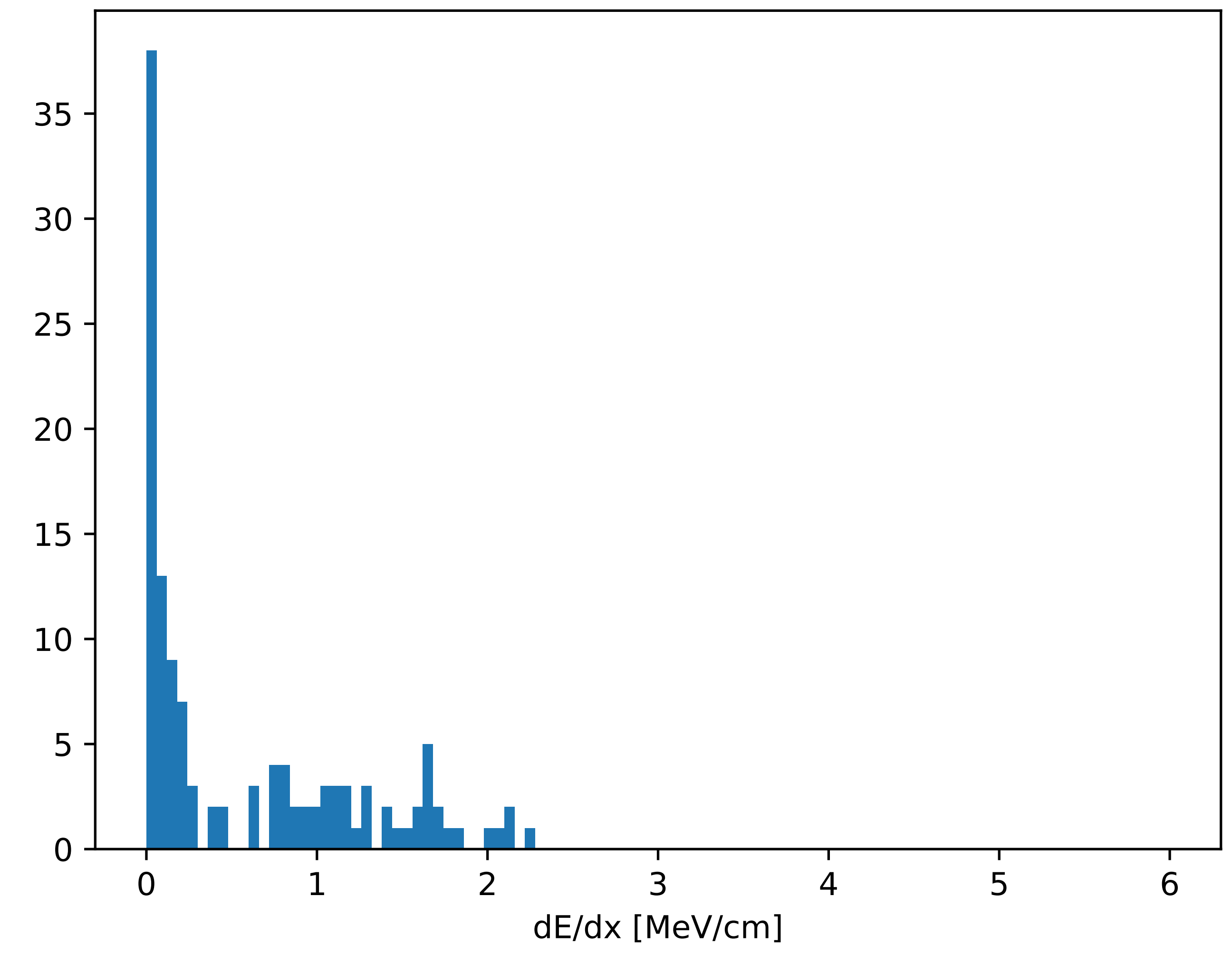
50 MeV nue-Ar CC: evt 73





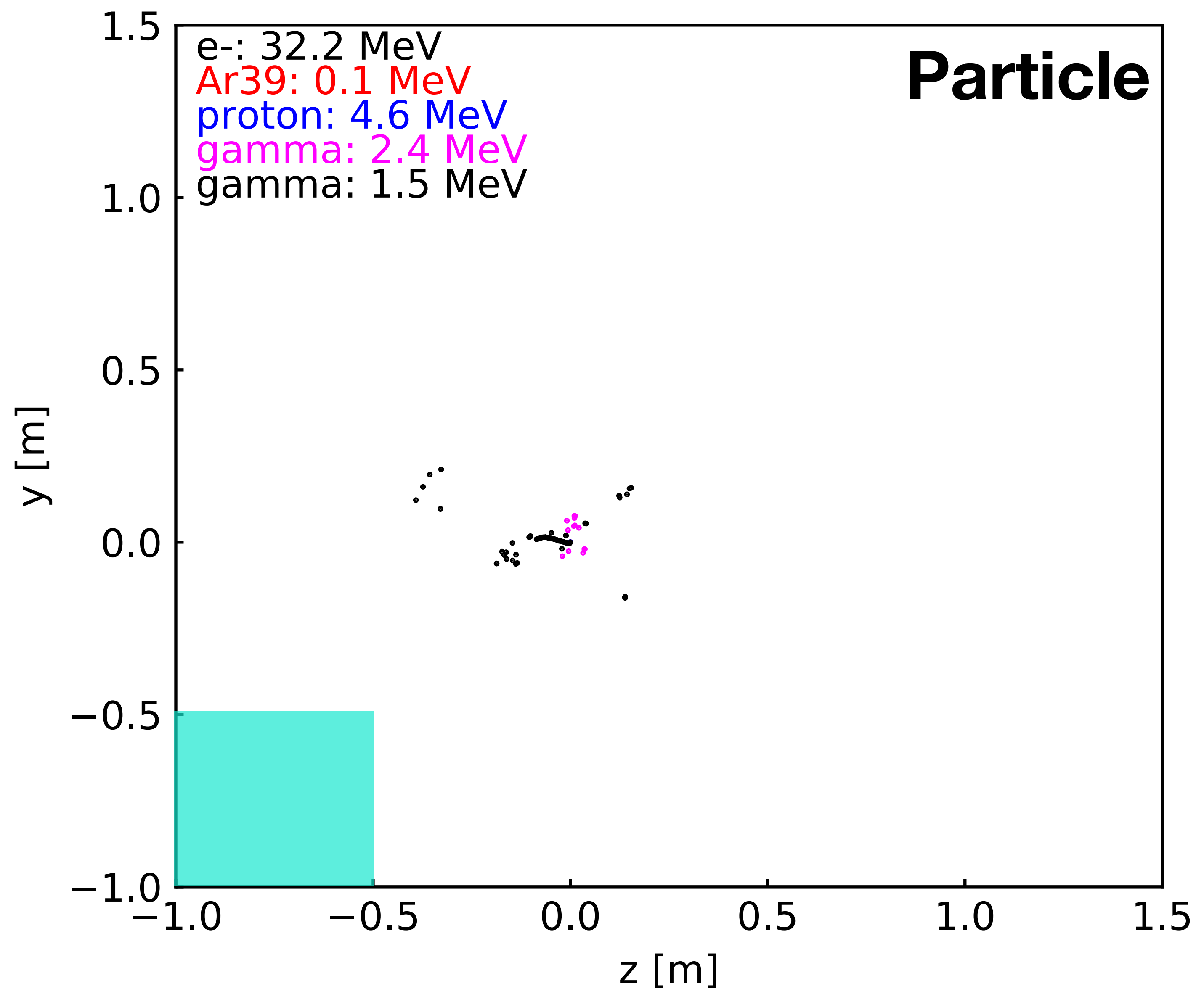
50x50cm PD module in current APEX design

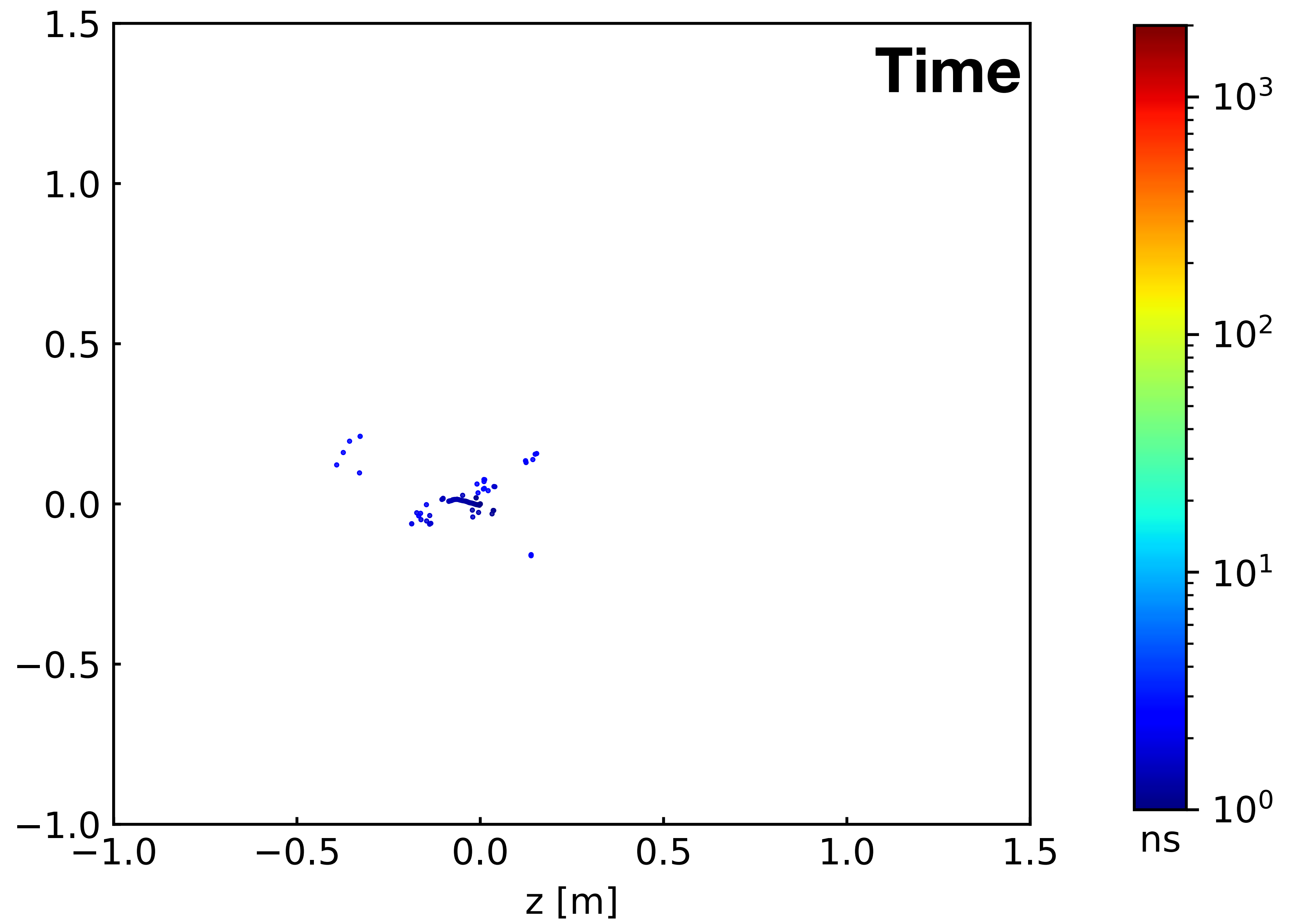


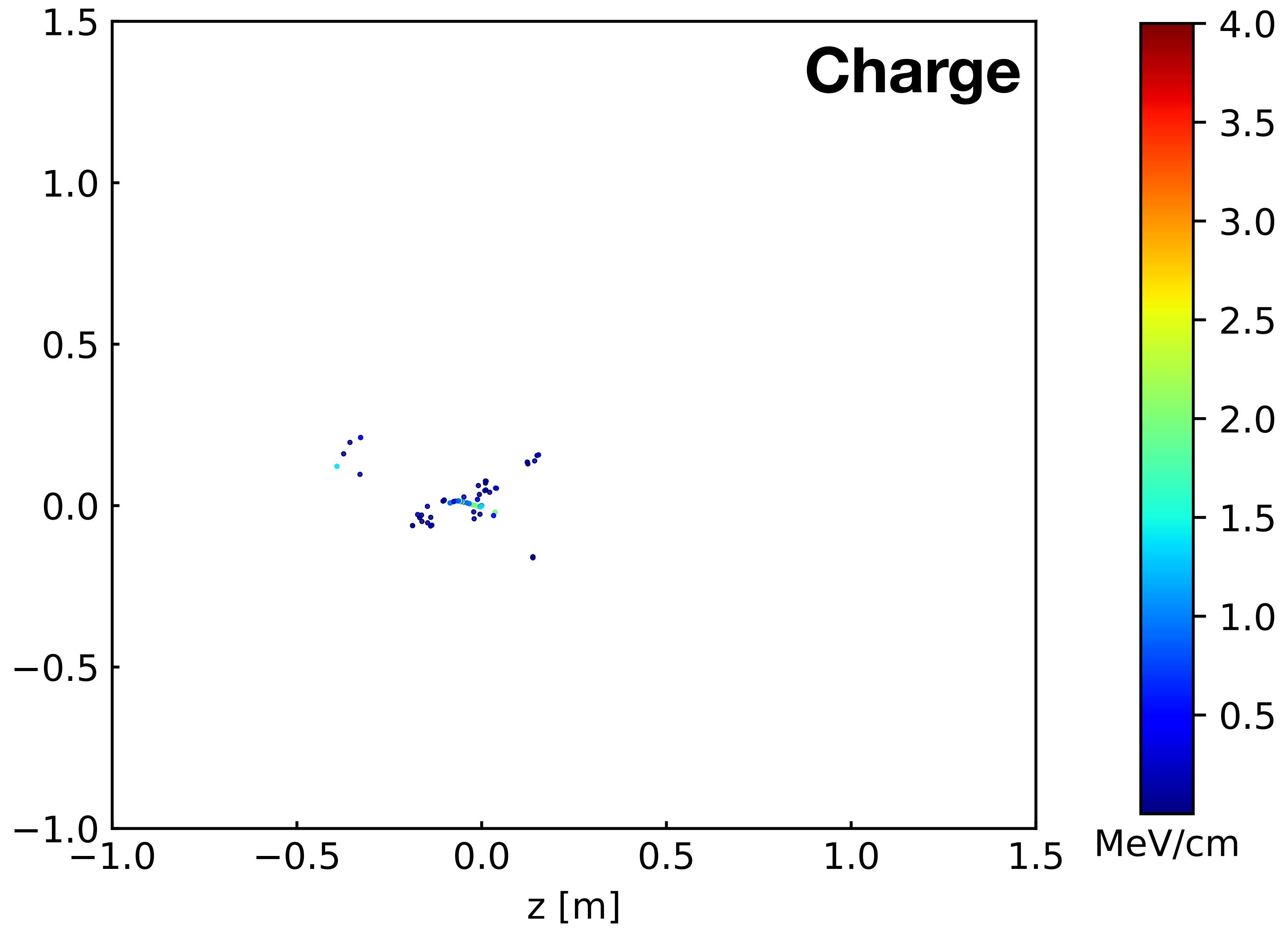


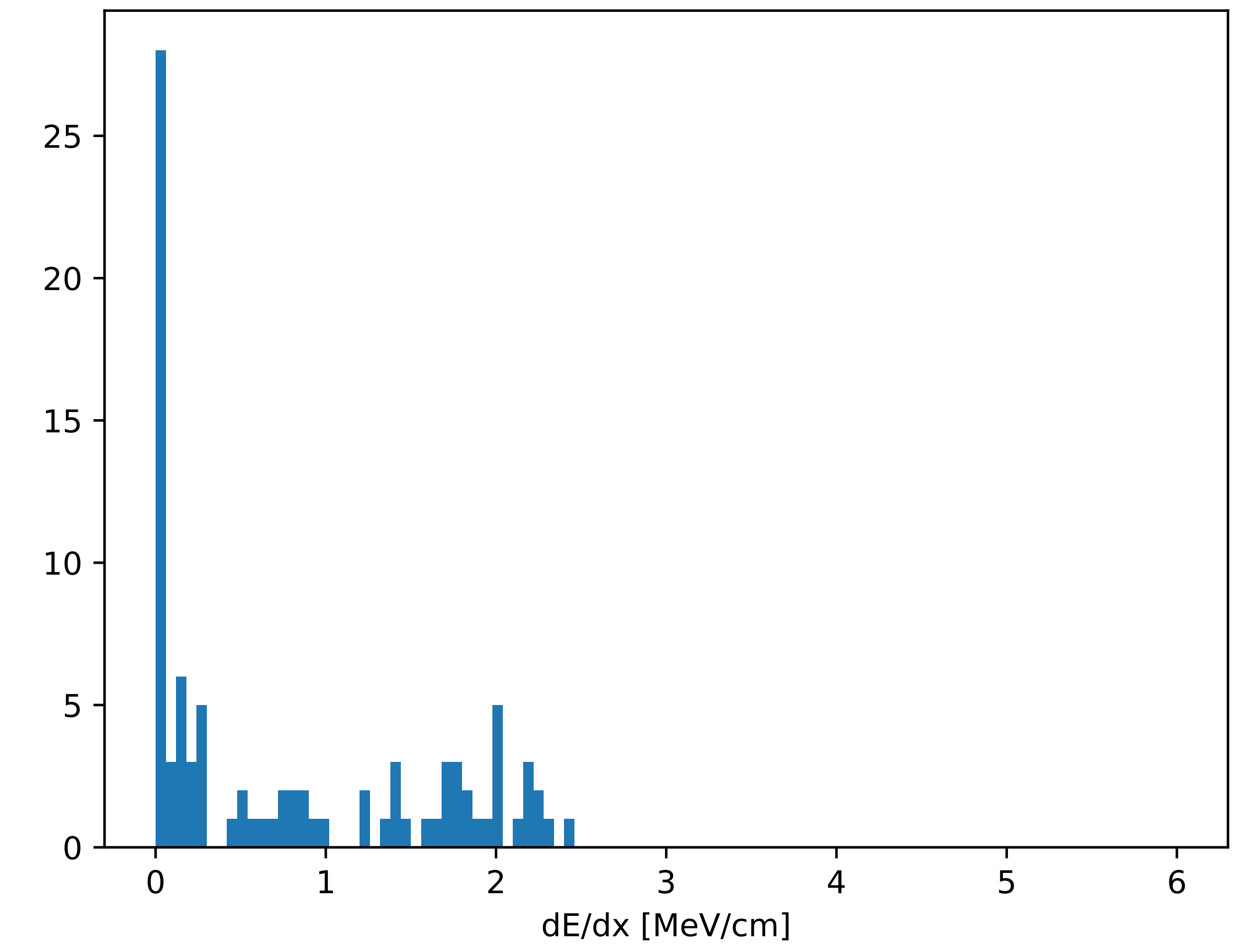
50 MeV nue-Ar CC: evt 346

50x50cm PD module in current APEX design









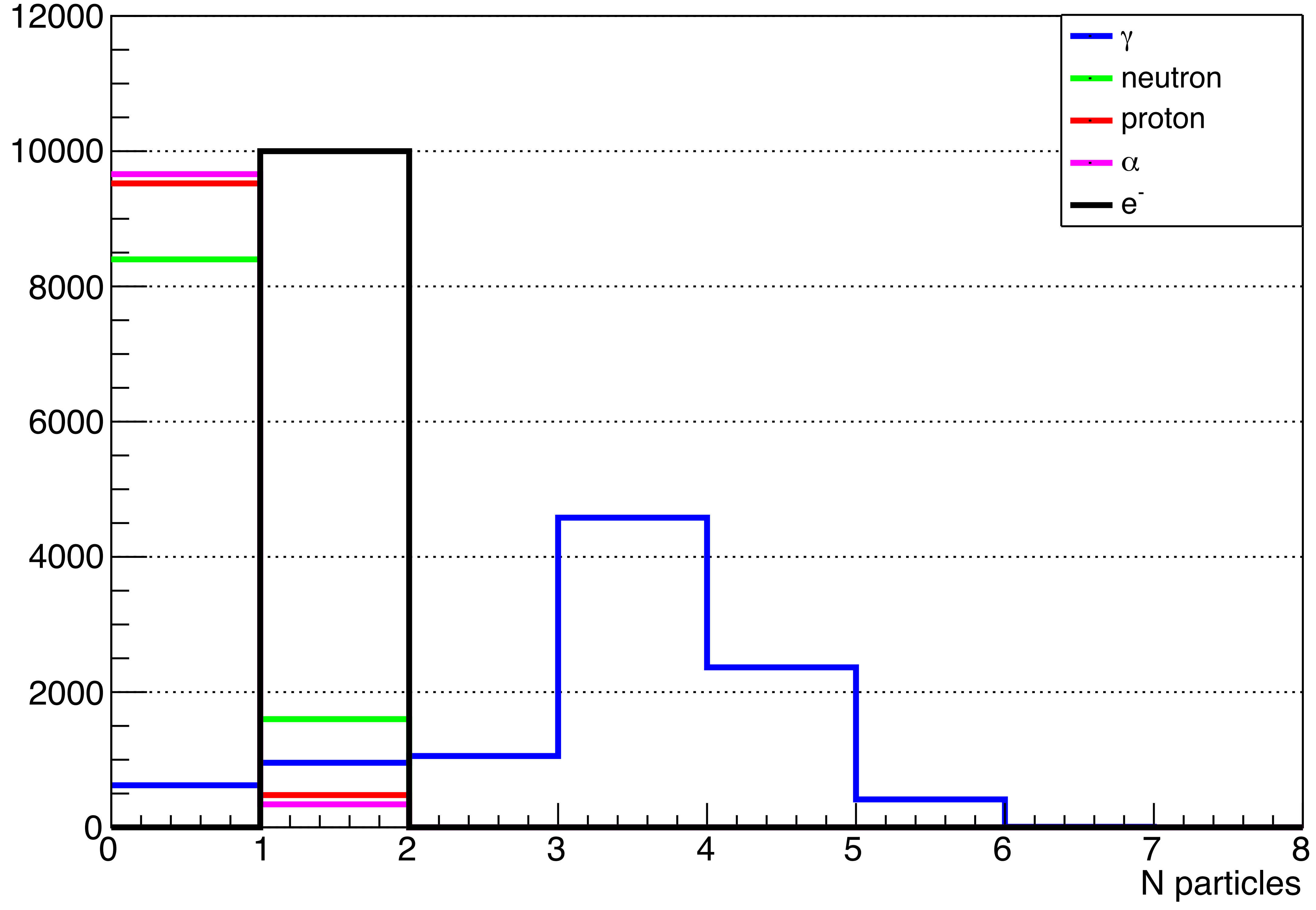
More in back up

Observations

- Topology: a primary electron + a few MeV gammas (+ nucleon/proton/nuclei at higher energy)
  - No pions, ν_e not energetic enough
  - Electron carry most of the ν_e energy
    - ~1 - 50MeV: scattering, ionization & bremsstrahlung
      - Critical energy in LAr is 30.5 MeV
    - Sub-cm up to 10s cm long track
  - De-excitation gammas (~1-10MeV)
    - Compton scattering dominant + subdominant pair production
    - Usually within 1m of vertex

- **PDS timing is critical**
  - Distinguish scattering deposits between neutron (10ns - a few us) and electron/gamma (<10ns)
  - Apply different corrections

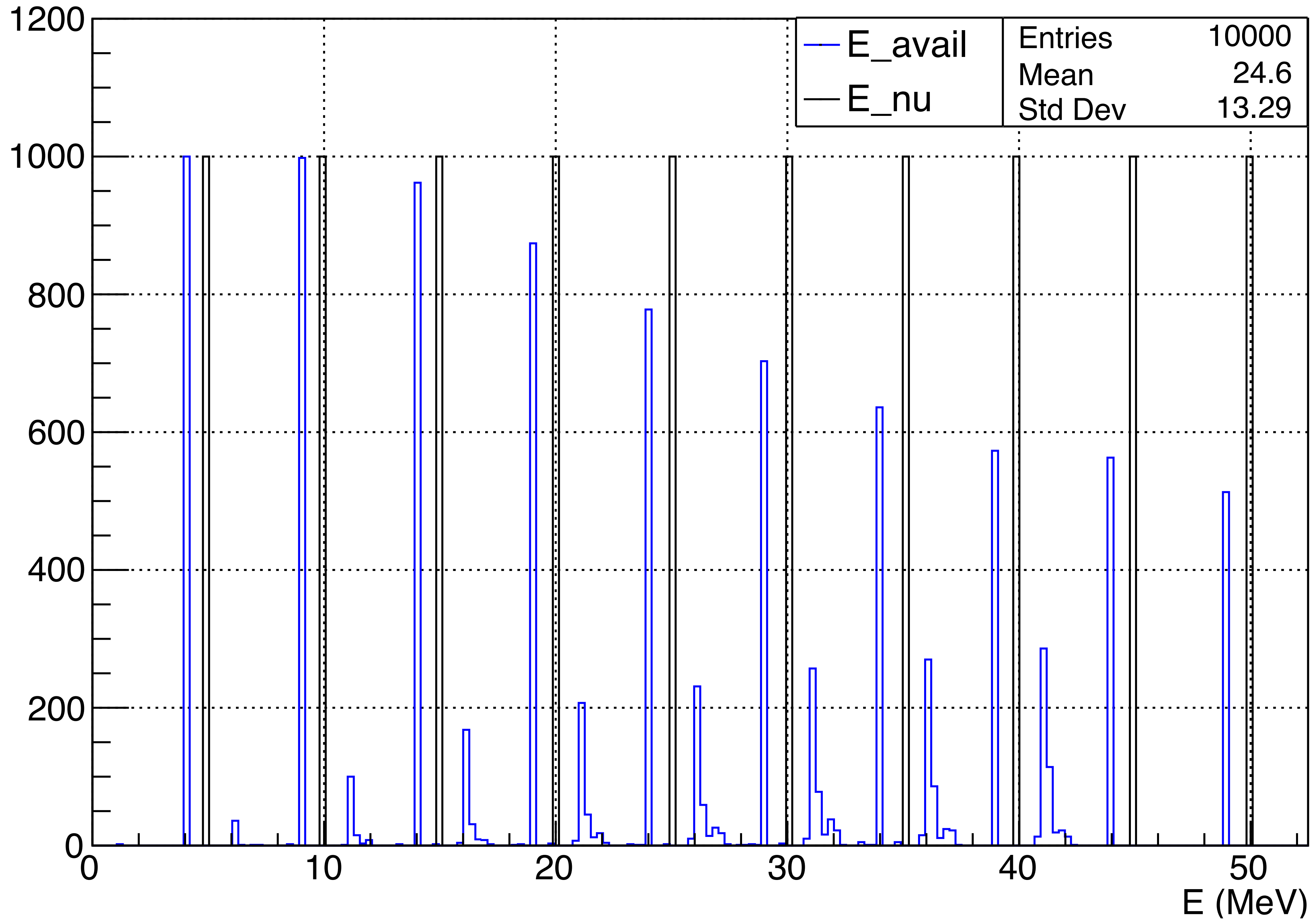
- Applying detector thresholds should eliminate more low energy deposits

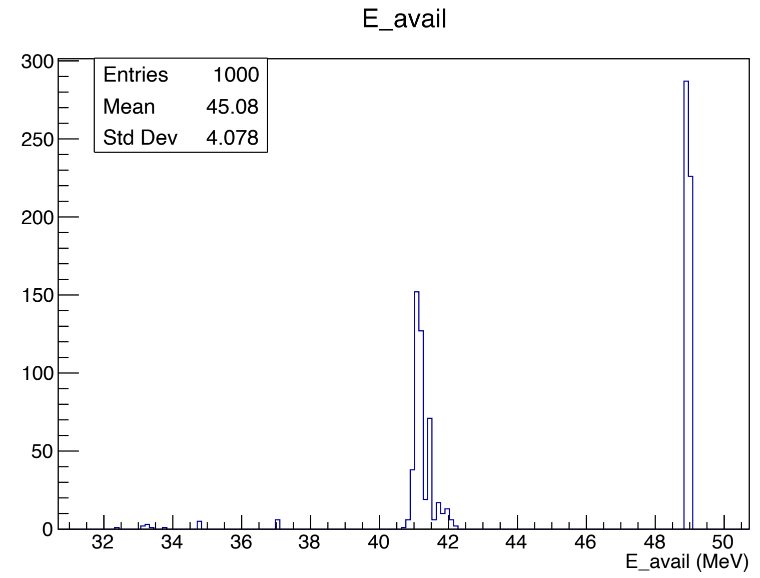


Energy Smearing at Generator Level

- **Available energy (E_{avail}):**
  - KE for: n, p, nuclei
  - Total energy (KE + mass) for electron, gamma

- At higher E_{ν_e}, more events have fixed energy loss
  - A secondary low energy peak that harms DSNB signal searches at lower energies
  - Possible cause: binding energy, intra-nuclear loss





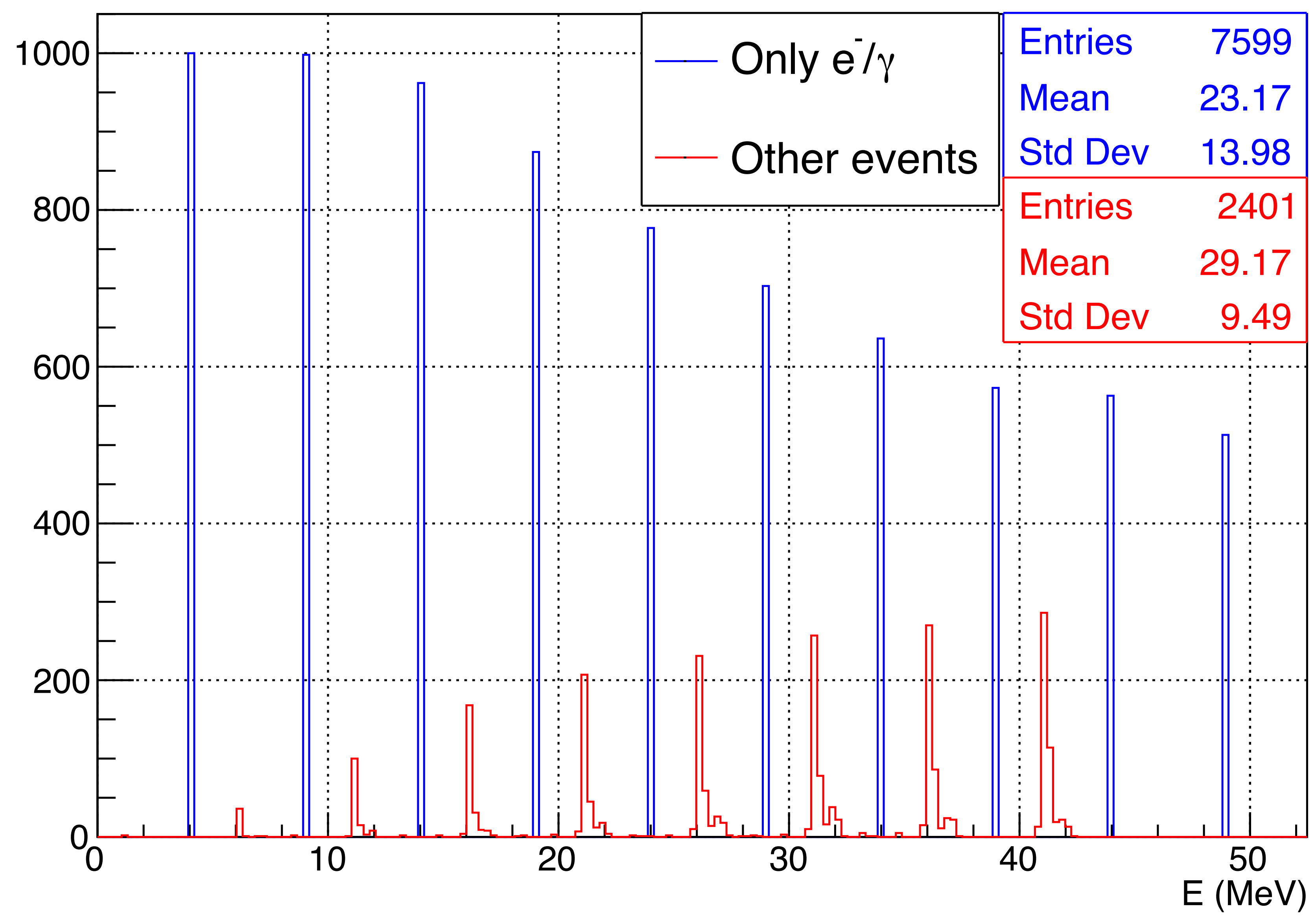
E_{avail} for E_{ν_e} = 50MeV

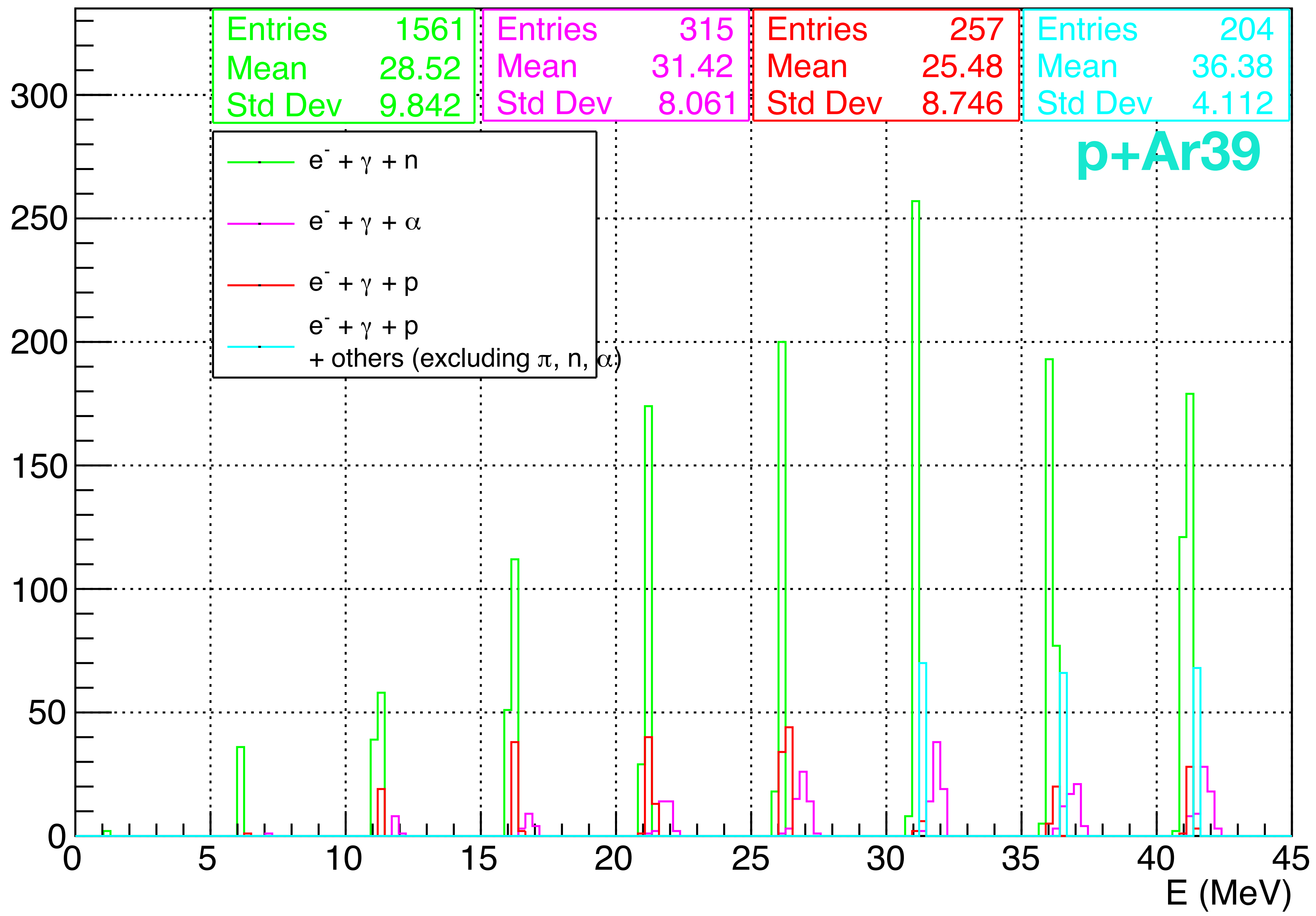
Energy Smearing at Generator Level

- Secondary peak are events with nucleon/nuclei
  - 1n (65%), 1α (13%), 1p (10.7%), 1p+Ar39 (8.5%)

- If we can tag the nucleon in the event, could add back the fixed energy loss (most likely an average binding energy)
  - n/p: ~8MeV, α: ~7MeV
    - n tagging: PDS timing
    - p/α tagging: high dE/dx, MicroBooNE blip analysis

electron + gamma + X: 2401 events
- n: 1561 events
- alpha: 315 events
- p: 257 events
- p + Ar39: 204 events
- deuteron + Ar38: 24 events
- n + alpha: 24 events
- n + p + Ar38: 15 events
- p + alpha: 1 event

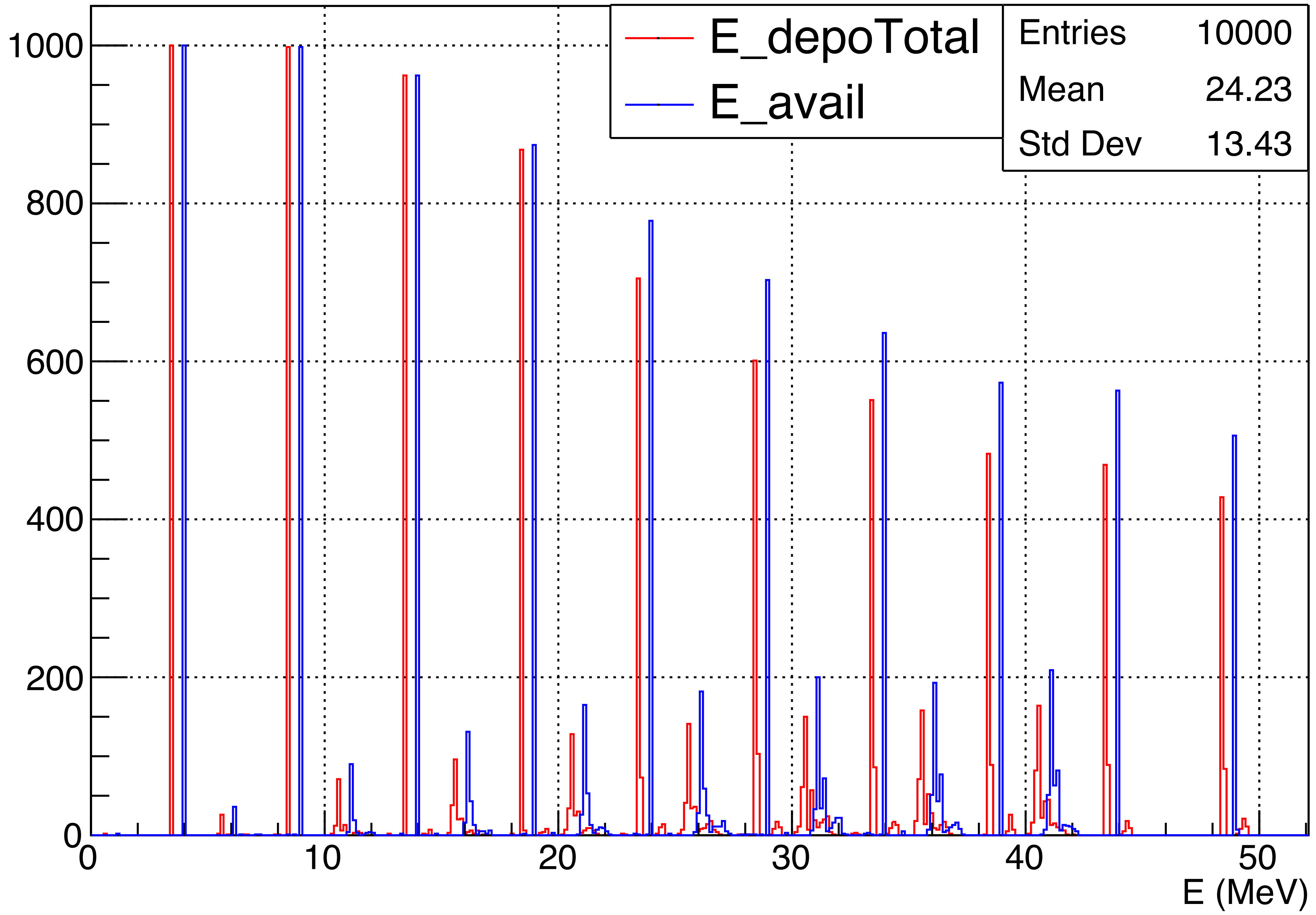


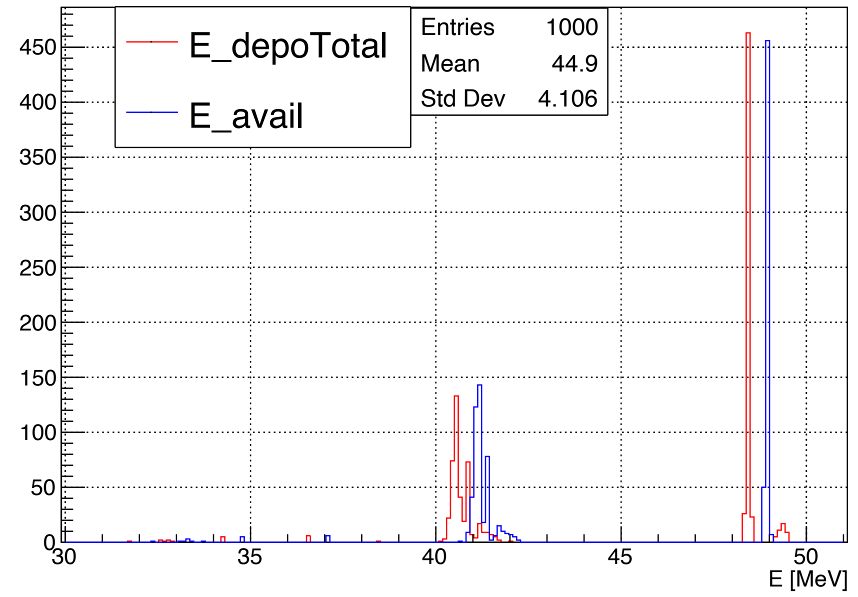


Smearing at Energy Deposition level

- **Deposited energy (E_{depo}):**
  - All energy deposition including all daughter particles (scatter, decay, de-excitation, etc.)

- Smaller smearing compared to generator level
  - Mean energy shift down ~ 1MeV
  - Some events over deposit energy
    - Neutron: n-capture for example (next slide)



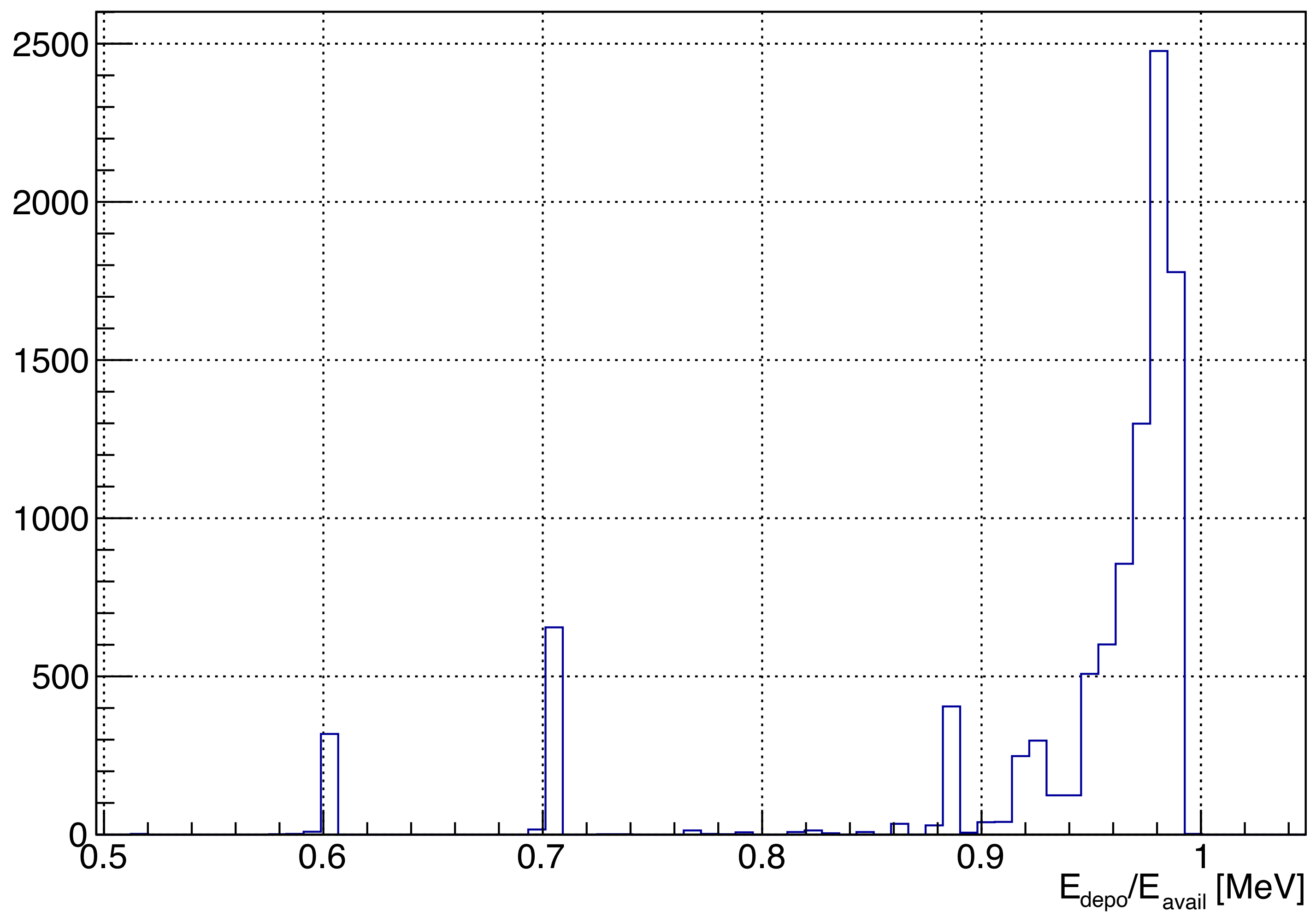


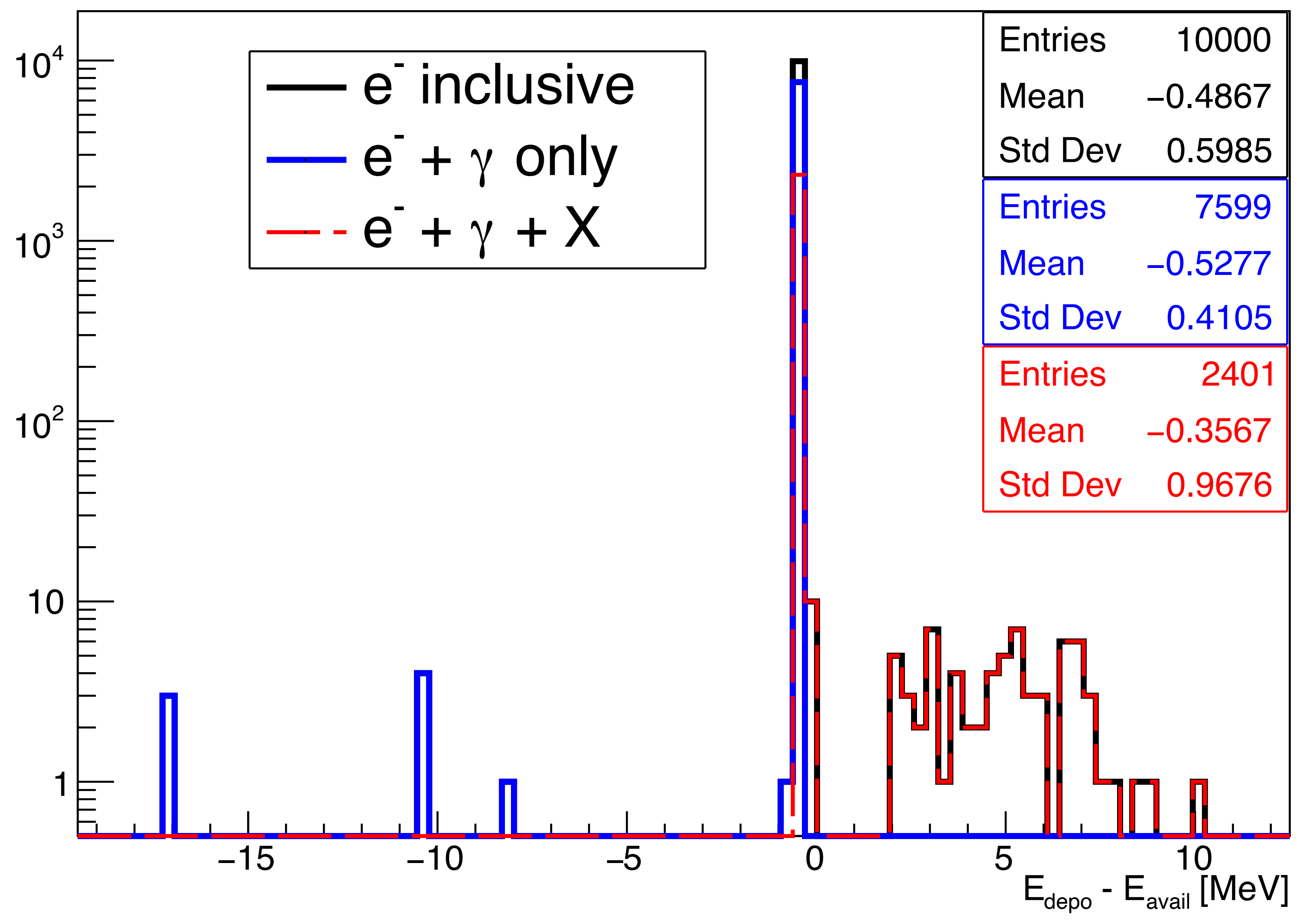
E_{ν_e} = 50MeV

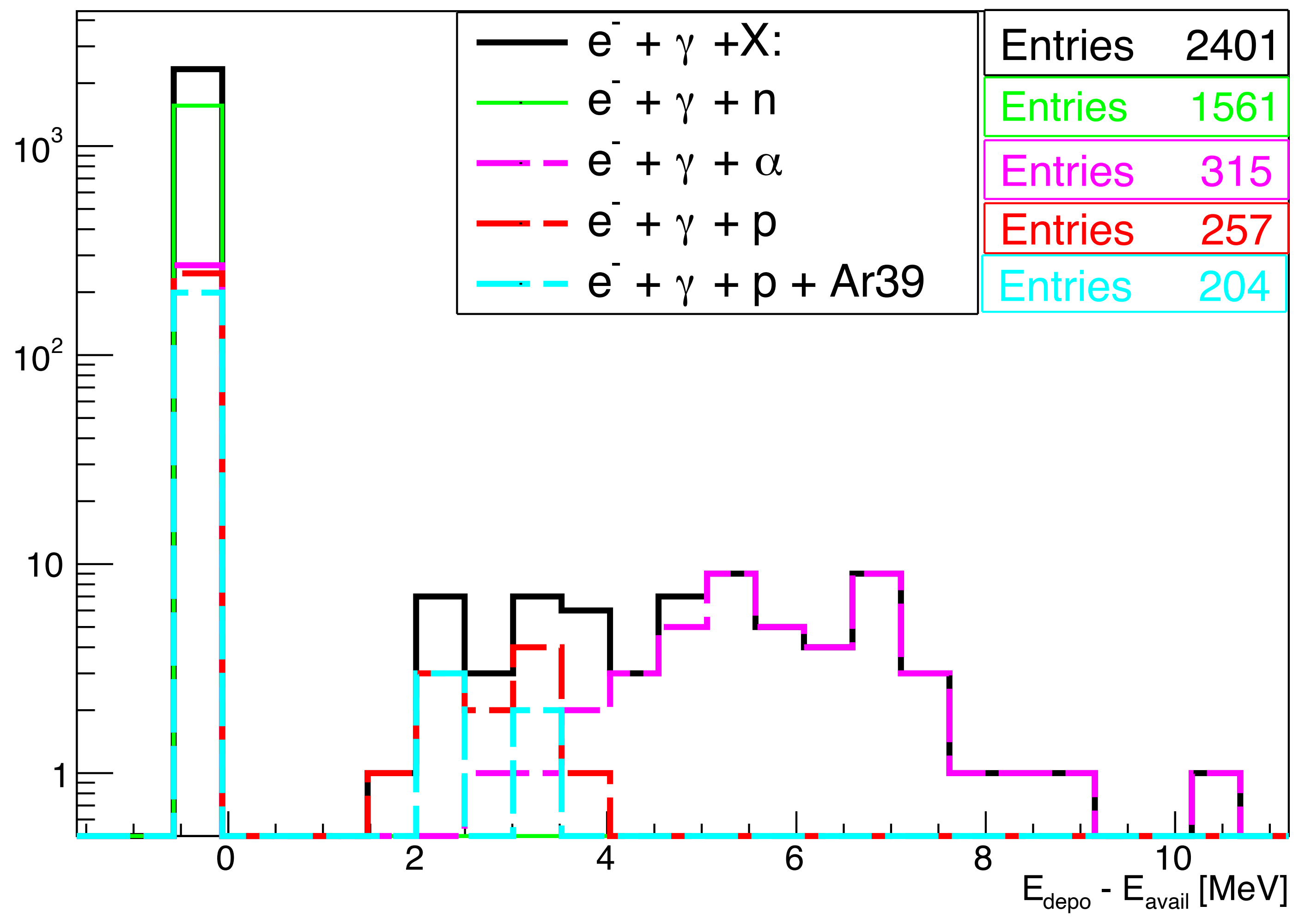
Electron

- Peak at 0.98

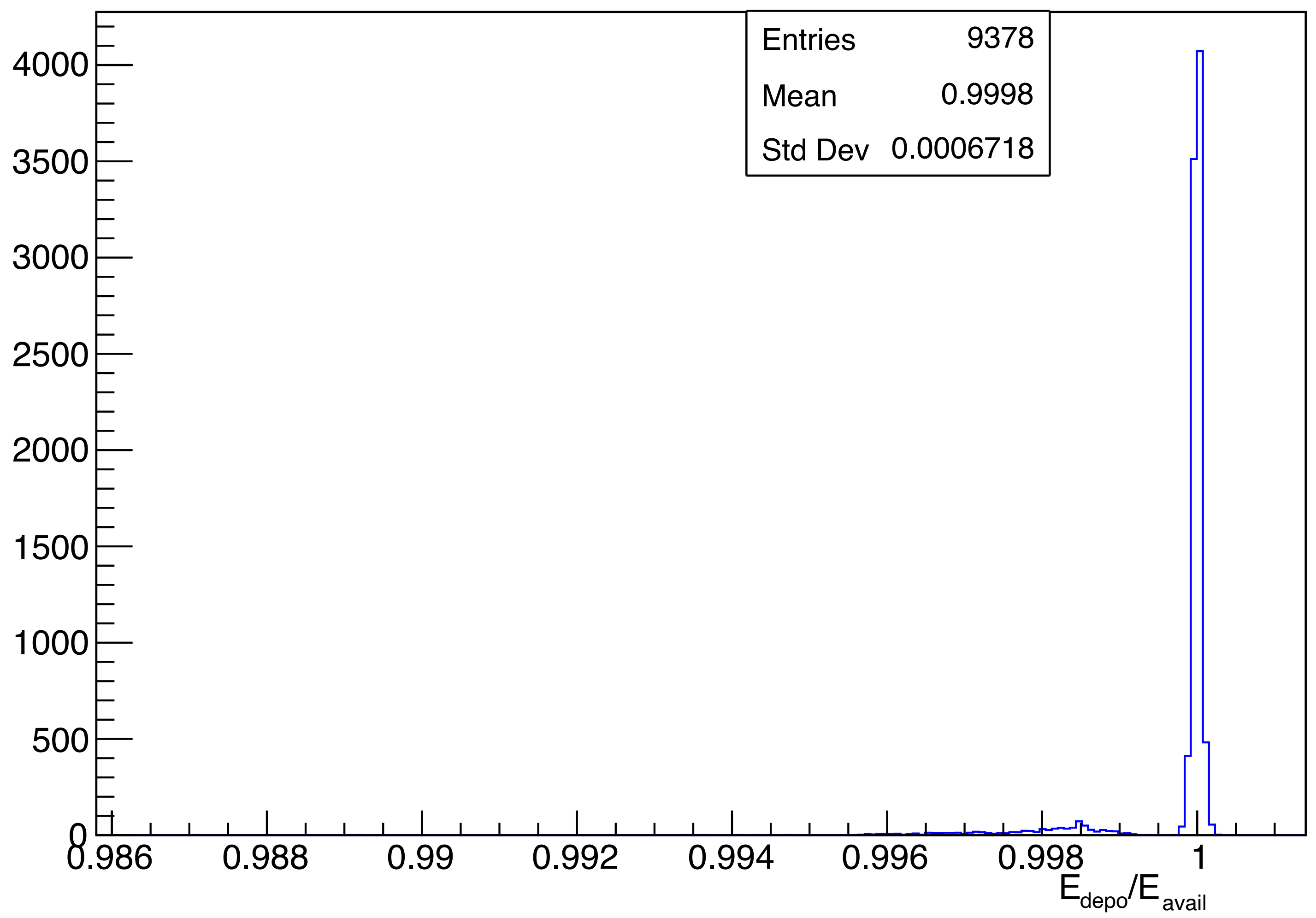
- <1% electrons have over deposited a few MeV energy
  - Mostly happen when extra nucleon (X) is present
  - Alpha events contribute to higher energy loss (> 4 MeV)
  - Proton events contribute to low energy loss (< 4 MeV)

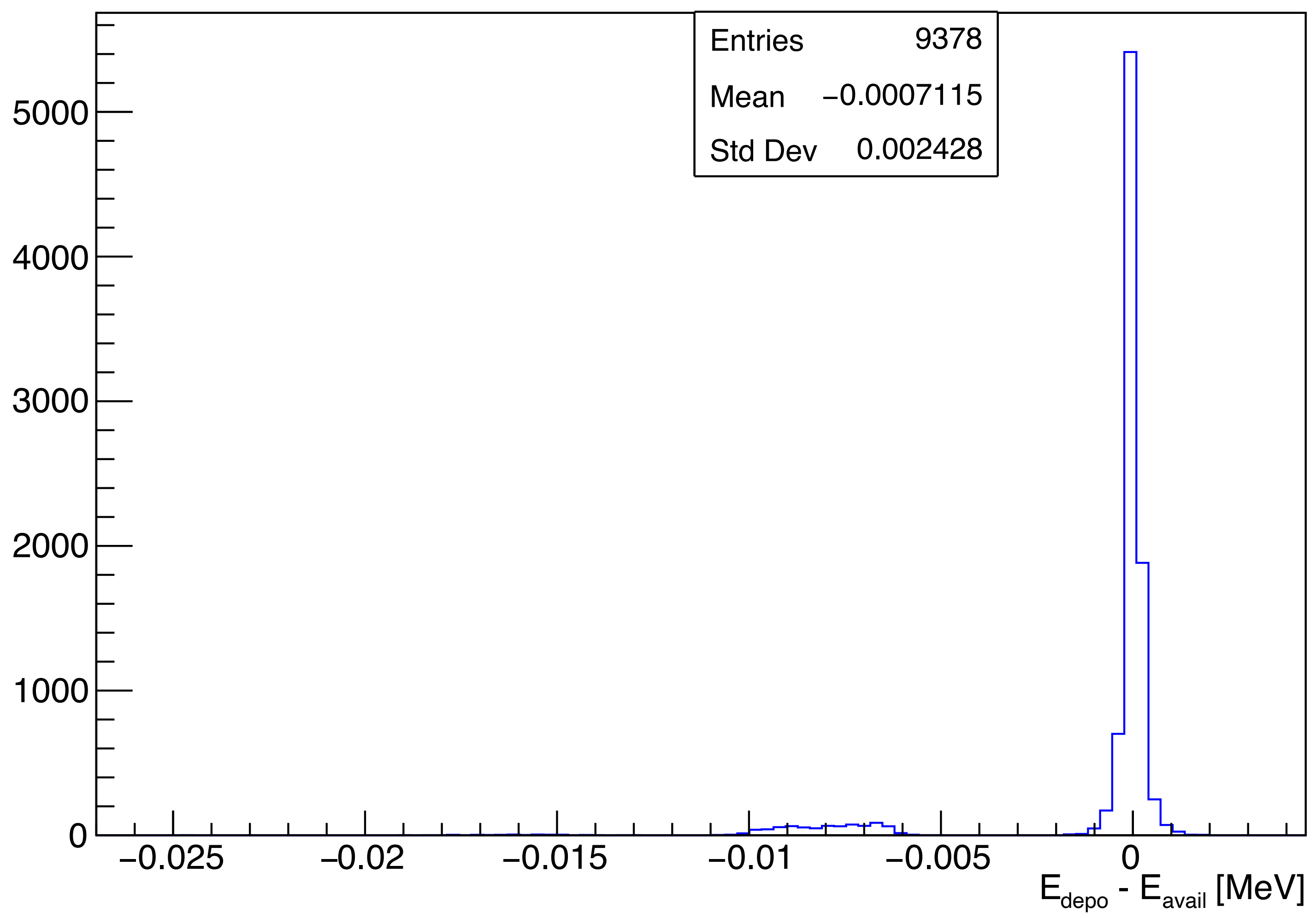






Gamma

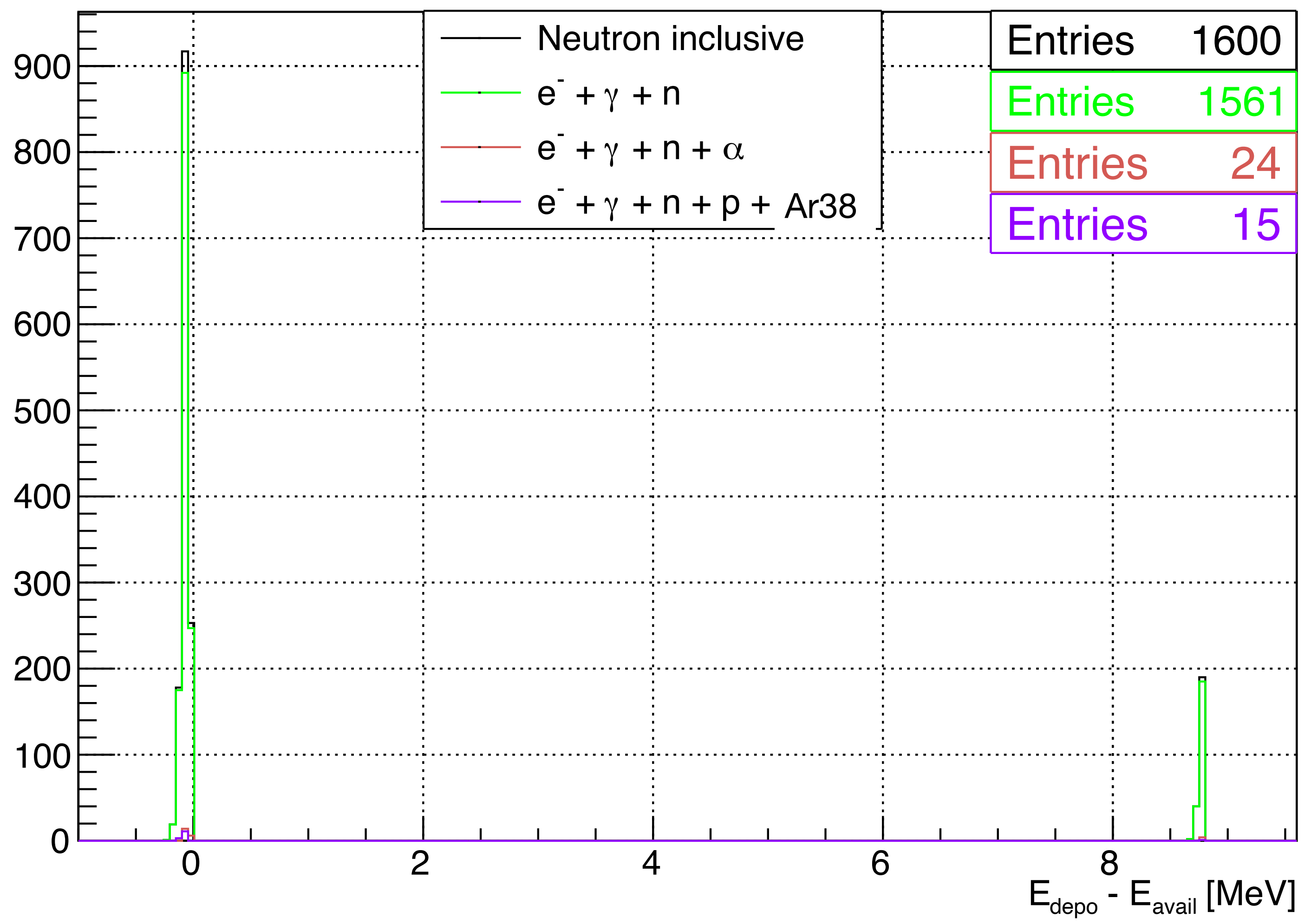


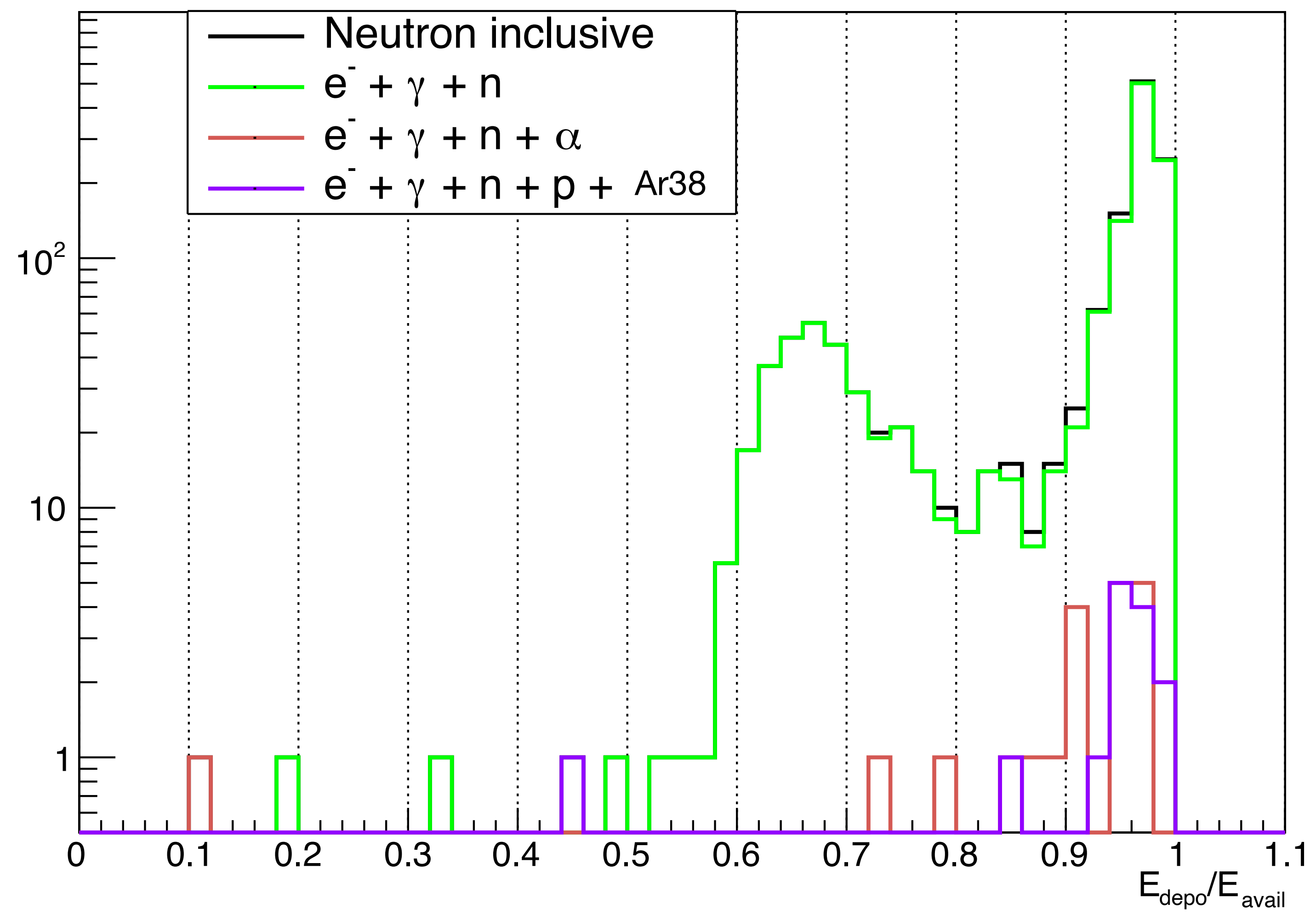


- Expected peak at 1, good!
- Apply detection thresholds may make it worse

Neutron

electron + gamma + X
- n: 1561 events
- n + alpha: 24 events
- n + p + Ar38: 15 events

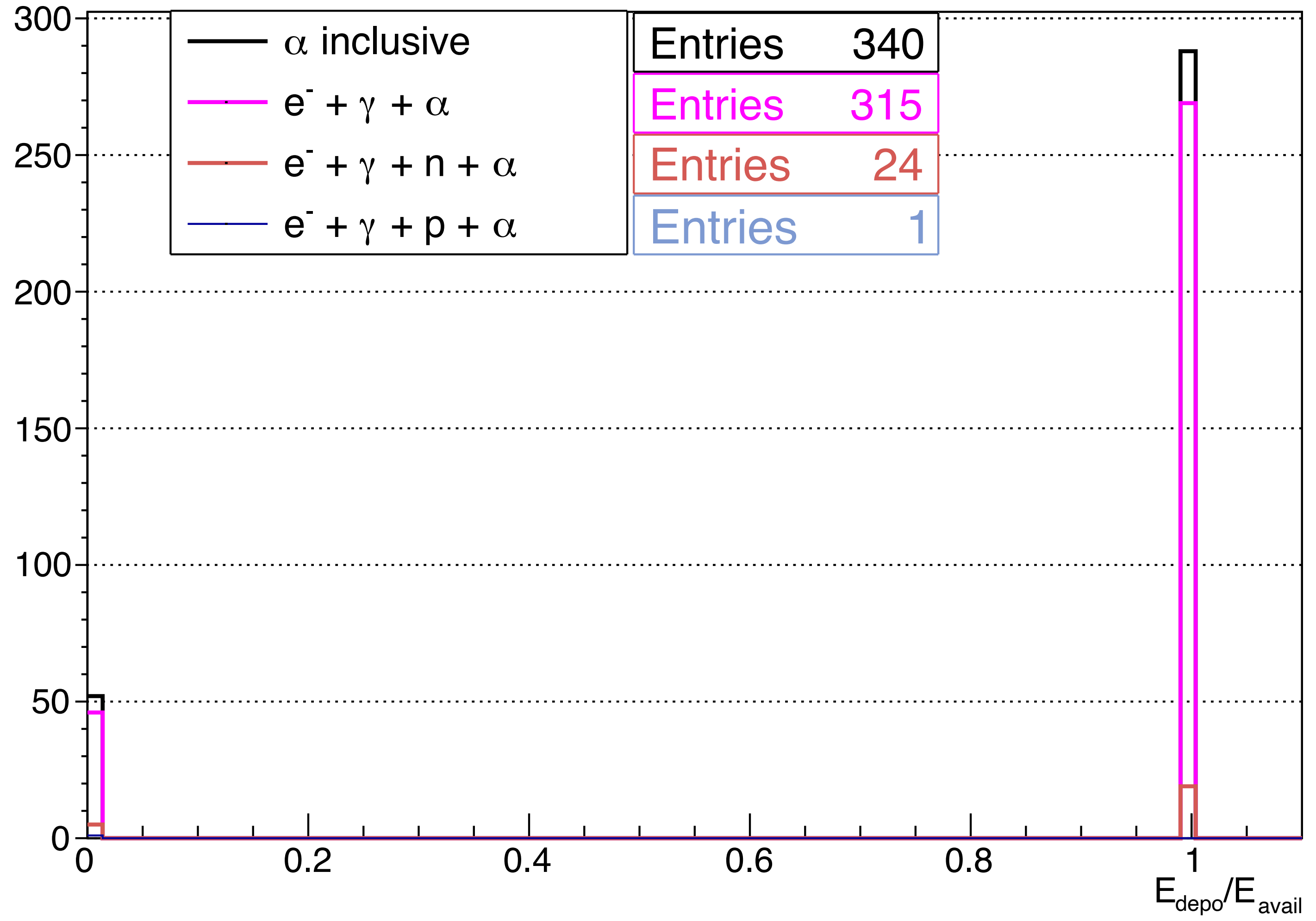


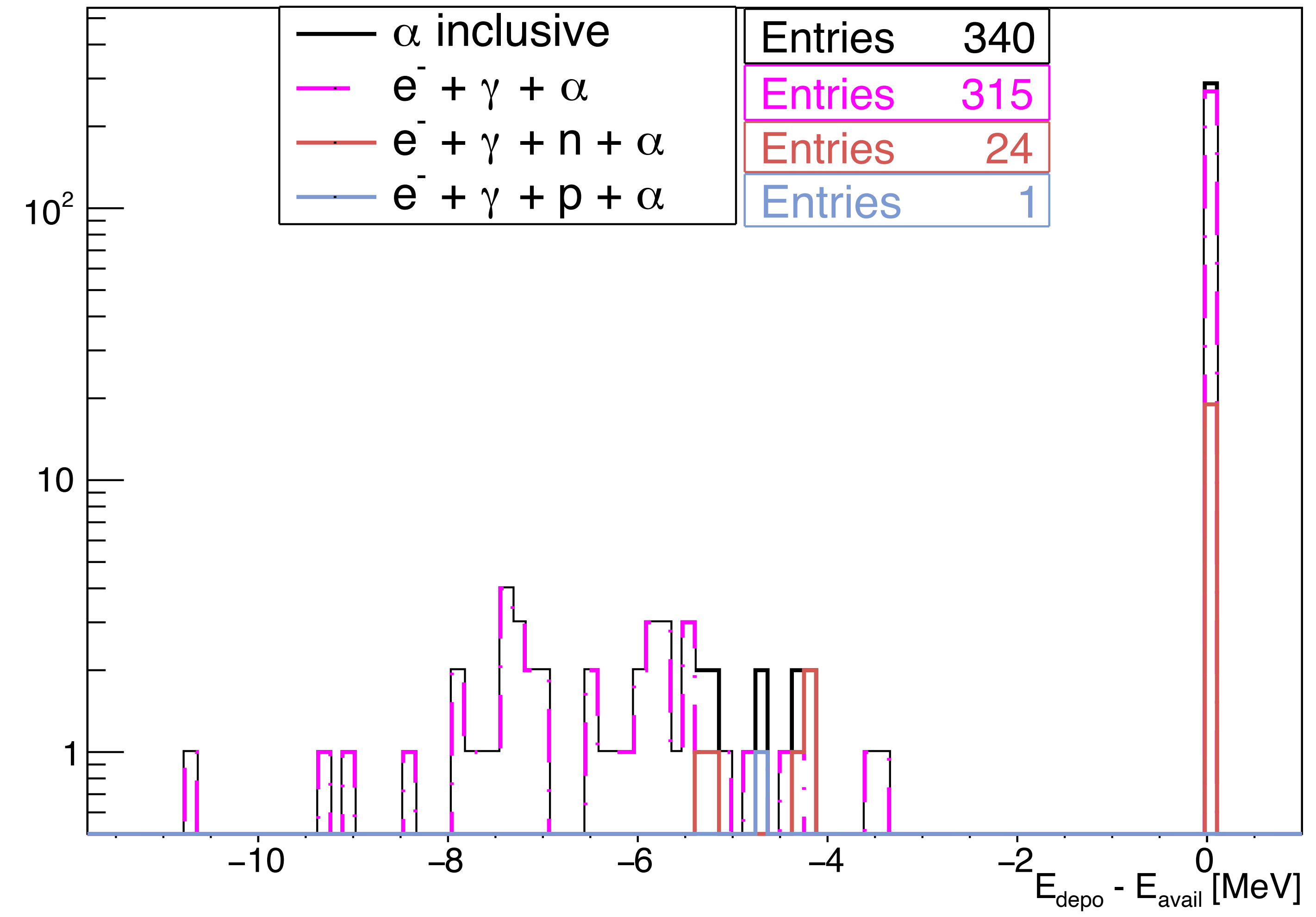


- ~15% n over deposit a fixed energy of ~8.7 MeV
  - If these events can be tagged, can subtract the 8.7MeV
  - Is this from n-capture?
    - n-capture on Ar-40 should produce 6.1MeV gamma cascade
    - n-capture events are fairly localized, could produce a unique signal(s) in PDS
- Peaks at 0.65 and 1 also observed in GeV events
  - Peak at 1 is likely n to p conversion, happens more often at MeV
  - Two peak feature is independent of E_{ν_e}
  - Peak at 0.65 is not a big concern as energy deposition loss is below 0.5 MeV

Alpha

electron + gamma + X
- alpha: 315 events
- alpha + n: 24 events
- alpha + p: 1 event

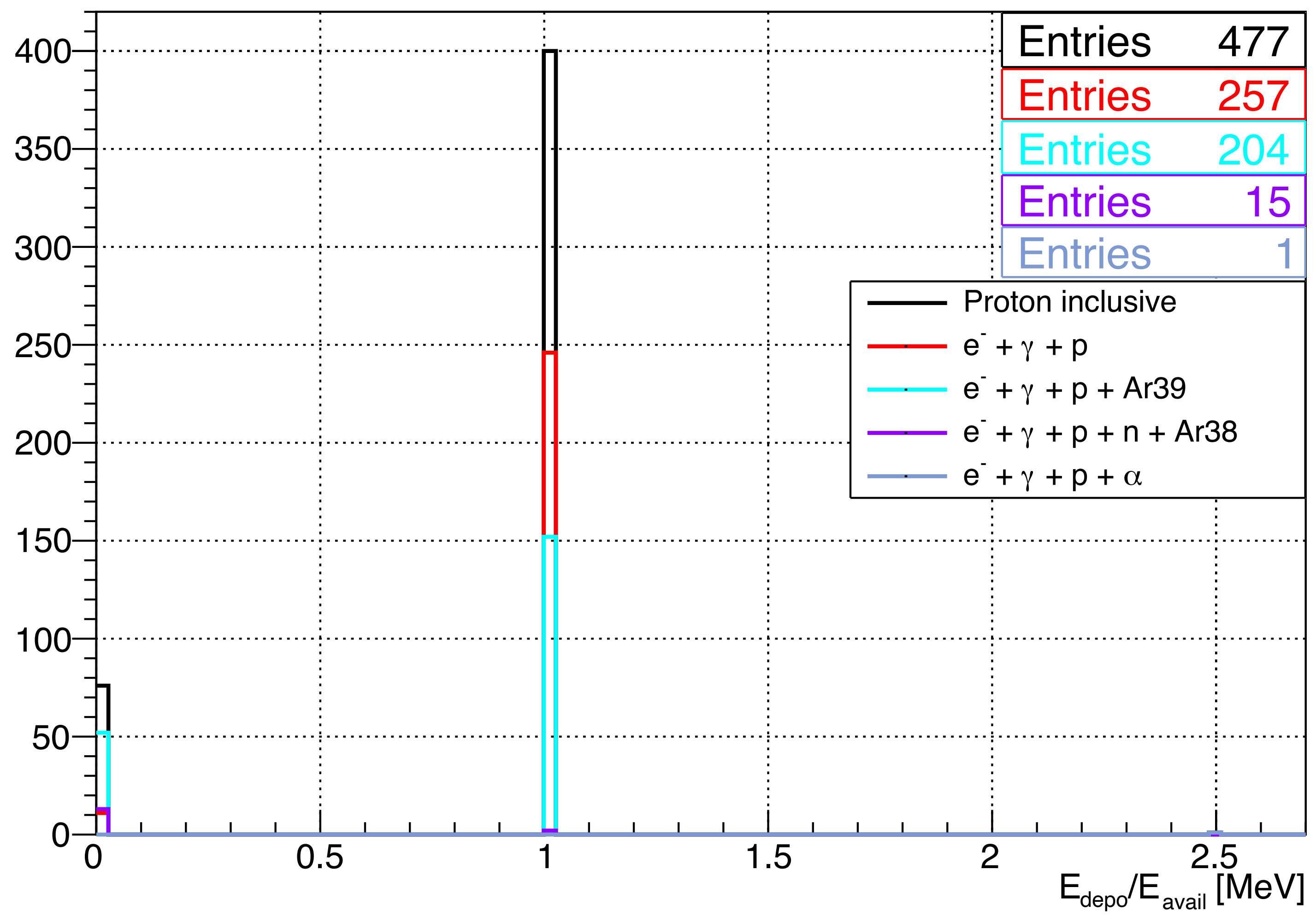




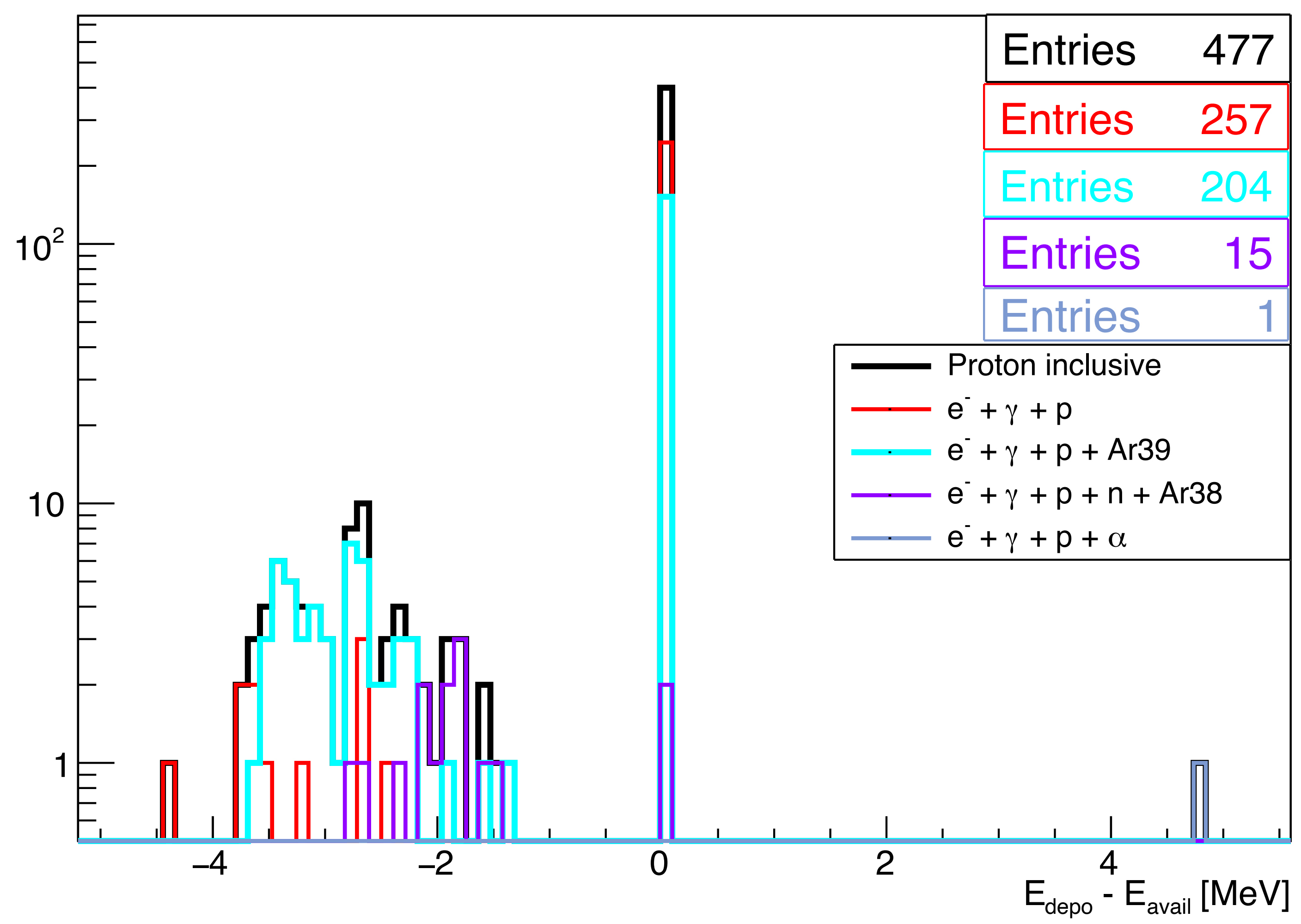
- Most α deposit all KE
- ~15% α lose a few MeV in deposition
  - These lost energy goes to electron deposition

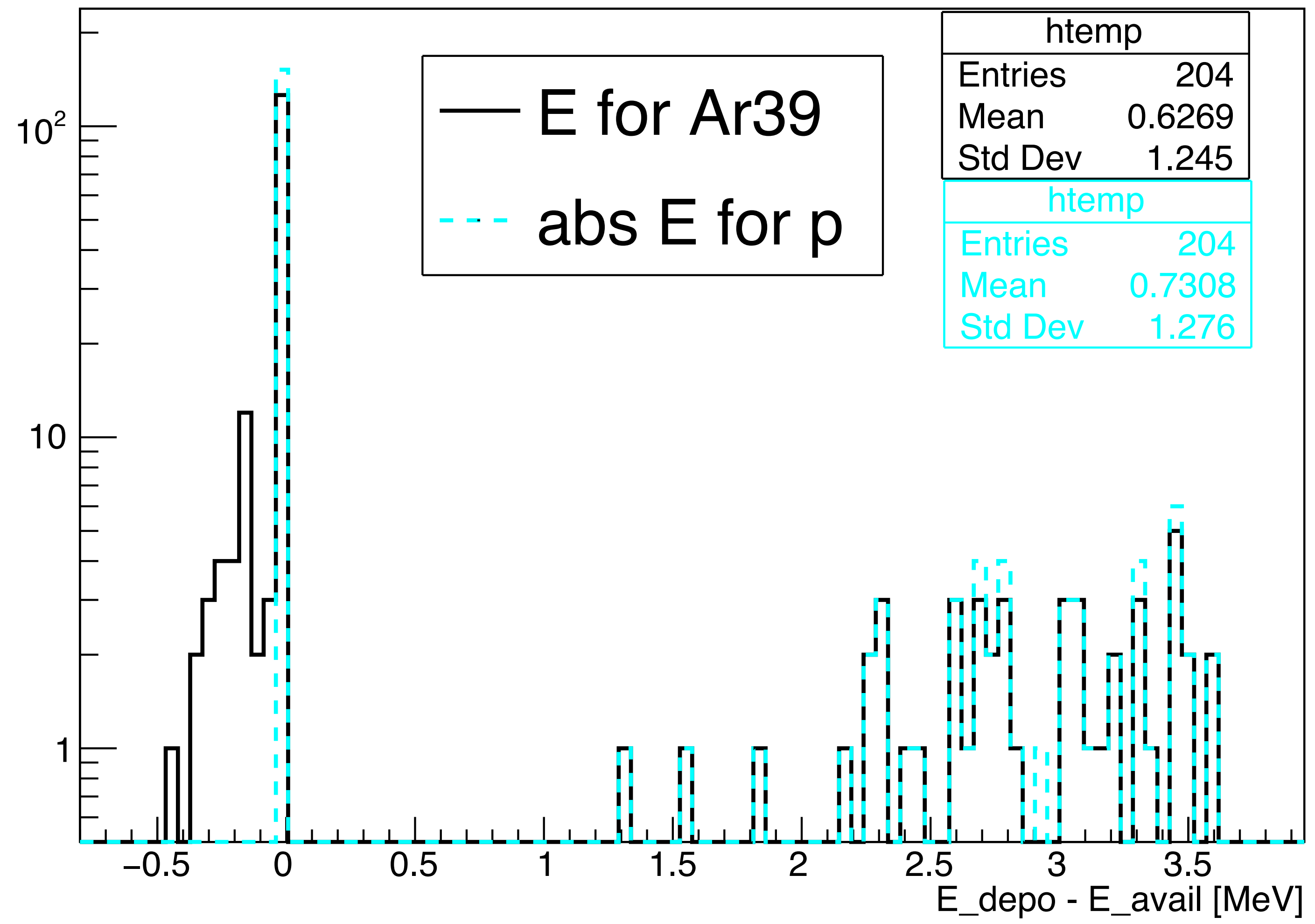
Proton

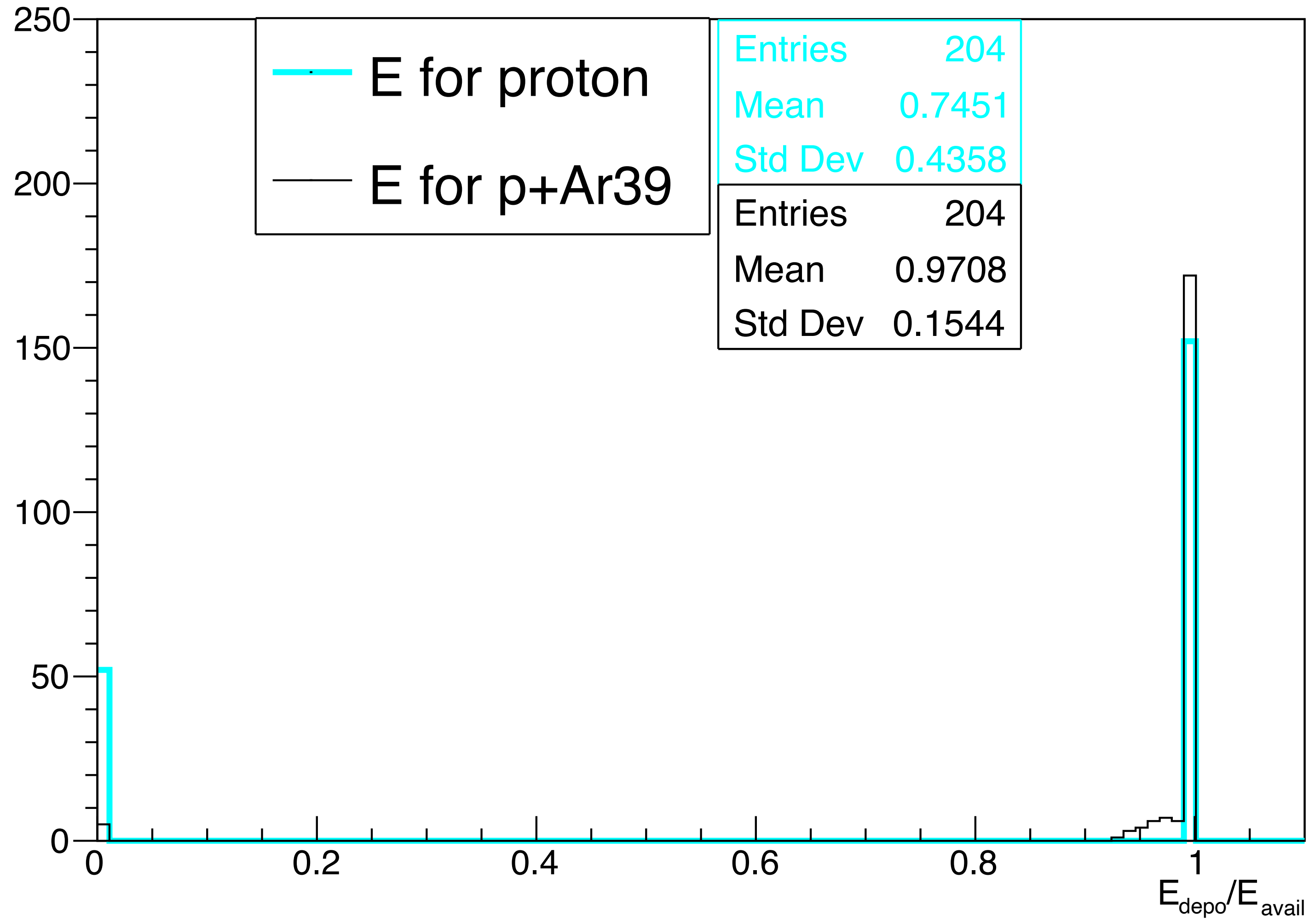
electron + gamma + X
- p: 257 events
- p + Ar39: 204 events
- p + n + Ar38: 15 events
- p + alpha: 1 event



- Most p deposit all KE
- 16% protons (mostly from p + Ar39) lose of a few MeV in deposition
  - This few MeV is primarily gained by Ar39, p + Ar39 is a system
  - Some lost energy is deposited by the primary electron

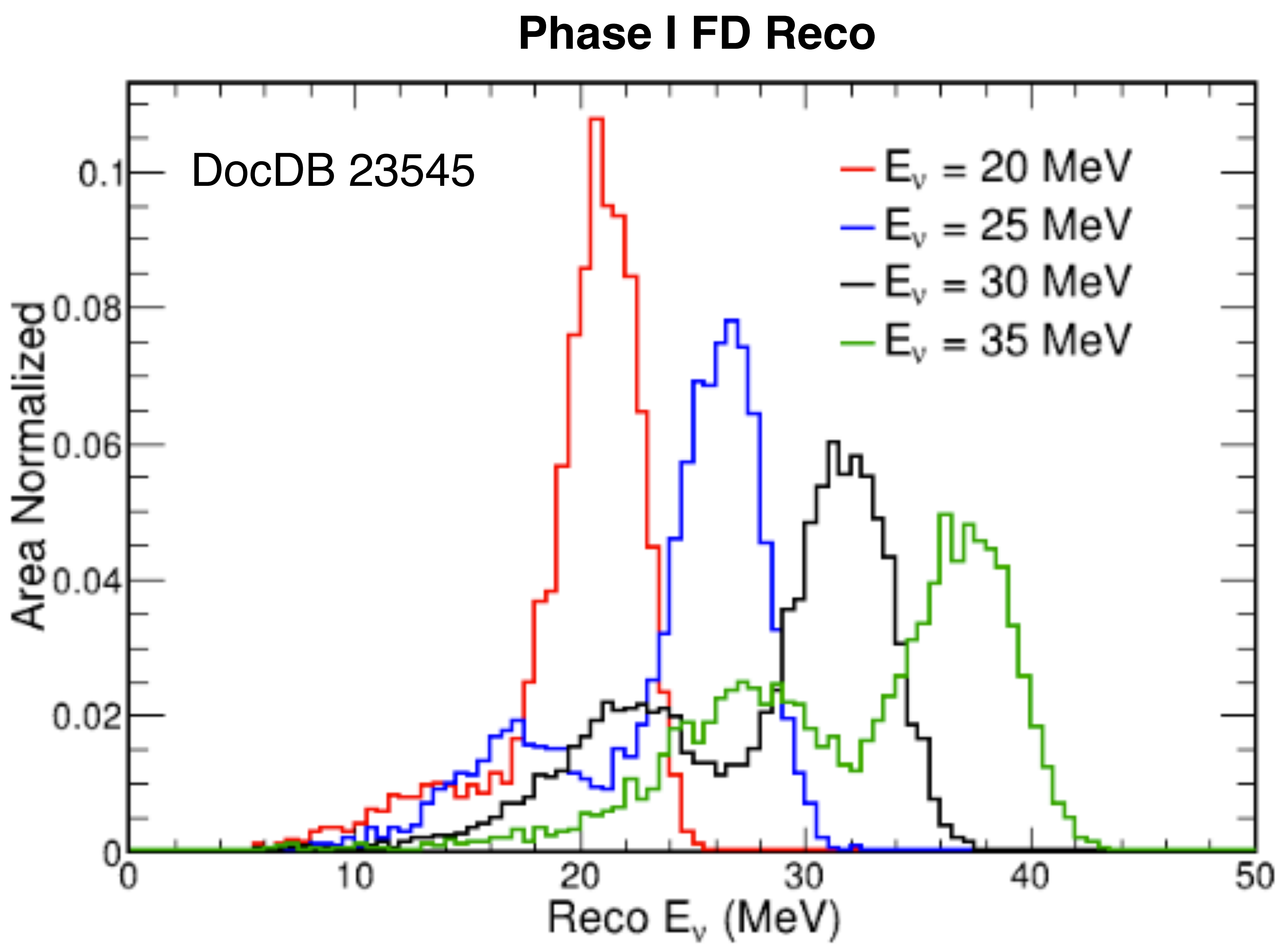


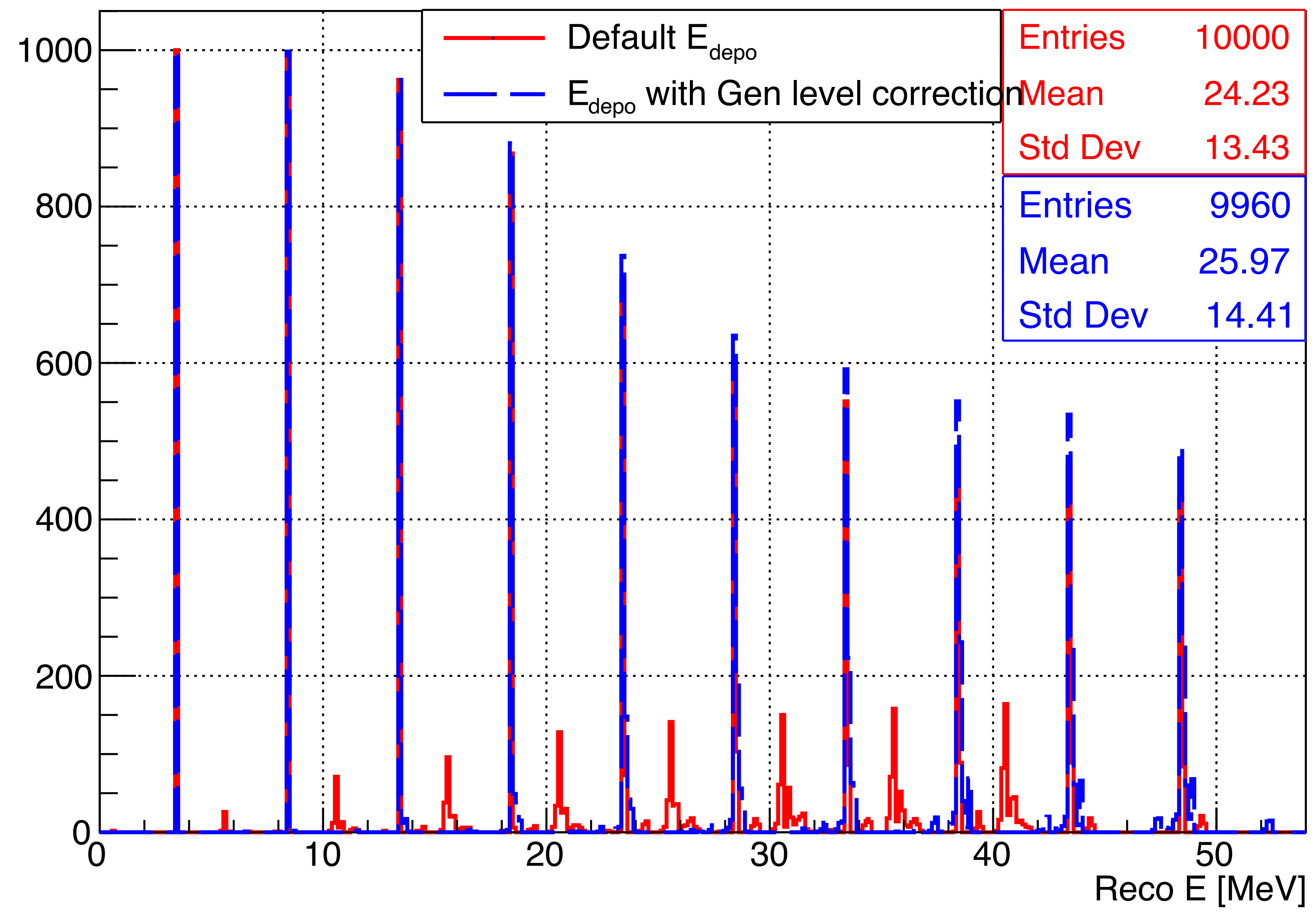




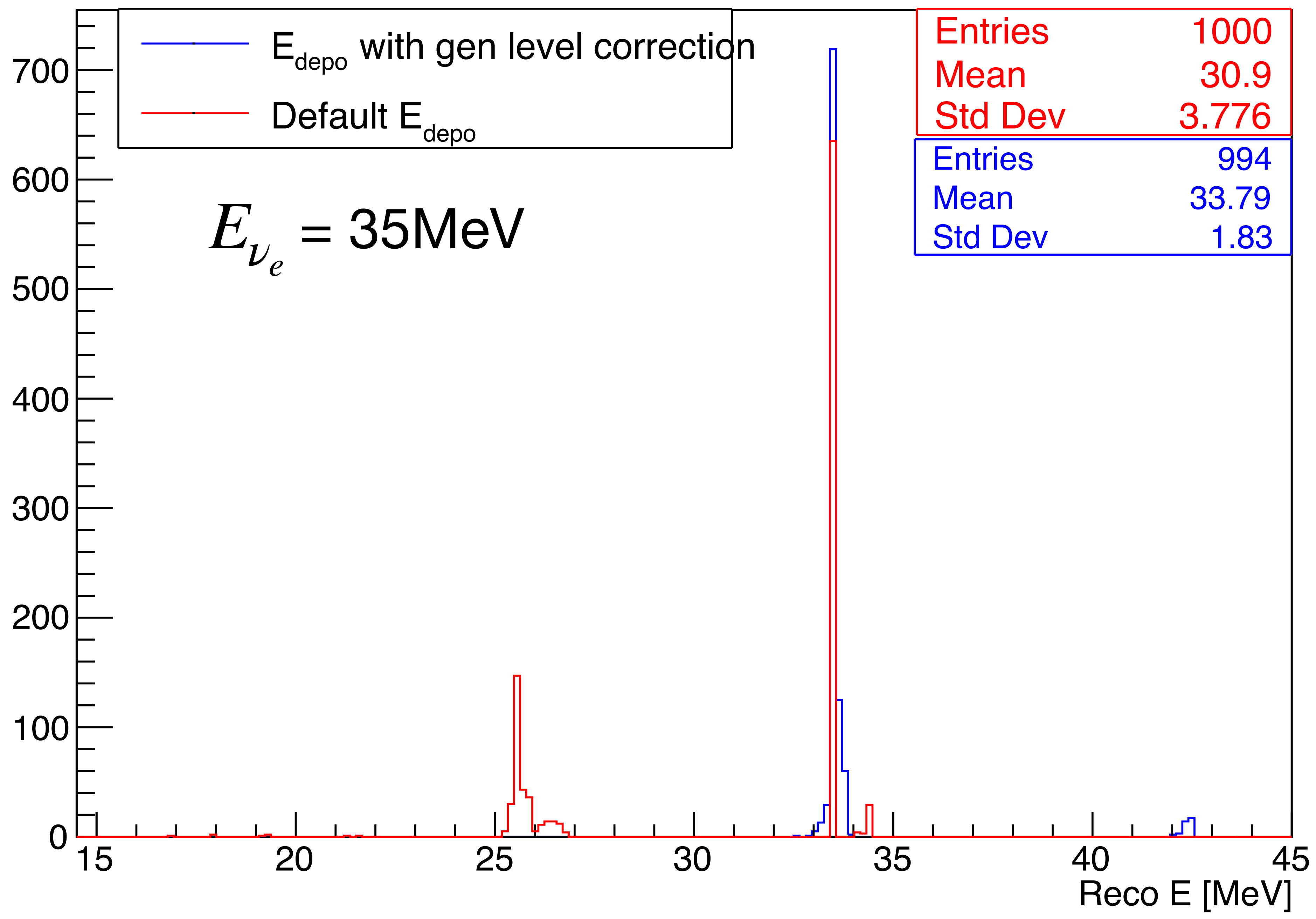
Reconstruction

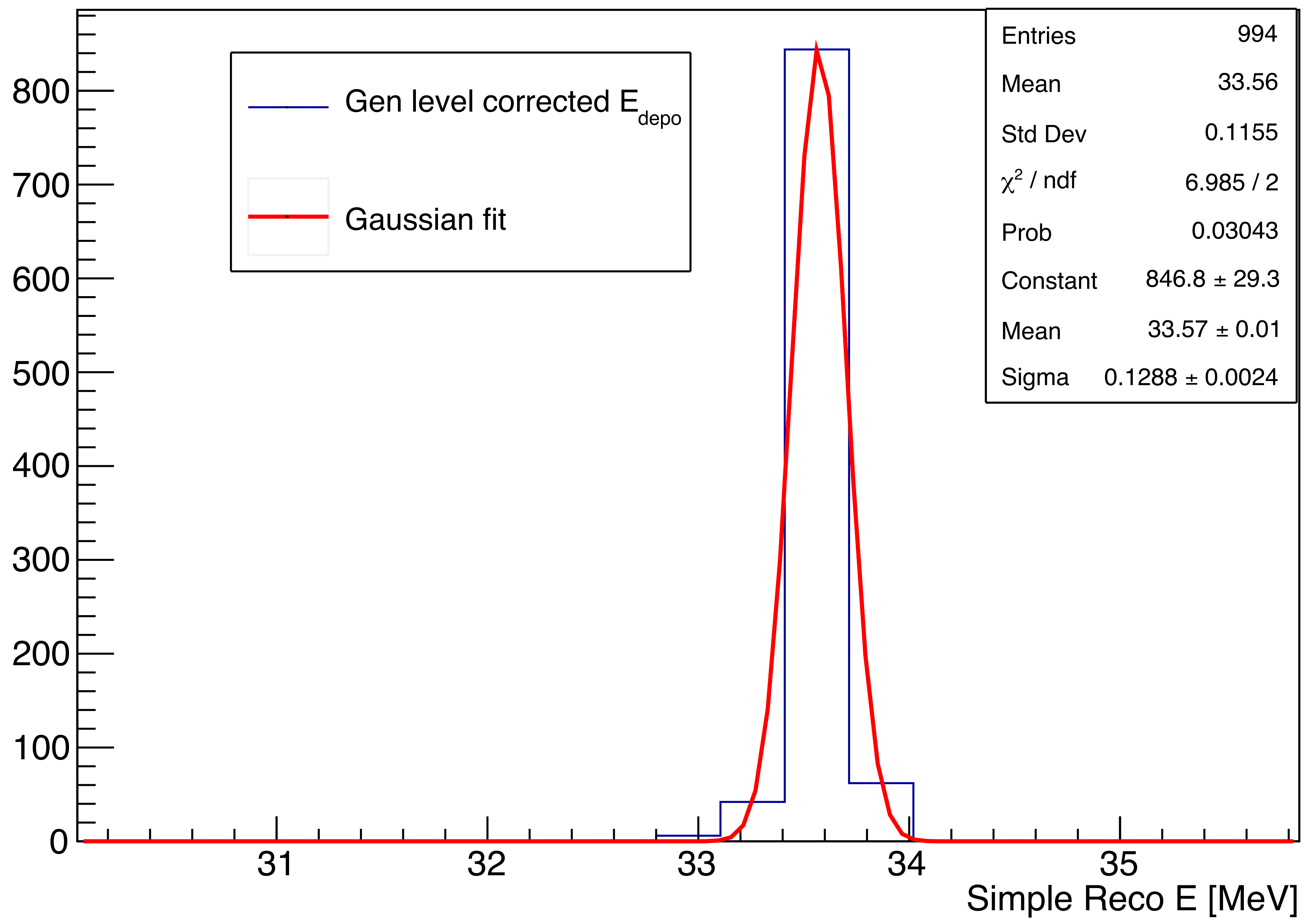
- **This study: generator level + LAr E deposition level (no detector/reco effects)**
  - Extra nucleon production at generator level is the main reason of the feed down peak at reconstructed energy
- **Generator level correction**:
  - Add binding energy back
  - Neutron/proton: ~8MeV, alpha: ~7MeV
- E_{depo} **level correction**:
  - Neutron: 15% over deposit from possible n-capture





Reconstruction





Sigma/mean ~0.38%

Summary

- A potential discovery of DSNB in the 22-30MeV small window is possible at DUNE

- Energy smearing affects DSNB search sensitivity, this presentation studied:
  - **Generator level**: fixed energy loss from nucleon average binding energy (7-8MeV) dominate energy feed down at 10s of MeV
  - **Energy deposition level**: a small fraction of neutrons getting captured and over deposit a fixed 8.7 MeV

- Corrections could be applied if we can perform good PID for single neutron, proton, alpha
  - Correction to generator level smearing: E resolution could reach ~0.38% at E_{ν_e} = 35MeV

- FD3 PDS timing is critical for PID
  - Correlate timing on PD module(s) could distinguish neutron (10ns - a few us) and e/γ (<10ns)
  - n-capture events may produce unique signals in PDS, help subtract the over deposited energy

- Higher and more uniform light yield in FD3 PDS further lowers the detector threshold and improves the energy resolution
  - Improve energy calibration, improve detector efficiency

Outlook

- Estimate “realistically achievable energy resolution” with FD3 PDS and improvement on DSNB sensitivity
  - Apply detection thresholds
  - Apply realistic charge (dQ/dx) and light (dL/dx) yield from dE/dx

- Derive benchmark light yield and timing requirement on FD3 PDS
  - Study particle identification/tagging performance for neutron, proton and alpha