Thoughts on Reconstruction with PDS

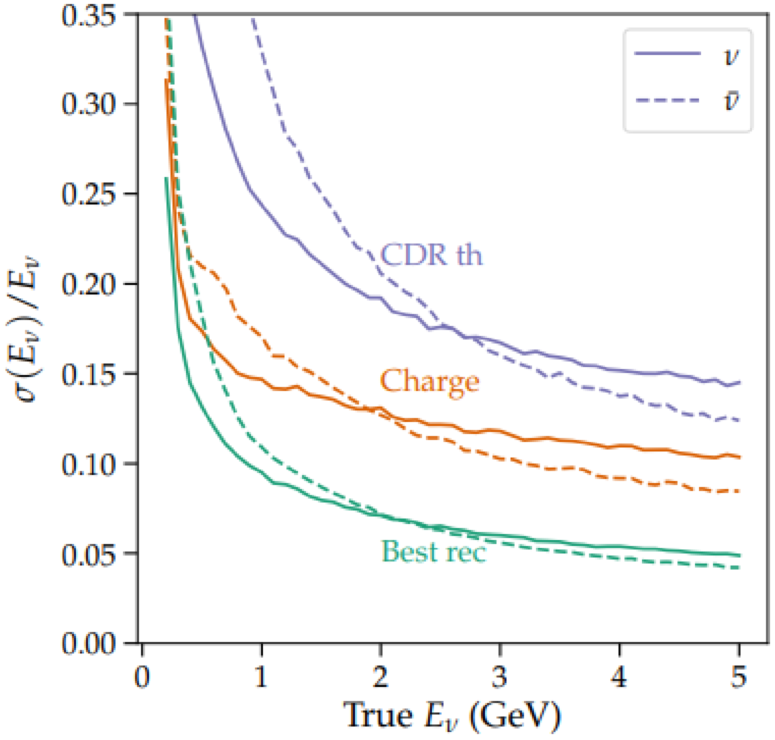
11/30/2023

Chao Zhang

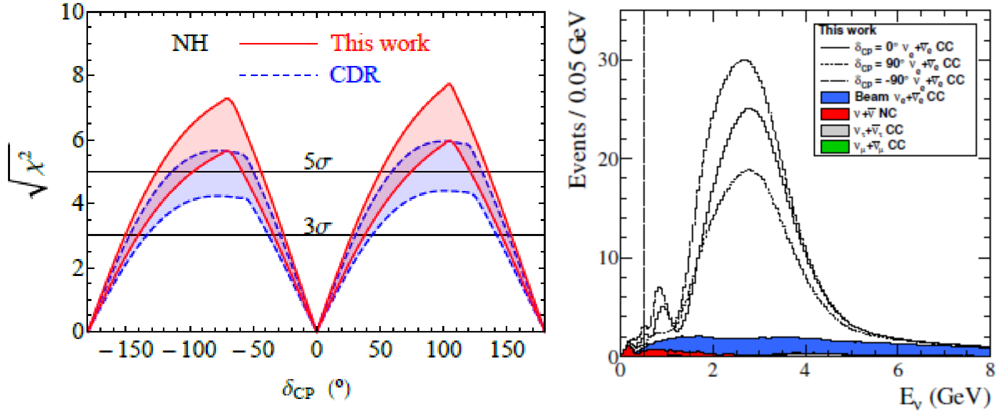
Motivation

Study how much a better PDS can improve oscillation physics

- ❑ Understand the limiting factors that affect neutrino energy resolution
  - previous study by Shirley Li and Friedland
- ❑ Study if photon detection can help neutrino energy reconstruction and improve energy resolution
  - Calorimetry from light
  - Timing from PDS to improve particle ID
- ❑ Study the CP sensitivity gain if neutrino energy resolution can be improved
  - Two recent talks at the DUNE collaboration meeting (Marta Torti , Luis Gustavo), but more study is needed
- ❑ Study the requirement for an optimized APEX design



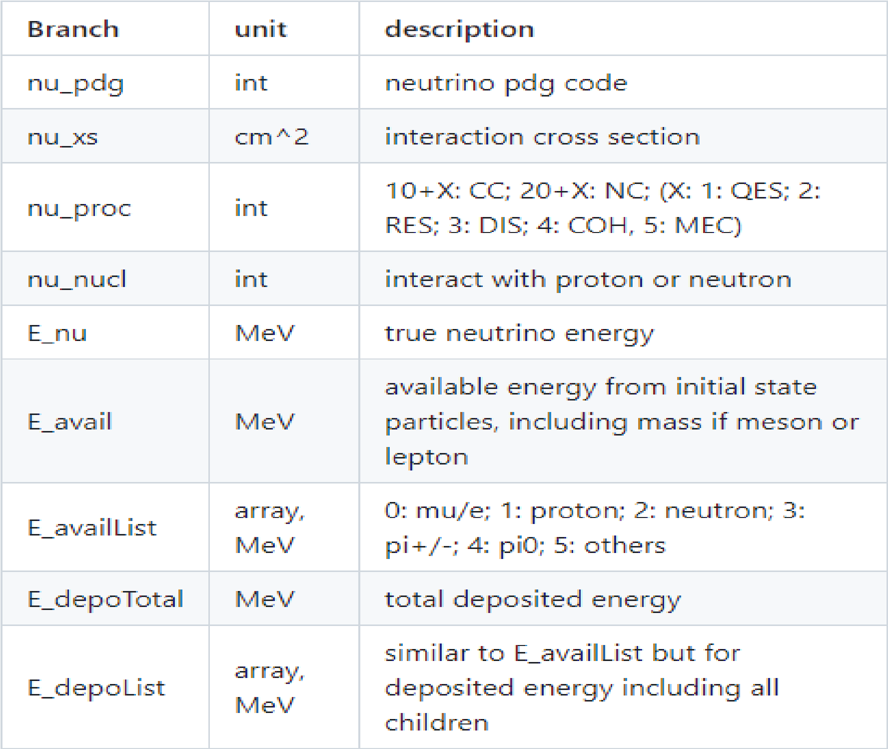
Phys. Rev. D 99, 036009 (2019)



JHEP 09 (2016) 030: δE~8%

Simulation Setup

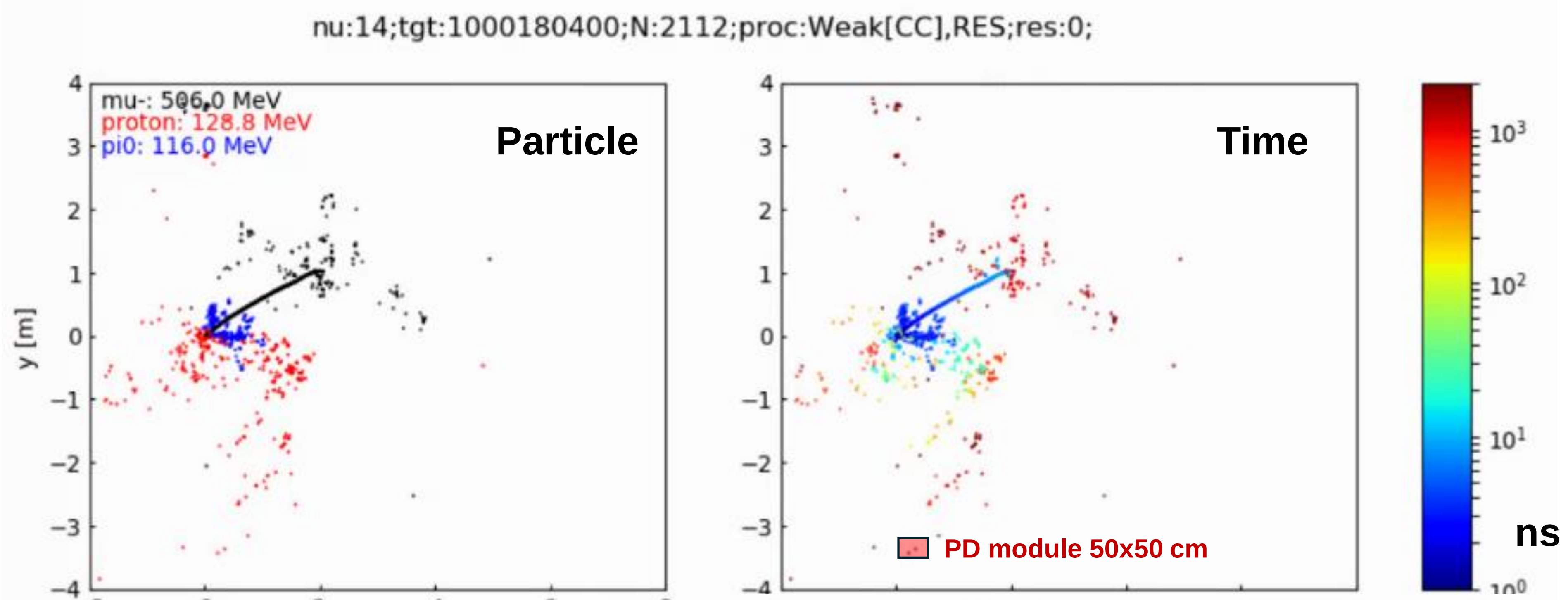
- Use Genie and edep-sim to simulate mono-energetic neutrino CC events from 0.5 – 5 GeV.
  - 1000 events per 0.5 GeV
  - Record all truth-level information including dE/dx along the tracks
  - Geometry: LArBath (a huge LAr Volume so that all events are contained)
- Simulation setup instruction on FNAL clusters (from Wei Shi)
- Further analysis code: https://github.com/czczc/PyEdep
- Next slides will show a few event displays



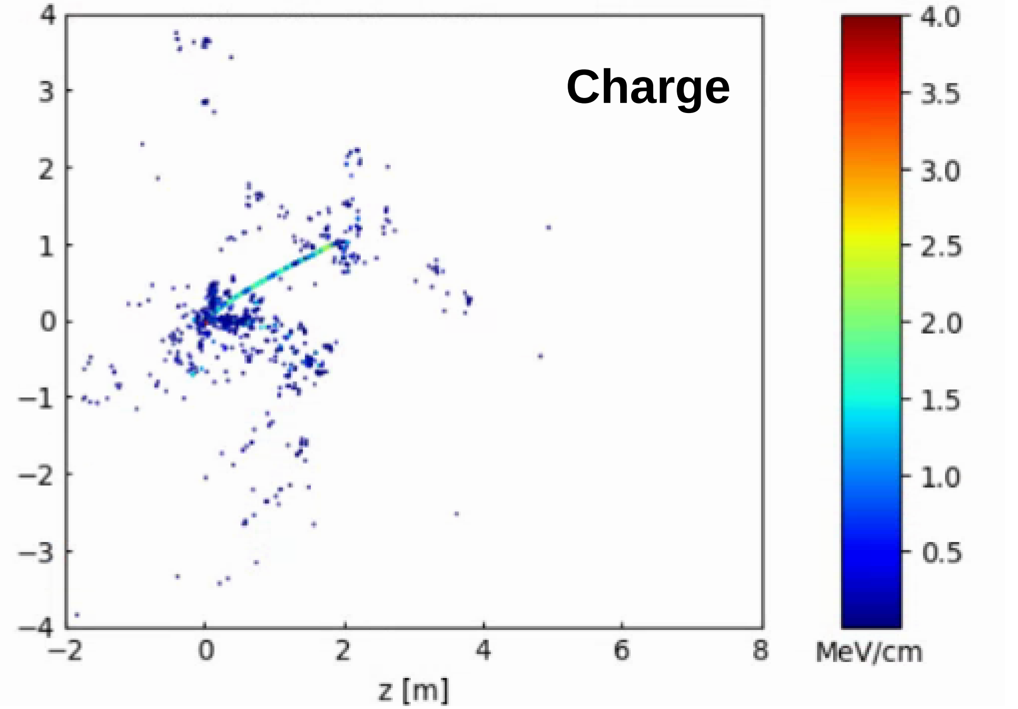
Branch	unit	description
nu_pdg	int	neutrino pdg code
nu_xs	cm^2	interaction cross section
nu_proc	int	10+X: CC; 20+X: NC; (X: 1: QES; 2: RES; 3: DIS; 4: COH, 5: MEC)
nu_nucl	int	interact with proton or neutron
E_nu	MeV	true neutrino energy
E_avail	MeV	available energy from initial state particles, including mass if meson or lepton
E_availList	array, MeV	0: mu/e; 1: proton; 2: neutron; 3: pi+/-; 4: pi0; 5: others
E_depoTotal	MeV	total deposited energy
E_depoList	array, MeV	similar to E_availList but for deposited energy including all children

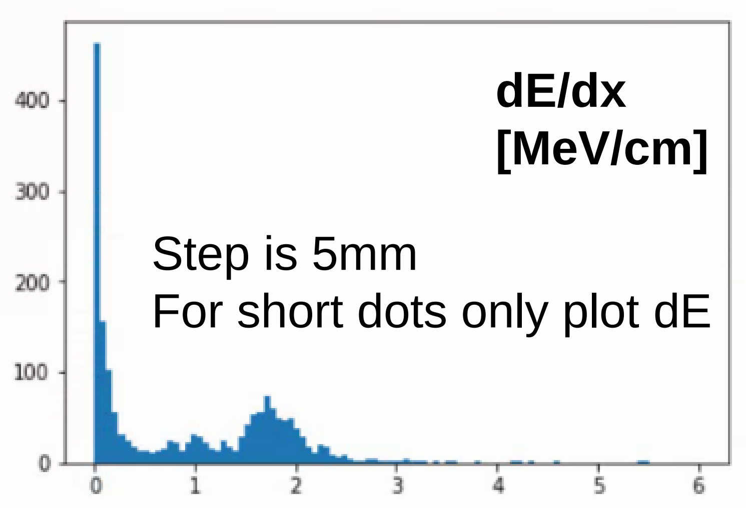
Possible contributors to v energy resolution

- Generator models
- "Missing energy"
  - Nuclear scatter
  - Muon/pion decay
  - muon capture
  - Detection threshold
- dE/dx -> dQ/dx
- Reconstruction and PID
- Others.



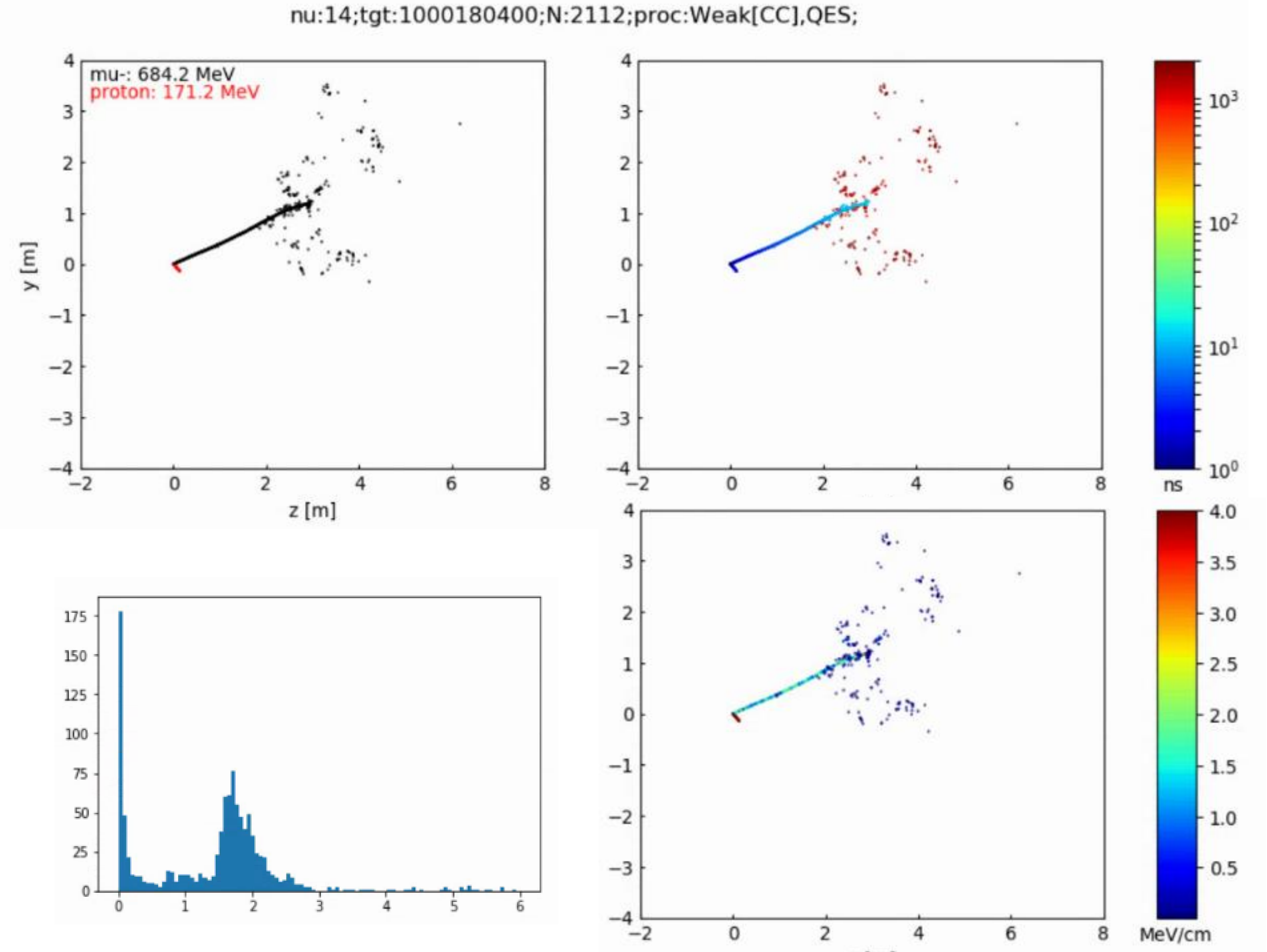
PD module 50x50 cm



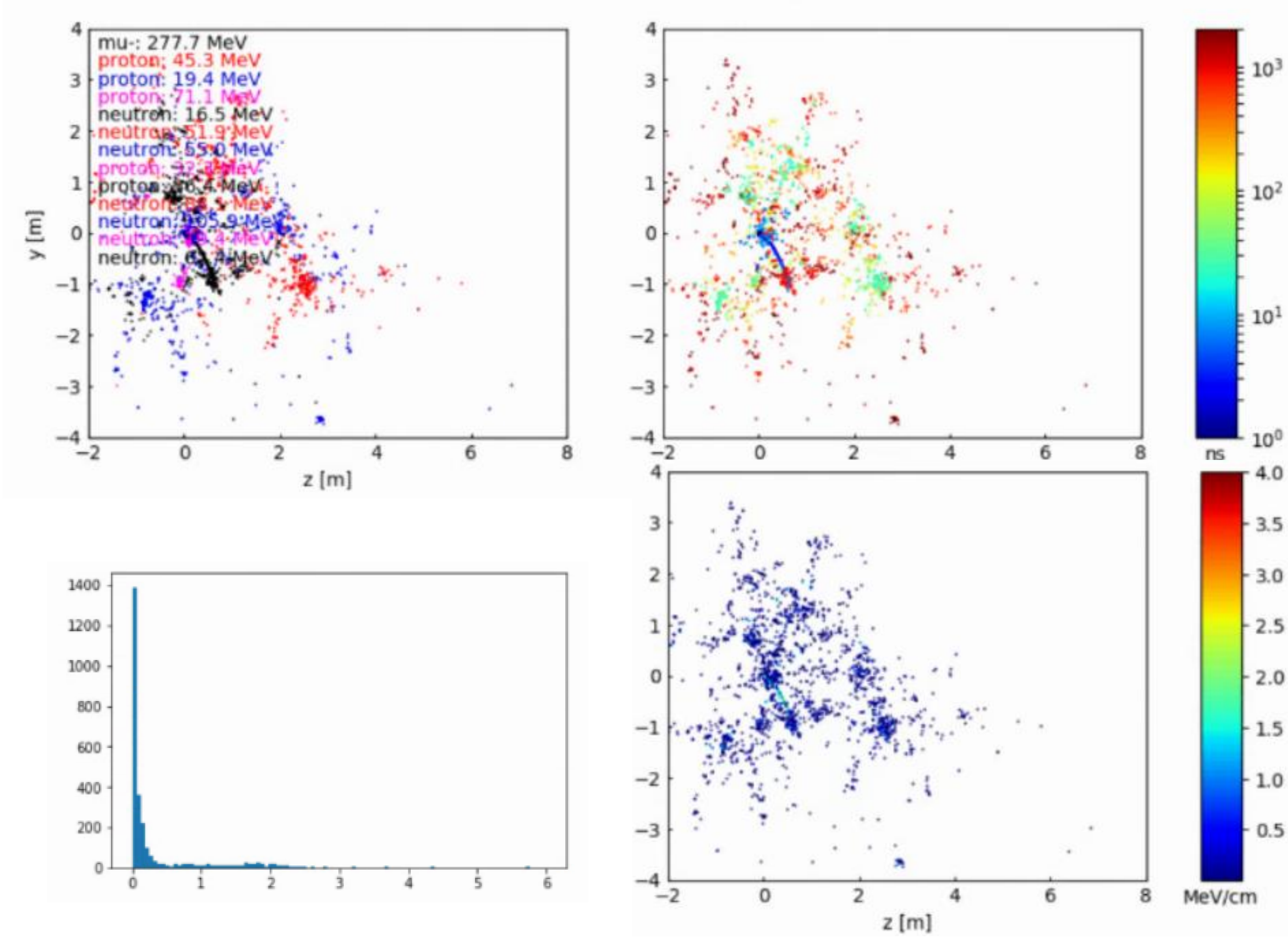


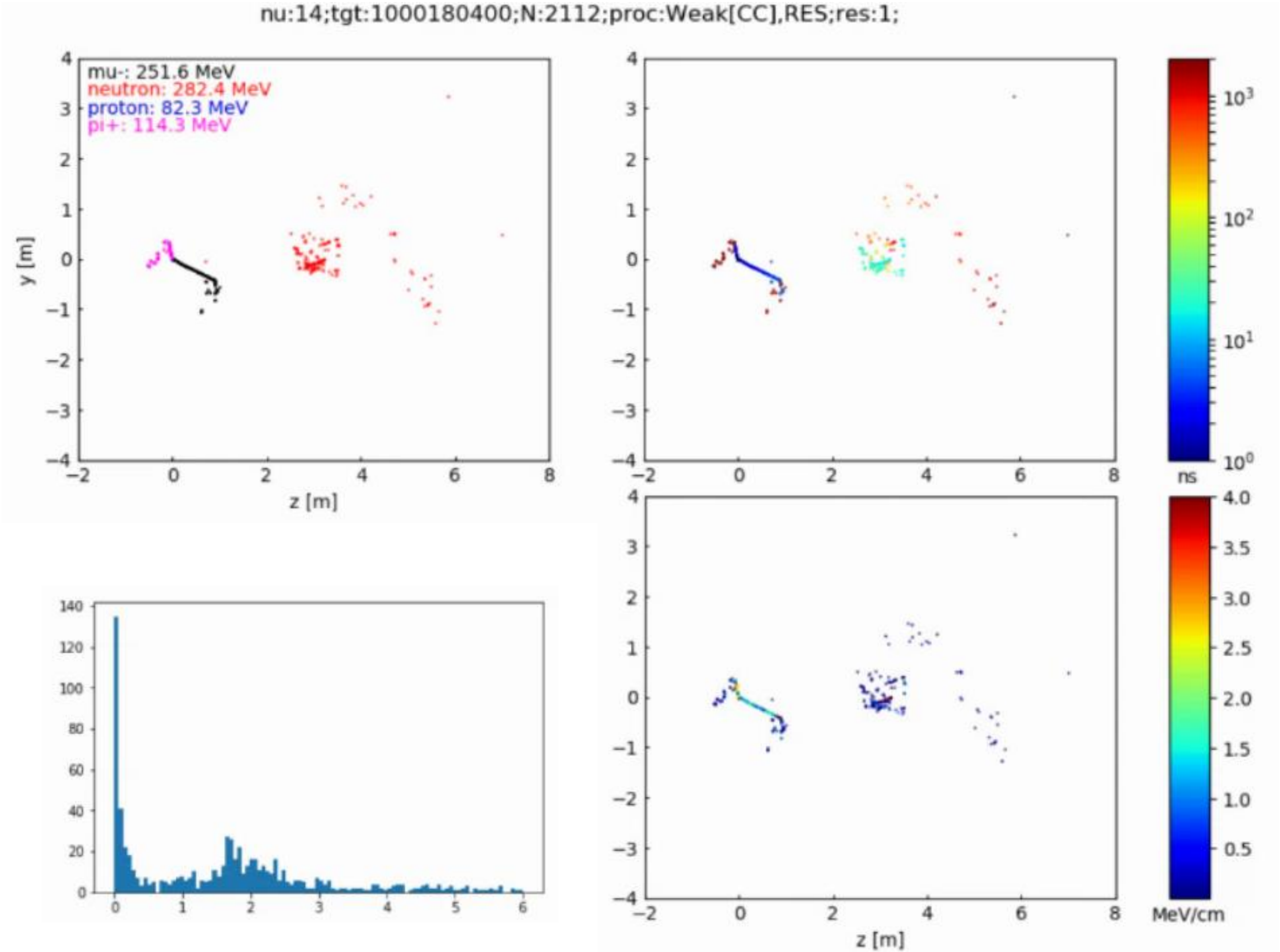
dE/dx [MeV/cm]

Step is 5mm
For short dots only plot dE


nu:14;tgt:1000180400;N:2112;proc:Weak[CC],QES;
mu-: 684.2 MeV
proton: 171.2 MeV
y [m]
z [m]
4
3
2
1
0
−1
−2
−3
−4
−2
0
2
4
6
8
10^3
10^2
10^1
10^0
ns
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
MeV/cm
175
150
125
100
75
50
25
0
1
2
3
4
5
6

nu:14;tgt:1000180400;N:2212;proc:Weak[CC],RES;res:0;



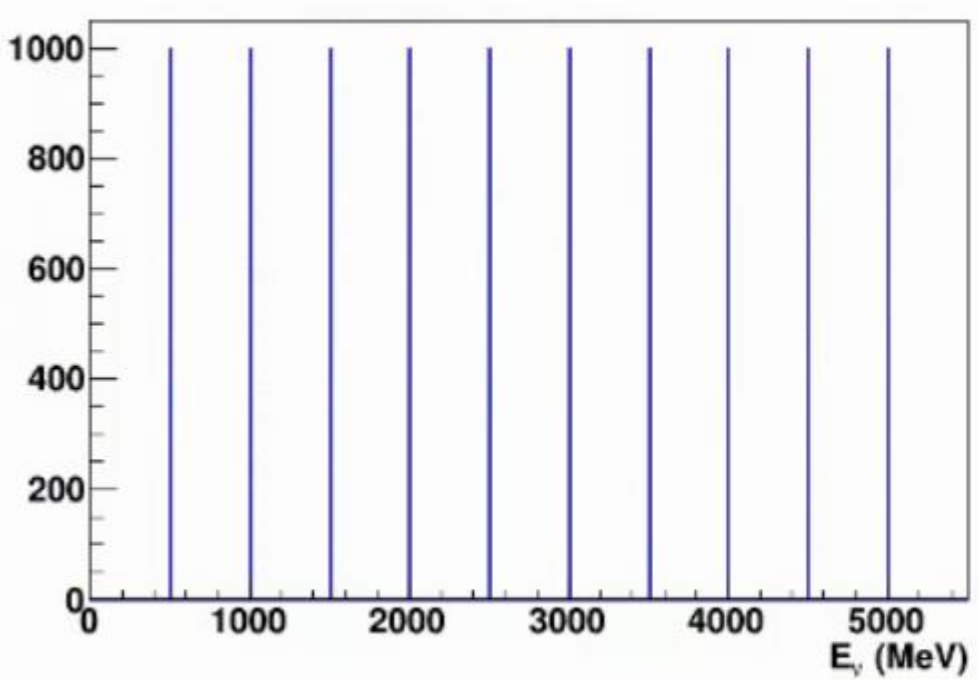

nu:14;tgt:1000180400;N:2112;proc:Weak[CC],RES;res:1;
mu-: 251.6 MeV
neutron: 282.4 MeV
proton: 82.3 MeV
pi+: 114.3 MeV
y [m]
z [m]
ns
MeV/cm
10^0
10^1
10^2
10^3
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

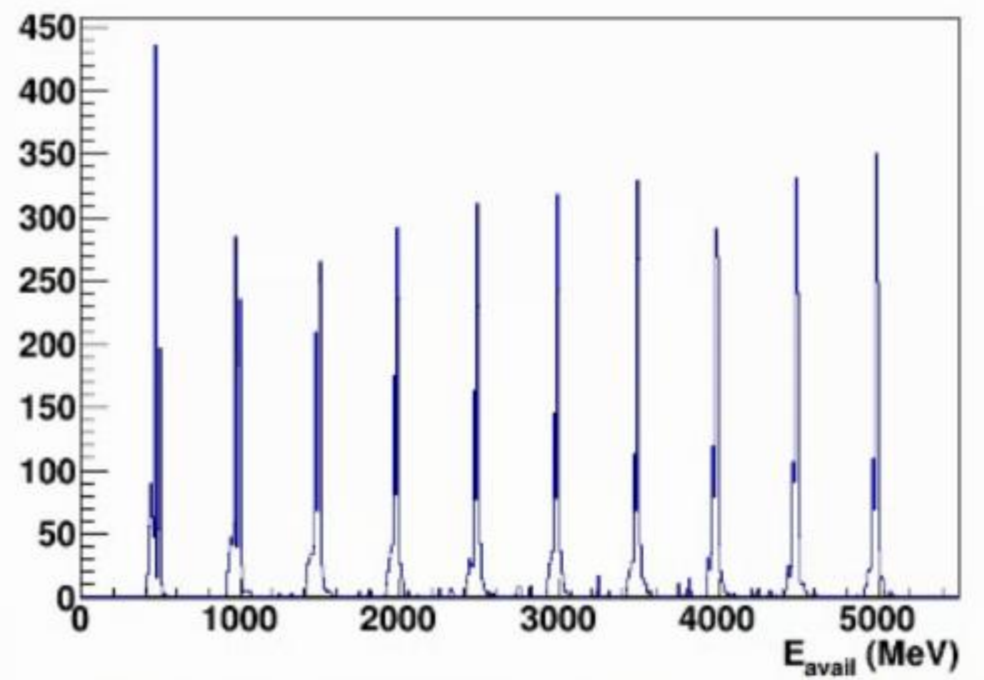
Observations

- ❑ Time distribution has more features than charge distribution
  - Tracks near vertex, EM showers (pi0): prompt (<few ns):
  - Fast track propagation: ~4 m per 10 ns
  - Neutron slow down and propagation: tens of ns
  - Particle decay: muon: 2 us; pion 26 ns
  - Muon capture: could emits neutrons that result in delayed components
- ❑ Using time distribution can help neutrino energy reconstruction in the following ways:
  - Distinguish dots between EM and Neutron interactions, so that we can apply different calibration constants
  - Identify decay/capture products so that we can exclude them from calorimetry (adding back the parent mass)
  - Reconstruct the direction of particle tracks for background rejection

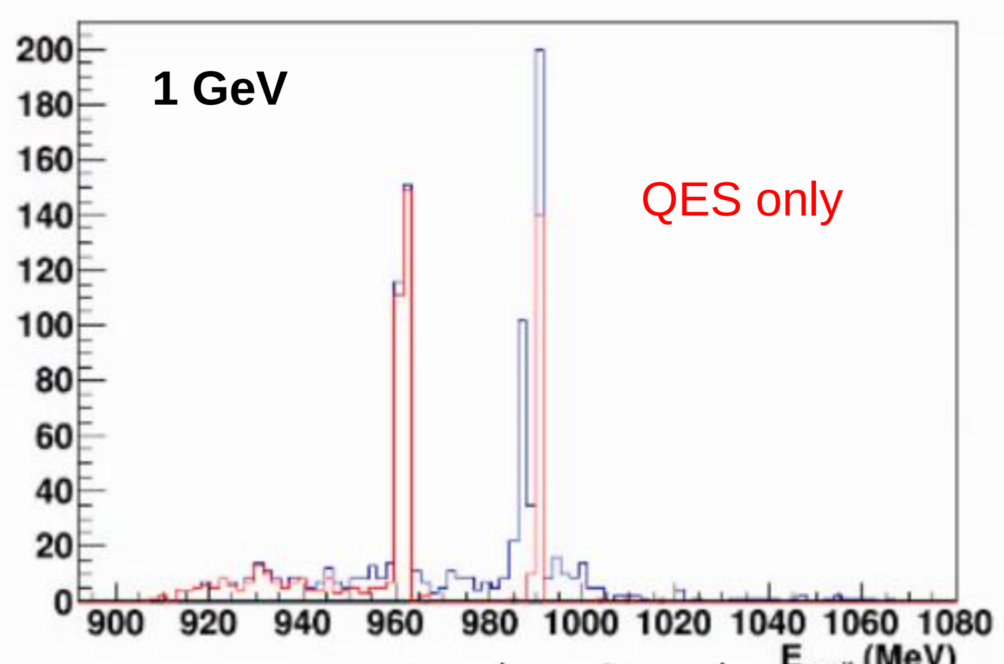
Nuclear smearing at Generator level

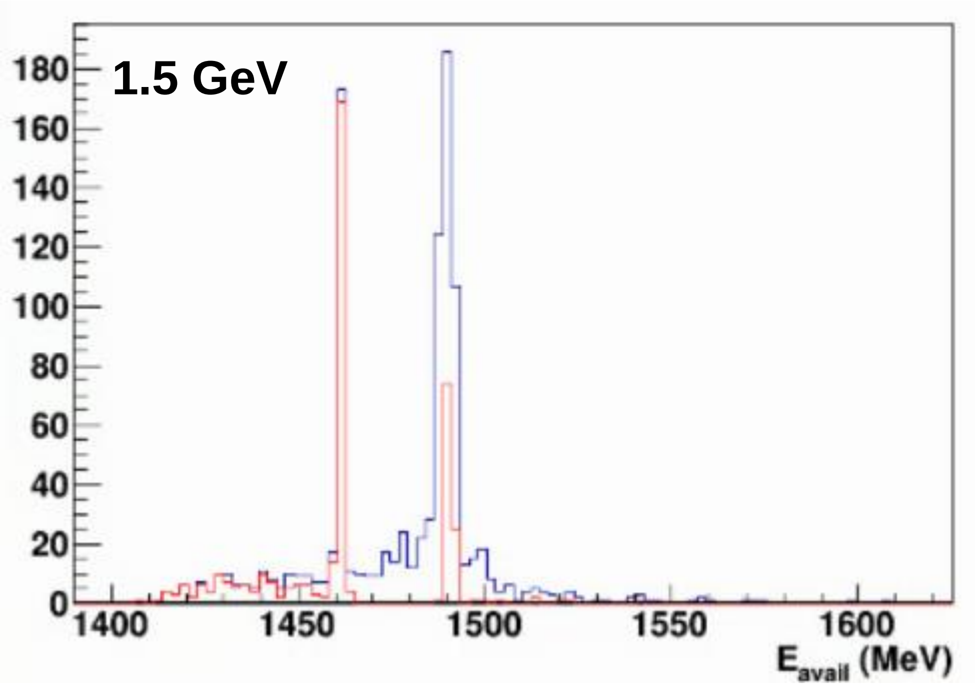
- ❑ Neutrino energy
  - ▪ 1000 events per 0.5 GeV
- ❑ Available energy:
  - ▪ KE for: p, n, nuclei
  - ▪ Total energy (KE + mass) for leptons and mesons: mu, e-, pi, pi0, etc
  - ▪ Smearing can be caused by
    - o binding energy
    - o intra-nuclear transport
  - ▪ Observation: smearing is less than tens of MeV, and is highest at 1.5 GeV where RES process is the highest

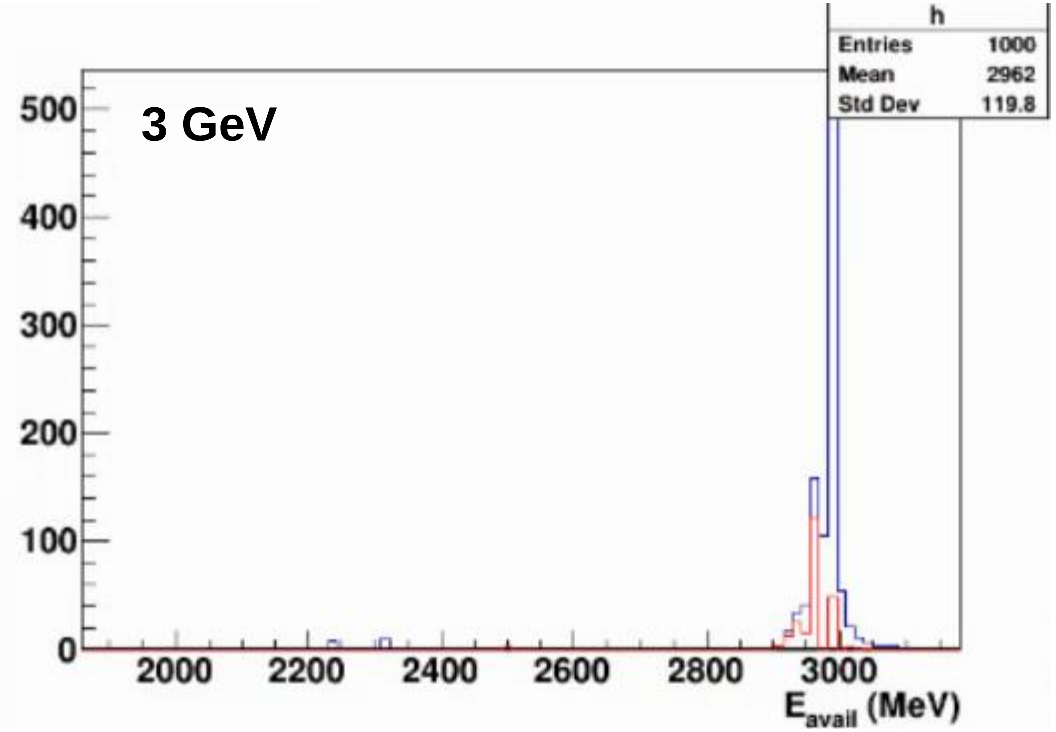




- ❑ Zoom in: available energy appears to have to 2 peaks, which come from the Quasi Elastic Scattering process
  - ▪ reasons unclear yet, may be related to the Genie generator

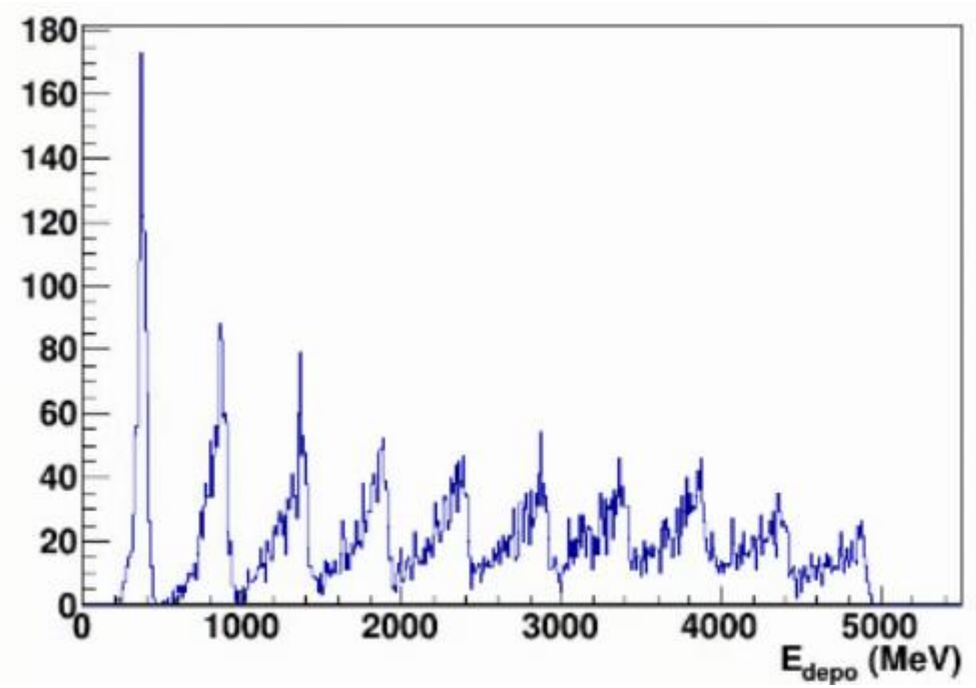


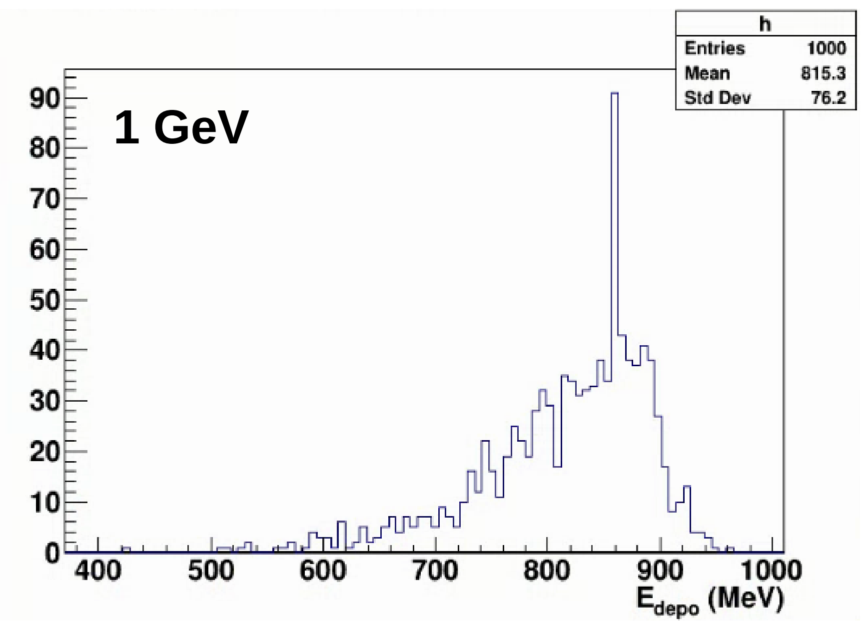


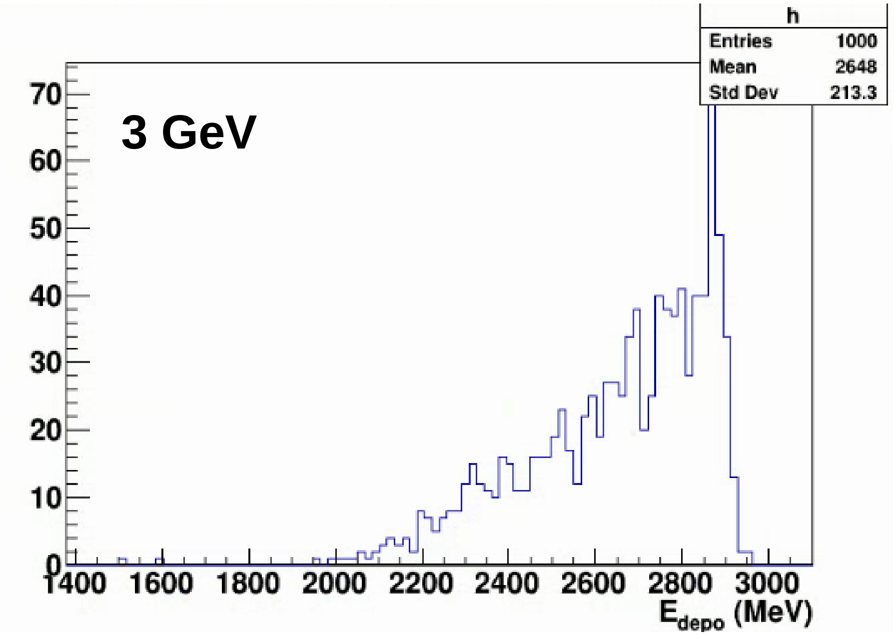


Smearing at energy deposition level

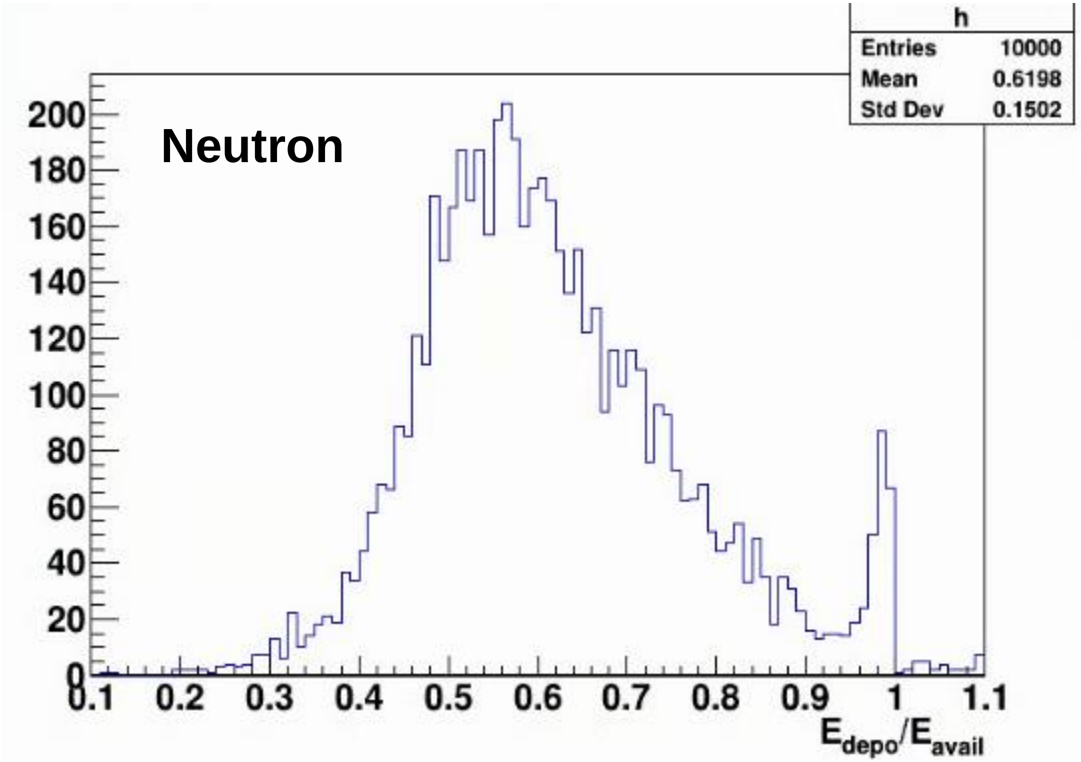
- ❑ Deposited energy:
  - All energy deposition including all daughter particles (scatter, decay, de-excitation, etc.)
  - Observation: large smearing (~10%) with a long low-energy tail.

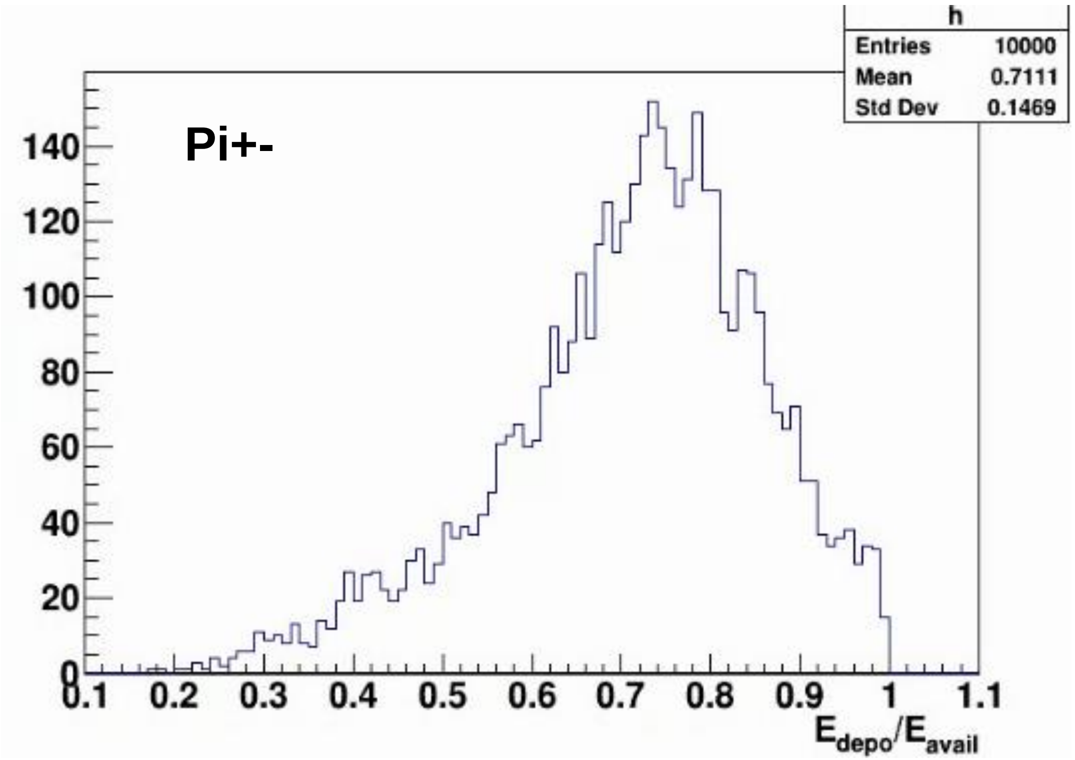




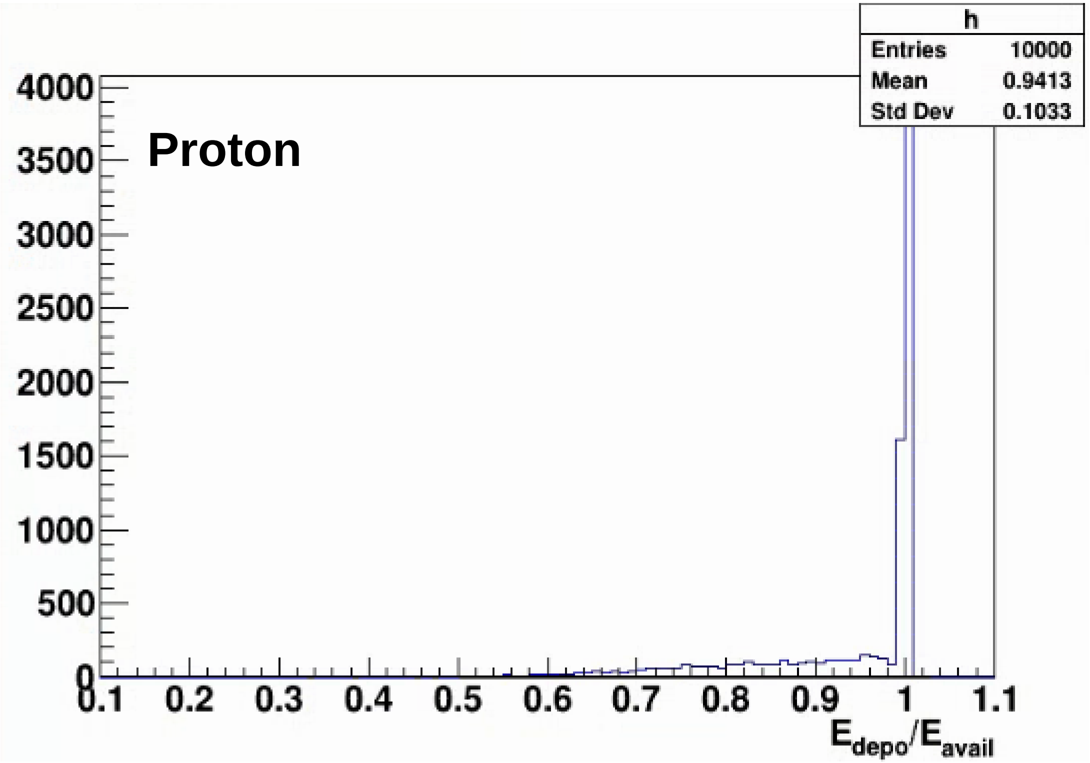


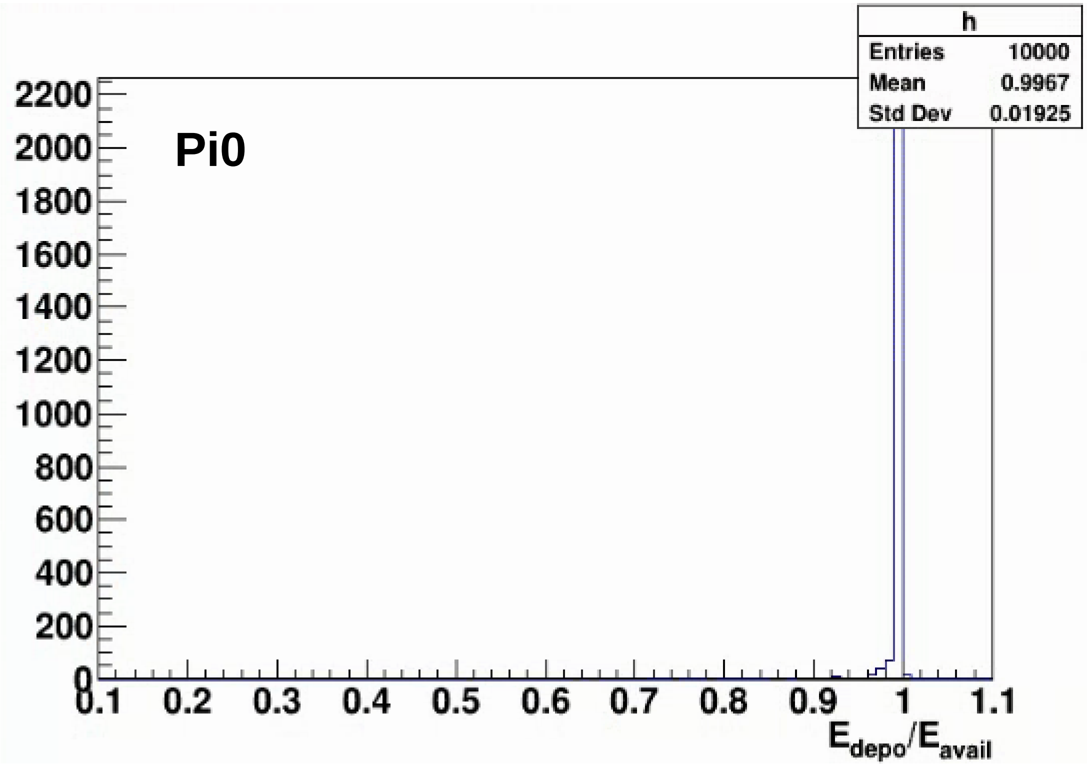
- ❑ Cause of the low energy tail
  - Energy lost to nucleus during nuclear scattering: neutrons, pions
  - Ratio of E_depo / E_avail appears to be largely independent of initial energy: can be used as a calibration constant if there is PID

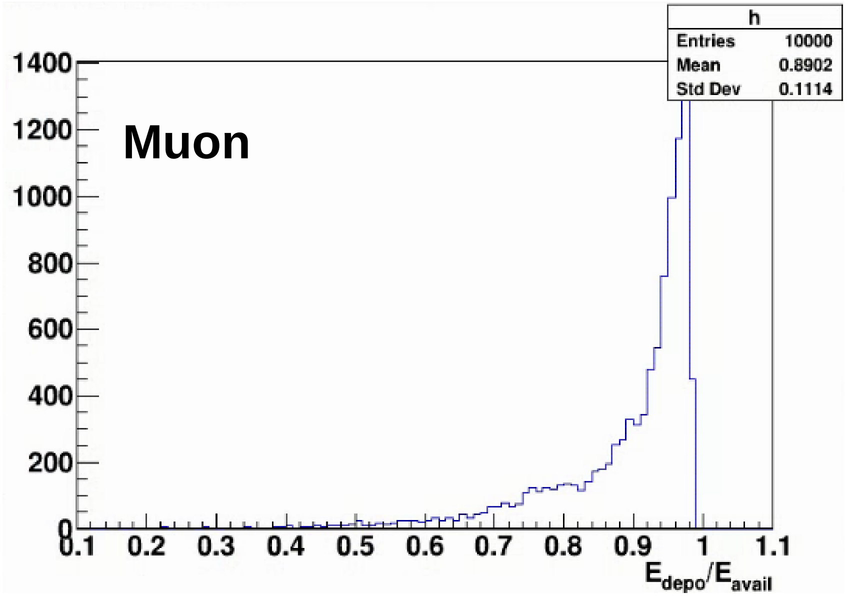




Some of Pion’s tail is also from decay/capture

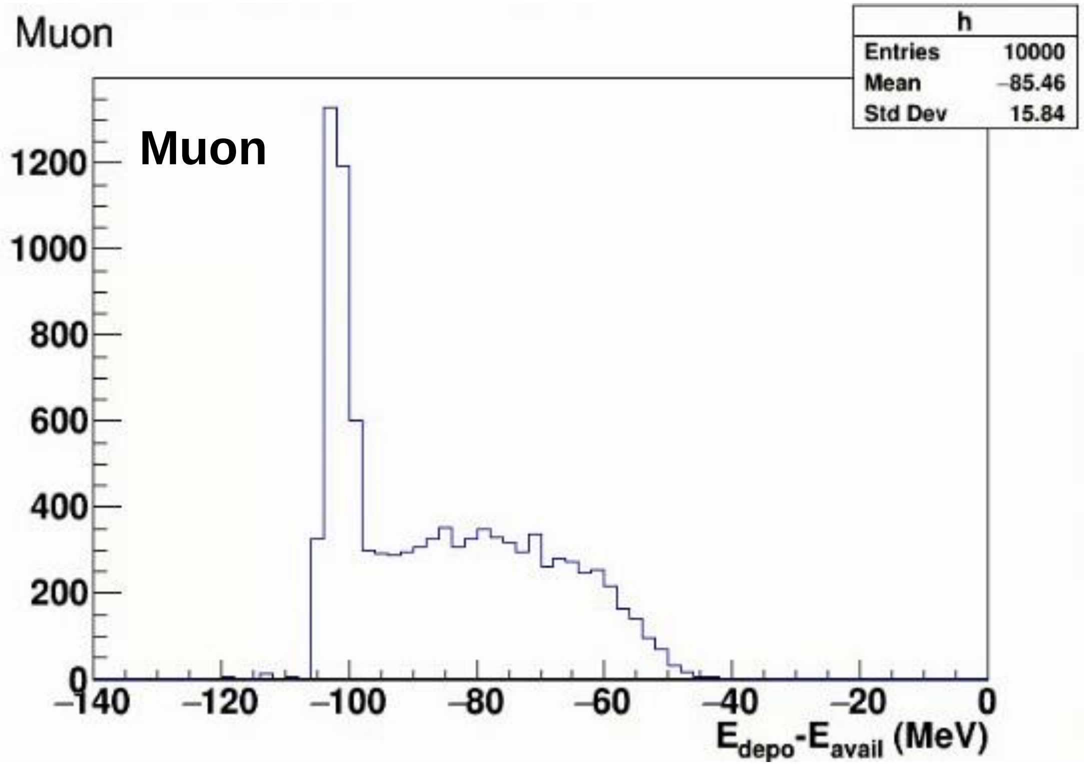


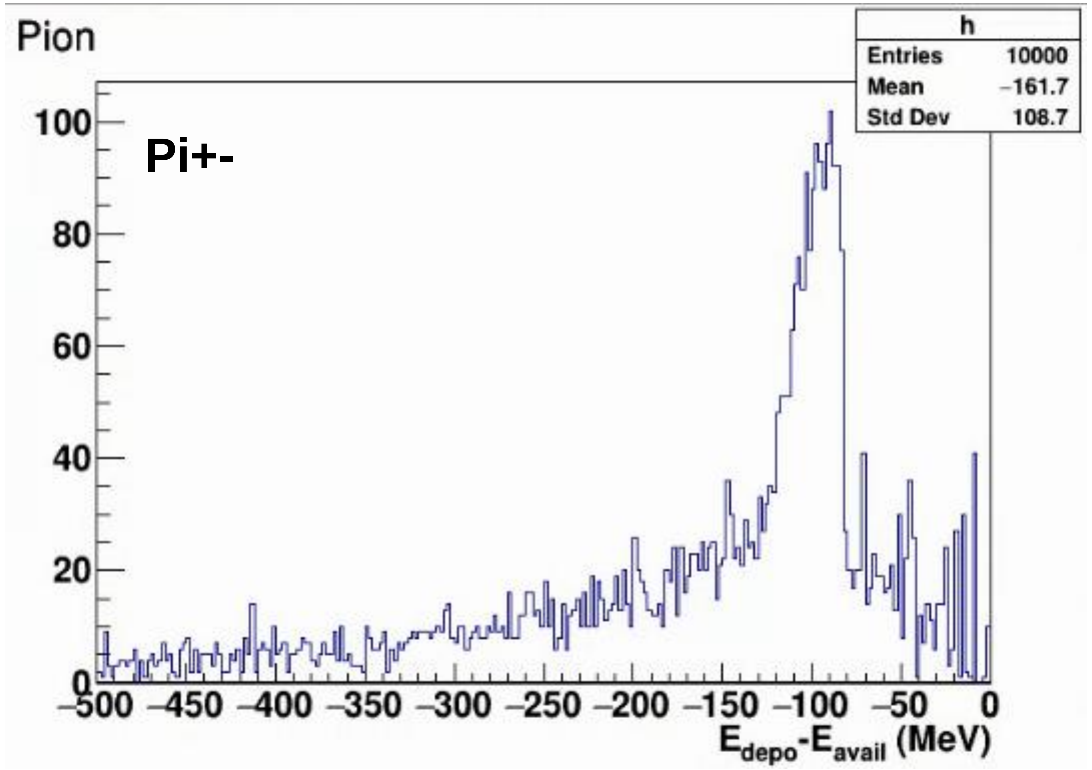




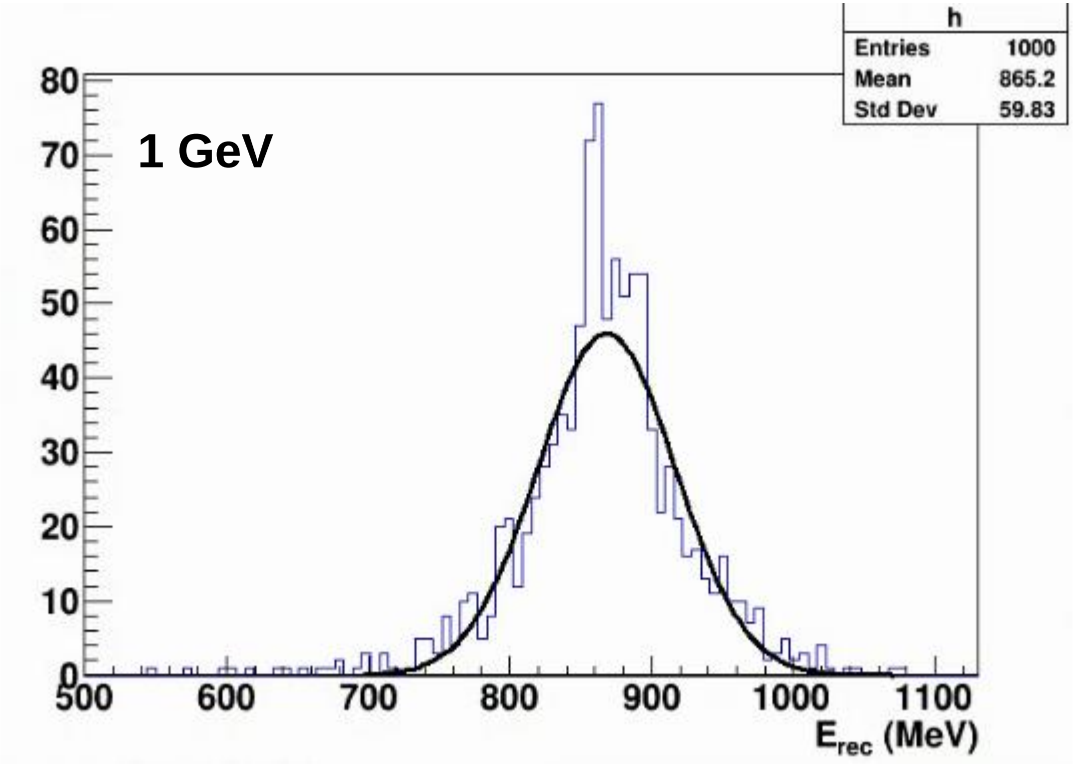
Muon’s tail is from decay/capture, see next slide

- Cause of the low energy tail
  - Energy lost to neutrinos during decay: muons, pions
  - Energy lost from muon- capture

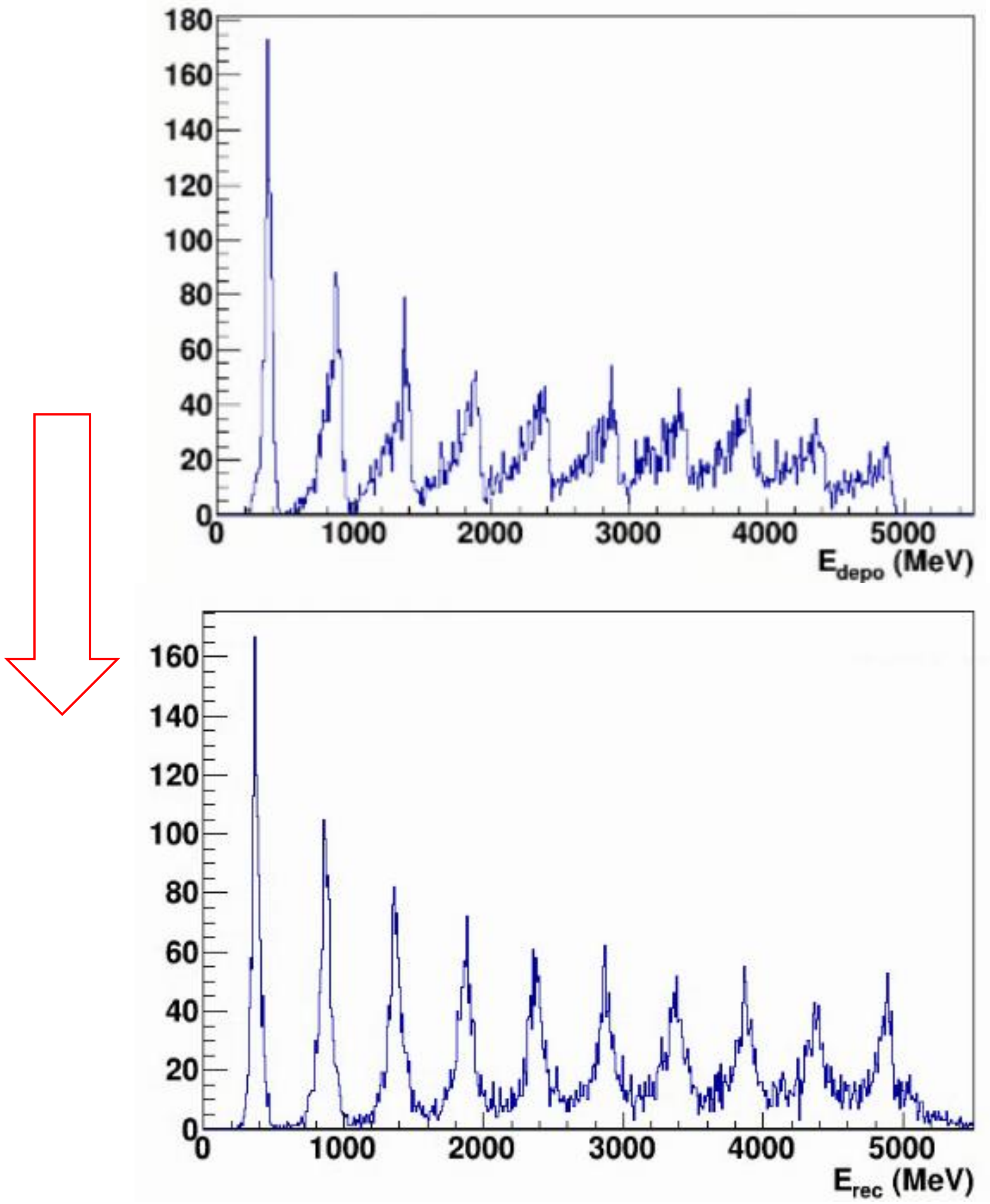


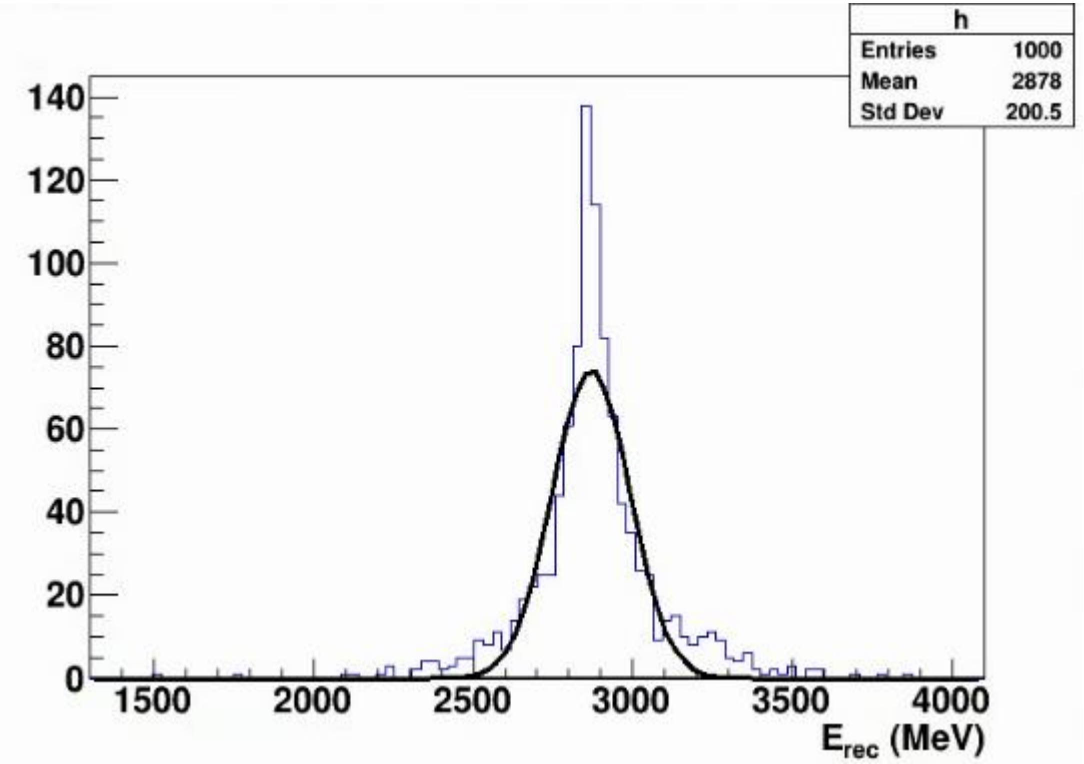


- Simple reconstruction
  - Neutron: scale E_{depo} by 1/0.62
  - Pi+-: scale E_{depo} by 1/0.71



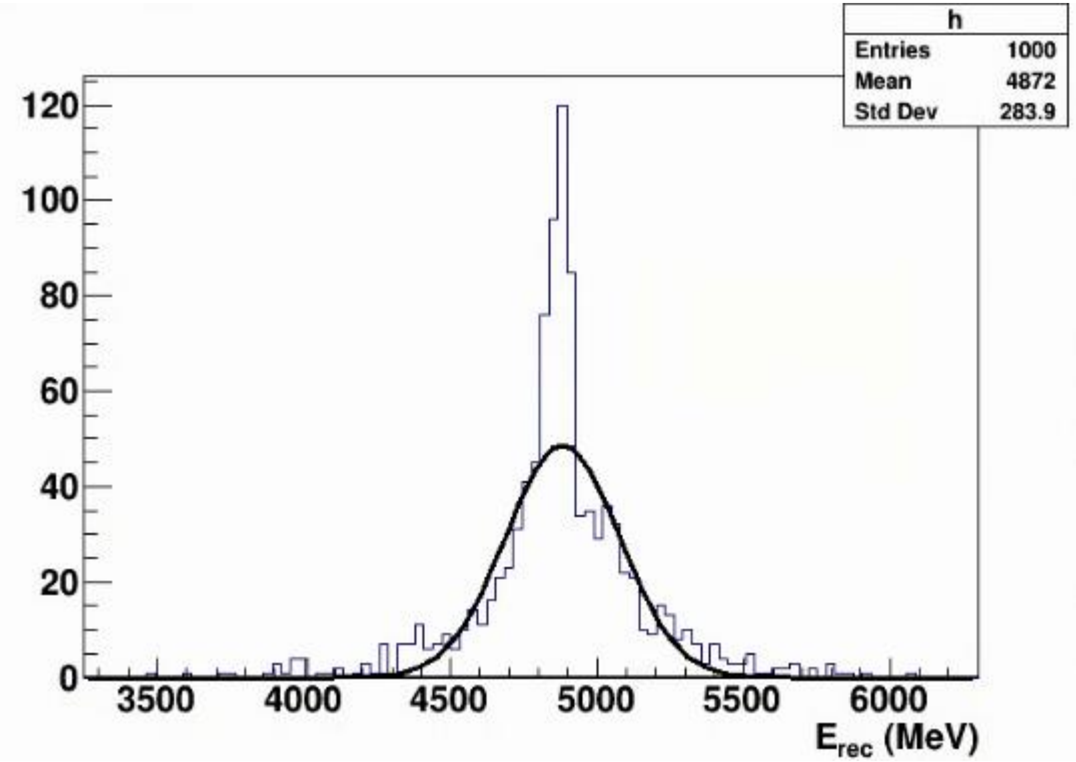
Fitted sigma = 50 MeV, ~5%





3 GeV
Fitted sigma = 120 MeV, ~7%

5 GeV
Fitted sigma = 200 MeV, ~9%

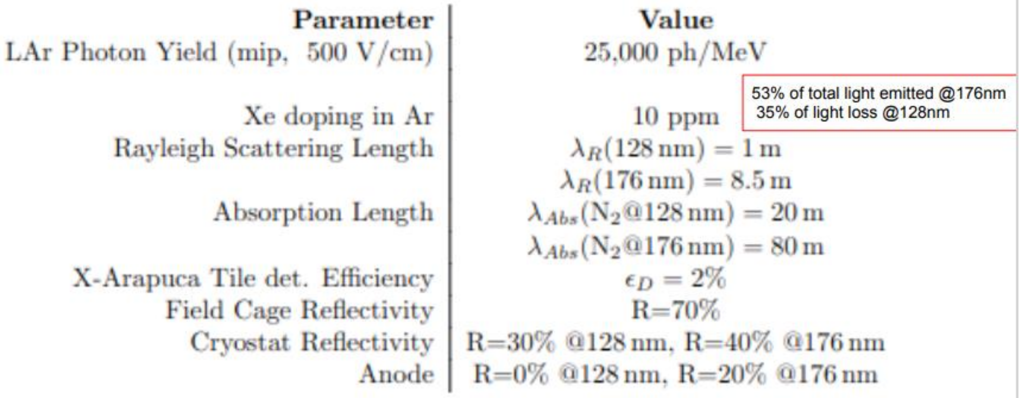


Next Steps

- ☐ Correct decay products: improve resolution
- ☐ Apply thresholds: worsen resolution
- ☐ Apply dE/dx -> dQ/dx: worsen resolution
- ☐ Apply dE/dx -> dL/dx: improve resolution

- ☐ Finally
  - Estimate “realistically achievable energy resolution” with photon information
  - If significantly better than TDR (~13%), study the improvement on CP sensitivity.

Thoughts on PDS timing requirement and optical simulation



Parameter	Value
LAr Photon Yield (mip, 500 V/cm)	25,000 ph/MeV
Xe doping in Ar	10 ppm
Rayleigh Scattering Length	$\lambda_R(128\,\mathrm{nm}) = 1\,\mathrm{m}$ $\lambda_R(176\,\mathrm{nm}) = 8.5\,\mathrm{m}$
Absorption Length	$\lambda_{Abs}(\mathrm{N_2}@128\,\mathrm{nm}) = 20\,\mathrm{m}$ $\lambda_{Abs}(\mathrm{N_2}@176\,\mathrm{nm}) = 80\,\mathrm{m}$
X-Arapuca Tile det. Efficiency	$\epsilon_D = 2\%$
Field Cage Reflectivity	R=70%
Cryostat Reflectivity	R=30% @128 nm, R=40% @176 nm
Anode	R=0% @128 nm, R=20% @176 nm

53% of total light emitted @176nm
35% of light loss @128nm

- ❑ LAr (doped with LXe) property
  - Scintillation time, fast and slow components
  - Rayleigh scattering
  - Absorption
  - Reflection from detector material
- ❑ PDS timing
  - Single photon time response -> t0 resolution
    - SiPM response, photon propagation inside the PDS module
  - Multiple photons: multiple-pulse separation
    - Sampling frequency
  - Module granularity