Calibration with the Pulsed Neutron Source

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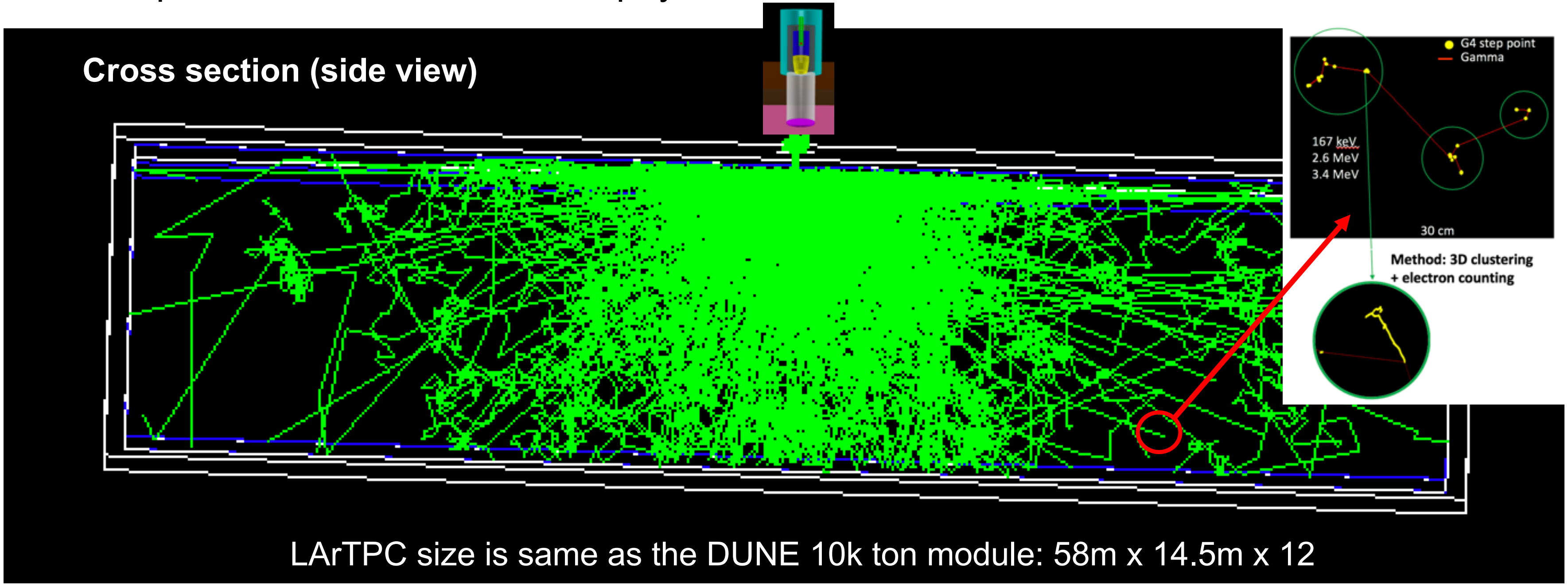
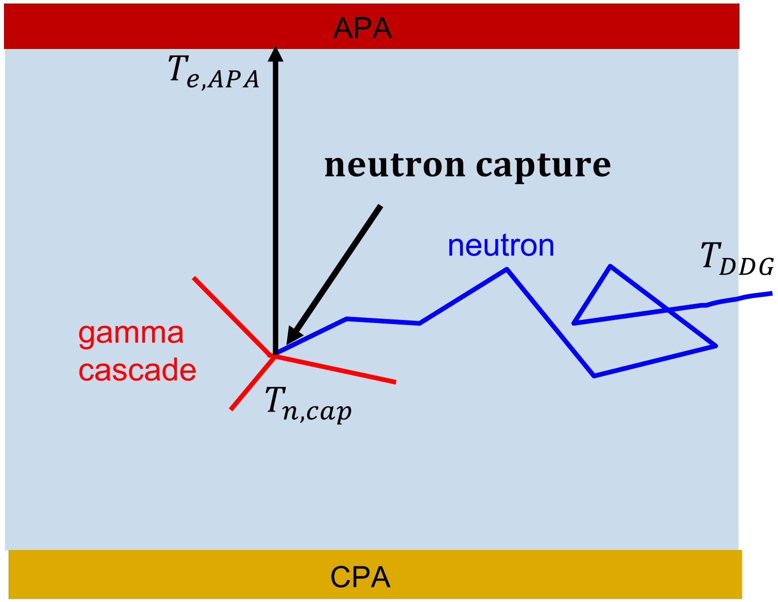
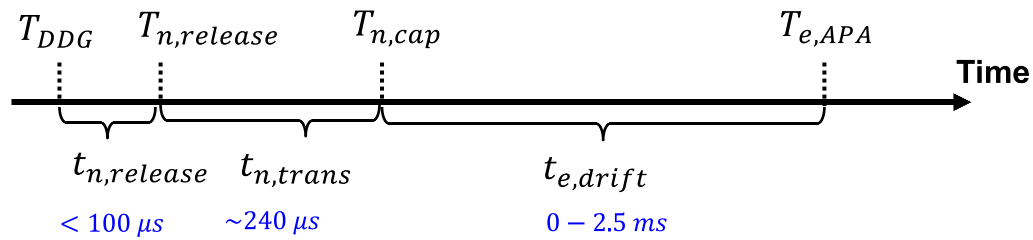
Introduction

- The Pulsed Neutron Source (PNS) is one of the main calibration systems for DUNE far detector.
  - Use DD generator to produce 2.5 MeV primary neutrons.
  - Can be deployed externally outside the cryostat stainless steel membrane
  - Can produce 6.1 MeV gamma cascade through neutron capture on 40-Ar
  - Can be used to study detector response to low-energy interaction. Relevant to supernova and solar neutrino physics.



What Can We do with the PNS?



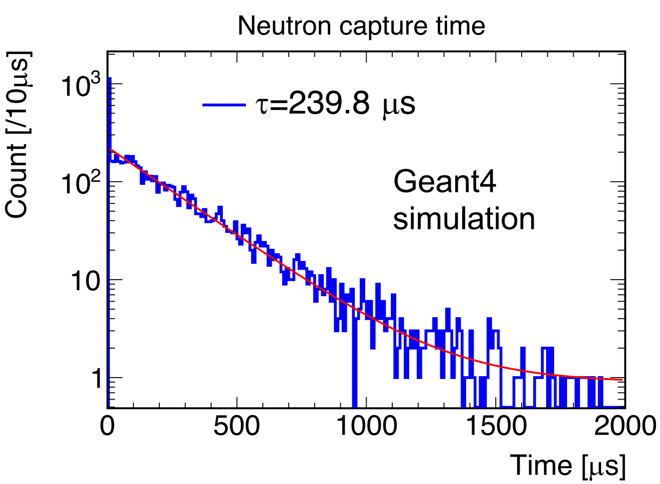


Scenario1: Rough t_0 provided by DDG. Position bias due to neutron transport

$$t_{meas} = T_{e,APA} - T_{DDG} = t_{n,release} + t_{n,trans} + t_{e,drift}$$

Scenario2: Precise t_0 provided by PDS. No position bias

$$t_{meas} = T_{e,APA} - T_{n,cap} = t_{e,drift}$$

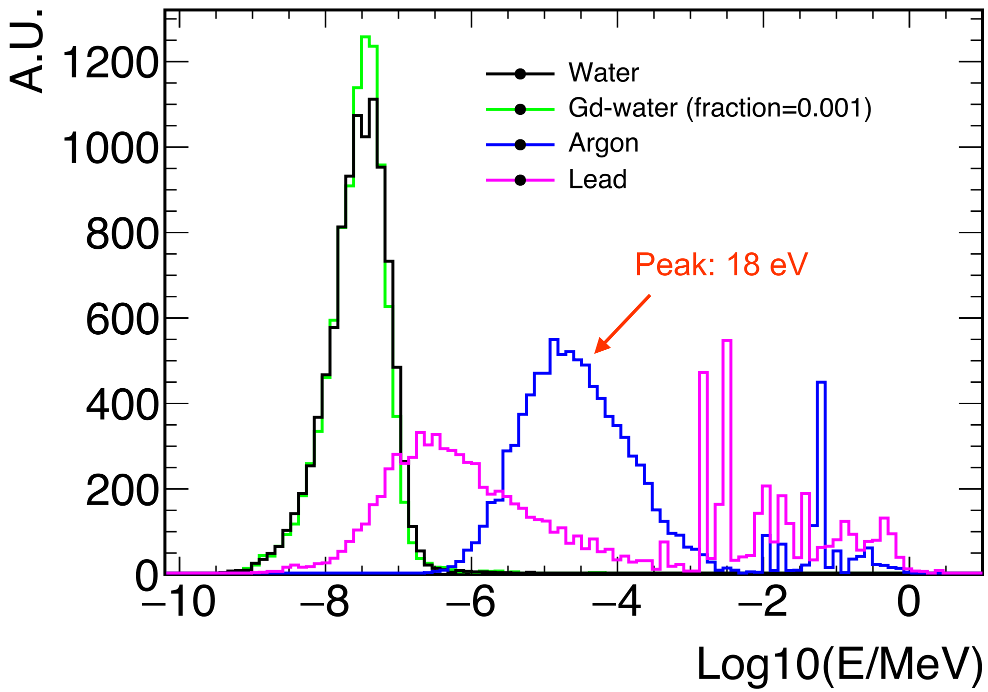


Neutron capture time is never measured

1. **Energy scale and resolution**
   - 6.1 MeV fixed energy as "standard candle'
   - Wide-spread neutrons for uniformity scan in space and time
2. **Electron lifetime in active TPC**
   - Extracted from the fit to $Q_{meas} = Q_{true} e^{-\frac{t_{meas}}{\tau}}$
3. **Supernova trigger efficiency**
   - Wide-spread gamma cascades mimic SN events

Are Neutrons Thermalized?

- According to simulation, the neutrons in liquid argon are not fully thermalized when they are captured: average energy is 18 eV
- The simulated energy distribution agrees with the prediction made by analytical toy models. It determines the neutron capture time in argon.
- Is it true? Need a measurement of neutron capture time

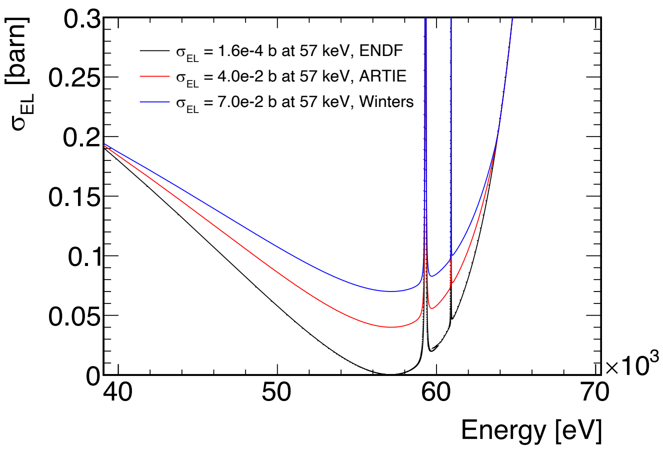


Geant4 simulation using ENDF library and NeutronHP model

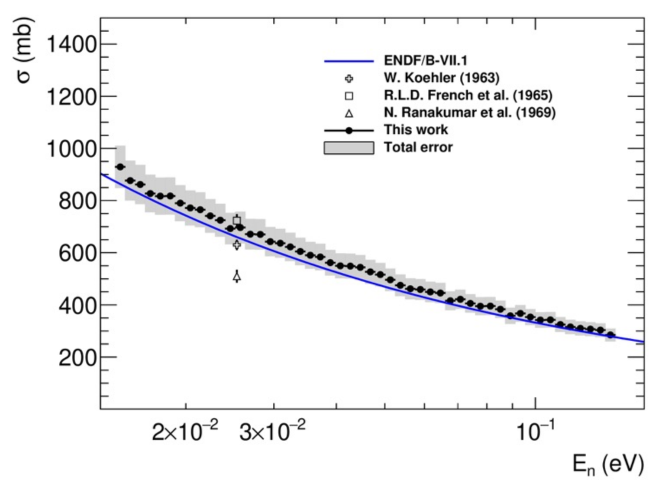
More Things to Understand

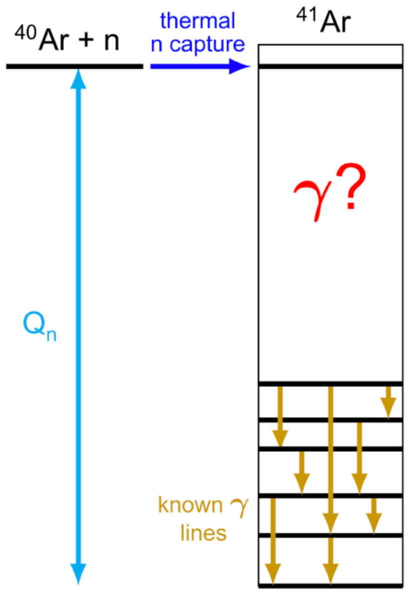
- The Geant4 simulation of neutrons is known to be not fully correct.
  - What is the neutron elastic cross-section at 57 keV?
  - Which is the correct neutron capture cross-section?
  - What are the neutron capture gammas like?
- We did measurements (ACED and ARTIE) using LANL Time-of-Flight neutrons beams (analysis is ongoing)

Dummy cross sections used in simulation



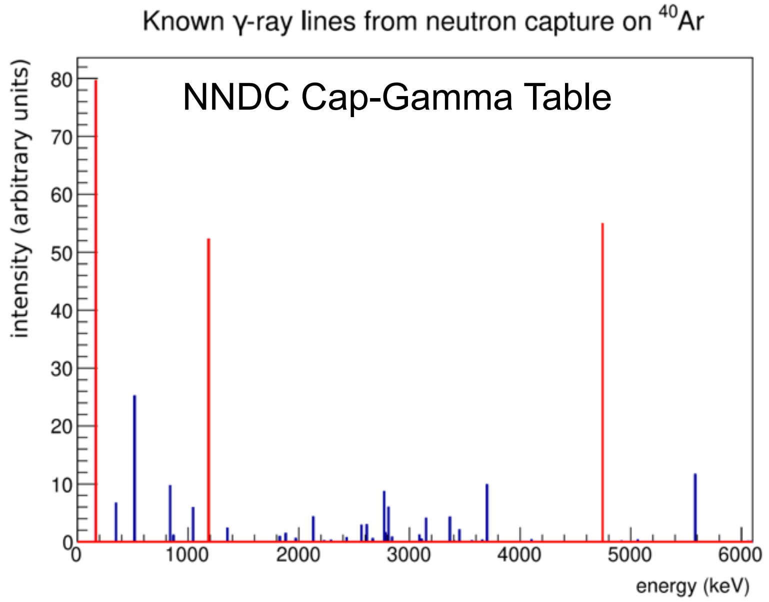
ACED measurement





Neutron Capture Gamma Generator

- In Geant/LArsoft, the neutron-argon interaction cross-sections can be changed by modifying the data files of ENDF library. We prepared different cross-section sets for simulation studies.
- The Cap-gamma physics models in Geant/Larsoft cannot reproduce the known gamma spectrum measured in previous experiments. We wrote a new physics model to generate the NNDC Cap-Gammas (only implemented for 40-Ar so far)
- The NNDC branching ratio is known to have a large uncertainty up to 15% for some lines. Need fine tuning of the branching ratios (Next step)



Cap-gamma physics model is modified to generate the NNDC gamma spectrum

First LArsoft Simulation

Event Generator

Two types of generators: (1) single neutron generator (2) gamma cascade generator

G4 simulation

Low-energy specific G4 simulation: (1) use low kinetic energy cut (2) keep shower daughters (3) use NeutronHP model (4) disable neutron tracking cut in time

Detector Simulation

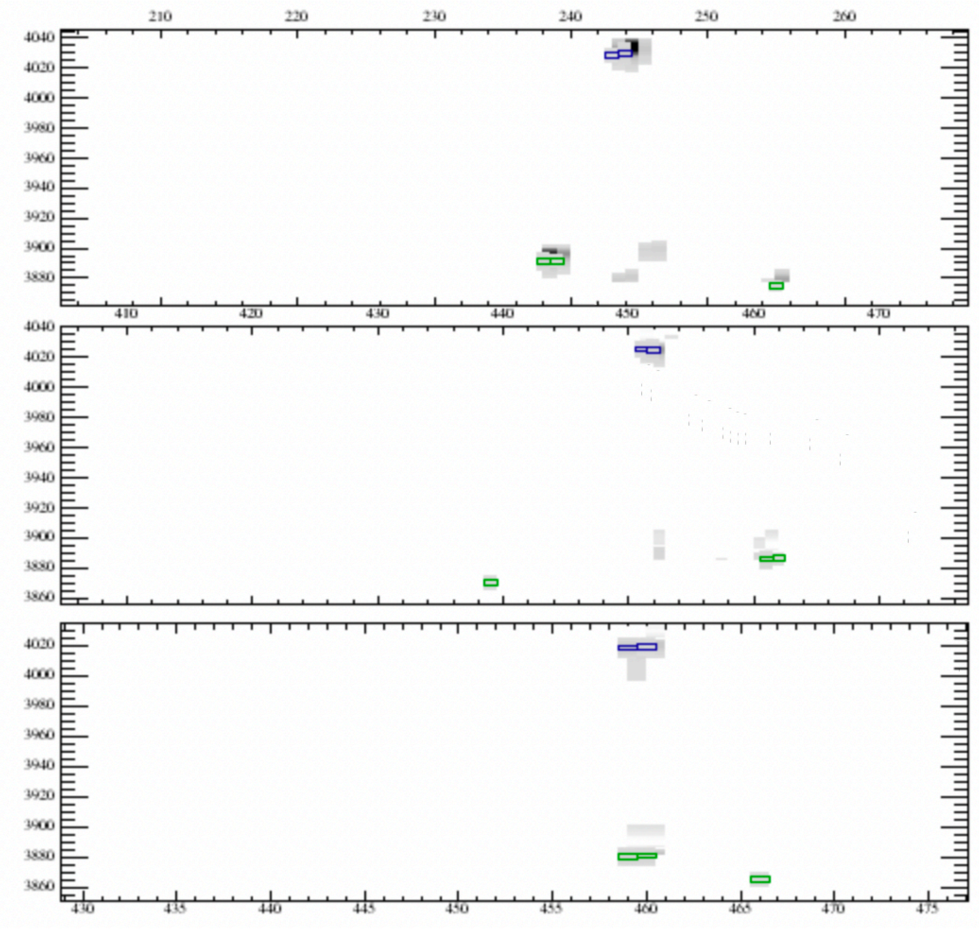
Standard detector simulation with the noise turned off

Reconstruction

Customized reconstruction: (1) use Space point solver after hit finding → 3D space points (2) use dbcluster3D for clustering

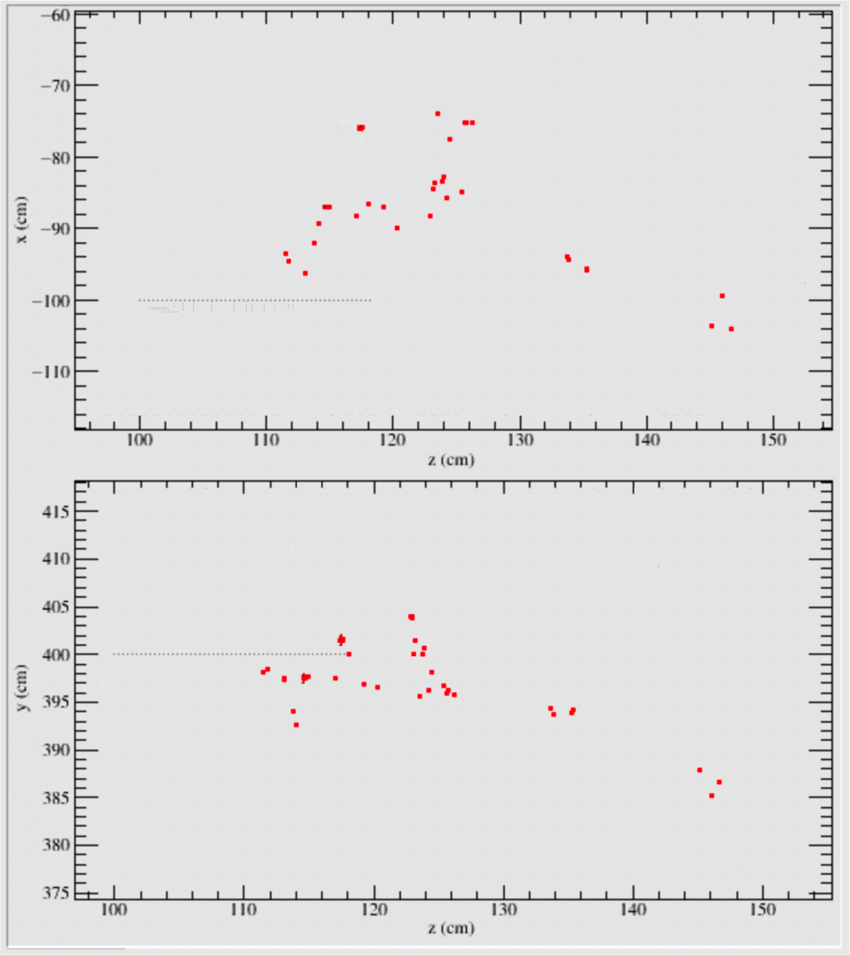
LArosft Neutron Capture Event

Time-wire display on collection plane

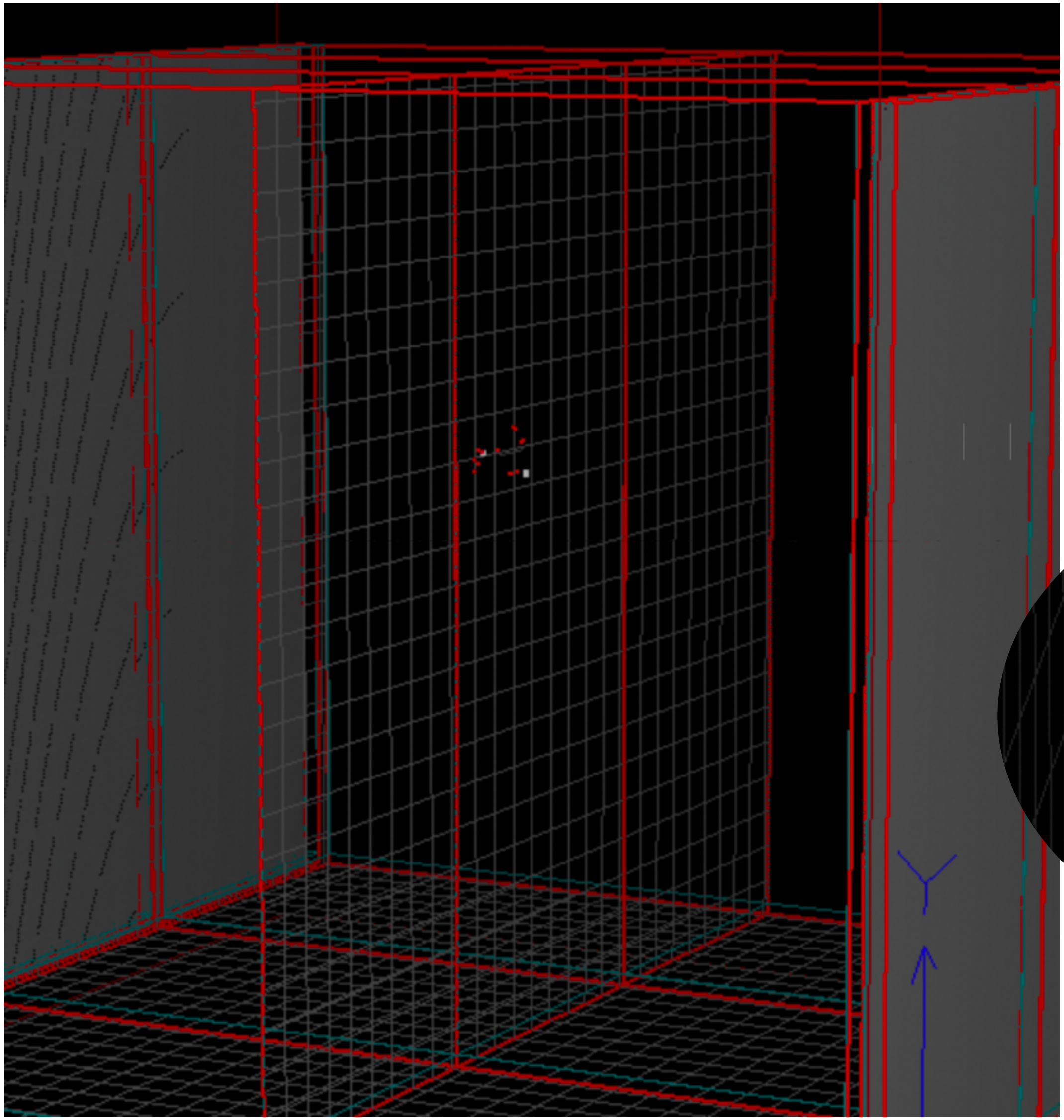


Ortho display

Dashed line: 0.025 eV neutron
Red points: MCTrueParticle

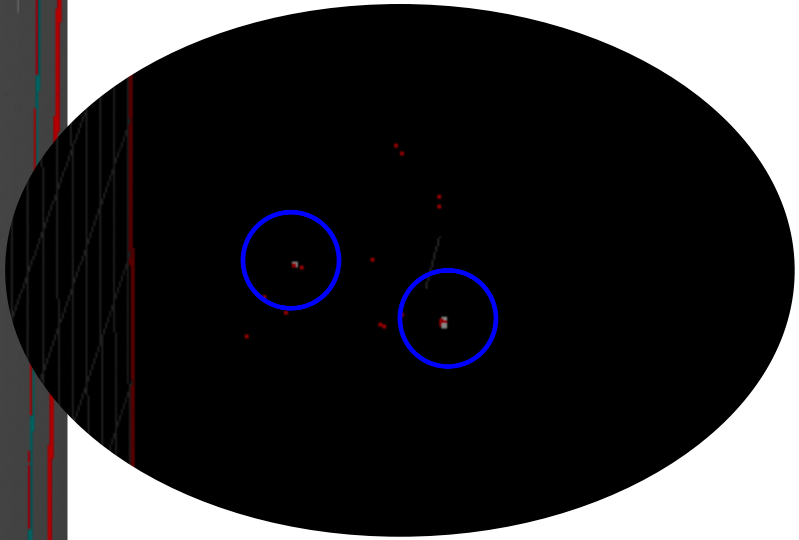


3D Space Points

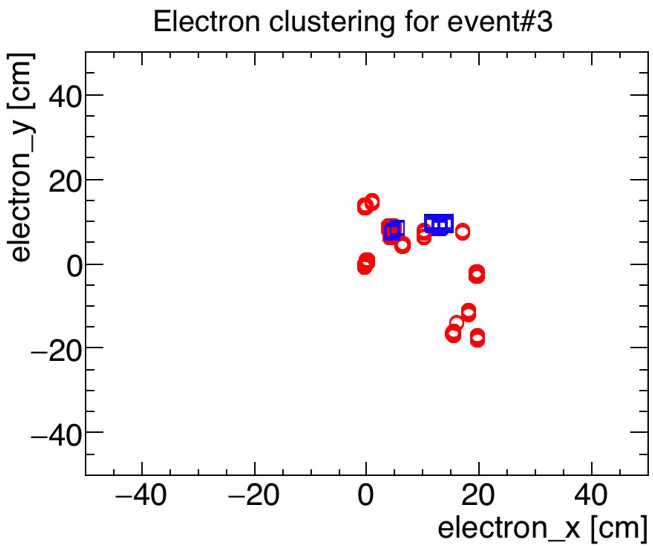


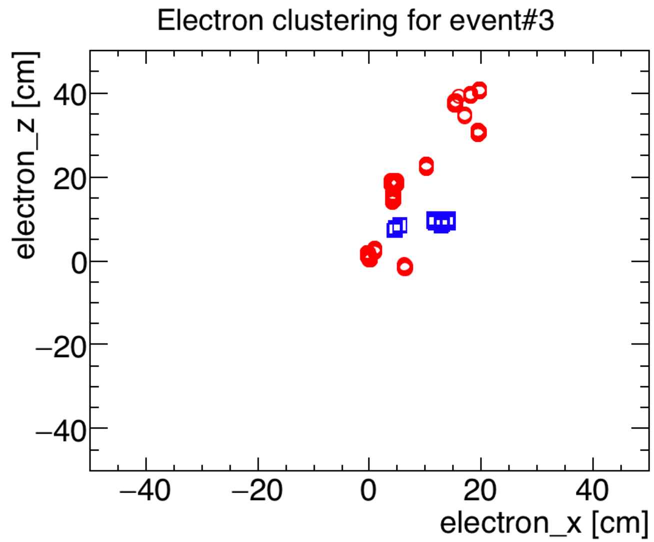
Red points: MCTruth particles

White points: Reconstructed 3D space points

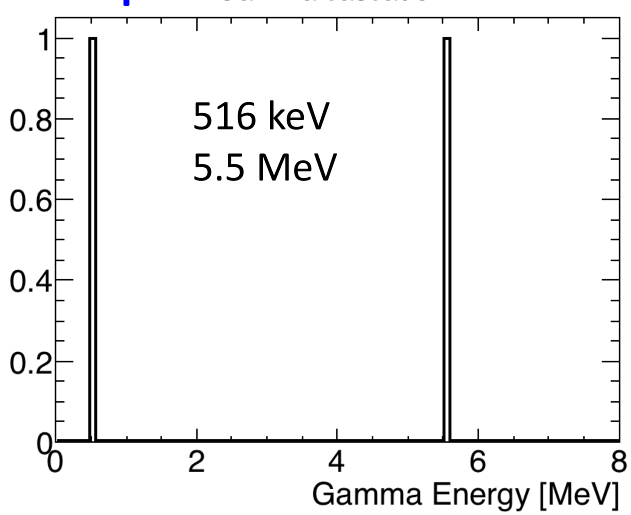


3D Clustering of MC Electrons

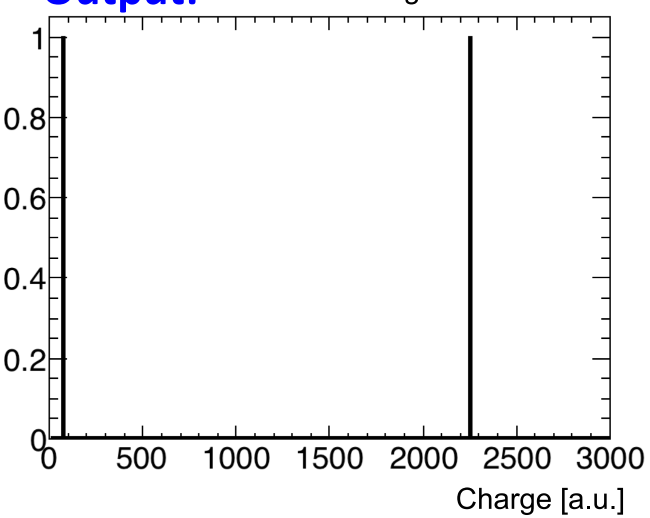




Input: Gamma cascade



Output: Clustered charge



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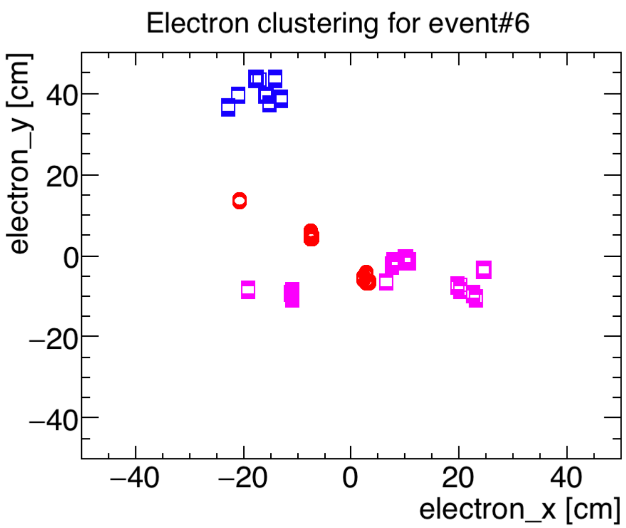
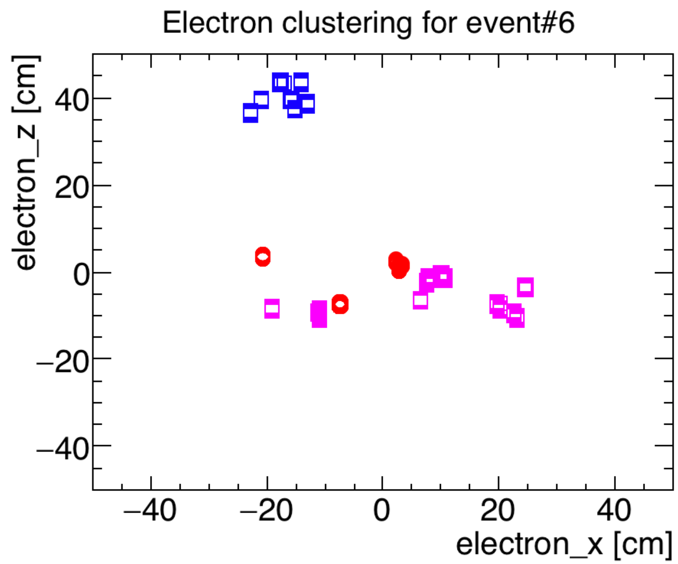
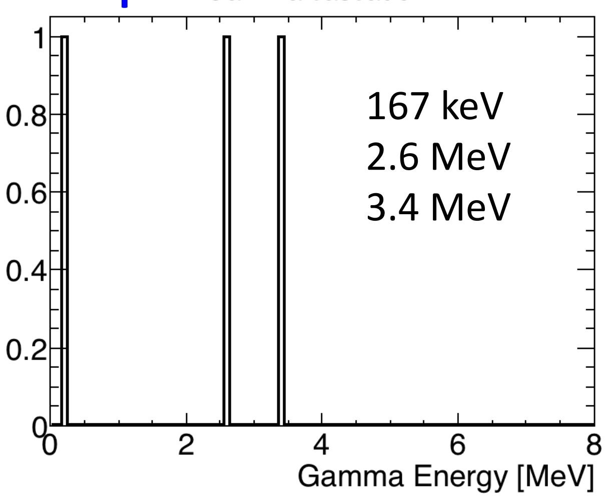
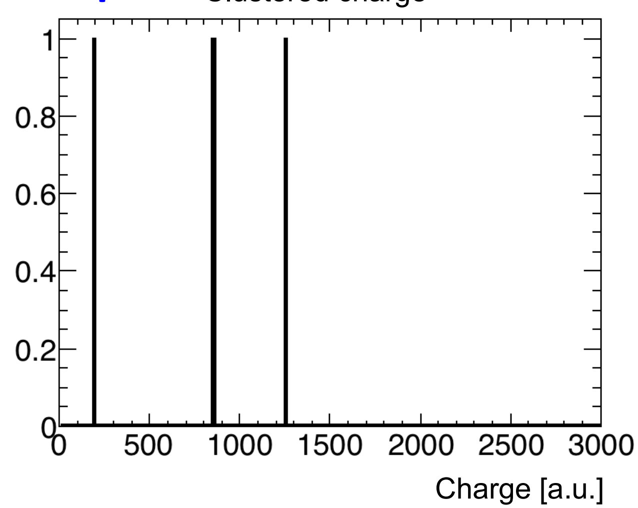




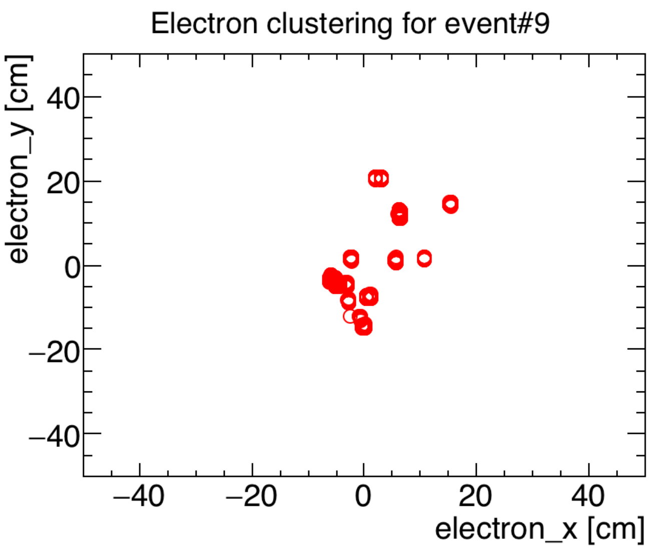
Input: Gamma cascade

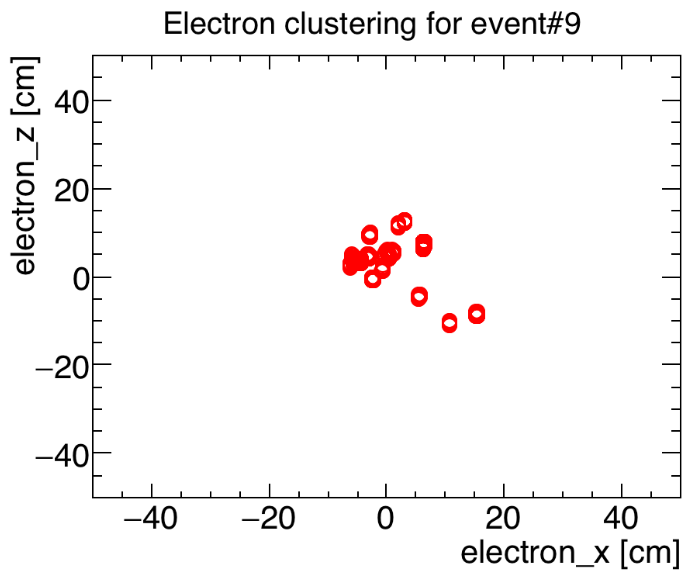


Output: Clustered charge

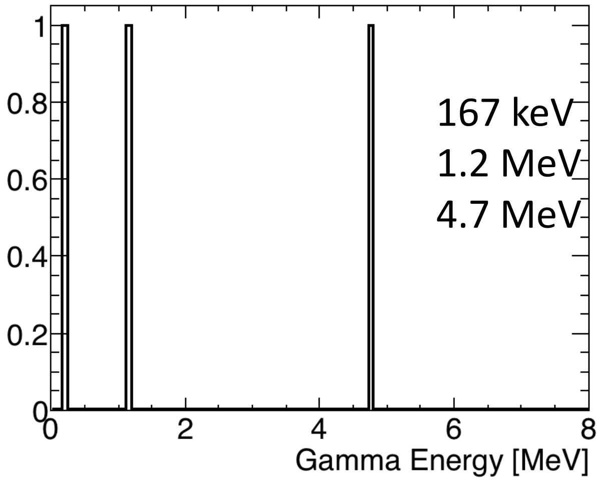


3D Clustering of MC Electrons

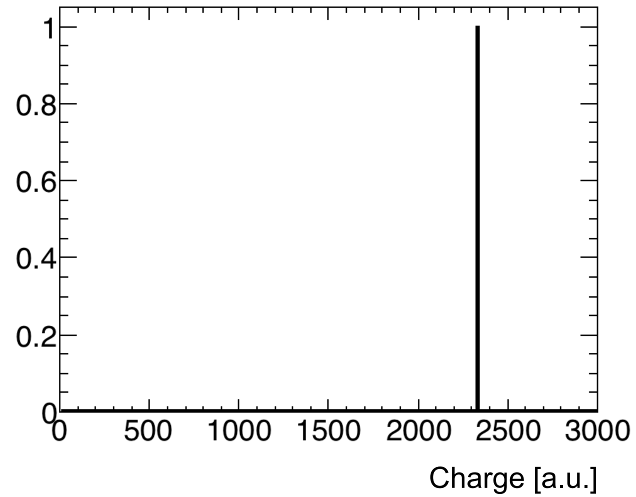




Input: Gamma cascade

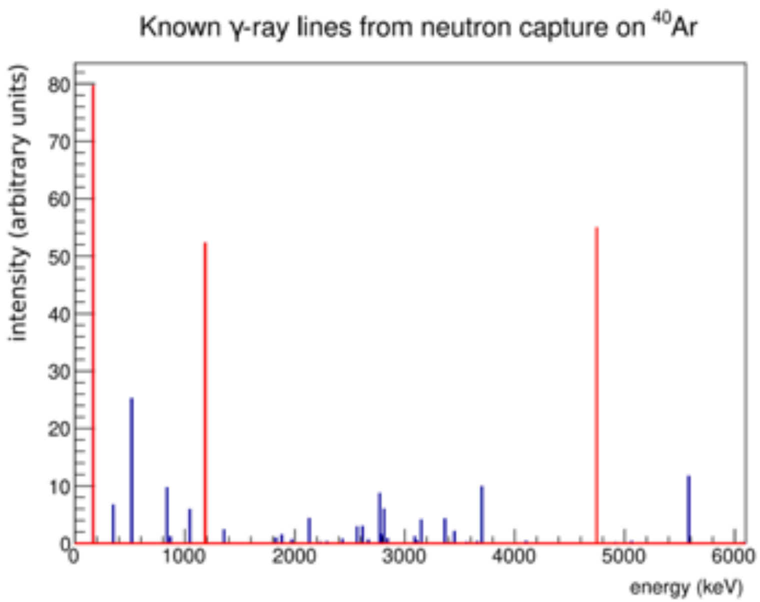


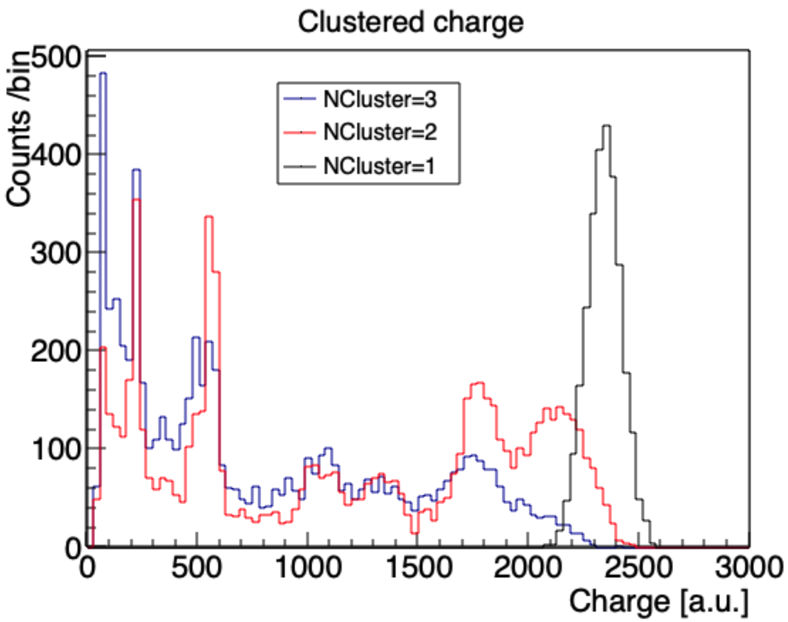
Output: Clustered charge



Neutron Capture Gamma

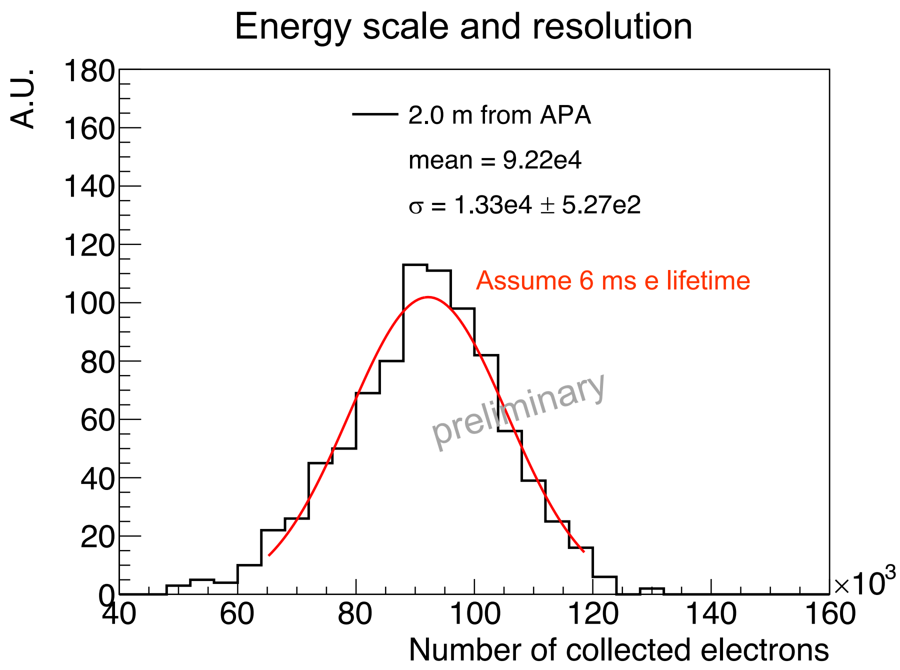
- The reconstruction of each individual gamma is not necessarily needed for calibration purpose, but could improve the data selection. The total charge of all the gammas will be used to calibrate the detector response.
- 3D clustering method can help suppress the background and select pure neutron capture samples, but the performance may be limited by the wire-based TPC readout





Simplified LArSoft Simulation

- Reconstructed charge on the collection plane for 6.1 MeV neutron capture gammas
  - 1000 neutron capture cascades at fixed location that is 2m from APA
  - No corrections for recombination or argon purity
  - Noise and background are turned off



Expected measured charge from 6.1 MeV: 1.8e-5 electrons (using ArgoNeuT recombination prediction in arXiv:1810.06502v1)

Mean charge: 9.22e4 electrons

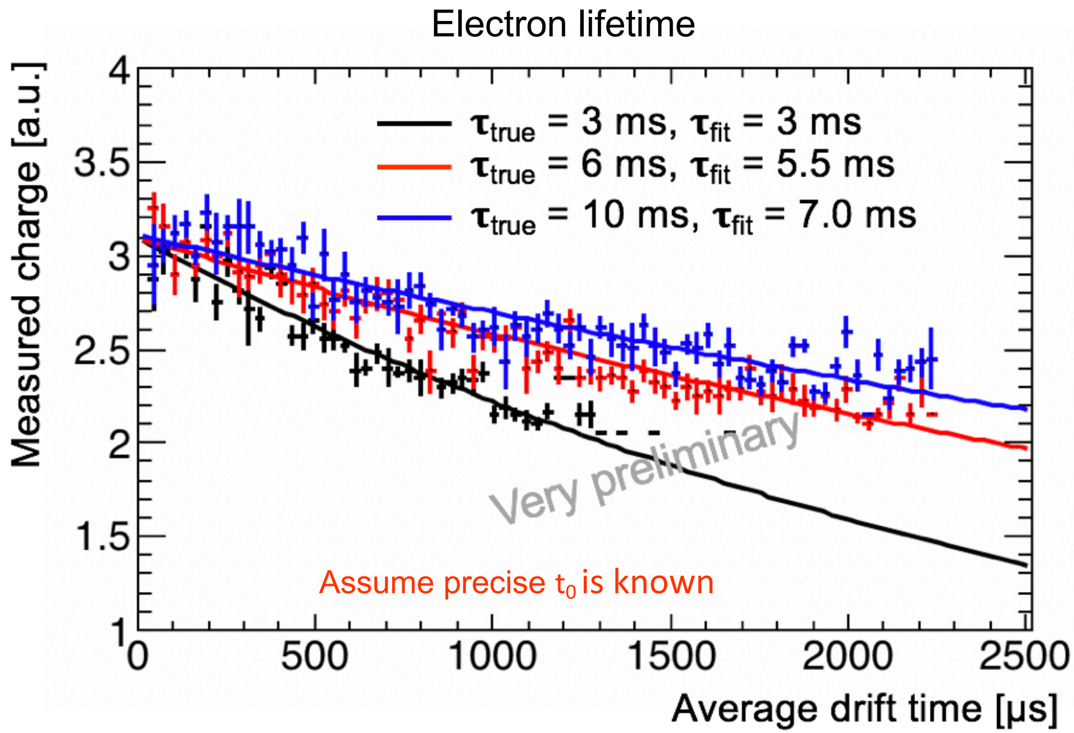
After lifetime correction and recombination correstion: 1.55e5 electrons → 5.2 MeV energy deposition

Lose about 14% of the total 6.1 MeV energy due to threshold effect

Electron Lifetime

- If the exact t_0 can be obtained using the photodetectors, the PNS system is sensitive to the electron lifetime. Sensitivity with the DD generator t_0 needs more studies.
- Analysis was done assuming the exact t_0 is known. The weighted average drift times of all the hits are taken as the drift time of the neutron capture related events.

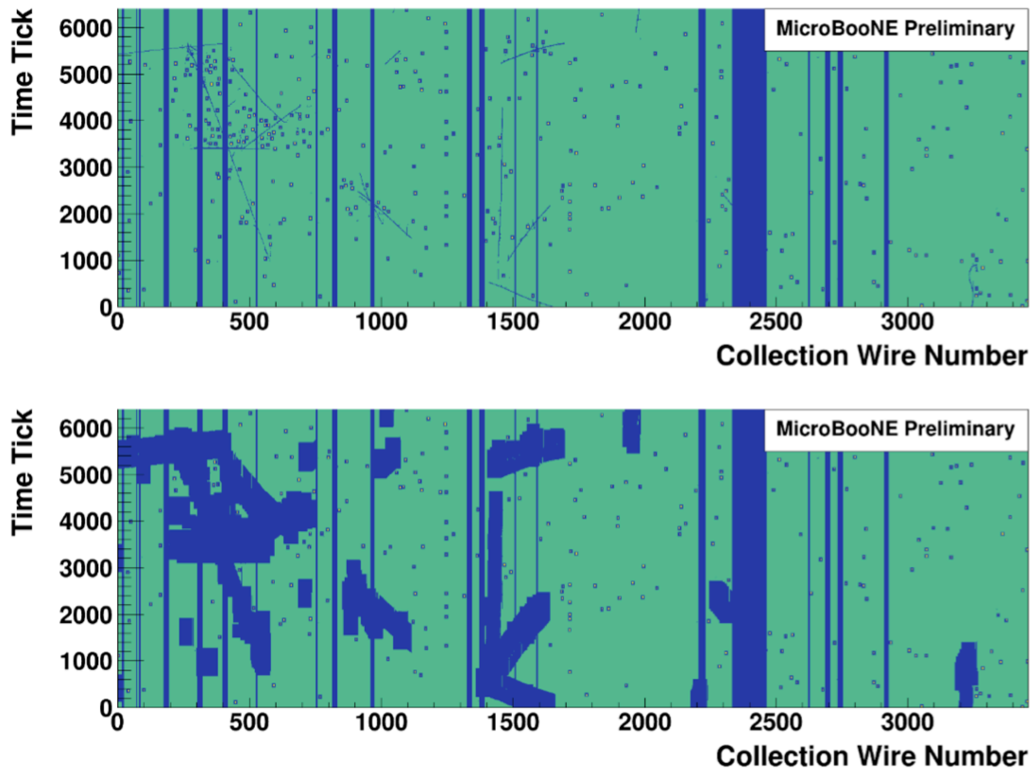
Simulation study has shown sensitivity, but the fit doesn't reproduce the input electron lifetime. The bias comes from the way how the average drift time is determined. Needs more in-depth study to validate the method.



Cosmic Background

- Cosmic ray could produce point-like events that can mimic neutron capture events.
- Need to identify the cosmic ray tracks and veto the point-like activities close to the tracks.
- The same technique is applied for the analysis of 39-Ar decay. Method tested in MicroBooNE, and is being developed for ProtoDUNE-SP

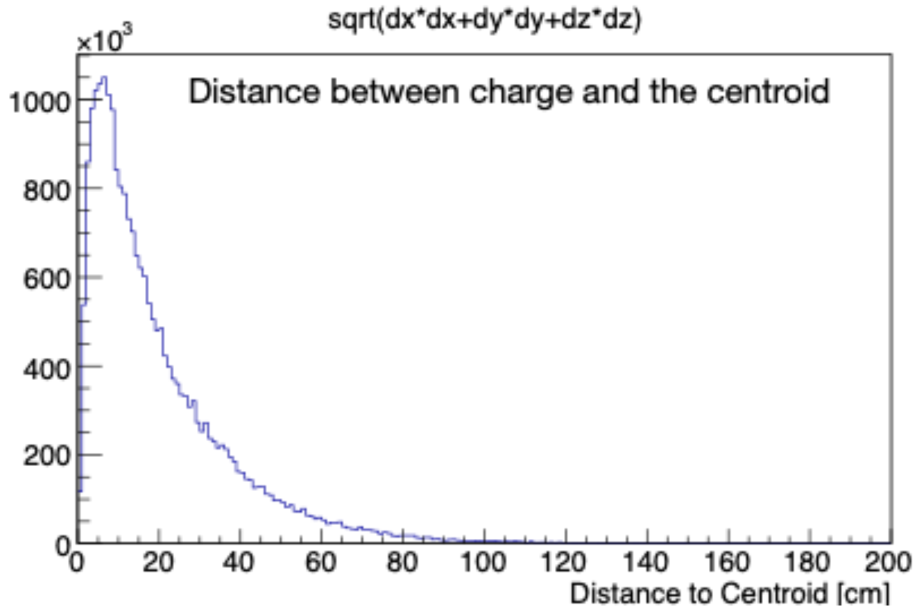
MicroBooNE Cosmic Veto



Alex Flesher and Michael Mooney

39-Ar Background

- ^{39}Ar decays with a single electron emission with an endpoint energy of 565 keV. The activity in liquid argon made from argon extracted from the air is about 1 Bq/kg. The chance of seeing an ^{39}Ar decay within the neutron capture event radius is 18%. This could be corrected based on our knowledge of ^{39}Ar decay rates and energy deposition.
- If PDS t0 is possible: The contribution from 39-Ar becomes negligible.



Geant4 Simulation of neutron capture shows the distance of the charge from the centroid of the charge for each event. 90% of the charge is absorbed within 45 cm of the centroid.

PNS Simulation Status

- **Neutron source design with new simulations**
  - Neutron moderator design in Geant4 (Done.)
  - Radiation shield design (Done.)
- **Neutron transport simulation with real TPC materials** (Done)
- **Neutron capture simulation and reconstruction**
  - Generator for correlated gamma cascade (Done)
  - Low-energy specific reconstruction (In progress).
  - Photodetector sim&reco for t_0 determination (Not done yet)
- **Analysis validation for PNS Calibration**
  - Validation with full simulation: field non-uniformity, electron lifetime, recombination, space charge… (In progress)

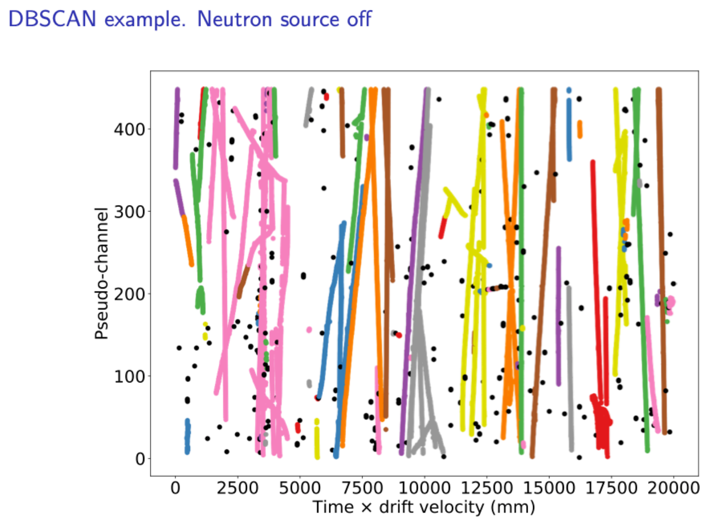
Any contribution & help is very welcome!

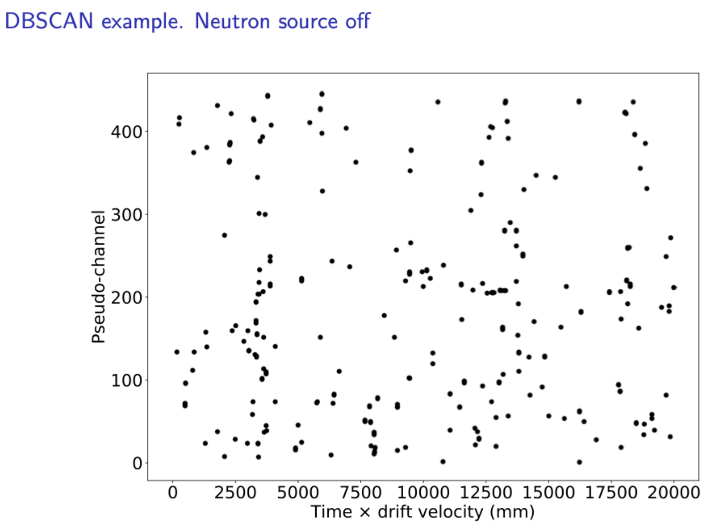
DDG Test at CERN

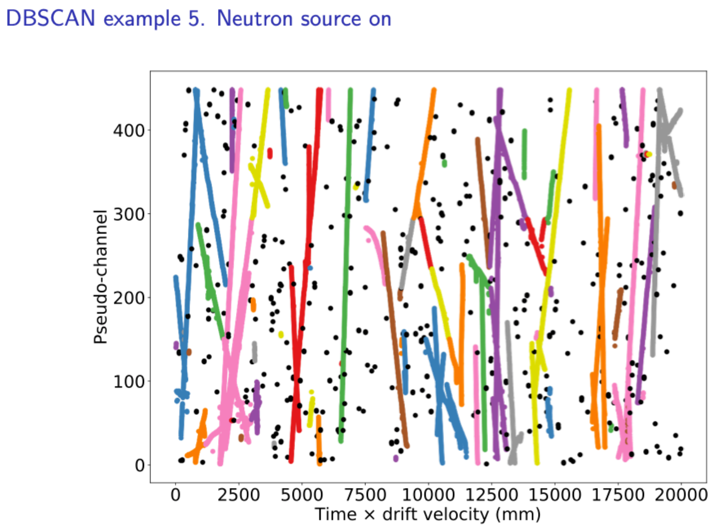
PNS Grp: UCDavis, LANL + CERN

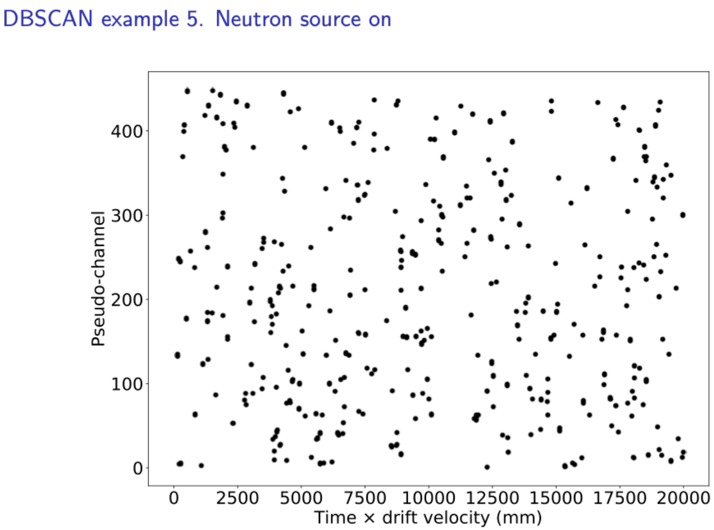
The deployment location and the shield are not ideal, but this is the only chance before the detector shutdown

ProtoDUNE neutron source hits



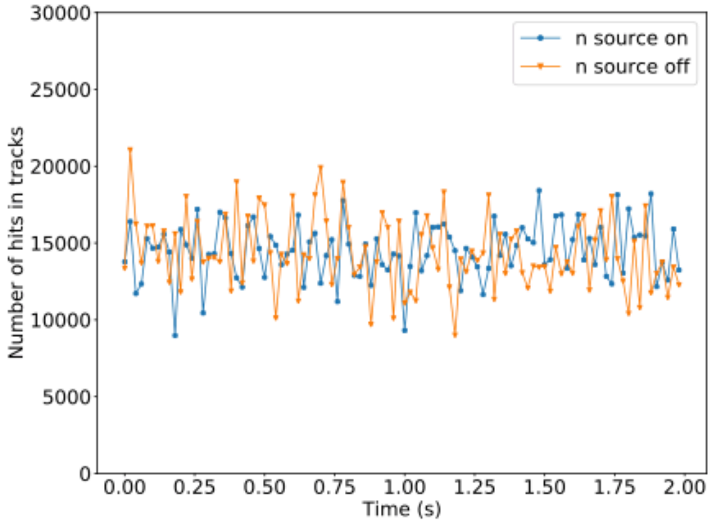


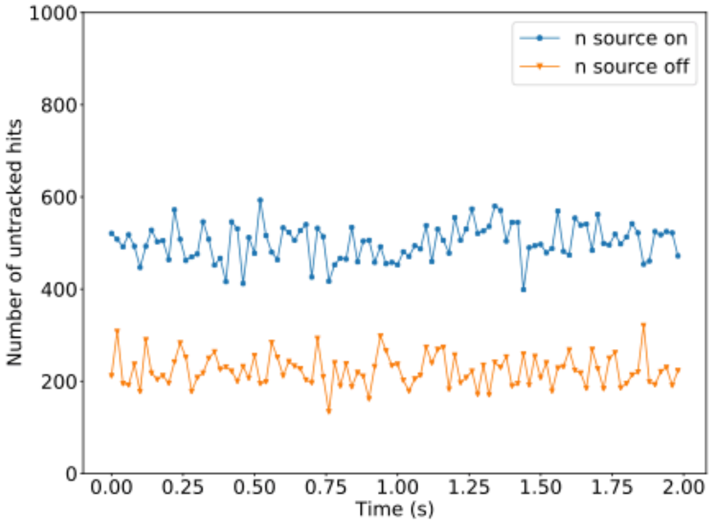




Philip Rodrigues: http://www-pnp.physics.ox.ac.uk/~rodrigues/protodune-neutron-source-2020-07-14.pdf

Clustered and unclustered hit rates





- Left: Number of hits clustered by DBSCAN (ie, tracked) in each 20ms window *vs* time
- Right: Number of unclustered hits (ie, neutron/EM candidates) in each 20ms window *vs* time
- (Just ran on 100 20ms windows to save time/memory)
- Tracked hits don't change with neutron source on. Untracked hits increase by about a factor of 2
- Clear evidence of neutron-like hits when source is on

Philip Rodrigues: http://www-pnp.physics.ox.ac.uk/~rodrigues/protodune-neutron-source-2020-07-14.pdf

Analysis Tasks

- **Cosmic veto:**
  - remove track related hits.
- **3d position reconstruction:**
  - position of isolated space points to test neutron spread model
- **Clustering:**
  - associate all gammas from a capture
- **Energy reconstruction (collection plane):**
  - Low energy specific reconstruction: ADC to charge, electron lifetime correction, recombination correction.

Conclusion

- Pulsed Neutron Source can be used as a calibration source that can produce 6.1 MeV fixed-energy gamma cascades.
- Reconstruction and analysis of low-energy gamma cascades is challenging. A realistic LArsoft end-to-end simulation is needed to verify the capability of the PNS system.
- CERN DD generator test has been completed at ProtoDUNE-SP
- Next: Analyze CERN data. Compare with the full LArsoft Simulation.