Low Energy Events in ArgoNeuT

Ivan Lepetic
Illinois Institute of Technology
For the ArgoNeuT Collaboration

Workshop on Fundamental Physics at the Second Target Station
ORNL

Outline

- Neutron interactions in liquid argon
- The ArgoNeuT study of MeV-scale activity in neutrino interactions
- Extending the reach of the ArgoNeuT study
- What else can you use LArTPCs for?

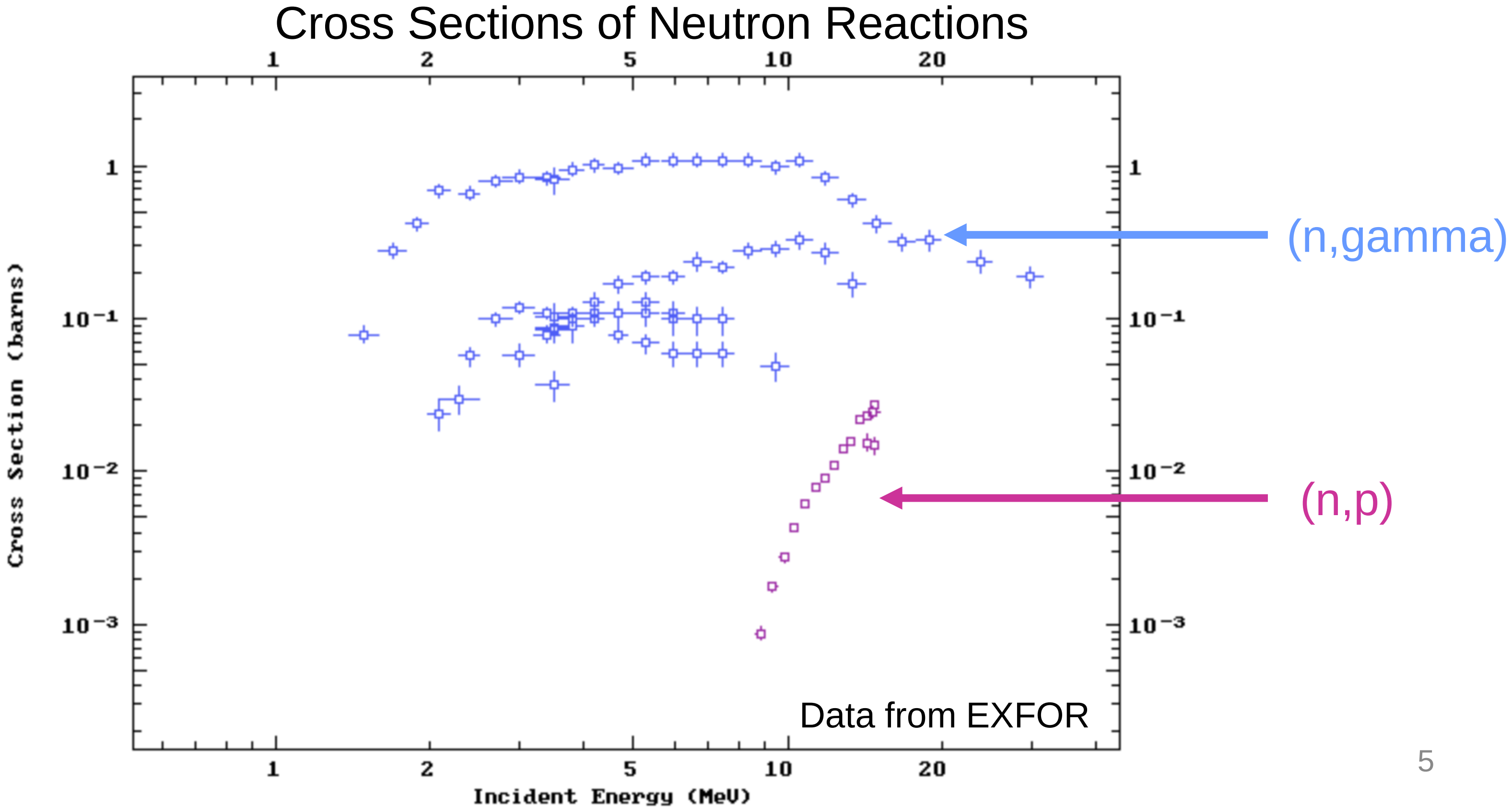
Neutron interactions in argon

Neutron Interactions in LAr

- There are several ways a neutron can interact in a medium.
  1. Elastic scattering
  2. Inelastic scattering
  3. Capture
- Inelastic scattering and capture produce 1-10 MeV photons.
  - Also protons
  - We can reconstruct activity from these photons.
  - Inelastic scattering requires a neutron KE ≥ 1.46 MeV.
  - Capture can take several hundred microseconds and might not occur in the TPC.
- The following looks at a simulation of 100 keV and 10 MeV neutrons
  - NeutronHP physics list in GEANT
  - Volume: enormous box of liquid argon

Protons vs Photons from Neutrons

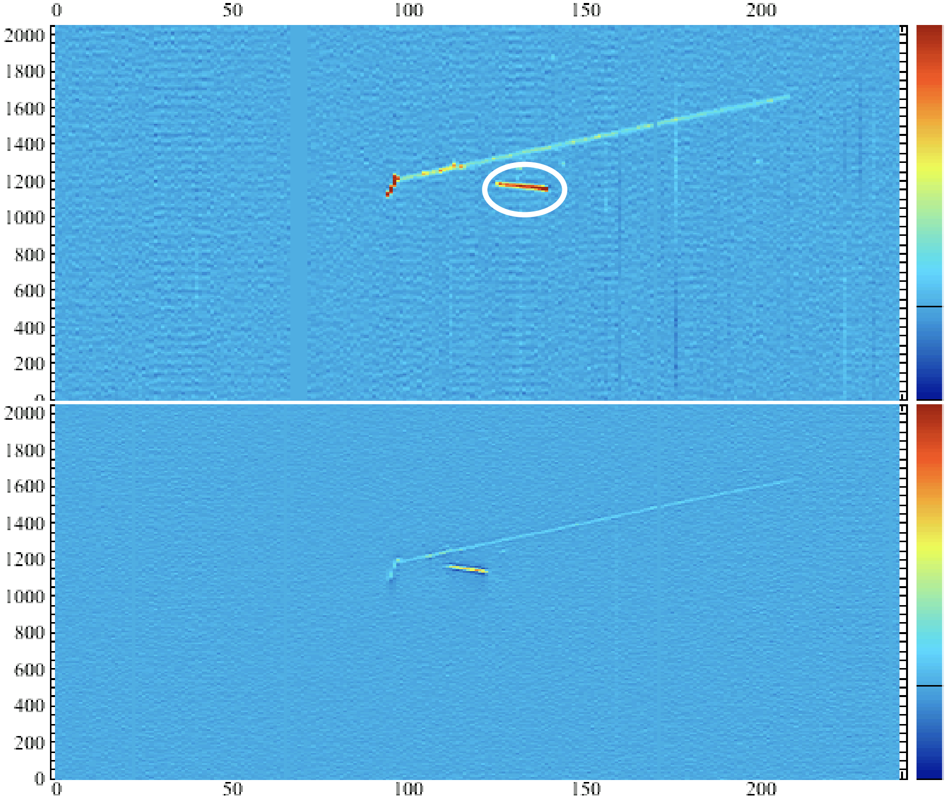
Photons are far more common for neutron energies typical in beam neutrino interactions.



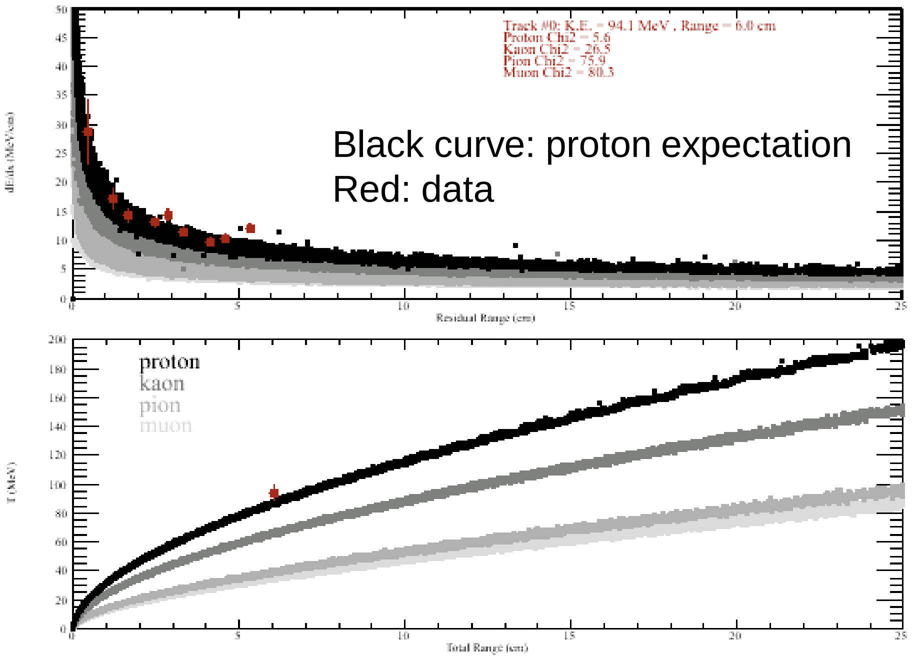
Protons From Neutrons

We have seen protons from neutrons in liquid argon detector data.

Event Display



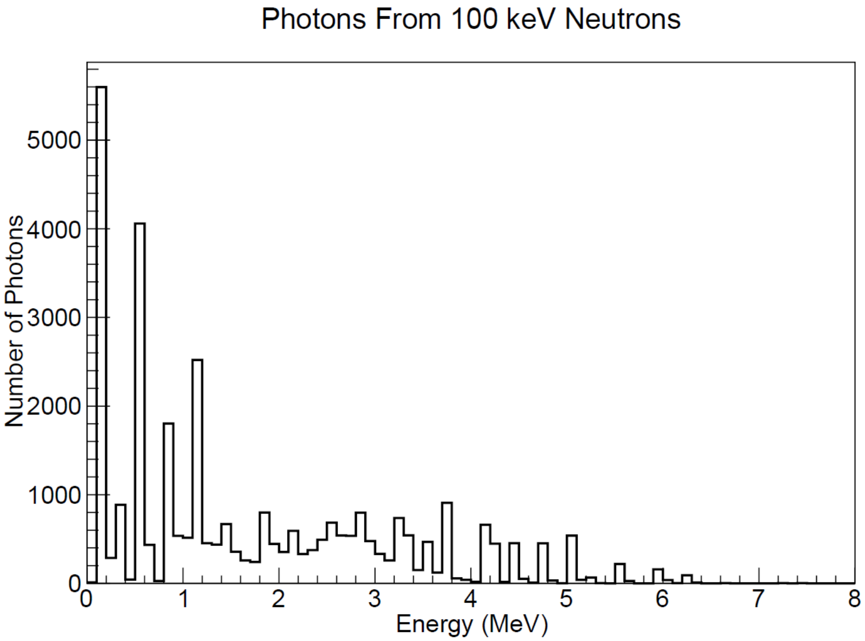
Calorimetry confirming track is a proton



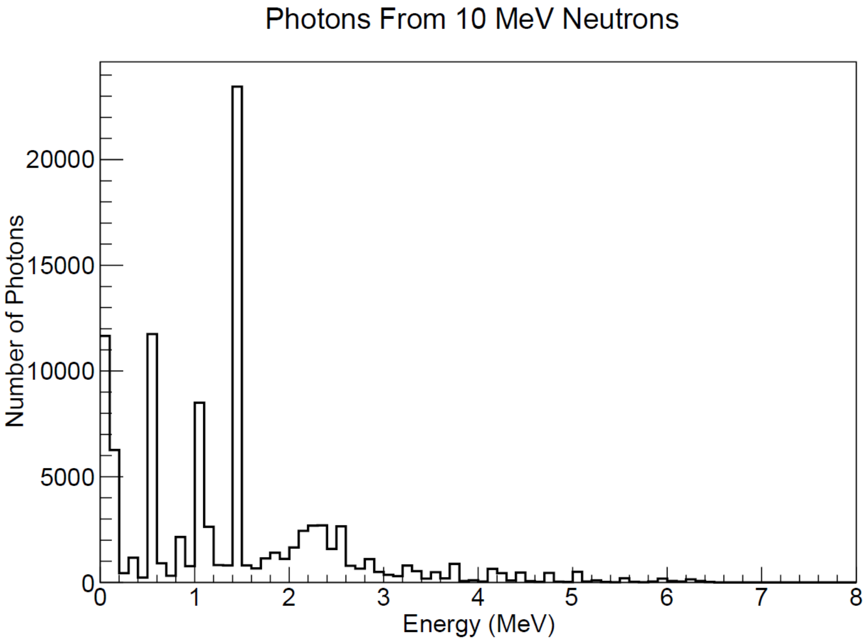
Images courtesy of Ornella Palamara

Energies of Individual Photons Created By Neutrons

Now on to photons

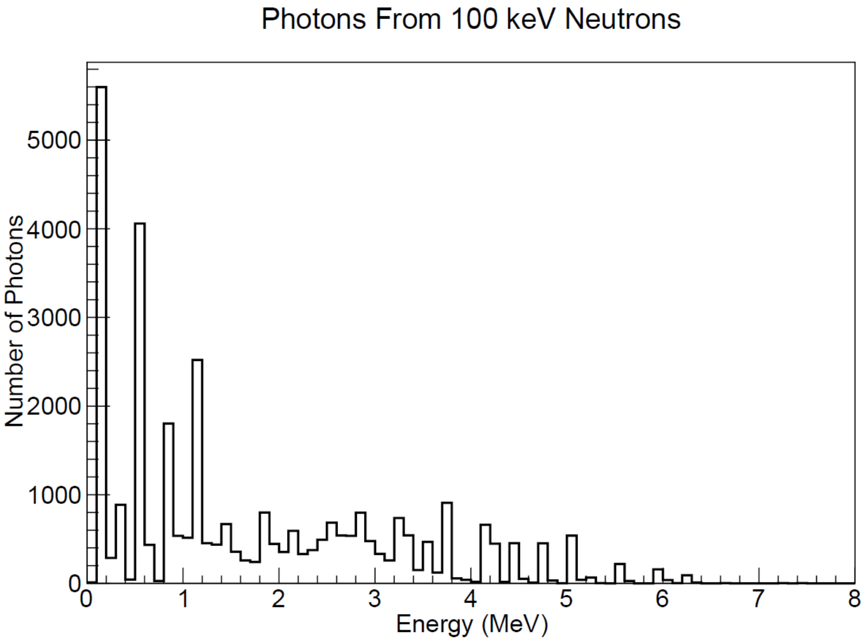


Only photons from neutron capture

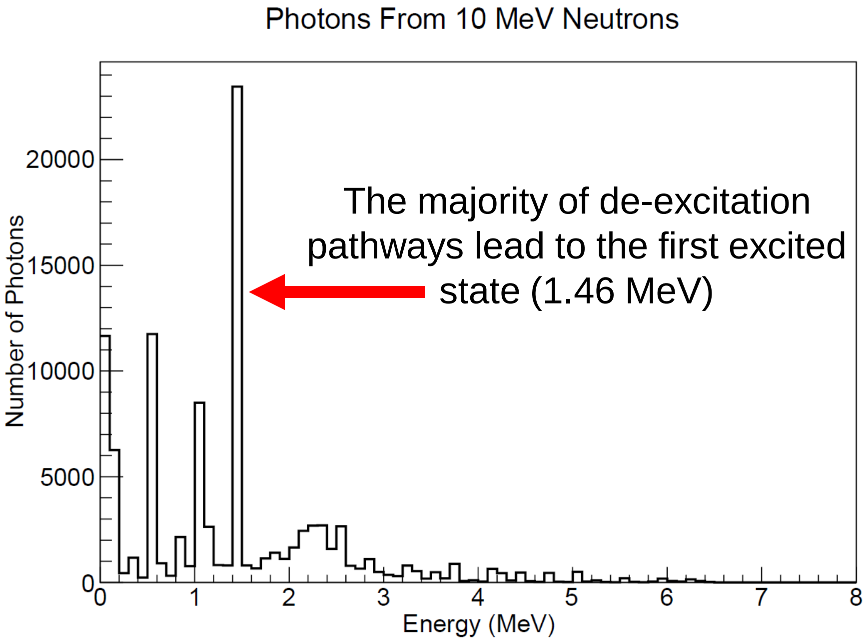


Mostly photons from inelastic scattering

Energies of Individual Photons Created By Neutrons

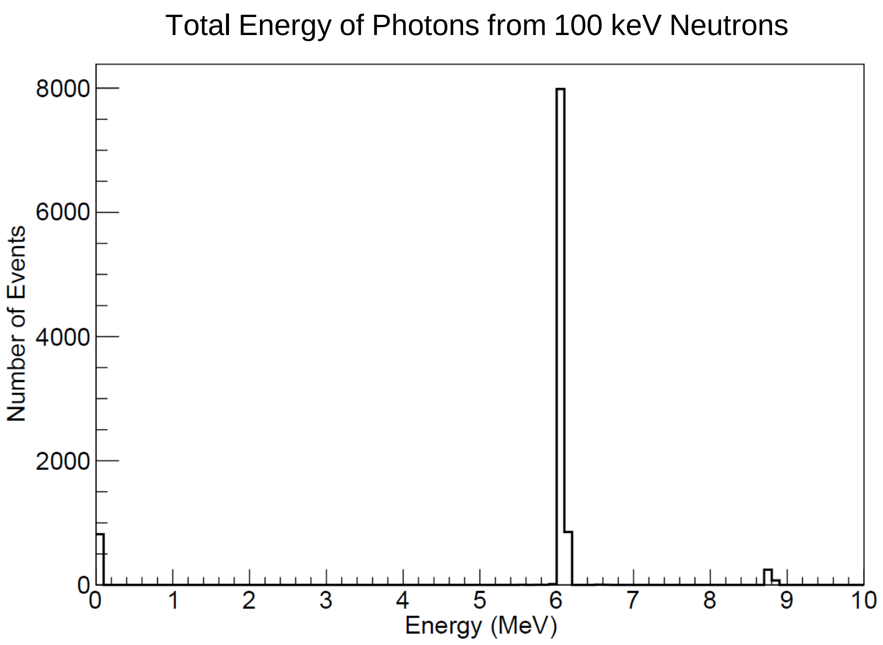


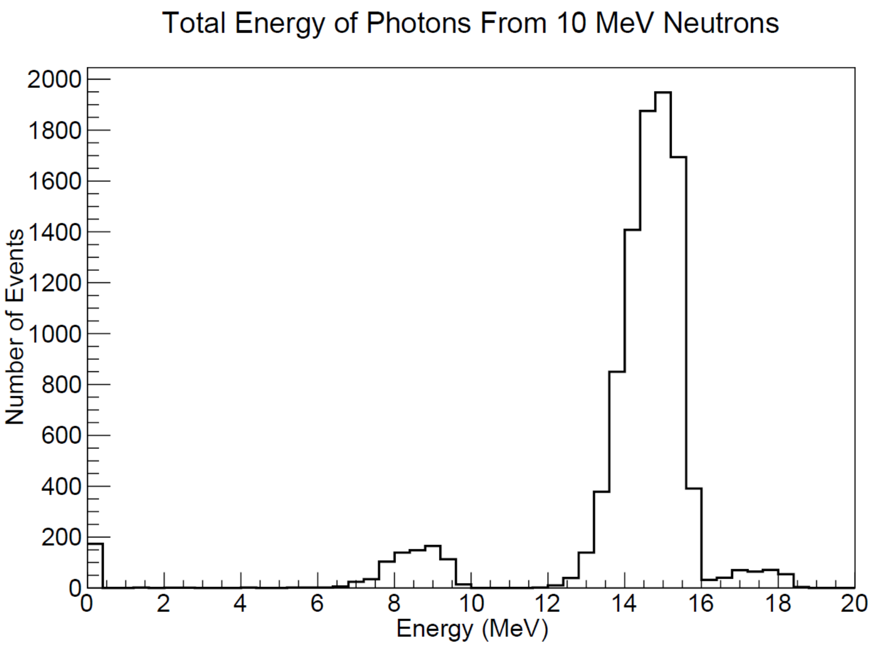
Only photons from neutron capture



Mostly photons from inelastic scattering

Total Energy of Photons Created By Neutrons



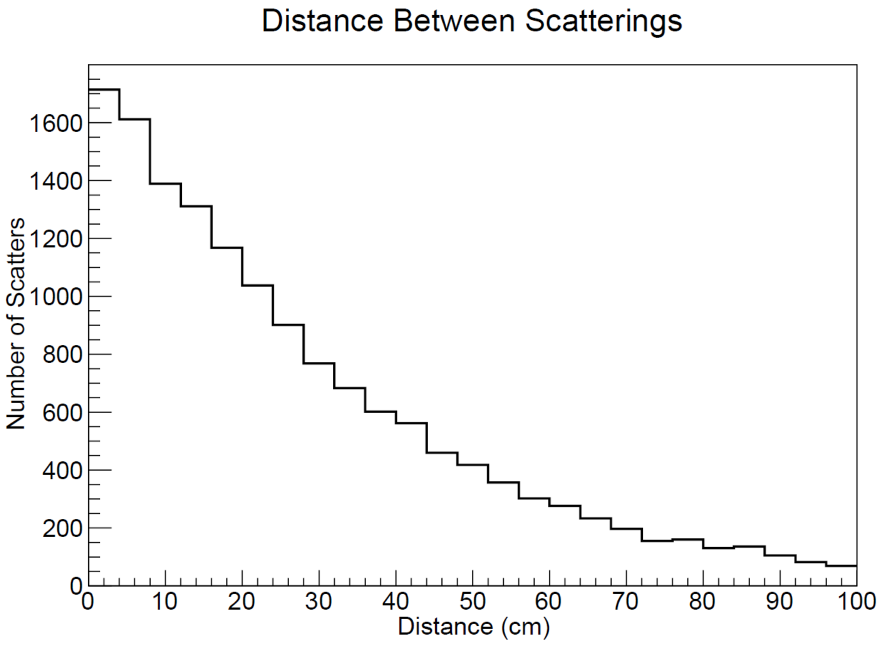


Characteristic peak at ~6 MeV for neutron capture

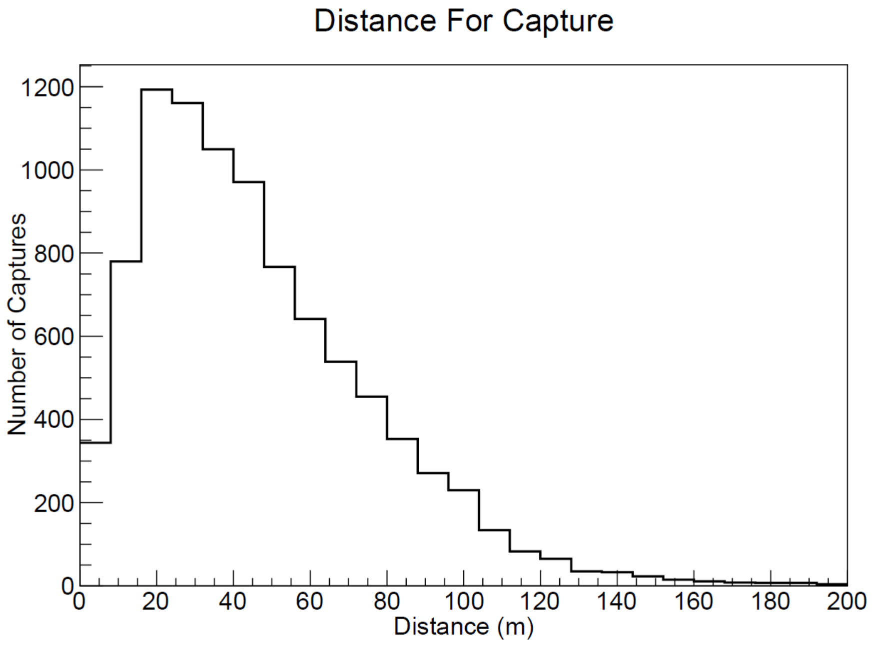
This includes photons from scattering and capture.
Some neutrons escape without being captured.

Neutron Interaction Distances

Argon is not the best medium for slowing down neutrons.



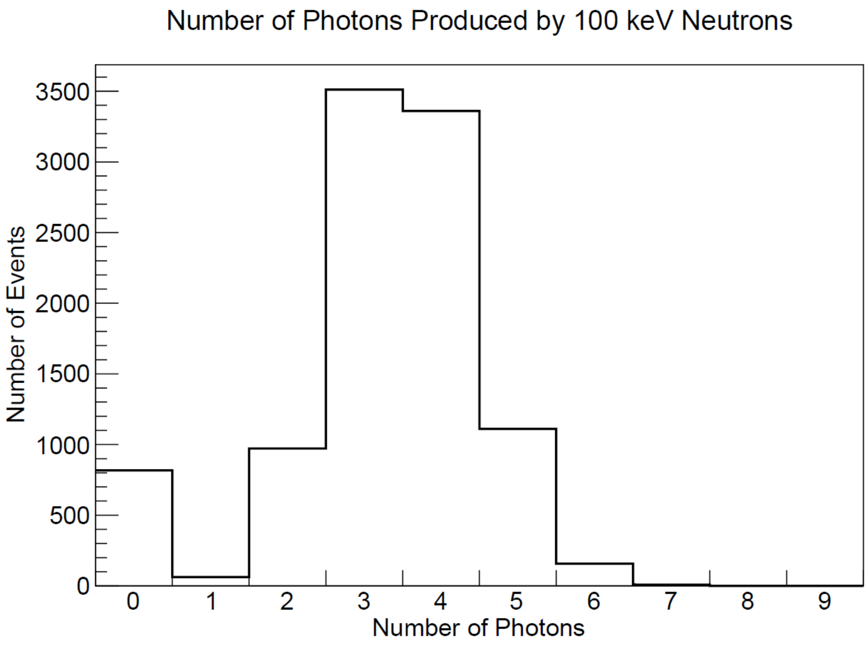
Scattering = inelastic neutron scattering
Average distance: 27 cm

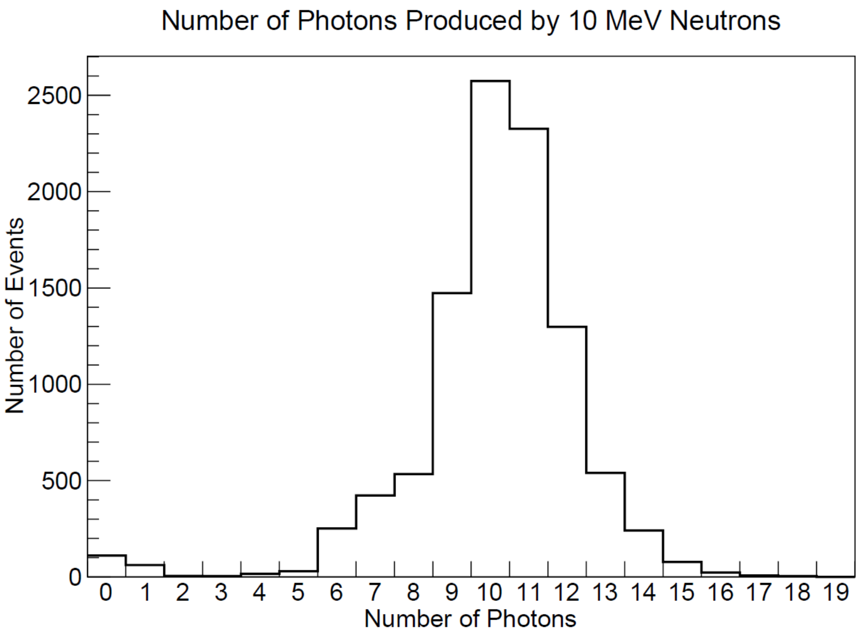


Note that this is in meters.
Average distance: 46 m

Photon Multiplicities

Lots of photons are produced, but can we see them?

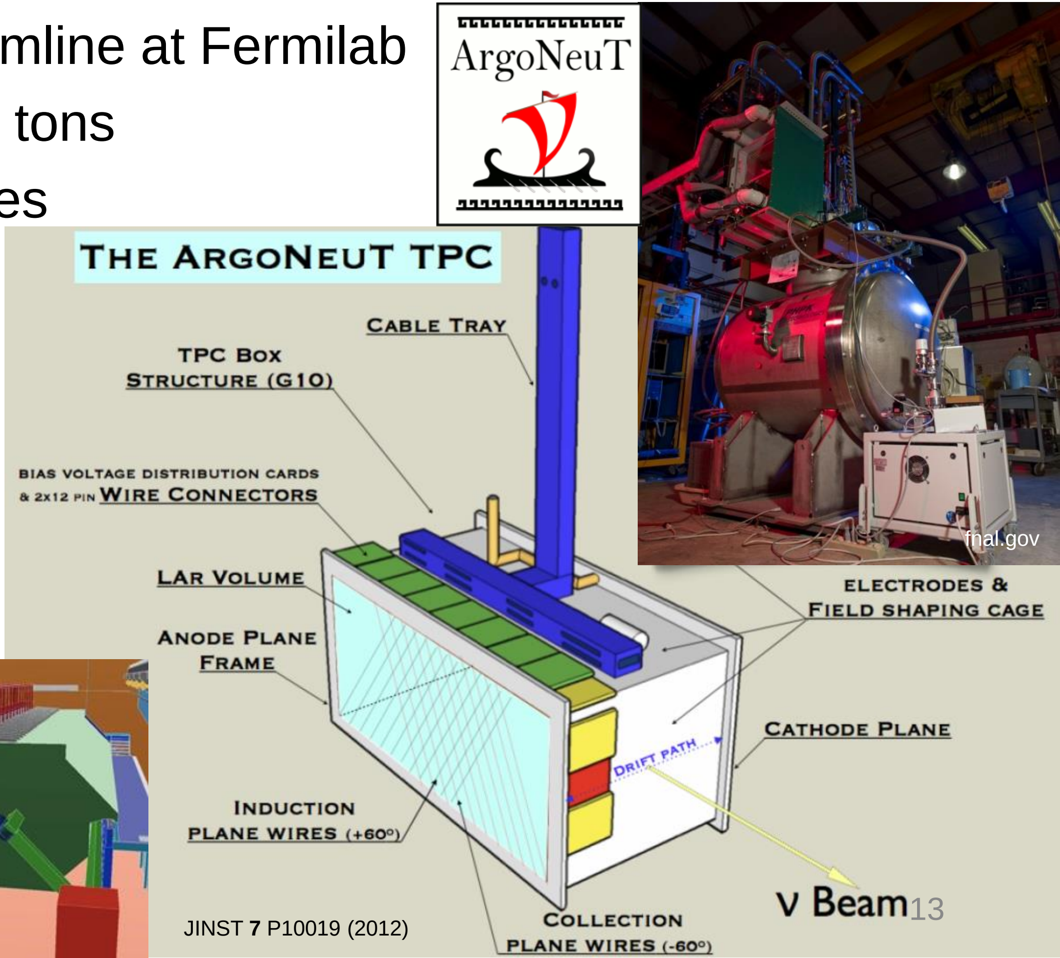




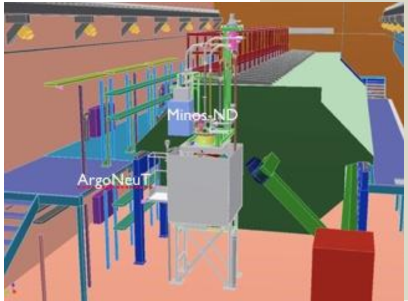
The ArgoNeuT study

ArgoNeuT

- LArTPC placed in the NuMI beamline at Fermilab
- $47(w) \times 40(h) \times 90(l)$ cm^3 = 0.24 tons
- Readout: Two planes of 240 wires
  - ± 60° to the beam
  - 4 mm pitch
- NuMI Neutrino Beamline
  - Antineutrino mode
  - Average ν_μ energy: 9.3 GeV
  - Average $\bar{\nu}_\mu$ energy: 3.6 GeV
- 100 m Underground

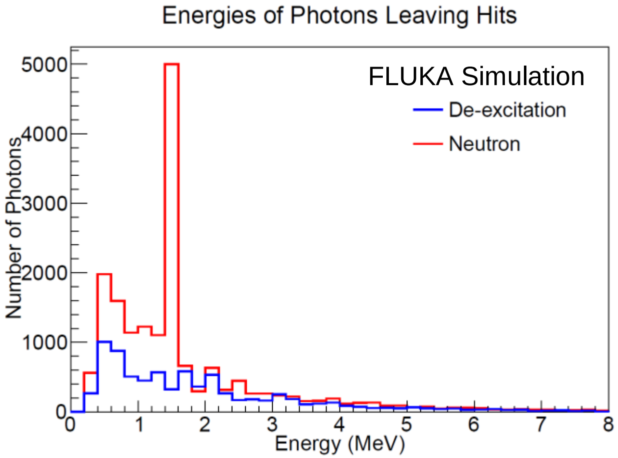


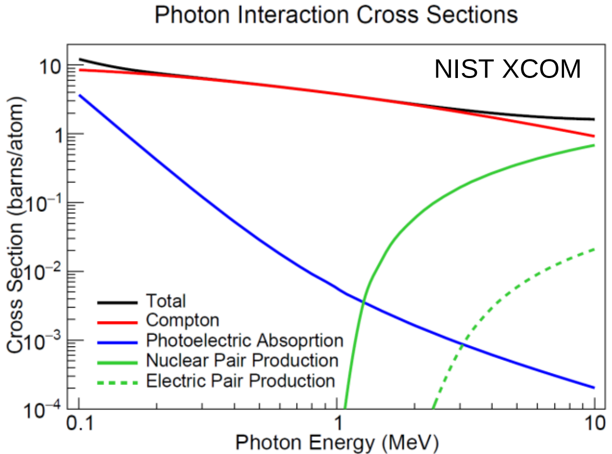
JINST **7** P10019 (2012)



Low Energy Photons

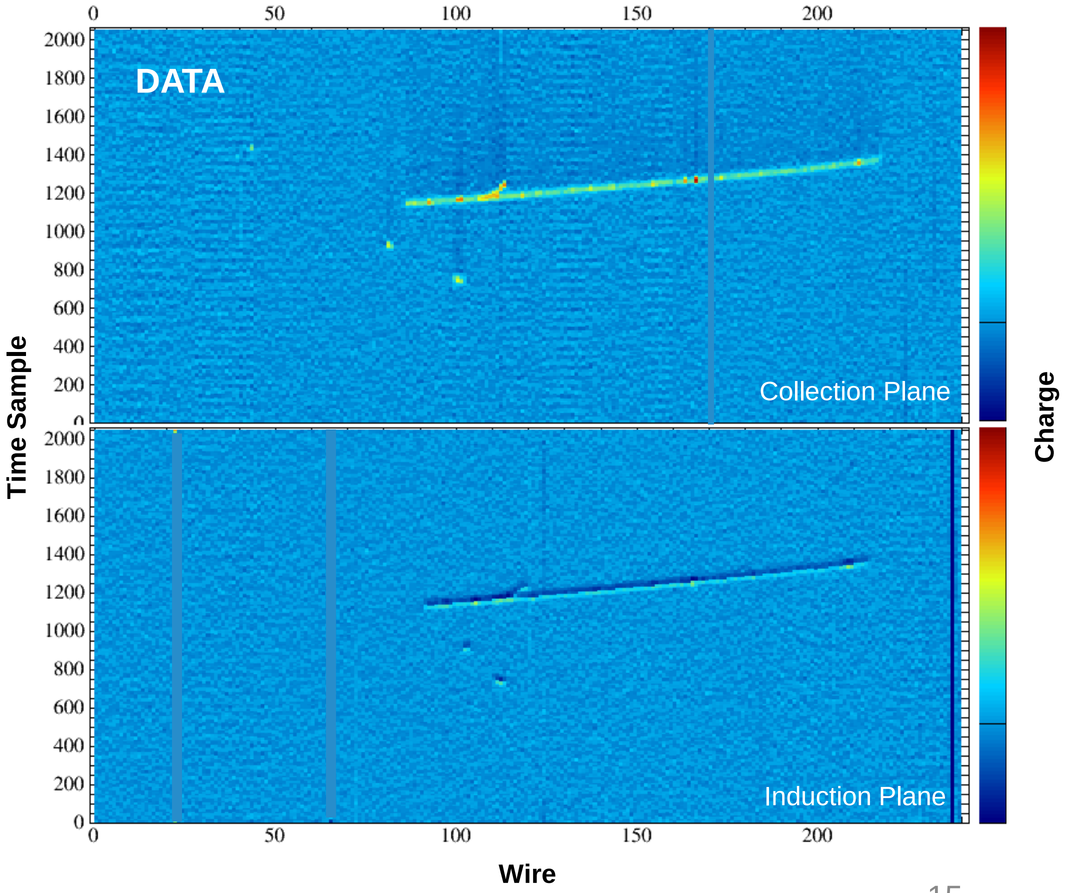
- Focus: photons from **neutrino-produced** nuclear de-excitation and inelastic neutron scattering
  - e.g. $\nu_\mu + {}^{40}\mathrm{Ar} \rightarrow \mu^- + p + {}^{39}\mathrm{Ar}^*$
    $n + {}^{40}\mathrm{Ar} \rightarrow n + {}^{40}\mathrm{Ar}^*$
  - Energies: 0.1 – 10 MeV
- Detect electrons produced primarily by Compton scattering
  - End up with low energy electrons (< 3 MeV)
  - Multiple small and topologically isolated energy depositions





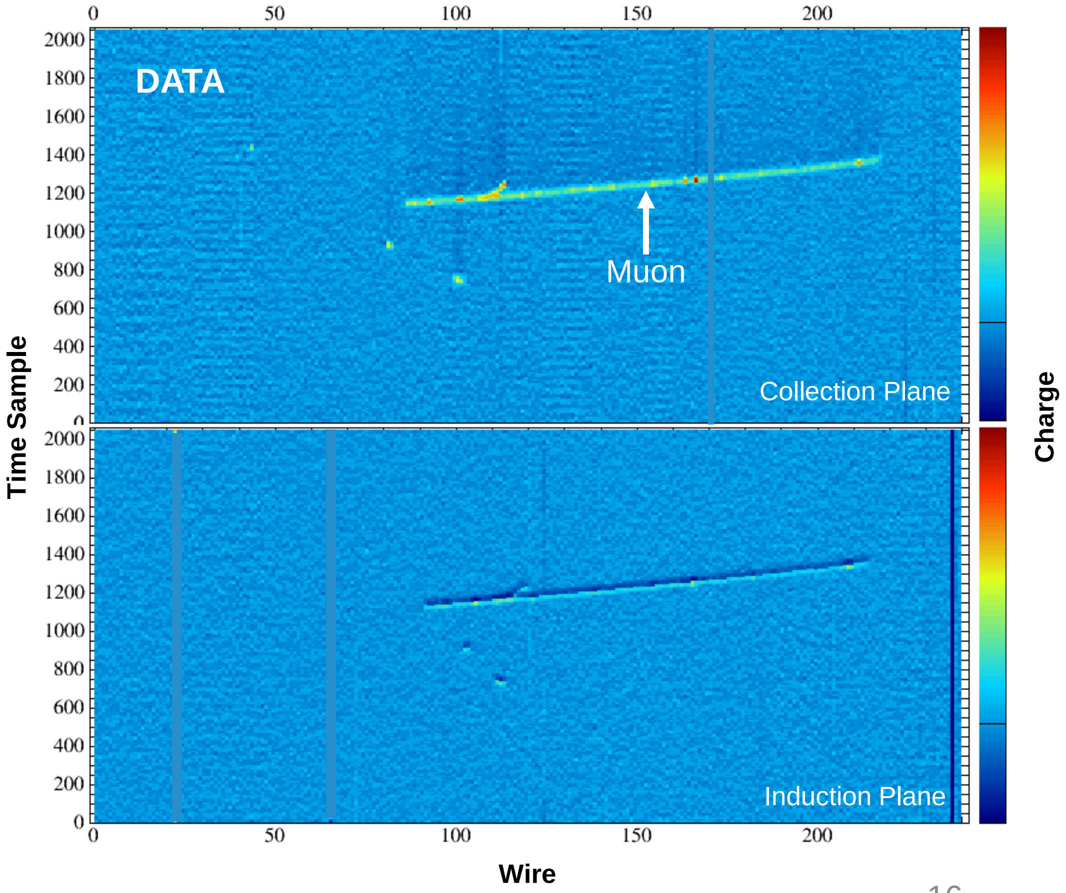
Signal Selection

- Let's look at a raw data event display.
  - ν_μ CC0π0p event



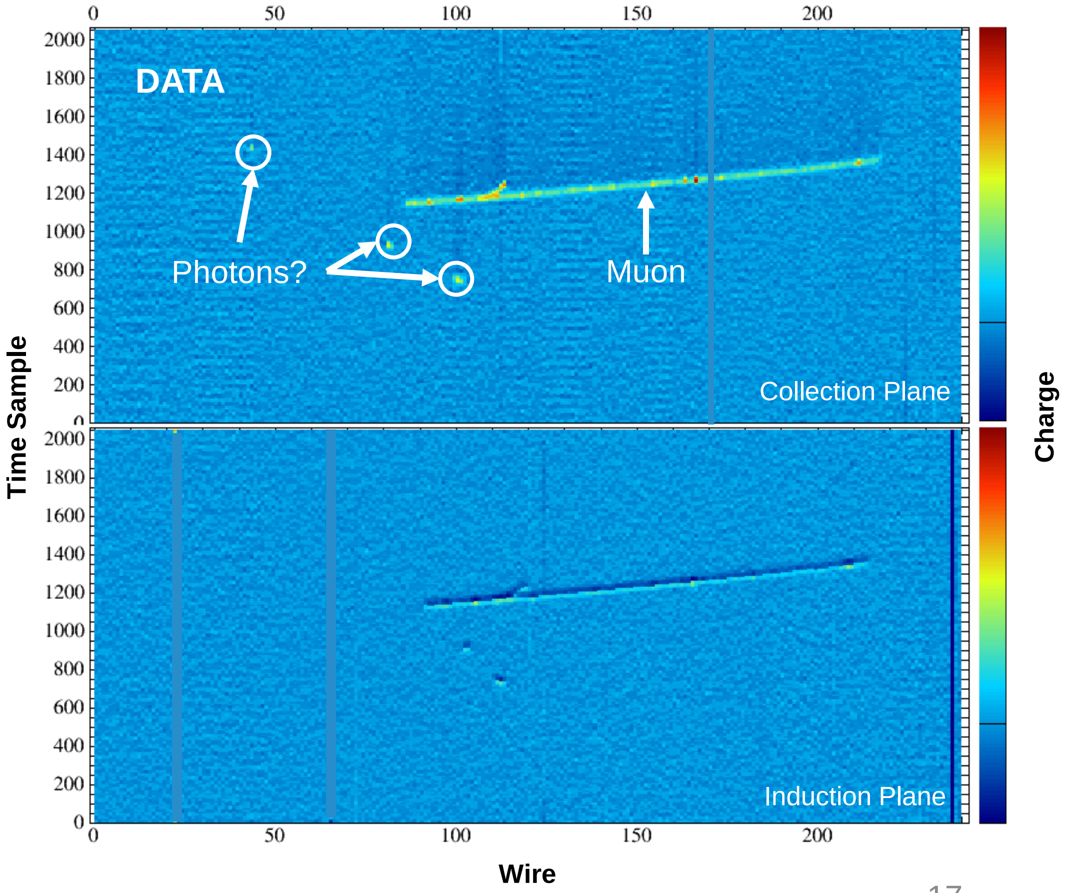
Signal Selection

- Let's look at a raw data event display.
  - ν_μ CC0π0p event
- We can easily identify the muon.



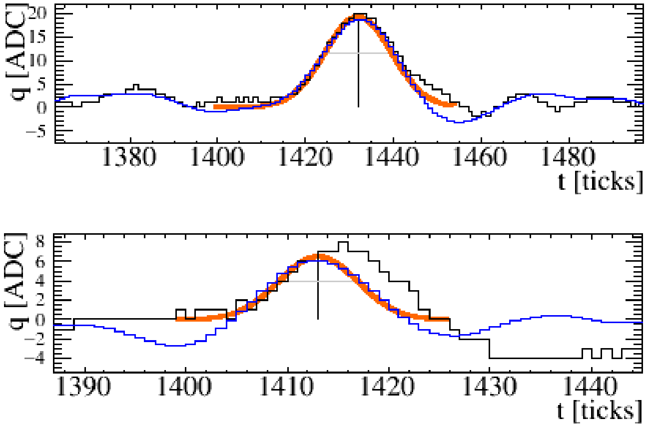
Signal Selection

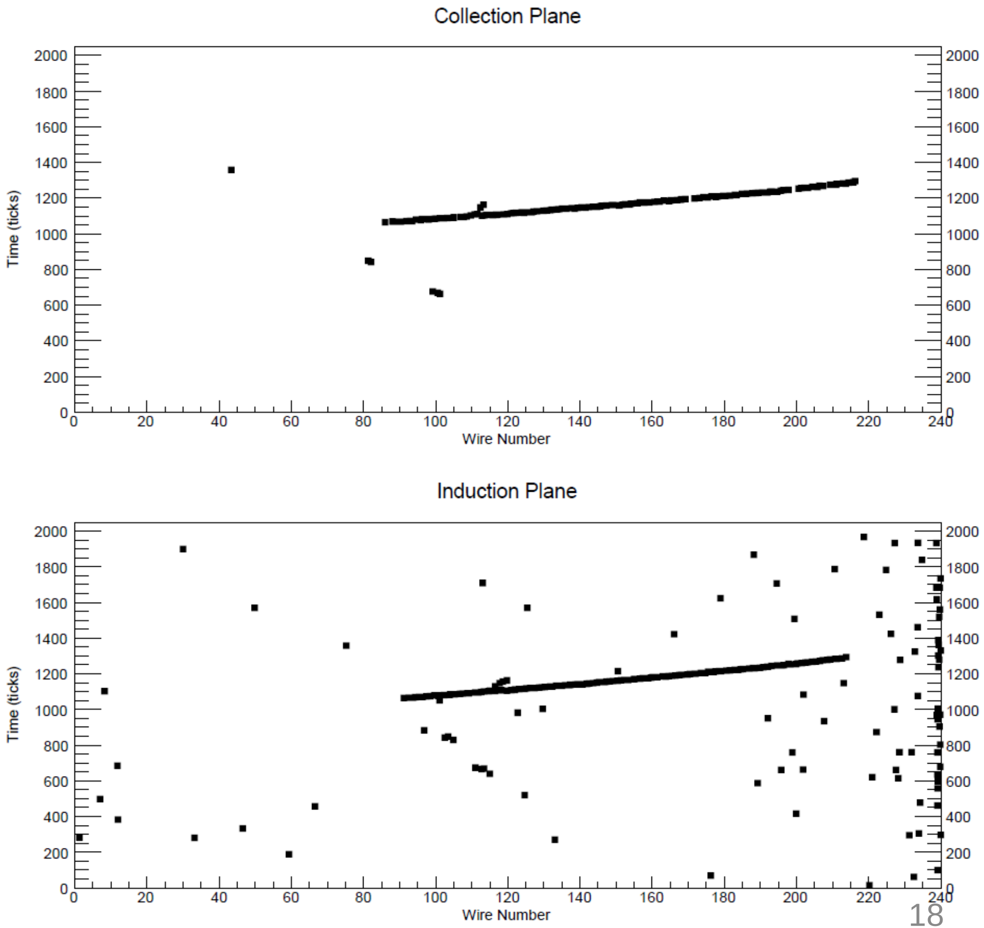
- Let's look at a raw data event display.
  - ν_μ CC0π0p event
- We can easily identify the muon.
- The small blips are possibly due to photons.
  - This is what we want to reconstruct.



Signal Selection

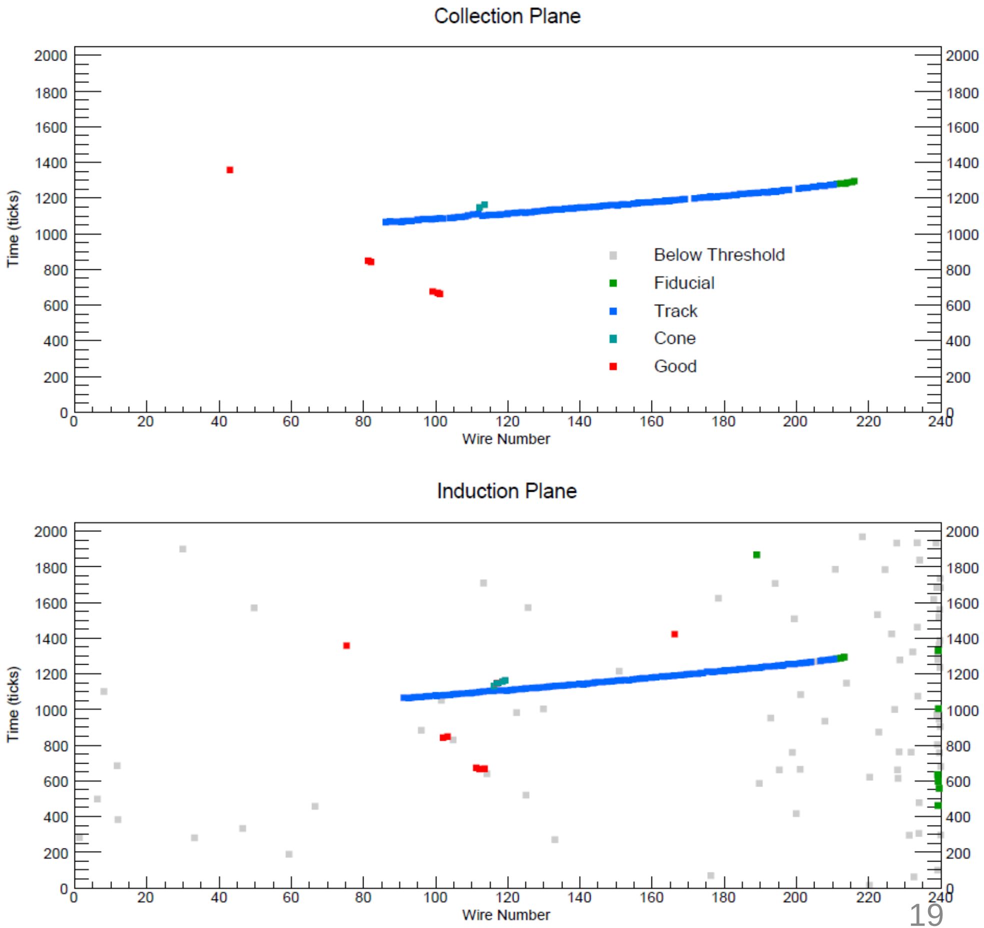
- During an automated reconstruction, wires are scanned for hits.
- We now need to determine which hits are due to photons.





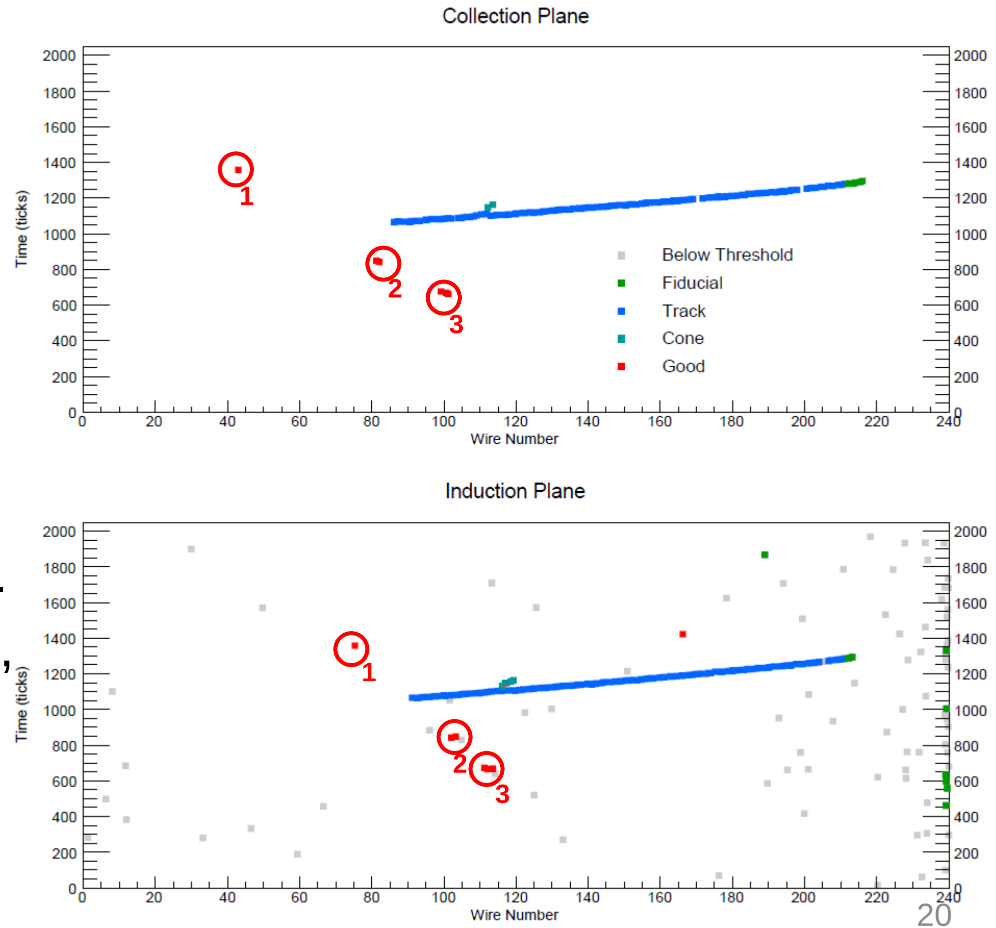
Signal Selection

- During an automated reconstruction, wires are scanned for hits.
- We now need to determine which hits are due to photons.
- We apply several cuts to hits.
  - To remove noise and high-energy activity
  - Hits that pass these cuts are in red.



Signal Selection

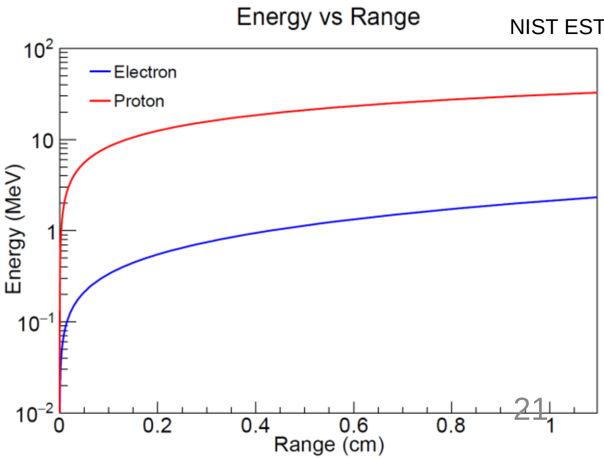
- During an automated reconstruction, wires are scanned for hits.
- We now need to determine which hits are due to photons.
- We apply several cuts to hits.
  - To remove noise and high-energy activity
  - Hits that pass these cuts are in red.
- We then group hits into clusters,
- And apply plane matching.
  - Circled hits are matched across planes in time.



Calorimetric Reconstruction of Clusters

- Several steps to turn collected electronic signal into energy.
  - Electronic calibration factor
  - Electron lifetime correction
  - Recombination correction
- Recombination correction depends on dE/dx.
- Low-energy electrons travel short distances.
  - Electrons with energy < 1 MeV travel less than 4 mm = wire spacing.
  - Often not in a straight line, >1 MeV electrons can also hit only one wire
  - Standard GeV-scale range-based methods are not adequate.

JINST **8** P08005 (2013)



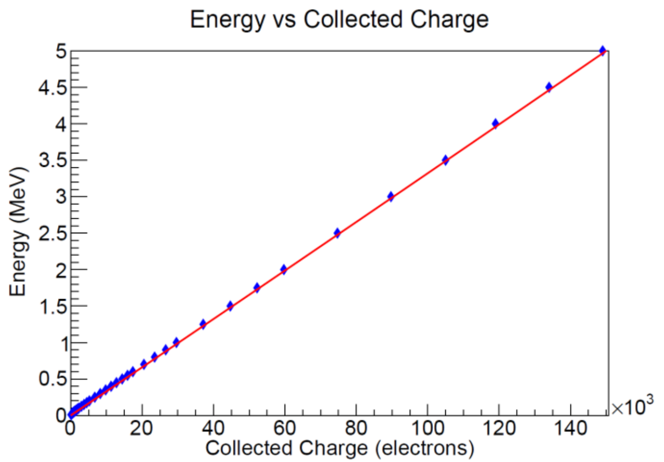
NIST ESTAR

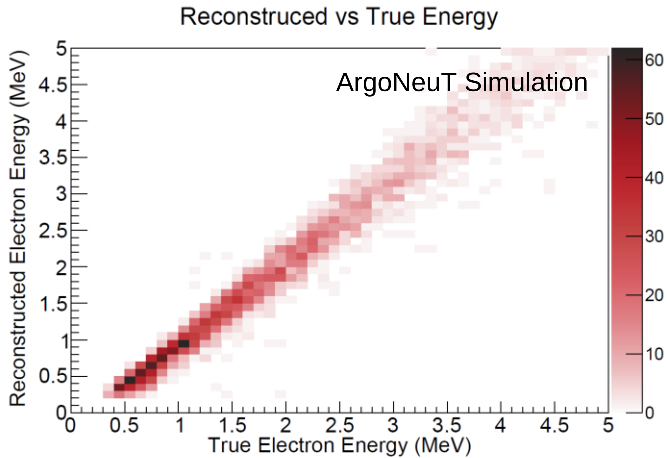
Calorimetric Reconstruction of Clusters

- We assume hits passing cuts are due to electrons only.
  - < 1% due to protons (according to MC)
- Method based on NIST table of electron track lengths
  - Determine dE/dx for each row of ESTAR* table.
  - Apply recombination factor from inverted Modified Box Equation**

$$\frac{dQ_{\mathrm{coll}}}{dx} = \frac{1}{\beta W_{\mathrm{ion}}} \ln\left(\beta \frac{dE}{dx} + \alpha\right)$$

  - Obtain track length and electron energy vs charge deposited





Comparison with Background

- Background: electronic noise, intrinsic radioactivity, “dirt” neutrons, ^{39}Ar decays
  - Not associated with a neutrino interaction final-state particle
- Background events: spills with no visible neutrino activity

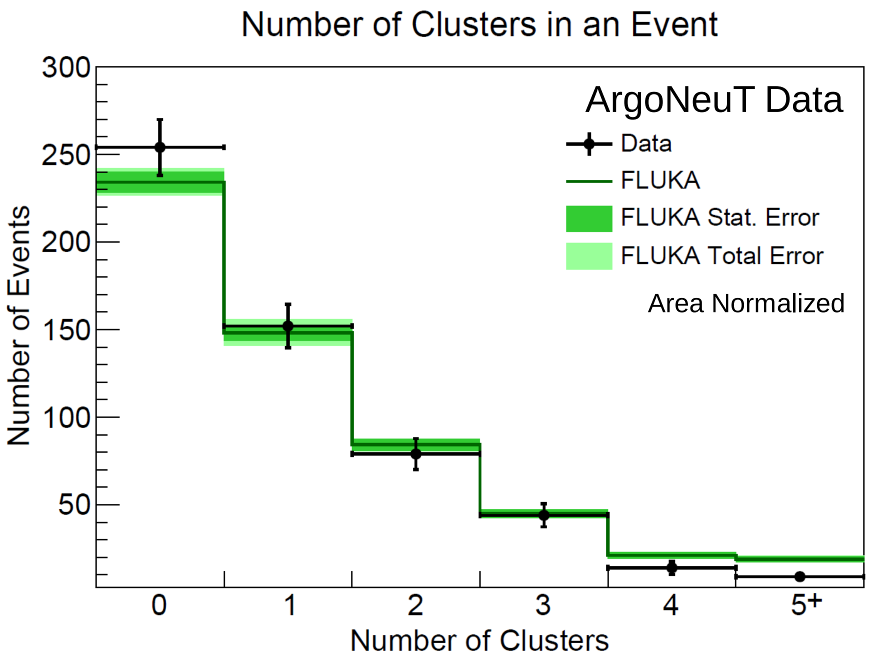
Metric	Neutrino Data	Background
Number of signal hits per event	1.30	0.21
Average total signal energy in an event (MeV)	1.11	0.19
Percent of events with at least one signal hit	54%	12%

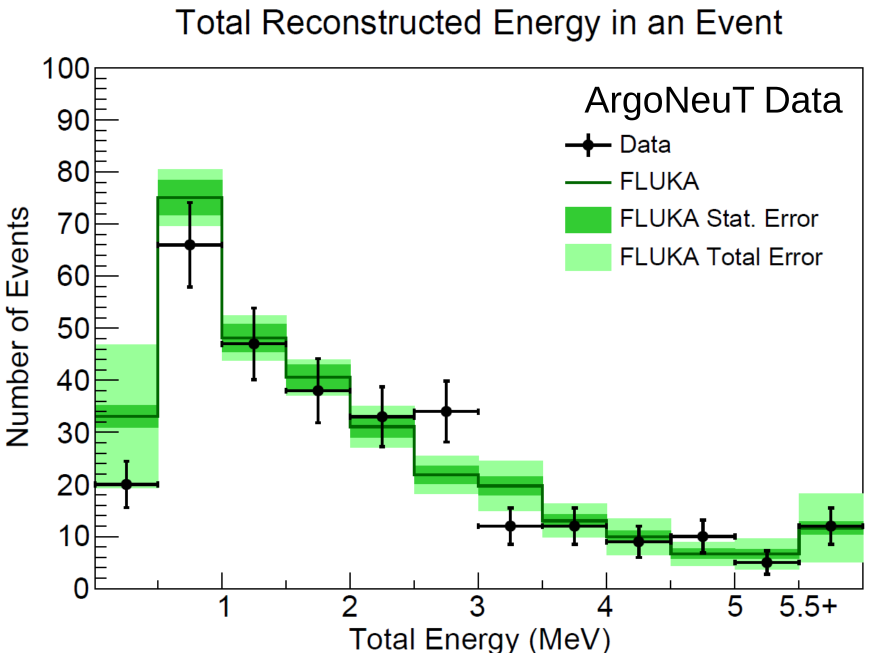
Neutrino and background datasets differ by 15 σ.

This can be interpreted as evidence of **neutrino induced** MeV-scale energy depositions.

Comparison With FLUKA

- We use FLUKA* because it produces de-excitation photons.
- FLUKA agrees very well with our data.

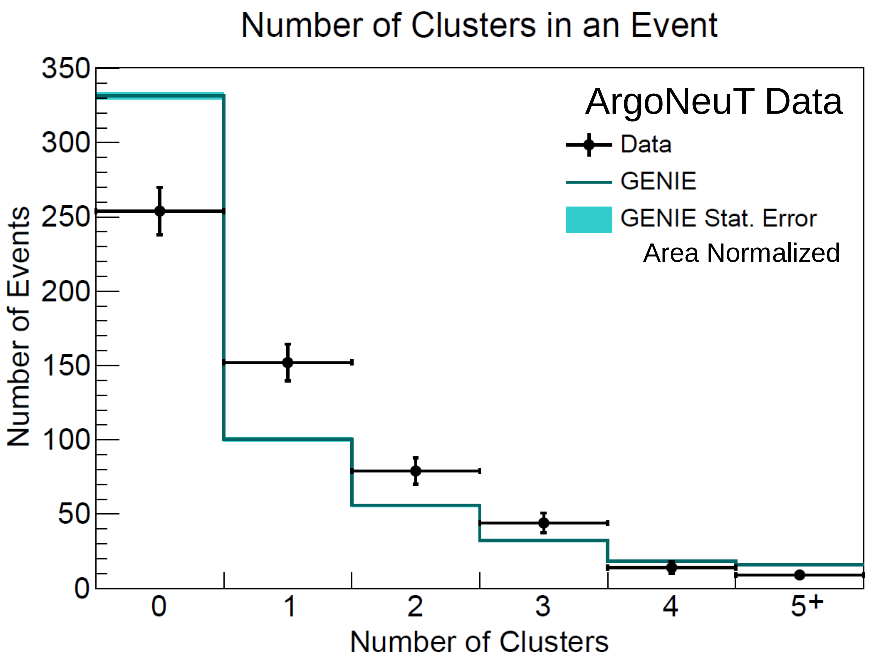


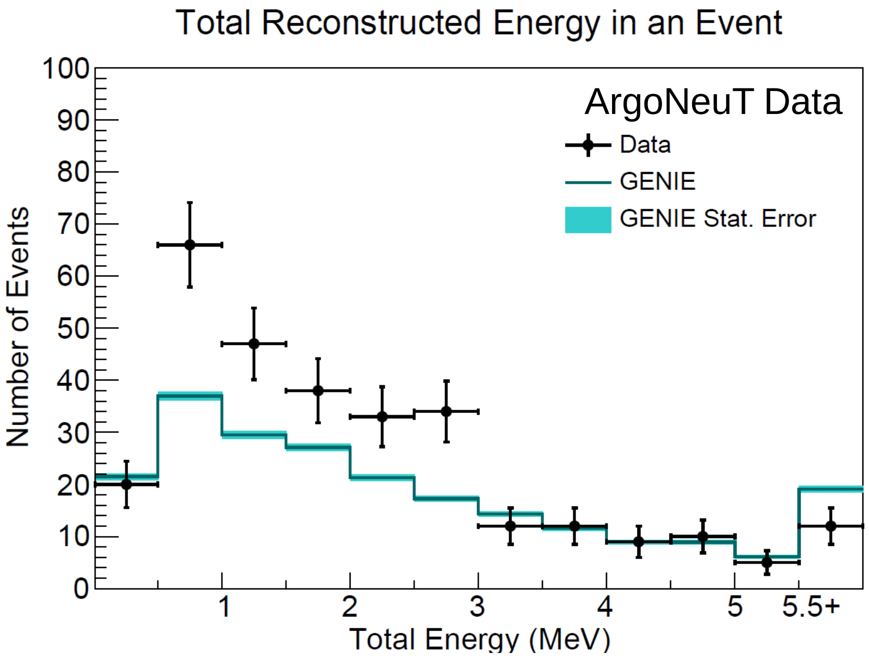


* “FLUKA: A Multi-Particle Transport Code” (CERN-2005-010 INFN/TC_05/11, SLAC-R-773)

Comparison with GENIE

- This simulation contains only neutron-produced photons.
- We see a lack of MeV-scale activity.

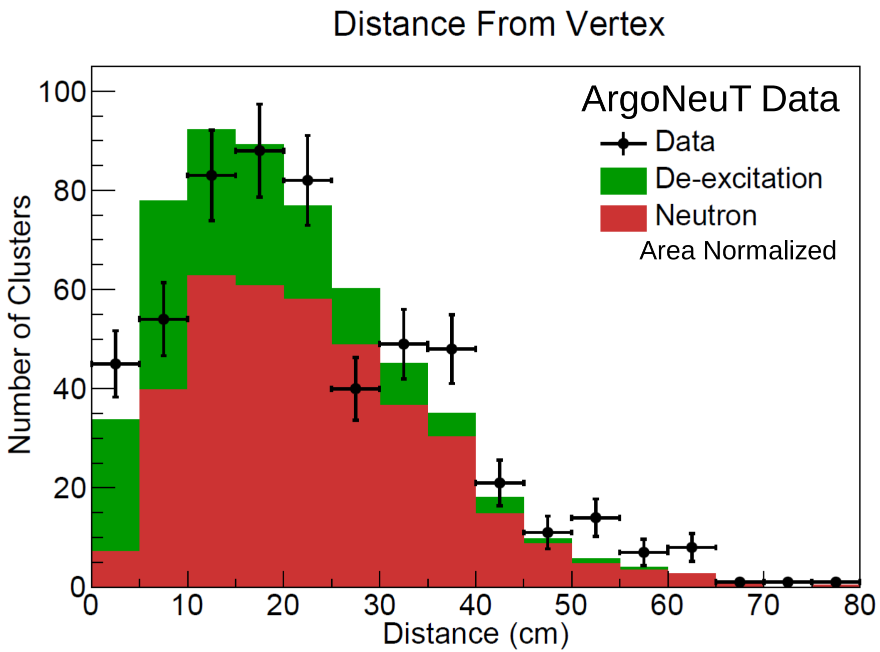




“The GENIE Neutrino Monte Carlo Generator” (Nucl. Instrum. Meth. A614 (2010))

Position Reconstruction

- LArTPCs have excellent spatial resolution.
  - Uncertainties of a few millimeters
- These electrons don't travel very far, so typically the distance traveled is negligible when compared to e.g. the distance from the vertex.
  - We're not looking at how far it traveled, just where it is.



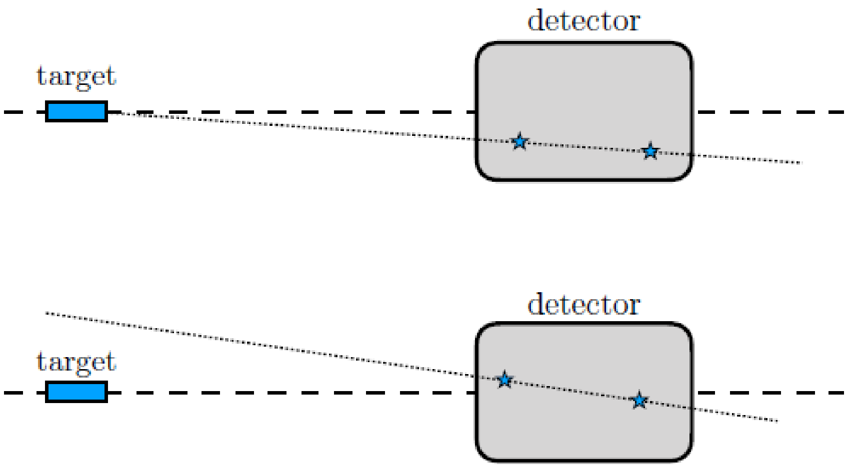
Summary of This Analysis

- This analysis represents the first-ever reported detection of de-excitation photons produced by beam neutrino interactions in argon.
- This is also the first detection of photons from neutron scattering.
- We have extended the LArTPC's range of physics sensitivities down to the sub-MeV level, reaching a threshold of 300 keV in this analysis.
- Published in Phys Rev D **99**, 012002 (2019)

What else can we do with a LArTPC?

Millicharged Particles

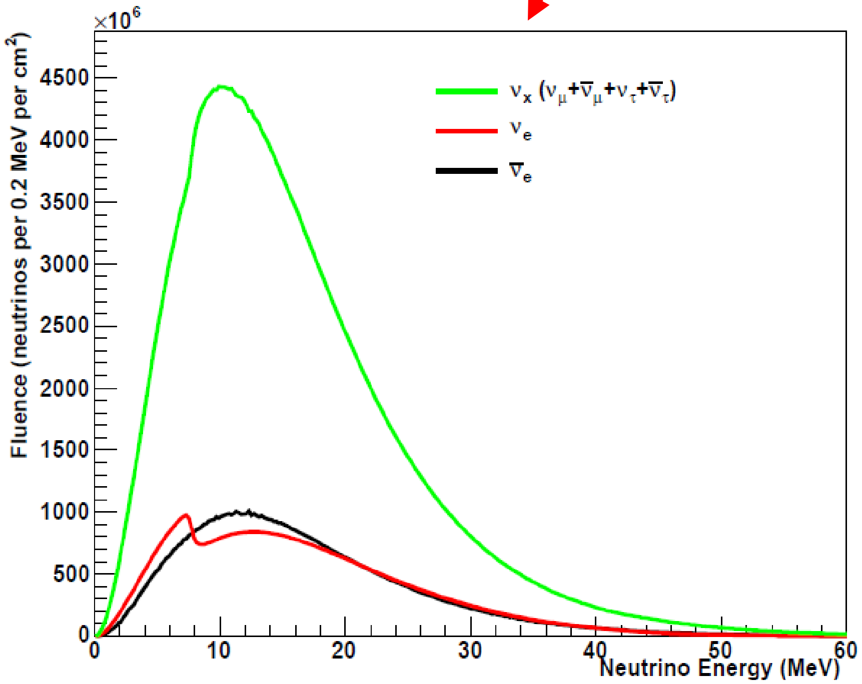
- We can use LArTPCs to search for millicharged particles.
- Signal: low energy depositions pointing back to the target



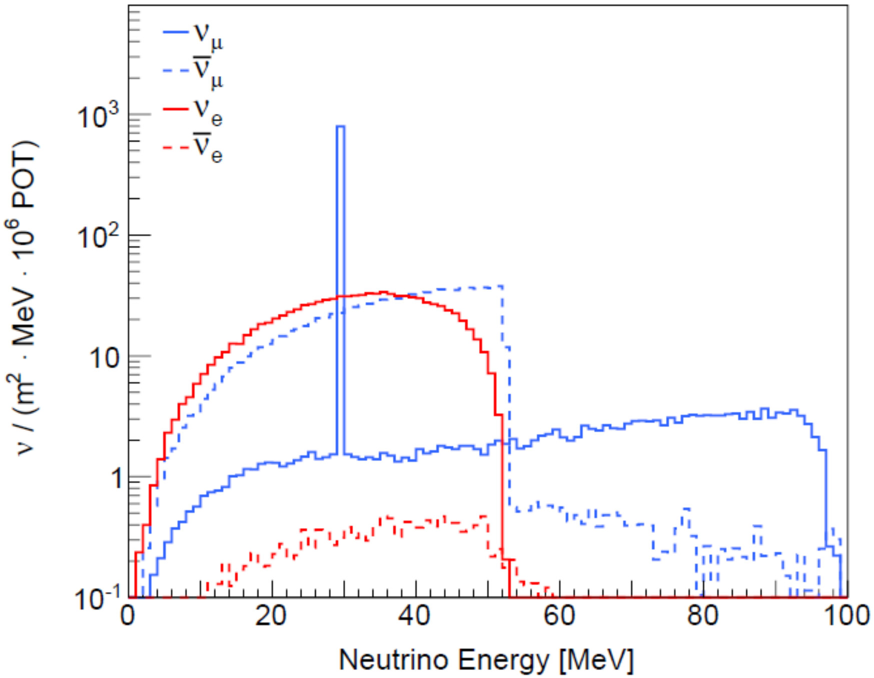
arXiv:1902.03246

Low Energy Neutrinos

Neutrinos from supernovae and pion decay at rest have energies <50 MeV

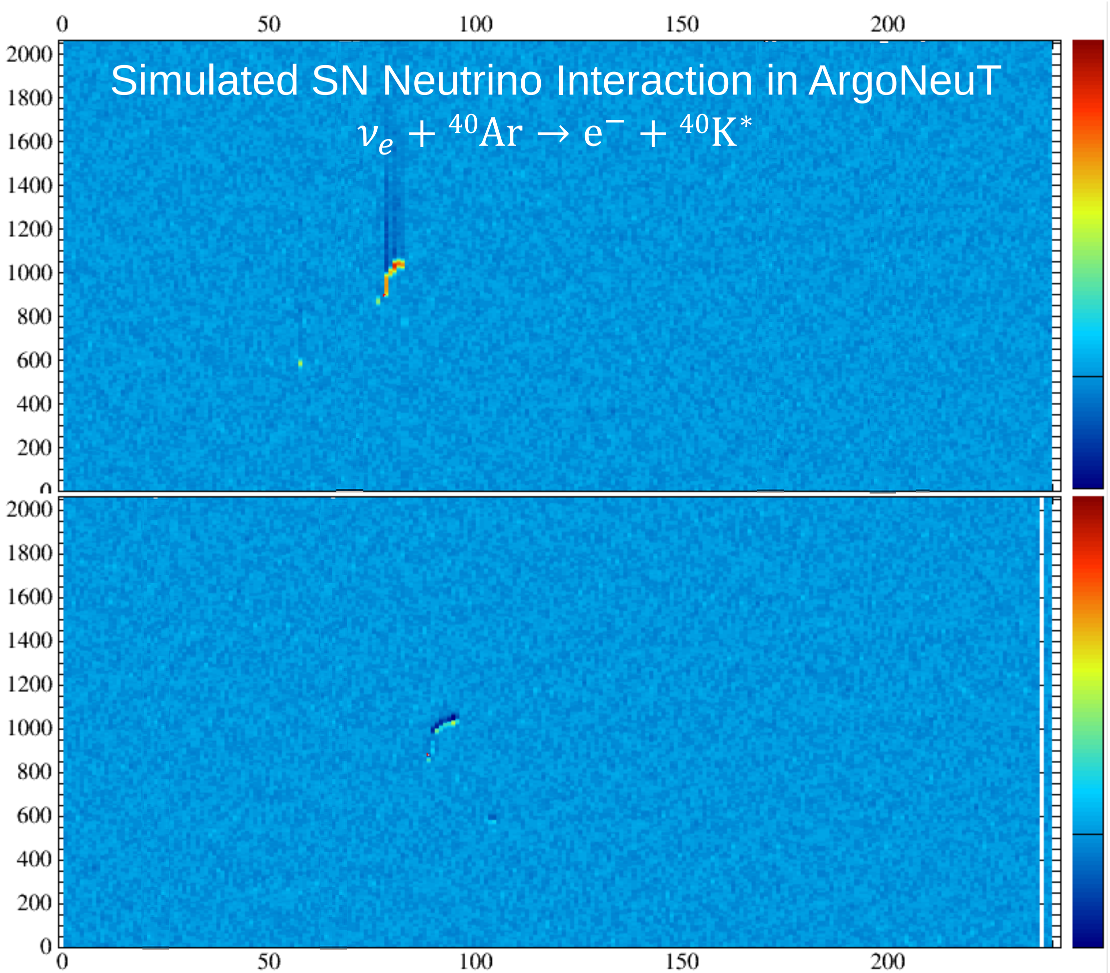


Nucl. Phys. Proc. Suppl., 91:331-337, 2001

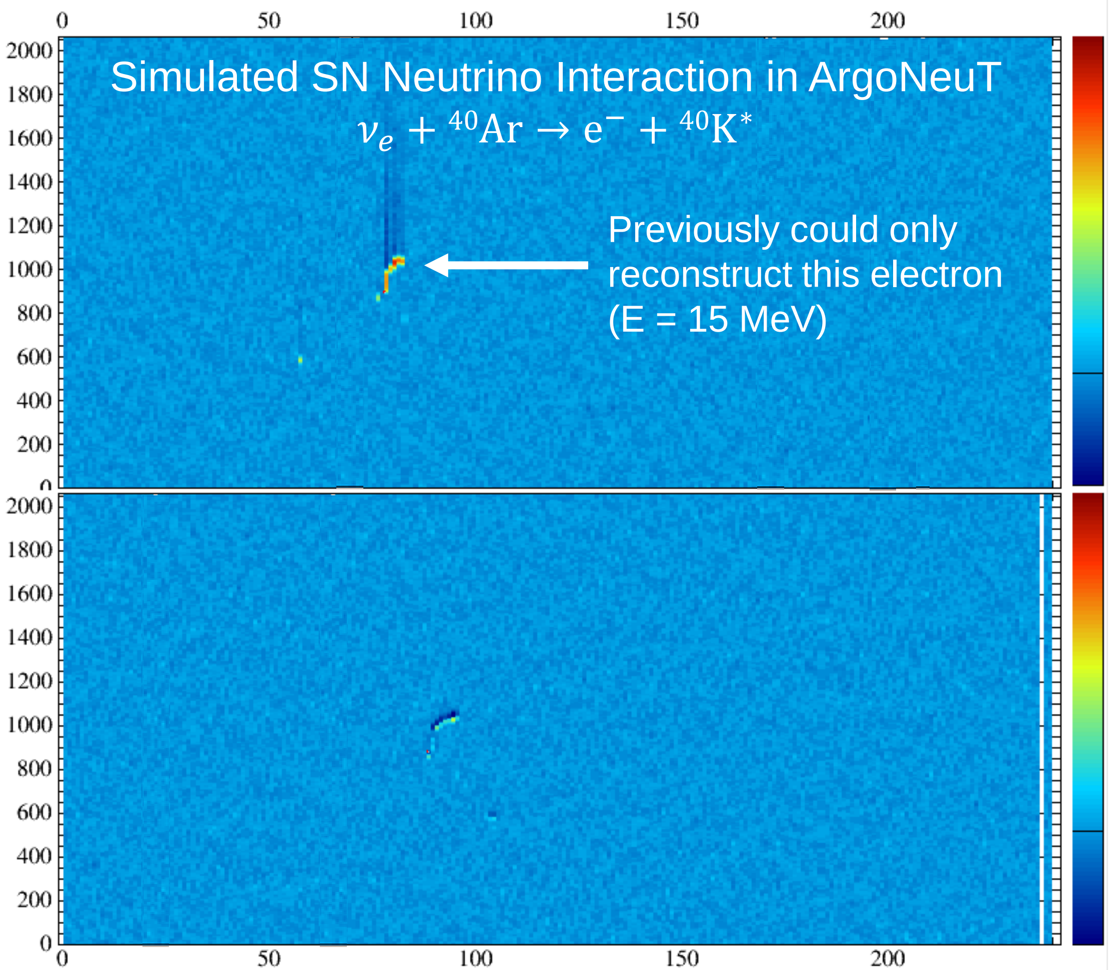


arXiv: 1510.08431

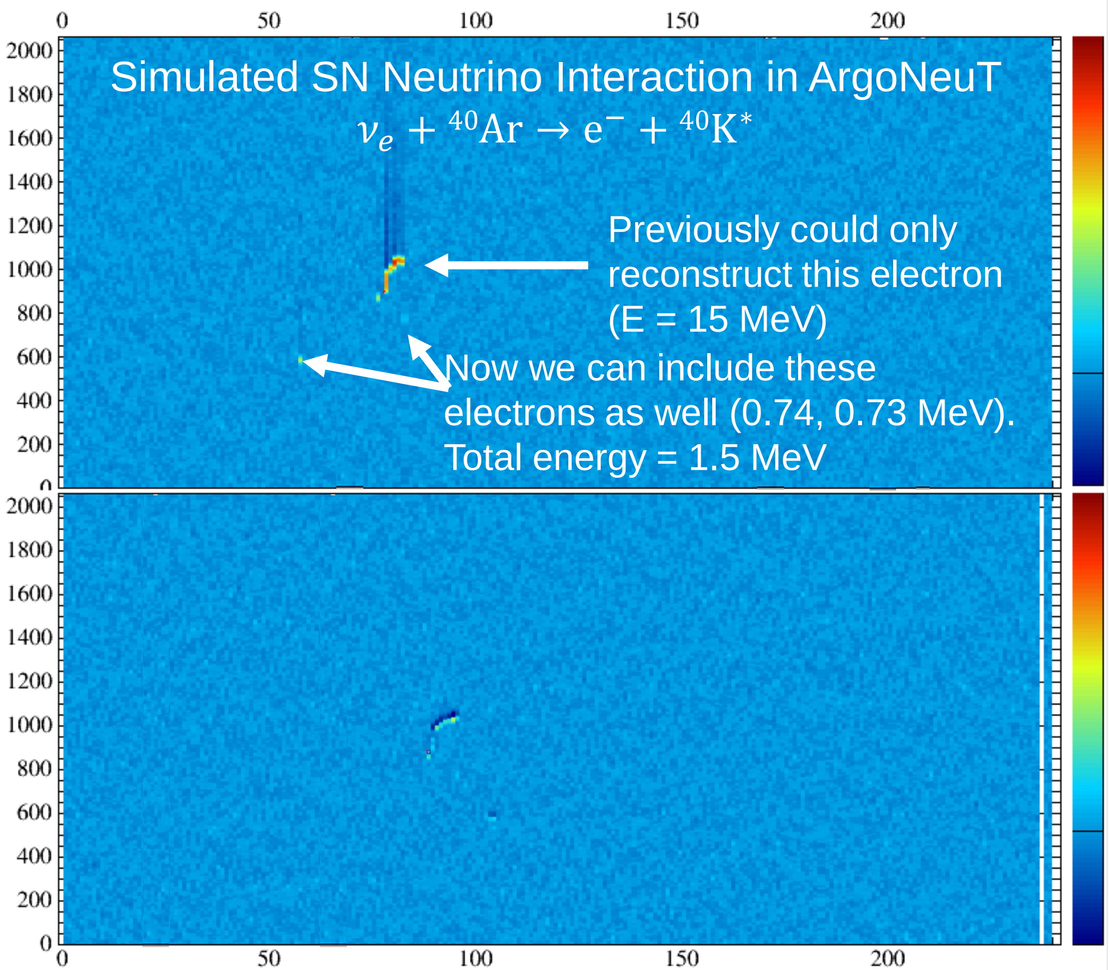
Supernova Neutrinos



Supernova Neutrinos



Supernova Neutrinos



Can We Improve on This?

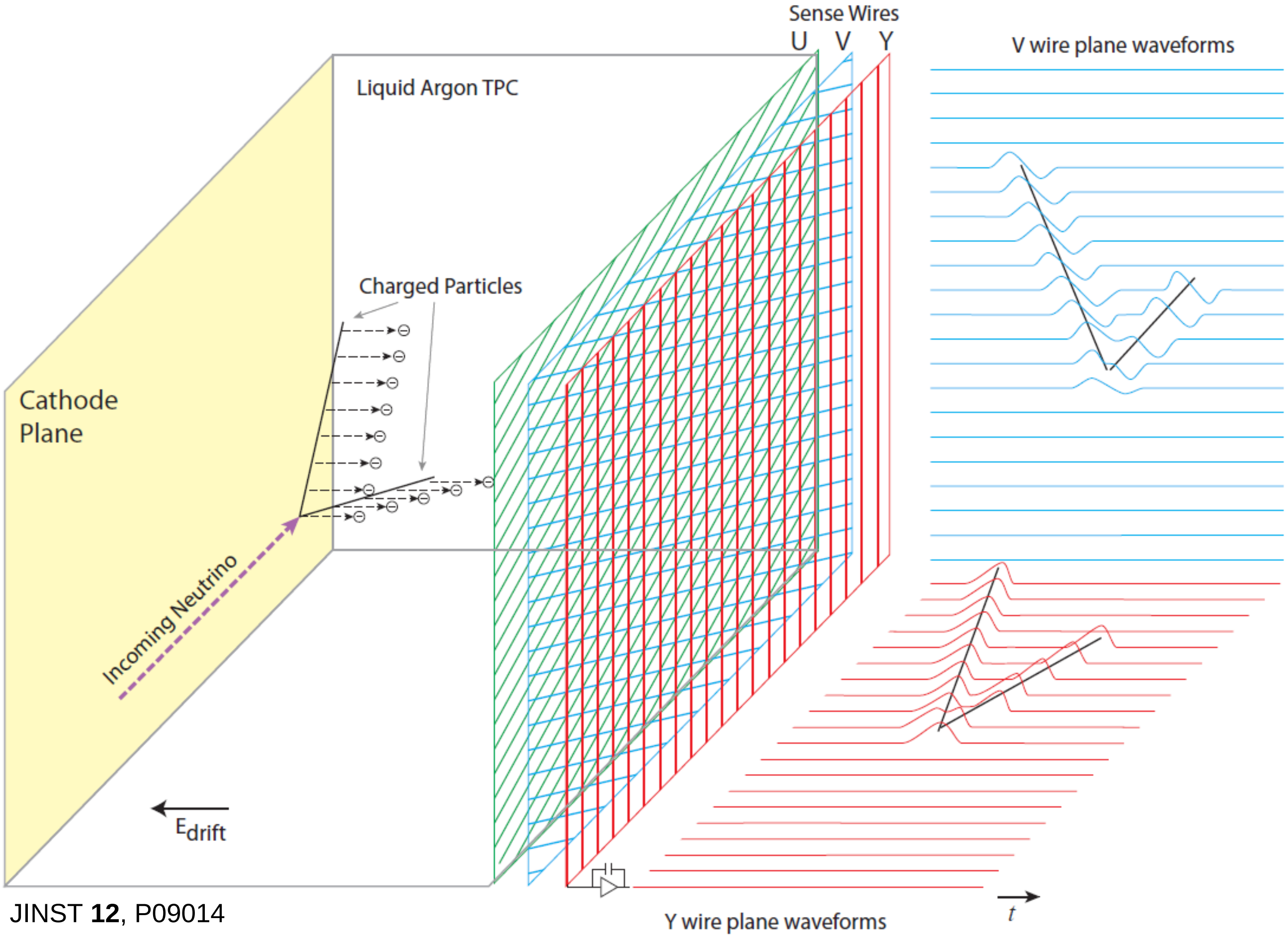
- Future thresholds will be lower.
  - Especially with DP detectors
- We might be able to see coherent elastic neutrino-nucleus scattering.
- We might be able to measure spectral features of photons from neutron scattering.
- We could measure neutron cross-sections
  - Would help current and future LArTPC experiments, like DUNE

Backups

The Liquid Argon Time Projection Chamber

- Major neutrino detection technology in the US
  - Several at Fermilab
  - Example: DUNE
- Two types: single phase and dual phase
- This talk discusses what's possible with a single phase detector.

The Liquid Argon Time Projection Chamber

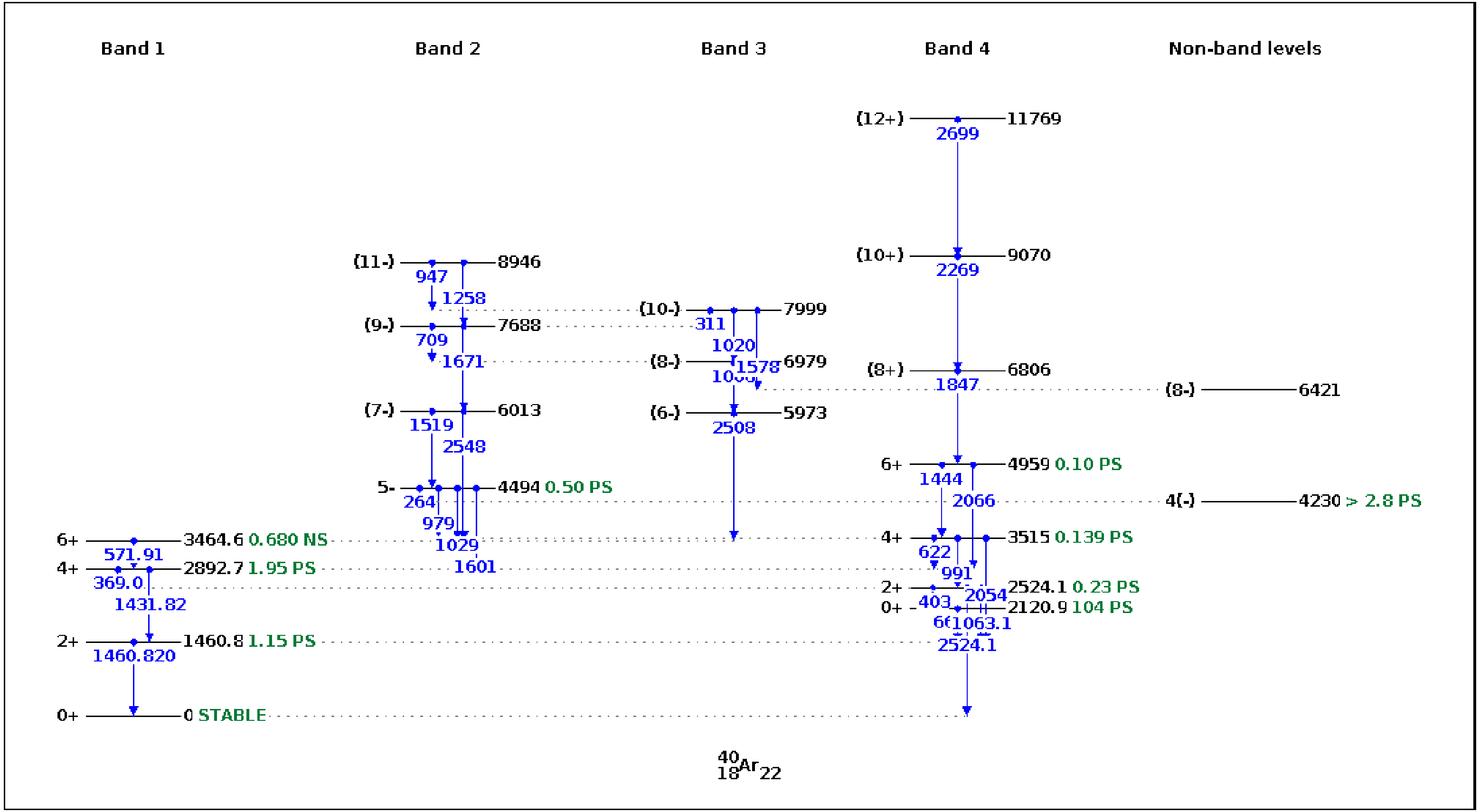


JINST **12**, P09014

Advantages of LArTPCs

- Scale to large sizes
- Excellent spatial resolution.
  - Uncertainties of a few millimeters
- Low energy (sub-MeV) thresholds.
- ArgoNeuT has recently demonstrated the ability to detect isolated electrons from Compton scatters.
  - Threshold: 300 keV
  - Electrons came from photons from nuclear de-excitation and inelastic neutron scattering.
  - Described in Phys Rev D **99**, 012002 (2019)

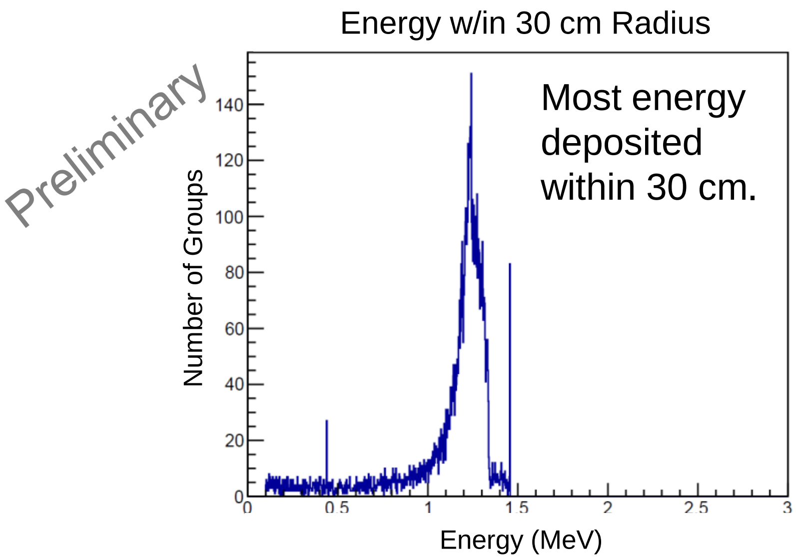
Energy Levels for ^{40}Ar

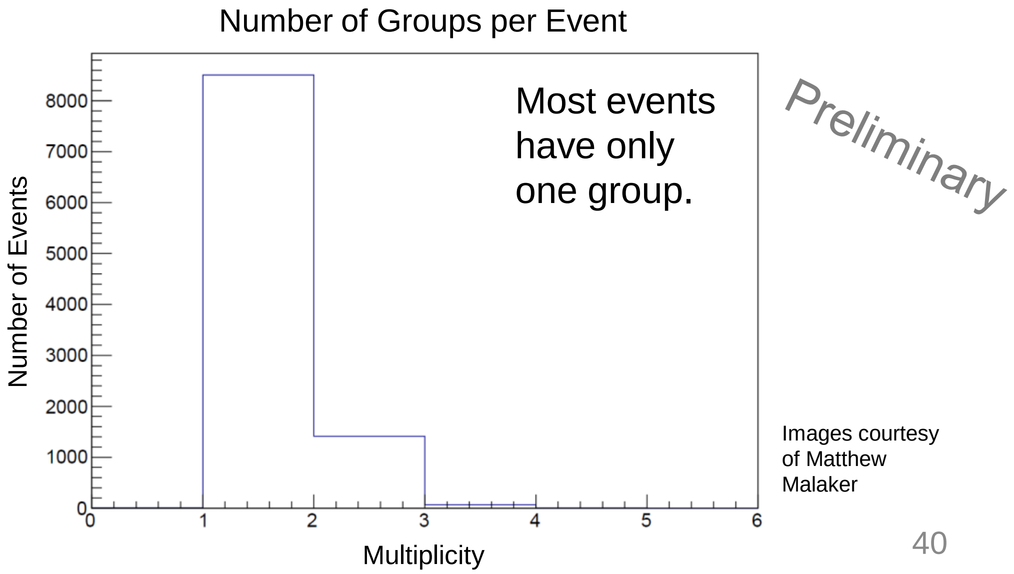


Source: NNDC. For more levels, see https://www.nndc.bnl.gov/chart/chartNuc.jsp

Spectral Features

- Can we reconstruct the energy of a photon?
- What if we grouped blips?
  - Group = blips within *x* cm of average blip location
- Plots below come from a simulation of 1.46 MeV photons.
  - Blips: truth information of electrons
  - 100 keV threshold





Images courtesy of Matthew Malaker

Spectral Features

- This isn't the whole story.
- What if we have more than one photon? Neutrons?
- 100 keV is a reasonable threshold, but can we do better?
- Will there be overlaps of groups?