Benefits of MeV-Scale Calorimetry in Large LArTPCs

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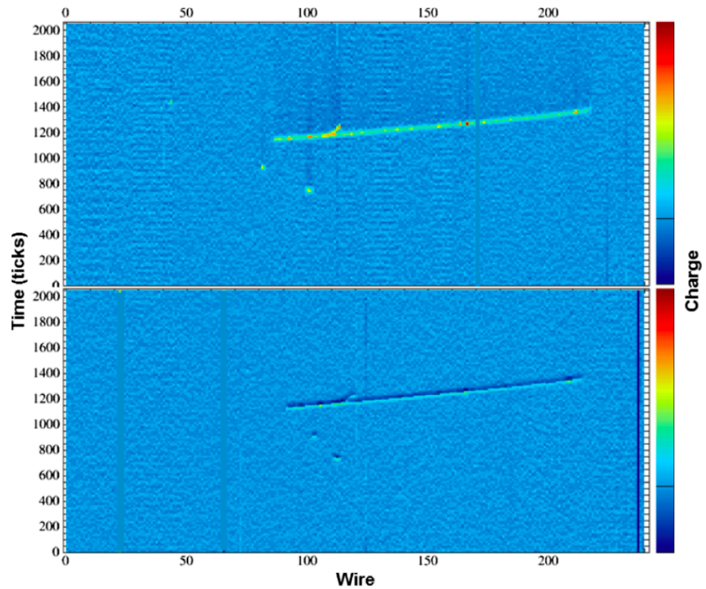
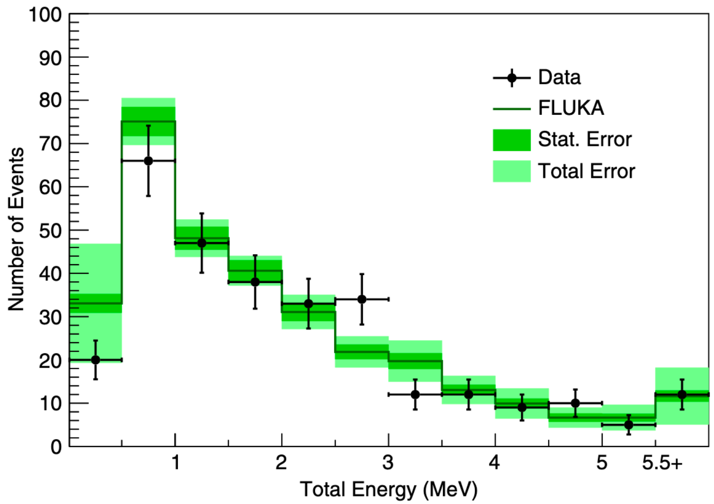
MeV-scale Calorimetry Overview

- LArTPCs have a low energy threshold
  - 24 eV mean ionization energy
  - High electron collection efficiency
  - Low noise
- Studies have shown LArTPCs are sensitive to sub-MeV scale physics
  - *ArgoNeuT:* 200-300 keV threshold by looking at de-excitation γ's [Phys. Rev. D 99, 012002]
- Recent paper, [arXiv:2006.14675], explores how low-energy capabilities can aid in:
  1. Supernova/solar neutrino energy reco and interaction channel ID
  2. Neutron ID and calorimetry
  3. EM shower reconstruction
  4. Particle discrimination
  5. Single-gamma spectroscopy

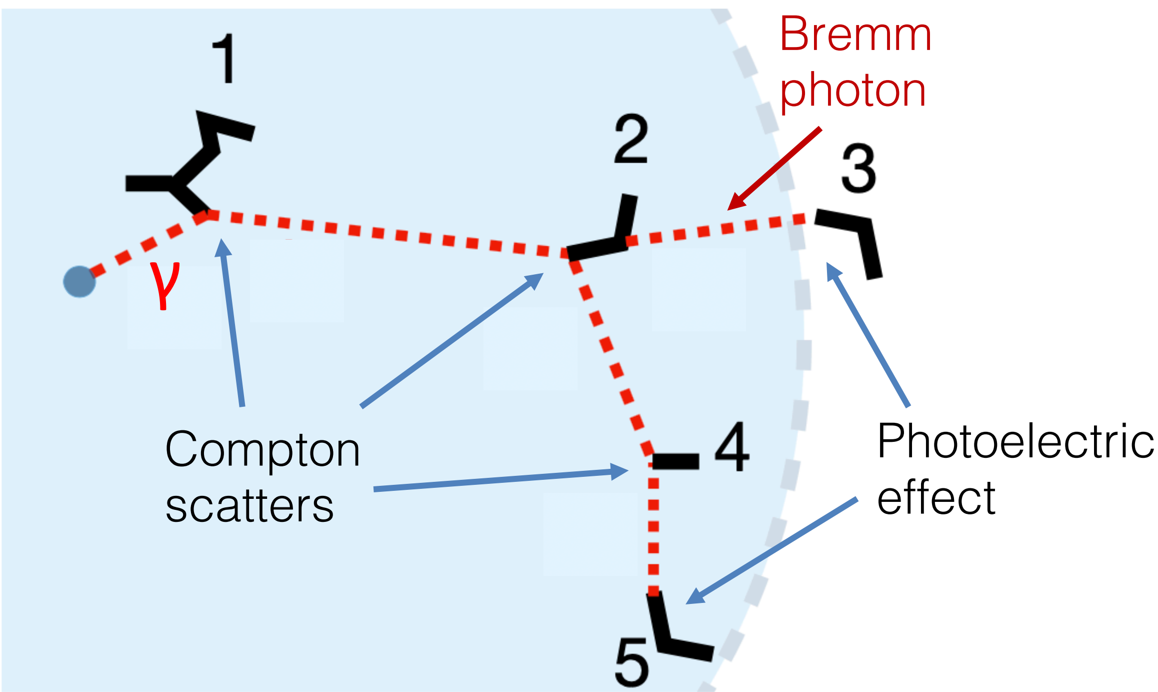




Defining a "blip"

Low-energy electrons (< ~5 MeV) scatter around as they thermalize, creating compact ionization clusters on the ~mm to ~cm scale

- Produced by photons that undergo Compton-scatter, photoelectric effect, or pair production
- Ionization extends along only 1-2 wires in reconstruction
- Result: spatially isolated "blips" of charge



Defining a "blip" (technical definition)

All studies shown here were done using truth-level Geant4 information.

Blips defined as:

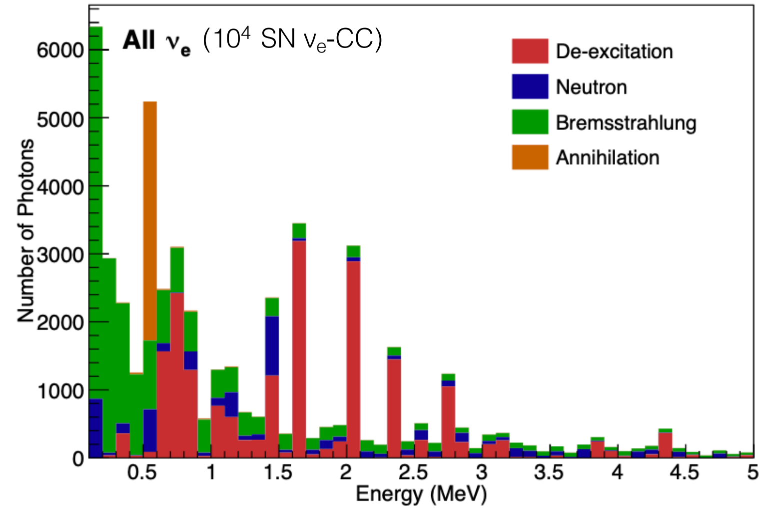
- Contiguous, spatially-isolated energy depositions from electrons
- Blips with < 2 mm separation are merged (these likely to be grouped into same hit or appear on adjacent wires/pads in any reasonable reco)
- E_{dep} > 75 keV
  - Lower than the 200-300 keV achieved in ArgoNeuT, based on expected improvement in cold electronics (JINST 12, P08003)

1) Supernova / solar neutrinos: calorimetry

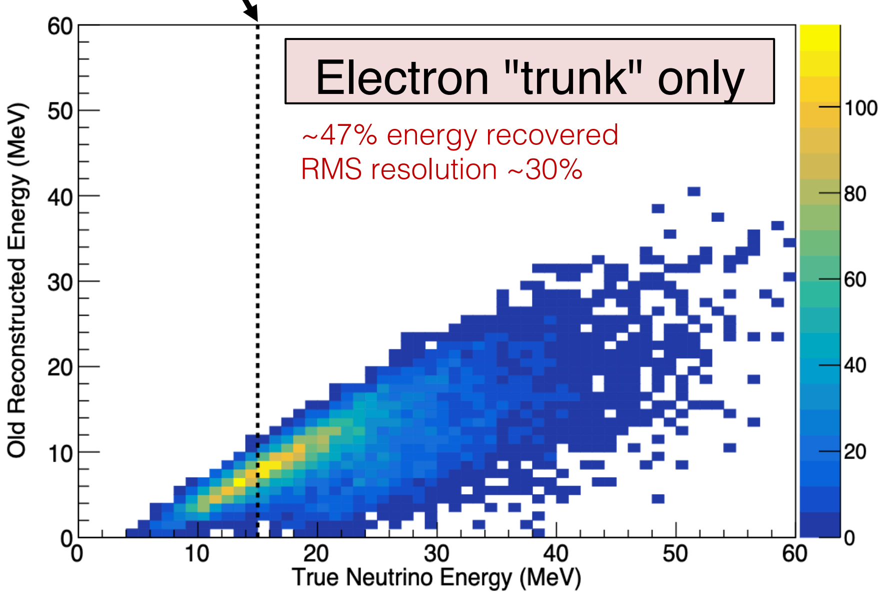
Supernova neutrino primary detection channel:

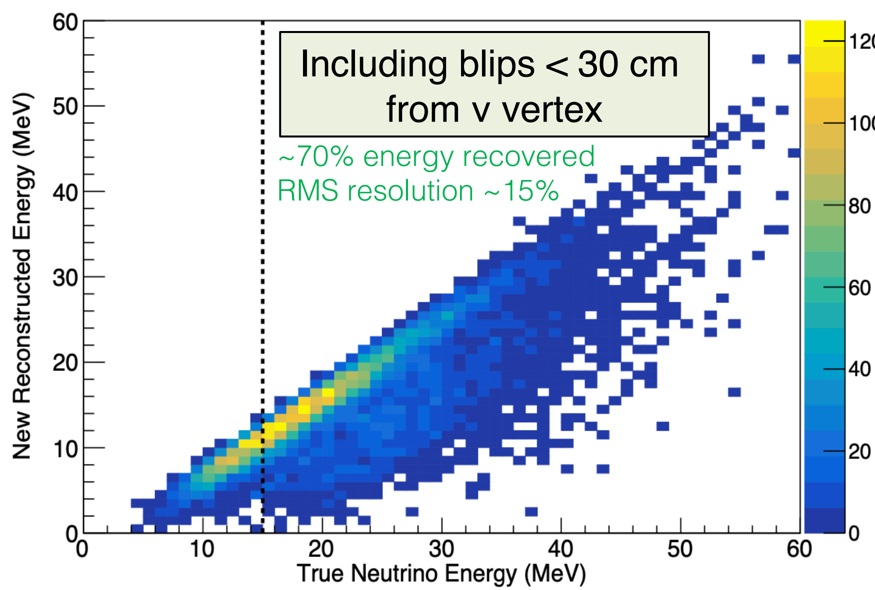
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

Final-state γ's produced



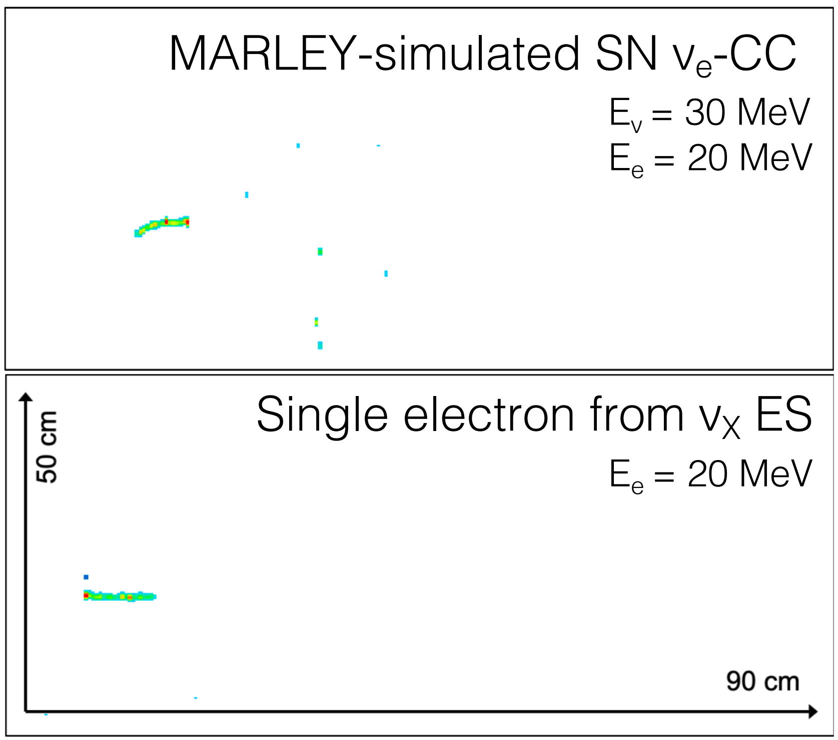
Endpoint of ^{8}B solar neutrino spectrum

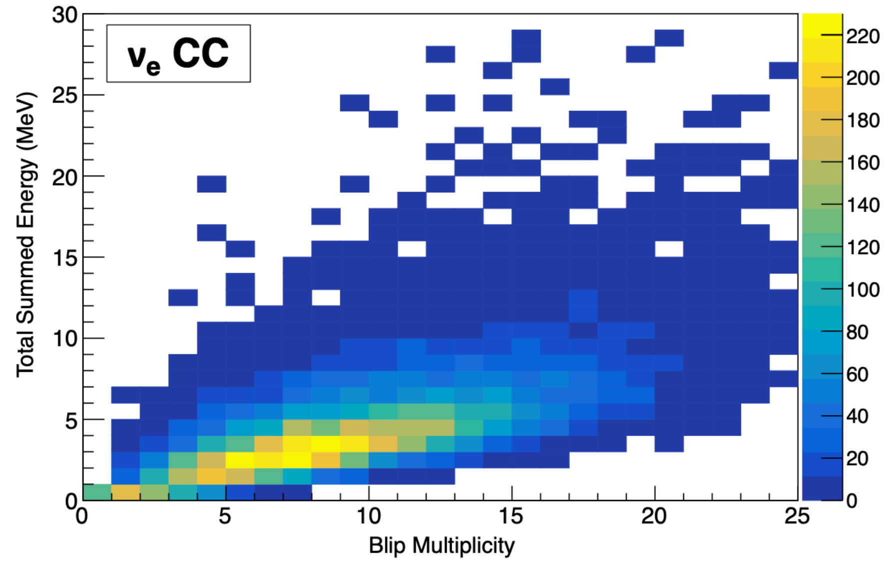


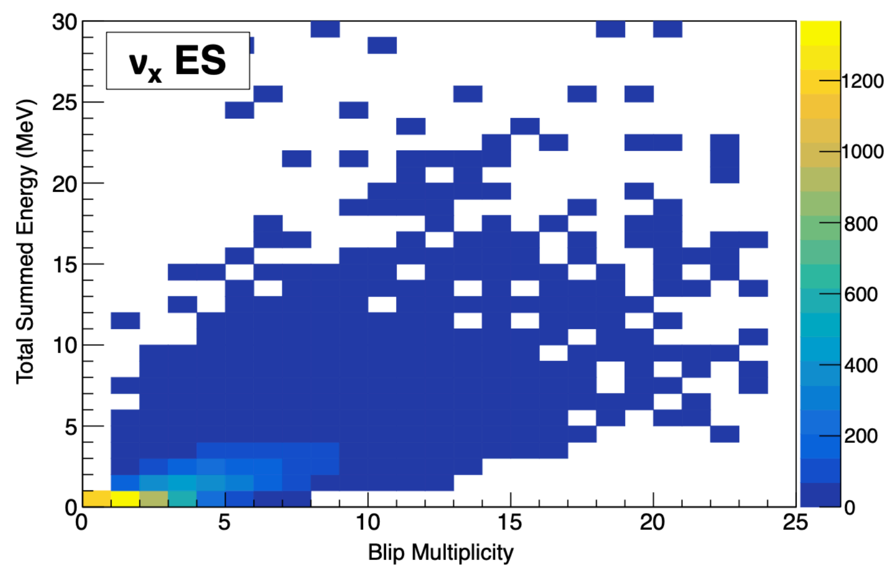


1) Supernova / solar neutrinos: interaction channel ID

Blip multiplicity and total summed energy can provide handle for identifying ν_e CC from ν_x electron scattering (ES).





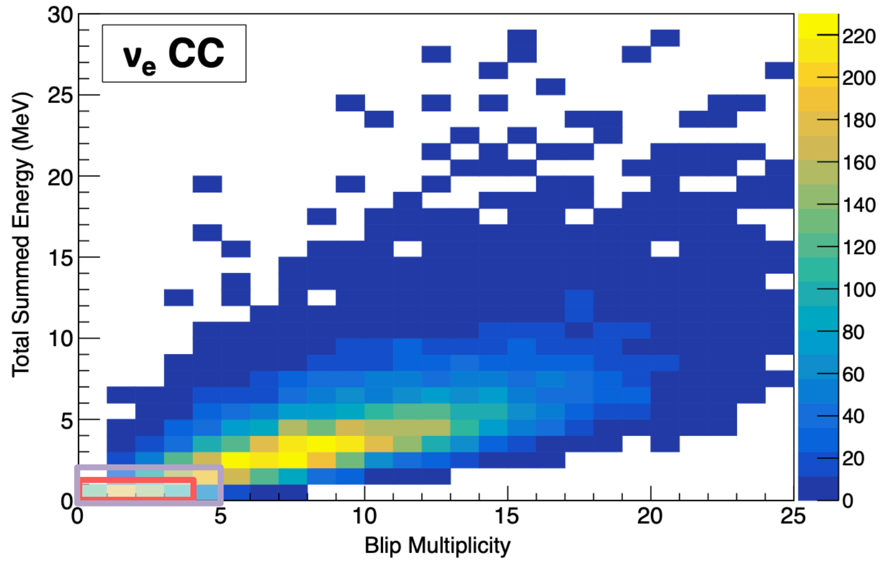


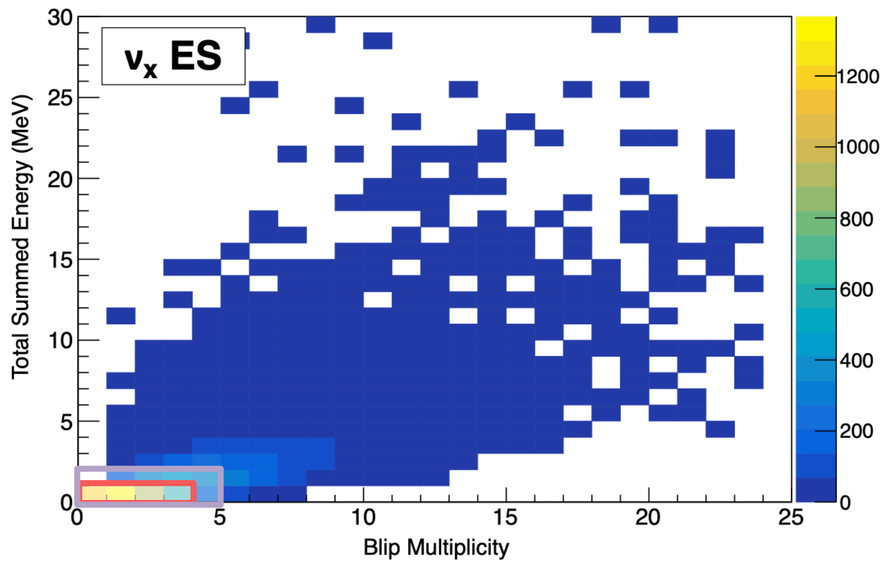
1) Supernova / solar neutrinos: interaction channel ID

Assuming CC:ES ratio of ~9:1...

Threshold	Sphere Radius	# Blips	Energy	Efficiency	Purity
75 keV	0.5 – 30 cm	–	< 1 MeV	44%	43%
75 keV	0.5 – 30 cm	< 4	–	56%	35%
75 keV	0.5 – 30 cm	< 4	< 1 MeV	40%	45%
75 keV	0.5 – 60 cm	–	< 2 MeV	59%	55%
75 keV	0.5 – 60 cm	< 5	–	58%	48%
75 keV	0.5 – 60 cm	< 5	< 2 MeV	51%	60%
300 keV	0.5 – 60 cm	–	< 1 MeV	46%	60%
300 keV	0.5 – 60 cm	< 2	–	46%	60%
300 keV	0.5 – 60 cm	< 2	< 1 MeV	40%	62%
300 keV	0.5 – 60 cm	< 1	–	21%	67%

TABLE II. Efficiency and purity in selecting ν_x ES events from a larger sample of ν_e CC events using only cuts on reconstructed blip activity. Efficiency and purity definitions are given in the text.

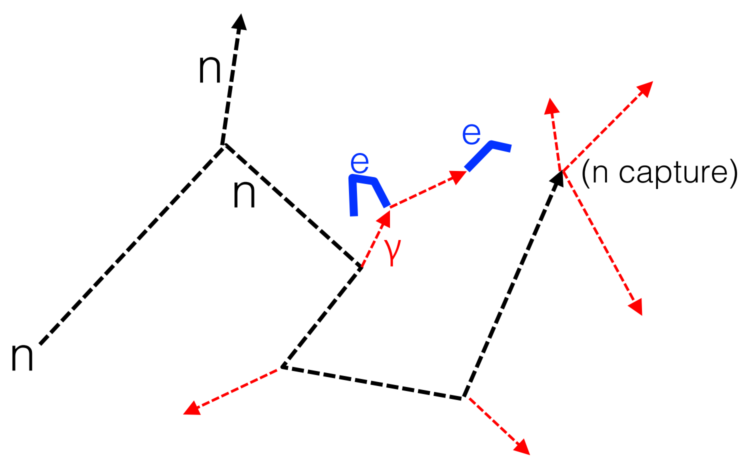


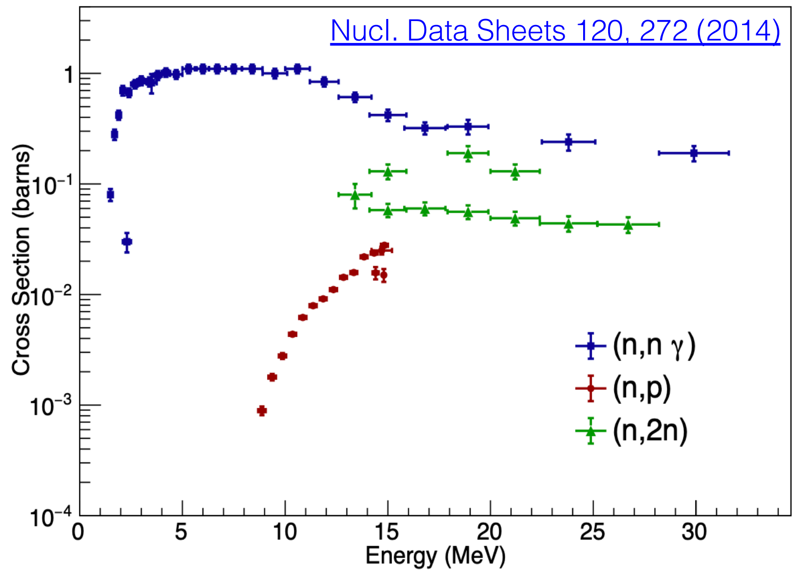


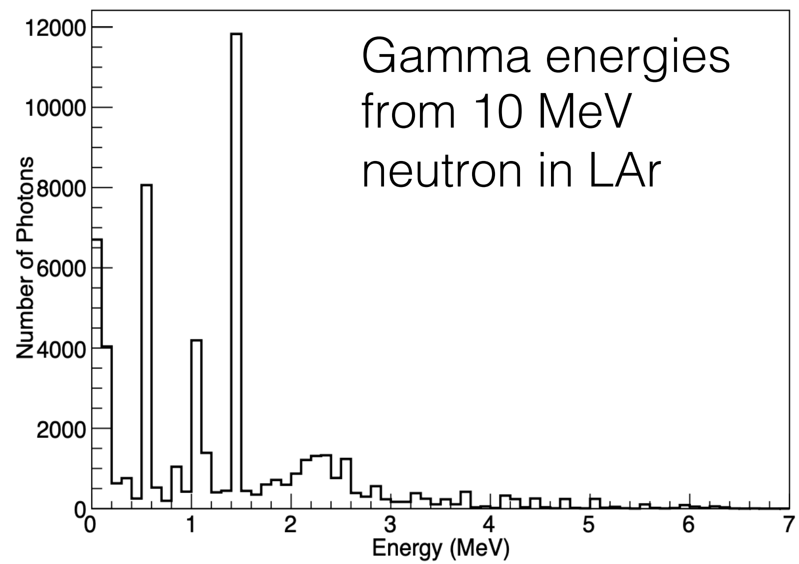
2) Final-state neutron ID and calorimetry

Some energy is "lost" in kinetic energy given to neutrons.

- Sub-MeV to 10s of MeV range
- Neutrons in 0-20 MeV range prefer γ-producing inelastic scatters
  — Also undergo n-producing inelastic scatters, the neutrons from which then go on to undergo γ-producing inelastic scattering...

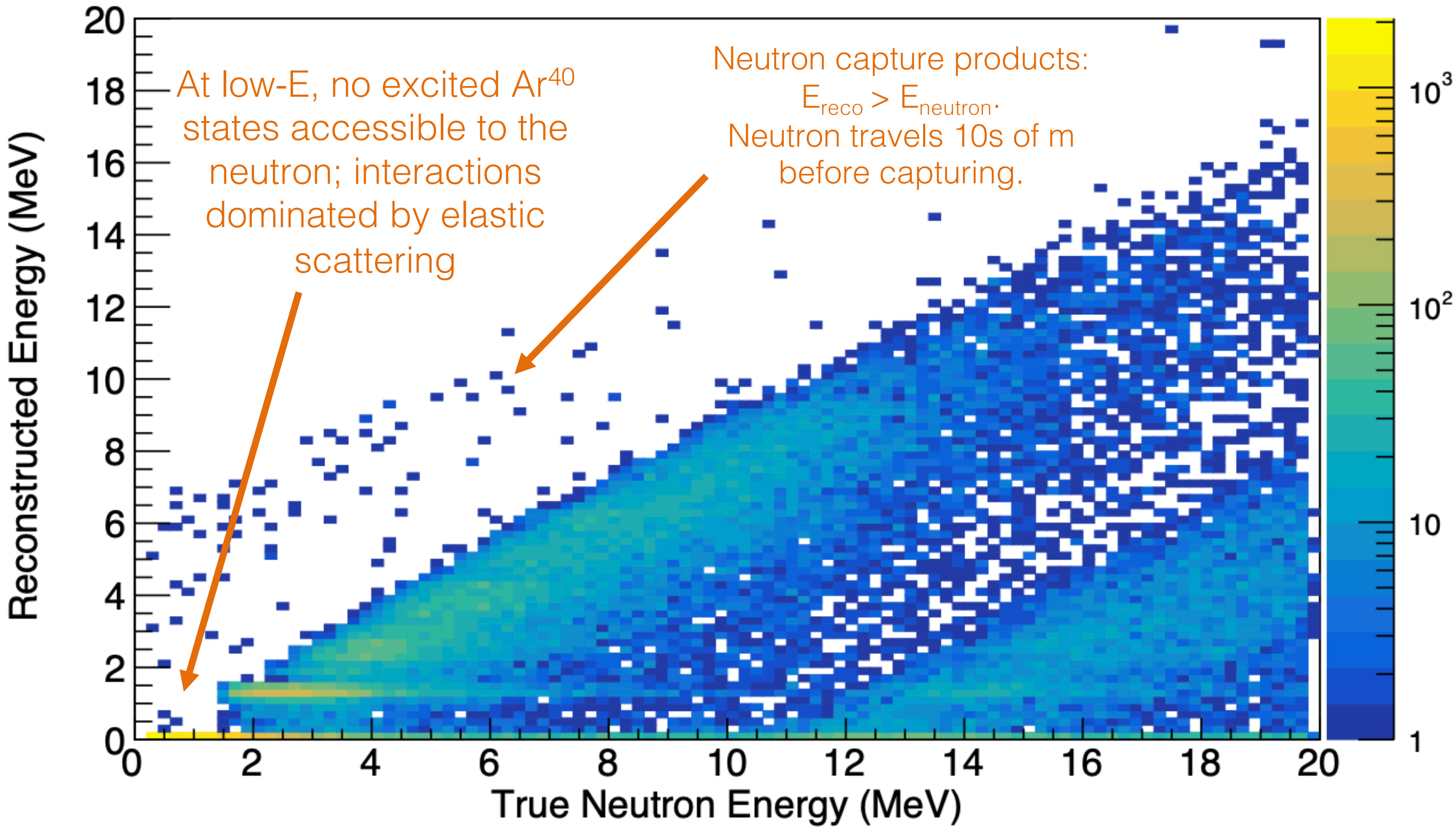






2) Final-state neutron ID and calorimetry

Adding up "blip" energies within 60 cm of neutron production point...



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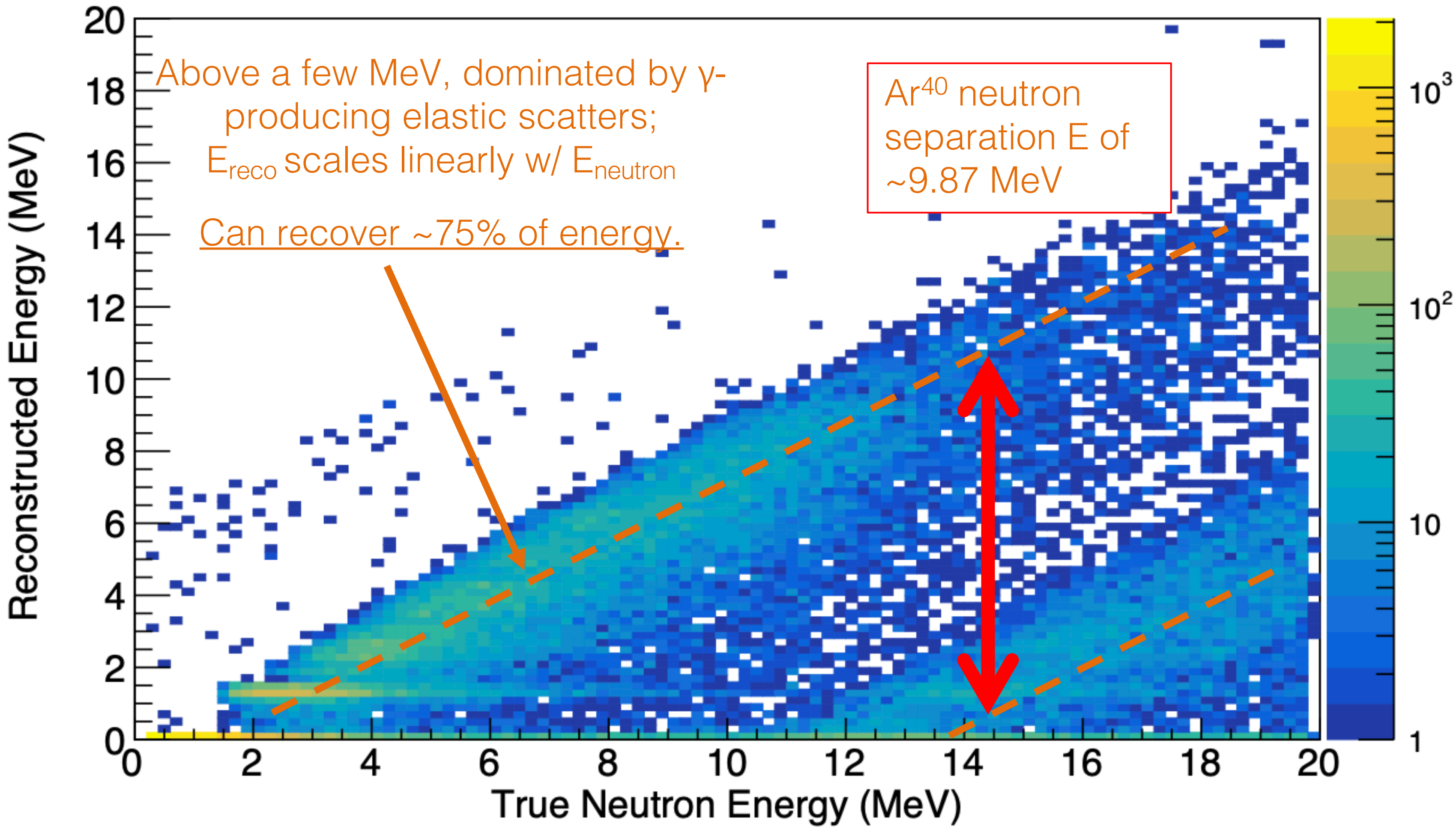
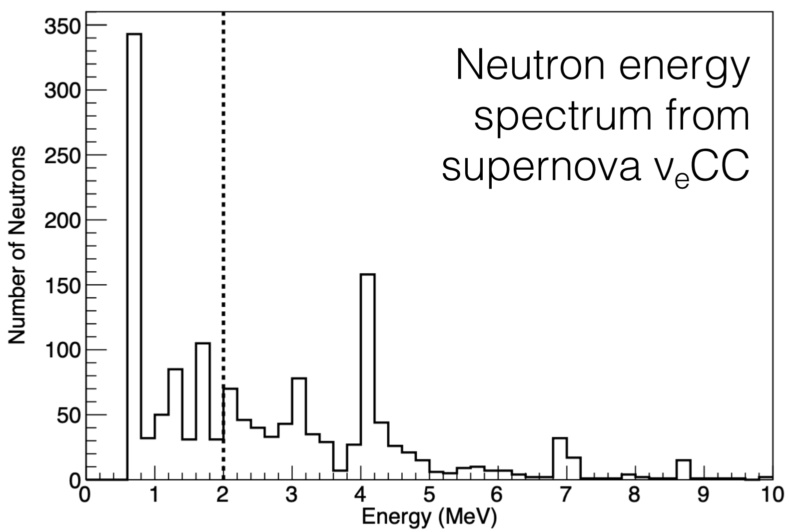


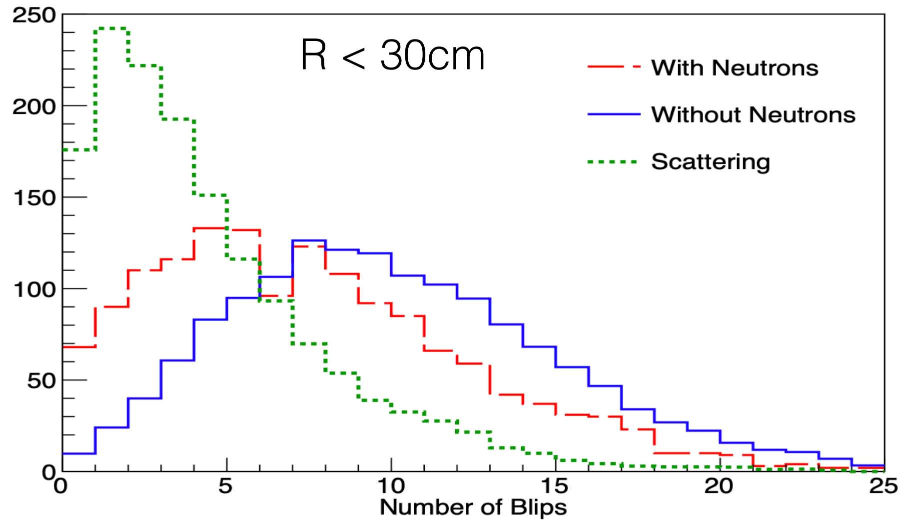
2) Neutron ID for supernova neutrinos

Blip activity will play critical role in determining energy content of neutrons at *low energies* (<100 MeV).

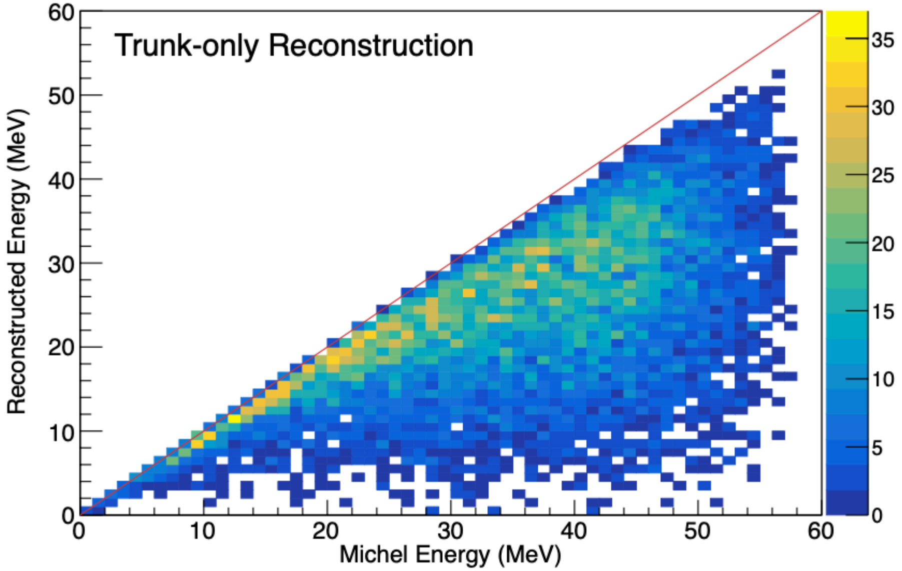
Supernova / solar neutrino events:

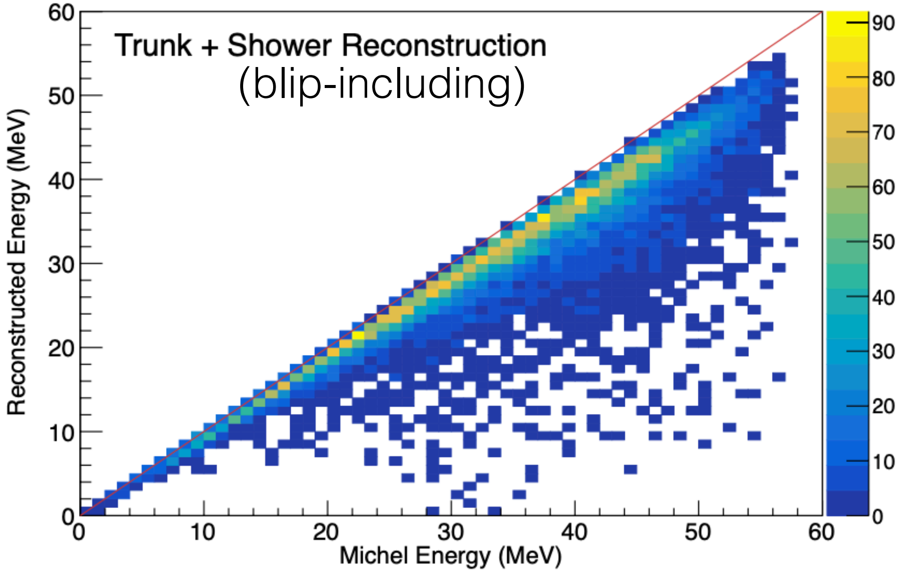
- 15% produce >1 neutron
- Neutrons carry only small fraction of total FS energy
- <u>But</u> 7.8 MeV of neutrino energy goes into freeing the neutron, *so being able to tag an event as n-producing can substantially improve energy resolution*
- Possible to exploit longer interaction distance of neutrons vs. gammas by using # blips and/or blip distance from vertex as input to BDT





3) Electromagnetic Shower Reconstruction





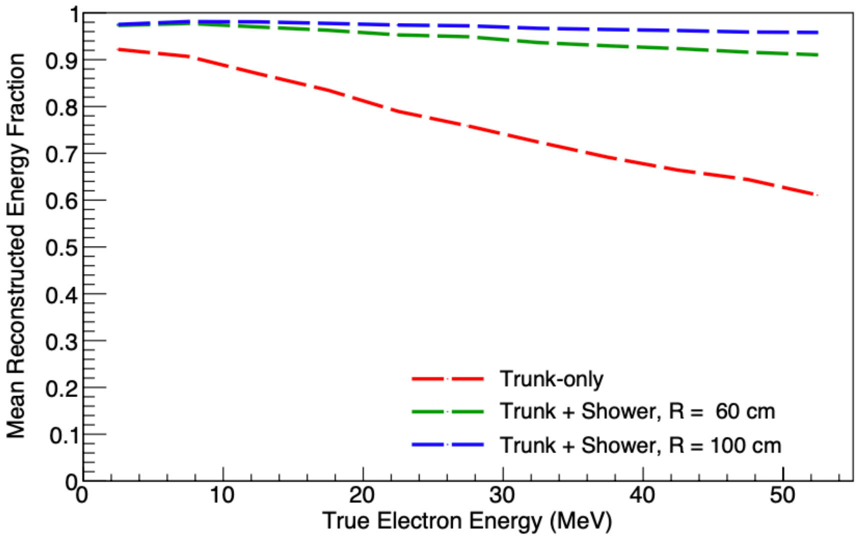
"Trunk" refers to the ionization from the contiguous electron track only.

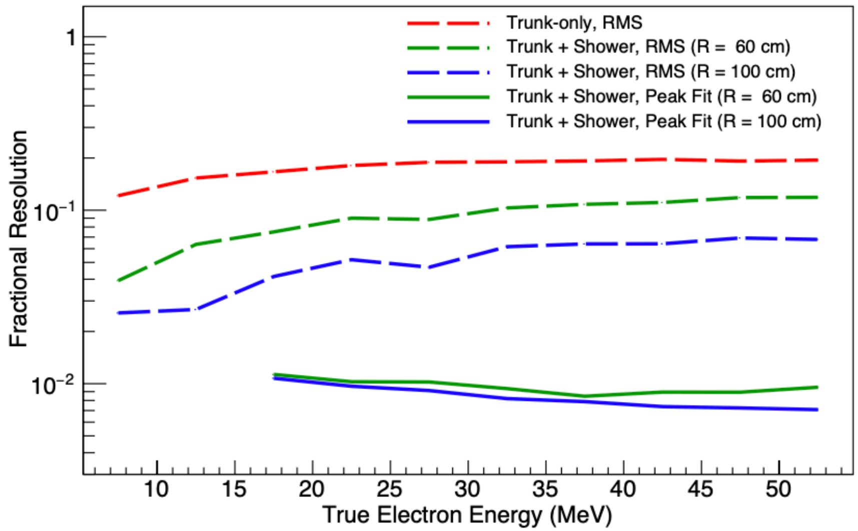
"Shower reconstruction" includes both trunk + isolated blips within 60 cm of electron starting point.

3) Electromagnetic Shower Reconstruction

Higher fraction of reconstructed energy as well as **better energy resolution** when blips are included.

Max achievable resolution of ~1% (75 keV threshold, no smearing)



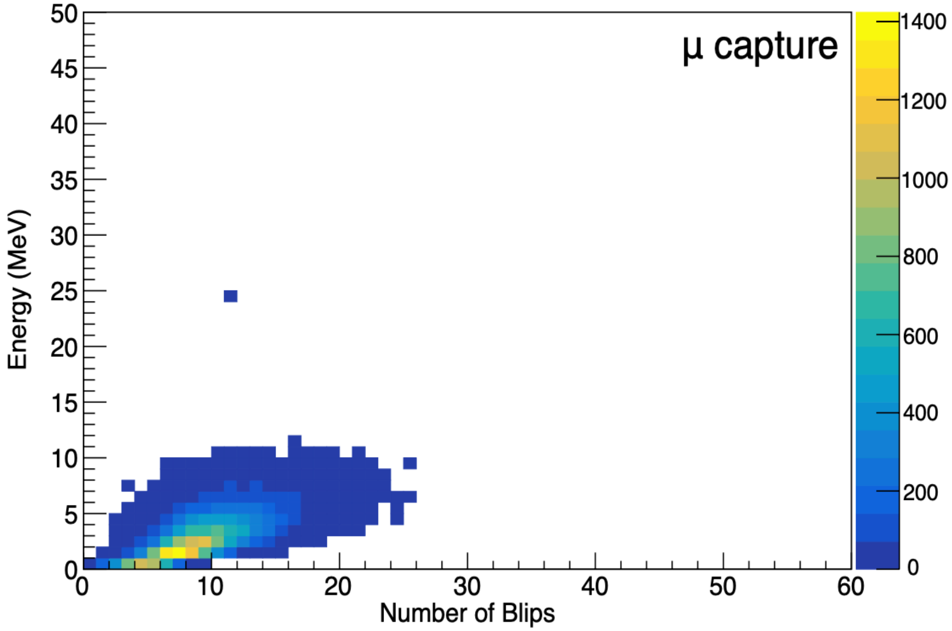


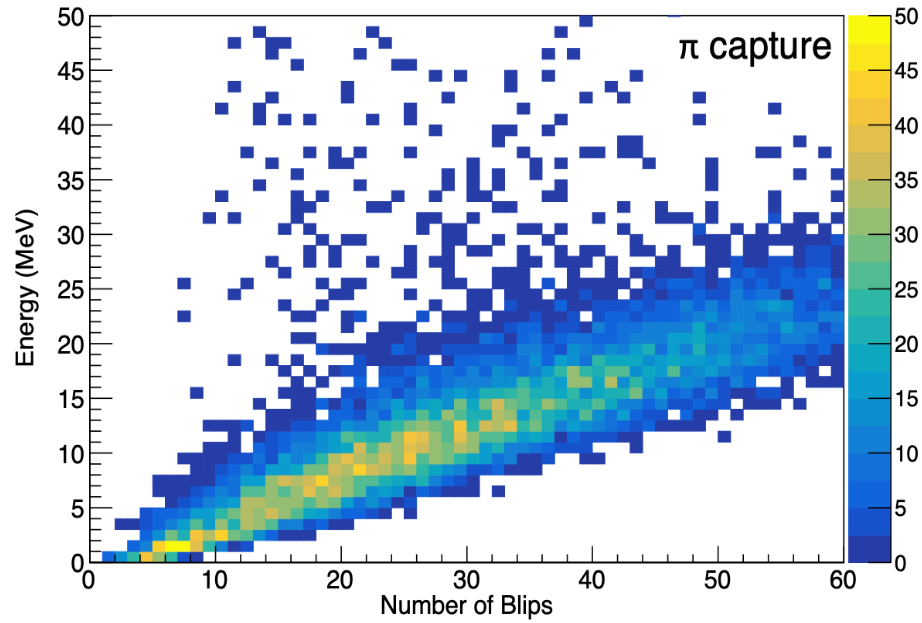
4) Particle Discrimination Capabilities

- Muon/pion separation is difficult
- Differing probabilities of capture/decay, as well as different capture final-states
- In principle, can use MeV-scale activity near candidate endpoint to help discriminate pion from muon

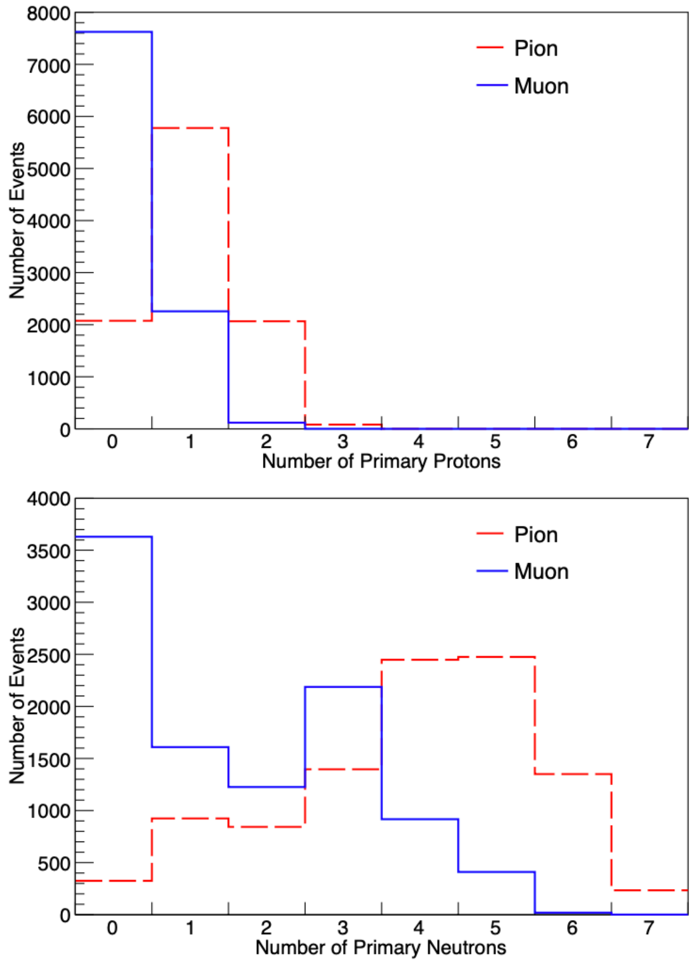
Particle	Decay (%)	Capture (%)	Other (%)
π^+	72	0	28
π^-	3	63	34
μ^+	100	0	0
μ^-	26	74	0

TABLE III. End-of-life processes for 100 MeV positively and negatively charged muons and pions as simulated in Geant4. Decay processes will produce Michel electrons, while capture and other processes (such as absorption and charge exchange) will not.





4) Particle Discrimination Capabilities



Blip multiplicity, blip energy, and vertex activity are used as metrics to make simple selection cuts.

Can obtain a statistically enhanced purity sample of π- capture-at-rest (CAR)

Radius	N_{blip}	E_{blip}	E_{vert}	μ CAR	μ Decay	π CAR
30 cm	> 7	–	–	34%	66%	85%
30 cm	–	$\geqslant$ 4 MeV	–	15%	45%	76%
30 cm	> 7	$\geqslant$ 4 MeV	–	12%	41%	73%
60 cm	> 14	–	–	6.0%	48%	85%
60 cm	–	$\geqslant$ 8 MeV	–	1.7%	41%	76%
60 cm	> 14	$\geqslant$ 8 MeV	–	0.80%	32%	75%
60 cm	–	–	$>$ 5 MeV	18%	0%	74%
60 cm	> 14	$\geqslant$ 8 MeV	$>$ 5 MeV	0.17%	0%	52%

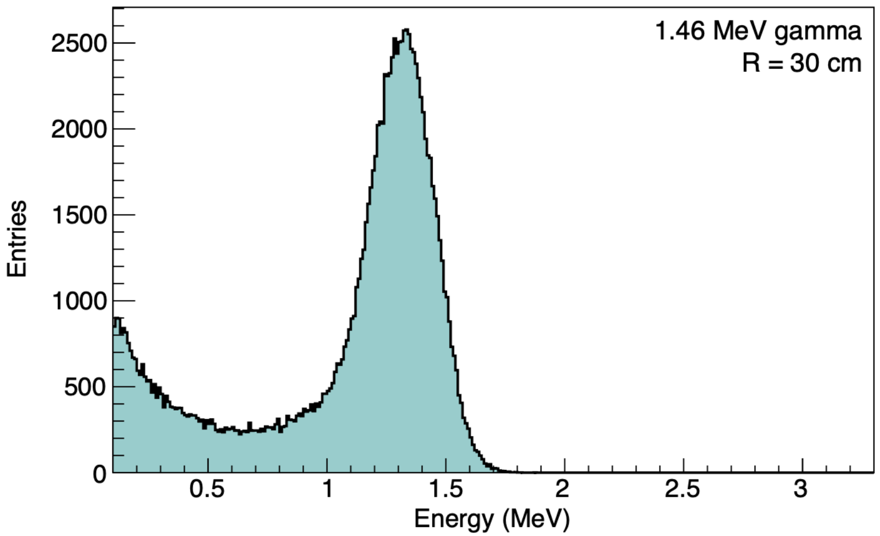
TABLE IV. Selection efficiency for various applied blip activity and vertex activity cuts for μ^- captures at rest (CAR), decaying μ^-, and π^- CAR. The vertex region is defined by a 0.5 cm radius sphere centered at the particle's decay or capture point; only blips found outside of this region are considered.

5) Single Gamma Spectroscopy

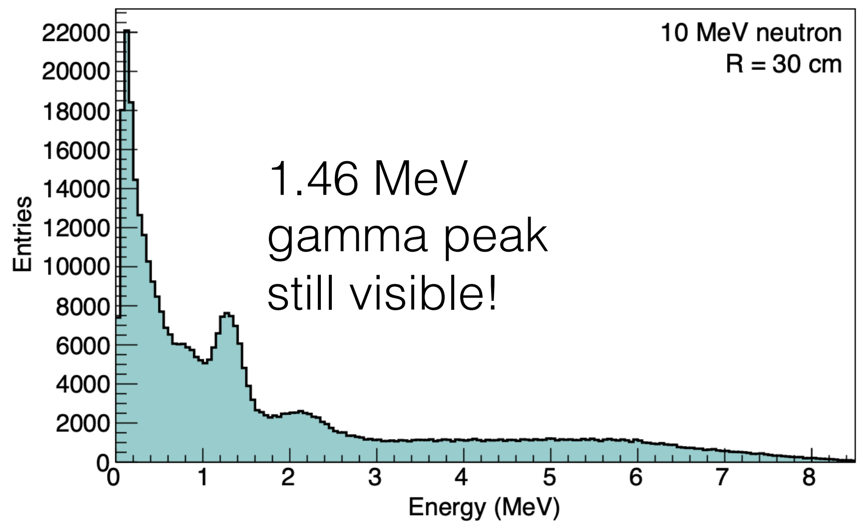
Using a simple proximity-based iterative grouping algorithm for blips, we can recover spectral features from single γ's produced by neutron scatters & captures.

- Smearing of 50 keV per blip is appliedl based on MicroBooNE study looking at integrated wire signals (MICROBOONE-NOTE-1050-PUB)

Single simulated gamma

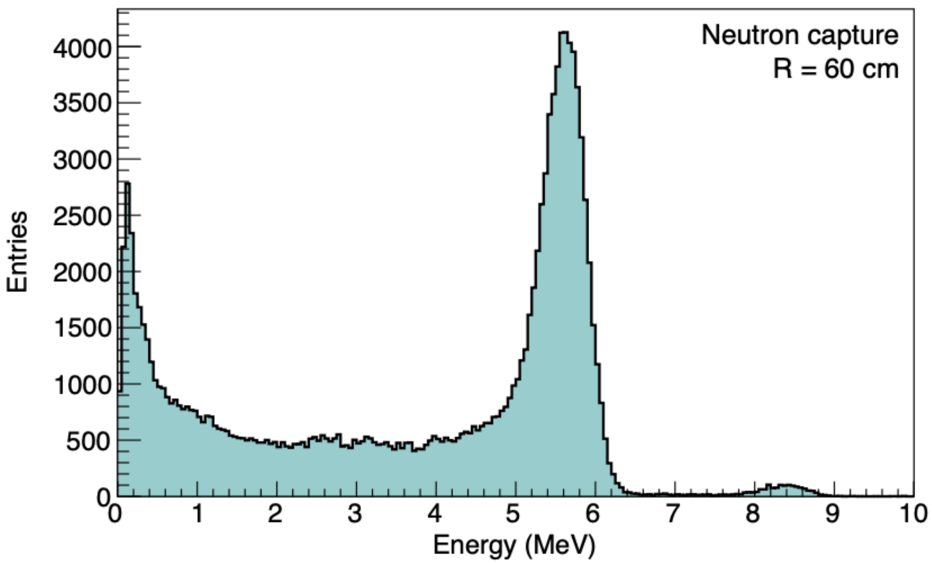


10 MeV neutron



5) Single Gamma Spectroscopy

~ at rest neutron



Same is done for <u>capturing</u> neutrons

6.1 MeV γ peak is reconstructable, though required sphere size is relatively large (R ~ 60cm)

Capture and inelastic scatter γ-ray signals will be present in any LArTPC (in neutrino signal or in cosmogenic background)

- Naturally occuring low-energy calibration signal

Summary

Reconstructing low-energy blip activity has a variety of benefits

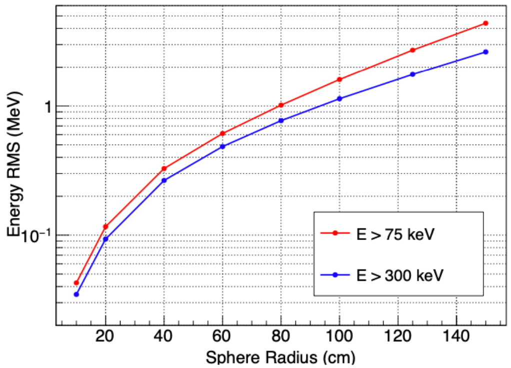
- Improved calorimetry and ID of supernova and solar neutrinos
- Improved calorimetry of EM showers
- Improved discrimination and potential sign-selection capabilities for pions/muons
- Spectroscopy of single MeV-scale γ-ray features
- Others too!

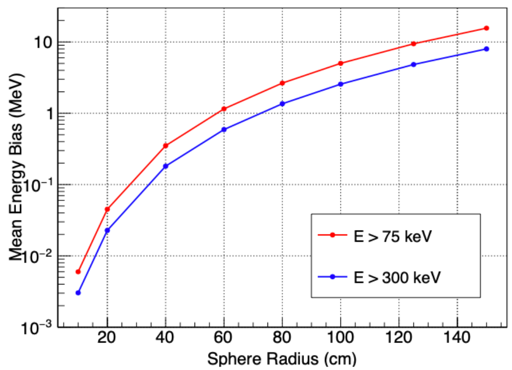
See paper for much more than I could reasonably fit in this talk.

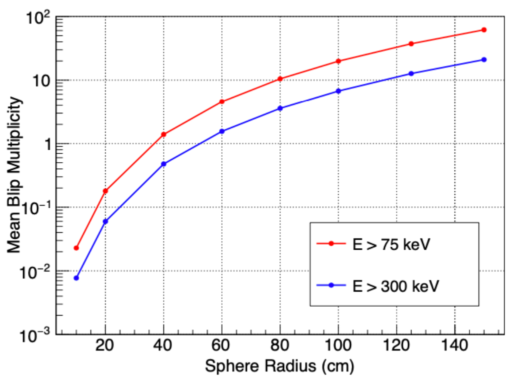
arXiV:2006.14675

Thank you!

Limitations from Ar39







- Presence of blips from Ar39, distributed randomly, will complicate things
- Using a simulated readout of Ar39 activity from DUNE, using radioactivity generator in LArSoft, and adding up activity within a 30cm sphere (using threshold of 75 keV):
  - Ave multiplicity ~ 5
  - E_{bias} = 0.1 MeV
  - RMS spread = 0.2 MeV

Limitations from electronics noise

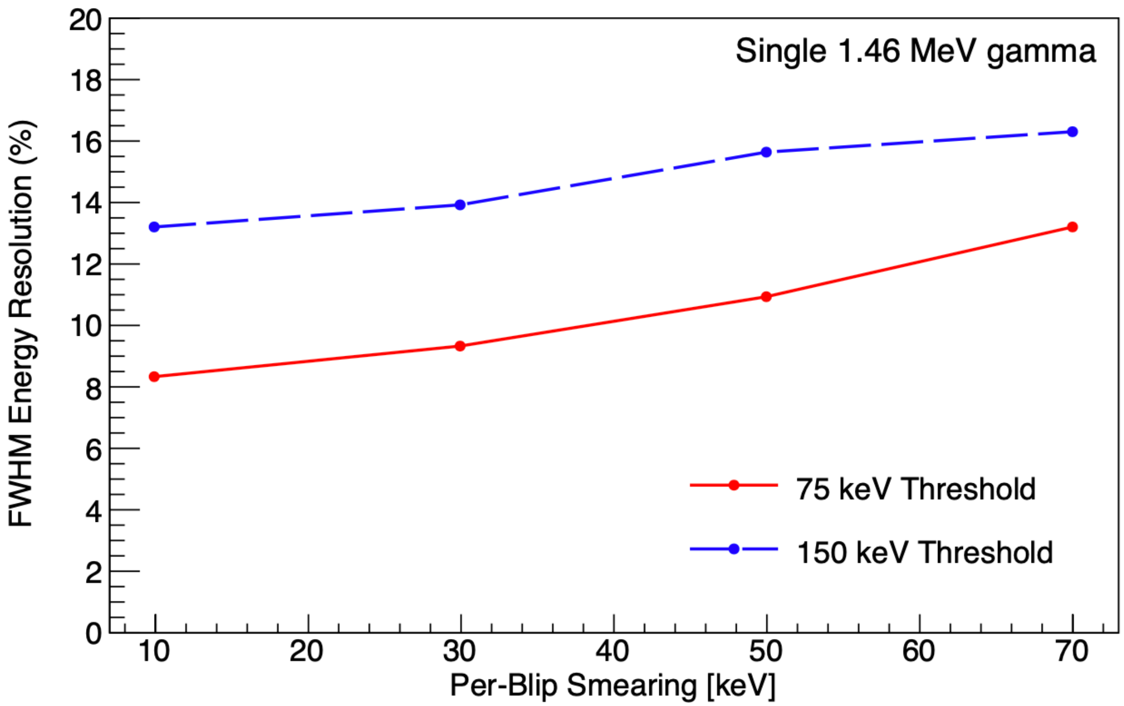


FIG. 20. The resolution of the full-energy peak for simulated 1.46 MeV γ-rays, over a range of different blip smearing levels, for both 75 keV and 150 keV energy thresholds. A proximity requirement of 30 cm is used. Resolution is calculated based on the FWHM of the peak using the relationship to standard deviation: $\sigma = \mathrm{FWHM}/(2\sqrt{2\ln 2})$.