Probing MeV-Scale Physics in Large Liquid Argon Time Projection Chambers

Will Foreman*, Whit Castiglioni*, Ivan Lepetic**, Bryce Littlejohn*, Matthew Malaker*, Andy Mastbaum**

* Illinois Institute of Technology

** Rutgers University

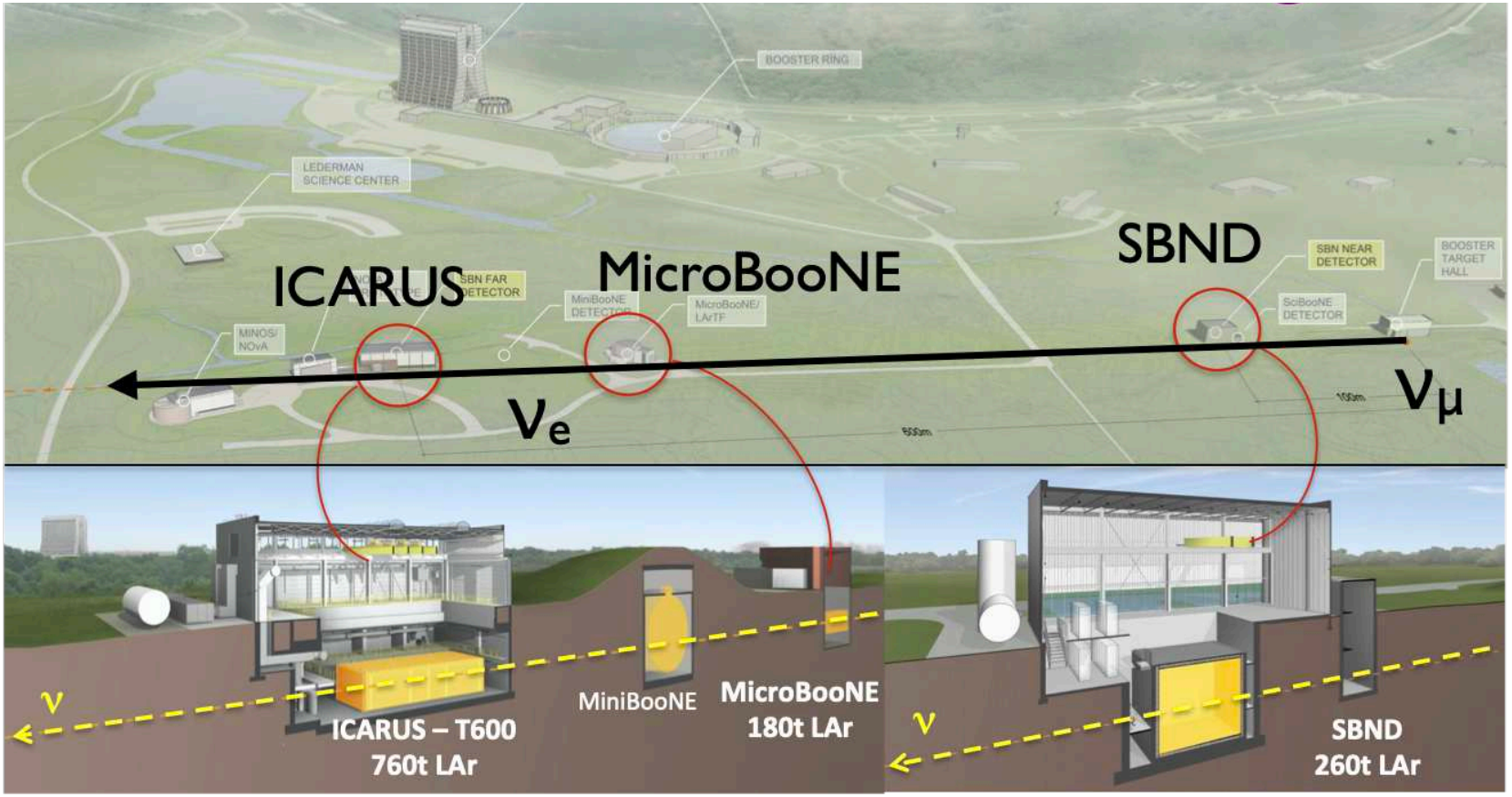
Fermilab Neutrino Seminar

October 1st, 2020

Outline

- ~~Brief introduction to neutrino physics~~
- Liquid Argon Time Projection Chambers (LArTPCs) for neutrino detection
- Probing MeV-scale energies with LArTPCs

Accelerator-based oscillation experiments: SBN



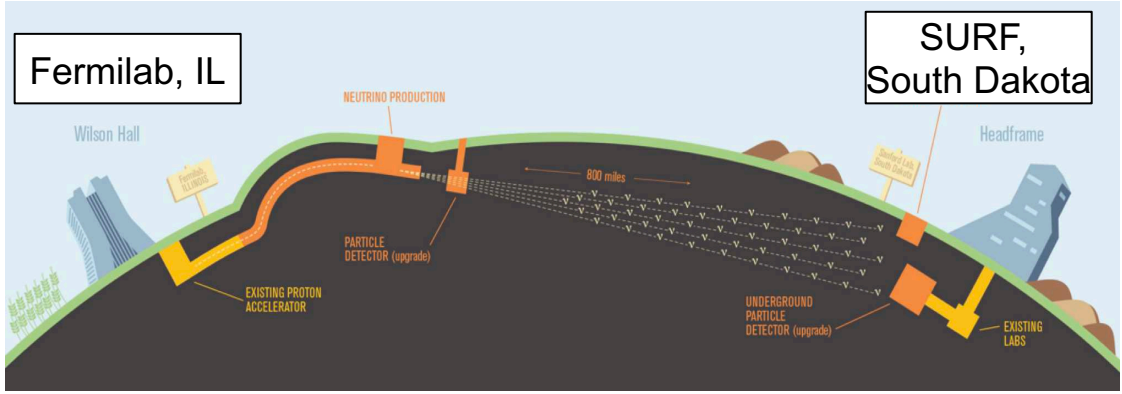
Fermilab's **Short-Baseline Neutrino (SBN) Program:** three Liquid Argon Time Projection Chambers (LArTPCs) in the Booster Neutrino Beamline to search for oscillations of ~O(1 km)

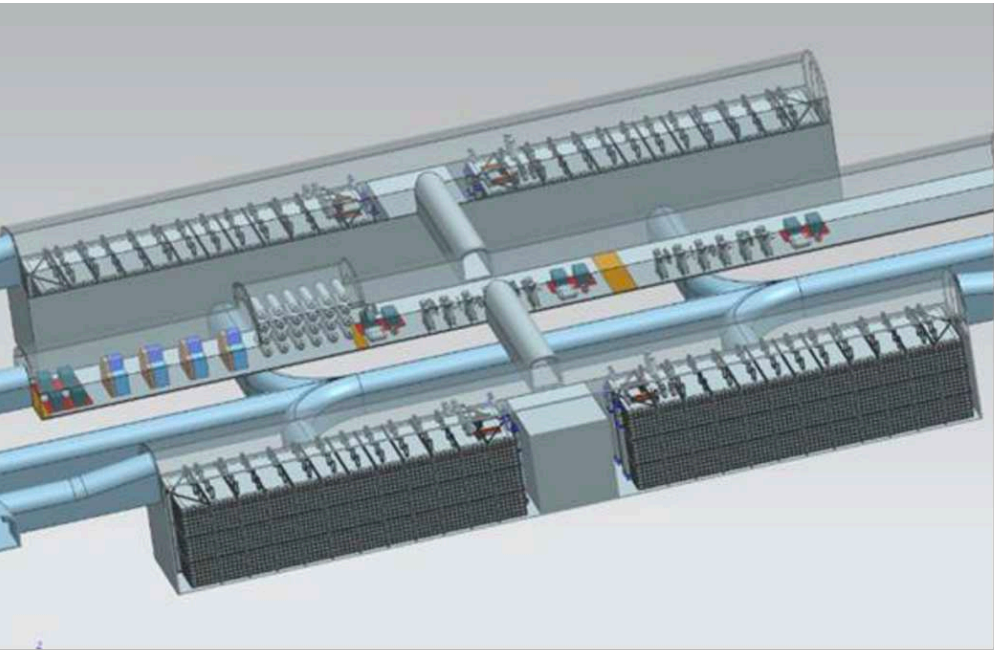
- Would hint at massive sterile neutrino at ~1 eV/c^2

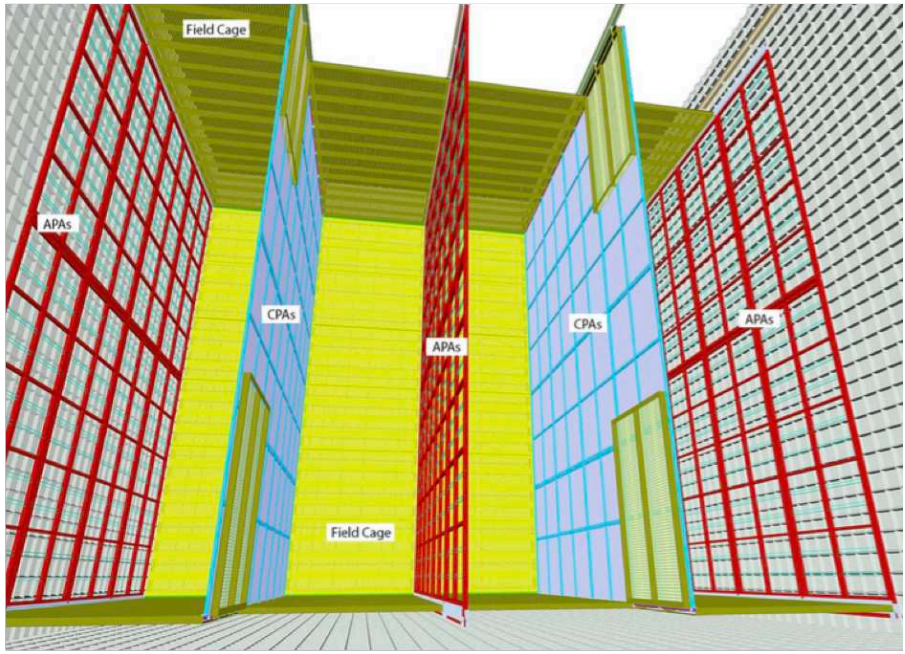
Accelerator-based oscillation experiments: DUNE

Deep Underground Neutrino Experiment (DUNE):
40kT of LAr at a baseline of
1300 km baseline

- Address CP-violation, mass hierarchy

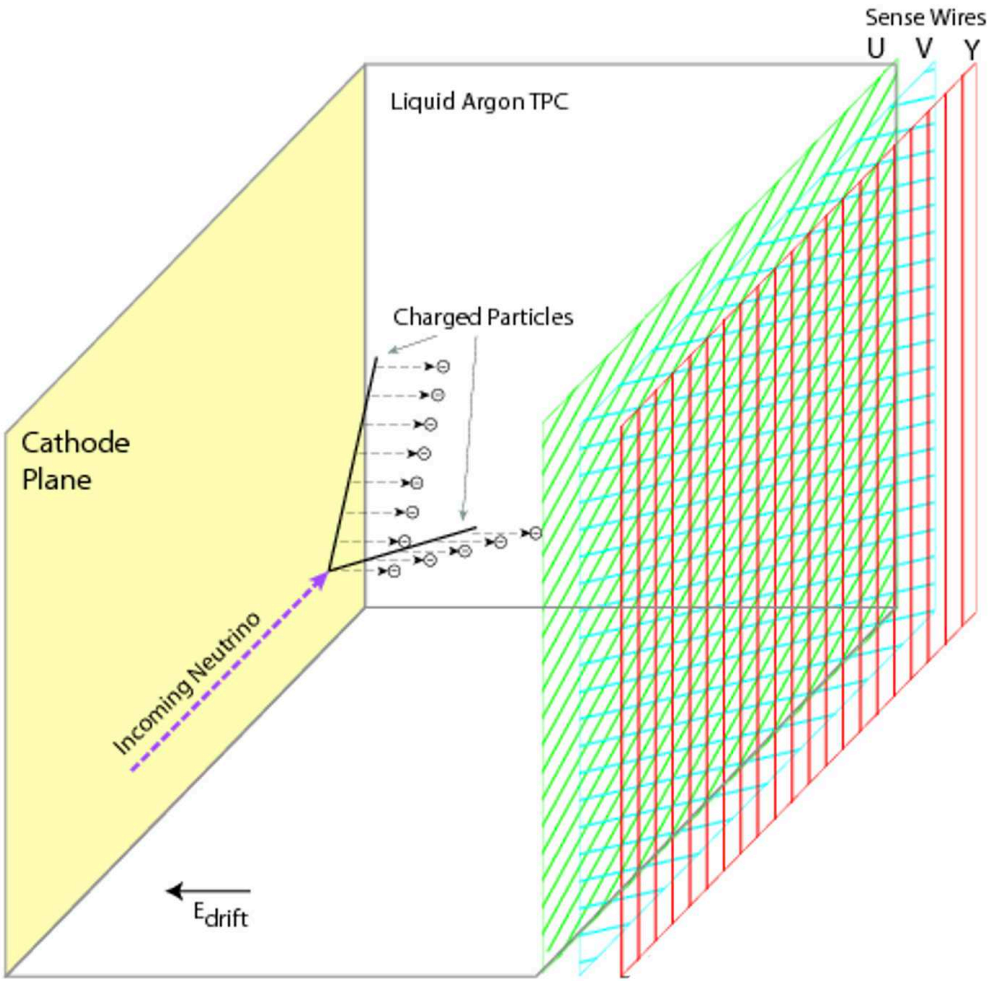






DUNE, arXiv:1601.02984 (2016)

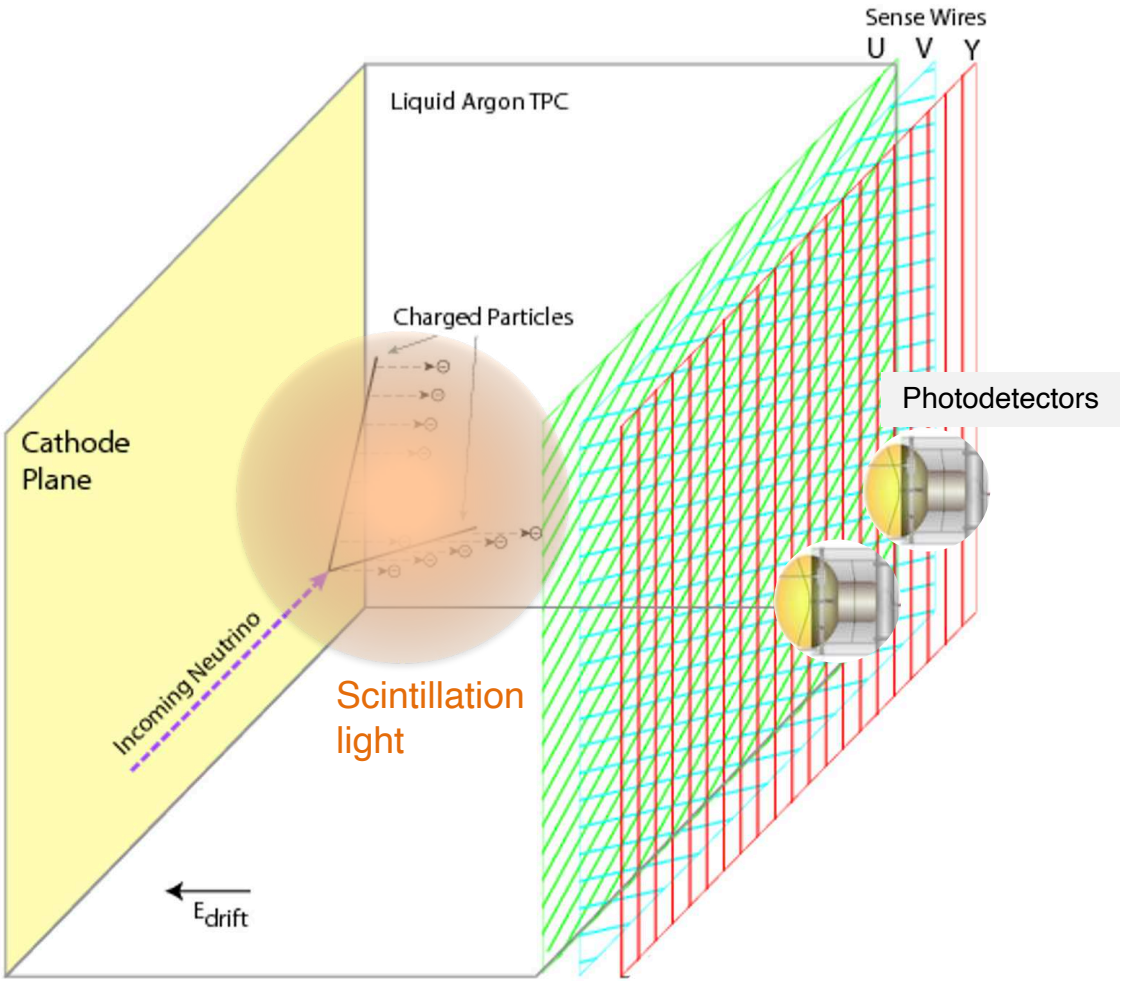
LArTPC: principle of operation



LArTPCs are ideal for neutrino detection in accelerator-produced beams

- Fine-grained tracking
- Calorimetry
- Scalability

LArTPC: principle of operation

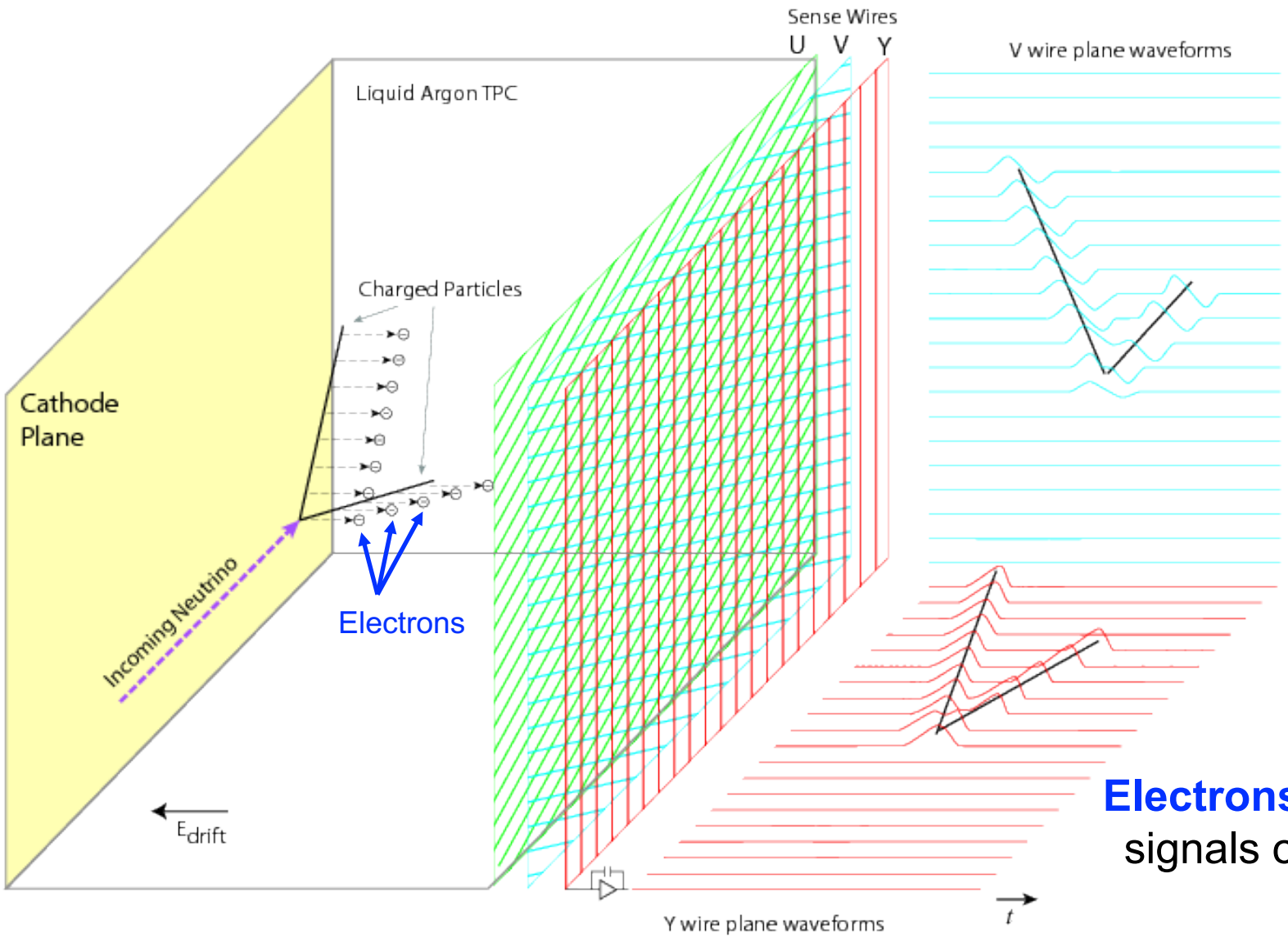


Scintillation photons emanate isotopically and very quickly -- first thing we "see" from the interaction.

Detecting this **light** provides an absolute reference "time-zero".

Electrons drift relatively slowly to the wires.

LArTPC: principle of operation

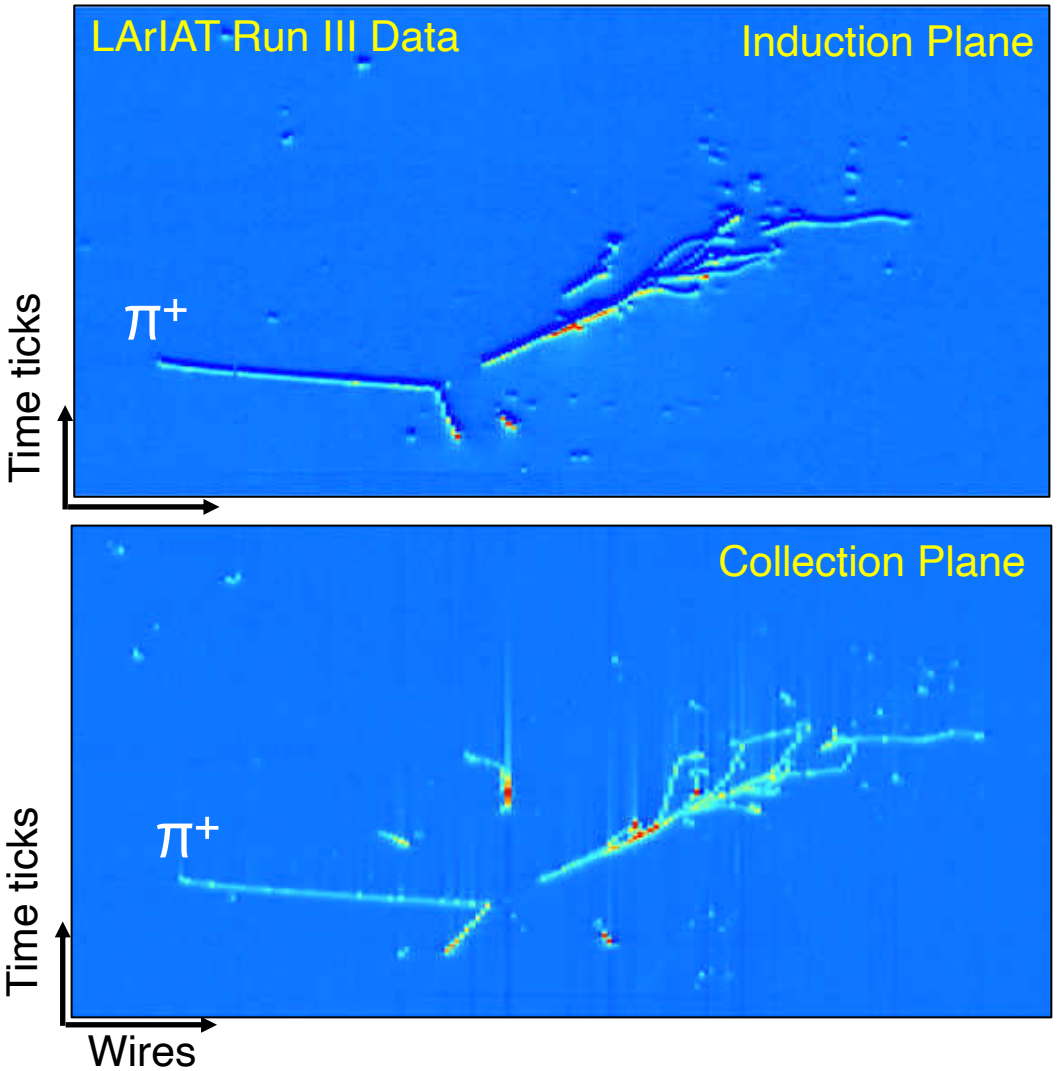


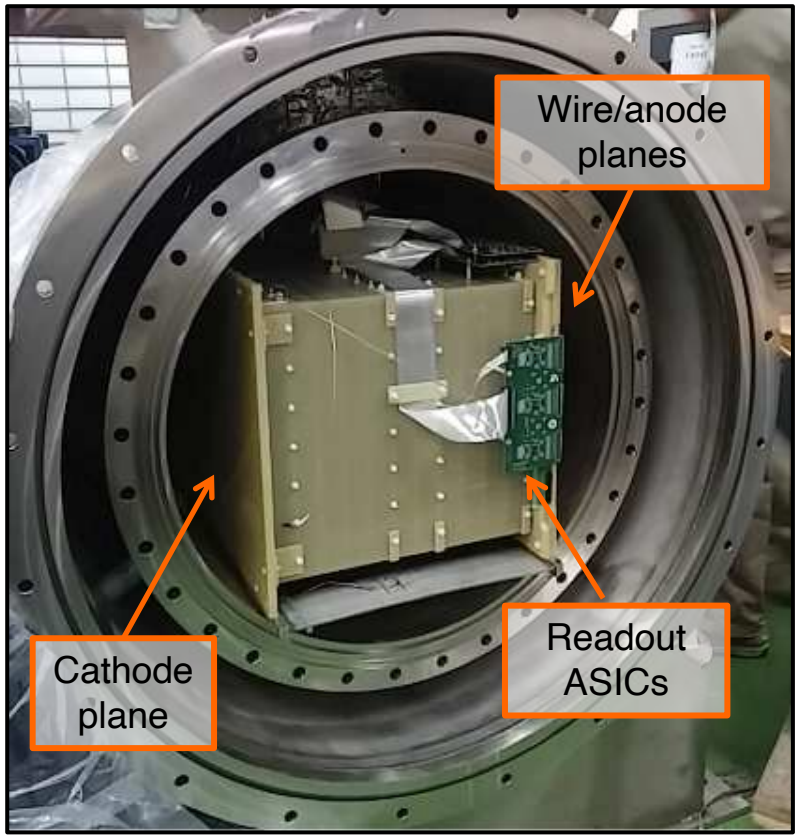
Electrons create signals on wires

Solid cathode plane
Field cage tubes
Anode wire readout planes

MicroBooNE

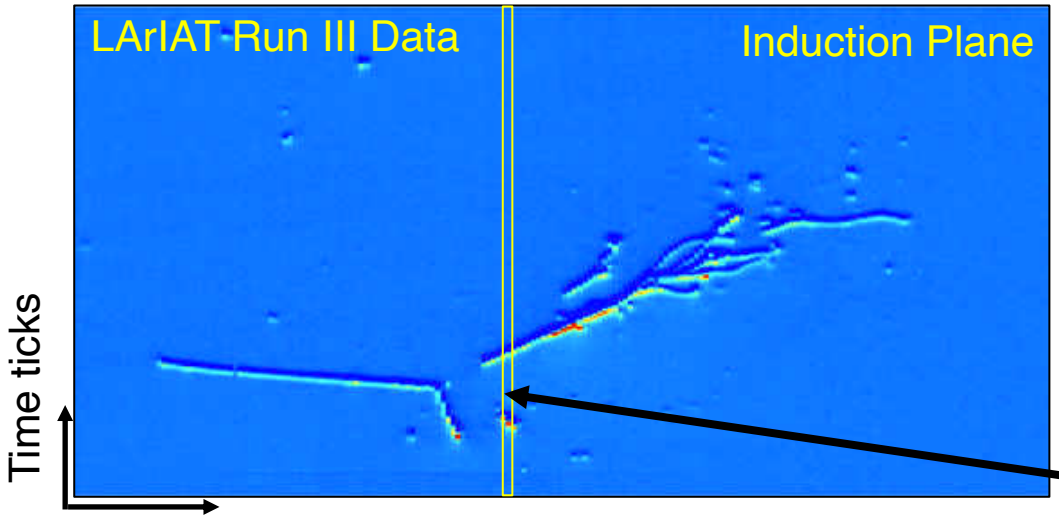
Example LArTPC event display

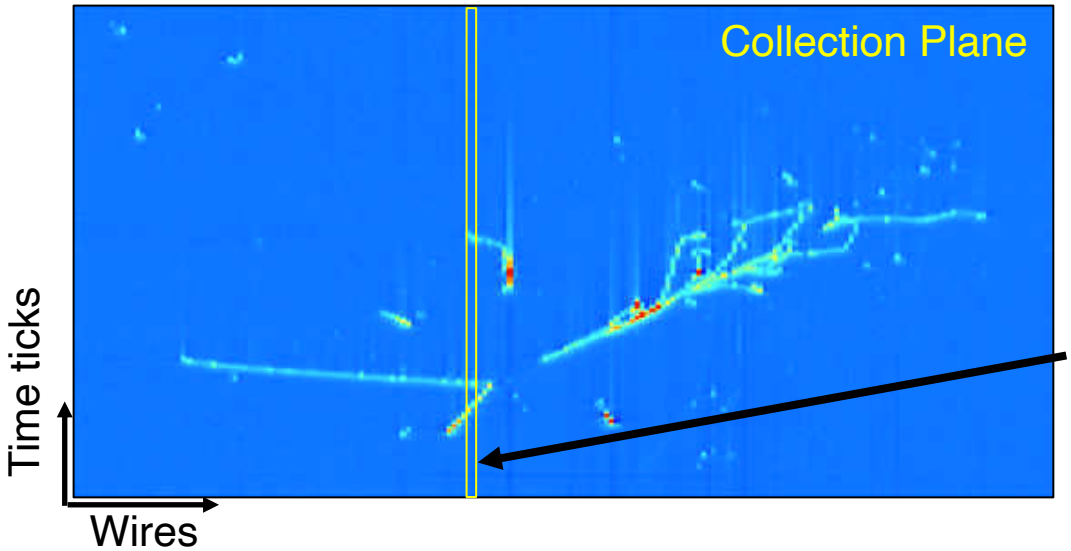


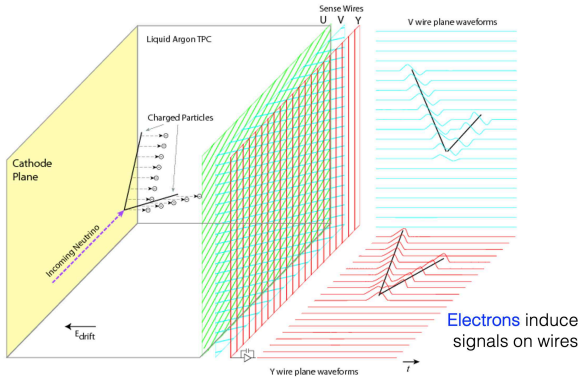


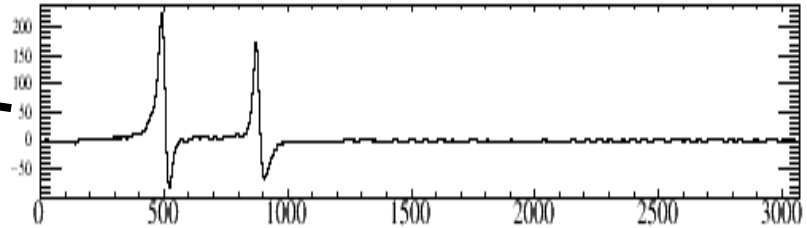
LArIAT, a small LArTPC placed in a charged hadron testbeam at Fermilab.

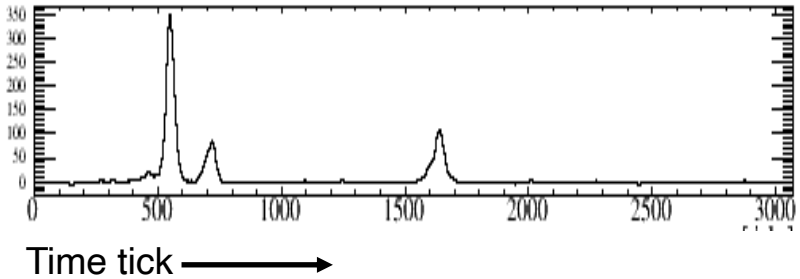
Example LArTPC event display

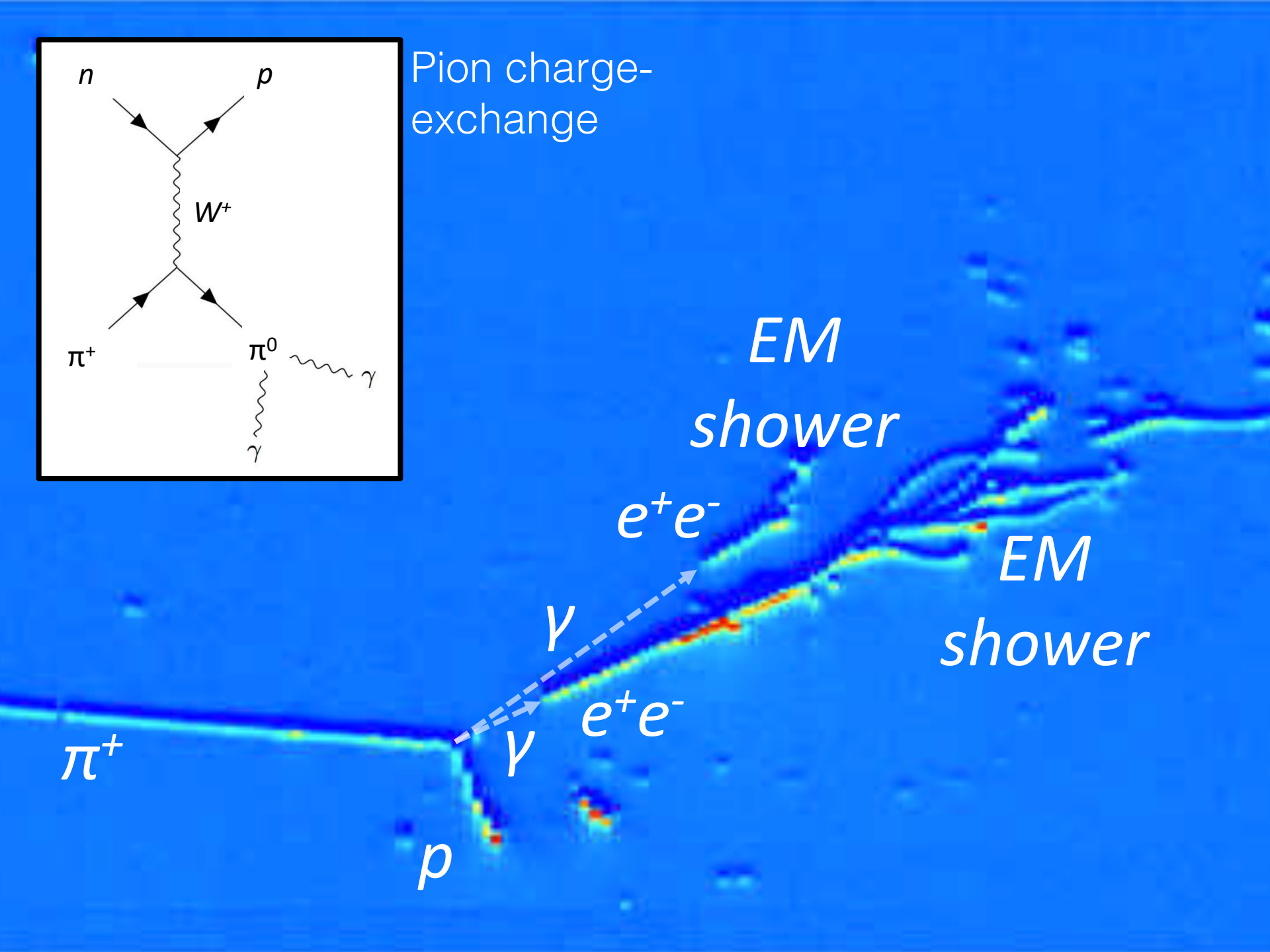








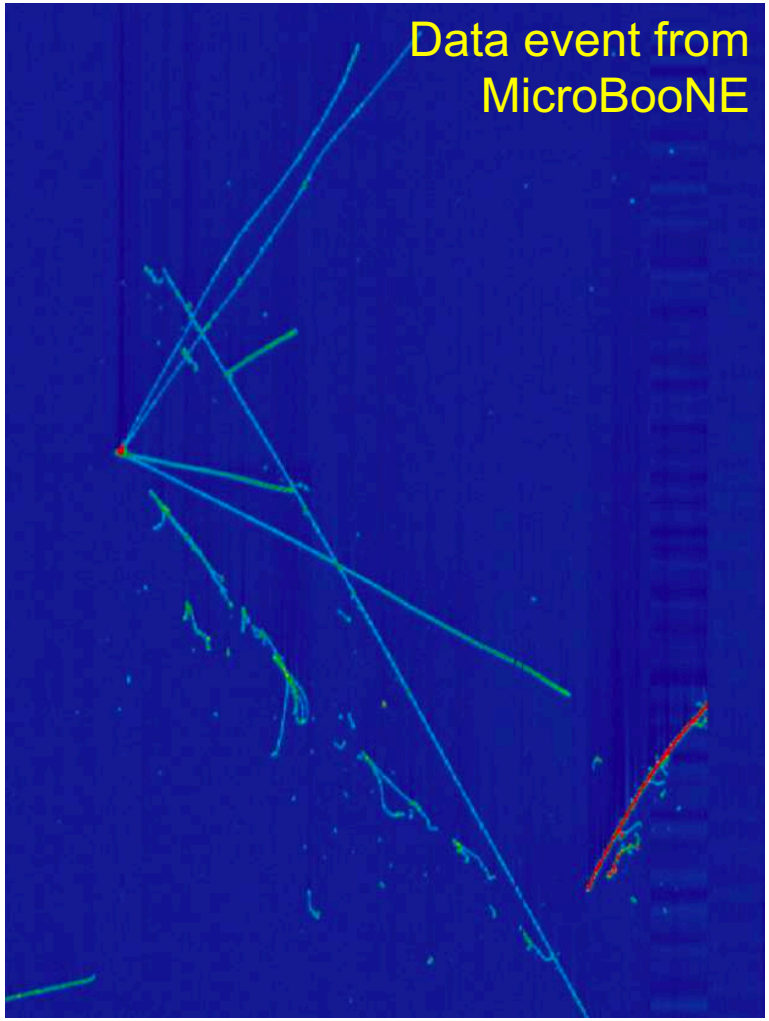



n
p
W+
π+
π0
γ
γ
Pion charge-exchange
EM shower
e+e-
EM shower
γ
e+e-
γ
π+
p

Present energy scale of LArTPC reconstruction

- **Major focus in LArTPC reconstruction has been at energies ranging from several 10s of MeV to GeV**

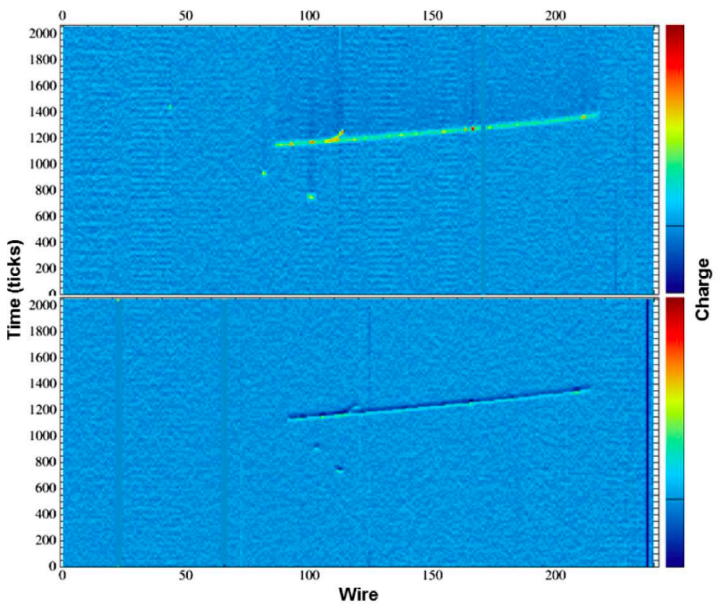
- Reliance on large-scale topological features in GeV-scale neutrino interactions
  - Range-based energy measurements
  - Calorimetry along extended, easily-reconstructed objects like tracks
  - Multiple Coulomb Scattering for muon track momentum estimation

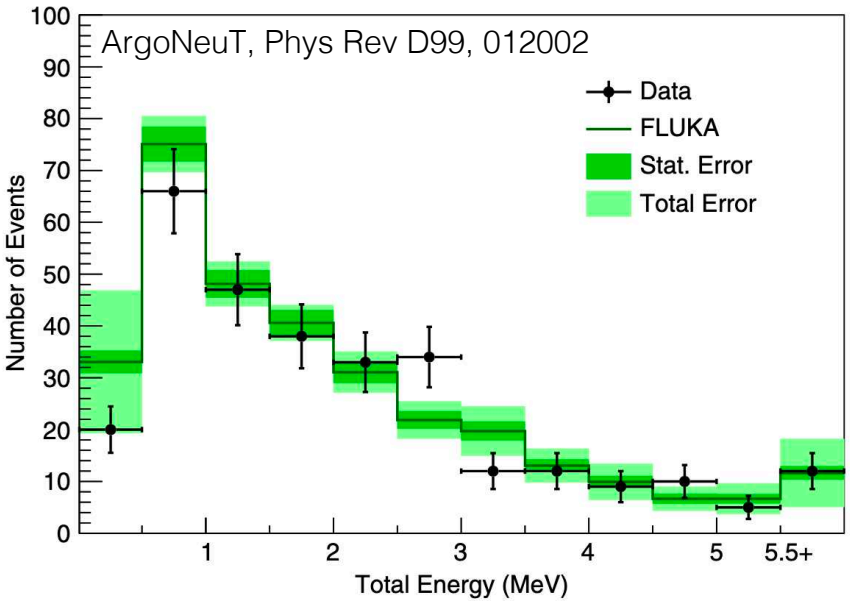


Low-energy capabilities in LArTPCs

- Relatively little attention given to *low energies* (~MeV-scale)
  - 24 eV Ar ionization energy
  - High electron collection efficiency
  - Low noise

- **But 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

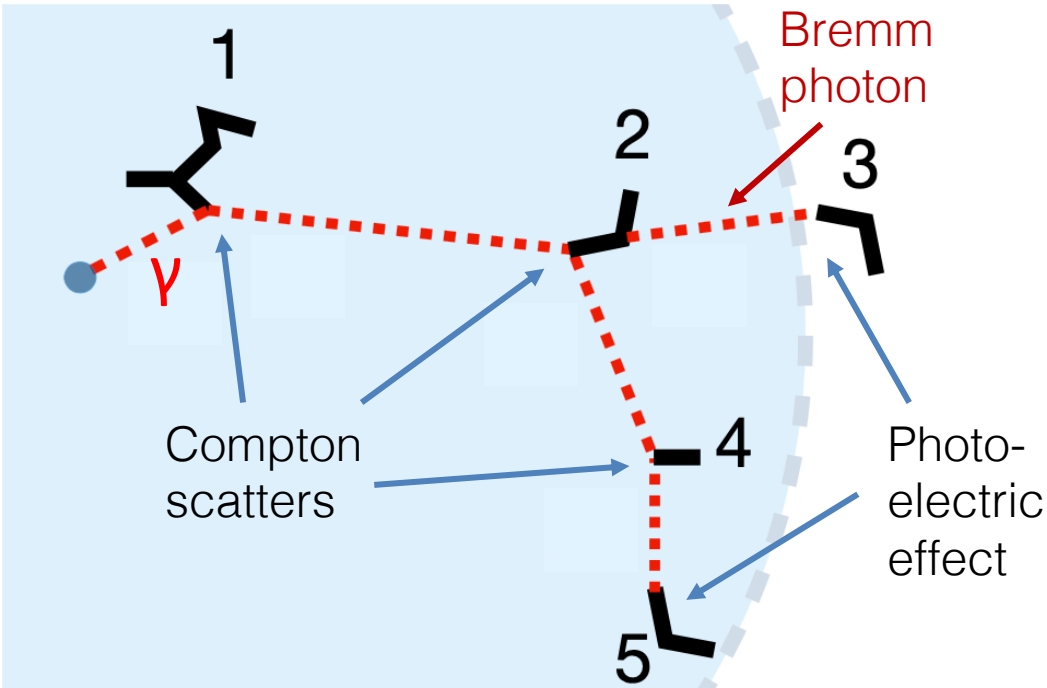




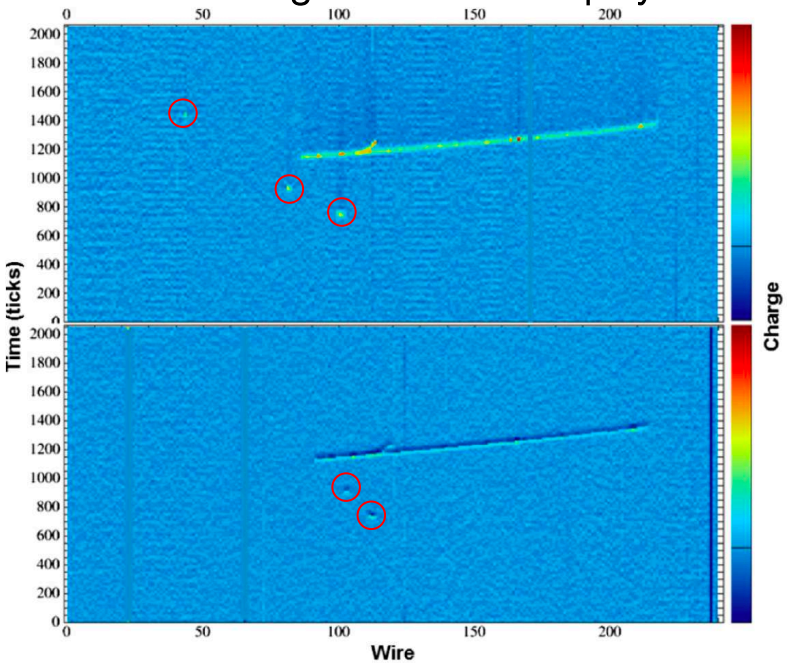
Defining a "blip"

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

- Such electrons often 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*

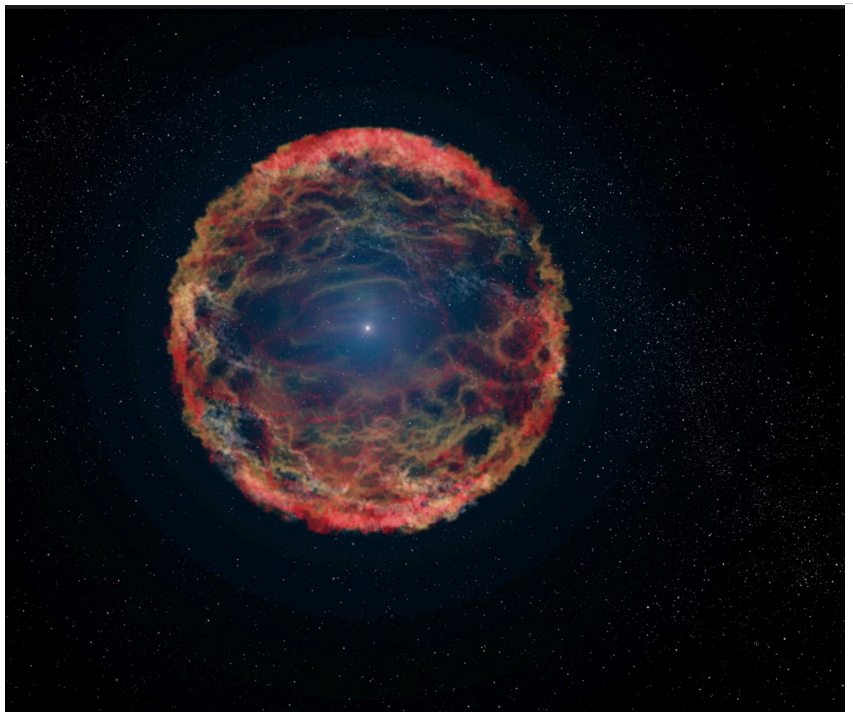


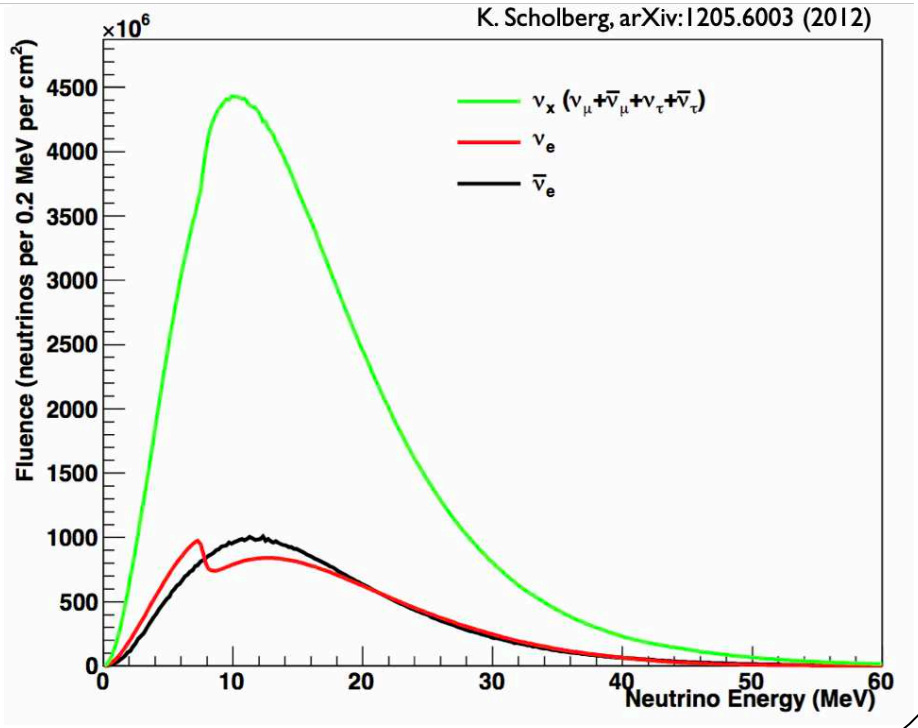
ArgoNeuT event display



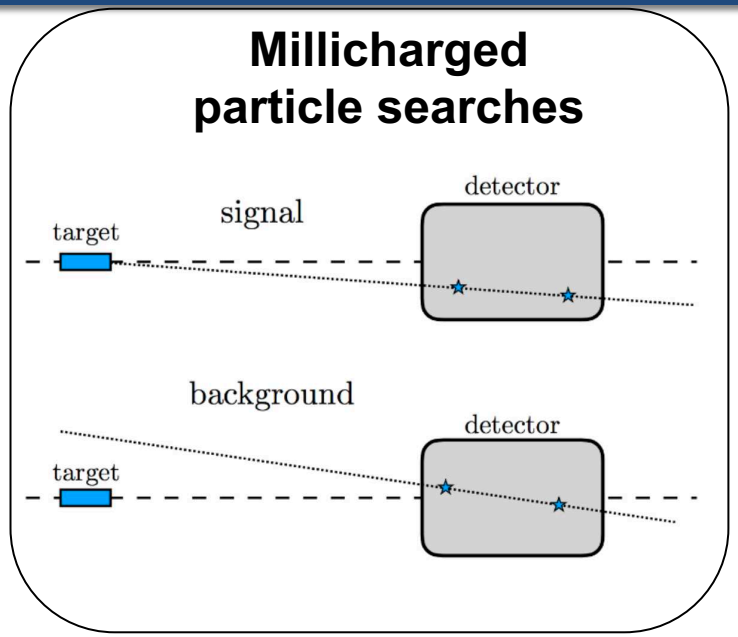
Extending the physics reach of LArTPCs using blips

Supernova neutrinos

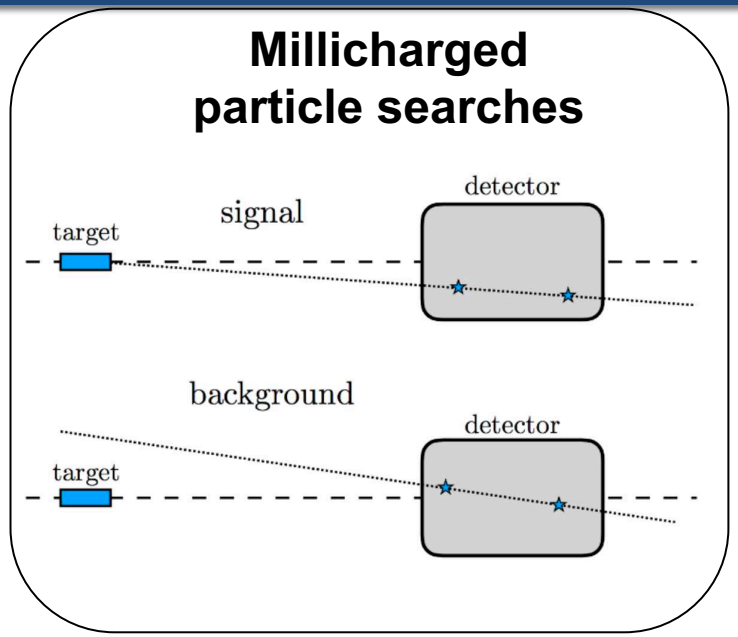




Extending the physics reach of LArTPCs using blips



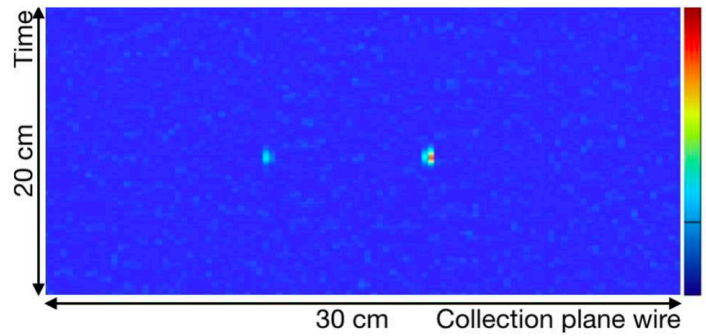
Extending the physics reach of LArTPCs using blips

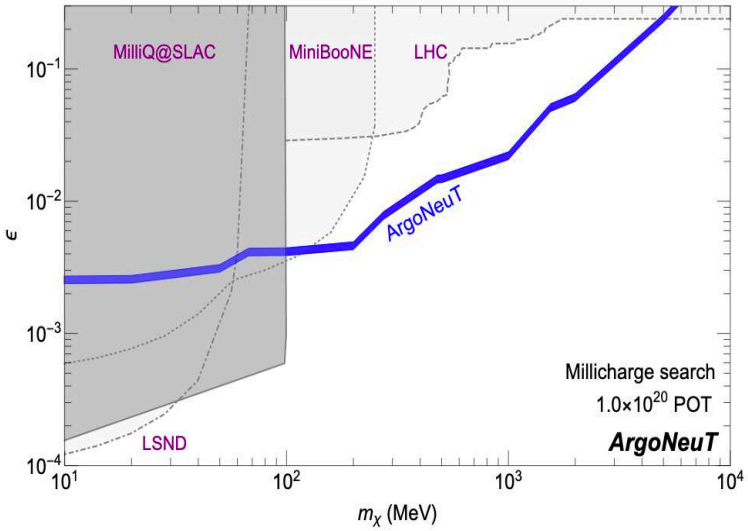


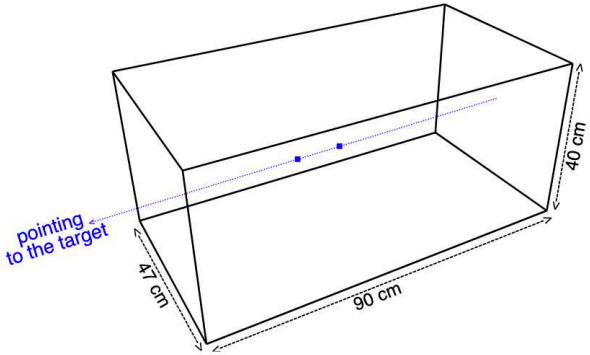
arXiv: 1911.07996

Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab

R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[1] D. Edmunds,[5] R.S. Fitzpatrick,[6] B. Fleming,[7] R. Harnik,[1] C. James,[1] I. Lepetic,[8,*] B.R. Littlejohn,[8] Z. Liu,[9] X. Luo,[10] O. Palamara,[1,†] G. Scanavini,[7] M. Soderberg,[11] J. Spitz,[6] A.M. Szelc,[12] W. Wu,[1] and T. Yang[1]
(The ArgoNeuT Collaboration)

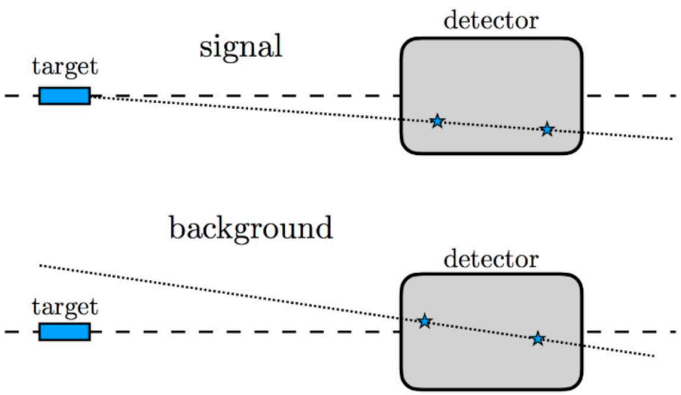




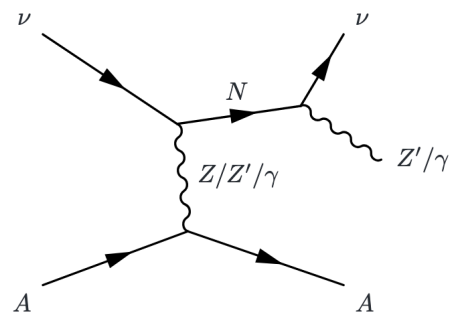


Extending the physics reach of LArTPCs using blips

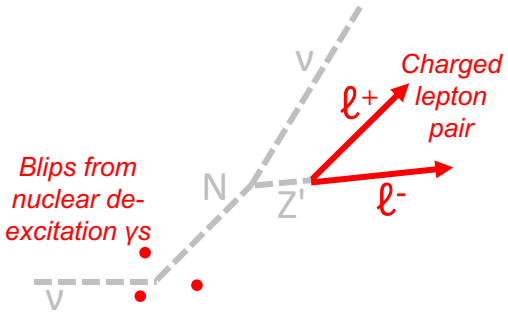
Millicharged particle searches



Up-scattered dark neutrino



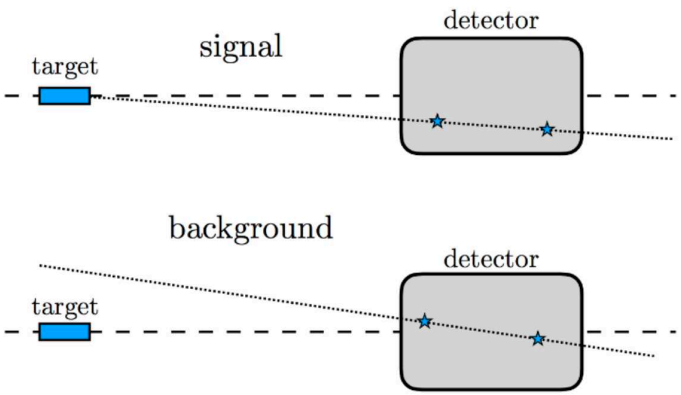
Feynman diagram



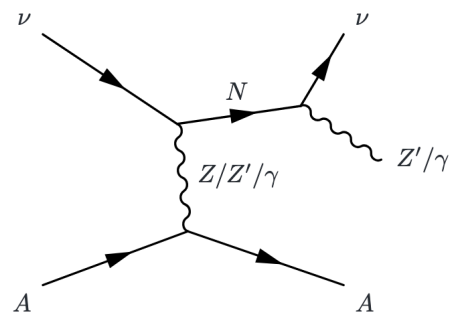
LArTPC topological signature

Extending the physics reach of LArTPCs using blips

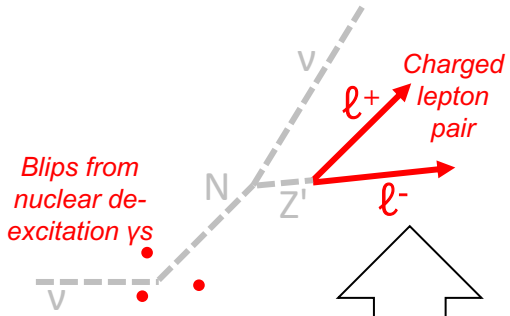
Millicharged particle searches



Up-scattered dark neutrino

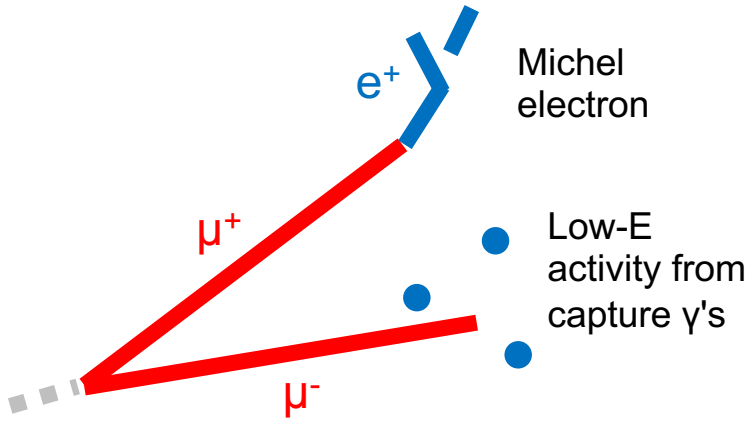


Feynman diagram



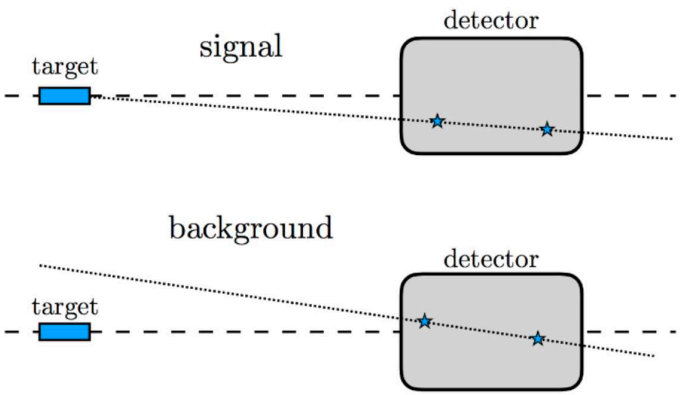
LArTPC topological signature

PID of stopping π/μ

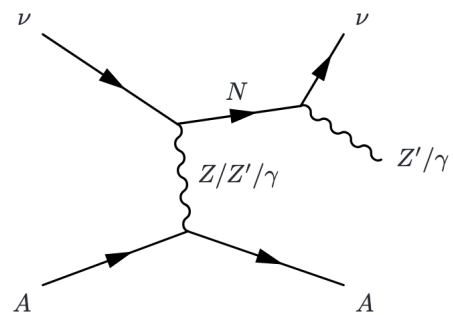


Extending the physics reach of LArTPCs using blips

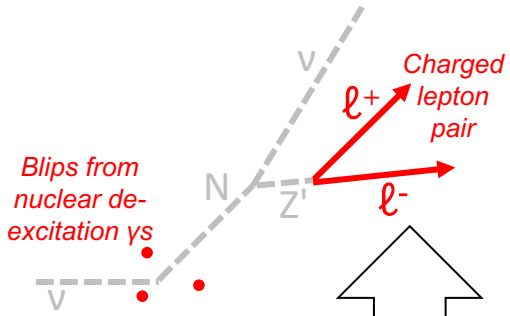
Millicharged particle searches



Up-scattered dark neutrino

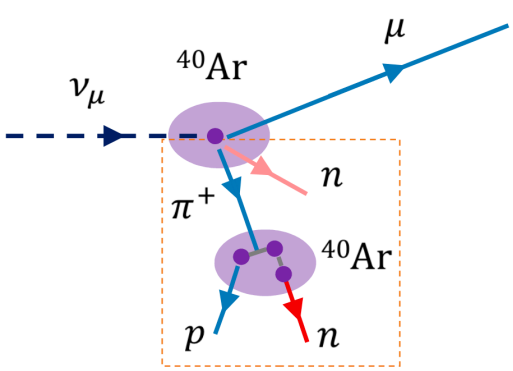


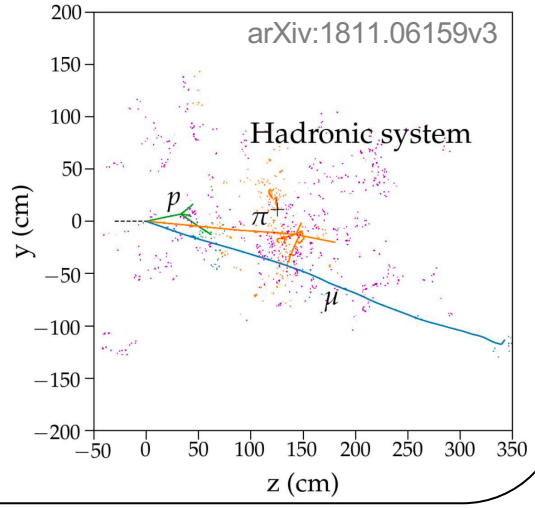
Feynman diagram



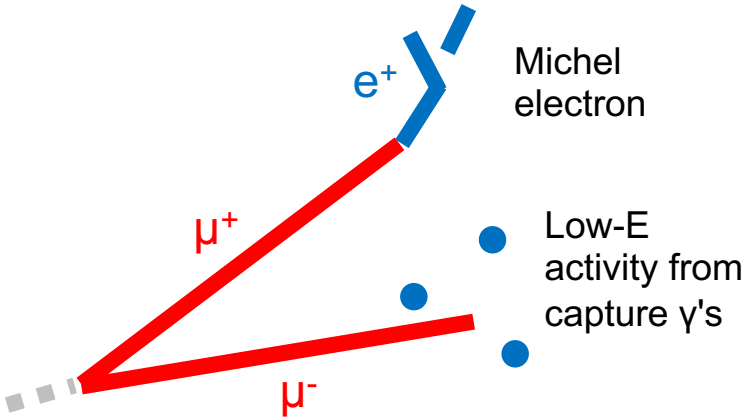
LArTPC topological signature

GeV-scale ν interaction final-states





PID of stopping π/μ



Low-energy calorimetry benefits

[Submitted on 25 Jun 2020]

Benefits of MeV-Scale Reconstruction Capabilities in Large Liquid Argon Time Projection Chambers

W. Castiglioni, W. Foreman, I. Lepetic, B. R. Littlejohn, M. Malaker, A. Mastbaum

- Our recent paper, arXiv:2006.14675, uses truth-level MC to explore 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" (technical definition for study)

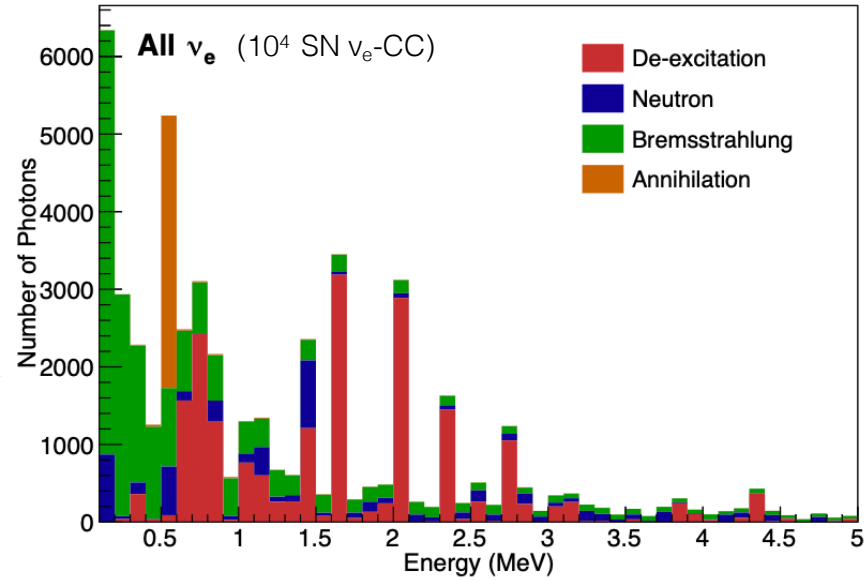
In order to keep results largely detector-agnostic, the studies that follow are done using truth-level Geant4 information.

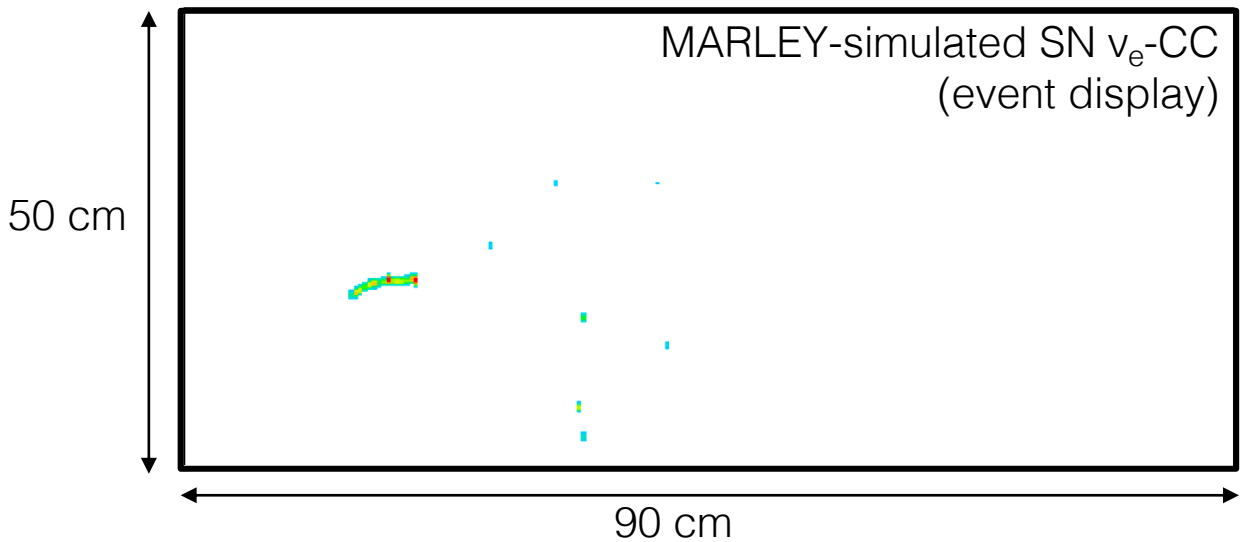
- Blips defined as contiguous, spatially-isolated energy depositions due to electrons
- Blips with < 2 mm separation are merged
  - Likely to be grouped into same hit or appear on adjacent wires/pads in any reasonable reco
- E_{dep} > 75 keV
  - Lower than the 200-300 keV achieved in ArgoNeuT, based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

Benefit #1: Supernovae and solar neutrinos

Supernova ν primary detection channel: charged current (CC) interaction

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow \underbrace{e^- + {}^{40}\mathrm{K}^*}_{\text{Final-state } \gamma\text{'s produced}}$$

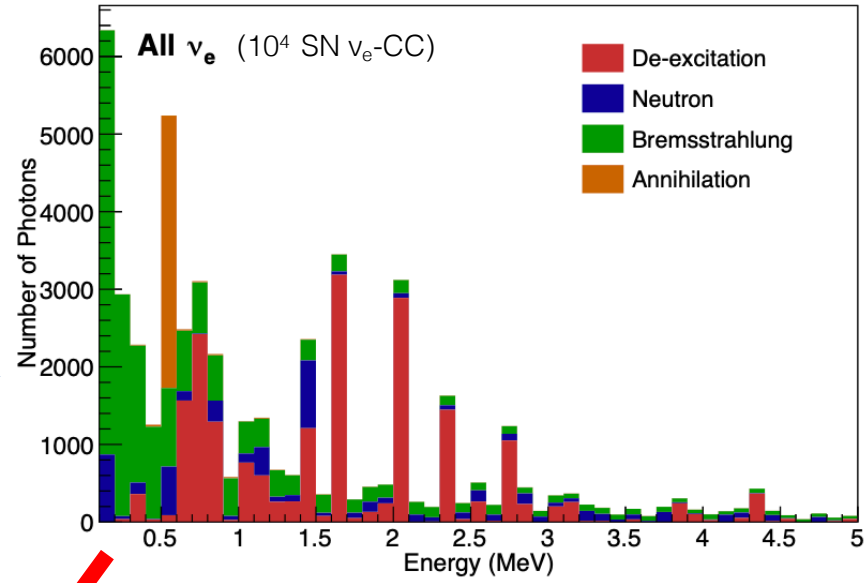


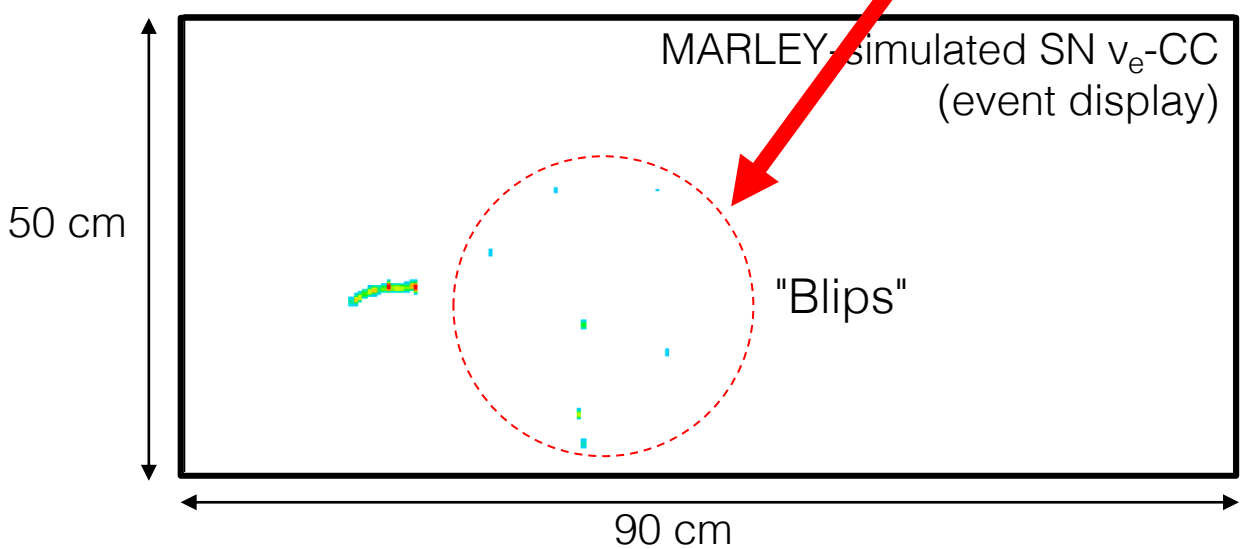


Benefit #1: Supernovae and solar neutrinos

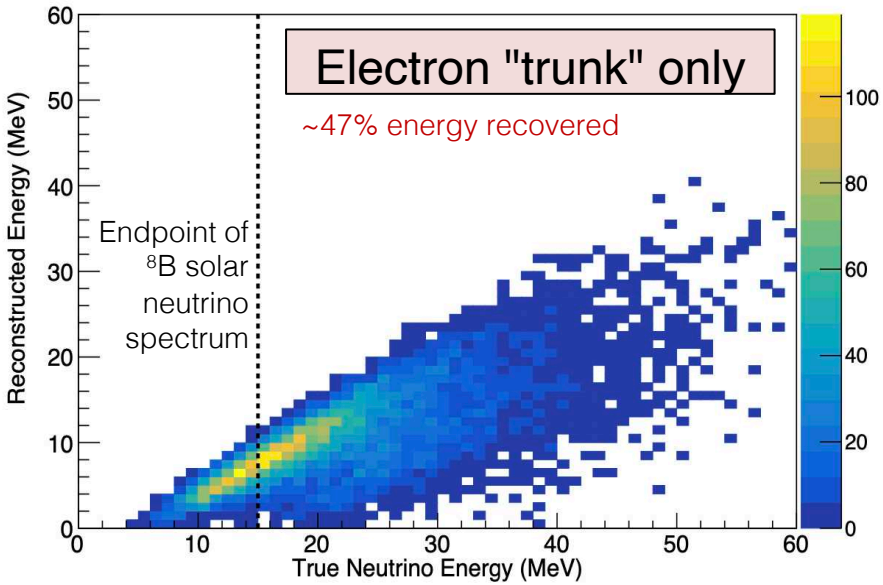
Supernova ν primary detection channel: charged current (CC) interaction

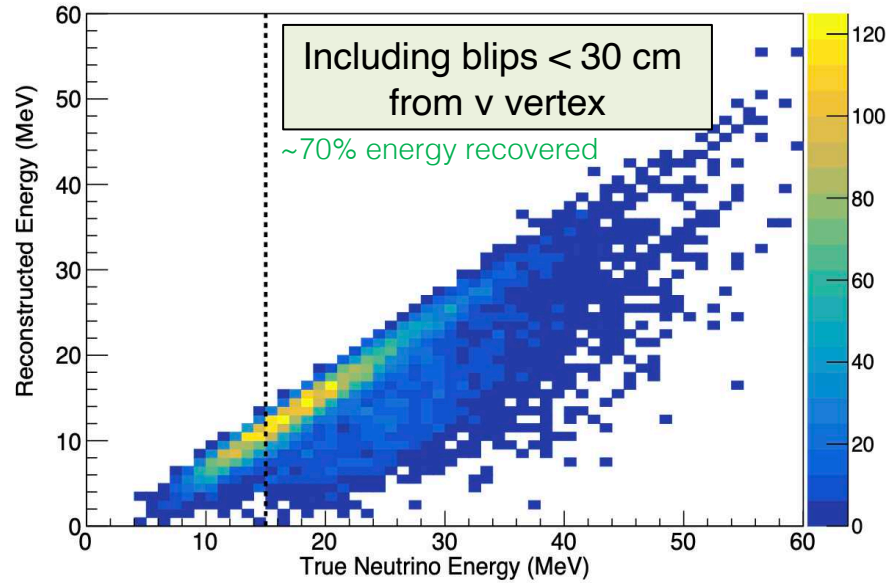
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow \underbrace{e^- + {}^{40}\mathrm{K}^*}_{\text{Final-state } \gamma\text{'s produced}}$$

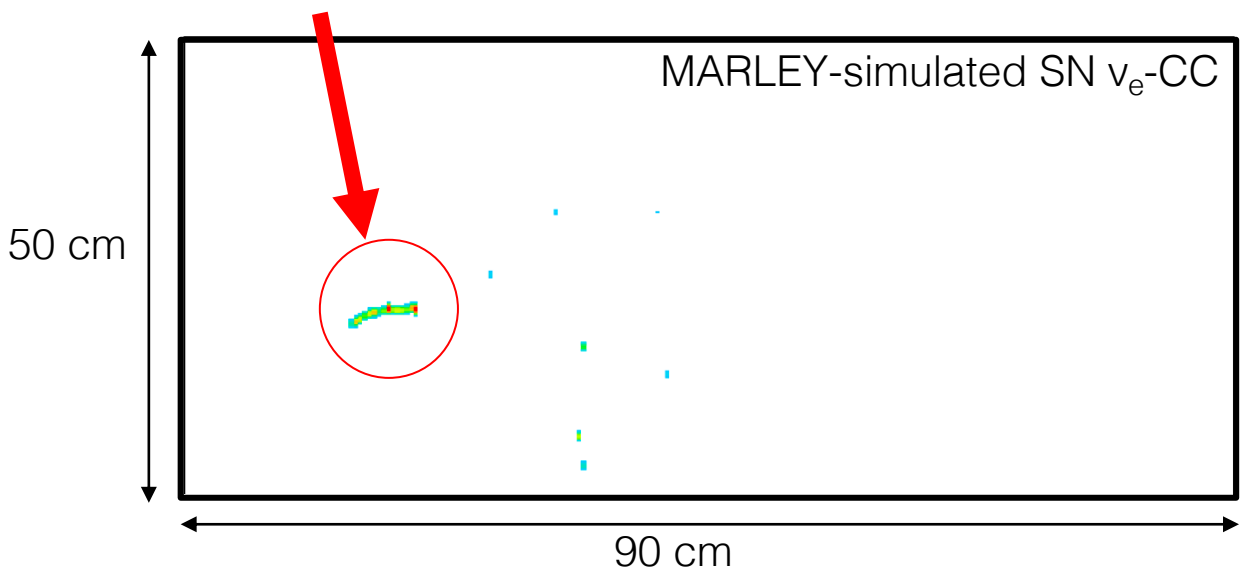




Benefit #1: Supernovae and solar neutrino calorimetry

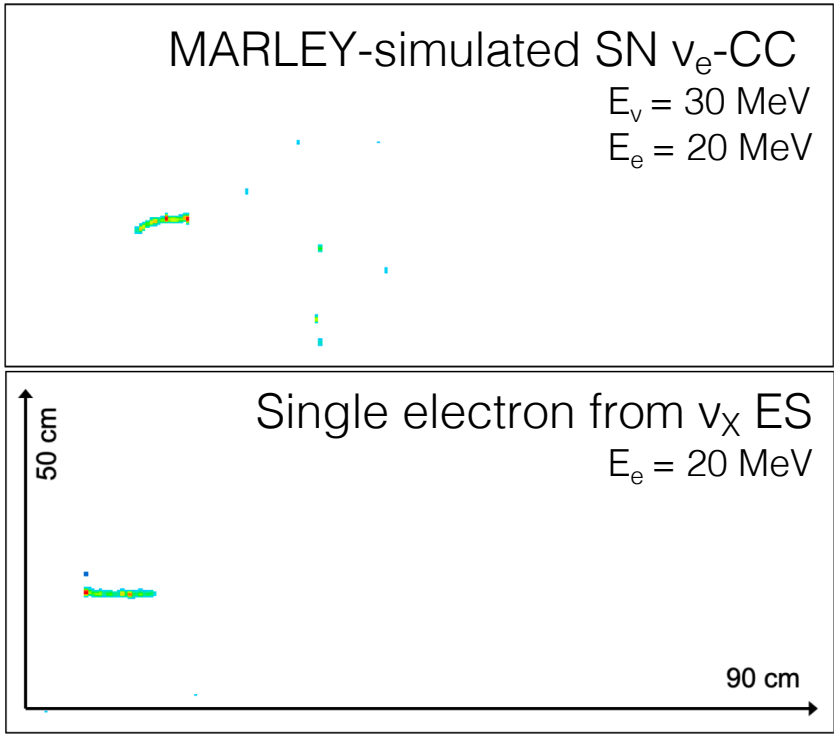






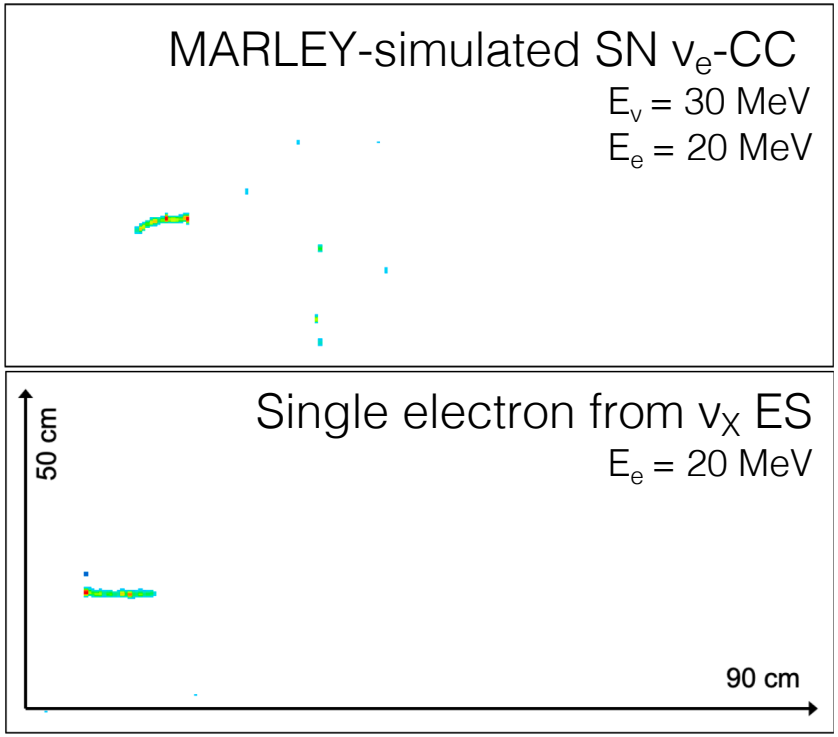
Benefit #1: Supernovae and solar neutrino channel ID

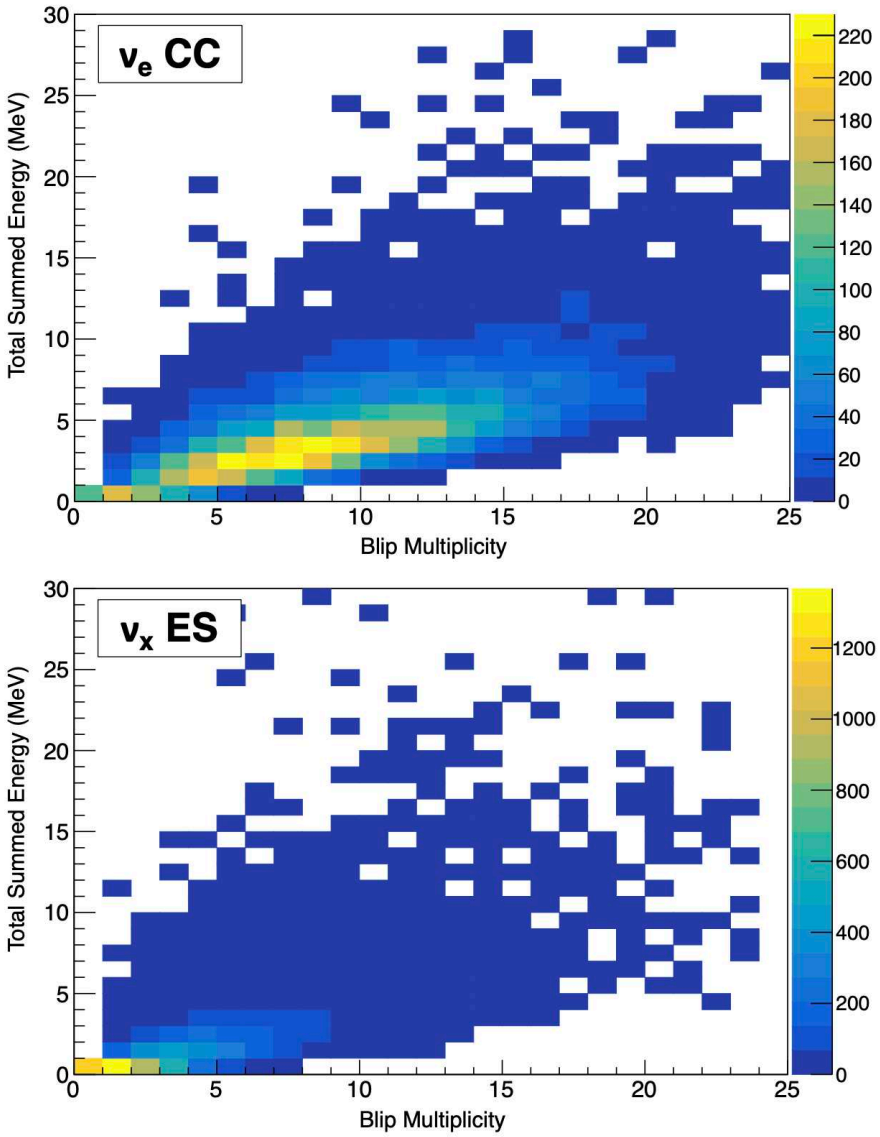
SN ν_x elastic scattering (ES) can also occur, results in a recoil electron.



Benefit #1: Supernovae and solar neutrino channel ID

Blip multiplicity and total blip energy provide avenue for separating out these two channels.





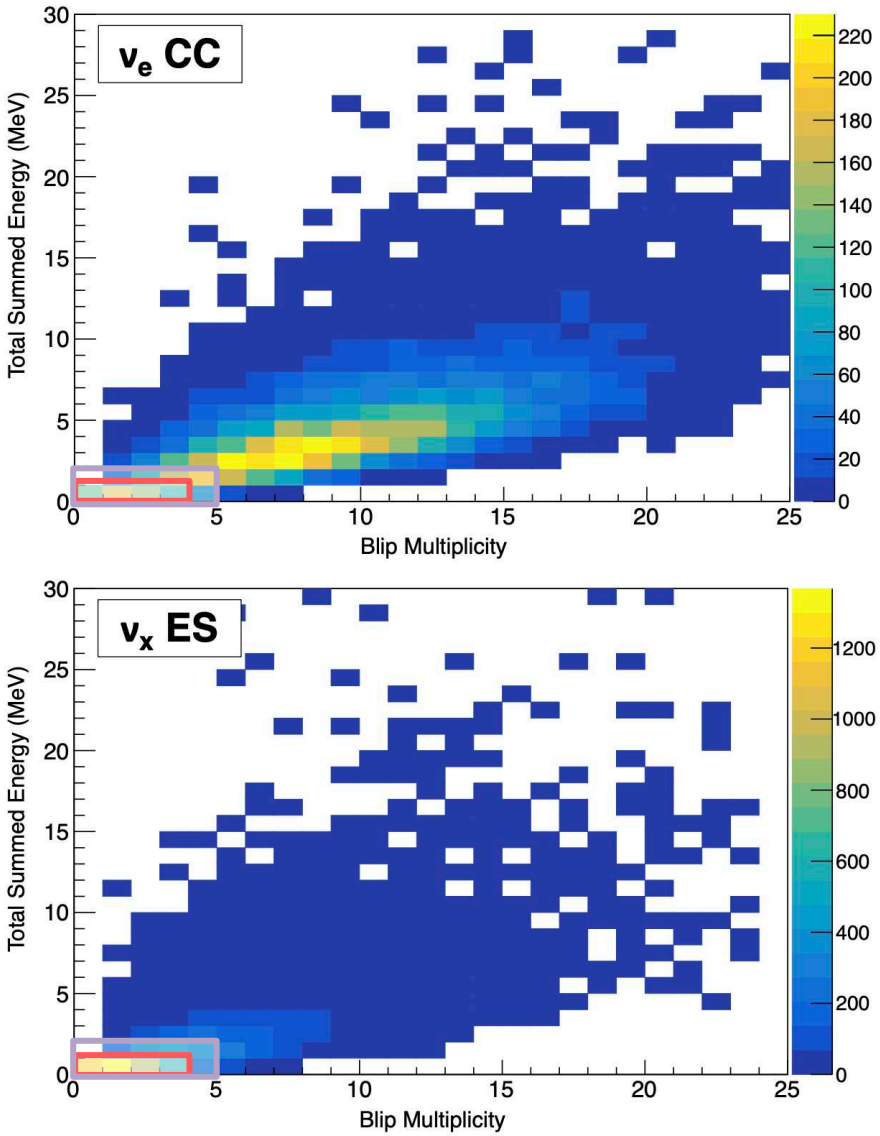
Benefit #1: Supernovae and solar neutrino channel ID

Assuming CC:ES ratio of ~9:1, by default we'd expect a purity of 10% in selecting ν_x-ES

2D box cuts = enhanced purity, at the expense of efficiency

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%

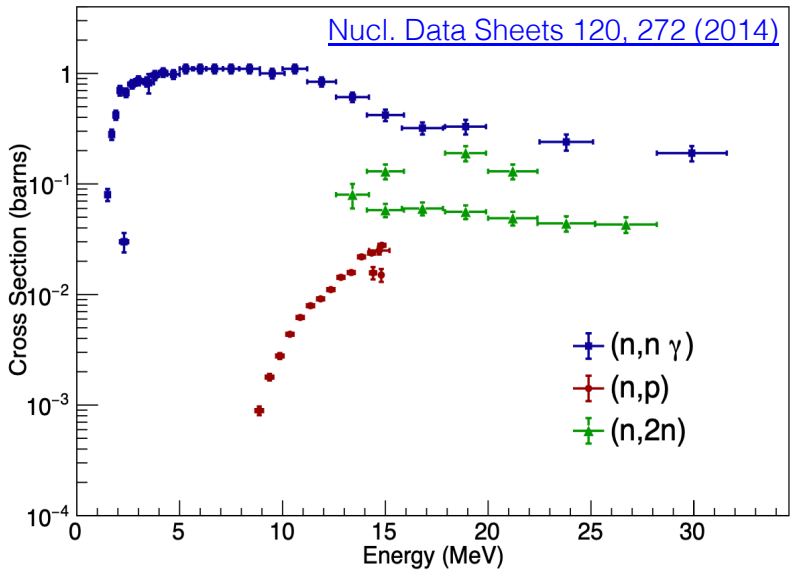
TABLE II. Efficiency and purity in selecting ν_x ES events from a larger sample of ν_e CC events using only cuts on reconstructed blip activity. Efficiency and purity definitions are given in the text.

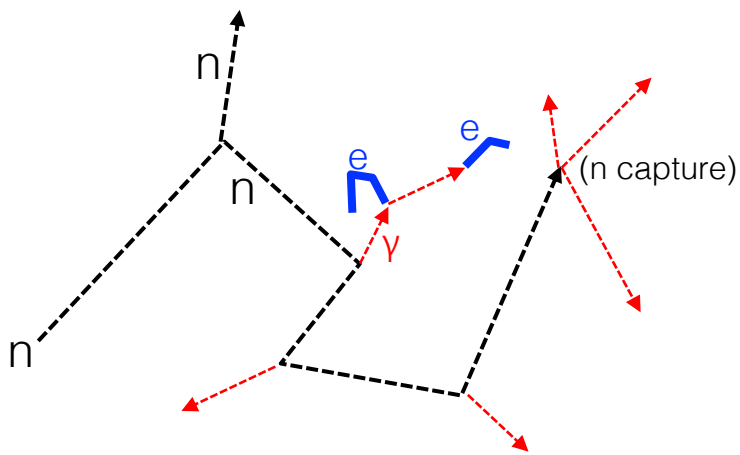


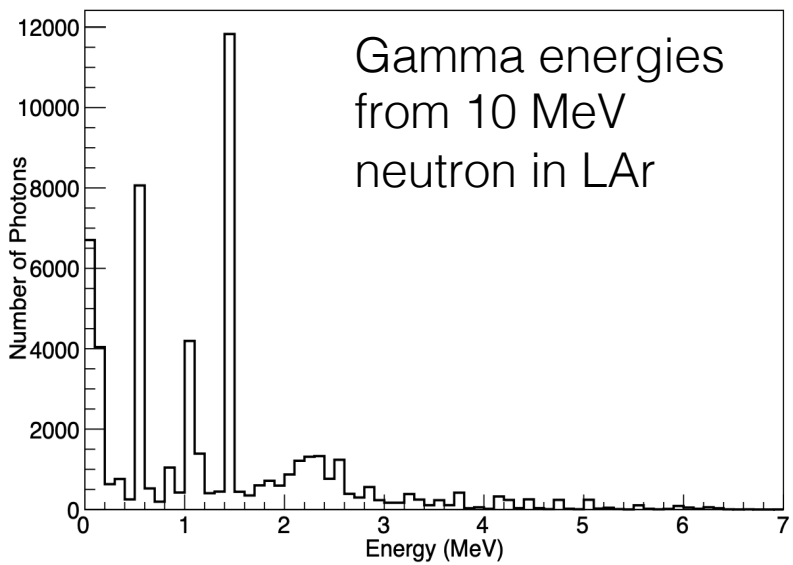
Benefit #2: Final-state neutron ID and calorimetry

Some energy in an event is often "lost" to neutrons (sub-MeV to 10s of MeV range)

- *At low energies*: neutrons undergo γ-producing elastic scatters (ES)
- *At higher energies*: neutron-producing *in*elastic scatters occur, the neutrons from which then go on to make more γ's via ES

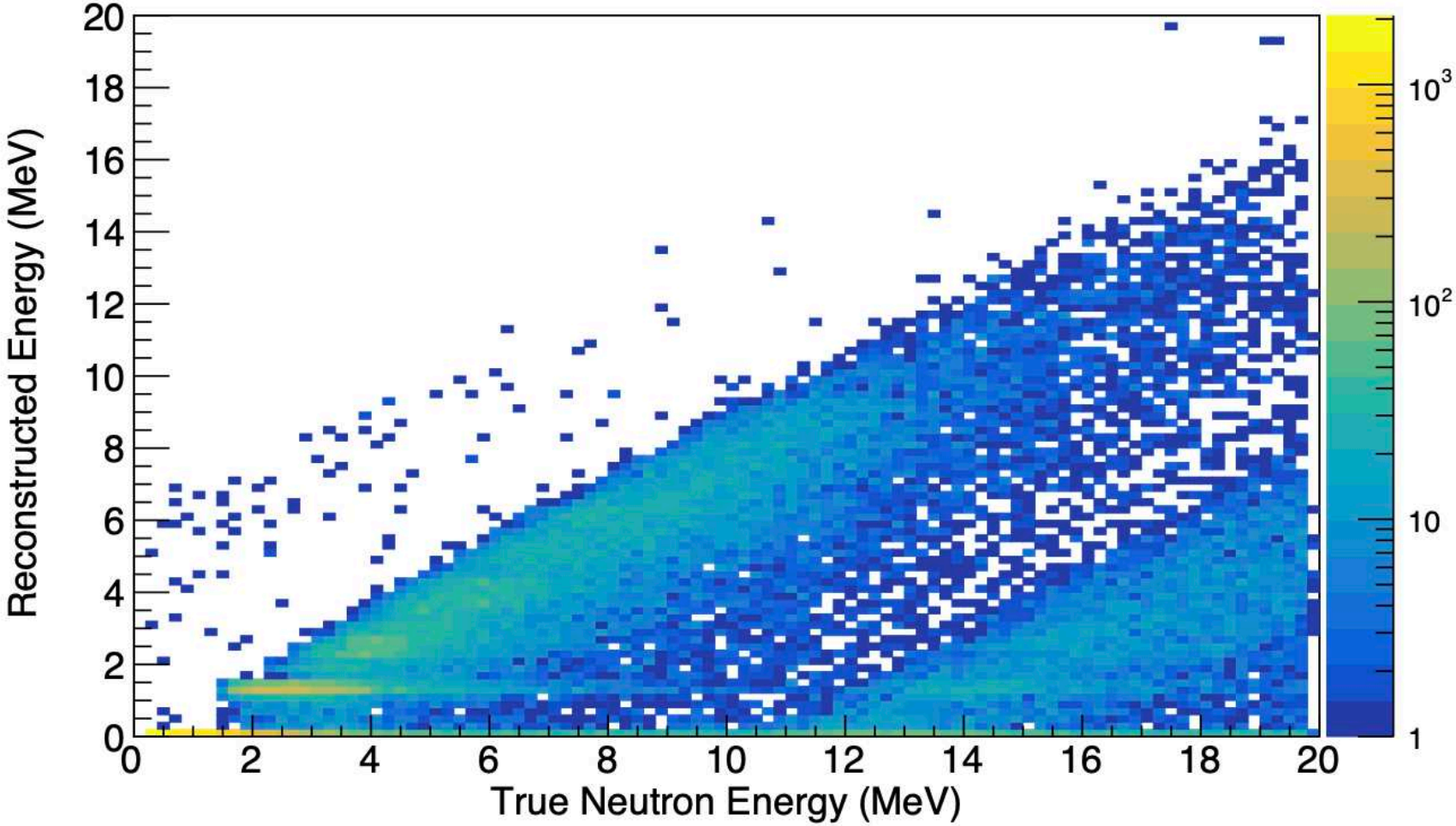






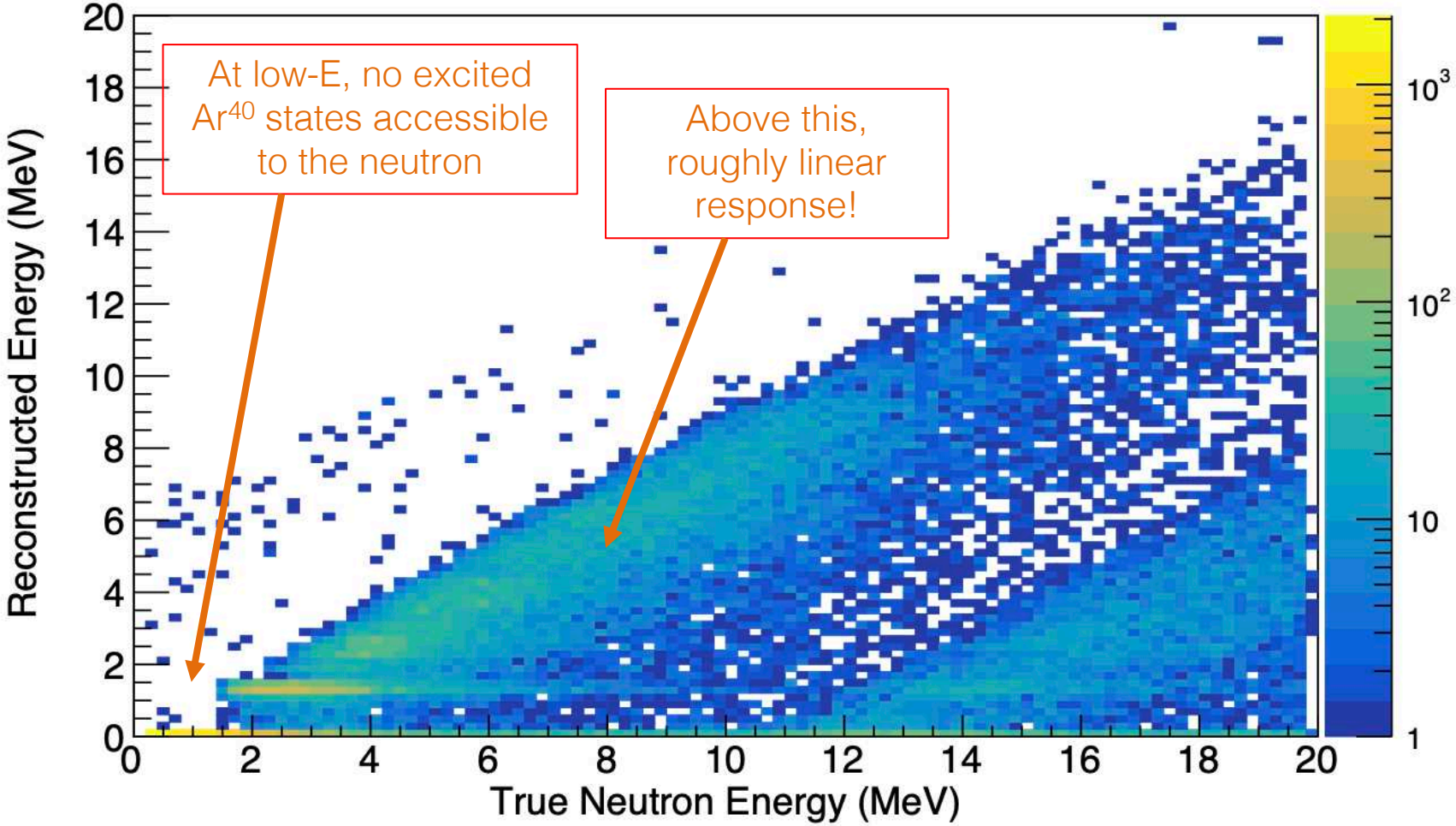
Benefit #2: Final-state neutron ID and calorimetry

Adding up "blips" within 60 cm of neutron production point...



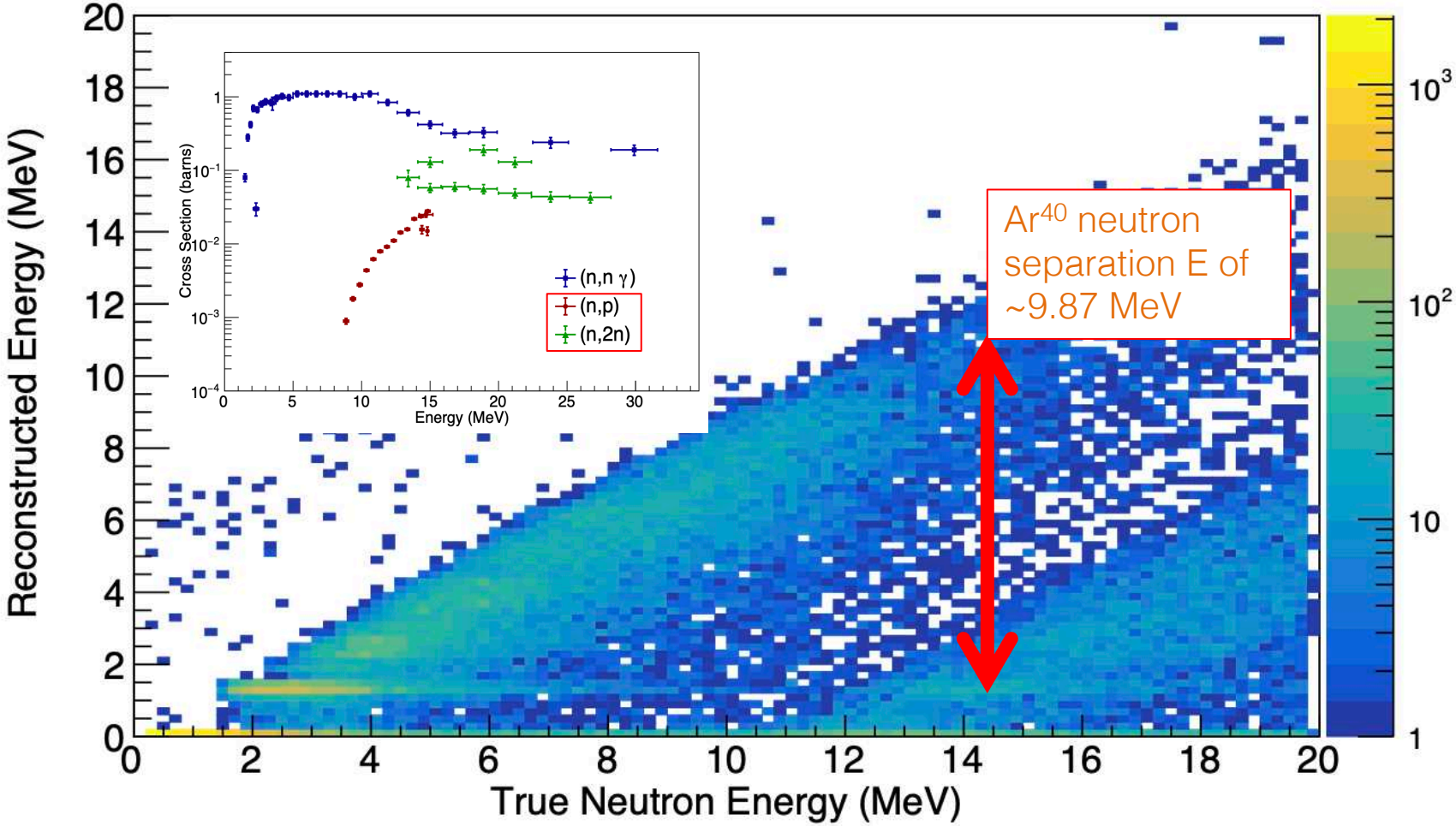
Benefit #2: Final-state neutron ID and calorimetry

Adding up "blips" within 60 cm of neutron production point...



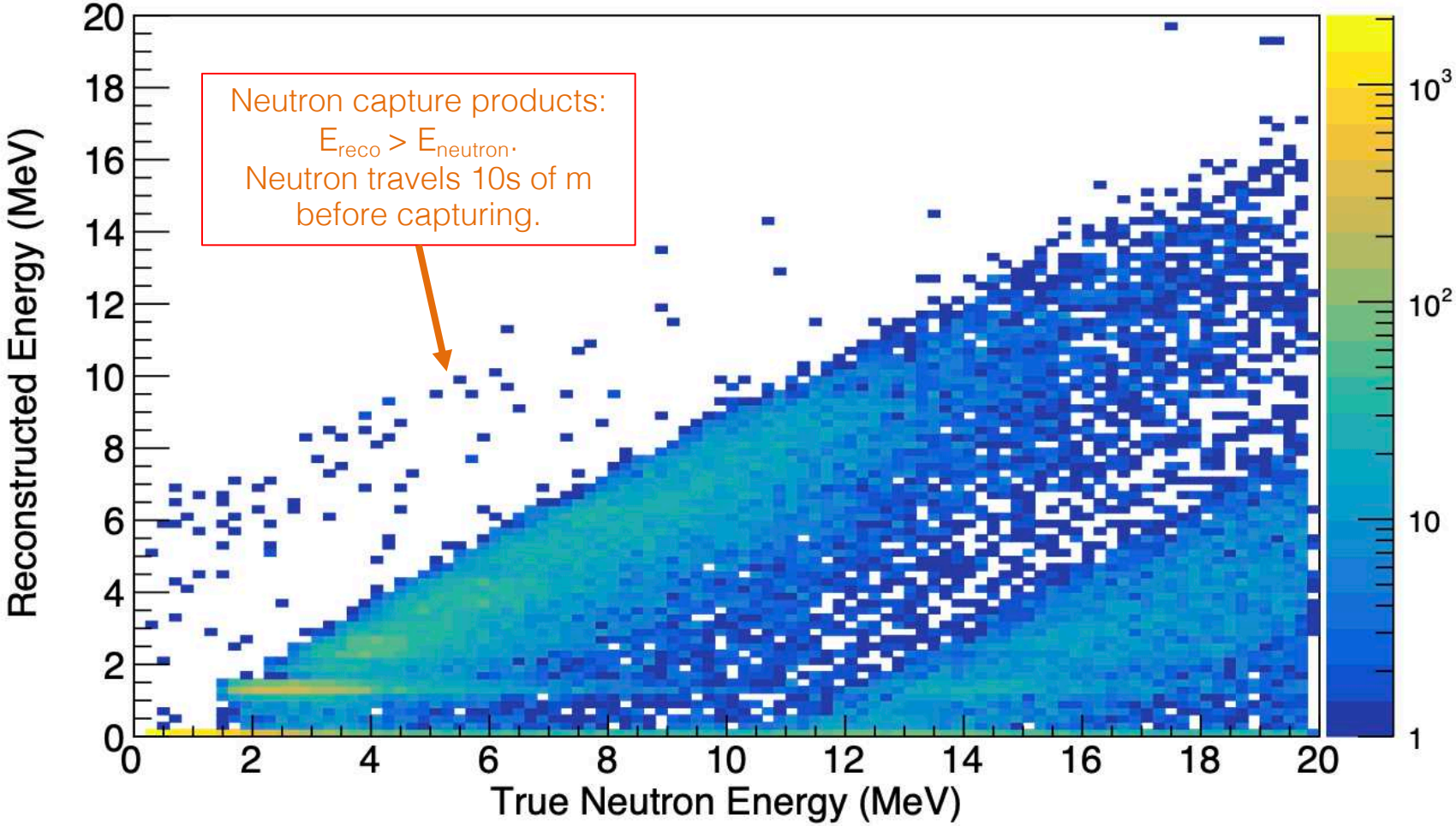
Benefit #2: Final-state neutron ID and calorimetry

Adding up "blips" within 60 cm of neutron production point...



Benefit #2: Final-state neutron ID and calorimetry

Adding up "blips" within 60 cm of neutron production point...

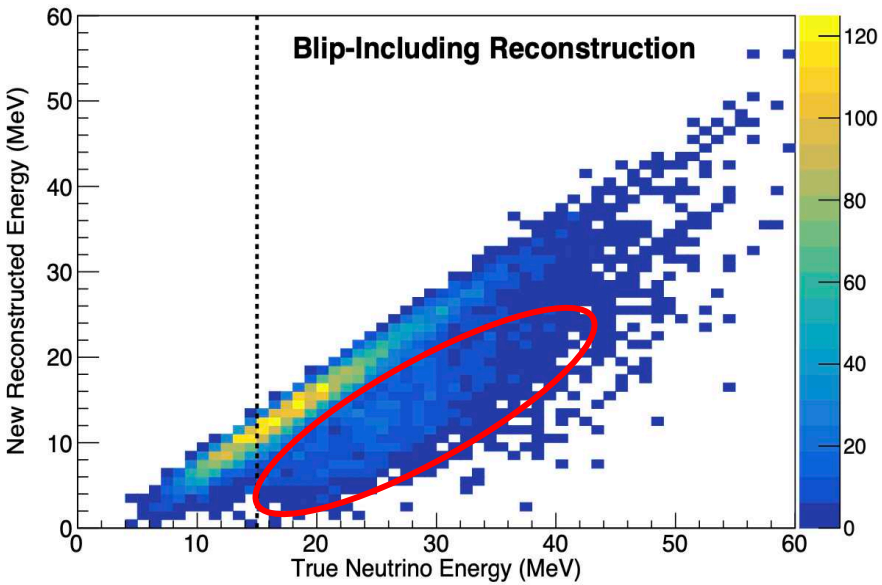


Benefit #2: Final-state neutron ID and calorimetry

Implications for SN ν:

~15% SN ν_e-CC make 1-2 neutrons

- Carry small fraction of FS energy
- Neutron presence implies 7.8 MeV of lost neutrino energy (neutron separation energy in K^{40})
- Tagging an event as *n*-producing could help resolve this for this population of events

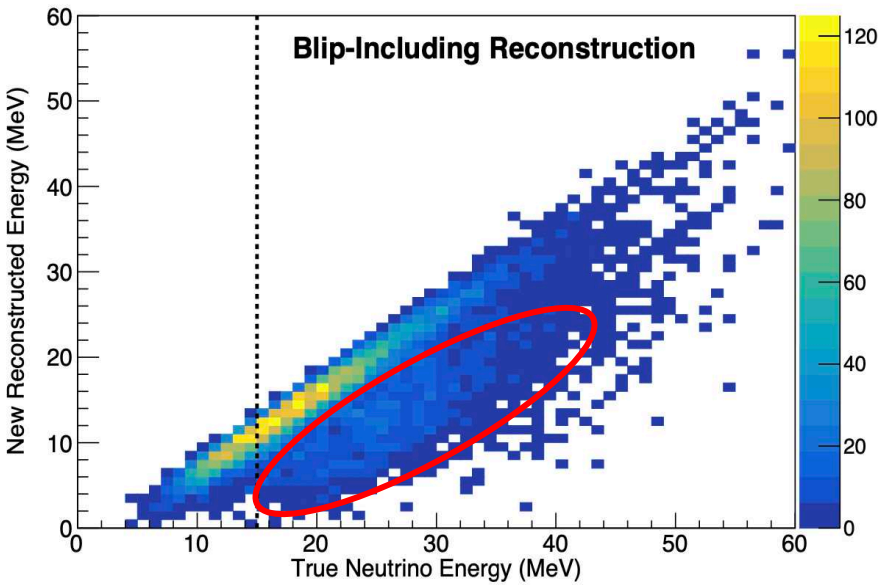


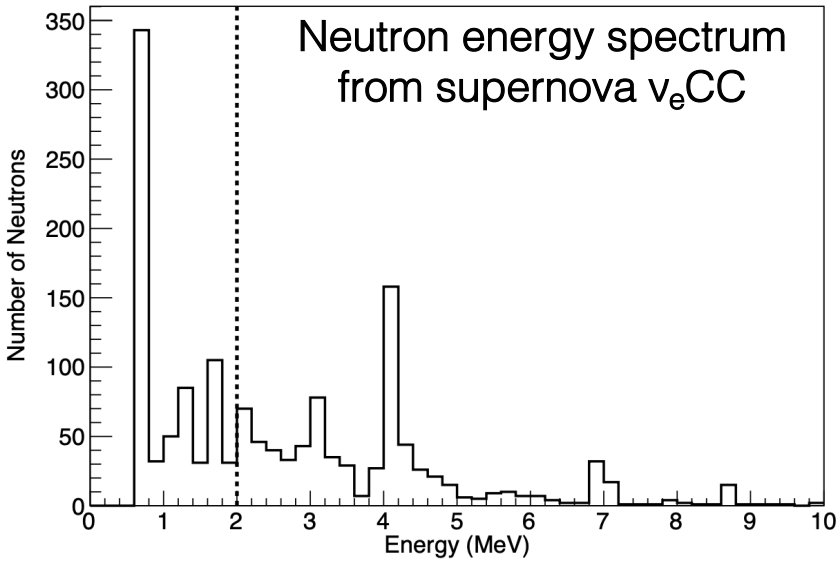
Benefit #2: Final-state neutron ID and calorimetry

Implications for SN ν:

~15% SN ν_e-CC make 1-2 neutrons

- Carry small fraction of FS energy
- Neutron presence implies 7.8 MeV of lost neutrino energy (neutron separation energy in K^{40})
- Tagging an event as *n*-producing could help resolve this for this population of events



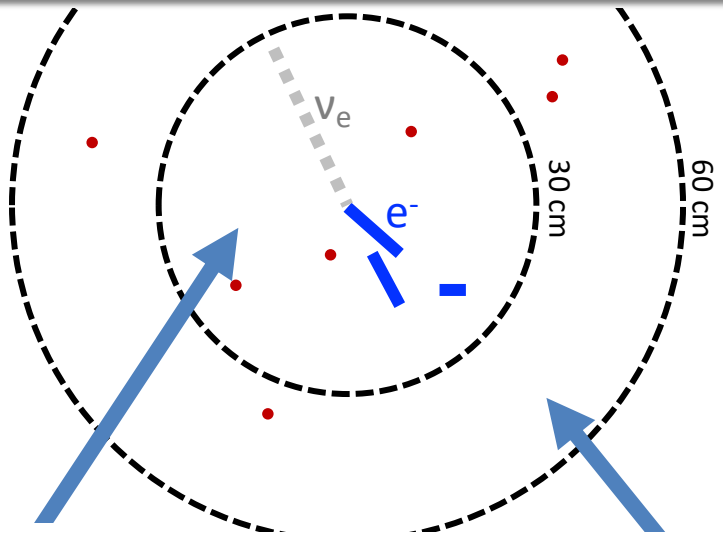


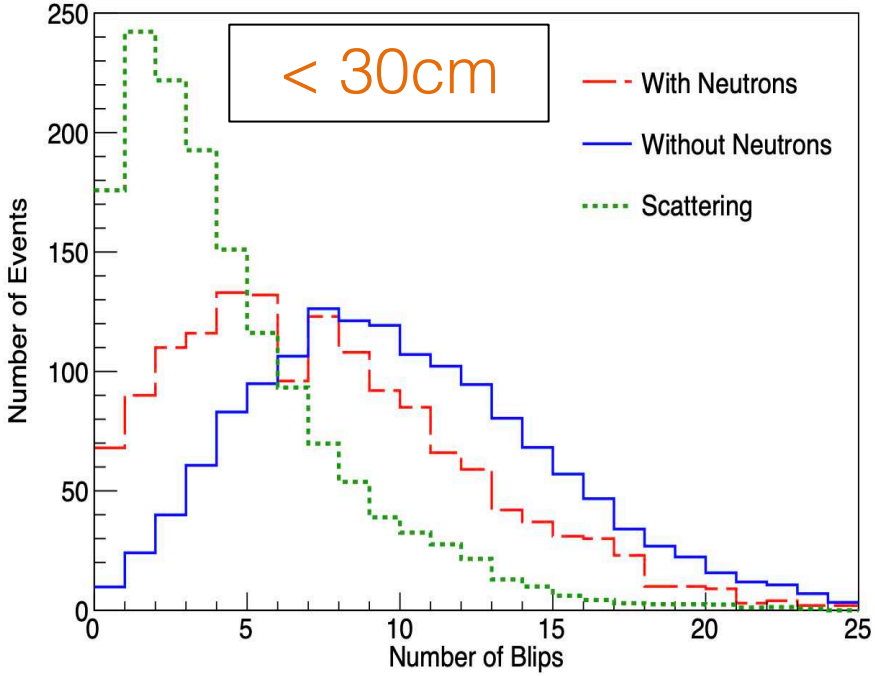
But ~46% of final-state neutrons are < 2 MeV, so effectively invisible in LArTPC...

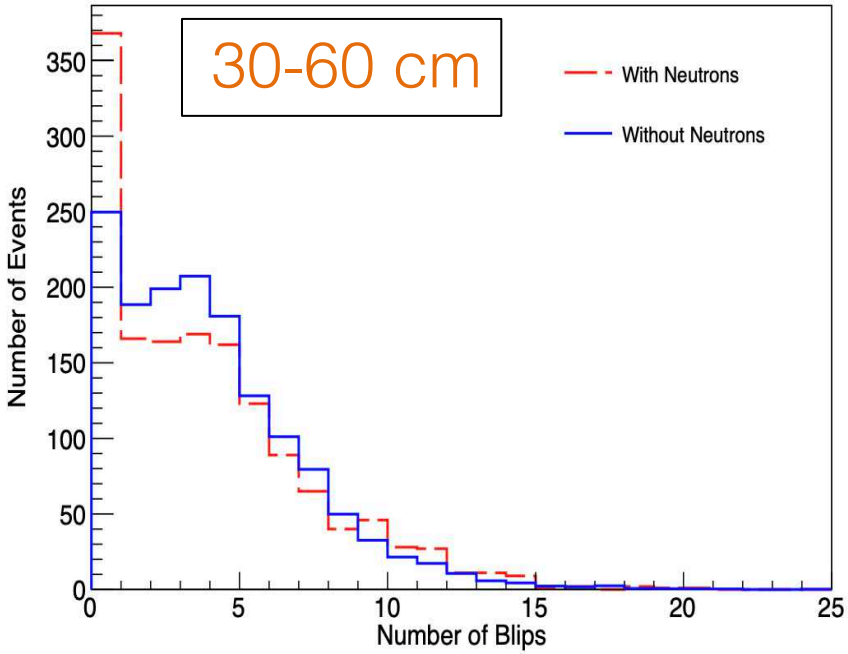
Benefit #2: Final-state neutron ID and calorimetry

Can exploit difference in *neutron / gamma* interaction distance

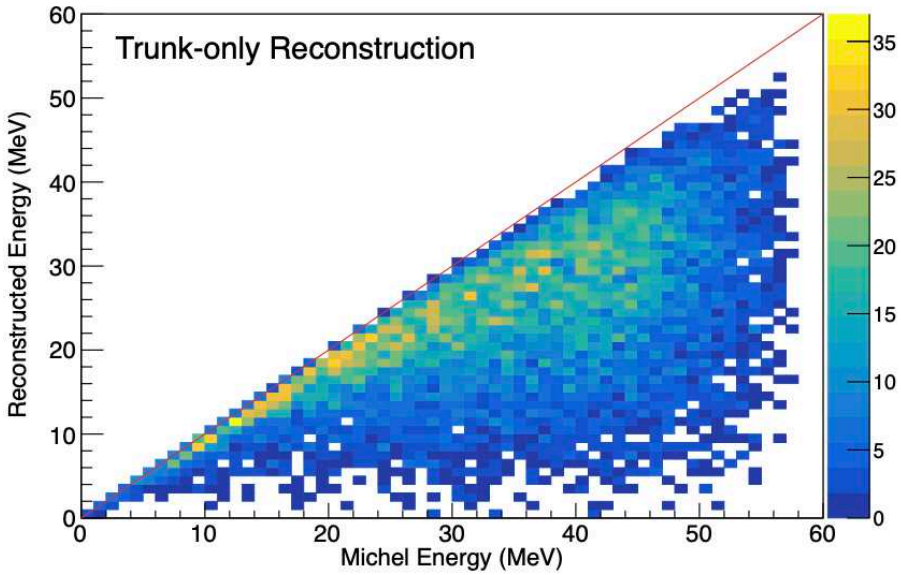
- Events that produce neutrons show <u>fewer</u> blips close to vertex
- Input to multi-variate fit?

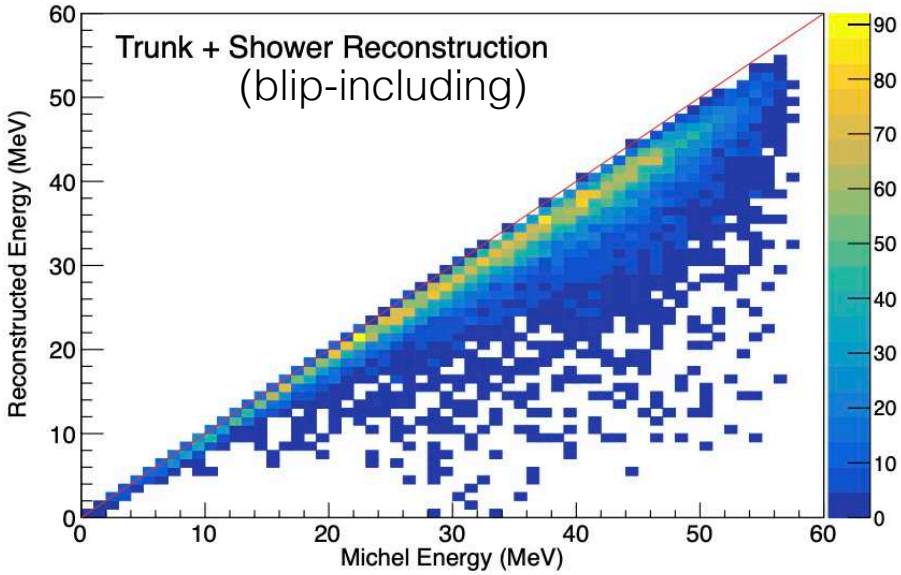




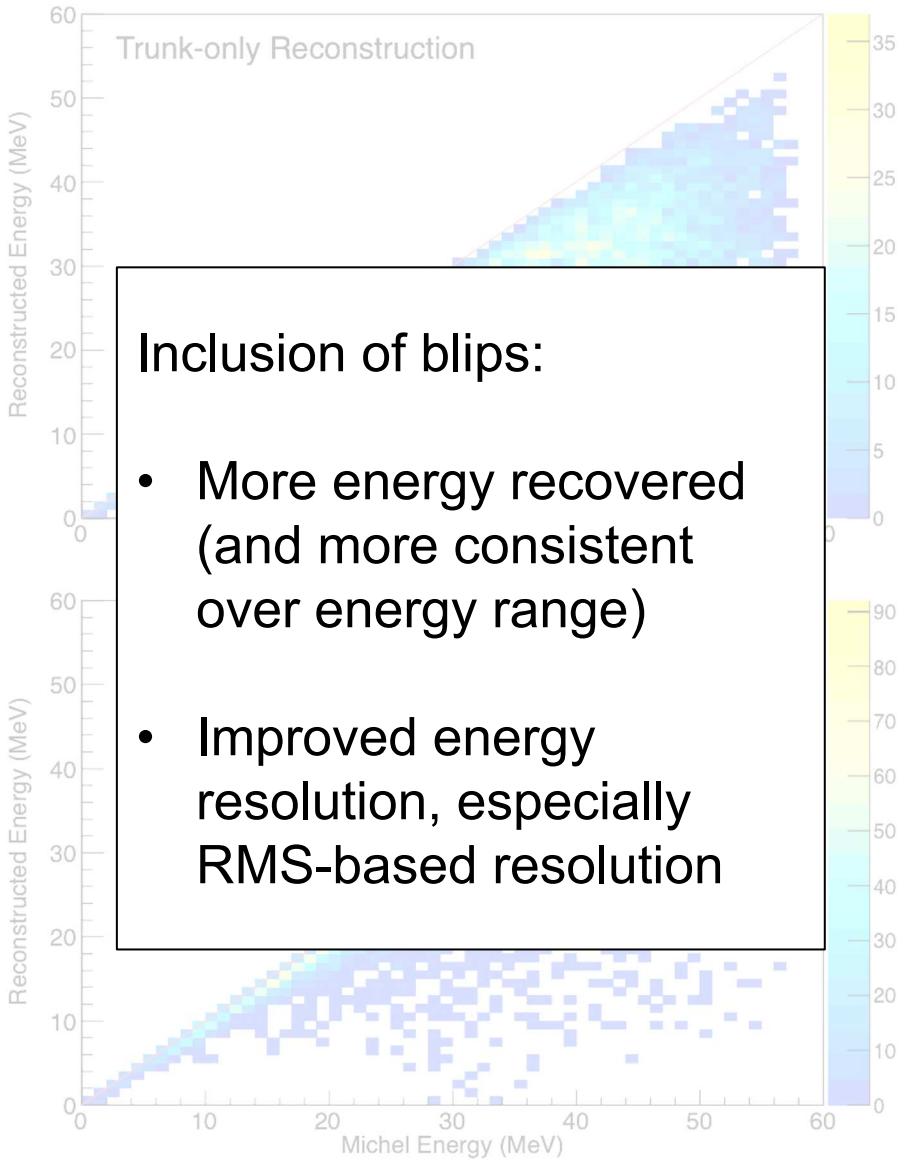


Benefit #3: Electromagnetic shower reconstruction



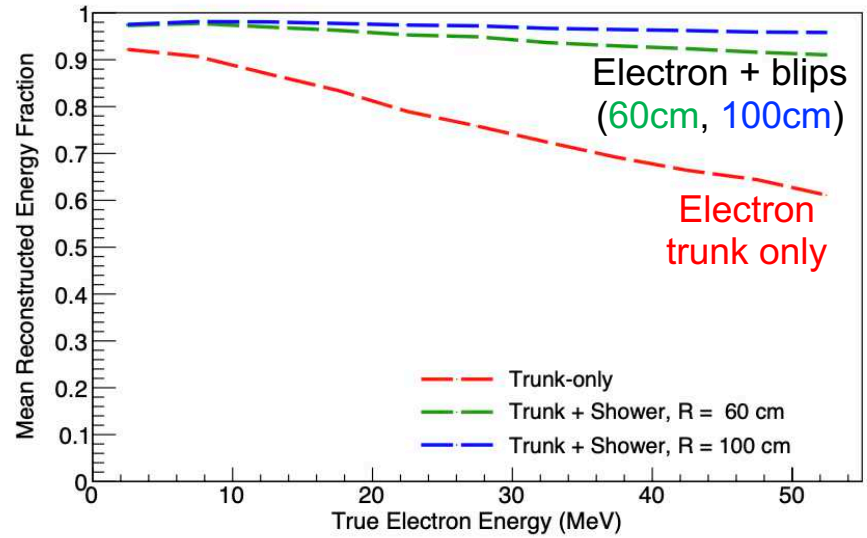


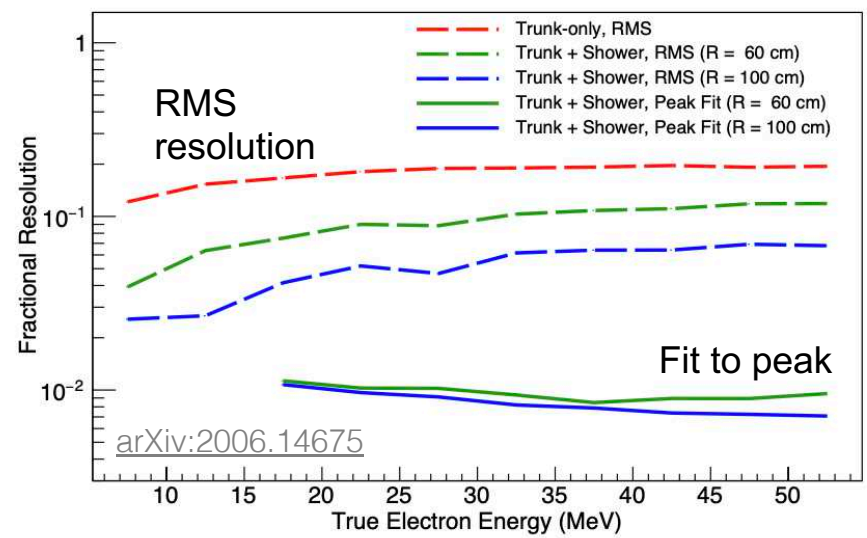
Benefit #3: Electromagnetic shower reconstruction



Inclusion of blips:

- More energy recovered (and more consistent over energy range)
- Improved energy resolution, especially RMS-based resolution



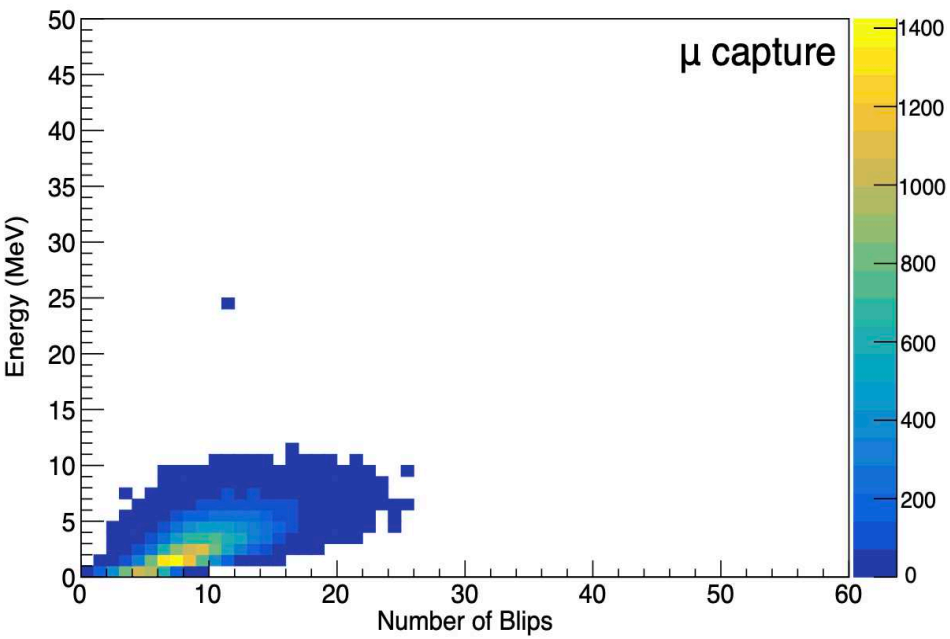


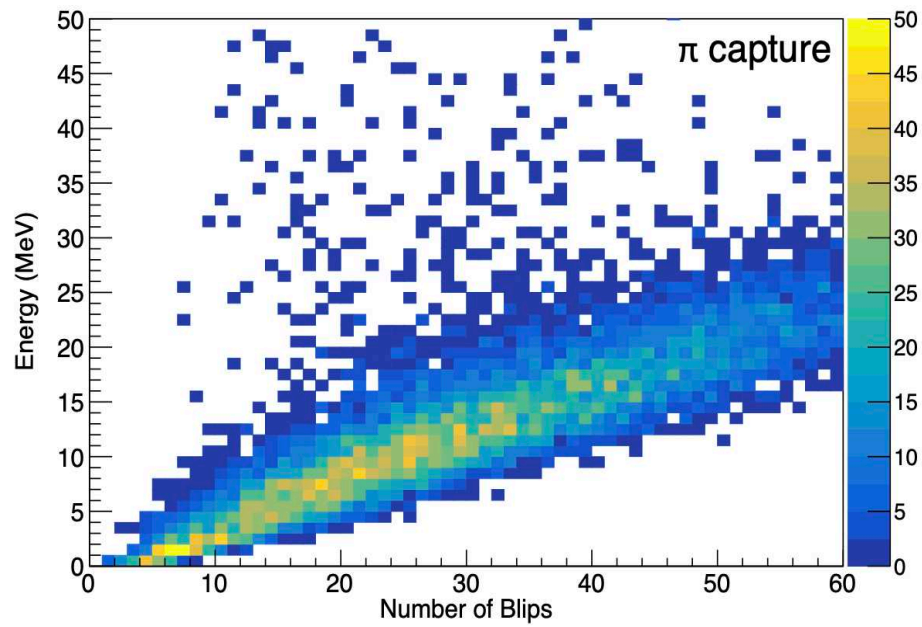
Benefit #4: Final-state particle discrimination

- Muon/pion separation is <u>difficult</u> in a LArTPC
- Differing probabilities of capture/decay, different capture final-states
  - *In principle, can use MeV-scale activity near candidate endpoint to help discriminate pion from muon*

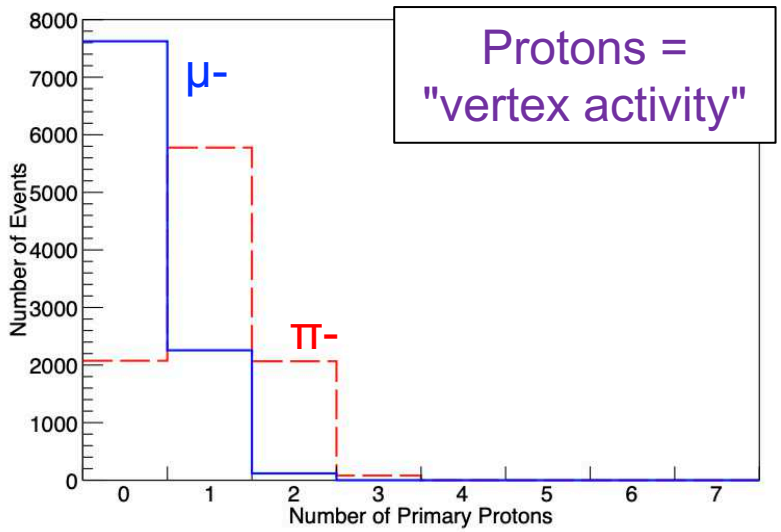
Particle	Decay (%)	Capture (%)	Other (%)
π^+	72	0	28
π^-	3	63	34
μ^+	100	0	0
μ^-	26	74	0

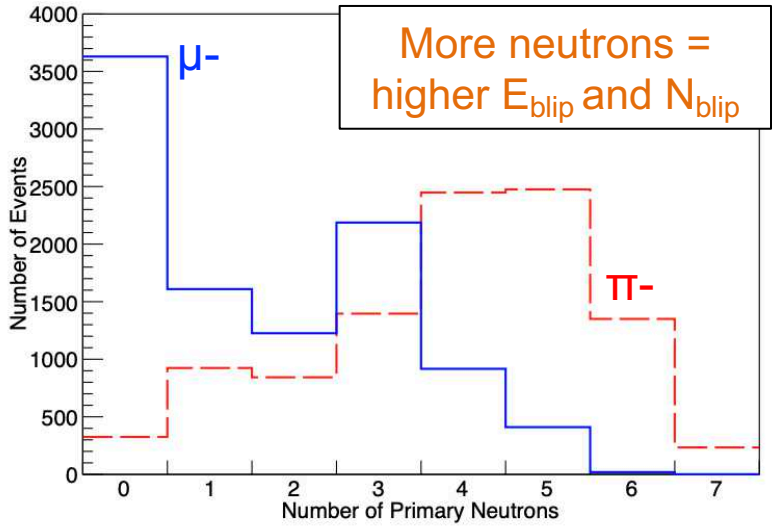
TABLE III. End-of-life processes for 100 MeV positively and negatively charged muons and pions as simulated in Geant4. Decay processes will produce Michel electrons, while capture and other processes (such as absorption and charge exchange) will not.





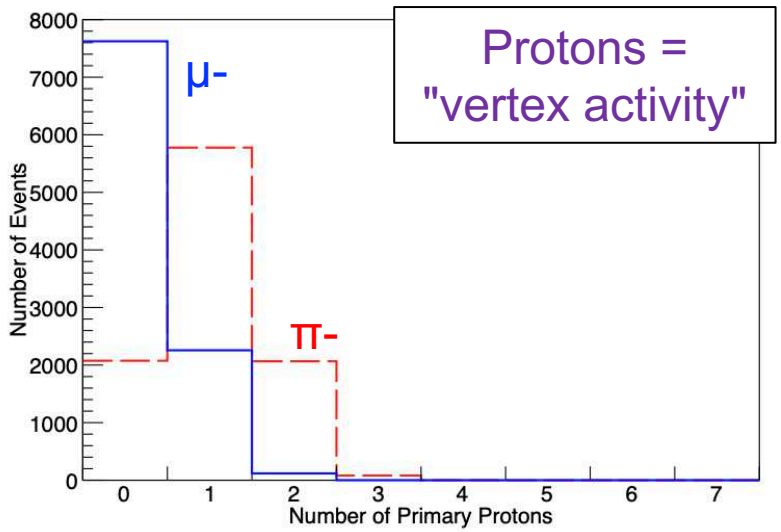
Benefit #4: Final-state particle discrimination

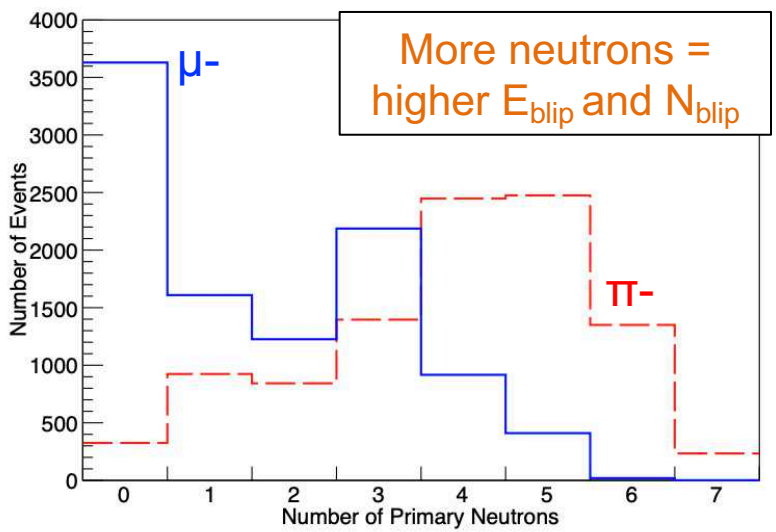




In our MC study, multiplicity, blip energy, and vertex activity are used as metrics to make simple cuts on pion/muon capture or decay events.

Benefit #4: Final-state particle discrimination





In our MC study, multiplicity, blip energy, and vertex activity are used as metrics to make simple cuts on pion/muon capture or decay events.

Can obtain statistically enhanced purity samples of π^- capture-at-rest (CAR)

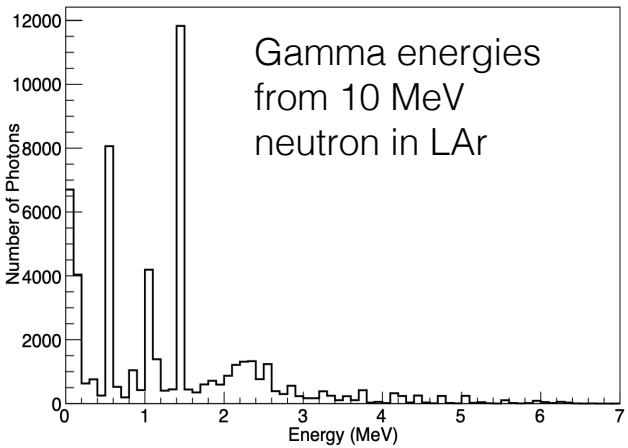
Radius	N_{blip}	E_{blip}	E_{vert}	μ CAR	μ Decay	π CAR
30 cm	> 7	–	–	34%	66%	85%
30 cm	–	$\geqslant 4$ MeV	–	15%	45%	76%
30 cm	> 7	$\geqslant 4$ MeV	–	12%	41%	73%
60 cm	> 14	–	–	6.0%	48%	85%
60 cm	–	$\geqslant 8$ MeV	–	1.7%	41%	76%
60 cm	> 14	$\geqslant 8$ MeV	–	0.80%	32%	75%
60 cm	–	–	> 5 MeV	18%	0%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

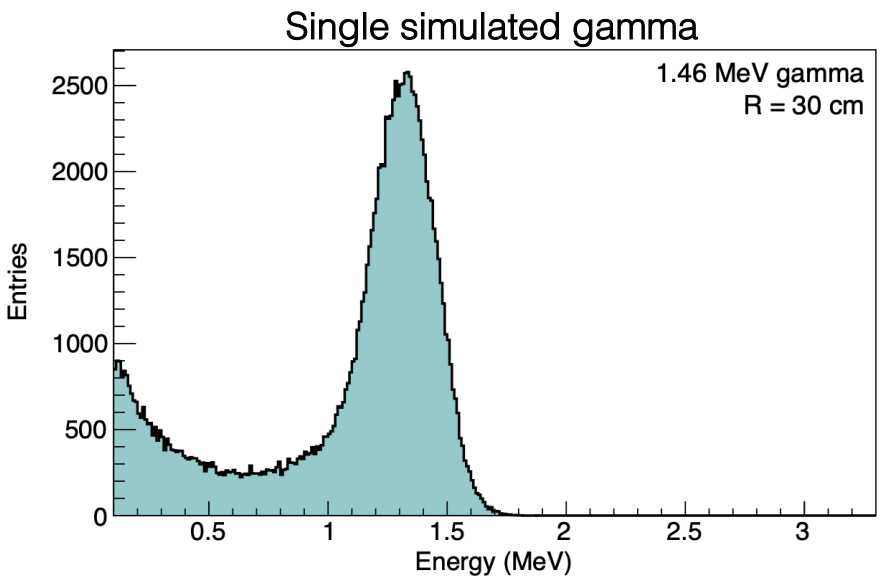
TABLE IV. Selection efficiency for various applied blip activity and vertex activity cuts for μ^- captures at rest (CAR), decaying μ^-, and π^- CAR. The vertex region is defined by a 0.5 cm radius sphere centered at the particle's decay or capture point; only blips found outside of this region are considered.

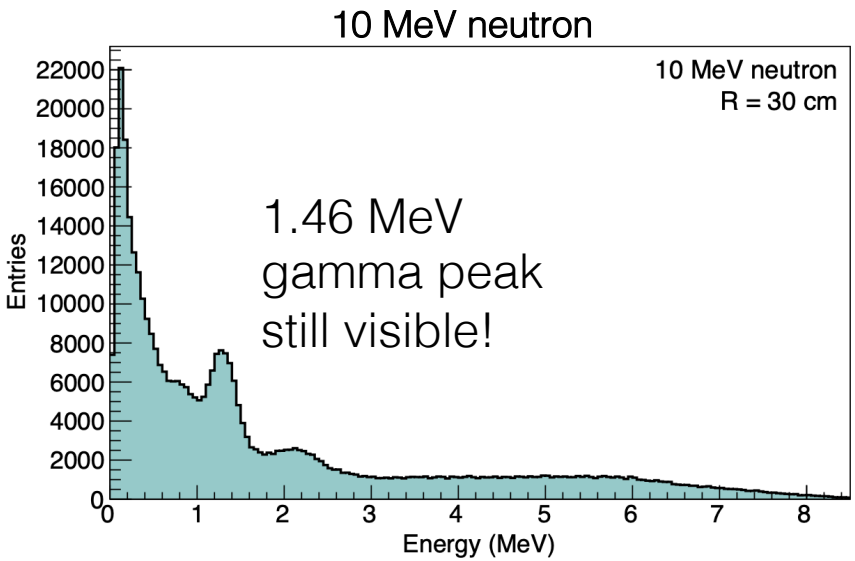
Benefit #5: Single gamma spectroscopy

Remember those γ-producing neutrons? Individual γ's can be reconstructed from their induced blip activity

- Simple proximity-based iterative blip-grouping algorithm
- Smearing of 50 keV per blip is applied based on MicroBooNE study looking at integrated wire signals (MICROBOONE-NOTE-1050-PUB)

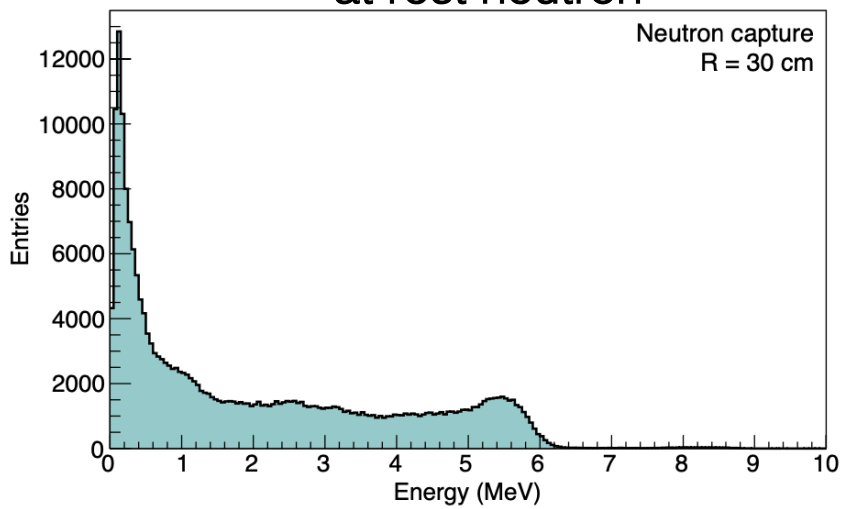


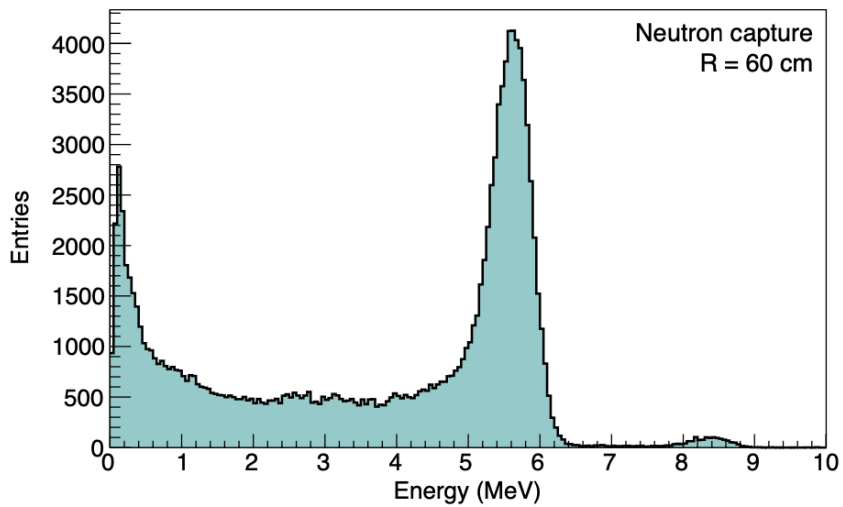




Benefit #5: Single gamma spectroscopy

~ at rest neutron





Same is done for capturing neutrons

6.1 MeV γ peak is recovered, though obviously more pronounced at larger blip-inclusion radii...

→ **Naturally occurring low-energy calibration signal!**

Summary

MeV-scale blips have a variety of benefits relevant to large LArTPCs for a wide range of physics topics.

Our paper on the arxiv (arXiv:2006.14675) reviews many of these benefits using truth-level MC studies.

Active discussions going for how to ensure DUNE will be sensitive to blip activity. Challenges include:

- Ar^{39} contamination
- Triggering and readout
- Data-reduction / zero-suppression

Comments, ideas, or just wanting to chat blips with us? Reach out!

wforeman @ iit.edu

Backup

Calculating energy from charge

Collected charge (Q) must be converted into deposited energy

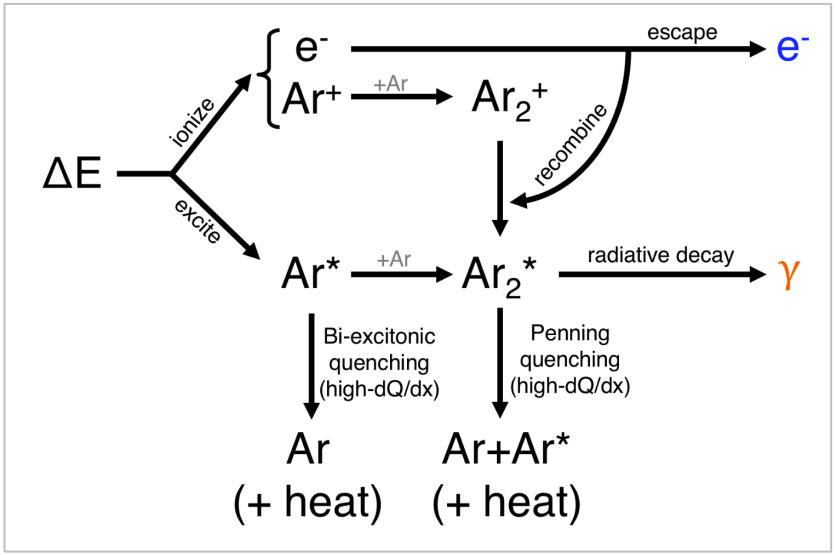
Number of electrons collected

$$E = Q \times R^{-1} \times (24\ \text{eV})$$

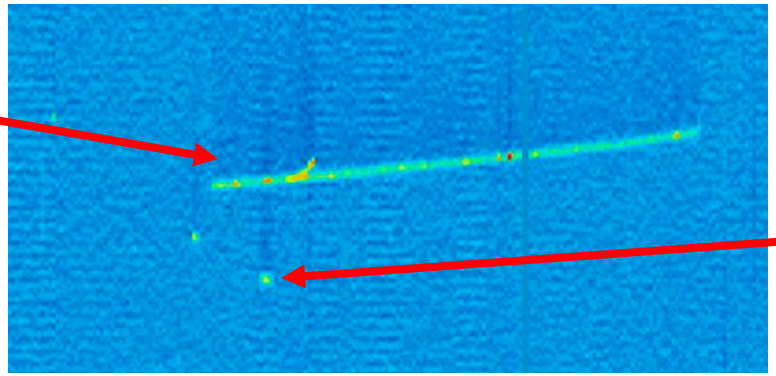
Electron recombination factor (function of dE/dx and E-field)

Average energy required to make e^-/Ar^+ pair

arXiv: 1909.07920



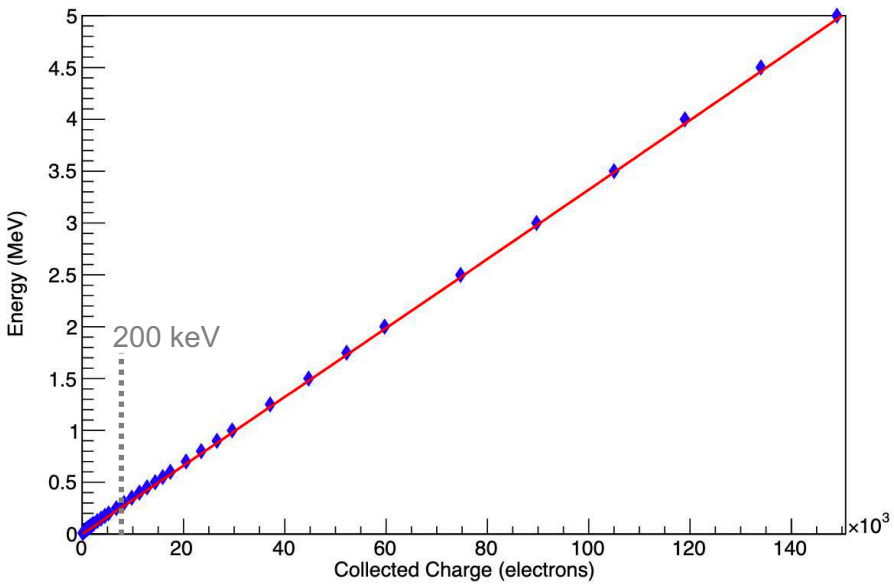
For *tracks,* we know the length and therefore dQ/dx for each hit.



For *blips*, no spatial extent: we lose that "dx" information!

Calculating energy from charge

- MicroBooNE (arXiv:1704.02927) and LArIAT (arXiv:1909.07920)
  - Analyses of Michel electron showers
  - For blips, assumed constant dE/dx (i.e., constant recombination)
- ArgoNeuT (arXiv:1810.06502)
  - Nuclear de-excitation γ analysis
  - Used NIST data on low-E electrons, together with recombination, to directly relate measured Q to energy



- ArgoNeuT method, while data-driven, results in a nearly linear response, which is basically *equivalent to assuming a constant dE/dx!*

So is there actually a better way to do this??

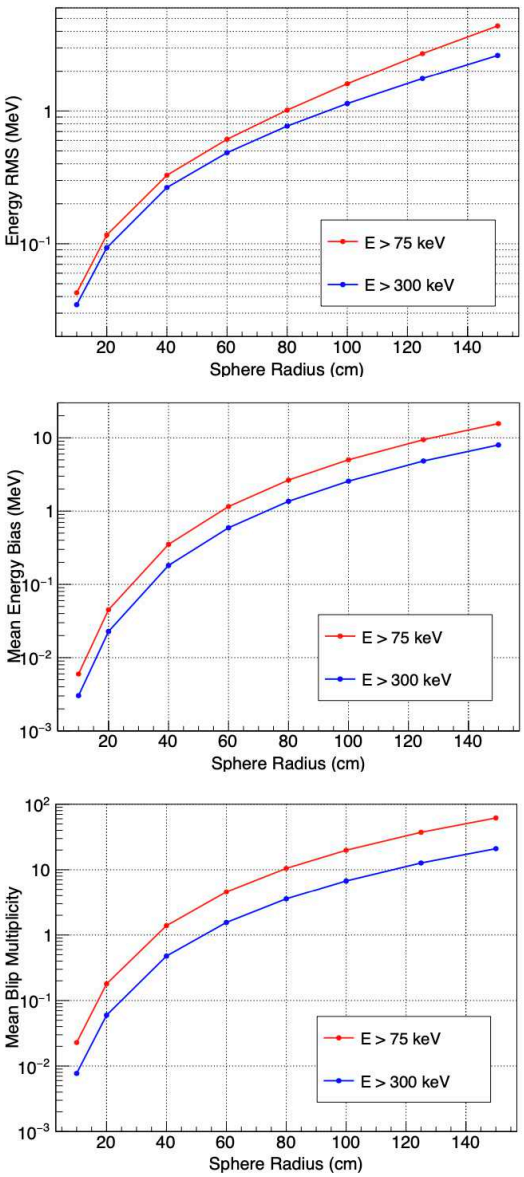
Ar^{39} contamination

- Produced from cosmic ray exposure, present at 1 Bq/kg
- β decay, Q value of 0.565 MeV
- Randomly distributed background of blips

For randomly-selected point in LAr volume, using 75 keV threshold, contribution from Ar^{39} in 30cm sphere:

- Energy ~ 0.1 MeV
- Energy RMS spread ~ 0.2 MeV
- N_{blips} ~ 0.5

This study is currently being updated and expanded.



Electronic noise

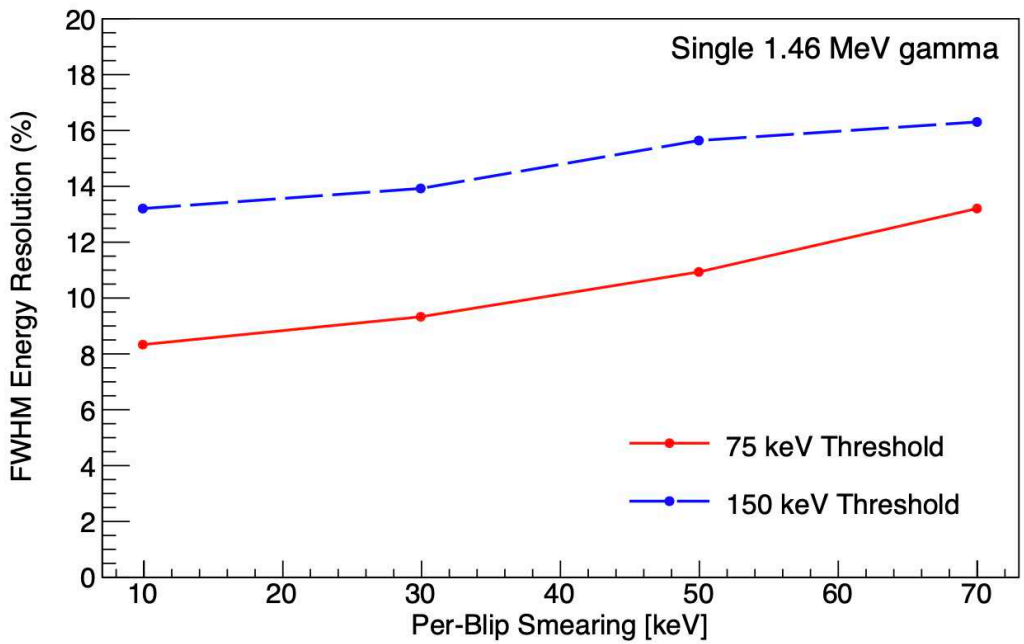


FIG. 20. The resolution of the full-energy peak for simulated 1.46 MeV γ-rays, over a range of different blip smearing levels, for both 75 keV and 150 keV energy thresholds. A proximity requirement of 30 cm is used. Resolution is calculated based on the FWHM of the peak using the relationship to standard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