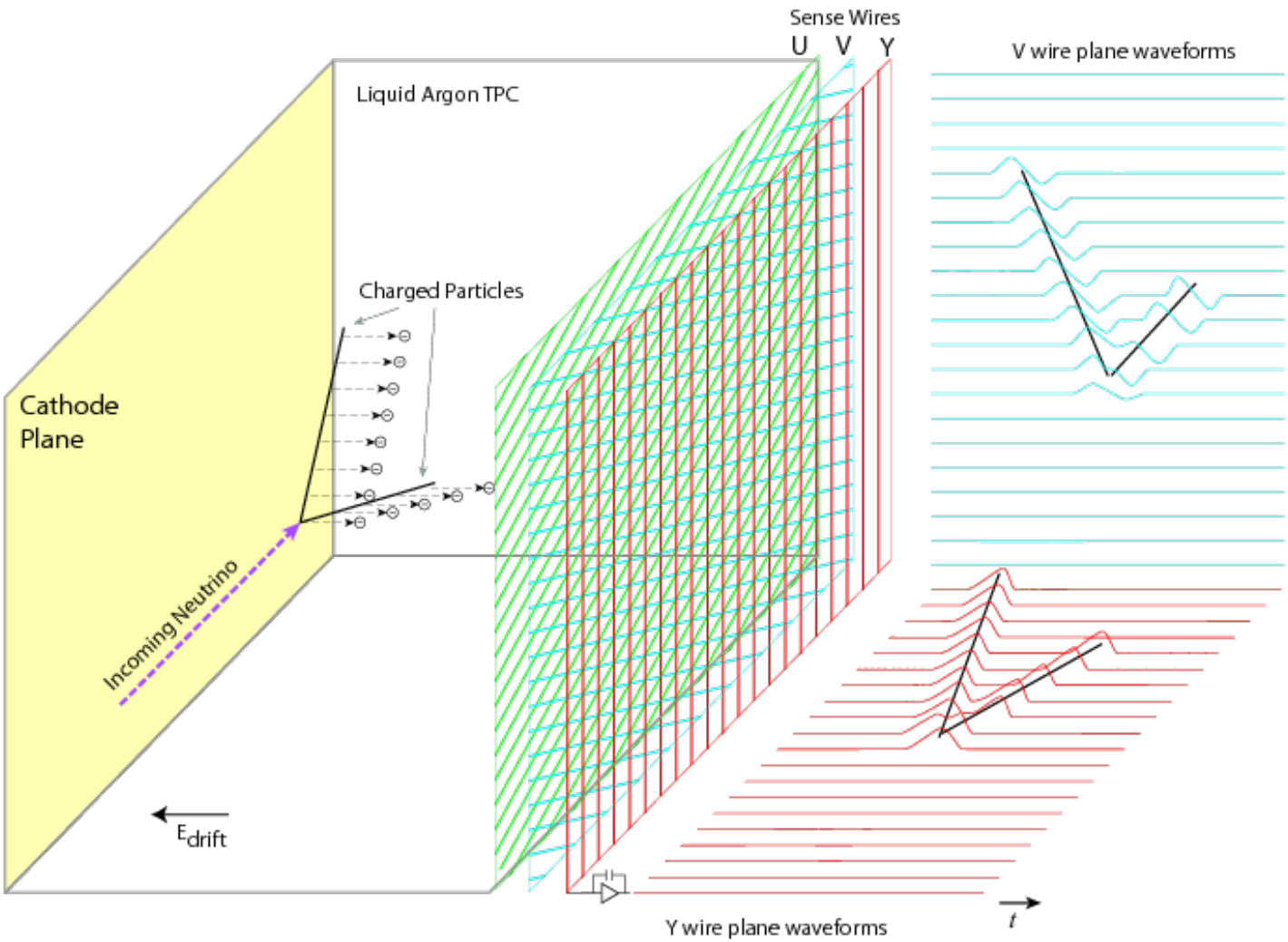
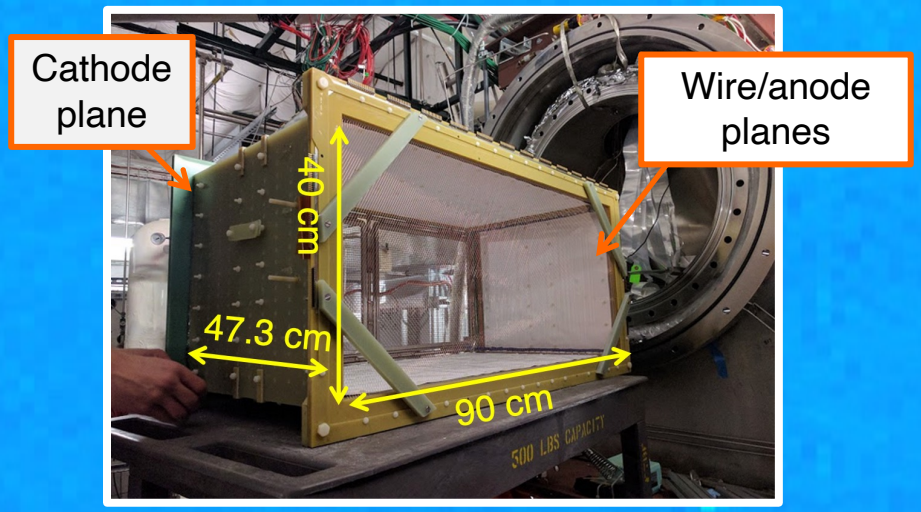
Physics at the MeV-Scale in Neutrino LArTPCs

Will Foreman
Illinois Institute of Technology

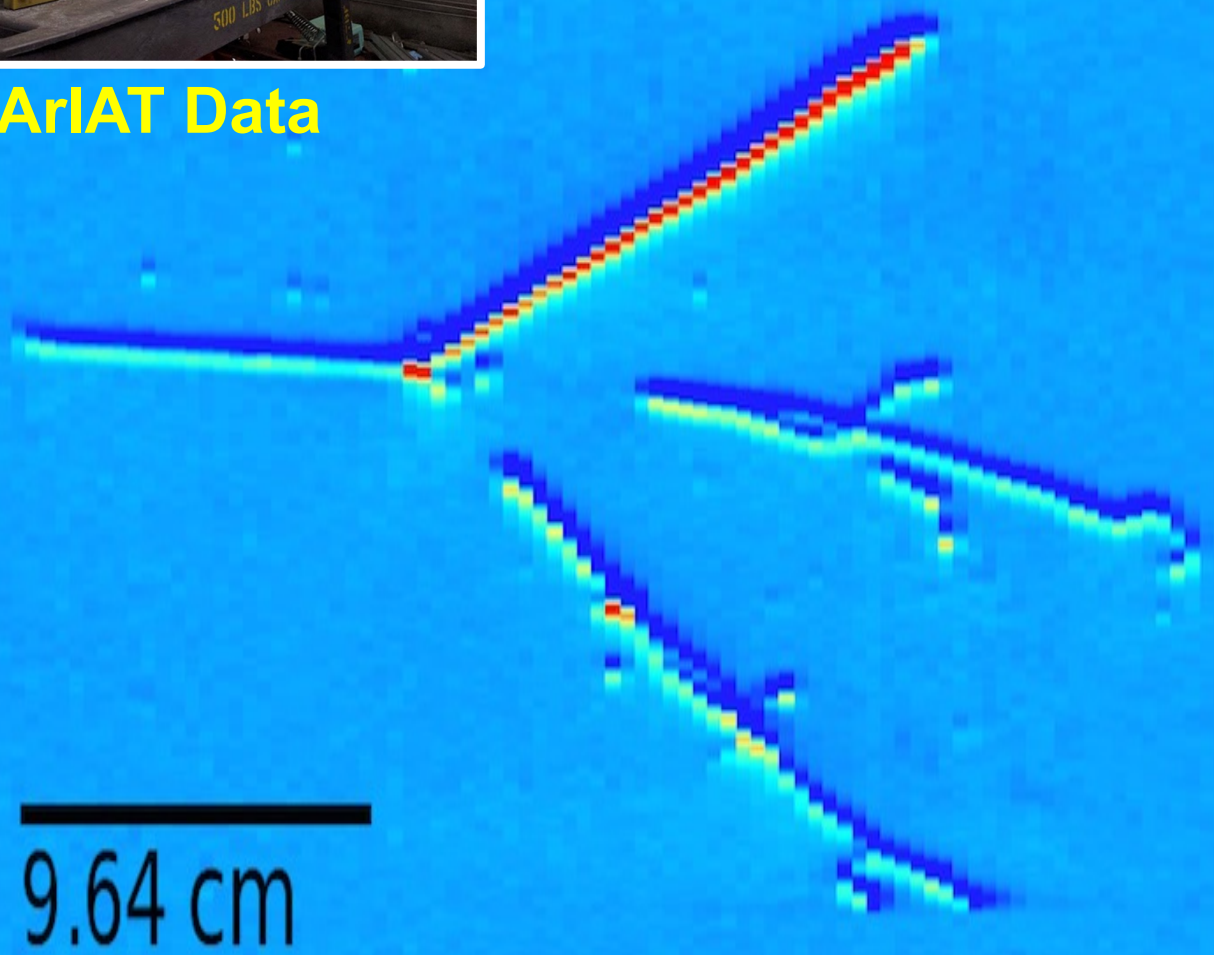
Snowmass Community Summer Study
University of Washington, Seattle
July 24, 2022

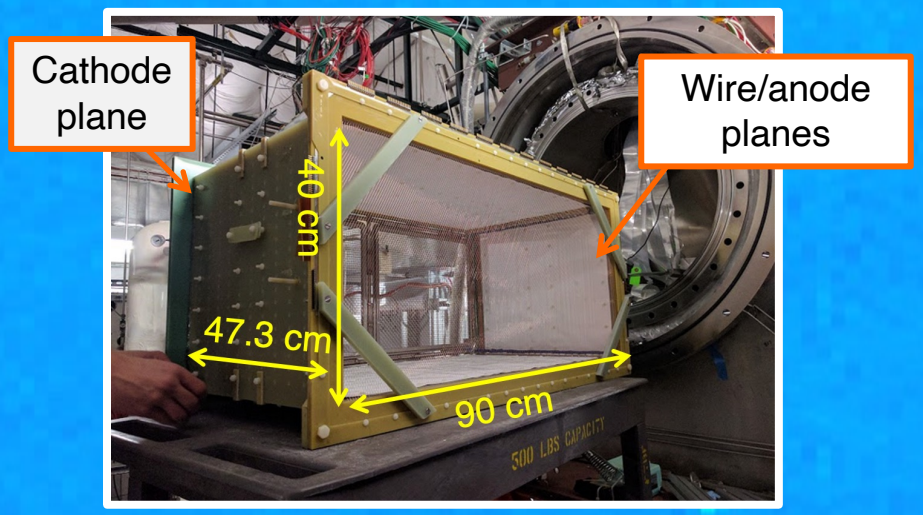
Liquid argon time projection chambers

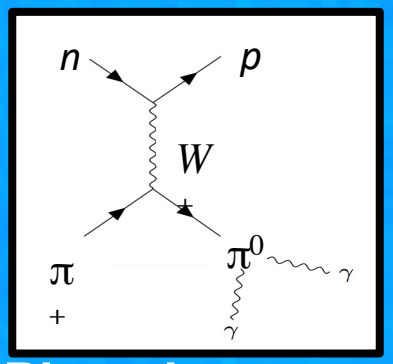



Cathode plane
Wire/anode planes
40 cm
47.3 cm
90 cm
500 LBS CAPACITY

LArIAT Data

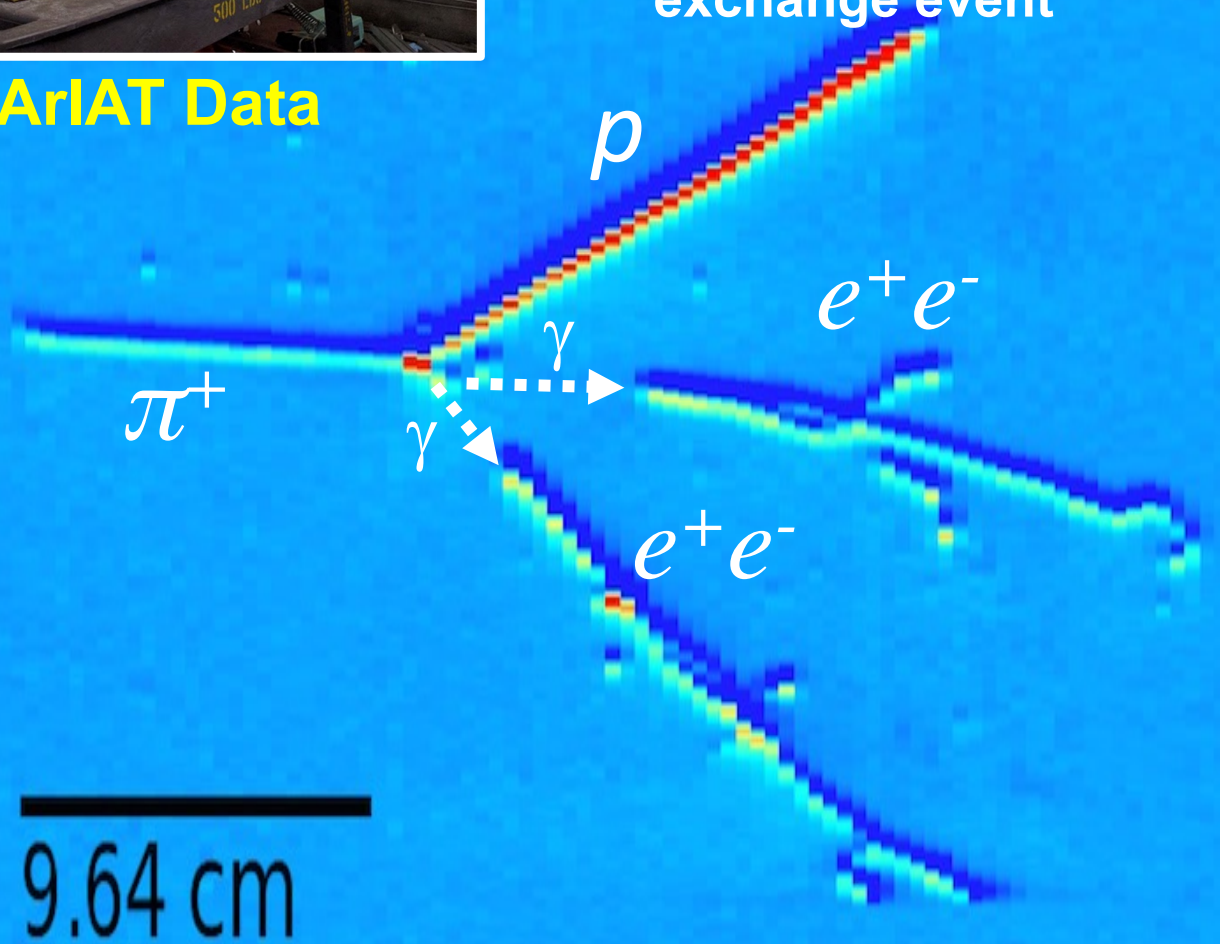

9.64 cm



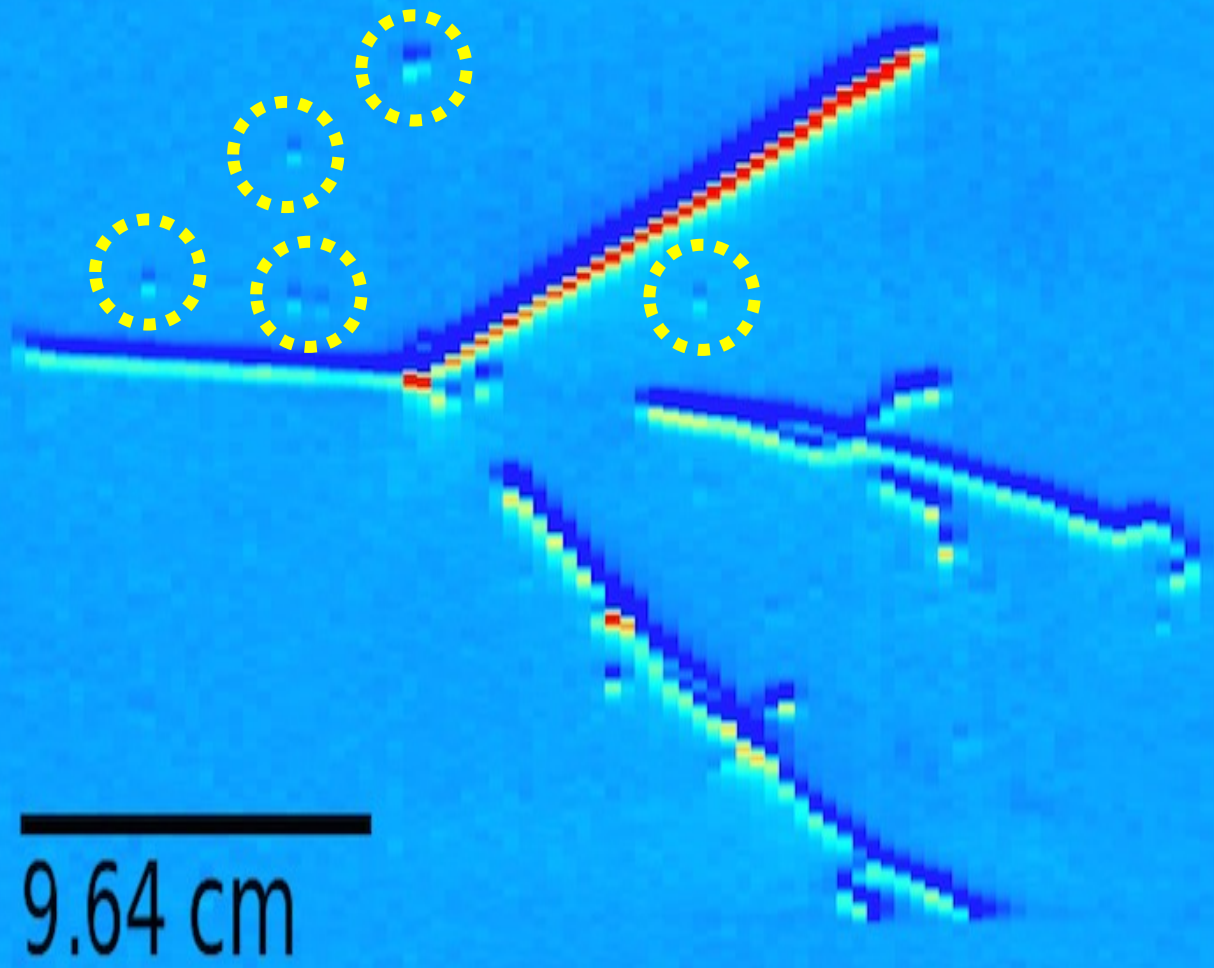


Pion charge-exchange event

LArIAT Data



MeV-scale activity from de-excitation γ's and neutrons



Energy scales in LArTPCs

- Most neutrino reconstruction tools tailored for higher-energy, GeV-scale tracks and EM showers found in ν-Ar final-states
- But LArTPCs are sensitive to **sub-MeV-scale** physics too!

Low-Energy Physics in Liquid Argon (LEPLAr)

- Snowmass workshop held in 2020
  - *Identify opportunities for DUNE in the <100 MeV regime*
  - *Develop standard set of signal/background assumptions*
  - *Exchange ideas between DUNE technical working groups*

LEPLAr Whitepaper (2020)
arXiv:2203.00740

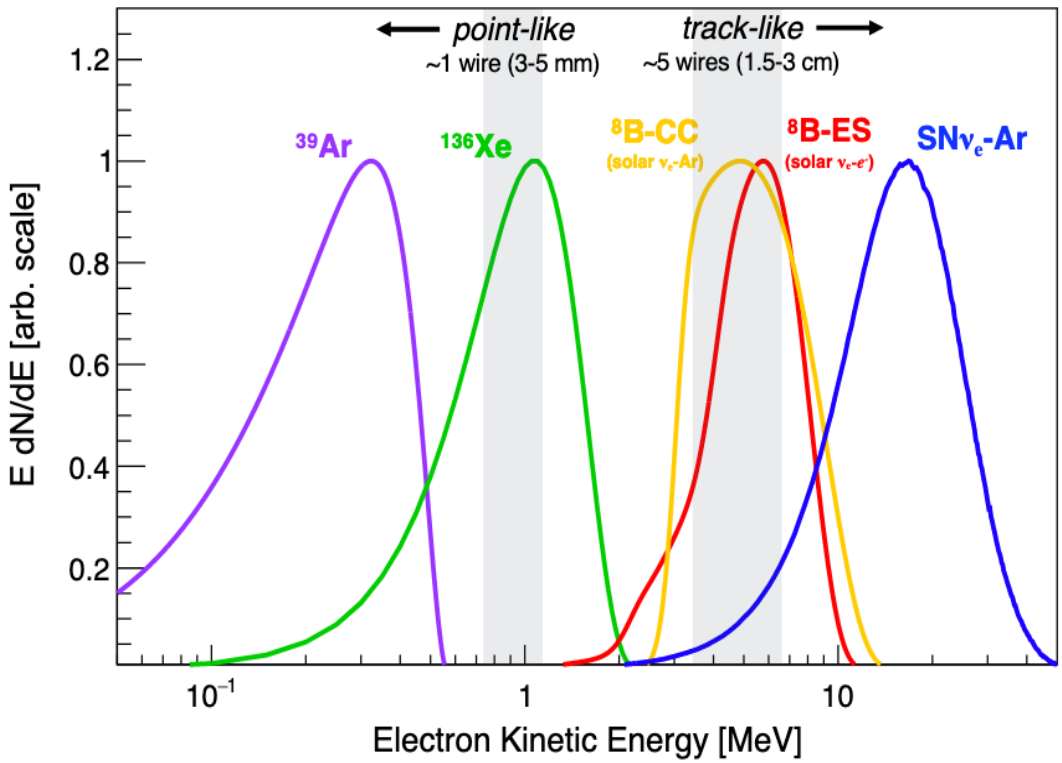
Low-Energy Physics in Neutrino LArTPCs

Contributed Paper to Snowmass 2021

D. Caratelli,[17,*] W. Foreman,[44,*] A. Friedland,[99,*] S. Gardiner,[33,*] I. Gil-Botella,[21,*] G. Karagiorgi,[26,*] M. Kirby,[33,*] G. Lehmann Miotto,[20,*] B. R. Littlejohn,[44,*] M. Mooney,[27,*] J. Reichenbacher,[100,*] A. Sousa,[23,*] K. Scholberg,[29,*] J. Yu,[108,*] T. Yang,[33,*]

S. Andringa,[69,†] J. Asaadi,[108,†] T. J. C. Bezerra,[104,†] F. Capozzi,[43,†] F. Cavanna,[33,†] E. Church,[87,†] A. Himmel,[33,†] T. Junk,[33,†] J. Klein,[89,†] I. Lepetic,[96,†] S. Li,[33,†] P. Sala,[47,†] H. Schellman,[85,33,†] M. Sorel,[43,†] J. Wang,[100,†] M. H. L. S. Wang,[33,†] W. Wu,[33,†] J. Zennamo,[33,†]

Reconstruction and energy scales



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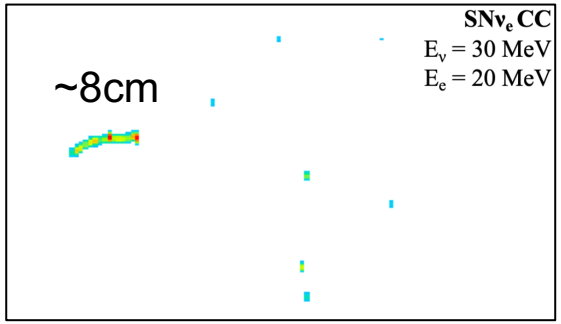
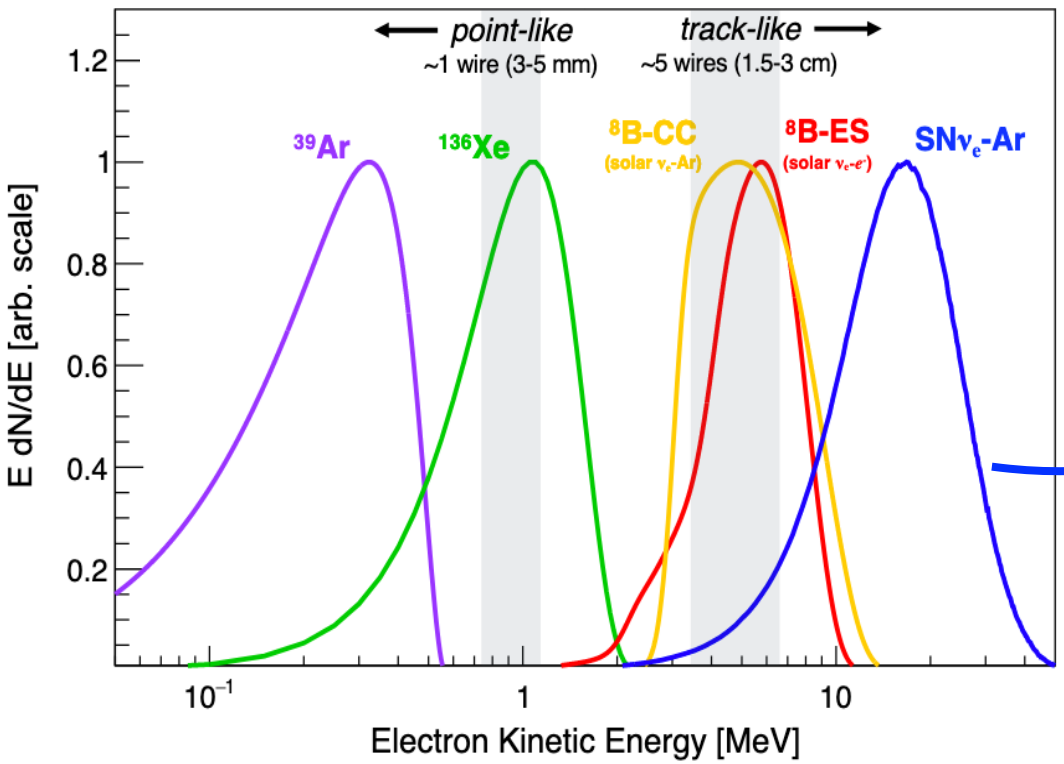
Reconstruction and energy scales

Simulated 20 MeV electron





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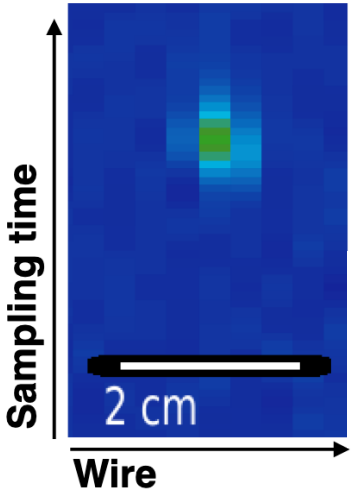
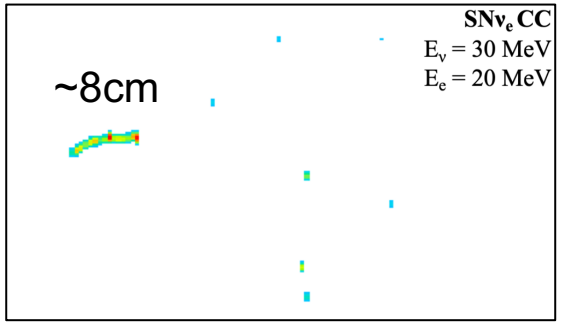
Reconstruction and energy scales

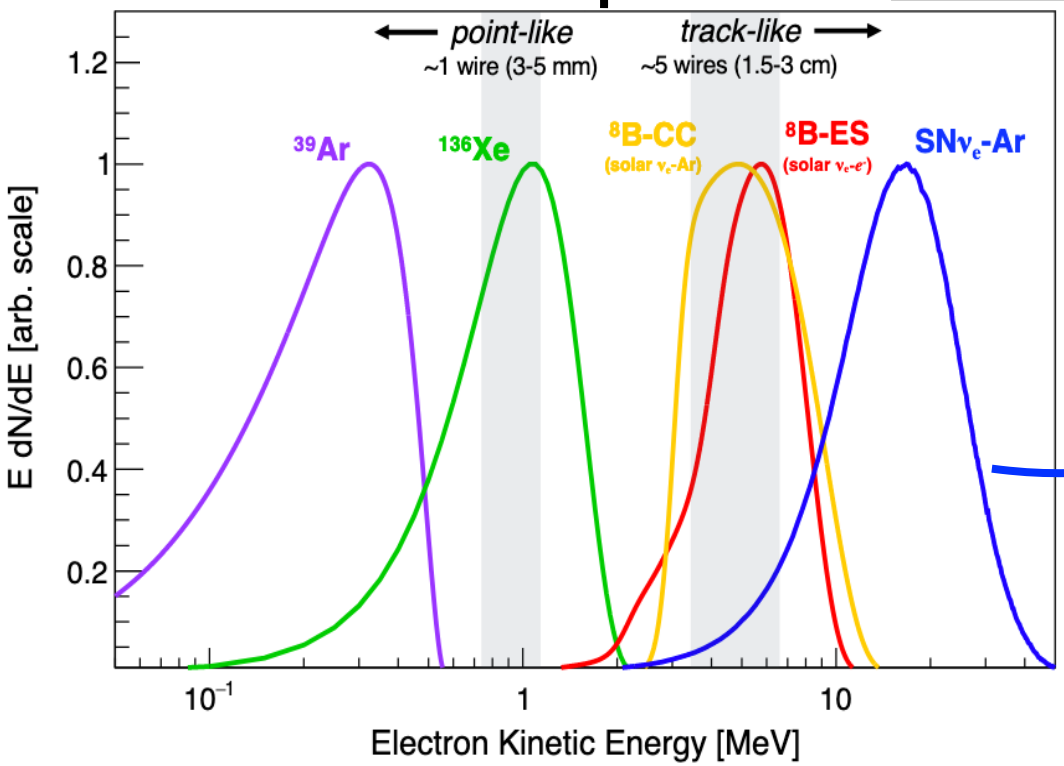


J. Zenammo, Snowmass CSS

Simulated 2.5 MeV electron raw data

Simulated 20 MeV electron





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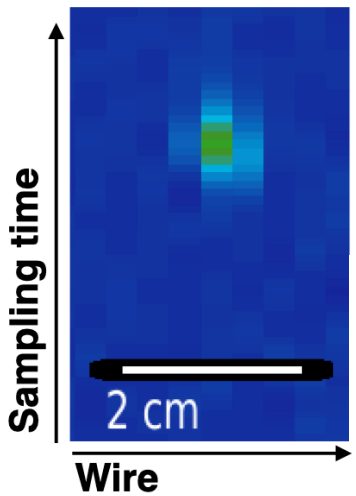
Reconstruction and energy scales



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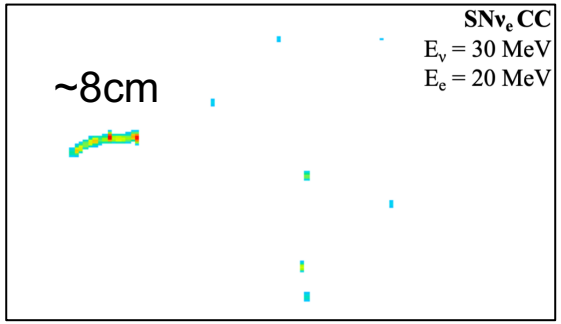

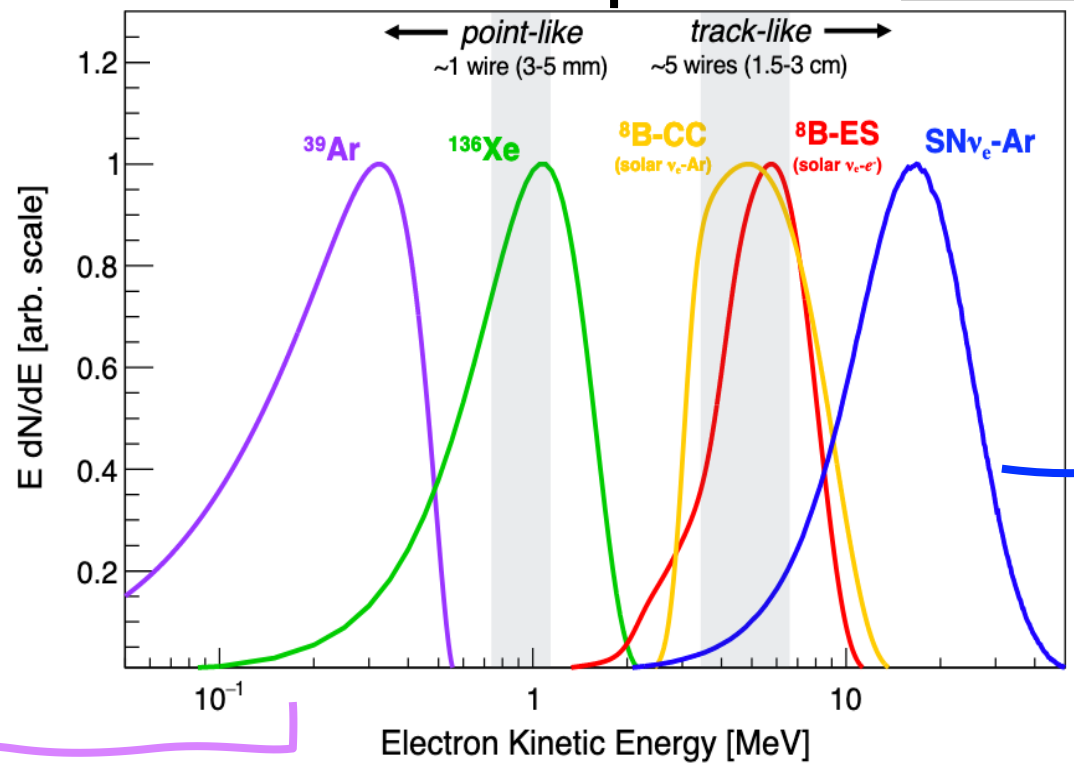

Single-channel signals!

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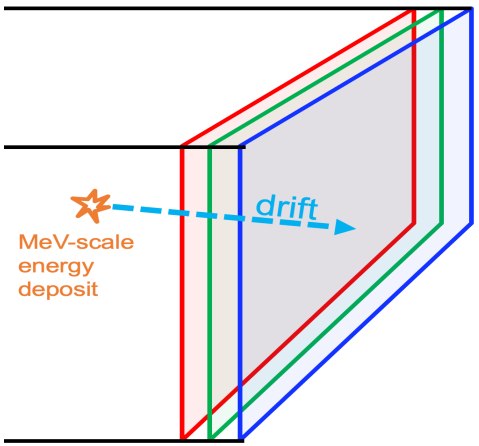
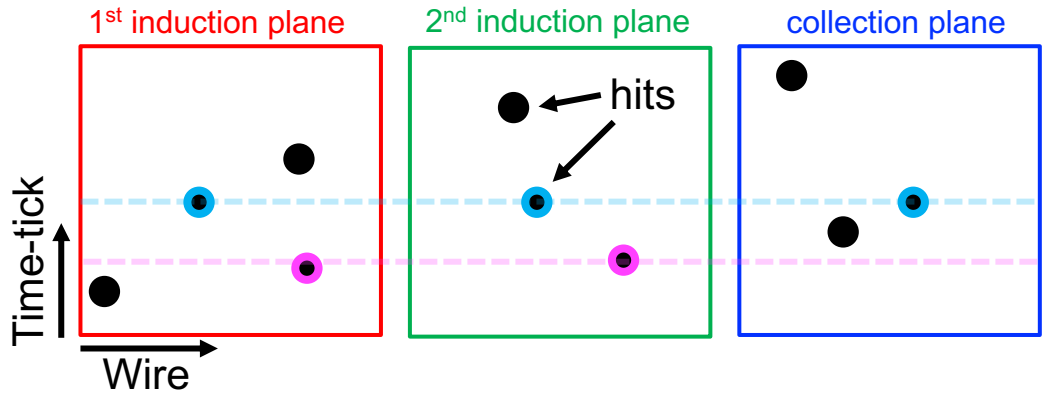
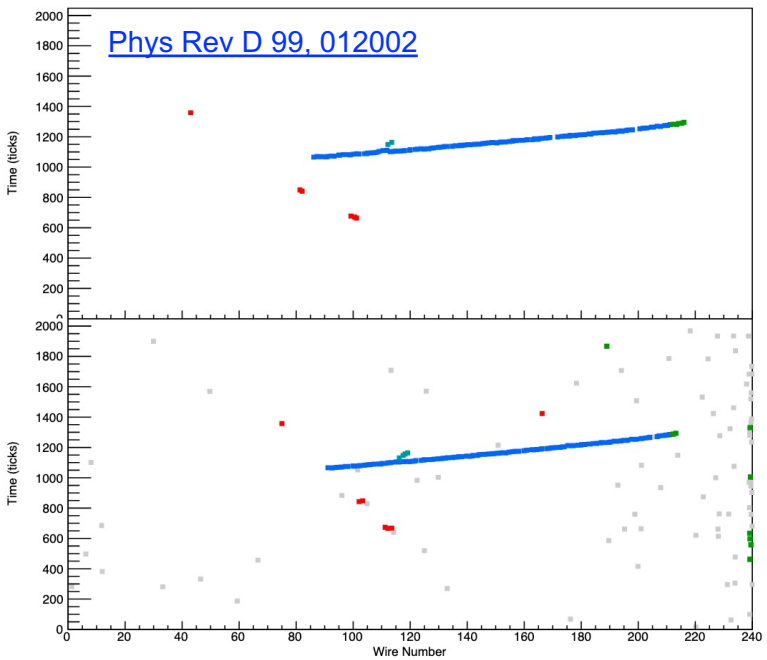
Reconstruction in a nut-shell





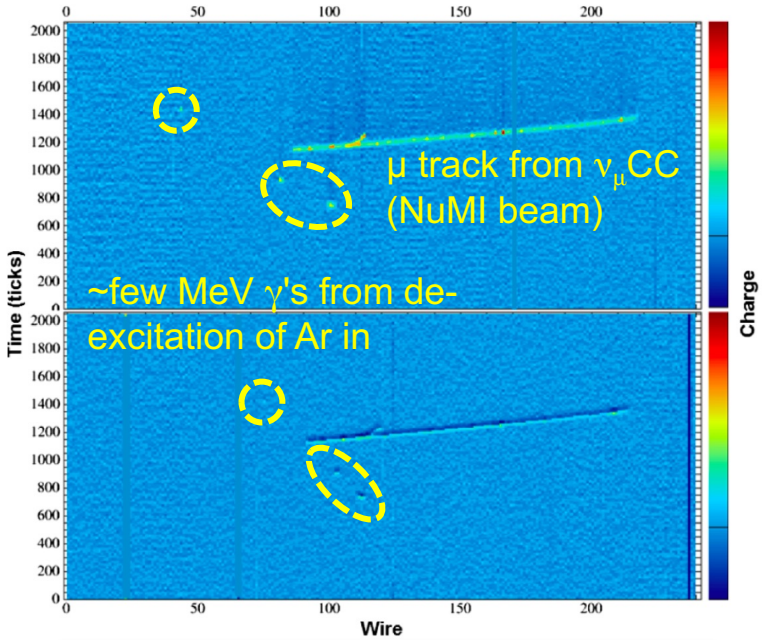


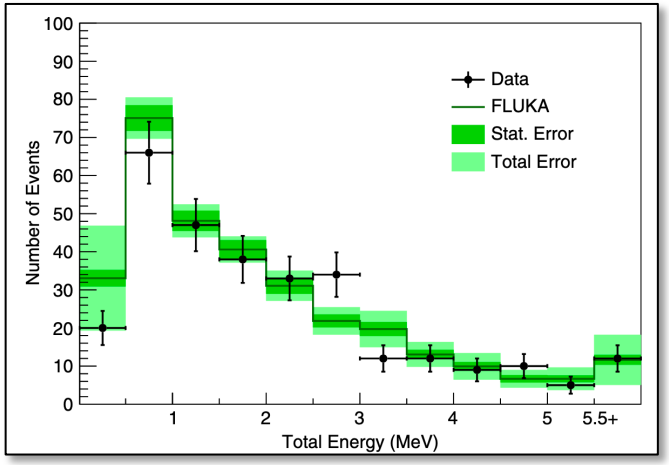
- Signals time-matched between wire readout planes
  - Wire intersections → YZ coordinate
- Easy with extended (multi-hit) signals
- More challenging at lower energy
  - Hit-finding thresholds
  - Noise hits create ambiguous fake matches
- ***Standardized toolset/algorithms under development for broad LArTPC use***

Demonstrations of MeV-scale signal sensitivity

ArgoNeuT

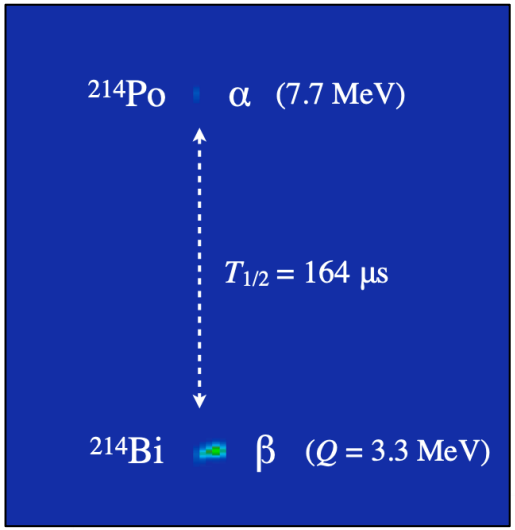
Phys Rev D 99, 012002

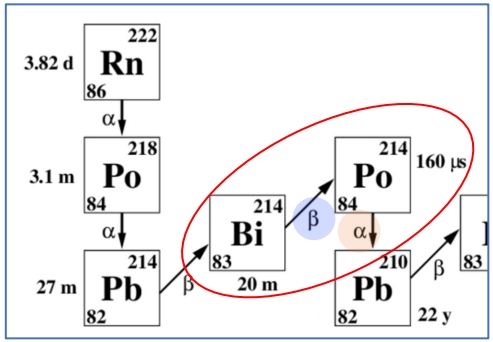


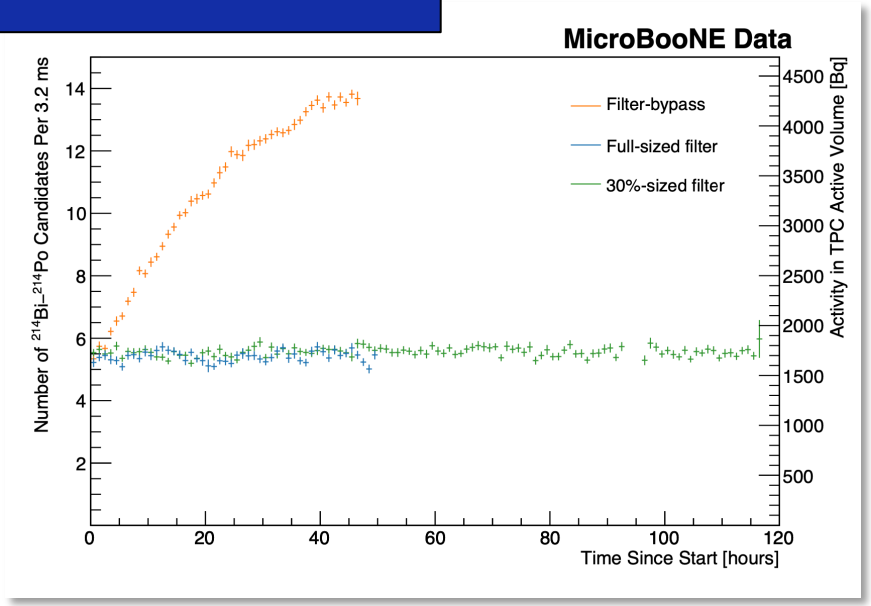


MicroBooNE

arXiv:2203.10147

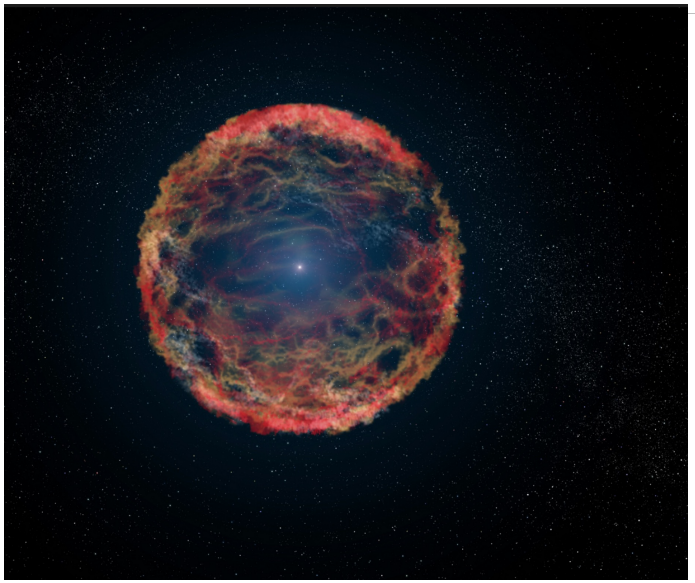


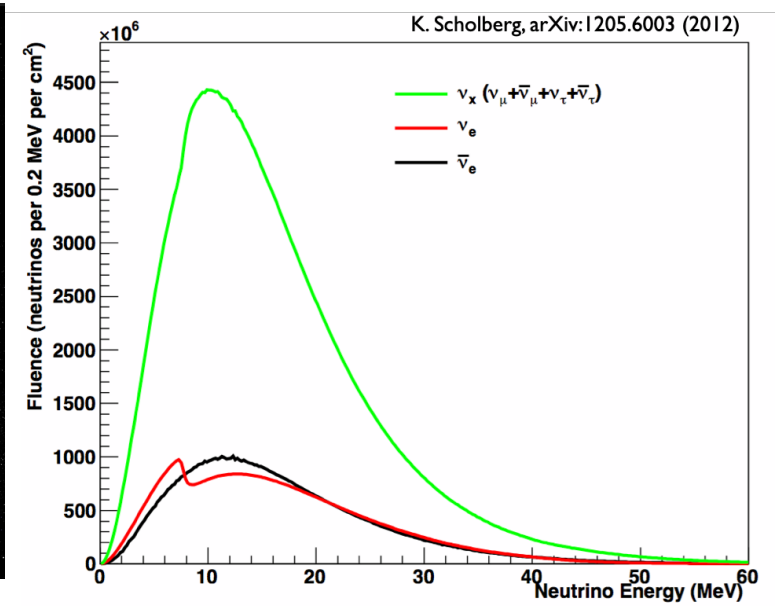




Extending the physics of LArTPCs with blips

Supernova neutrinos





See talk by Thiago right after this

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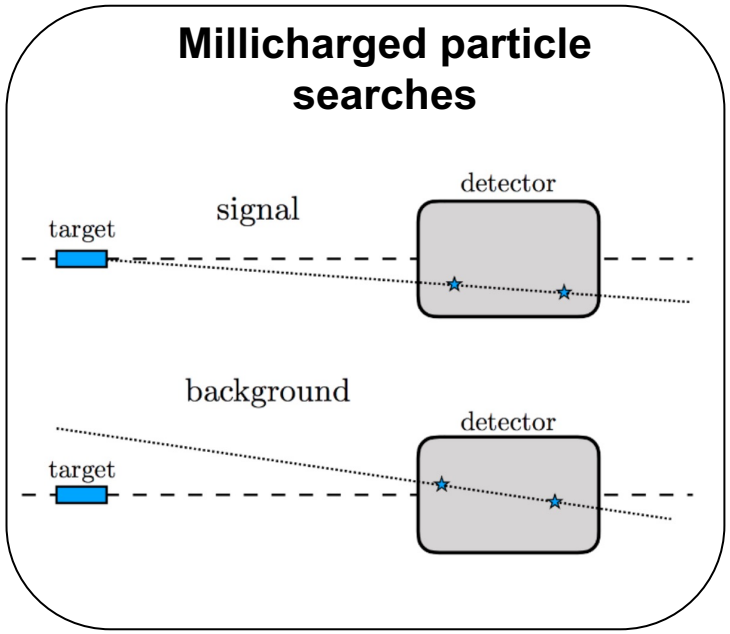
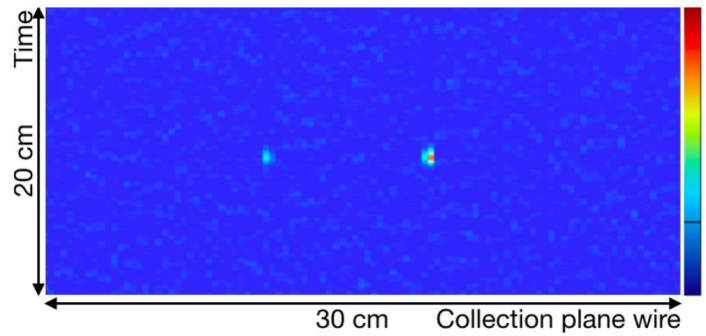
Extending the physics of LArTPCs with blips

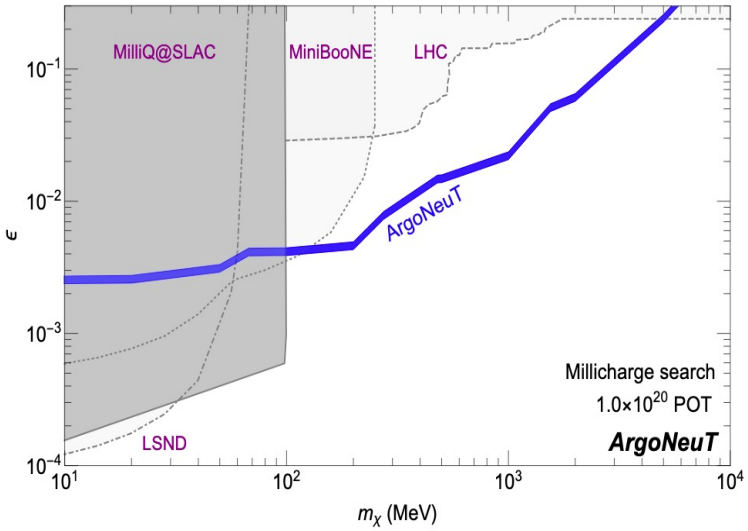


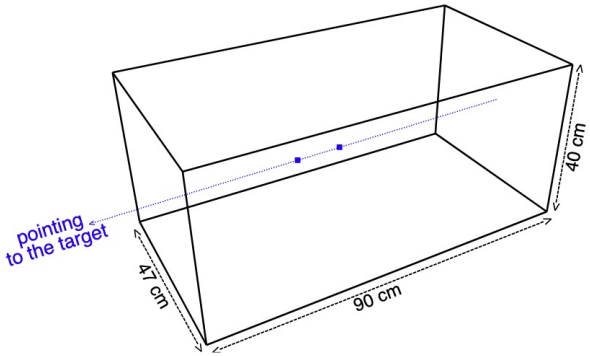
arXiv: 1911.07996

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)







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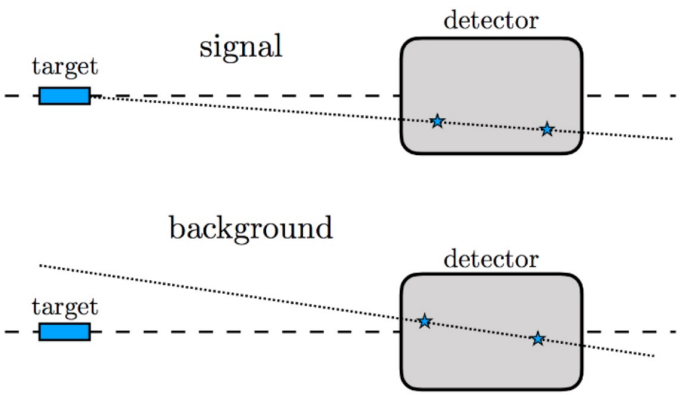
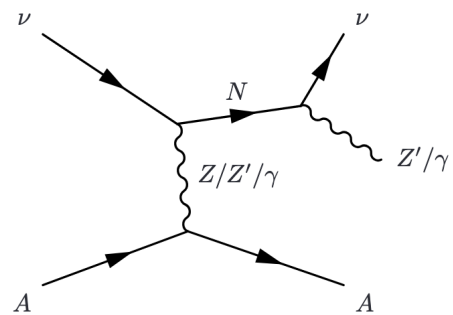
Extending the physics of LArTPCs with blips

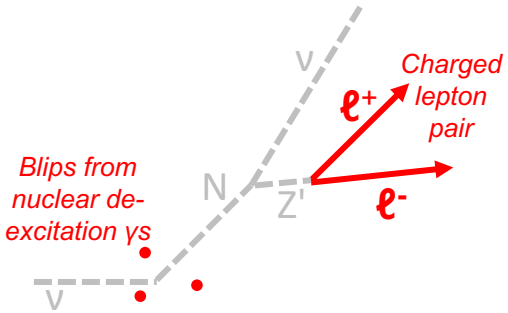
Millicharged particle searches



Up-scattered dark neutrino



Feynman diagram



LArTPC topological signature

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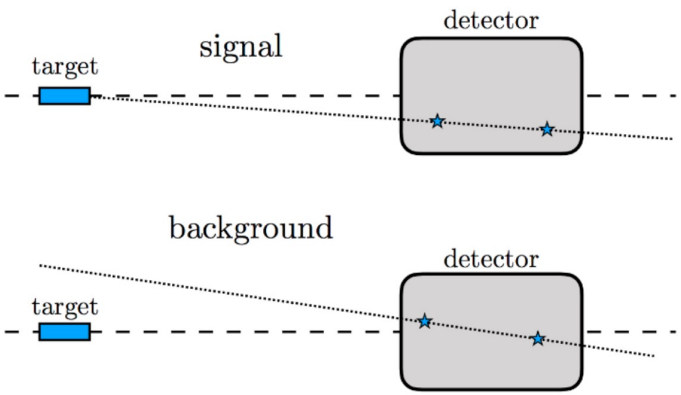
Extending the physics of LArTPCs with blips

Millicharged particle searches



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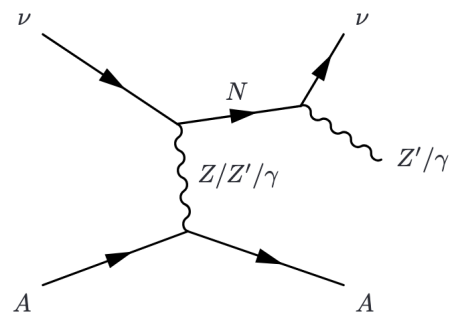

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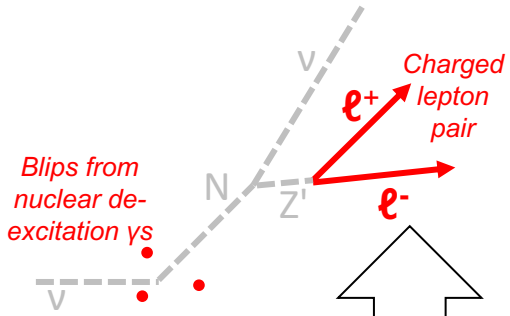
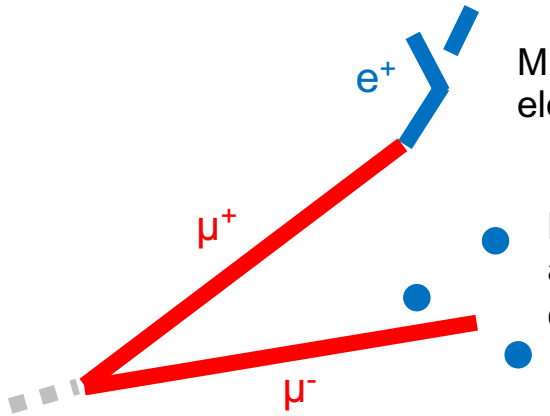


LArTPC topological signature

PID of stopping π/μ



Michel electron

Low-E activity from capture γ's

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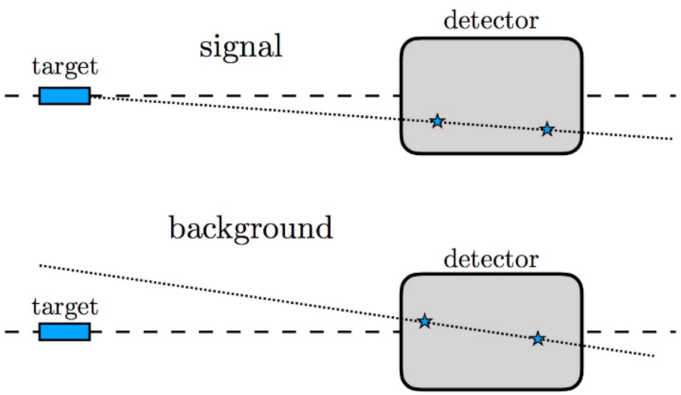
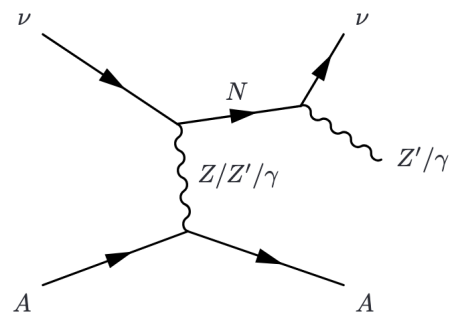
Extending the physics of LArTPCs with blips

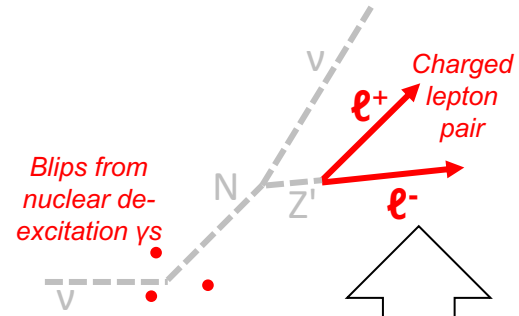
Millicharged particle searches



Up-scattered dark neutrino

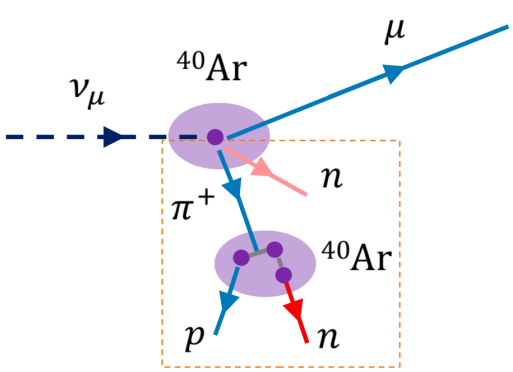


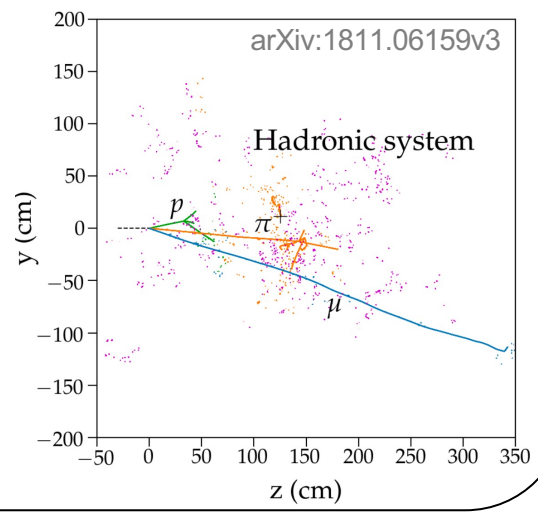
Feynman diagram



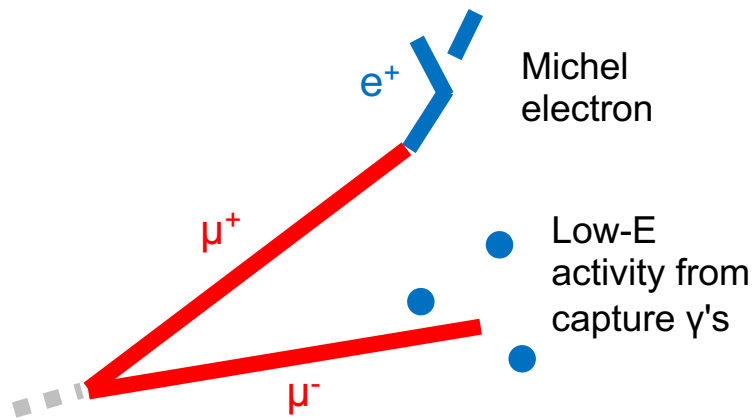
LArTPC topological signature

GeV-scale ν interaction final-states



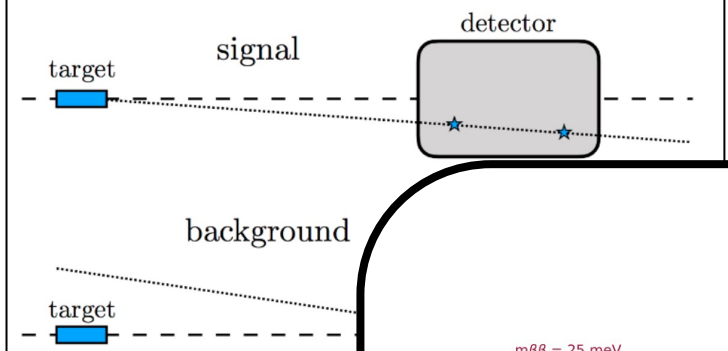


PID of stopping π/μ



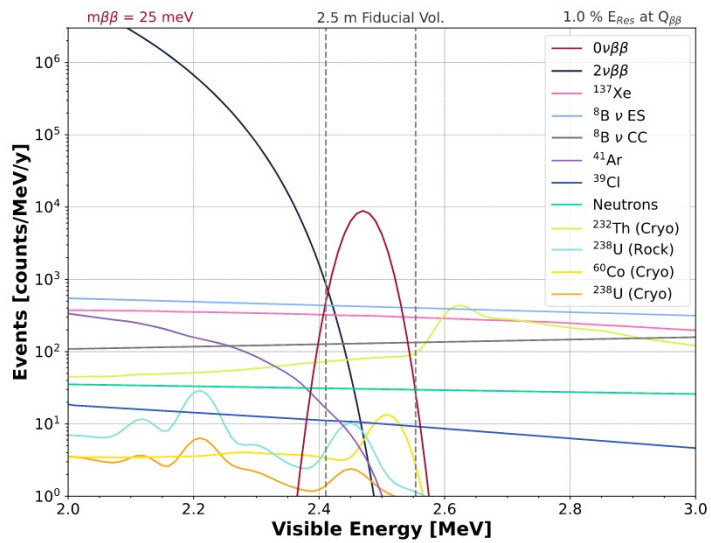
Extending the physics of LArTPCs with blips

Millicharged particle searches



Up-scattered dark neutrino

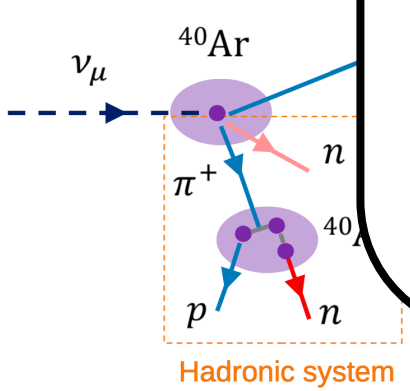
0νββ

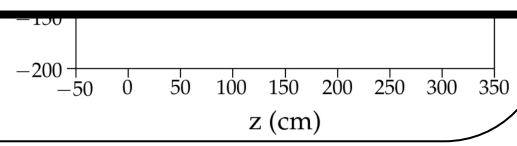


https://arxiv.org/pdf/2203.14700.pdf

Talk by Fernanda later

GeV-scal





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Simulation studies

Phys Rev D 102, 092010 / arXiv:2006.14675

Generic 'DUNE-like' MC used to explore some of these benefits

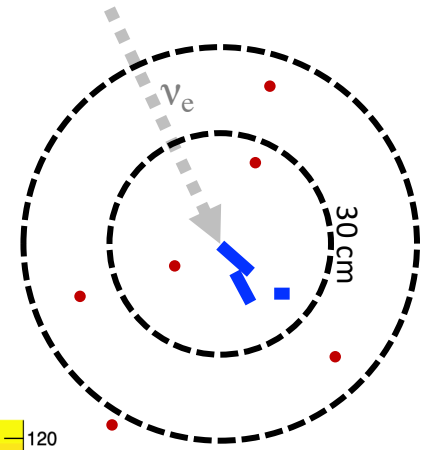
[Submitted on 25 Jun 2020]

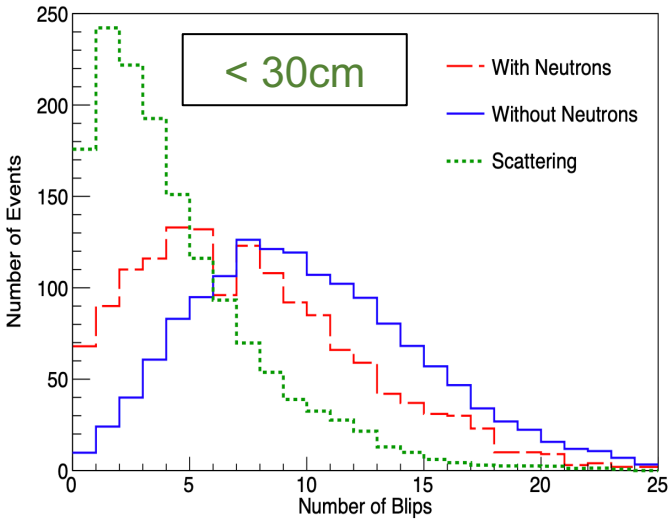
Benefits of MeV-Scale Reconstruction Capabilities in Large Liquid Argon Time Projection Chambers

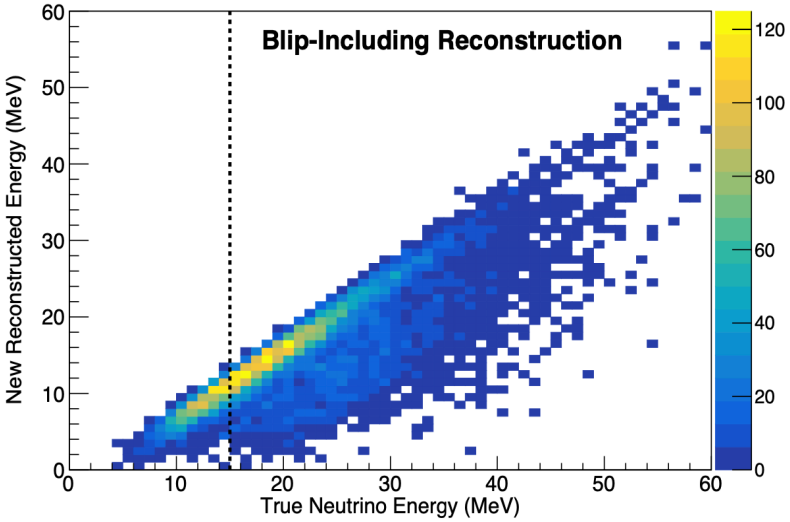
W. Castiglioni, W. Foreman, I. Lepetic, B. R. Littlejohn, M. Malaker, A. Mastbaum

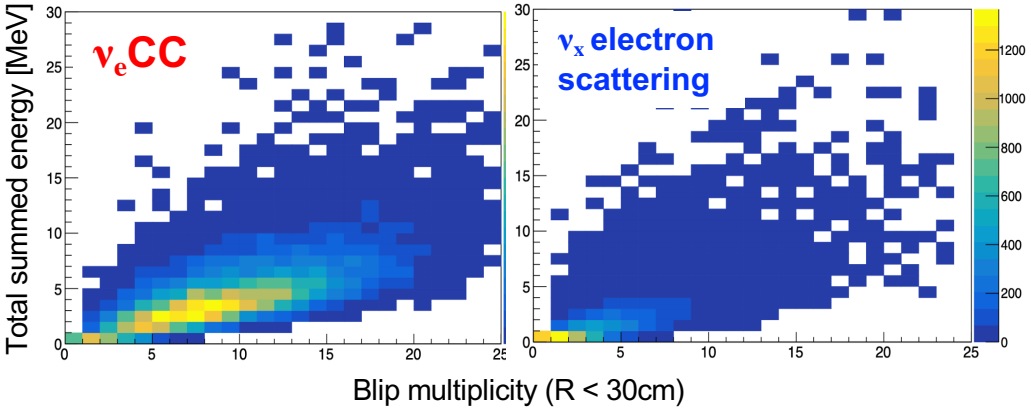
Supernovae neutrinos

- 50% more ν energy recovered when including isolated blips
- Channel ID capabilities
- Tagging neutron-producing evts
  - Recover 7.8 MeV of lost ν energy (n-separation energy in K^{40})









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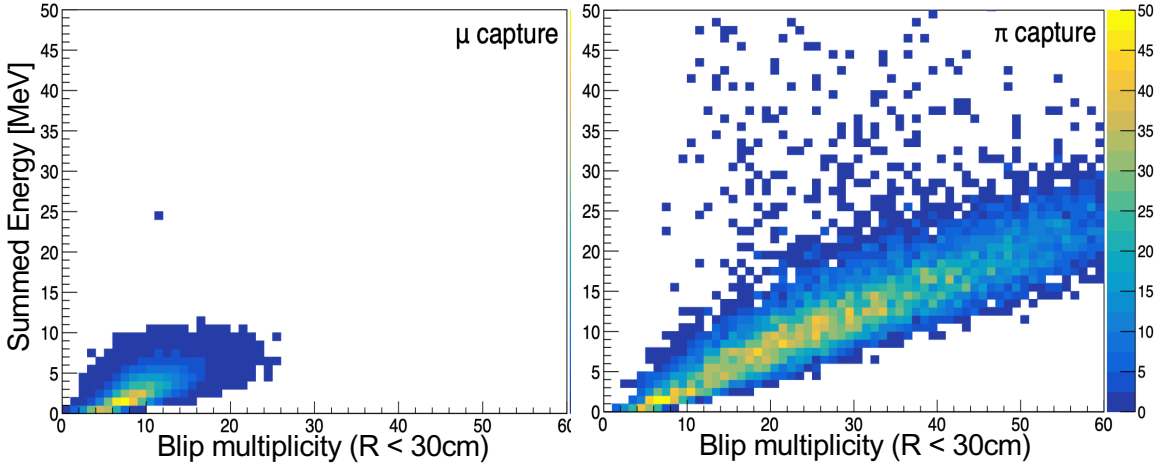
Simulation studies

Phys Rev D 102, 092010 / arXiv:2006.14675

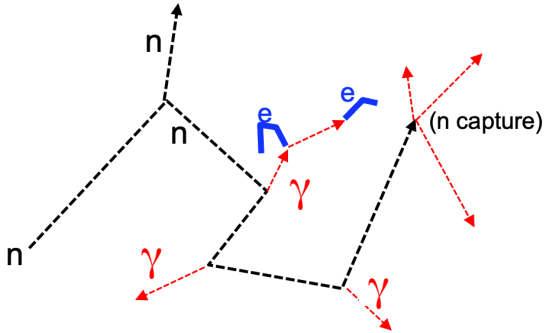
$\pi^{+/-}$ / $\mu^{+/-}$ separation

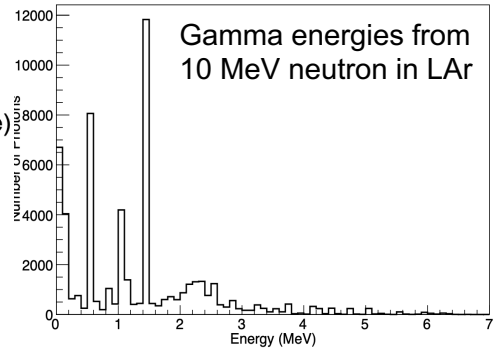
- Differing probabilities of capture/decay + different capture final-states
- Can use activity near endpoints as discriminating metric

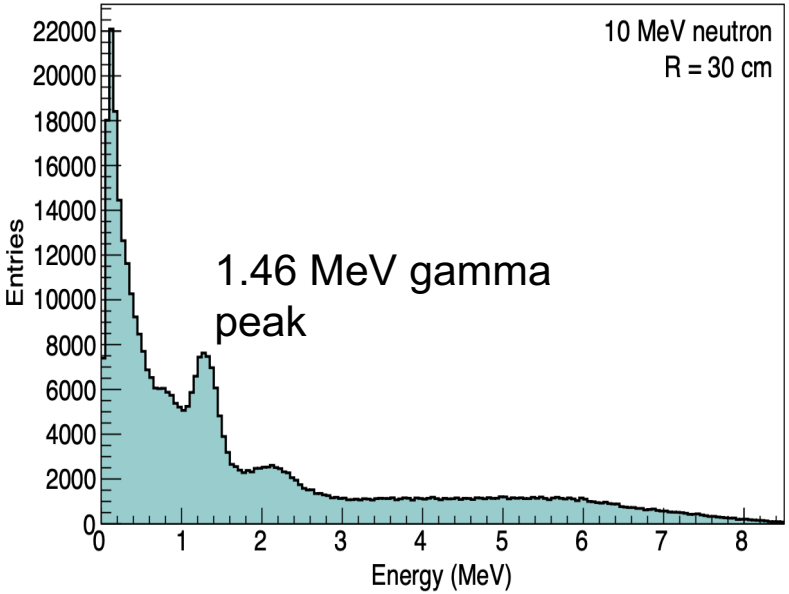


Single-γ spectroscopy

- Neutron scattering produce 1.46 MeV γ's
- Naturally-occurring calibration source!







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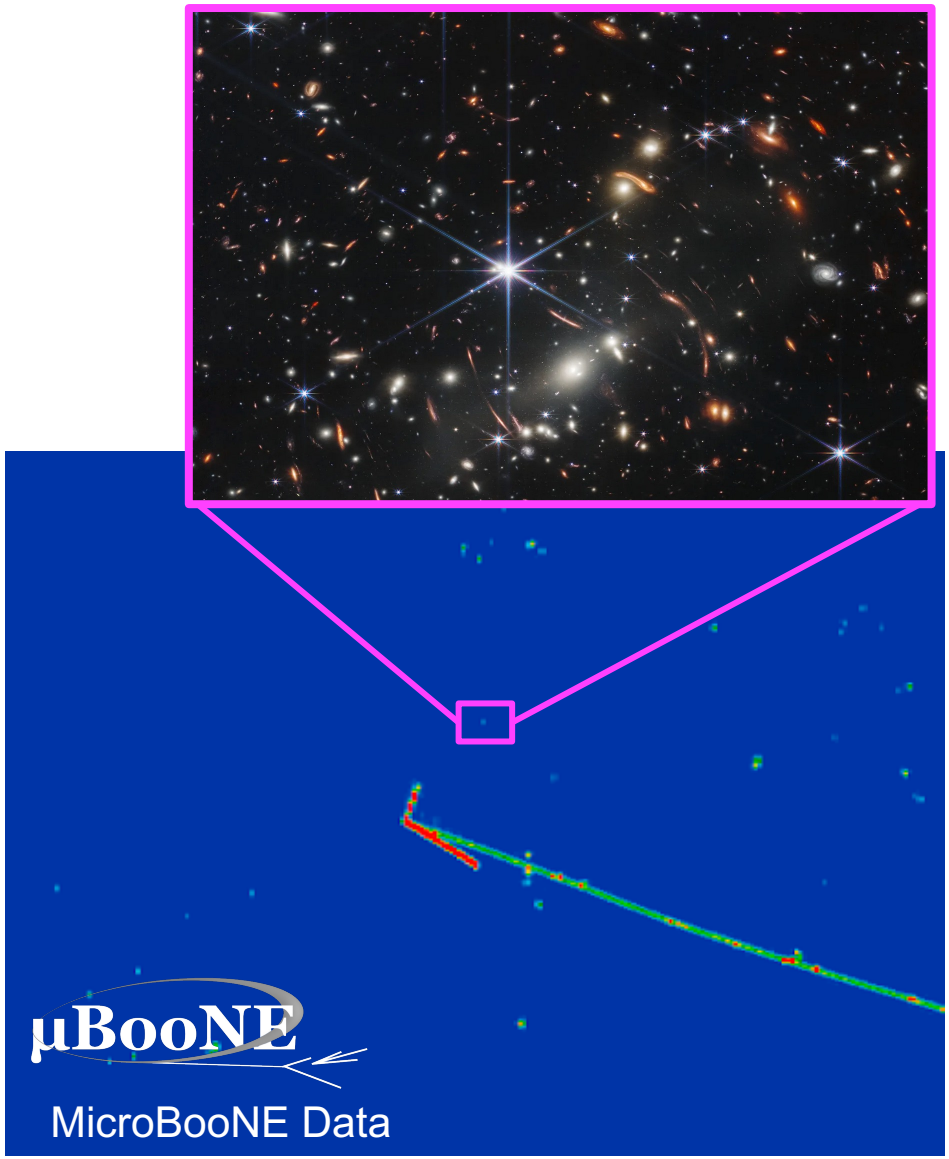
Summary

- MeV-scale reconstruction is the 'next frontier' in neutrino LArTPC physics!

- The LEPLAr Snowmass White Paper presents a broad and detailed overview of the applications and challenges ahead
  - **Much** more than I could include in this talk

Thank you!



Backup

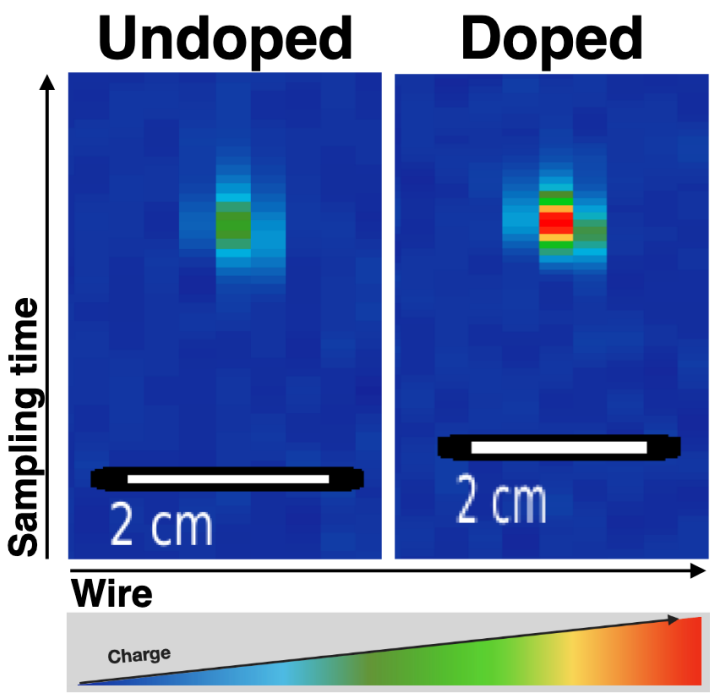
Related references

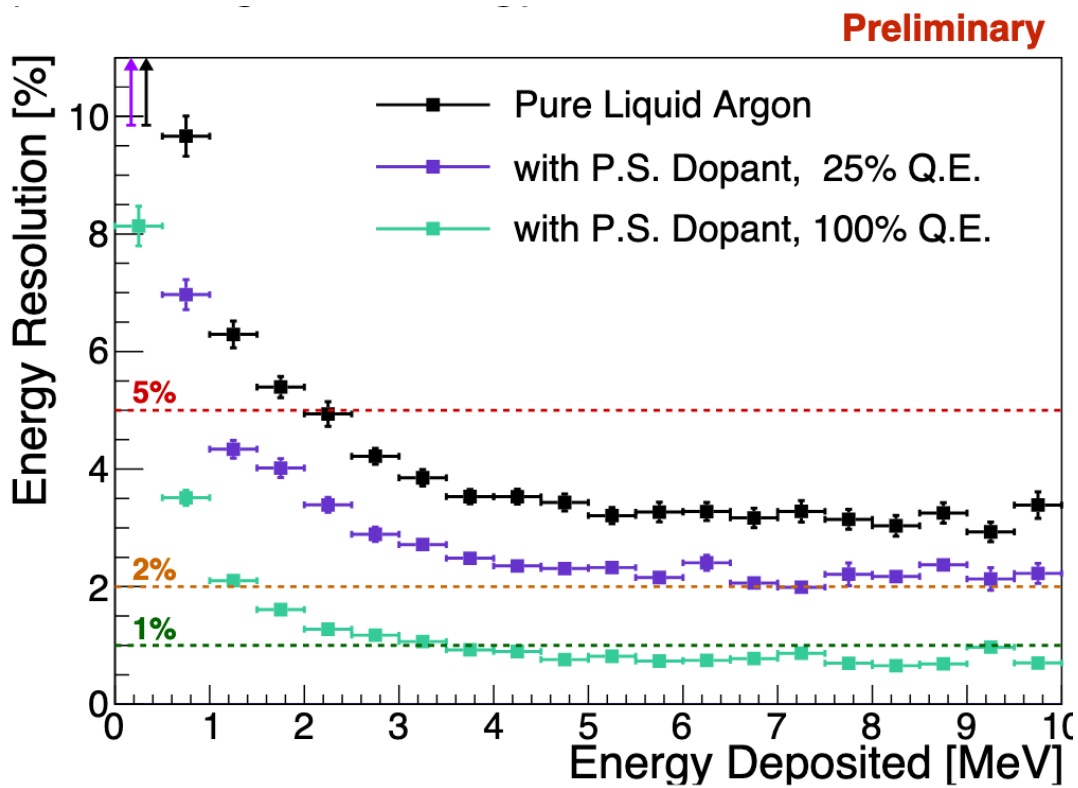
- Study of reconstructed 39Ar Beta Decays at the MicroBooNE Detector

Snowmass contributions:

- Low-Energy Electron-Track Imaging for a Liquid-Argon Time-Projection Chamber using Probabilistic Deep Learning (poster), Micah Buuck et. al., arXiv:2207.07805
- Improving LArTPC Performance with Photo-Ionizing Dopants, Joseph Zennamo
- Low-Energy Physics Opportunities with DUNE, Daniel Pershey
- DUNE-Beta: Searching for Neutrinoless Double Beta Decay with a Large LArTPC (LOI), Joseph Zennamo, Fernanda Psihas, Andy Mastbaum
- LArTPC Pixelated Readout, Brooke Russel

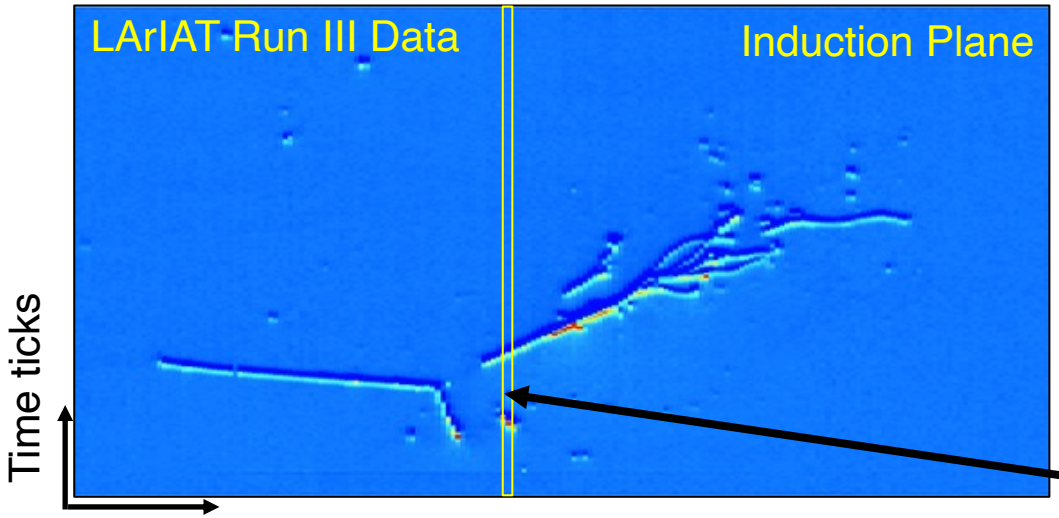
Photo-ionizing dopants in LAr for improved response at low energies

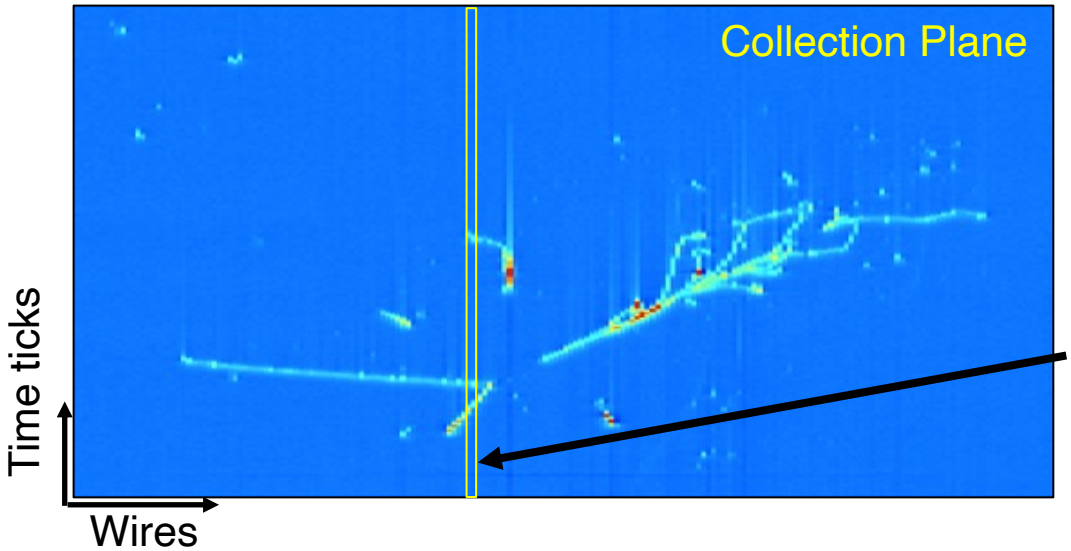


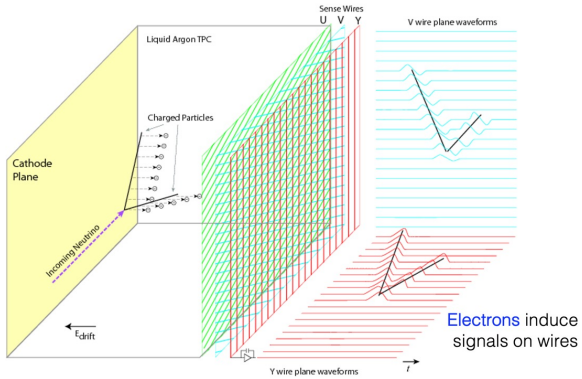


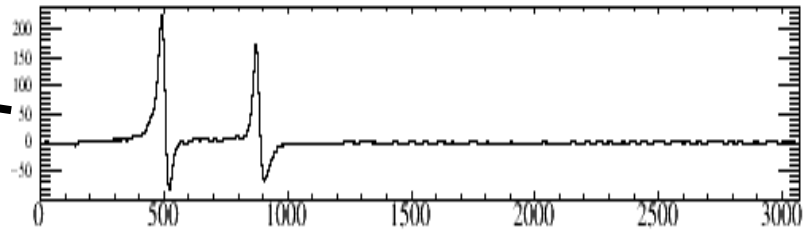
Improving LArTPC Performance with Photo-Ionizing Dopants, Joseph Zennamo

LArTPC example event display

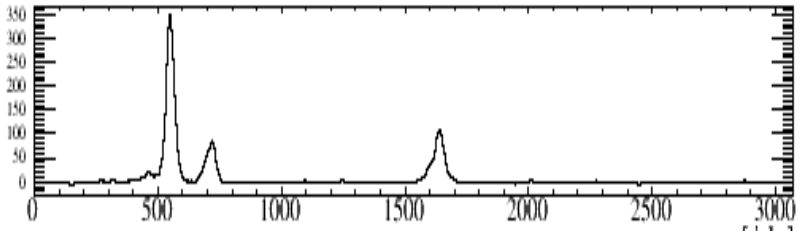








Time tick



Time tick

Calculating energy from charge

Collected charge (Q) must be converted into deposited energy

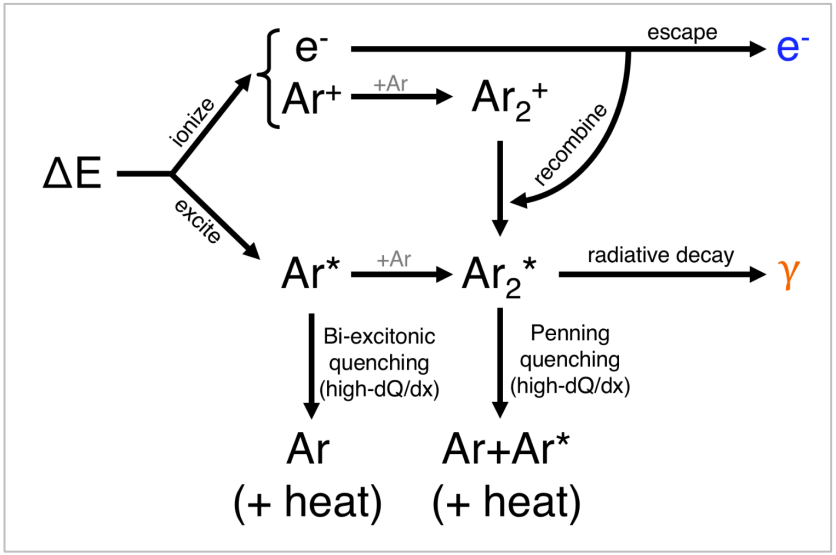
Number of electrons collected

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

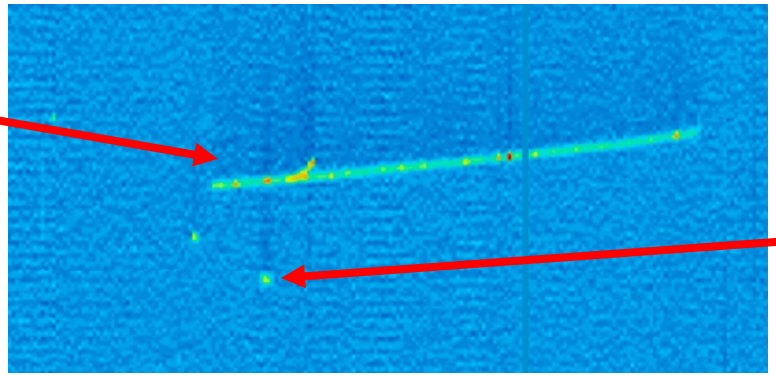
Electron recombination factor (function of **dE/dx** and **E-field**)

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!

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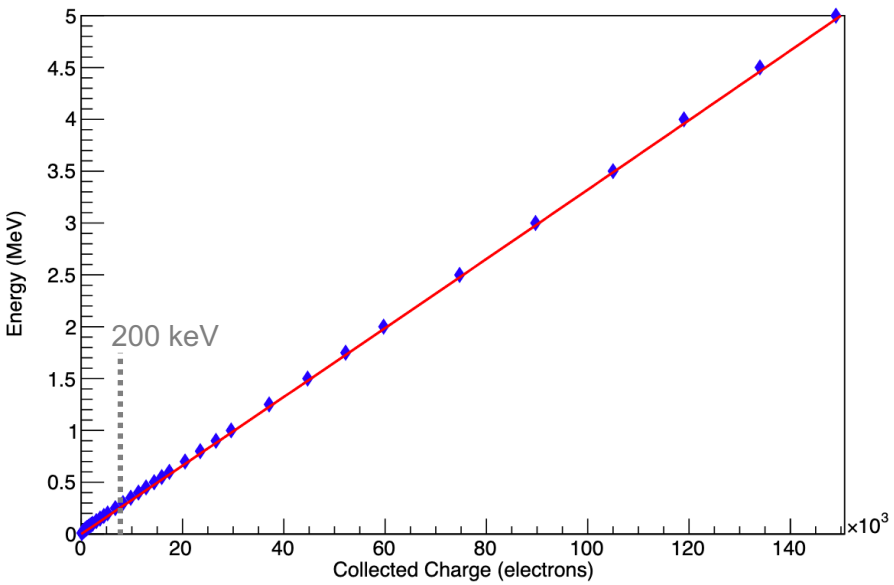
Calculating energy from charge

- 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



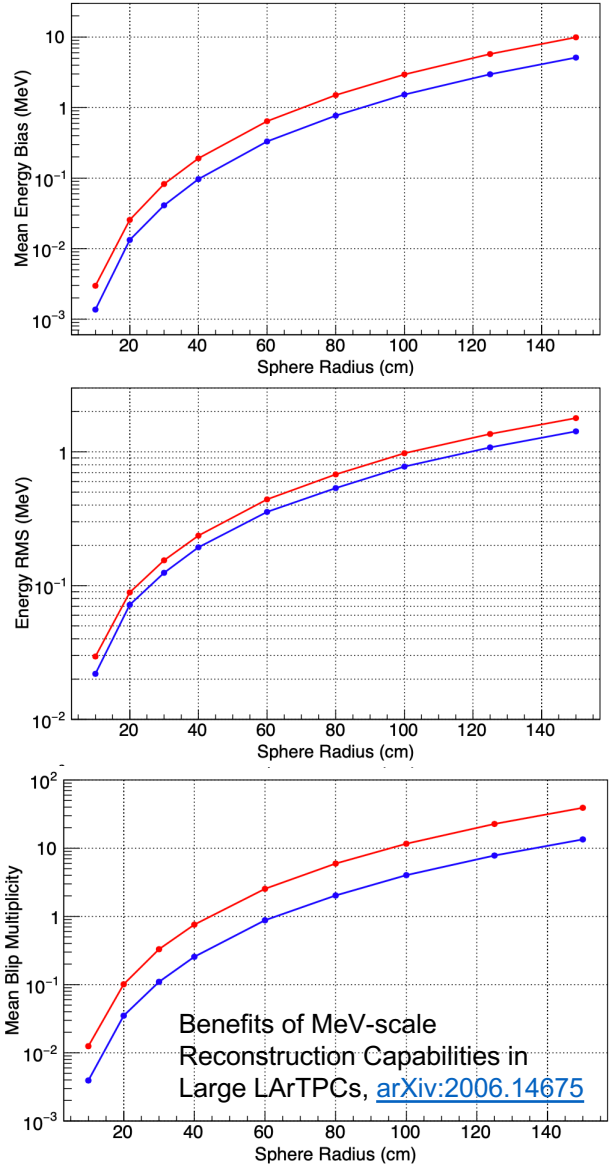
Ar39 contamination in a large LArTPC

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

Simulated decays in a DUNE-sized drift region (2.2ms data acquisition window).

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

- Energy ~ 0.08 MeV
- Energy RMS spread ~ 0.15 MeV
- $N_{blips} \sim 0.3$



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Effect of electronic noise

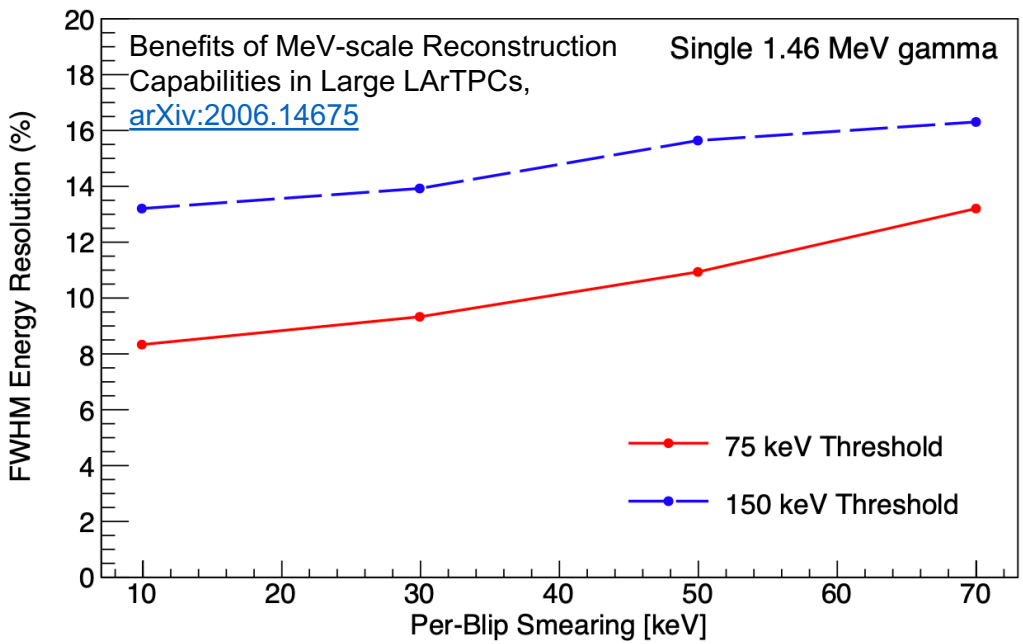
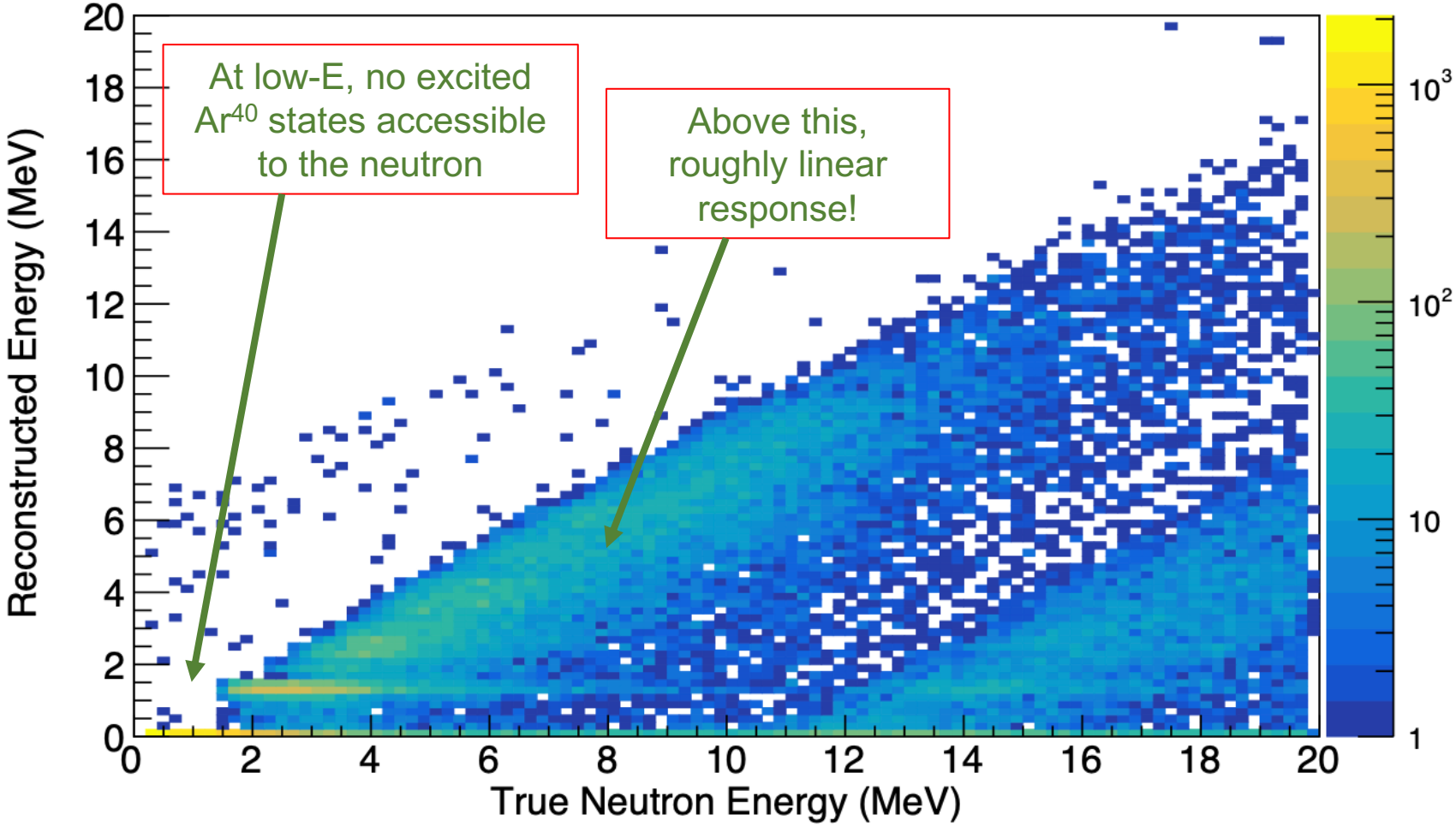


FIG. 20. The resolution of the full-energy peak for simulated 1.46 MeV γ-rays, over a range of different blip smearing levels, for both 75 keV and 150 keV energy thresholds. A proximity requirement of 30 cm is used. Resolution is calculated based on the FWHM of the peak using the relationship to standard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

Final-state neutron ID and calorimetry

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



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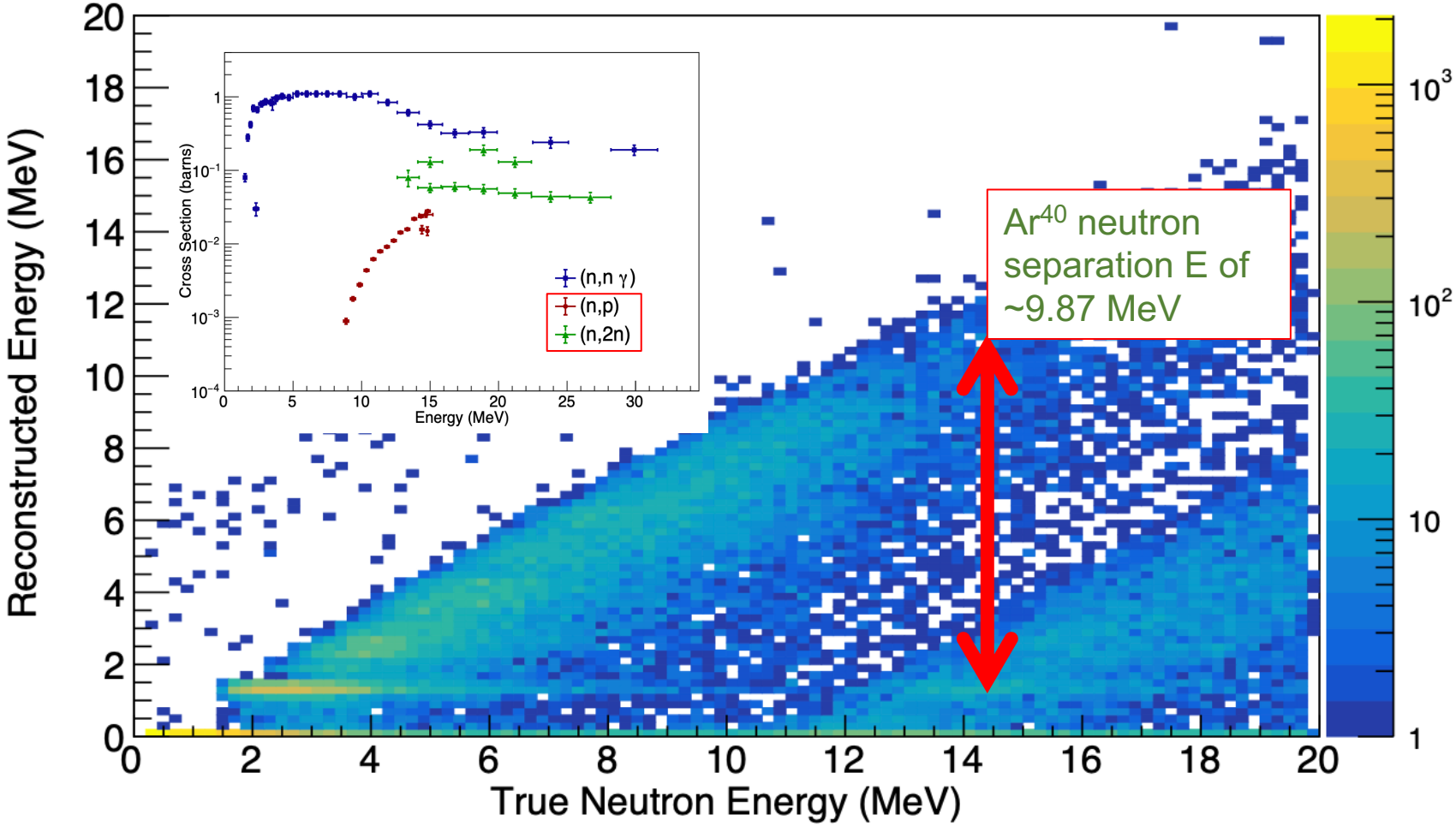

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