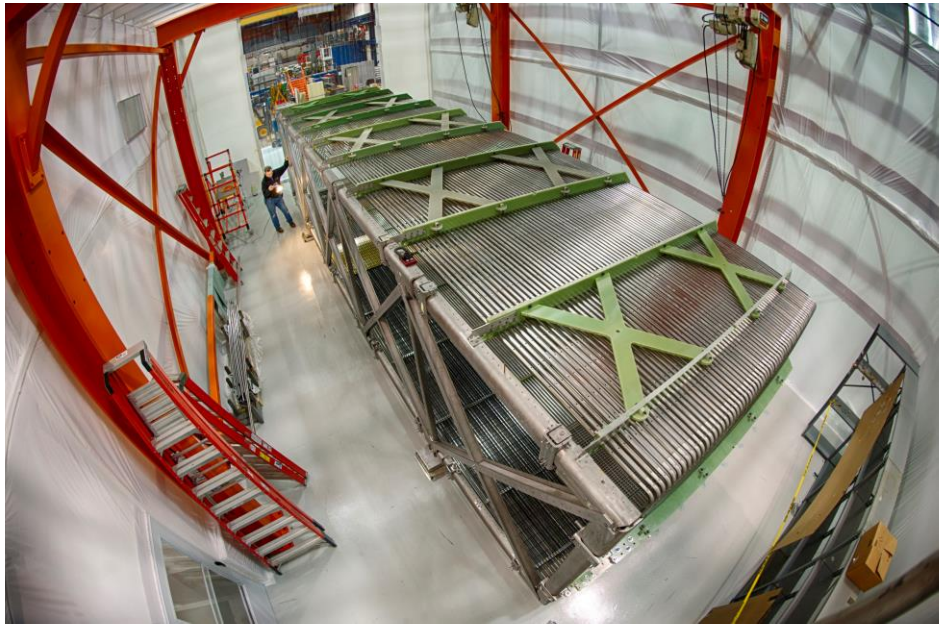
Event Reconstruction Experience From LArTPC



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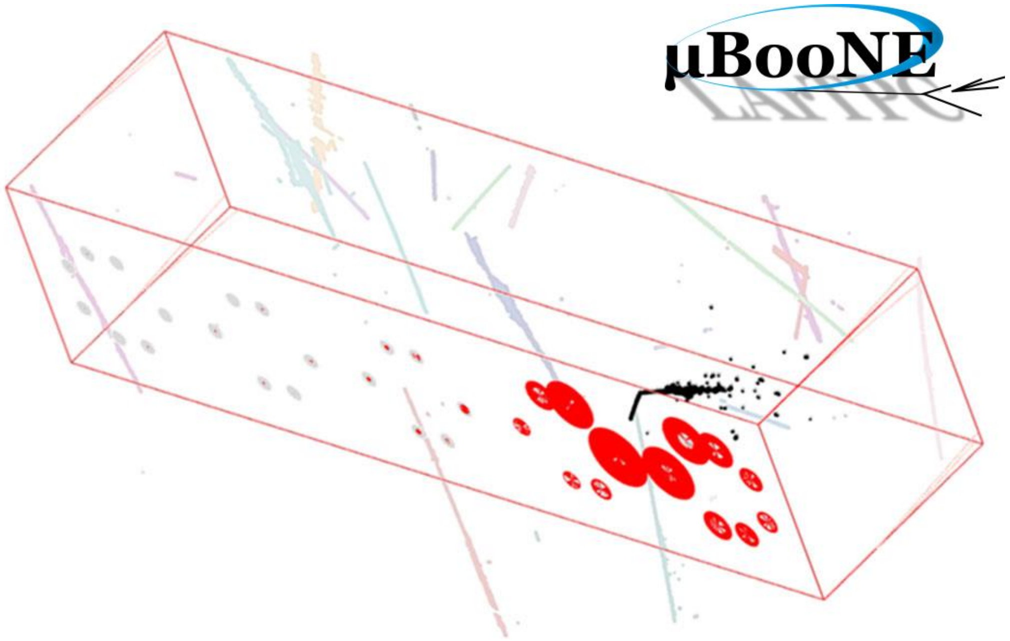
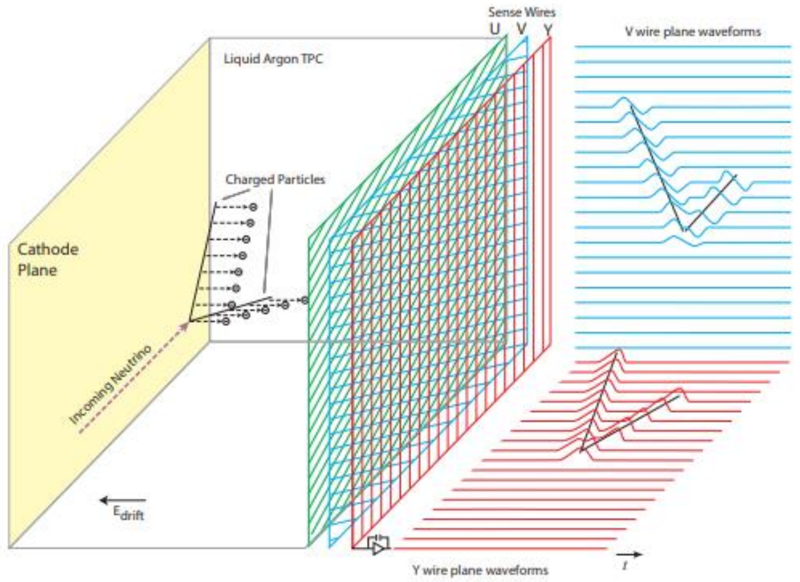
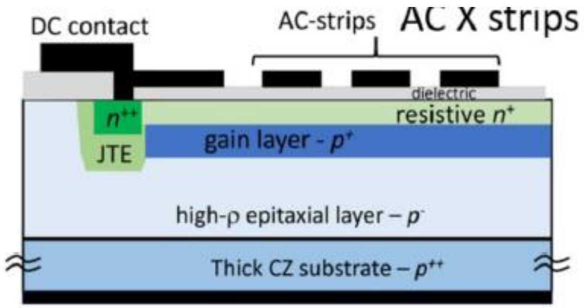


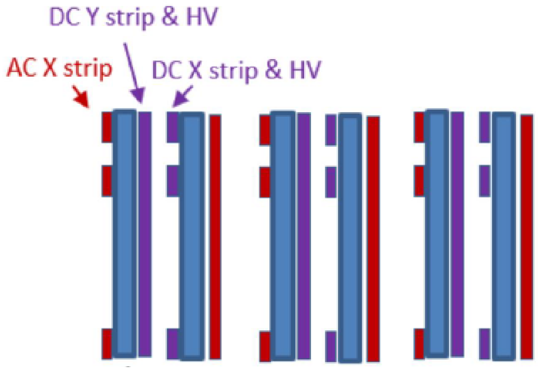
Rare Pion Decay Workshop @UCSC, 10/7/2022

Outline

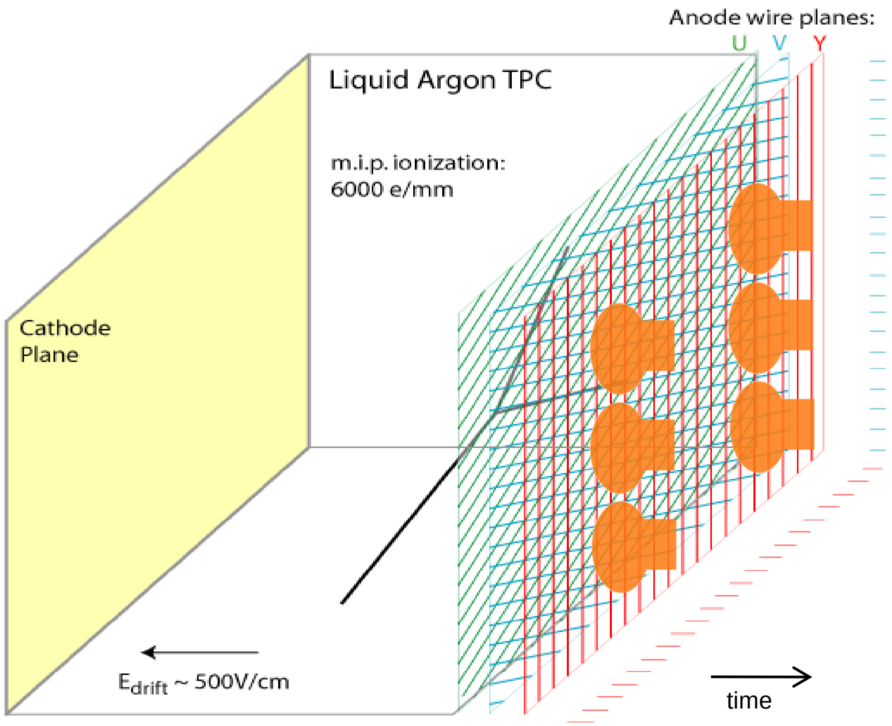
- Introduction to LArTPC
- Similarity between LArTPC and ATAR
- Signal/Background in LArTPC vs ATAR
- Experience from LArTPC reconstruction that may be useful for ATAR
- Tools in LArTPC reconstruction that may be adopted for ATAR







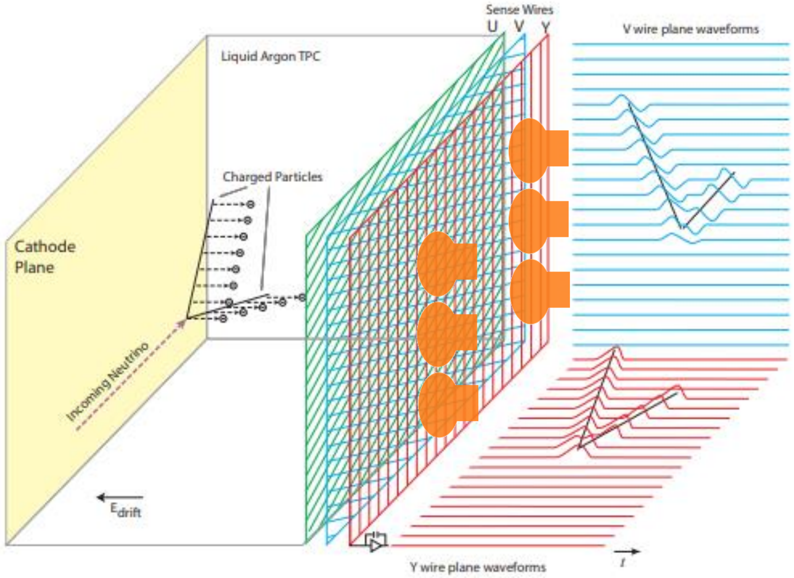
Liquid Argon Time Projection Chamber



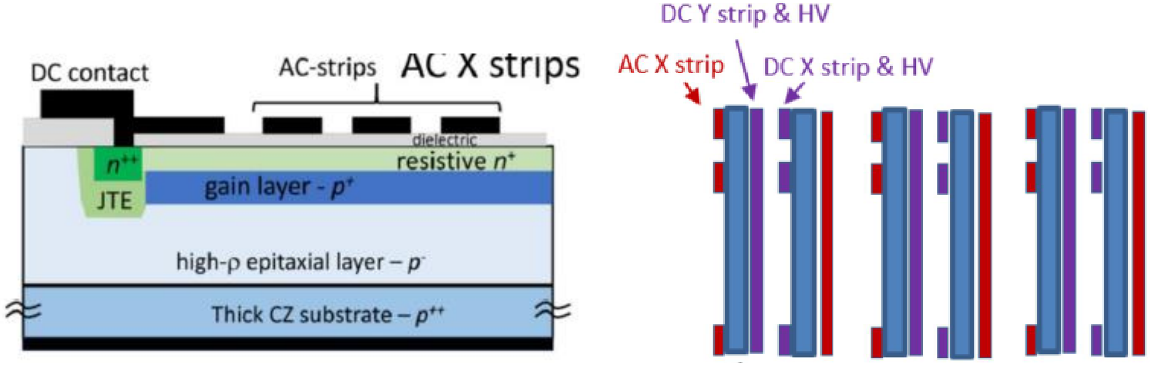
https://lar.bnl.gov/properties/

- 3D Tracking + Calorimetry
  - Position resolution: ~ 1-3 mm
  - Energy resolution: ~ 5-10%
  - Drift speed: ~ 1 meter / milisec
- Scintillation for timing
  - W_{scint}: ~ 20 eV/photon
  - 30% fast: ~6 ns; 70% slow: ~1600 ns
- Ideal for neutrino detection
  - High density, cost-effective, long e^- lifetime (>10 ms) after purification
  - Short-Baseline Neutrino Program: MicroBooNE, SBND, ICARUS (sterile ν, ν-Ar cross section, BSM, etc.)
  - DUNE (CPV, ν mass order, proton decay, supernova ν, etc.)

LArTPC vs ATAR



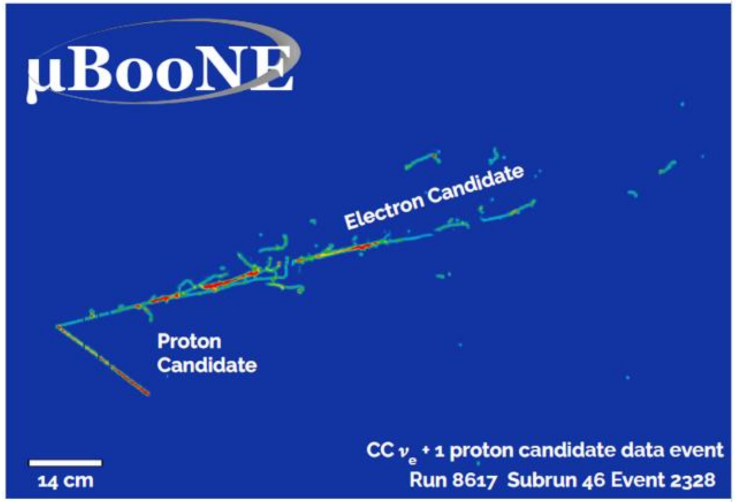
- World’s largest tracking calorimeter?
- Field response: electrons drift in LAr active volume
- 3 wire planes with different wire orientations → X-Y position
- Drift time (* drift velocity) → Z position
- Photon detectors (PD) for timing

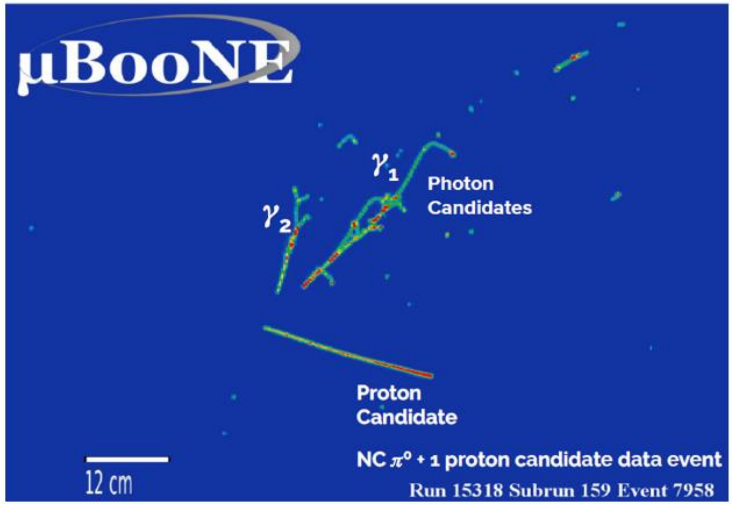


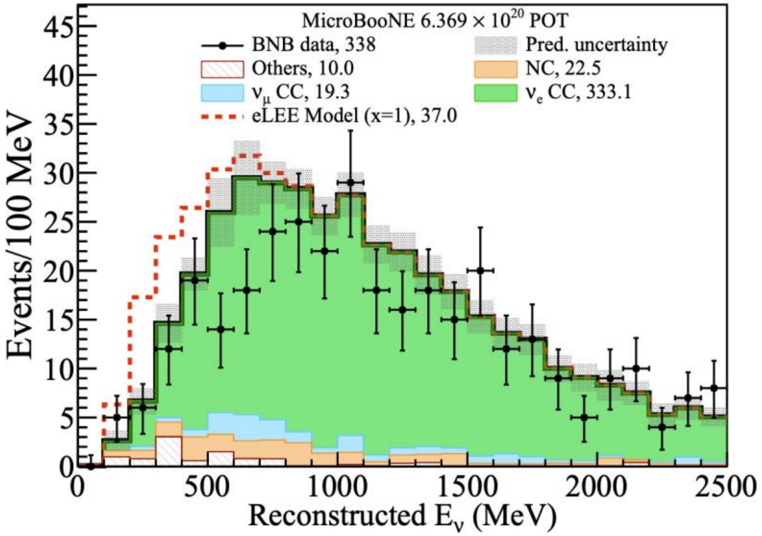
- World’s smallest tracking calorimeter?
- Field response: e-/holes drift in Si active volume
- alternating X + Y strip readout (possibly double-sided) → X-Y position
- Layer position → Z position
- Additional PDs for full calorimetry

Signal / Background in LArTPC

MicroBooNE inclusive ν_e spectrum with Wire-Cell reconstruction Phys. Rev. Lett. 128, 241801 (2022)







Signal: ν_eCC (beam intrinsic or from ν_μ oscillation)

Background: ν_μCC, NCπ^0, cosmic ray

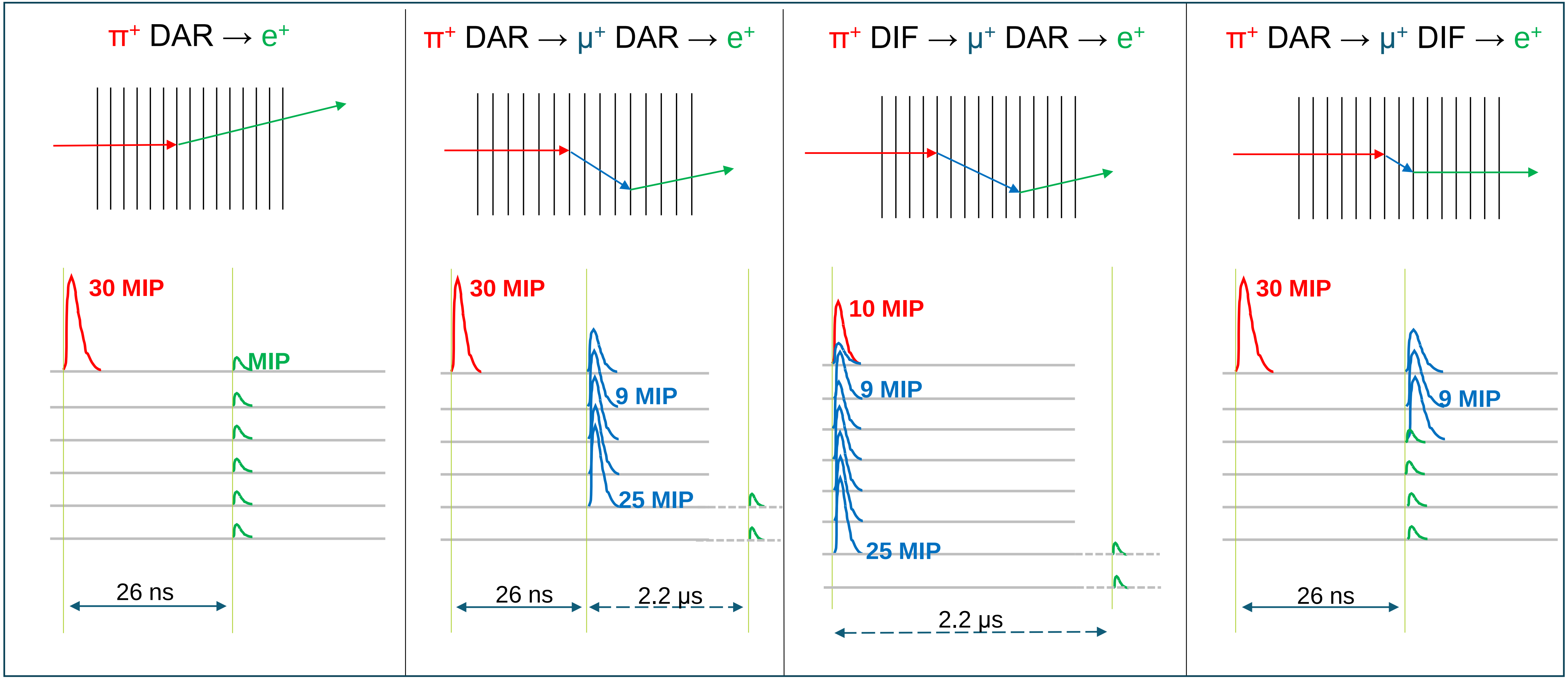
Separate Signal vs Background:

- Topology
- Calorimetry
- Timing

- (e/γ) vs (p, μ, $\pi^\pm$):
  - Topology: EM showers vs tracks
  - Calorimetry: dE/dx and the Bragg peak
- e/γ separation
  - Topology: gap identification at ν vertex
  - Calorimetry: dE/dx at the beginning ~3cm or ~10 wires:
- Cosmic ray removal
  - Timing: in-beam/out-beam matching Photon signals with TPC charge signals

Signal / Background in ATAR

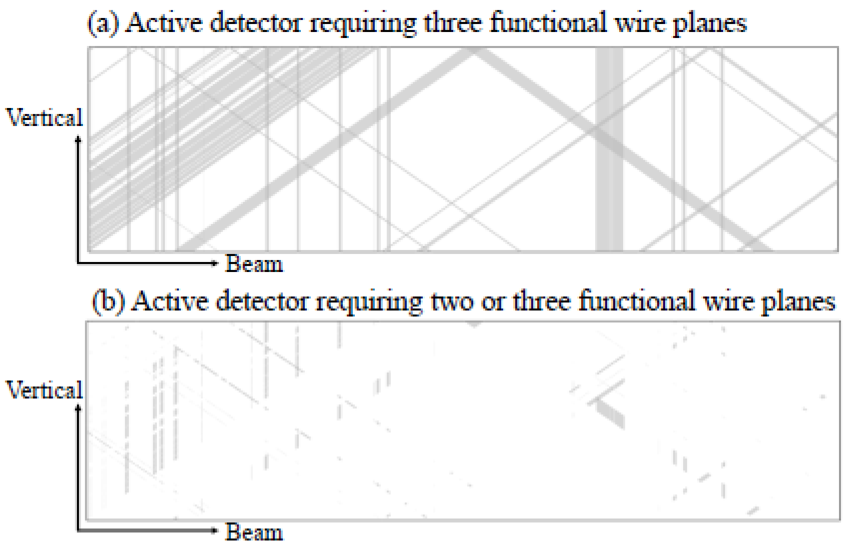
❑ Topology ❑ Calorimetry ❑ Timing

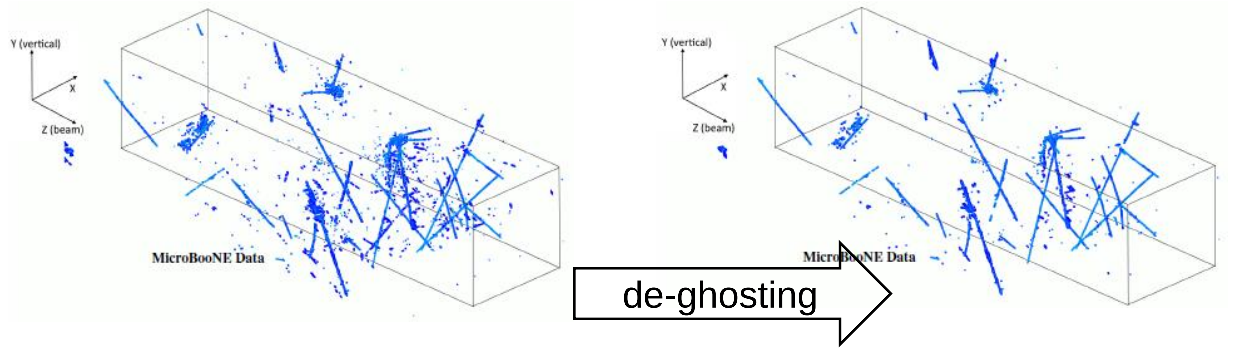


Experience From LArTPC

1. It’s crucial to have a good hardware performance

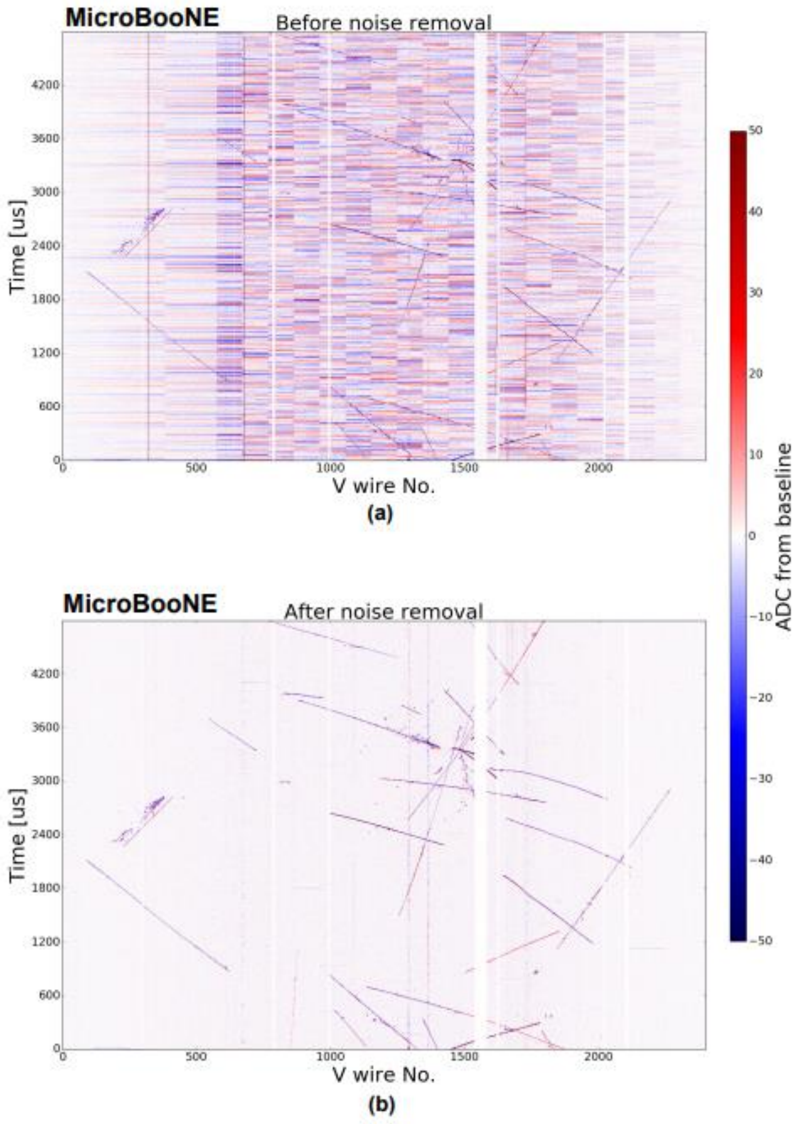
- MicroBooNE has ~10% dead channels, which caused lots of problems in later analysis
  - Require all 3 planes: 30% dead region
  - Require 2 planes: → 3% dead region but creates a lot more ambiguities (ghost hits) depending on the topology of the event; need dedicated de-ghosting algorithms.





Experience From LArTPC

Example event from MicroBooNE before and after noise filtering
JINST 12, P08003 (2017)



2. It's crucial to have low electronic noise

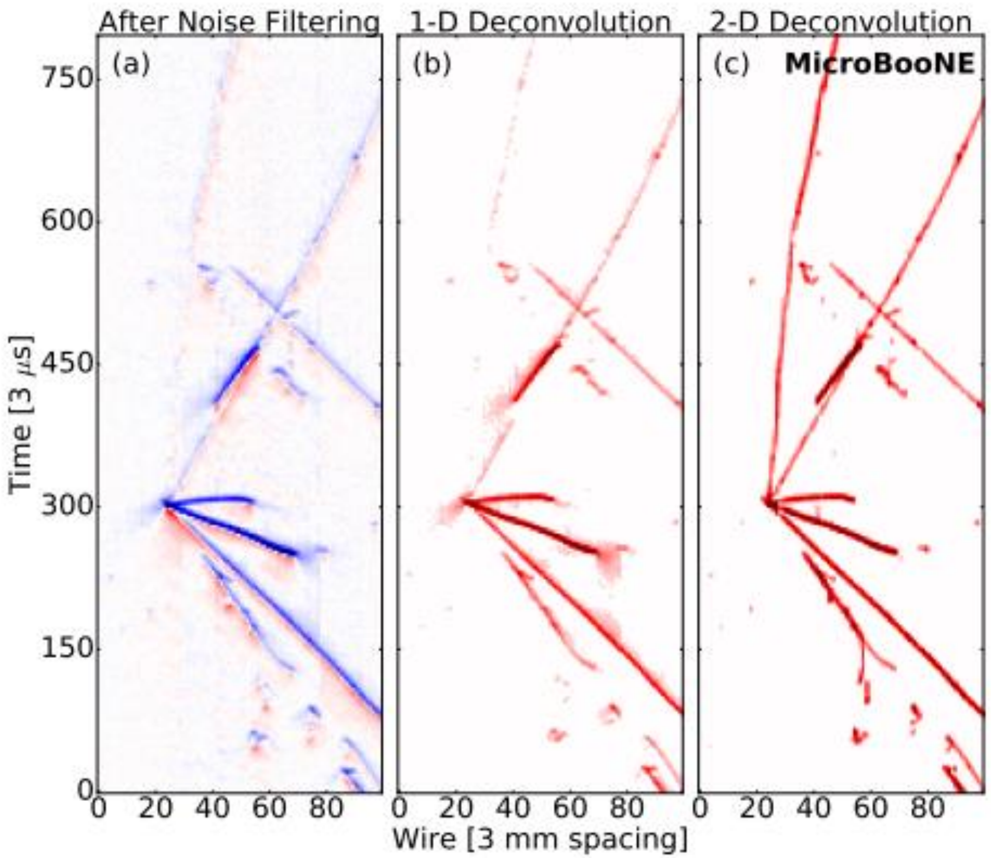
- MicroBooNE adopted BNL cold electronics (preamplifier inside LAr), which reduced the electronic noise by x5 compared warm electronics
  - **~40:1** (20:1) MIP peak-to-noise ratio in the collection (induction) wire plane
- Coherent noise on multiple channels is particularly troublesome
  - Coherent noise filtering offline often removes signals from tracks, leading to many gaps
  - MicroBooNE had a dedicated hardware upgrade to mitigate the low frequency coherent noise from voltage regulators on board

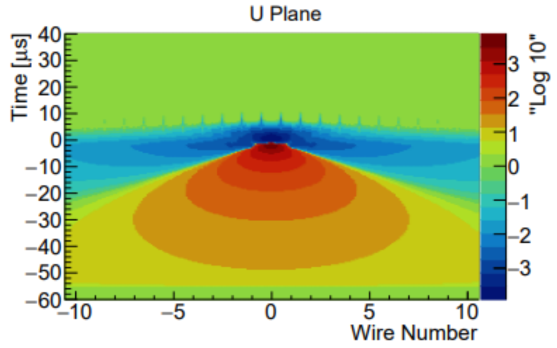
Experience From LArTPC

3. Low-level signal processing is important

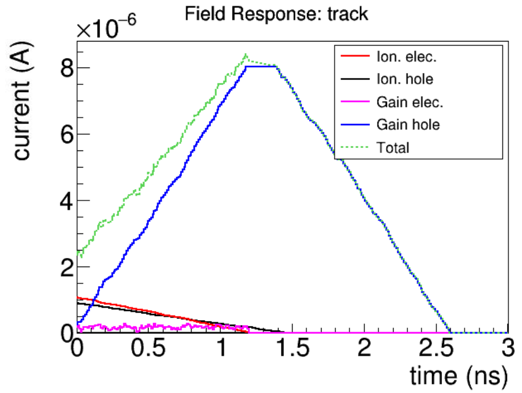
- Field response can distort the signal shape. Need proper signal processing to restore it.
  - Particularly bad for bi-polar field response and long signals (tracks along the wire)

Example event from MicroBooNE before and after signal processing *JINST 13, P07006 (2018)*





LArTPC, long range induction effect up to ±10 wires

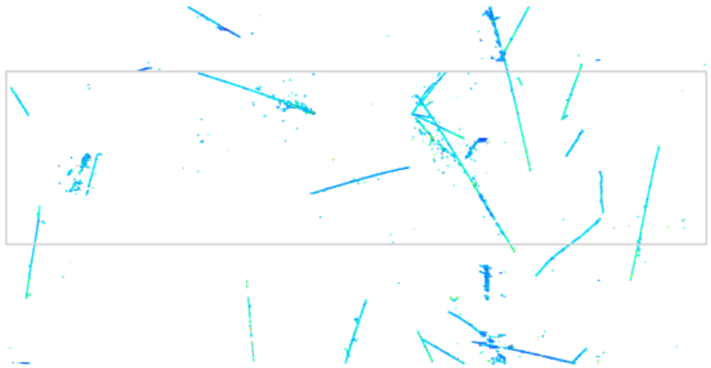


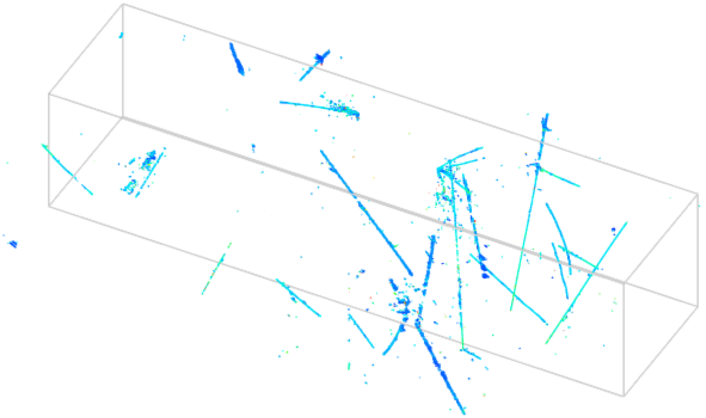
ATAR, field response functions from 4 different charge carriers

Experience From LArTPC

4. 3D reconstruction is important for Pattern Recognition (PR)

- It's tempting to do analysis based on 2D Pattern Recognition, which is easier for simple topologies. But 3D PR is easier for more complicated topologies
  - PR: avoid overlapping tracks in 2D
  - PID: calculate correct track segment length for dE/dx
  - Visual scan: identify corner cases
  - PIONEER: old muons, Bhabha scattering, etc.
- 3D reconstruction requires association of different views and solving ambiguities





Experience From LArTPC

5. Multiple-view in the same layer is desired to resolve ambiguity

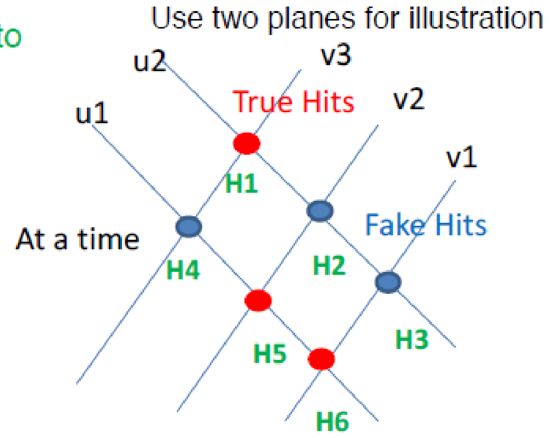
- ❑ Wire/Strip readout has intrinsic ambiguity caused by information loss from n^2 pixels to ~n wires
- ❑ Can be largely resolved by a constructing a system of linear equations: geometry + charge + sparsity
  - Same charge measured by multiple views: prefer double-sided readout in ATAR (otherwise suffer from dE/dx change/fluctuation in consecutive layers)
  - Benefit certain topologies, such as when a track goes along the strip

Measured charges on wires

True charge hits to be solved

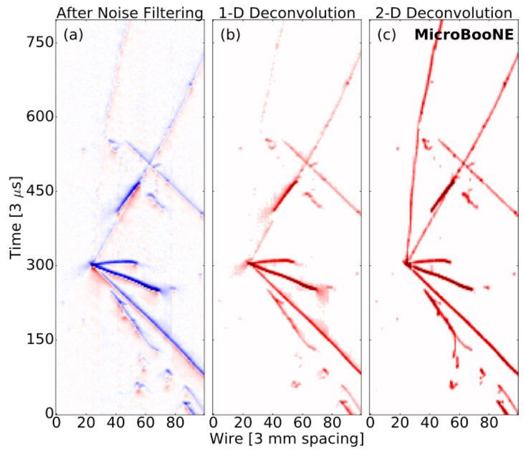
$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H1 \\ H2 \\ H3 \\ H4 \\ H5 \\ H6 \end{pmatrix}$$

Matrix determined by geometry

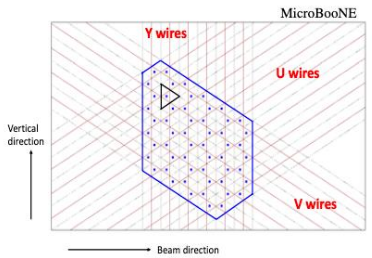


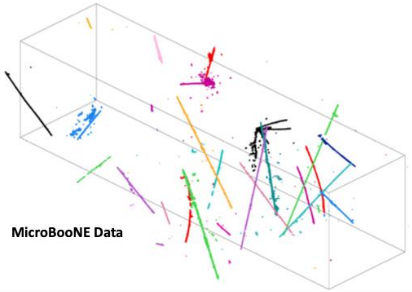
LArTPC Event Reconstruction: Wire-Cell

TPC simulation noise filtering signal processing	3D imaging clustering charge-light matching	3D trajectory & dQ/dx fitting cosmic muon tagger	multi-track fitting DL-3D vertexing particle identification	Model validation Statistics Data Analysis

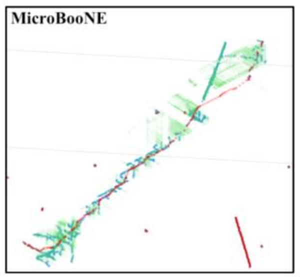


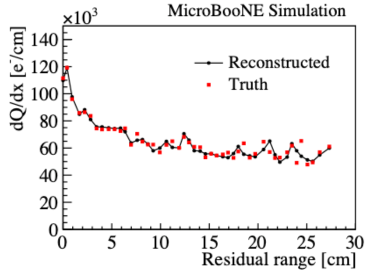
JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)
JINST 16 P01036 (2020)



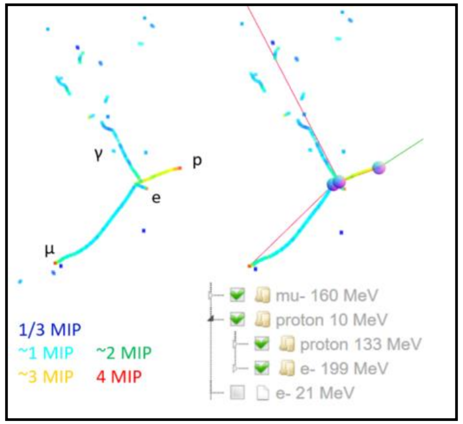


JINST 13 P05032 (2018)
JINST 16 P06043 (2021)

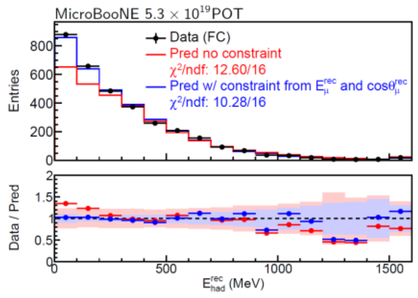




PRApplied 15 064071 (2021)



JINST 17 P01037 (2022)



PRD 105, 112005 (2022)
PRL 128, 151801 (2022)

Wire-Cell-Toolkit: a Data Flow Programming Framework: https://github.com/WireCell/wire-cell-toolkit
(developed and maintained by the BNL team)

Useful Tools from LArTPC Reconstruction

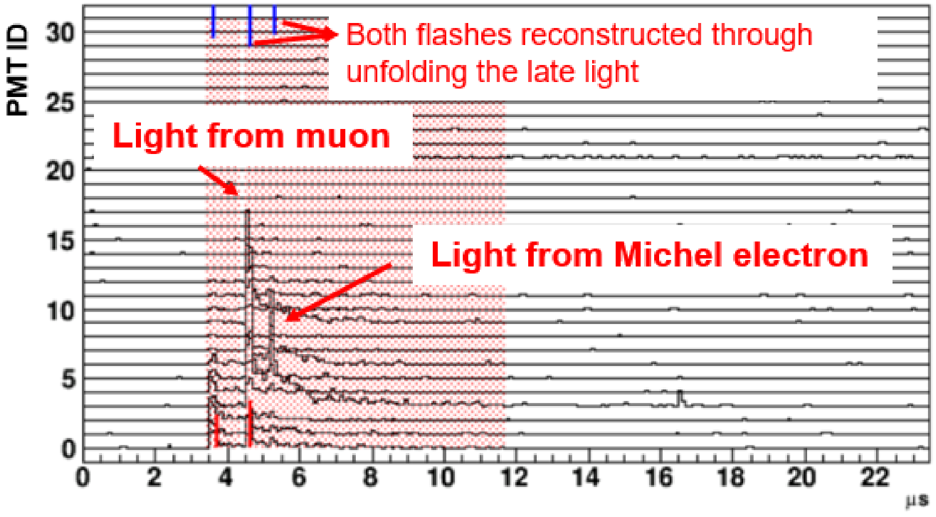
- ❑ Signal simulation: electron drift + electronics simulation
- ❑ Noise filter: harmonic / coherent noise removal
- ❑ Signal processing: ROI finding, 2D deconvolution
- ❑ Various compressed sensing algorithms: tomographic 3D imaging, light reconstruction, charge-light matching, etc.
- ❑ Various pattern recognition algorithms: point cloud, graph theory, deep neutral network
- ❑ A web-based interactive 3D event display (example events):

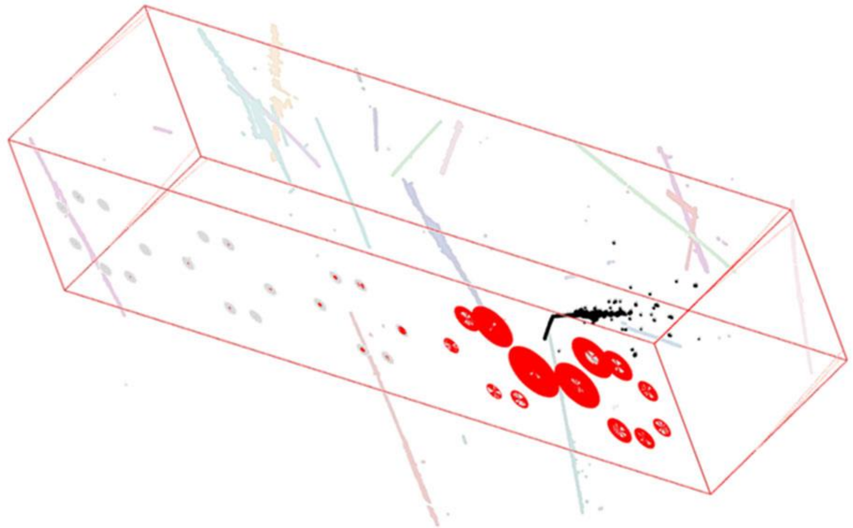
Many LArTPC tools are generic and can be adopted for ATAR reconstruction

LAr Light Reconstruction

- Light reconstruction is important for LArTPC to provide accurate timing of events during the slow drift
  - Important for cosmic ray to correctly determine its z-position (drift direction)
- "Wire-Cell" light reconstruction
  - PMT waveform analysis: deconvolution of SPE response
  - Pile-up analysis because of the large slow component (70% slow: ~1600 ns)
  - TPC-PMT signal matching (many-to-many)
  - Future extension: energy and track reconstruction with light signals

Example from MicroBooNE data





These tools can be adopted for PIONEER's LXe or other scintillation calorimeter's reconstruction

Thank you for your attention!