LArTPC Reconstruction Challenges

LArTPC = Liquid Argon Time Projection Chamber

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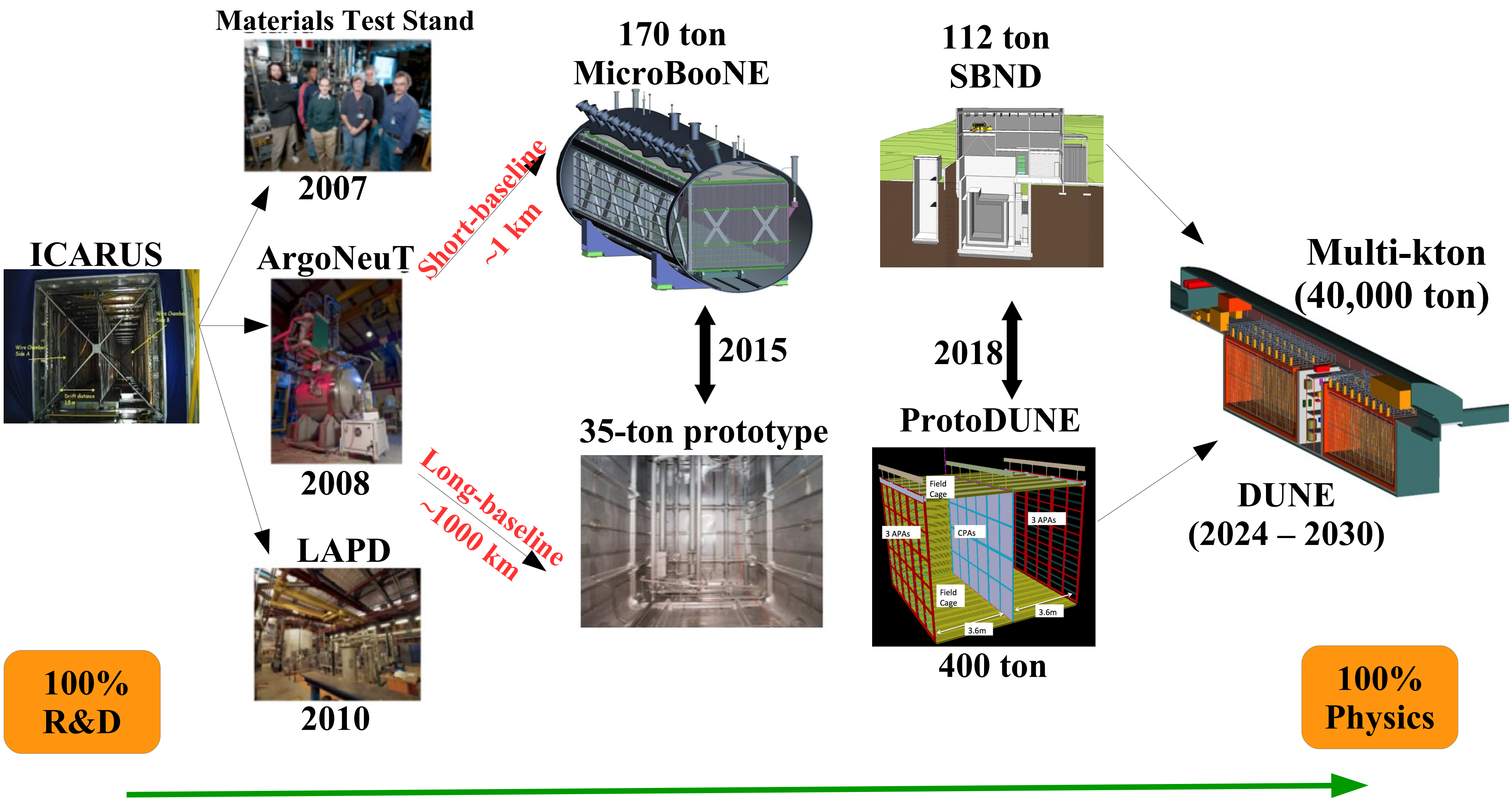
NuEclipse Workshop
August 20 – 22, 2017
University of Tennessee, Knoxville

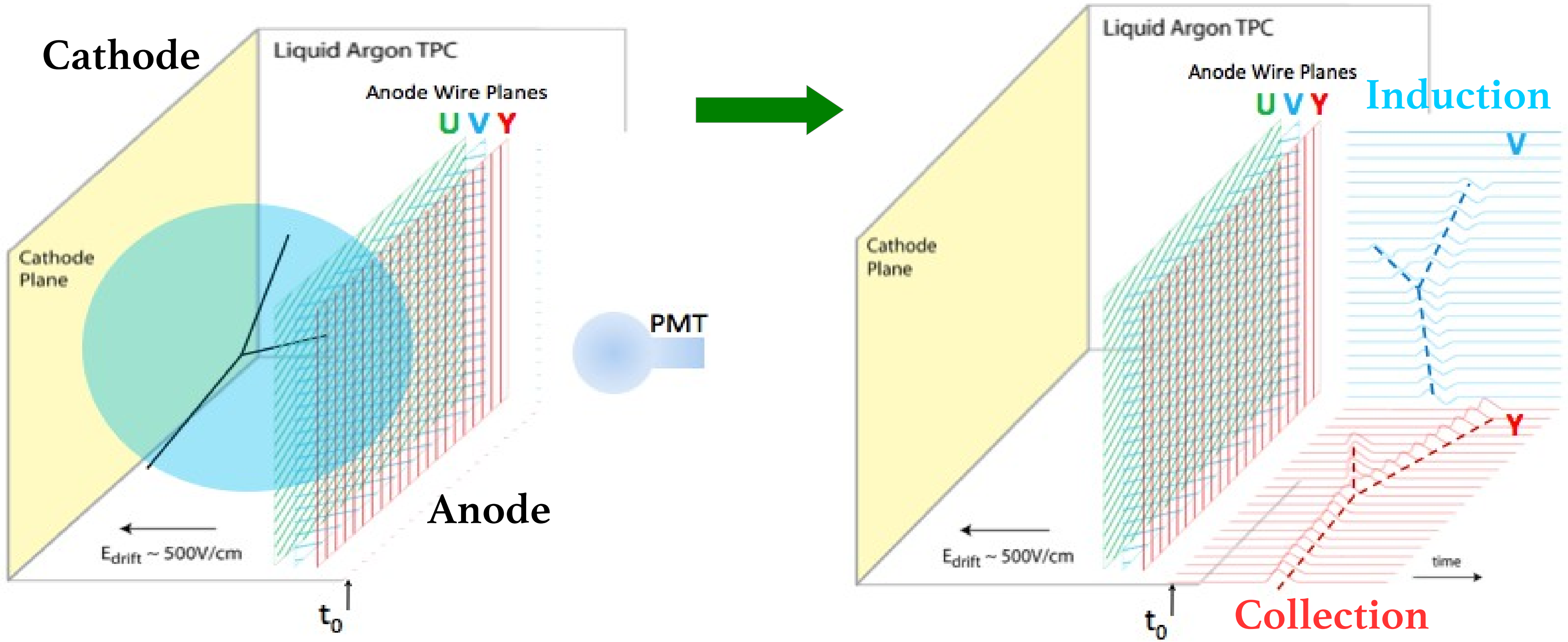
LArTPC program – the big picture

The LArTPC technology is driving the future of neutrino physics



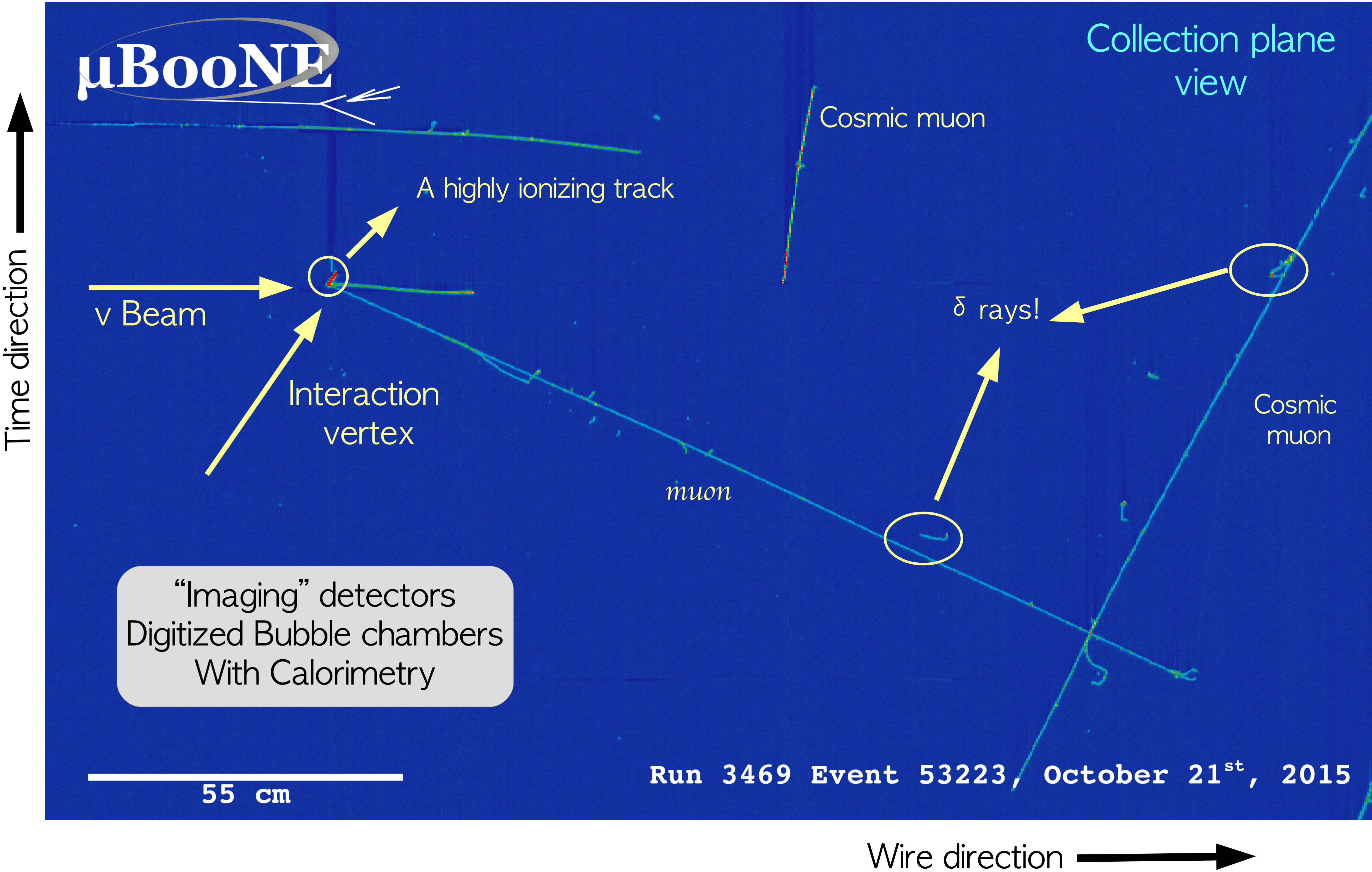
Other: LArIAT, ICARUS, ProtoDUNE Single Phase vs Dual Phase

The LArTPC Principle – single phase



- Induction and Collection plane wires
- Wire planes + Signal Arrival Time = 3D image
  Hence a Time Projection Chamber
- Finely (mm-scale) segmented anode wires → excellent resolution!
- Combine energy and topology information for particle ID

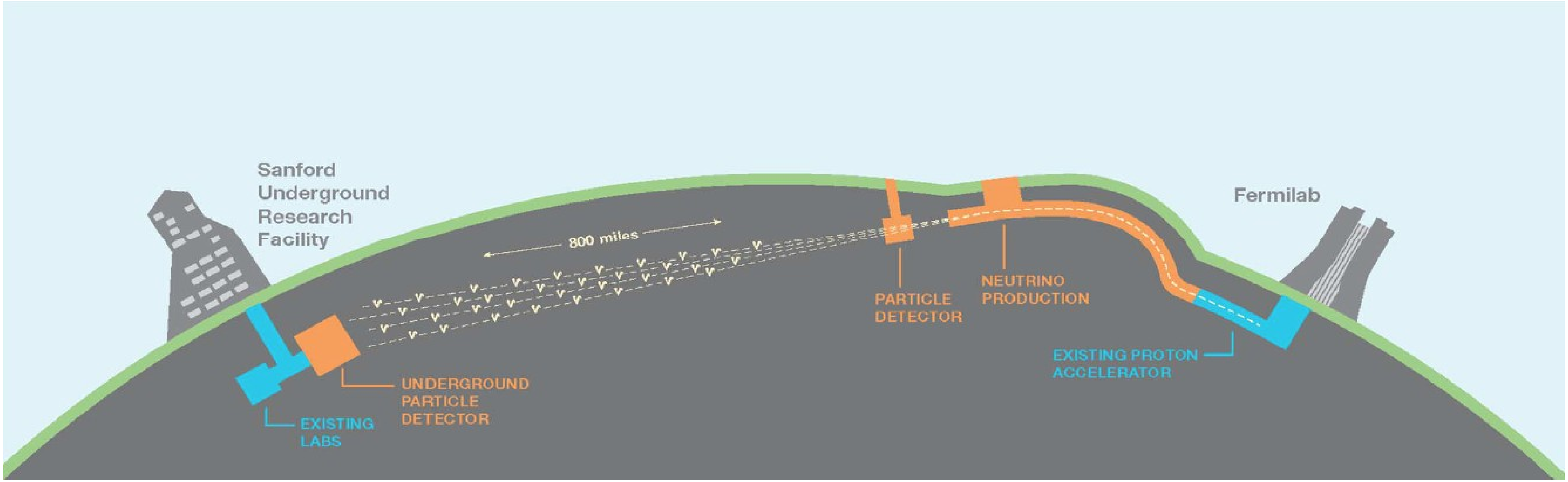
Neutrino Interactions in HD!



Reconstruction in LArTPC is challenging

- Large amount of information
- Typically no magnetic field: challenges with sign determination
- Interaction can happen anywhere in the detector volume no apriori unlike collider experiments
- Energies and Momenta range from MeV to GeV – measuring them accurately in the "same" detector is a challenge (unlike collider experiments which has external additional trackers and calorimeters)
- Interaction patterns have different scale and complexity (cascades, decays, stubs,…)
- Tracks and showers overlap near the neutrino vertex – separation of signals at the interaction point is a challenge
  - Additionally ghost/fake hits are a known problem

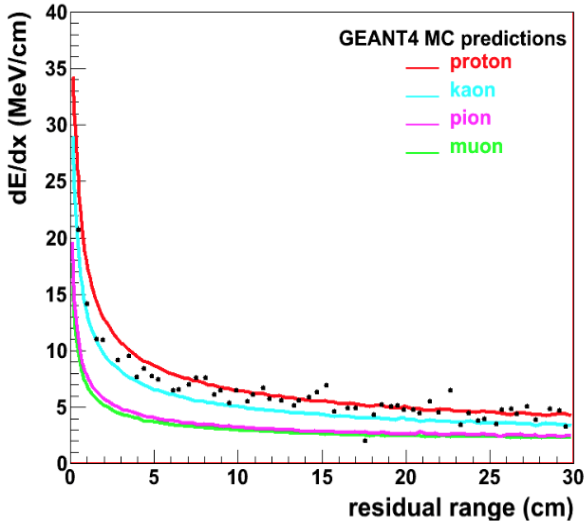
Deep Underground Neutrino Experiment: Physics goals

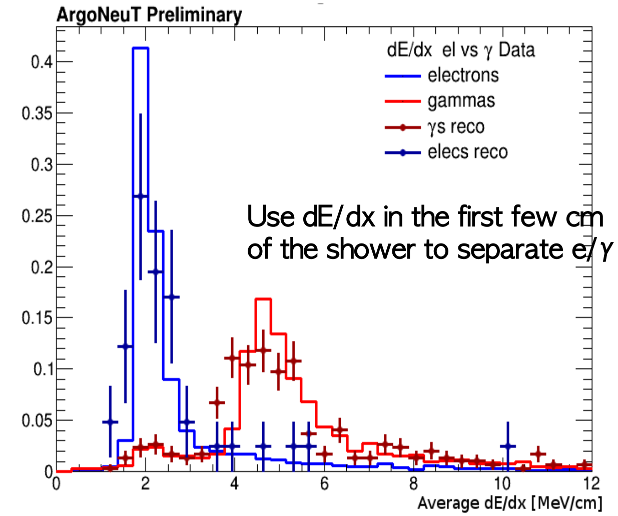


- The biggest LArTPC ever to be built
- A range of physics goals:
  - CP Violation, neutrino mass hierarchy, search for proton decay, and Supernovae burst neutrinos
- Achieving this wide set of physics goals (ranging from MeV to GeV) requires excellent spatial and energy reconstruction capabilities.

DUNE reconstruction requirements for Physics

- Beam and Atmospheric neutrinos
  - Good neutrino vertex reconstruction
  - Muon reconstruction
  - Muon/pion/proton identification and separation
  - Electron reconstruction (energy and directionality)
  - e/γ separation with high efficiency
- Supernovae Physics D. Caratelli (next talk)
  - Low energy event reconstruction and identification
    - Ability to tag electrons and de-excitation gammas from nuclear transitions
    - Good measurement of Time, energy and direction of events
    - Reconstructing small number of hits
- In general
  - Light reconstruction is essential
  - Calorimetric reconstruction greatly depends on accurate measurement of charge per unit length



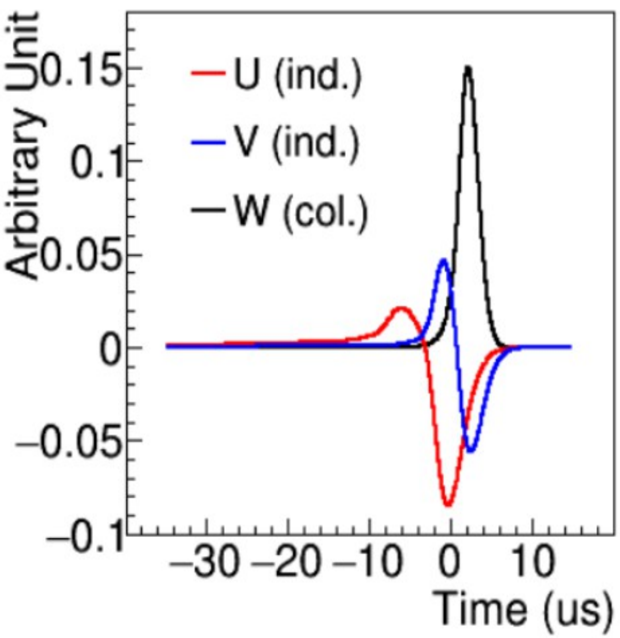


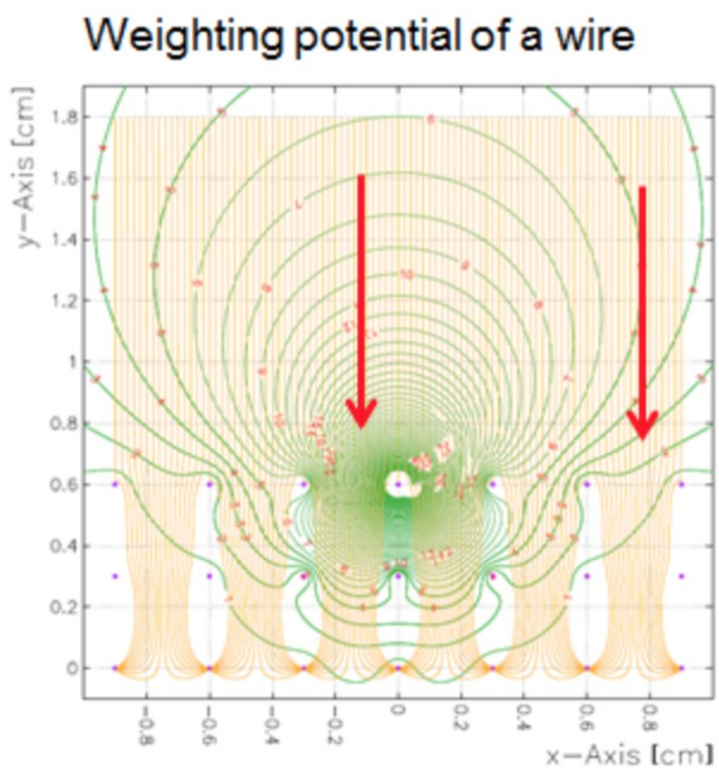
Signal Formation in a LArTPC

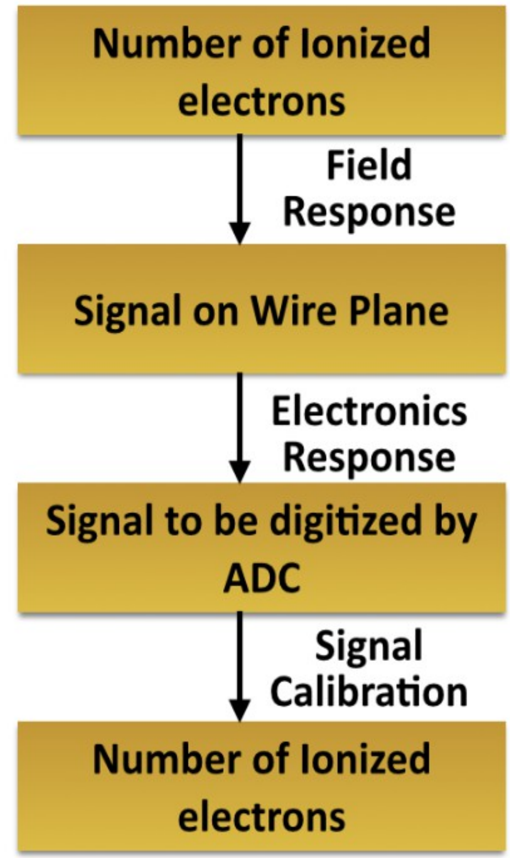
- Current induced on a read-out wire is described by Shockley Ramo Theorem:

$$i = q \cdot \vec{E}_w \cdot \vec{v}_q$$

q = charge; E_w = weighting field; v_q = drift velocity







http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1017-PUB.pdf

Traditional TPC Reconstruction chain

Raw Signal Processing (Deconvolution, Noise removal) — Remove Field and electronics response through deconvolution

↓

2D pattern recognition (Hits, Clusters) — Define regions of interests above a certain threshold and fit a gaussian (Gaussian hit finder) to form hits. Group hits belonging to the same particle into clusters.

↓

2D Matching and 3D reconstruction (Tracks, Showers, Vertices) — Match 2D Clusters b/n different views based on timing information to form 3D objects

↓

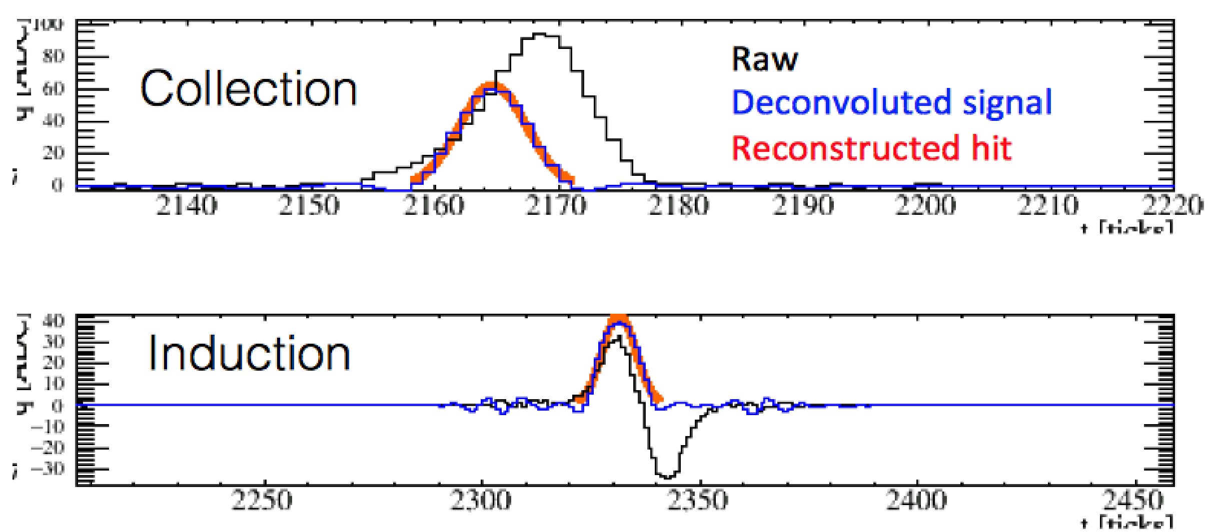
Calorimetry (Energy, Particle ID) — Extract charge per length information from 3D objects and combine with topology for Calorimetry

Traditional:

- **Pandora**
- **Projection Matching Algorithm**
- TrajCluster

Non-traditional:

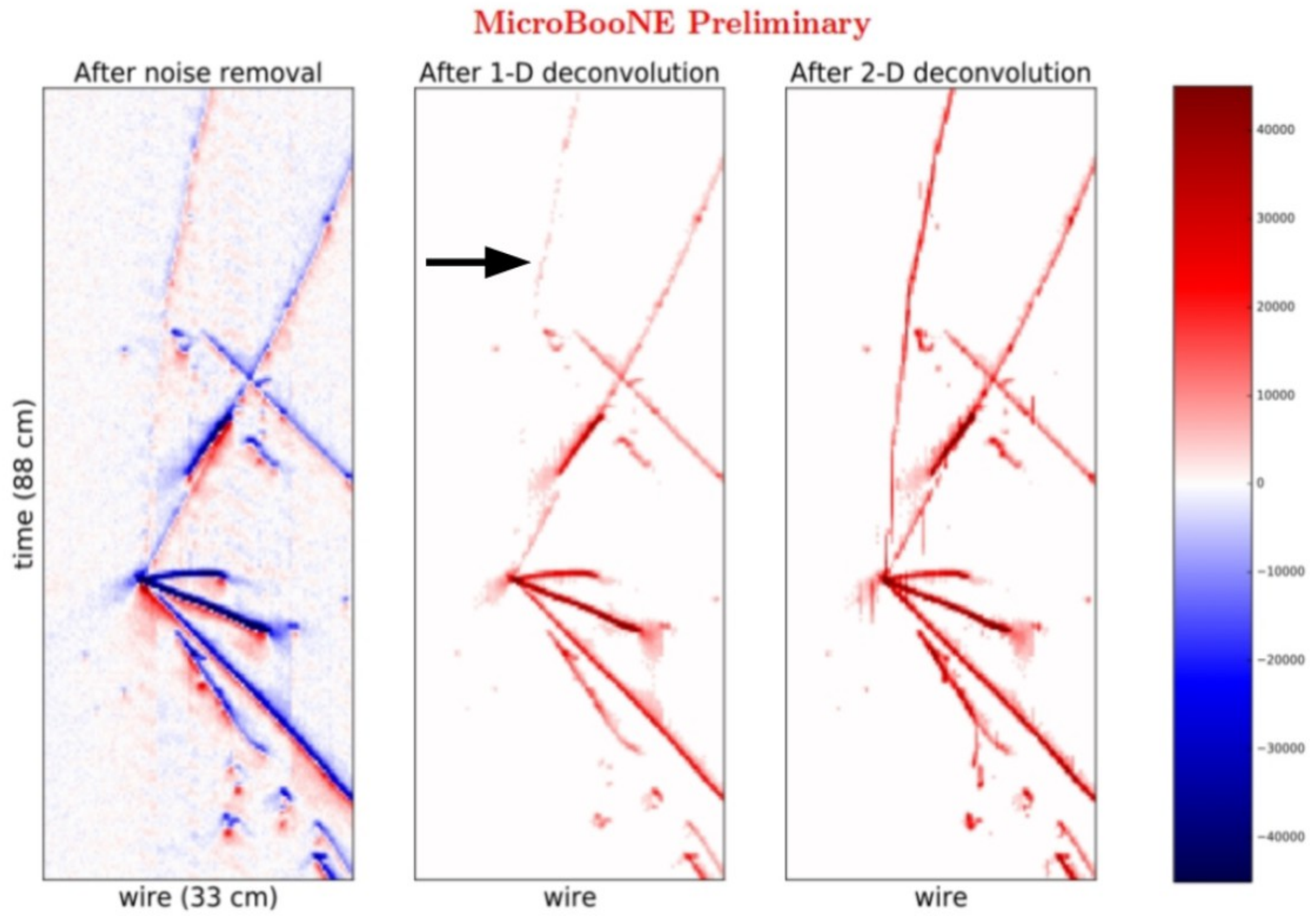
- 3D Tomographic approach (WireCell)
- Deep Learning



Challenges with Signal Processing: Deconvolution

Dynamic Induced Charge (DIC)

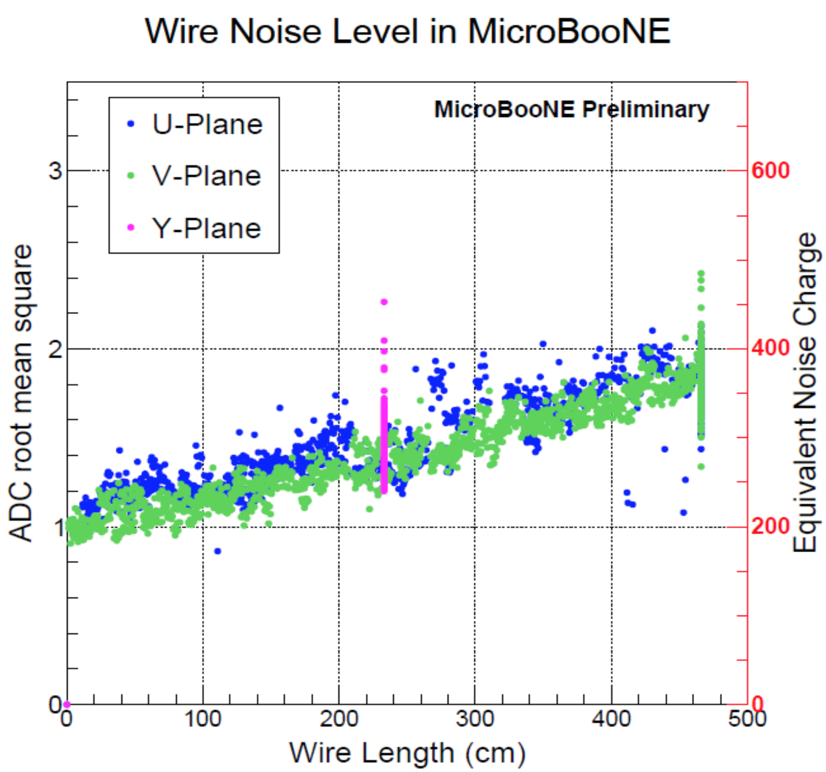
- Typically expect signal to be induced on only one wire. But, in reality, near-by wires also see some signal
- This induced charge is dynamically dependent on track angle
- Not accounting for DIC during deconvolution results in charge lost

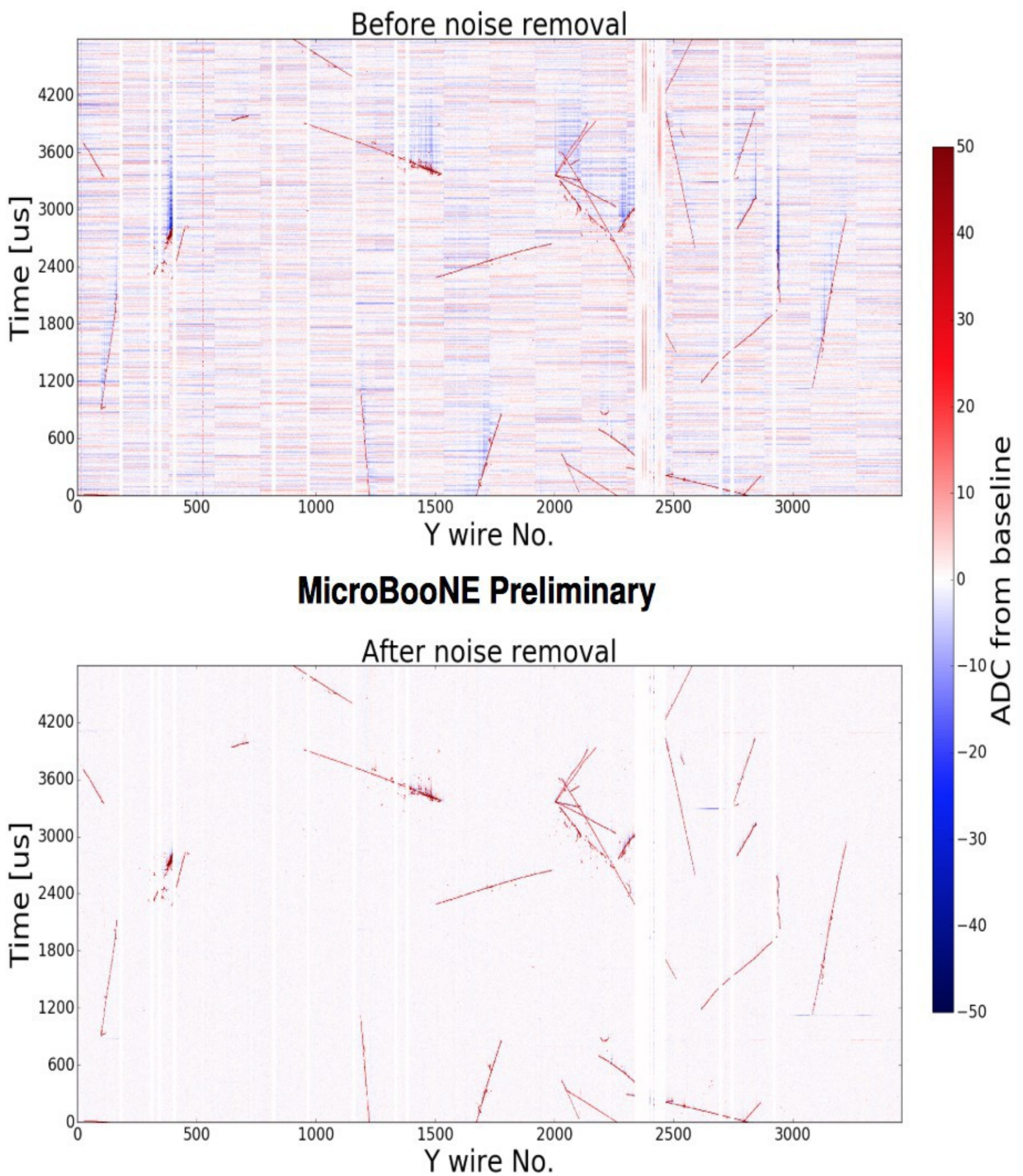


- 1D deconvolution based on direct signal works well for collection planes but for induction planes, DIC needs to be taken into account for deconvolution (2D)
  - Proof of principle exists; full integration under work; – BNL leading the effort

Challenges with Signal Processing: Noise

- Cold Front-end electronics critical for nois
  - 5 to 6 times better compared to warm electronics
- Low noise levels achieved in a 100-ton scale LArTPC
  - Several software noise filtering algorithms



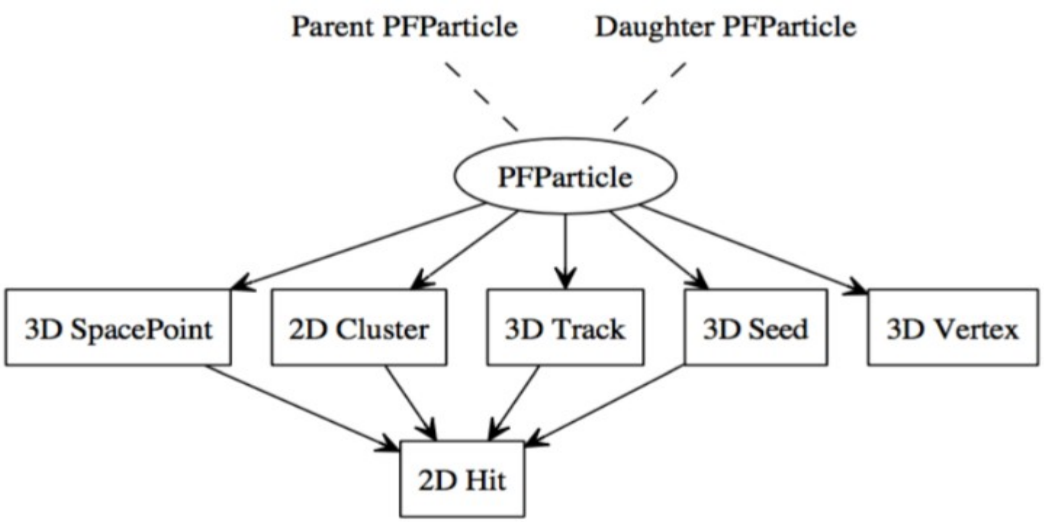


Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC", JINST 12, P08003 (2017)

Pandora and PMA algorithms

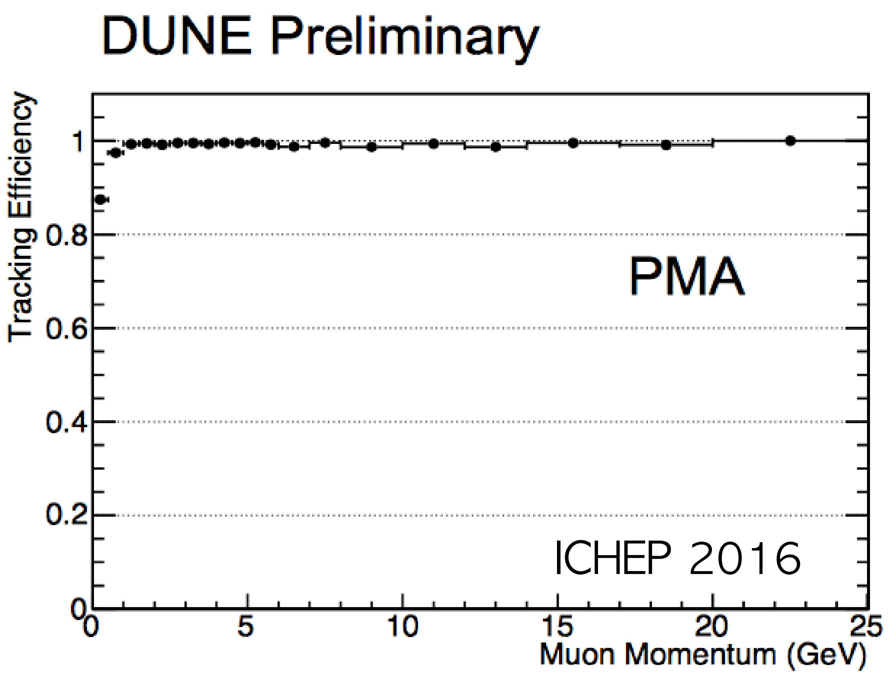
Pandora

- Fine-grained pattern recognition algorithm
- Optimized and Automated pattern recognition approach
- Take hits as input and produce 2D/3D objects called "PFParticles" with hierarchy
- Step 1: PandoraCosmic (remove cosmics)
- Step 2: PandoraNu (neutrino identification)

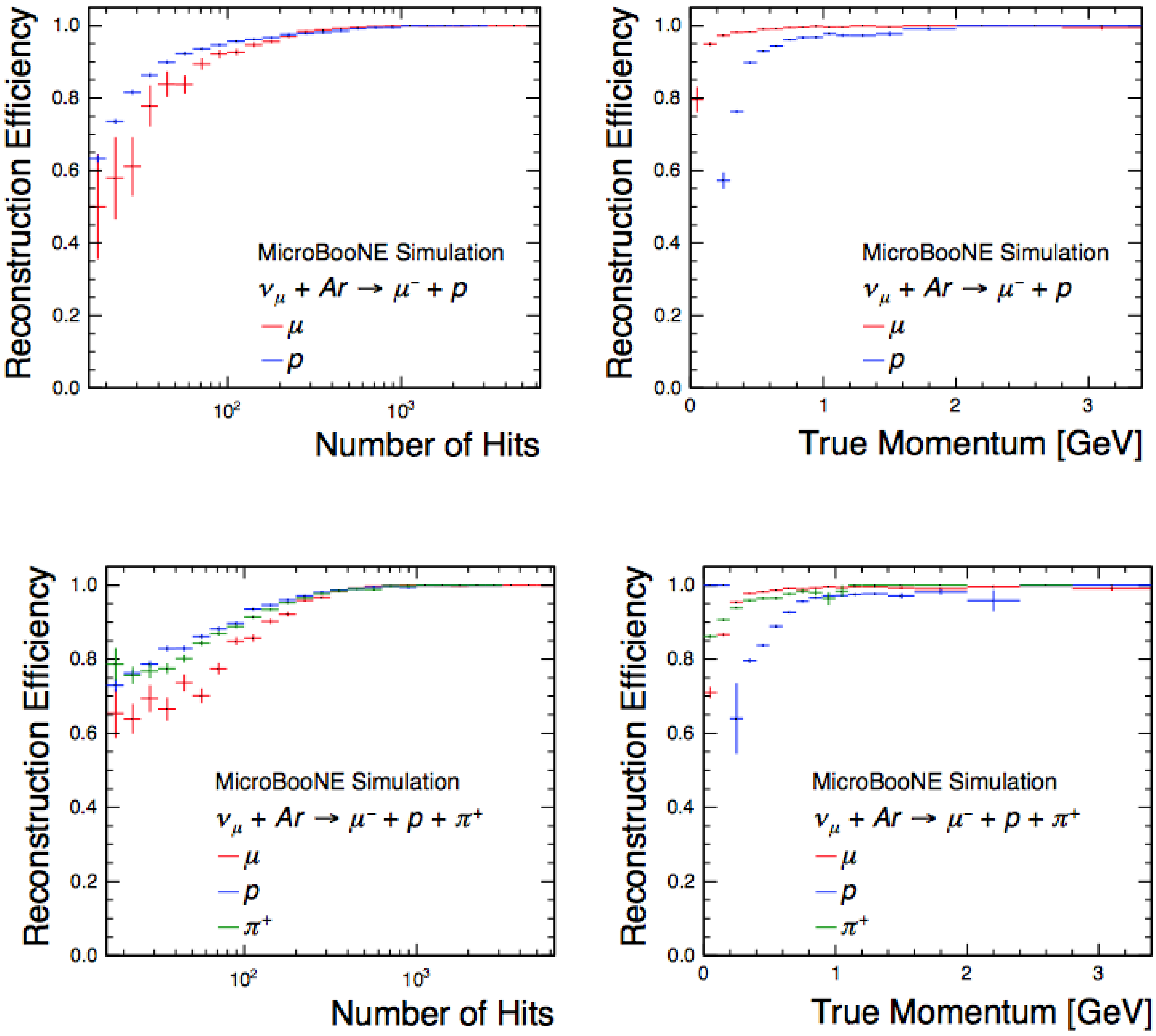


Project Matching Algorithm

- Instead of building 3D object by matching 2D hits between different views, build 3D object by minimizing the object's 2D projection to 2D hits distance
- A technique derived from ICARUS AHEP 1601 p.260820 (2013)
- Promising performance



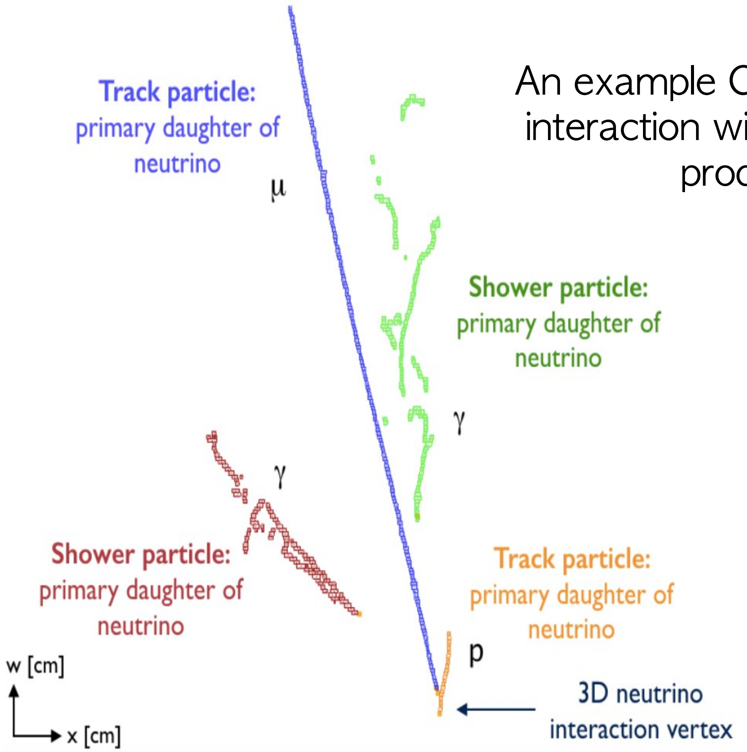
Pandora Reconstruction Performance

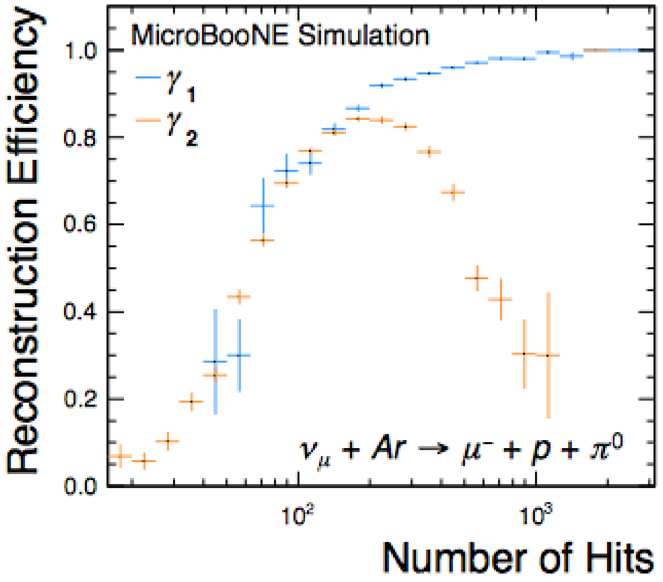


Pandora Reconstruction Performance

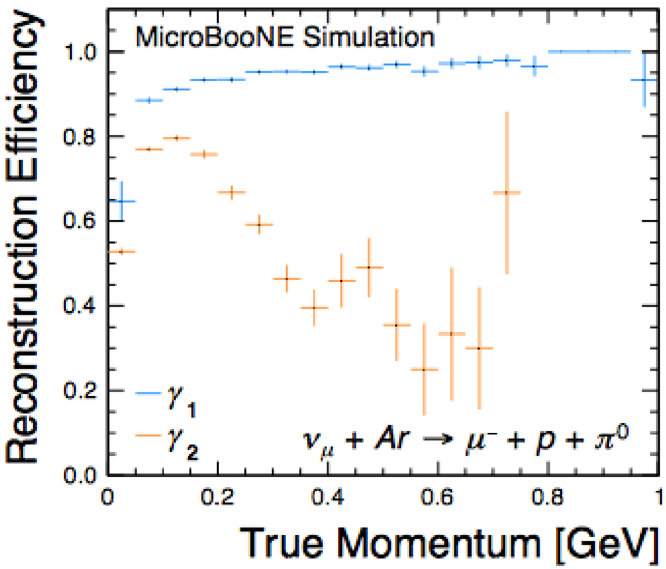
https://arxiv.org/pdf/1708.03135.pdf

An example CC muon neutrino interaction with resonant pion production





#Matched Particles	0	1	2	3+
μ	3.7%	94.8%	1.5%	0.0%
p	9.9%	85.5%	4.3%	0.3%
γ_1	6.8%	88.0%	4.8%	0.4%
γ_2	29.9%	66.4%	3.6%	0.2%



3D Tomographic Reconstruction: Wire Cell

Raw Signal Processing
(Deconvolution, Noise removal)

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2D image reconstruction
(Time+Geometry+Charge)

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3D image reconstruction

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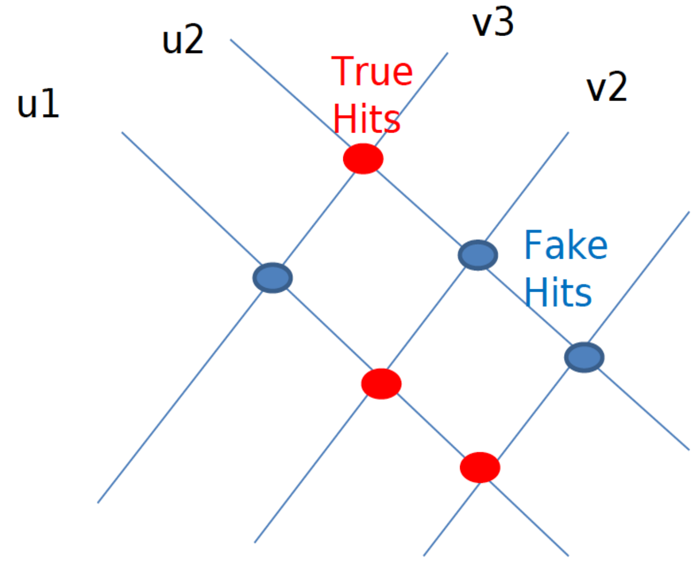
3D Pattern Recognition
(tracks, showers etc.)

↓

Kinematic reconstruction
(energy, PID)

- In traditional reconstruction
  - Charge information not used in early steps
  - Hypotheses on pattern recognition are tried early on ⟶ could lead to biases?
- WireCell approach: Reduce degeneracy by using charge information early on
  - Don't start with pattern recognition like traditional algorithms rather use robust information at the beginning of the chain
  - Pattern recognition a later step



Pattern recognition for LArTPCs in general is very difficult

- **Deep Learning** efforts actively being pursued recently JINST 12, P03011 (2017)

Reconstructing Ionization charge and position

- Precise determination of ionization charge and position, from the point of formation to the point of collection, with as less bias as possible is critical for both energy scale reconstruction and detector resolution

- There are many effects that can impact this, E.g.,

Energy scale
- Argon purity (e^- lifetime)
- Electron-ion recombination
- Space charge
- Electronics calibration
- DIC

Position/timing Resolution
- Diffusion
- Space charge
- Noise
- Wire response
- DIC

The biggest challenge is that these effects are correlated!

Calorimetric Reconstruction

- Calorimetry along with topology forms best tools for PID
- Calorimetry requires knowing dE/dx as a function of residual range
- **The goal of calorimetry is to convert dQ/dx (ADC/cm) to dE/dx (MeV/cm)**
  - Step 1: dQ/dx (ADC/cm) → dQ/dx (e/cm)
    - Electronics calibration factor i.e., need to know electrons per ADC-tick
    - Can use stopping muons to determine this
  - Step 2: dQ/dx (e/cm) → dQ*/dx (e/cm)
    - Correct for charge lost due to impurities during transit **(electron lifetime)**
    - Many ways to measure this: cosmic muons, laser, purity monitors etc.
  - Step 3: dQ*/dx (e/cm) → dE/dx (MeV/cm)
    - Correct for the electrons lost due to **recombination** with argon ions
    - Can be done using stopped muons or protons
- **Space charge has a significant impact on all of this!**
  - Space charge is an issue for surface detectors, not so much for DUNE

Summary

- LArTPC technology is the technology of choice for current and future neutrino experiments.
- While LArTPCs have the potential to provide excellent energy and position resolution capabilities, reconstruction is a challenge
  - Signal processing is the key step for reconstruction
  - Precise determination of ionization charge and position requires thorough calibration of the detector – very much needed to achieve the energy and position resolution
- A lot of pioneering work has been done recently towards signal processing and noise removal by the MicroBooNE experiment
- There are many more challenges that need to be addressed:
  - Robust pattern recognition, 2D deconvolution, cosmic removal tools, etc.
  - Deep Learning, CNNs, Boosted decision trees are all leading to hybrid approaches
- After many years, we have an automated reconstruction chain for LArTPCs
- Stay tuned for more updates!

Backup

Wire-Cell Imaging