Pandora Pattern Recognition in LArTPCs

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10 November 2021 / Institute of Physics / Opportunities with Atmospheric Neutrinos

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LArTPC Program

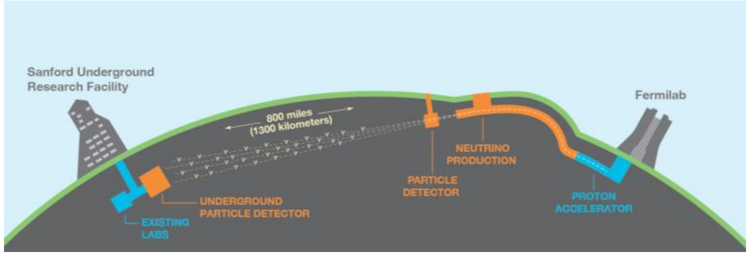
Pandora was originally developed in the context of linear colliders
Adapted to support Liquid Argon Time Projection Chambers
Common functionality provided by Software Development Kit (SDK)
Library for LArTPC-centric algorithms

Short-baseline program

ICARUS MicroBooNE SBND

- Three LArTPC detectors located along the Booster Neutrino Beam (BNB) at Fermilab
- Main goal is to investigate the potential sterile neutrino signals from LSND and MiniBooNE
- Precision cross-section measurements for neutrino interactions on argon

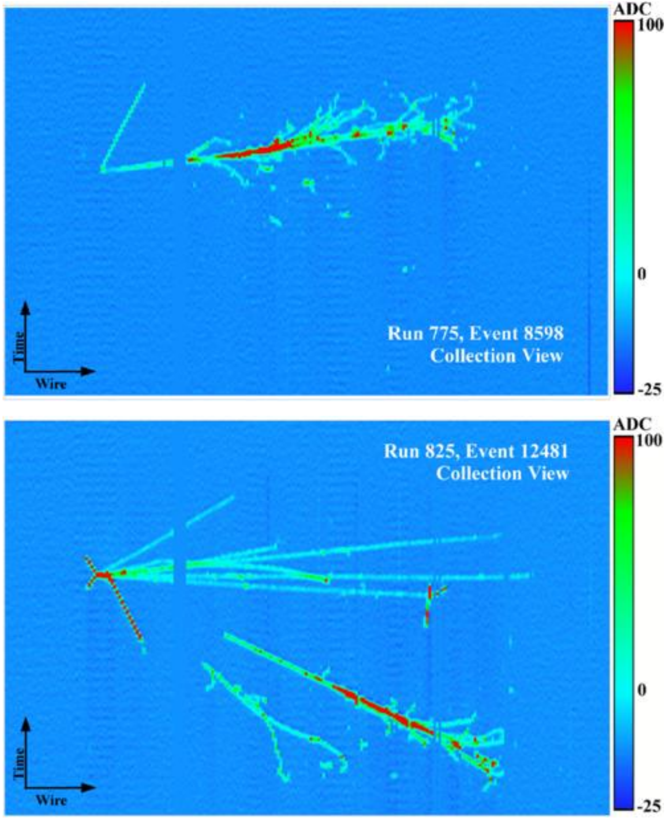
Long-baseline program



DUNE FD NDLAr ProtoDUNEs

- Neutrino oscillation physics:
  - CP violation in the leptonic sector
  - Mass hierarchy
  - Precision parameter measurement
- Proton decay
- Supernova neutrinos

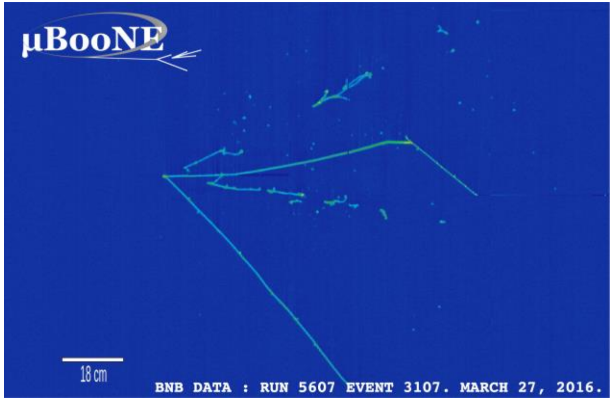
What do we get from Liquid Argon?

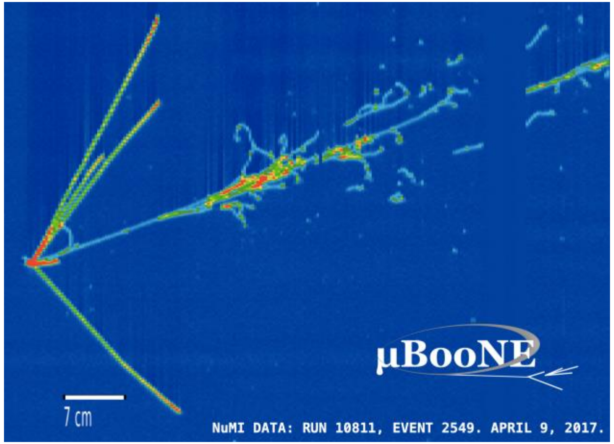


R. Acciari *et al*, Phys. Rev. D 95, 072005 (2017)

- LArTPC detectors are fully active and fine grain, offering superb spatial and calorimetric resolution:
  - Reconstruction of multi-prong final states.
  - Particle identification:
    - μ/p/K in particle tracks
    - e/γ in electromagnetic showers
- Scalable to multi-kiloton masses

Where does Pandora fit in?





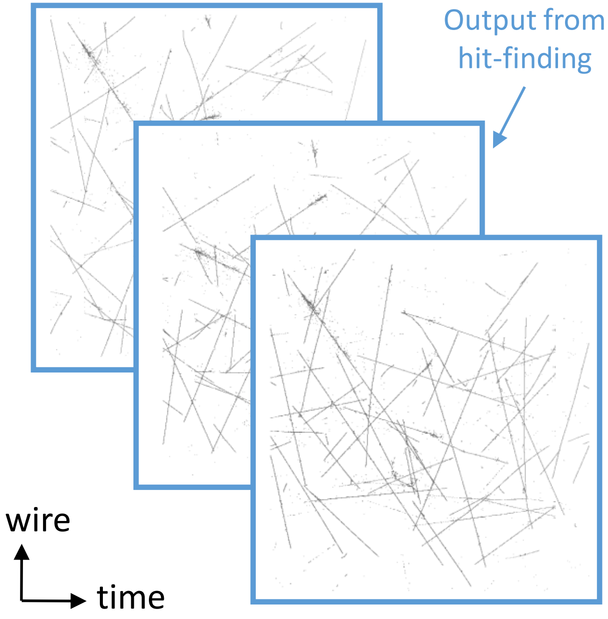
- The conversion of raw LArTPC images into analysis-level physics quantities:
- Low-level steps:
  - Noise filtering
  - Signal processing to create 2D hits

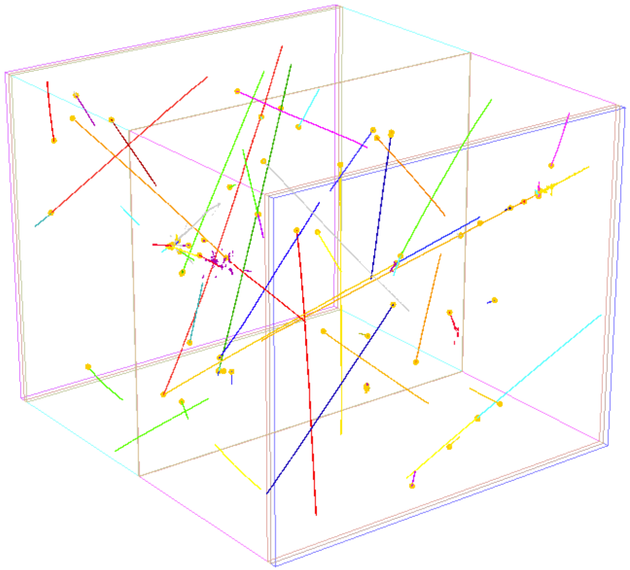
Pandora

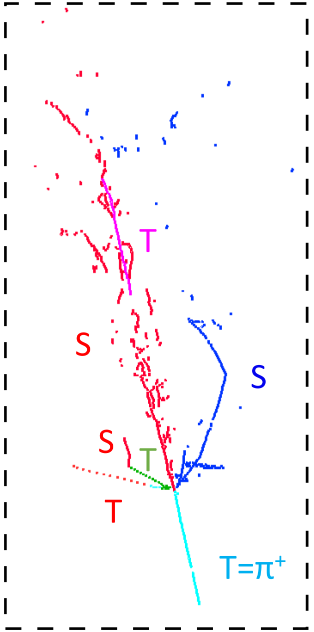
- **Pattern recognition:**
  - **The bit you do by eye!**
  - **Assign 2D hits to clusters**
  - **Match features between planes**
  - **Output a hierarchy of 3D particles**
- High-level characterisation:
  - Particle identification
  - Neutrino flavour and interaction type
  - Neutrino energy, etc…

LArTPC Pattern Recognition

- The main aims of the pattern recognition step are to:
  - Produce 3D reconstructed particles, based on inputs of 3 x 2D images.
  - Reconstruct the hierarchy of particles resulting from an interaction.







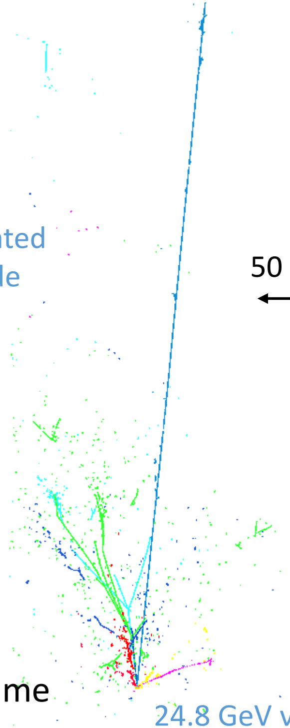
Simulated π+ Pandora Reconstruction at ProtoDUNE-SP

LArTPC Pattern Recognition

It is a significant challenge to develop automated, algorithmic LArTPC pattern recognition

- Complex, diverse topologies:

μ truncated on slide



50 cm

w, wire

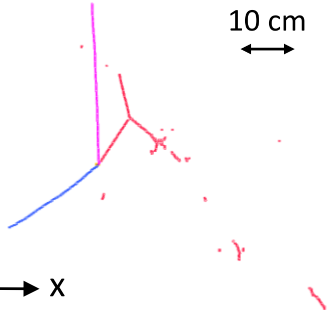
x, time

24.8 GeV ν_μ CC DIS

10 cm

w

x

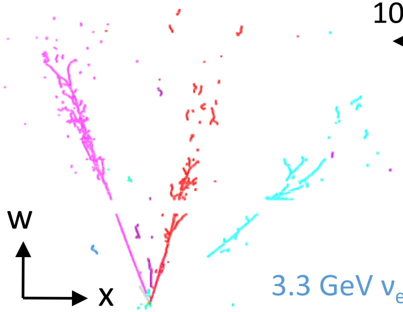


1.8 GeV ν_μ CC RES w/ π^+

10 cm

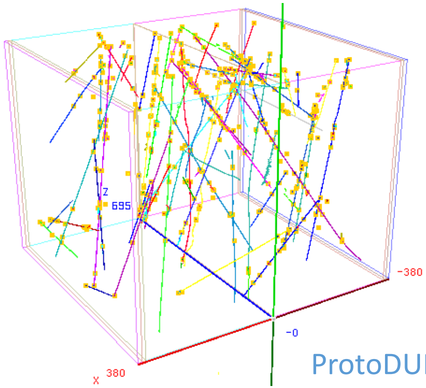
w

x



3.3 GeV ν_e CC DIS

- Also, LArTPCs have long exposures, due to lengthy drift times (up to few ms).
- Significant cosmic-ray muon background in surface-based detectors.



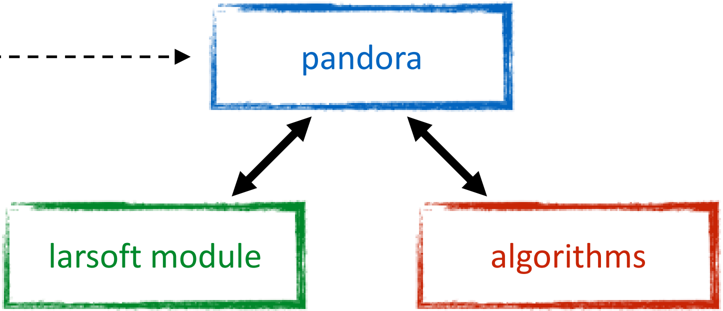
ProtoDUNE-SP

Multi-Algorithm Approach

- Single clustering approach is unlikely to work for such complex topologies:
  - Mix of track-like and shower-like clusters
- Use Pandora multi-algorithm approach to build up events gradually:
  - Each step is incremental - aim not to make mistakes (undoing mistakes is hard…)
  - Deploy more sophisticated algorithms as picture of event develops
  - Build physics and detector knowledge into algorithms

pandora sdk and visualization

Re-usable libraries support multi-algorithm approach



EPJC (2015) 75: 439
EPJC (2018) 78: 82
github.com/PandoraPFA

larpandora

Handles input/output
LArSoft ↔ Pandora

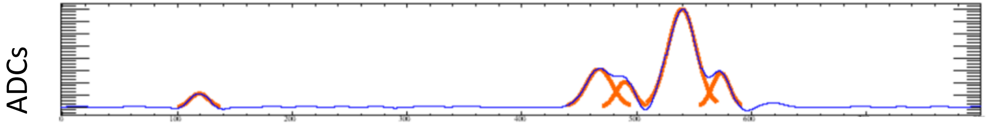
larpandoracontent

100+ algorithms and tools, specifically for LArTPC usage

Inputs to Pattern Recognition

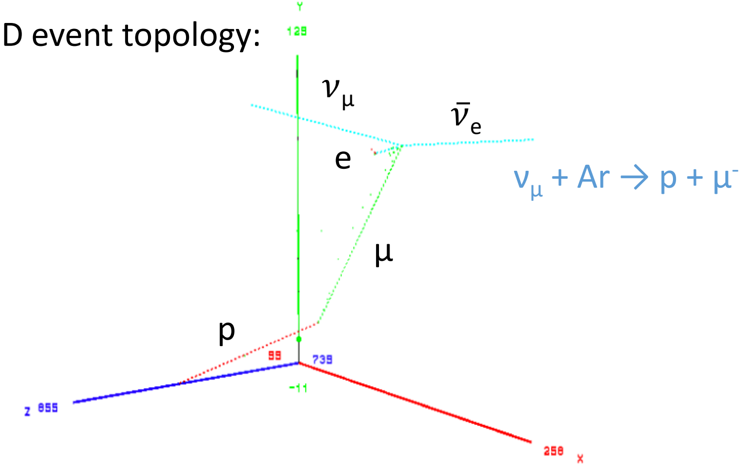
Input: 3 sets of 2D hits, known wire positions [cm] vs. recorded positions from drift times [cm]

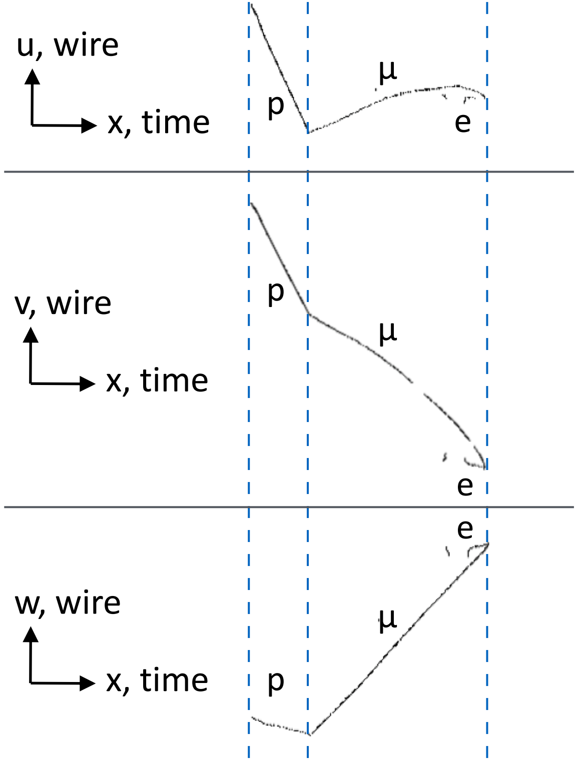
E.g. Hits found for an individual wire:



T. Yang, (ICHEP 2016)

E.g. True 3D event topology:



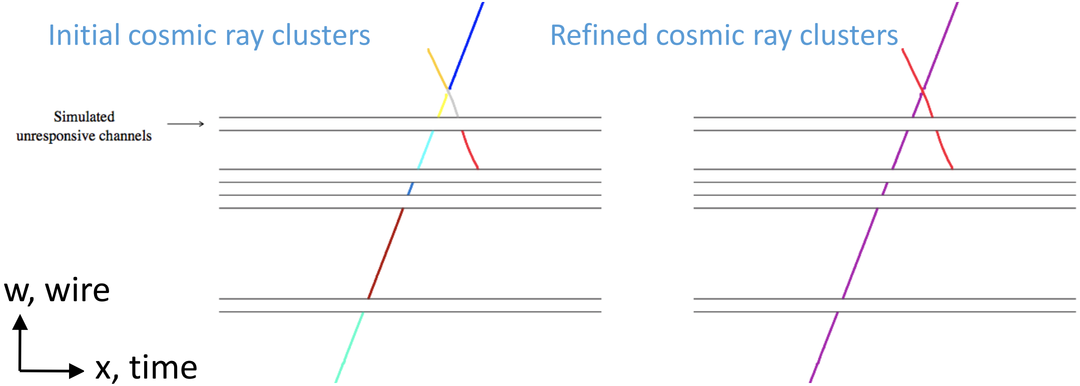


3x2D representations with common coordinate derived from drift time, “x”

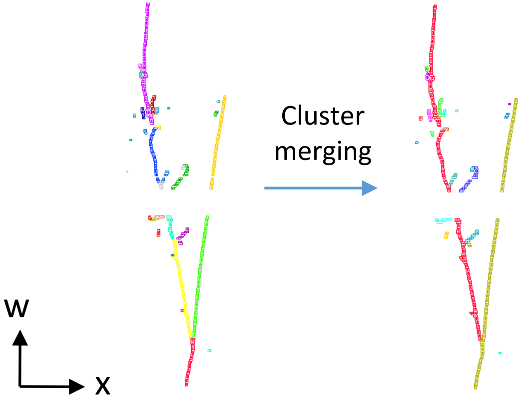
“Traditional” Approaches

For each wire plane, create a list of 2D clusters that represent continuous, unambiguous lines of hits:

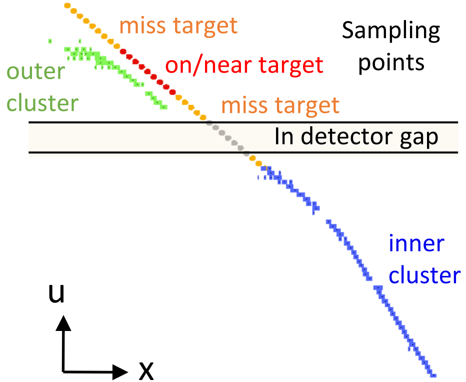
Separate clusters for each structure, with clusters starting/stopping at any branch or ambiguity.



LongitudinalAssociation Algorithm



CrossGapsAssociation Algorithm



MicroBooNE simulation
EPJC (2018) 78: 82

Initial clusters are refined by a series of cluster-merging and cluster-splitting algorithms that use topological info.

"Detector-Physics" Approaches

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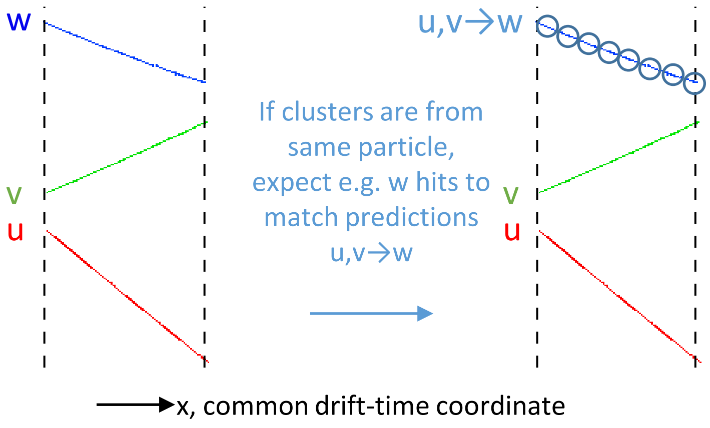
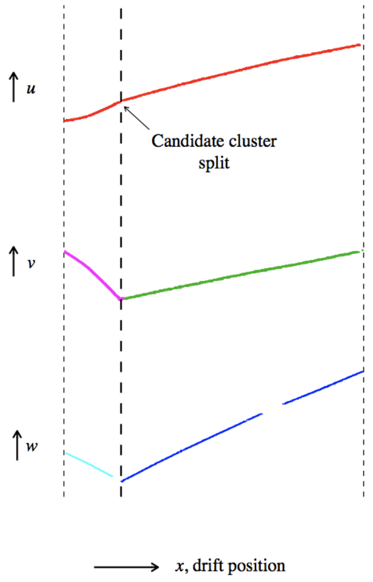
- Our original input was 3 sets of 2D hits from charged particles in the detector.
- Should now have reconstructed three separate 2D clusters for each particle:
  - Compare 2D clusters from u, v, w planes to find the clusters representing same particle.
  - Exploit common drift-time coordinate and our understanding of wire plane geometry.



- Power of the approach most evident when the 2D clustering "disagrees" between wire planes:
  - Automated detection of 2D PatRec issues, with treatment for specific cases, e.g.:



u:*v*:*w*
1:2:2

Two clusters in w and v, matched to common u cluster.

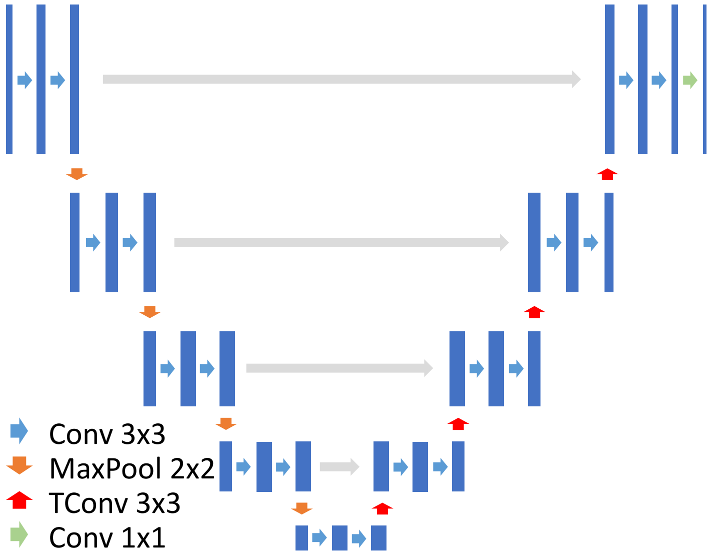
Split u cluster; truly two particles.

Check to see if is a kink topology in 3D

MicroBooNE simulation
EPJC (2018) 78: 82

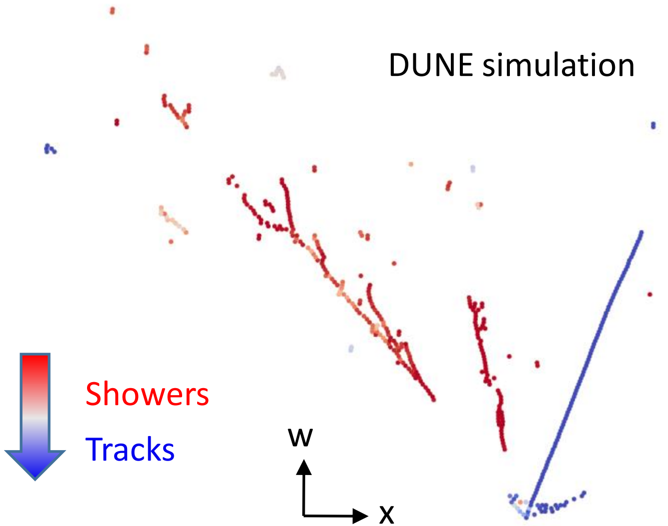
"Deep-Learning" Approaches

- Pandora can run Pytorch networks within the reconstruction algorithm chain
- U-Net assigns track/shower probability to input hits



https://arxiv.org/abs/1505.04597

- Can assess the "trackiness" of Pandora clusters and process the track-like and shower-like clusters in separate streams to target specific topologies
- Multi-algorithm approach provides flexibility to target many other areas with deep-learning



Summary

- A broad program of LArTPC experiments offers high-resolution imaging of neutrino interactions
- Impressive hardware capabilities need effective software to reconstruct interactions and deliver physics goals
- Pandora pattern recognition applies a multi-algorithm approach combining traditional techniques and machine learning to reconstruct interactions
- A mature (but still developing) workflow exists for beam experiments
- A workflow targeting atmospheric neutrinos is in development (more information in Maria’s talk next)

Backup

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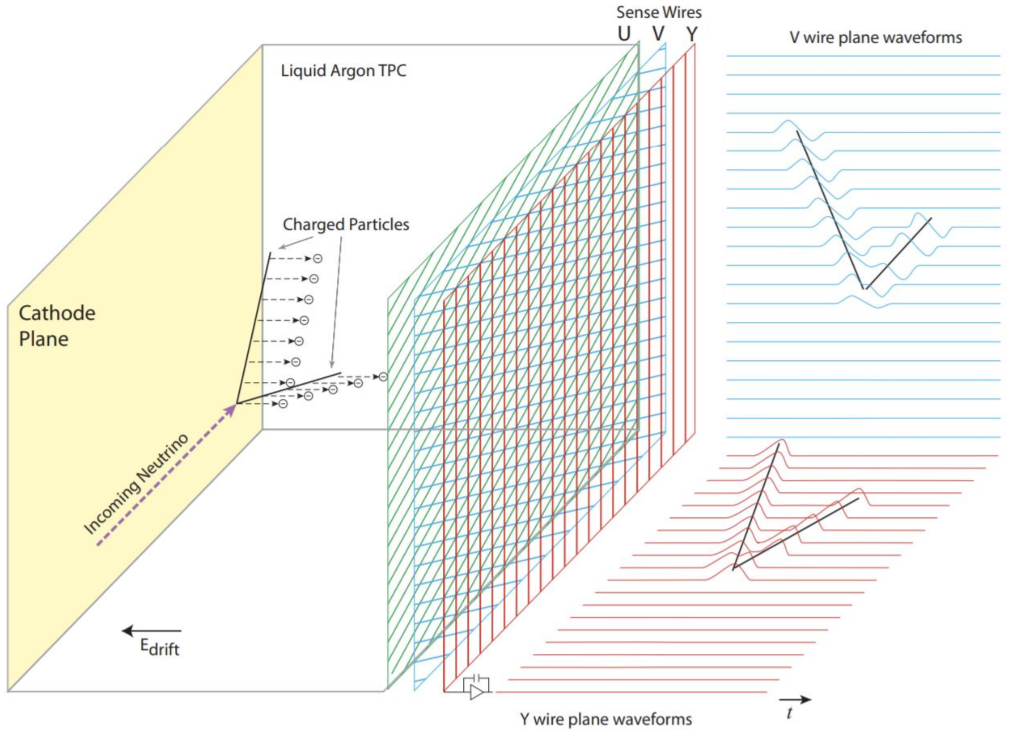
LArTPC operation



R. Acciari *et al*, JINST 12(02), P02017 (2017)