Lancaster University

Liquid Argon Simulation/Reconstruction

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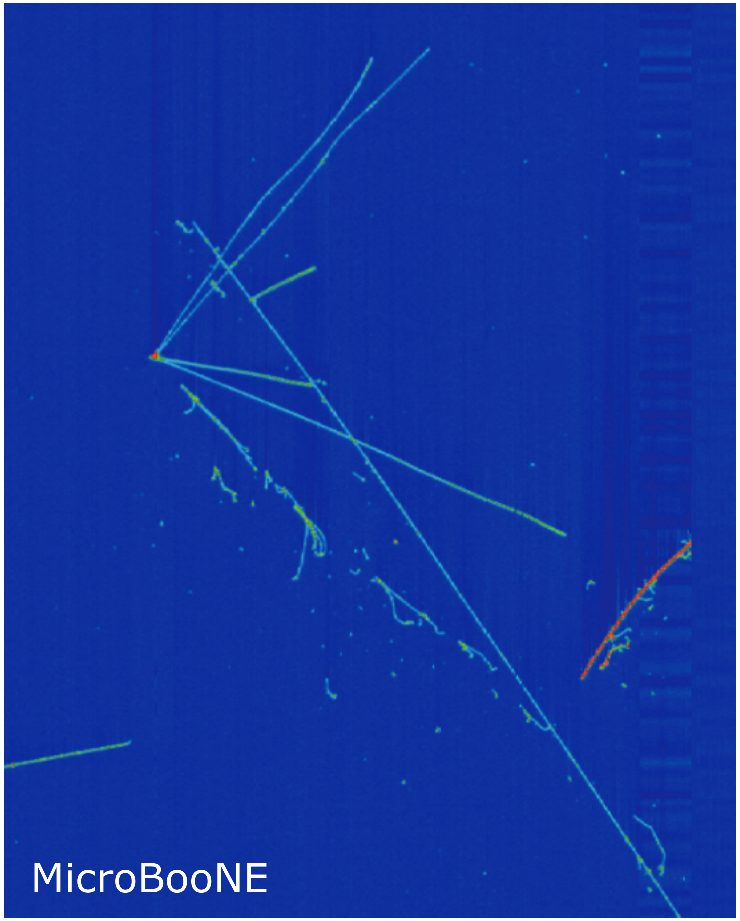
Overview

- ◆ LAr-TPC Detectors.
  - ➢ Why Liquid Argon?
- ◆ Neutrino Event Reconstruction.
  - ➢ LAr-TPC Challenges.
- ◆ Simulation & Reconstruction:
  - ➢ Low-level Signal Processing.
  - ➢ Pattern Recognition.
  - ➢ High-level Reconstruction.
- ◆ Summary

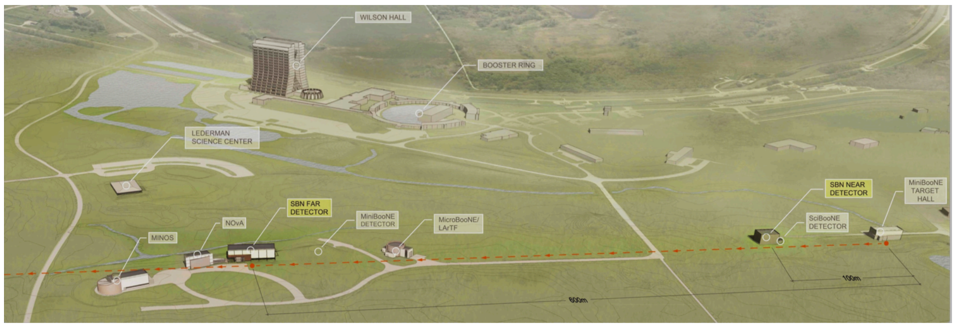


Will mainly focus on LAr-TPC event reconstruction in this review talk

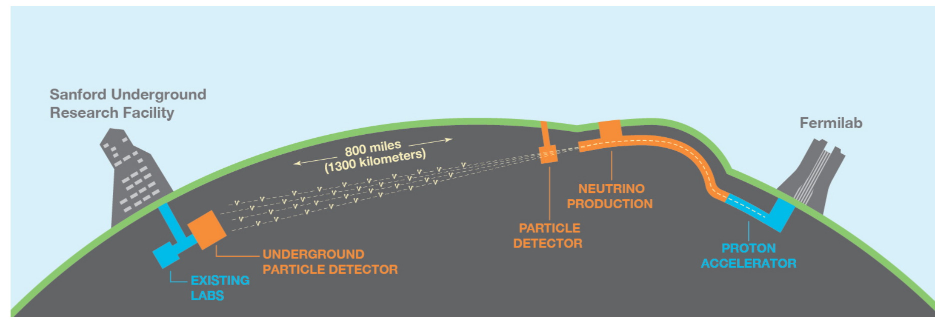
Introduction

◆ One of the key technologies in the current and future neutrino physics programmes is the Liquid Argon Time Projection Chamber (LAr-TPC).

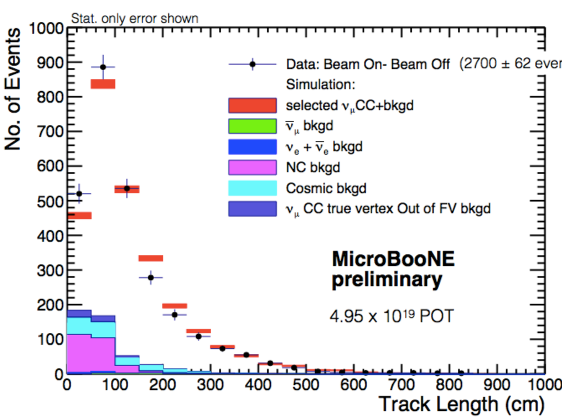
Short-baseline Programme



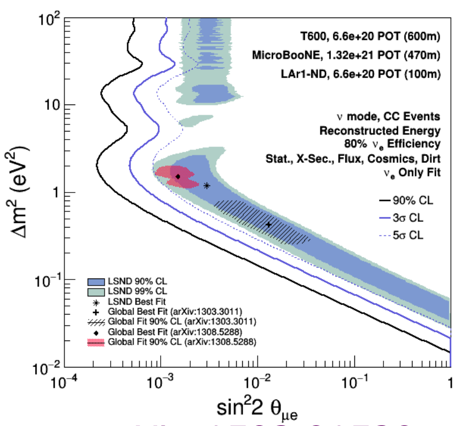
Long-baseline Programme



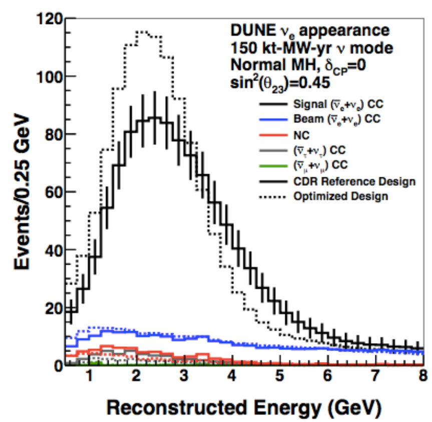
ICARUS MicroBooNE SBND DUNE ProtoDUNE’s

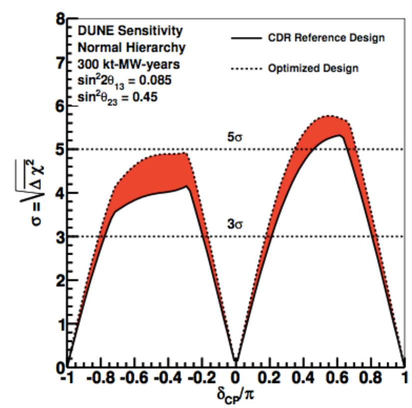


M. Toups, Neutrino 2016



arXiv:1503.01520

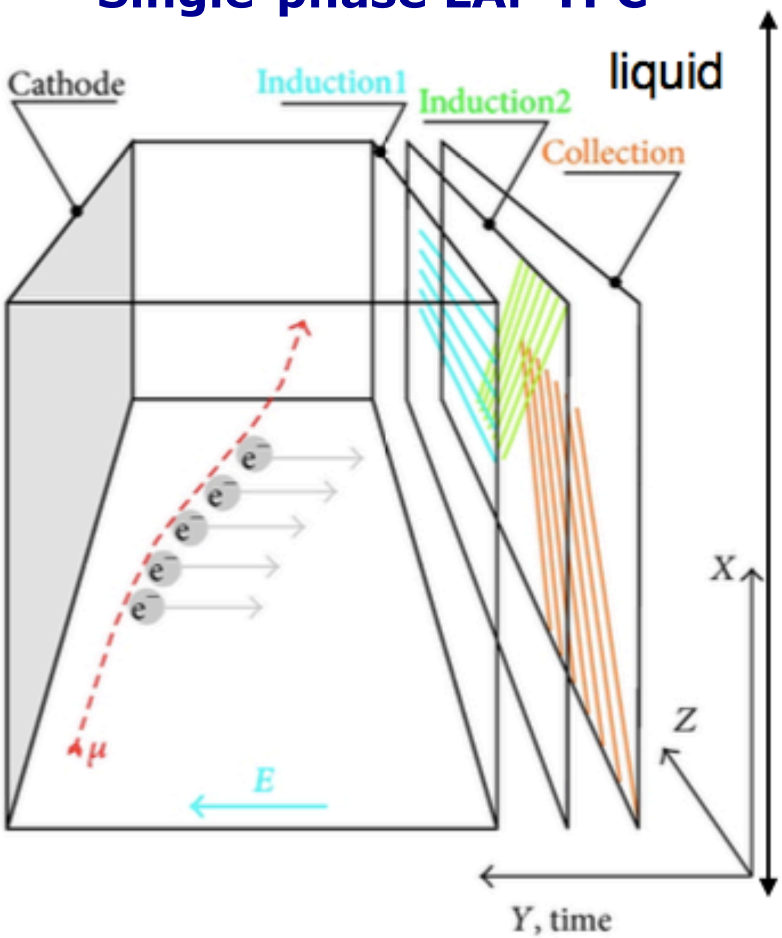




arXiv:1512.06148

LAr-TPC Neutrino Detectors

Single-phase LAr-TPC



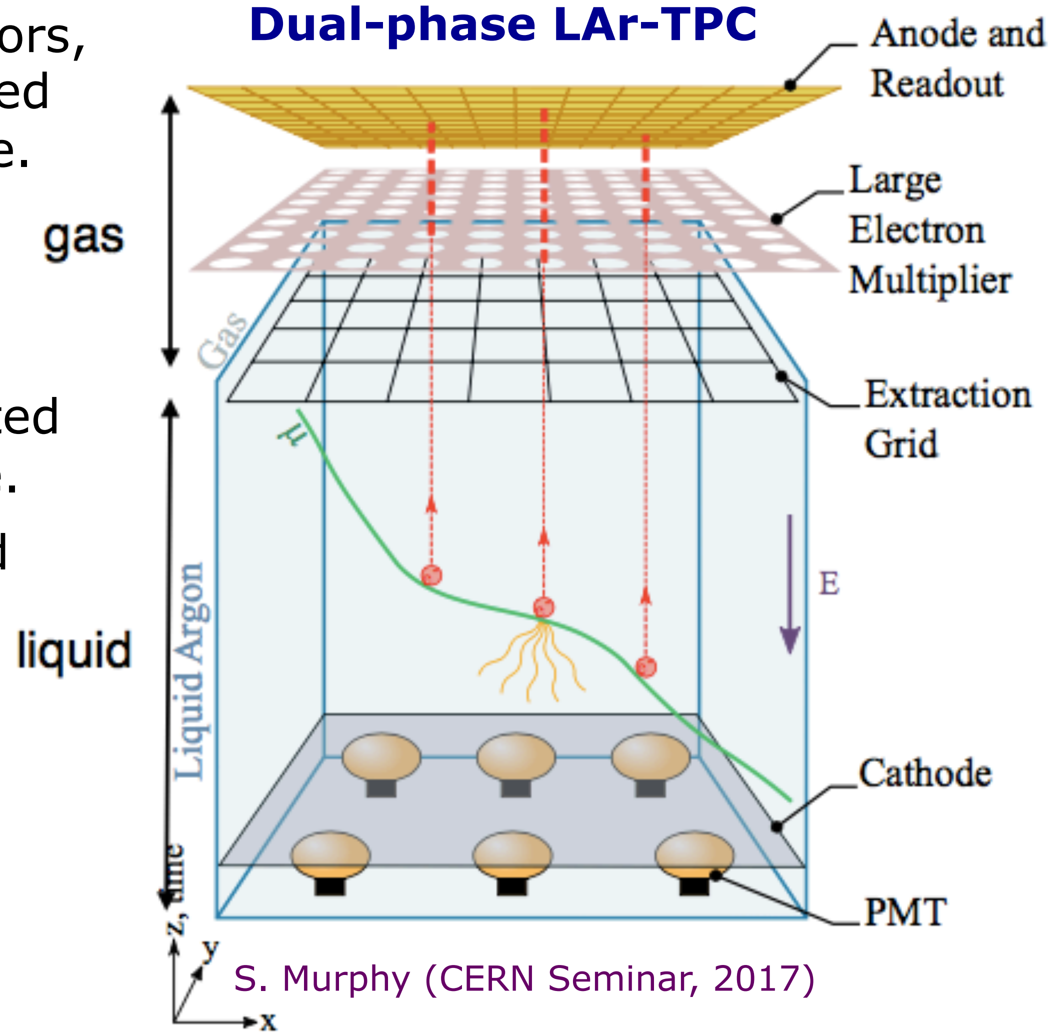
S. Murphy (CERN Seminar, 2017)

- How does a LAr-TPC detector work?
  - Charged particles produced by neutrino interactions deposit ionisation trails in the Liquid Argon.
  - The ionisation electrons drift in an applied electric field.
- In a **single-phase** LAr-TPC detector, the electrons are detected by a series of wire planes.
  - Two types of wire plane: induction and collection.
- Single-phase LAr-TPC detectors:
  - Past: ICARUS, ArgoNeuT.
  - Current: MicroBooNE, LArIAT.
  - Coming soon: SBND, ICARUS (@SBN), ProtoDUNE.

LAr-TPC Neutrino Detectors

- In **dual-phase** LAr-TPC detectors, the ionisation charge is extracted from the liquid into a gas phase.
  - ➢ Once in the gas phase, the signal is amplified using Large Electron Multipliers.
  - ➢ The amplified signal is collected using a 2D segmented anode.
  - ➢ Amplification yields clean and high-amplitude signals.
- Dual-phase LAr-TPC detectors:
  - ➢ 5t demonstrator (3×1×1 m^3) currently operating at CERN.
  - ➢ Coming soon: ProtoDUNE.

Dual-phase LAr-TPC

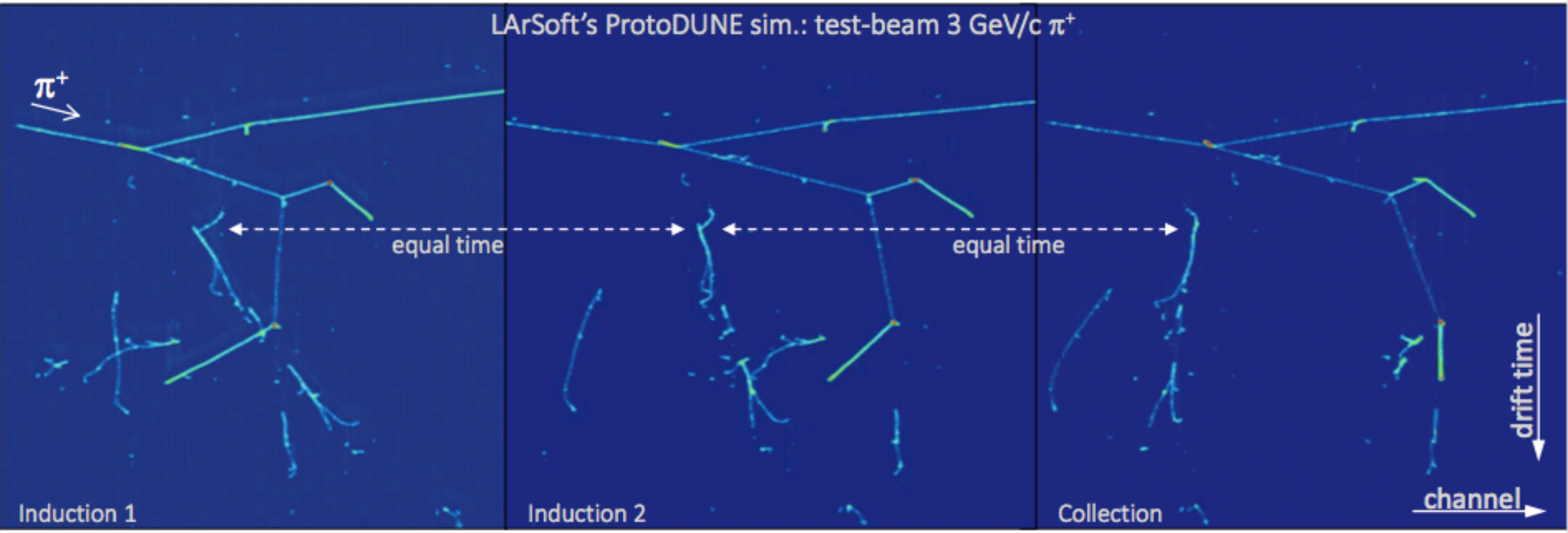


S. Murphy (CERN Seminar, 2017)

LAr-TPC Images

- Both types of LAr-TPC detector output multiple 2D images which each display "channel *vs* time".

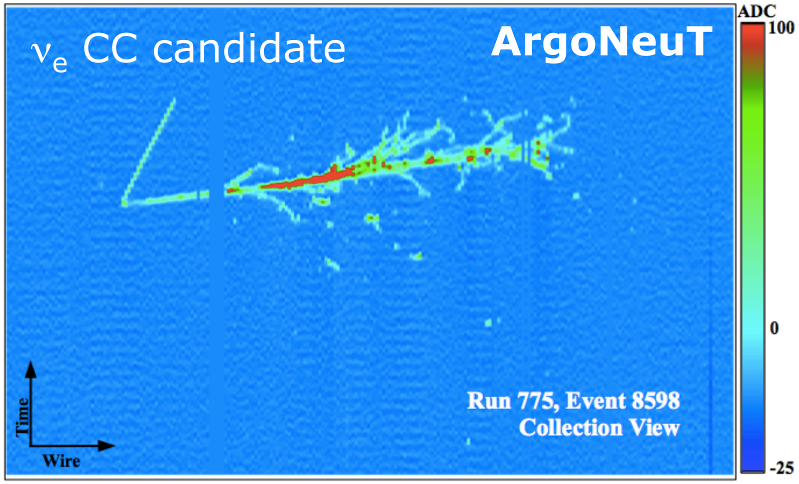
e.g. Simulated π^+ event in single-phase ProtoDUNE:

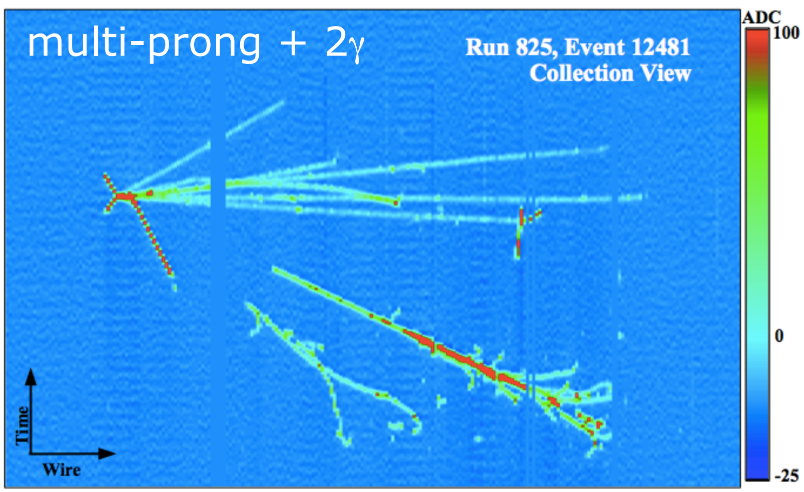


R. Sulej (CERN Seminar, 2017)

- Need to recombine these 2D images to reconstruct 3D events.

Why Liquid Argon?





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

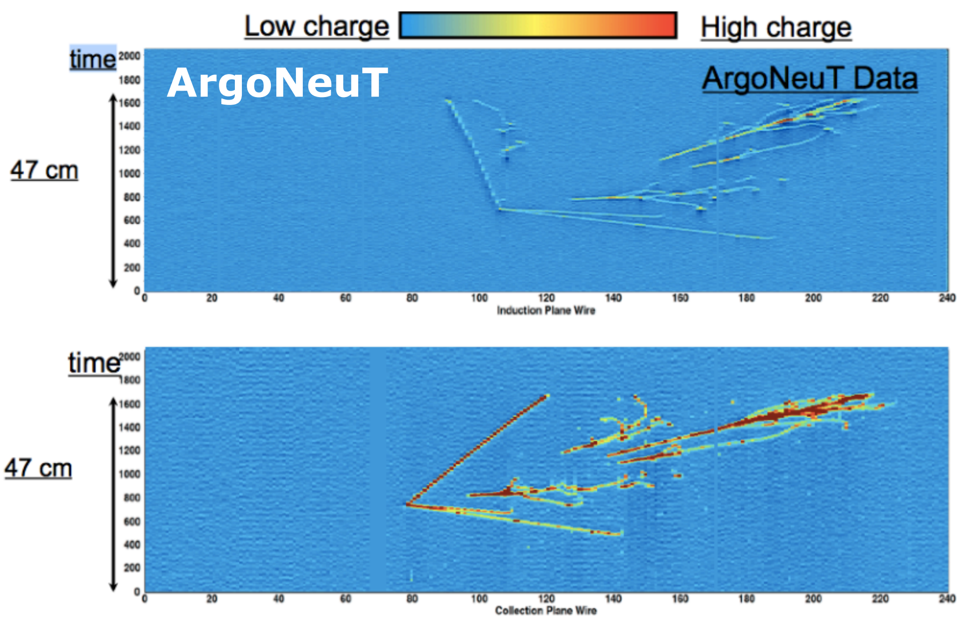
- LAr-TPC detectors are fully active and fine grain, offering superb spatial and calorimetric resolution.
  - Reconstruction of multi-prong final states.
  - Particle identification:
    - μ/p/K in particle tracks.
    - e/γ in electromagnetic showers.
  - High efficiency & low background in most channels.
- In particular, this means they are highly effective detectors for $\nu_\mu \rightarrow \nu_e$ oscillation searches.
  - Golden oscillation channel!
- LAr-TPC detectors are scalable to multi-kiloton masses.

Neutrino Event Reconstruction

- ◆ A precise reconstruction of neutrino interactions is required to achieve the physics goals of the LAr-TPC neutrino programme.

Neutrino event reconstruction = Conversion of raw LAr-TPC images into analysis-level physics quantities.

LAr-TPC Images



C. Anderson *et al*, JINST 7 P10019 (2012)

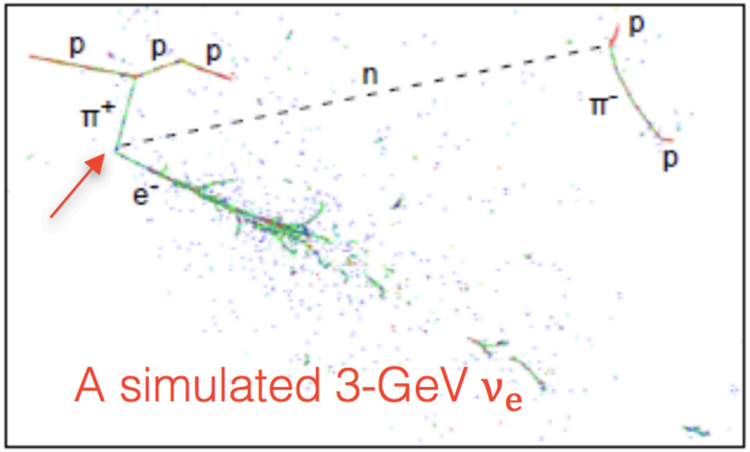
Physics Quantities

- ★ Neutrino flavour and interaction type.
- ★ Interaction vertex.
- ★ Final-state particles and four-momenta.
- ★ Neutrino energy.

(etc…)

Neutrino Event Reconstruction

- The LAr community is developing advanced and automated techniques of neutrino event reconstruction that can fully exploit the fine detail in LAr-TPC images and can handle the large volumes of data.
- Reconstruction of LAr-TPC images presents a number of challenges:
  - Many images to process!
  - Each image has many pixels, including a variety of sources of noise.
  - Loss of 3D information in 2D images.
  - Detector effects baked into images.
  - Complex final-state event topologies, with unknown interaction vertices.
  - High rates of cosmic-ray background in surface-based experiments.

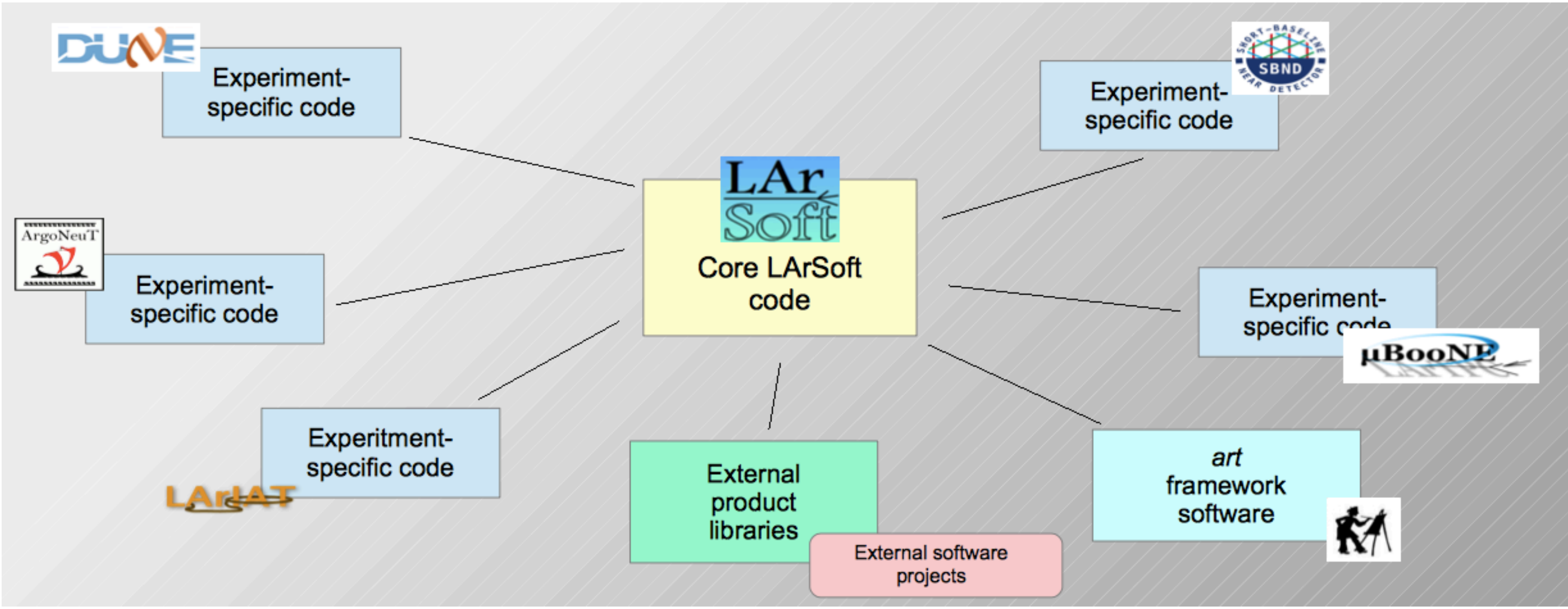


H. Wei (DPF 2017)

- This reconstruction effort remains a work in progress, but considerable progress has been made over the past few years.

Common Software

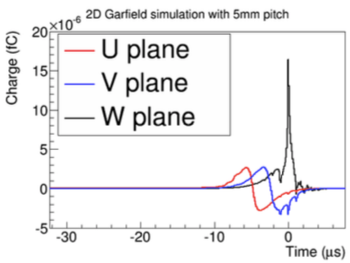
- Most LAr-TPC simulation and reconstruction software is available via a common framework **LArSoft**.
  - Means that software and expertise are shared between experiments. Also fosters collaboration within the LAr neutrino programme.



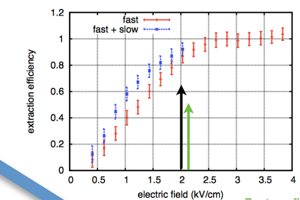
C. Jones, CHEP 2016 www.larsoft.org

LAr-TPC Signal Formation

SINGLE PHASE



DUAL PHASE



Ionisation Electrons

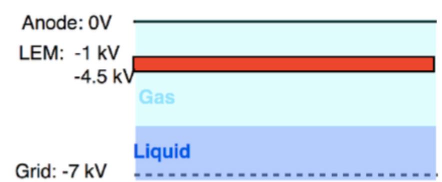
Drift, diffusion, Recombination

Field Response

Efficiency

Signal on Wire Plane

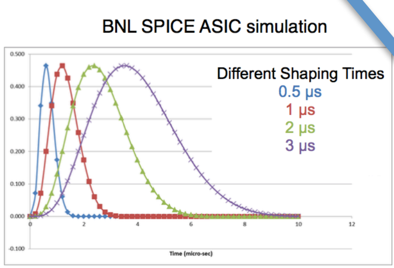
Extraction to Gas Phase



Gain

Amplified Signal From LEM

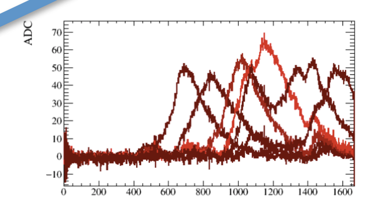
Electronics Response



Noise

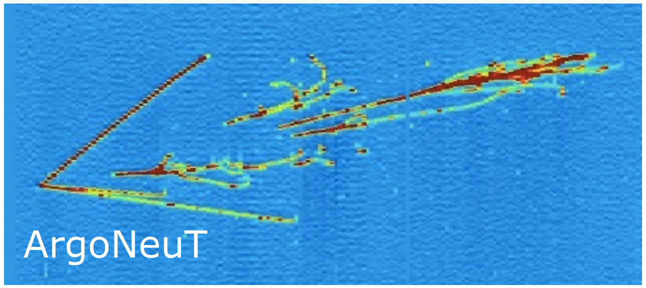
Response

Digitised Signal



Reconstruction Chain

LAr-TPC Images



Noise Filtering

Signal Processing

Hit Reconstruction

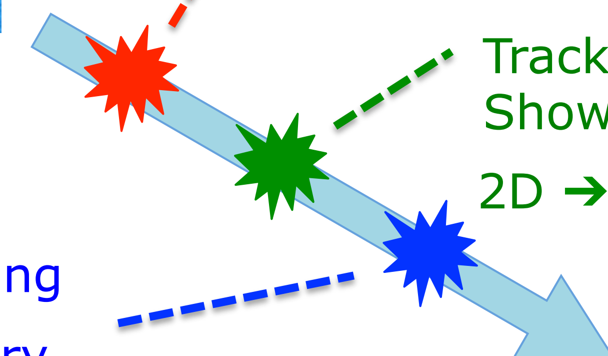
Low-Level Recon.

Clustering

Tracks & Showers

2D → 3D

Pattern Recognition



High-Level Recon.

Track Fitting

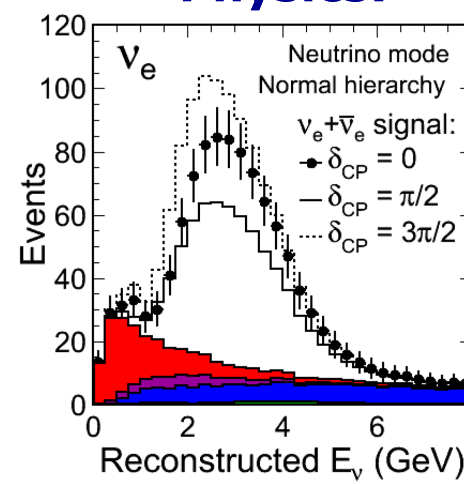
Calorimetry

Particle Identification

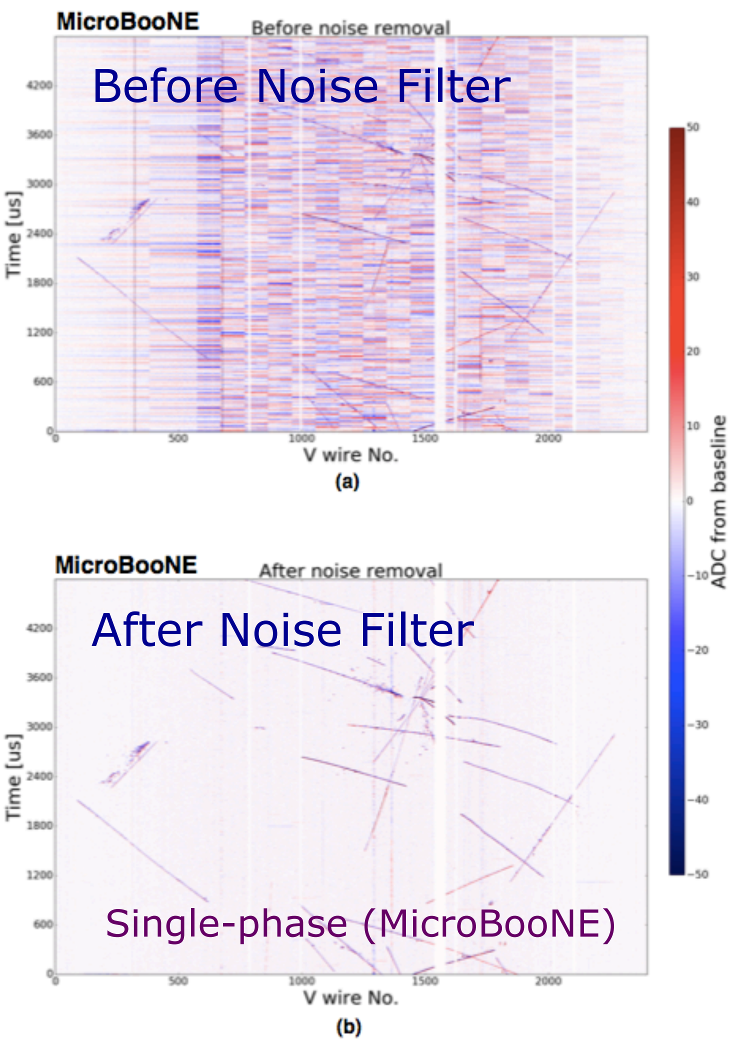
Energy Estimation

Neutrino Flavour Identification

Physics!

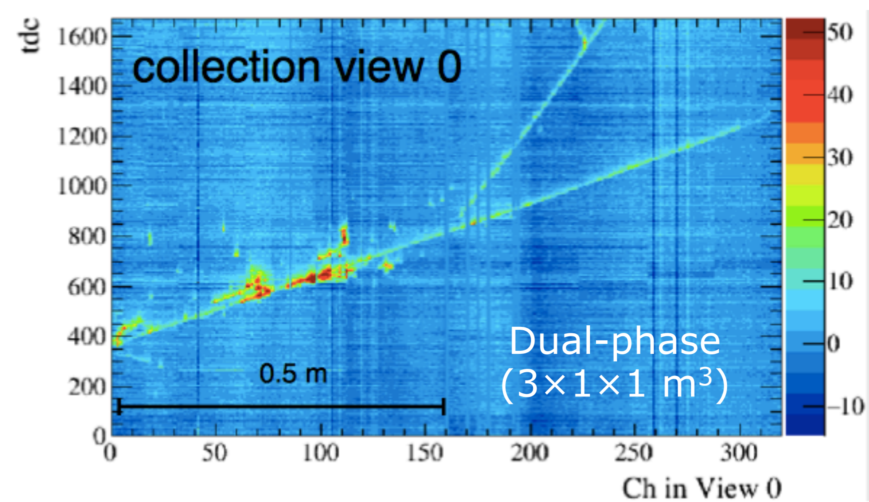


Noise Filtering



R. Acciarri *et al*, JINST 12, P08003 (2017)

- ◆ First apply offline filters to raw waveforms to reduce excess noise.
  - ➢ Techniques include masking characteristic frequencies and subtracting coherent noise.
- ◆ Significant improvement in signal-to-noise!
  - ➢ Single-phase: e.g. MicroBooNE obtains Peak-Signal-to-Noise ratios of ~10-50.
  - ➢ Dual-phase: Very clear images!

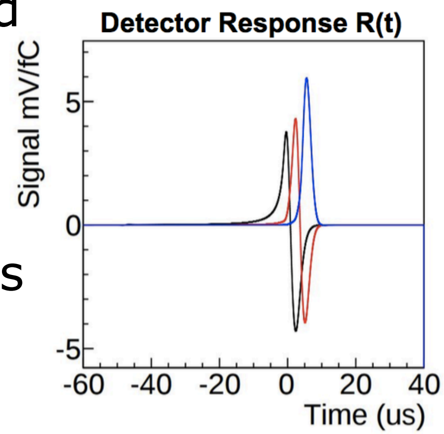


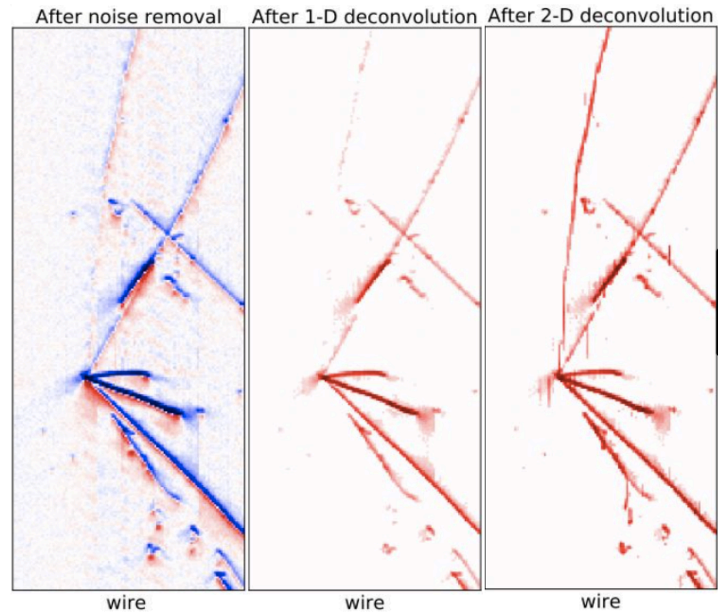
S. Murphy (CERN Seminar, 2017)

Deconvolution & Hit-Finding

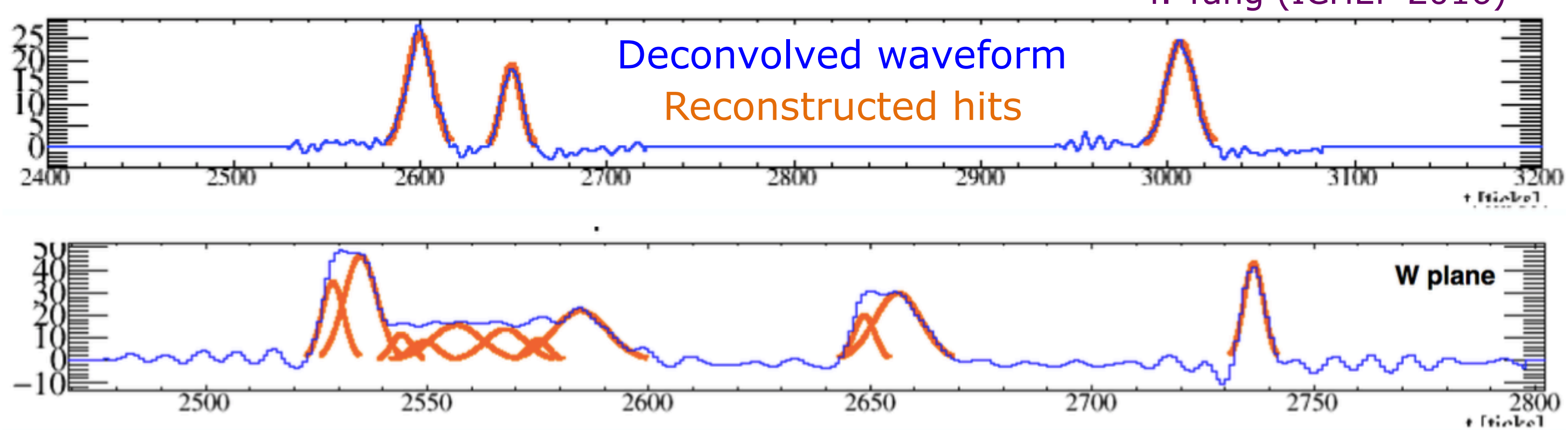
- In single-phase detectors, the ionisation signal is reconstructed by deconvolving the LAr-TPC image.
  - ➢ This unfolds the field and electronics responses of the detector.
- After signal processing is complete, identify regions of interest within image and reconstruct "hits".

B. Kirby (DPF 2017)



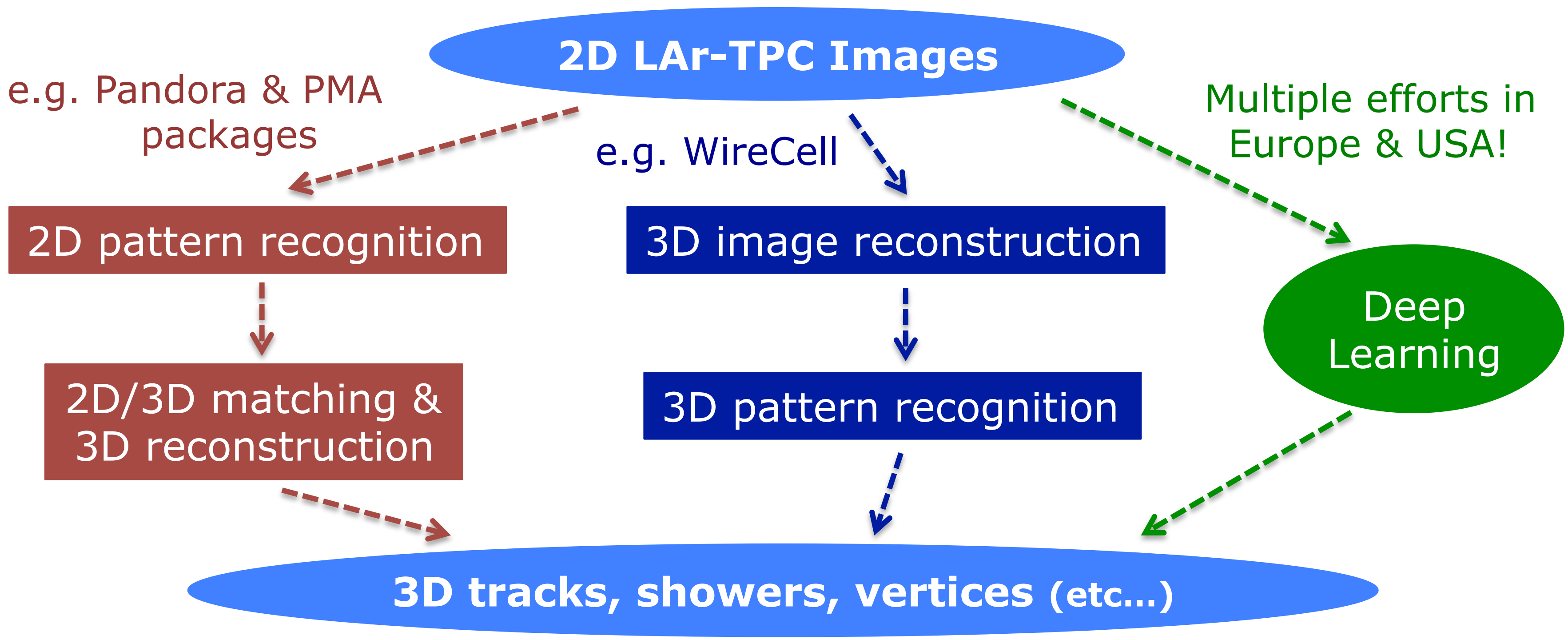


T. Yang (ICHEP 2016)



Pattern Recognition

- In recent years, much of the effort has focused on the development of fully-automated techniques of pattern recognition.
  - ➢ Two challenges: (1) Identifying features such as tracks/showers.
    (2) Combining 2D images to form 3D events.
- A number of different approaches are now emerging:



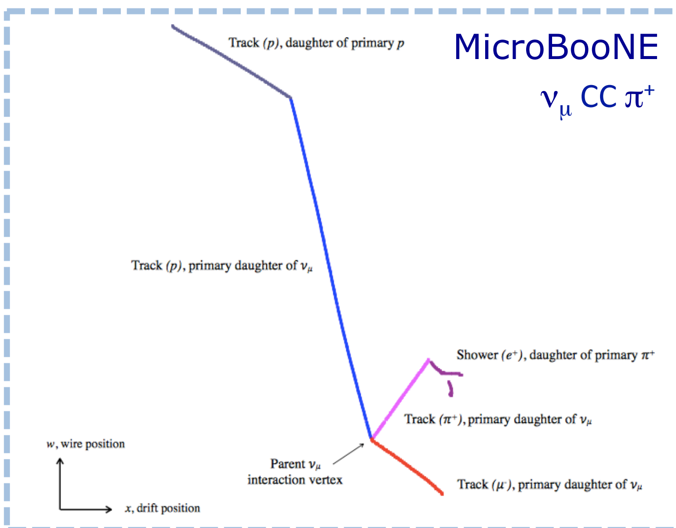
Pandora

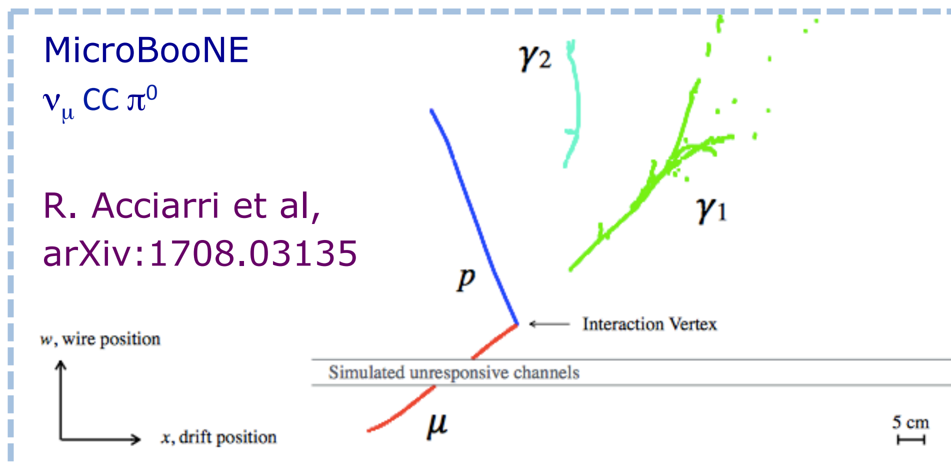
- **Pandora** is a well-established toolkit for pattern recognition in fine-grain detectors.
- Implements a **multi-algorithm approach**:
  - Uses many (~100) focused algorithms to incrementally build up the event.
- Takes 2D hits as its input, and outputs 3D tracks/showers/vertices and their parent-daughter relationships.

2D Pattern Recognition
(Multiple algorithms)

Iterative 2D/3D Matching
- Match up 2D clusters to form 3D clusters.
- Use 3D information to refine 2D clustering.

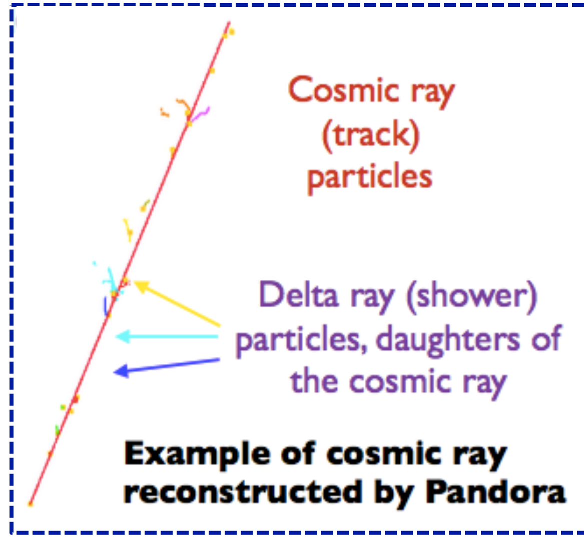
3D Event Building
(Multiple algorithms)



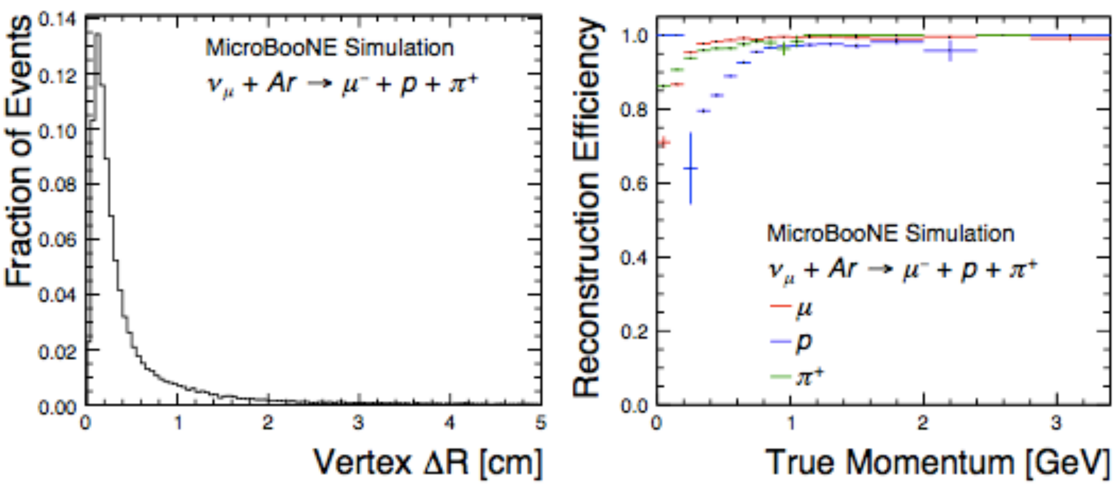


Pandora

- Highly modular approach enables the re-use of Pandora algorithms for different reconstruction applications.
- Two reconstruction paths developed so far:
  - PandoraCosmic – optimised for cosmic muons.
  - PandoraNu – optimised for neutrino events.
- Pandora reconstruction has formed the basis of the preliminary results from MicroBooNE.



Simulated BNB CC π^+ interactions:



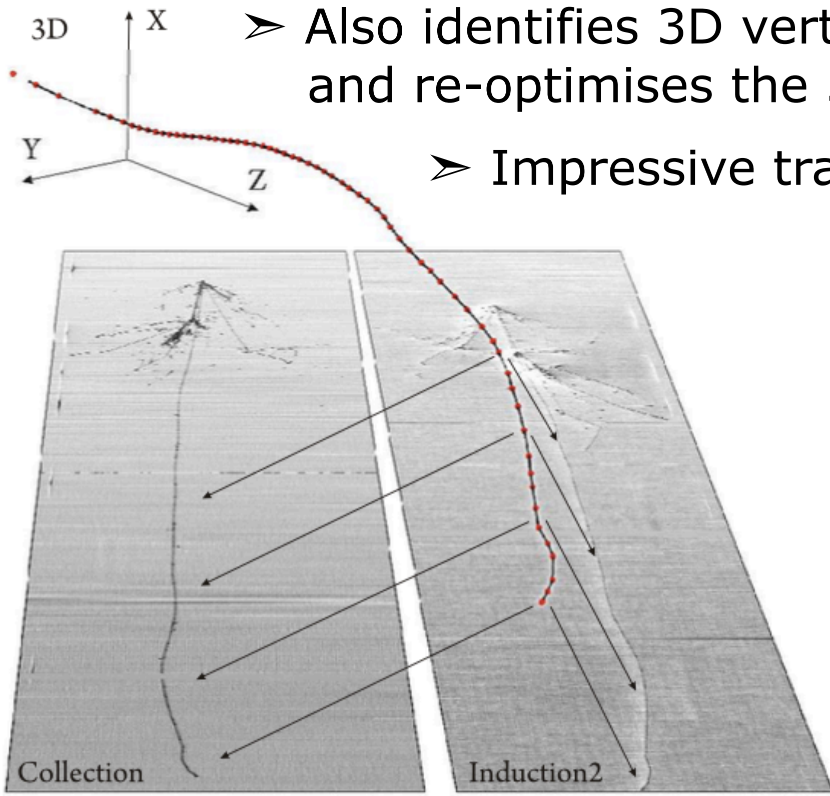
L. Escudero (Rencontres du Vietnam 2017)

R. Acciarri et al, arXiv:1708.03135

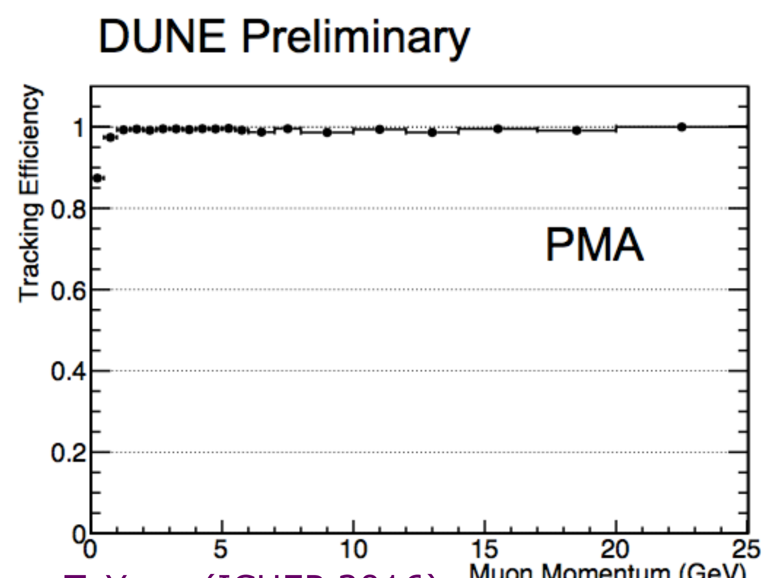
#Matched Particles	0	1	2	3+
μ	3.5%	95.1%	1.4%	0.0%
p	9.0%	86.8%	4.0%	0.3%
π^+	6.9%	80.9%	11.4%	0.8%

Projection Matching

- **Projection Matching Algorithm** (PMA) is a precise multi-trajectory track-fitting algorithm originally developed for ICARUS.
  - ➢ Fits a series of 3D polygonal trajectories to an event by optimising their 2D projections relative to the underlying 2D hits.
  - ➢ Also identifies 3D vertices in events (interactions and decays) and re-optimises the 3D tracks accordingly.
  - ➢ Impressive tracking efficiency in DUNE ν_μ CC events!



M. Antonello et al, AHEP 2013, 260820 (2013)



T. Yang (ICHEP 2016)

3D Tomography

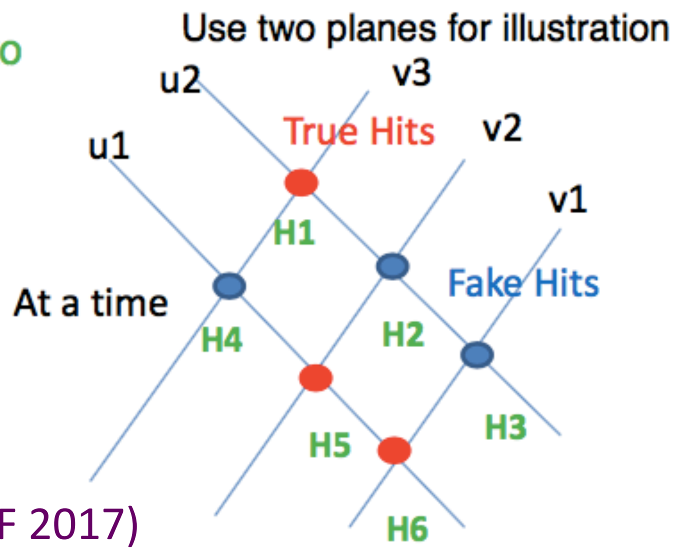
- The **WireCell** toolkit exploits the analogy between 3D reconstruction in LAr-TPC detectors and Computerised Axial Tomography (CAT).
  - ➢ In CAT scanners, a 3D image is reconstructed from a series of 2D voxelised projections.
- Applying similar mathematical methods, set up a system of equations connecting 2D LAr-TPC images to true 3D patterns of ionisation:

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

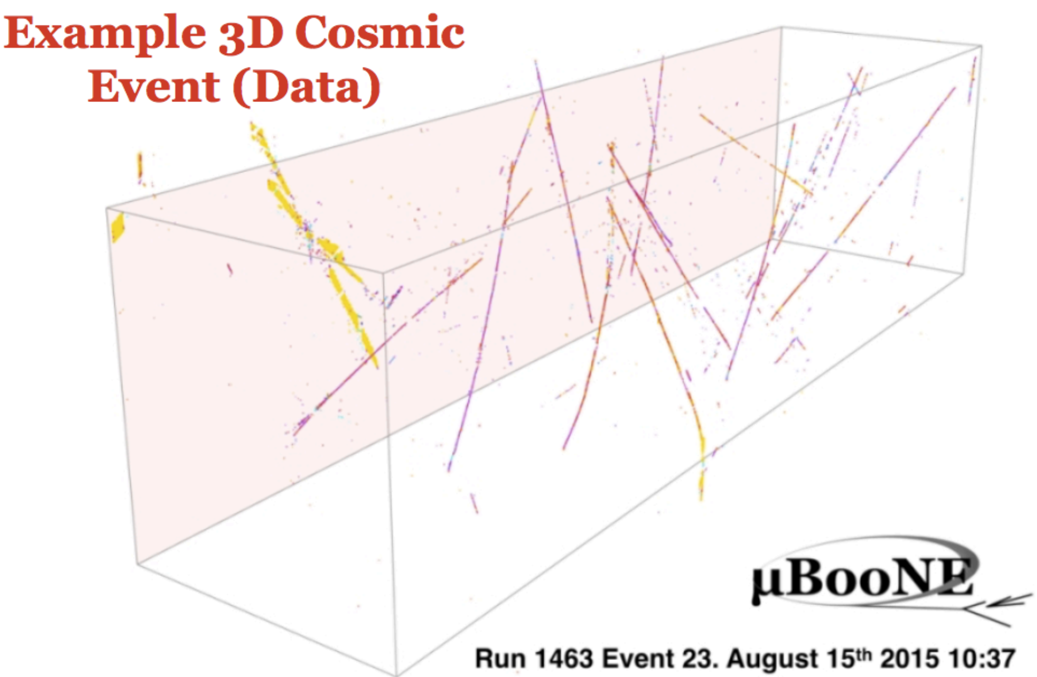


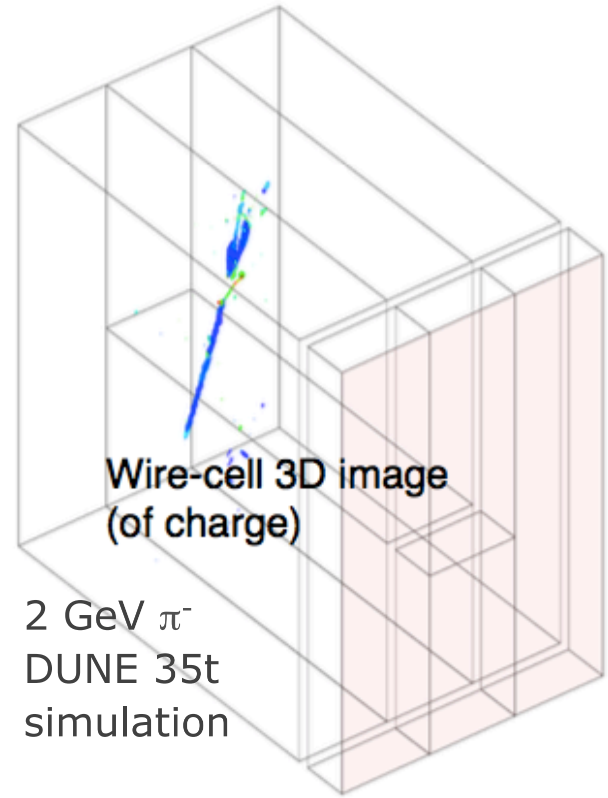
H. Wei (DPF 2017)

(Use L1-regularization to remove ambiguities and reduce complexity).

3D Tomography

- On solving tomographic equations, obtain these superb 3D images:



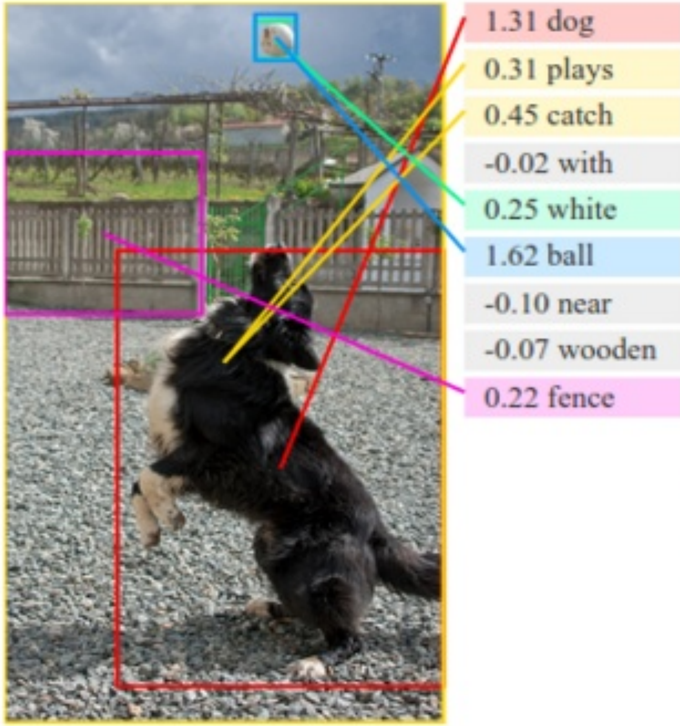


http://www.phy.bnl.gov/wire-cell/bee/

- Development of 3D pattern recognition algorithms is now underway.

Deep Learning

- The past few years has seen a revolution in the science of big data, particularly in the areas of computer vision and image recognition.

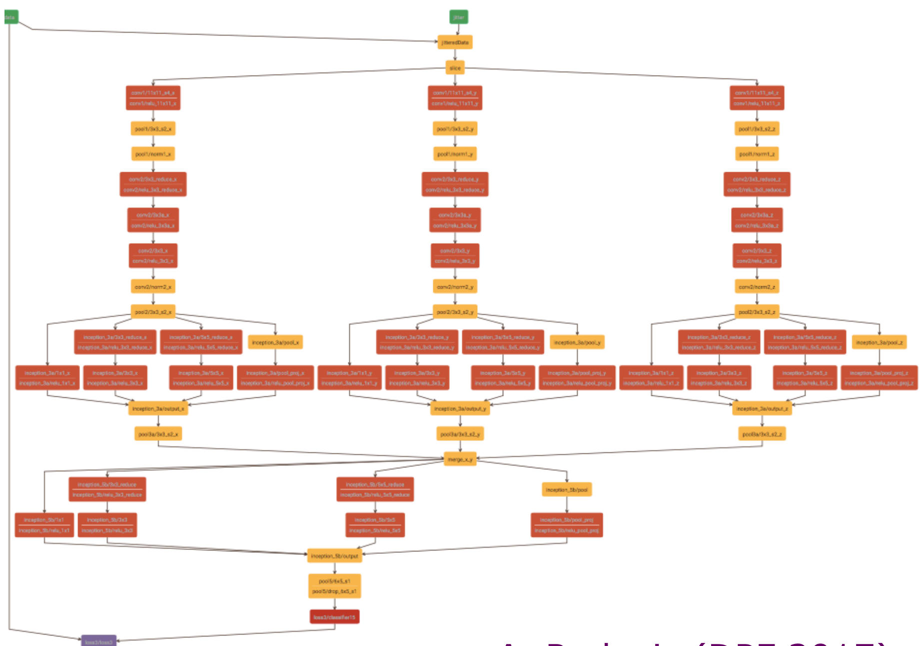


A. Radovic (DPF 2017)

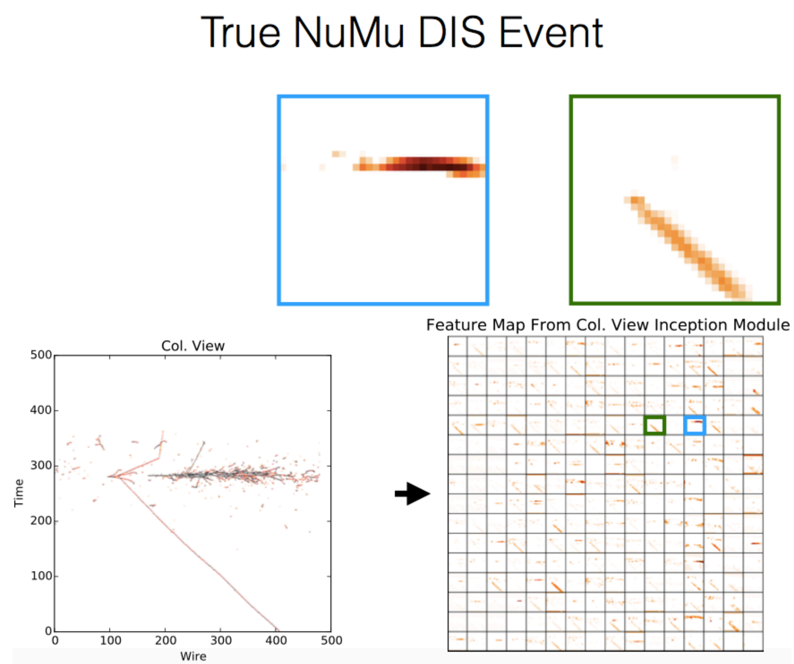
- These powerful image-processing techniques have clear applications in pattern recognition for fine-grain neutrino detectors.
  - ➢ A possible game-changer for neutrino physics experiments?

Deep Learning

- A number of neutrino experiments have demonstrated the use of **convolutional neural networks** (CNNs) for pattern recognition.
  - CNNs are artificial neural networks with many hidden layers.
  - They identify characteristic features within images by applying many successive convolutional filters and pooling the outputs.
  - The technique naturally lends itself to LAr-TPC image analysis.



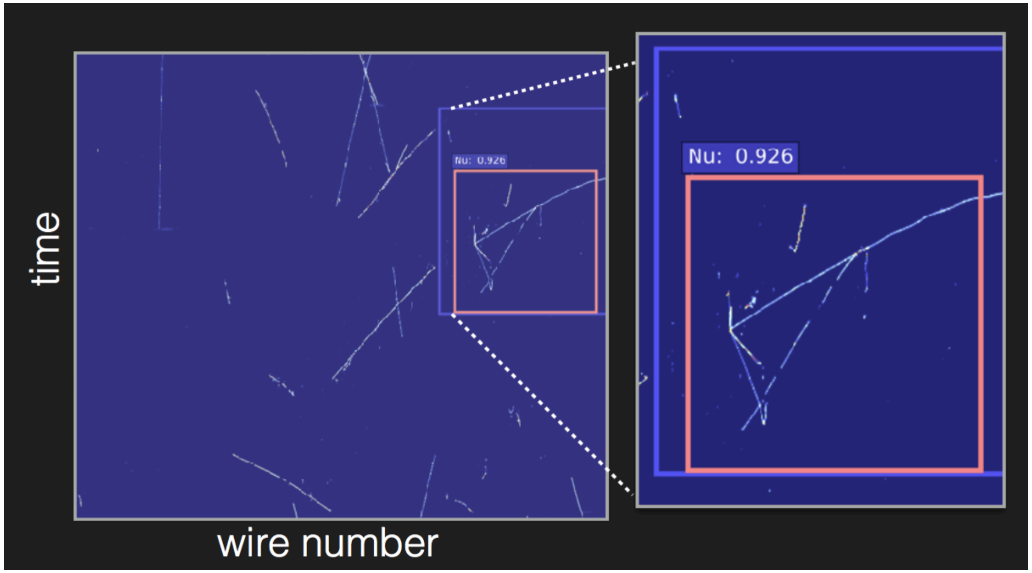
A. Radovic (DPF 2017)



Deep Learning

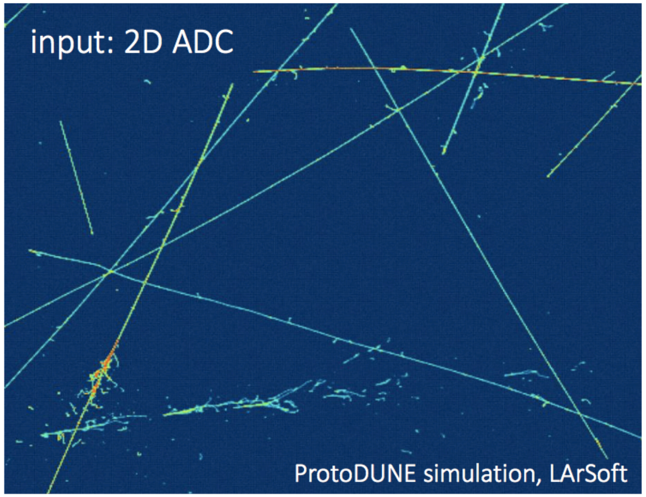
- A variety of CNN techniques have been successfully demonstrated on LAr-TPC data by MicroBooNE and DUNE.
  - ➢ Event Classification.
  - ➢ Object Detection.
  - ➢ Pixel Labeling (Semantic Segmentation).

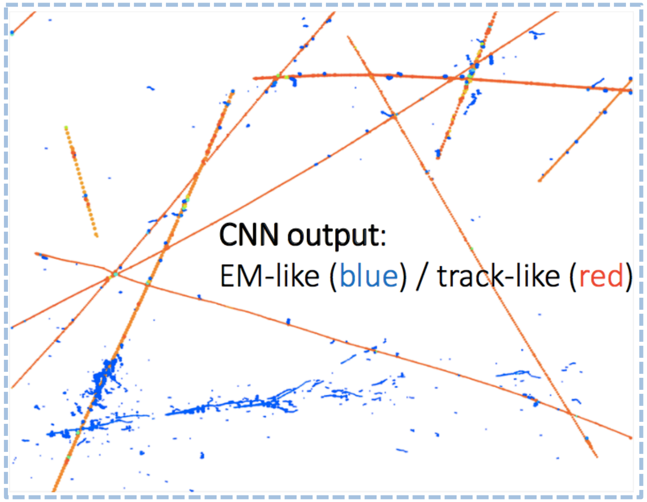
Object Detection:



T. Wongjirad (DPF 2017)

Semantic Segmentation:





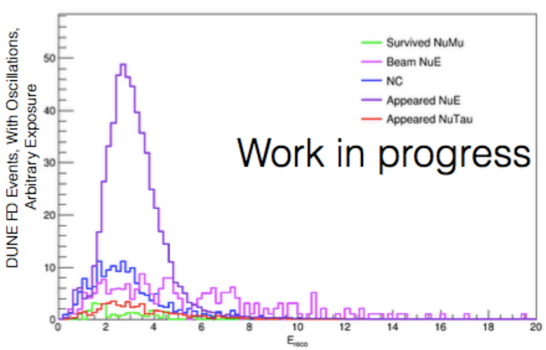
R. Sulej (CERN Seminar, 2017)

Deep Learning

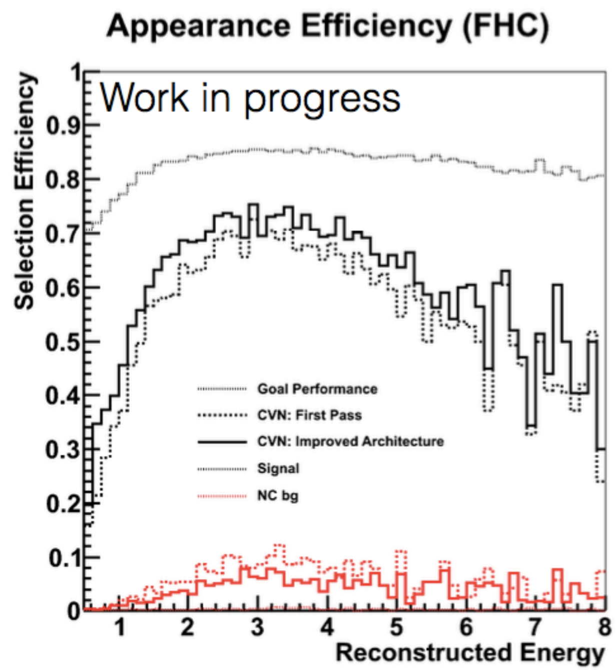
- The early results from MicroBooNE and DUNE are extremely promising!
- Have only touched the surface so far.
  - Much room for future advancement. Will also be tested on real data.

DUNE Far Detector

Neutrino Beam

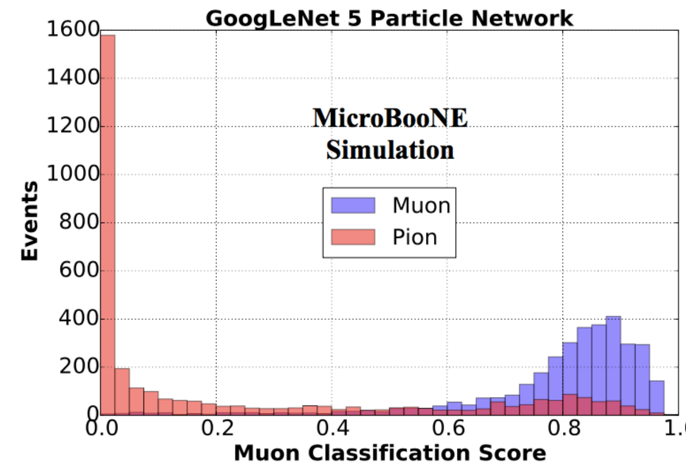


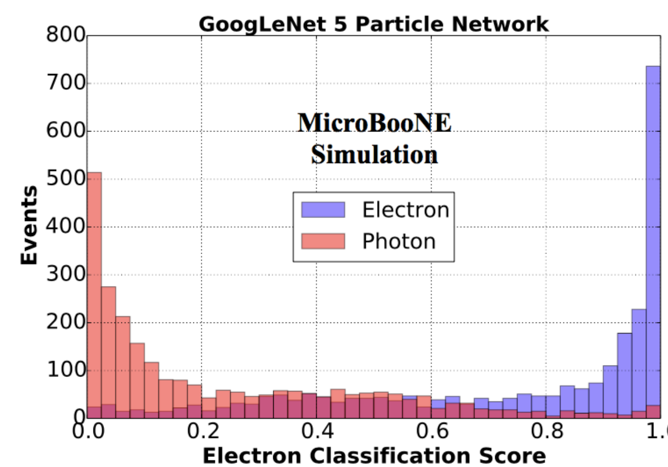
	Appeared NuE	NuMu	Beam NuE	NC	NuTau
Efficiency	67.5				
Rejection		99.8	52.1	98.6	85.8



A. Radovic (DPF 2017)

MicroBooNE





R. Acciarri *et al*, JINST 12, P03011 (2017)

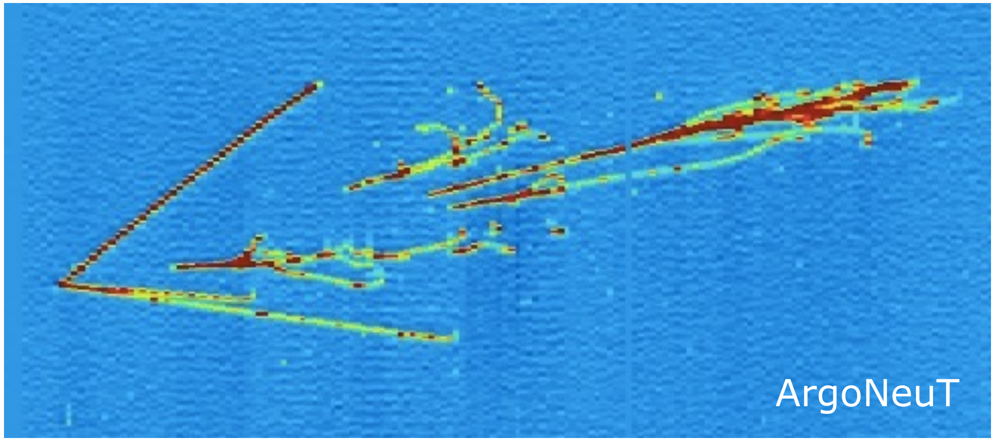
High-Level Reconstruction

- The measurement of event-level physics quantities involves a variety of reconstruction tasks, for example:

Calorimetry:
Calculate dE/dx from ionisation charge.

Particle Identification:
Determine PID from dE/dx information.
Use end of track for μ/K/p separation.
Use start of track for e/γ separation.

Neutrino Events:
Background Rejection.
Flavour ID.
Energy Estimation.



π^0 mass Reconstruction

Michel Electrons

Energy Estimation:
Muon tracks.
Electromagnetic showers.
Hadronic activity.

Track Fitting:
Determine track direction and trajectory.
For exiting tracks, determine momentum.
From multiple Coulomb Scattering.

ICARUS

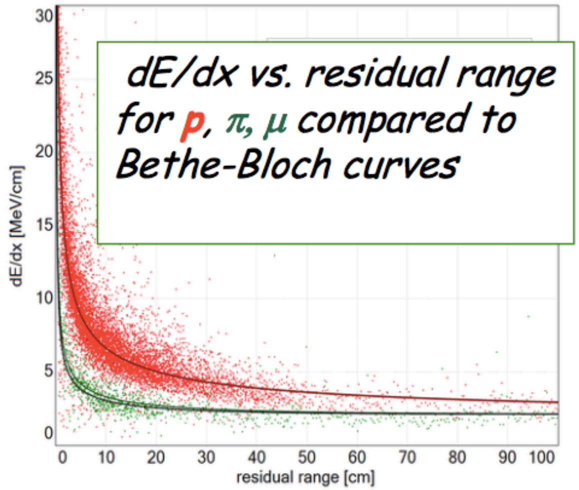
◆ A complete chain of high-level reconstruction was developed by ICARUS:

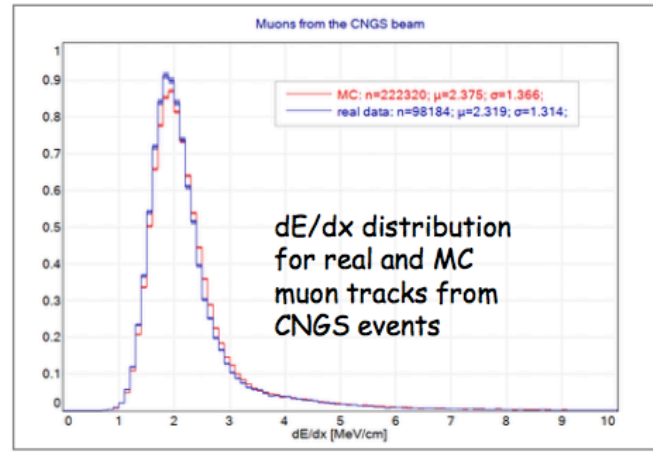
Tracks:

Calorimetry using dE/dx information

Muon momentum from multiple Coulomb scattering

Event-building



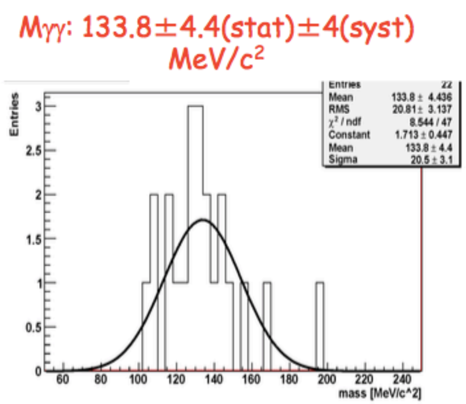


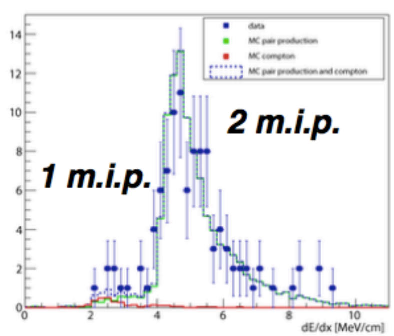
Showers:

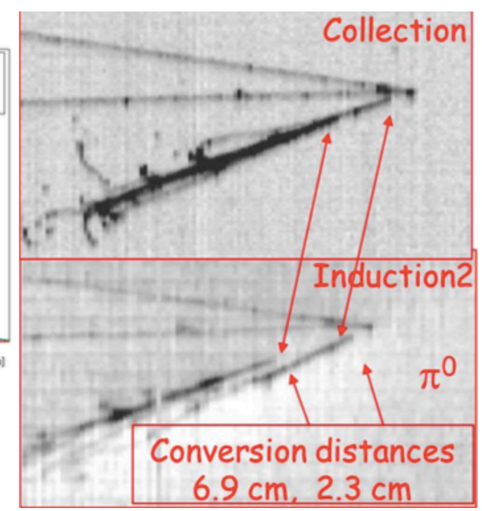
π^0 mass

e/γ separation

Energy estimation







LAr TPC: very good e/γ separation: excellent rejection of NC background to ν_e events

J. Kisiel (New Trends in HEP, 2016)

ArgoNeuT

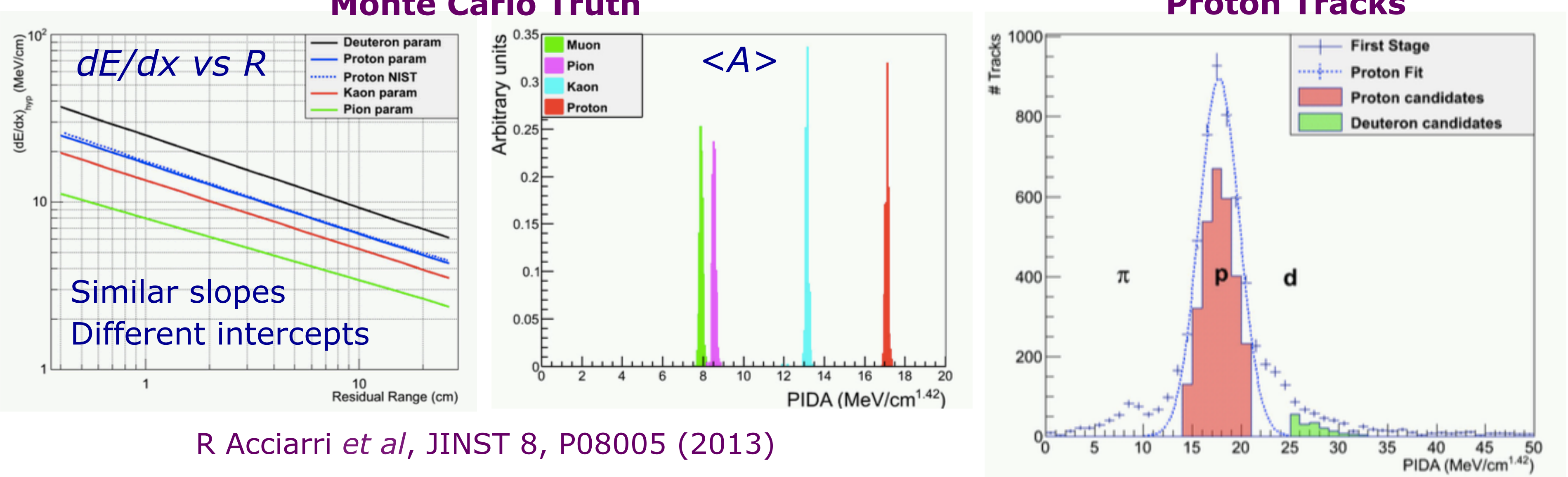
◆ The neutrino results from ArgoNeuT (and test-beam results from LArIAT) are also based on a complete high-level reconstruction.

For example, powerful demonstration of PID capabilities using calorimetry:

➢ Ionisation loss in Bragg peak can be parameterised as: $dE/dx \approx A\,R^{-0.42}$
(where *R* = residual range, and *A* is characteristic of the particle type)

➢ Can determine *A* by averaging *dE/dx* values: $A = \langle\,(dE/dx)_i \times R_i^{+0.42}\,\rangle$

Monte Carlo Truth **Proton Tracks**

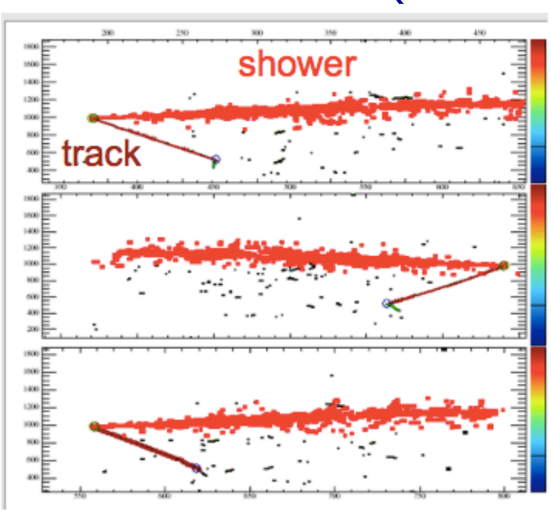


R Acciarri *et al*, JINST 8, P08005 (2013)

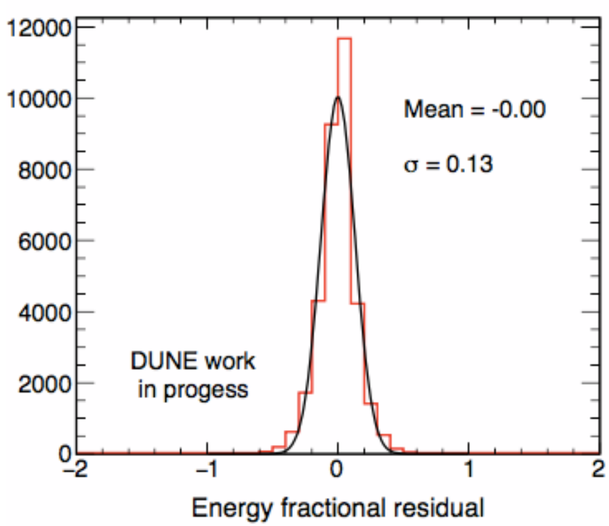
High-Level Reconstruction

- Among the current efforts on high-level reconstruction:
  - ➢ Adapt and develop tools for new projects (e.g. ProtoDUNE's).
  - ➢ Connect high-level tools with fully-automated pattern recognition.
  - ➢ Apply to real data – and analyse physics! (e.g. MicroBooNE).
- Many promising results (too many to fit on one slide…):

Fully-automated ν_e CC event reconstruction (DUNE simulation):

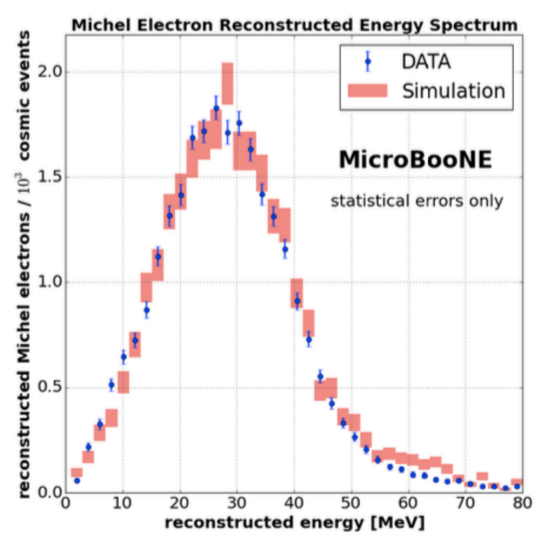


M. Wallbank (EPS-HEP 2017)



N. Grant (DPF 2017)

Fully-automated reconstruction of Michel electrons (MicroBooNE):



R Acciarri *et al*, JINST 12, P09014 (2017)

Summary

- The use of Liquid Argon technology is one of the cornerstones of the current and future neutrino programmes.
  - A number of new LAr-TPC detectors will come online in the next couple of years.
- High-performance reconstruction techniques are required to meet the physics goals of the LAr neutrino programme.
  - LAr-TPC reconstruction presents many challenges!
- The LAr community is making great strides in the development of advanced and fully-automated reconstruction algorithms.
  - Many innovative ideas are being explored and demonstrated, particularly in the area of pattern recognition.
  - The common framework of LArSoft is facilitating this effort.
- This is a work in progress, and further advances will follow. Watch this space!