Pandora

Generic LArTPC Reconstruction

Ryan Cross - SWIFT-HEP & ExaTEPP

2024/11/11

WARWICK
THE UNIVERSITY OF WARWICK

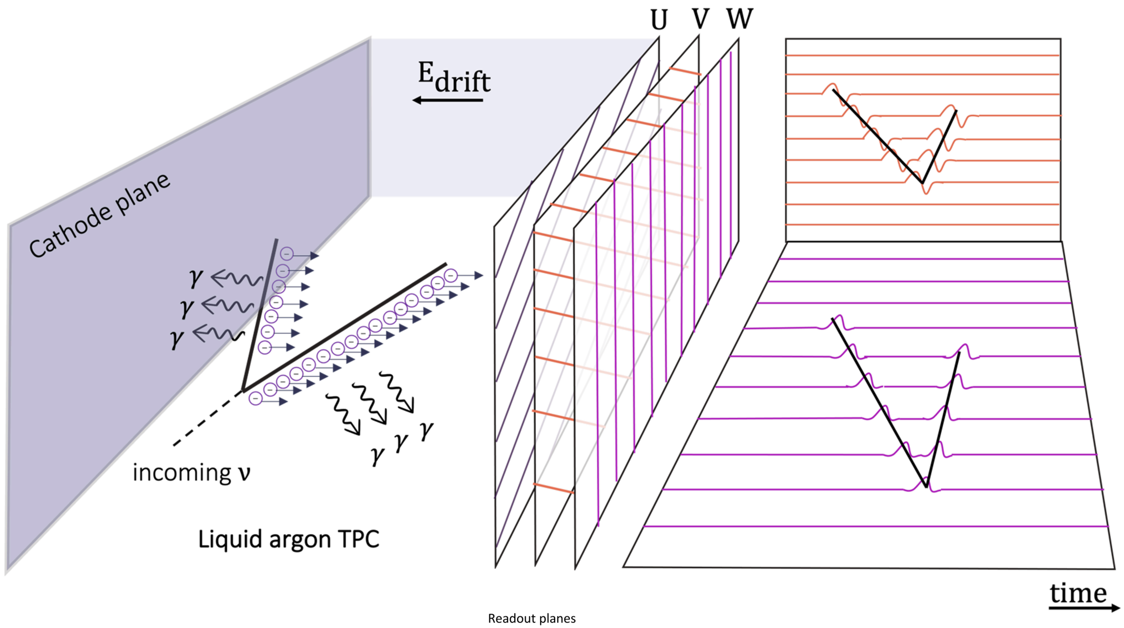
Overview

This talk will cover:

1. **An overview of LArTPCs & LArTPC Reconstruction.**
2. **Introduction to Pandora**
3. **Recent Innovations**

Liquid Argon Time Projection Chamber (LArTPC)

In a LArTPC, charged particles produce ionisation electrons as they travel through the LAr. This charge can be drifted to readout planes to track the path of the particles and provide calorimetry.

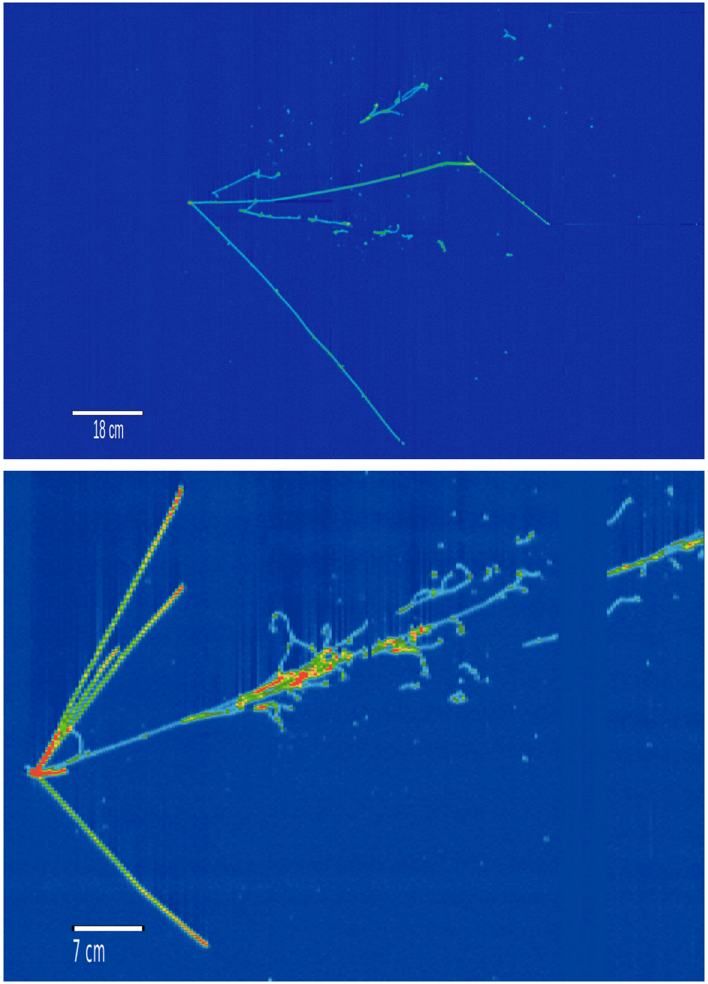


Along with photon detectors to get an accurate start time, you can produce multiple 2D readouts of readout channel vs time, producing detailed readouts.

There are many variations of LArTPCs, with 1/2/3 readout planes, differing readout technology etc.

LArTPC Event Reconstruction

Converting the raw LArTPC outputs to be suitable for analysis can be split into a few steps:



- Low Level Reco:
  - Noise Filtering
  - Signal Processing

- Pattern Recognition:
  - The most 'visual' step
  - Images -> 2D Hits
  - Sparse 2D Hits -> Clusters
  - 2D Clusters -> 3D Particle Representation
  - Produce a full 3D particle flow hierarchy

- High-level Characterisation:
  - Particle ID
  - Energy / Flavour / Interaction ID

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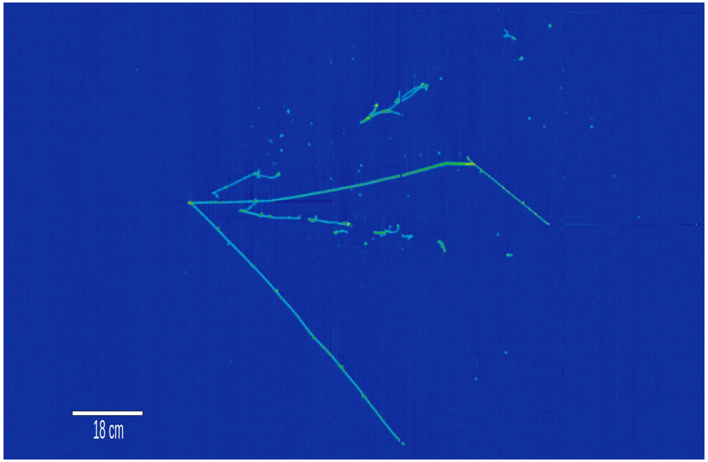

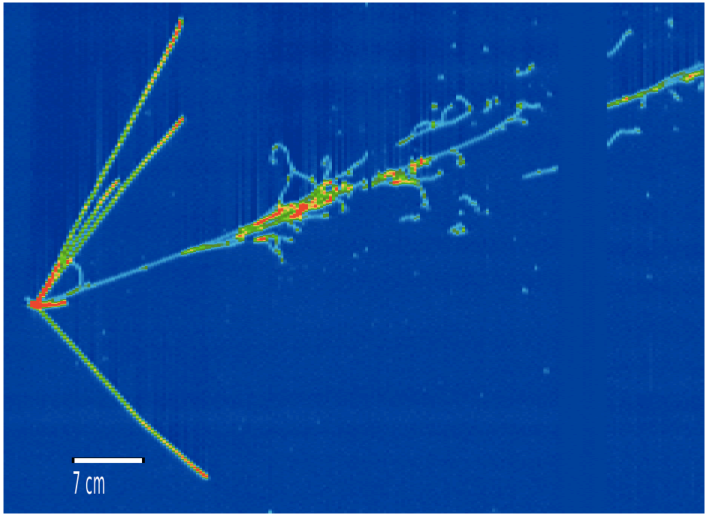

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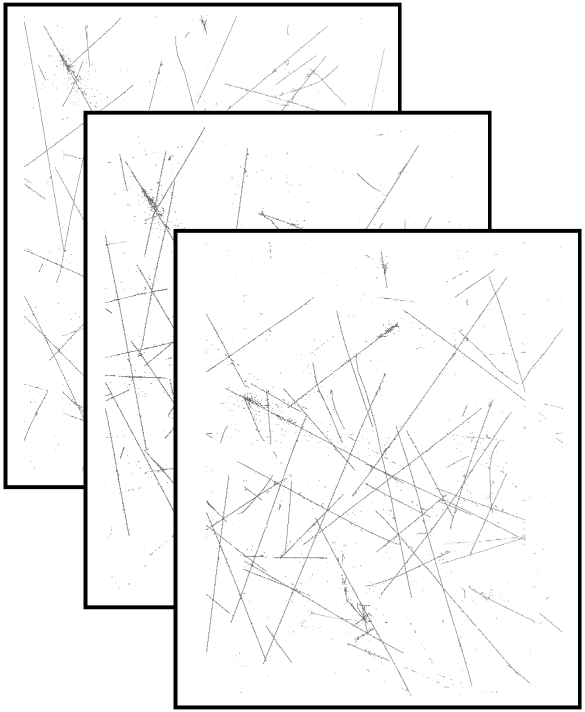
Pattern Recognition

During the Pattern Recognition step, there is a few main goals:

- Produce 3D reconstructed particles, from the input 2D images.
- Build up a 3D particle-interaction hierarchy, starting from the initial neutrino or test beam.



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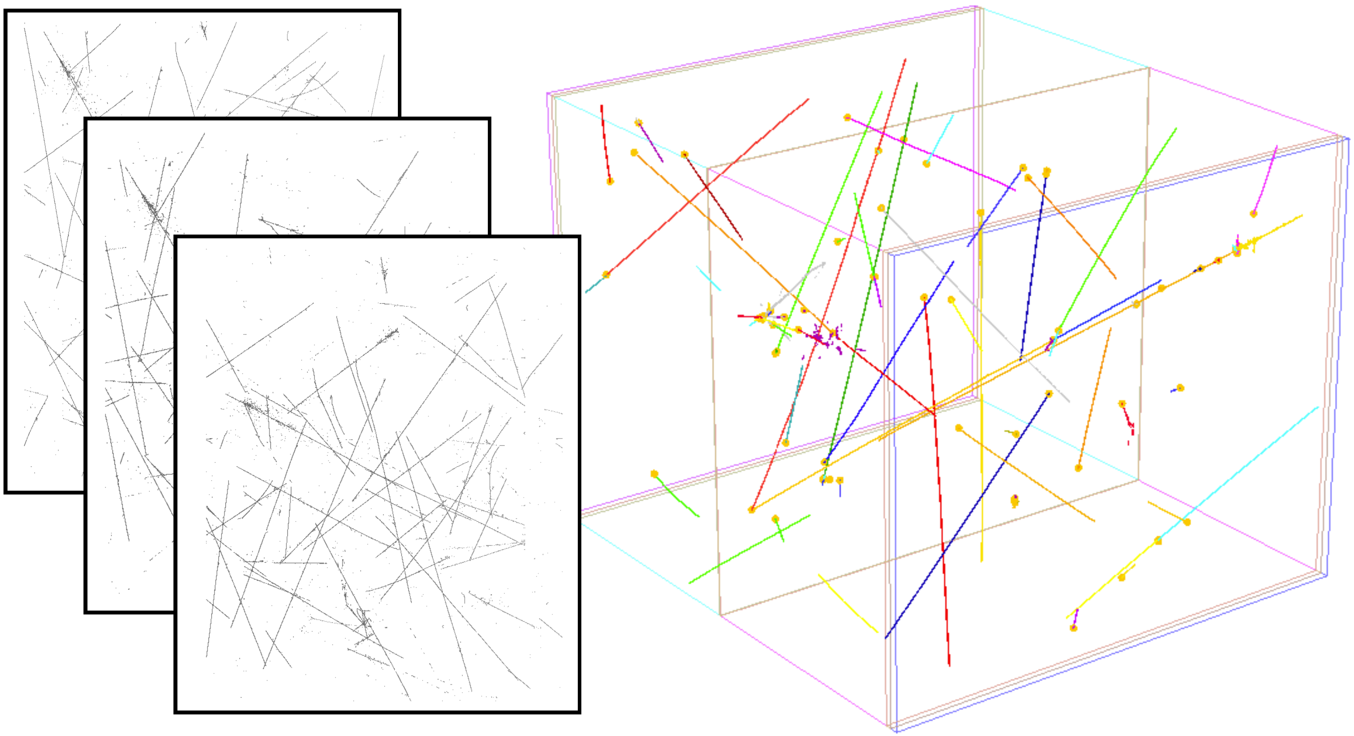

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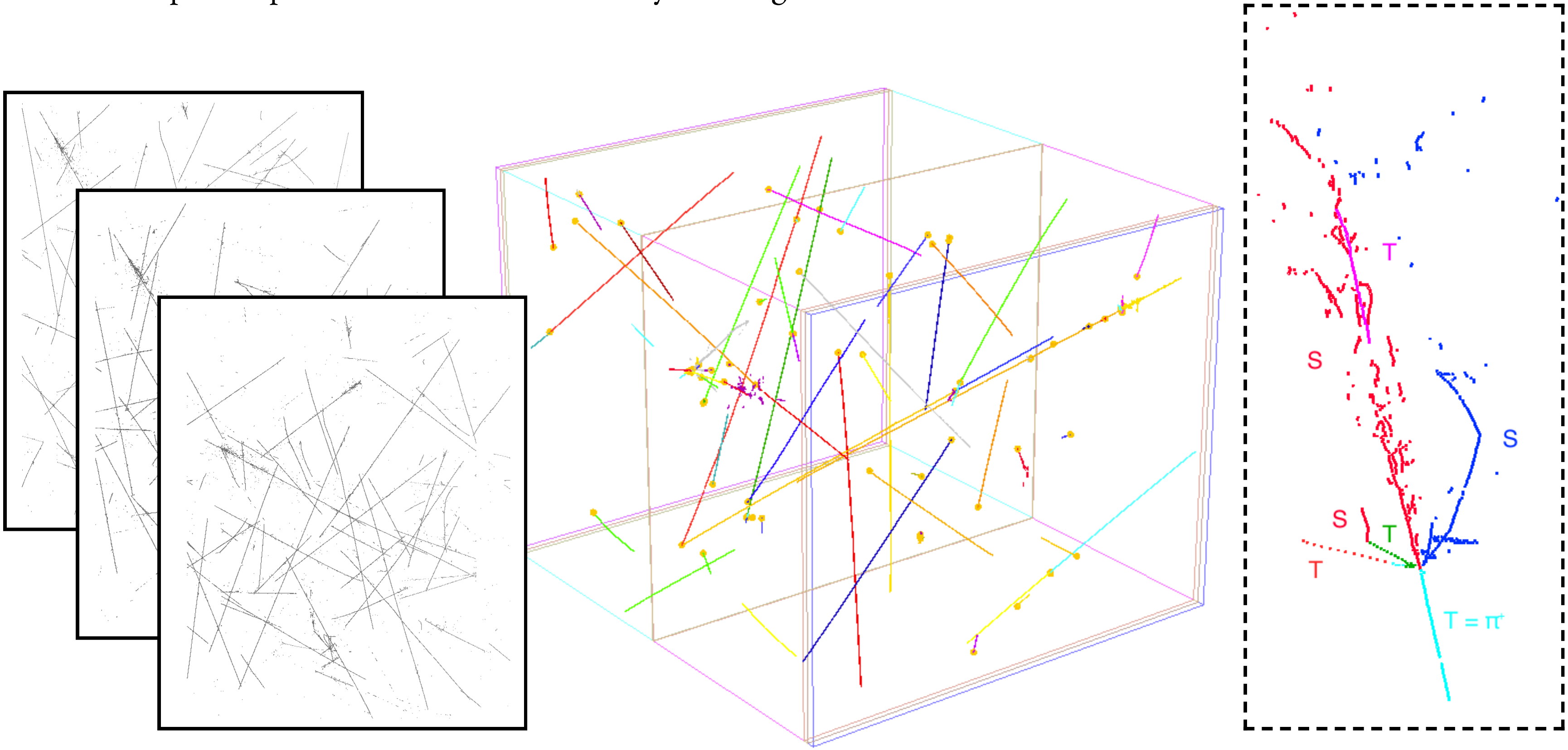
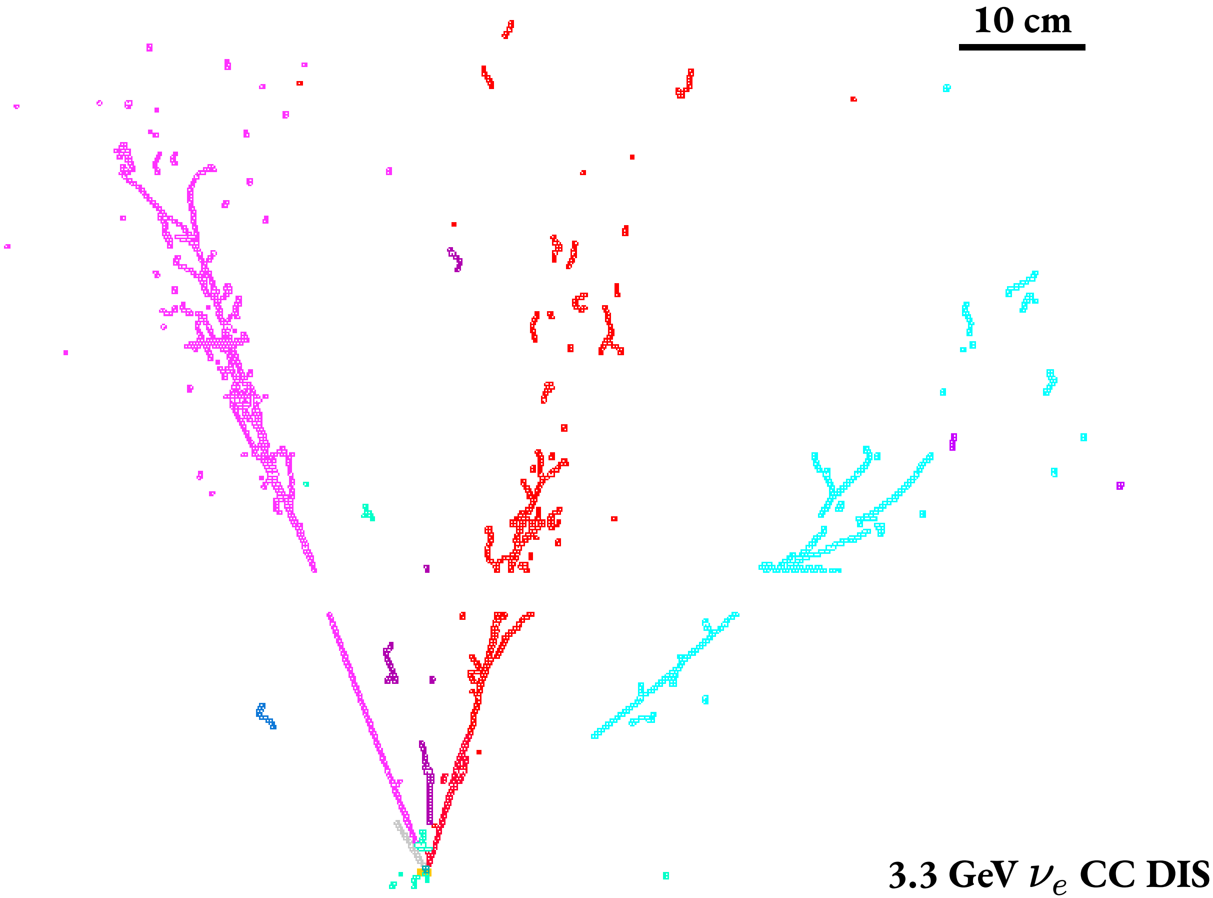


Challenges for LArTPC Pattern Recognition

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

There is a diverse set of complex interaction topologies:



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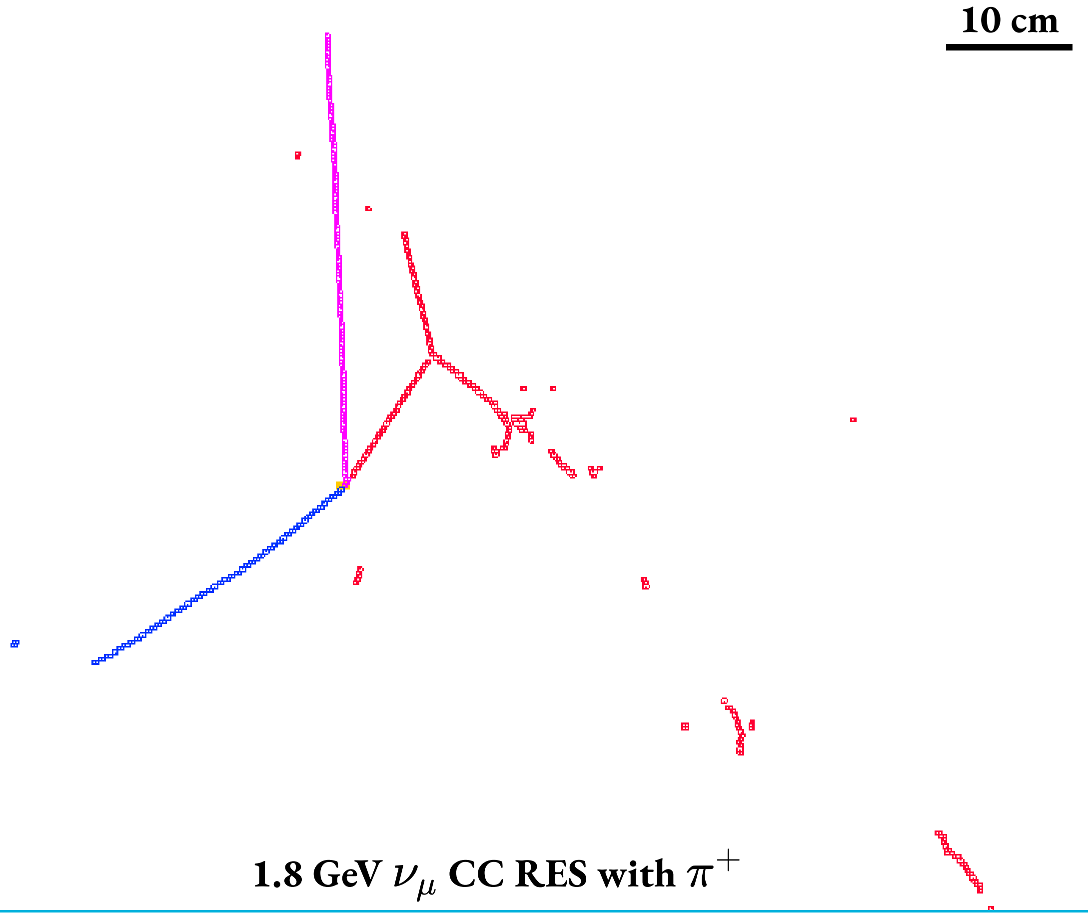

1.8 GeV ν_μ CC RES with π^+

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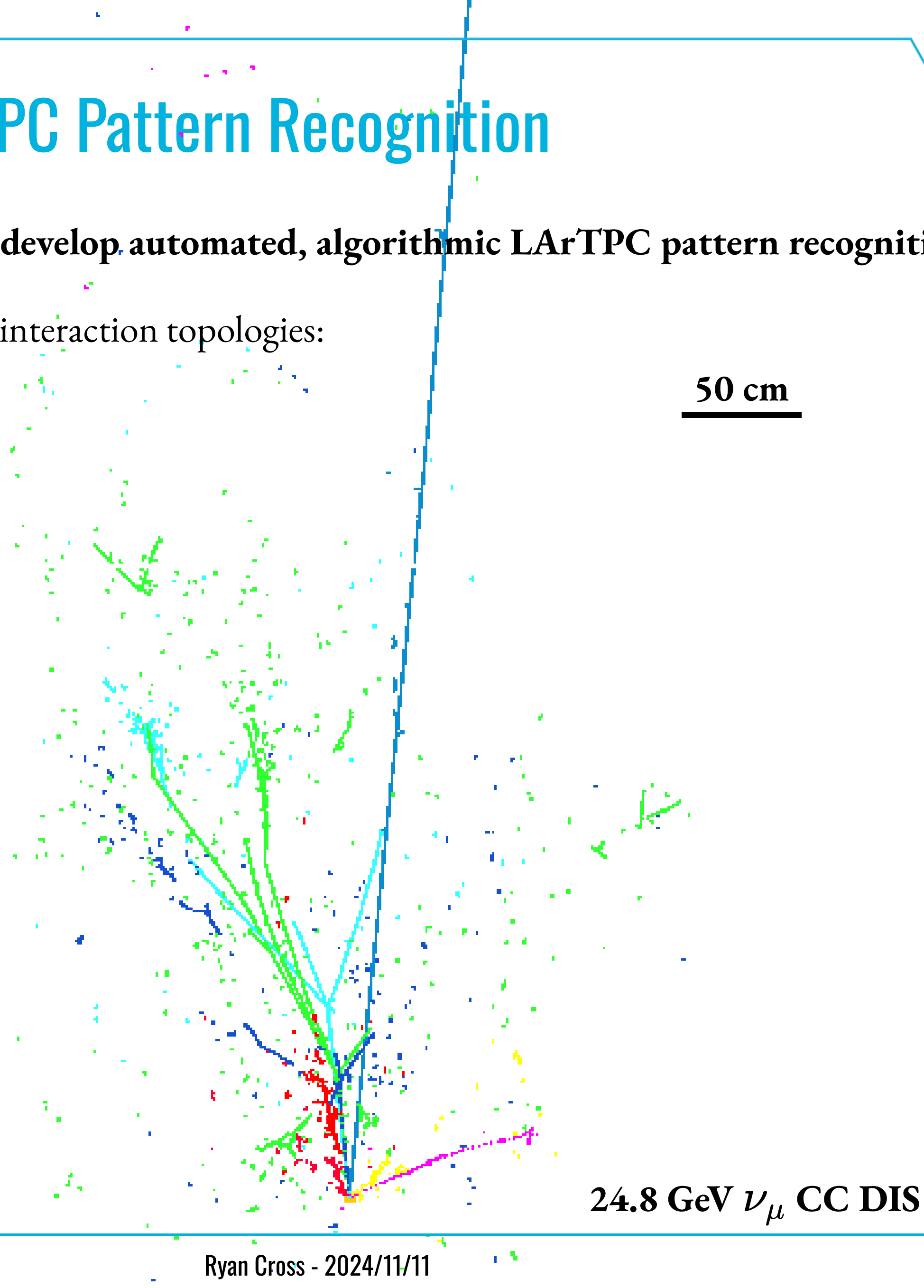

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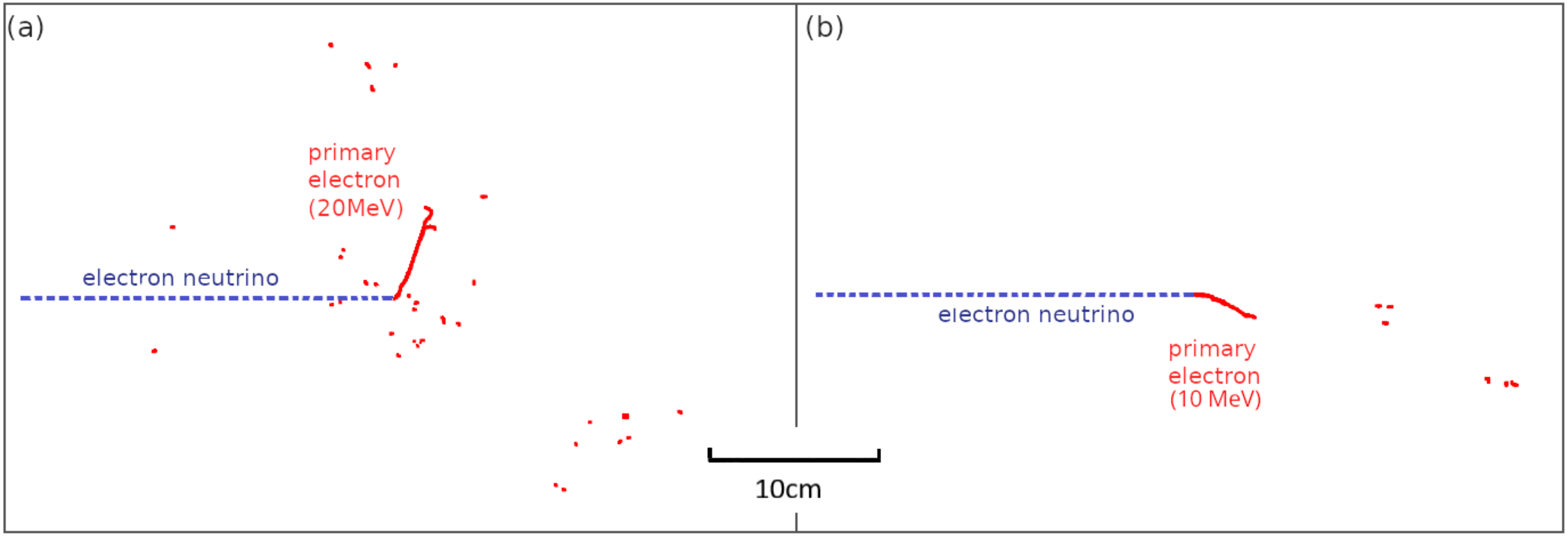

Taken from recent paper - 2407.10339

Supernova - 10s of MeV

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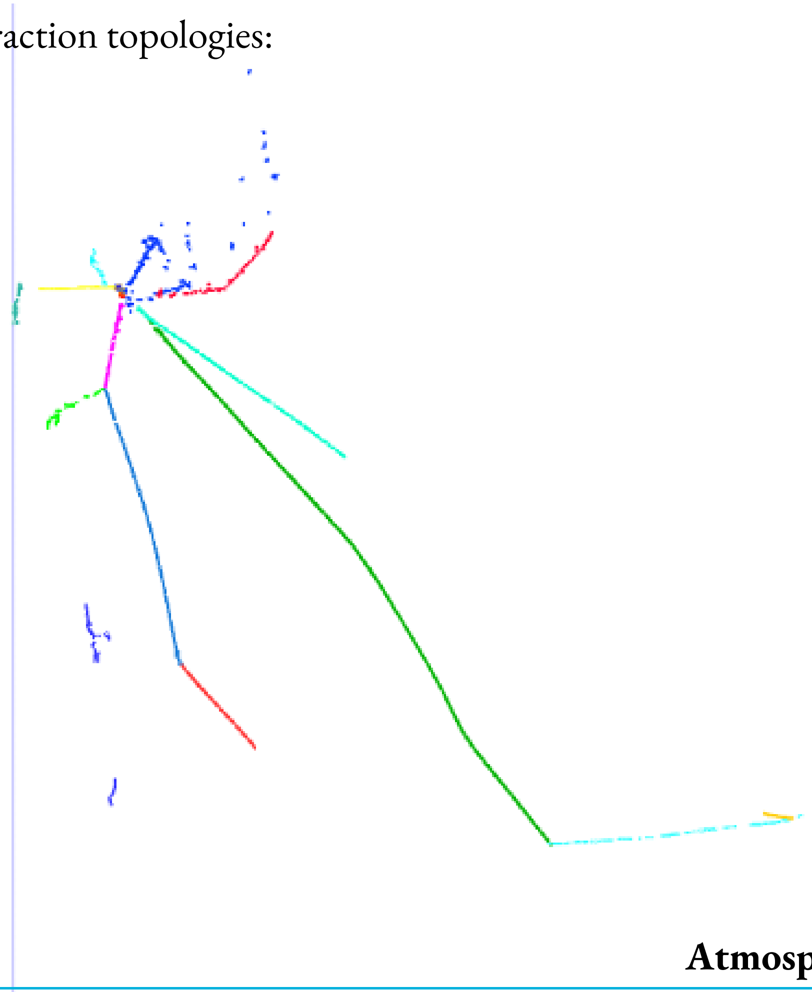

Atmospheric

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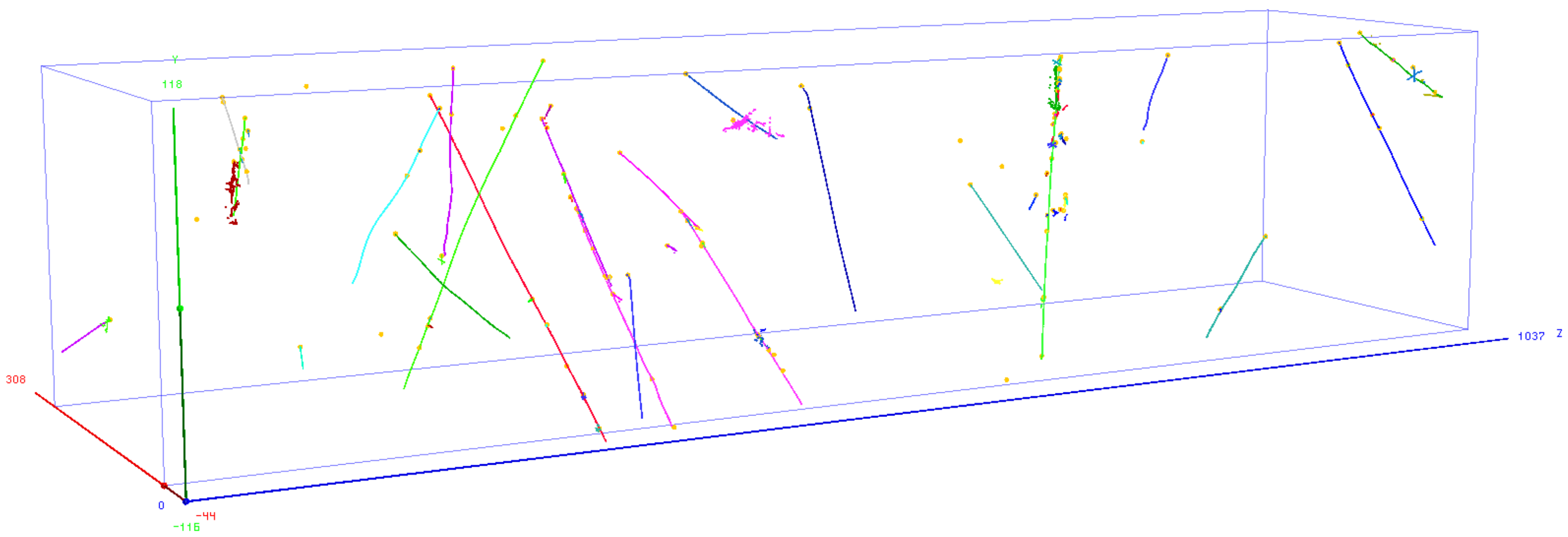

MicroBooNE - 3 View, Single Volume, Horizontal, Surface-Based, Neutrino Beam

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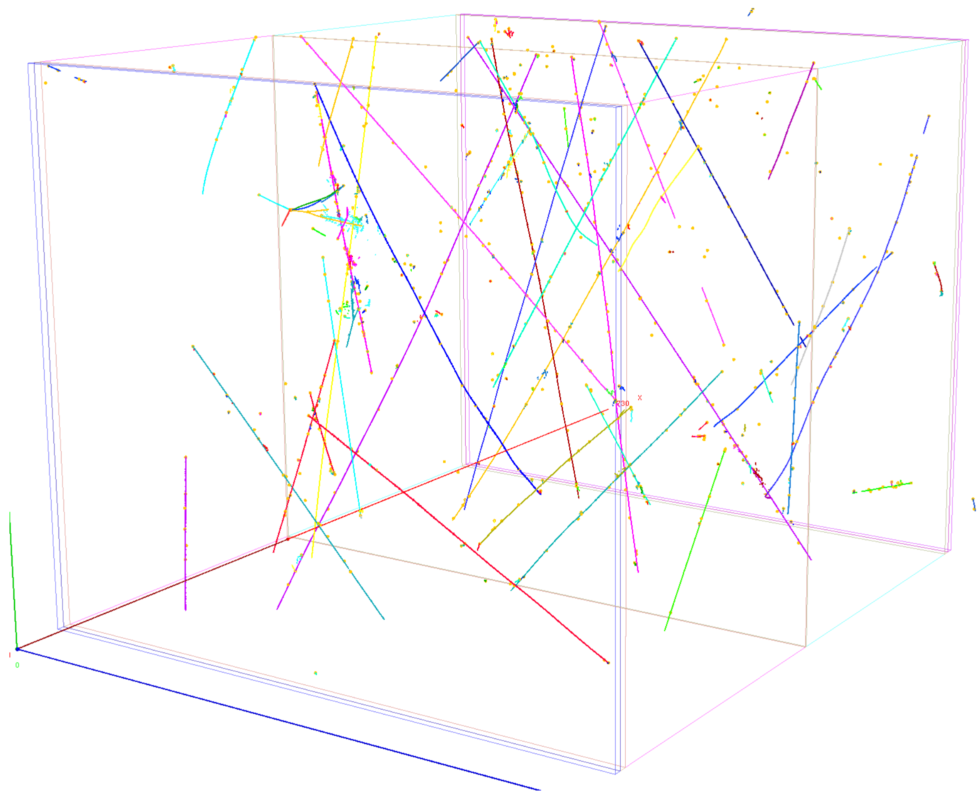

ProtoDUNE - 3 View, Multi-Volume, Horizontal + Vertical Drift, Surface-Based, Test Beam

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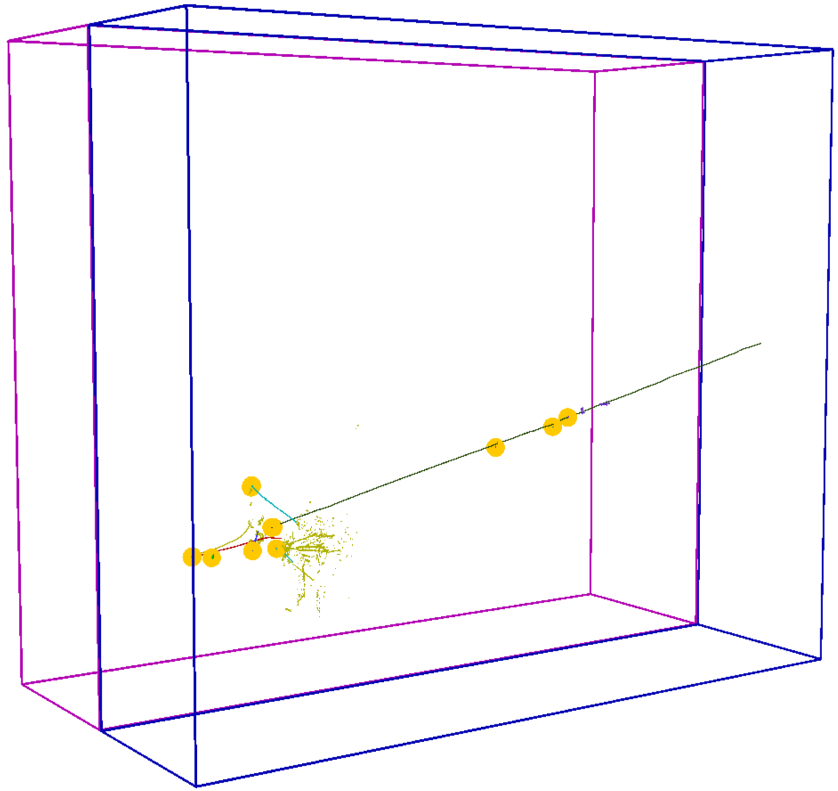

DUNE Far Detector - 3 View, Multi-Volume, Horizontal + Vertical, Underground, Neutrino Beam

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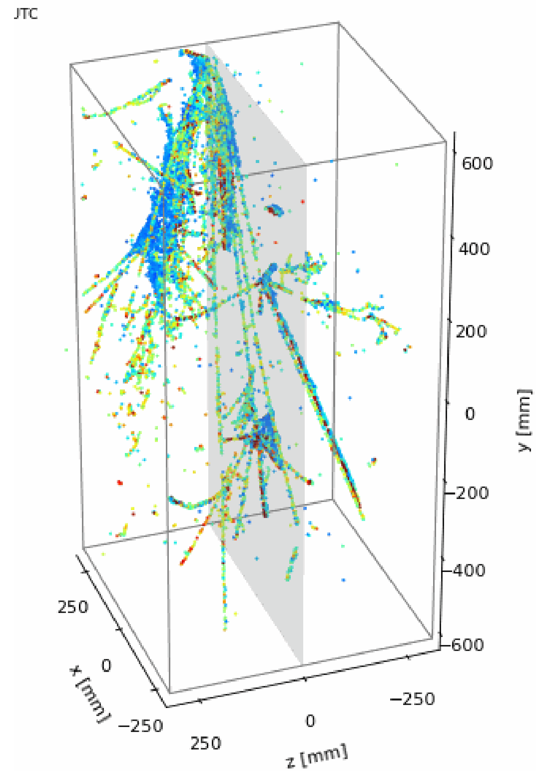

DUNE Near Detector - 3D Readout, High Pileup, Built into a suite of detectors

Pandora: The Multi-Algorithm Approach

Pandora starts with a simple idea: *It is unlikely a single algorithm, even a DL one, can resolve the complex interaction topologies we have in HEP.*

Instead, we can build up events using a multi-algorithm approach, with algorithms able to exploit whatever technology is the most appropriate:

- *Traditional* algorithms for clustering

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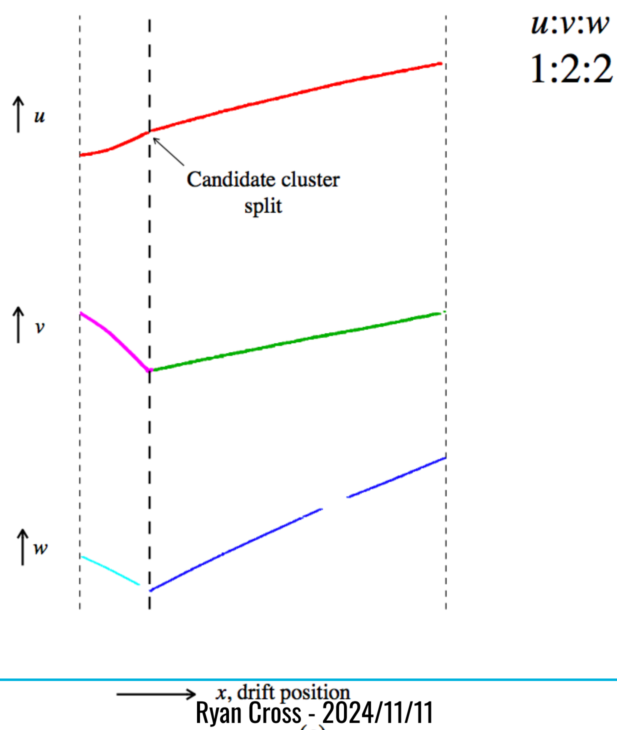
Instead, we can build up events using a multi-algorithm approach, with algorithms able to exploit whatever technology is the most appropriate:

- Build Physics + Detector knowledge into algorithms, exploiting knowledge we already have.



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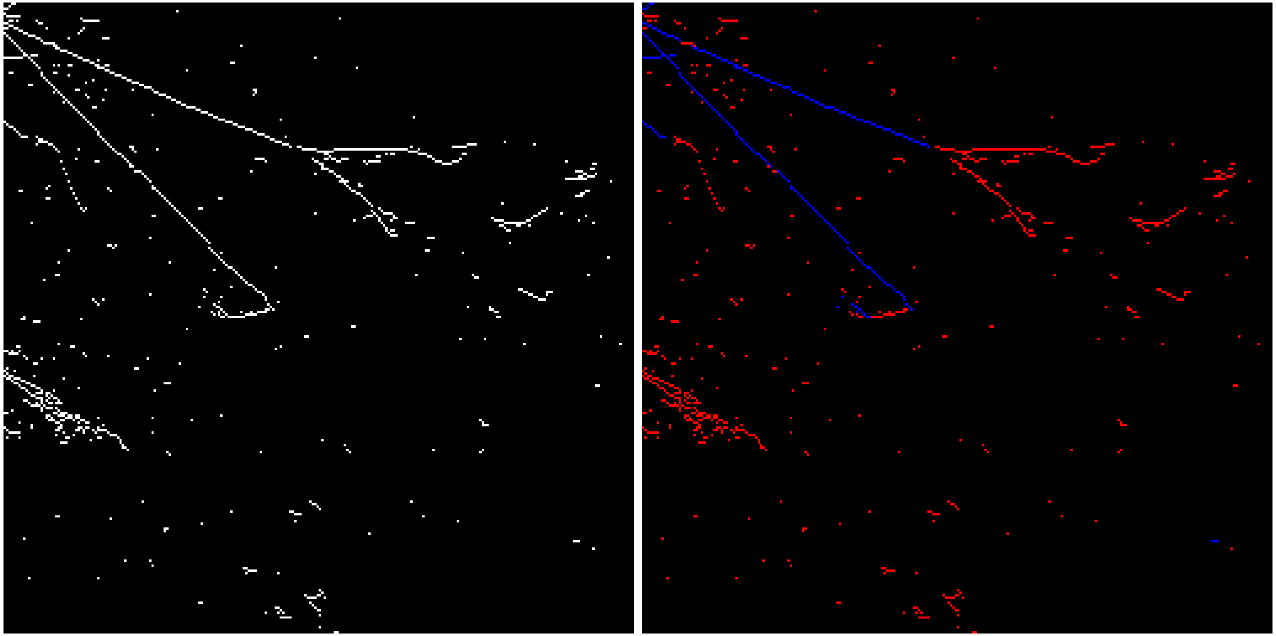
Instead, we can build up events using a multi-algorithm approach, with algorithms able to exploit whatever technology is the most appropriate:

- Exploit ML and DL for steering algorithms or for problems that benefit from newer methods.



The Pandora Team

Pandora was originally created by John Marshall and Mark Thomson for the ILC/CLIC, being carefully engineered and maintained before becoming the go-to software for reconstruction of events in LArTPC detectors

John Marshall (Warwick) and Andrew Blake (Lancaster) coordinate the Pandora project, with a host of Post-Docs: Andy Chappell, John Back & Myself (Warwick), Dom Brailsford, Isobel Mawby (Lancaster), Leigh Whitehead and Steve Dennis (Cambridge). There is a whole host of other contributions that can't easily be captured on a single slide, so check out our GitHub for further info.

Most of the person-power outlined here is targeted at DUNE, though there is also dedicated point of contact for every experiment, such that Pandora is able to provide help across all supported experiments.

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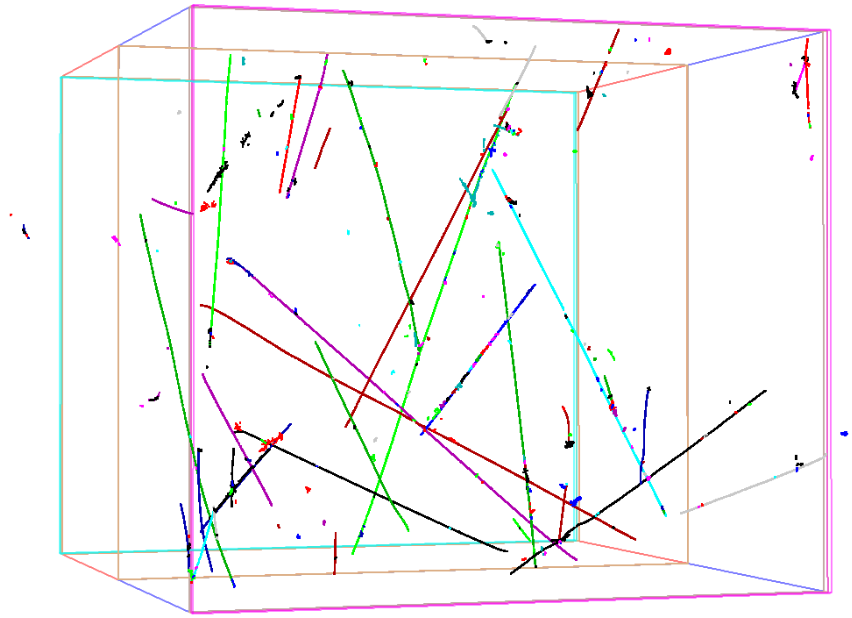
DUNE RS & DC

Under DUNE-UK, we define the **Reconstruction Software** part of the **Reconstruction Software & Distributed Computing** project, with `Rucio` and `justIN` covering the distributed computing part.

The project is funded from April 24 - Sept 28, to deliver Physics-ready software, in time for the DUNE Far Detector commissioning.

Pandora is in use at DUNE across both Far Detector modules, ProtoDUNE, and the full DUNE ND suite.

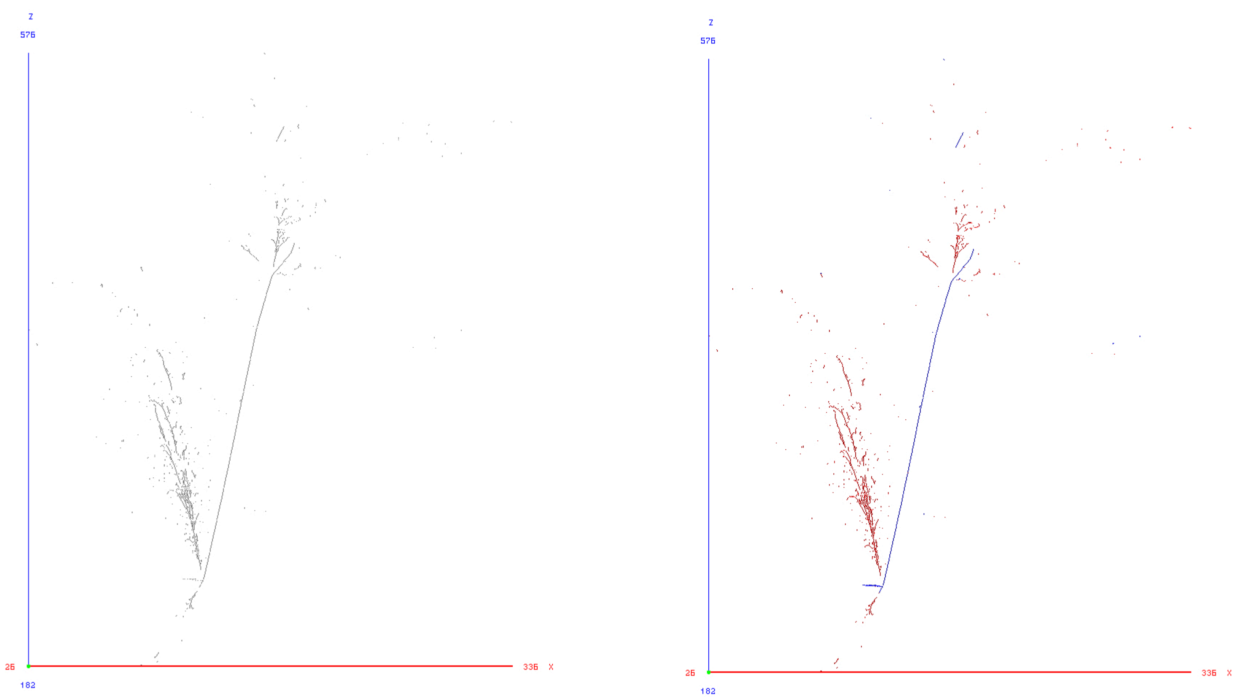


Taken from 2206.14521

Recent Pandora Developments - Deep Learning

There has been many recent developments to Pandora, primarily targeted towards DUNE/ProtoDUNE, but also SBND and MicroBooNE, with changes at one experiment being ported to the others.

One of the largest jumps forward is the addition of deep-learning support in any algorithm, supplied by the C++ interface to PyTorch. This is being utilised across a range of algorithms and is under constant development.



Poster on hit tagging here.

Deep Learning Vertexing - Visually

One of the headline algorithms exploiting deep learning is a deep learning based vertexing algorithm.

Given some input hits from a view...

Deep Learning Vertexing - Visually

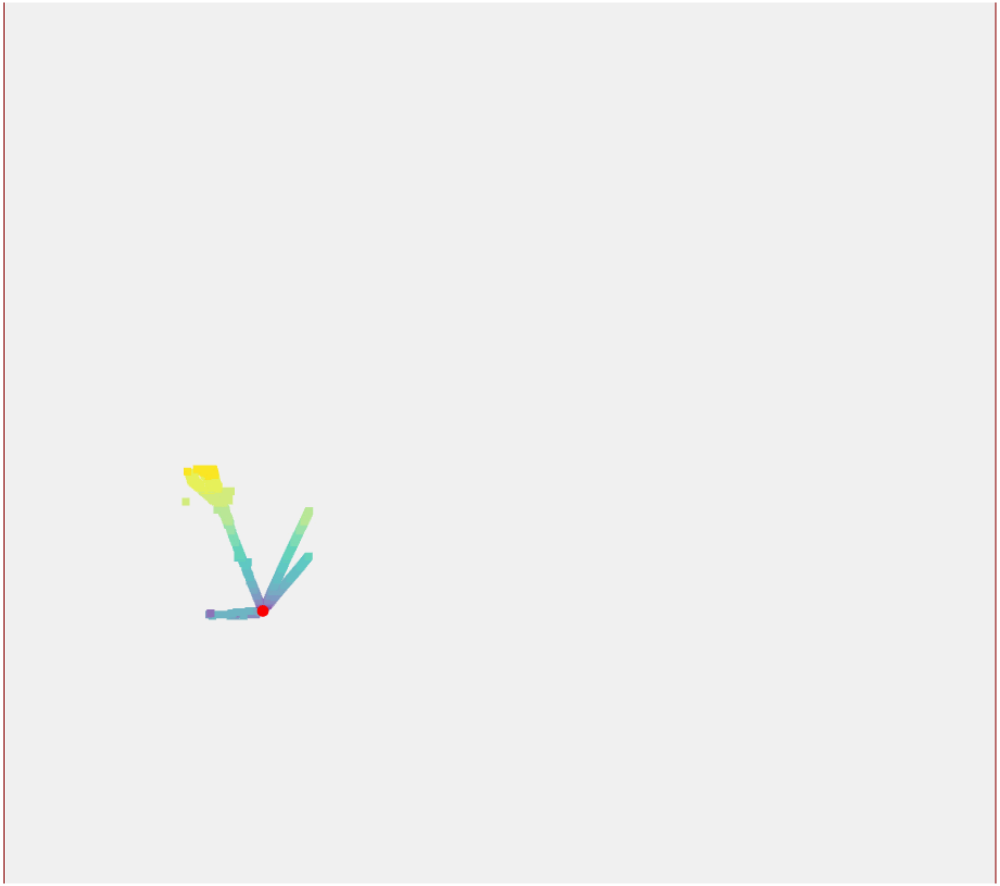
We use DL to identify the interaction vertex of the neutrino, a very visual task suited to the use of CNNs.

We get out heat maps per hit, pointing us to the most probable vertex location...

Deep Learning Vertexing - Visually

After some post-processing, we can then zoom into, look closer at the region the first network proposed.

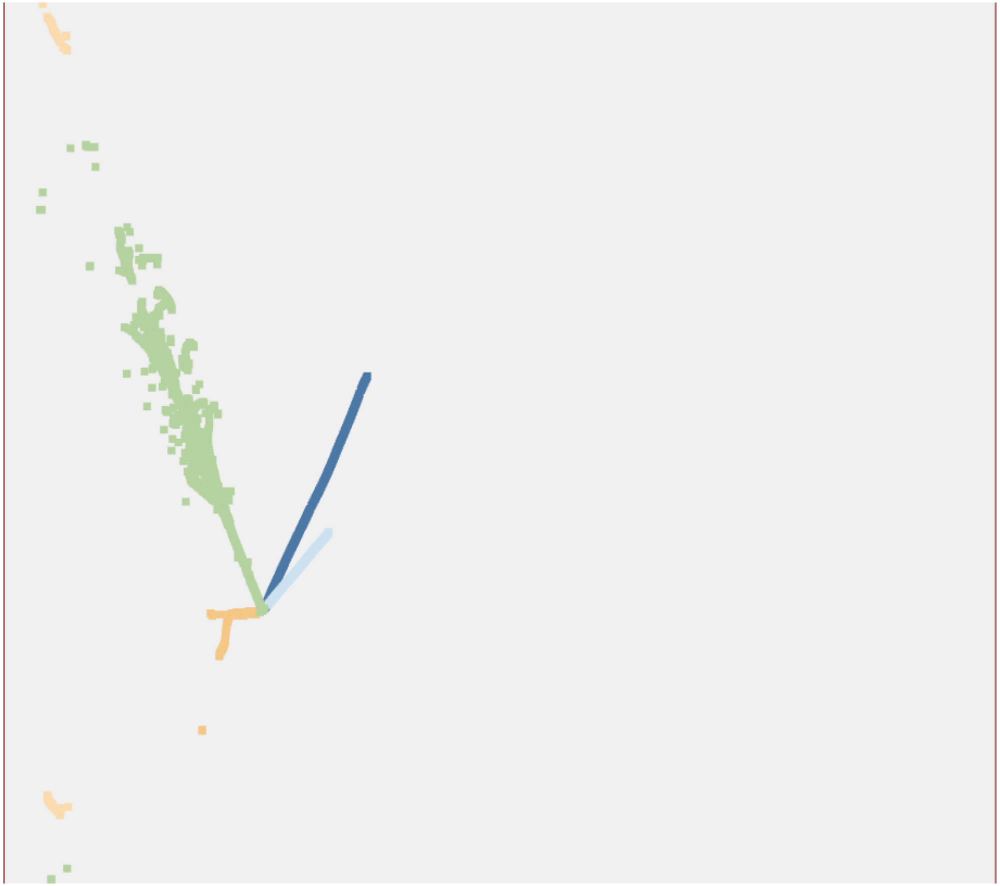
This helps boost the accuracy, and give us a primary interaction vertex:



Deep Learning Vertexing - Visually

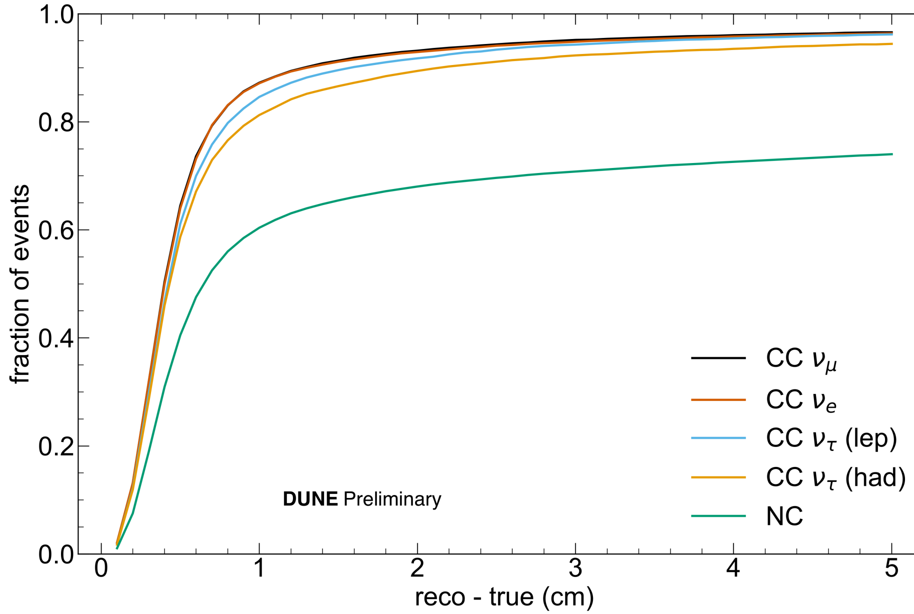
At that point, with a sensible start location, every clustering task becomes much easier.

Dealing with complex interaction regions becomes much easier with an accurate start location.



Deep Learning Vertexing

The new deep learning vertexing is the most performant vertexing algorithm for LArTPC interactions to date, getting a vertex less than 1 cm from the true position over 80 % of the time.



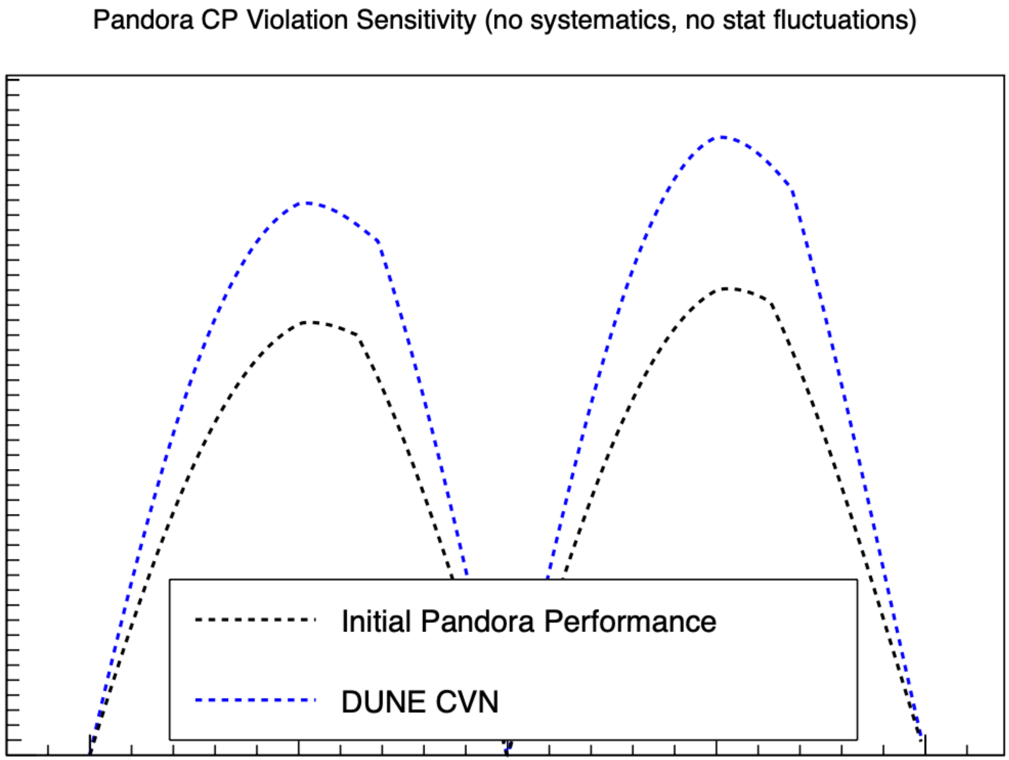
This new vertexing is currently developed for beam interactions in the DUNE far detector, and work is ongoing to also deploy it for atmospheric interactions, the near detector, as well as use at MicroBooNE and other LArTPC experiments.

Compared to 61% with the old method.

Analysis Driven Development

A key focus of Pandora is the so-called "reco-analysis continuum". Developing reconstruction improvements in a vacuum is both difficult, and can be hard to quantify the impact made.

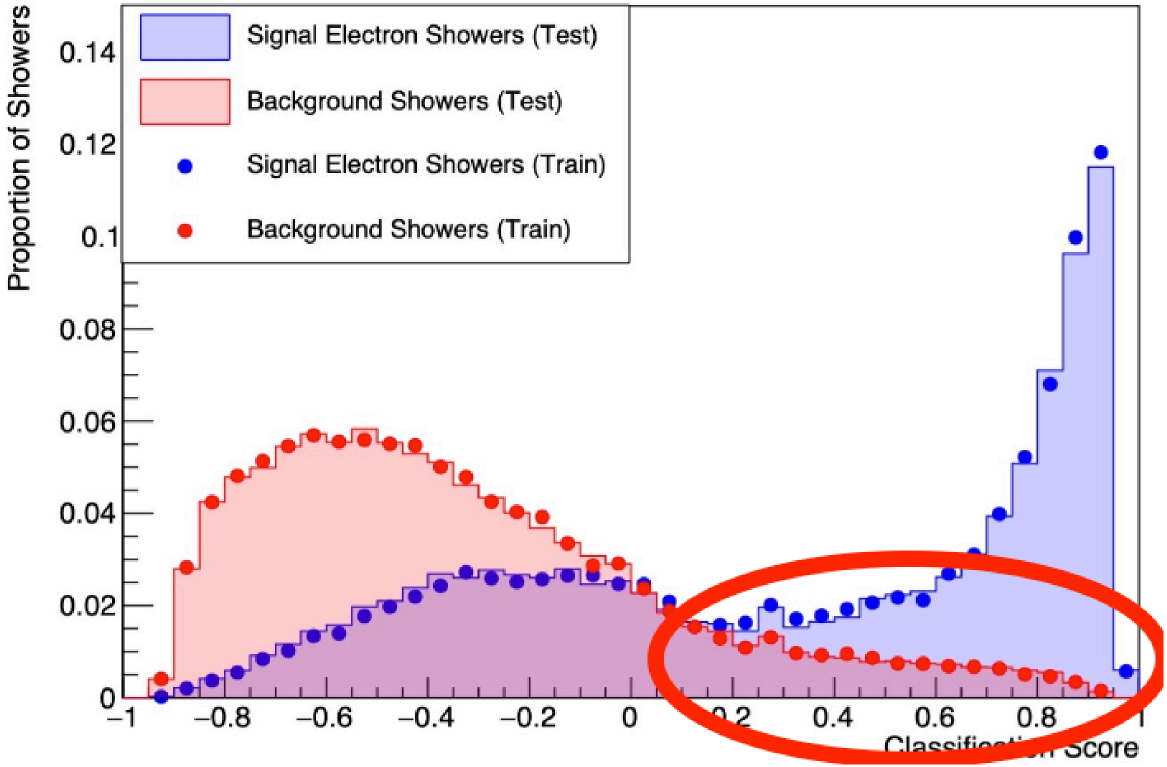
Instead, we can target improving an analysis with bespoke developments, as shown in work by Isobel Mawby for DUNE, to identify pain points for the CPV analysis.



Analysis Driven Development

With the seen difference, they then started to look into the actual reconstruction difference driving that difference, by using a suite of "cheating" algorithms.

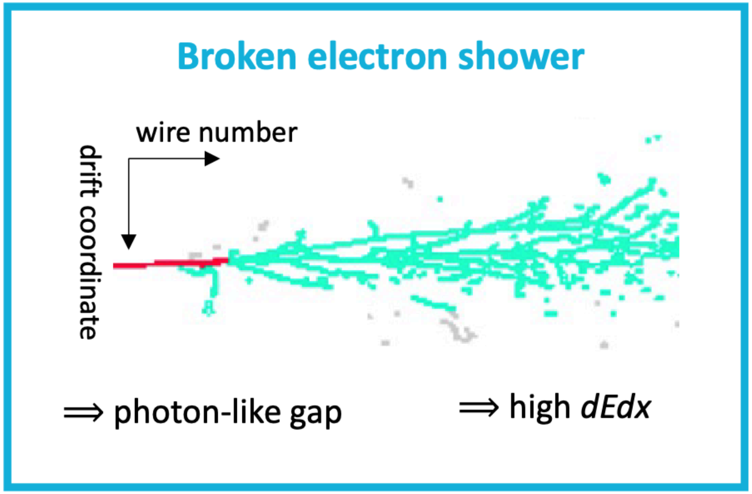
Through this, they found a key limiting factor was distinguishing between the target and background showers, due to reconstruction failures.

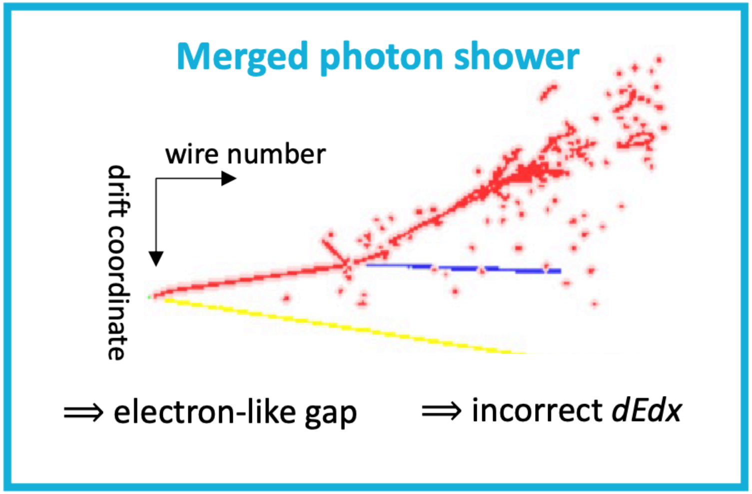


Analysis Driven Development

We can then target development at the specific issues causing failures in that analysis, fixing the things causing failures.

This means can fix the issues of a specific analysis, whilst being done in a way that benefits all other analyses.

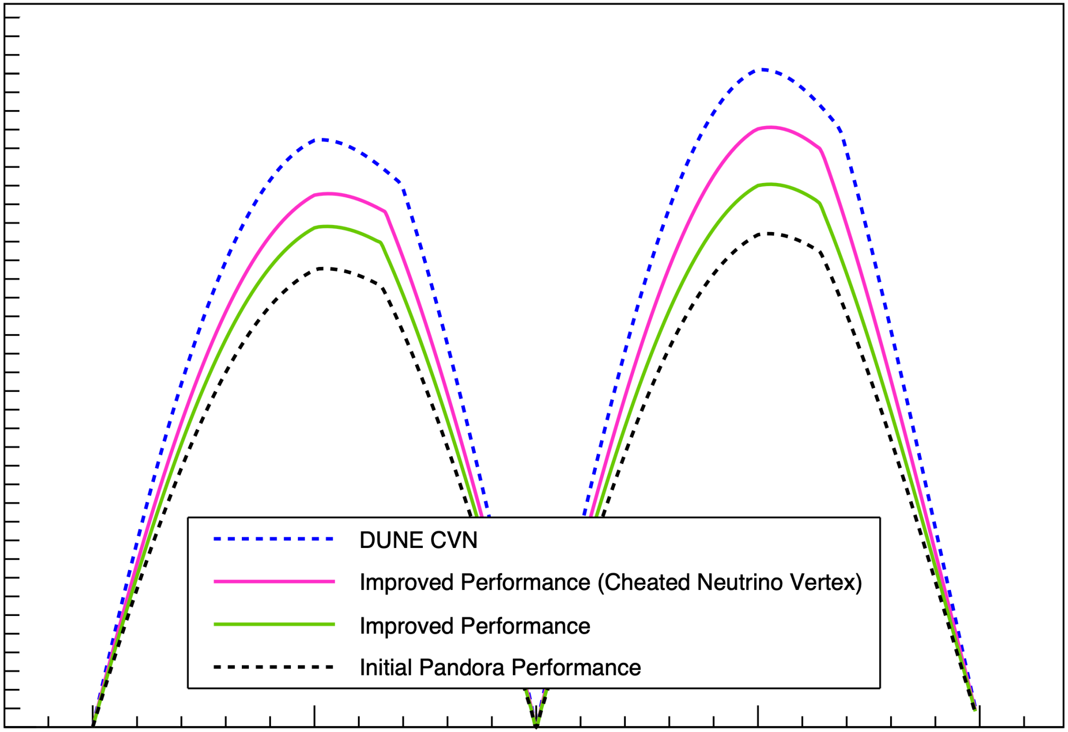




Analysis Driven Development

This leads to direct improvement, after a single round of reconstruction improvements.

You can see some further potential gains from further developments, starting the cycle again. Cheating algorithms can be used throughout the Pandora chain, enabling performance ceilings to be outlined.



Looking Ahead

Deep Learning is becoming a bigger and bigger part of Pandora, so there is constant experimentation to utilise newer techniques to improve the reconstruction of LArTPC events.

A few examples of this include:

- Work to implement a `DLSlicing` approach: Using deep learning to split up hits from neutrino interactions from hits from cosmic rays.
- Similarly, `DLSignalID` to distinguish hits from supernova neutrinos from the diffuse background hits common when looking at such low energies.
- Additionally, work is ongoing to target one of the main "confusion topologies" in Pandora, where close by electromagnetic showers can become merged due to their proximity and overlap. A Graph-based neural network approach is in development to successfully distinguish these topologies such that different clustering hypothesis can be compared and chosen between.
    - Similarly, work is ongoing to extend the `DLVertexing` to include secondary vertices, further simplifying the full reconstruction chain.
- Finally, exploratory work is ongoing looking into the utility of transformer networks and state space machines in Pandora.

Conclusion

Pandora's key functionality is to support the multi-algorithm approach, breaking down pattern-recognition problems into smaller steps.

- These steps can then be addressed by algorithms (traditional, ML, DL), integrating detector and physics knowledge where useful.
- The Pandora framework is a UK-developed and UK-supported framework, with major UK support and development for LArTPCs.
- There is significant work ongoing inside Pandora to support DUNE (and every detector under that umbrella), as well as SBND, MicroBooNE and more, with developments at one experiment benefiting all experiments.
- Deep Learning is now deeply integrated into Pandora and utilised as a matter of routine, with further extensions planned and in progress.
- Paper on the Pandora SDK: EPJC volume 75, Article number: 439 (2015).
- MicroBooNE LArTPC Paper: EPJC volume 78, Artcile 82 (2018)
- ProtoDUNE Paper: EPJC volume 83, Article 618 (2023)
- Code & Tutorials : github.com/PandoraPFA

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