Pandora

Generic LArTPC Reconstruction

Ryan Cross - GridPP and Swift-HEP

2023/03/30

WARWICK
THE UNIVERSITY OF WARWICK

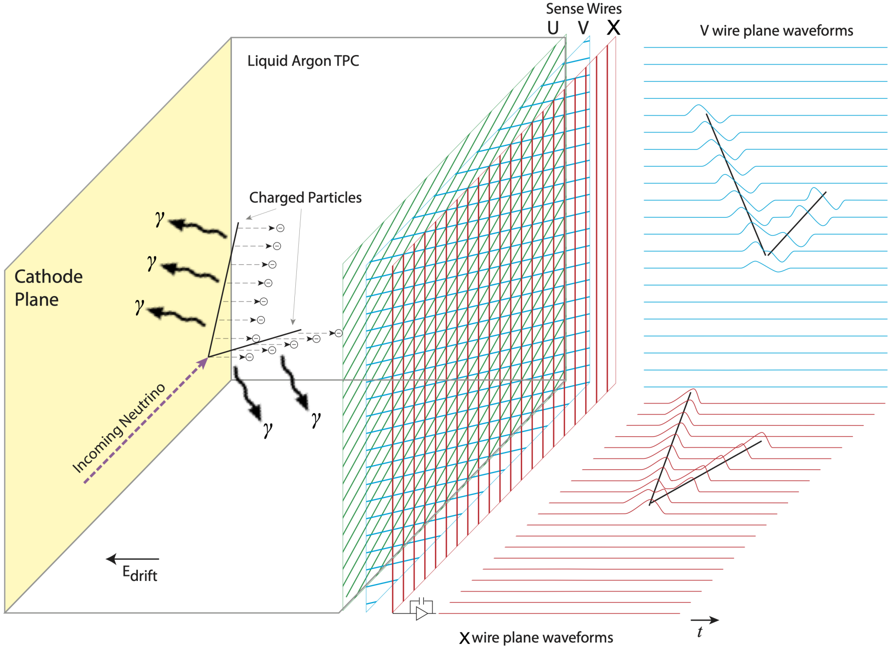
Overview

This talk will cover:

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

Liquid Argon Time Projection Chamber (LArTPC)

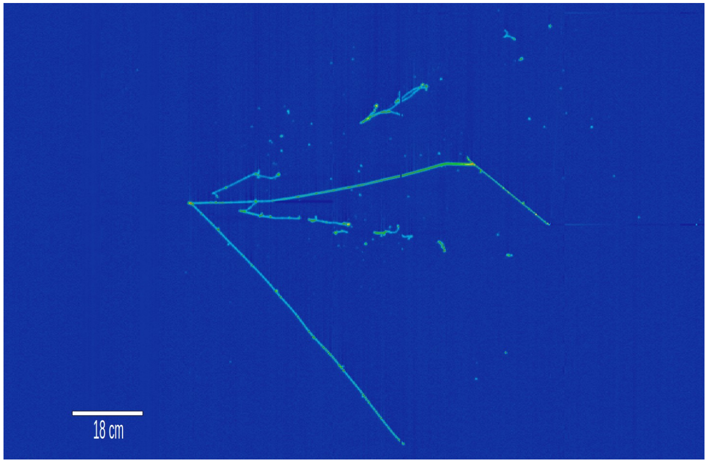
- When an interaction occurs in the liquid argon, the charged particles produce ionisation electrons as they travel through the detector medium.
- This charge can be drifted to readout planes on the edge of the detector, to track the path of the charged particles.
- Photon detection systems are used to tag the start of interactions by detecting scintillation photons produced when the interaction occurs.
- End result is (usually) multiple 2D outputs of wire number vs time, which can in turn be processed into a fully 3D output by matching 2D hits across readout planes.

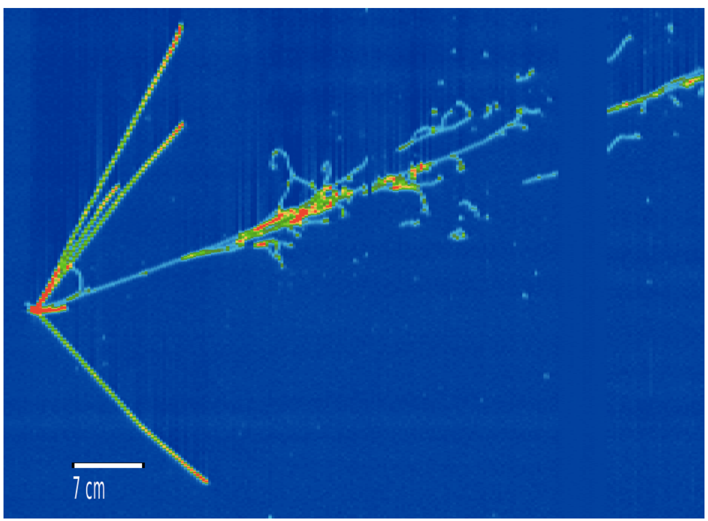


There are many variations of LArTPCs, with 1/2/3 readout planes, differing readout technology etc.

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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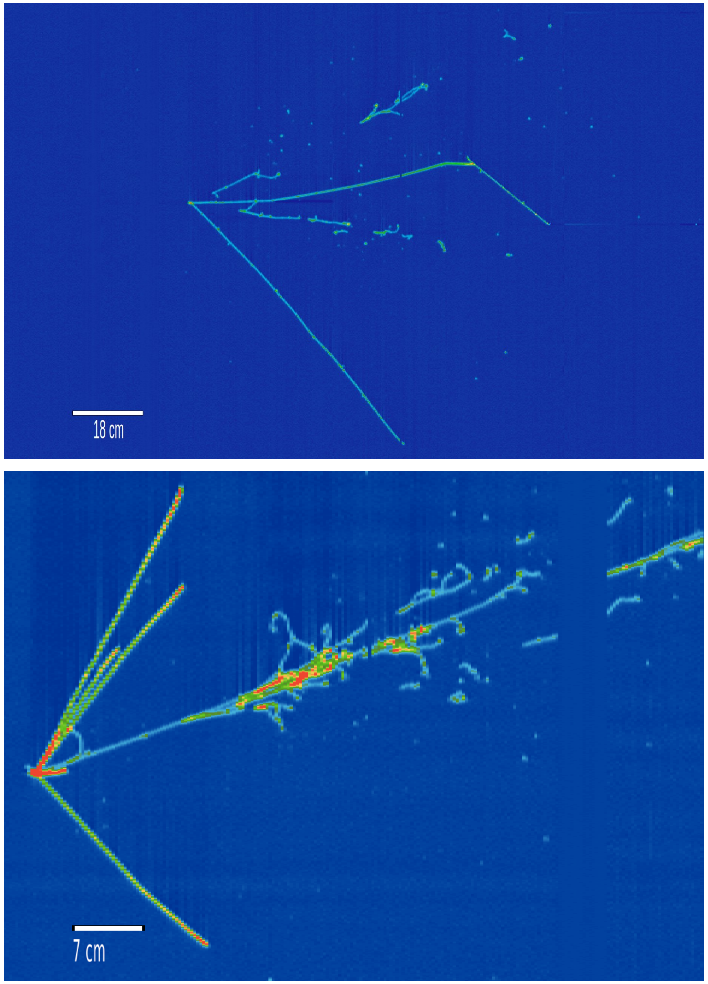

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Pattern Recognition

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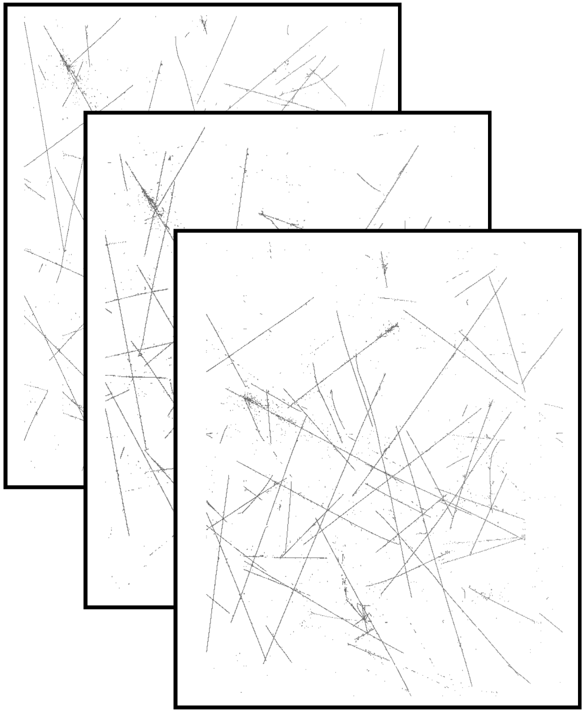
- Produce 3D reconstructed particles, from the input 2D images.
- Build up a 3D particle-interaction hierarchy, starting from the initial neutrino or test beam.



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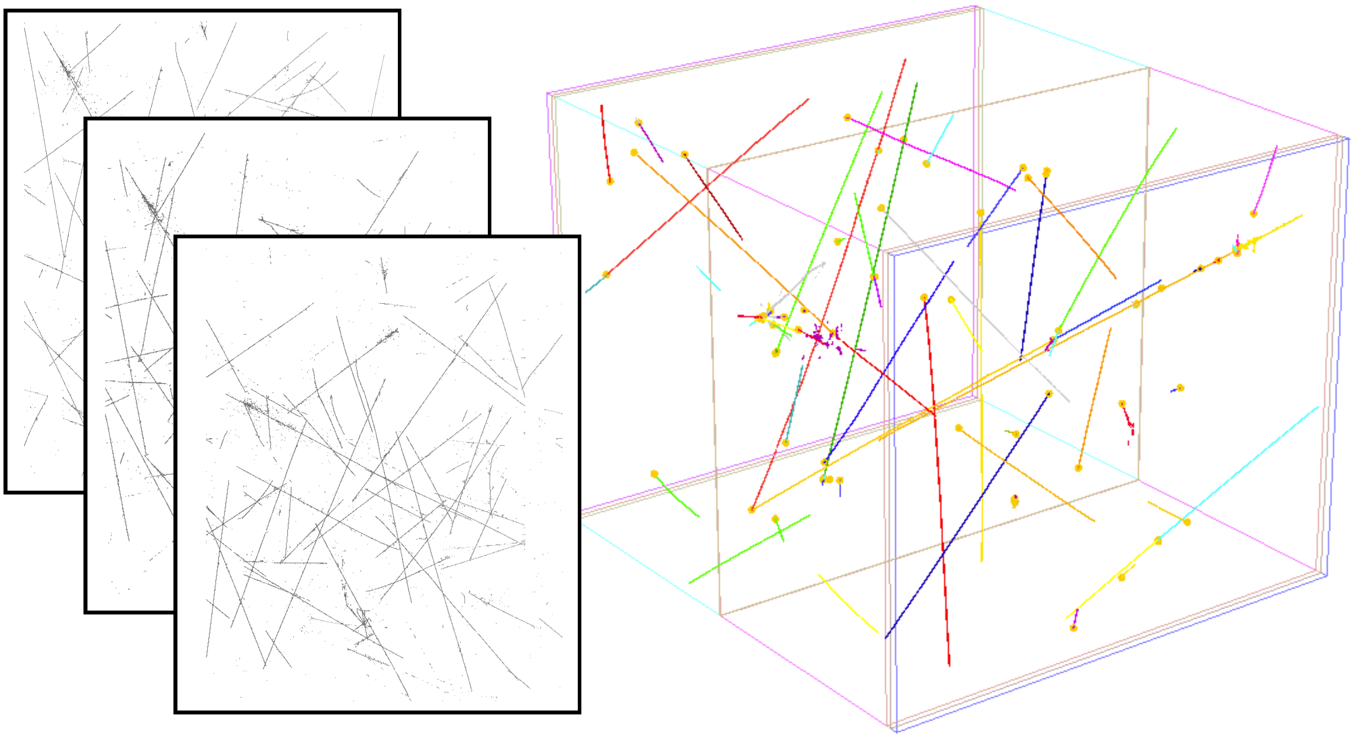

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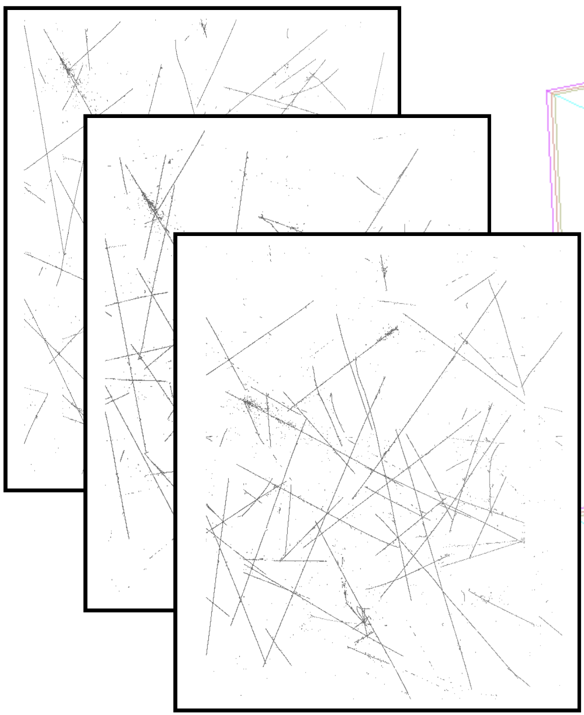
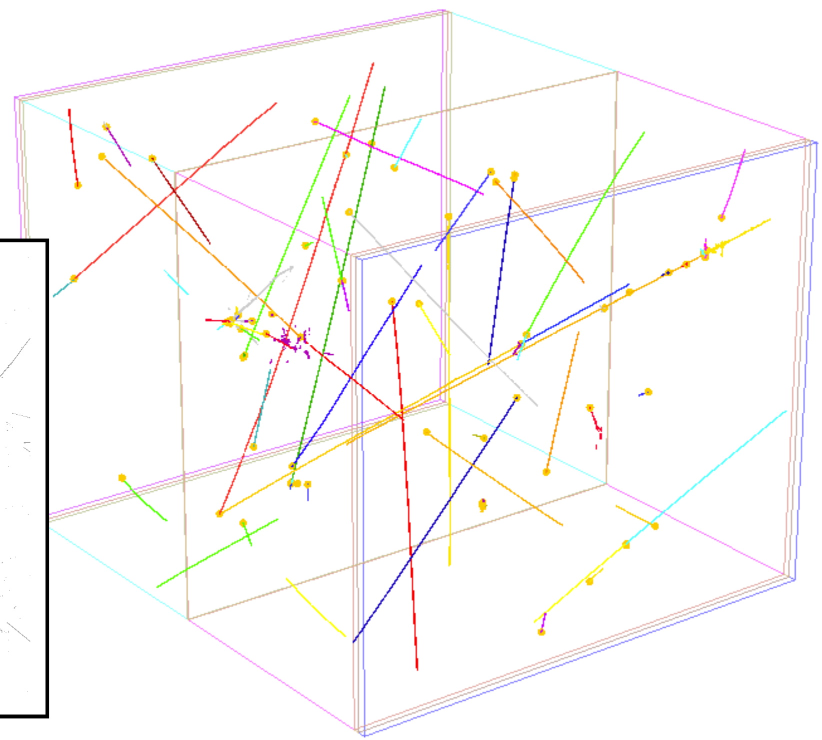
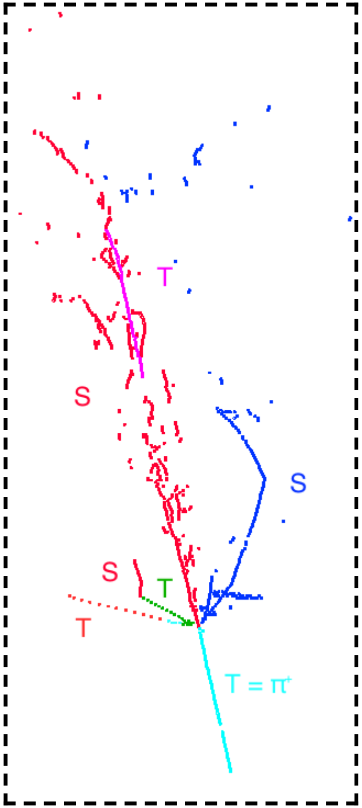


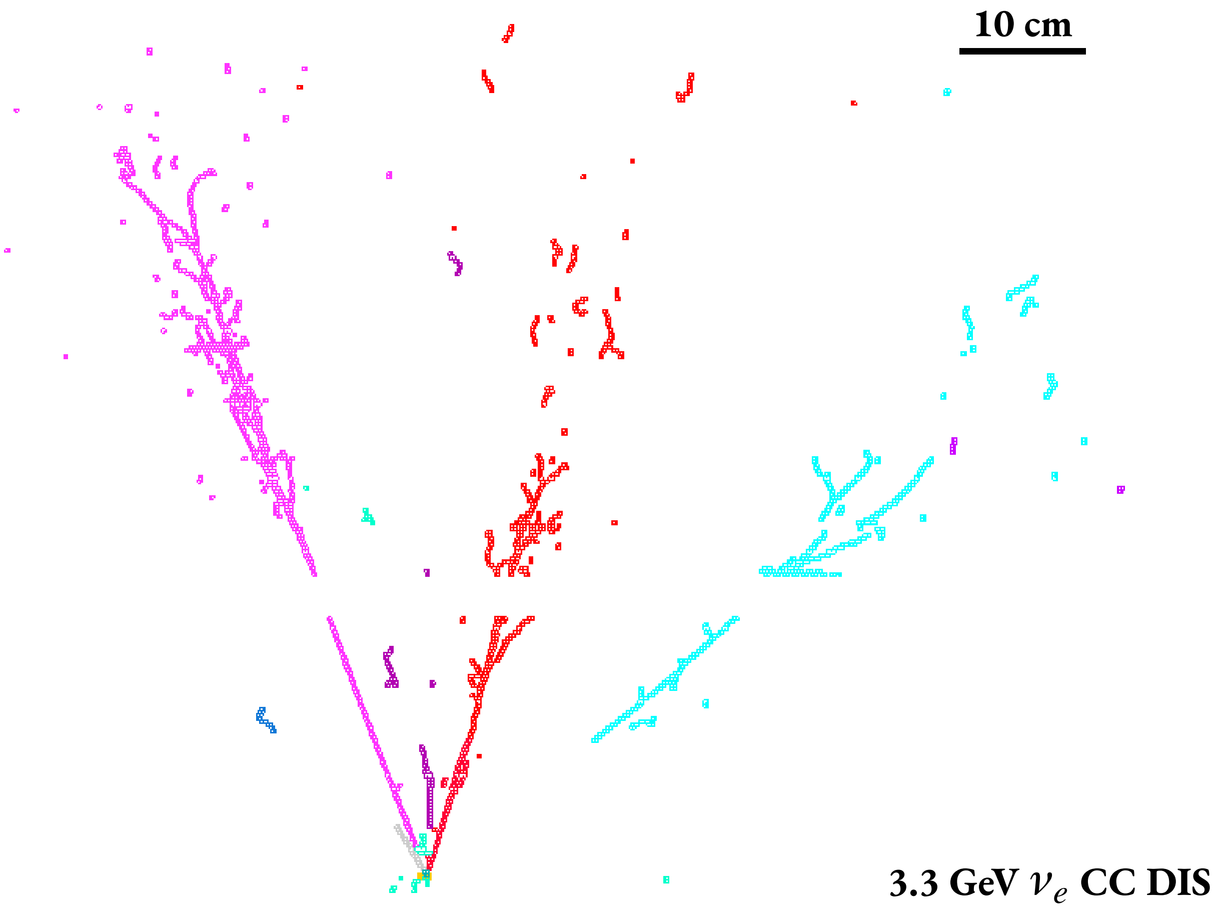




Challenges for LArTPC Pattern Recognition

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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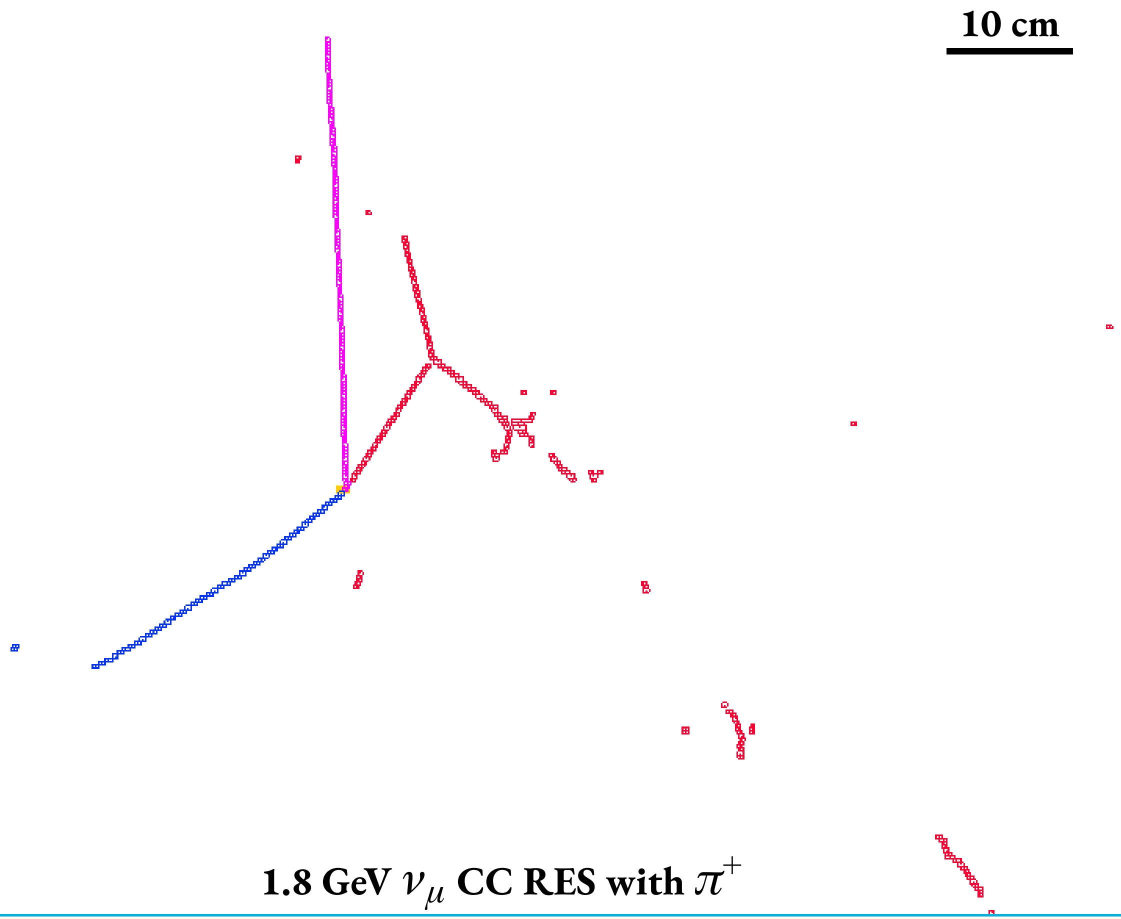

1.8 GeV ν_μ CC RES with π^+

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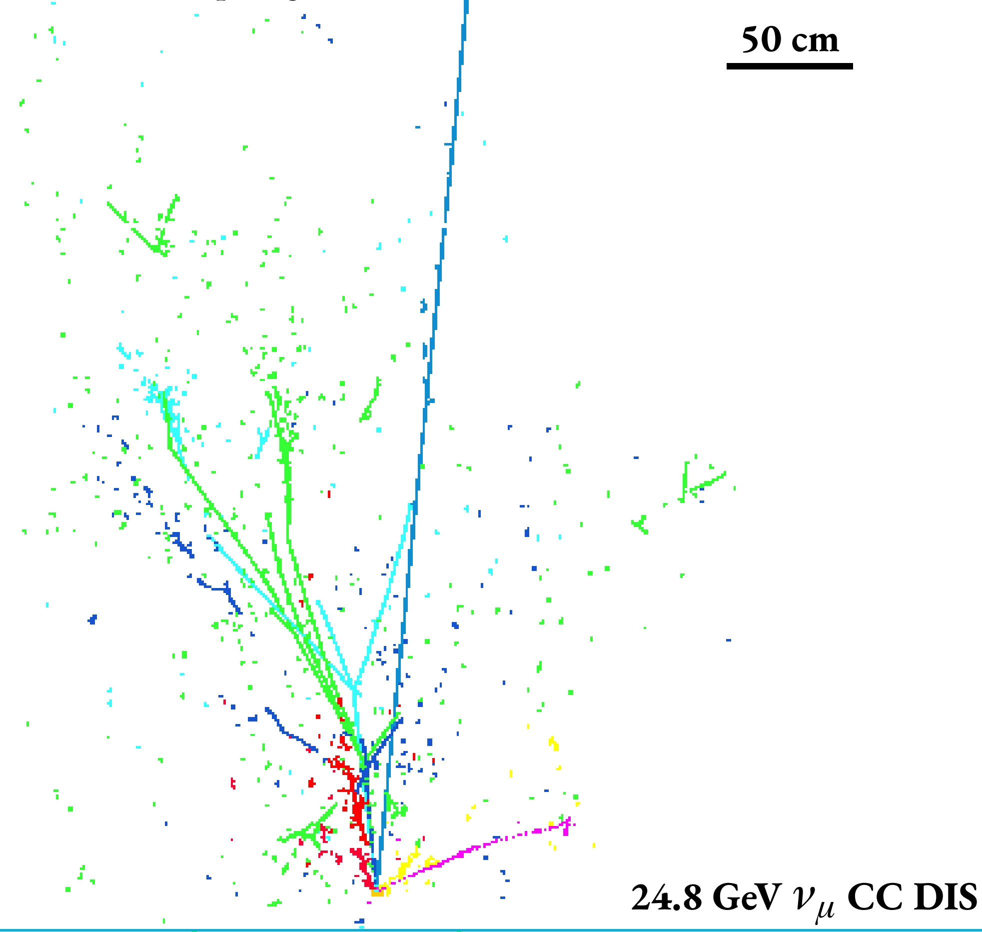

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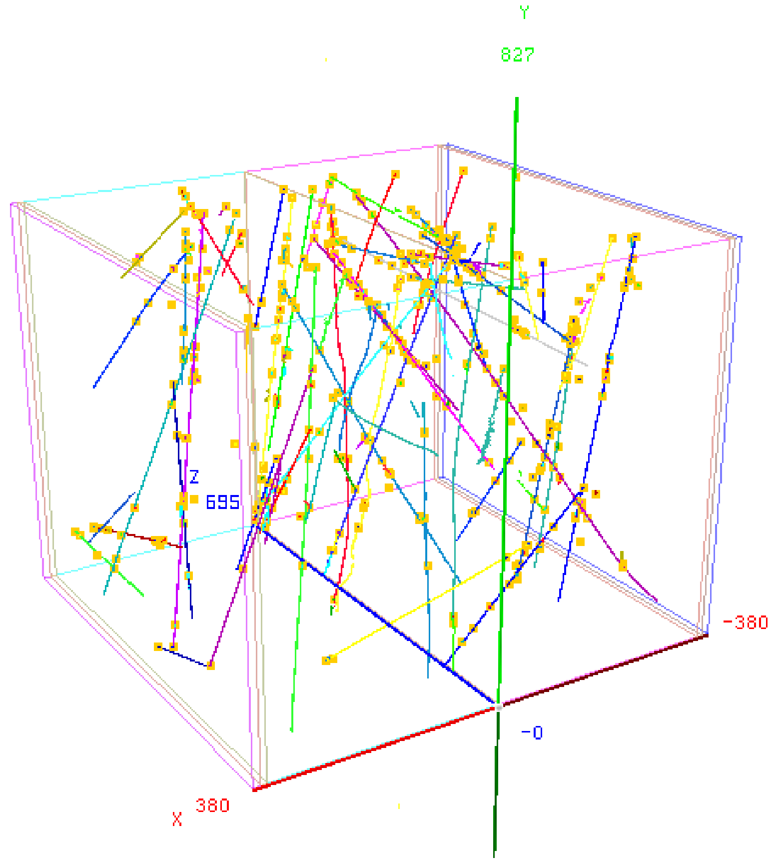
Also, due to the long readout times of the detector technology, surface based detectors have significant cosmic-ray muon backgrounds.

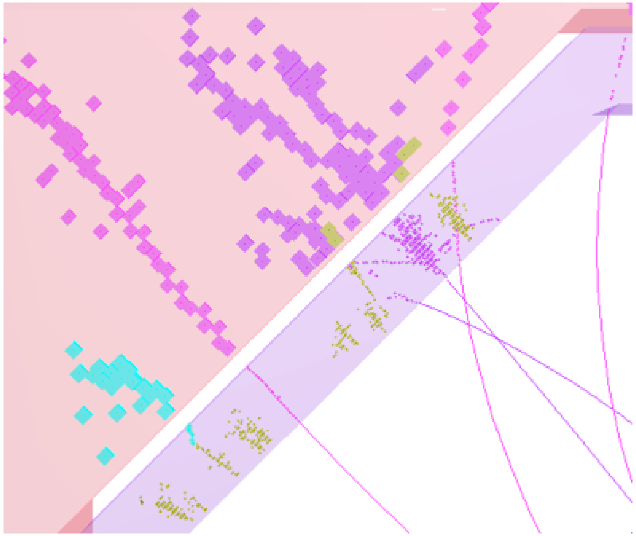


Pandora Multi-Algorithm Approach

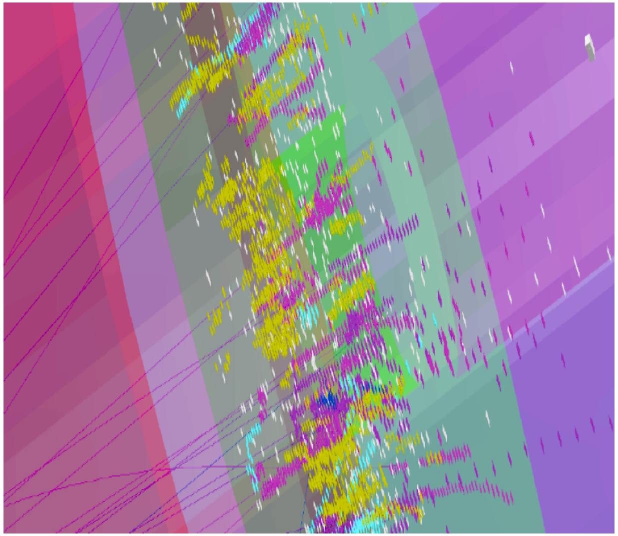
A single approach to clustering is unlikely to work for the complex topologies in a LArTPC, with a mix of track-like and shower-like clusters.

Pandora project has tackled similar problems before, utilising a multi-algorithm approach:

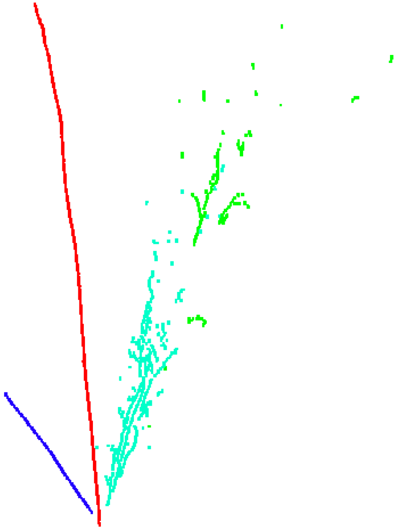
- Build up events gradually.
- Use incremental steps, avoiding mistakes.
- Deploy more sophisticated algorithms as the event picture develops.
- Integrate Physics and Detector knowledge into algorithms.



Typical ILC Event Topologies - 3D
NIMA.2009.09.009 NIMA.2012.10.038



Typical showers in CMS HGCAL - 3D
LHCC-P-008



BNB Interaction at MicroBooNE - 3 x 2D

Pandora Multi-Algorithm Approach

Pandora is in use at essentially every large LArTPC experiment, with dedicated PDRA support for each experiment and configuration, acting as a direct point of contact for support.

This covers a wide range of differing experiments and concerns, covering:

- DUNE
  - ProtoDUNE-HD + ProtoDUNE-VD
  - DUNE FD HD + DUNE FD VD
  - DUNE ND: ND-LAr (Native 3D Readout), ND-GAr, SAND
- MicroBooNE
- SBND
- ICARUS

Which covers a large combination of different detector technologies, locations, sizes and interaction types, without even considering all the differing styles of analysis that happens in each experiment!

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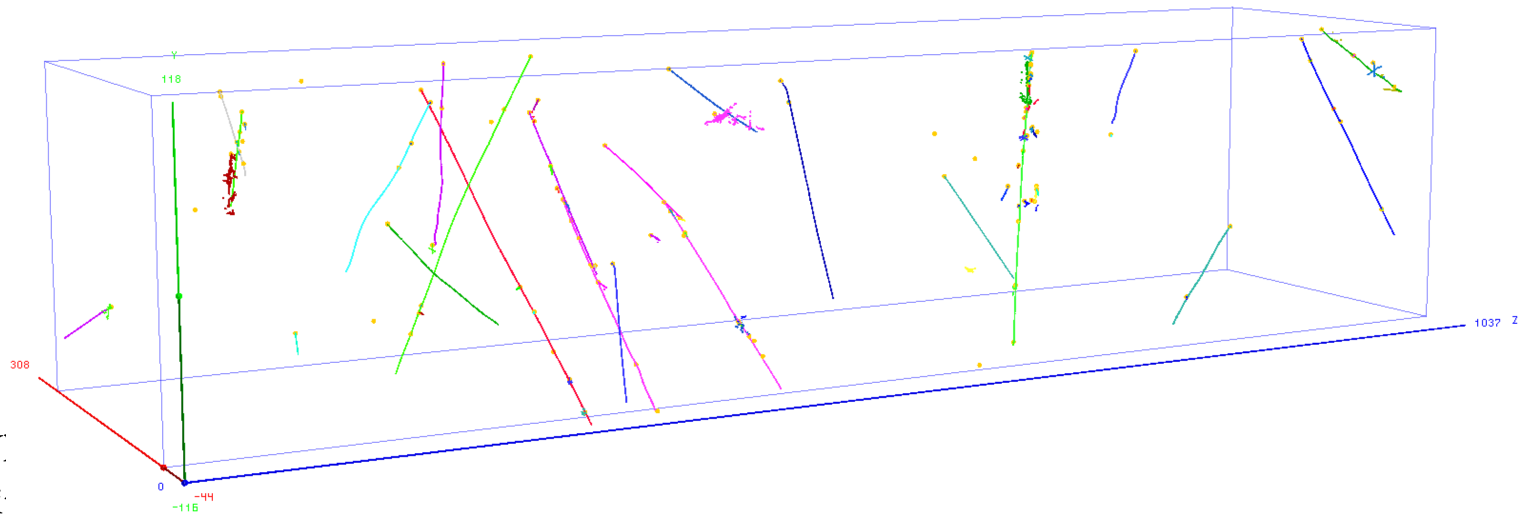

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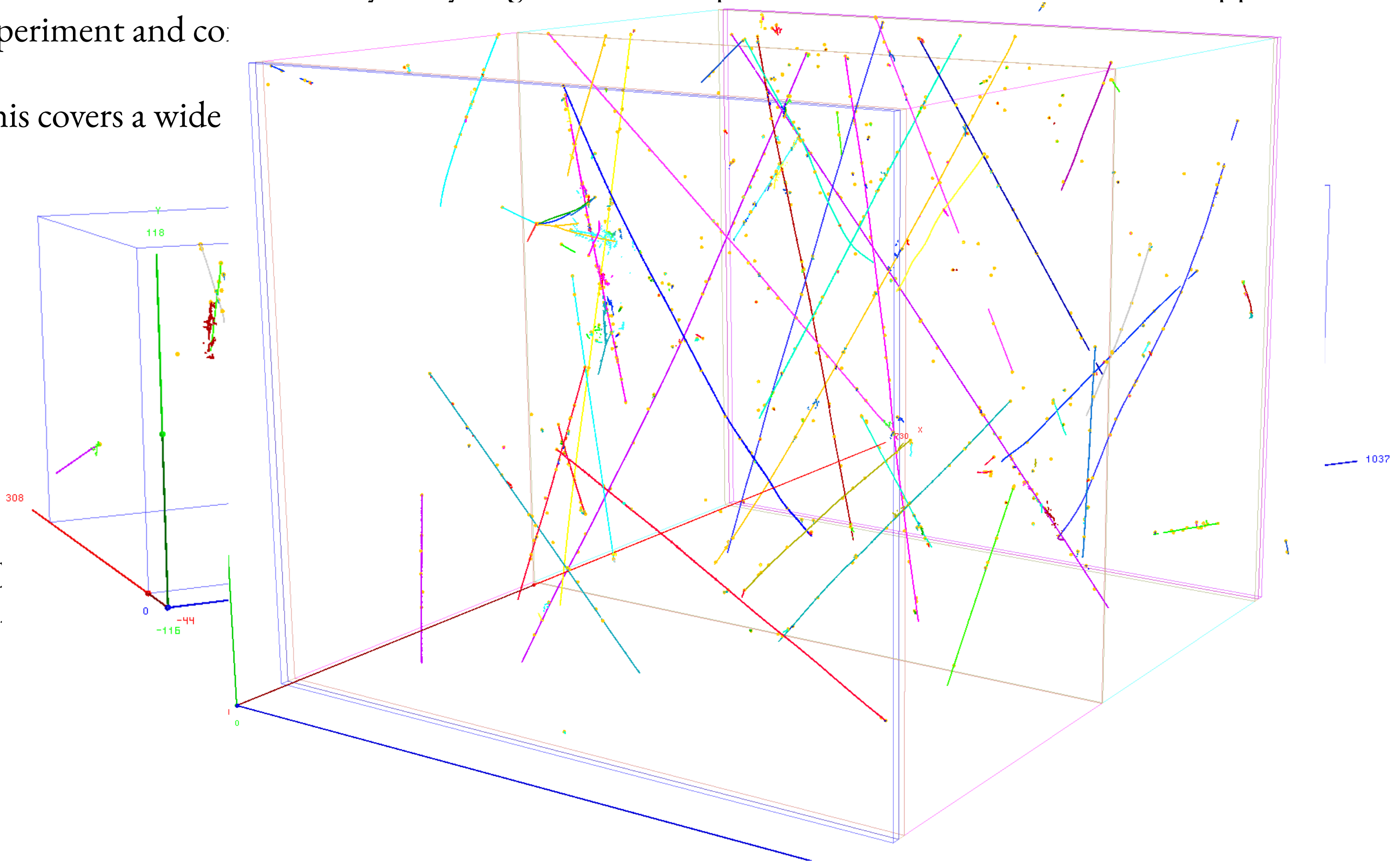

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In One Slide

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, and support for ILC/CLIC.
- Paper on the Pandora SDK: EPJC volume 75, Article number: 439 (2015).
- MicroBooNE LArTPC Paper: EPJC volume 78, Artcile 82 (2018)
- Github, including documentation, and a week-long workshop! : github.com/PandoraPFA

The Pandora Team

Pandora is a UK-based reconstruction effort, with the original framework developed and supported in the UK. It is in use at LArTPC experiments and the ILC/CLIC (though support there is provided from outside the UK). It was created by John Marshall and Mark Thomson in Cambridge.

John Marshall (Warwick) and Andrew Blake (Lancaster) coordinate the Pandora project, with a host of Post-Docs: Andy Chappell, Maria Brigida Brunetti (Warwick), Dom Brailsford, Isobel Mawby (Lancaster) and then 50% of the time from myself (Warwick), Leigh Whitehead and Steve Dennis (Cambridge).

Most of the person-power outlined here is targeted at DUNE, though as mentioned previously 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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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.

Pandora's algorithms can be any thing with a `Run()` method. Because of this, Pandora has supported basic machine learning (SVMs, BDTs etc.) for a while. Recently however, Pandora has added PyTorch as a build dependency, allowing for deep learning-based algorithms to be deployed. This has been used for advanced hit tagging, drastically improved vertexing and there is many more improvements on the way.

Poster on hit tagging here.

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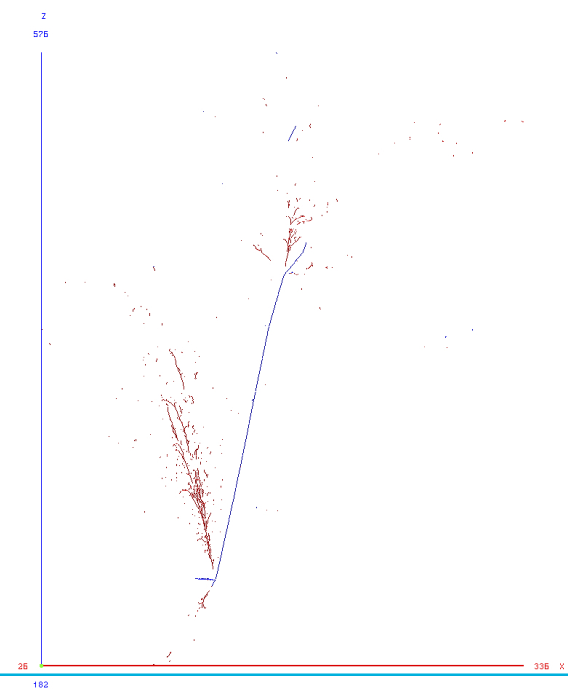


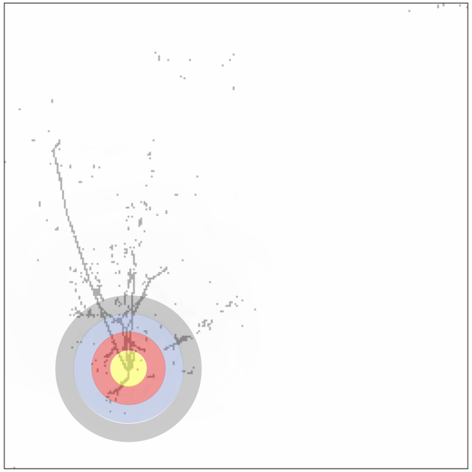
Poster on hit tagging here.

Deep Learning Vertexing

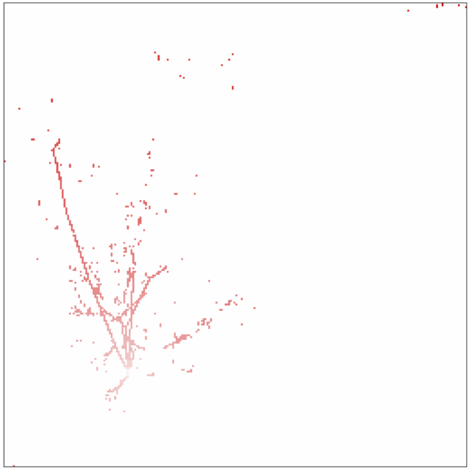
One of the headline features utilising the deep learning support in Pandora is a new deep learning-based vertex reconstruction for DUNE.

The identification of an interaction vertex is a key part of reconstructing neutrino interactions, as its location massively impacts the clustering produced for a given set of hits.

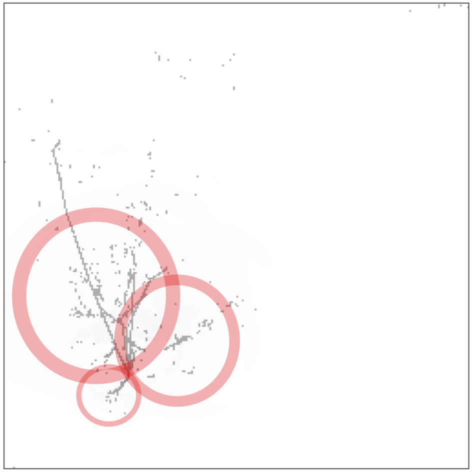
In training hits are assigned a class according to distance from true vertex



Network trained to learn those distances from input images

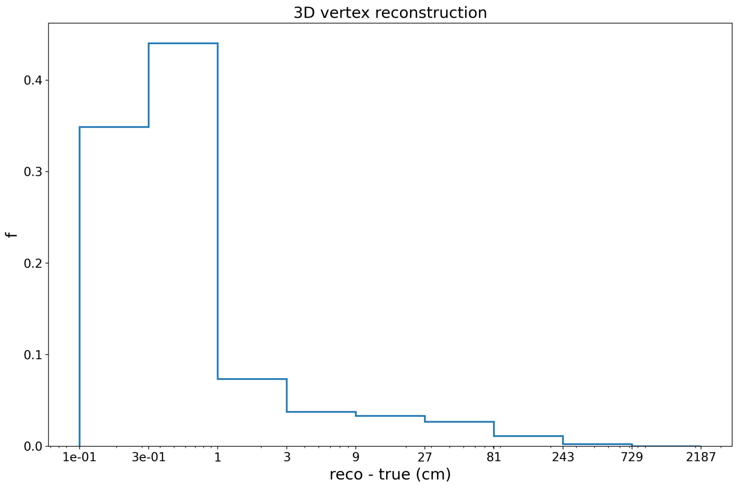


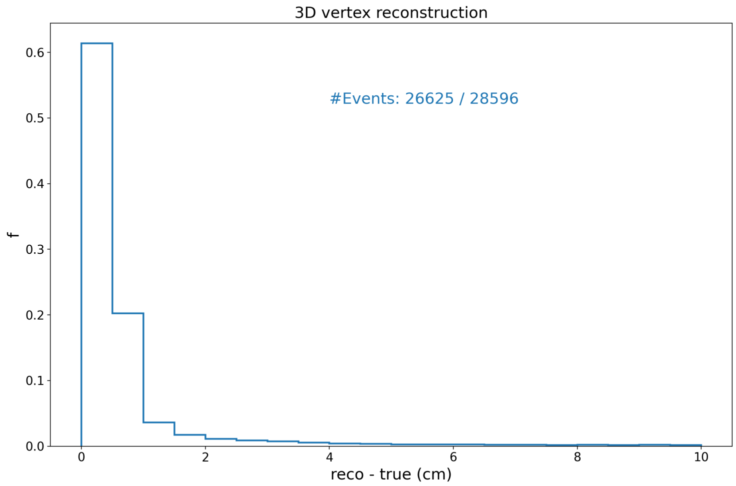
Network infers hit distances and resultant heat map isolates candidate vertex



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.





Compared to 61% with the old method.

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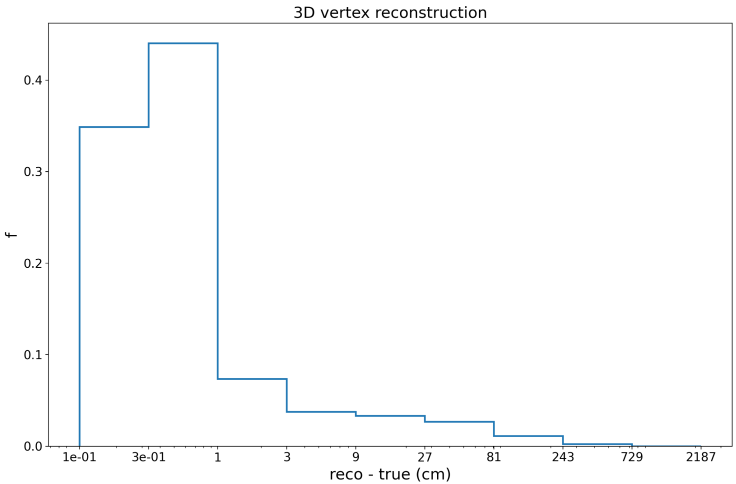
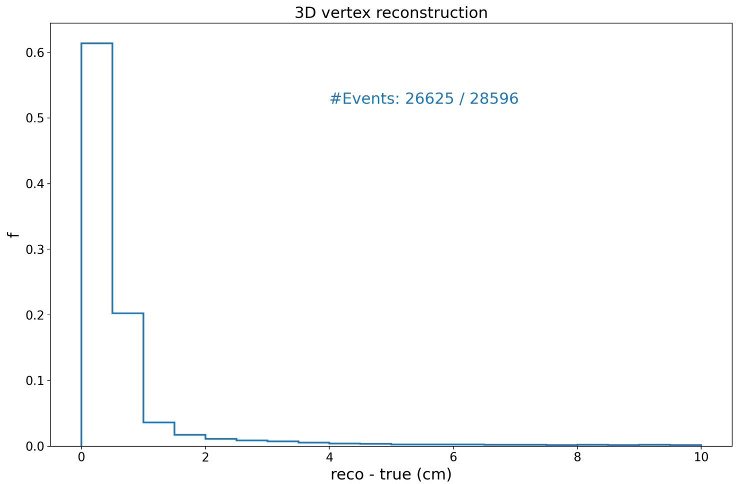




This new vertexing is currently developed for beam interactions in the DUNE horizontal drift detector, but work is ongoing to also deploy it for atmospheric interactions, the vertical drift and near detector, as well as use at MicroBooNE and other experiments.

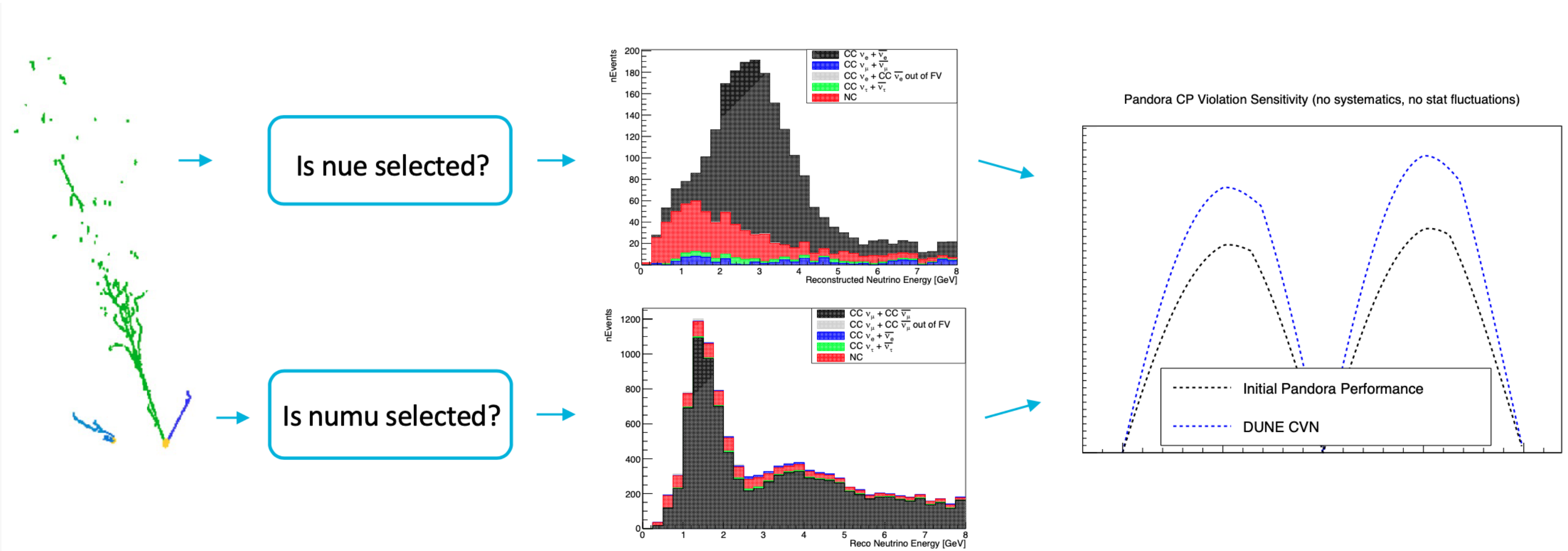
Compared to 61% with the old method.

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, an analysis can be targeted, with sophisticated studies performed that show the impact of individual algorithms to identify the weakest or a missing algorithm, and how directed changes to that algorithm could impact the overall analysis.

This means developments to Pandora are directed to the areas that need it most and have the largest impact on ongoing analysis in working groups.



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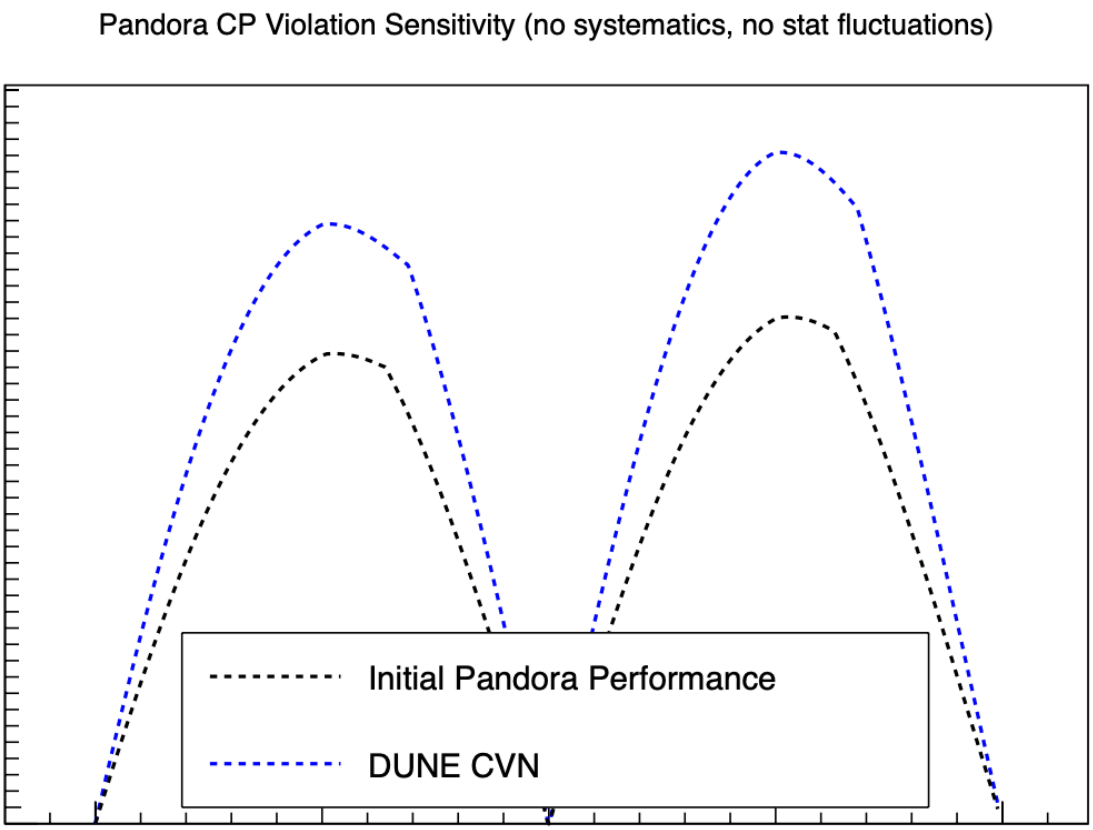
The best example of this style of approach is the work by Isobel Mawby for DUNE, to identify pain points for the CPV analysis.



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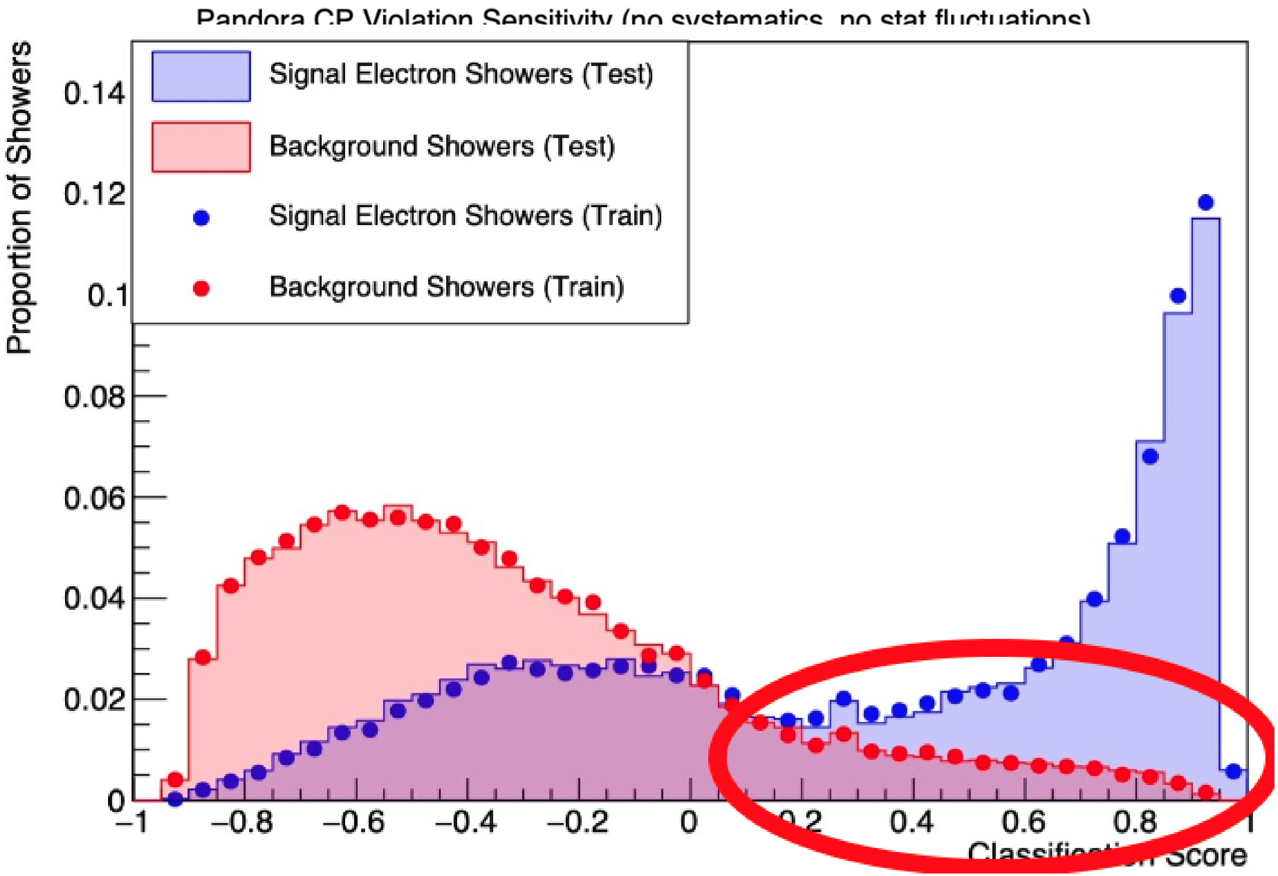

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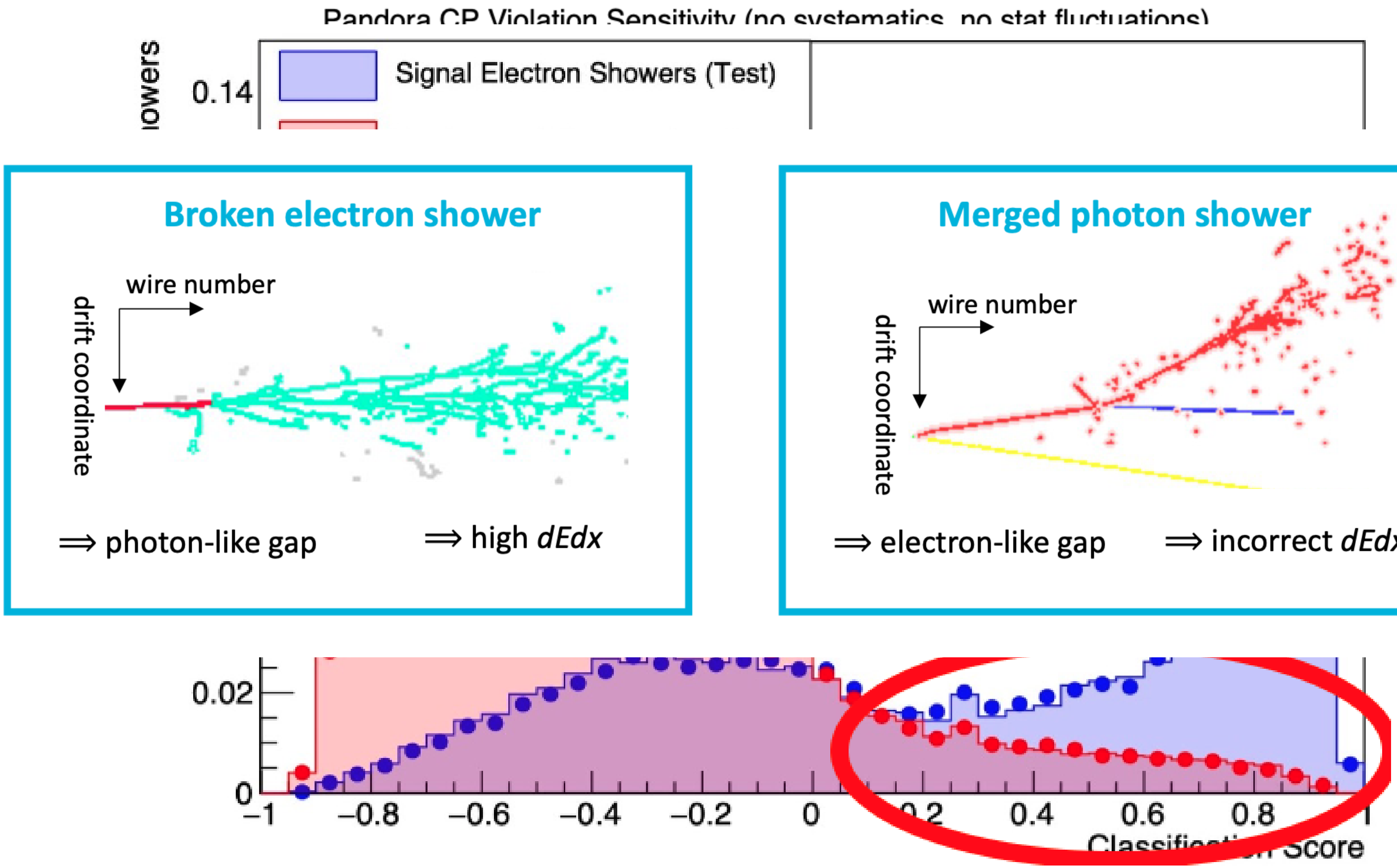

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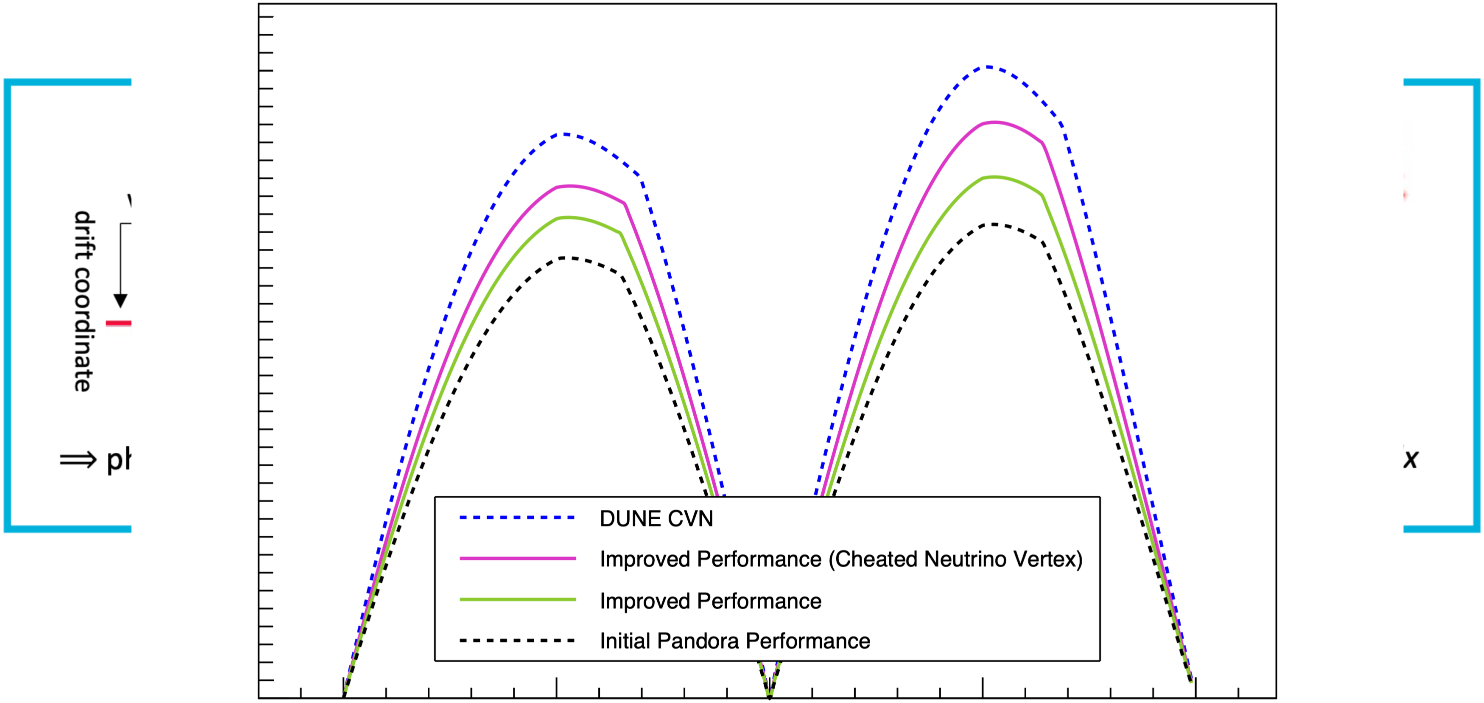

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- These steps can then be addressed by algorithms (traditional, ML, DL), integrating detector and physics knowledge where useful.
- The Pandora framework is a UK-developed and UK-supported framework, with major UK support and development for LArTPCs, and support for ILC/CLIC.
- There is significant work ongoing inside Pandora to support DUNE (and every detector under that umbrella), as well as SBND 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.
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