Pandora: The Hope Left in the Jar for Reconstruction at The Deep Underground Neutrino Experiment

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Contents

- Neutrino Oscillations
- The Deep Underground Neutrino Experiment
- Pandora Pattern Recognition
- Pandora at the Far Detector
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Neutrino Oscillations

- Flavour eigenstates associated with the weak interaction, mass eigenstates associated with the Hamiltonian

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}c_{23} \end{pmatrix}$$

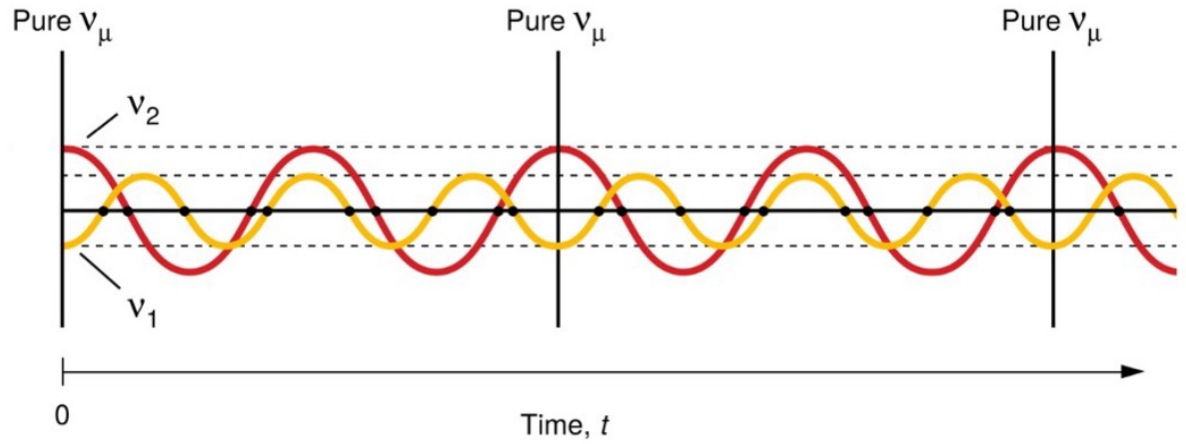
- In the two-flavour approximation:

$$|\nu\rangle = A_1(t)|\nu_1\rangle + A_2(t)|\nu_2\rangle$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{2E}\right)$$

mixing angle

mass splitting $\Delta m^2 = m_1^2 - m_2^2$



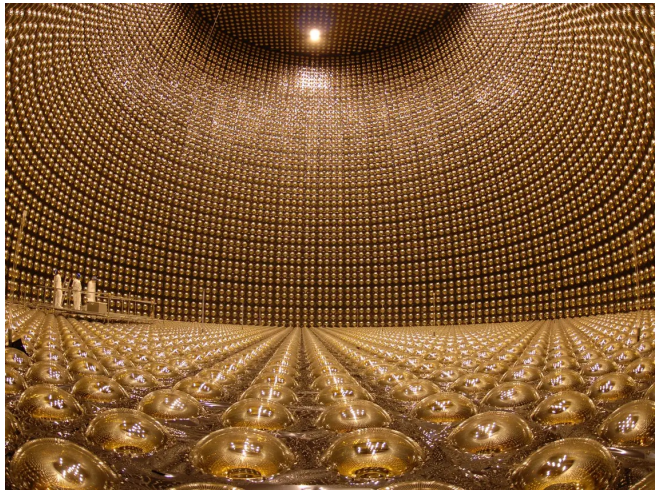
Measuring the Oscillation Parameters

A very simplified experiment:

1) Create a neutrino beam
2) Sample un-oscillated neutrino flux at a near detector - use to constrain flux, cross-section and detector models
3) Sample oscillated neutrinos at far detector
4) Simultaneously fit both ND and FD samples to extract oscillation parameters – relies on common detector technology!

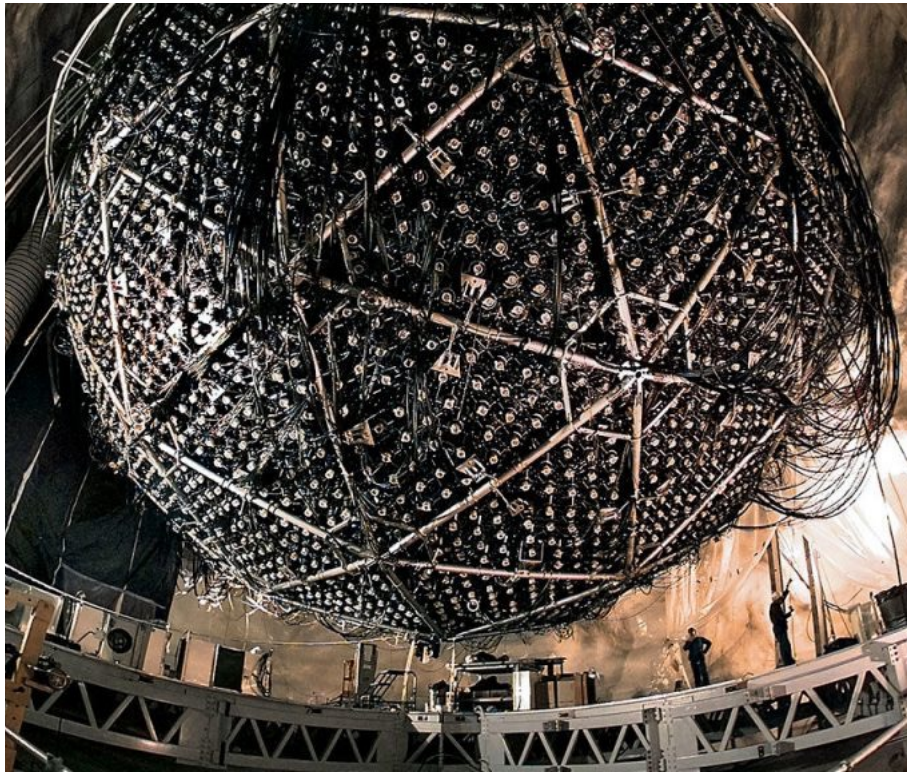
J-PARC

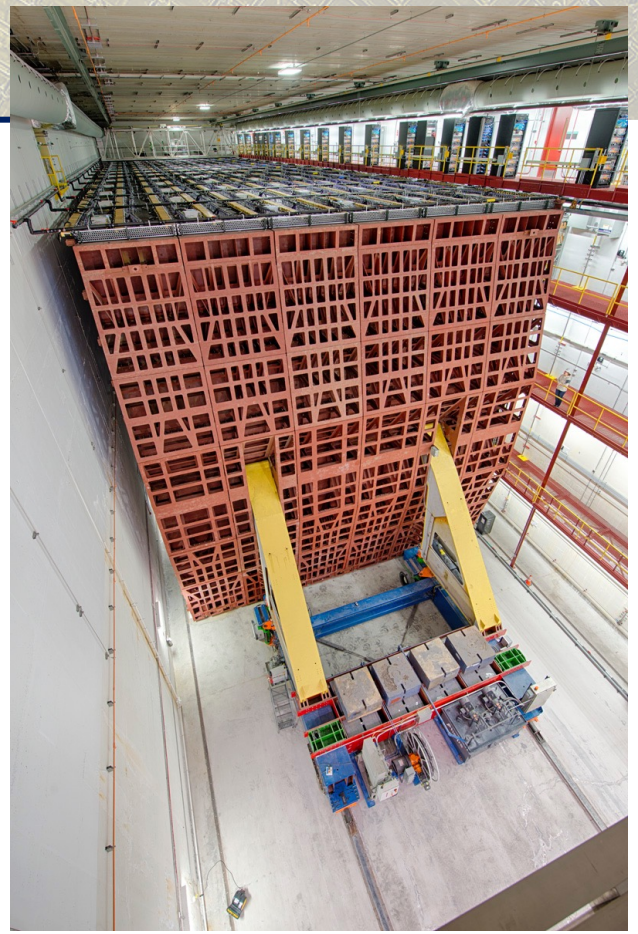
T2K ND

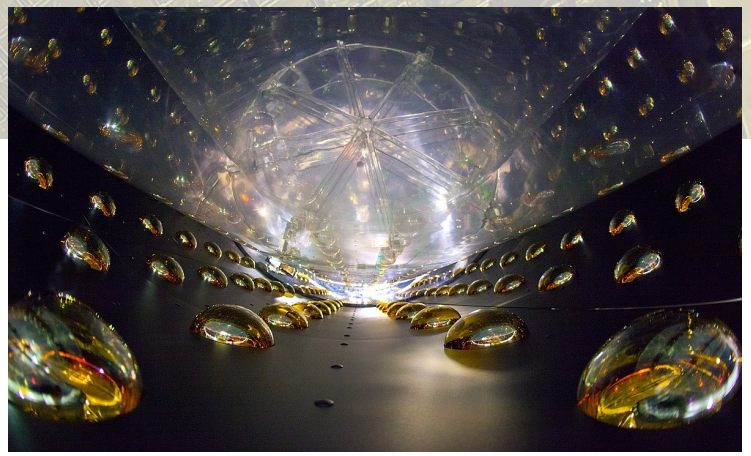


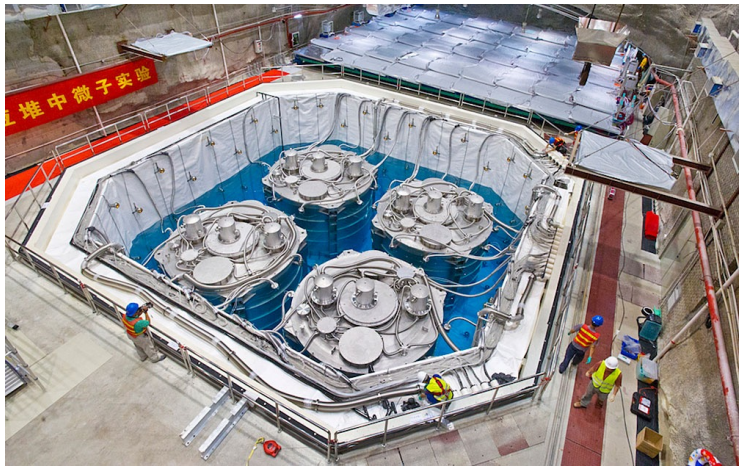
Super-K

The Knowns









Long-baseline reactor experiments & solar experiments (e.g. SNO)

$\rightarrow \theta_{12}, \Delta m^2_{21}$

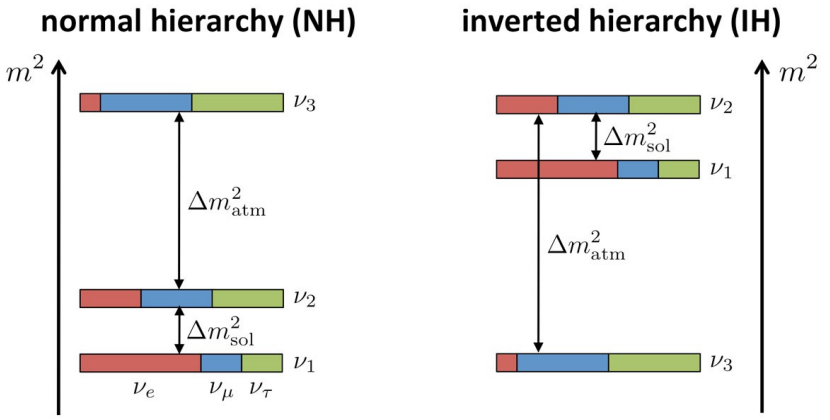
Long-baseline accelerator experiments (e.g. NOνA, T2K)

$\rightarrow \theta_{23}, |\Delta m^2_{32}|$

Short-baseline reactor experiments (e.g. Daya Bay)

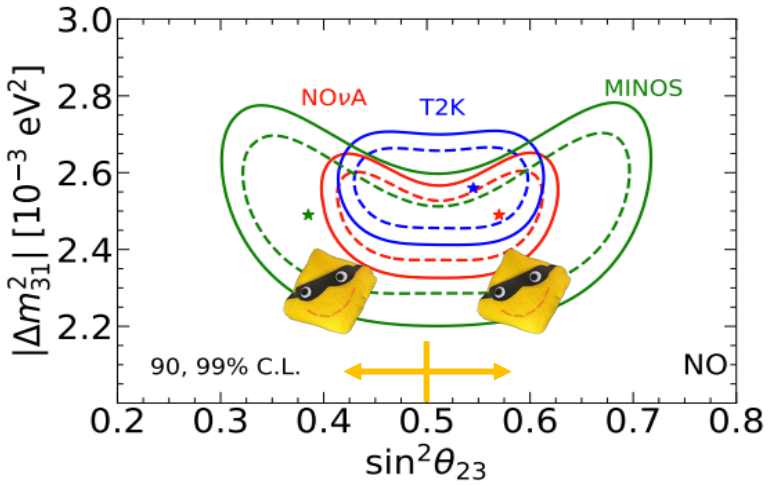
$\rightarrow \theta_{13}$

The Unknowns

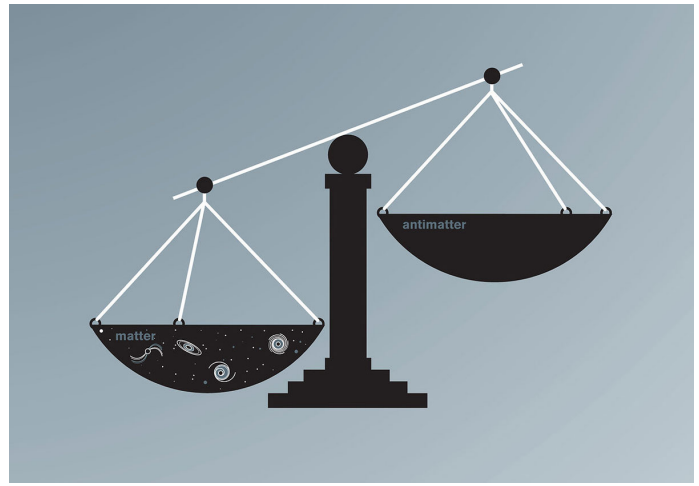


Normal $(m_1 < m_2 < m_3)$ ordering?

Inverted $(m_3 < m_1 < m_2)$ ordering?



Whether θ_{23} occupies the lower or higher octant?



Whether CP is violated in the leptonic sector?

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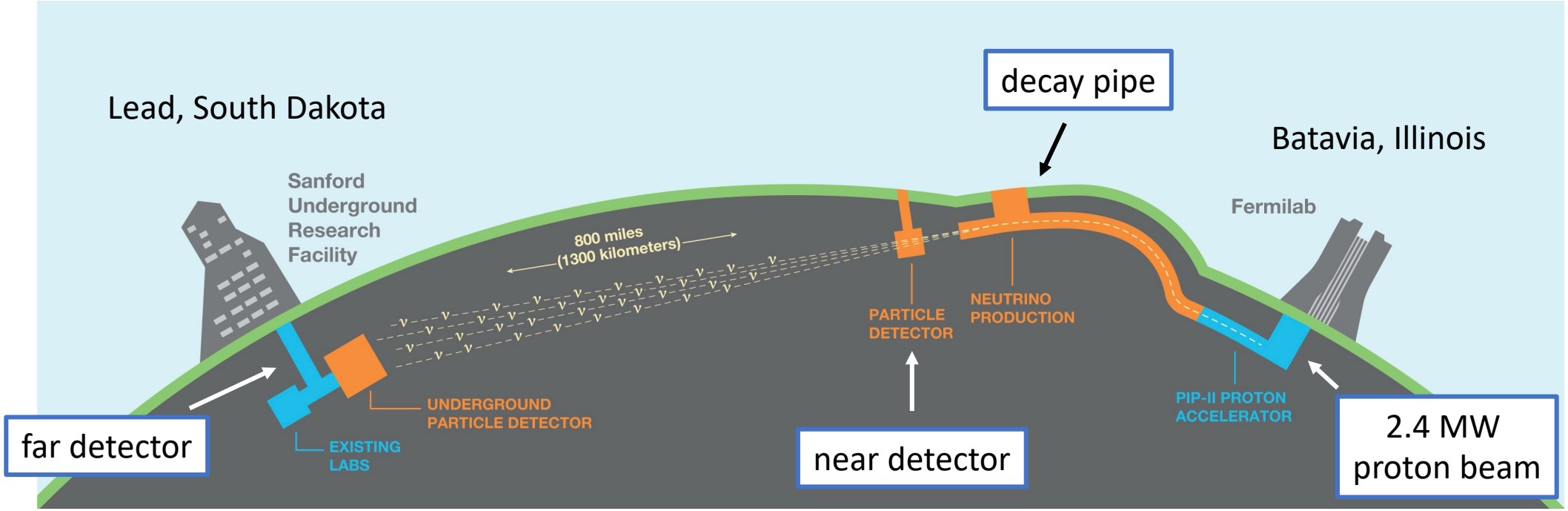
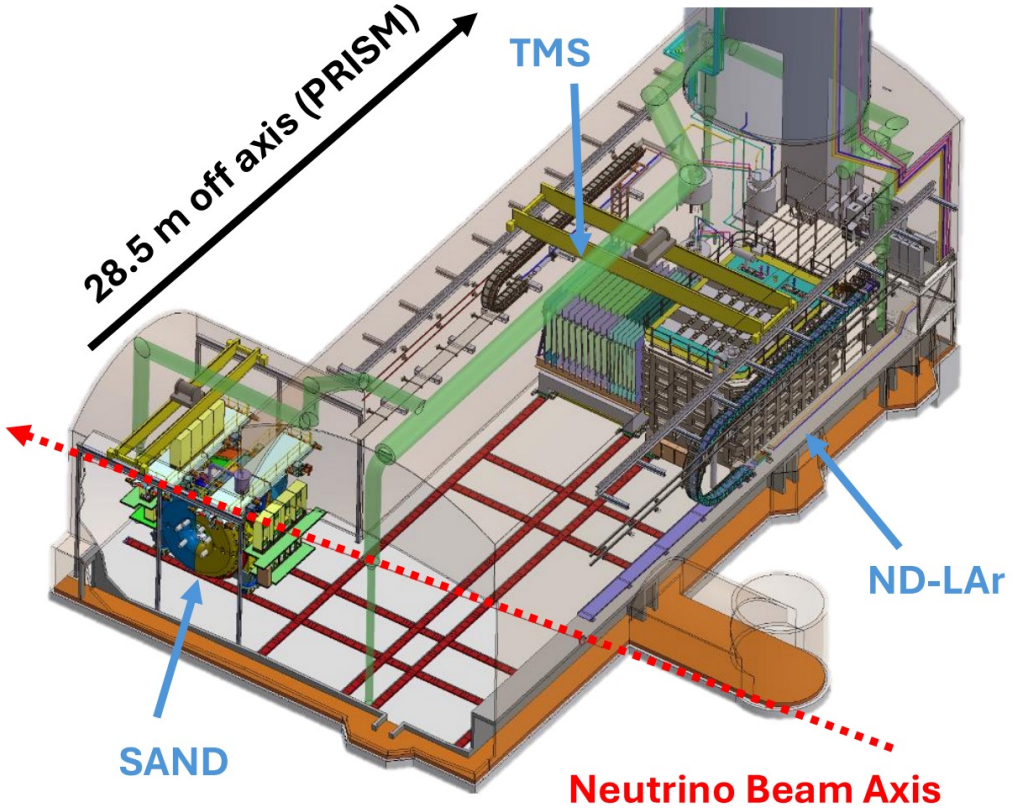
The Deep Underground Neutrino Experiment

Primary goals:

- Precisely measure all neutrino oscillation parameters in a single experiment
- Search for beyond the standard model physics e.g. proton decay
- Detect low energy neutrinos e.g. those from a supernova burst



The Near Detector Complex



1) ND-LAr:

- Measure neutrino interactions with same detector technology as the far detector (LArTPCs)

2) TMS (phase I), ND-GAr (phase II)

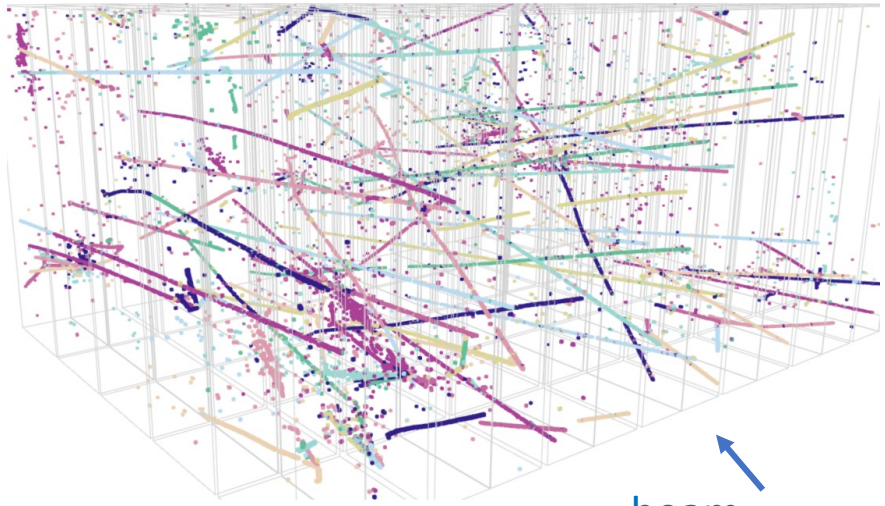
- Catch muons exiting ND-LAr to preserve neutrino energy resolution
- Magnetised – $\nu/\bar{\nu}$ separation
- Better understand neutrino cross-sections, constraining systematics

3) SAND

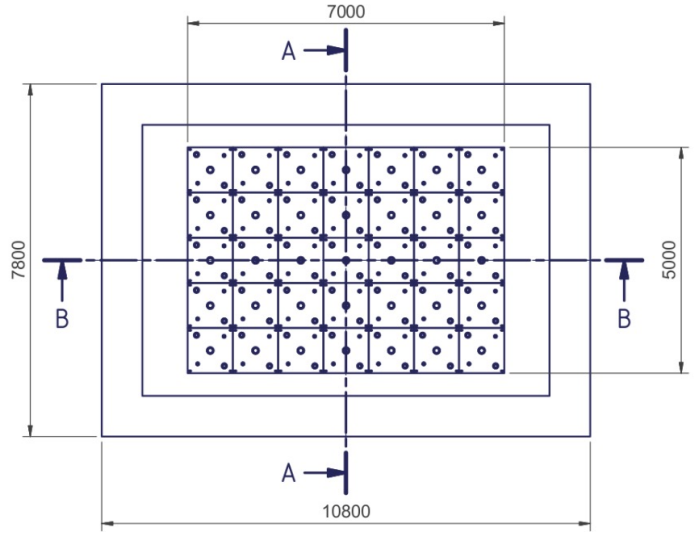
- Beam monitor

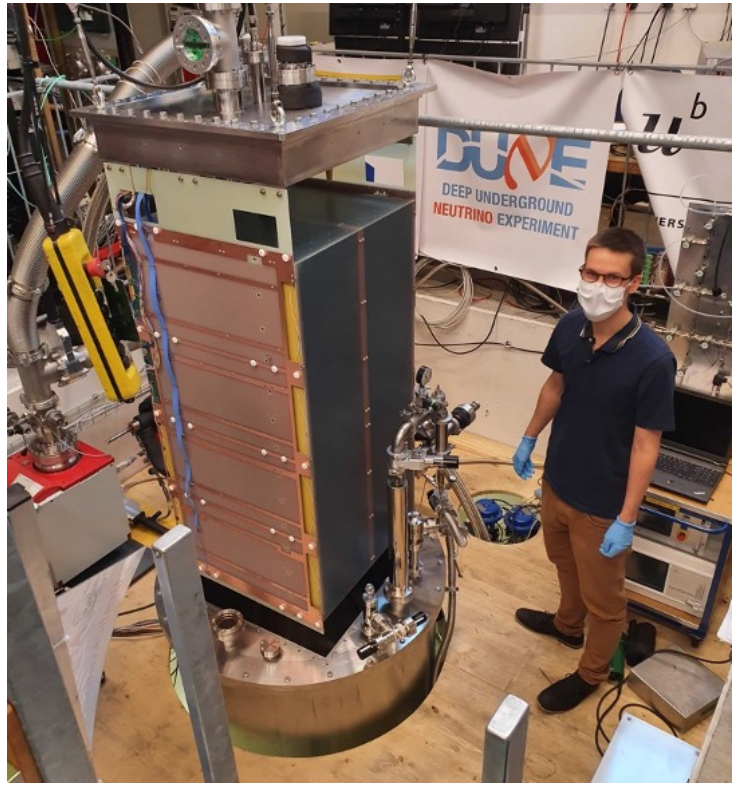
ND-LAr

- ~574m downstream from the world's most intense neutrino beam
- ~50(!) neutrino interactions per beam spill
  - Alongside a dense cosmic-ray and rock-muon environment…



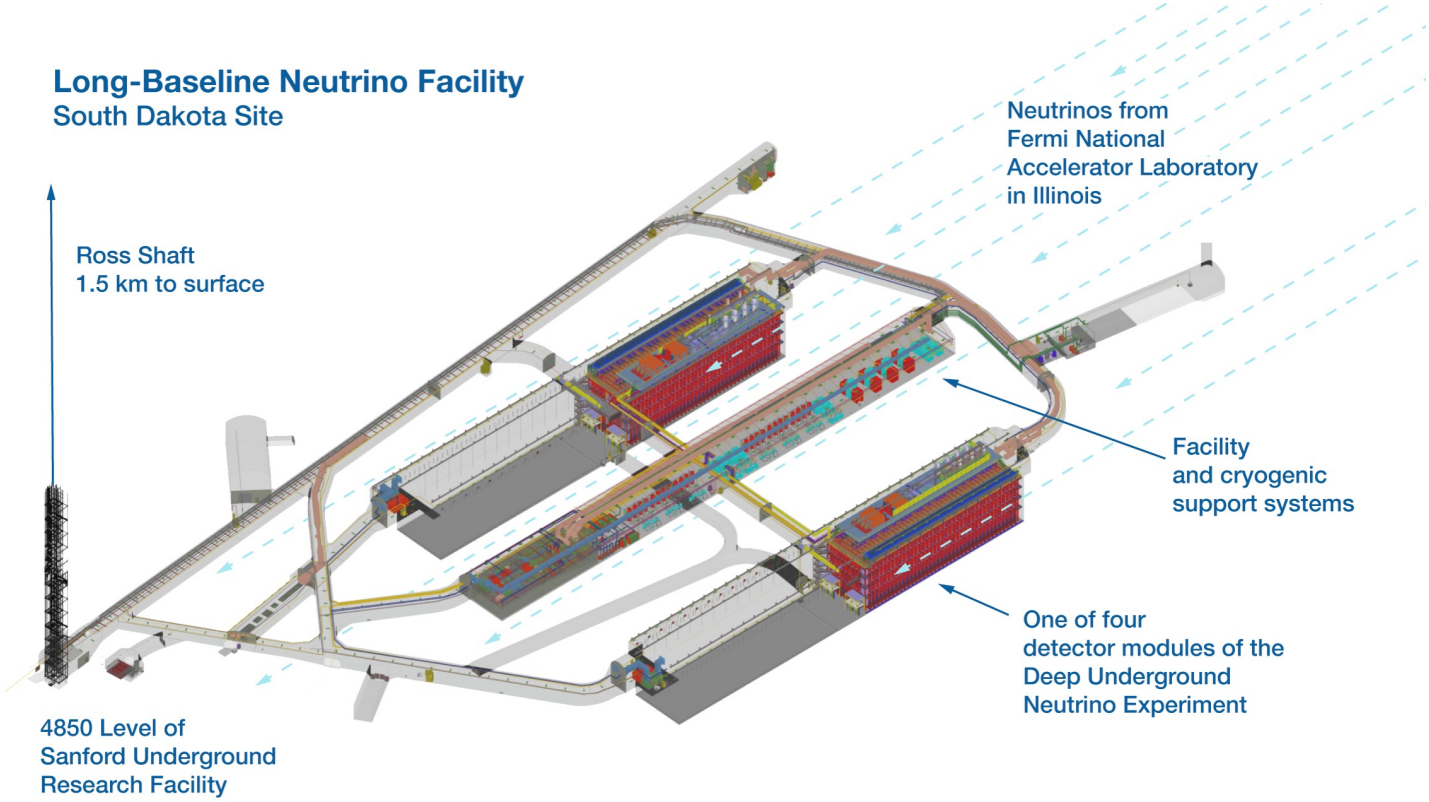
- Traditional, monolithic, projective wire readout modules would be stretched far beyond their limits
  - → Employ a modular structure, in which each module is optically isolated
  - → Use a pixel readout ⇒ 3D input



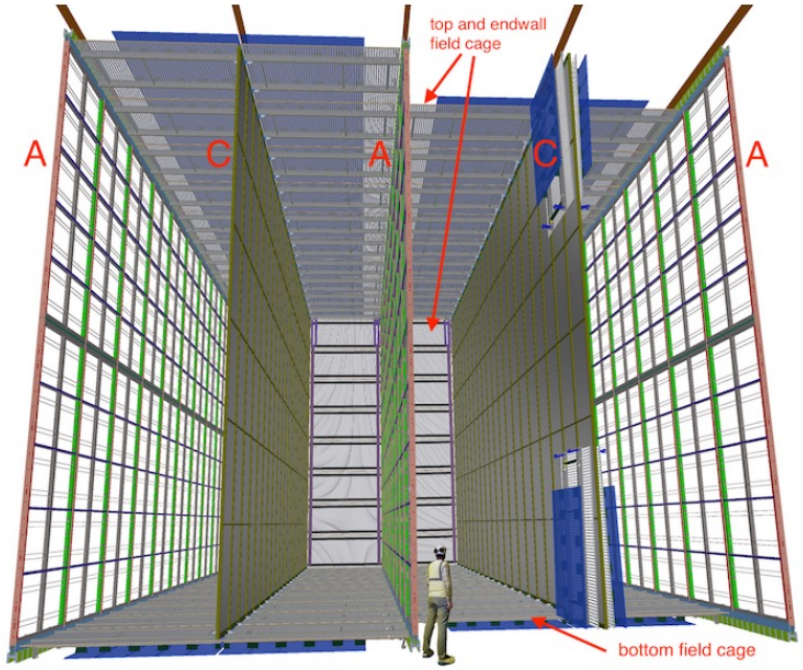


Module for the ND-LAr prototype: final module will be twice as tall, with five times the volume!

The Far Detector Complex



In this talk, I'll mostly focus on the horizontal drift detector:



- Three of four far detector modules will use LArTPC technology
- Technology of 'module of opportunity' is TBC
- ∽1 mile 'deep underground', significantly reducing the number of cosmic-rays

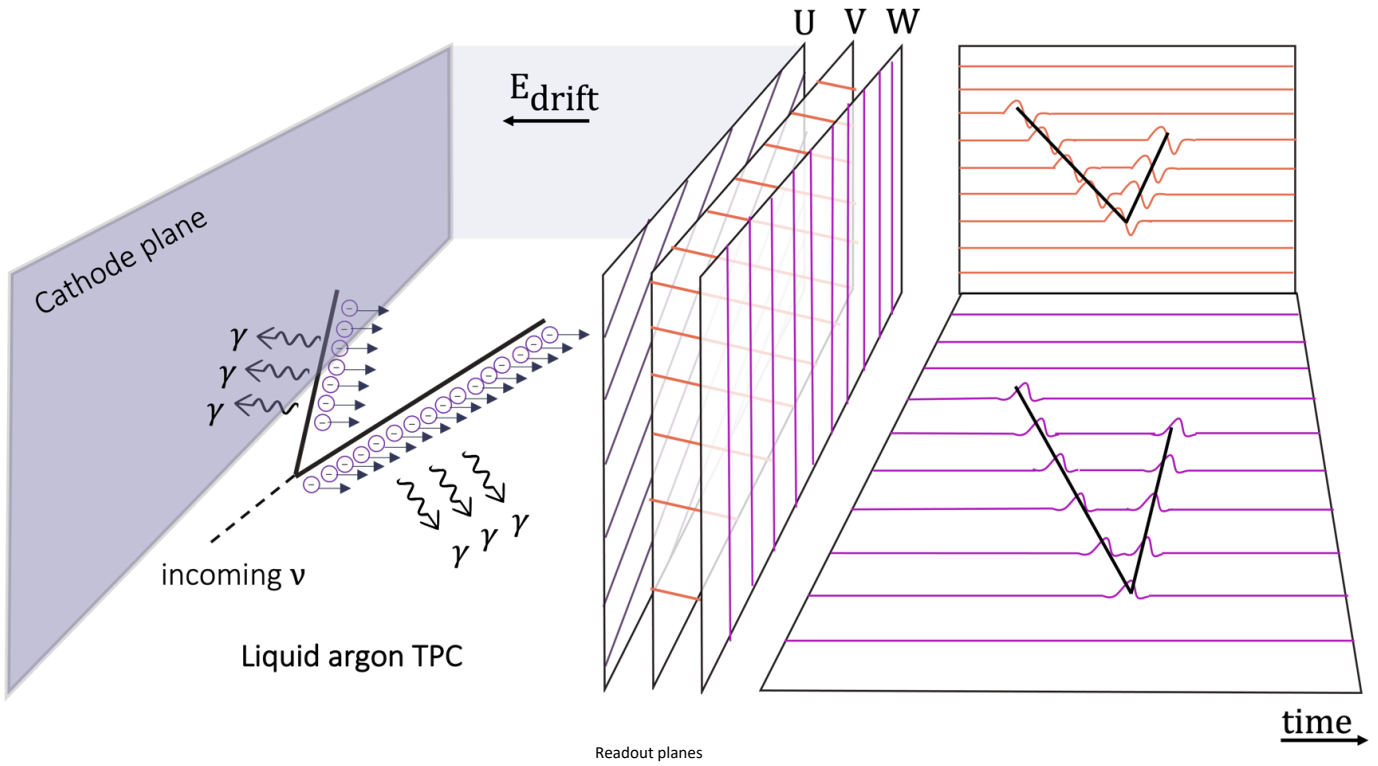
To put the size of these modules into scale:

- 3 adult giraffes tall
- 2.5 tennis courts long
- 10kt fiducial volume

Liquid Argon Time Projection Chambers

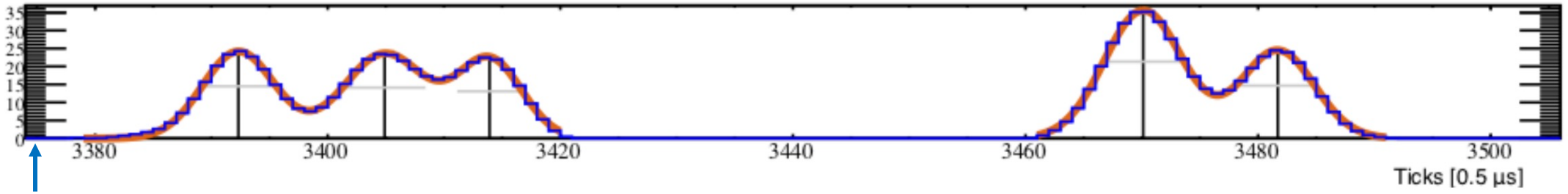
- The DUNE far detector modules will employ liquid argon time projection chamber (LArTPC) technology:
  - Neutrinos enter the detector and interact with argon nuclei
  - Outgoing charged particles ionise the liquid argon as they traverse the detector
  - An applied electric field drifts the ionisation electrons to a series of wire planes where they are detected

- Photon detection system is used to identify neutrino interaction time



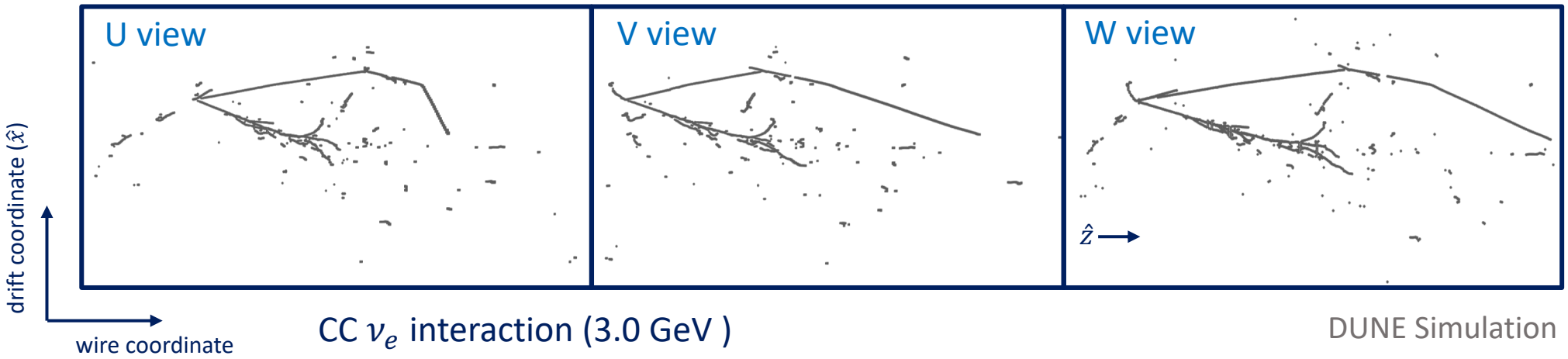
Detector Response to 2D Images

- Each wire observes ‘waveform’s i.e. charge induced/collected on/by a wire as a function of time



x-axis: time taken for the ionisation electrons to drift to wire-plane (with respect to trigger)

- Waveforms are converted to ‘hit’s – with a charge, wire-coordinate, drift-coordinate and width (obtained by Gaussian fits)
- Hits form the 2D images that are the input to our reconstruction!



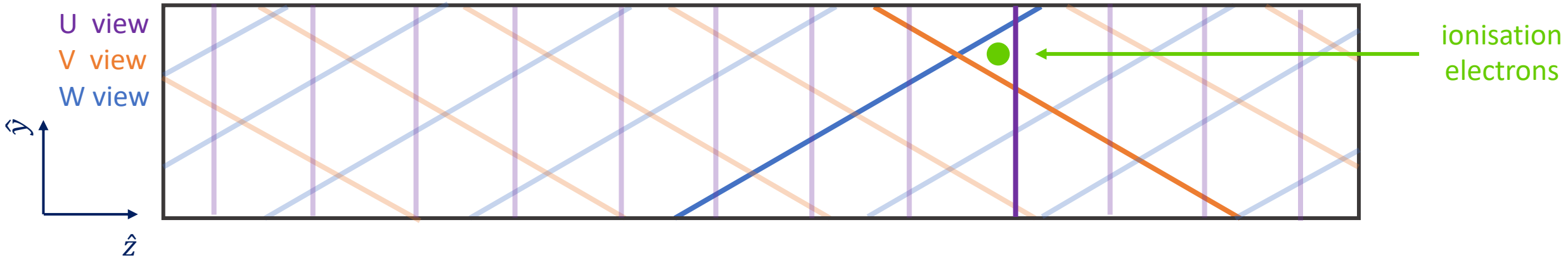
CC ν_e interaction (3.0 GeV)

DUNE Simulation

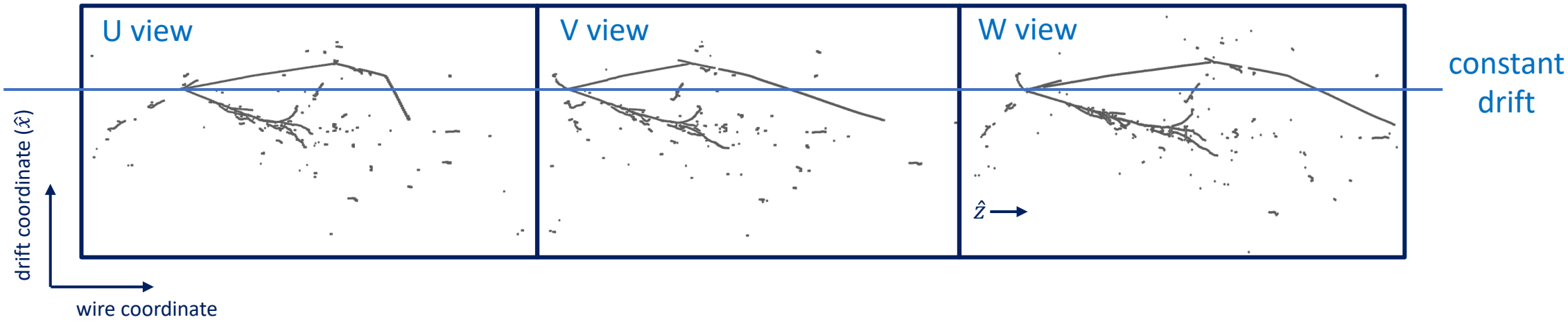
We can see neutrino interactions in incredible detail!

Moving to 3D

- We have three planes of wires, each with a different orientation, and a common-drift coordinate (x)



- Two wires can locate the particle's position in the y-z plane, combined with x we have a 3D coordinate!



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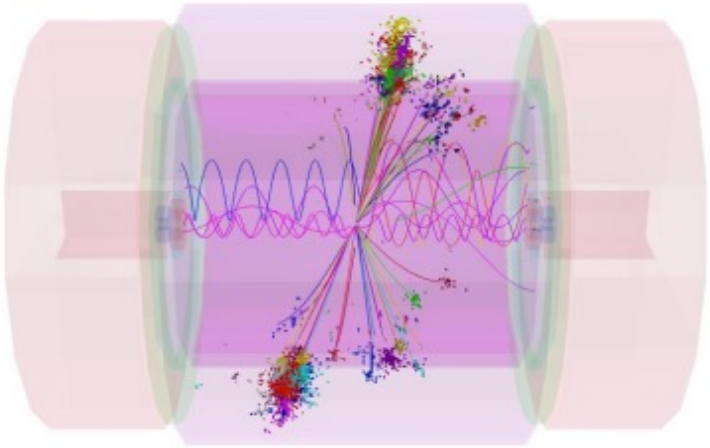
Pandora – The Hope Left in the Jar [1]

2006 - 2009:

- Concepted and developed by CERN DG Mark Thompson for the ILC

2010 - 2012:

- 6 - 12 months of software design (John Marshall) resulting in ‘Pandora SDK’
- Enabled application to CLIC with *ease*



[1]

2013 – present:

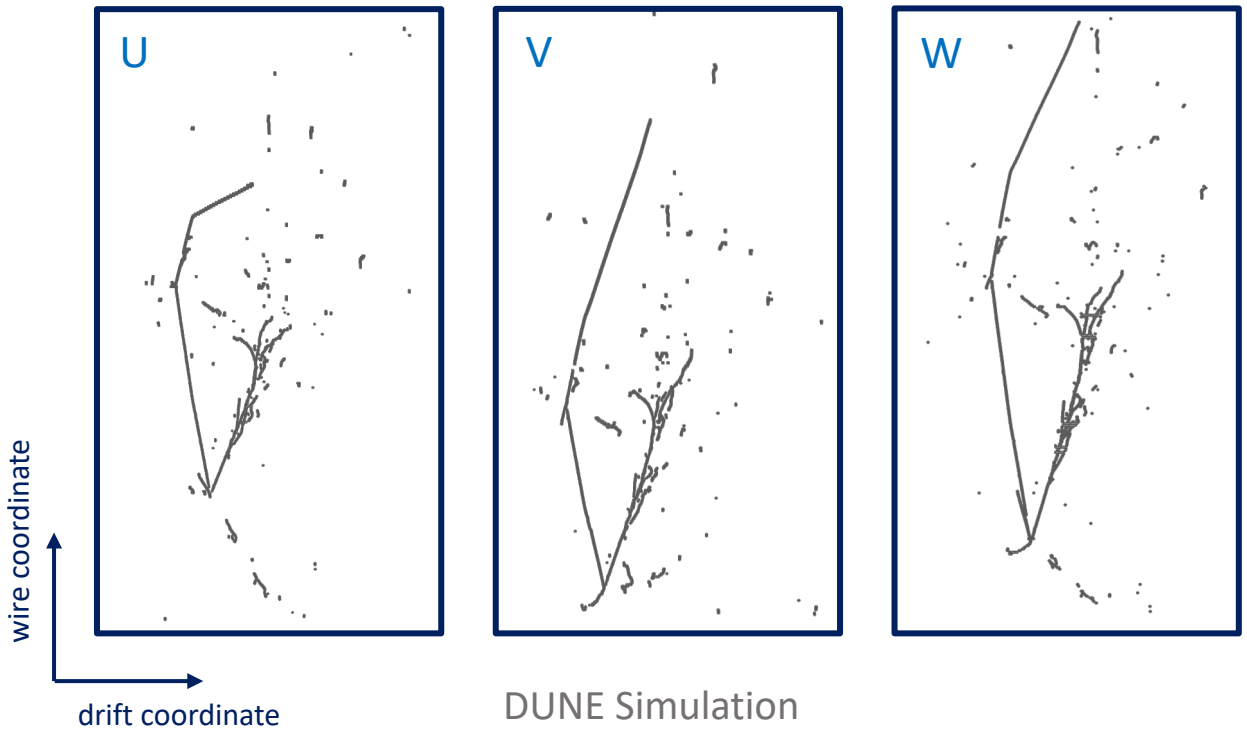
- The Pandora team joined MicroBooNE and LBNE (DUNE)
- No automated reconstruction existed for neutrino interactions
- An initial suite of LArTPC reconstruction algorithms was developed and deployed for MicroBooNE
- 49 (out of 76) MicroBooNE papers cite Pandora (as of Sept 2025)

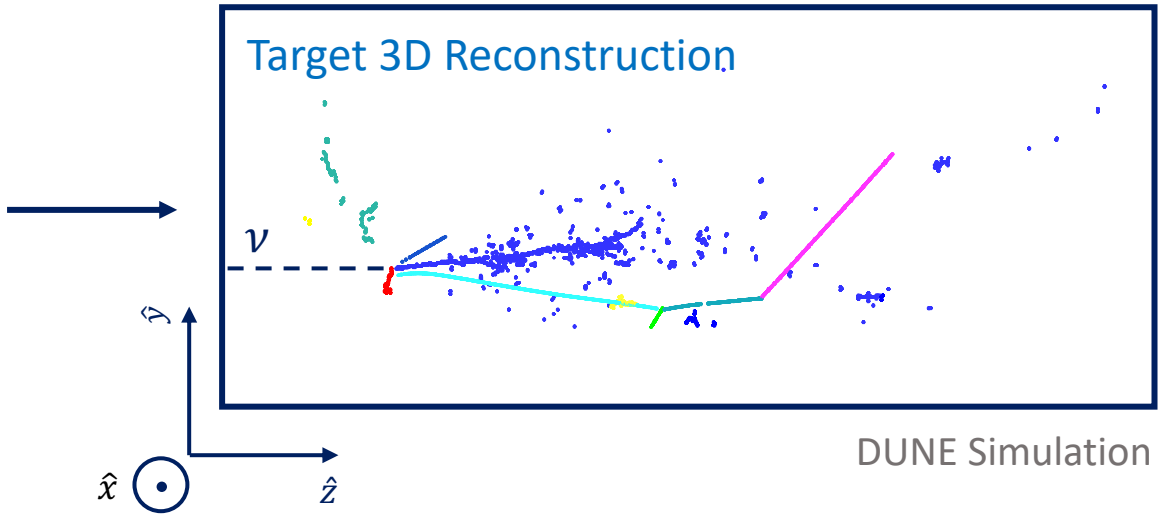
(2019 – present)

- STFC award £3.8 million to the RS&DC project, funding Pandora far detector development for physics-ready reconstruction in 2028
- Far detector development team (5 postdocs, 1 PhD) – including me (senior developer)
- Near detector development team (4 postdocs, 2 students)
- One of the leading reconstruction packages used at SBND, ICARUS, ProtoDUNE and DUNE

Reconstruction Task at DUNE FD

CC ν_e interaction (3.0 GeV)

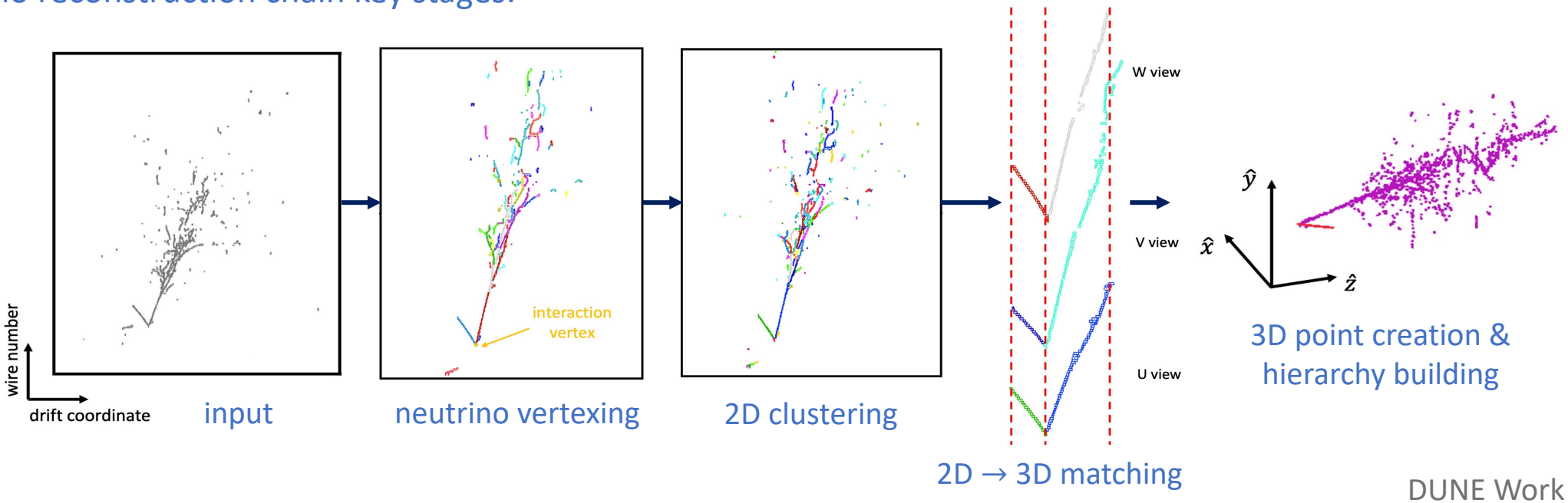




The Multi-algorithm approach

- Pandora uses a 'multi-algorithm approach' employing hundreds of algorithms to slowly build up the reconstruction output
- Algorithms are designed to be detector-agnostic ⇒ can be used in all LArTPC experiments
- Multi-algorithm approach allows for interaction (e.g. neutrino, cosmic-ray, test-beam) and analysis specific (e.g. beam, atmospheric, supernova neutrino) optimised reconstruction chains

e.g. neutrino reconstruction chain key stages:



input | neutrino vertexing | 2D clustering | 2D → 3D matching | 3D point creation & hierarchy building

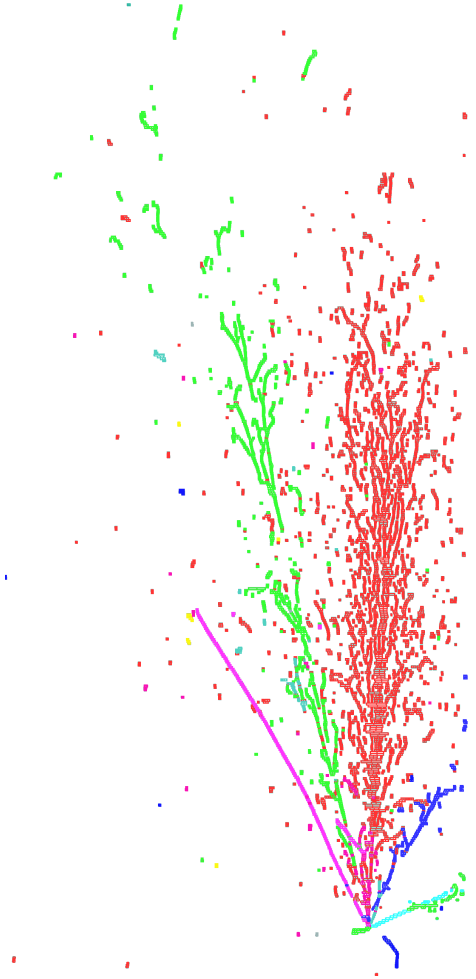
DUNE Work In Progress

AI in Pandora

- The team's strong ML expertise ensures the latest ML techniques are adopted by algorithms where appropriate e.g. transformers

- We aim to target our use of ML:
  - At their core, most Pandora algorithms make a decision on which to act on
    - e.g. should these clusters be merged?
  - Often 'hand-engineered' logic can successfully make these decisions
    - e.g. do the cluster directions align? Are they close?
  - But sometimes these decisions are very difficult, and an ML approach is more performant
    - e.g. shower cluster merging in high shower multiplicity environments

- We're going to see lots of ML examples throughout this talk



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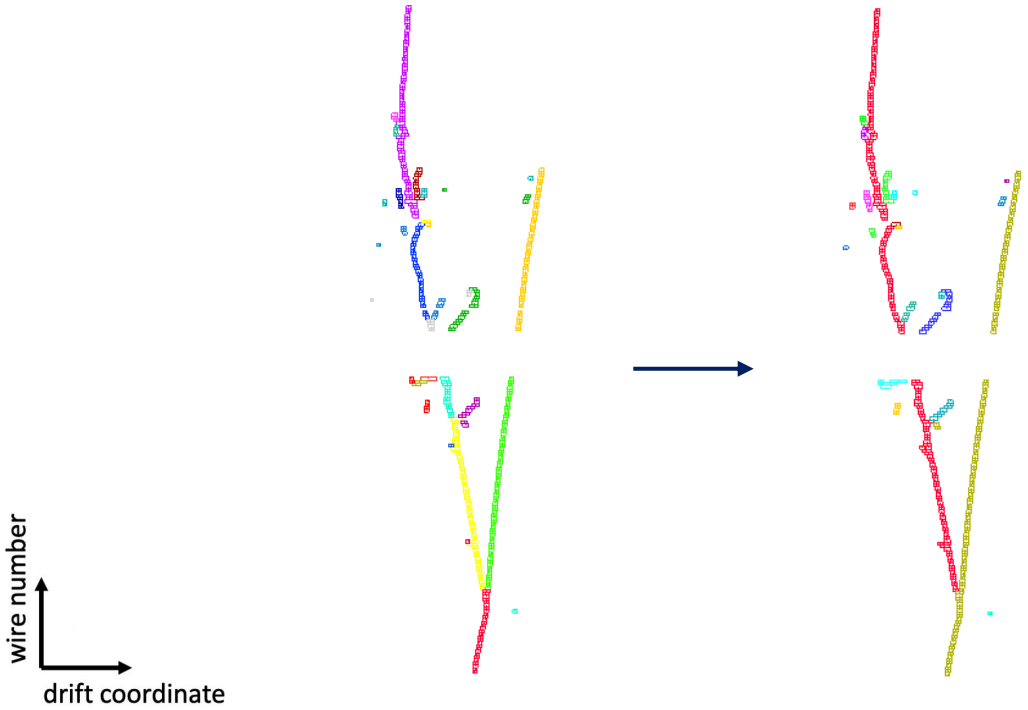
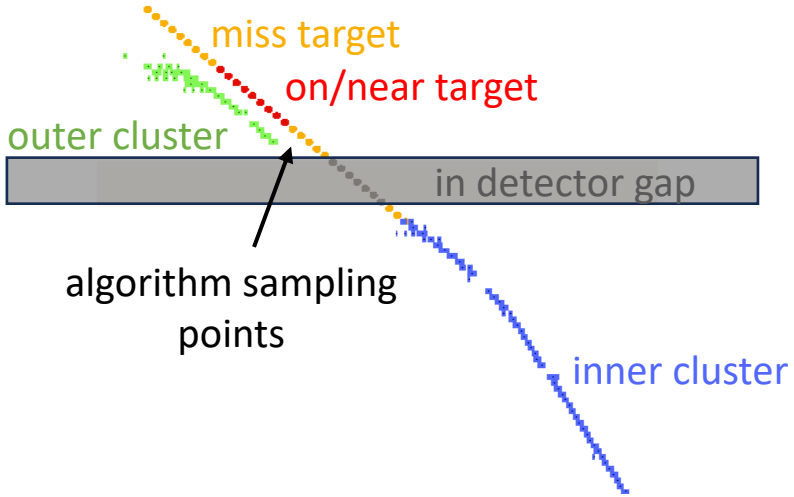
- Initially, in each view, a cautious clustering algorithm uses proximity-based logic to group hits into seed clusters
- 15 cluster-merging and cluster-splitting algorithms grow and refine the seed cluster based on topological information
  - Each algorithm targets a specific topology!



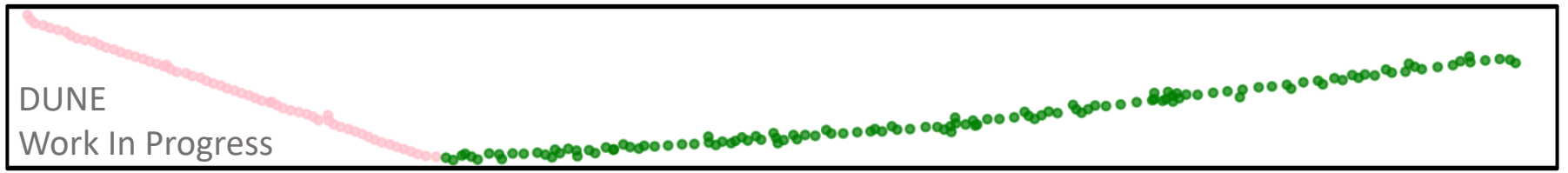
LArLongitudinalAssociation: merges clusters that align in the general energy direction



LArCrossGapsAssociation: merges clusters that that cross known detector gaps

I. Mawby

- Cluster splitting algorithms fix instances where clustering algorithms have over-merged, e.g.



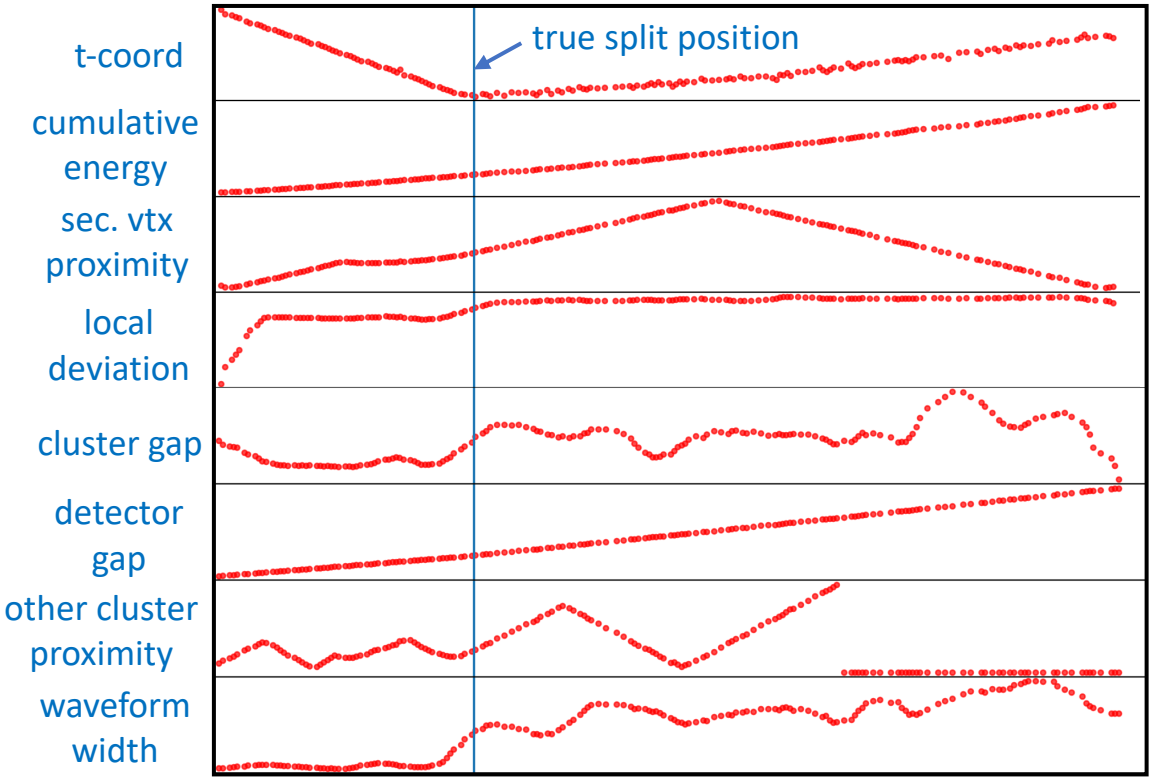
DUNE Work In Progress

- A couple of cautious hand-engineered splitting algorithms are employed
  - Fitting procedure smooths out some kinks
  - Uses large thresholds to avoid incorrect splits

⟹ Accompanied by an ML approach (DLClusterSplittingAlgorithm)

DLClusterSplittingAlgorithm:

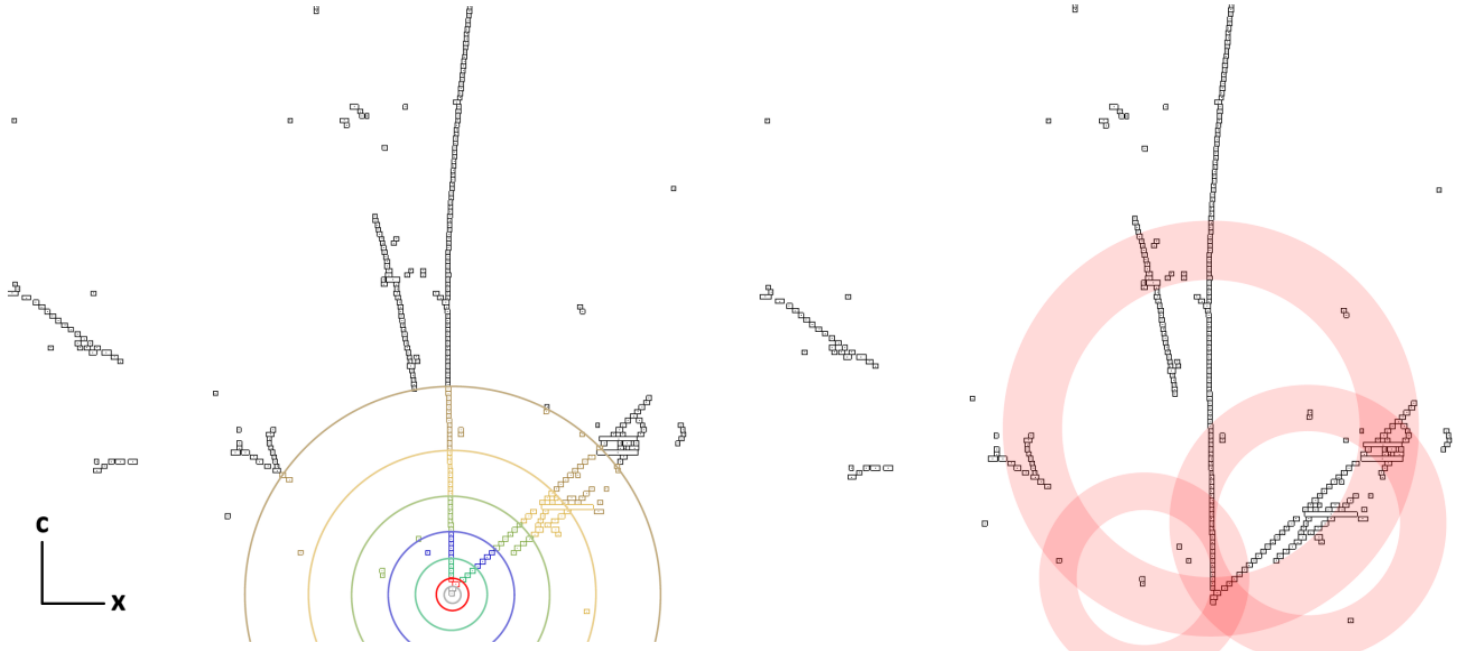
- Constructs multi-variable time series from input 2D clusters
- Consider variables with strong separation power e.g. dE/dx alongside those that resolve ambiguities e.g proximity to other clusters
- Allows us to correct these subtle cases whilst still being cautious!



- Common challenge in neutrino physics – unknown neutrino interaction vertex position
- The interaction vertex anchors our reconstruction logic
  - ⟹ mis-placements are fatal, causing particles to be split and resulting in an incorrect neutrino hierarchy

- DLVertexingAlgorithm: targeted use of ML to identify the neutrino interaction vertex:

1. CNN U-ResNet based network predicts each hit's distance from the neutrino vertex (in terms of a distance class)
2. Predicted classes are used to build a heat map, locating the neutrino vertex

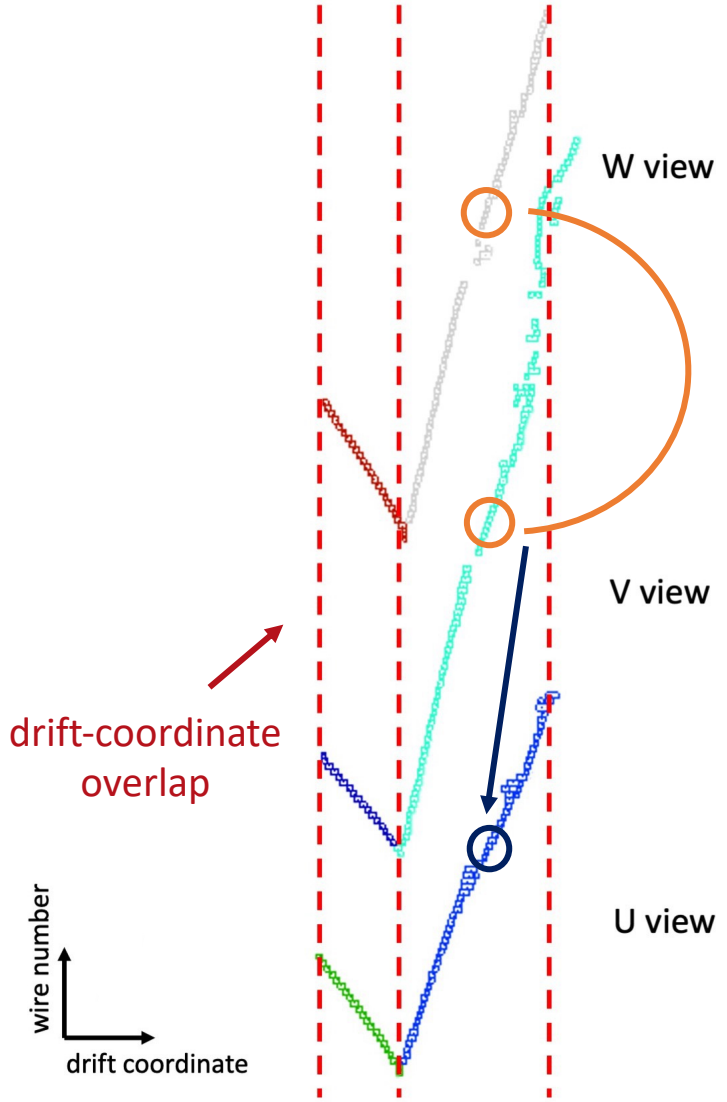


- Published in EPJC: Eur. Phys. J. C 85, 697 (2025)

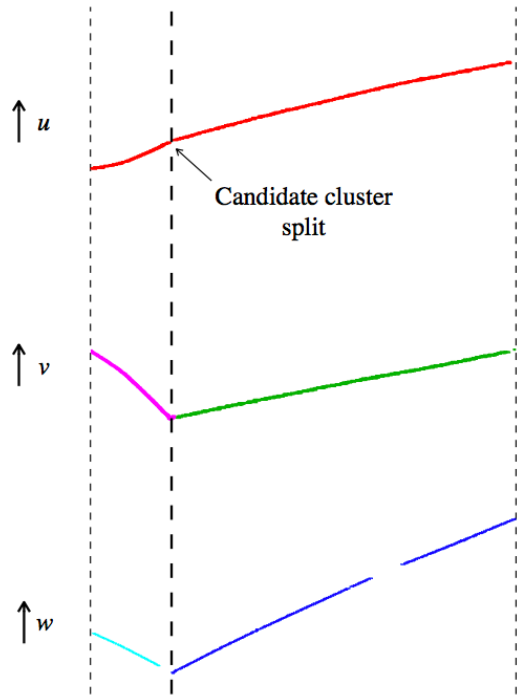
This network has been retrained for different use-cases across Pandora!

- Each particle can be expected to have a 2D cluster in each view
- In the track creation stage, the aim is to group 2D track-like clusters into particles

- Remember, the drift-coordinate is common, and so:
  1. Search for clusters that exist in the same drift region
  2. Take a cluster triplet e.g. {U cluster, V cluster, W cluster}
  3. Walk along x and use the positions in U and V to predict the corresponding position in W
  4. Compare with the W cluster positions
  5. Repeat for each permutation
  6. If in good agreement, group the clusters!

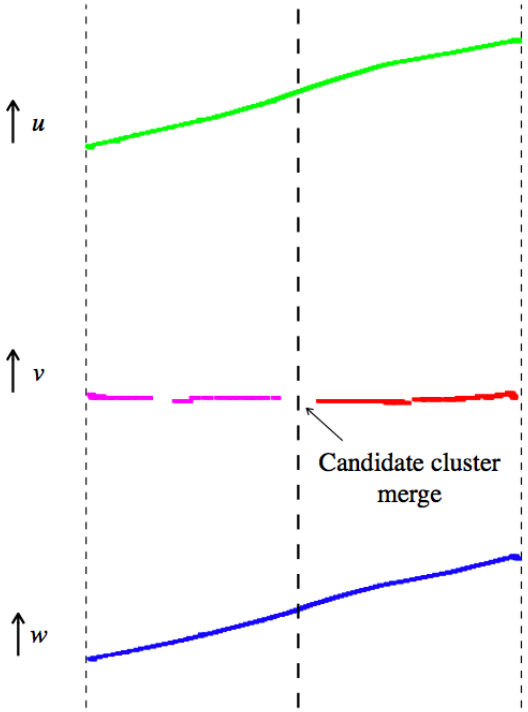


- Having three views (as opposed to two) corrects un-avoidable mistakes!



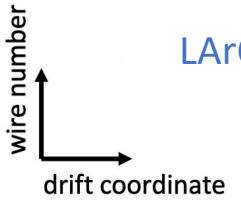
u:*v*:*w*
1:2:2

two {V, W} cluster pairs match to one W cluster
⇒ split W cluster



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

one {U, W} cluster pair matches to two V clusters
⇒ merge V clusters



LArOvershootTracksTool: aims to split clusters that are otherwise seen to be ‘straight’

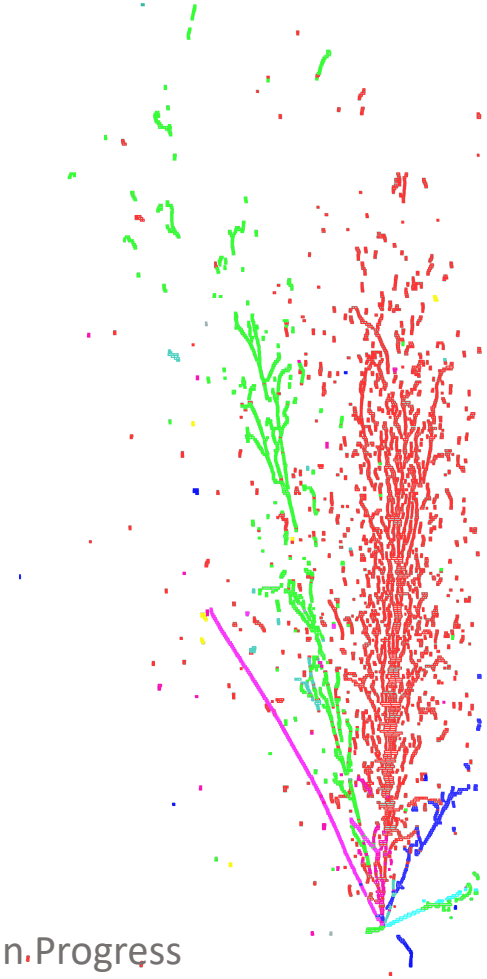
LArUndershootTracksTool: aims to merge clusters that have been broken due to detector gaps or ‘poor’ signal processing

CC $\bar{\nu}_e$ interaction

Track clustering output

DUNE Work in Progress

Truth clustering
(track + shower clustering target)



DUNE Simulation

- MicroBooNE-era ‘hand-engineered’ shower growing algorithm pushed to its limits at DUNE

⇒ LArDLTwoDShowerGrowing algorithm:

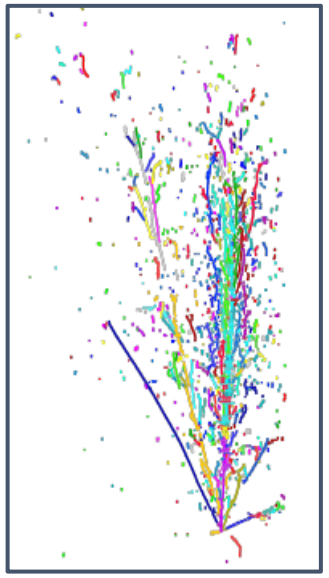
- Targeted use of ML to predict cluster similarity
- Hand-engineered logic to merge clusters

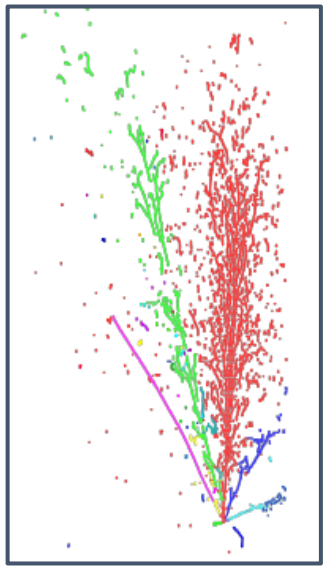
AI

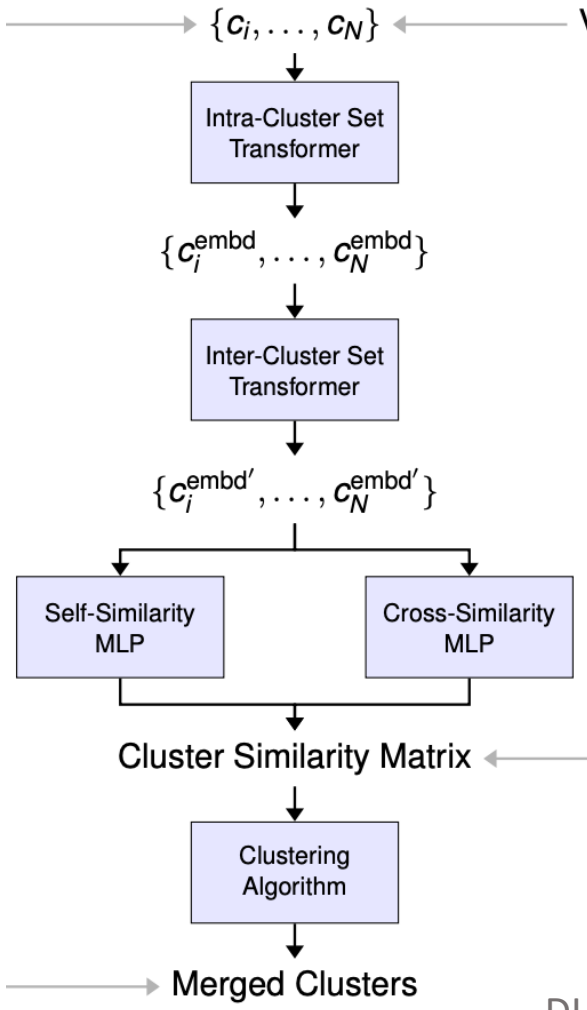
1. Initial transformer predicts the similarity of hits in each cluster
2. Second transformer predicts the similarity of clusters in the event

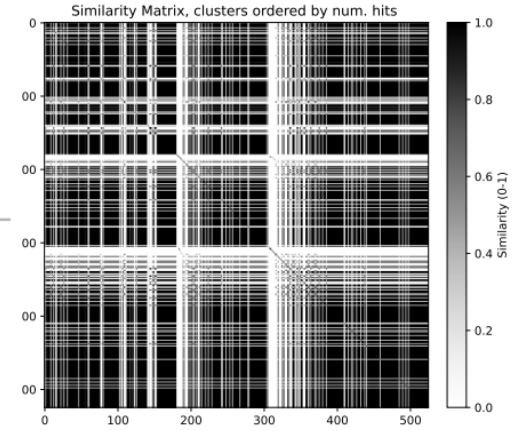
Hand-engineered:

3. Similarity matrix formed and used to construct graphs of connected clusters that are later merged



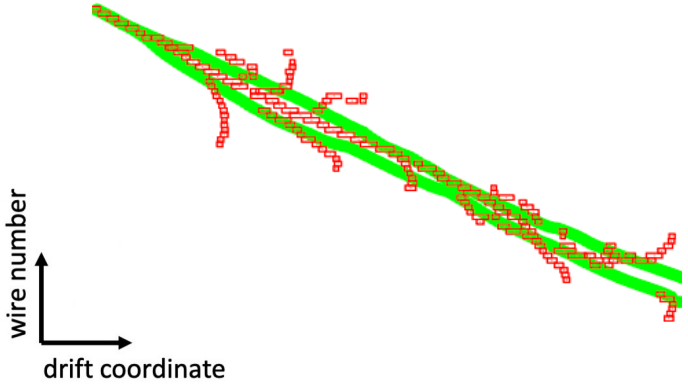


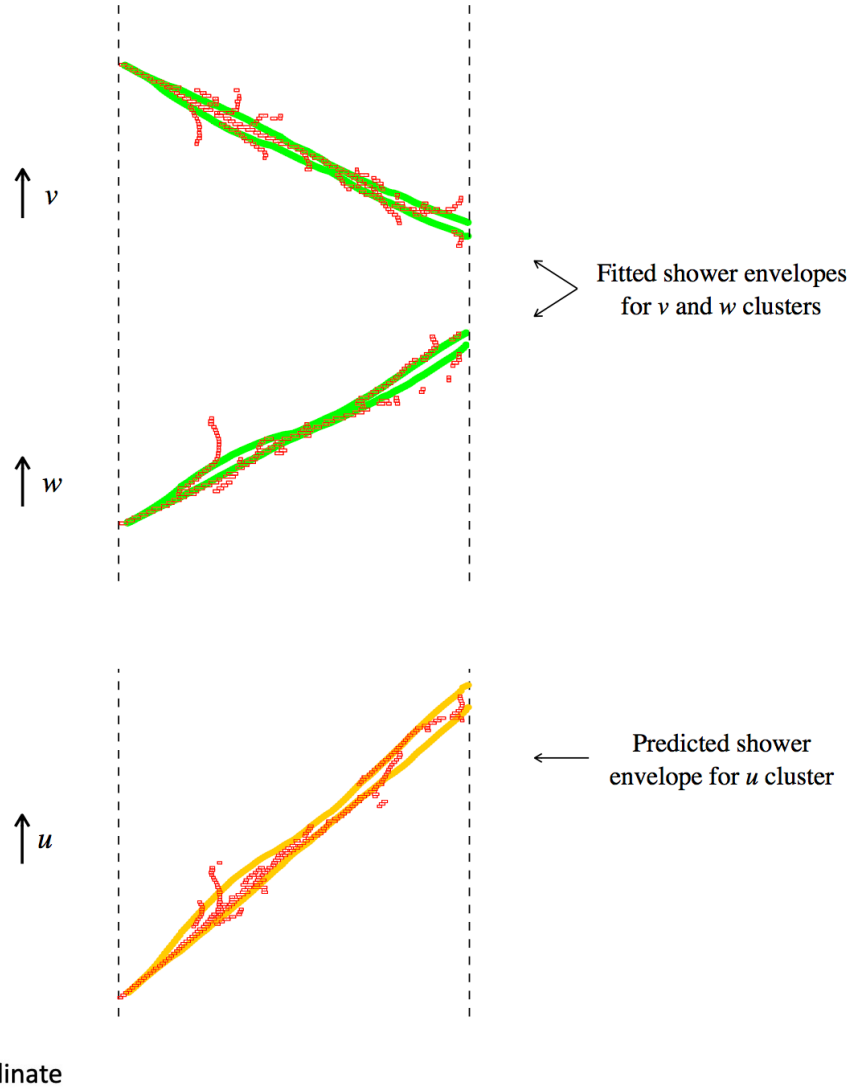




DUNE Work in Progress

- Shower creation is completely analogous to the track creation stage
- However, first the shower-like clusters must first be parameterised by fitted 2D envelopes

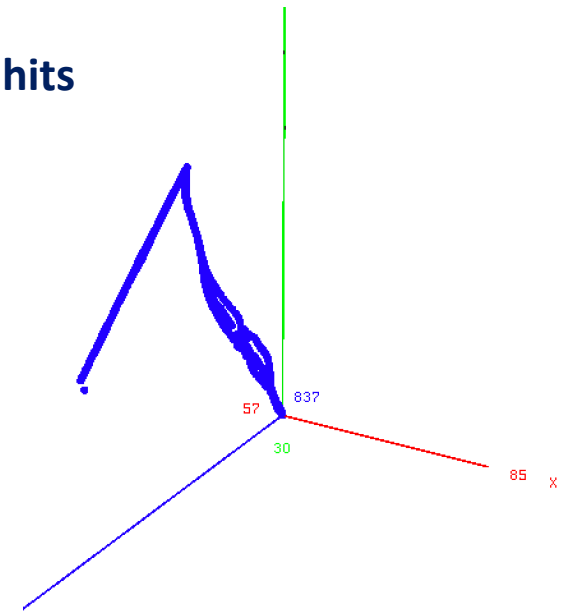




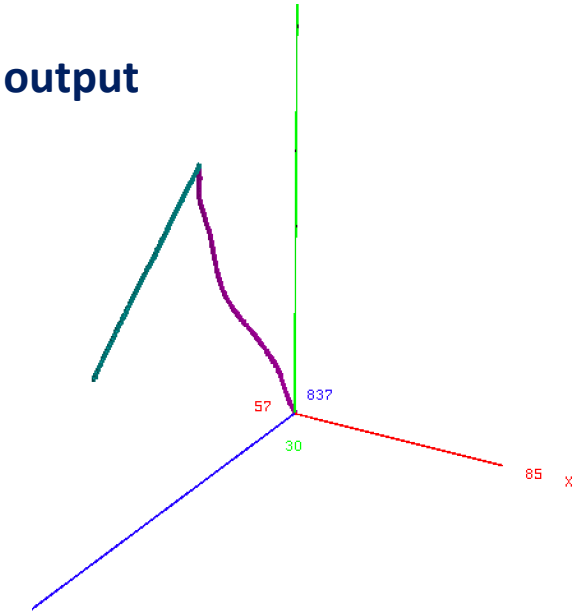
1. Search for a triplet of 2D clusters {U, V, W} that share a common drift-span
2. Walk along each envelope edge, using the position in two views {V, W} to predict that in third view {U}
3. Compare with U-view cluster
4. Repeat for each permutation

- Each particle's 2D clusters are now combined to produce 3D trajectories
- For each 2D hit, in each view, the 'other-view' clusters are sampled at the same drift-coordinate, obtaining u_{in}, v_{in} and w_{in}
- To obtain the most consistent 3D position, the following analytic expression is minimised:
  - $\chi^2 = (u_{out} - u_{in})^2 / \sigma_u^2 + (v_{out} - v_{in})^2 / \sigma_v^2 + (w_{out} - w_{in})^2 / \sigma_w^2$ (where, U/V/W can be written in terms of $x/y/z$)
- We then iterate on this, using a fit to current 3D hits (extra terms in χ^2), to produce a smooth trajectory

first pass 3D hits

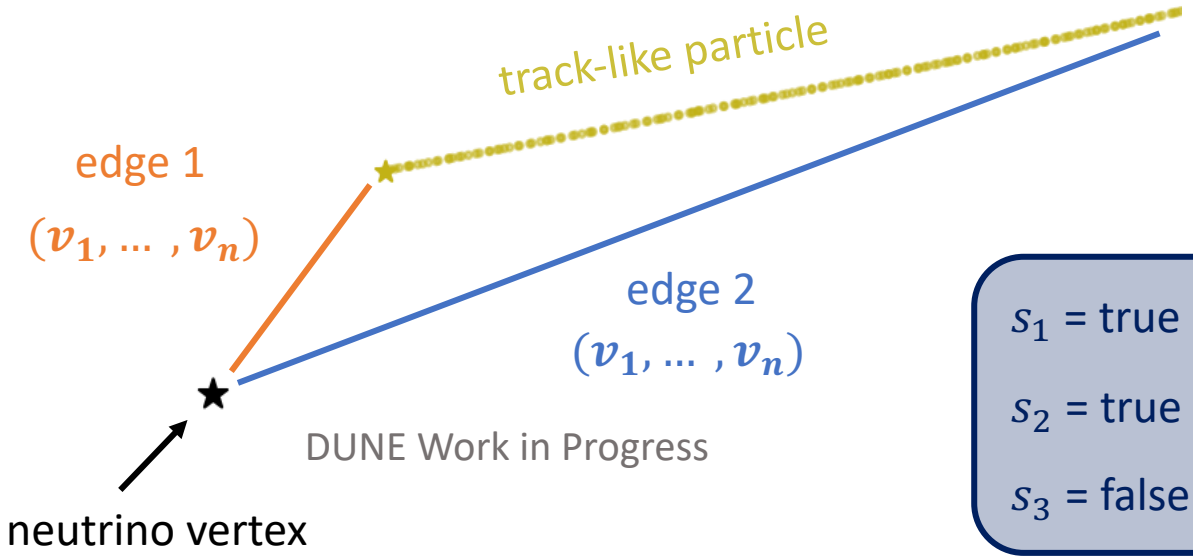


final 3D output

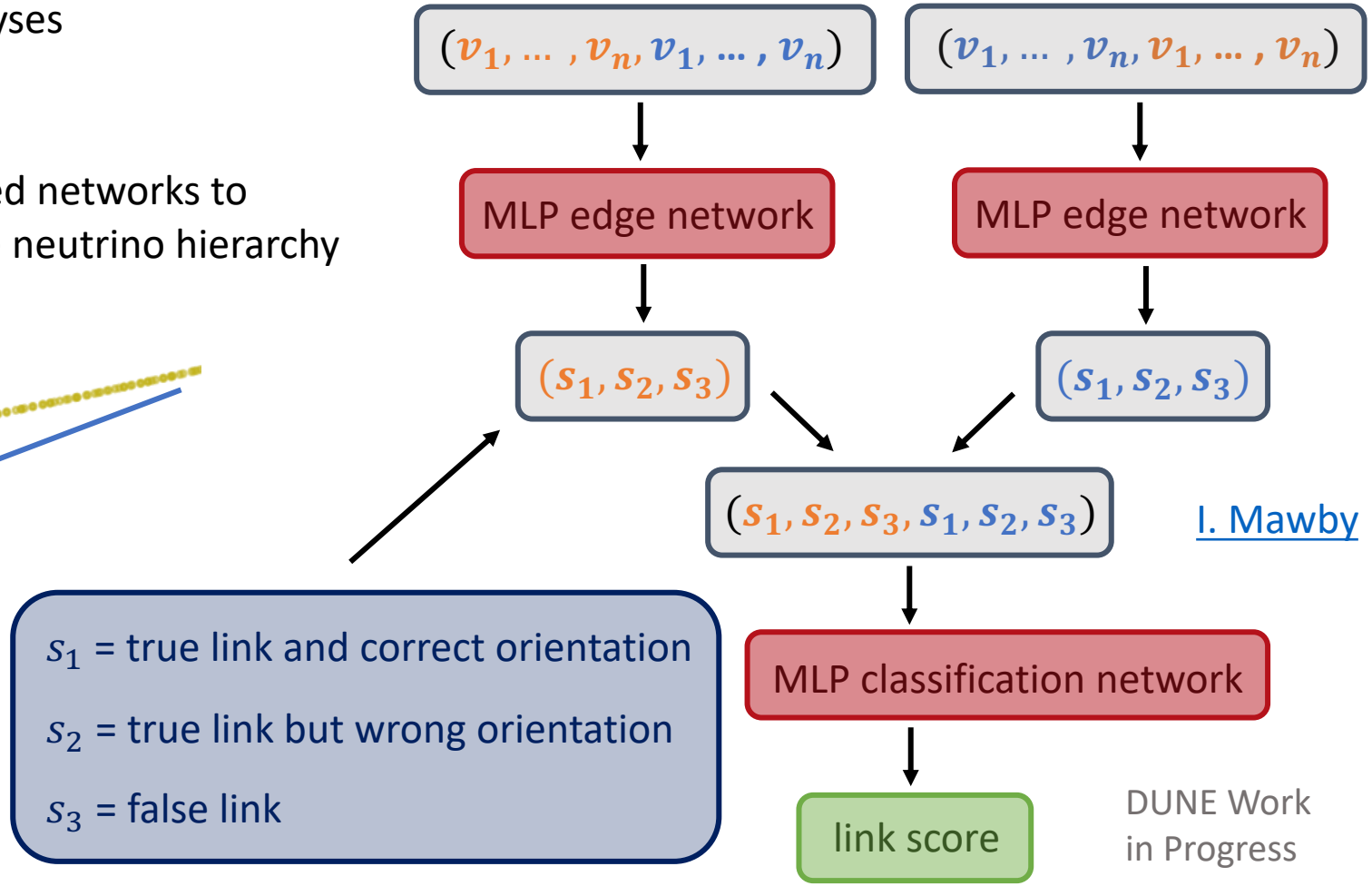


- The neutrino hierarchy is the family tree of the neutrino
- The starting point for almost all neutrino analyses
  ⇒ correctness is vital

- DLNeutrinoHierarchyAlgorithm uses MLP based networks to identify correct parent-child links, building the neutrino hierarchy



Track primary link network structure:

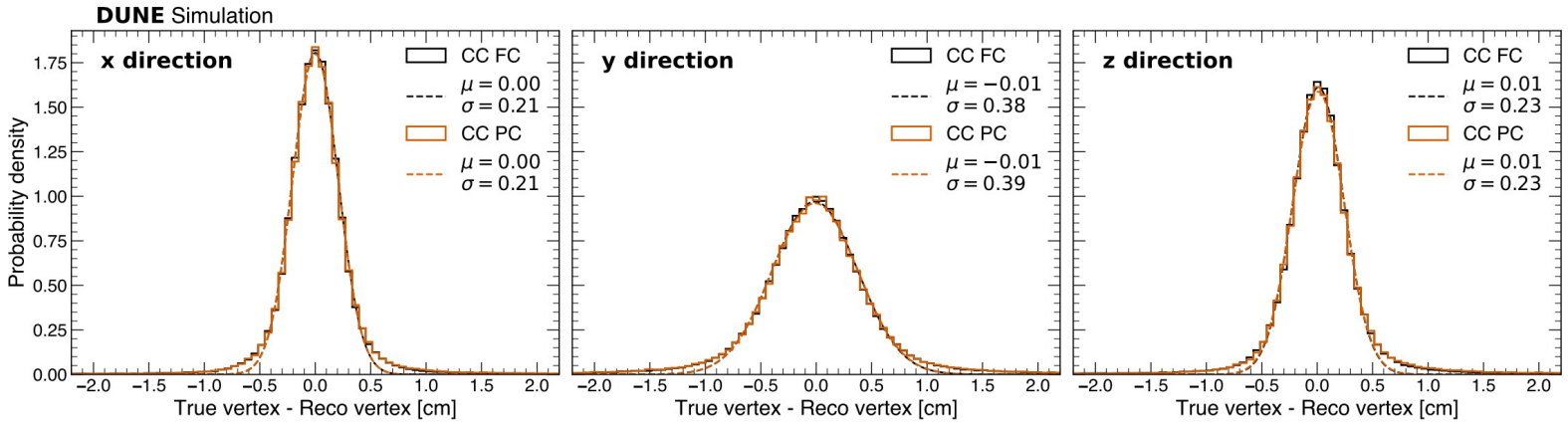


Use in DUNE's Physics Programme

- R&D: Pandora's reconstruction output informed the vertical-drift far detector design studies

- DUNE's beam physics programme: Pandora's long-baseline reconstruction provides the 3D reconstruction used in published DUNE oscillation parameter sensitivities [2] [3]
  - During my PhD I developed the reconstruction to optimise the resulting CP-violation sensitivity achieved by a Pandora based numu/nue selection [4]

- DUNE's atmospheric programme: Pandora's atmospheric reconstruction provides the 3D reconstruction used to predict atmospheric sensitivities (paper in the works)
  - Pandora reconstruction is the bases for recently submitted reconstruction paper [5]



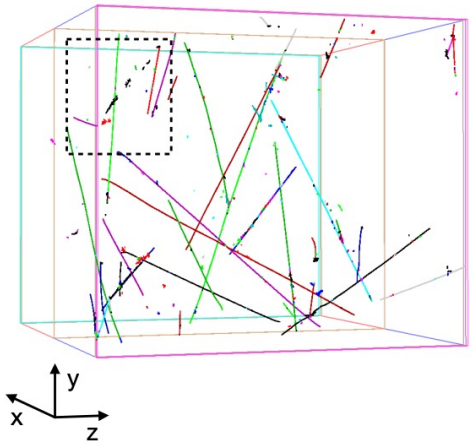
[5]

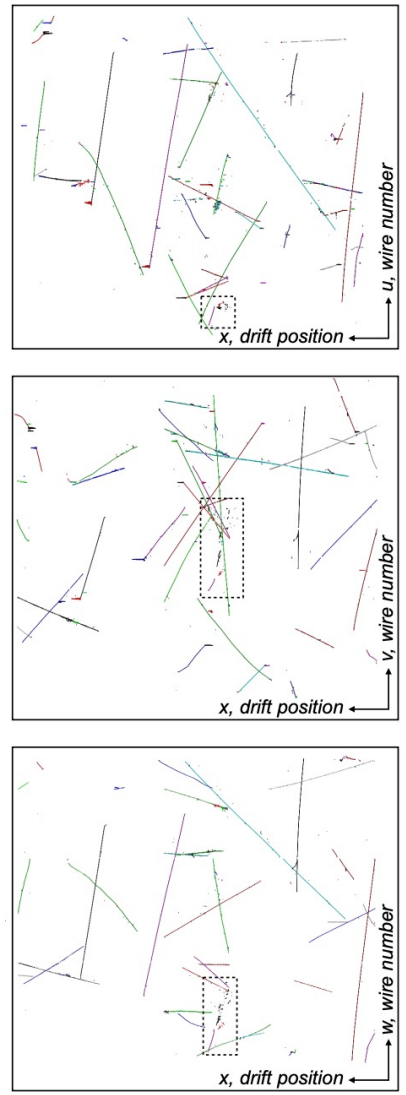
Use in DUNE's Physics Programme

- DUNE's low-energy physics programme: Pandora's low-energy reconstruction used to estimate DUNE's sensitivity to different core-collapse supernova neutrino flux models (paper in the works)

- ProtoDUNE: Pandora ProtoDUNE reconstruction provides the 3D reconstruction used in almost all analyses e.g.
  - Cross-section
    - π^+-Ar and p-Ar total inelastic cross-sections [6]
    - Exclusive π^+-Ar cross-section [7]
    - K^+ total inelastic cross-section [8]
  - Calibration
    - Space-charge effect via cosmic-ray muons [9]
    - Energy-scale determination via cosmic-ray muons [9]
    - Low-energy electron scale via Michel electrons [10]

  - Additionally, Pandora's ProtoDUNE reconstruction performance characterised in focused paper [11]





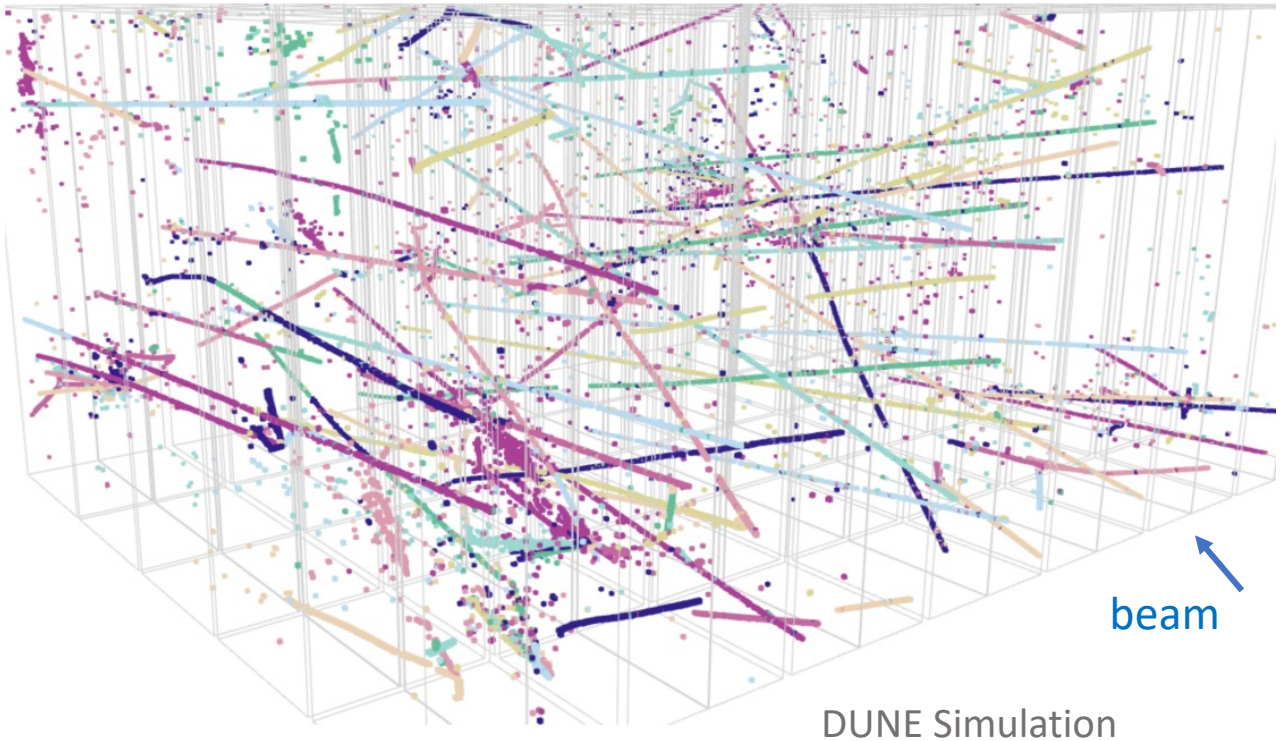
[11]

Contents

- Neutrino Oscillations
- CP-violation
- The Deep Underground Neutrino Experiment
- Pandora Pattern Recognition
- Pandora at the Far Detector
- Pandora at the Near Detector

Moving to the ND

- For several years, there's been a small (yet heroic) effort to create a Pandora configuration for ND-LAr
- We now have a 'large' (2 lecturers, 4 postdocs, 2 students) US-heavy team leading this effort!
- Pandora 'easily' applied to e.g. SBND, ND-LAr also uses LArTPC technology, so what's different here?



DUNE Simulation

Shown: neutrino interactions and rock muons
Not-shown: cosmic-rays!

- 3D pixel-based readout
- Pileup: ~50 in FV neutrino interactions, ~100 rock muons
- High multiplicity of rock muons and cosmic-rays
- Modular structure: ND-LAr will consist of 35 modules [3]

- ND simulation-reconstruction workflow lives outside the standard LArTPC software

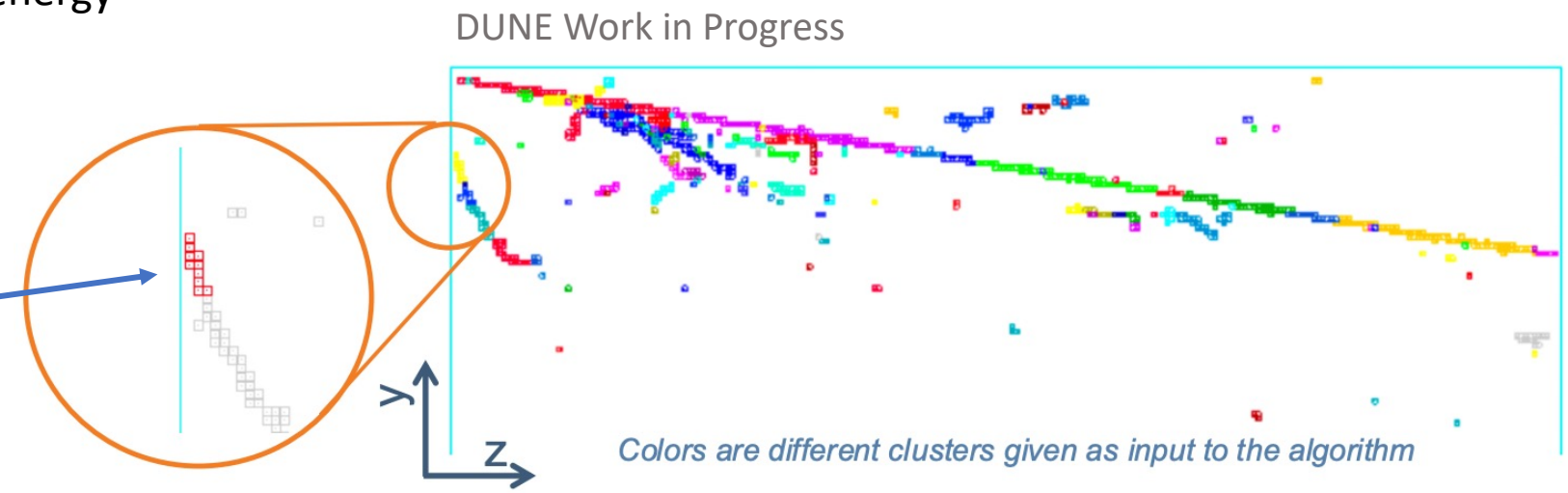
Moving to the ND: 3D Input

- In Pandora's nominal LArTPC approach, we initially build our objects in 2D before extending them into 3D
  - but here we have a 3D input!
- In the 'out-of-the-box' approach, the 3D input is projected into 2D, recreating the 'expected' 2D images
- This isn't ideal! We lose information! - hits that are close together in 2D maybe far apart in 3D…

⇒ there's ongoing efforts to 3D-ify existing 2D algorithms

e.g. LArLongitudinalAssociation algorithm:
merges clusters that align in the general energy direction (z in 2D, but z-y plane in 3D)

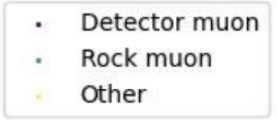
Cluster with small z extension is now recovered by 3D version!



Moving to the ND: Rock Muons

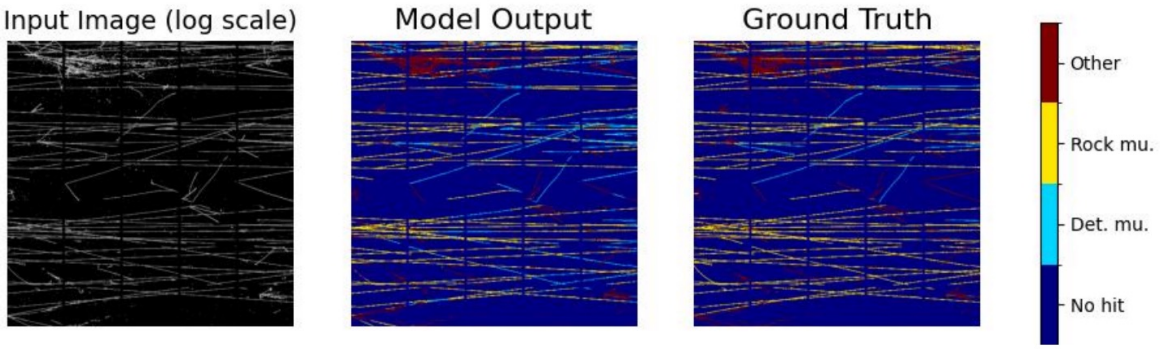
- In the ND, neutrino interactions sit in a high density cosmic-ray/rock-muon environment
- We need to identify and 'remove' cosmic-rays and rock-muons so that we can focus on the neutrino reconstruction

from neutrino interactions occurring outside the detector

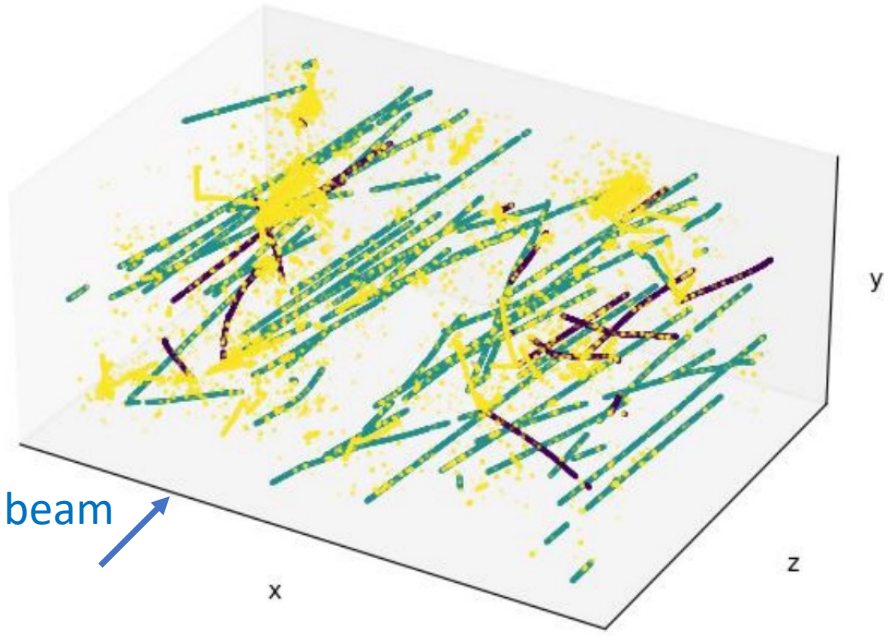


- We can identify rock muons that enter and exit the detector, but what if they stop?
  - They align with the beam time ⟹ they look like muons from CC ν_μ interactions!

- We use an ML approach here, retraining the vertexing U-ResNet to identify rock muons
- This is a 2D approach, but 3D aware solutions are under development (see slicing slide)



DUNE Work In Progress



Shown: neutrino interactions and rock muons
Not-shown: cosmic-rays!

DUNE Work In Progress

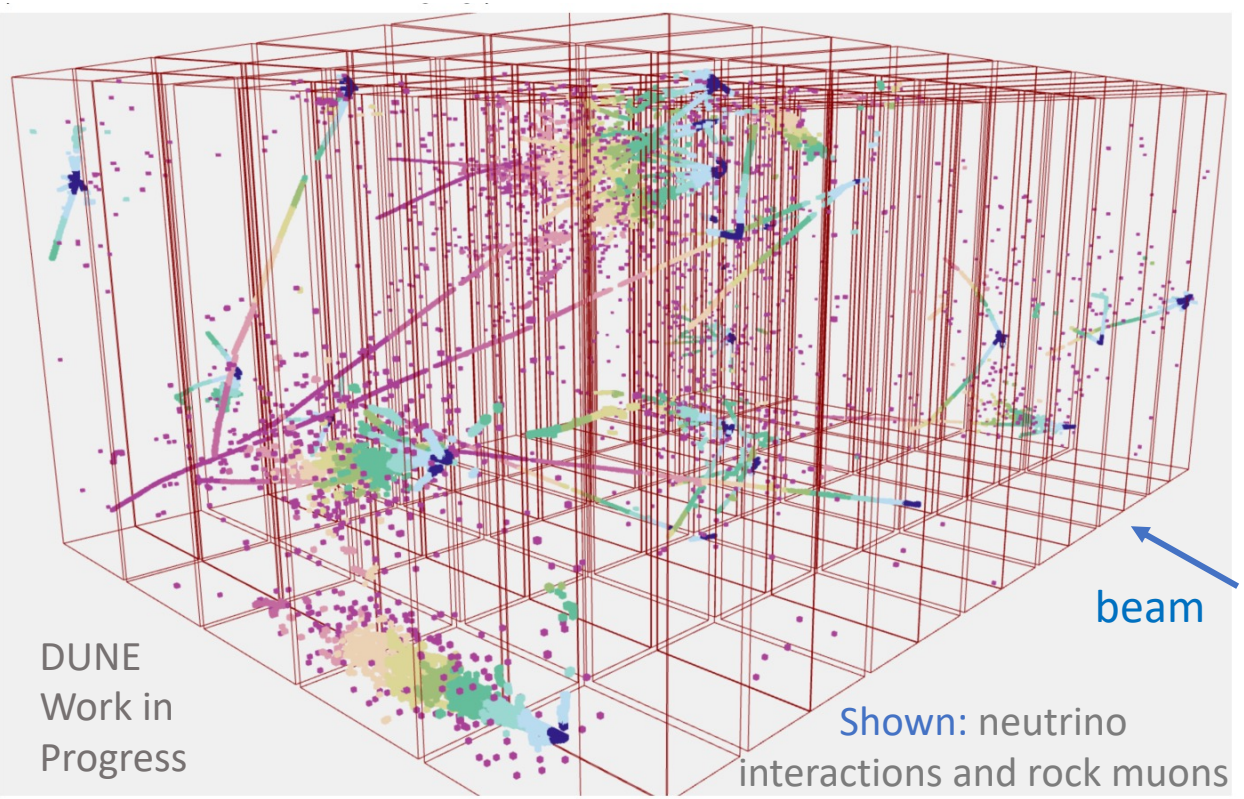
Moving to the ND: Slicing

- After removing the cosmic-rays and rock-muons, we're hopefully left with neutrino interactions
- We now need to isolate the hits of each neutrino interaction so that we can reconstruct them - we call this 'slicing'
- Slicing is not new, and is performed at MicroBooNE, ProtoDUNE and SBND

- But the high-multiplicity of neutrino interactions makes this a far more complex problem, and exceeds the limits of our existing slicing algorithms

- We therefore use an AI-assisted approach:
  - AI: A graph neutral network (GNN) predicts the distance of 3D hits to their local neutrino interaction vertex
  - Hand-engineered: Each vertex is used as an anchor to build each slice

- The team plan to repurpose this GNN to identify rock muons!

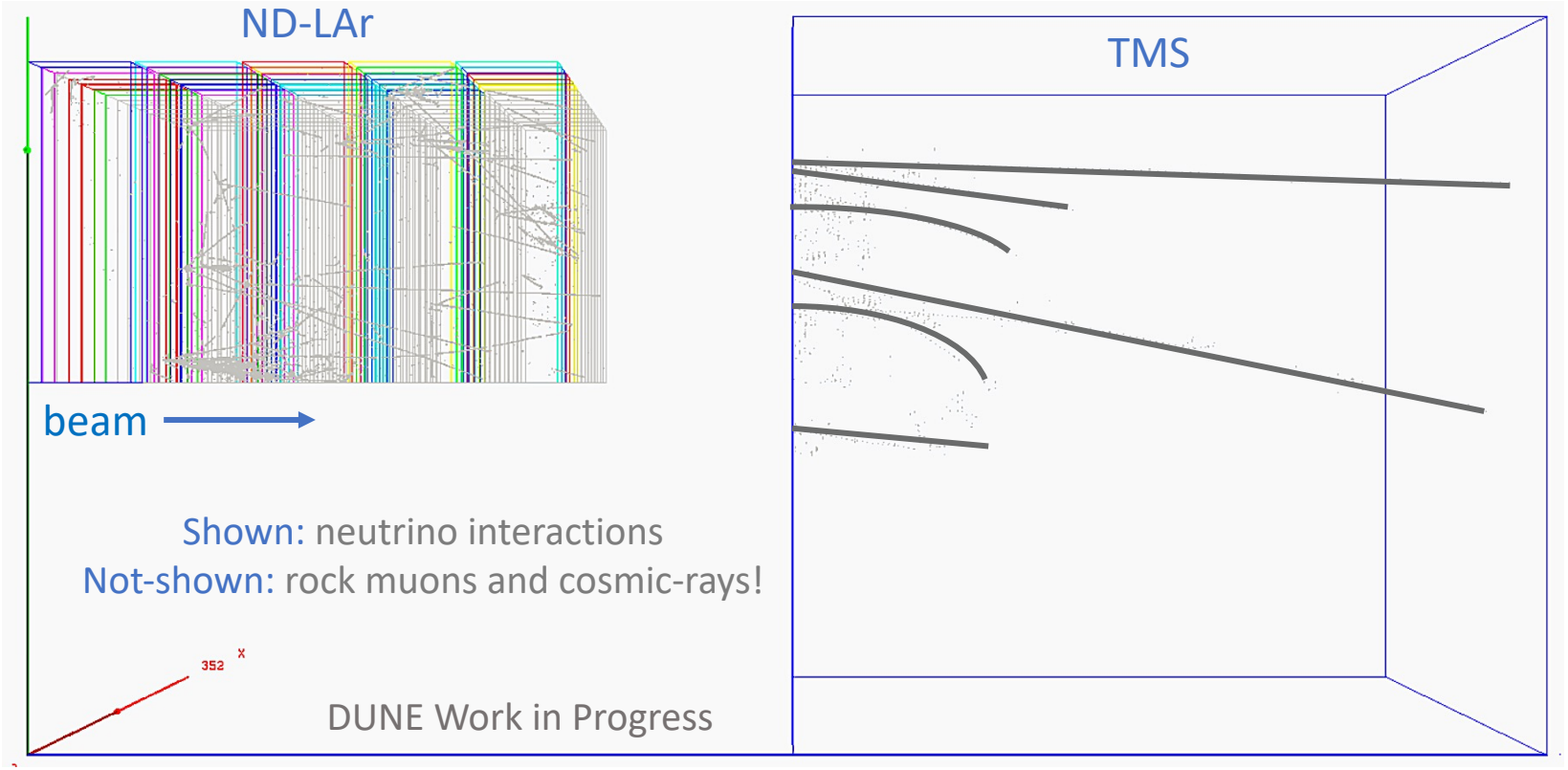


Moving to the ND: TMS

- ND-LAr is not designed to not contain muons, and so TMS is used to capture them ⇒ maintain an excellent neutrino energy resolution
- Pandora ND-LAr tracks are successfully matched to the TMS reconstructed (by the Mainz team) tracks, allowing for downstream characterisation

But… what about Pandora for TMS?

- Extra downstream information can aid ND-LAr reconstruction (reminiscent of Mark's initial motivation for Pandora)
- But TMS is a *very* different detector…
- John Back has been a pioneer here, creating a Pandora configuration that runs a LArTPC reconstruction on both (albeit separately) ND-LAr and TMS
- Obviously, the output is not great, but this is a huge first step!



Conclusions

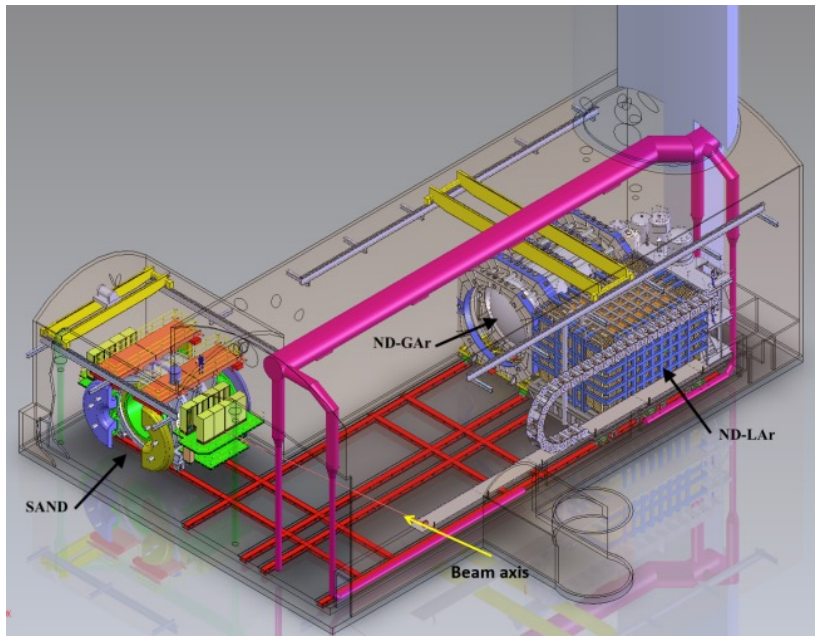
- Pandora is a highly successful pattern recognition software that is used to reconstruct neutrino interactions in LArTPCs:
  - Main reconstruction package used by MicroBooNE during its lifetime (cited by 49 (out of 76) MicroBooNE papers)
  - Provides the reconstruction used in all published ProtoDUNE physics analyses
  - Immediately picked up by SBND and used in current physics analyses
  - Employed by DUNE across the entire physics programme: informing beam, atmospheric and low-energy physics sensitivities

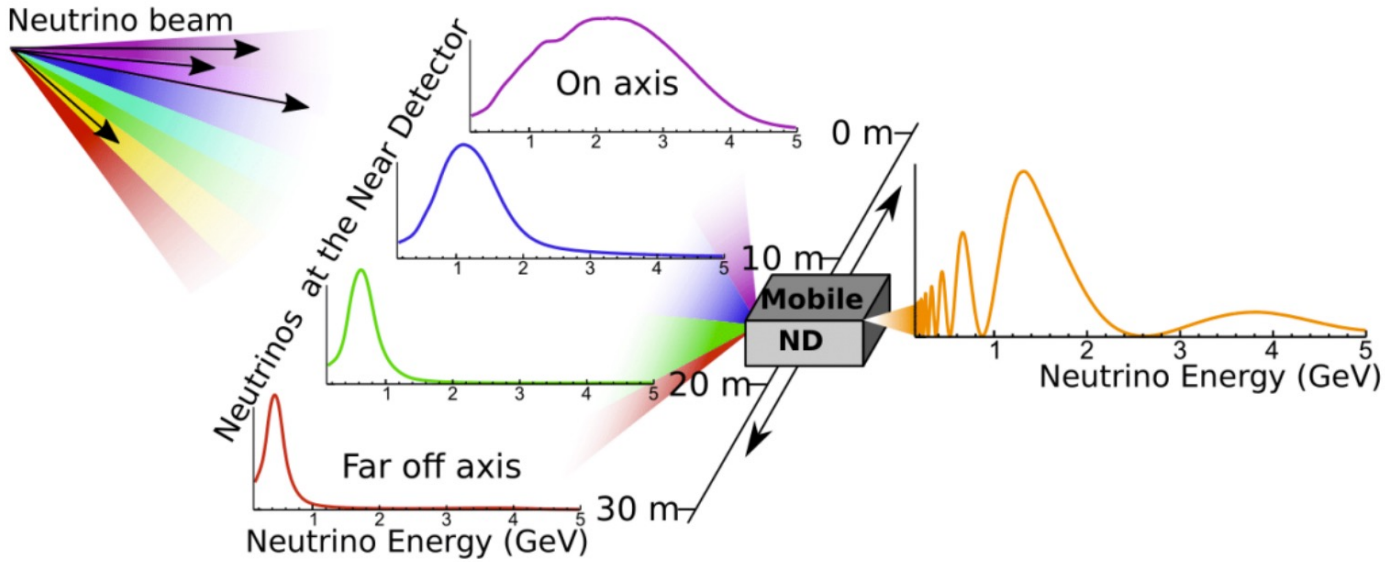
- Pandora is an active project!
  - Large FD and ND development teams working tirelessly to develop physics ready reconstruction for DUNE!
  - Incorporating the latest and greatest ML approaches to deliver the best reconstruction that we can!

Thank you for listening!

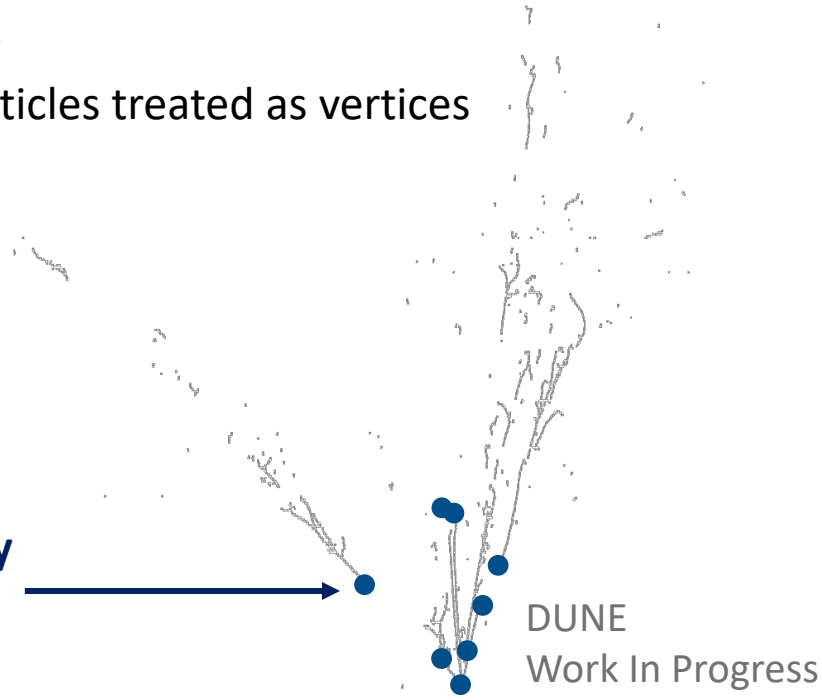
DUNE PRISM

- ND-LAr + TMS/ND-GAr can move up to 3.2° off-axis
- As one moves off axis, the beam's energy becomes more peaked and moves to lower energies
- We can also use it also build a data-driven far detector oscillated flux prediction
- Alternatively, provides additional data sets which constrain the flux and cross section systematics

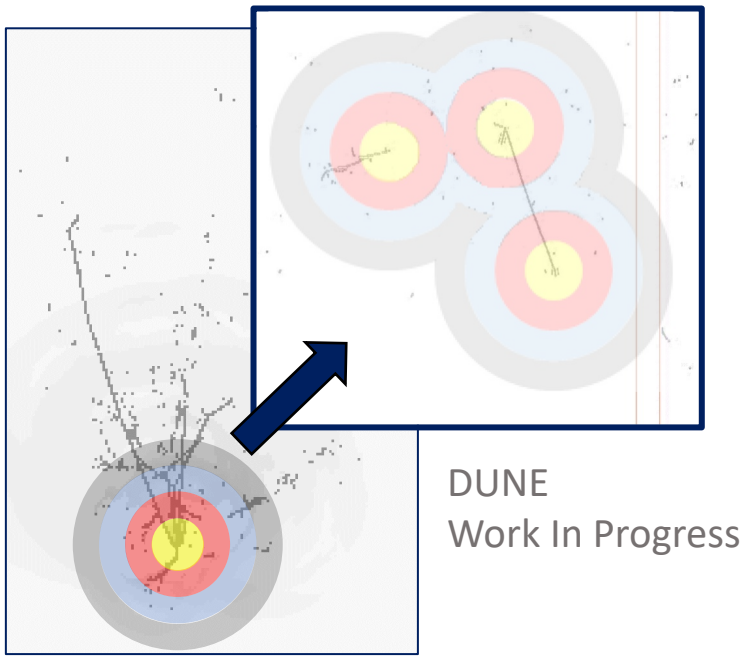




- The neutrino interaction vertex network has been extended to identify higher-order vertices
- **Aim: identify the higher-order vertices found with a (trained) eye**
  - Tag start of charge deposition for photons as a vertex, rather than true vertex
  - Ignore small elastic scatters
  - Track endpoints/exiting particles treated as vertices



Method: predict distance from hits to closest, rather than primary vertex



+ hand-engineered refinement algorithm