WARWICK
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6th UK LArTPC Software Analysis Workshop

Reconstruction Algorithms

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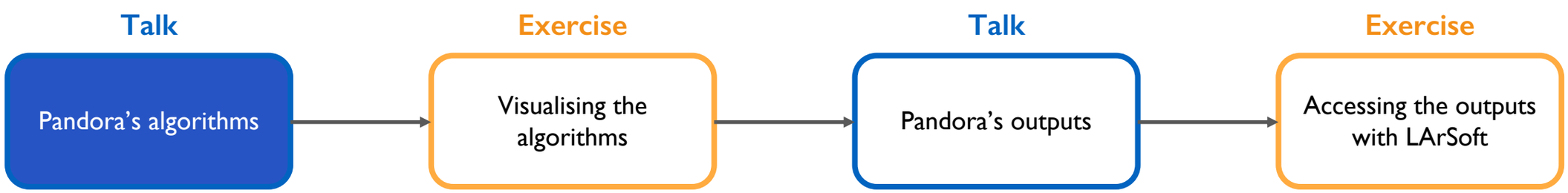
2nd November 2021

Reconstruction Session

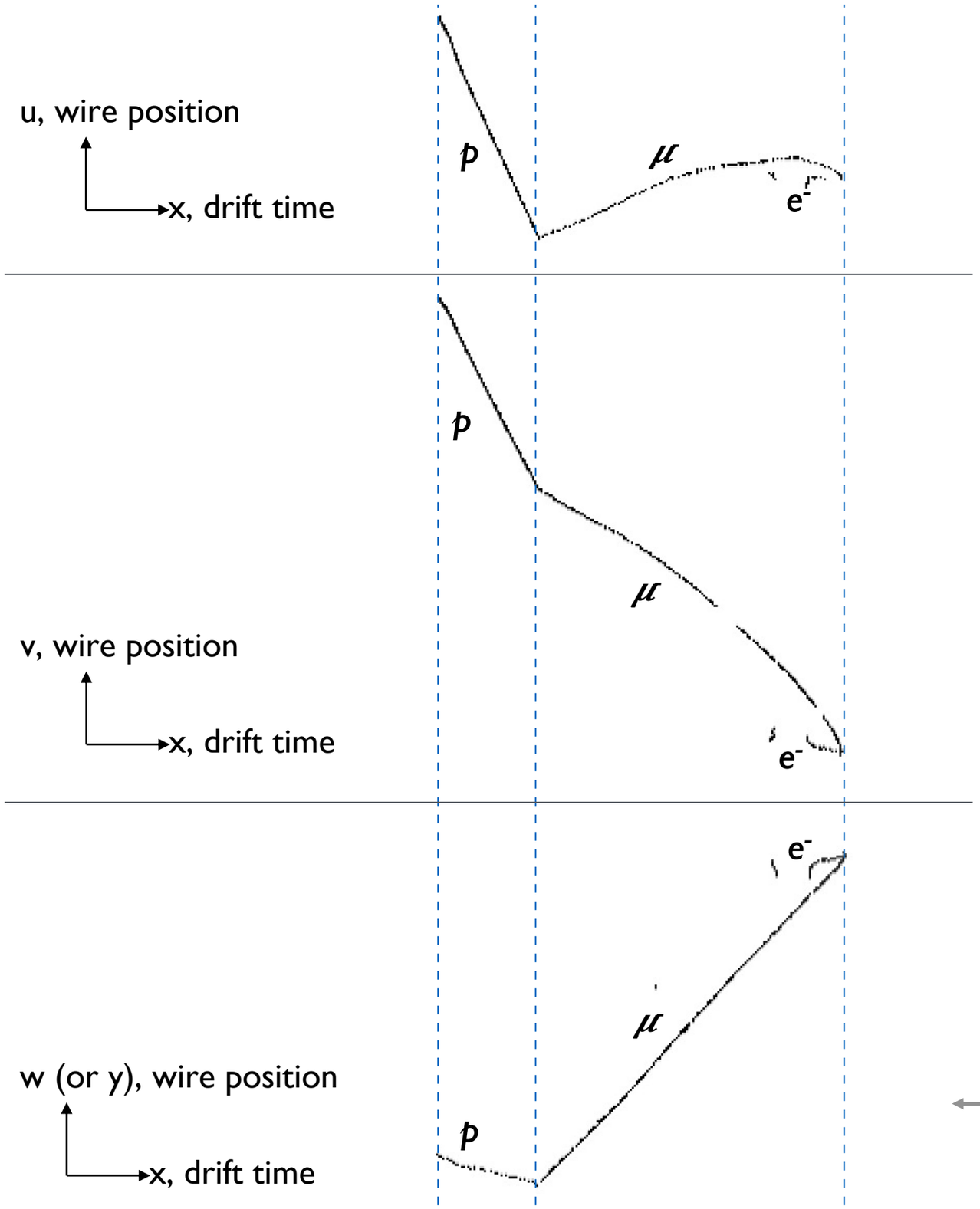
Session structure

Credit: John Marshall, who originally produced these slides

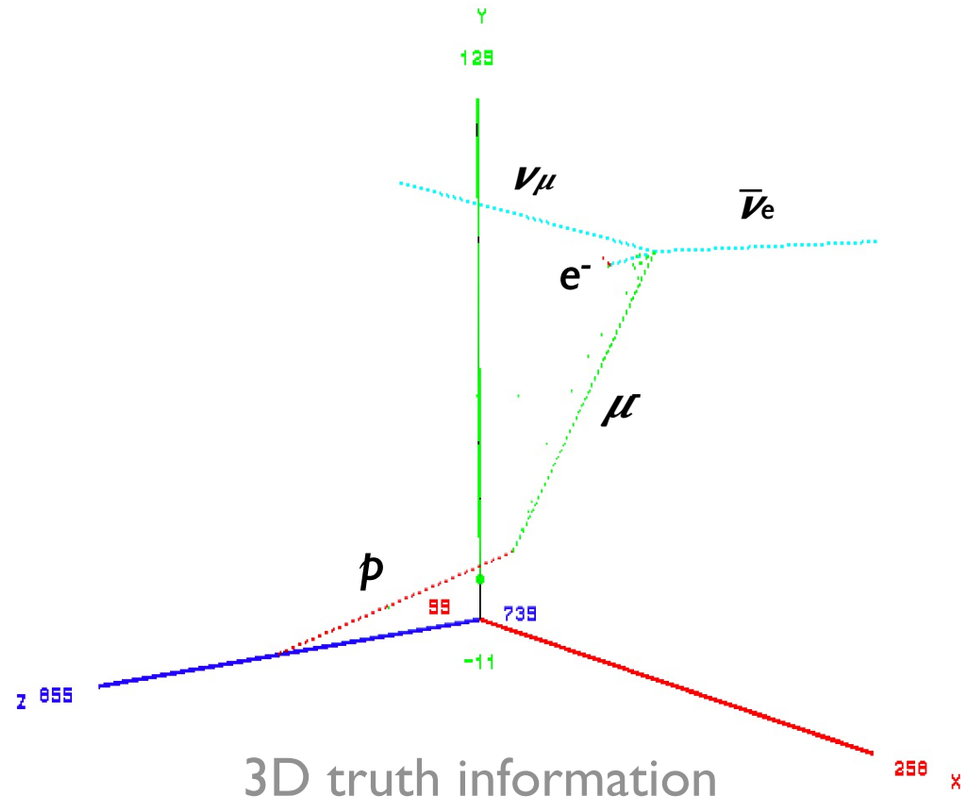


A key reference: [Eur. Phys. J. C (2018) 78: 82]

Reminder: Input Hits



E.g. CC QE: $\nu_\mu + Ar \rightarrow p + \mu^-$



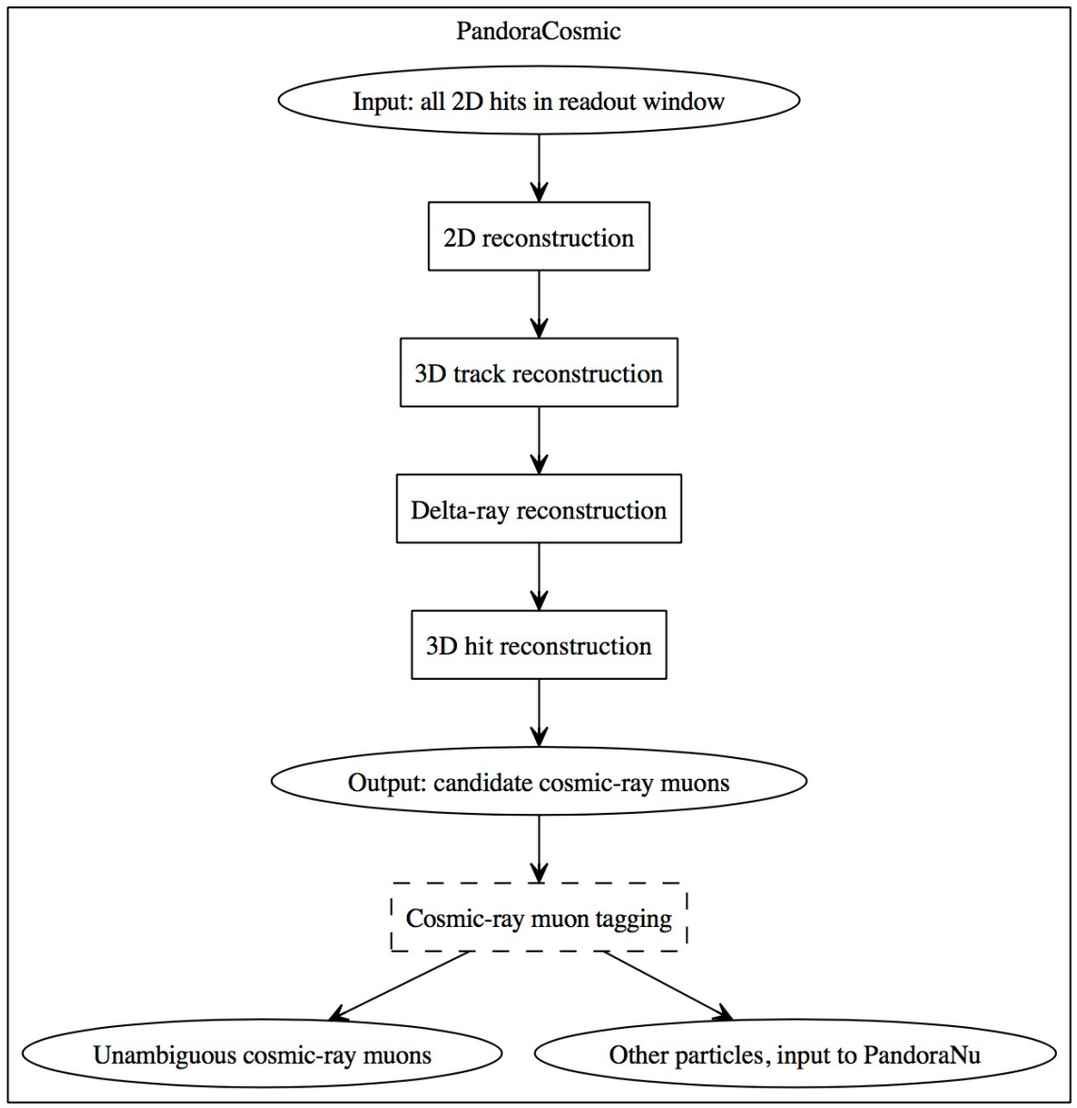
3D truth information

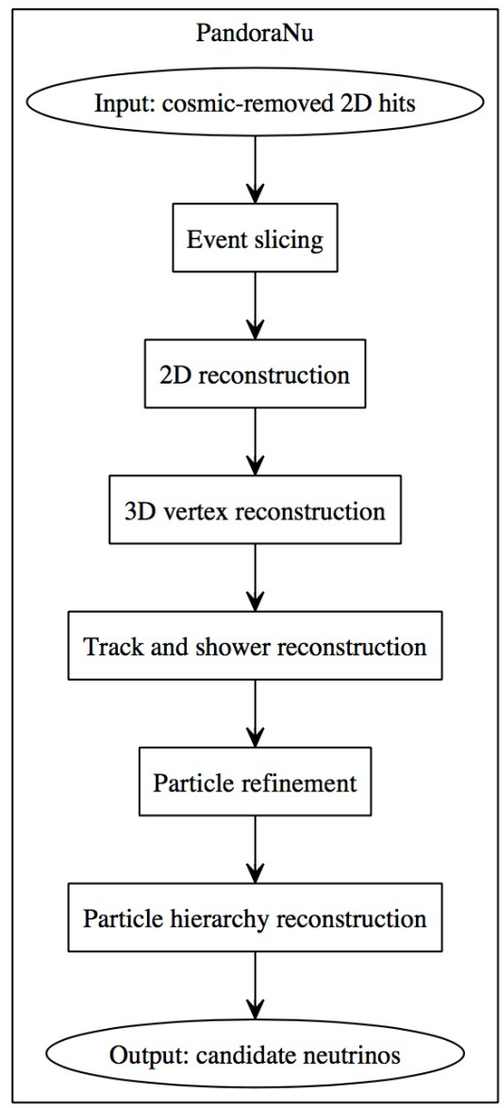
← Three 2D representations with common x coordinate, derived from drift time

Algorithm Chains

- **Two Pandora algorithm chains created for LArTPC use, with many algs in common:**
  - **PandoraCosmic:** strongly track-oriented; showers assumed to be delta rays, added as daughters of primary muons; muon vertices at track high-*y* coordinate.
  - **PandoraNu:** finds neutrino interaction vertex and protects all particles emerging from vertex position. Careful treatment to address track/shower tensions.

Initially use a two-pass approach:
Input to PandoraNu excludes hits from unambiguous cosmic rays.

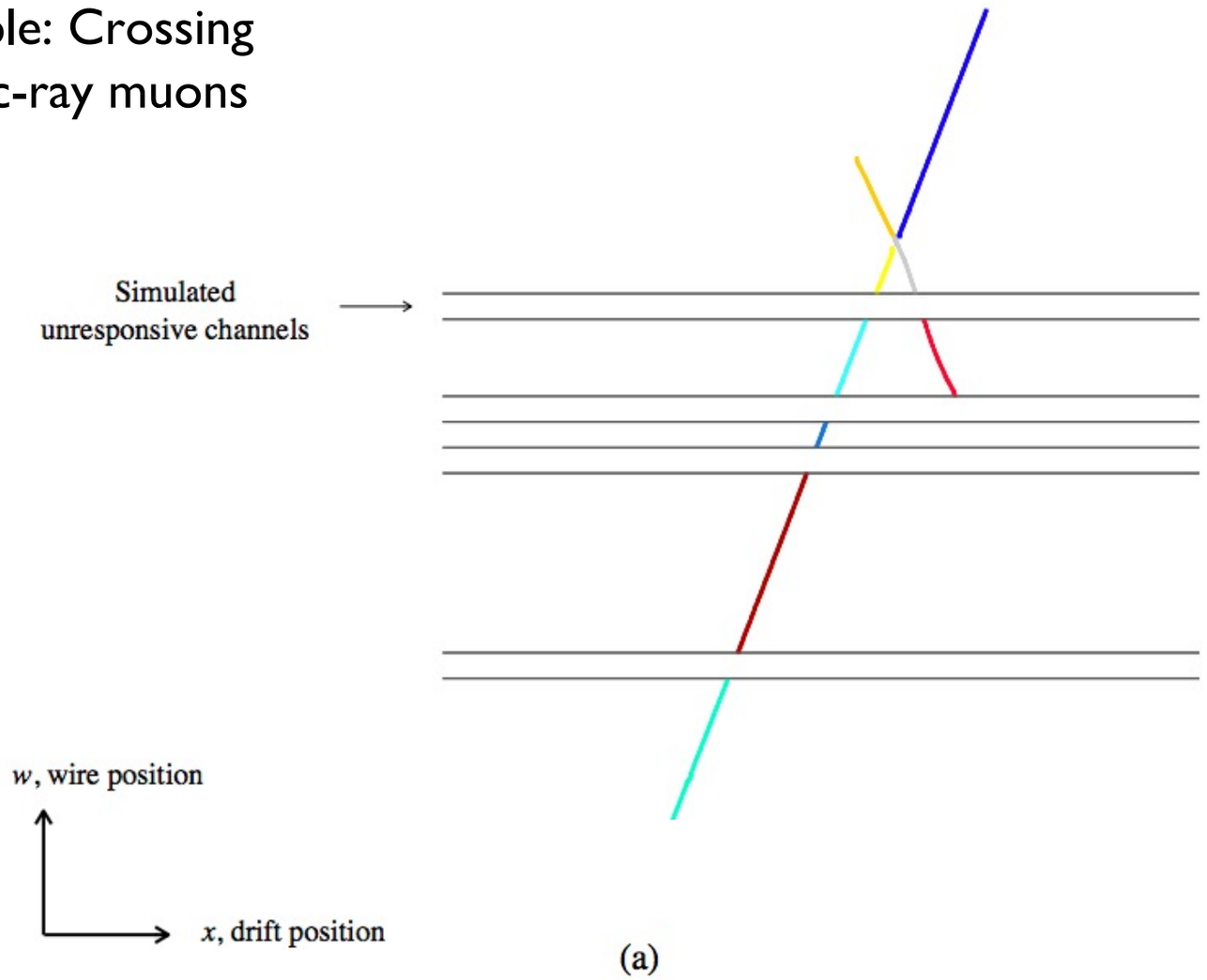


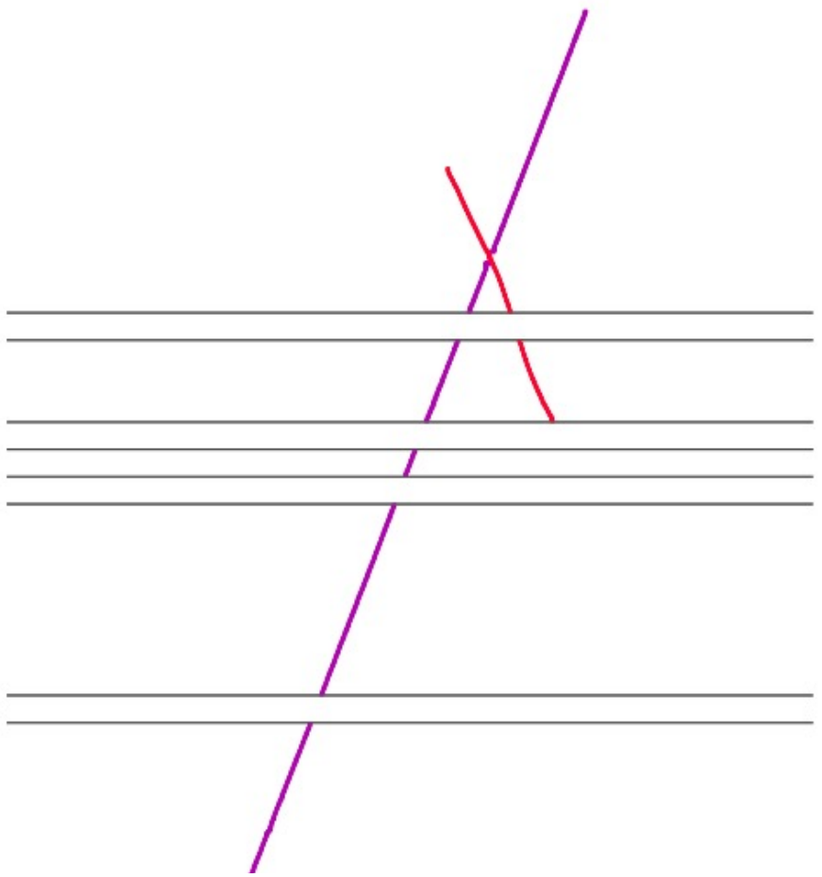


Cosmic-Ray Muon Reconstruction - 2D

- For each plane, produce list of 2D clusters that represent continuous, unambiguous lines of hits:
  - Separate clusters for each structure, with clusters starting/stopping at each branch or ambiguity.
- Clusters refined by series of 15 cluster-merging and cluster-splitting algs that use topological info.

Example: Crossing cosmic-ray muons

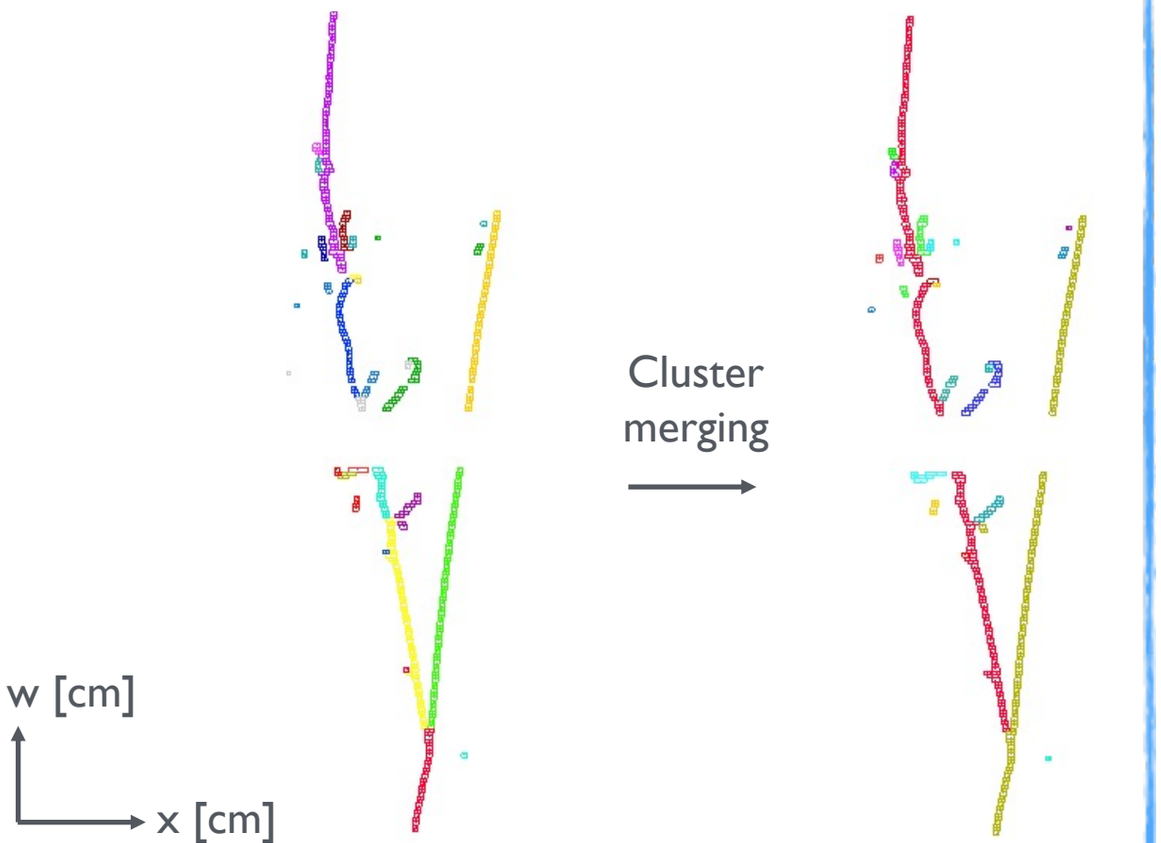




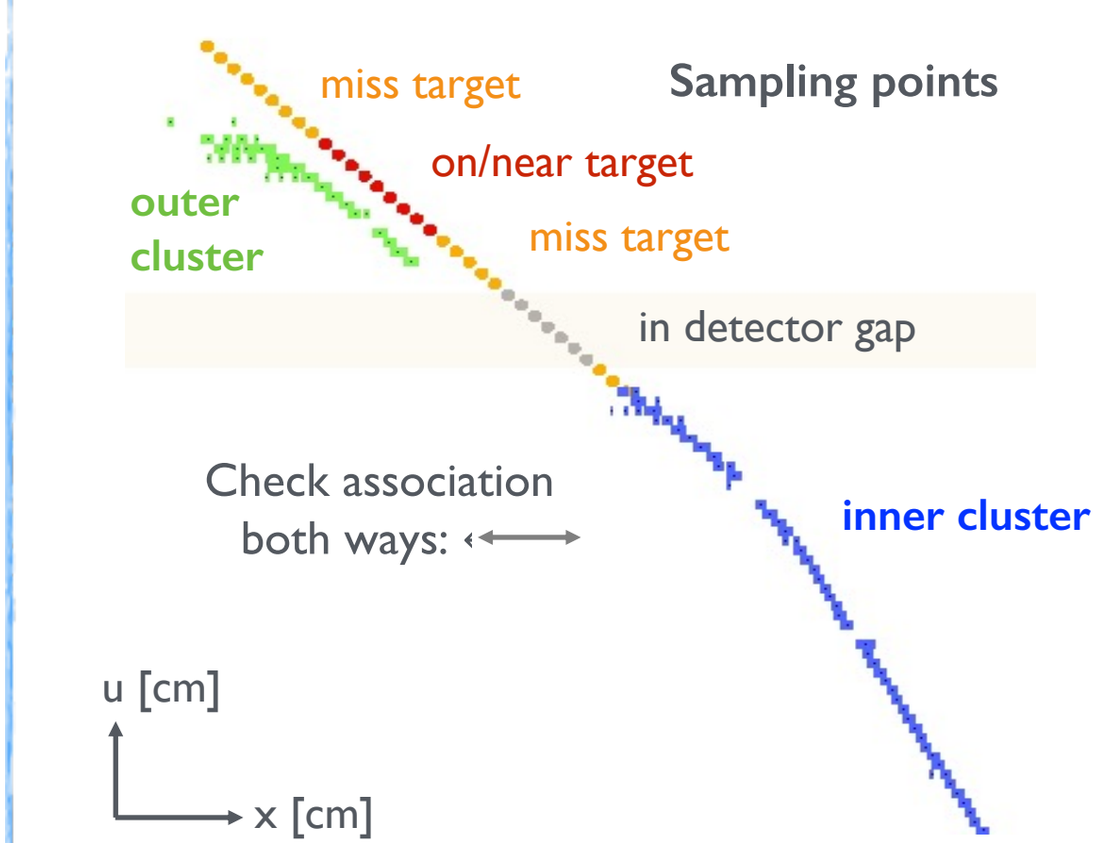
Topological Association - 2D

- **Cluster-merging algorithms identify associations between multiple 2D clusters and look to grow the clusters to improve completeness, without compromising purity.**
  - The challenge for the algorithms is to make cluster-merging decisions in the context of the entire event, rather than just considering individual pairs of clusters in isolation.
  - Typically need to provide a definition of association (for a given pair of clusters), then navigate forwards and backwards to identify chains of associated clusters that can be safely merged.

E.g. LongitudinalAssociation

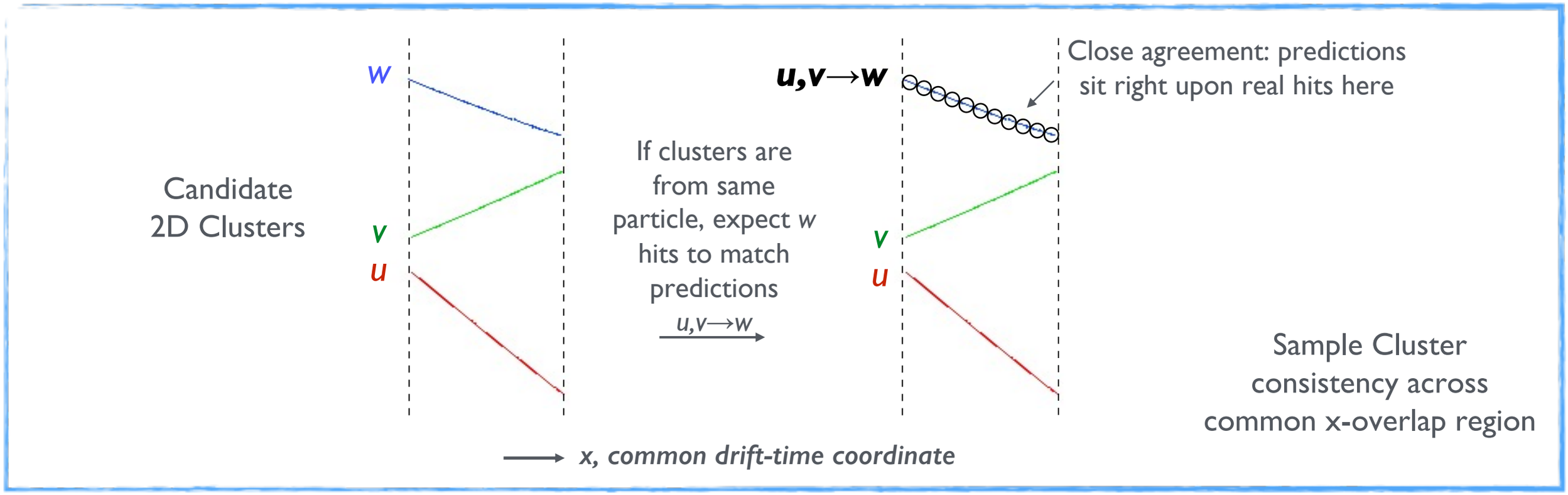


E.g. CrossGapsAssociation



Track Pattern Recognition - 3D

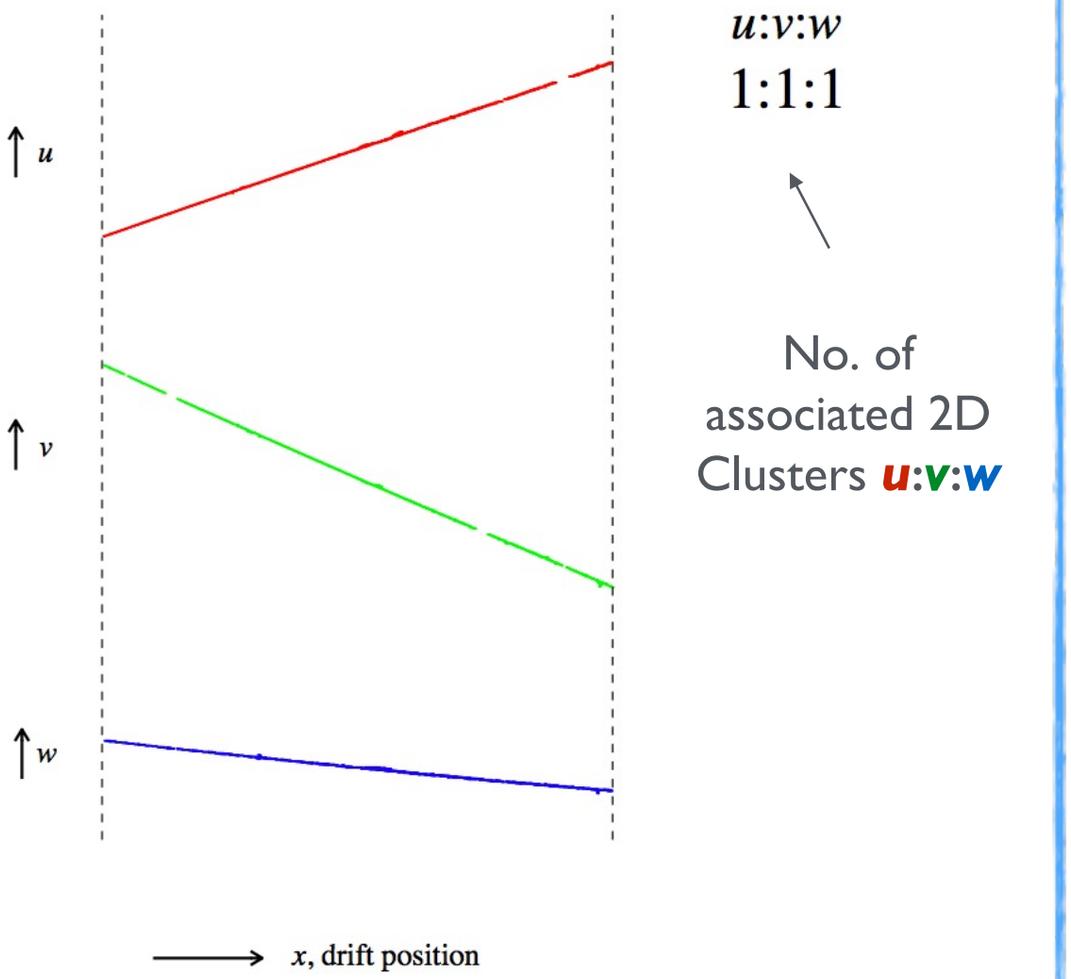
- **Our original input was 3x2D images of charged particles in the detector.**
- **Should now have reconstructed three separate 2D clusters for each particle:**
  - Compare 2D clusters from *u*, *v*, *w* planes to find the clusters representing same particle.
  - Exploit common drift-time coordinate and our understanding of wire plane geometry.
  - At given *x*, compare predictions {*u*,*v*→*w*; *v*,*w*→*u*; *w*,*u*→*v*} with cluster positions, calculating χ^2



Store all results in a **"tensor"**, recording *x*-overlap span, no. of sampling points, no. of "matched" sampling points and χ^2. **Documents all 2D cluster-matching ambiguities.**

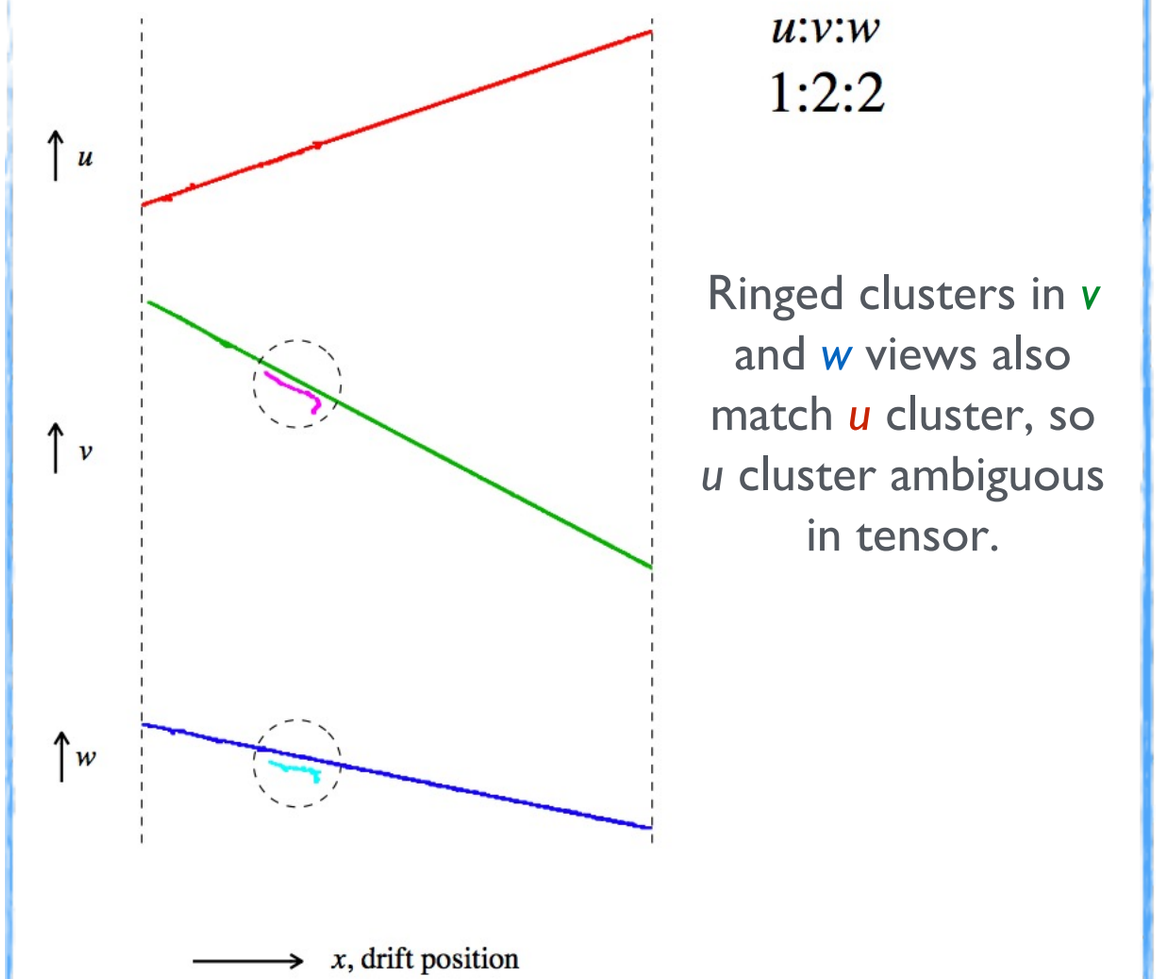
Track Pattern Recognition - 3D

Tensor stores overlap details for trios of 2D clusters. Tools make 2D reco changes to resolve any ambiguities. If a tool makes a change (e.g. splits a cluster), all tools run again.



Find unambiguous elements in the tensor, demanding that the common x-overlap is 90% of the x-span for all three clusters.

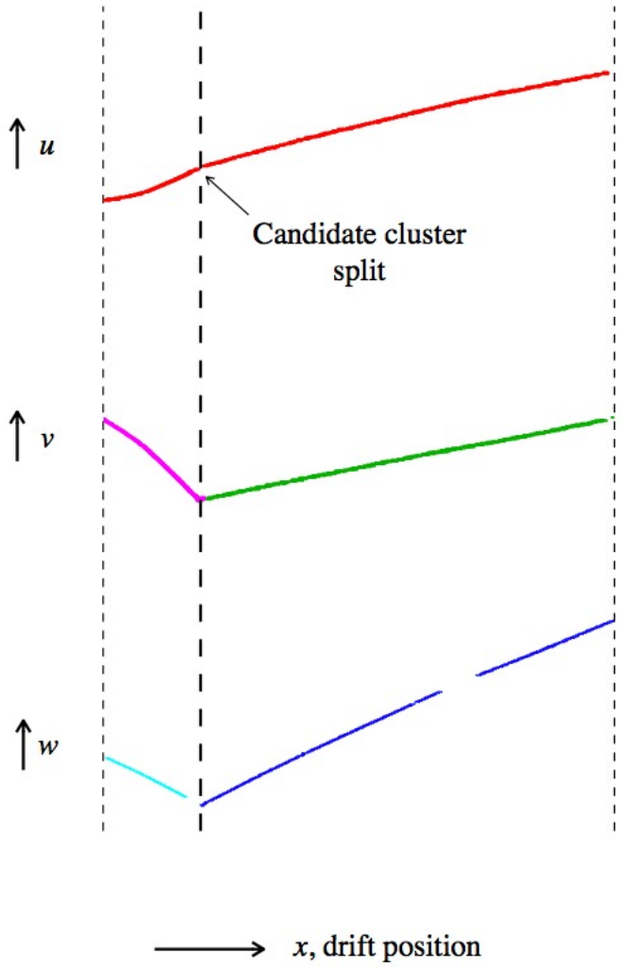
Clear Tracks Tool



Resolve **obvious** ambiguities: clusters are matched in multiple configurations, but one tensor element is much "better" than others.

Long Tracks Tool

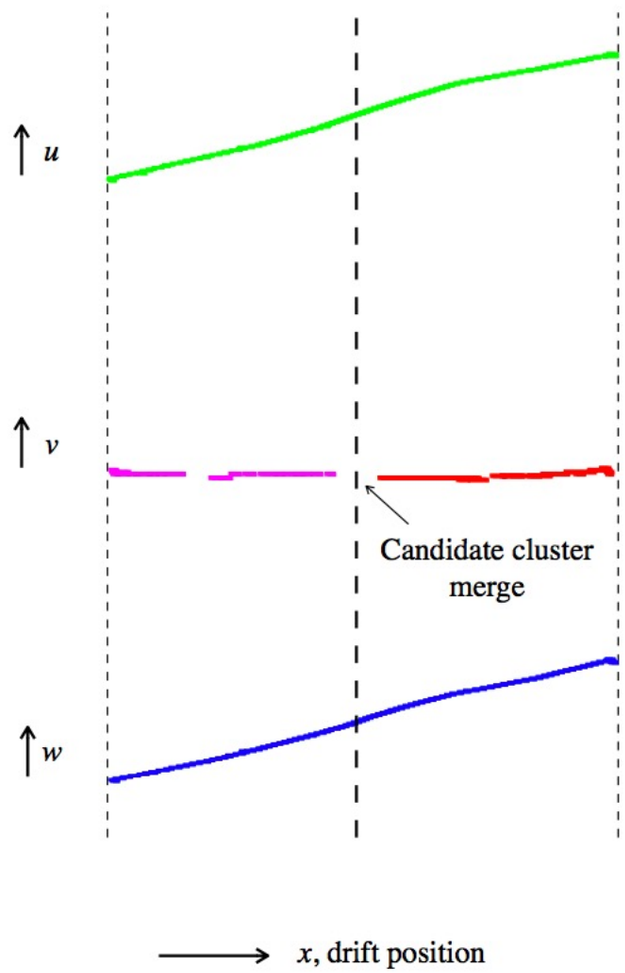
Track Pattern Recognition - 3D



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

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

Overshoot Tracks Tool



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

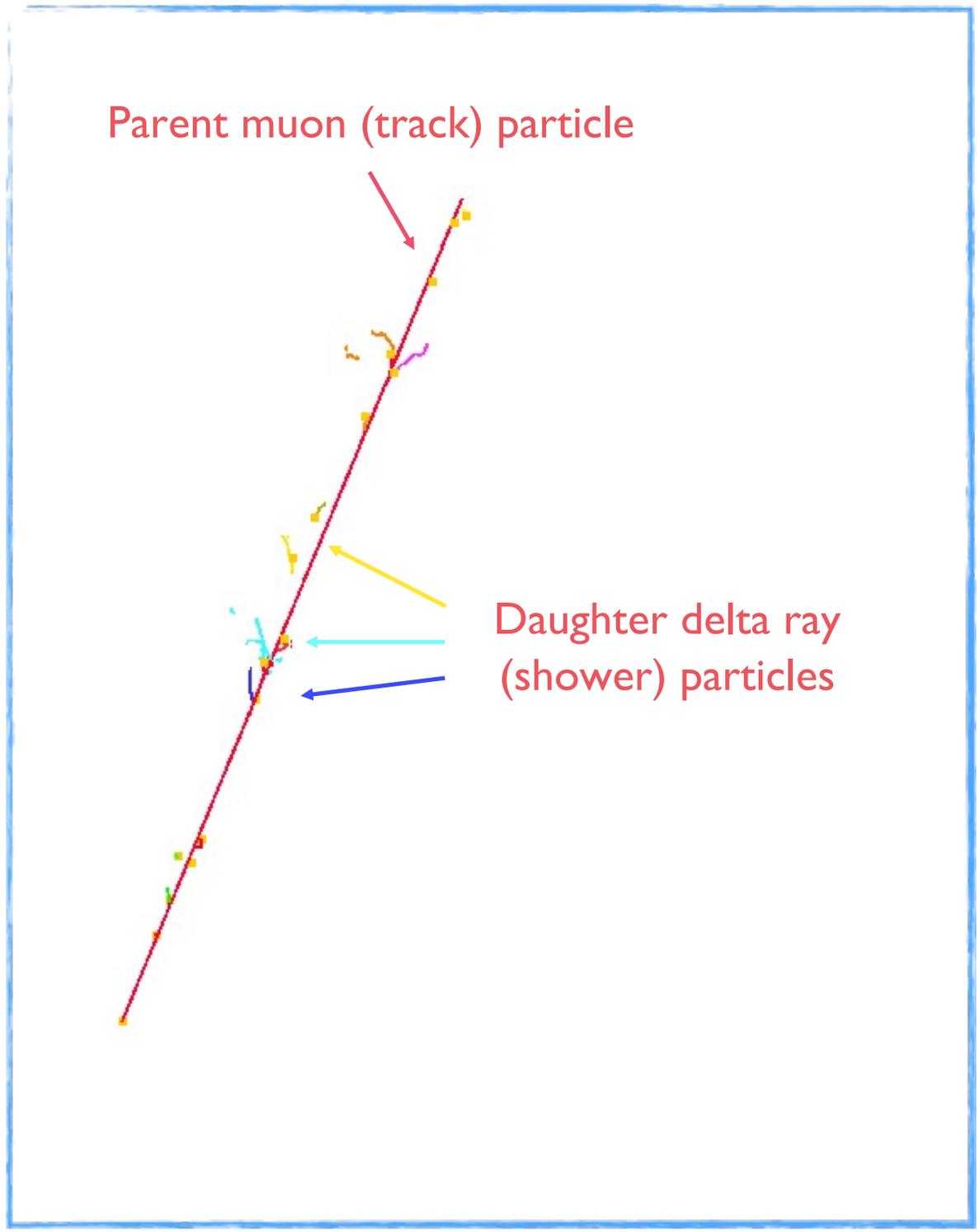
Two clusters in *v* view, matched to common clusters in *u* and *w* views.
Merge *v* clusters.

Undershoot Tracks Tool

- Use all connected clusters to assess whether this is a true 3D kink topology.
- Modify 2D clusters as appropriate (i.e. merge or split) and update cluster-matching tensor.
- Initial ClearTracks tool then able to identify unambiguous groupings of clusters and form particles.

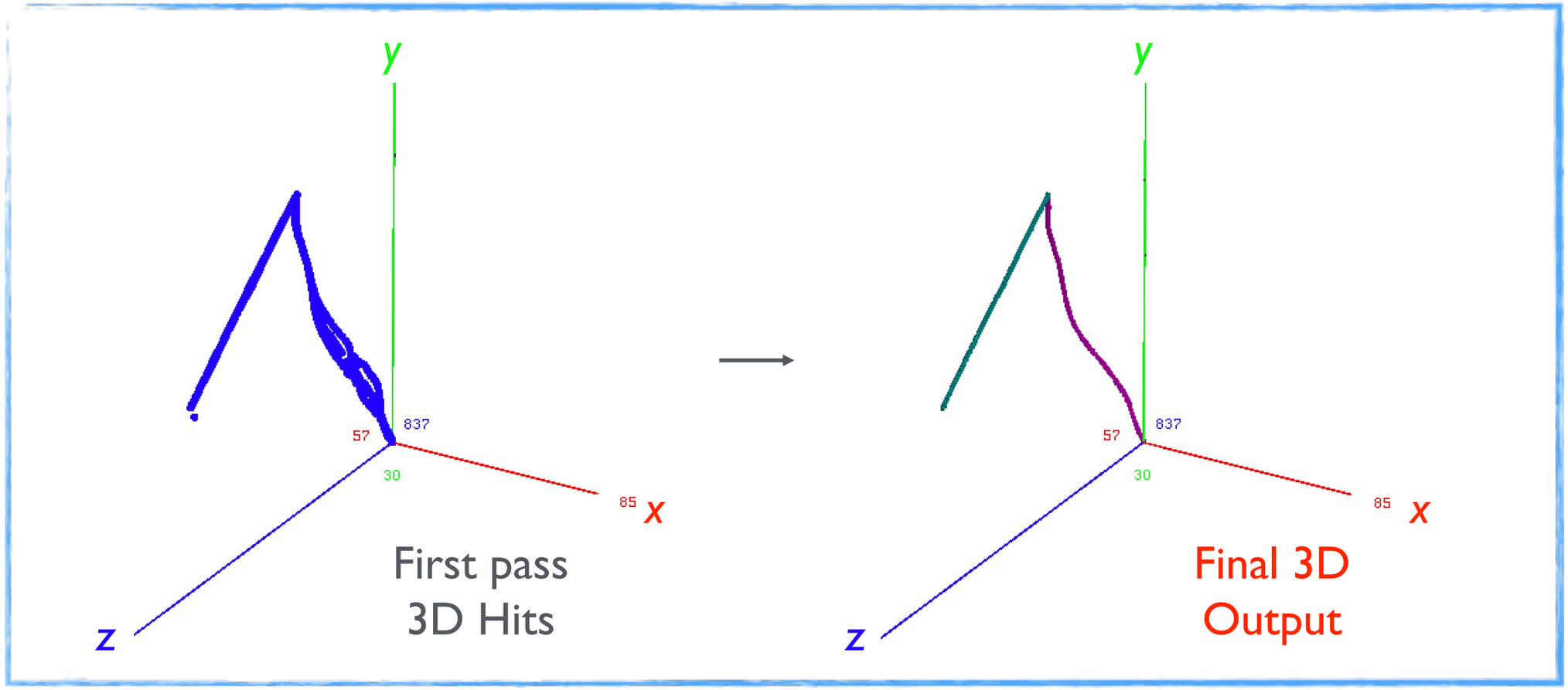
Delta-Ray Reconstruction - 2D, 3D

- **Assume any 2D clusters not in a track particle are from delta-ray showers:**
  - Simple proximity-based reclustering of hits, then topological association algs.
  - Delta-ray clusters matched between views, creating delta-ray shower particles.
  - Parent muon particles identified and delta-ray particles added as daughters.

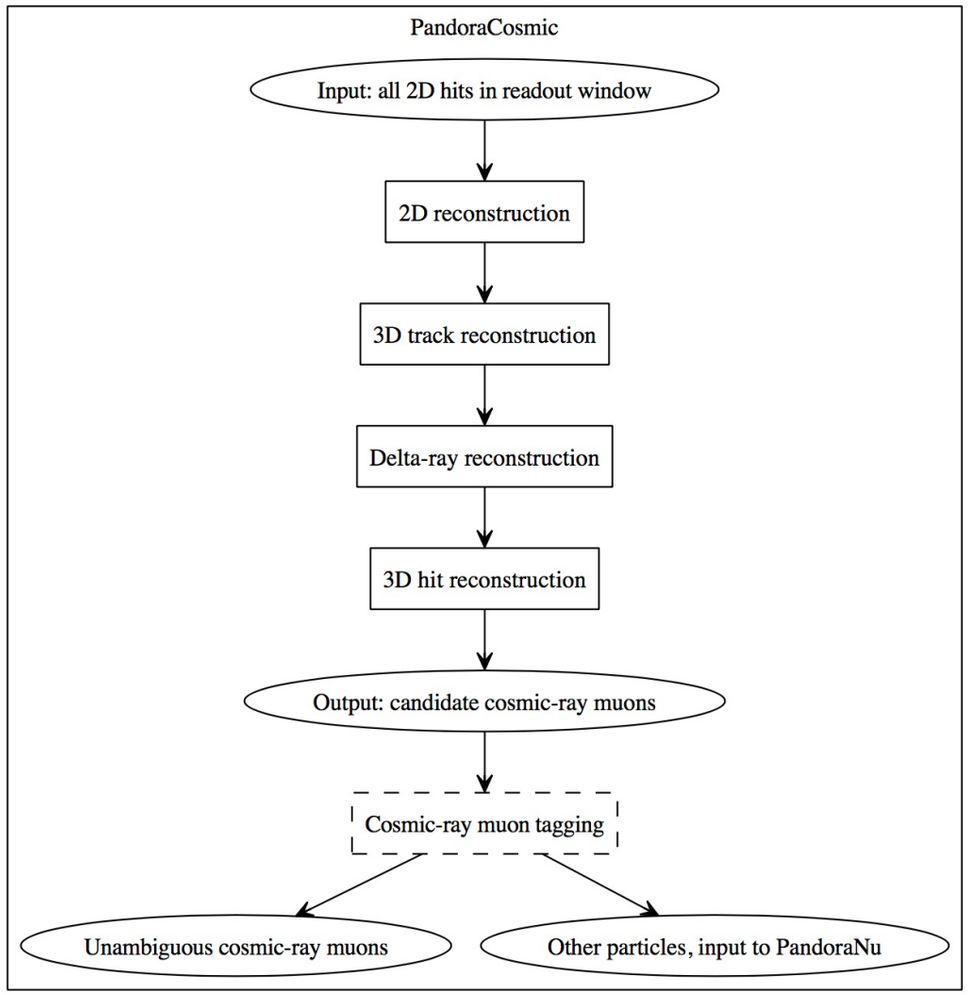


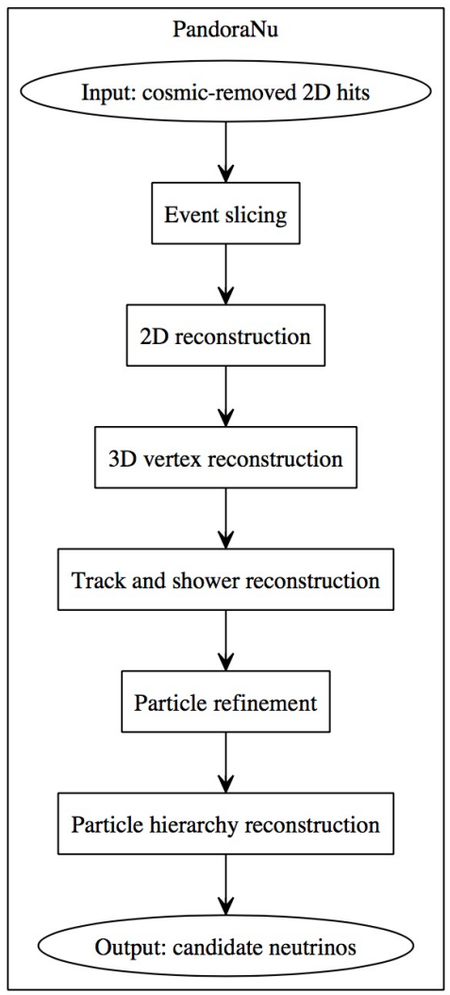
3D Hit/Cluster Reconstruction

- For each 2D Hit, sample clusters in other views at same *x*, to provide u_{in}, v_{in} and w_{in} values
- Provided u_{in}, v_{in} and w_{in} values don't necessarily correspond to a specific point in 3D space
- Analytic expression to find 3D space point that is *most consistent* with given u_{in}, v_{in} and w_{in}
  - $\chi^2 = (u_{out} - u_{in})^2 / \sigma_u^2 + (v_{out} - v_{in})^2 / \sigma_v^2 + (w_{out} - w_{in})^2 / \sigma_w^2$
  - Write in terms of unknown *y* and *z*, differentiate wrt *y*, *z* and solve
  - Can iterate, using fit to current 3D hits (extra terms in χ^2) to produce smooth trajectory



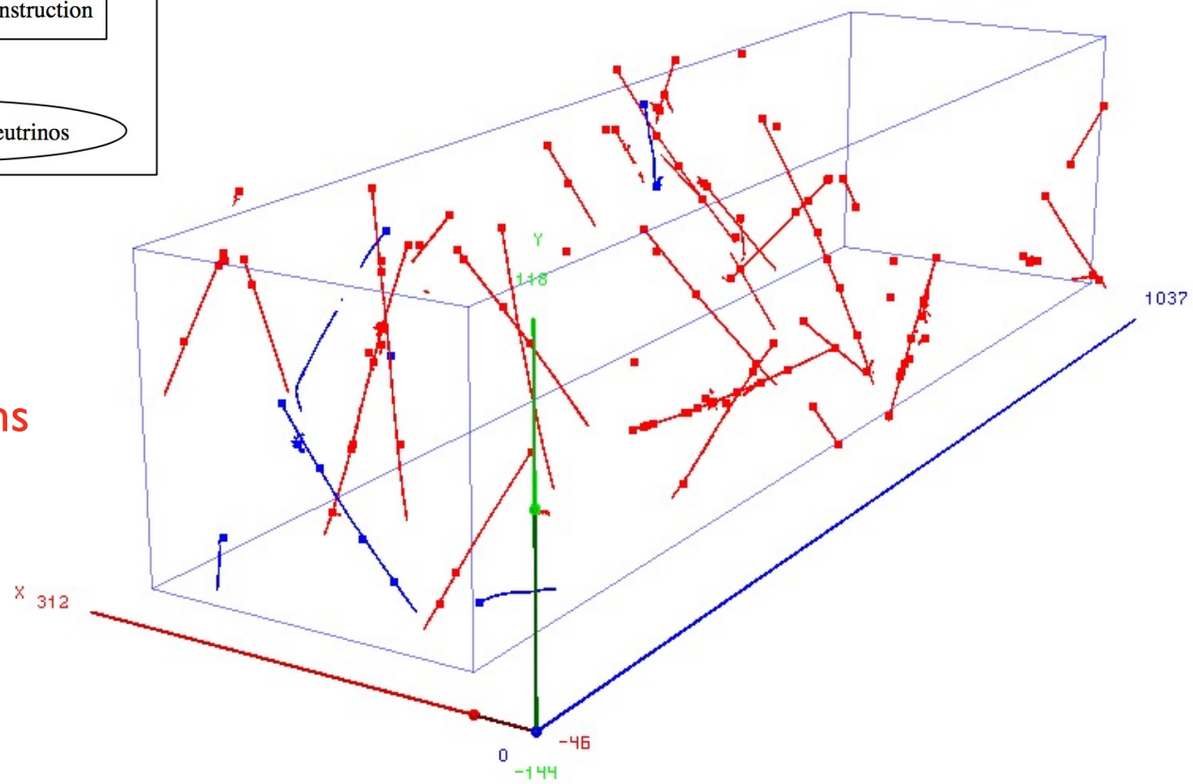
PandoraCosmic → PandoraNu





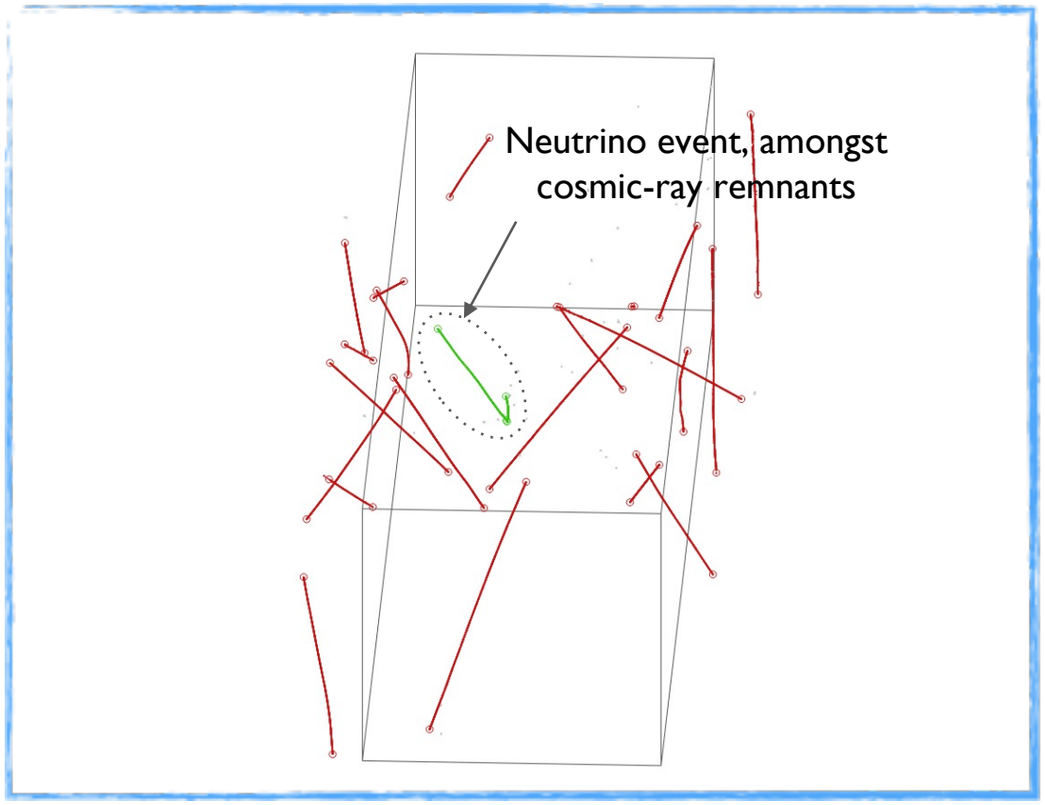
Other particles,
input to PandoraNu

Unambiguous
cosmic-ray muons

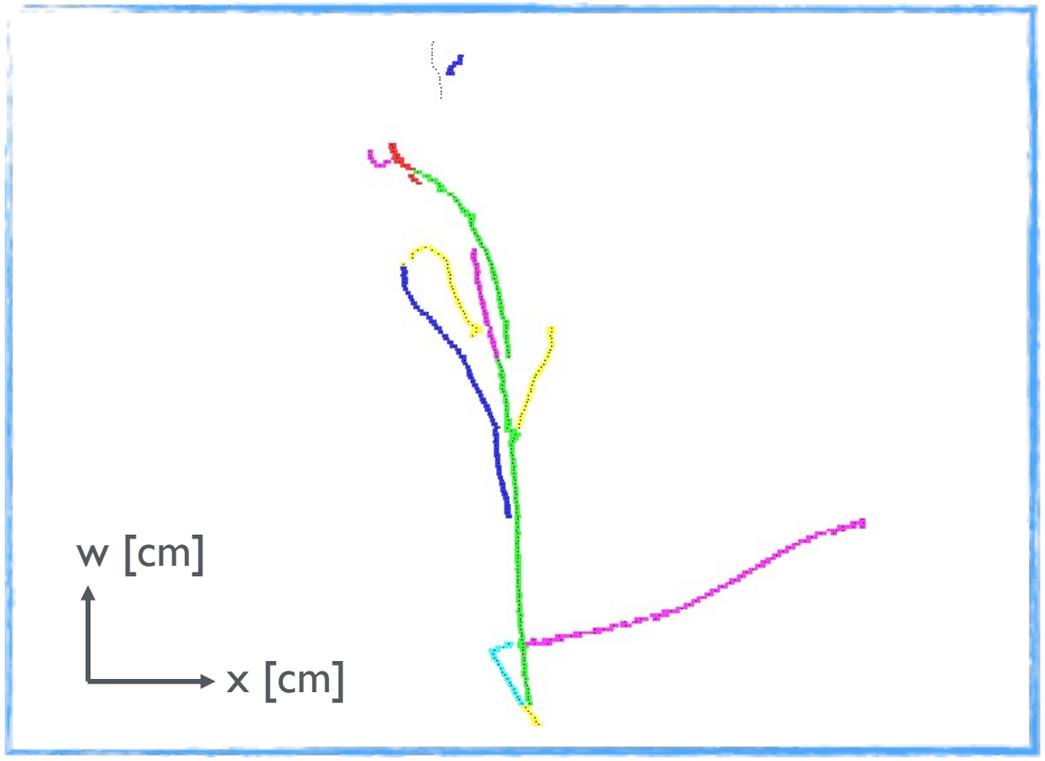


Neutrino Reconstruction

- **Must be able to deal with presence of any cosmic-ray muon remnants.**
  - Run fast version of reconstruction, up to 3D hit creation
  - "Slice" 3D hits into separate interactions, processing each slice in isolation.
  - Each slice ⇒ candidate neutrino particle.



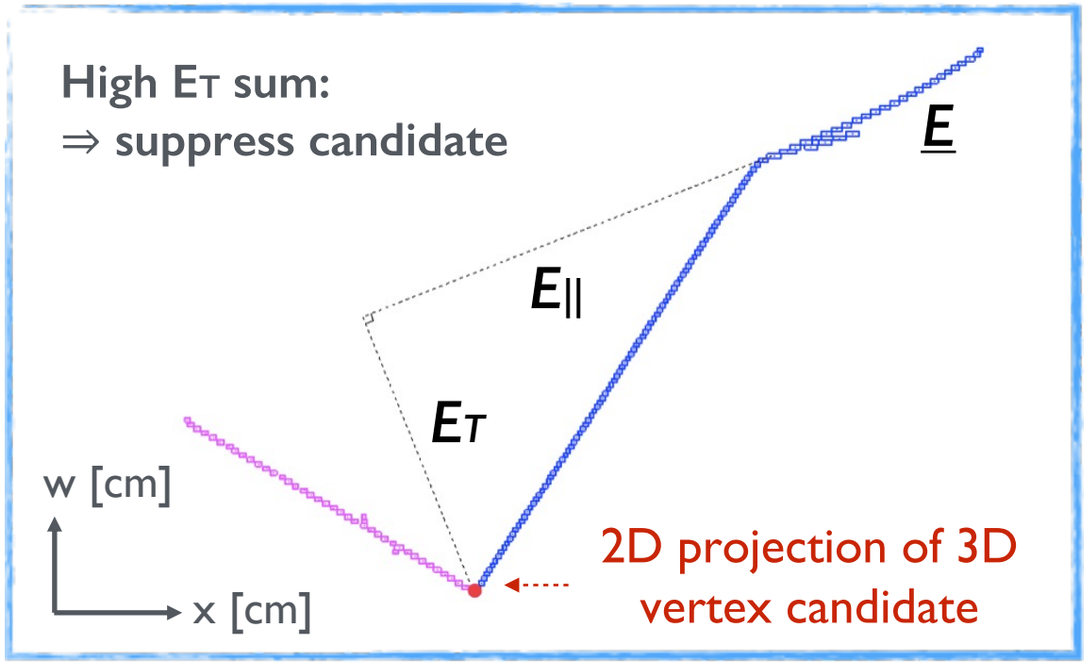
- **Neutrino pass reuses track-oriented clustering and topological association.**
  - Topological association algs must handle rather more complex topologies.
  - Specific effort to reconstruct neutrino interaction vertex.
  - More sophisticated efforts to reconstruct showers.

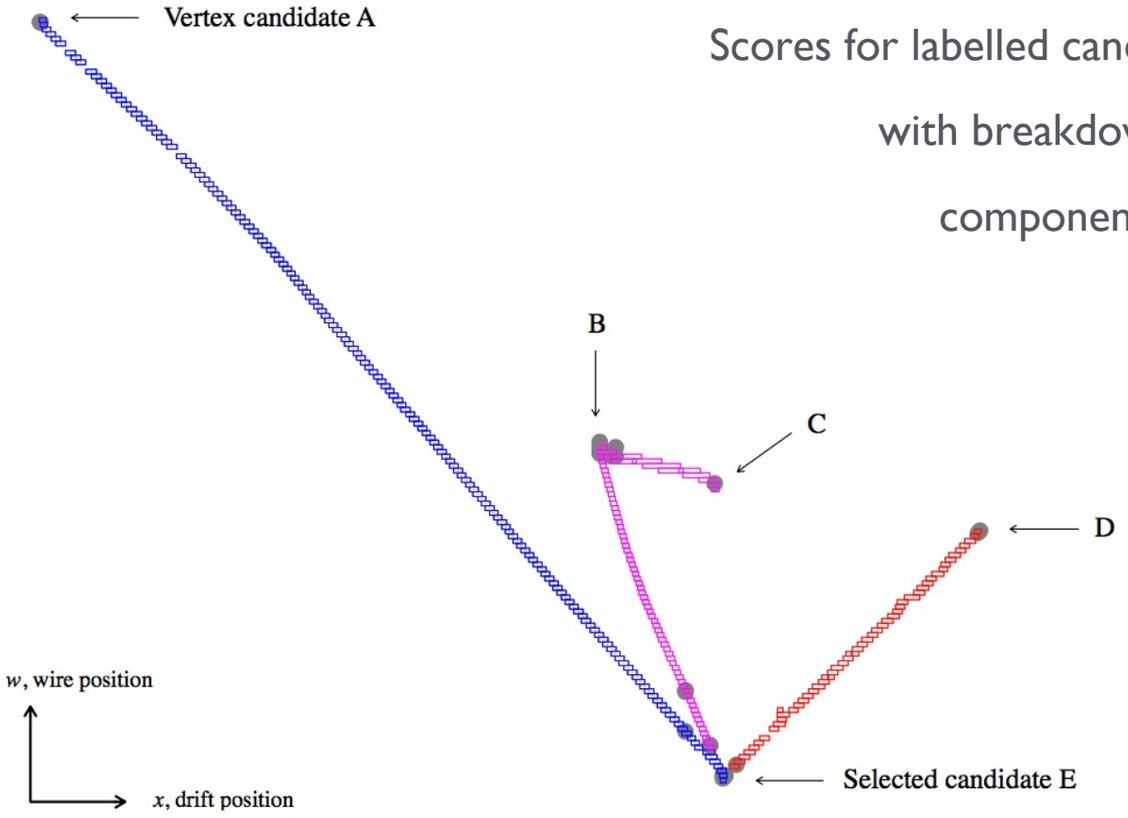


Vertex Reconstruction - 3D

Search for neutrino interaction vertex:

1. Use pairs of 2D clusters to produce list of possible 3D vertex candidates.
2. Examine candidates, calculate a score for each and select the best.





Scores for labelled candidates, with breakdown into component parts:

Candidate	S	$S_{\text{energy kick}}$	$S_{\text{asymmetry}}$	$S_{\text{beam deweight}}$
A	4.9E-07	3.5E-06	1.00	0.14
B	1.3E-02	3.1E-02	0.99	0.42
C	1.1E-03	2.4E-03	0.95	0.46
D	5.7E-10	1.1E-09	1.00	0.52
E	9.0E-01	9.0E-01	1.00	0.99

Downstream usage:

- Split 2D clusters at projected vertex position.
- Use vertex to protect primary particles when growing showers.

Vertex Reconstruction - 3D

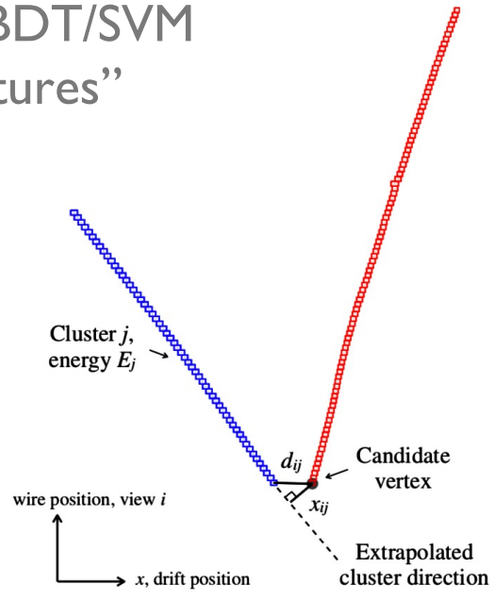
Interaction vertex is an important feature point in our LArTPC images:

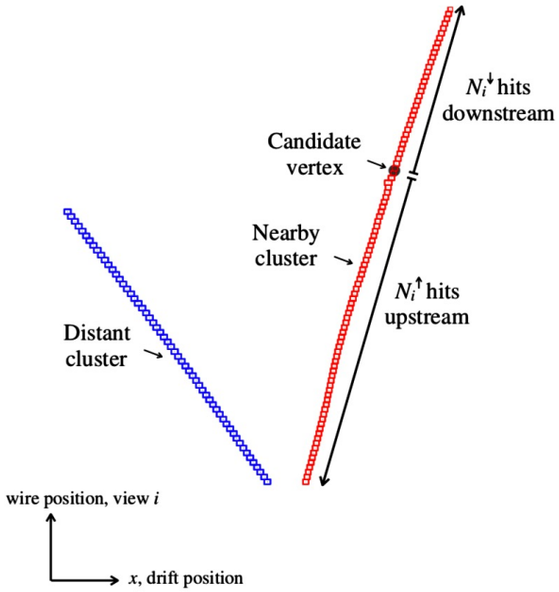
Continued development, ever-more sophisticated approaches to finding 3D vertex position

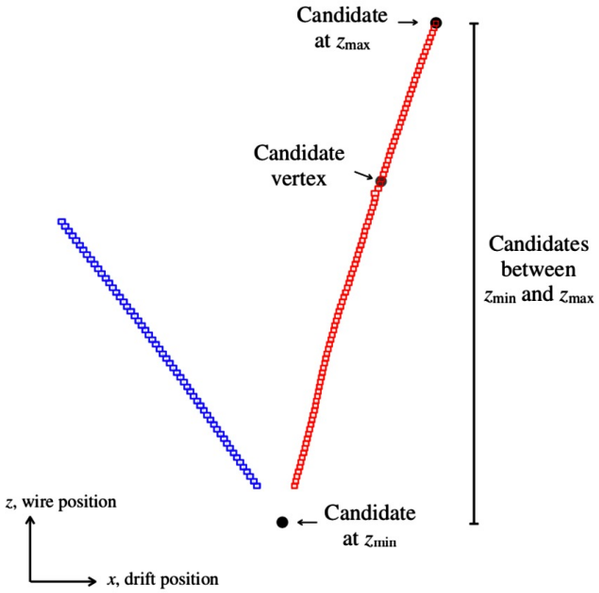
Boosted Decision Trees (BDTs) or Support Vector Machines (SVMs) to select best candidate

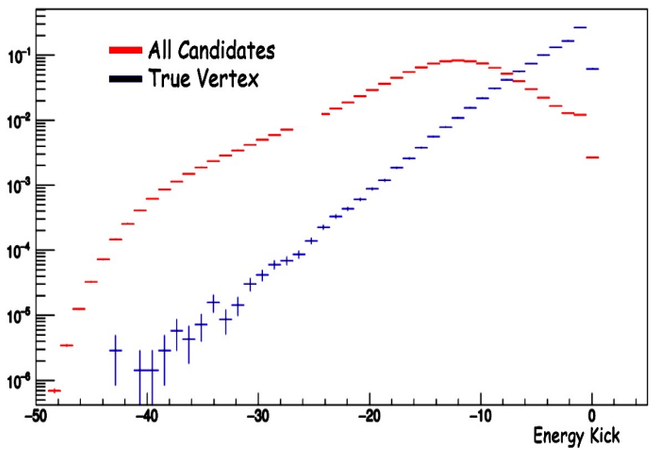
Exploit Convolutional Neural Networks (CNNs) ⇒ Deep Learning talk/tutorial tomorrow

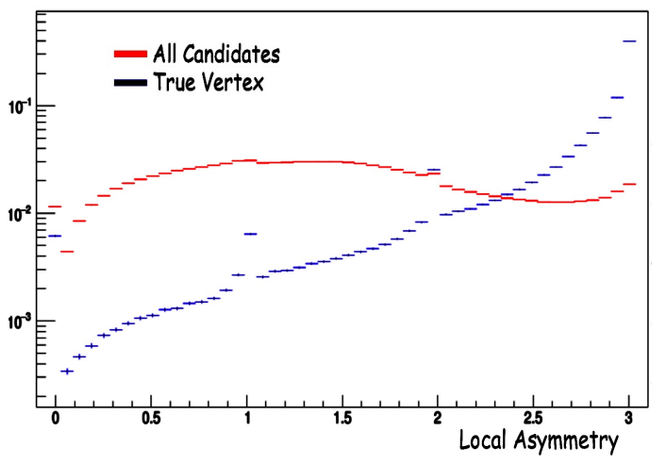
E.g BDT/SVM "features"

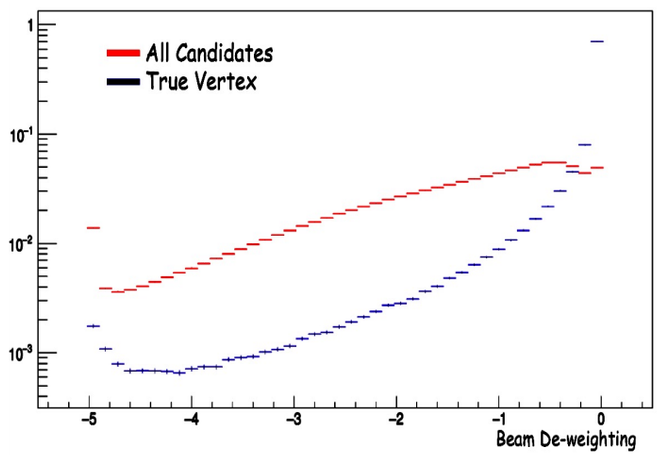








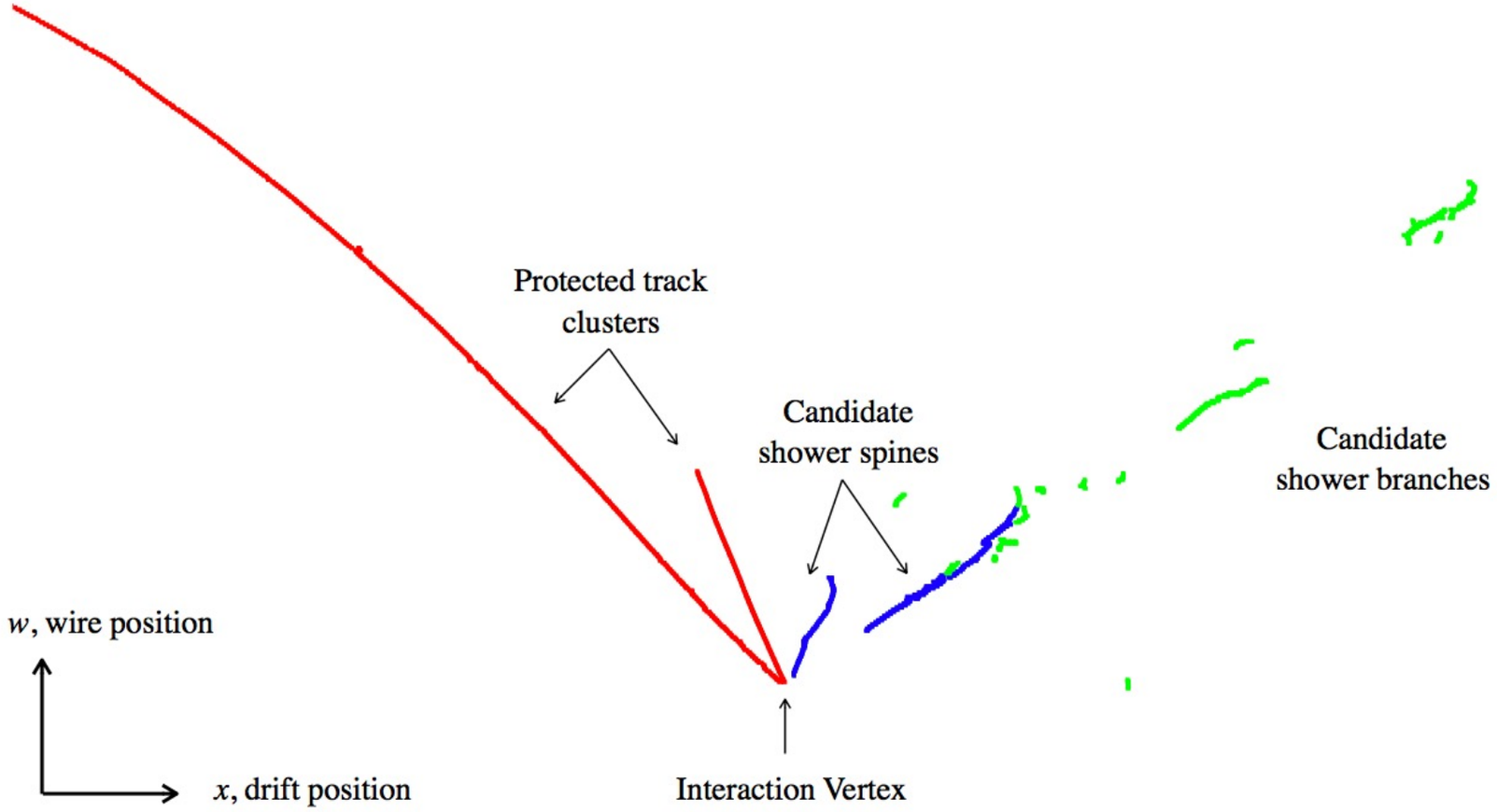




Shower Reconstruction - 2D

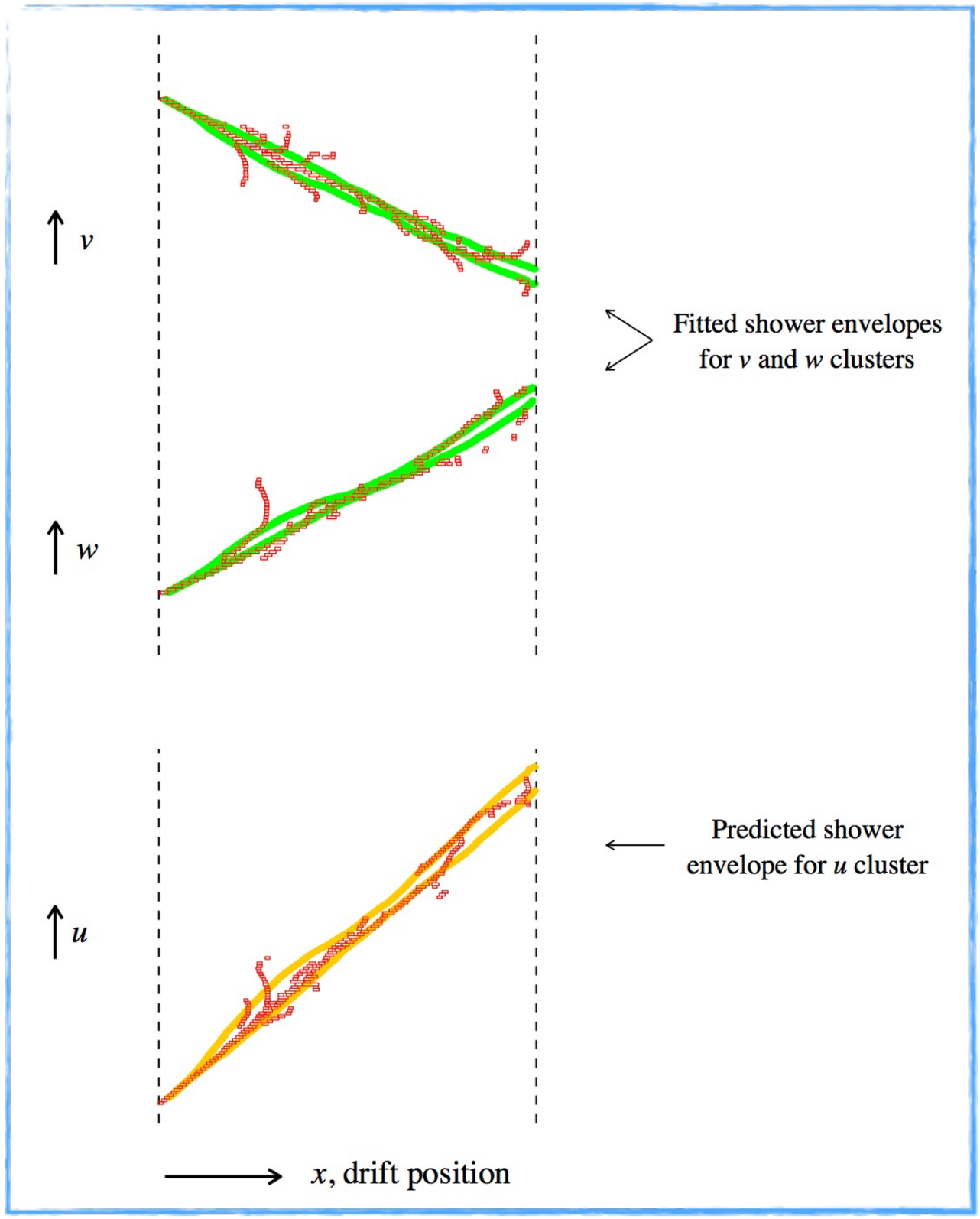
Track reconstruction exactly as in PandoraCosmic, but now also attempt to reconstruct primary electromagnetic showers, from electrons and photons:

- Characterise 2D clusters as track-like or shower-like, and use topological properties to identify clusters that might represent shower spines.
- Add shower-like branch clusters to shower-like spine clusters. Recursively identify branches on the top-level spine candidate, then branches on branches, etc.



Shower Reconstruction - 3D

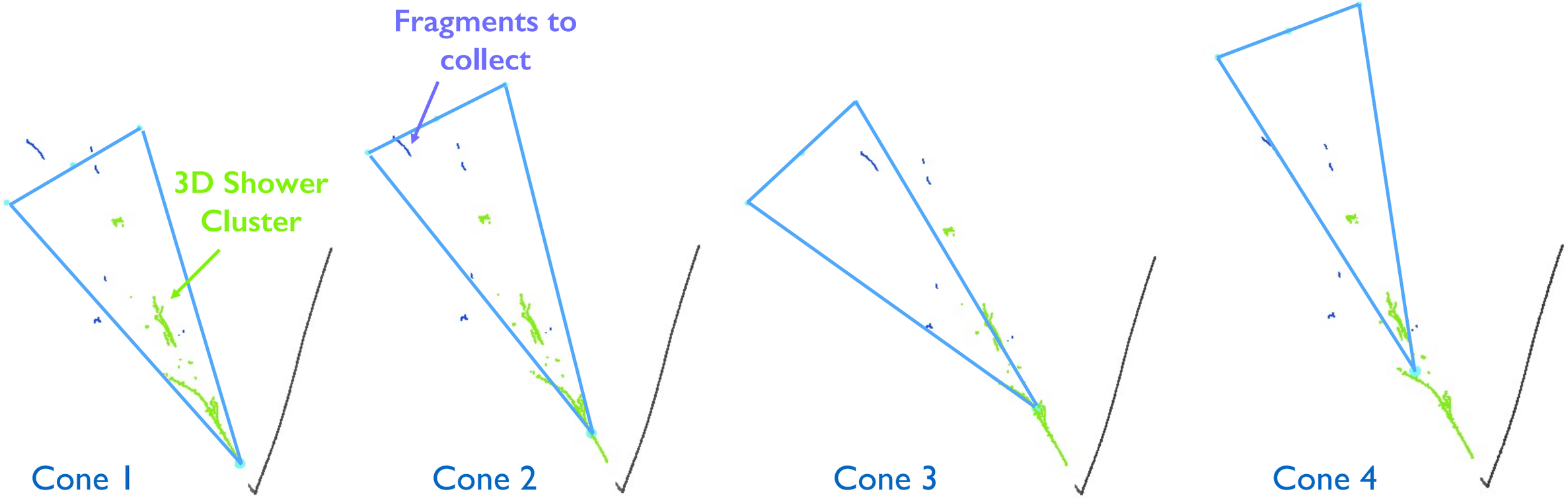
- **Reuse ideas from track reco to match 2D shower clusters between views:**
  - Build a tensor to store cluster overlap and relationship information.
  - Overlap information collected by fitting shower envelope to each 2D cluster.
  - Shower edges from two clusters used to predict envelope for third cluster.



Particle Refinement - 2D, 3D

Series of algs deal with remnants to improve particle completeness (esp. sparse showers):

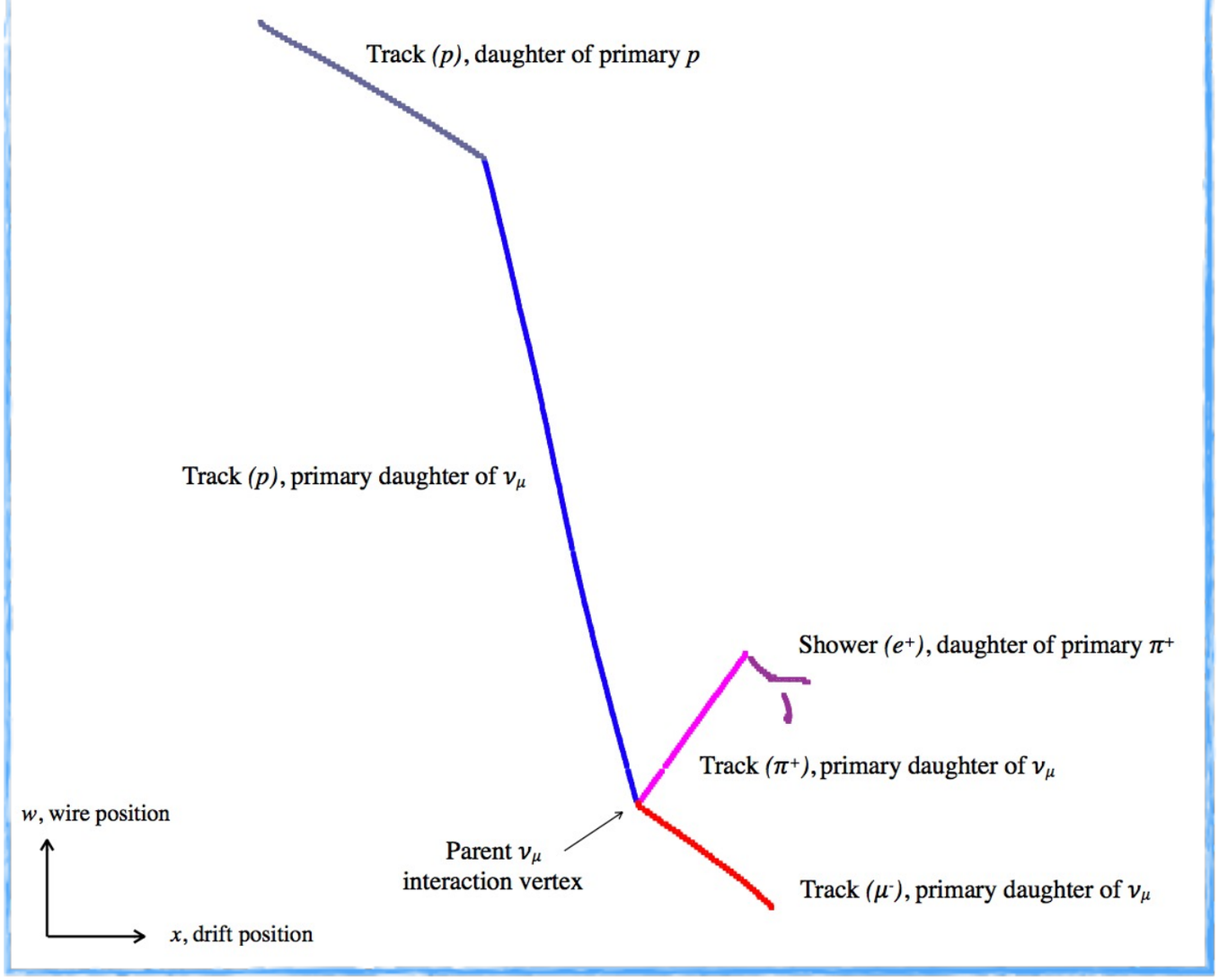
- Pick up small, unassociated clusters bounded by the 2D envelopes of shower-like particles.
- Use sliding linear fits to 3D shower clusters to define cones for merging small downstream shower particles, or picking up additional unassociated clusters.
- If anything left at end, dissolve clusters and assign hits to nearest shower particles in range.



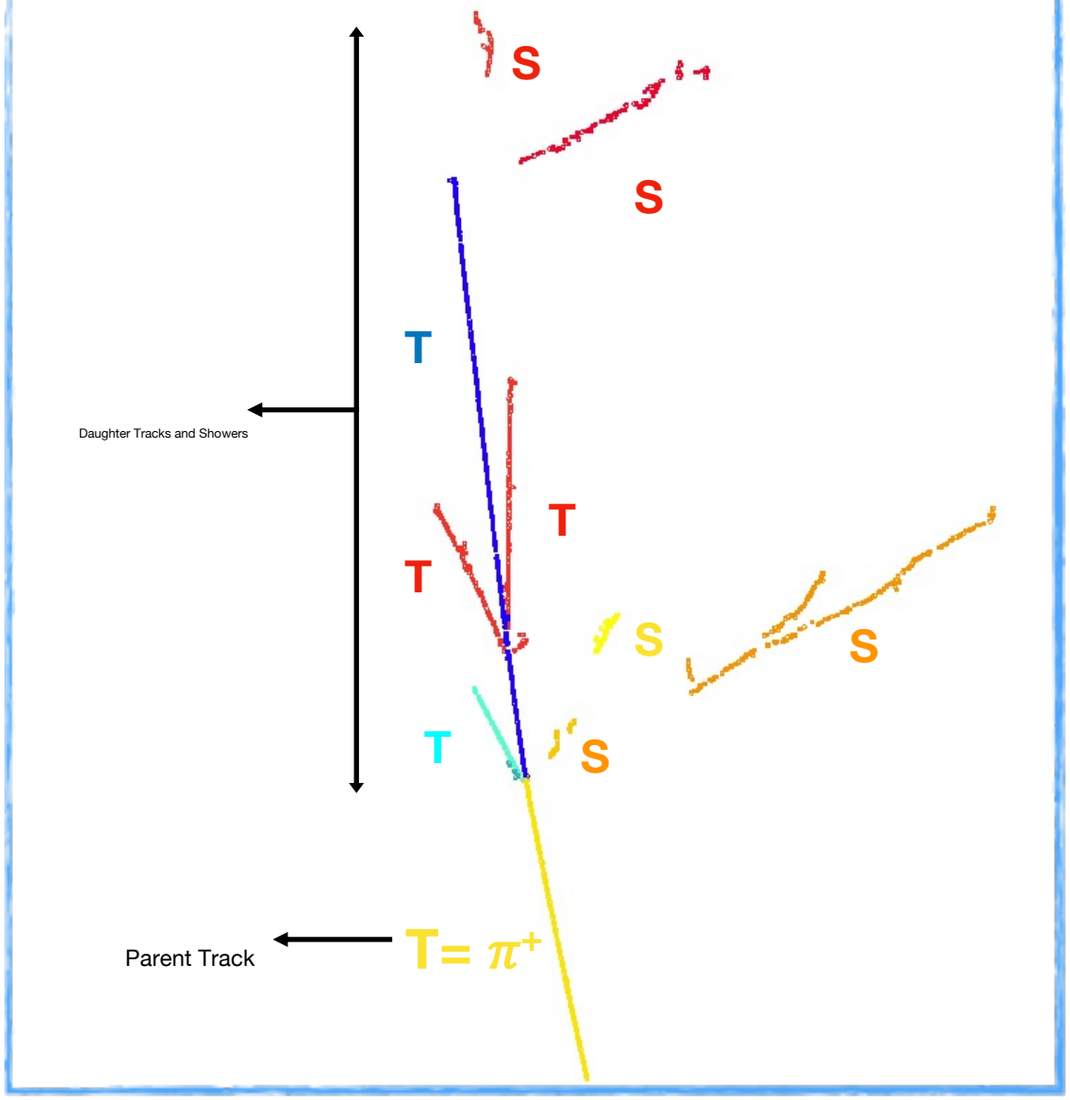
Particle Hierarchy Reconstruction - 3D

Use 3D clusters to organise particles into a hierarchy, working outwards from interaction vtx:

Simulated ν_μ Pandora Reconstruction at MicroBooNE



Simulated π^+ Pandora Reconstruction at ProtoDUNE-SP



EPJC (2018) 78:82

We will now try visualising actions of individual algorithms

Pandora Development Team

Pandora is an open project and new contributors would be extremely welcome.
We'd love to hear from you and we will always try to answer your questions.

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