Pandora: Particle Flow Reconstruction

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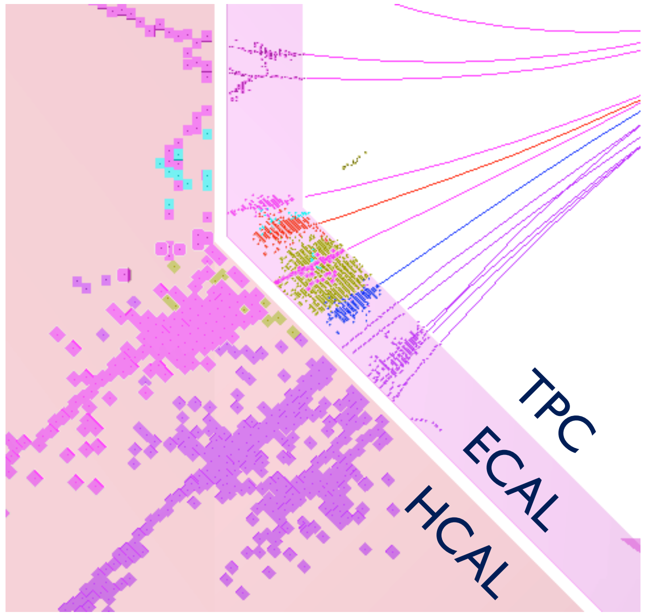
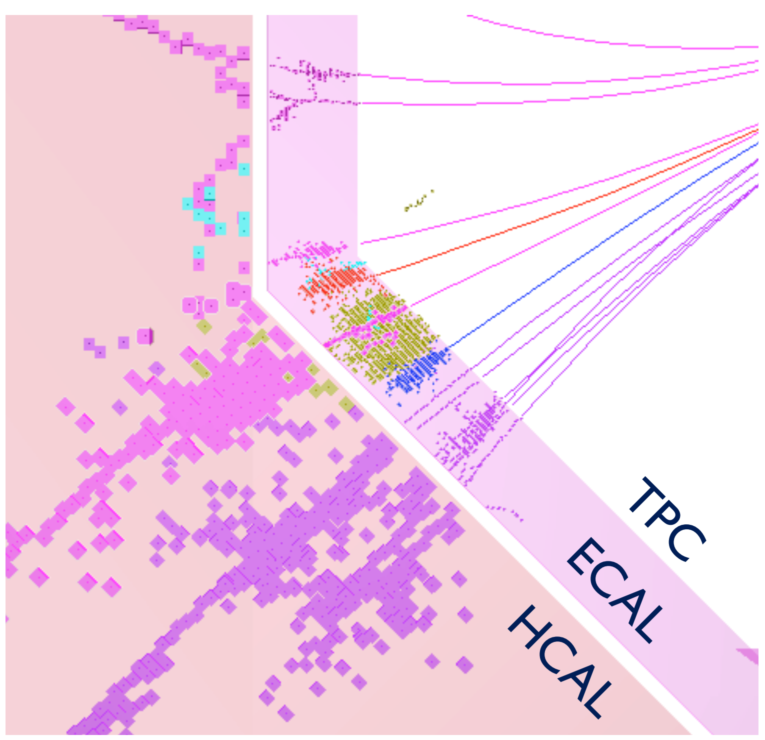


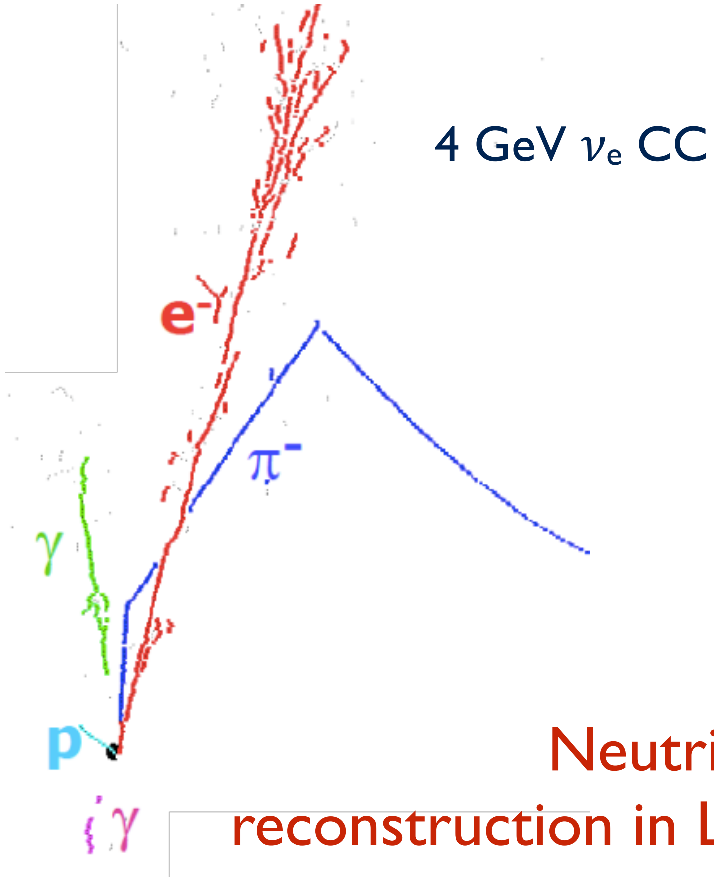
Pandora brings two key elements to the reconstruction of events in fine granularity detectors:

1. A reconstruction philosophy: "it's easier to put clusters together, than to split them up again". Large numbers of independent algorithms address specific event topologies, without mistakes.
2. A sophisticated software framework for developing pattern-recognition algorithms. All core memory management is performed by the framework, keeping algorithms simple and efficient.

Use same core software, with different algorithm logic, for two use-cases in HEP reconstruction:



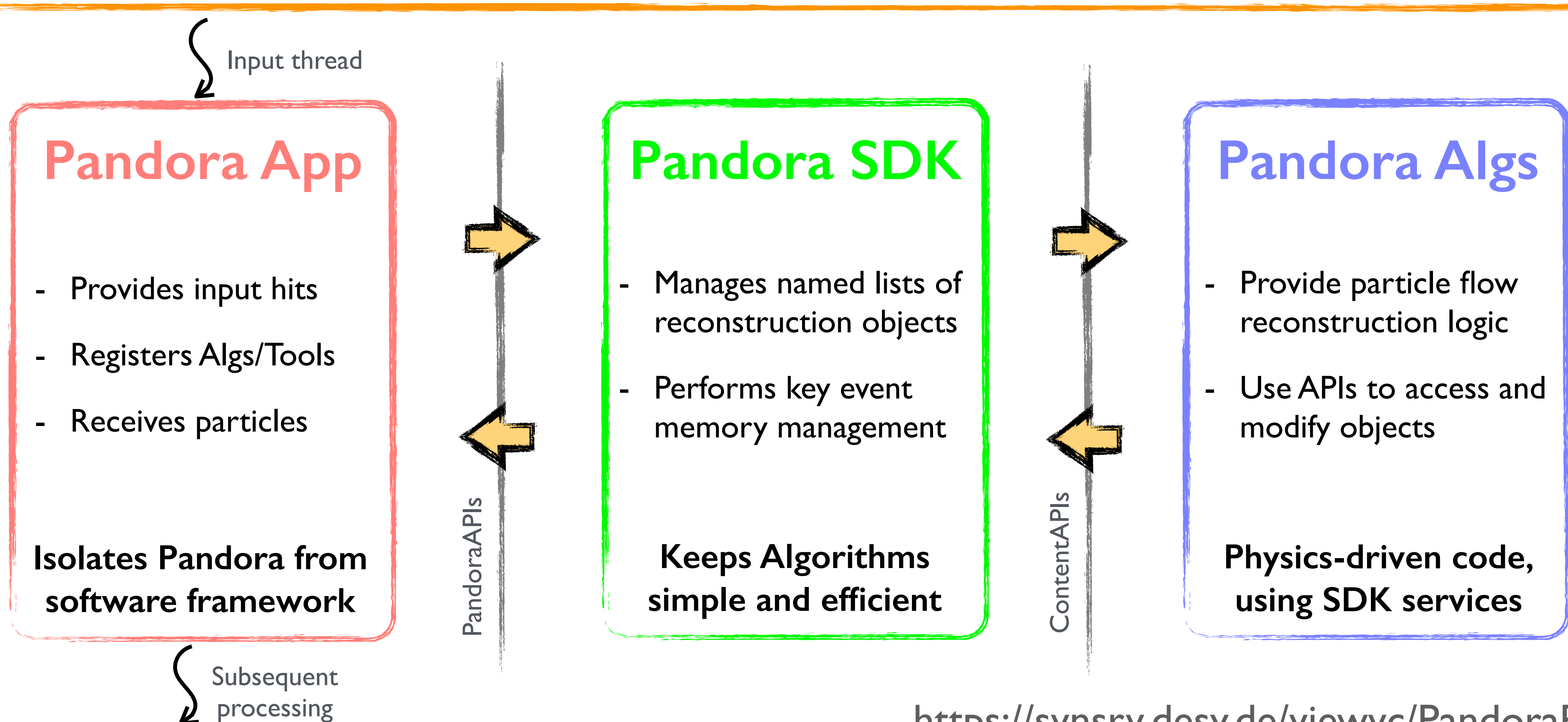
Particle flow calorimetry at a e^+e^- collider



Neutrino event reconstruction in LAr TPCs

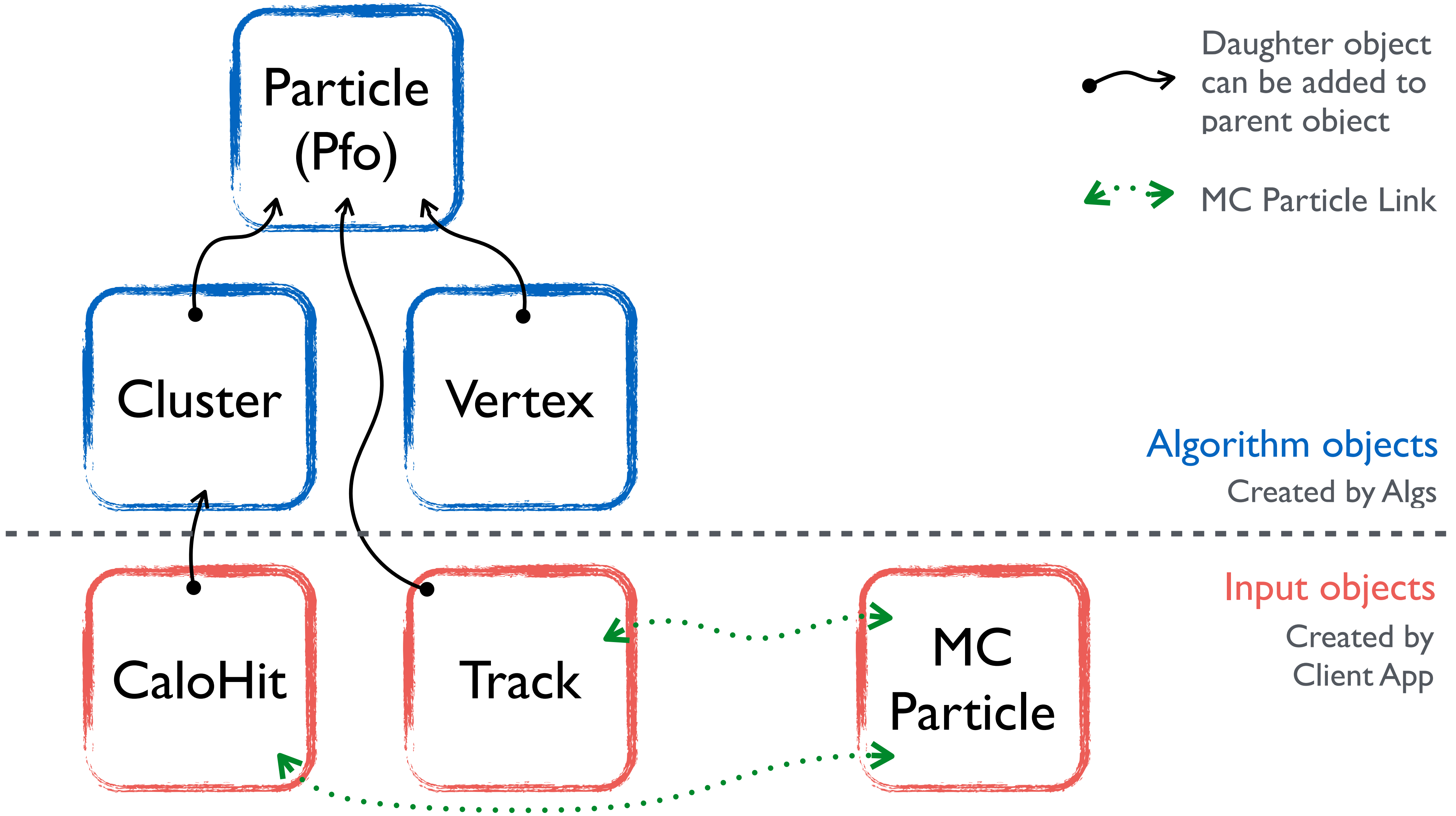
Pandora SDK

- A Pandora Client App passes details of each event (building-blocks for pattern-recognition) to Pandora, which creates and manages its own self-describing reconstruction objects.
- Reconstruction logic is provided by large numbers of Pandora Algorithms. Each Algorithm tries to address a particular event topology, making pattern-recognition changes without mistakes.
- Algorithms can only perform non-const operations (e.g. create/split/merge Clusters) by asking Pandora to provide the service. Pandora then performs memory-management and book-keeping.



https://svnsrv.desy.de/viewvc/PandoraPFANew/

Pandora Event Data Model



- EDM is flexible and re-usable, but sufficiently fully featured to make Pandora an excellent development environment. Pandora Monitoring allows easy pop-up of 3D event displays in Algs.
- Pandora persistency (can write Pandora self-describing objects to binary or xml files) allows for rapid development in a standalone Pandora environment; only need to run Client App once!

Pandora LC Event Reconstruction

Traditional calorimetric approach:

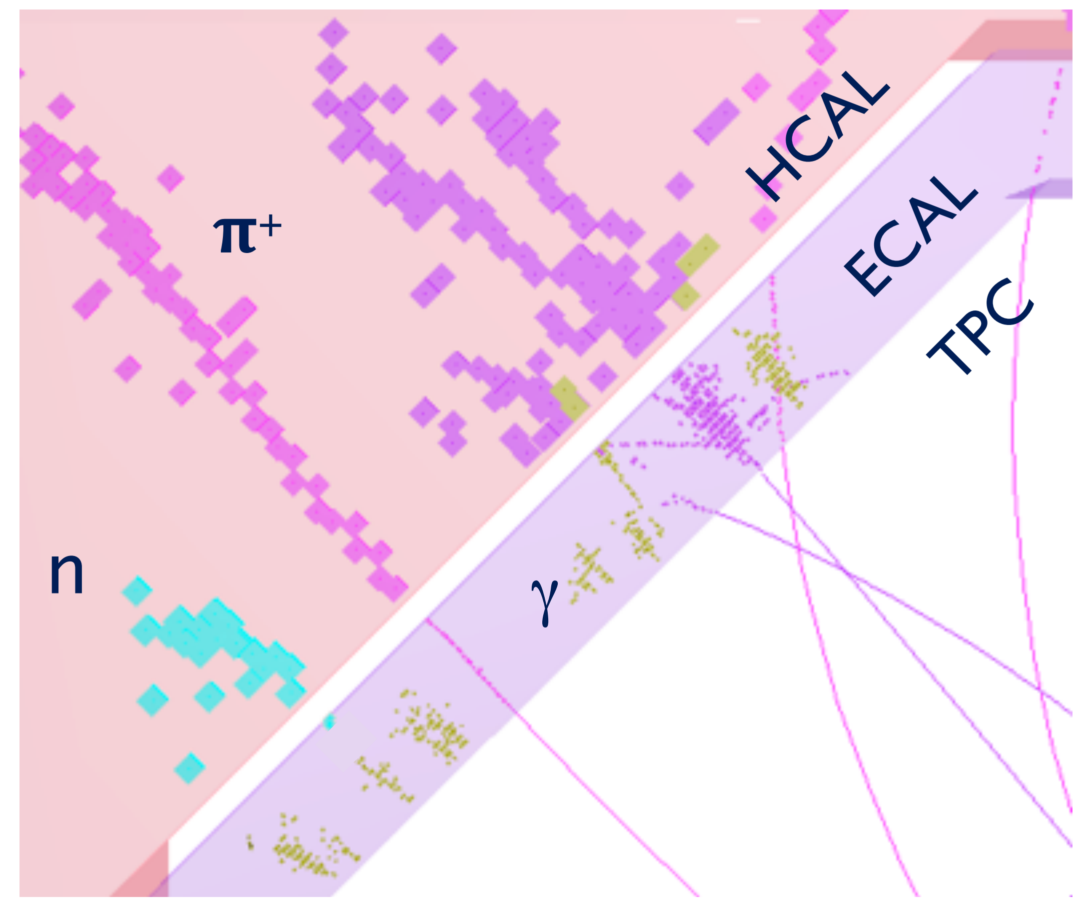
- Measure all components of jet energy in ECAL/HCAL
- Approximately 70% of energy measured in HCAL: $\sigma_E/E \approx 60\% / \sqrt{E(\mathrm{GeV})}$

Particle Flow Calorimetry:

- Trace paths of individual particles through the detector.
- Charged particle momentum measured in tracker (essentially perfectly)
- Photon energies measured in ECAL: $\sigma_E/E < 20\% / \sqrt{E(\mathrm{GeV})}$
- Only neutral hadron energies (10% of jet energy) measured in HCAL.

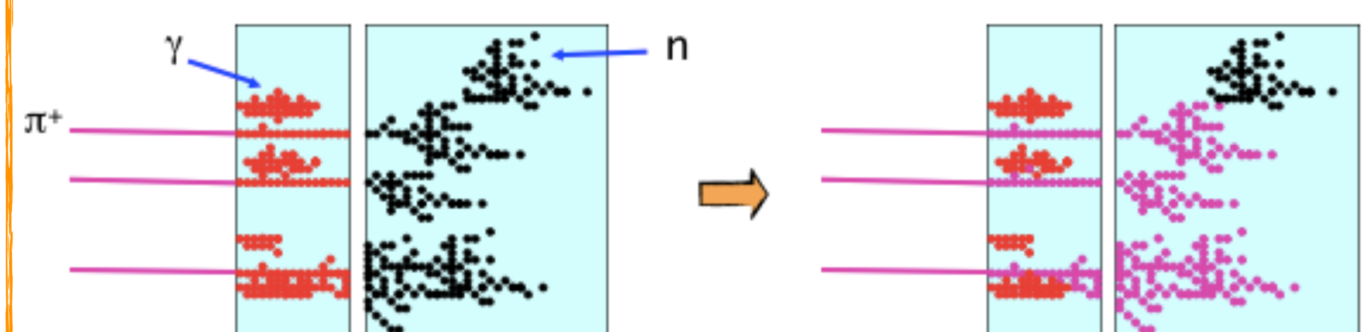
Particle Flow Calorimetry requires:

- Fine-granularity calorimeters
- Sophisticated software algorithms



Traditional calorimetry

Particle flow calorimetry

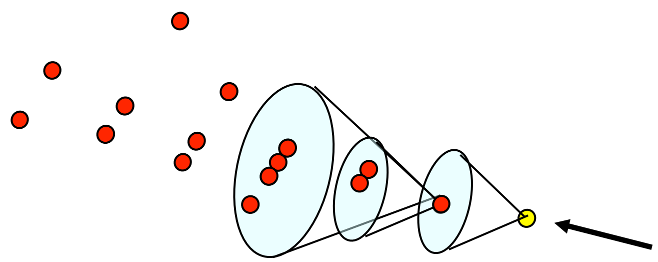


$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

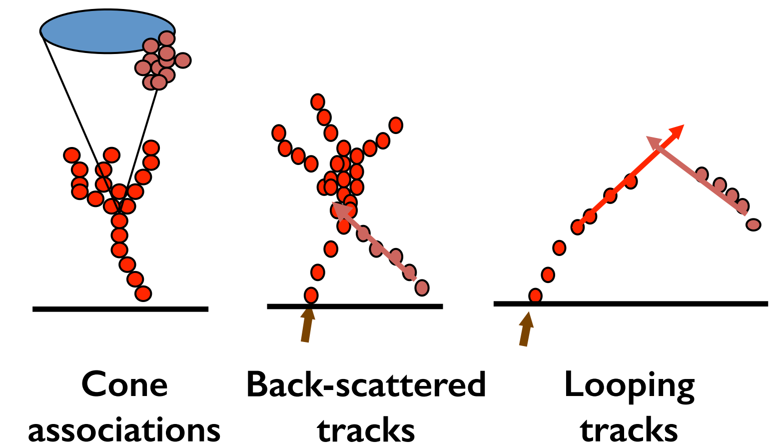
Pandora LC Algorithms

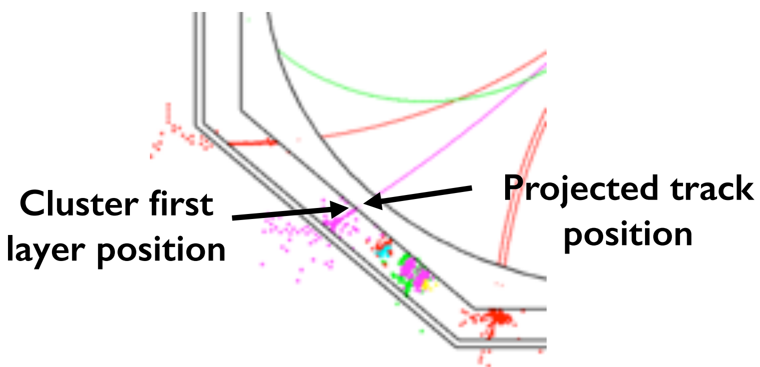
"Basic" reconstruction uses 56 algorithms:



ConeClustering Algorithm

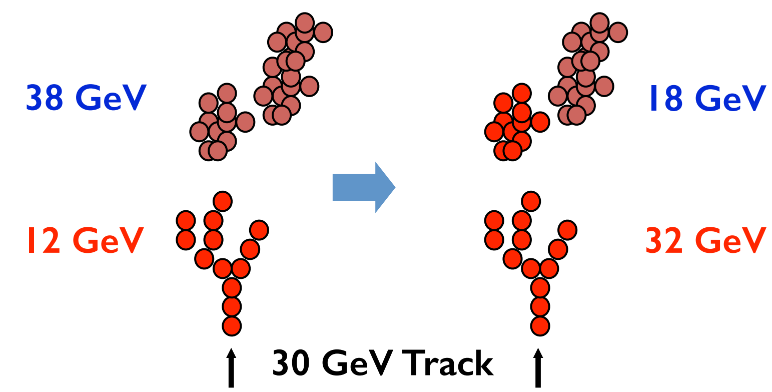
Topological Association Algorithms

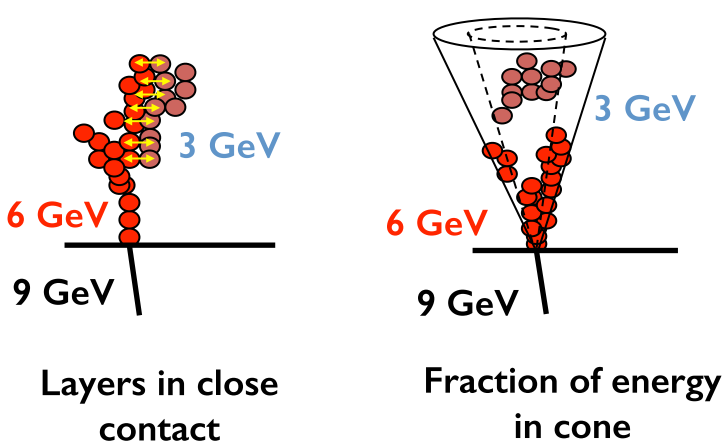




Track-Cluster Association Algorithms

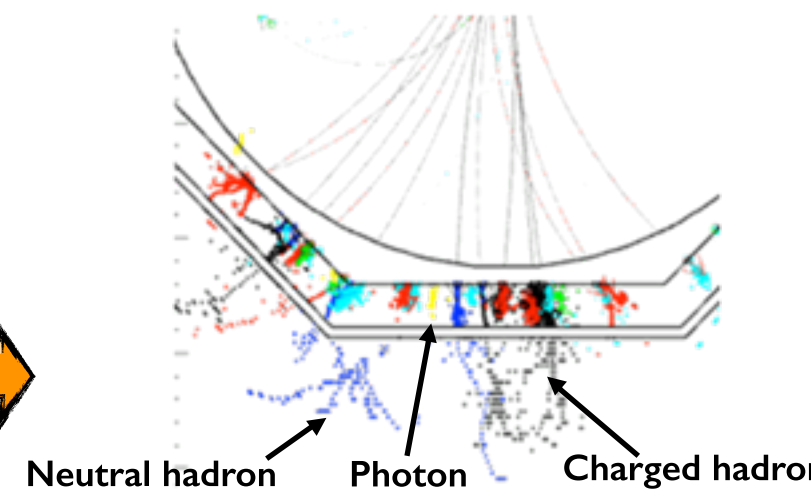
Reclustering Algorithms





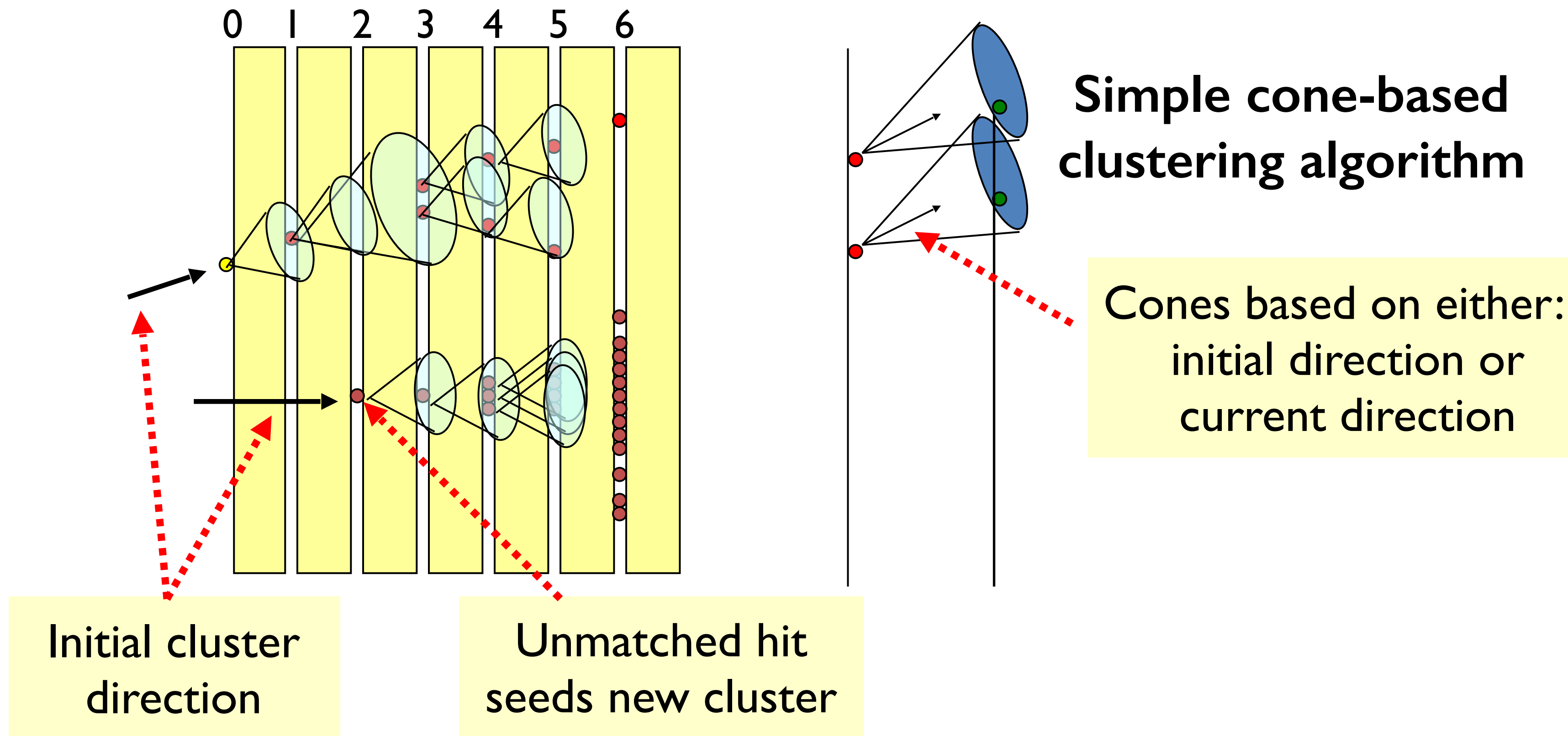
Fragment Removal Algorithms

PFO Construction Algorithms

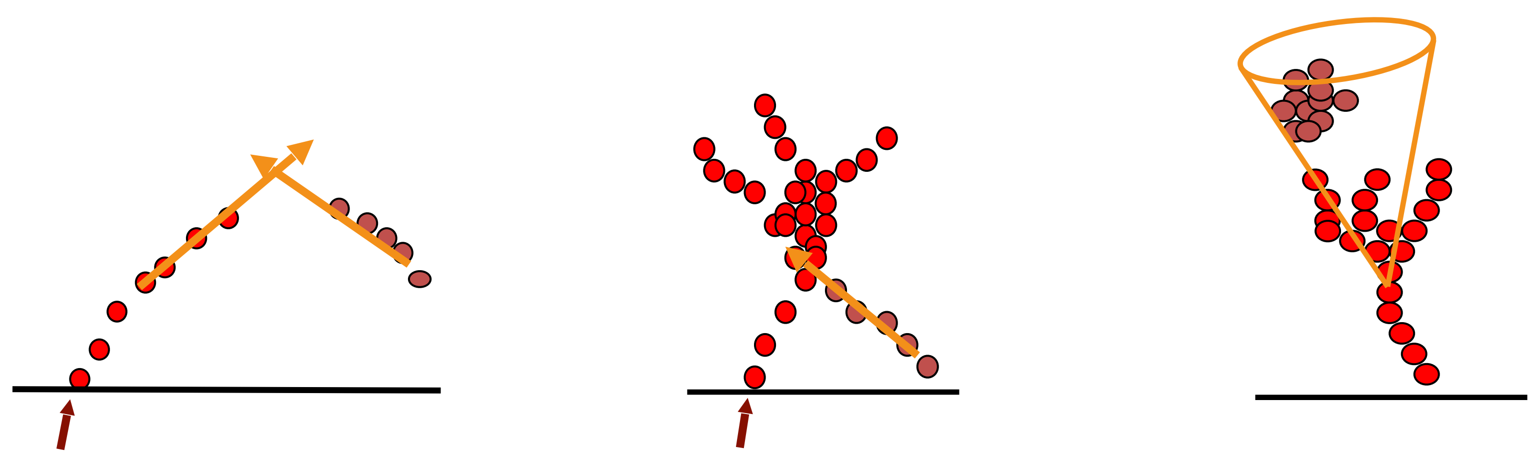


Pandora Clustering

- **Philosophy:** "It's easier to put clusters together, than to split them up again."
- Clustering algorithm opts to fragment single particles, rather than risk merging separate particles.



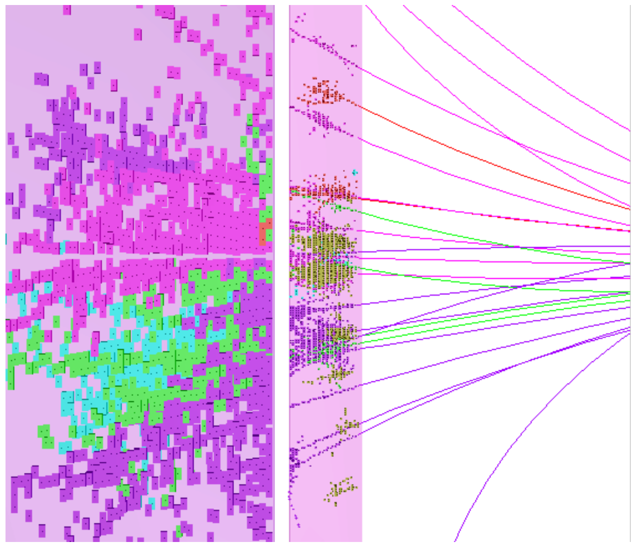
- Fine granularity of the calorimeters exploited to merge cluster fragments that are clearly associated.
- Very few mistakes made.



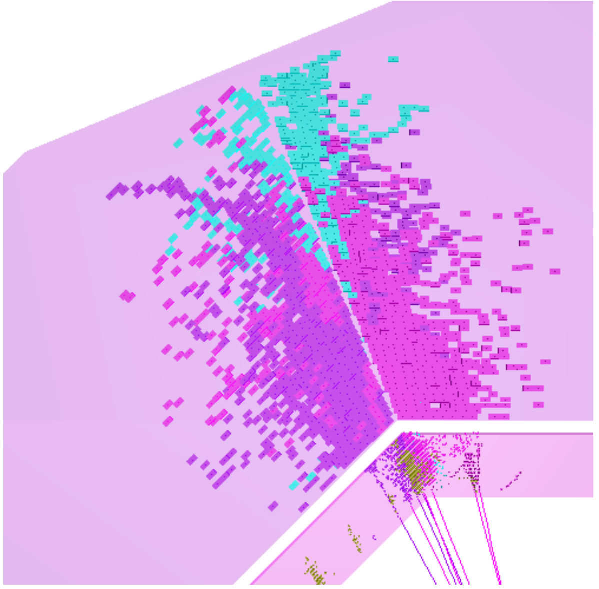
Looping tracks **Back-scattered tracks** **Cone associations**

Pandora Reclustering

- Key aspect of particle flow calorimetry is association of calorimeter clusters to inner detector tracks.
- Look for consistency between cluster properties and helix-projected track state at front face of calorimeter:
  - Close proximity between cluster and track positions.
  - Consistent track and initial cluster directions.

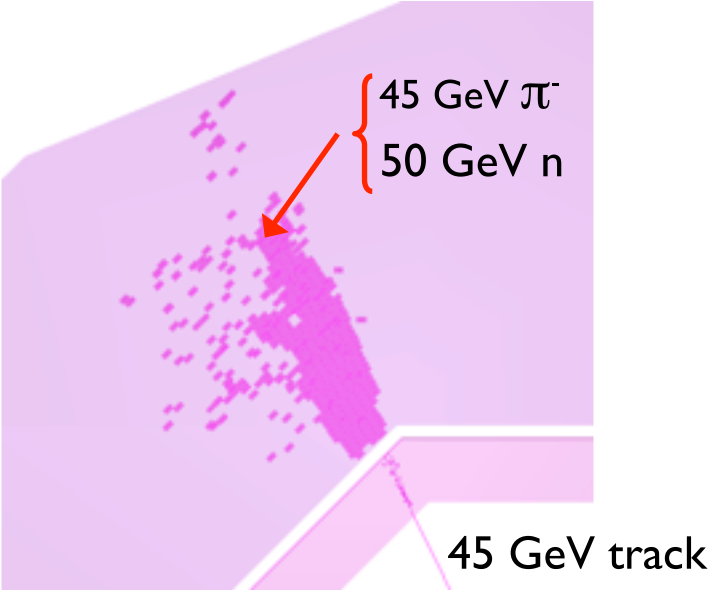


- At some point, in high energy jets, cannot cleanly resolve neutral hadrons in hadronic showers.
- Use information from track-cluster associations to identify pattern-recognition problems:



After topological association

Compare E/p values to find problems



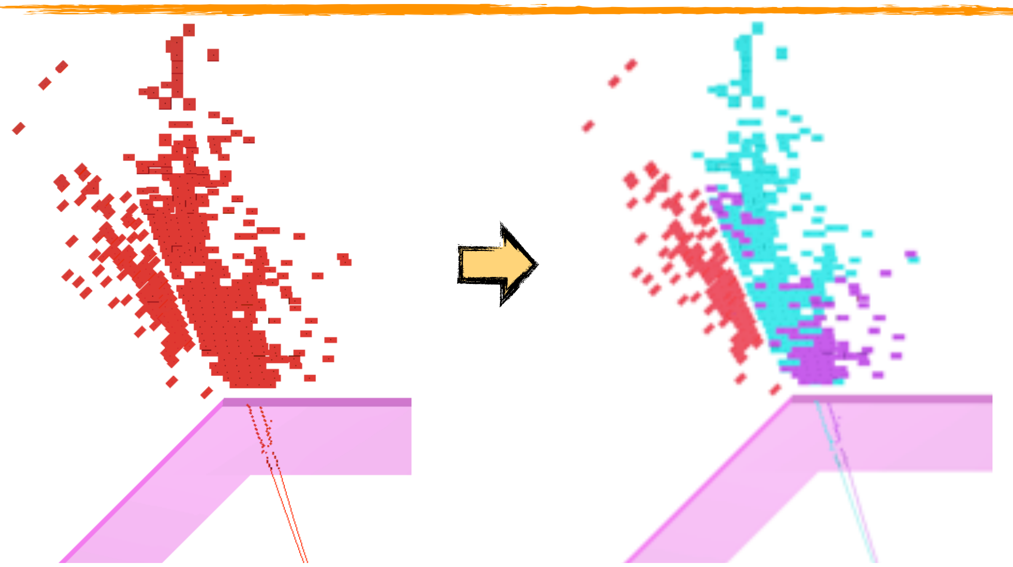
Find n absorbed into π^- cluster

e.g. 45GeV track associated to 95GeV cluster:

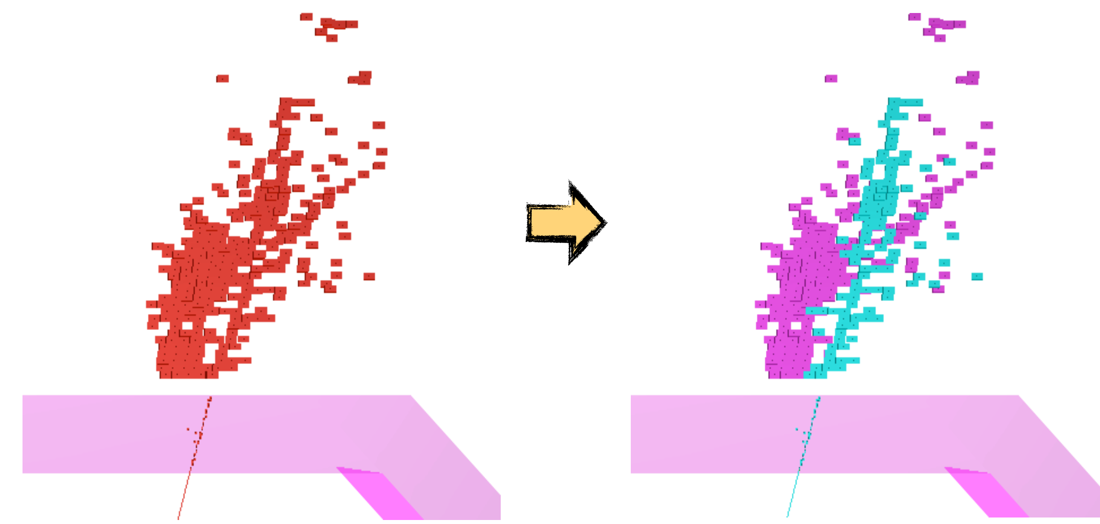
identify and address clustering problem

Pandora Reclustering

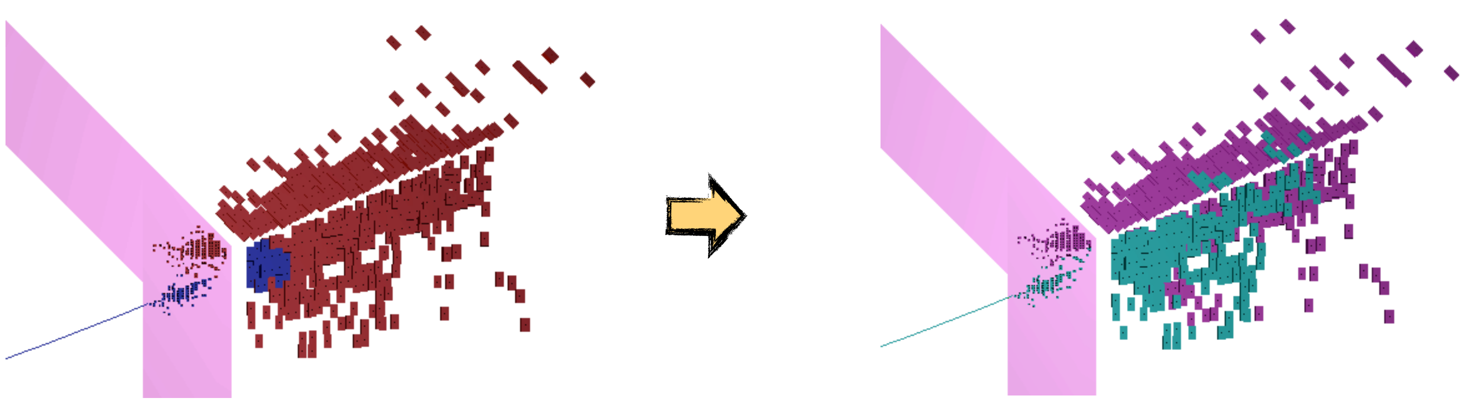
If identify significant discrepancy between cluster energy and associated track momentum, choose to recluster. Alter clustering parameters until cluster splits to obtain track-cluster consistency.



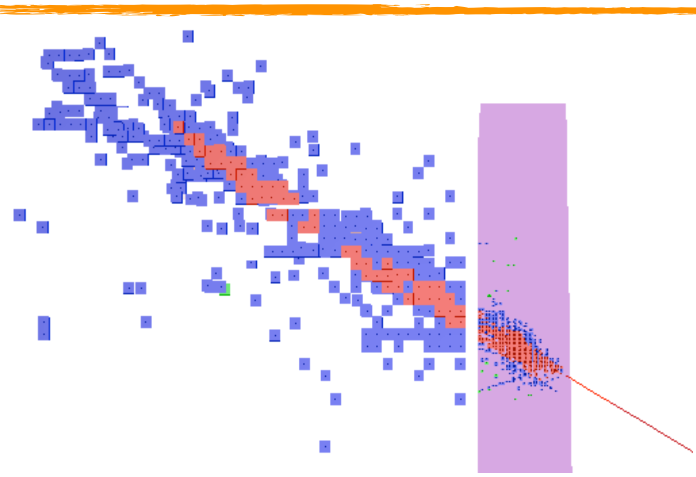
1. Multiple tracks associated to single cluster – split cluster.



2. Cluster energy much greater than track momentum – split cluster.



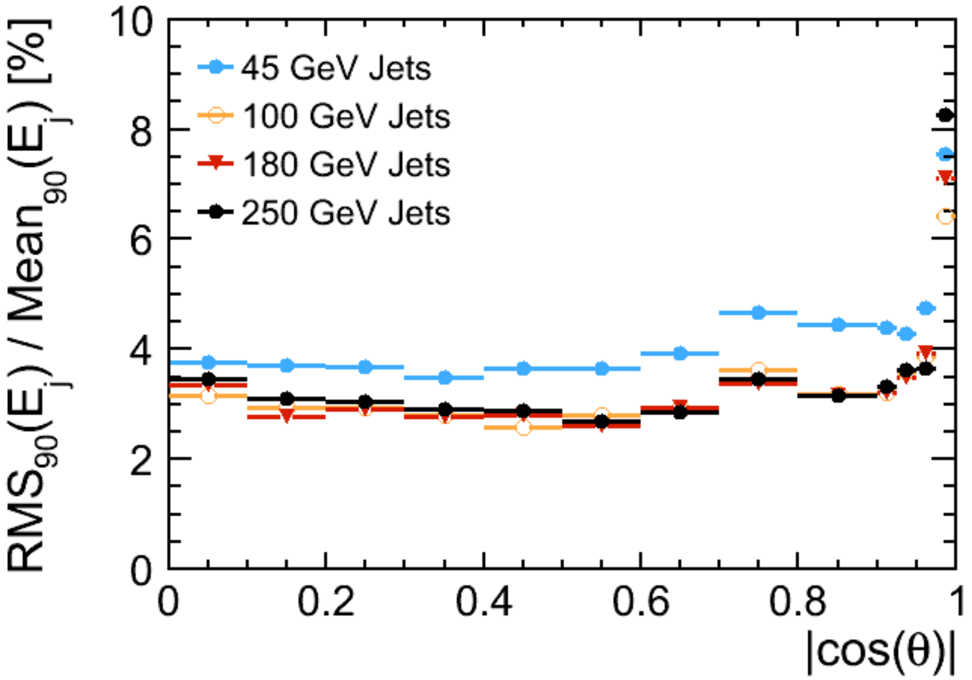
3. Track momentum much greater than cluster energy – bring in nearby clusters and reconfigure.

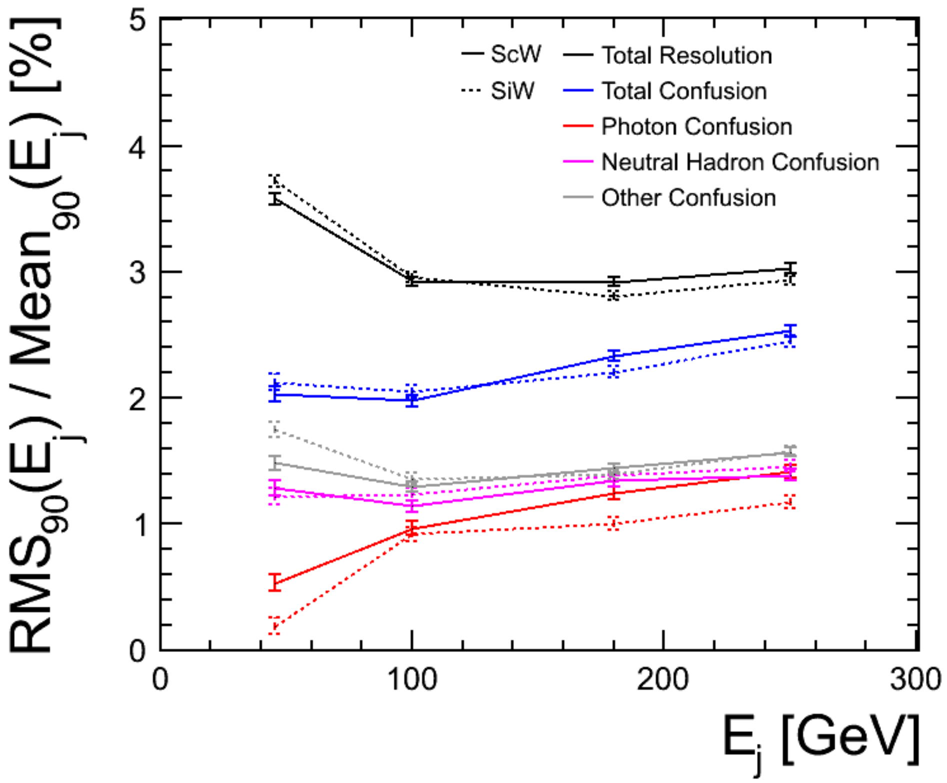


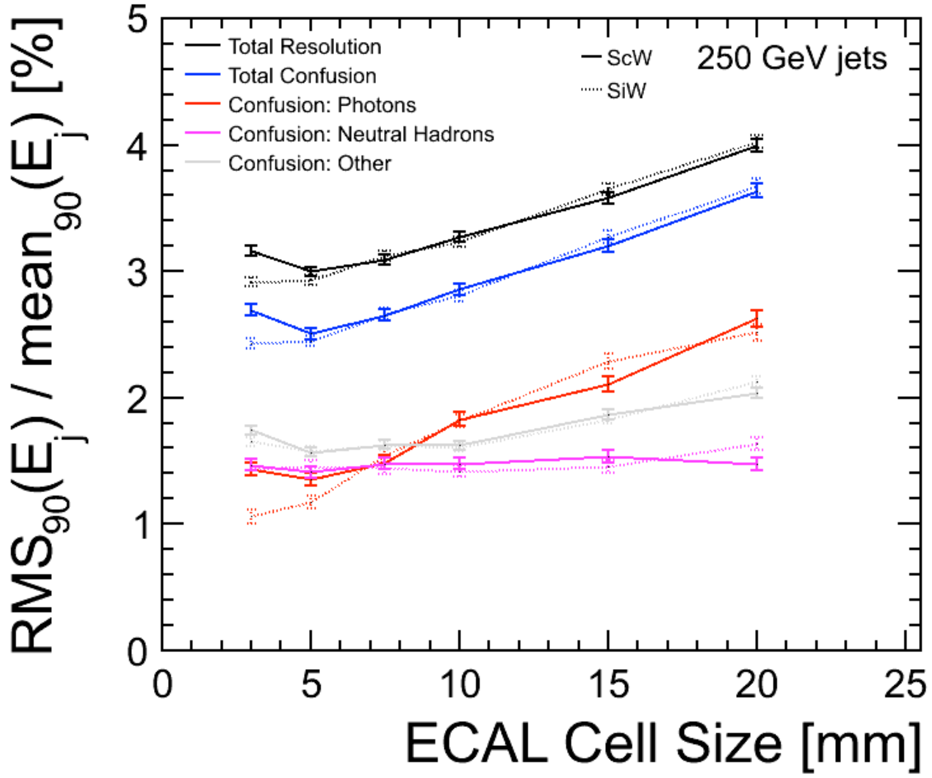
4. If, and only if, no E/p match emerges, can force track-cluster consistency ⇒ energy flow.

Pandora Performance

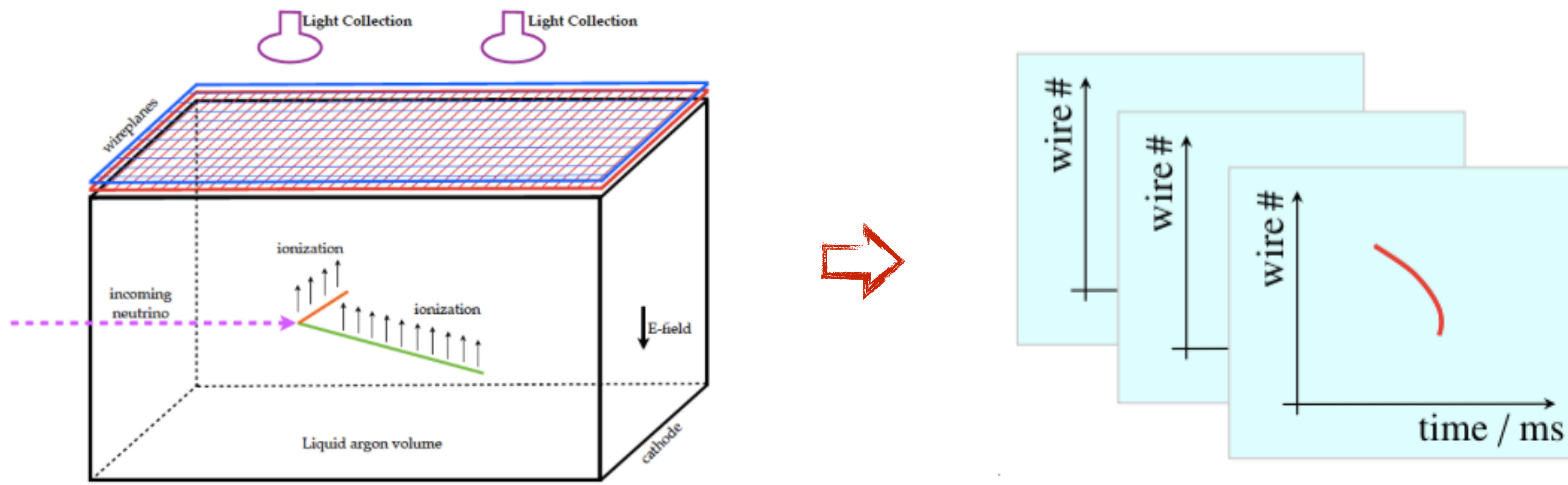
- Motivation for fine granularity particle flow:
  Jet energy resolution: $\sigma_E/E < 3.5\%$
- Benchmark performance using jet energy resolution in Z decays to light quarks.
- Full GEANT4 simulations used.
- Use jet energy resolution as figure of merit for detector optimisation studies.





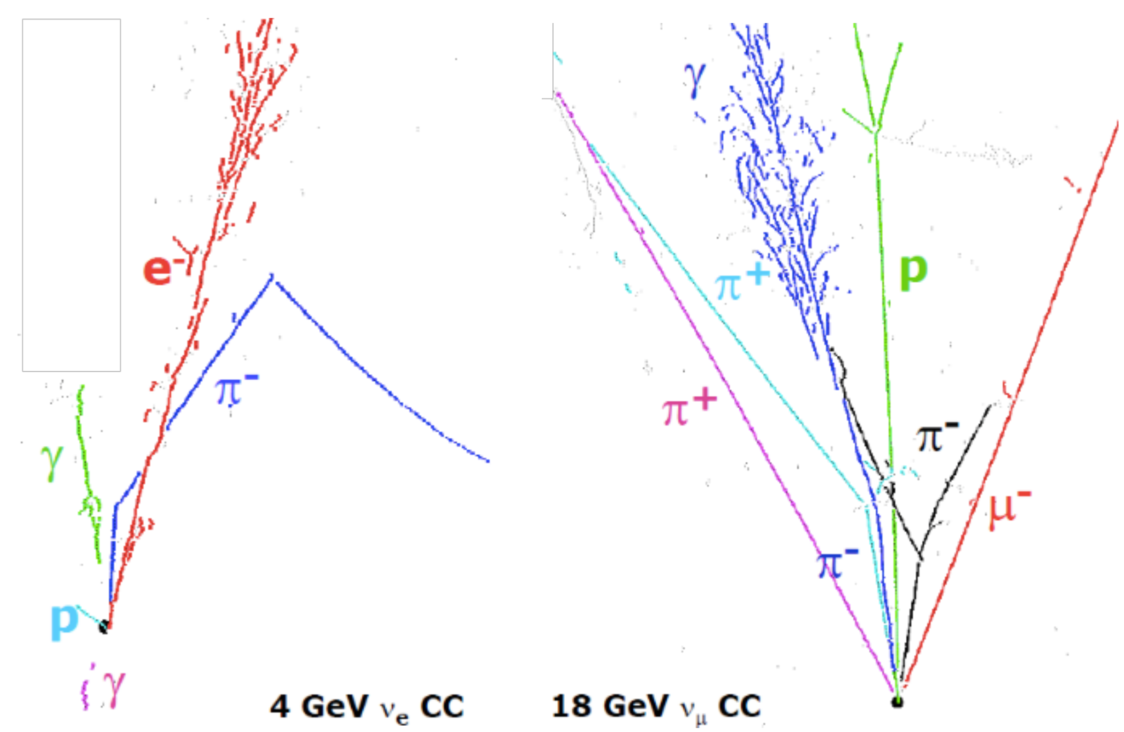


Pandora LAr TPC Reconstruction



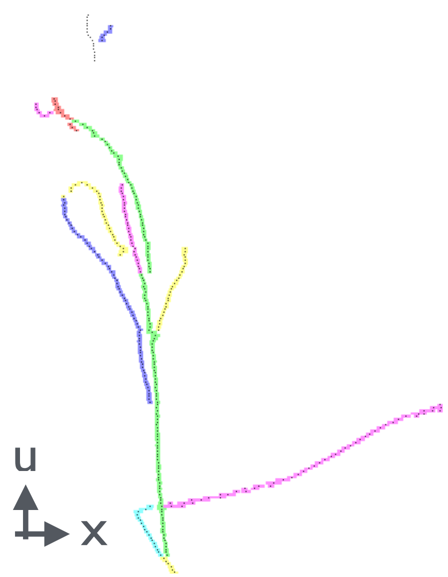
Picture from M. Soderberg

- Ionisation electrons detected by series of wire planes, enabling particle tracking and calorimetry.
- Reveal neutrino interactions in unprecedented detail. Obtain 3 "images": wire no. vs drift time.
- **Software challenge:**
  - 3x2D reconstruction, combine results to obtain 3D image of neutrino interaction.
  - Many 'hits', diverse event topologies, 2D views with features often obscured in 1+ view.



Pandora LAr Algorithms

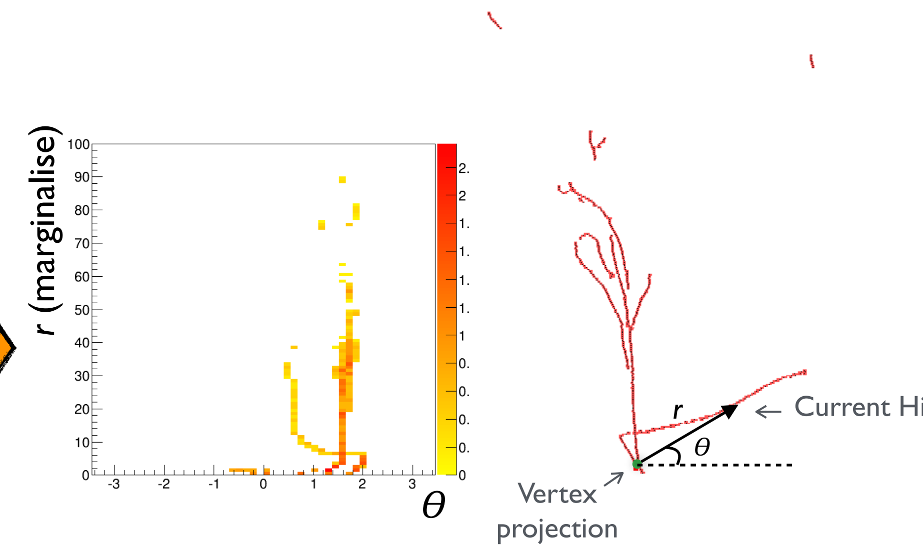
CosmicRay + Neutrino reconstruction uses 50 algorithms and 23 algorithm tools:



2D Track Clustering

↓

3D Vertex Reconstruction



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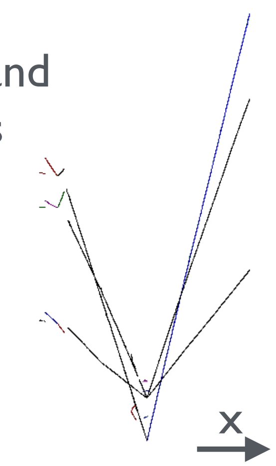
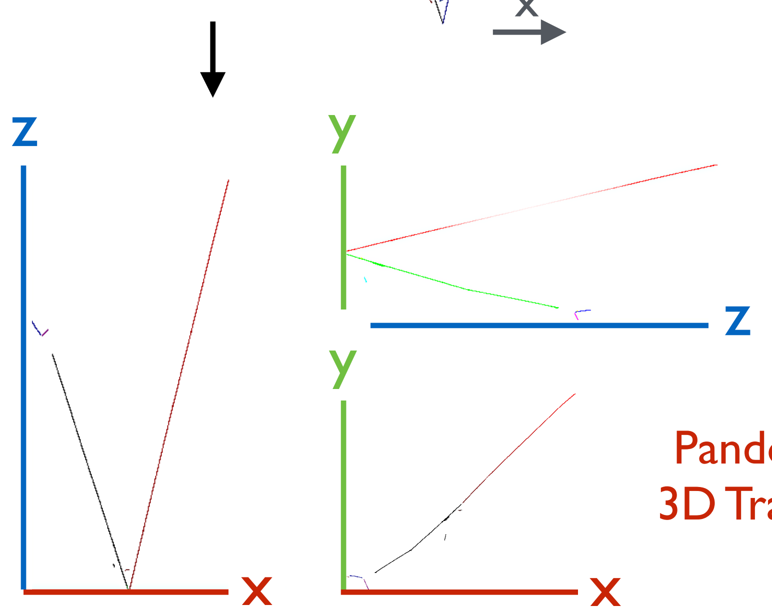
3D Track Reconstruction

Overlay U,V and W Clusters





Pandora 3D Tracks

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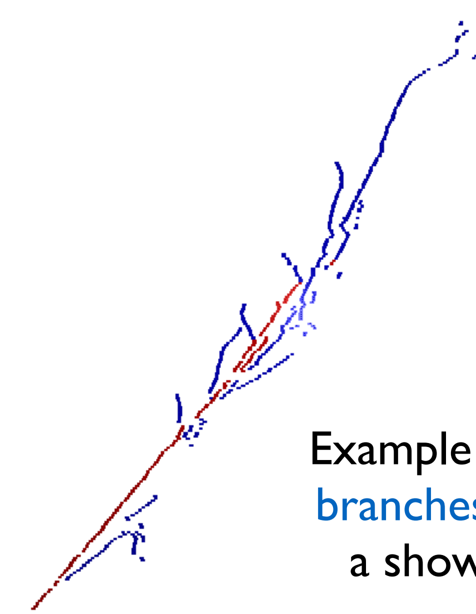
2D Shower Branch Growing

↓

3D Shower Reconstruction

↓

Neutrinos



Example of shower branches added to a shower spine

Pandora 2D Clustering

- 2D Clustering
- 2D Cluster merging and splitting

```
<algorithm type = "LArClusteringParent">
    <algorithm type = "LArTrackClusterCreation" description = "ClusterFormation"/>
    <InputCaloHitListName>CaloHitListW</InputCaloHitListName>
    <ClusterListName>ClustersW</ClusterListName>
    <RestoreOriginalCaloHitList>false</RestoreOriginalCaloHitList>
</algorithm>
<algorithm type = "LArLayerSplitting"/>
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<algorithm type = "LArLongitudinalExtension"/>
<algorithm type = "LArTransverseExtension"/>
<algorithm type = "LArBranchSplitting"/>
<algorithm type = "LArKinkSplitting"/>
```
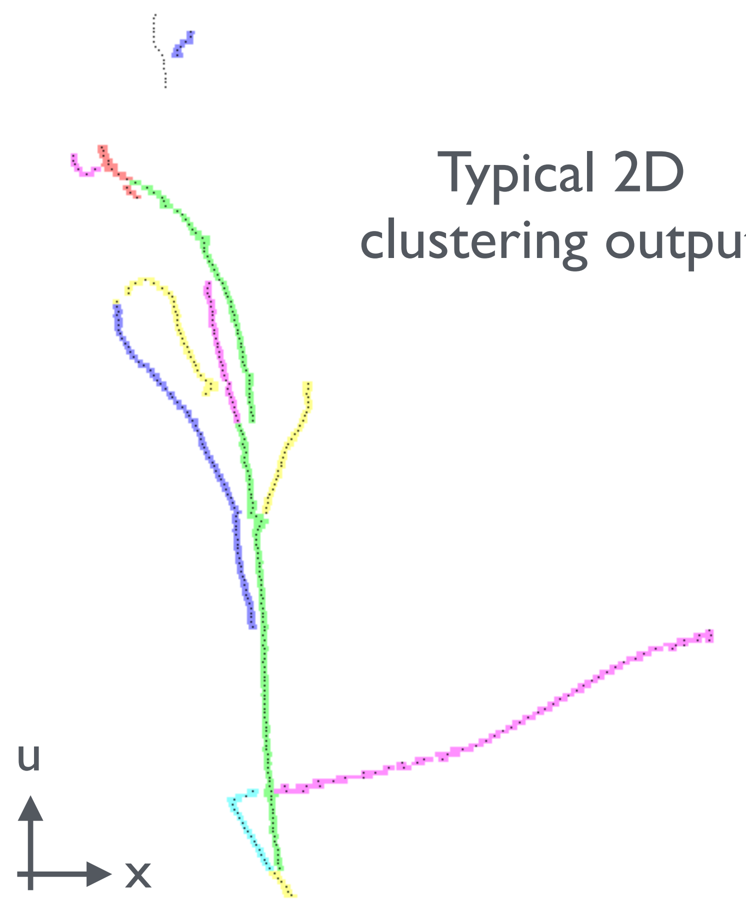

Snippet from PandoraSettings xml file

- **Philosophy:** "It's easier to put clusters together, than to split them up again."
- Start with a track-oriented 2D clustering algorithm. Important not to over-cluster at this early stage.
- Use a series of topological-association algorithms to extend clusters as best as possible in 2D.
- Try to push clusters through showers in order to obtain shower "spines", but must not artificially extend tracks.

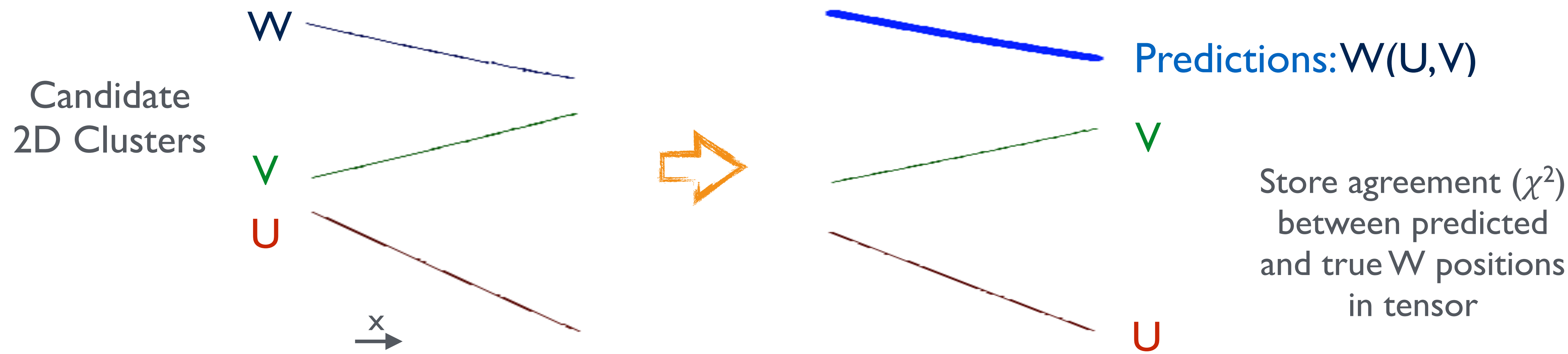


Typical 2D clustering output

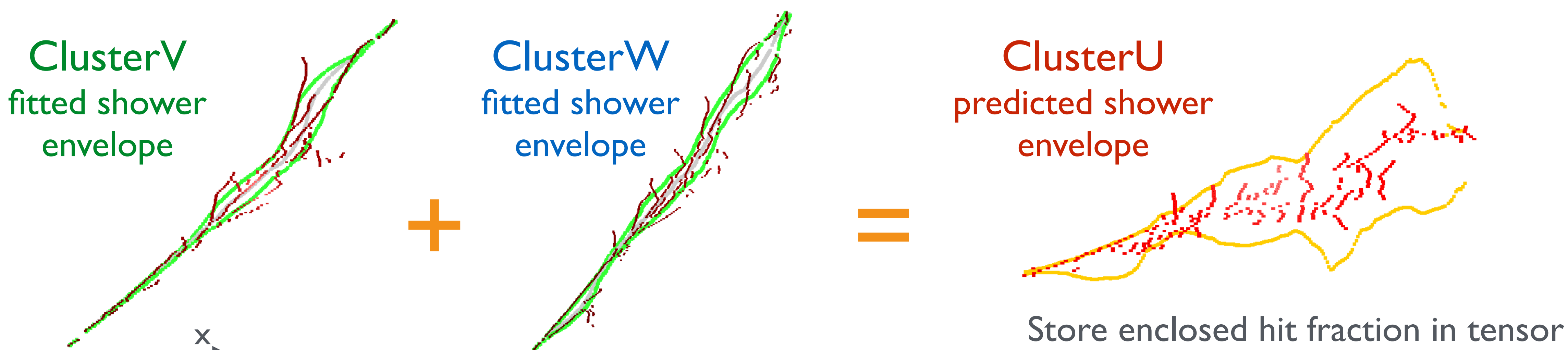
Pandora 3D Reconstruction

- The 3D reconstruction step collects together clusters from each of the 2D views (U,V,W) that represent a single particle. Use the common, drift-time (x), coordinate to help identify matches.
- Use a **tensor** to store overlap details for trios of 2D clusters. Without 2D reconstruction failures, tensor will be diagonal. Use AlgTools to make 2D changes in order to diagonalise tensor.

3D Track Matching



3D Shower Matching

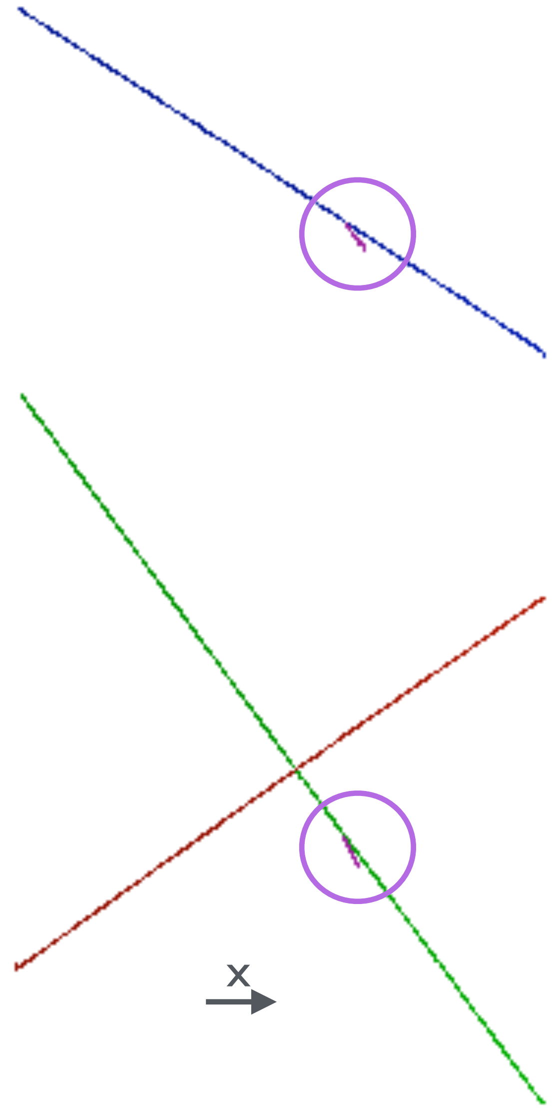


Pandora 3D Track Reconstruction

- **Diagonalise a tensor.** If a tool makes a change (e.g. splits cluster), the full list of tools runs again.

Clusters in V and W views also match with U cluster, so U cluster is ambiguous in tensor.

e.g. U:V:W
1:2:2

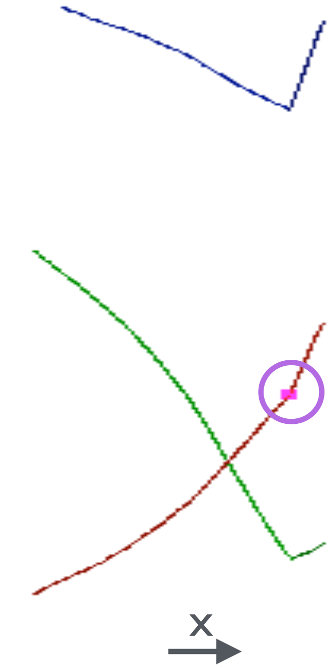


Resolve **obvious** ambiguities: clusters are matched in multiple configurations, but one tensor element is much better than others.

Long Tracks Tool

1:2:2

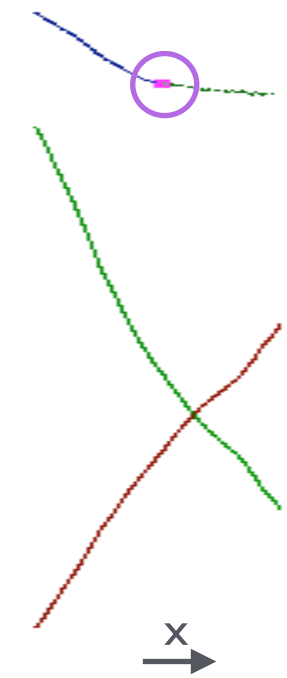
Two clusters in W and V views, matched to common cluster in U. Split U cluster.



Overshoot Tracks Tool

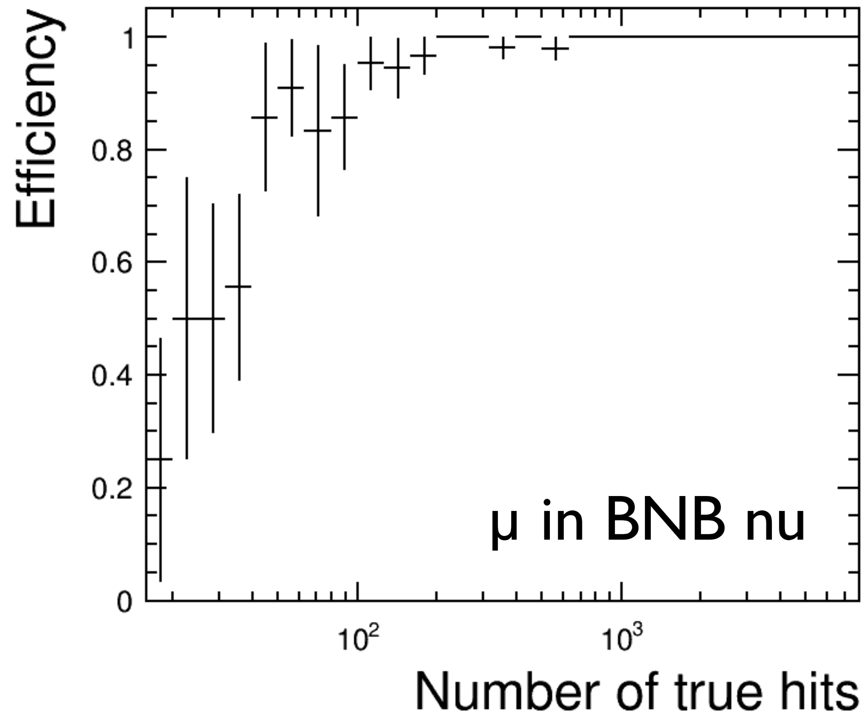
1:1:2

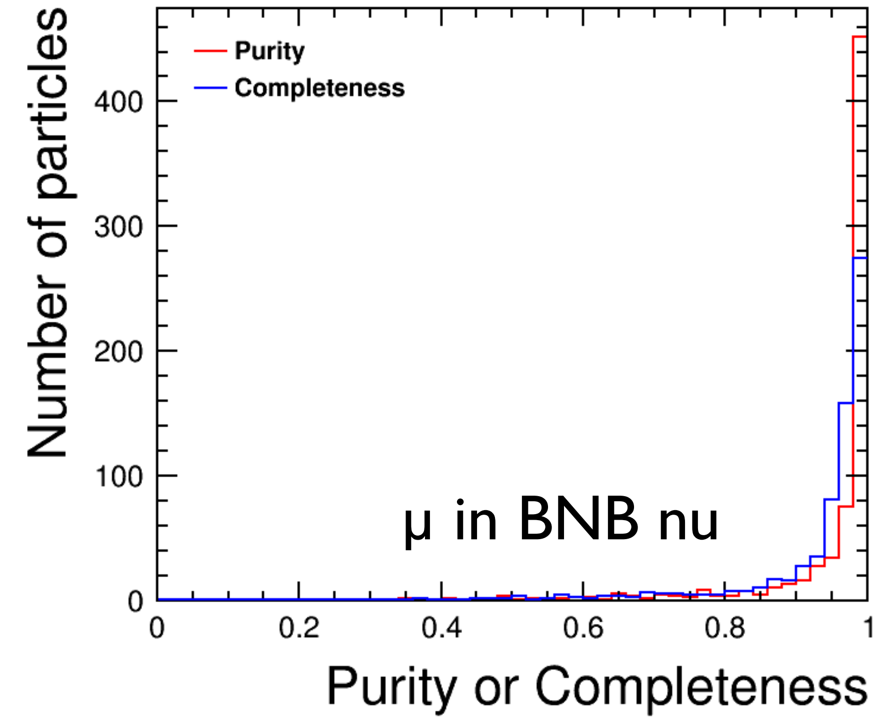
Two clusters in W view, matched to common clusters in U and V views. Merge W clusters.

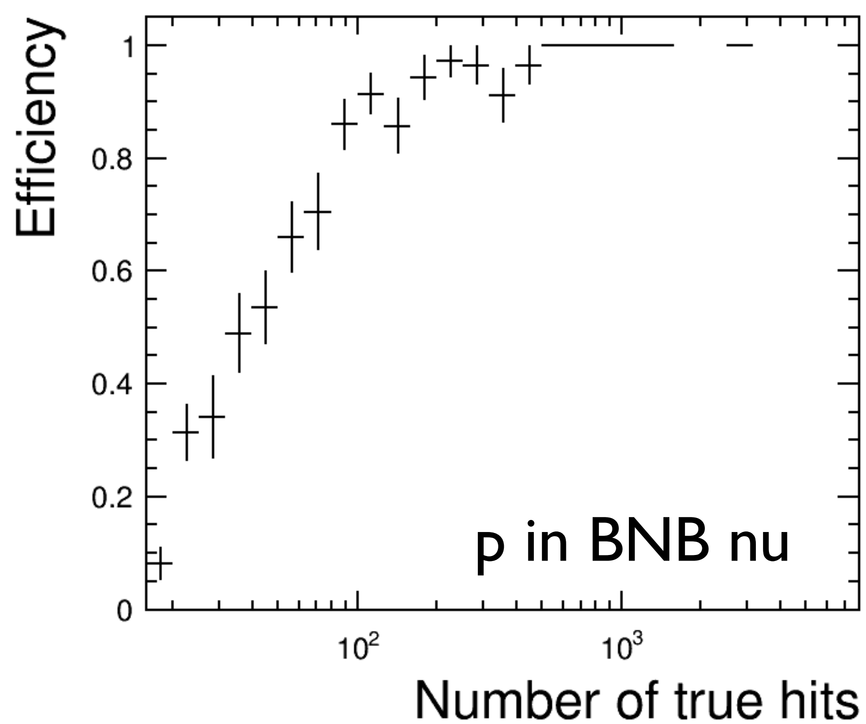


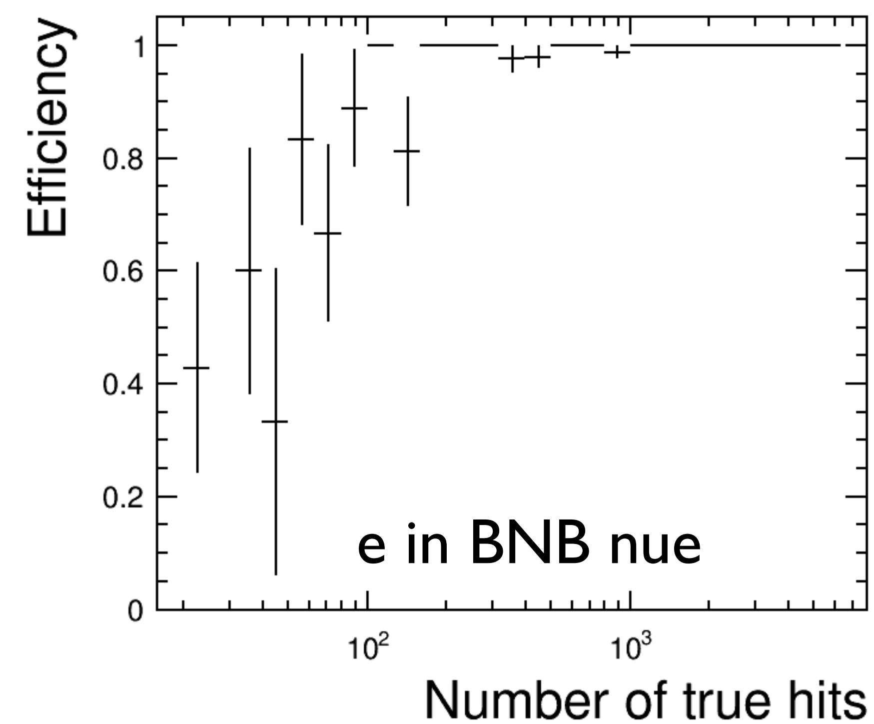
Undershoot Tracks Tool

Pandora Reconstruction Efficiency









'Efficiency' = fraction of true particles with matched reco particles.
'Completeness' = fraction of 2D hits in true particle matched with the reco particle.
'Purity' = fraction of 2D hits in reco particle matched with the true particle.

Pandora Summary

- **Pandora:** a reusable reconstruction philosophy and a reusable and reliable software framework.
- Using different algorithm logic, address pattern-recognition problems in two areas of HEP.
- Algorithms for both use-cases are in active, everyday use and have a genuine Physics impact.