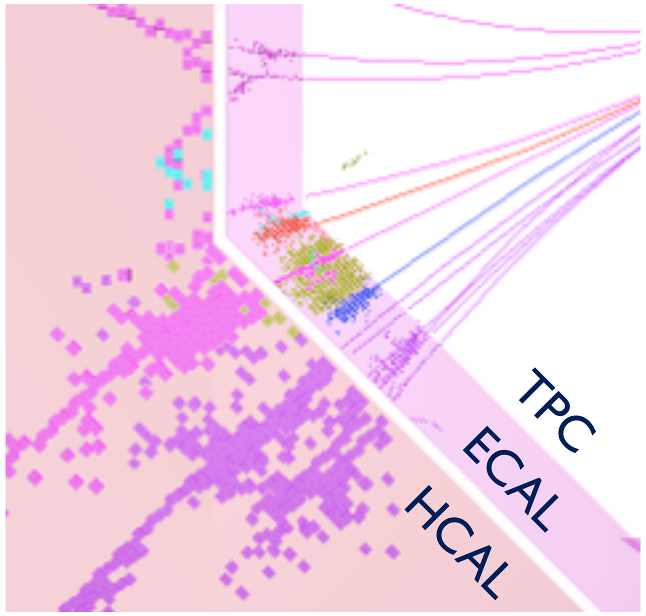
# Pandora: Particle Flow Reconstruction




S. Green on behalf of:

J. S. Marshall, M. A. Thomson

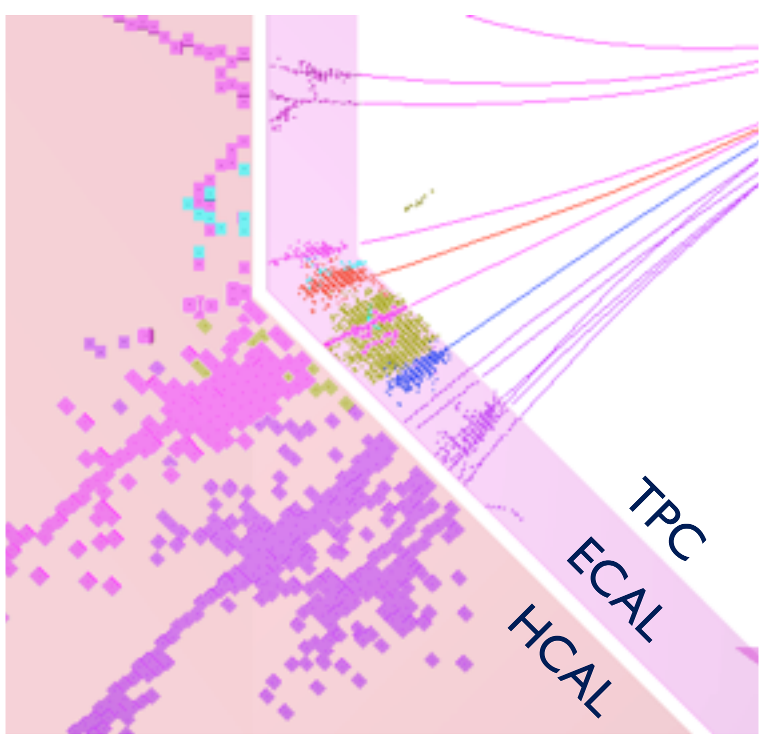
3 June 2015

# Pandora Approach

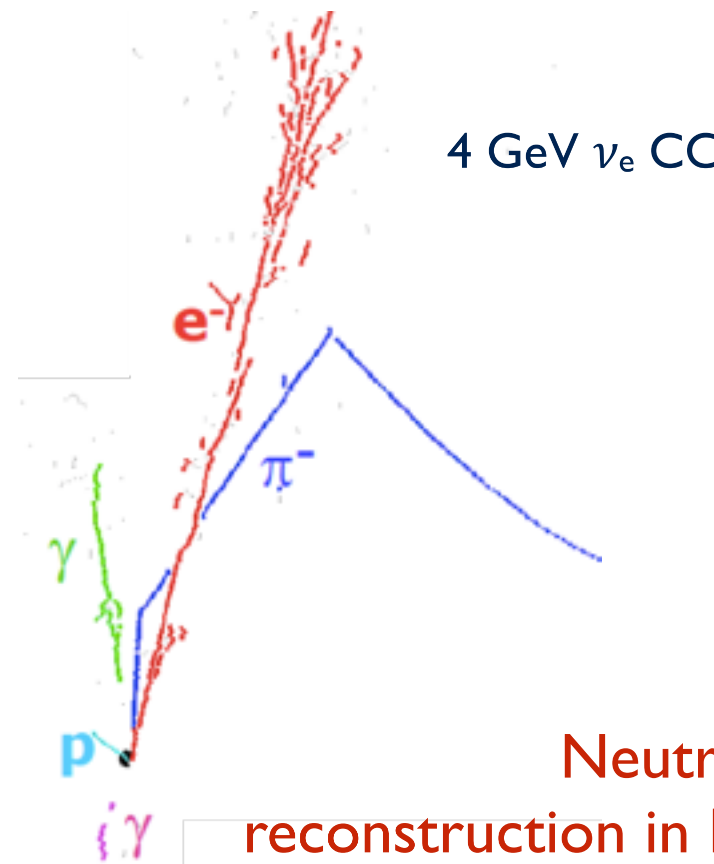
**Pandora** brings two key elements to the reconstruction of events in fine granularity detectors:

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:



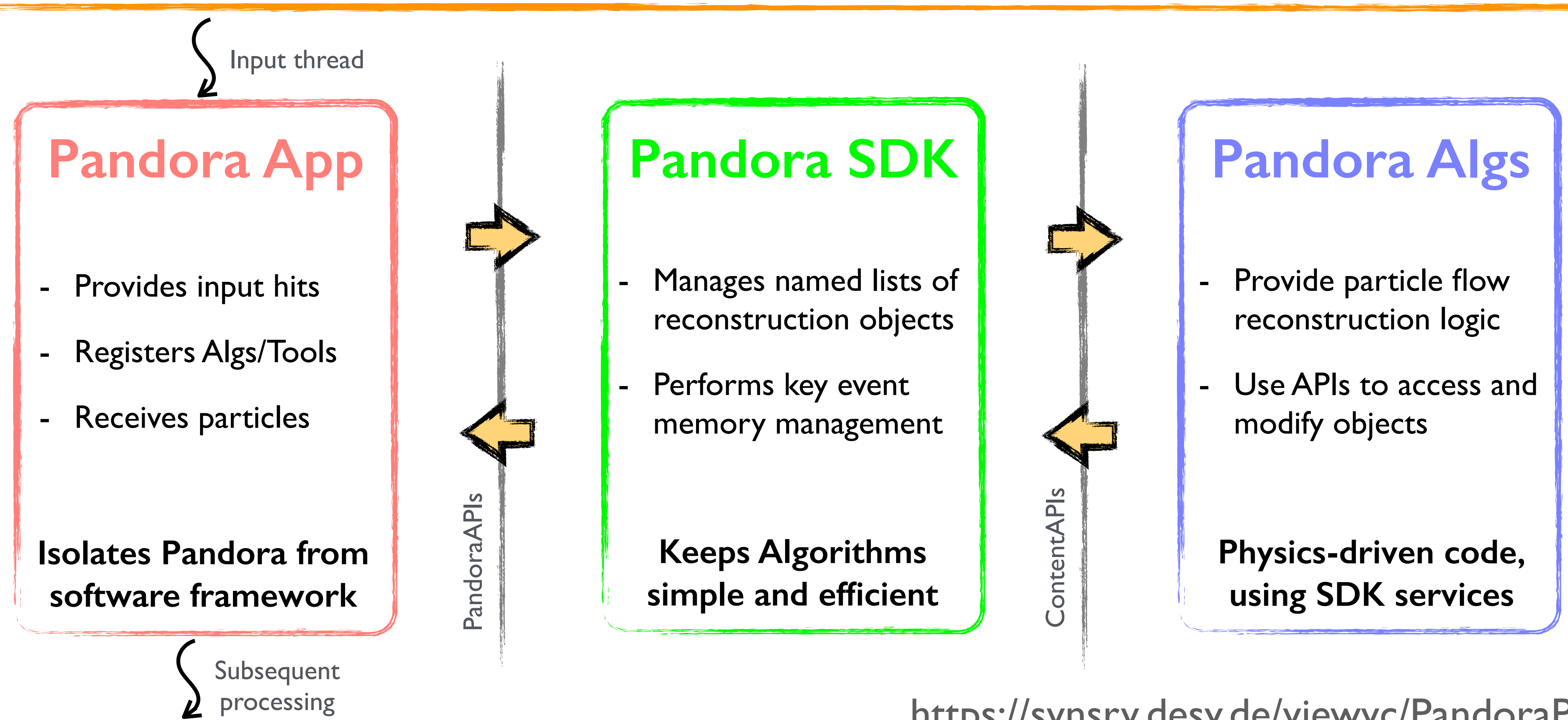

Particle flow calorimetry at a $e^+e^-$ collider




Neutrino event reconstruction in LAr TPCs

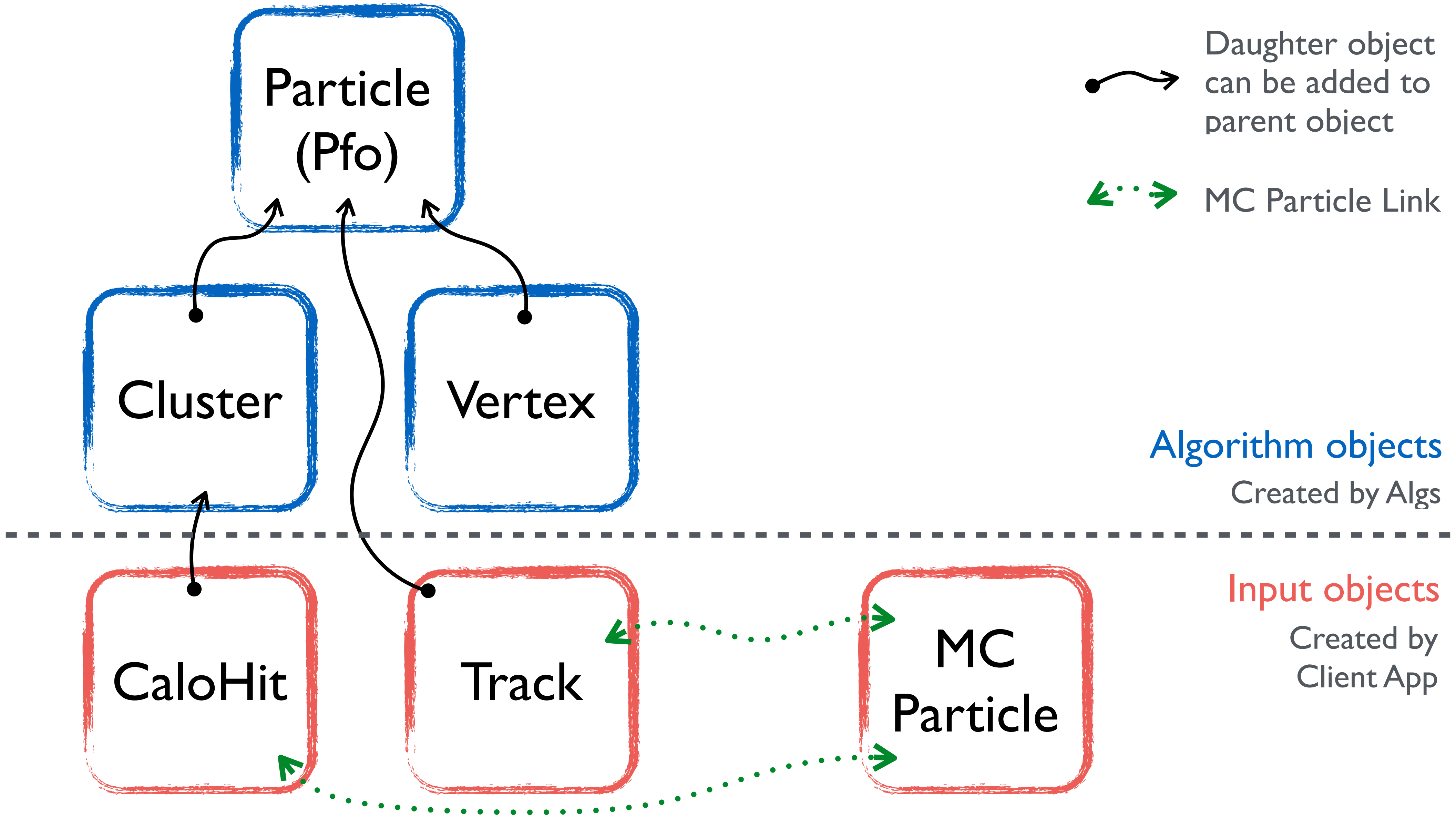
# Pandora SDK

- 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!

**Traditional calorimetric approach:**

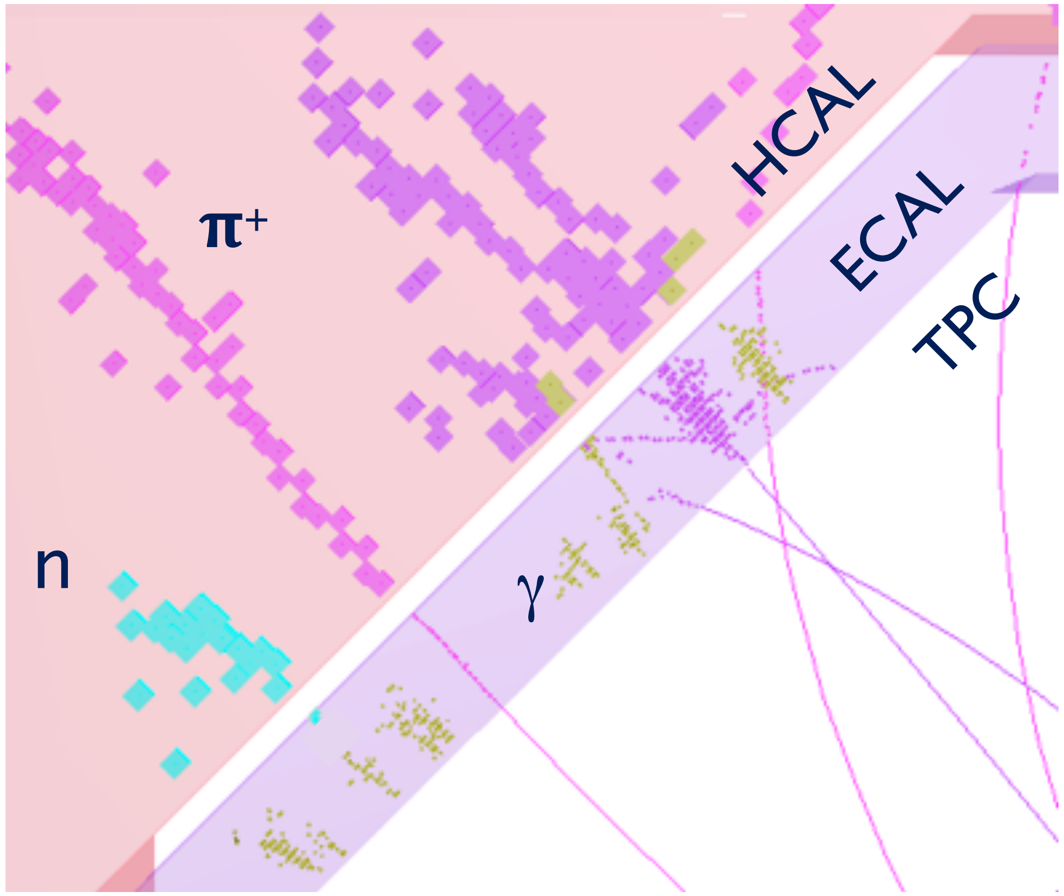
- Measure all components of jet energy in ECAL/HCAL
- Approximately 70% of energy measured in HCAL: $\sigma_E/E \approx 60\% / \sqrt{E(GeV)}$

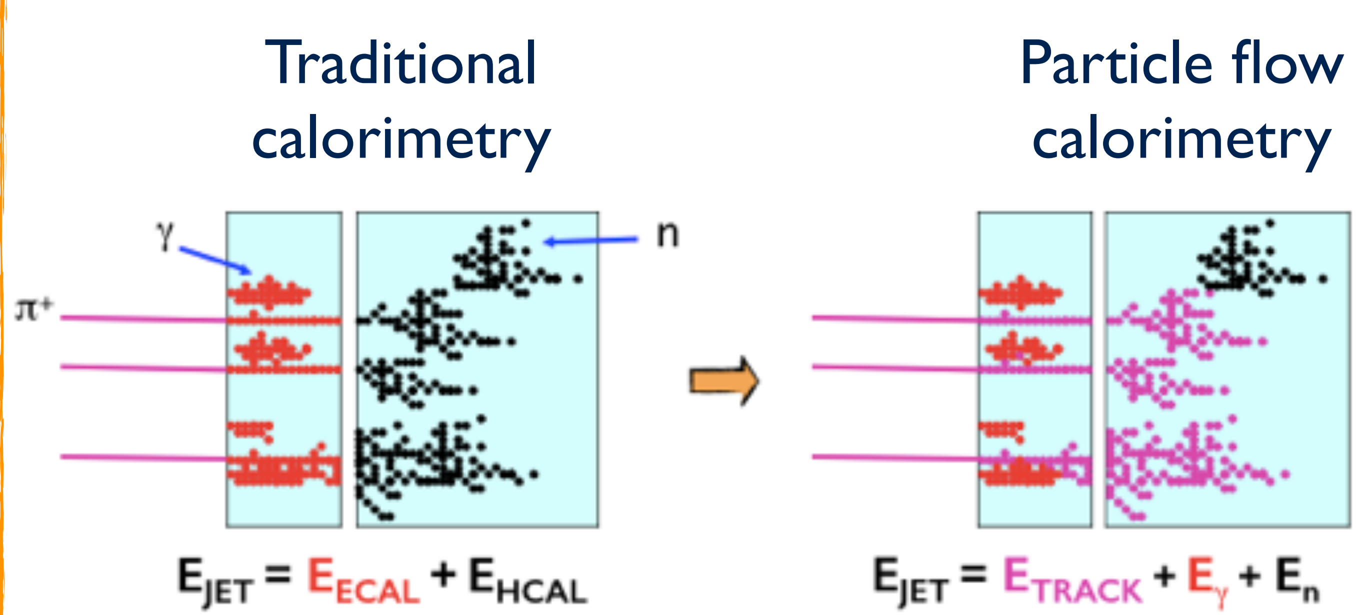
**Particle Flow Calorimetry:**

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

**Particle Flow Calorimetry requires:**

- Fine-granularity calorimeters
- Sophisticated software algorithms

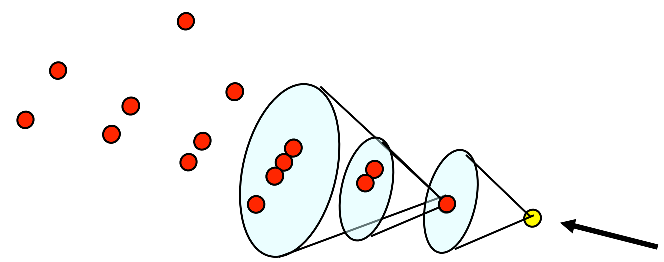


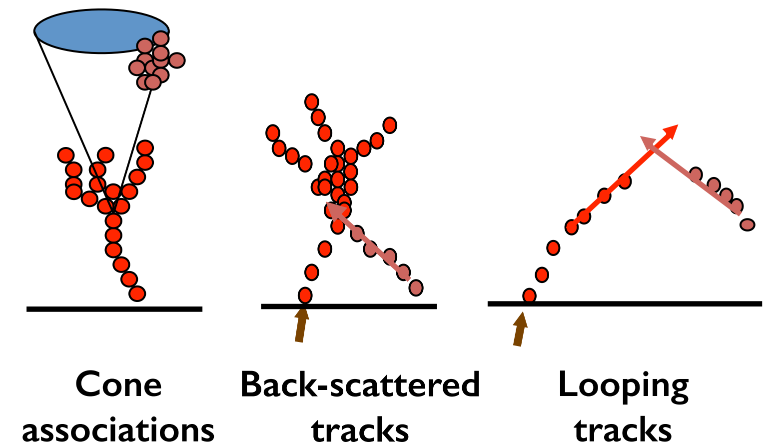
# Pandora LC Algorithms

"Basic" reconstruction uses 56 algorithms:

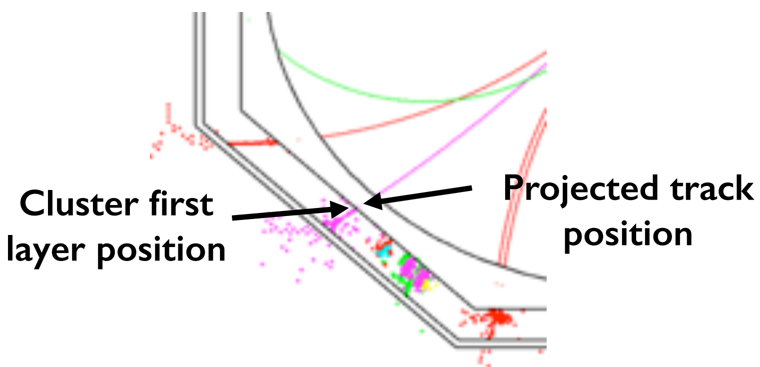
**ConeClustering Algorithm**



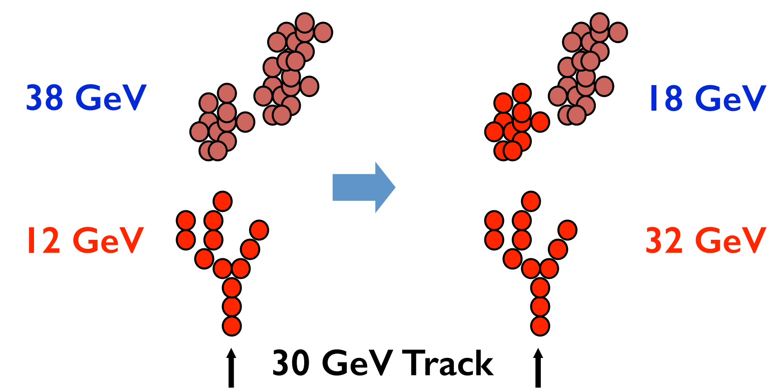
**Topological Association Algorithms**



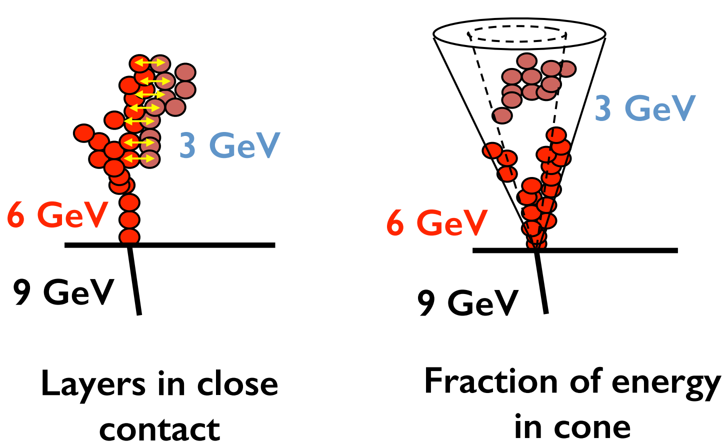

**Track-Cluster Association Algorithms**



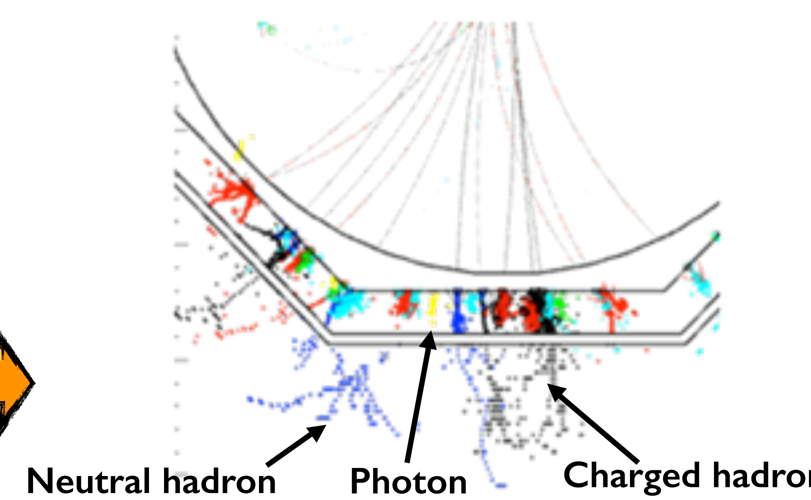

**Reclustering Algorithms**




**Fragment Removal Algorithms**

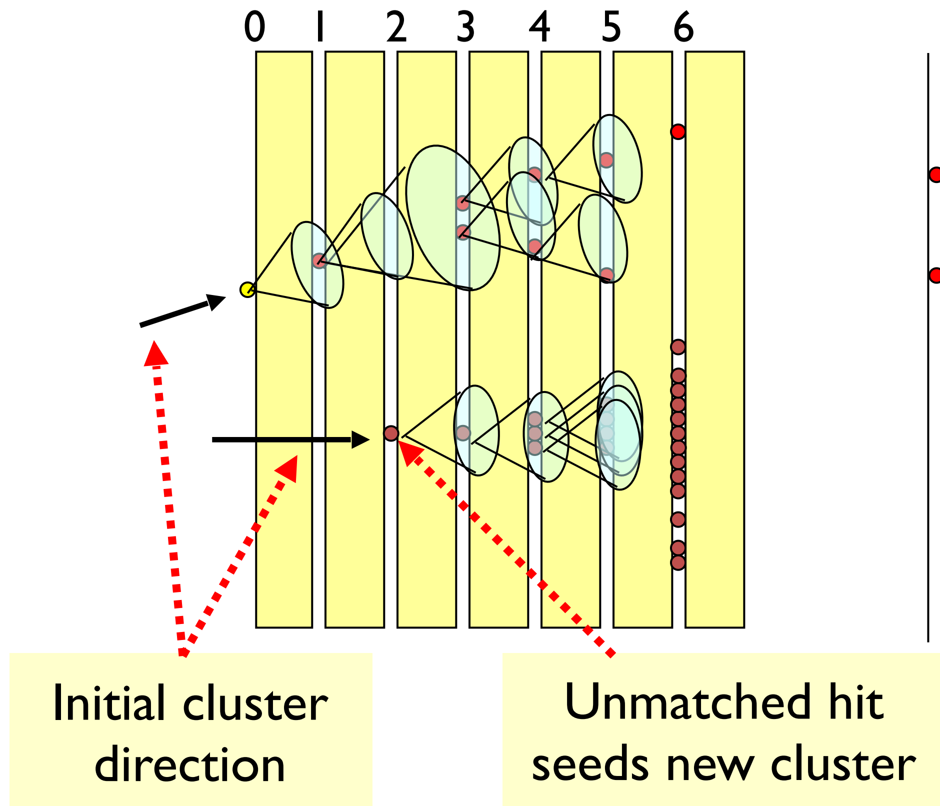


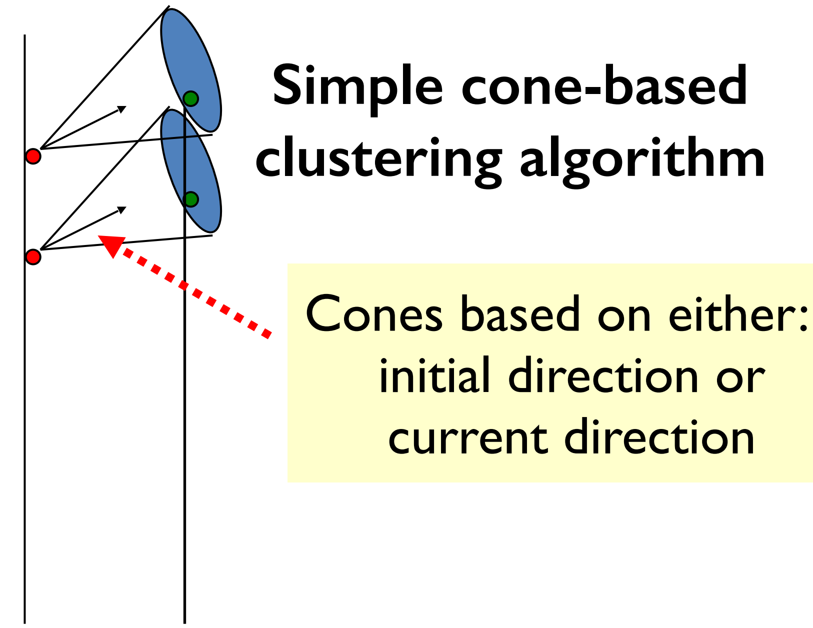

**PFO Construction Algorithms**



# Pandora Clustering

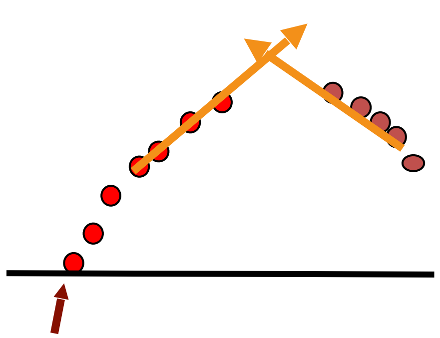
- **Philosophy:** "It's easier to put clusters together, than to split them up again."
- Clustering algorithm very careful to avoid accidentally merging energy deposits from separate particles.



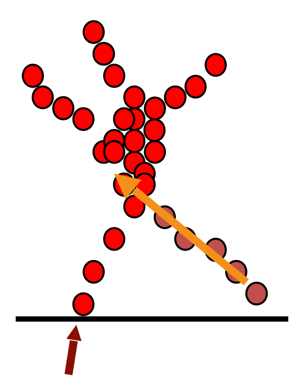




**Simple cone-based clustering algorithm**

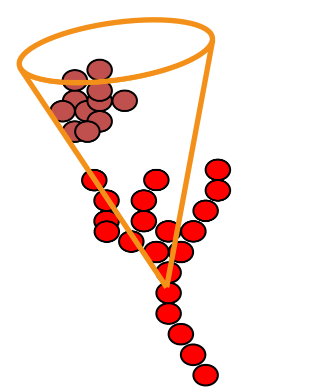
- Fine granularity of the calorimeters exploited to merge cluster fragments that are clearly associated.
- Very few mistakes made.



**Looping tracks**



**Back-scattered tracks**

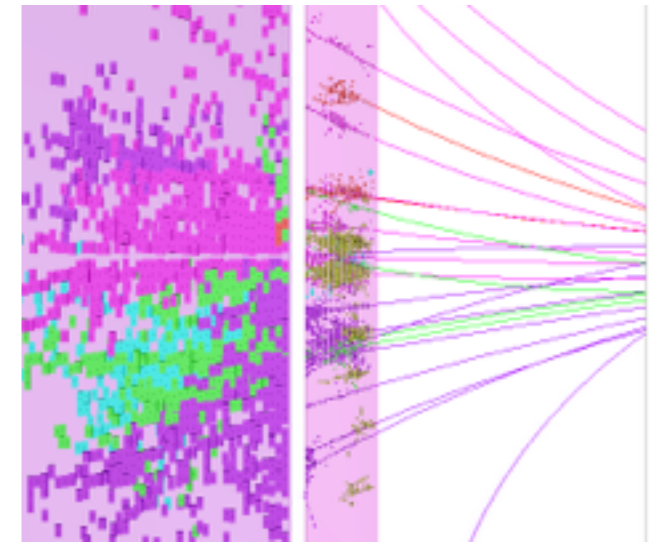


**Cone associations**

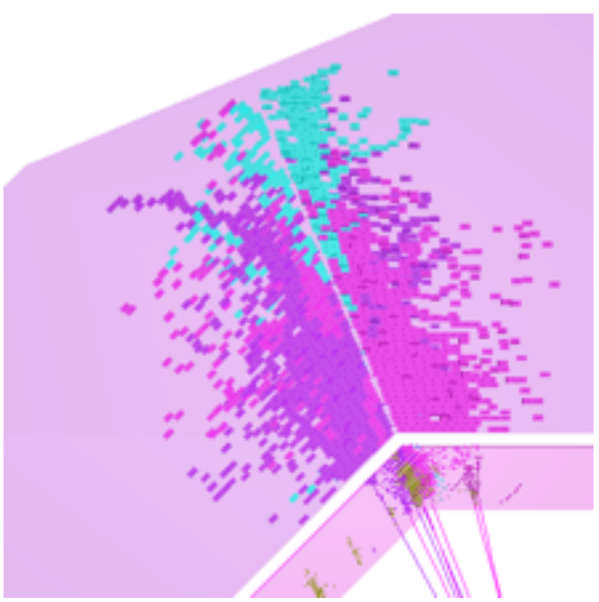
# Pandora Reclustering

- 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.

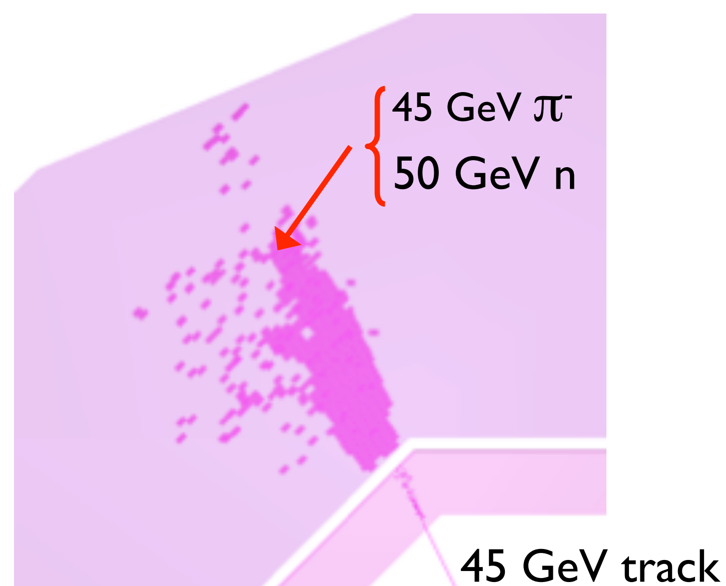



- At some point, in high energy jets, cannot cleanly resolve neutral hadrons in hadronic showers.
- Use information from track-cluster associations to identify pattern-recognition problems:



After topological association

Compare E/p values to find problems



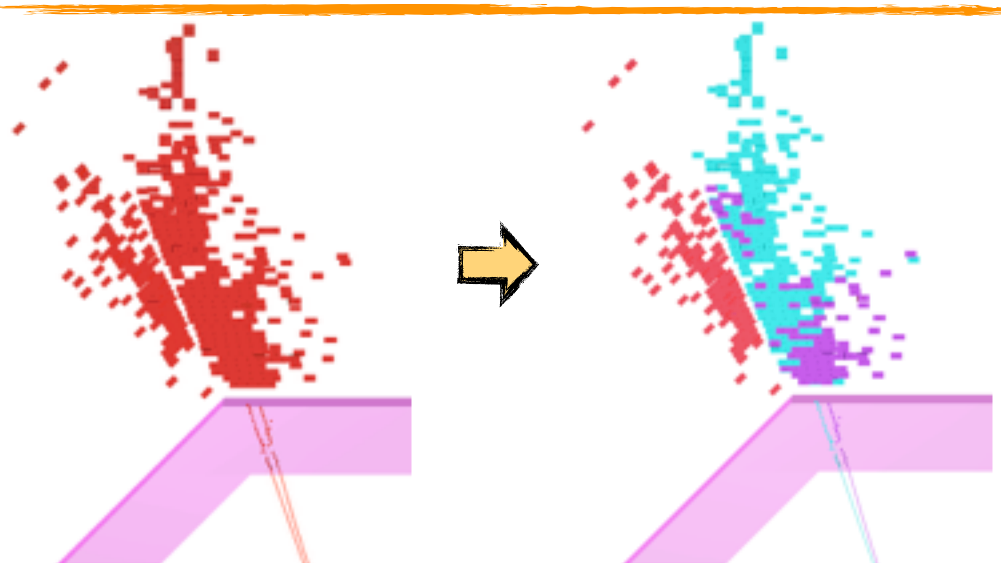

Find n absorbed into $\pi^-$ cluster

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

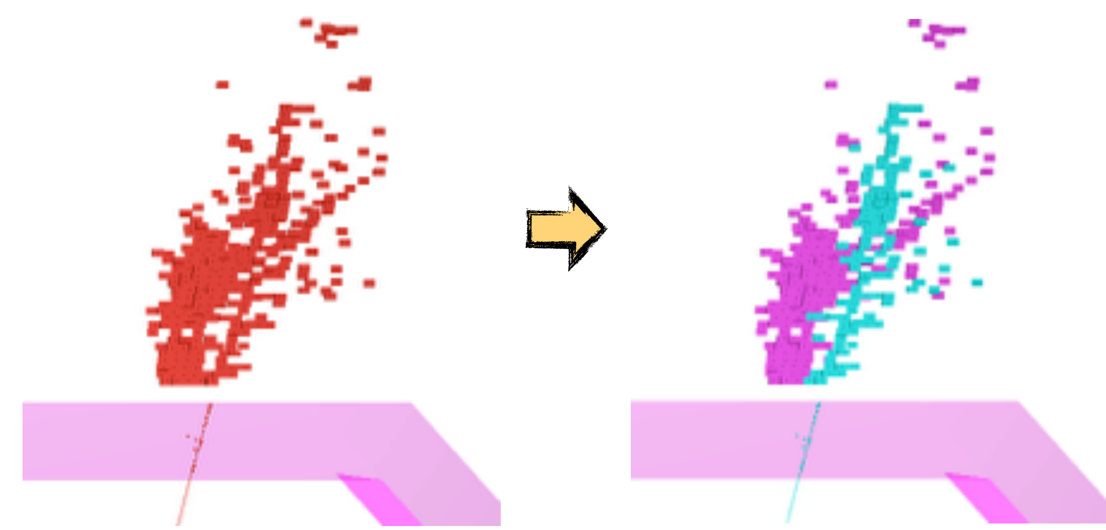
identify and address clustering problem

# Pandora Reclustering

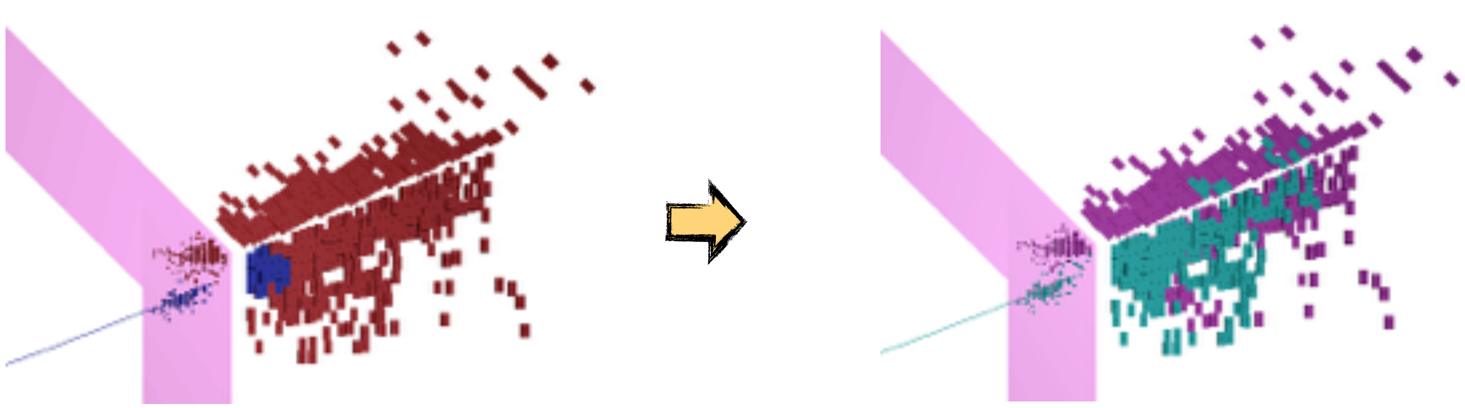
If identify significant discrepancy between cluster energy and associated track momentum, choose to recluster. Alter clustering parameters until cluster splits to obtain track-cluster consistency.



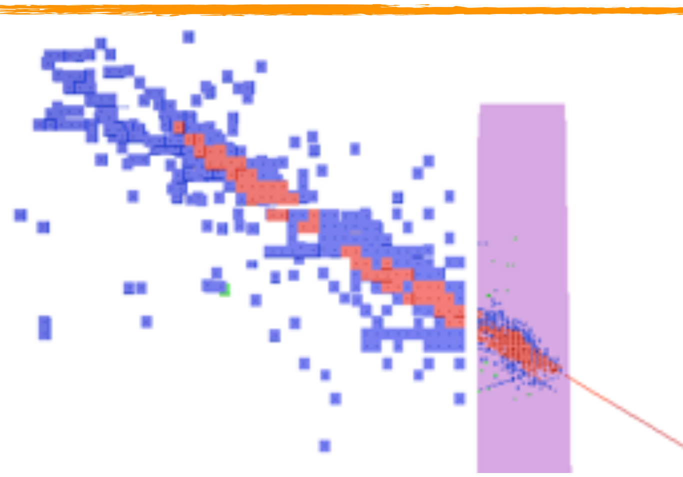
1. Multiple tracks associated to single cluster – split cluster.



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



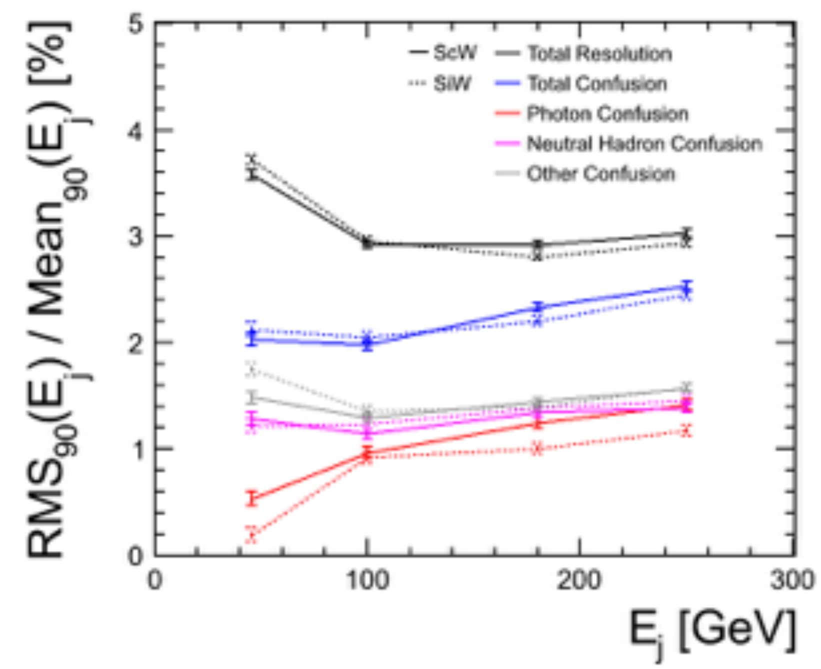
3. Track momentum much greater than cluster energy – bring in nearby clusters and reconfigure.



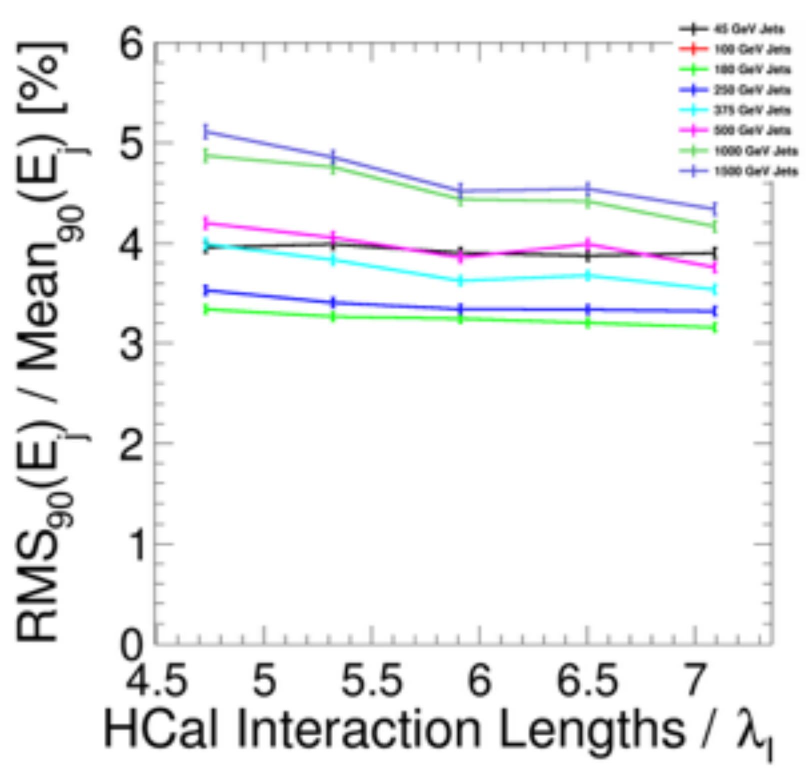
4. If, and only if, no E/p match emerges, can force track-cluster consistency ⇒ energy flow.

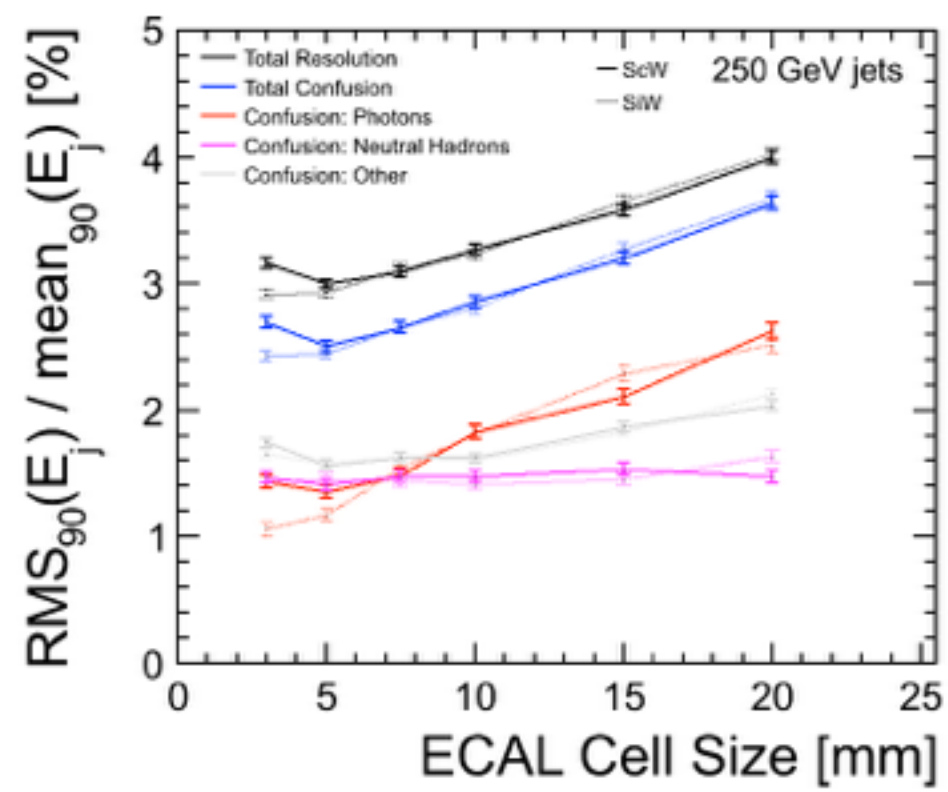
# Pandora Performance

- Motivation for fine granularity particle flow:
  Jet energy resolution: $\sigma_E/E < 3.5\%$
- Benchmark performance studies 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.



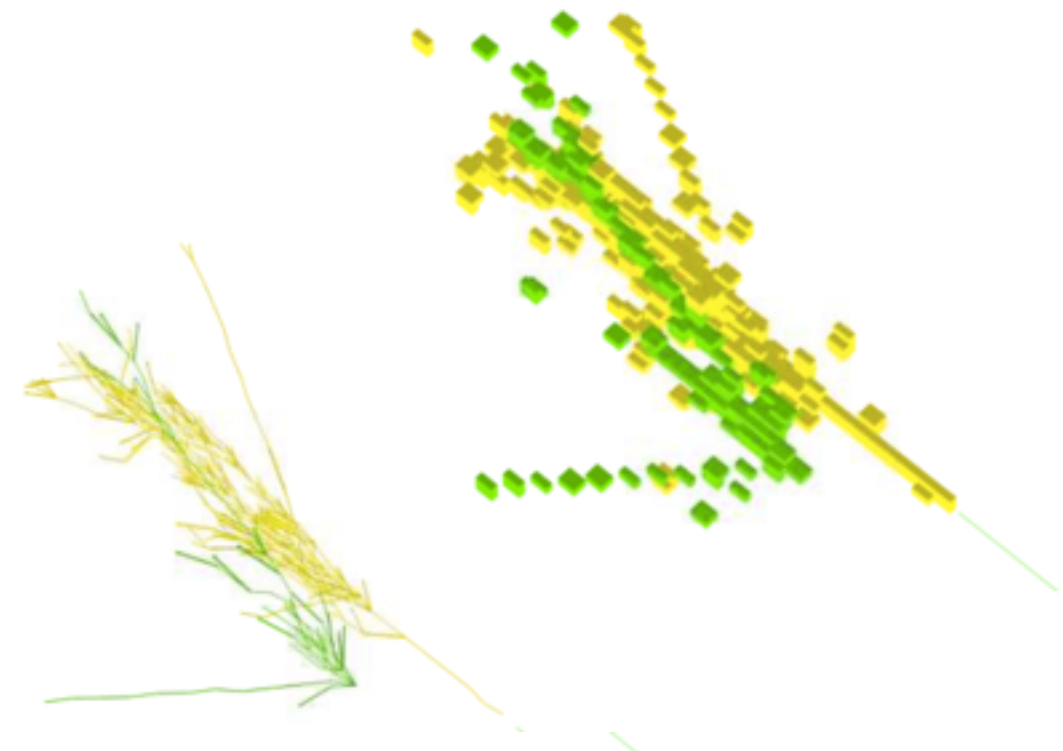

- Recent successful application of Pandora LC algorithms to reconstruction of events in CMS HGCal upgrade geometry.



R. Ete.

Current status of Arbor(-like)PFA in PandoraSDK (R. Ete, IPNL)



Implementation for the SDHCAL prototype

* Package ArborPFA
→ https://github.com/SDHCAL/ArborPFA

* Developed for SDHCAL test beam data

* Single particle study

* Separation of close-by hadronic showers

Implementation for full detector (i.e ILD)

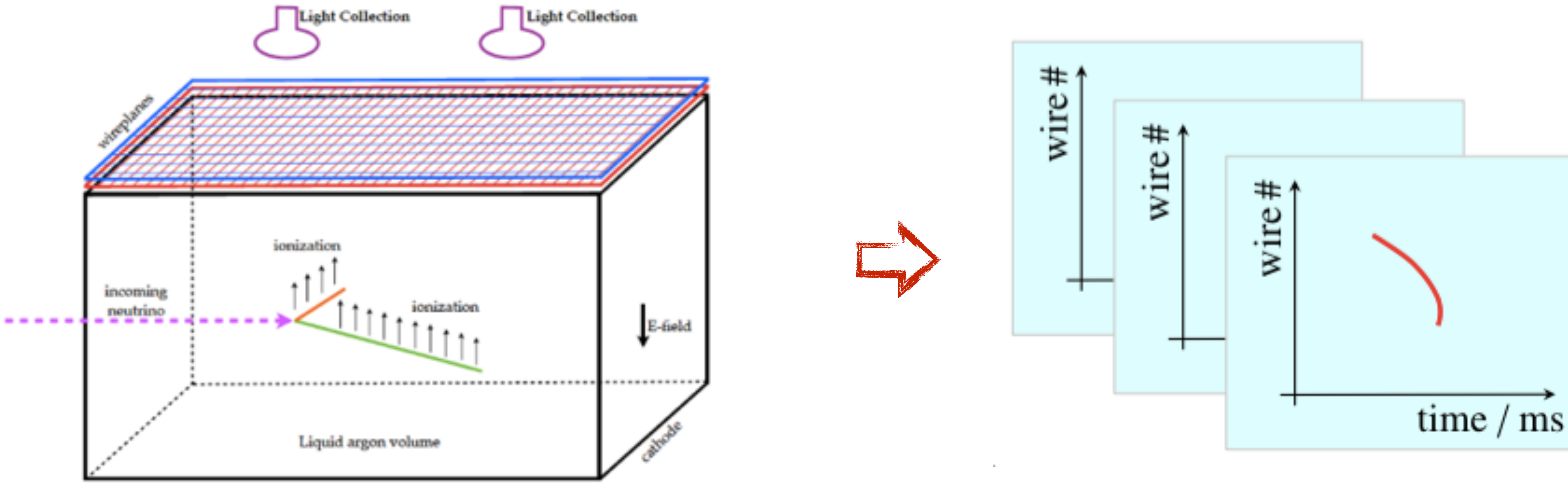
* Package ArborContent (algorithms) + MarlinArbor (marlin interface)
→ https://github.com/rete/ArborContent
→ https://github.com/rete/MarlinArbor

* Uses the new PandoraSDK (v01.00.01) object extension functionality → extension of CaloHit (arbor_content ::CaloHit)

* Algorithms currently being reviewed and new ones added for full detector implementation
→ Ecal specific impl, energy estimators, Ecal-Hcal link, gap handling, reclustering, etc...

* Refactorization of algorithms with AlgorithmTools to test new ideas on key points (specific seeding, cleaning, branching, etc ...)

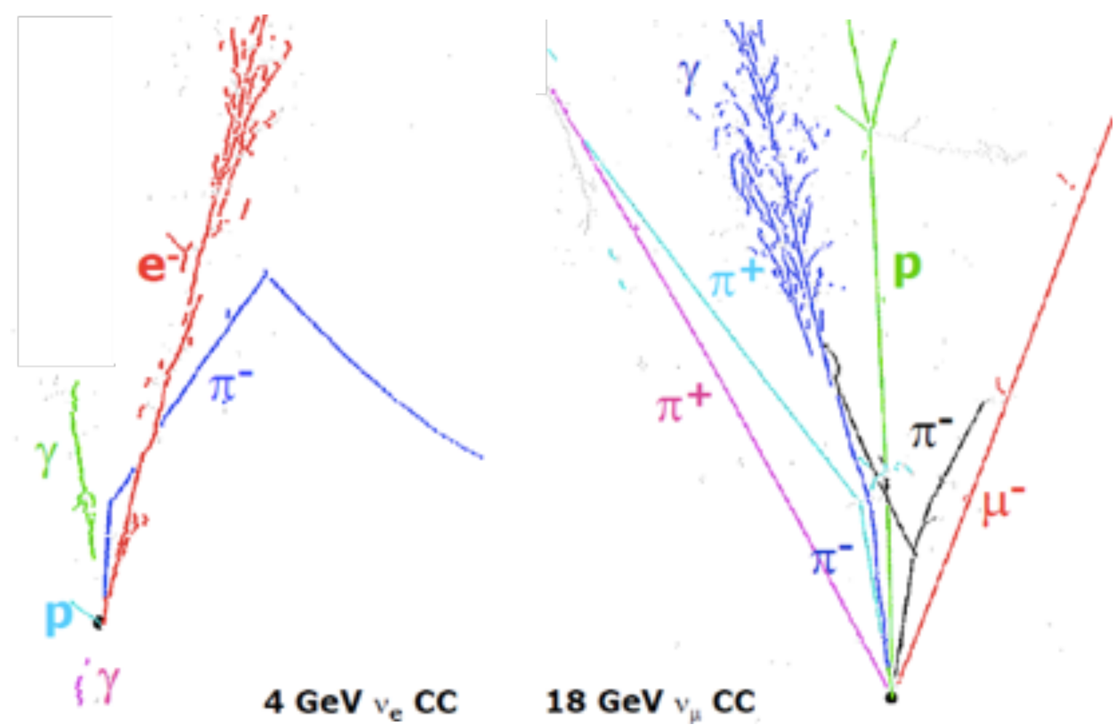
# Pandora LAr TPC Reconstruction




*Picture from M. Soderberg*

Contributions also from A. S. T. Blake

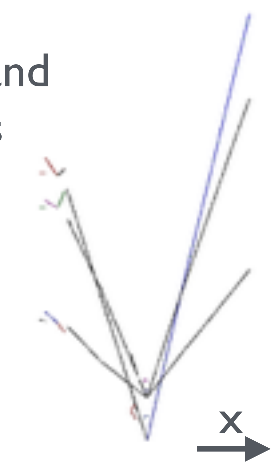
- Ionisation electrons detected by series of wire planes, enabling particle tracking and calorimetry.
- Reveal neutrino interactions in unprecedented detail. Obtain 3 "images": wire no. vs drift time.
- **Software challenge:**
  - 3x2D reconstruction, combine results to obtain 3D image of neutrino interaction.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

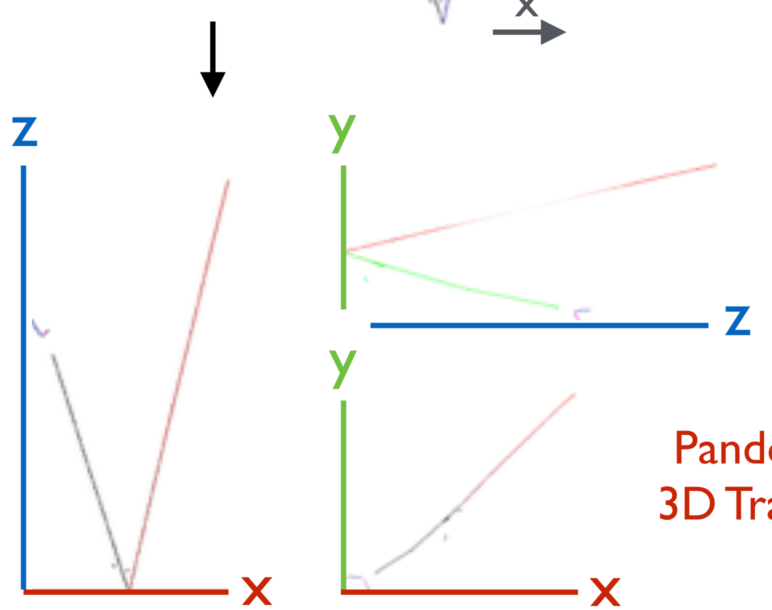


# Pandora LAr Algorithms

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

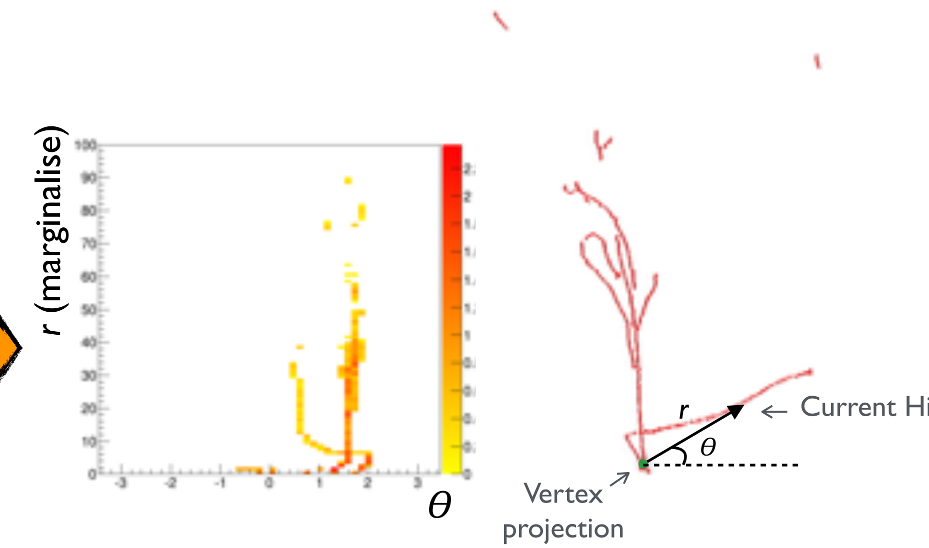

Overlay U,V and W Clusters

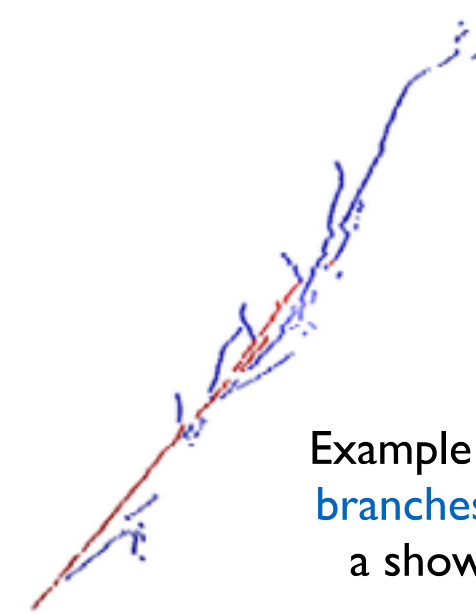



Pandora 3D Tracks

- 2D Track Clustering
- 3D Vertex Reconstruction
- 3D Track Reconstruction
- 2D Shower Branch Growing
- 3D Shower Reconstruction
- Neutrinos



Example of shower branches added to a shower spine

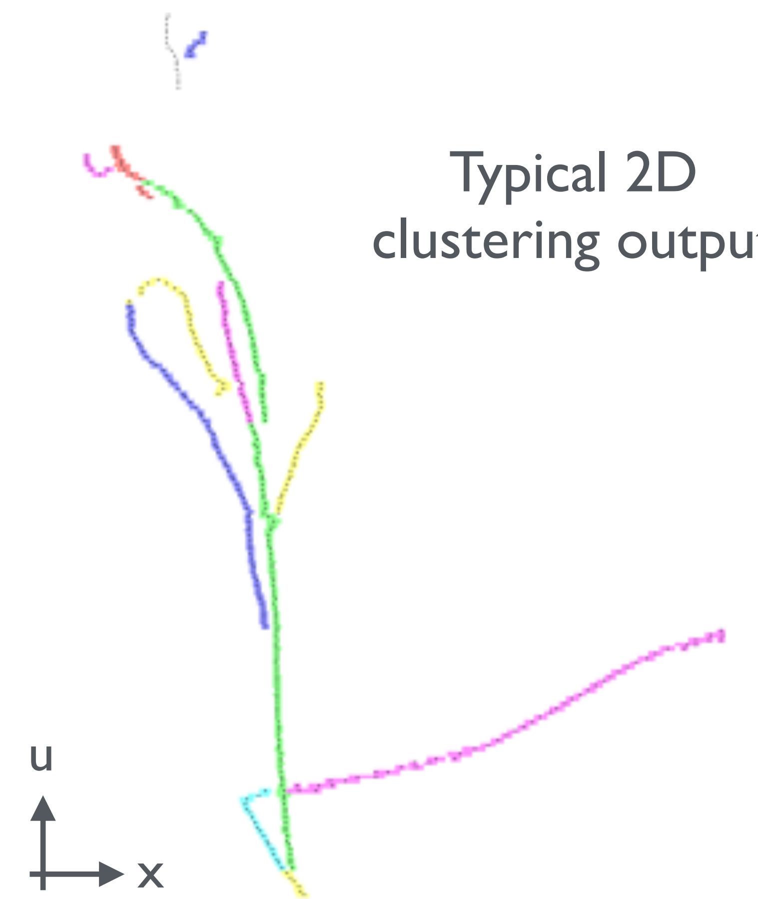
# Pandora 2D Clustering

- 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"/>
<algorithm type = "LArLongitudinalAssociation"/>
<algorithm type = "LArTransverseAssociation"/>
<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.



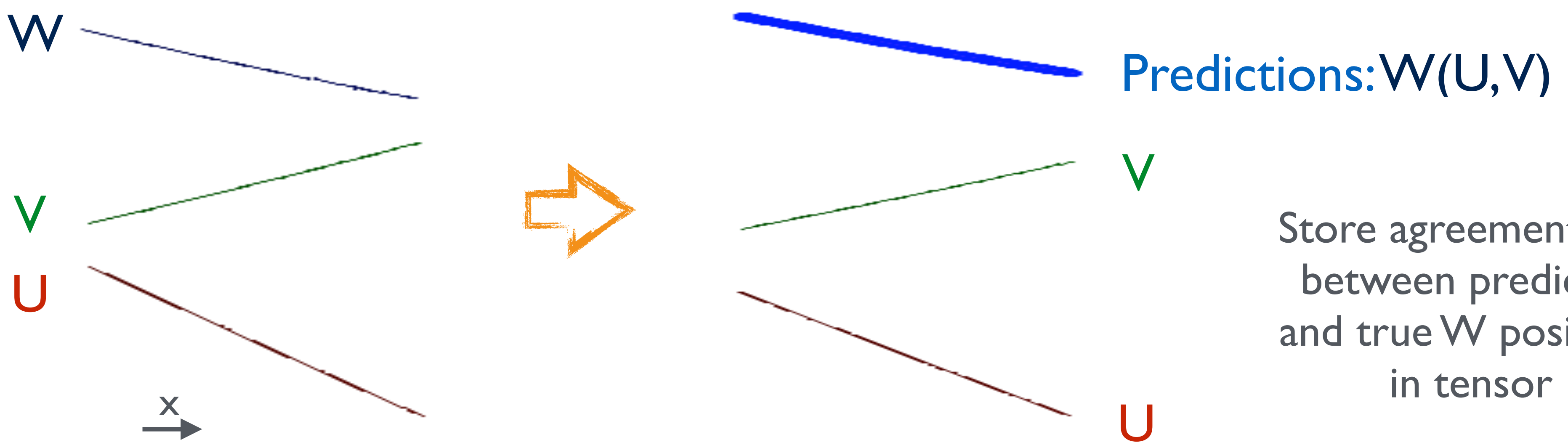

Typical 2D clustering output

# 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

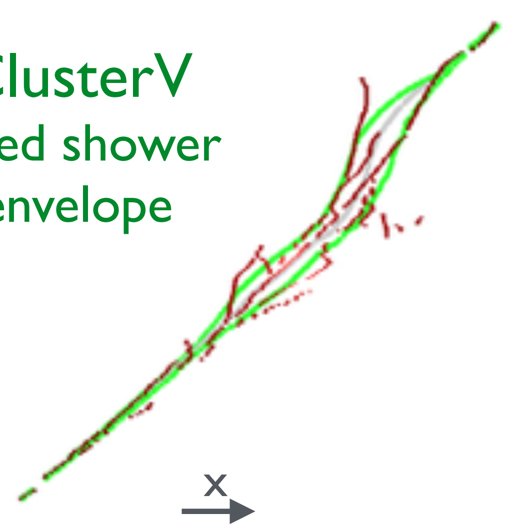
Candidate 2D Clusters




Store agreement ($\chi^2$) between predicted and true W positions in tensor

## 3D Shower Matching

Cluster V fitted shower envelope




+

Cluster W fitted shower envelope

=

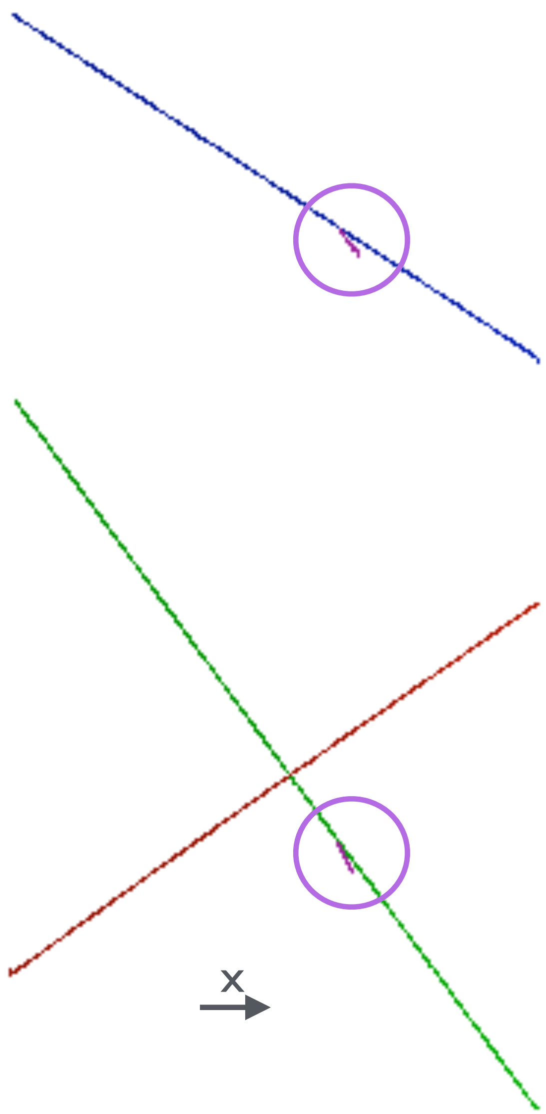
Cluster U predicted shower envelope

Store enclosed hit fraction in tensor

# 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.

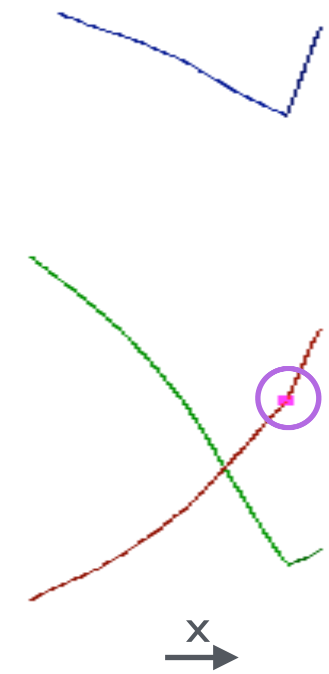



**e.g. U:V:W**
**1:2:2**

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

## Long Tracks Tool

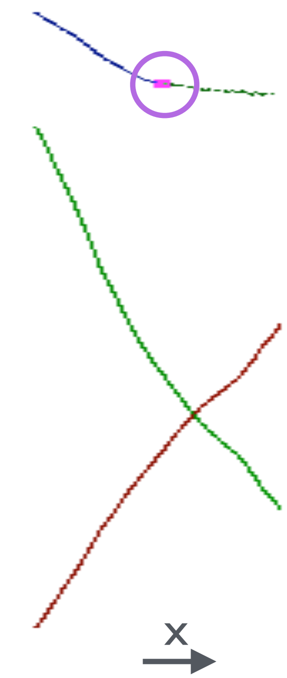
**1:2:2**




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

## Overshoot Tracks Tool

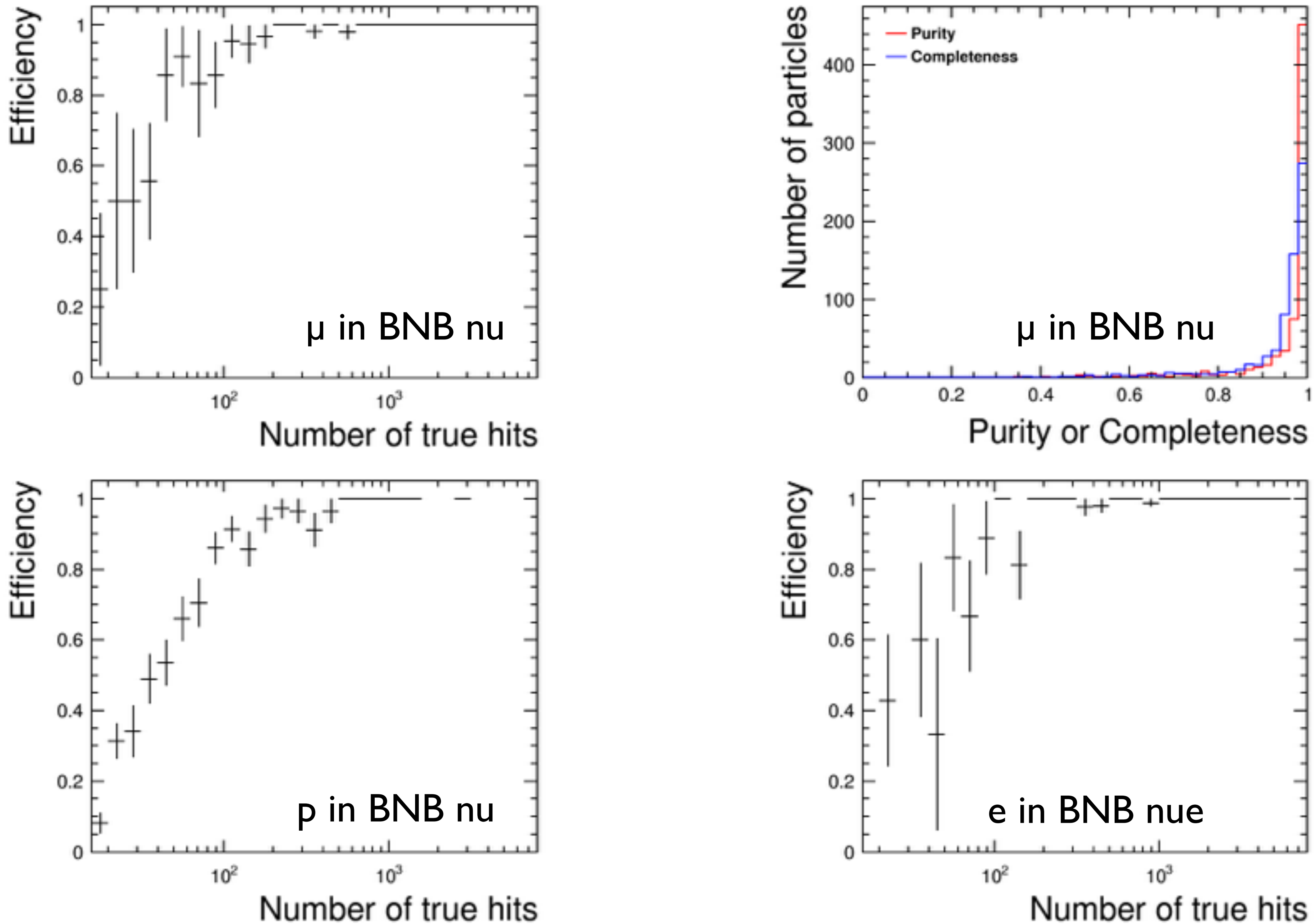
**1:1:2**




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.

# AIDA2020 Summary

## Technical (WP3.4)

- Provide support for multi-threading
- Pandora2:
  - Lower-level internal base classes
  - Cleaner division between different applications

## Generic Algorithm (WP3.7)

- Provide a suite of "standard" tools
- Borrow heavily from existing computational algorithms

  e.g. from imagine processing

## Targeted Applications (WP3.7)

- Linear Collider - Pflow improvements
- Support CERN/Fermilab LAr neutrino programme
- Support HL-LHC Pflow applications