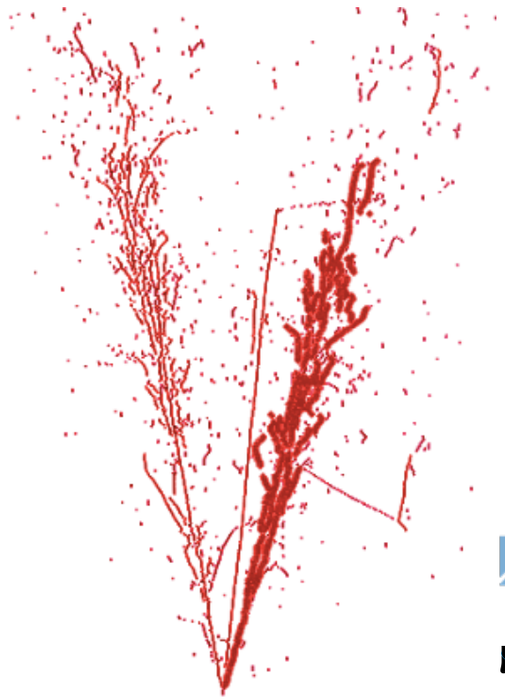
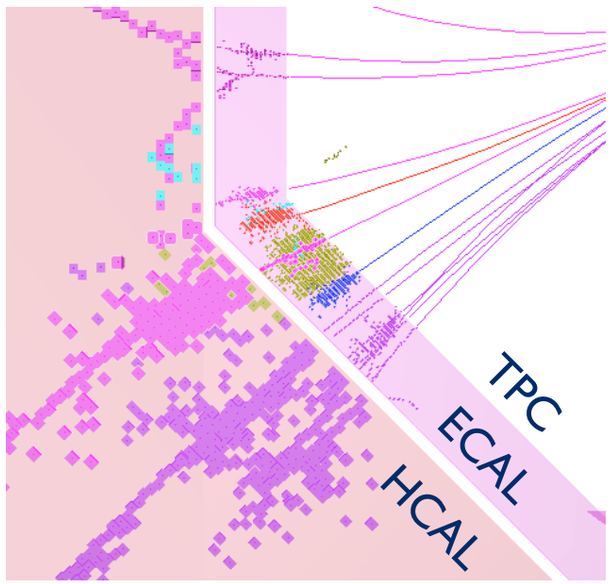


Pandora LAr TPC Reconstruction

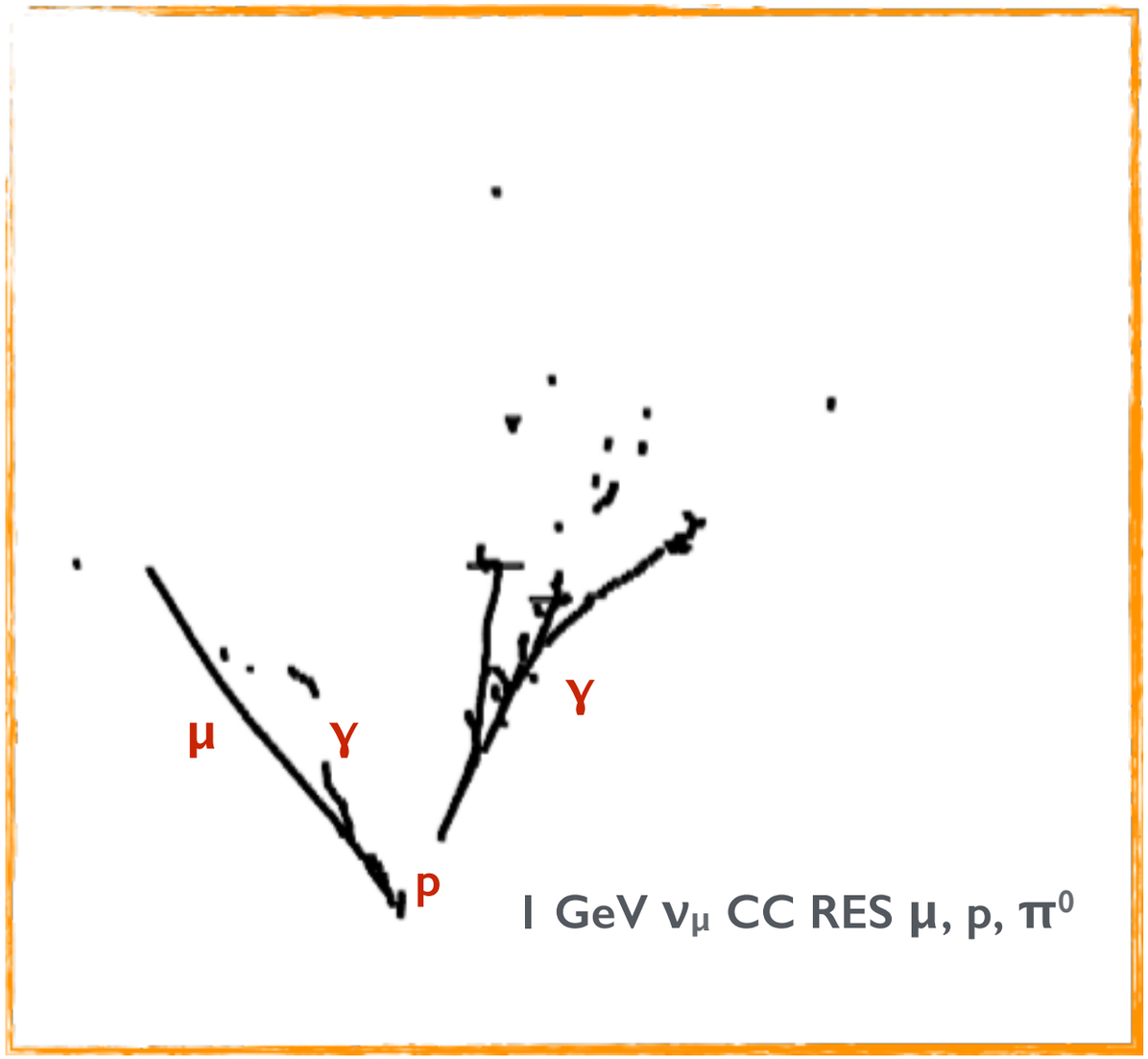
J. S. Marshall, A. S. T. Blake, M. A. Thomson

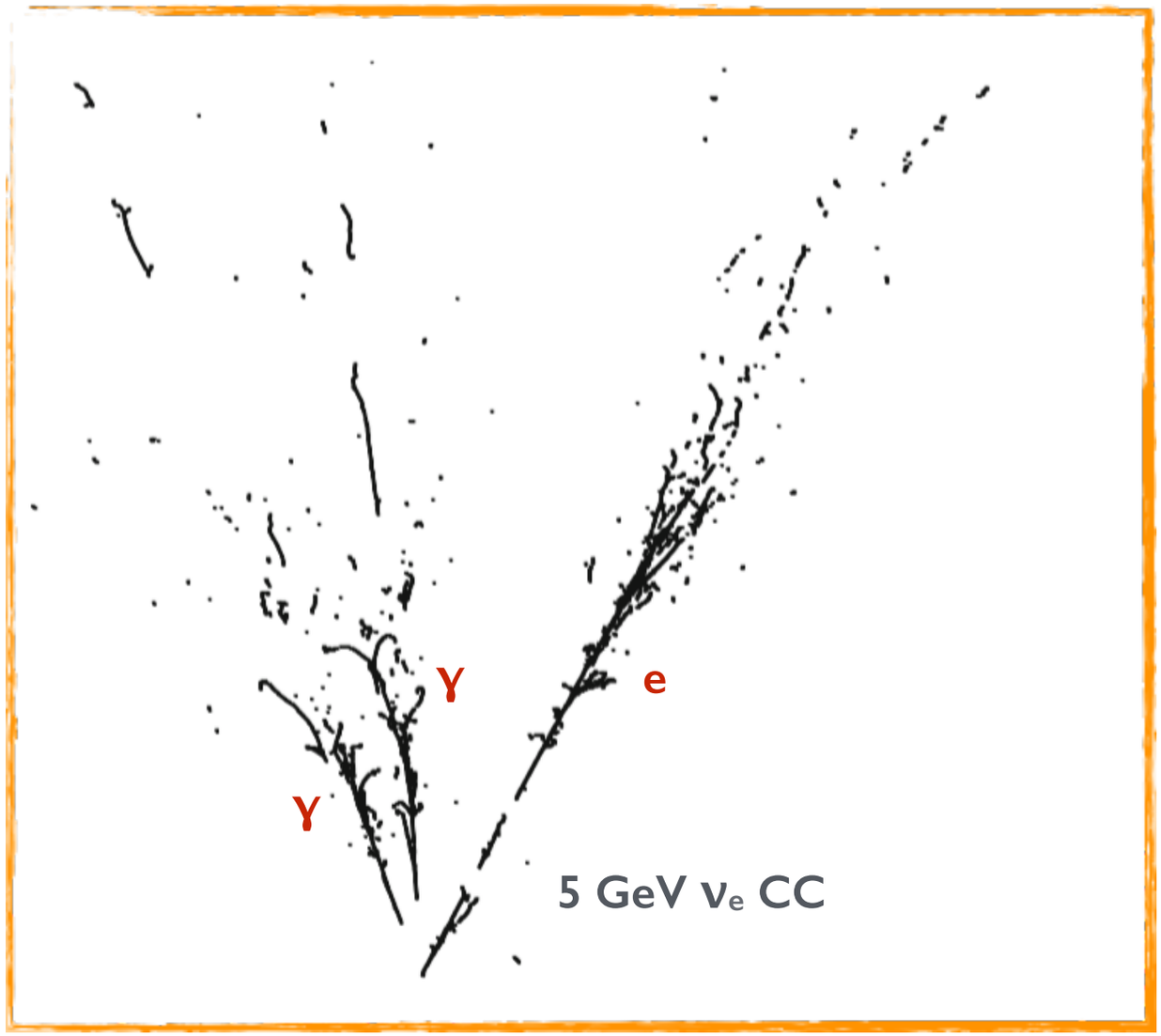
19 October 2015



LAr TPC Pattern Recognition

- LAr TPCs provide "photograph quality" images
- The human brain can readily reconstruct most event topologies.
- Guides the Pandora approach to automated computer pattern recognition

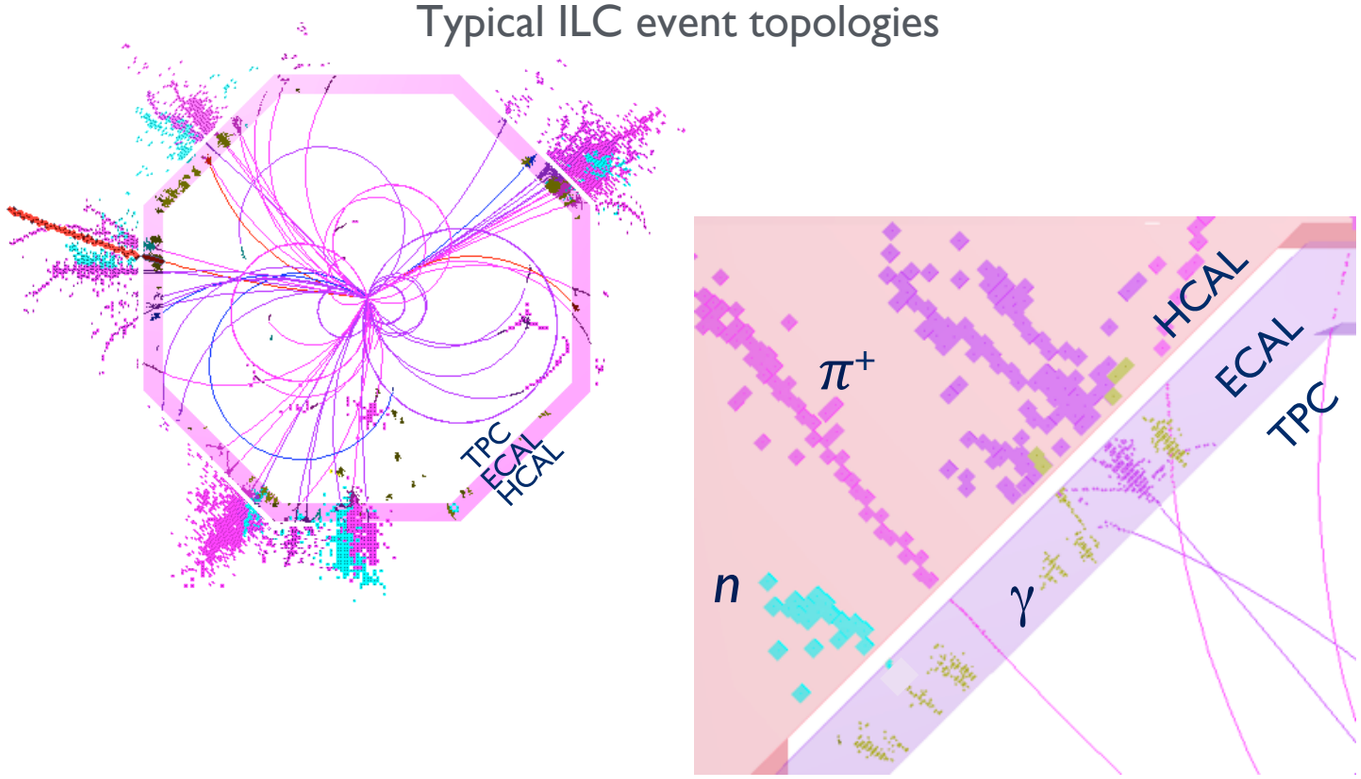




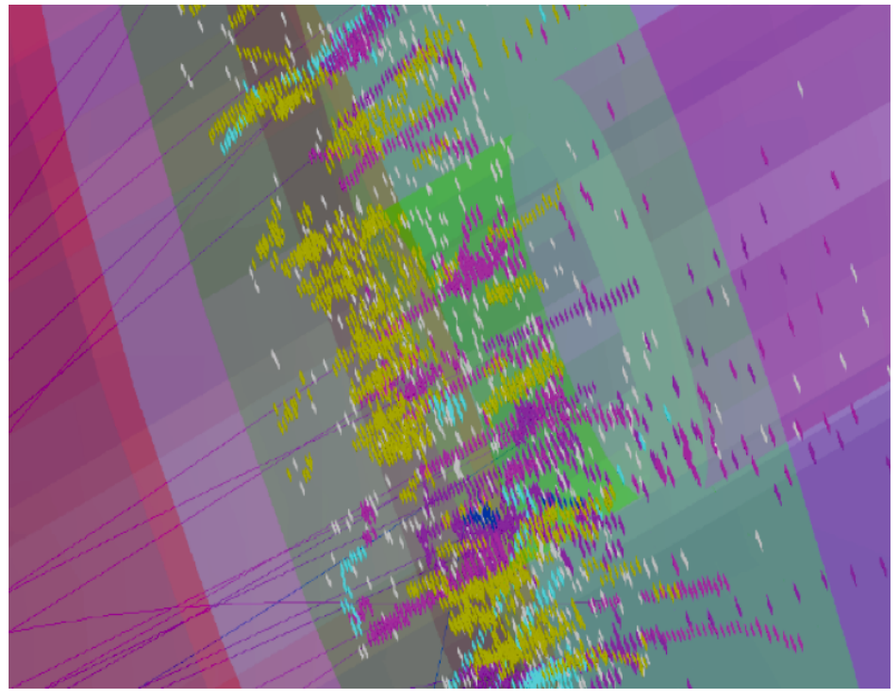
Multi-Algorithm Reconstruction

- Pandora is a framework for implementing a multi-algorithm (70+) approach
- Each algorithm addresses a specific event topologies/task - avoiding mistakes
- Significant change from traditional approach of single algorithms for e.g. track finding, track fitting, shower finding. Can provide a truly robust reconstruction.

Typical ILC event topologies



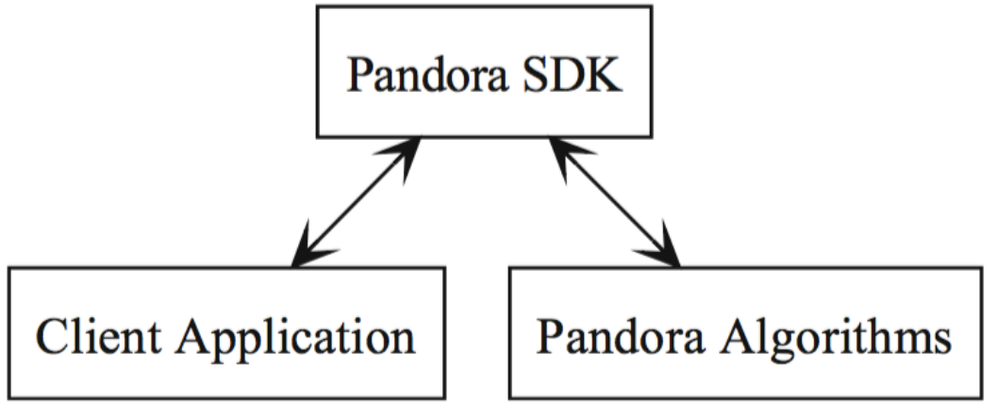
Showers in CMS HGCAL



- Build upon previous successes with event reconstruction in fine granularity detectors at collider expts: ILC (NIMA.2009.09.009), CLIC (NIMA.2012.10.038) and CMS upgrade (LHCC-P-008).

Pandora Introduction

- Multi-algorithm event reconstruction is difficult to implement,
- Pandora Software Development Kit is engineered specifically for this approach



https://www.github.com/PandoraPFA

EPJC.75.439

Algorithm 1 Cluster creation pseudocode. The logic determining when to create new Clusters and when to extend existing Clusters will vary between algorithms.

```
1:  procedure CLUSTER CREATION
2:      Create temporary Cluster list
3:      Get current CaloHit list
4:      for all CaloHits do
5:          if CaloHit available then
6:              for all newly-created Clusters do
7:                  Find best host Cluster
8:              if Suitable host Cluster found then
9:                  Add CaloHit to host Cluster
10:             else
11:                 Add CaloHit to a new Cluster
12:     Save new Clusters in a named list
```

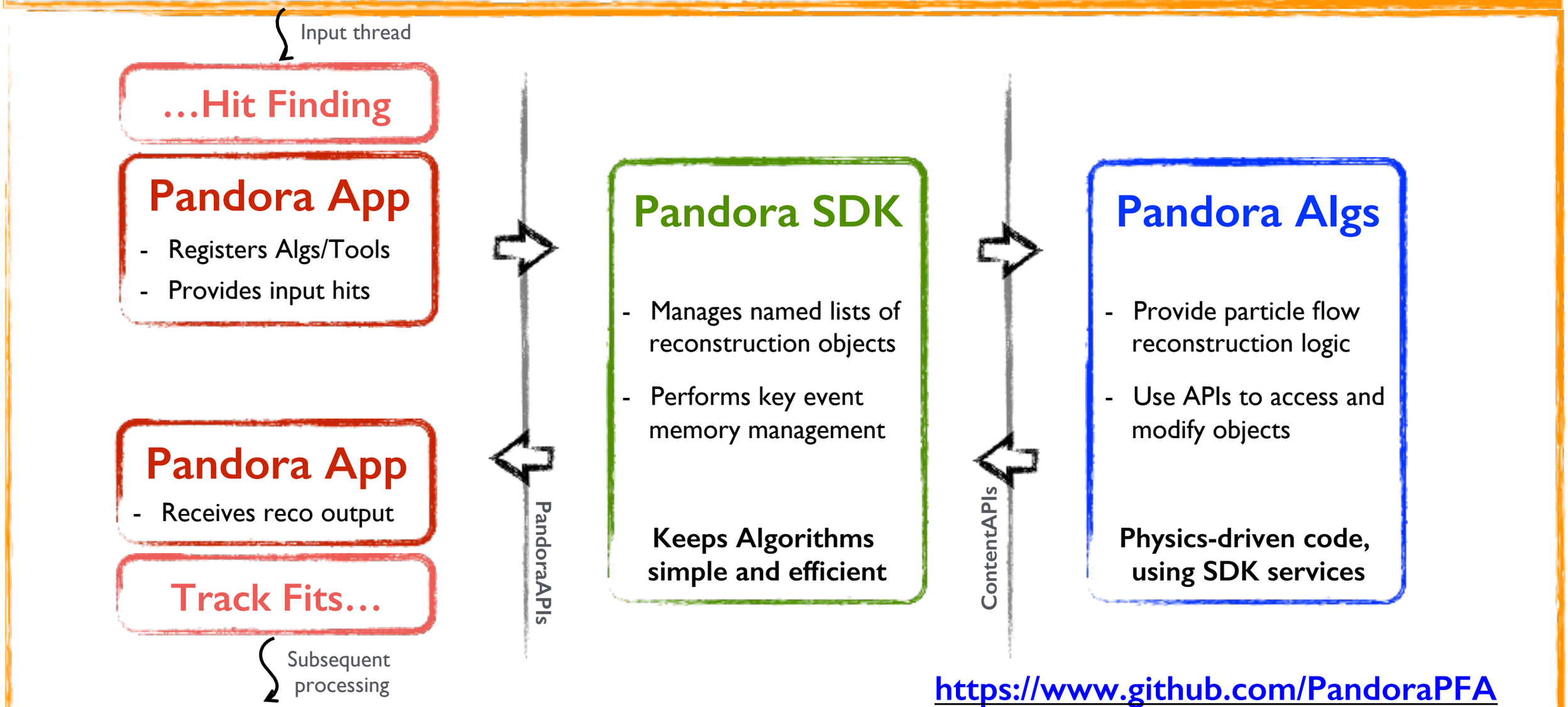
The Pandora SDK provides a software environment in which:

1. It is easy for users to provide the building-blocks that define a pattern recognition problem.
2. Logic required to solve pattern recognition problems is cleanly implemented in algorithms.
3. Operations to access or modify building-blocks, or to create new structures, are requested by algorithms and performed by the Pandora framework.

Promotes the use of large numbers of algorithms, each addressing specific event topologies.

Pandora in LArSoft

- Pandora is **not** a replacement/alternative to LArSoft.
- It is a framework for the TPC **pattern recognition** step.
- Carefully designed APIs enable multi-algorithm approach.
- Art producer module creates Pandora instance(s), registers algorithms and provides algorithm configuration. Each event, passes details about the Hits to Pandora and receives final output.



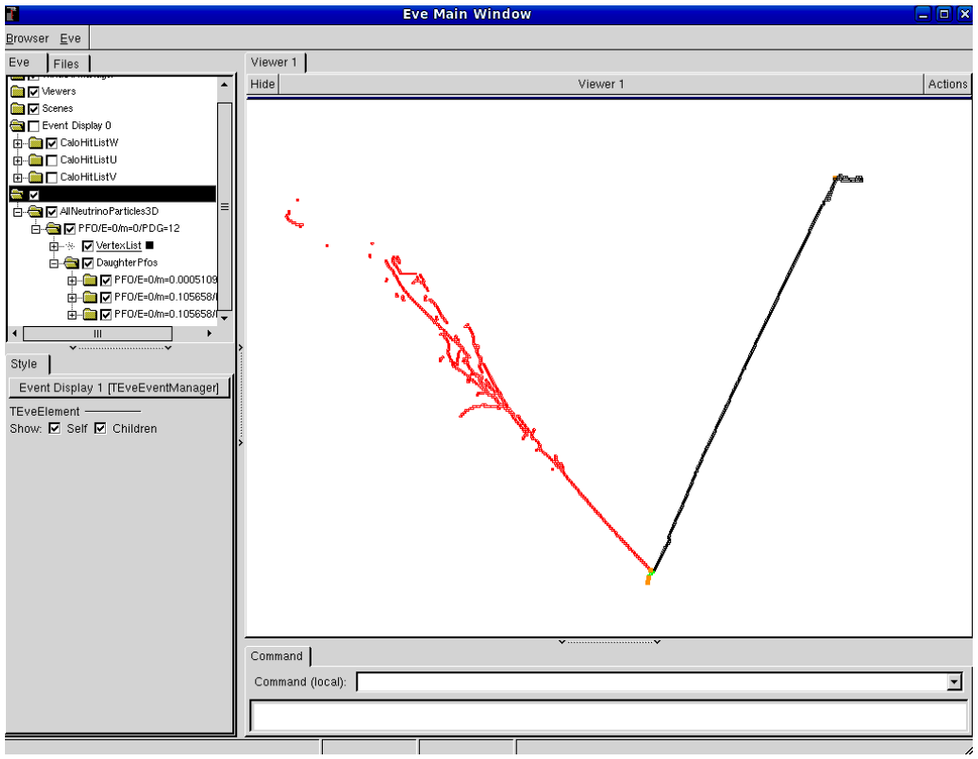
https://www.github.com/PandoraPFA

Pandora Algorithms

- Using the Pandora SDK, algorithms can focus on physics (Pandora performs most memory-management/book-keeping). Rapid development is possible in a visual debugging environment.
- Implemented over 150 algorithms, tools, plugins, helper functions, etc. for LAr TPC reconstruction, grouped in the LArPandoraContent library.
- Some algorithms are complex and sophisticated. Others are under active development. The algorithms gel together to perform a coherent and robust reconstruction.

- The choice of algorithms, and the algorithm configuration, is specified via the PandoraSettings XML file. Currently available for LAr TPC reconstruction are:
  - Dedicated reconstruction for cosmic ray muons
  - Dedicated reconstruction for neutrino events
  - Cheated event reconstruction (for development use only!)
  - Reconstruction that performs 3D "event slicing"
    Can then apply either cosmic ray or neutrino reco to each slice.

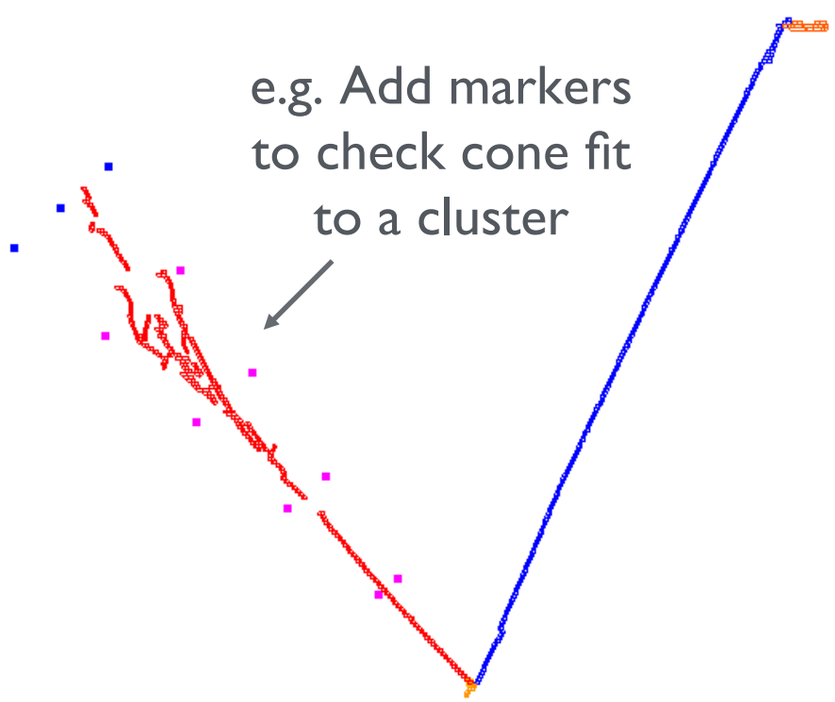
Pandora Visualisation




```
. . .
<algorithm type = "LArLayerSplitting"/>
<algorithm type = “LArLongitudinalAssociation"/>
<algorithm type = "LArVisualMonitoring">
    <ClusterListNames>ClustersU</ClusterListNames>
</algorithm>
<algorithm type = “LArTransverseAssociation"/>
<algorithm type = "LArVisualMonitoring">
    <ClusterListNames>ClustersU</ClusterListNames>
</algorithm>
<algorithm type = "LArLongitudinalExtension"/>
<algorithm type = "LArTransverseExtension"/>
<algorithm type = "LArOvershootSplitting"/>
<algorithm type = "LArBranchSplitting"/>
<algorithm type = “LArKinkSplitting"/>
. . .
```

e.g. Add two event display algs to examine changes as reconstruction progresses

- Pandora algorithms can choose to use the Pandora Monitoring library, which has a ROOT dependency.
- ROOT Event Visualisation Environment provides 2D or 3D displays of hits, clusters, particles or vertices.
- Reusable Pandora event display alg can be added to XML to view status of reconstruction at any point.
- Alternatively, algs can use visualisation APIs to provide custom visual debugging - **rewarding way to work.**



Pandora Key Points

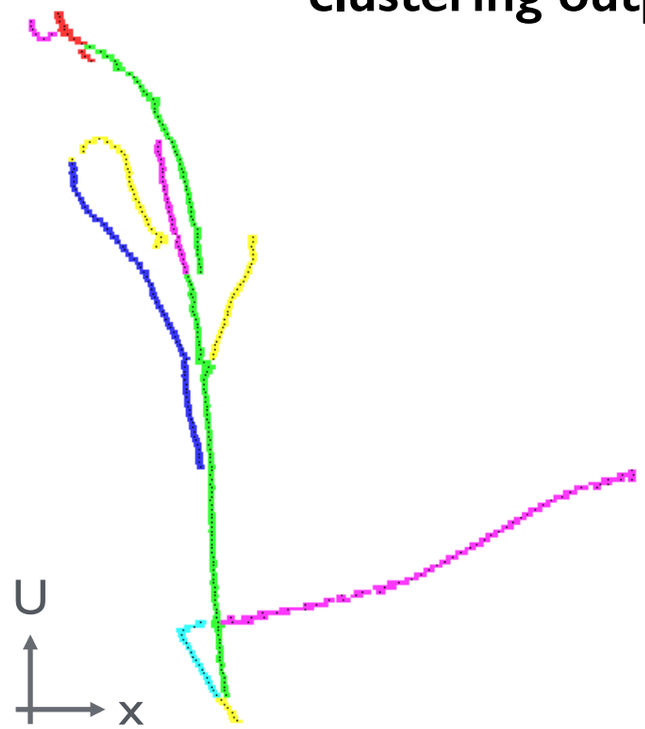
- Pandora is not trying to be LArSoft. It is a framework for pattern recognition algorithms.
- It is generic and is used successfully across multiple (very different) projects.
- Its powerful functionality enables complex algorithms using e.g. recursion or reclustering.
- Design philosophy: support multi-algorithm approach, gradually build-up picture of event.

Will now discuss LArTPC algorithms/performance…

1. Track Clustering in 2D

- Start with cautious, track-oriented 2D clustering. Important to avoid mistakes at this early stage.
- Use series of topological-association algorithms to carefully merge/split the 2D proto-clusters.

Typical 2D clustering output



2D Reco Snippet from PandoraSettings XML file:

```
<algorithm type = "LArClusteringParent">
    <algorithm type = "LArTrackClusterCreation" description = "ClusterFormation"/>
    <InputCaloHitListName>CaloHitListW</InputCaloHitListName>
    <ClusterListName>ClustersW</ClusterListName>
    <ReplaceCurrentCaloHitList>false</ReplaceCurrentCaloHitList>
    <ReplaceCurrentClusterList>true</ReplaceCurrentClusterList>
</algorithm>

<algorithm type = "LArLayerSplitting"/>
<algorithm type = "LArLongitudinalAssociation"/>
<algorithm type = "LArTransverseAssociation"/>
<algorithm type = "LArLongitudinalExtension"/>
<algorithm type = "LArTransverseExtension"/>
<algorithm type = "LArOvershootSplitting"/>
<algorithm type = "LArBranchSplitting"/>
<algorithm type = "LArKinkSplitting"/>
```

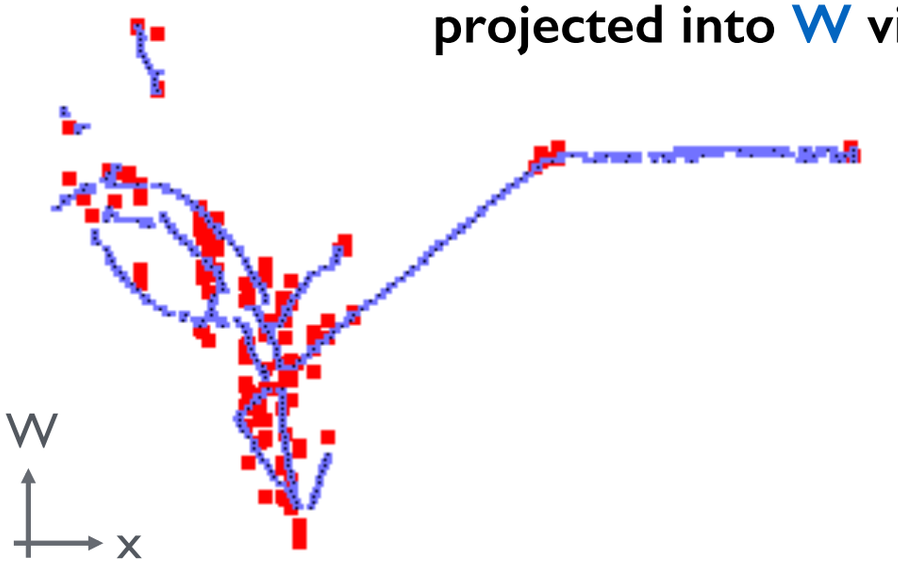
2D Cluster Creation

2D Cluster Merging/Splitting

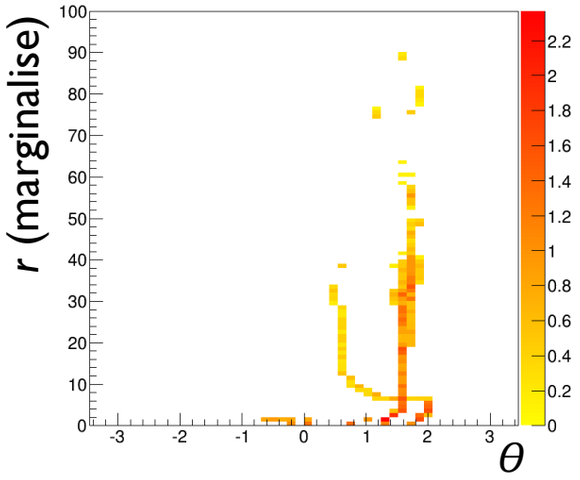
2. Vertex Reconstruction in 3D

- Use pairs of 2D clusters to produce list of possible 3D vertex positions.
- Examine candidate vertices, calculate a score for each and select the best.
- Can then e.g. split 2D clusters at projected vertex position, if required.
- Use vertex position to protect primary particles when growing showers.

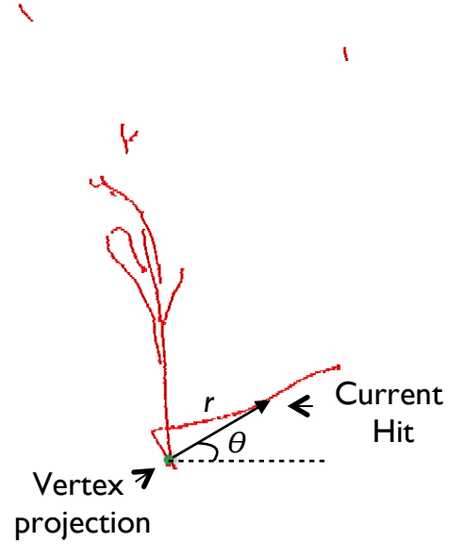
3D candidate vertices projected into W view

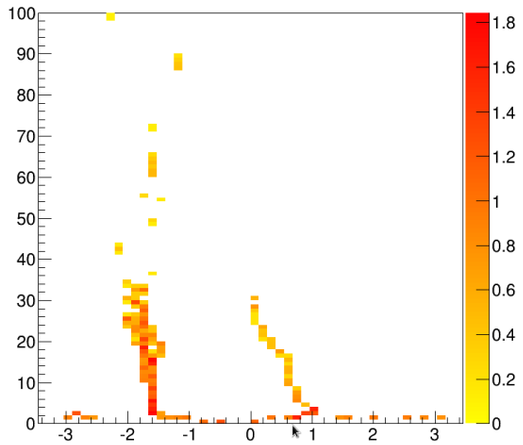


Calculate a score for each vertex candidate

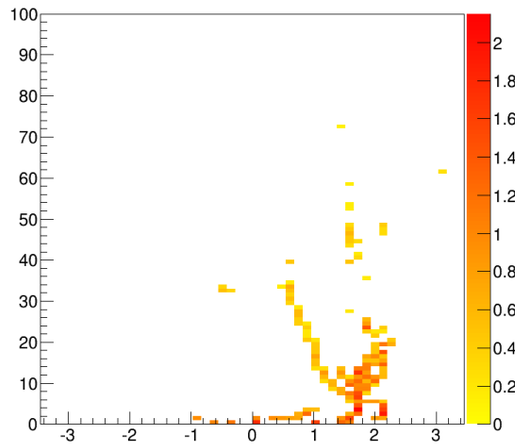


U





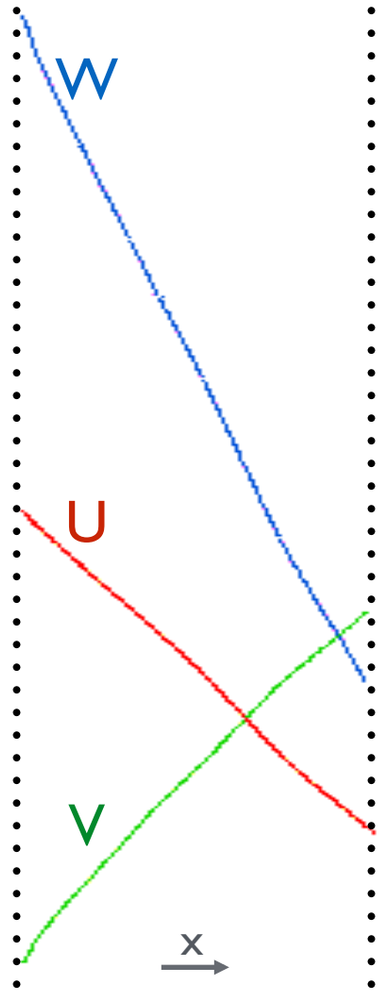
V



W

3. Track Reconstruction in 3D

Create a tensor, storing overlap details for trios of 2D clusters. Tools make 2D cluster changes in order to diagonalise tensor. If a tool makes a change (e.g. splits a cluster), all tools run again.



1:1:1

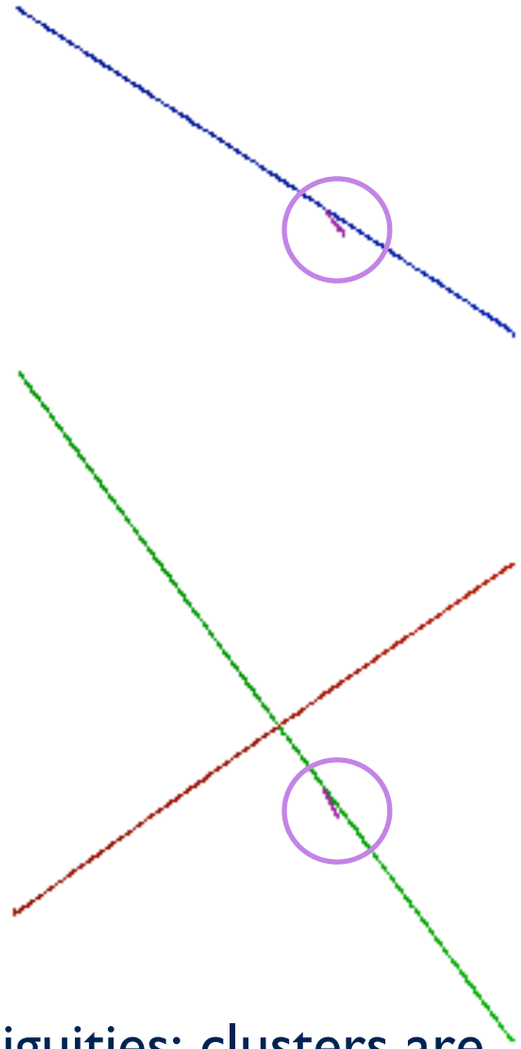
Aim: group together 3 x 2D clusters in a new track "particle"

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

e.g. 1:2:2

Ringed clusters in V and W views also match U cluster, so U cluster is ambiguous in tensor.

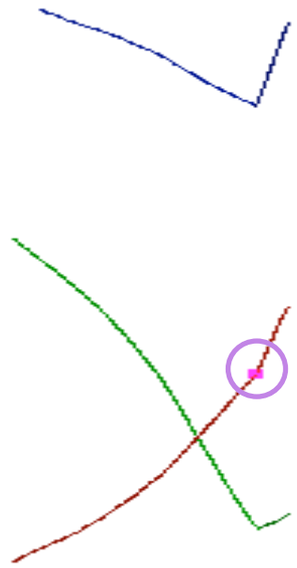


Resolve **obvious** ambiguities: clusters are matched in multiple configurations, but one tensor element is much better than others.

Long Tracks Tool

3. Track Reconstruction in 3D

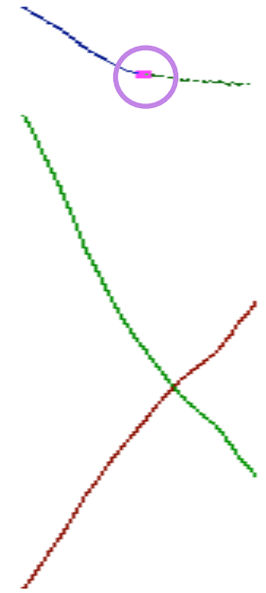
1:2:2



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

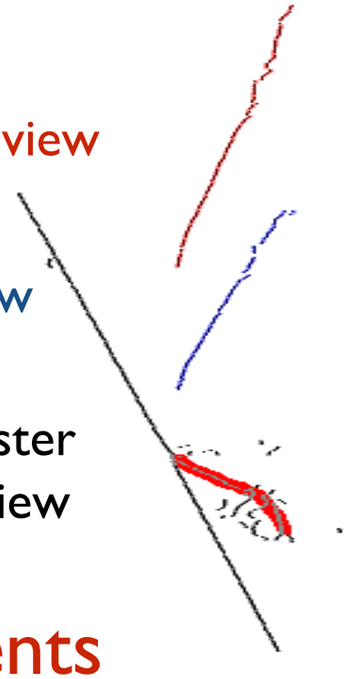
2:2:1

Clear match between U, V and W clusters, but W cluster unavailable.

Track overlap in W view:
create two-cluster particle.

Missing Tracks Tool

1:1:Fragments



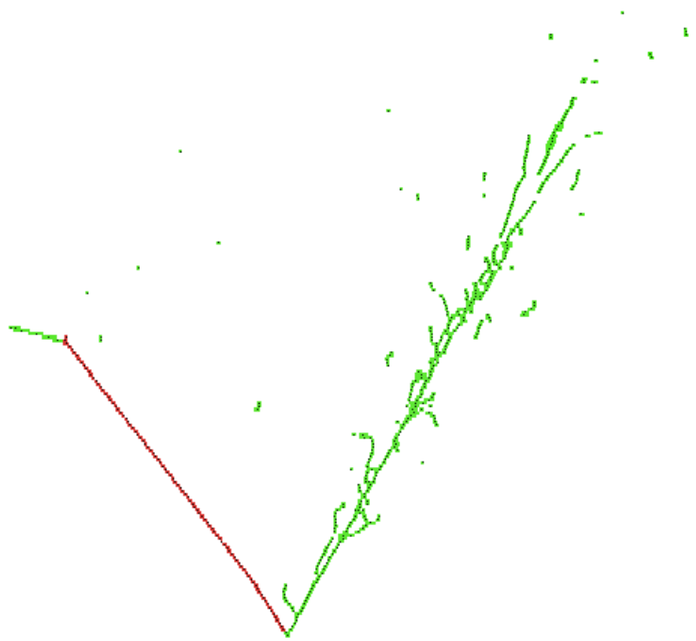
Clear Track Fragments

4. Shower Reconstruction in 2D

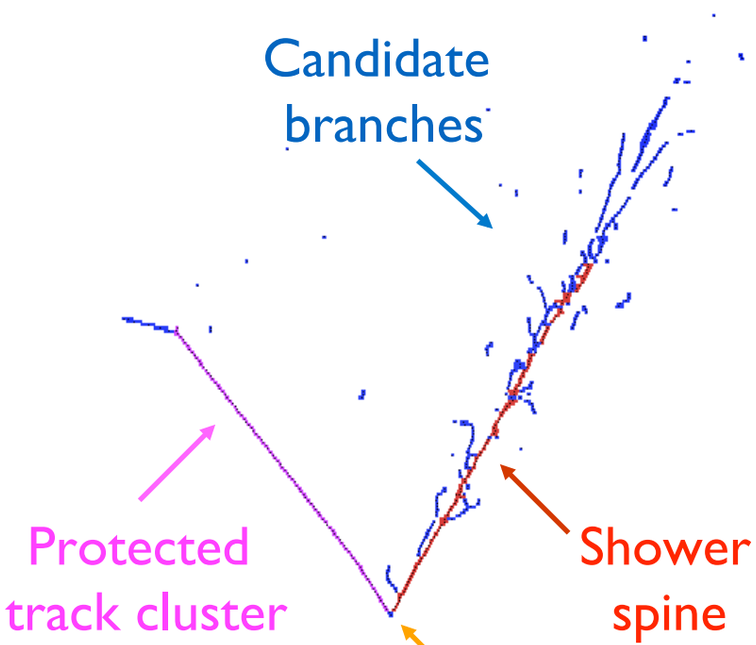
Attempt to add branches to long clusters representing shower spines. Long clusters may already exist in track particles. Grow 2D showers using three key ideas:

1. Characterise 2D clusters as track-like or shower-like.
2. Identify long (often vertex-associated), shower-like 2D clusters that represent shower spines.
3. Add branches to the list of spines: work recursively, finding branches for top-level spine, then branches on branches, etc. For every branch, record strength of association to each spine.

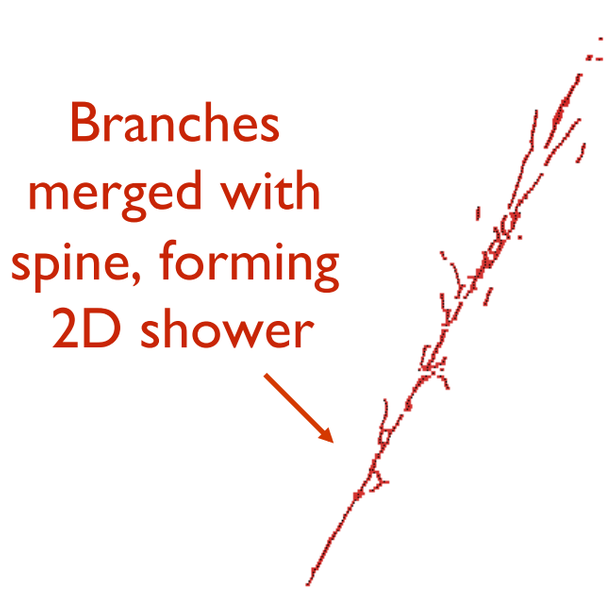
1.



2.



3.

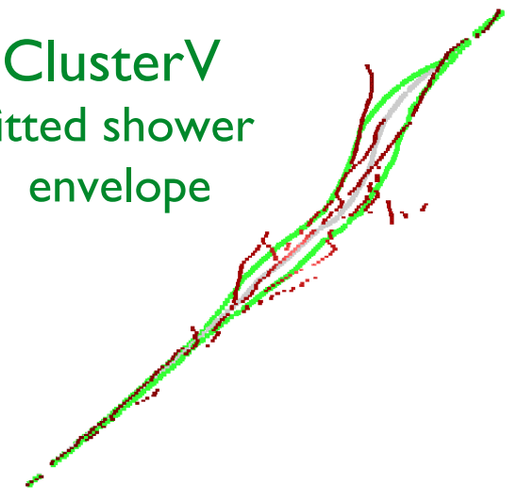


Any track particle acquiring branches is deleted

5. Shower Reconstruction in 3D

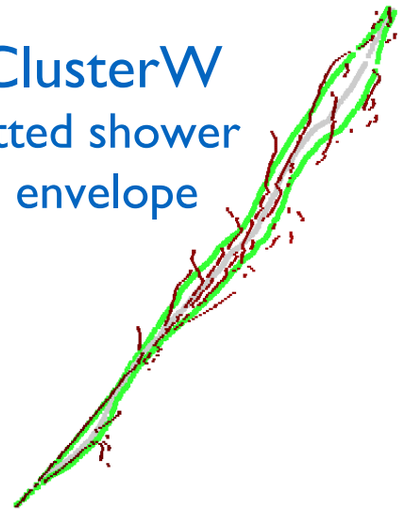
Re-use ideas and base classes from 3D track reconstruction: build and diagonalise a tensor

ClusterV
fitted shower
envelope



+

ClusterW
fitted shower
envelope



=

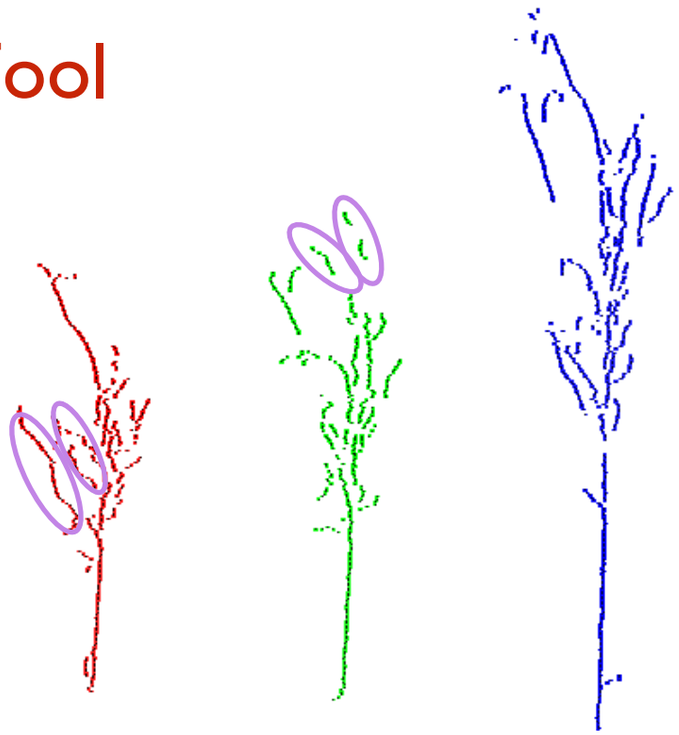
ClusterU
predicted shower
envelope

Store enclosed hit fraction in tensor

Clear Showers Tool

e.g. 3:3:1

Small problems cause ambiguities, but best combination obvious



U: 3 V: 3 W: 1

Split Showers Tool

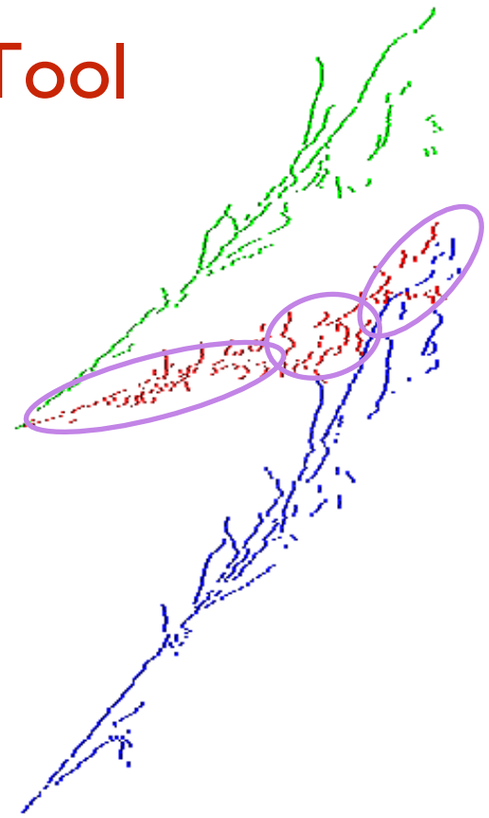
e.g. 3:1:1

V: 1

U: 3

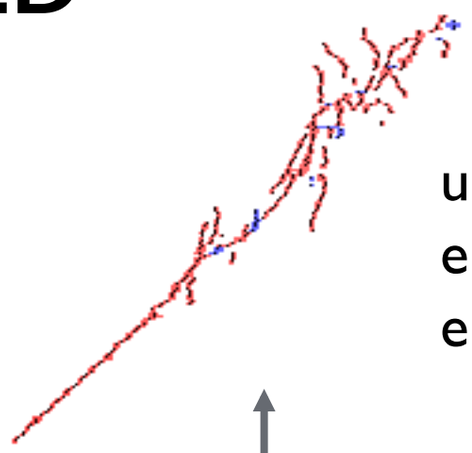
W: 1

Tensor elements have two clusters in common



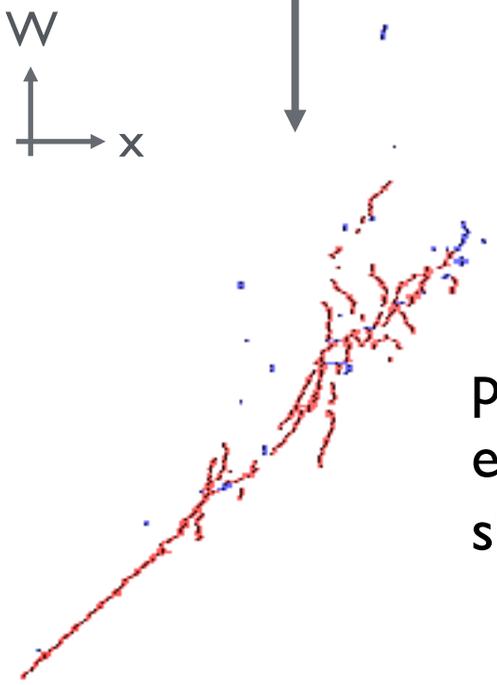
6. Mop-Up in 2D and 3D

2D



BoundedCluster mop-up, picks-up lone clusters enclosed in shower envelopes.

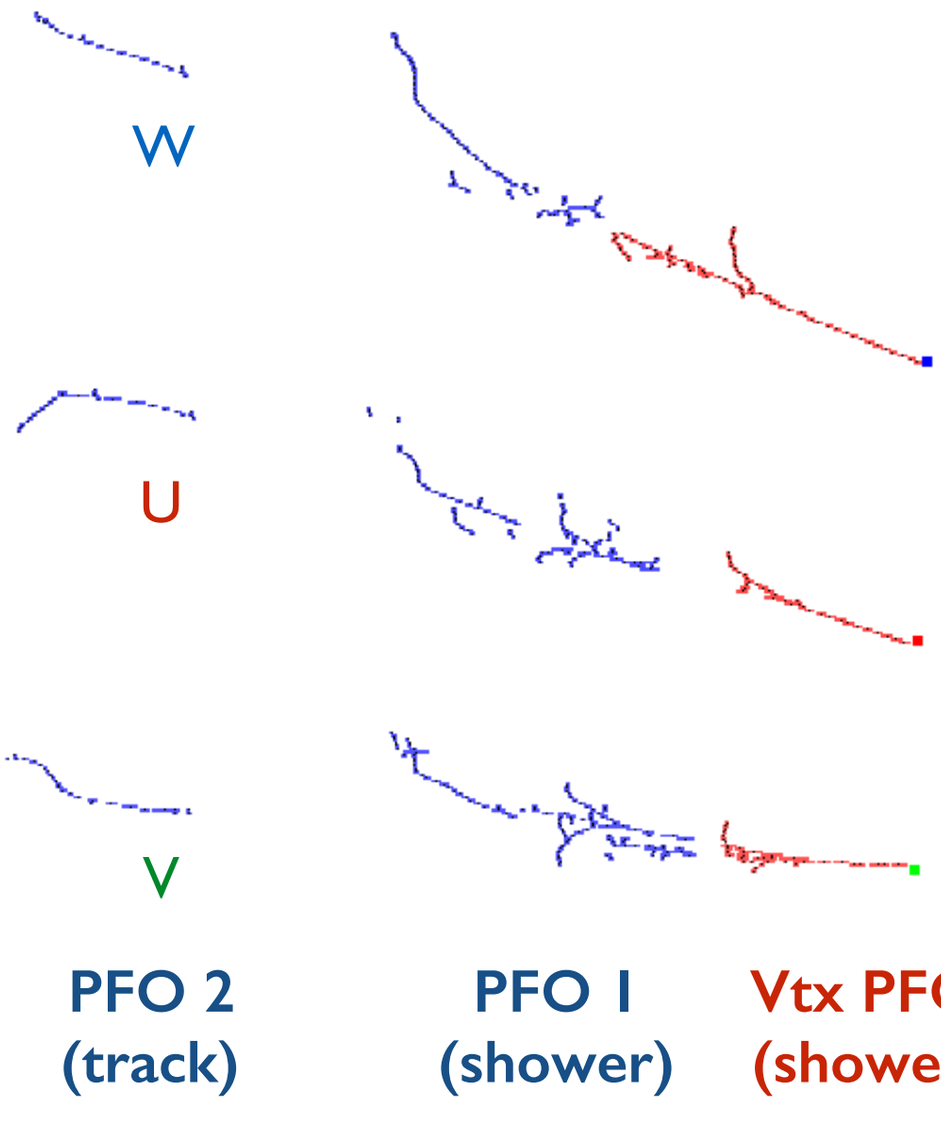
Compare



ConeBased mop-up, picks-up clusters enclosed in a cone about shower.

3D

VertexBasedPFO mop-up, important for sparse showers.



PFO ⇔ Particle Flow Object

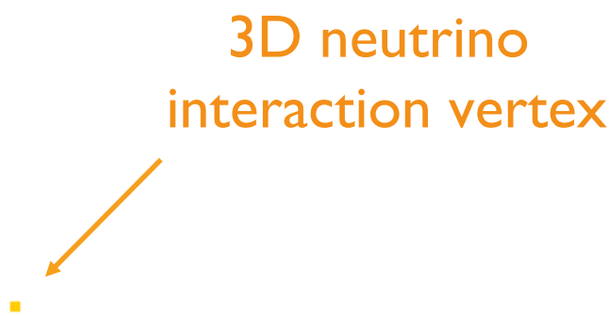
7. Event Building in 3D

The final algorithms and tools create 3D SpacePoints for each reconstructed particle. The full particle hierarchy is also reconstructed, so a typical event output is as shown below:

5 GeV ν_e CC: Display 1/4

The reconstructed neutrino particle contains:

- Metadata: PDG code, 4-momentum, etc
- A 3D interaction vertex
- A list of daughter particles



7. Event Building in 3D

The final algorithms and tools create 3D SpacePoints for each reconstructed particle. The full particle hierarchy is also reconstructed, so a typical event output is as shown below:

5 GeV ν_e CC: Display 2/4

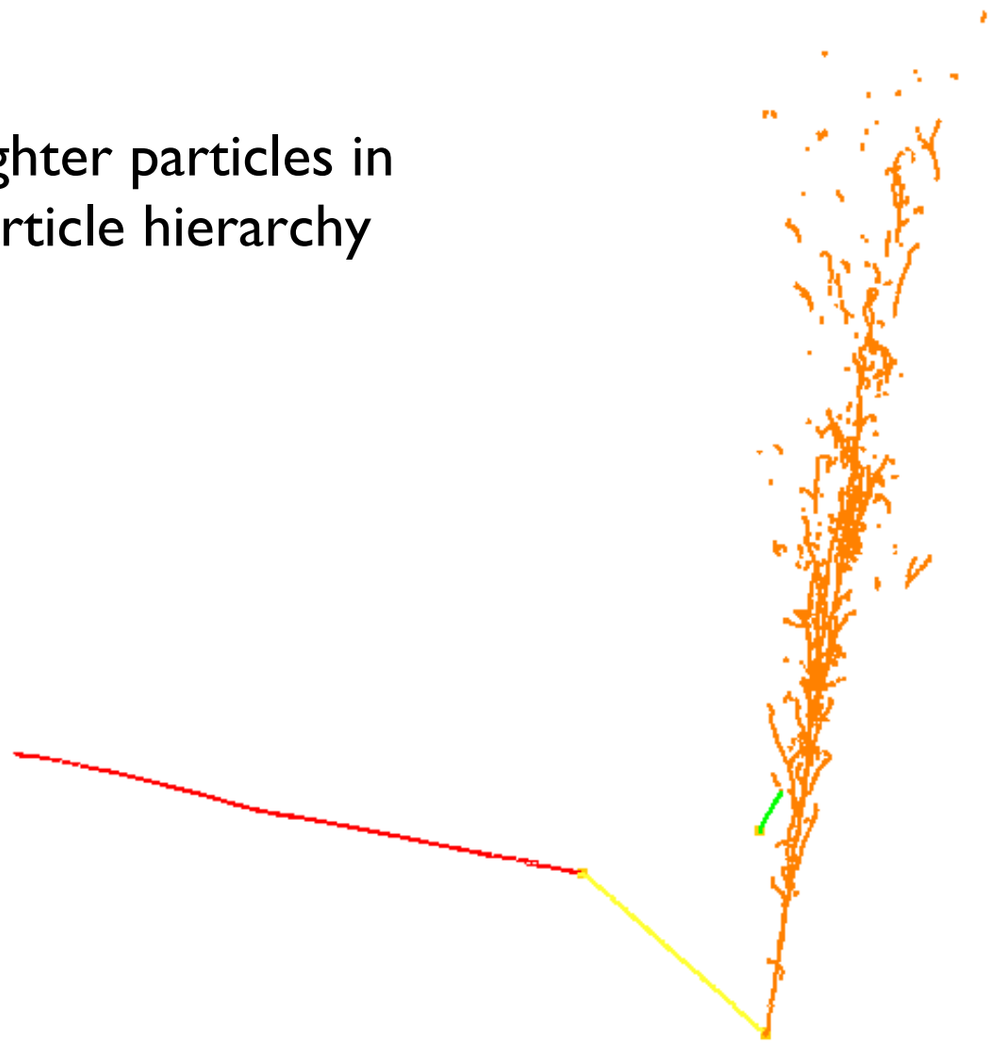
+ Primary daughter particles of the neutrino, each of which has:
  - Particle metadata
  - A list of 2D clusters and a 3D cluster
  - A 3D interaction vertex
  - A list of any further daughter particles

7. Event Building in 3D

The final algorithms and tools create 3D SpacePoints for each reconstructed particle. The full particle hierarchy is also reconstructed, so a typical event output is as shown below:

5 GeV ν_e CC: Display 3/4

+ Complete list of daughter particles in the reconstructed particle hierarchy

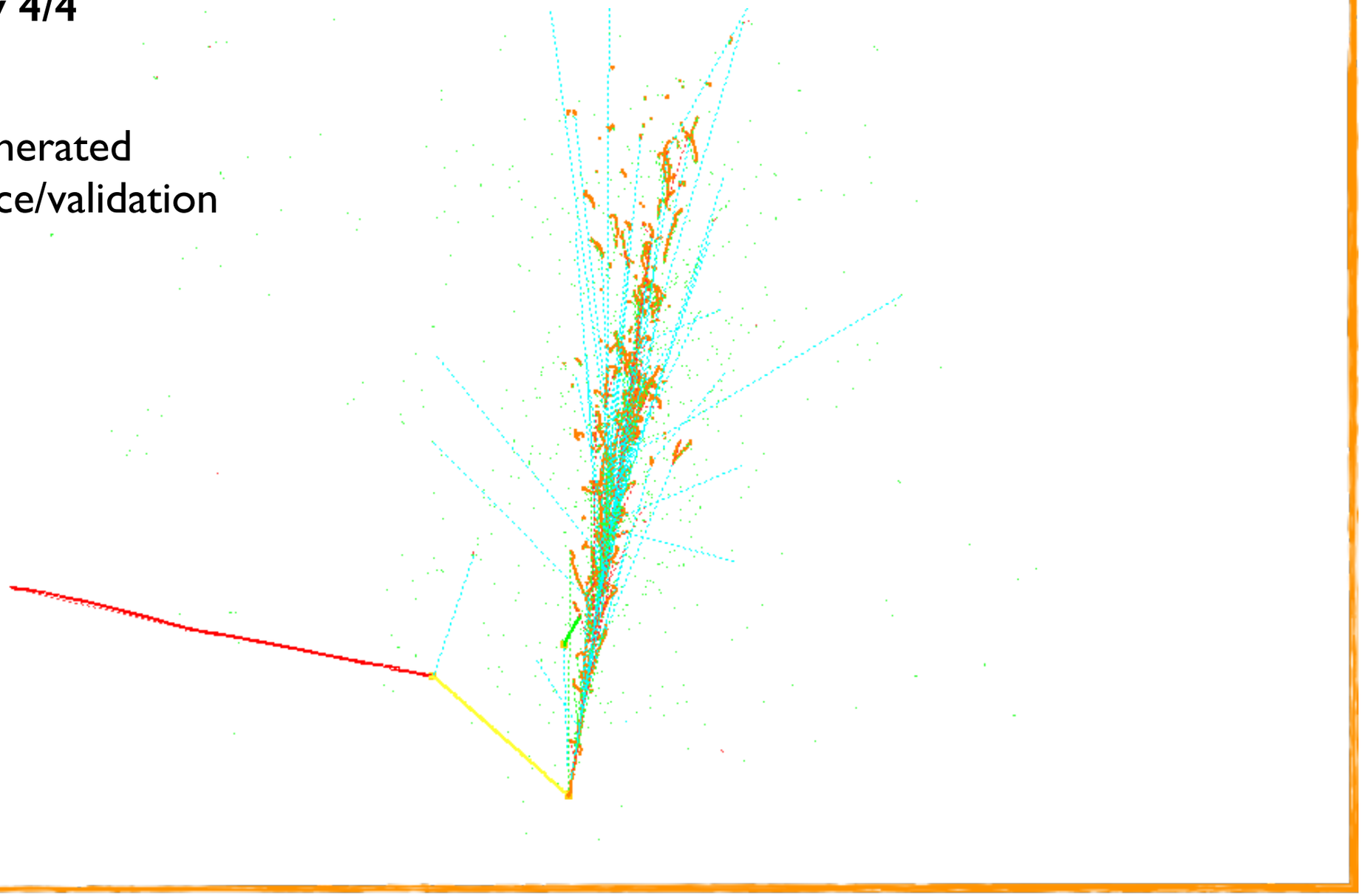


7. Event Building in 3D

The final algorithms and tools create 3D SpacePoints for each reconstructed particle. The full particle hierarchy is also reconstructed, so a typical event output is as shown below:

5 GeV ν_e CC: Display 4/4

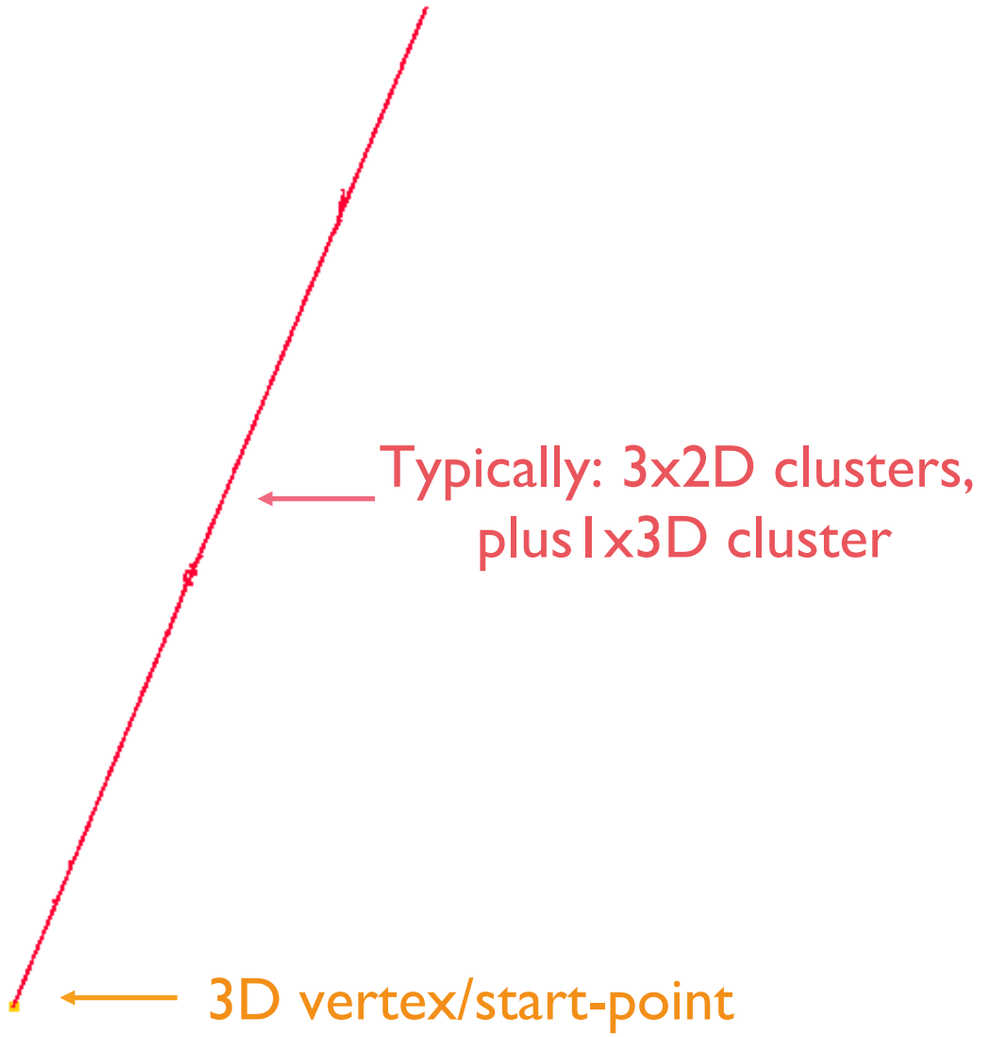
+ Overlay details of generated particles, for reference/validation



Cosmic Ray Muon: Display 1/2

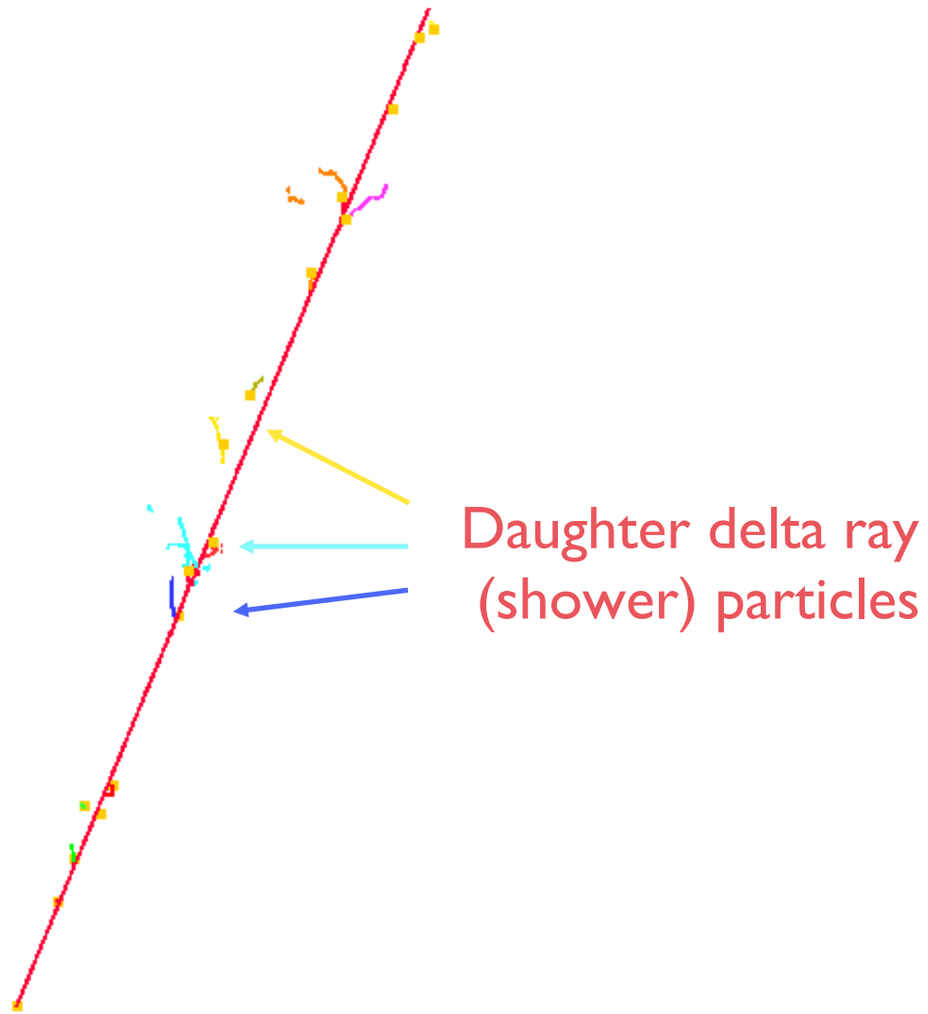
The reconstructed cosmic ray contains:

- Particle metadata
- A 3D vertex/start-point
- A list of 2D and 3D muon clusters
- A list of daughter particles



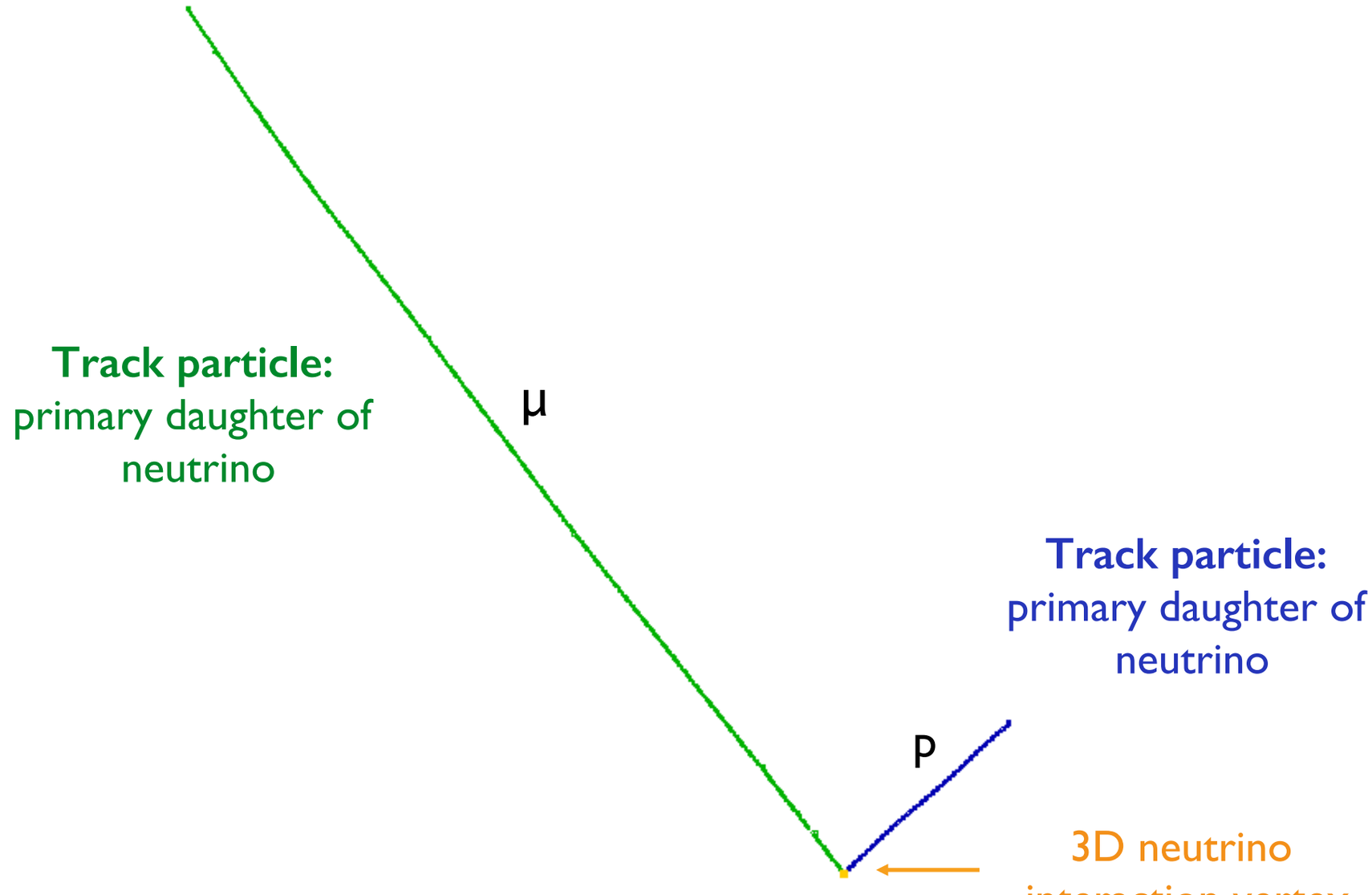
Cosmic Ray Muon: Display 2/2

+ Daughter delta-rays, each of which has:
  - Particle metadata
  - A list of 2D clusters and a 3D cluster
  - A 3D vertex position



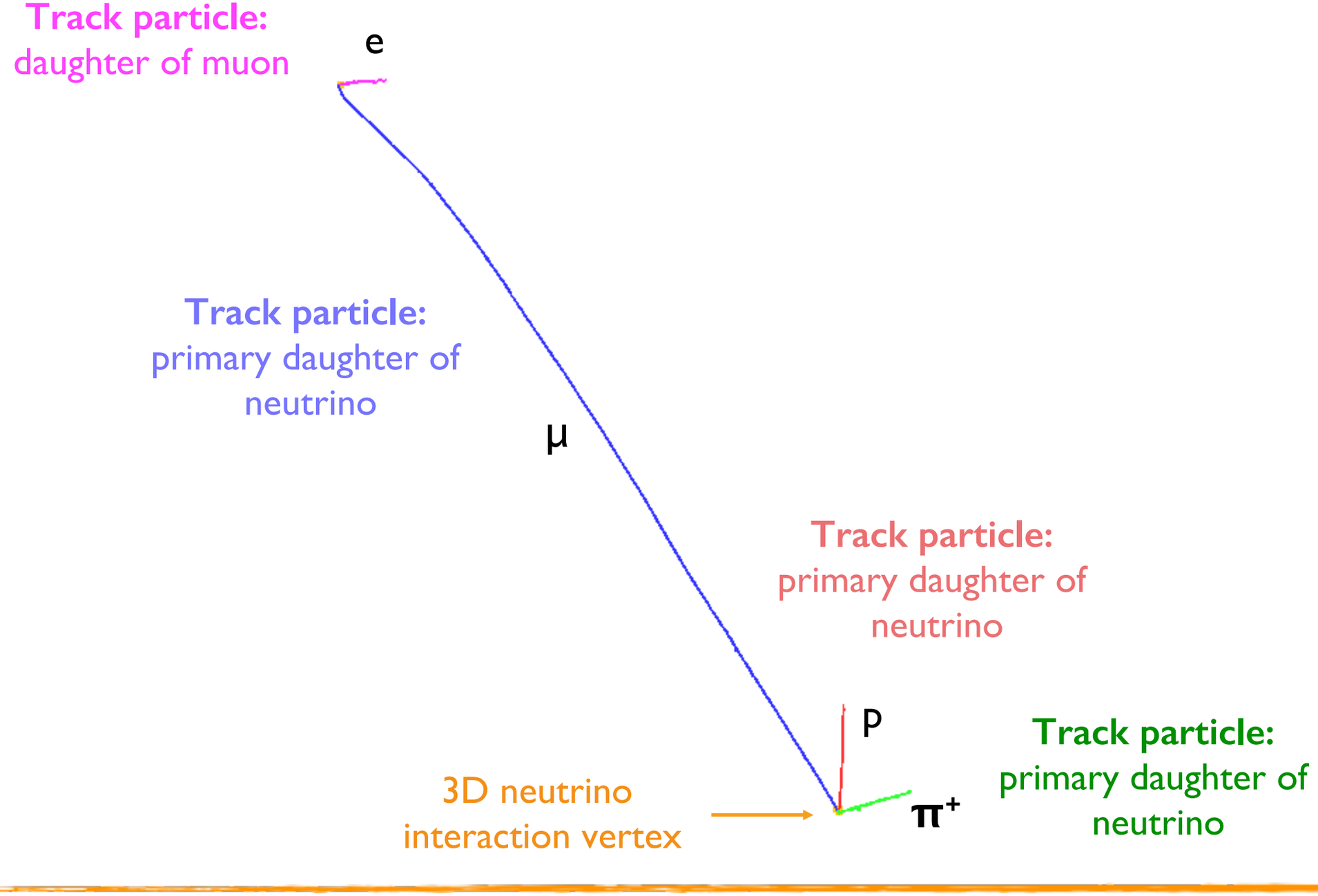
Pandora Example Events

BNB ν_μ CC QEL: Combined display



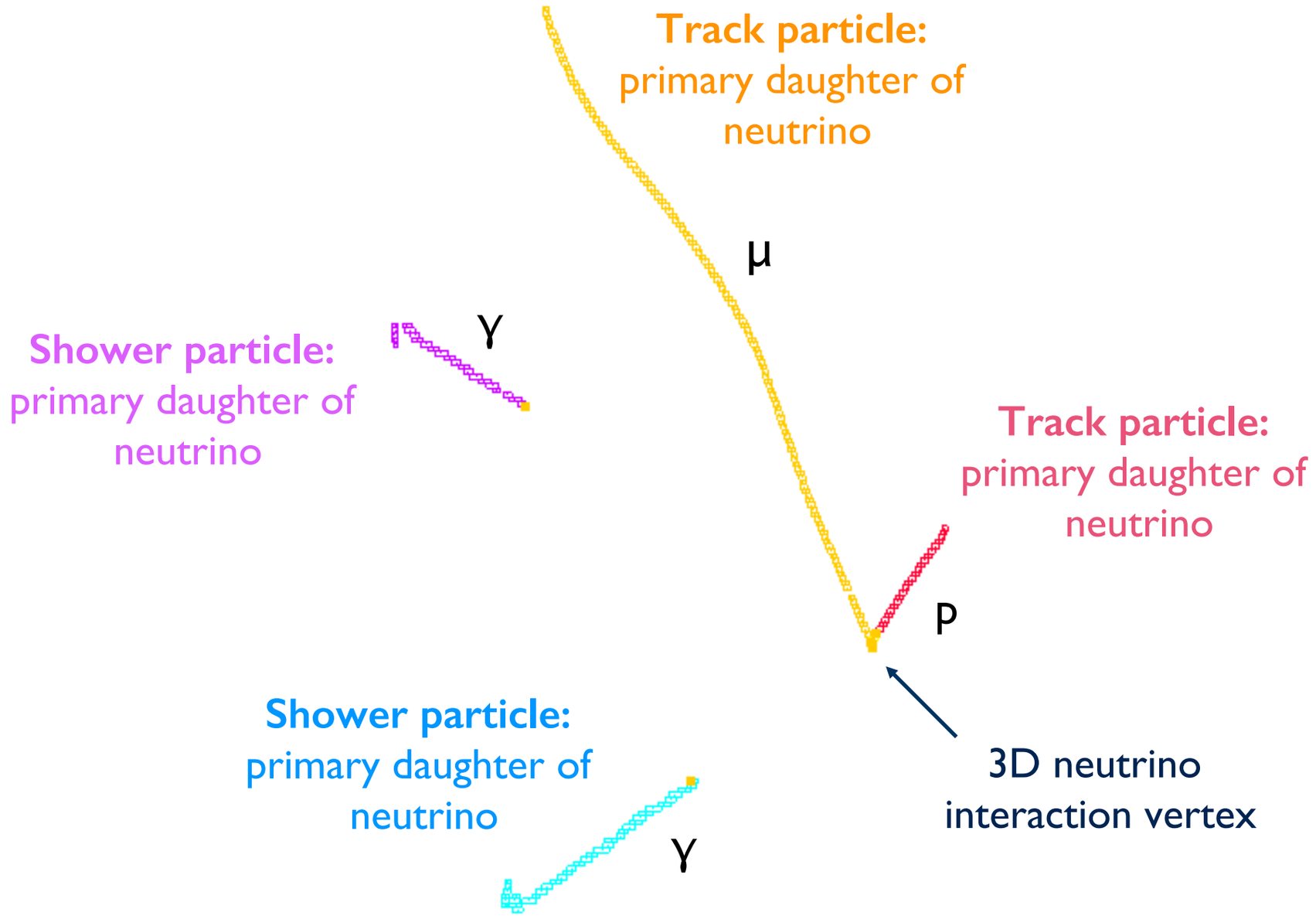
Pandora Example Events

BNB ν_μ CC RES μ, p, π^+: Combined display



Pandora Example Events

BNB ν_μ CC RES μ, p, π^0: Combined display



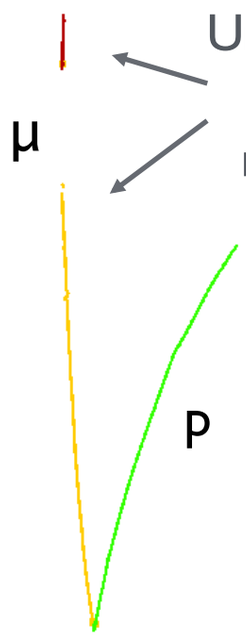
Pandora LAr TPC Algorithms Key Points

- Algs mostly developed in context of MicroBooNE, but 35-t (DUNE) applications exist.
- Pandora delivers particles, e.g. for MicroBooNE get list of “Cosmics” + “Neutrinos”
- Pandora particles contain rich information, much more than just tracks or clusters.
- The algs perform rather well in tests using MicroBooNE simulation. See next slides…

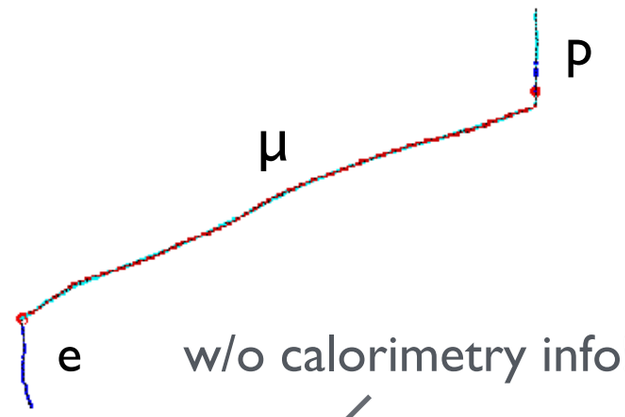
Pandora Performance

- **Use performance metrics to assess reconstruction output and drive development:**
  - Look at specific types of neutrino interactions in MicroBooNE simulation.
  - Carefully match reconstructed particles to each true (primary) particle; see backup slide.
  - Count reconstructed particles for each true particle and assess quality of matches.
- Well-defined validation approach, but not very forgiving. Events with minor errors, dismissed by eye (i.e. output agrees with basic visual event interpretation), will often be classed as failures.
- **Striving for perfection - look to accurately match one reco particle to each true particle.**

What kind of things go wrong? e.g. BNB ν_μ CC QEL μ, p

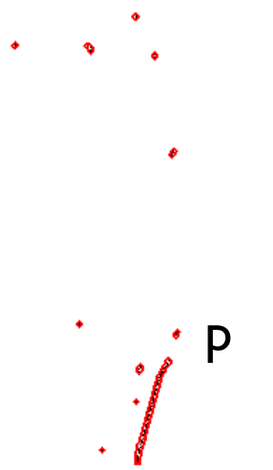


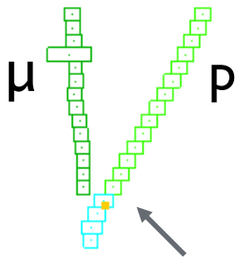
Unexpected gap in hits - split reco particles



w/o calorimetry info!

Distinguish between proton and electron? True vtx: high Z.



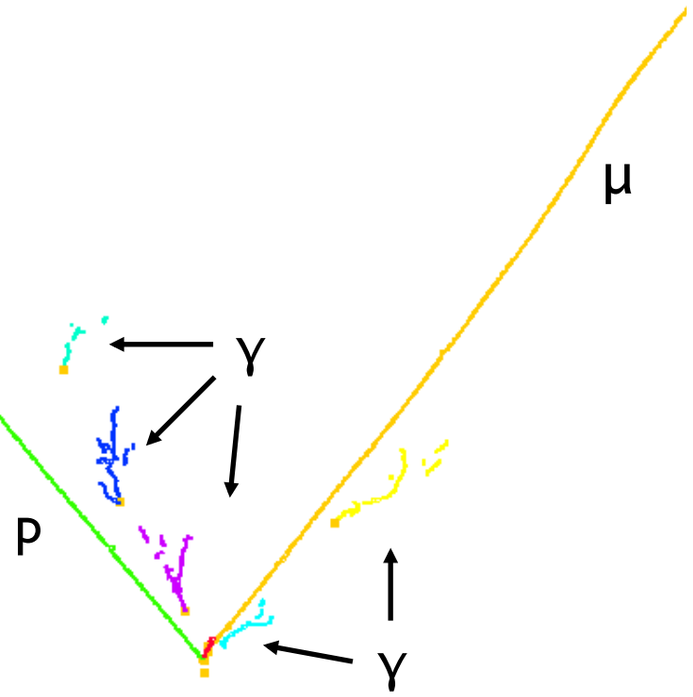


Misplaced vtx

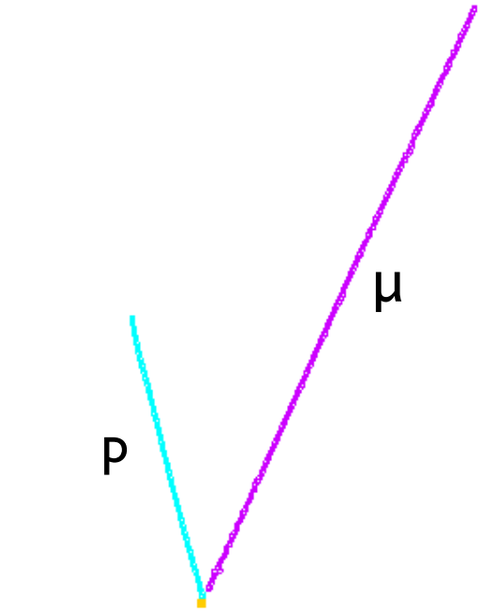
True "isolated" hits unlikely to be included in reco particles.

Pandora Performance

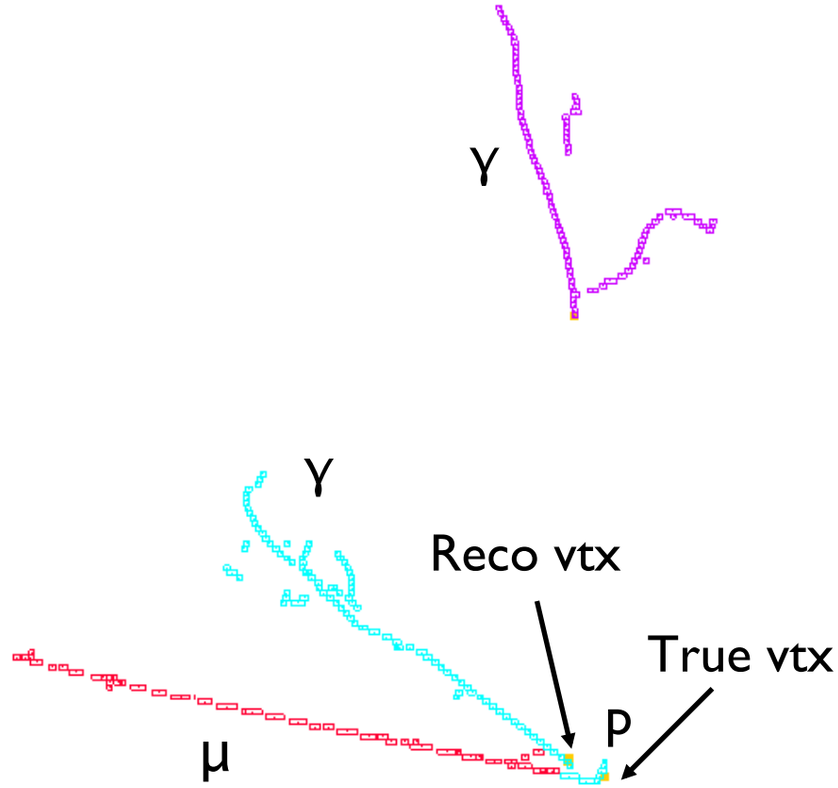
What kind of things go wrong? e.g. BNB ν_μ CC RES μ, p, π^0



Sparse photon-induced showers reconstructed as multiple particles



No Hits for second photon exist in HitFinder output



Reconstructed vertex slightly displaced, so proton is lost

Pandora Performance

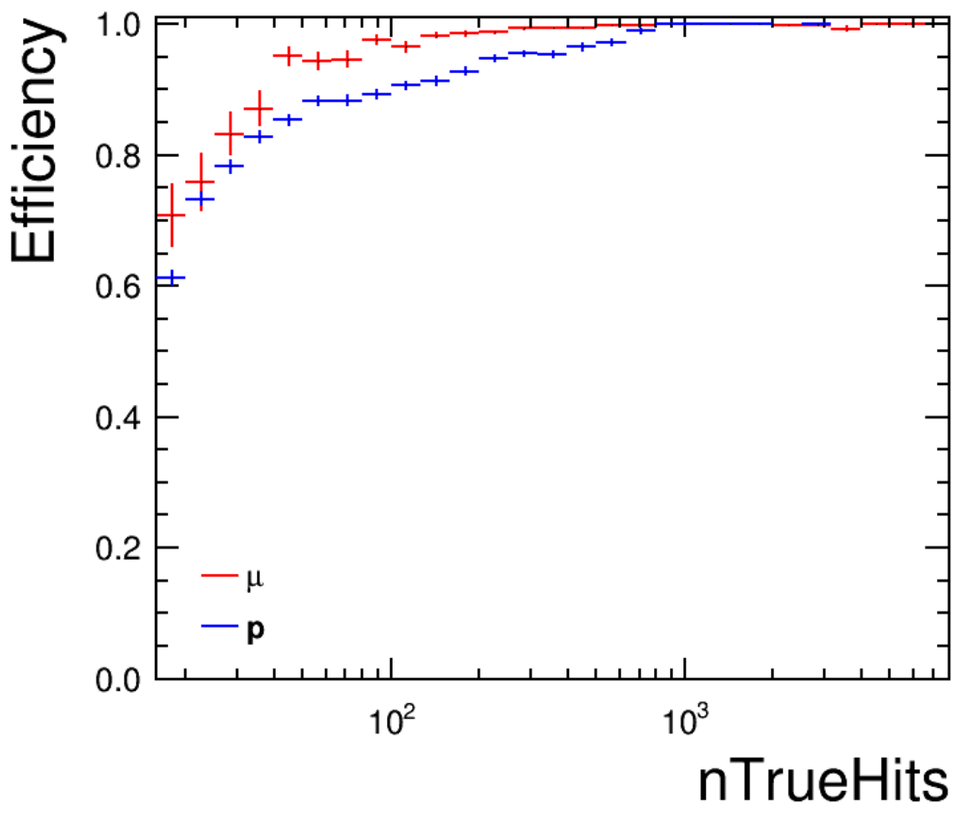
MicroBooNE simulation: BNB ν_μ CC QEL μ, p

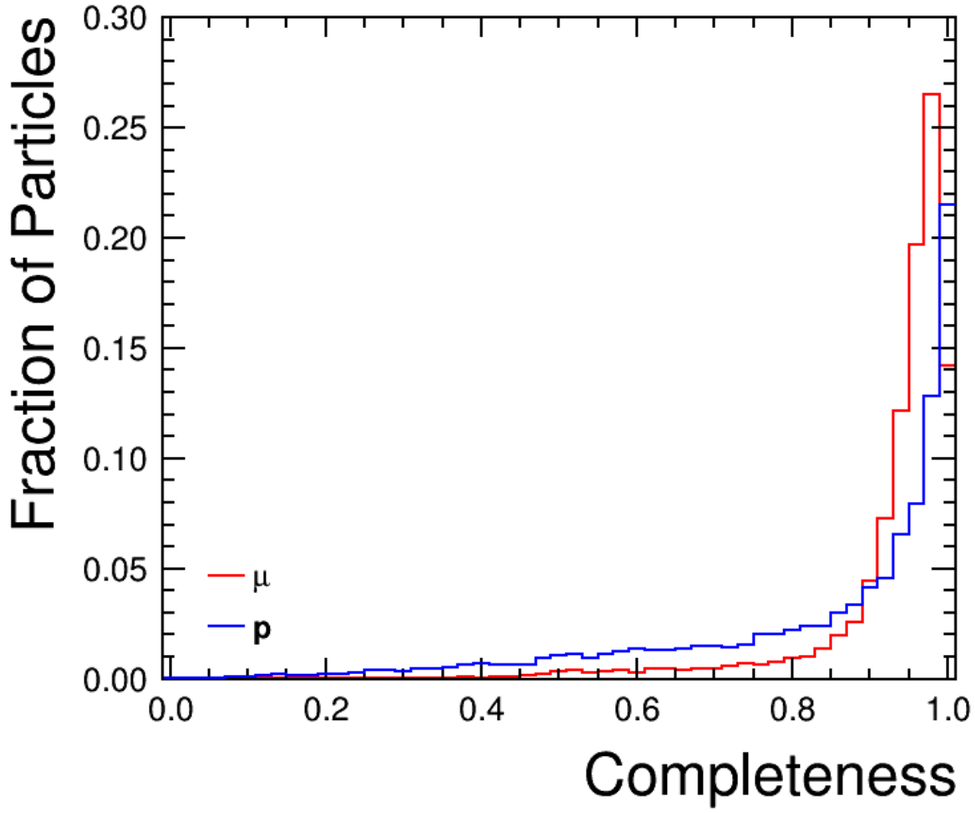
#MatchedPFOs		0	1	2	3+
Particles	μ	231	20,346	1,430	139
	p	3,079	18,212	740	115

#Events: 22,146

#Perfect: 78%

If muon and proton merged into a single reco particle, this particle is more likely to be matched to muon





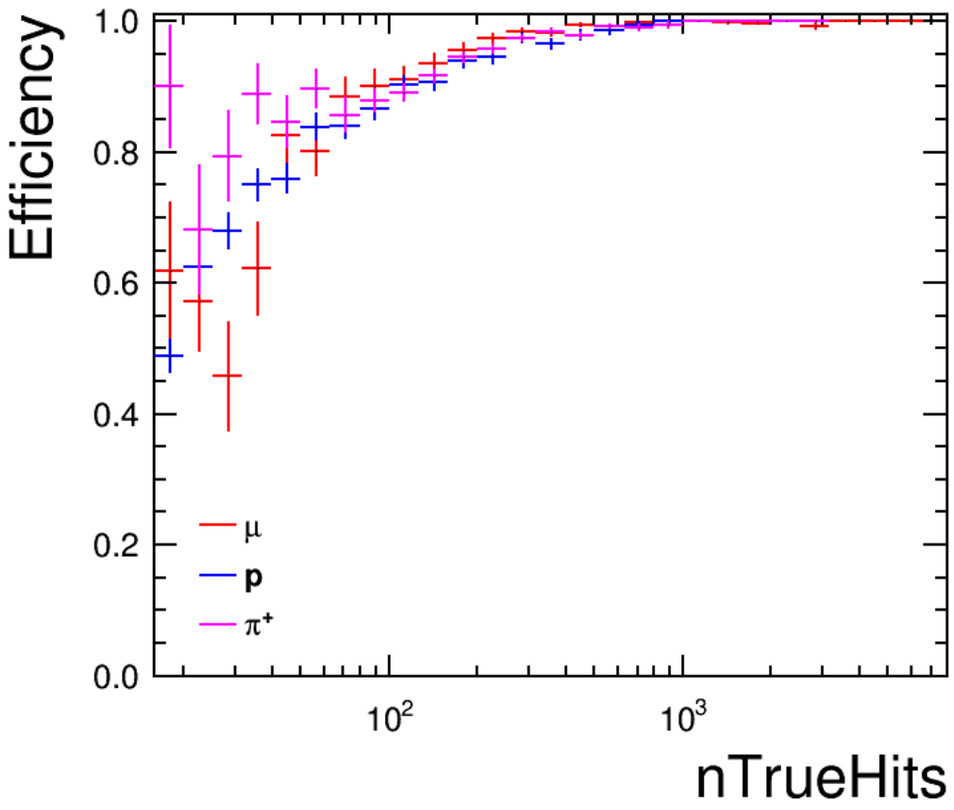
Pandora Performance

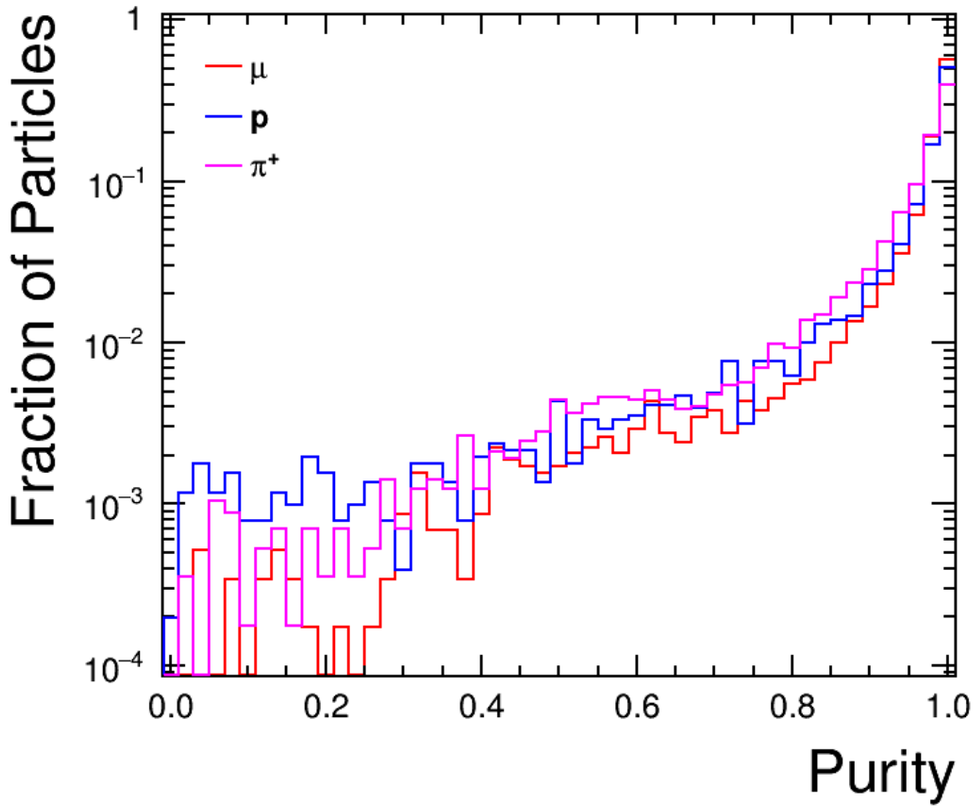
MicroBooNE simulation: BNB ν_μ CC RES μ, p, π^+

#MatchedPFOs		0	1	2	3+
Particles	μ	202	5,474	321	20
	p	910	4,772	296	40
	π^+	322	4,619	798	279

#Events: 6,018

#Perfect: 58%





Pandora Performance

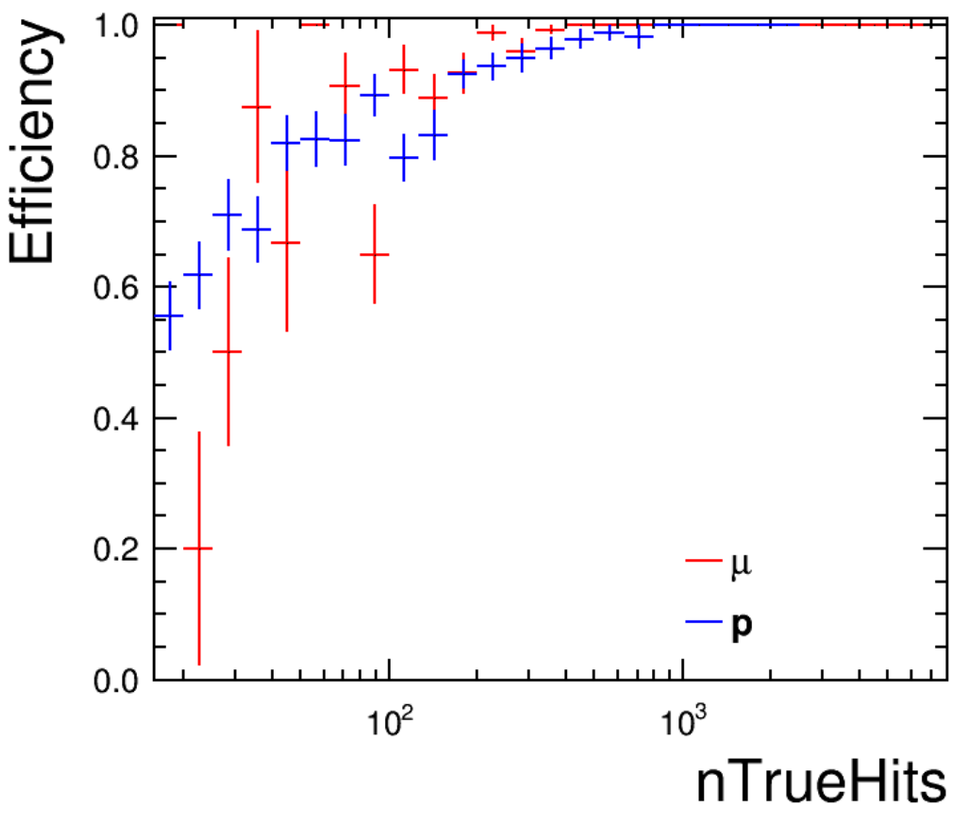
MicroBooNE simulation: BNB ν_μ CC RES μ, p, π^0

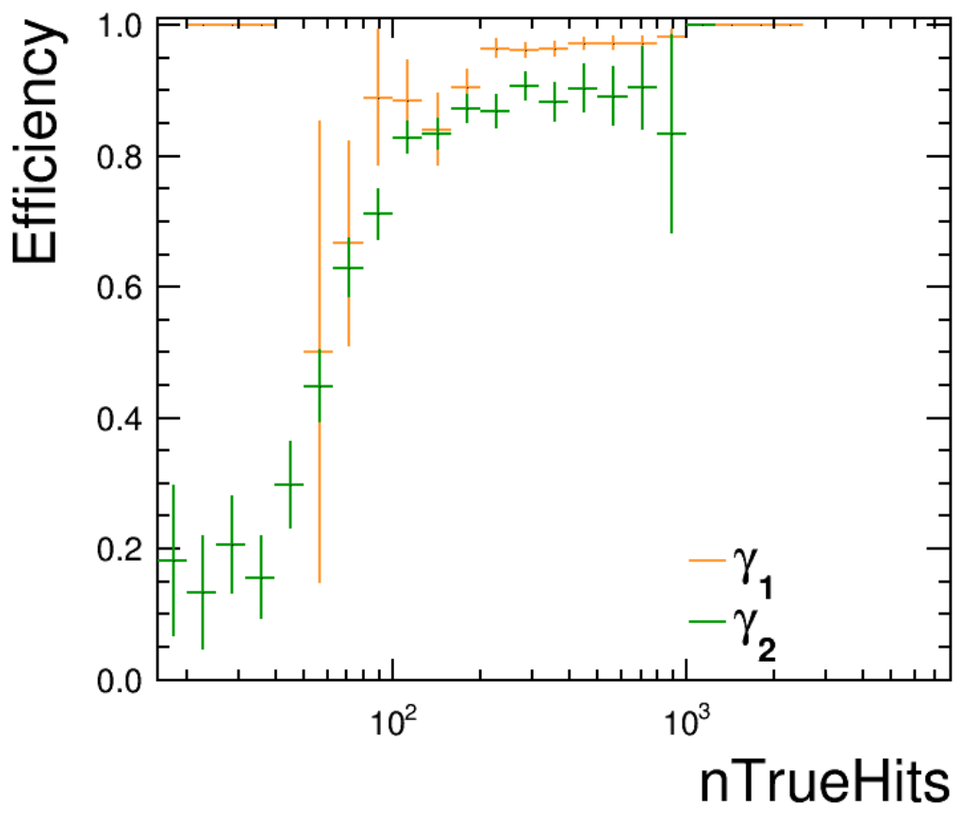
	#MatchedPFOs	0	1	2	3+
Particles	μ	54	1,544	87	10
	p	261	1,294	123	17
	γ_1	71	942	433	249
	γ_2	394	1,004	211	86

#hits(γ_1) > #hits(γ_2)

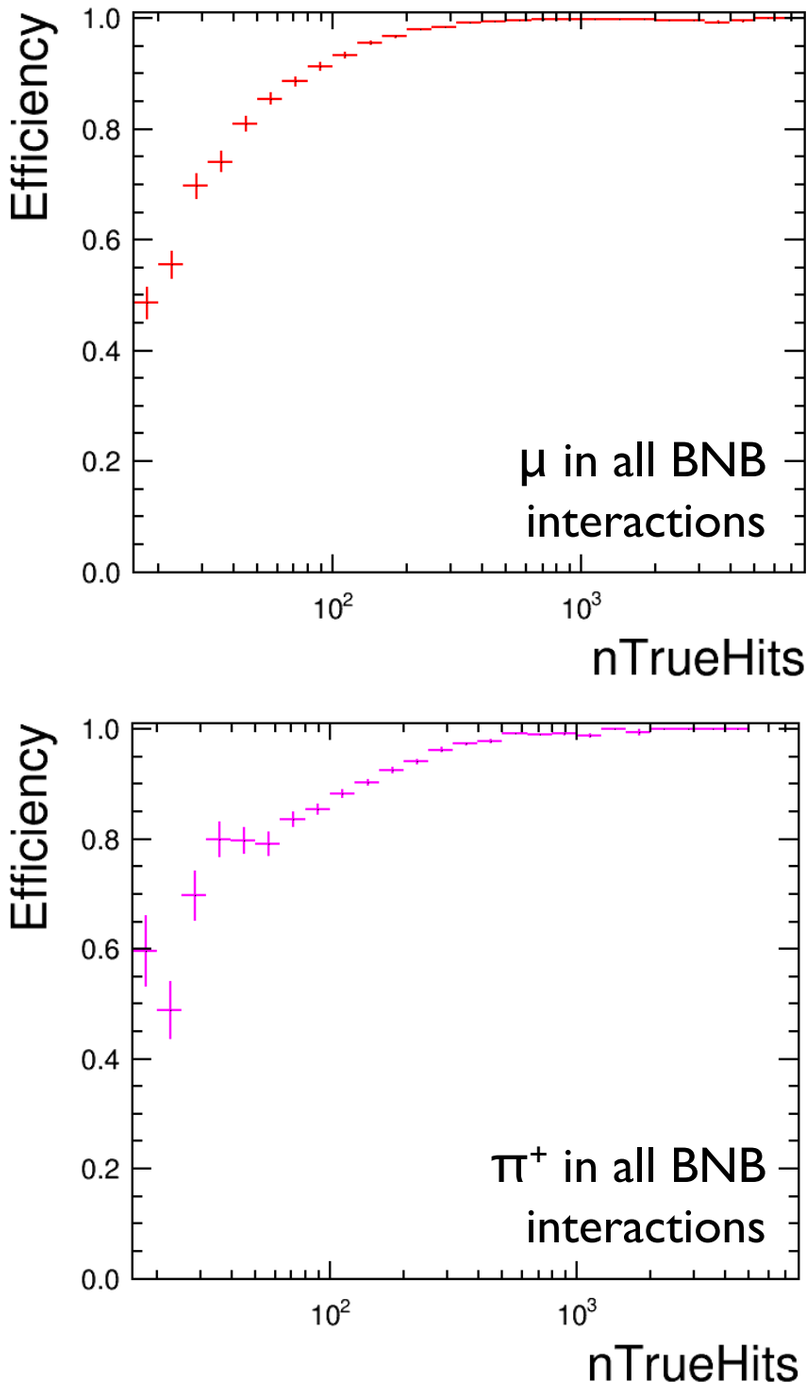
#Events: 1,695

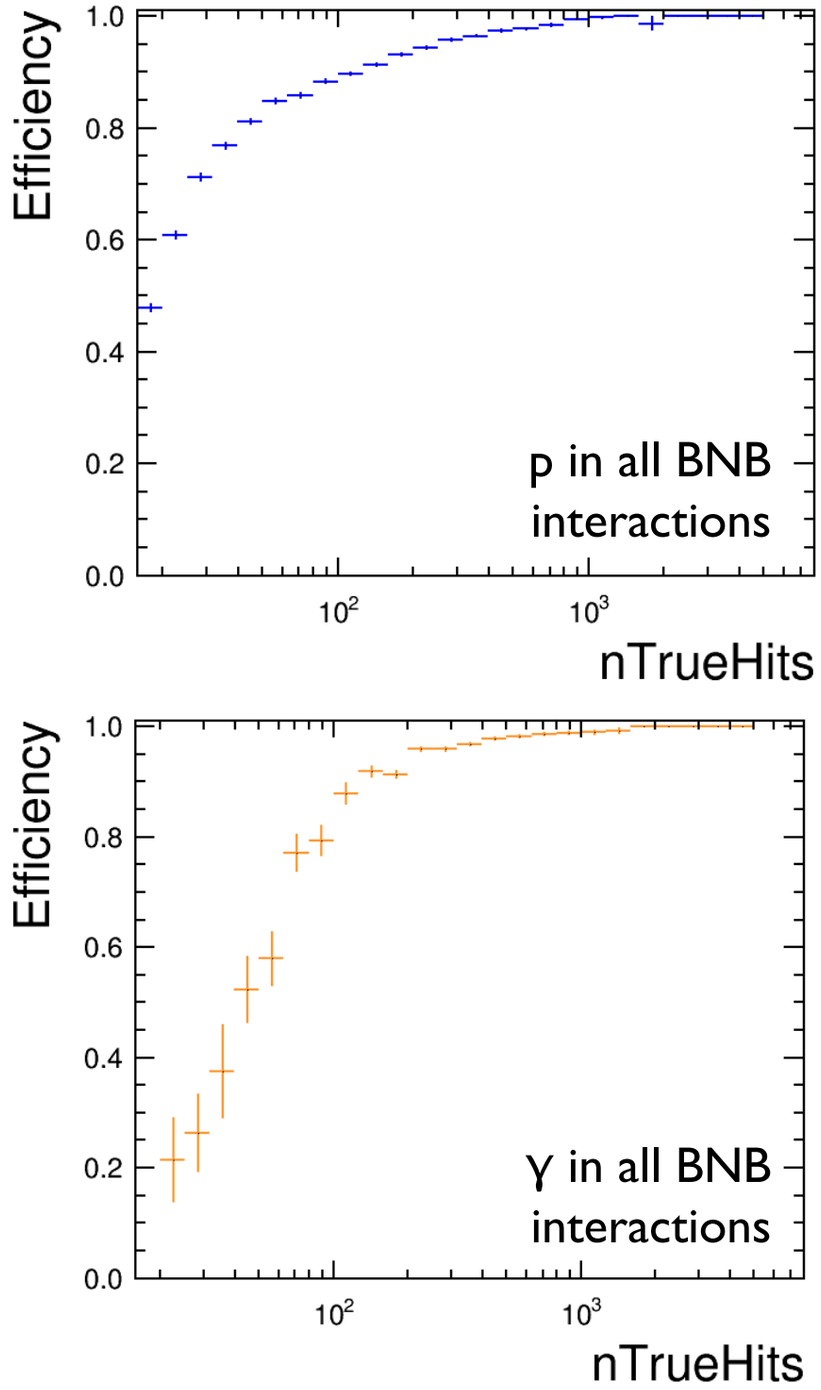
#Perfect: 24%





Pandora Performance

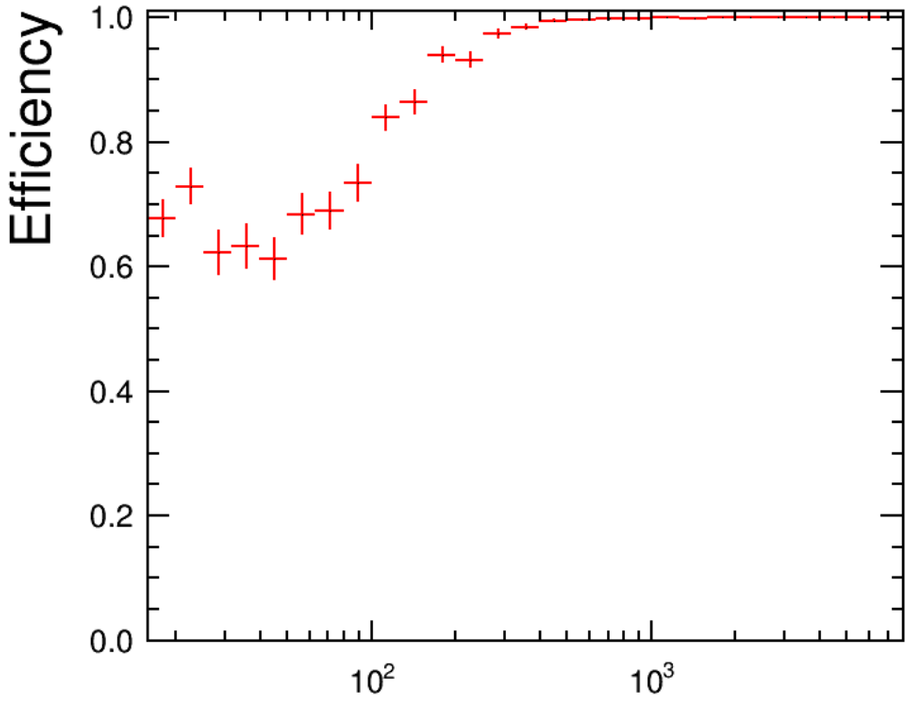


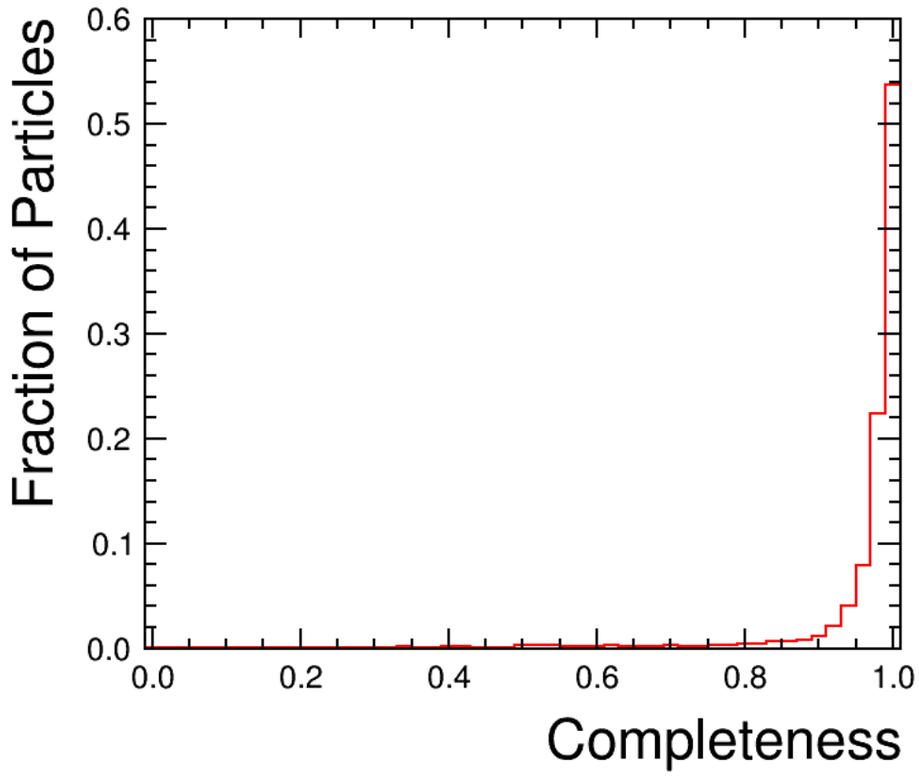


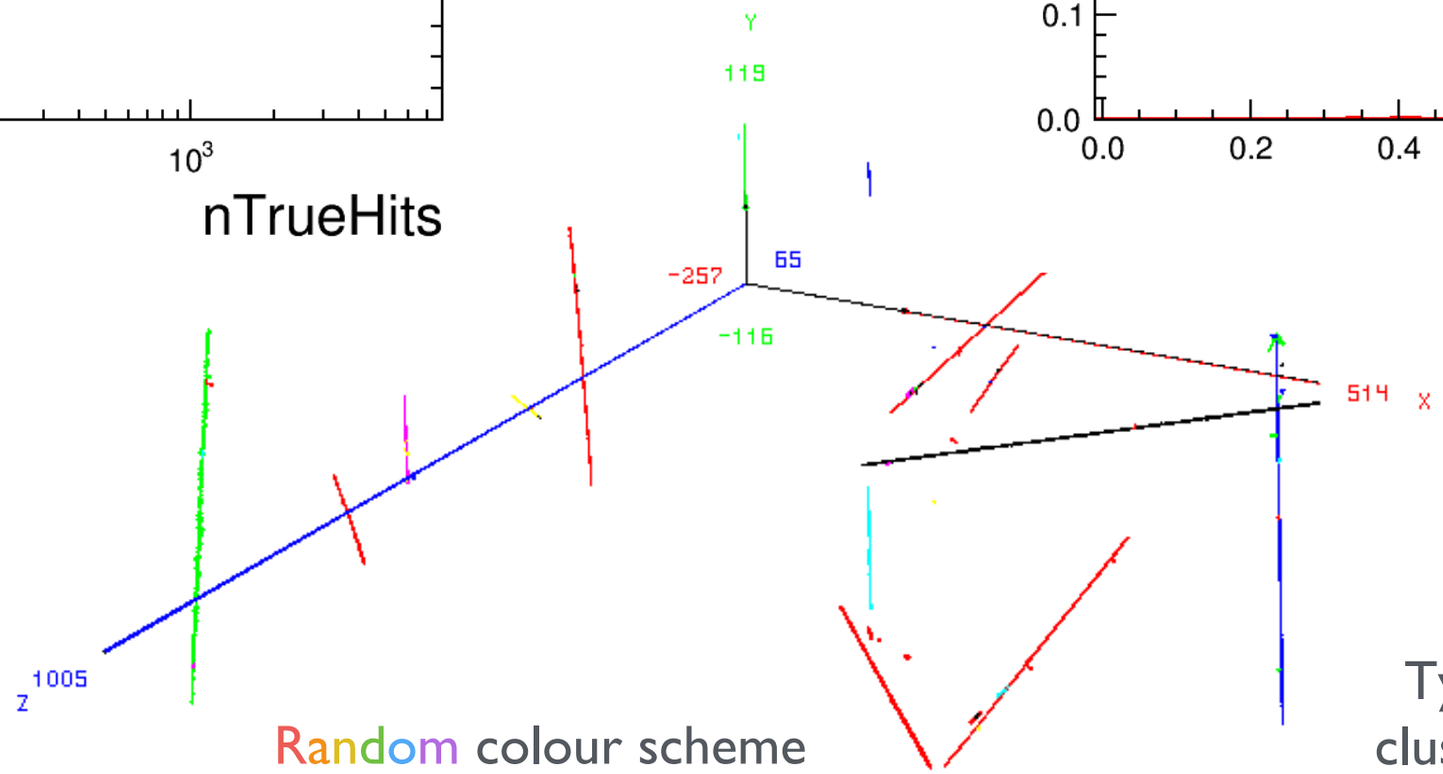
"Lost" long particles e.g. muons? Typically occur when multiple long, true particles are merged into a single reco particle. This is then matched to only one of the true particles (based on #hits shared).

Pandora Performance

MicroBooNE simulation: Cosmic Ray Muons







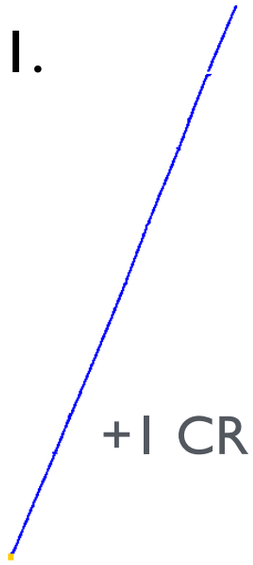
Random colour scheme

Typical 3D cluster display

Pandora Performance

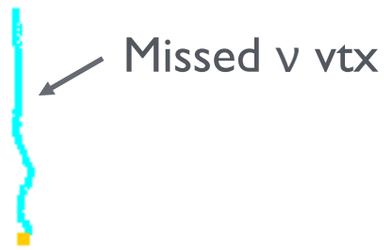
Example BNB nu events, after CR removal and Pandora 3D event slicing (first 7 in file):

1.



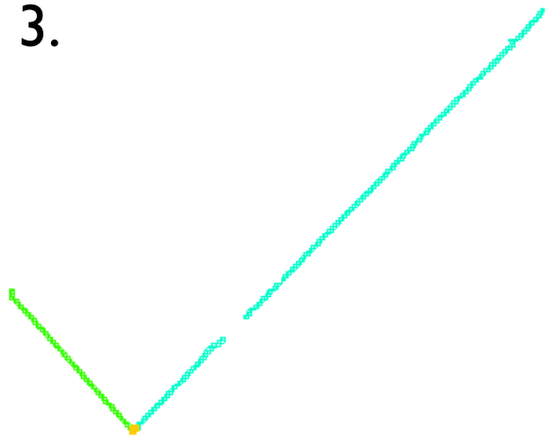
+1 CR remnant

2.



+3 CR remnants

3.



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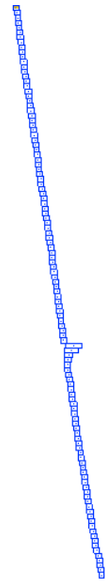

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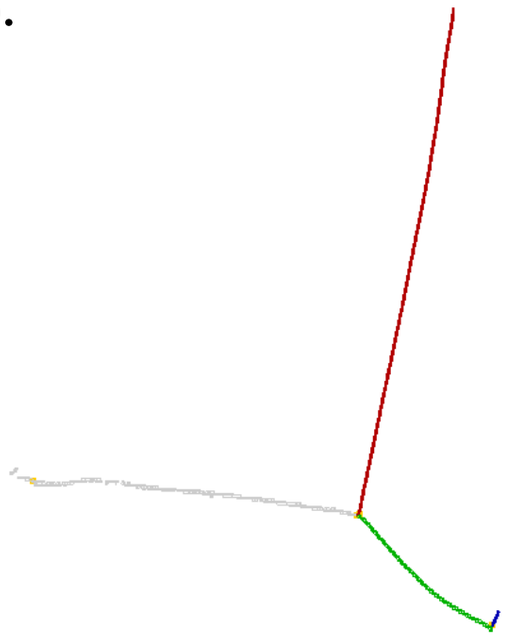

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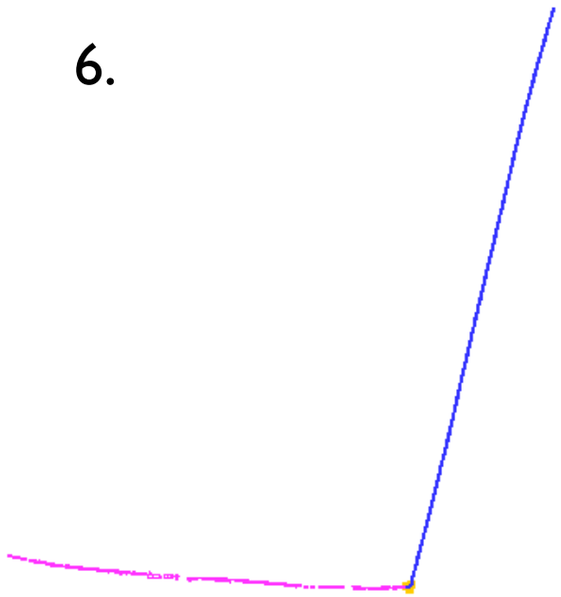
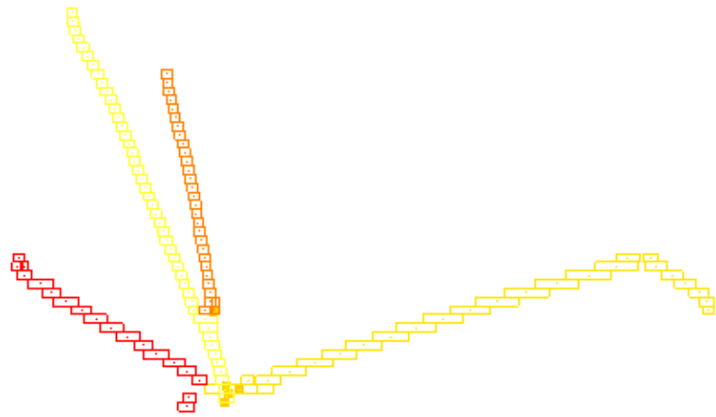


+2 CR remnants

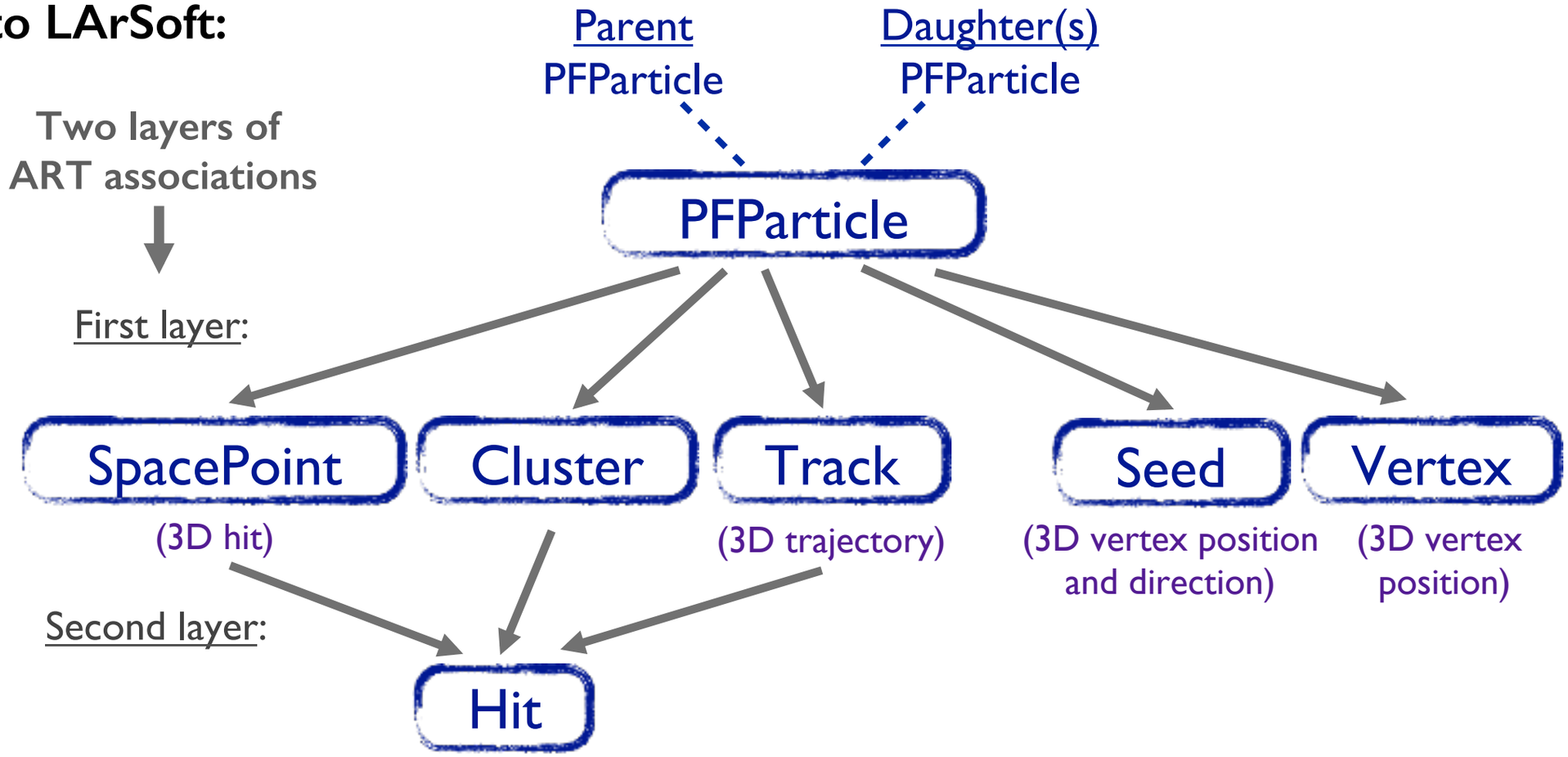
7.



+1 CR remnant

Pandora Output

Output to LArSoft:



- LArSoft output initially looks rather complex, but, once Showers have been added, should provide a comprehensive translation of results obtained in the Pandora Event Data Model.
- Extremely important that we now get people to try/test this new PFParticle output, checking that all the information from Pandora is persisted correctly.
- Help would be greatly appreciated to complete the LArSoft output by, i), producing Shower objects and, ii), discovering why the Kalman Filter vetoes many clean-looking Pandora Tracks.

Pandora Development Key Points

- Pandora provides an easy and fast development platform.
- It has no external dependencies beyond ROOT, which it uses purely for event visualisation and monitoring purposes.
- Visualisation APIs provide simple access to user-customised event displays in algorithms, enabling a rapid visual approach to debugging/development.
- Pandora can provide a complete standalone environment for rapid development. Need only run the LArSoft app once to persist input Hits in Pandora binary or XML formats.
- Pandora is ideally suited for distributed development i.e. people can work on standalone algorithms, which can then be slotted into the reconstruction via simple XML config.

https://www.github.com/PandoraPFA

EPJC.75.439

Pandora Summary

- Pandora brings together a large number of exciting new pattern recognition ideas for LAr TPC reconstruction in a novel multi-algorithm approach.
- The multi-algorithm approach is a realised using the advanced functionality provided by the well-documented Pandora SDK
- Successfully used elsewhere in community, e.g. CMS HG-ECAL studies
- LAr TPC algorithms continue to develop and improve
- Performance is encouraging
- Current development path is to identify “failure” modes and refine algorithms or address problem with new algorithms
- Would like to encourage people to start examining the Pandora LArSoft outputs, alongside the “other/default” reconstruction: feedback will drive future development
- Very strongly welcome new developers

Pandora A Few More Details

Concerning Performance Metrics

Use performance metrics to drive development:

1. Determine the primary true particle in each 2D hit.
   - Take the particle with the largest energy contribution.

True particles must have ≥15 true hits

Reco/true particles must share ≥5 hits to match

2. Match reconstructed particles to true particles:
   - For each reco/true combination, find the number of 'matched' 2D hits (common to both the reco and true particles). Fold all daughter reco and true particles back into parent primaries.
   - Matching algorithm, find all "strong" matches, then pick-up remaining "weak" matches:
     i. Find the strongest (most shared hits) match between any reco and true particle
     ii. Repeat step i, using reco and true particles at most once, until no further matches possible
     iii. Assign any remaining reco particles to the true particle with which they share most hits

3. Calculate performance metrics:

'Efficiency' = fraction of true particles with at least one matched reco particle.

'Completeness' = fraction of 2D hits in true particle shared with the reco particle.

'Purity' = fraction of 2D hits in reco particle shared with the true particle.

Pandora Documentation

http://arxiv.org/abs/1506.05348

or EPJC.75.439

The Pandora Software Development Kit for Pattern Recognition

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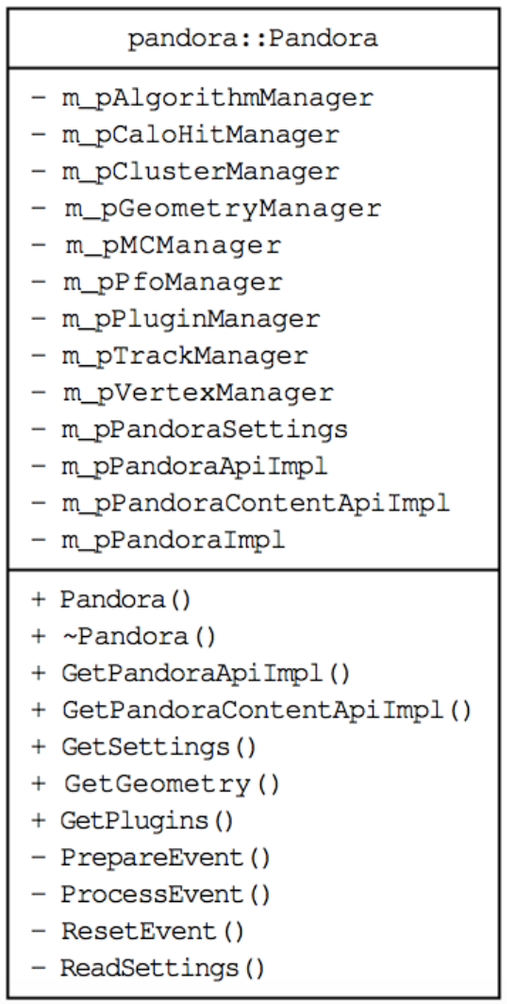
Abstract

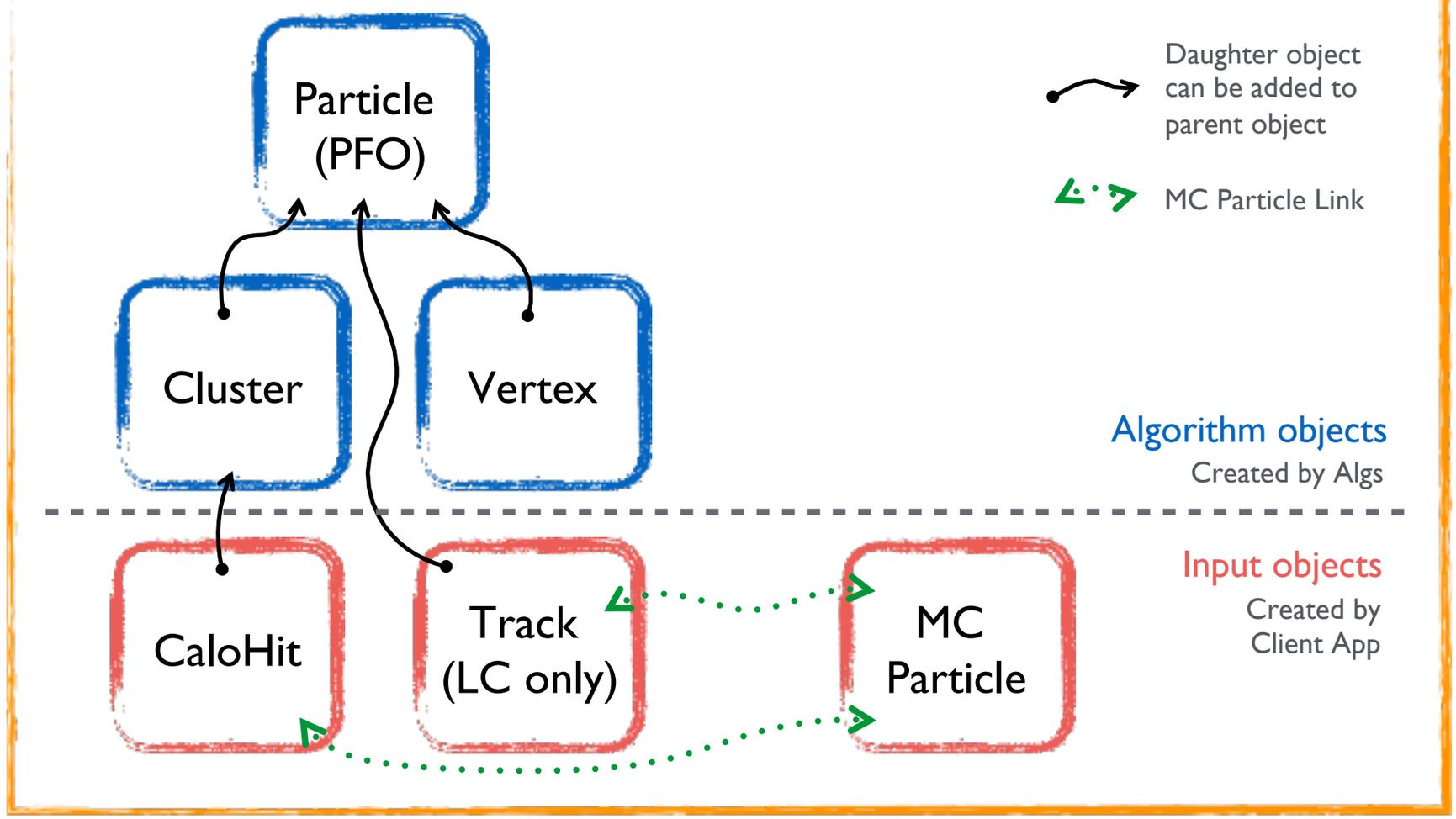
The development of automated solutions to pattern recognition problems is important in many areas of scientific research and human endeavour. This paper describes the implementation of the Pandora Software Development Kit, which aids the process of designing, implementing and running pattern recognition algorithms. The Pandora Application Programming Interfaces ensure simple specification of the building-blocks defining a pattern recognition problem. The logic required to solve the problem is implemented in algorithms. The algorithms request operations to create or modify data structures and the operations are performed by the Pandora framework. This design promotes an approach using many decoupled algorithms, each addressing specific topologies. Details of algorithms addressing two pattern recognition problems in High Energy Physics are presented: reconstruction of events at a high-energy e^+e^- linear collider and reconstruction of cosmic ray or neutrino events in a liquid argon time projection chamber.

Keywords: Software Development Kit, Pattern recognition, High Energy Physics

Pandora SDK

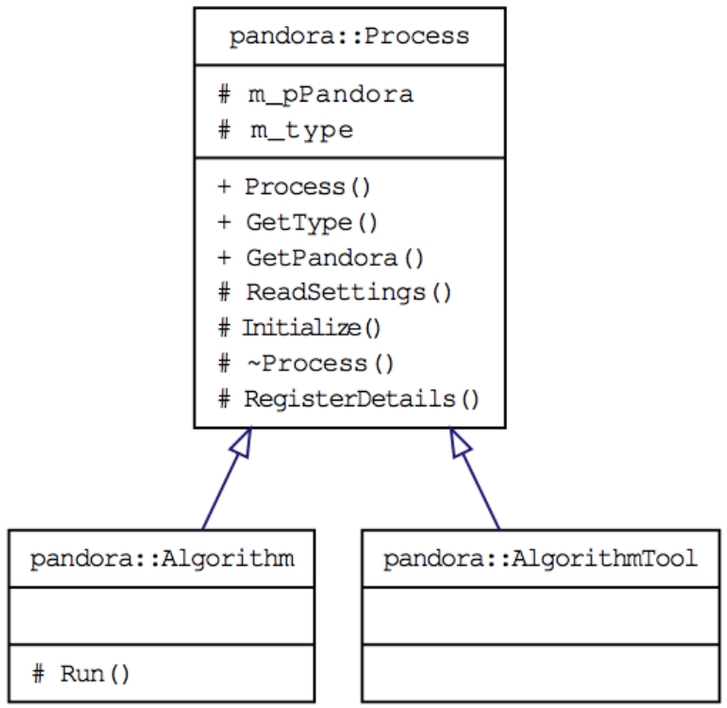
- The Pandora SDK provides a comprehensive **Event Data Model** (EDM) for managing pattern recognition problems. Instances of objects in the EDM are owned by **Pandora Managers**.
- The object instances are stored in named lists and the Managers are able to create new objects, delete objects, create and save new lists and move objects between lists.
- The Managers provide a complete set of low-level operations that allow the high-level operations requested by pattern recognition algorithms to be satisfied.





Pandora Algorithms

- Pandora algorithms contain the step-by-step instructions for finding patterns in the provided data.
- They use the APIs to access objects and to request the Managers to make new objects or modify existing objects.
- They inherit from the **Process** class, which provides functionality for handshaking with Pandora, XML config and function callbacks.



Algorithm 1 Cluster creation pseudocode. The logic determining when to create new Clusters and when to extend existing Clusters will vary between algorithms.

```
1:  procedure CLUSTER CREATION
2:      Create temporary Cluster list
3:      Get current CaloHit list
4:      for all CaloHits do
5:          if CaloHit available then
6:              for all newly-created Clusters do
7:                  Find best host Cluster
8:              if Suitable host Cluster found then
9:                  Add CaloHit to host Cluster
10:             else
11:                 Add CaloHit to a new Cluster
12:     Save new Clusters in a named list
```

Algorithm 2 Cluster merging pseudocode. The logic governing the identification of suitable parent Clusters and daughter Clusters will vary between algorithms.

```
1:  procedure CLUSTER MERGING
2:      Get current Cluster list
3:      for all Clusters do
4:          if Cluster is suitable parent then
5:              for all Clusters do
6:                  Find best daughter Cluster
7:              if Suitable daughter Cluster found then
8:                  Merge daughter Cluster into Parent
```

Pandora Client App

- To use the Pandora SDK, a user must create a Pandora client application. This provides the input building-blocks to describe the pattern recognition problem and receives the final output.
- The client application is responsible for controlling the pattern recognition reconstruction. It creates the Pandora instance(s) and uses Pandora APIs to send requests to these instances.

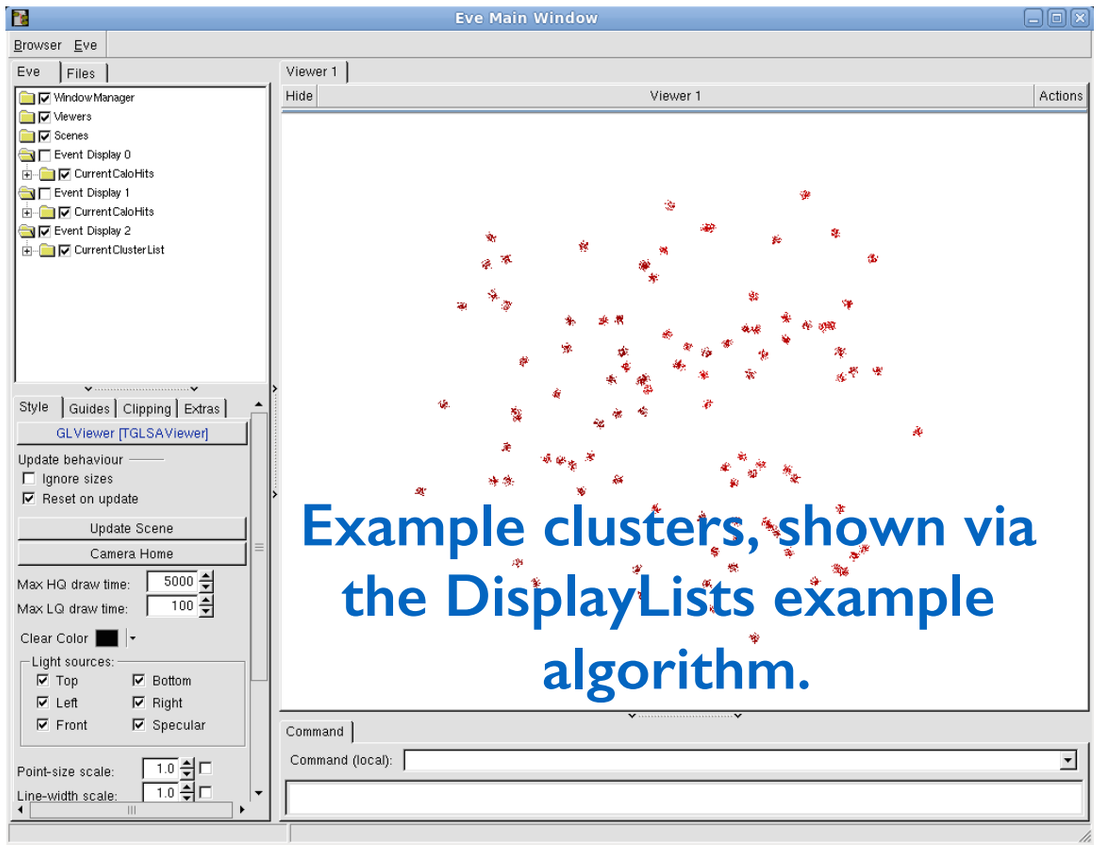
- For LArSoft, the Pandora client application is **LArPandoraInterface**
- All Algorithms and Plugins are built as part of the LArContent library.
- Pandora Hits (and, optionally, MCParticles), are extracted from named art producers.
- The output consists of collections of PFParticles, Clusters, Tracks, Showers, Vertices

Algorithm 3 Pseudocode description of a client application for LAr TPC event reconstruction in a single drift volume

```
1:  procedure MAIN
2:      Create a Pandora instance
3:      Register Algorithms and Plugins
4:      Ask Pandora to parse XML settings file
5:      for all Events do
6:          Create CaloHit instances
7:          Create MCParticle instances
8:          Specify MCParticle-CaloHit relationships
9:          Ask Pandora to process the event
10:         Get output PFOs and write to file
11:         Reset Pandora before next event
```

Pandora Learning Library

- Pandora algorithms create and/or modify clusters, vertices and PFOs. Their decisions (the algorithm logic) whether to proceed with operations can be complex and use-case specific.
- The aim of the Pandora ExampleContent library and test application is to demonstrate the key Pandora functionality in a very simple testing and learning environment.
- The ExampleContent library is structured in exactly the same manner as the LCContent and LArContent libraries, currently in use for Linear Collider and LAr TPC reconstruction.



Example clusters, shown via the DisplayLists example algorithm.

- The library consists of example Algorithms, AlgorithmTools, Plugins and Helper functions:
  - Example list access and display
  - Example Cluster, Vertex and PFO creation
  - Cluster manipulation, including merging, deletion, fragmentation and reclustering
  - Creating and saving new lists of objects
  - Using Algorithm Tools and Plugins
  - Writing a tree using PandoraMonitoring.

https://github.com/PandoraPFA/Documentation