UNIVERSITY OF CAMBRIDGE

Pandora pattern recognition tutorial

24th June 2019 - Fermilab

LArSoft Summer Workshop 2019

Andrew Smith - For the Pandora team

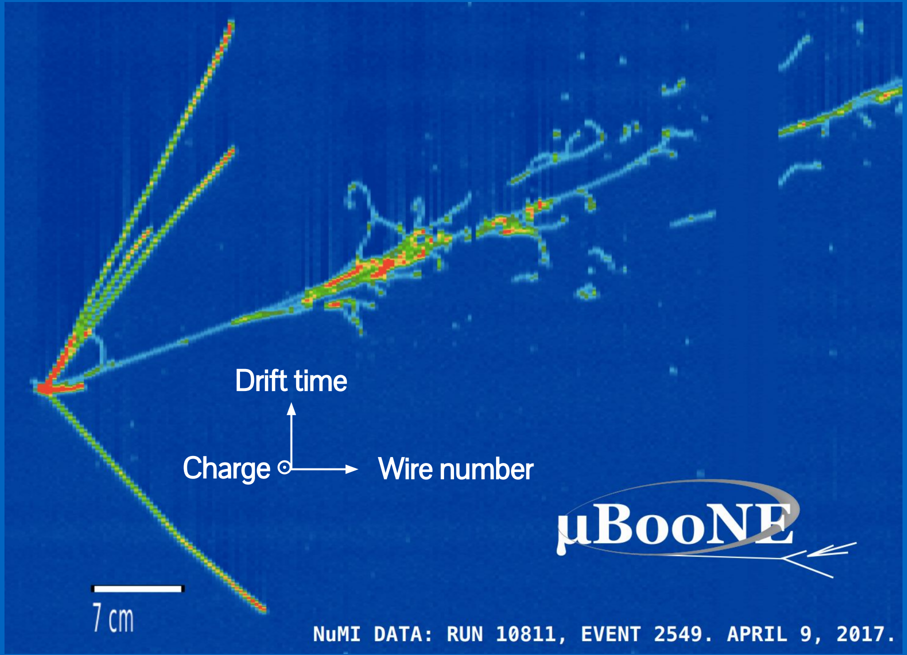
Overview

- The aim of this talk is to, answer the following questions:
    - What is pattern recognition and what is Pandora?
    - How does Pandora work?
    - How does Pandora fit into LArSoft?
    - How do I use the outputs of Pandora?
    - How can I learn more?

Pattern recognition in LArTPC experiments

From images to physics

- LArTPC detectors produce high resolution images of particle interactions that are rich with information we can exploit
- To do physics with this data, we need to **reconstruct** these interactions from the raw images
- One key component of the reconstruction process is **pattern recognition (patrec)**, in which we:
  - Identify the individual particles and their relationships to each other
  - Arrange these particles into hierarchies
  - Determine their 3D trajectories



A neutrino interaction image from one wire plane in MicroBooNE

- LArTPCs provide us with
  - mm-scale resolution calorimetric imaging
  - Low energy thresholds
  - 3D imaging

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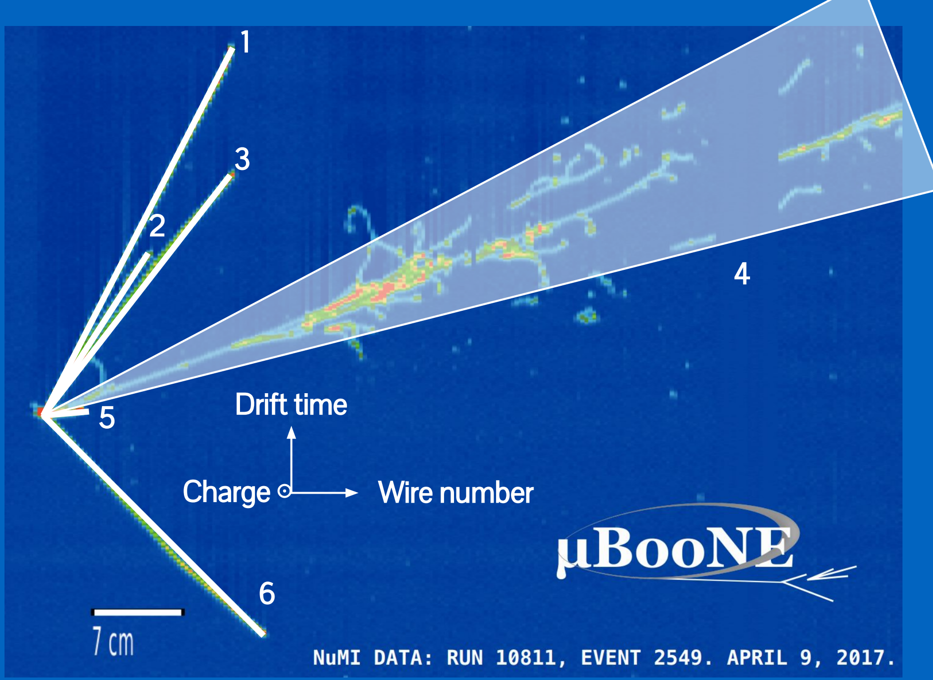
- Human brain excels at pattern recognition
- An automated, algorithmic solution is required



A neutrino interaction image from one wire plane in MicroBooNE

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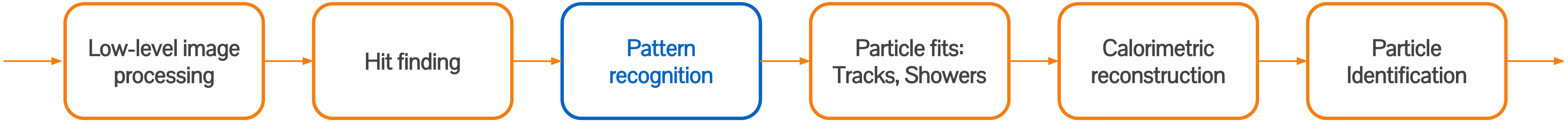
  - mm-scale resolution calorimetric imaging
  - Low energy thresholds
  - 3D imaging

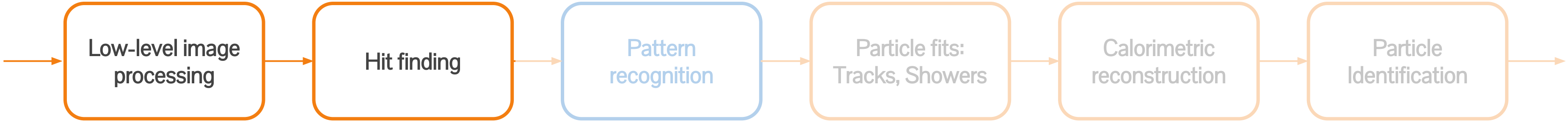
The scope of pattern recognition

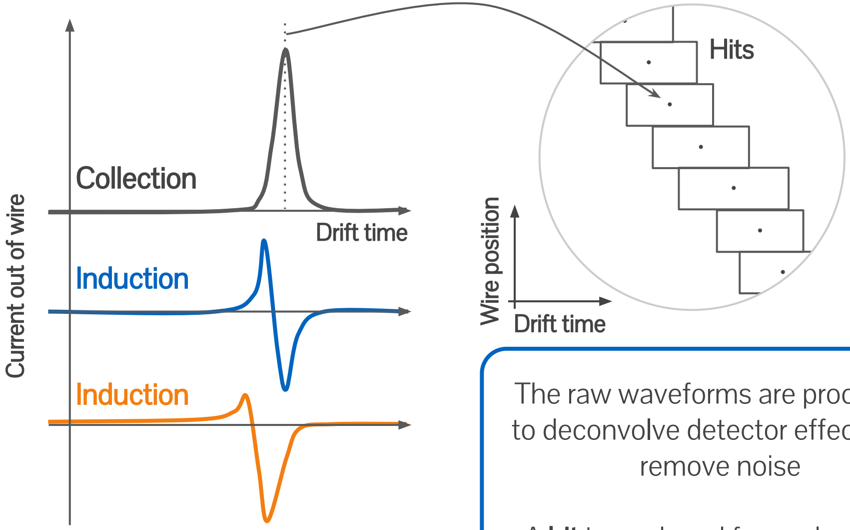
The reconstruction pipeline



The scope of pattern recognition

The reconstruction pipeline





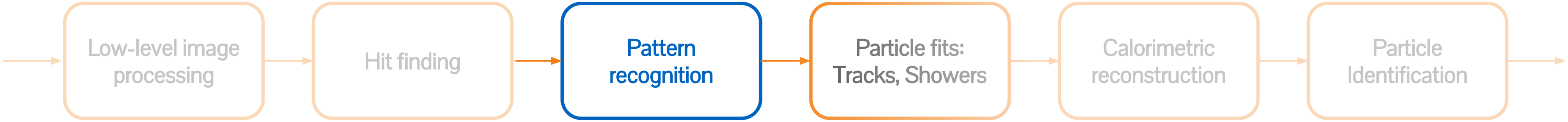
Cartoon wire responses to ionization charge drifting past a wire on induction and collection planes

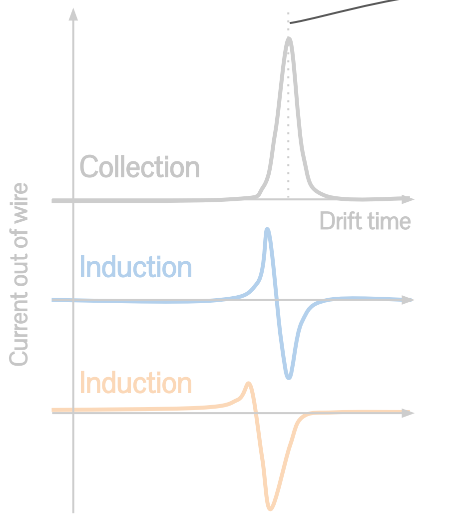
The raw waveforms are processed to deconvolve detector effects and remove noise

A **hit** is produced for peaks in the processed waveforms. These form the input to the patrec stage

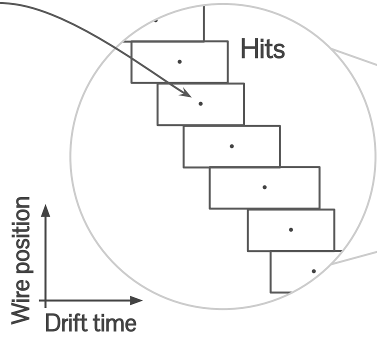
The scope of pattern recognition

The reconstruction pipeline





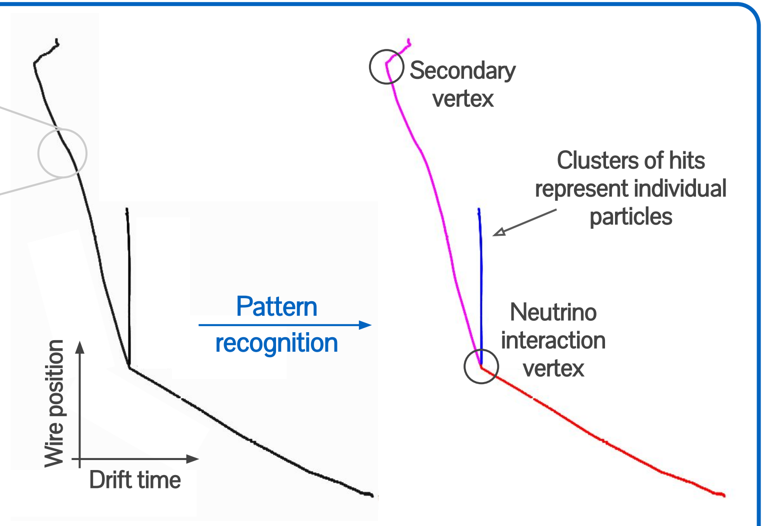
Cartoon wire responses to ionization charge drifting past a wire on induction and collection planes



The main job of the patrec is to:

Cluster the hits together to represent individual particles

Identify the hierarchical relationship between particles

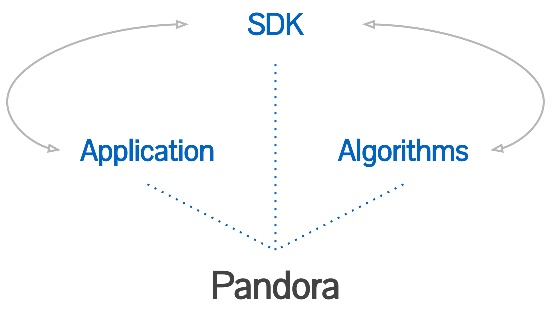


Hits from the collection plane for a simulated neutrino interaction in MicroBooNE, before and after patrec

Eur.Phys.J. C78 (2018) no.1, 82

Pandora’s approach

The Pandora project



- General purpose open-source framework for pattern recognition
- Initially used for future linear collider experiments, but now well established on many LArTPC experiments too!

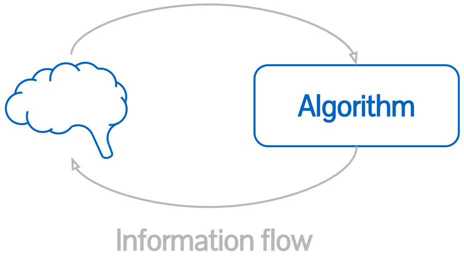
GitHub Repository
github.com/PandoraPFA

Software development kit
Eur.Phys.J. C75 (2015) no.9, 439

μBooNE Algorithms
Eur.Phys.J. C78 (2018) no.1, 82

The Pandora multi-algorithm approach

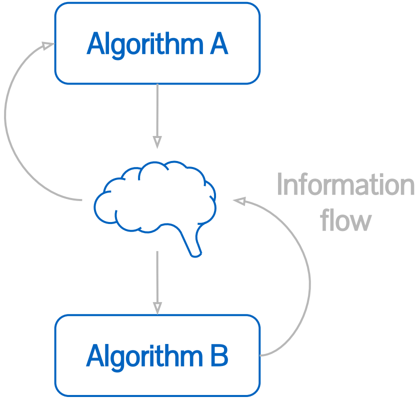
- Break the problem up into smaller well defined tasks and develop careful, targeted algorithms for each task
  - E.g. Cluster together two hits if …



Algorithms update our current understanding of the event

- Algorithm complexity varies from simple cuts up to more advanced machine learning techniques
- The application runs many algorithms (~100) to gradually build our understanding until a complete picture of the event develops

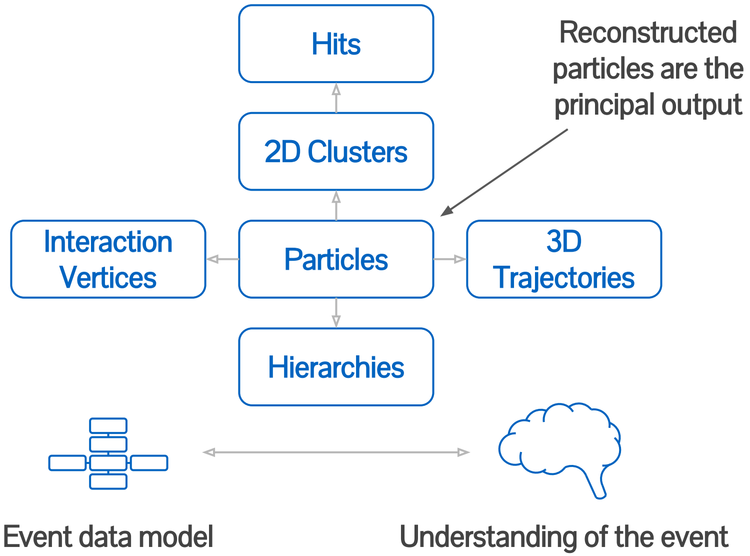
- Iteration is used to allow 2-way information flow between algorithms

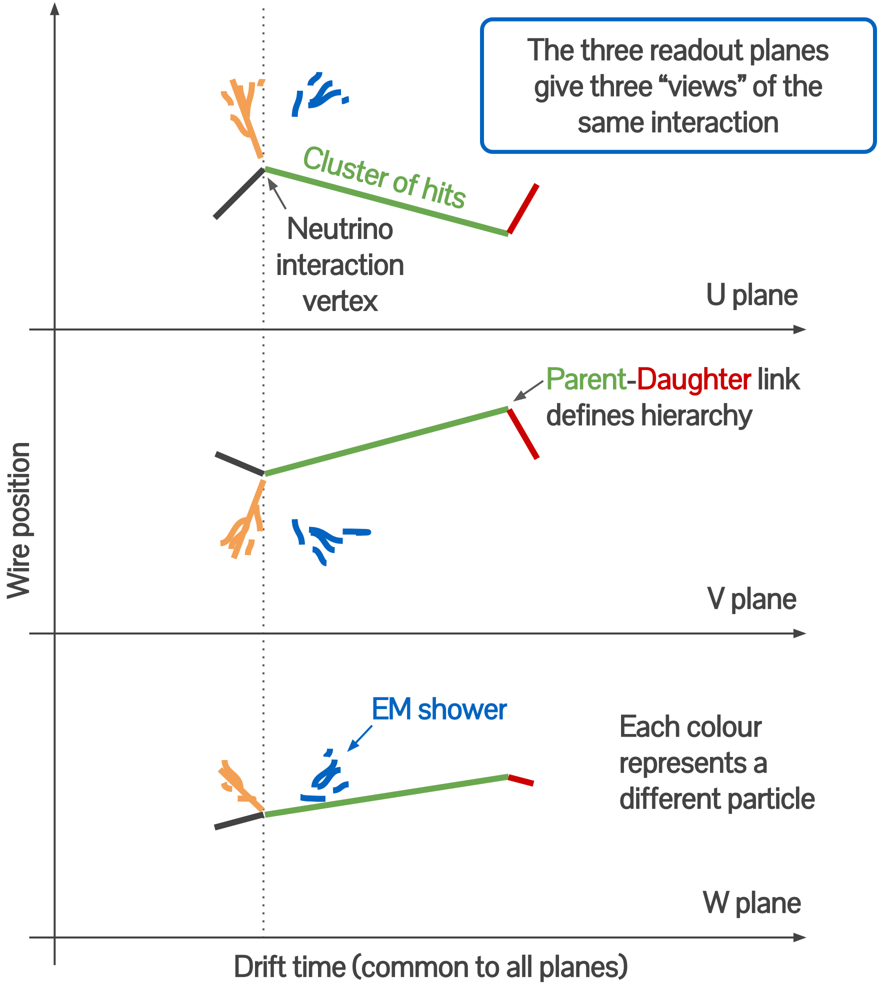


- Iteration provides powerful feedback loops - a technique that Pandora frequently utilizes

The event data model

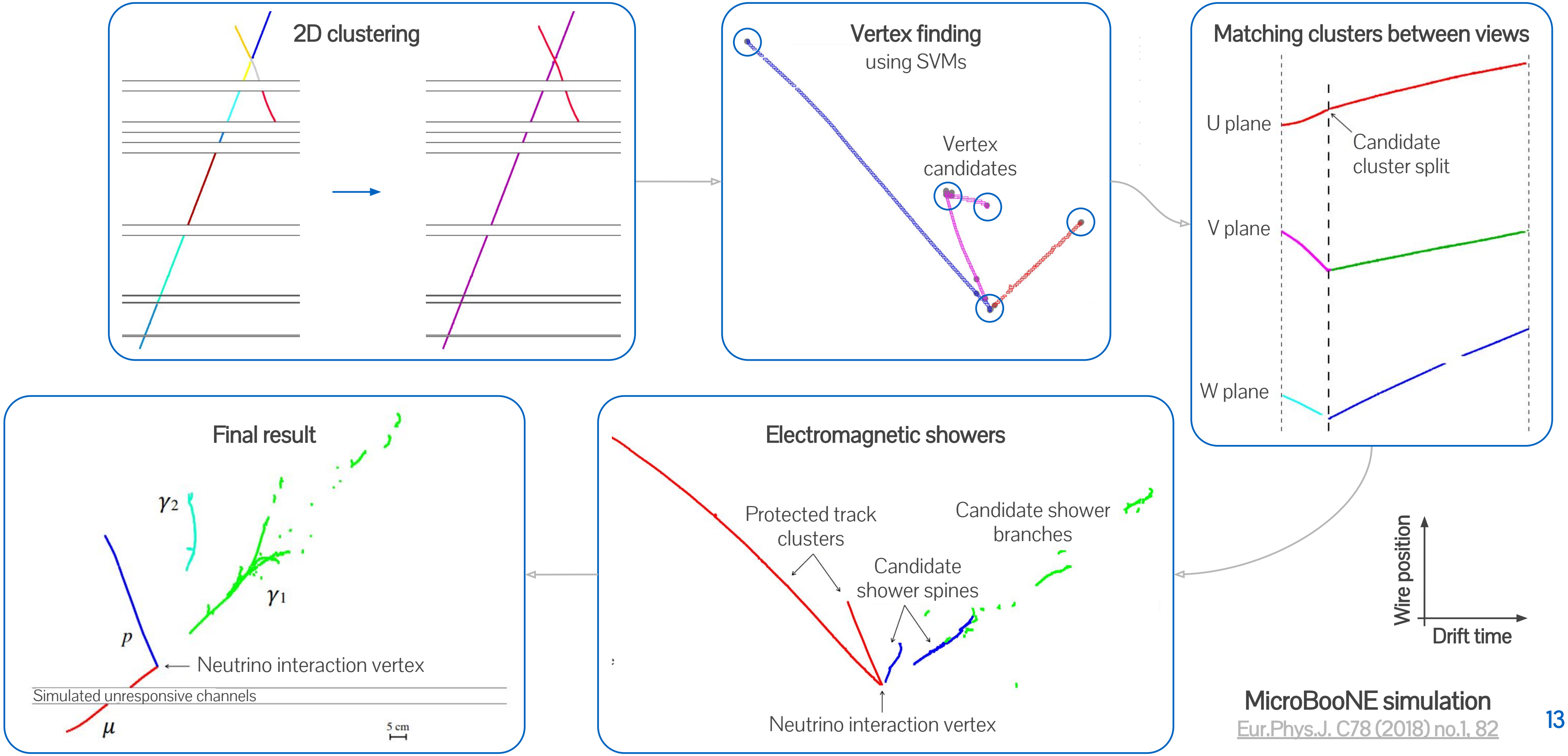
- We encapsulate our current understanding of the event via the **event data model**
- After the patrec is finished, these are the objects which are available in LArSoft for downstream analysis





A cartoon LArTPC pattern recognition problem

Pandora's algorithms for neutrino interactions



MicroBooNE simulation
Eur.Phys.J. C78 (2018) no.1, 82

Pandora's other algorithm chains

Neutrino / test-beam chain

- As described on previous slides, algorithms are designed for neutrino or test-beam interactions
- Identify the primary interaction vertex early in the patrec to inform later algorithms
- Includes special chains of algorithms for electromagnetic showers

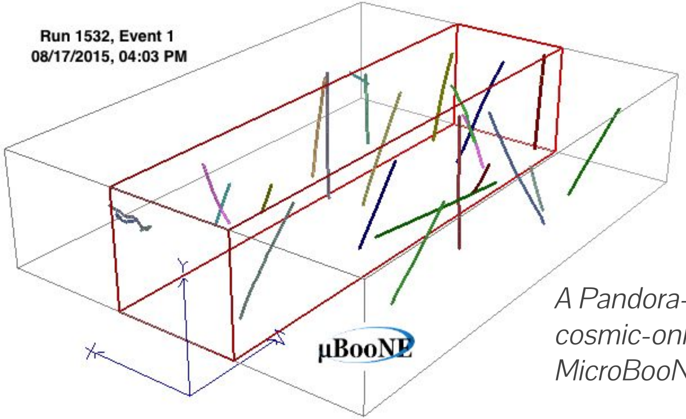
Each algorithm chain works well on the types of interactions it's designed for

For surface detectors, we need a way of dealing with events that contain **both** neutrino/test-beam interactions and cosmic-rays

Solution: "Consolidated approach"

Cosmic-ray chain

- Optimised to reconstruct cosmic-ray muons
- More strongly track-oriented than the neutrino / test-beam hypothesis
- Includes algorithms to identify and reconstruct delta-rays of energetic cosmic-rays

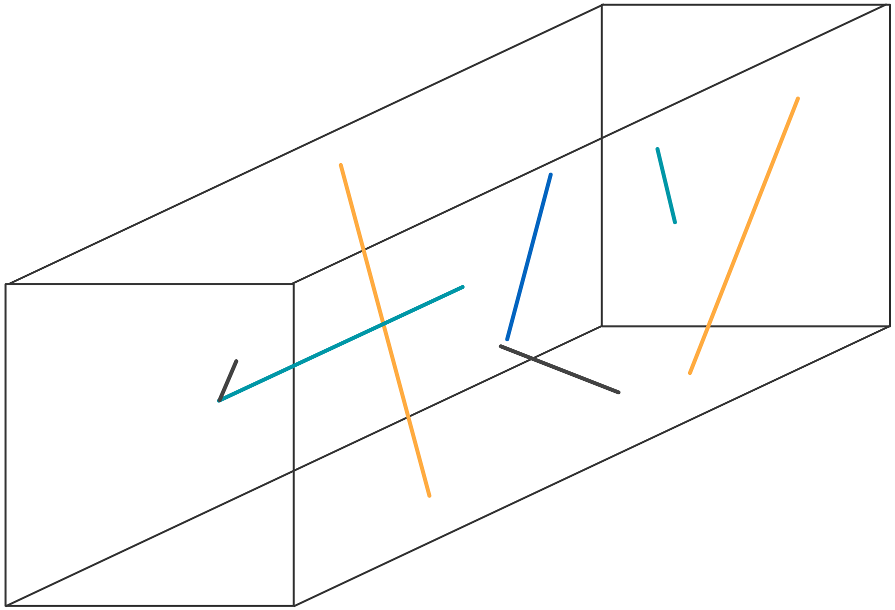


A Pandora-reconstructed cosmic-only data event in MicroBooNE

The consolidated approach - 1

Input hits → Cosmic-ray chain

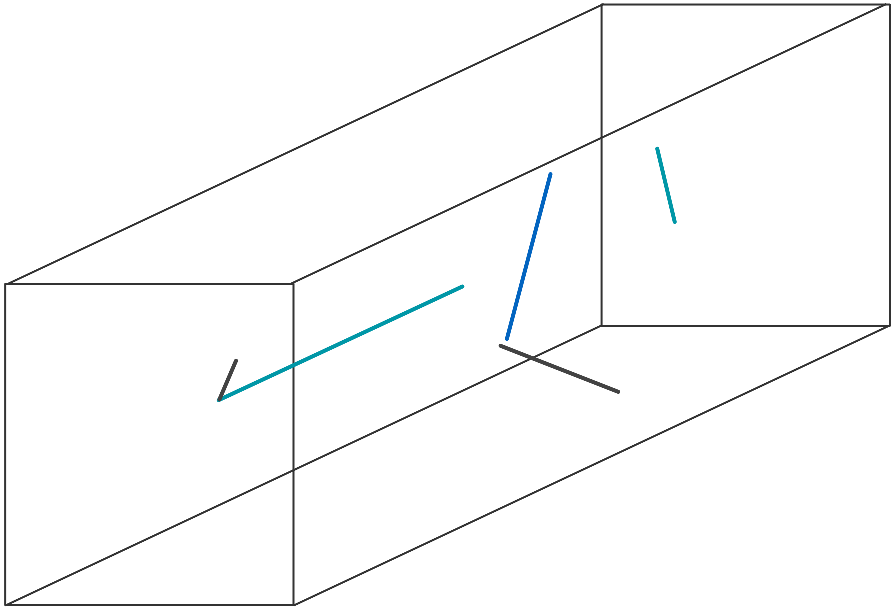
Reconstruct all input hits under the cosmic hypothesis



The consolidated approach - 2

Input hits → Cosmic-ray chain → Unambiguous cosmic-ray tagging + removal → Remaining hits

Identify unambiguous cosmic-rays and remove their hits



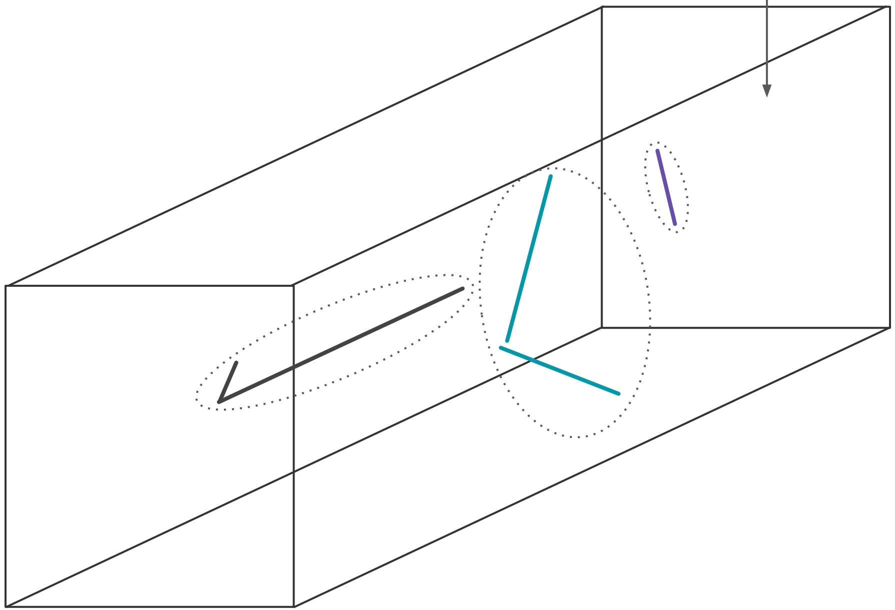
The consolidated approach - 3

µBooNE

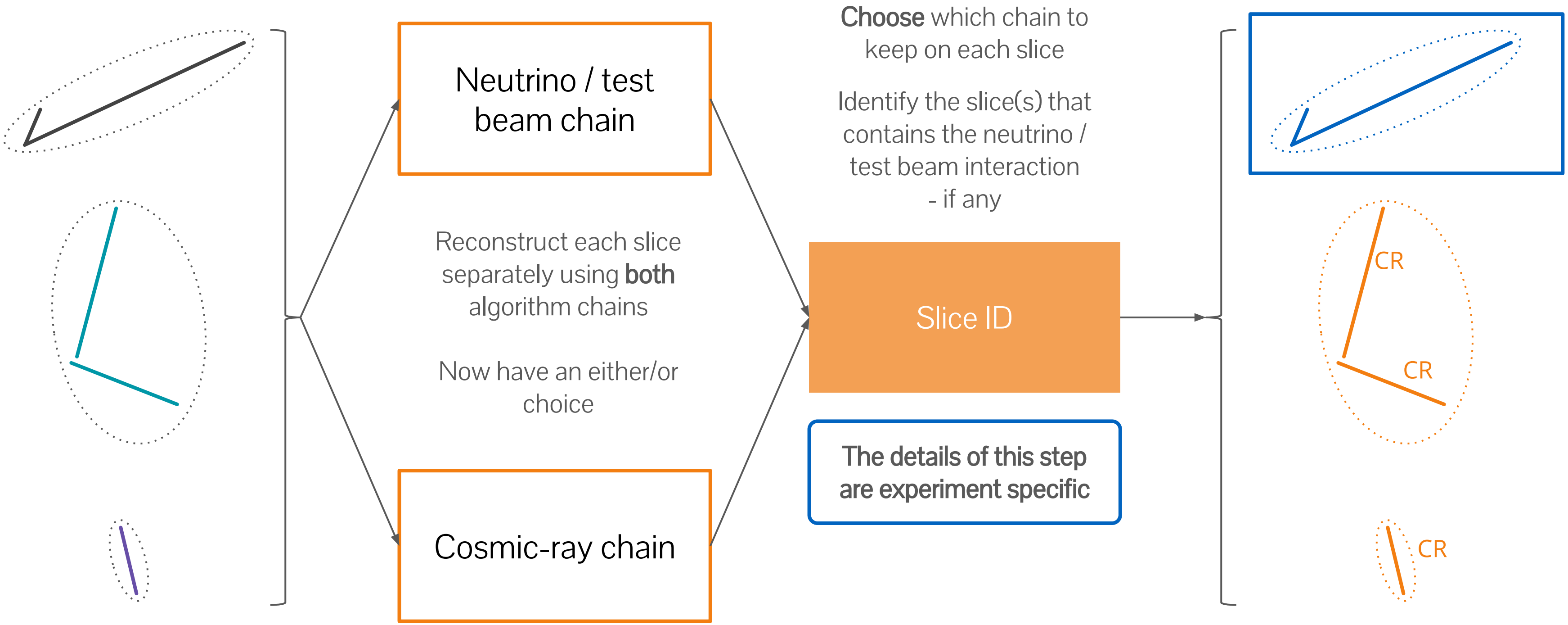
Input hits → Cosmic-ray chain → Unambiguous cosmic-ray tagging + removal → Remaining hits → Event slicing

Group the remaining hits into topologically associated “**slices**”

Group based on **proximity** and **pointing**

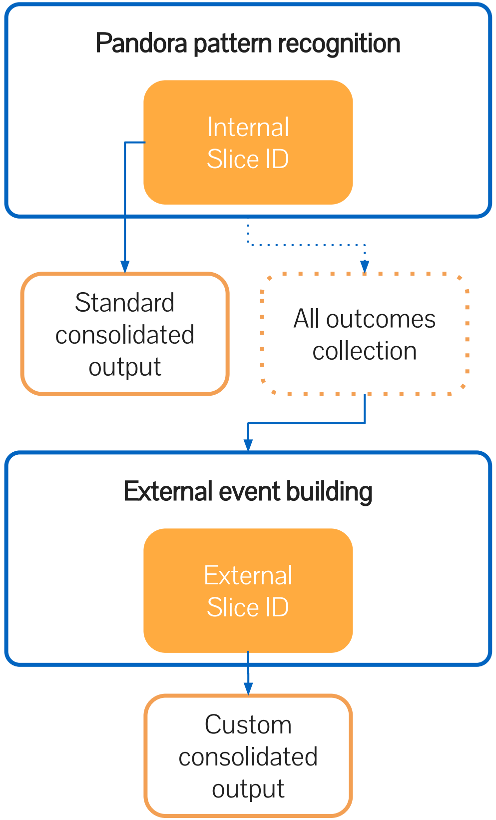


The consolidated approach - 4



Custom slice ID via external event building module

- In some cases, it's necessary to make this decision **outside of the Pandora framework** e.g. to use optical information, cosmic ray tagging system, etc.
- Pandora's "**all outcomes**" collection contains the slices as reconstructed under **BOTH** chains allowing downstream users to make slice-ID decision with full power of LArSoft
- Must be used carefully, as you don't want to read both outcomes directly into your analysis - each slice is necessarily counted twice!
- "**External event building**" LArSoft module does the bookwork to safely interface with this collection to produce a new consolidated output. No detailed knowledge of Pandora required

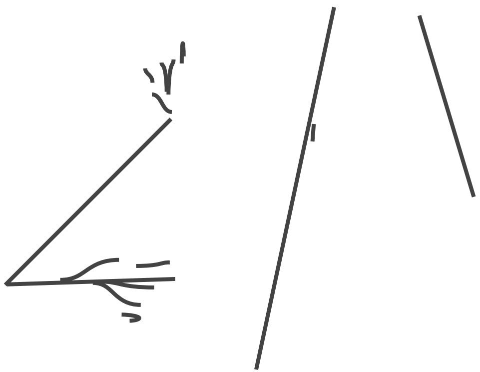


If you are interested in writing an external slice ID, let us know for more technical details

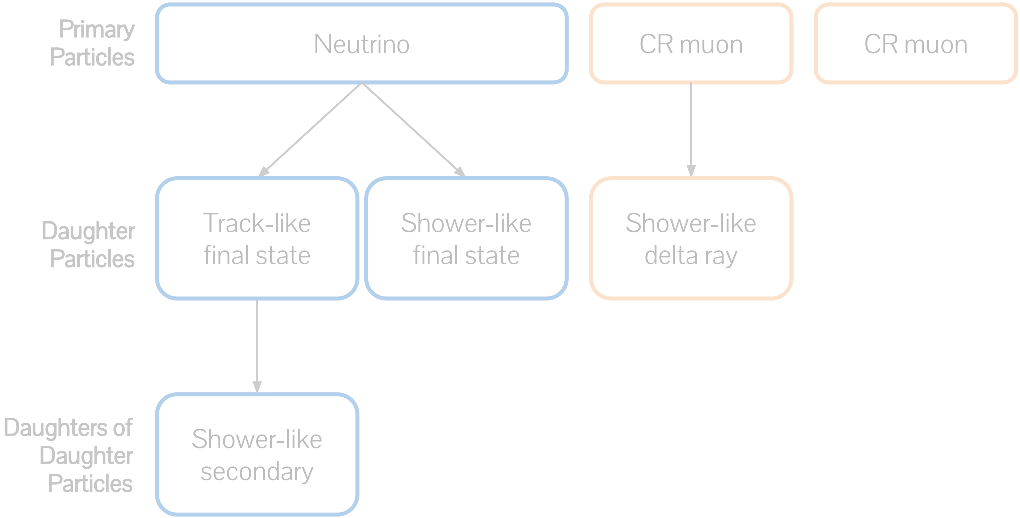
The consolidated output hierarchy

Output from the neutrino chain

Output from the cosmic chain

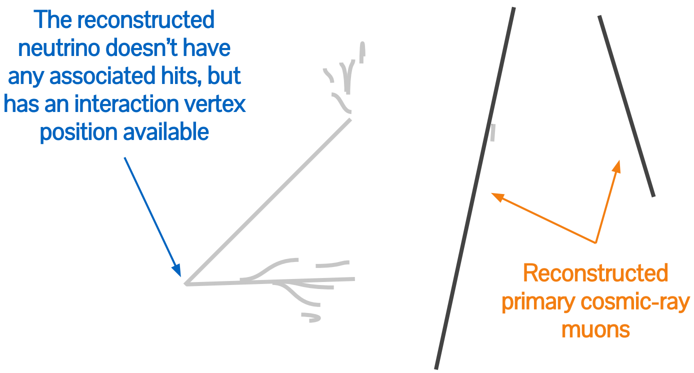


An example output (neutrino experiment)



The consolidated output hierarchy

Primary Particles



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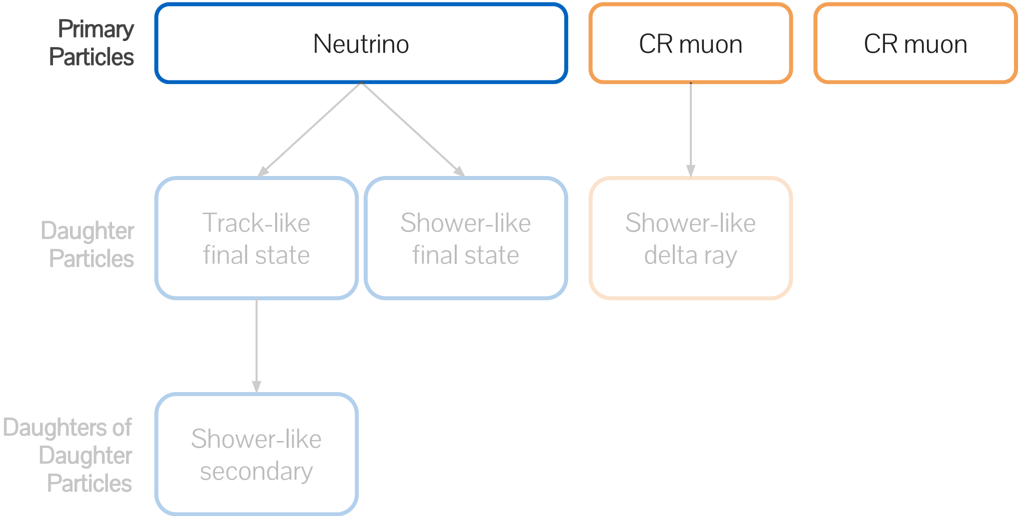
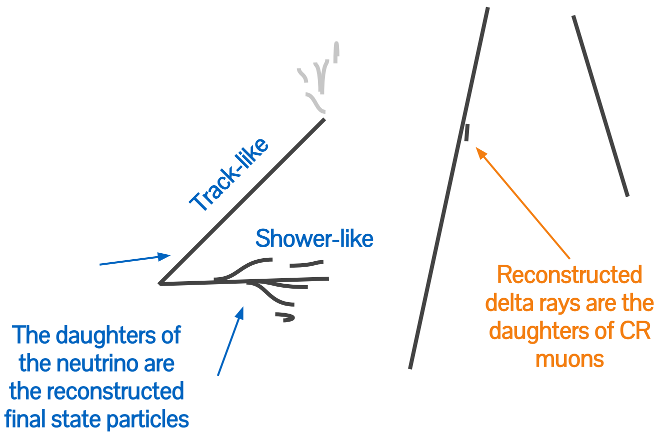
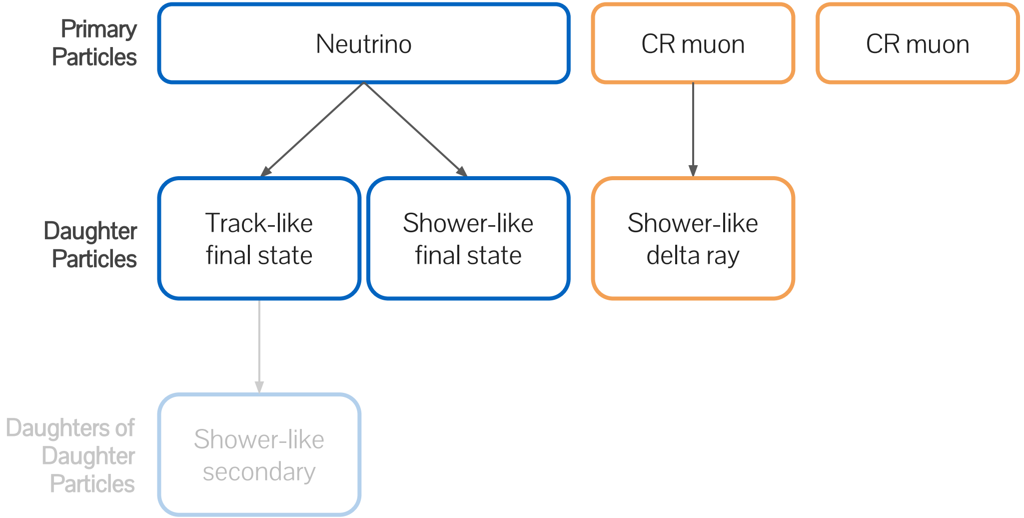


The consolidated output hierarchy

Daughter Particles



An example output (neutrino experiment)



The consolidated output hierarchy

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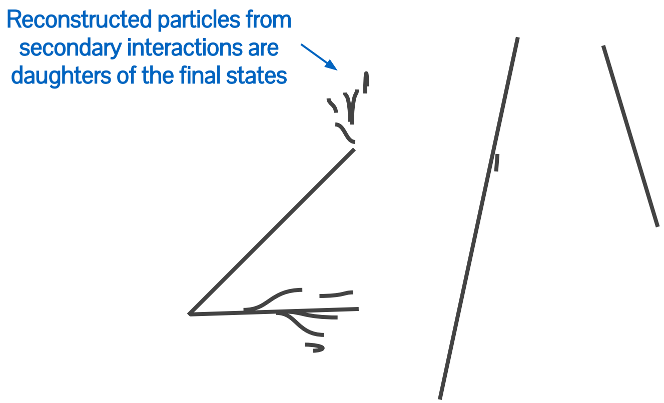
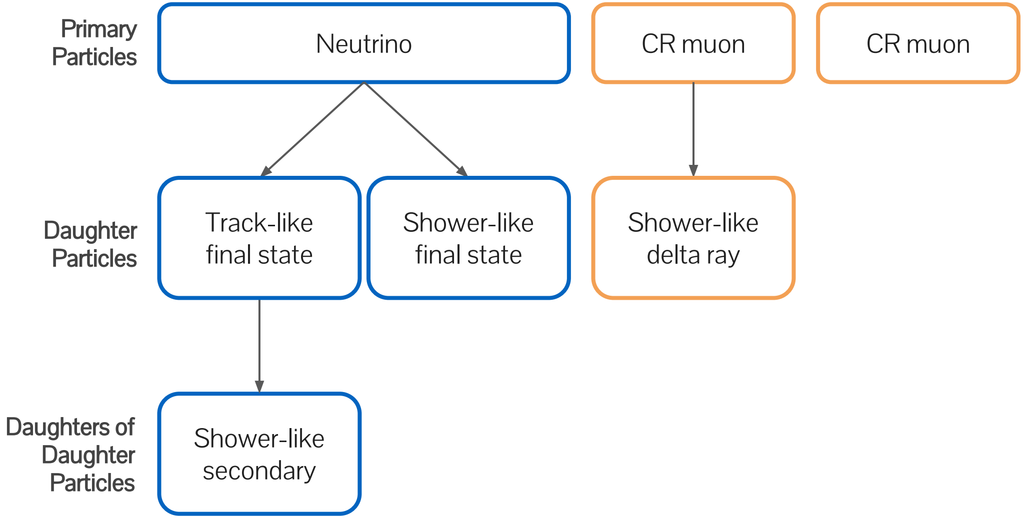
Daughters of Daughter Particles



An example output (neutrino experiment)



Pandora in LArSoft

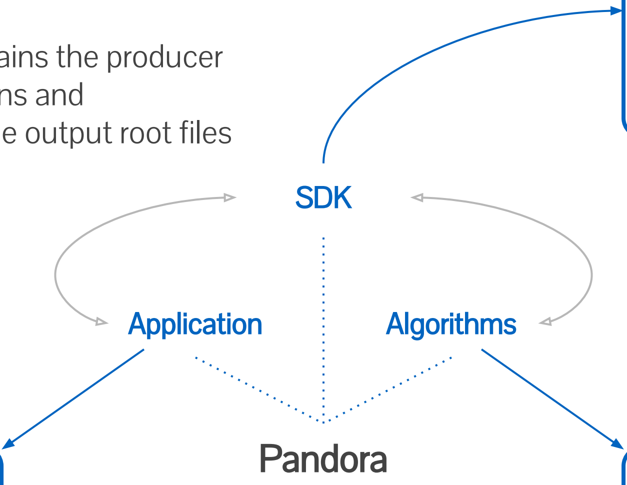
Pandora in LArSoft

- Pandora can be used as a standalone piece of software or integrated into a larger framework, such as LArSoft

- The larpandora application, contains the producer module that makes the collections and associations that are stored in the output root files

pandora (external)

External package shared amongst all experiments - contains Pandora's core software development kit - Provides application ↔ algorithm interface



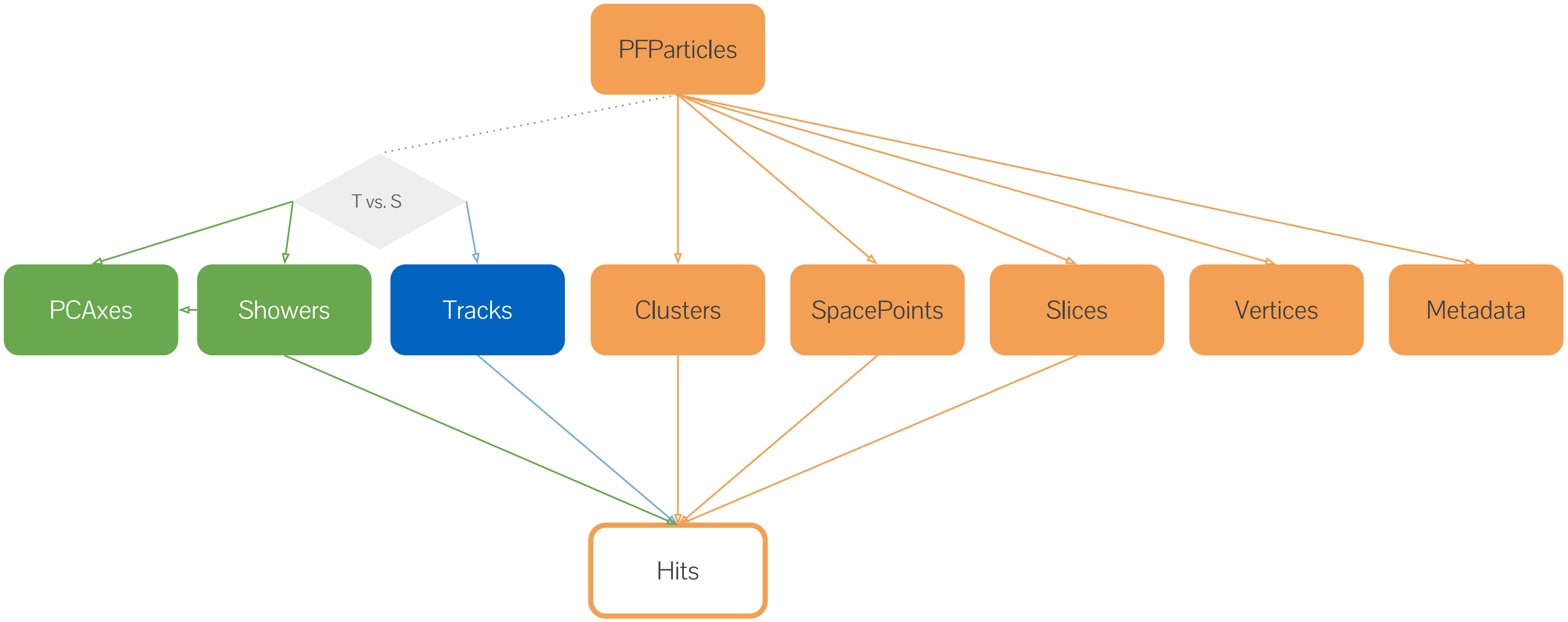
larpandora

LArSoft repository that contains the application that runs pandora - in charge of inputs and outputs - shared amongst all LArTPC experiments

larpandoracontent

LArSoft repository that contains the algorithms themselves - shared amongst all LArTPC experiments

Pandora's outputs to LArSoft



Pandora's outputs to LArSoft

µBooNE

PFParticles

The core output is the **PFParticle** - these are the reconstructed particles identified by Pandora

Accessors

int	**PdgCode** () const Return the type of particle as a PDG ID. More...
bool	**IsPrimary** () const Returns whether the particle is the root of the flow. More...
int	**NumDaughters** () const Returns the number of daughter particles flowing from this one. More...
size_t	**Self** () const Returns the index of this particle. More...
size_t	**Parent** () const
size_t	**Daughter** (size_t idx) const Returns the ID of the specified daughter. More...
const std::vector< size_t > &	**Daughters** () const Returns the collection of daughter particles. More...

Each PFParticle is assigned a PDG code which is Pandora's best guess at the particle's type, limited to track-like, shower-like, cosmic-ray or neutrino / test-beam particle - the full PID is done downstream

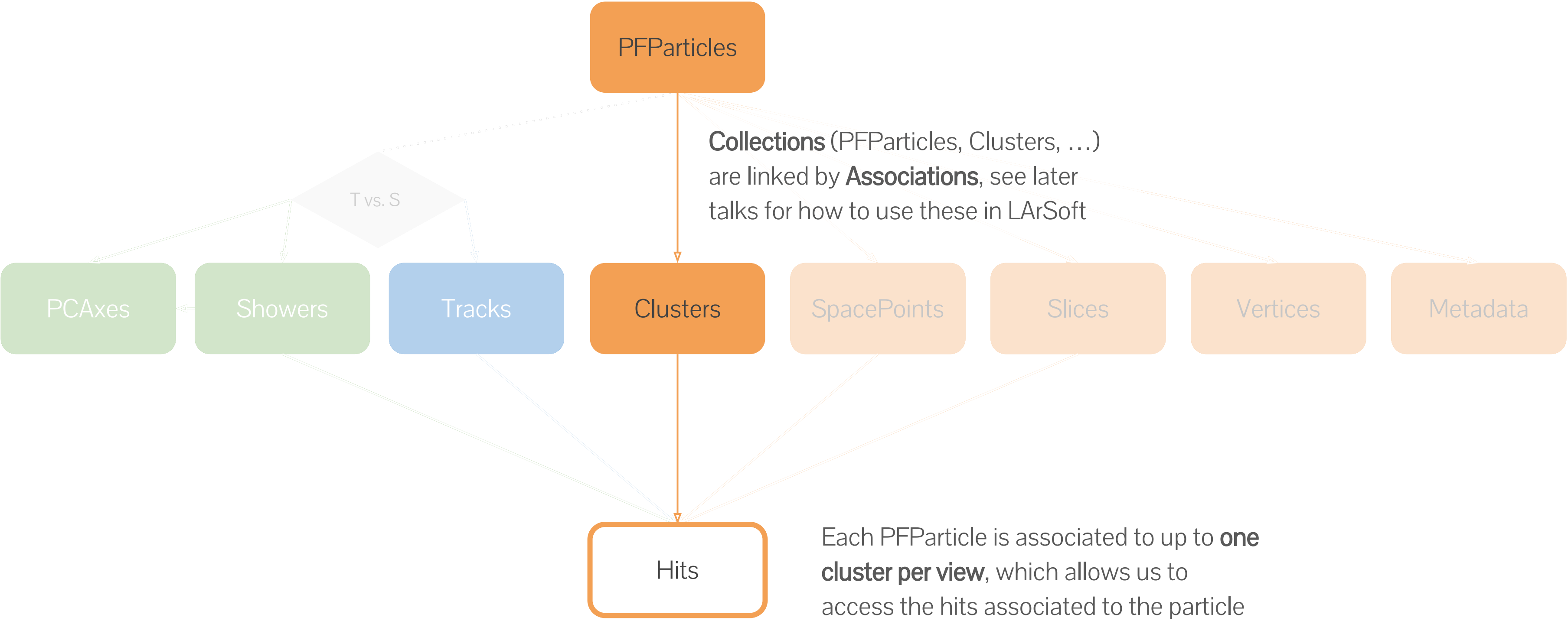
A primary particle is one without a parent PFParticle, e.g. primary CR muon, neutrino, test-beam particle

Each PFParticle has a unique ID which is accessed using the `Self()` method

The `Parent()` and `Daughters()` methods give the unique ID's of the parent and daughter PFParticles respectively - this is how we navigate the hierarchy

See `recob::PFParticle` documentation for more details

Pandora's outputs to LArSoft

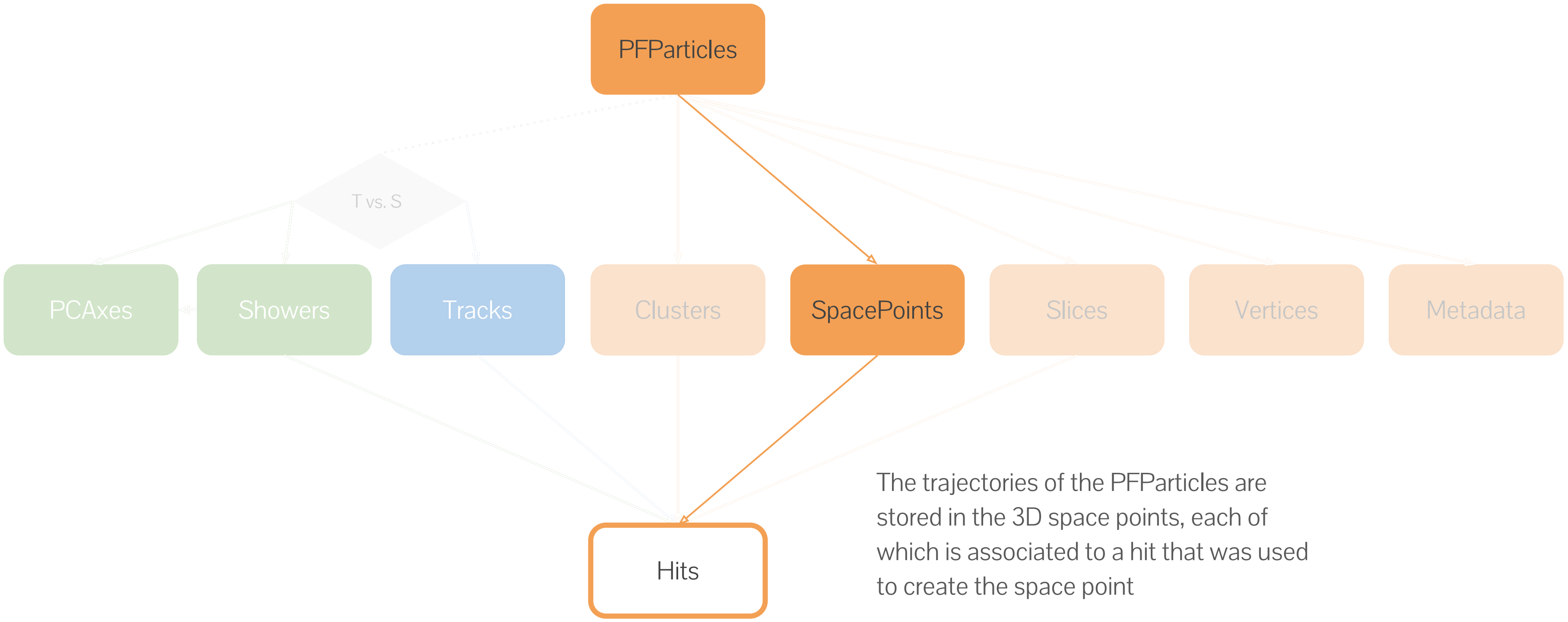


Collections (PFParticles, Clusters, …) are linked by **Associations**, see later talks for how to use these in LArSoft

Each PFParticle is associated to up to **one cluster per view**, which allows us to access the hits associated to the particle

See `recob::Cluster` documentation for more details

Pandora's outputs to LArSoft

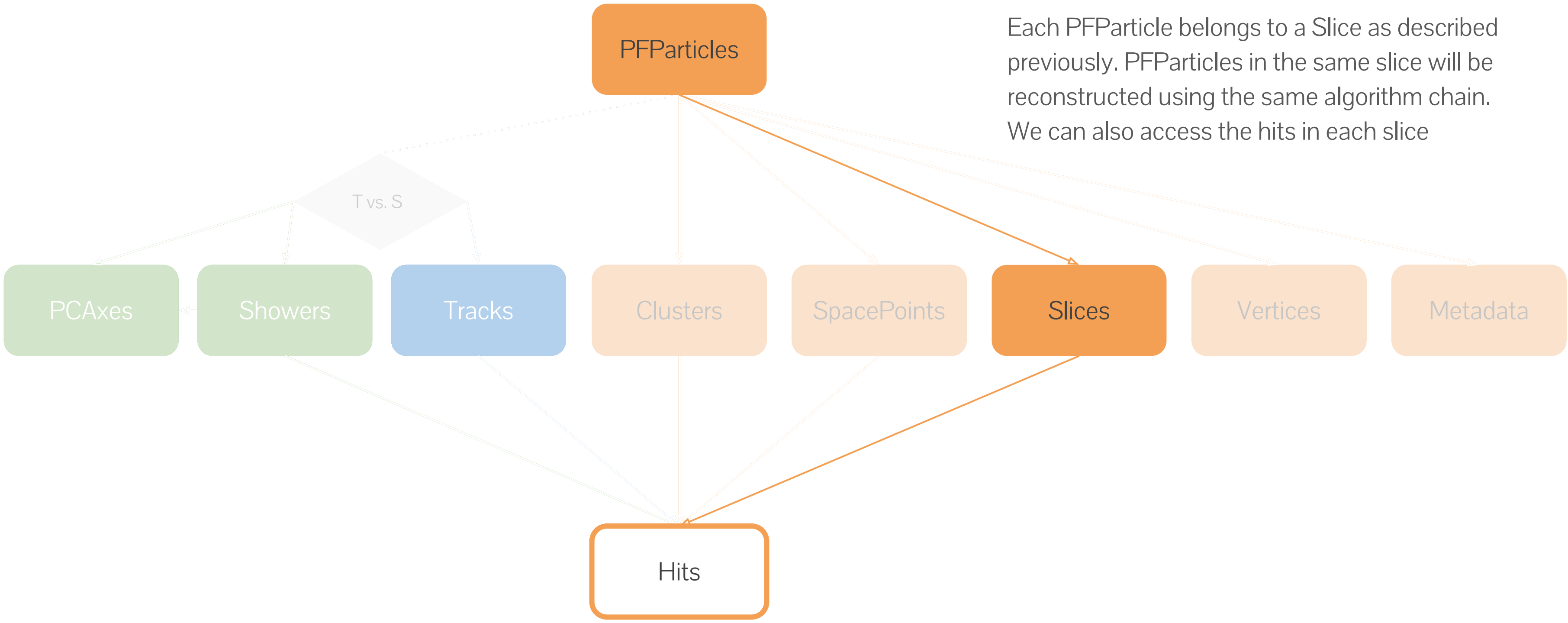


The trajectories of the PFParticles are stored in the 3D space points, each of which is associated to a hit that was used to create the space point

See `recob::SpacePoint` [documentation]() for more details

Pandora's outputs to LArSoft

µBooNE

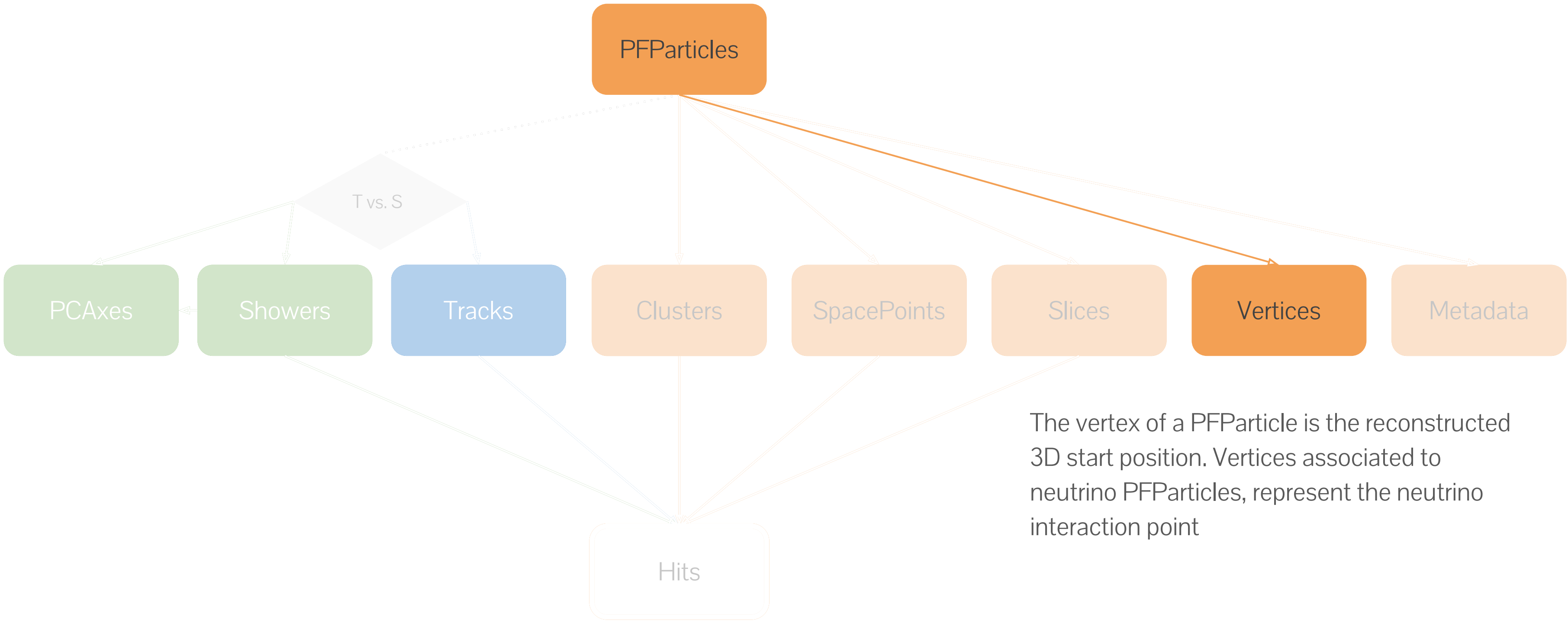


Each PFParticle belongs to a Slice as described previously. PFParticles in the same slice will be reconstructed using the same algorithm chain. We can also access the hits in each slice

See `recob::Slice` [documentation]() for more details

Pandora's outputs to LArSoft

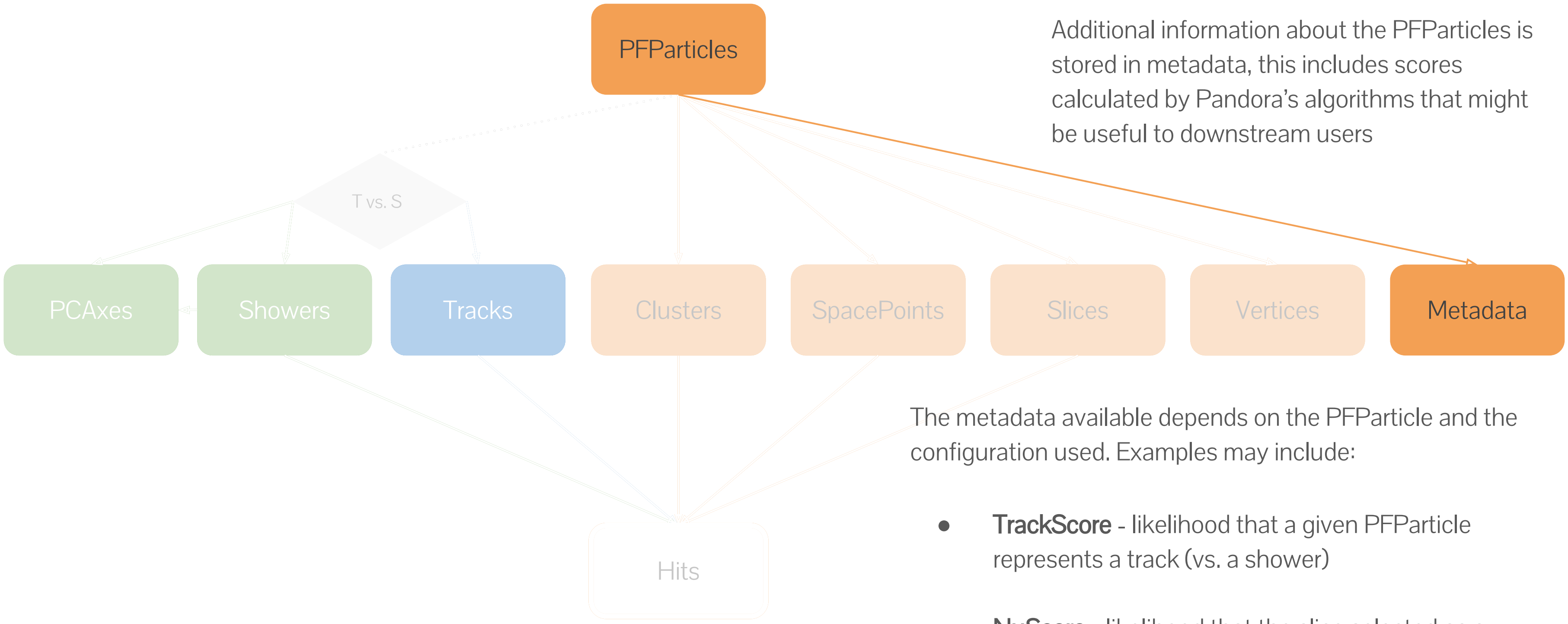
μBooNE



The vertex of a PFParticle is the reconstructed 3D start position. Vertices associated to neutrino PFParticles, represent the neutrino interaction point

See `recob::Vertex` documentation for more details

Pandora's outputs to LArSoft



Additional information about the PFParticles is stored in metadata, this includes scores calculated by Pandora's algorithms that might be useful to downstream users

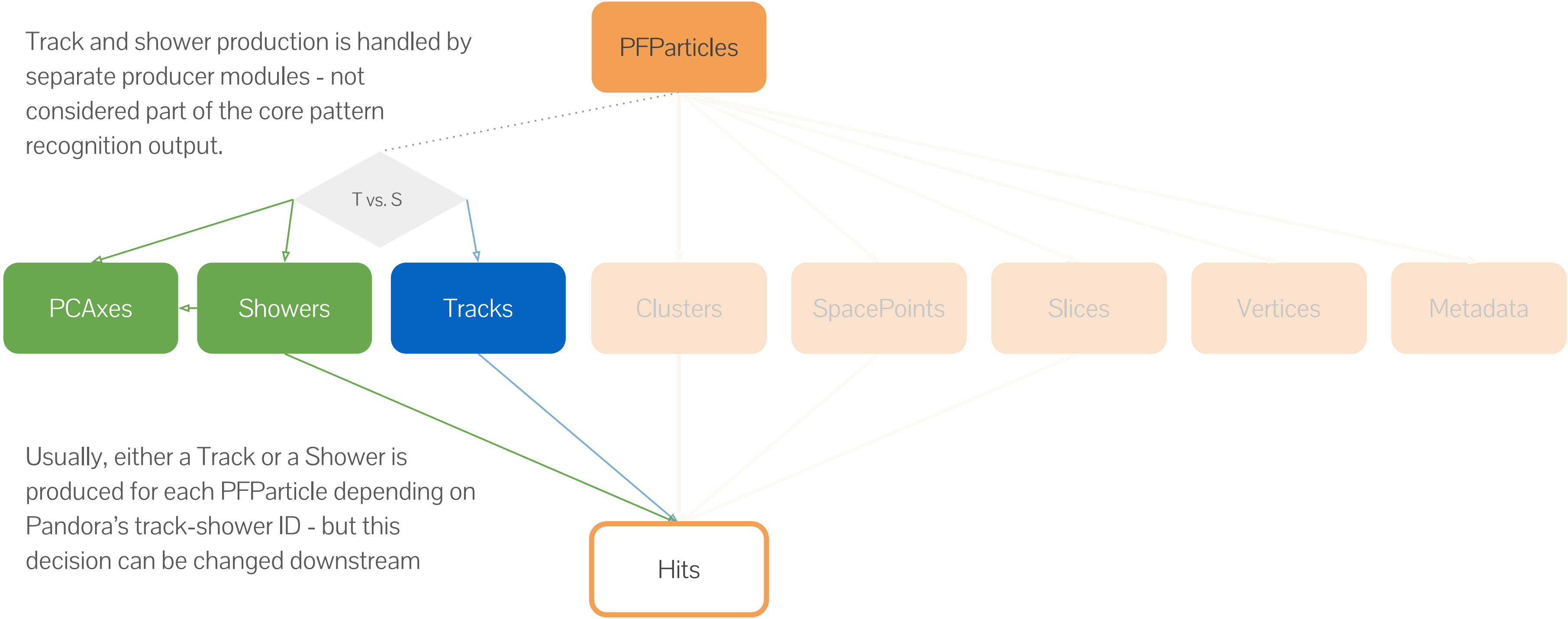
The metadata available depends on the PFParticle and the configuration used. Examples may include:

- **TrackScore** - likelihood that a given PFParticle represents a track (vs. a shower)
- **NuScore** - likelihood that the slice selected as a neutrino represents a true neutrino

See `larpandoraobj::PFParticleMetadata` documentation for more details

Pandora's outputs to LArSoft

Track and shower production is handled by separate producer modules - not considered part of the core pattern recognition output.



Usually, either a Track or a Shower is produced for each PFParticle depending on Pandora's track-shower ID - but this decision can be changed downstream

The tracks & showers form the input to downstream calorimetry and PID modules

See `recob::Track` documentation or `recob::Shower` documentation for more details

Pandora's "event dump" in LArSoft

(see backup for instructions for how to run the event dump)

Dumping a Pandora event to the terminal

Each event starts with a summary block

```
- Event ---------------------------
run: 1 subRun: 1674 event: 16740
pandora
----------------------------------
N PFParticles : 69
N SpacePoints : 10285
N Clusters    : 135
N Vertices    : 67
N Metadata    : 69
N Tracks      : 20
N Showers     : 46
N PCAxes      : 46
----------------------------------
```

All PFParticles are listed, and arranged according to the hierarchy

```
--------------------------------
PFParticle
--------------------------------
- Key           0
- Id            0
- Primary
- PDG           13
--------------------------------
- # SpacePoint  1186
- # Cluster     3
- # Vertex      1
- # Track       1
- # Shower      0
- # PCAxis      0
- # Metadata    1
-- Property     IsClearCosmic, value 1
--------------------------------
- # Daughters   10
--------------------------------
```

Can see associations of PFParticles to other collections (e.g. Tracks/Showers)

Metadata is available to learn more about the PFParticles
(This one was tagged as an unambiguous cosmic ray, so never was considered as the neutrino / beam particle)

Indent ⇒ daughter (print for each daughter)

```
    --------------------------------
    PFParticle
    --------------------------------
    - Key           3
    - Id            3
    - Parent        0
    - PDG           11
    --------------------------------
    - # SpacePoint  1193
    - # Cluster     3
    - # Vertex      1
    - # Track       0
    - # Shower      1
    - # PCAxis      1
    - # Metadata    1
    --------------------------------
    - # Daughters   0
    --------------------------------
```

Dumping a Pandora event to the terminal

```
--------------------------------
PFParticle
--------------------------------
- Key          1
- Id           1
- Primary
- PDG          12
--------------------------------
- # SpacePoint  0
- # Cluster     0
- # Vertex      1
- # Track       0
- # Shower      0
- # PCAxis      0
- # Metadata    1
-- Property     IsNeutrino, value 1
-- Property     NuScore, value 0.934322
-- Property     SliceIndex, value 1
--------------------------------
- # Daughters   1
--------------------------------
```

The reconstructed neutrino has IsNeutrino = 1, and an electron neutrino PDG code (12)

The NuScore is the output of the internal slice-ID for the slice, which in this case had index 1
(this is a MicroBooNE event, different experiments use different techniques)

```
    --------------------------------
    PFParticle
    --------------------------------
    - Key          0
    - Id           0
    - Parent       1
    - PDG          11
    --------------------------------
    - # SpacePoint  715
    - # Cluster     3
    - # Vertex      1
    - # Track       0
    - # Shower      1
    - # PCAxis      1
    - # Metadata    1
    -- Property     TrackScore, value 0.00116577
    --------------------------------
    - # Daughters   0
    --------------------------------
```

Indent ⇒ daughter (print for each daughter)

The reconstructed final state particles are the daughter of the neutrino

In this case there is a single final state electron

How do I use Pandora’s consolidated output?

LArPandoraHelper class

The LArPandoraHelper class has many useful functions to help you use Pandora's outputs, E.g.

```
/**
 *  @brief Collect the reconstructed PFParticles from the ART event record
 *
 *  @param evt the ART event record
 *  @param label the label for the PFParticle list in the event
 *  @param particleVector the output vector of PFParticle objects
 */
static void CollectPFParticles(const art::Event &evt,
                               const std::string &label,
                               PFParticleVector &particleVector);

/**
 *  @brief Determine whether a particle has been reconstructed as a neutrino
 *
 *  @param particle the input particle
 *
 *  @return true/false
 */
static bool IsNeutrino(const art::Ptr<recob::PFParticle> particle);
```

Typical task : Getting neutrino identified PFParticles

For more example code please see ConsolidatedPFParticleAnalysisTemplate_module.cc and the LArPandoraHelper class which has many useful functions!

```
// Get the PFParticle collection from the event record
PFParticleVector pfParticles;
LArPandoraHelper::CollectPFParticles(event, pfParticleLabel, pfParticles);
```

This is the art::Event record given to you by LArSoft - it contains all of the collections and associations available

This is the label of the Pandora module - it depends on your experiment but it's usually "pandora" or "pandoraPatRec"

```
// Find the PFParticles that have been identified as neutrinos by the slice ID
PFParticleVector neutrinos;
for (const auto &particle : pfParticles)
{
      // Query the PFParticle's PDG code using a helper function to see if it's been identified
      // as a neutrino by the slice ID - if so, then add it to our vector of neutrinos
      if (LArPandoraHelper::IsNeutrino(particle))
            neutrinos.push_back(particle);
}
```

Typical task : Getting neutrino final state PFParticles

For more example code please see ConsolidatedPFParticleAnalysisTemplate_module.cc and the LArPandoraHelper class which has many useful functions!

```
// Make a map from PFParticle.Self() -> PFParticle object for navigation of the hierarchy
PFParticleMap pfParticleMap;
LArPandoraHelper::BuildPFParticleMap(pfParticles, pfParticleMap);

// Find the daughter PFParticles of each primary neutrino PFParticle
for (const auto &neutrino : neutrinos)
{
      for (const auto &daughterId : neutrino->Daughters())
      {
            const auto daughter = pfParticleMap.at(daughterId);

            // Do something with the daughter particle! E.g. find associated tracks / showers
      }
}
```

Where can I find more information?

Papers and documentation

- The Pandora SDK paper
  - Details the design of the software development kit and how algorithms interface with the application that is running Pandora (e.g. larpandora)

- The Pandora MicroBooNE paper
  - Gives details of Pandora's algorithms in MicroBooNE at the time of publication, but generally applicable to other LArTPC experiments too

- All Pandora code is self-documented using doxygen and is available on github
  - https://github.com/PandoraPFA

Recent workshops & hands-on exercises

- Multi-day Pandora workshop in Cambridge, UK - 2016
  - Talks about how the algorithms work and step-by-step exercises about how you might develop a new algorithm using Pandora!

- LArSoft workshop in Manchester, UK - 2018
- Workshop on advanced computing & machine learning, Paraguay - 2018
  - Talks and exercises about running and using Pandora within LArSoft, including tutorials on using Pandora's custom event display

- Experiment specific resources:
  - ProtoDUNE analysis workshop, CERN - 2019
  - MicroBooNE Pandora workshop, Fermilab - 2018

Summary

- Pattern recognition is an important step in the reconstruction of LArTPC events
- Pandora is a solution to the patrec problem that's widely used by LArTPC experiments
- Pandora uses a multi-algorithm approach to gradually build up our understanding of the event
- Pandora's consolidated algorithm flow allows us to deal with neutrino / test-beam interactions in dense cosmic-ray environments
- Pandora can be run as part of LArSoft so its outputs are available for use in your own code
- The core outputs are PFParticles and their hierarchical relationships
- There are a number of good resources if you want to learn more about Pandora or get started with some hands on exercises, but don't be afraid to get in touch with a member of the team!

Pandora team for LArTPC reconstruction

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.

Pandora SDK development	John Marshall Mark Thomson	john.marshall@warwick.ac.uk thomson@hep.phy.cam.ac.uk
LArTPC algorithm development	John Marshall Andy Blake	 a.blake@lancaster.ac.uk
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WARWICK
THE UNIVERSITY OF WARWICK

github.com/PandoraPFA

PandoraPFA.slack.com

Backup

Example FHiCL file for running Pandora’s event dump

```
BEGIN_PROLOG
pandora_event_dump:
{
 module_type: "LArPandoraEventDump"
}
dump: @local::pandora_event_dump
dump.PandoraLabel: "pandora"
dump.TrackLabel: "pandoraTrack"
dump.ShowerLabel: "pandoraShower"
dump.VerbosityLevel: "detailed"
END_PROLOG

#include "services_dune.fcl"
services:
{
 scheduler: { defaultExceptions: false }
 RandomNumberGenerator: {} #ART native random number generator
 FileCatalogMetadata: @local::art_file_catalog_mc
}
process_name: LArPandoraEventDump
source:
{
 module_type: RootInput
}
physics:
{
 analyzers:
 {
 dump: @local::dump
 }
 stream1: [ dump ]
 end_paths: [ stream1 ]
}
outputs: {}
```

Module itself lives here

These labels will depend on which experiment you are working on

Choose between “brief”, “summary”, “detailed” or “extreme”

Choose the services for your experiment

Run using standard lar command:

```
>> lar -c <my_fhicl_file_name> -s <my_root_file> -n <n_events>
```