Pandora Particle Flow in Key4hep

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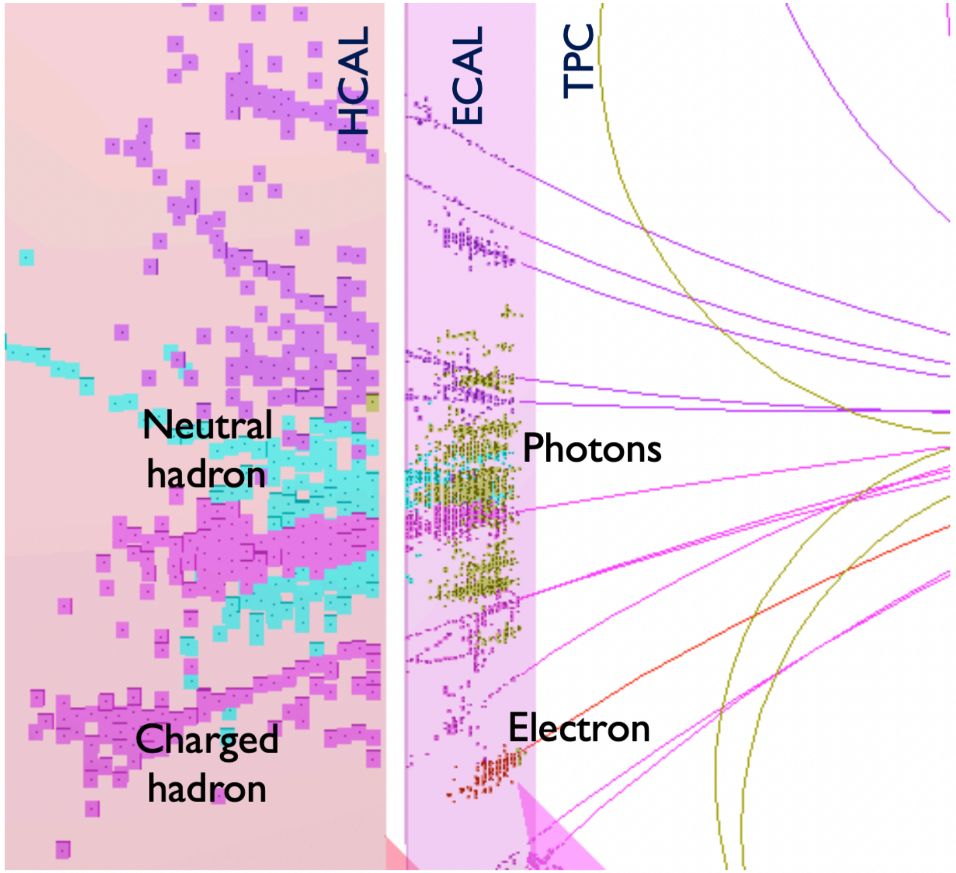
R&D on EXPERIMENTAL TECHNOLOGIES

Introduction

- Important ingredient for performance of future Higgs factory experiments: particle flow reconstruction for optimal jet energy resolutions
- Pandora particle flow algorithm (PandoraPFA) developed to study particle flow calorimetry
  - PandoraPFA combines the tracking information with hits in high granularity calorimeters
  - Reconstruction of every individual particles in the event
  - DDMarlin Pandora is the Marlin integration of Pandora to iLCSoft framework to study particle flow at high granularity CALICE calorimeters

Pandora Particle Flow Algorithm: A larger picture

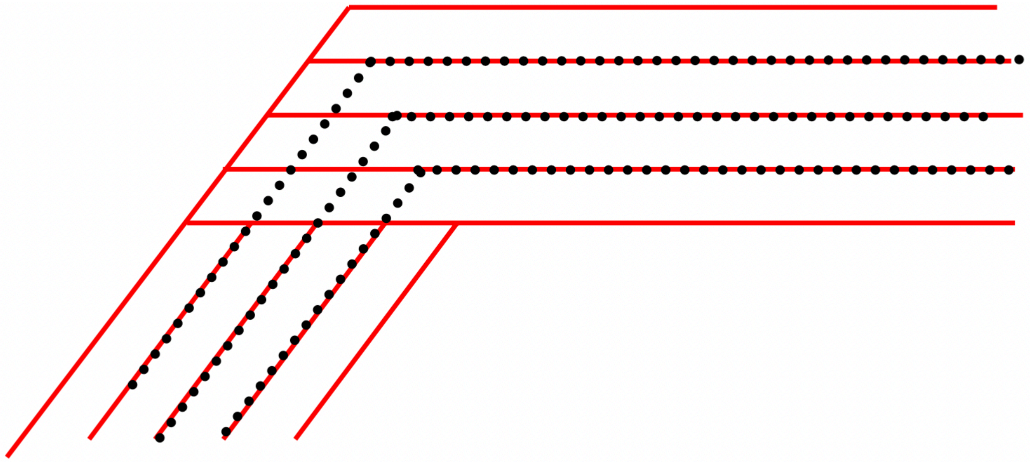
- Particle flow: requires the reconstruction of all individual particles
  - Charged particles (62%) through the tracker, photons (27%) through the ECAL and neutral hadrons (10%) through HCAL
- Particle Flow Objects (PFO) built from tracks and (associated) clusters:
  - Calorimeter energy resolution not critical - most energy obtained from tracks



Pandora Particle Flow Algorithm : Preparation

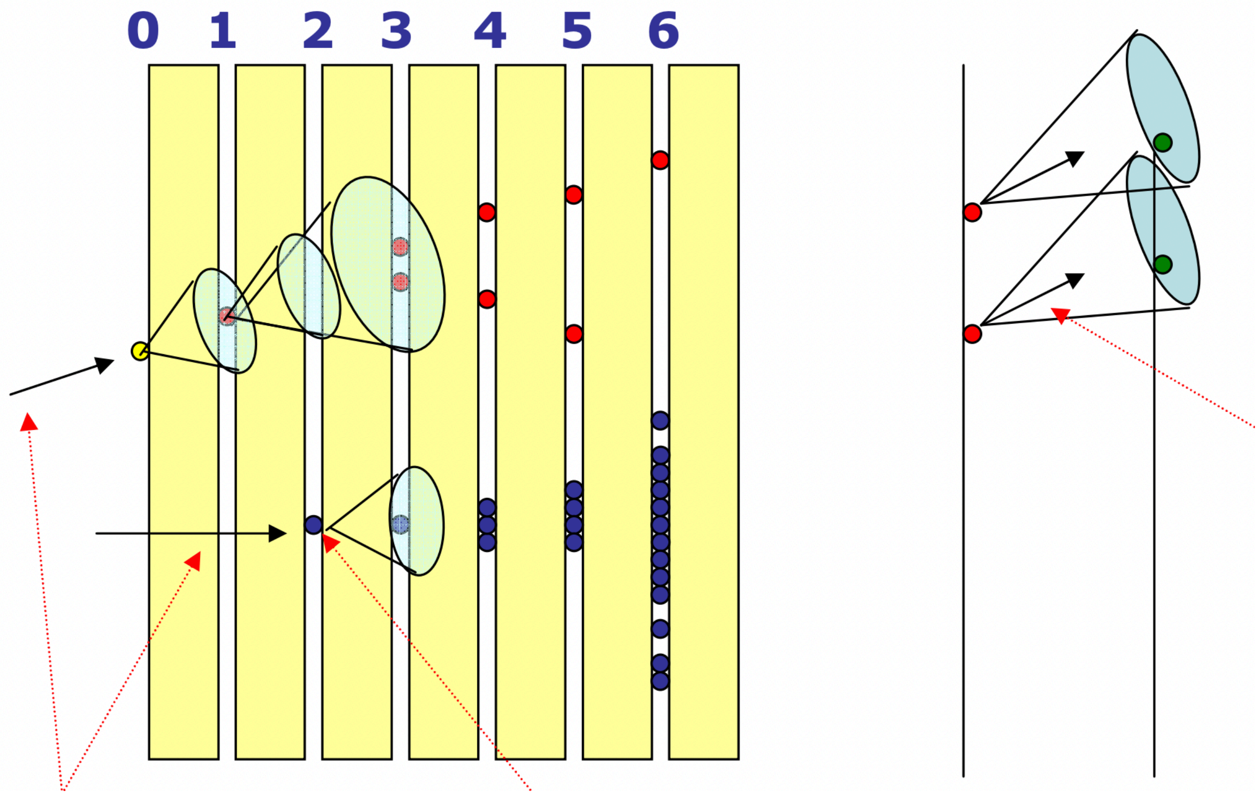
- Isolating hits:
  - Isolated energy deposits are of little use
  - Difficult to associate with any particular hadronic shower and therefore removed

- Ordering of hits:
  - The remaining hits are ordered into *pseudo-layers*
  - Information related to geometry and surrounding hits are stored
  - The hits become self describing and as much as possible detector independent



Clustering

- Cone-based forward projective method working from innermost to outermost pseudo layer
- Hits either added to existing clusters or to seed new clusters



Cones based on either initial cluster direction or current cluster direction

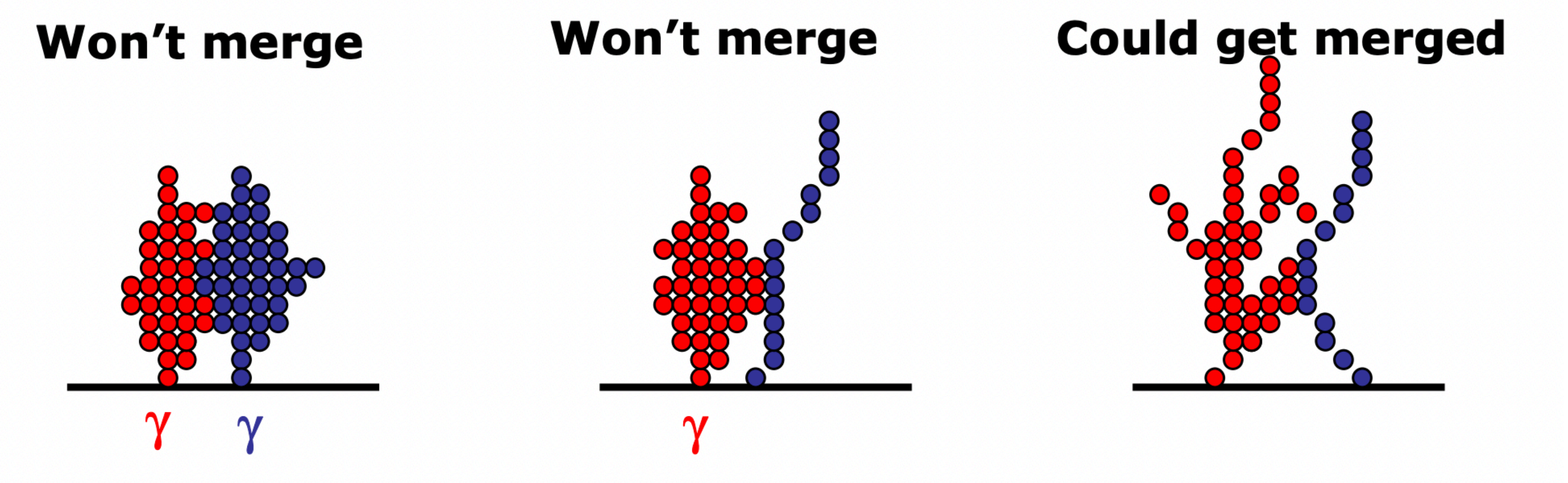
Initial Cluster direction

Unmatched hits seeds new cluster

- ECAL hits first considered to identify photon energy deposits
- In second stage rest of the hits clustered

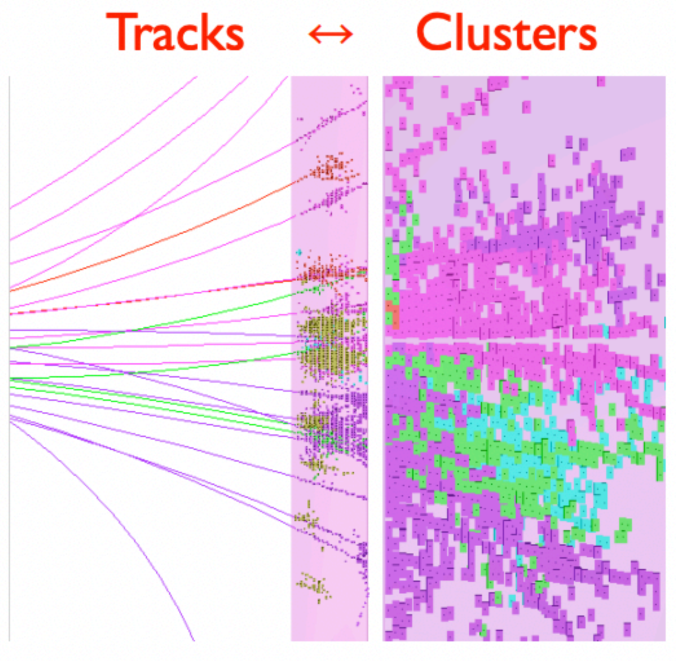
Cluster Association

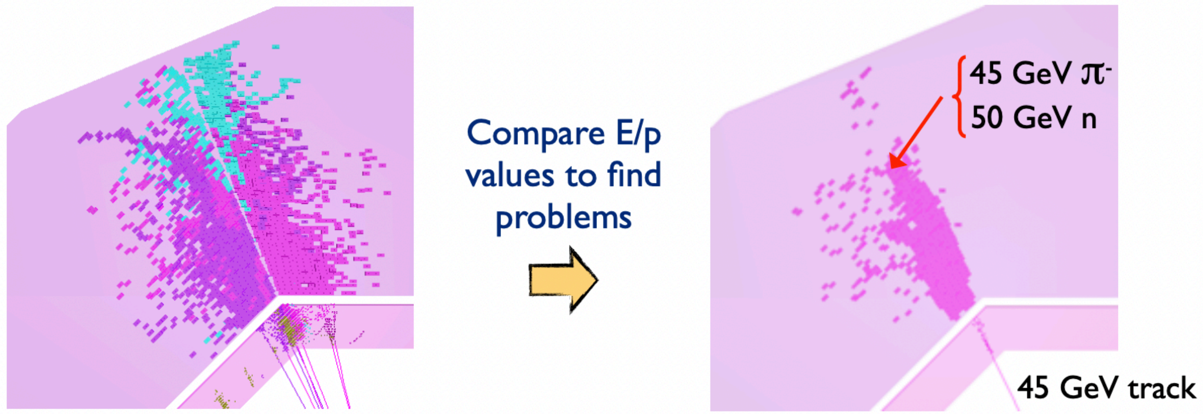
- Philosophy : Easier to put things together than split them up
- Clusters are associated together in two stages:
  - Tight cluster association - clear topologies
  - Loose cluster association - what is missed but rather crude
- Photon clusters: Clusters tagged as photons are immune for association procedure



Association of tracks to clusters

- Track-cluster association: match cluster positions and directions with helix-projected track states at calorimeter
- Identify pattern recognition problem by looking for significant discrepancies between cluster E and track p
- Recluster until cluster splits and consistent E/p is achieved
- In very high density jets resolving neutral hadrons can become challenging





After topological association

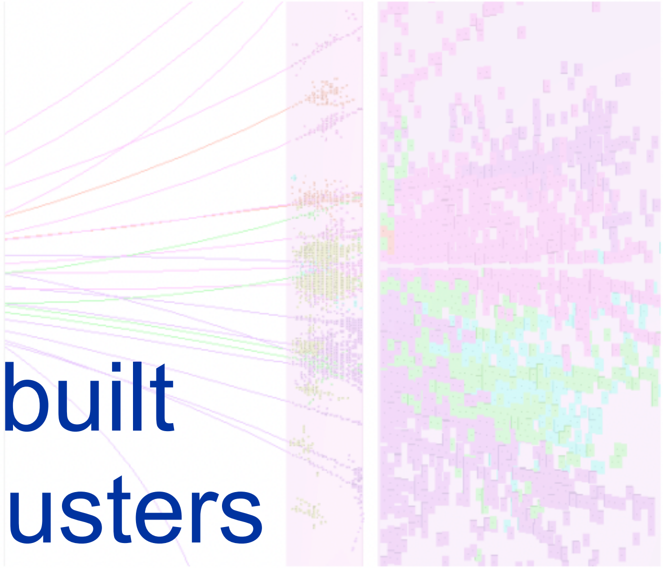
Find n absorbed into π^- cluster

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

identify and address clustering problem

Association of tracks to clusters

Tracks ↔ Clusters

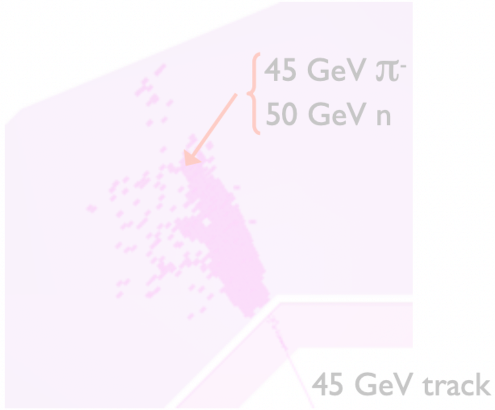


- Track-cluster association: match cluster positions and directions with helix-projected track states at Calorimeter
- Identify pattern recognition problem by looking for significant discrepancies between cluster E and track p
- Recluster until cluster splits and consistent E/p is achieved
- In very high density jets resolving neutral hadrons can become challenging

Particle Flow Objects are thus built from tracks and (associated) clusters

After topological association

Compare E/p values to find problems



Find n absorbed into π⁻ cluster

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

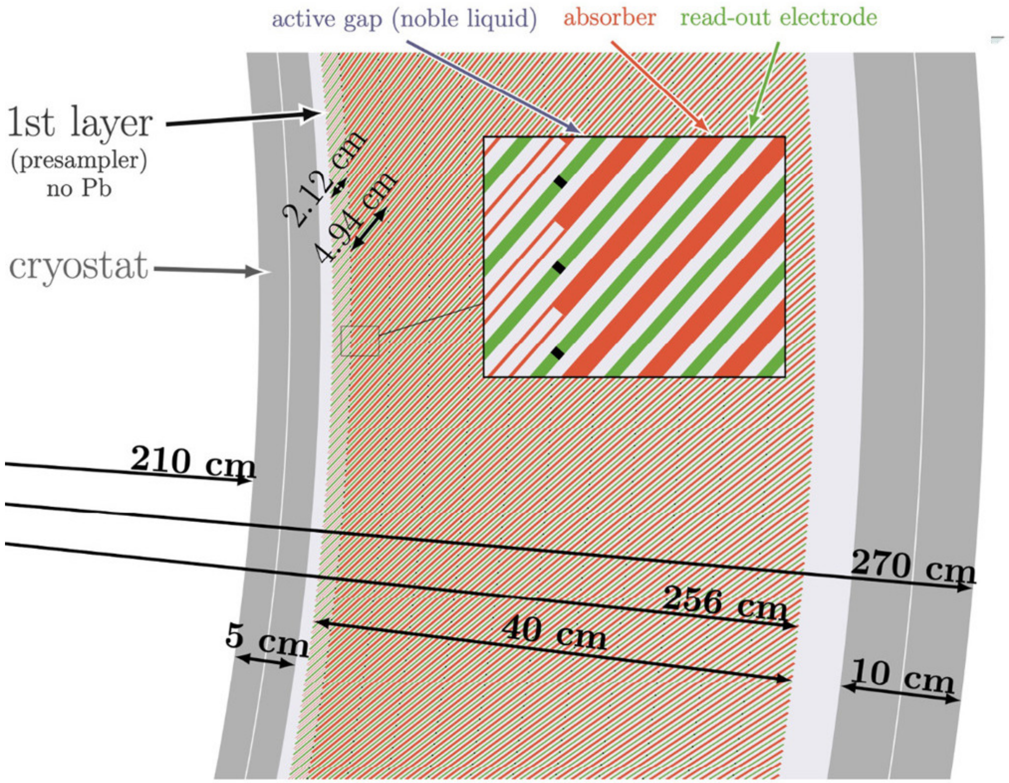
identify and address clustering problem

Key4hep and PandoraPFA

- Key4hep project offers a flexible framework that allows different experiments to benefit from its synergy
- To enable use of PandoraPFA across multiple detector models, important to integrate it into Key4hep
- The two goals of this study:
  - See if DDMarlinPandora along with the k4MarlinWrapper works for detector models other than CALICE calorimeters e.g. Liquid-Argon Calorimeter
  - Replace the DDMarlinPandora and k4MarlinWrapper combination with DDGaudiPandora

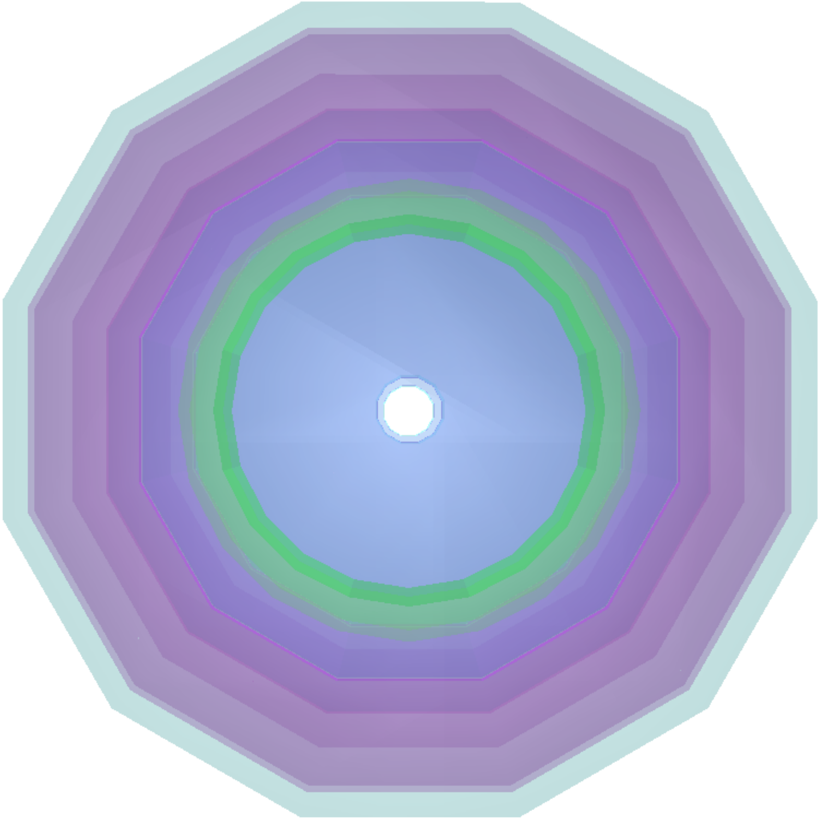
The Noble Liquid Argon Calorimeter

- The FCC detector - ALLEGRO has chosen the Liquid Argon (LAr) calorimeter as its Electromagnetic calorimeter
- This calorimeter consists of liquid argon as the sensitive material with steel/Pb absorbers and readouts inclined at an angle of 50 degrees wrt the radius
- The LAr calorimeter has 12 different layers
- Makes a good candidate studying Pandora PFA on a completely different detector model



Geometry Adaptations to CLD

- Challenge - no full simulation for ALLEGRO in Key4hep yet
- Need tracks for Pandora PFA
- Using CLD detector as a base for full simulation and reconstruction a detector model as **`CLD_o4_v05`** was created with LAr calorimeter as the ECAL
- The LAr ECal is almost three times the size of the CLD ECAL
- To include LAr instead of the CLD ECAL the geometry of the detector needs to be adapted to avoid the overlaps between the subdetectors
- HCAL, Solenoid and the Yoke moved out further to accommodate LAr in the detector



Pandora PFA and Layered Calorimeter Data

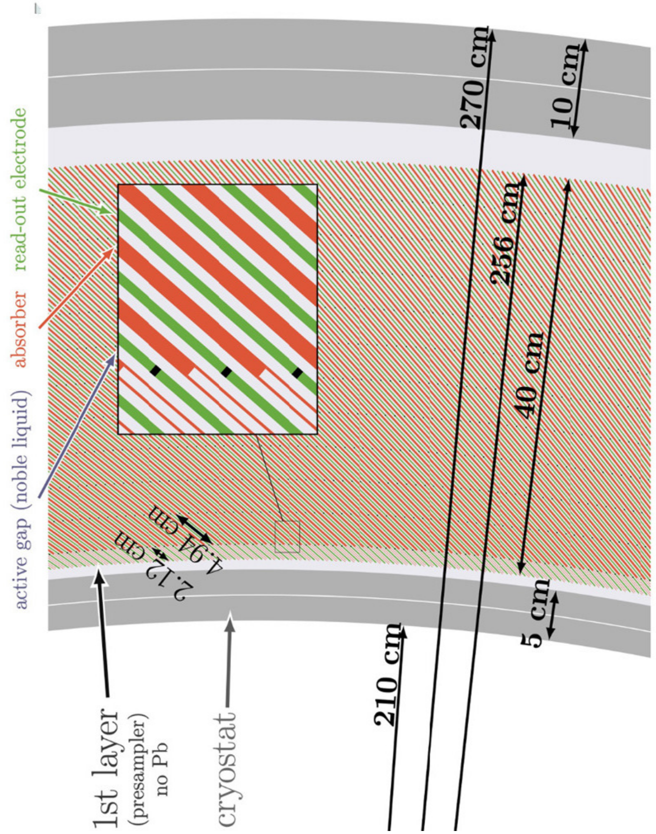
- PandoraPFA uses material properties e.g. radiation lengths and interaction lengths to determine the depth of the particle shower in the detector
- Particle flow clustering with Pandora uses the extensions attached to the detector geometries to provide the properties of the calorimeter
- The **`DD4hep::rec::LayeredCalorimeterData`** provides details like radiation length, interaction length and dimensions to the reconstruction algorithms

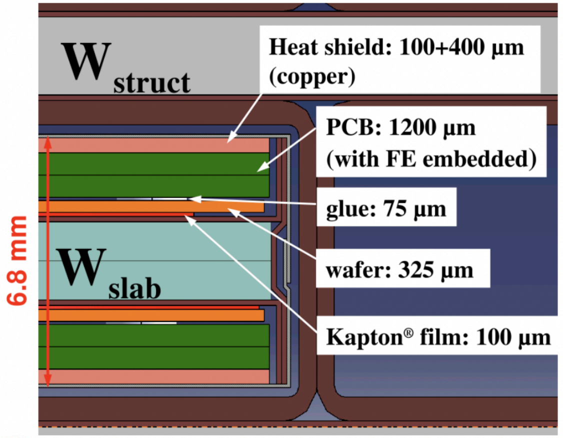
```
dd4hep::rec::LayeredCalorimeterData::Layer caloLayer;

caloLayer.distance = rad_first;
caloLayer.inner_nRadiationLengths   = value_of_x0/2.0;
caloLayer.inner_nInteractionLengths = value_of_lambda/2.0;
caloLayer.inner_thickness           = difference_bet_r1r2/2.0;
```

Geometry information for PandoraPFA

- DDMarlinPandora designed with high granularity CALICE sandwich calorimeters
- LAr calorimeter has a very different structure : an ensemble of different materials in a cell varying in density and homogeneity
- Density of material also varies from the inner radius to the outer radius of the barrel
- Moreover, the inclination of the segments play a role
- Challenging to calculate radiation length or interaction length for LAr





Material Manager

- Such information for the LAr calorimeter is obtained in a more dynamic way
- **`MaterialManager`** is a tool from DD4hep that helps extracting the necessary information between arbitrary space points
- **`MaterialManager`** returns the list of materials and their thickness along the vector
- By averaging the material between the arbitrary points material properties of the averaged material was extracted
- Crosscheck: The sum of the radiation lengths across the layers sums up to 22 X_0 as expected for the calorimeter

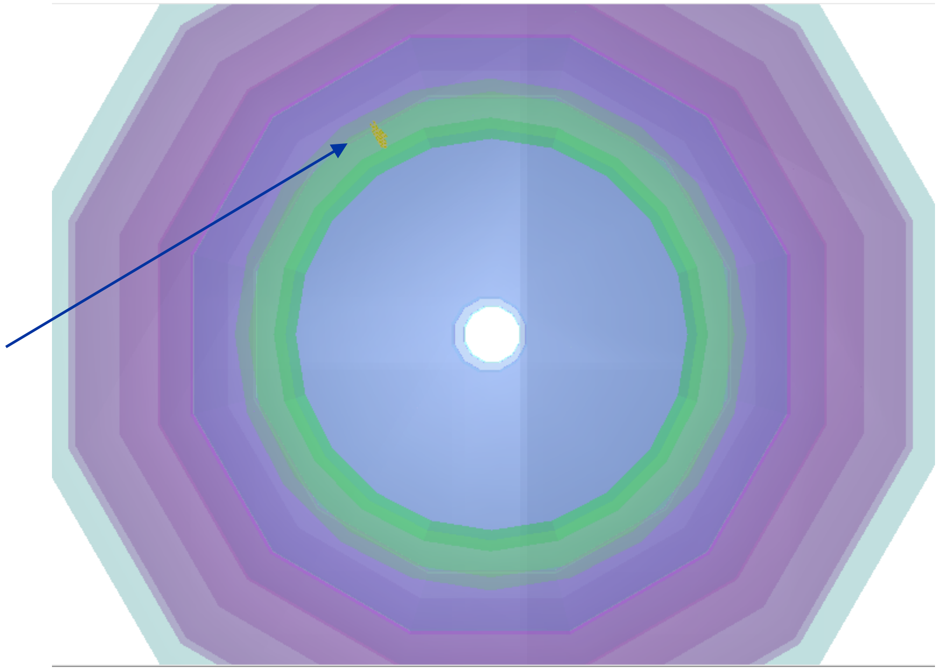
```
const dd4hep::rec::MaterialVec& materials = matMgr.materialsBetween(ivr1, ivr2);
auto mat = matMgr.createAveragedMaterial( materials) ;
nRadiationLengths = mat.radiationLength();
nInteractionLengths = mat.interactionLength();
double difference_bet_r1r2 = (ivr1-ivr2).r();
double value_of_x0 = layerHeight[il] / nRadiationLengths;
double value_of_lambda = layerHeight[il] / nInteractionLengths;
```

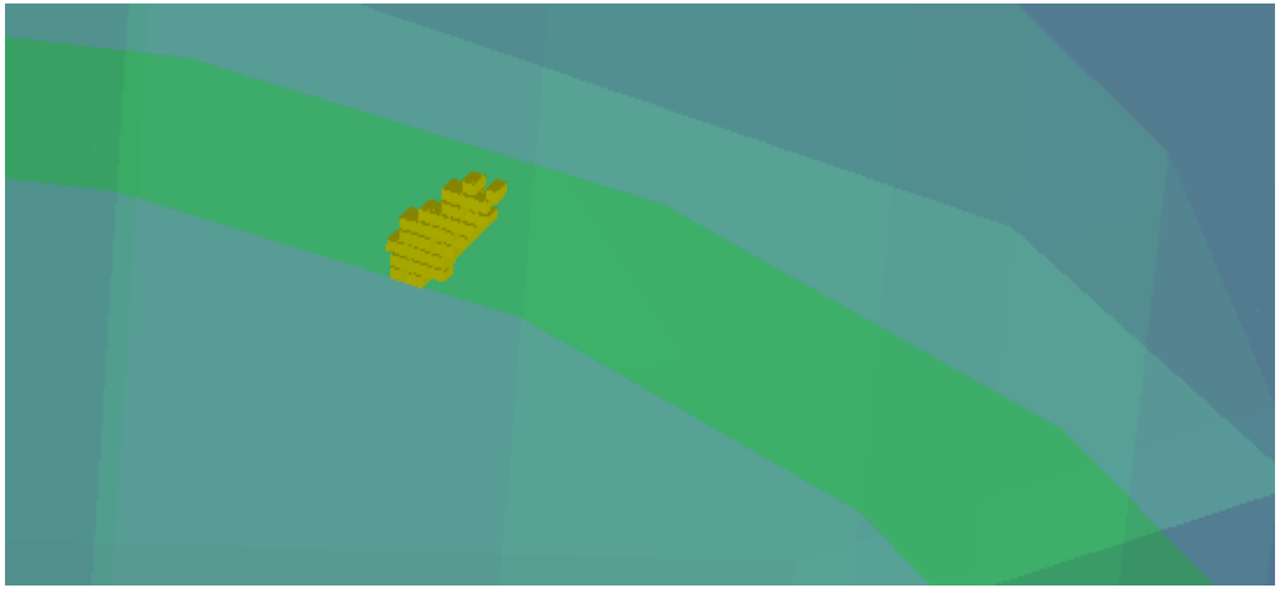
Between raw data and reconstruction

- PandoraPFA cannot directly process RawCalorimeterHit or the TPCHit
- The raw data needs to be digitized before giving to the particle flow algorithm
- The standard digitization processor for the linear colliders (`DDCaloDigi`) used to provide the digitized hit collection to Pandora defines the geometry of the ECal Barrel with staves
- LAr calorimeter however does not have staves in its barrel
- The LArDigi which is designed for LAr calorimeter that calibrates for all the twelve layers in the calorimeter becomes a good solution

Can Pandora run for LAr?

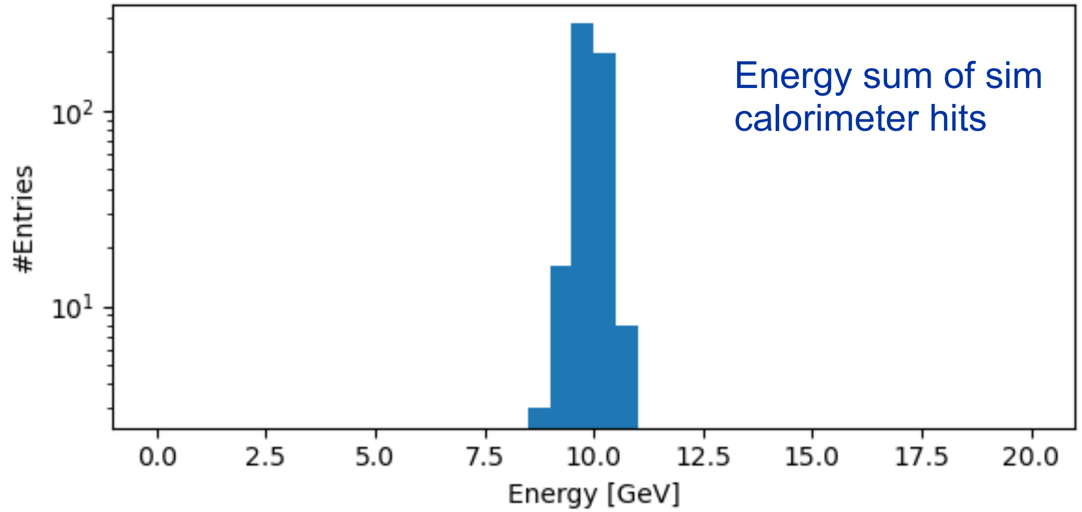
- 500 events of photons using a particle gun was simulated at an energy of 10 GeV for the CLD_LAr detector model
- By running reconstruction with all the digitized hit collections provided to Pandora, Pandora particle flow objects (PandoraPFO's) from LAr calorimeter could be observed 🥳

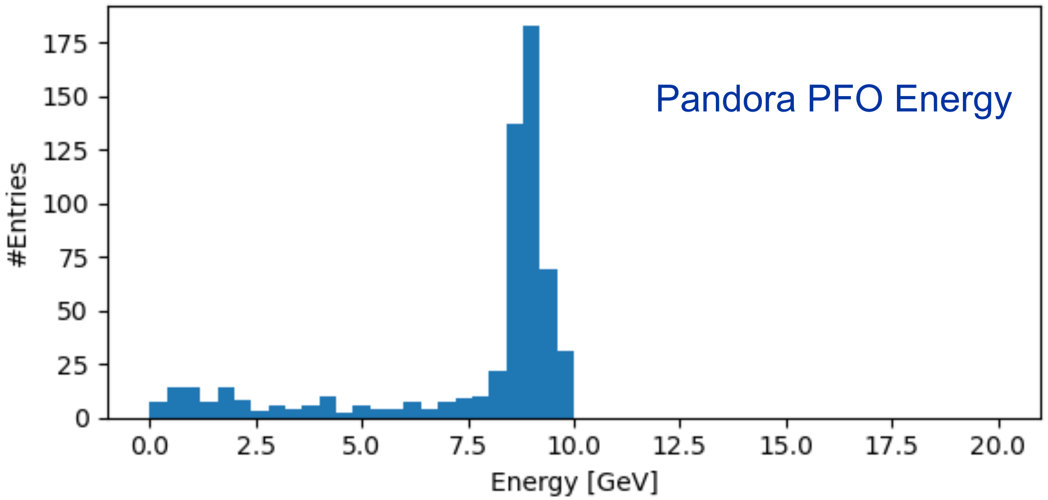




Energy of Pandora PFO

- The sum of the energies of the sim calorimeter hits peaks nicely at 10 GeV as expected
- The energy of the pandora PFO obtained seen in the second figure mostly peaked at 9 GeV and has a tail
- The correction factor for photon energies needs to be adapted to the LAr calorimeter from CLD
- With the corrections even better results expected: work in progress





Summary

- To integrate PandoraPFA into Key4hep and use it across the detector models it was tested on the Nobel Liquid Argon Calorimeter for FCC
- Dynamic ways to obtain important information about the material properties of the calorimeter used
- ThePandoraPFOs could be observed for the LAr Calorimeter also using the LAs Digitiser and the energy of the PFOs look reasonable

Acknowledgement:

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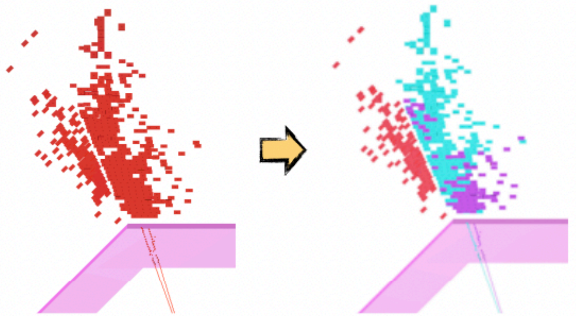
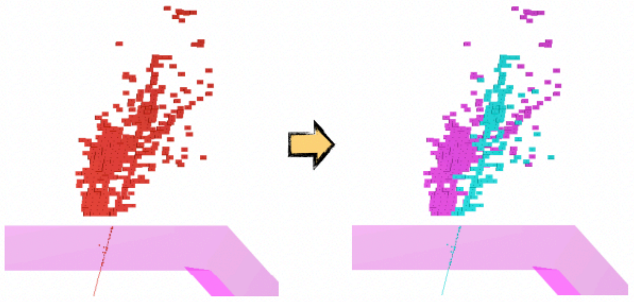
BACKUP SLIDES

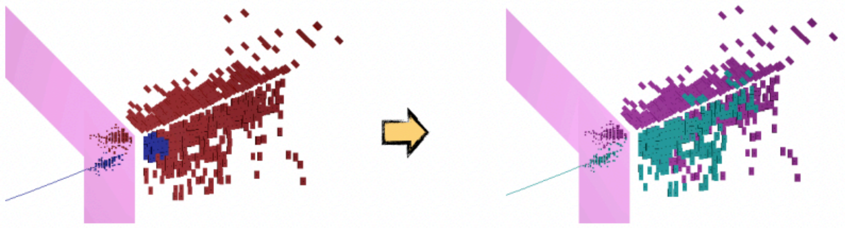
Reclustering Strategies



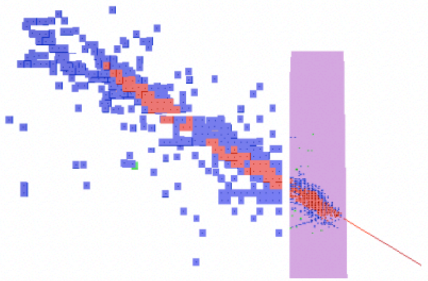
1. Multiple tracks associated to single cluster – split cluster.



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

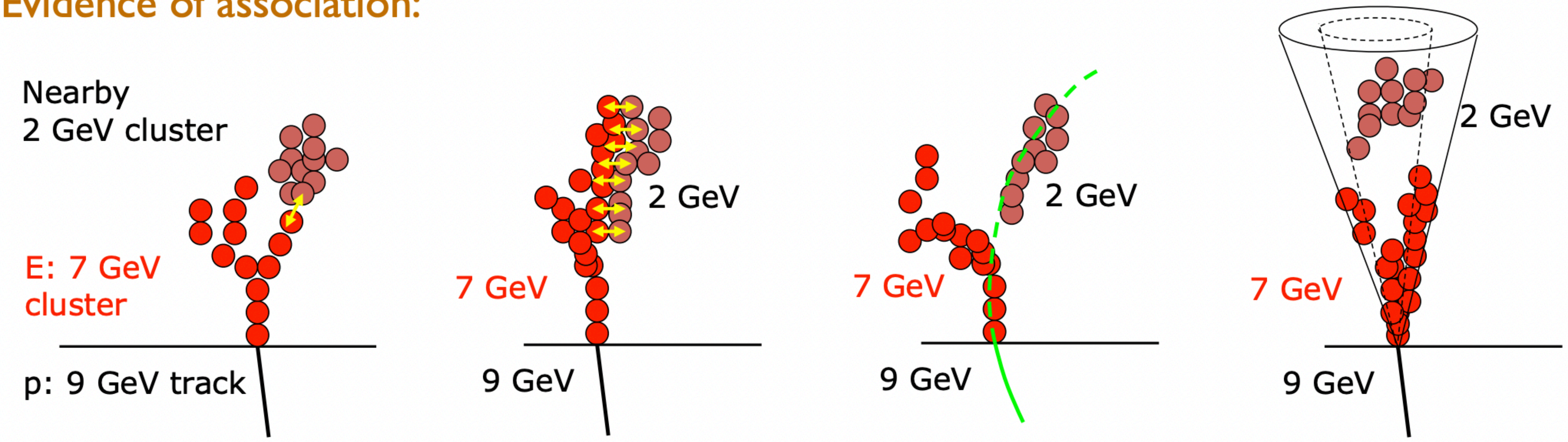


3. Track momentum much greater than cluster energy – bring in nearby clusters and reconfigure.



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

Evidence of association:



Small distance of closest approach

Multiple layers in close contact

Small distance to track extrapolation

Large fraction of energy in cone