Pandora Particle Flow Concept in Key4hep

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Introduction

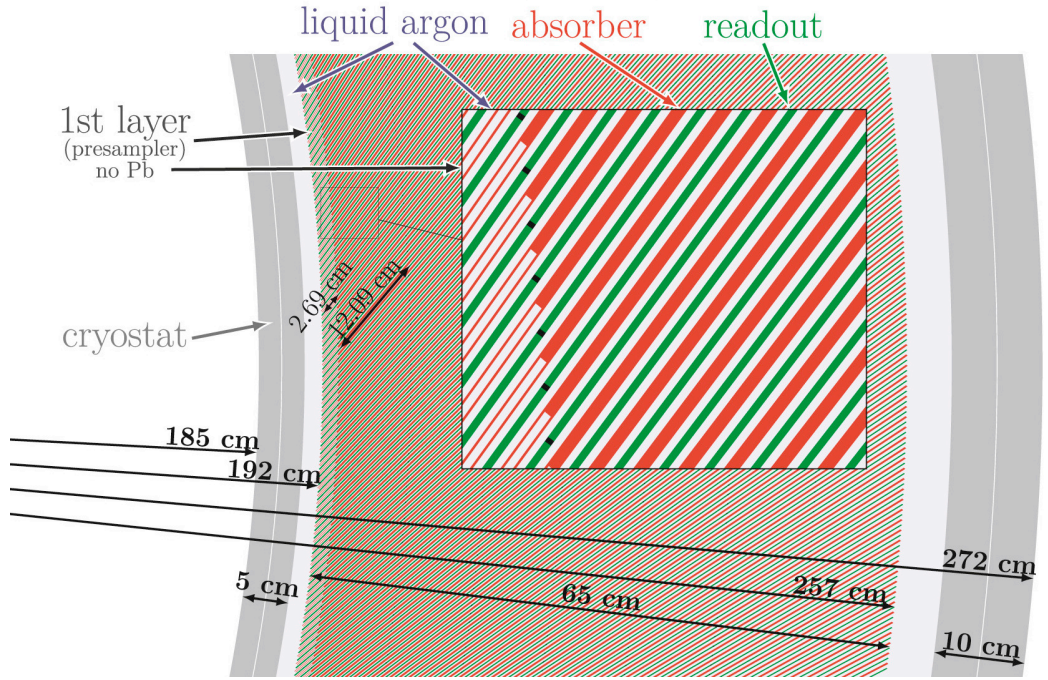
- Important ingredient for performance of future Higgs factory experiments: particle flow reconstruction for optimal jet energy resolutions
- Particle flow: requires the reconstruction of all individual particles
  - Charged particles (62%) through the tracker, photons (27%) through the ECAL and neutral hadrons (10%) through HCAL
  - Less dependent on the HCAL with lower energy resolutions
- Pandora particle flow algorithm (PandoraPFA) developed to study particle flow calorimetry
  - DDMarlin Pandora is the Marlin integration to iLCSoft framework to study particle flow at high granularity CALICE calorimeters

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

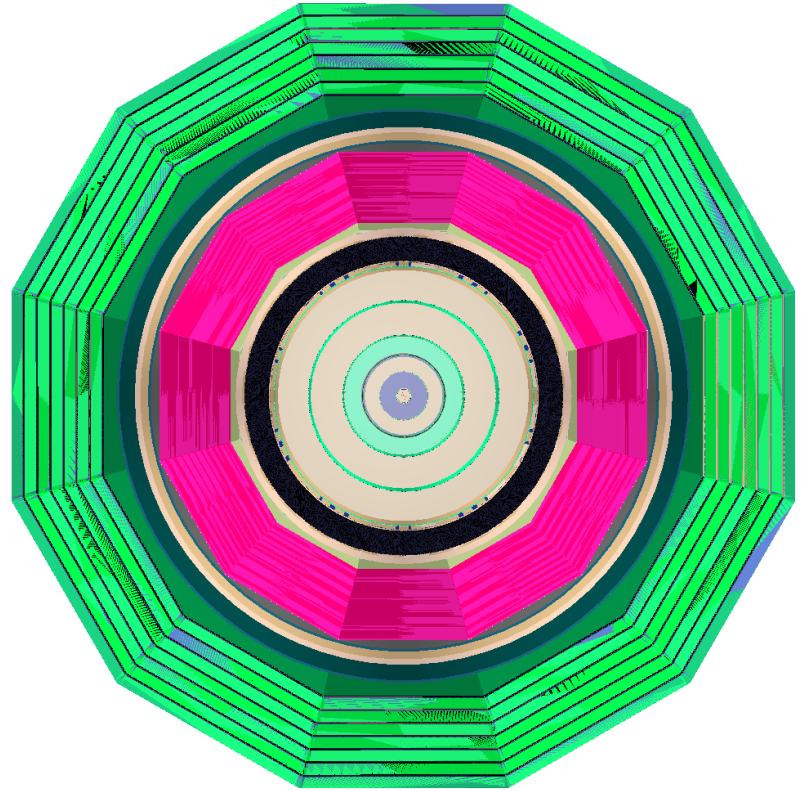
The Noble Liquid Argon Calorimeter

- 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

- One challenge for this was that there is no full simulation for ALLEGRO in Key4hep yet
- Therefore using the 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
- For including LAr instead of the CLD ECAL the geometry of the detector needs to be adapted to the new requirements to avoid the overlaps between the subdetectors
- Therefore the HCAL, Solenoid and the Yoke were moved out further to accommodate LAr in the detector



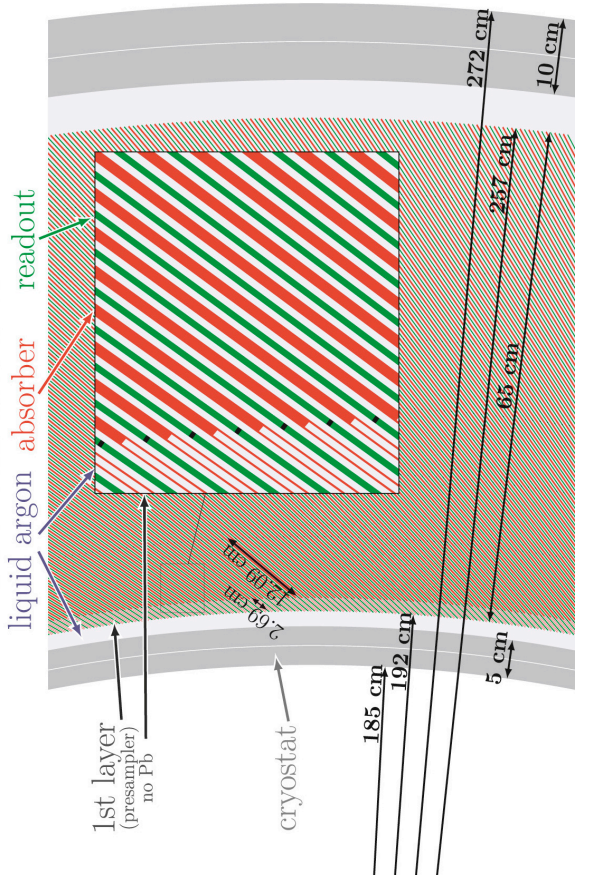
Pandora PFA and Layered Calorimeter Data

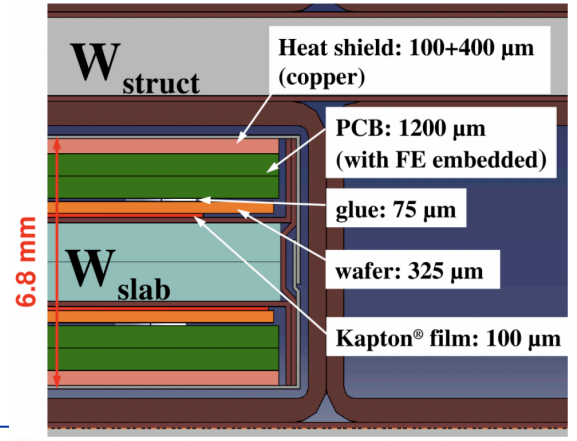
- PandoraPFA uses material properties e.g. radiation lengths and interaction lengths to determine the depth of the particle shower in the detector
- Particle flow clustering with Pandora uses the extensions attached to the detector geometries to provide the properties of the calorimeter
- The **`DD4hep::rec::LayeredCalorimeterData`**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

Material properties for PandoraPFA

- DDMarlinPandora designed for 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





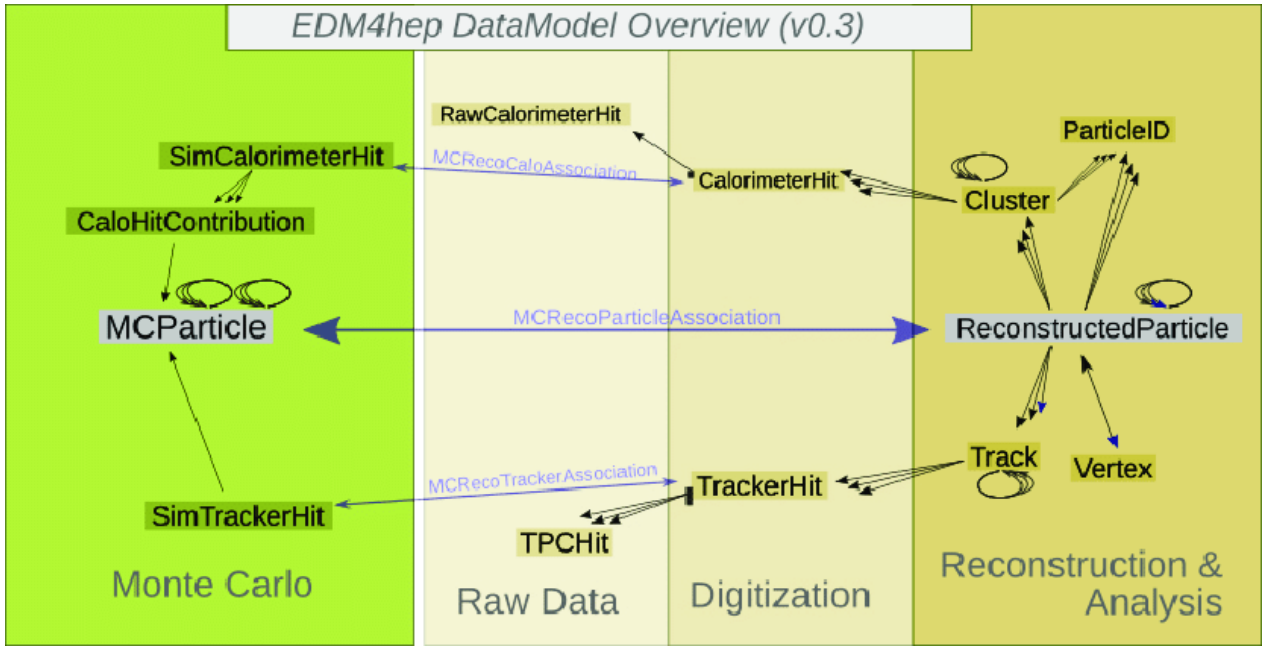
Material Manager

- 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

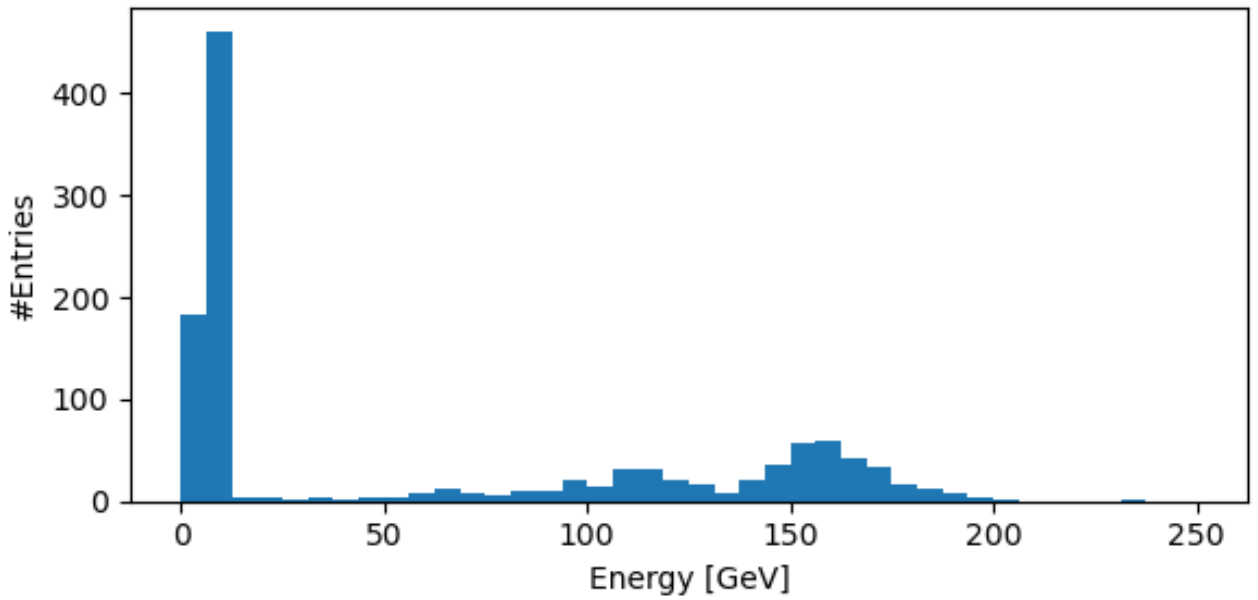


Simple Muon Digi for Digitization

- The **`SimpleMuonDigi`** processor mainly used to process hits from the Yoke but can however be used across the detectors for digitization
- However, the simplicity of SimpleMuonDigi does not take the details of the detector geometry into account
- Nevertheless, the SimpleMuonDigi is used as a temporary solution for digitizing the LAr ECal hits
- Until LArDigi which is designed for LAr calorimeter can be used instead

Can Pandora run for LAr?

- 1000 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, the first Pandora particle flow objects (PandoraPFO's) from LAr calorimeter could be observed 🥳



Summary and Outlook

- 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 needed
- The first PandoraPFOs could be observed for the LAr Calorimeter 🥳
- The Digitizer designed for LAr needs to be implemented and the photon energy to be calibrated
- Need to get PandoraPFA for Key4hep in gaudi framework
- Study the jet energy resolution