HCAL of ALLEGRO: Tile Calorimeter

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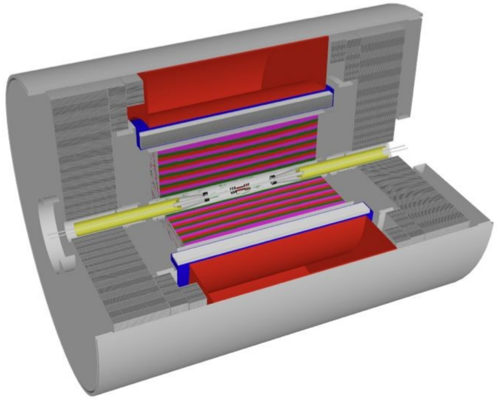
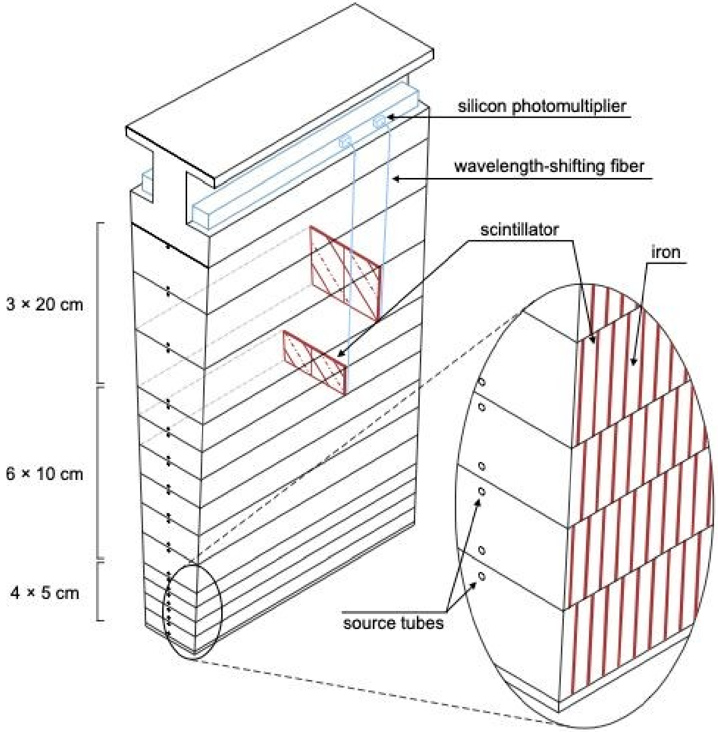
ALLEGRO detector concept

- General-purpose detector for FCC-ee
- A Lepton coLlider Experiment with Granular calorimetry Read-Out
- Highly-granular noble liquid ECAL
- Vtx detector, drift chamber and ECAL inside 2 T solenoid, sharing cryostat
- HCAL and Muon system outside solenoid



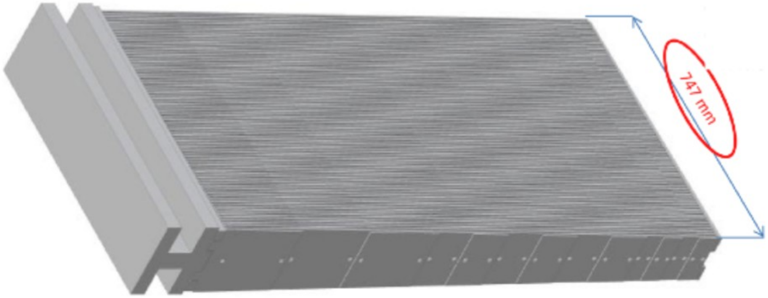
Hadronic Tile Calorimeter design

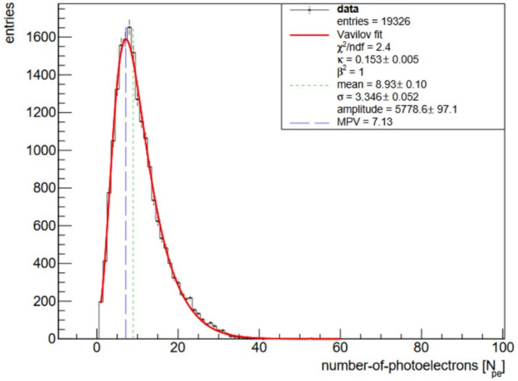
- HCAL design based on **alternating steel and scintillator layers**
  - Well studied and tested design (similar to ATLAS TileCal)
  - 5 mm absorbers, 3 mm scintillators
- **SiPM readout** allows high granularity in θ
- 128 modules in ϕ
  - 2 tile per module → $\Delta\phi$ ~ 0.025 rad
- Magnetic properties allowing use as **return yoke for solenoid**
- In situ calibration with ^{137}Cs source
- Keeps electronics out of detector volume
  - improves maintainability, availability of services (power, cooling, etc)



Towards building testbeam modules

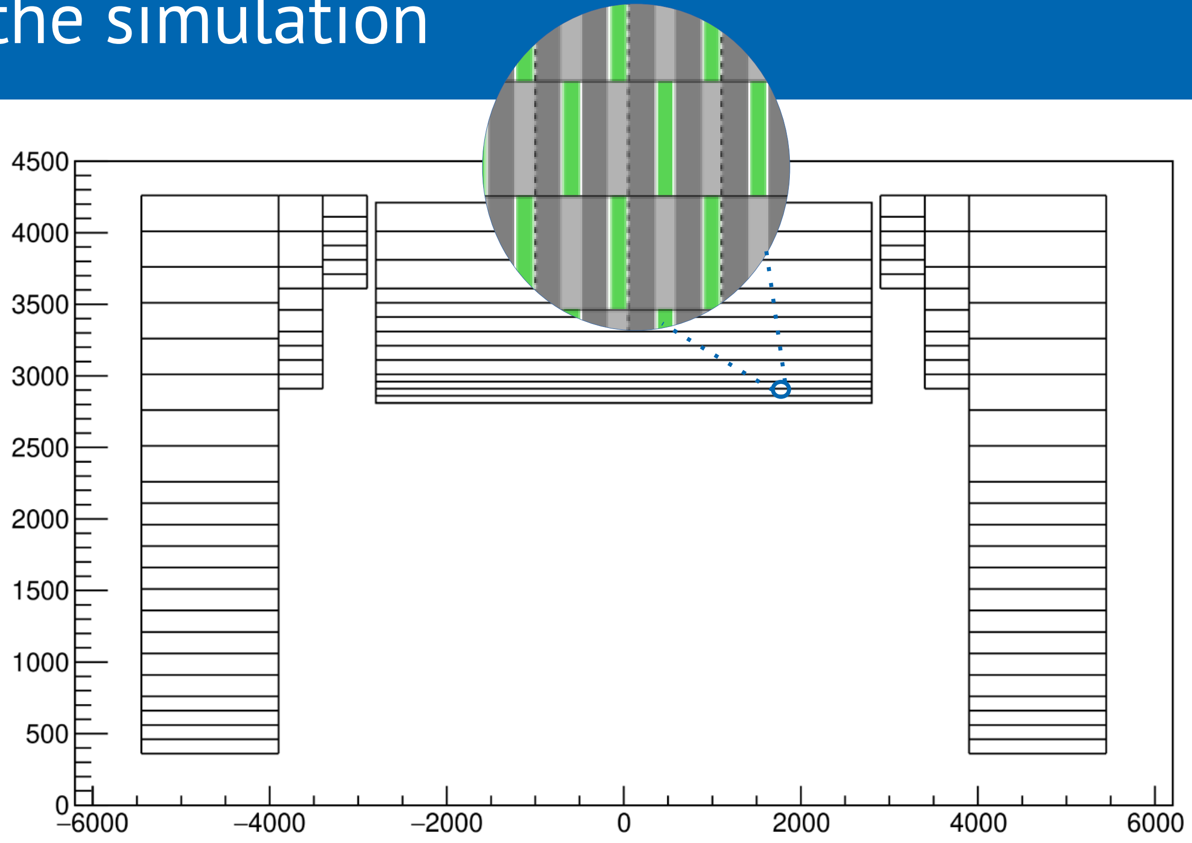
- Ongoing work to build 3 to 5 mini-modules for use at testbeams
  - over 70cm wide and ~1 ton each
- 3D printed fiber flange design iterated
- 8x8 SiPM matrix being tested with LED pulser at Prague with clear fibres and WLS
- HPK single channel SiPM (S13360-1325C) is being tested at CERN with cosmic muons on a scintillating tile coupled to a WLS
- New scintillator developments
  - work at LIP and Institute for Polymers and Composites (Univ. of Minho)
  - different samples produce (PEN, PET, mix of both, adding dopant (BBOT and POPOP))
  - measuring emission spectra, transmittance, light response to ^{90}Sr
  - Reference: P. Conde Muíño et. al, NIM-A Volume 1066, 2024





TileCal implementation in the simulation

- Using key4hep package, both **barrel** and **endcap** geometry implemented in the k4geo model description.
- **Barrel**: 13 radial layers
- **Endcap**: 6 / 9 / 22 radial layers
- Each layer is a sequence of rows consisting of 3 absorber plates and 1 scintillating tile
- Current design of the endcap has a mechanical constraint
  - Scintillating tile width at inner layers is so small that impossible to attach fibers
  - Design must be improved



To fulfill the requirements of the FCC-ee physics program, the geometry/design optimization should be carried out using a **Particle Flow algorithm** (combining tracks and ECal+HCal info)

Readout segmentation in theta

Currently, two different readout segmentations are implemented:

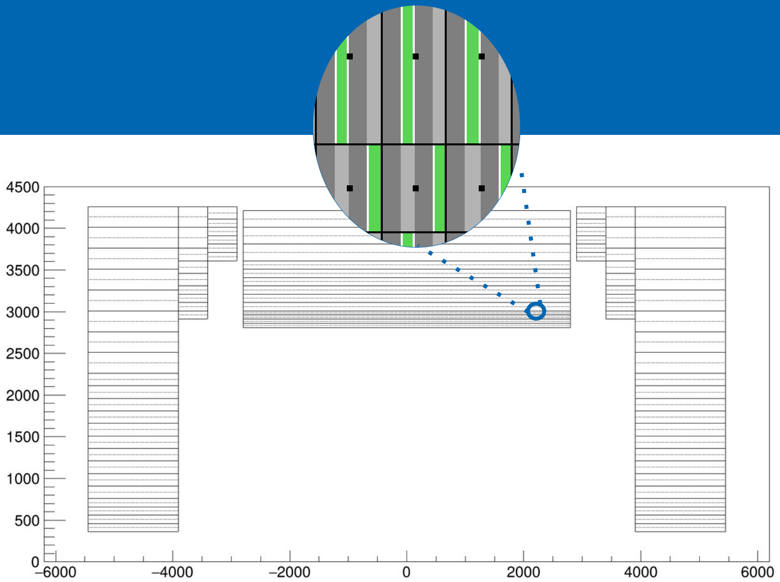
Segmentation with the highest granularity possible

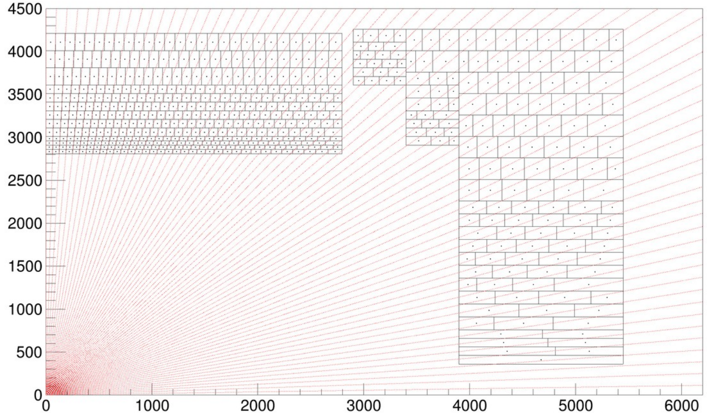
- Each row (3 absorber plates + 1 scint.) in a layer is considered as a single readout cell
  - width of the cell: 18 mm
- 310 cells per layer in the Barrel
- 27 / 27 / 85 cells per layer in the Endcap in one side

Fixed theta segmentation

- Several tiles are grouped in a single readout cell
- Grouping is done to closely follow the theta projective towers with the size of $\Delta\theta \sim 0.022$ rad

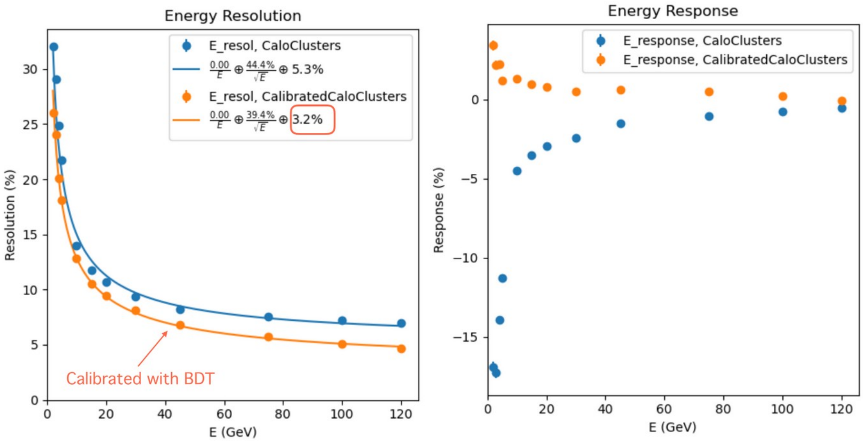
Optimization should be carried out using a Particle Flow Algorithm





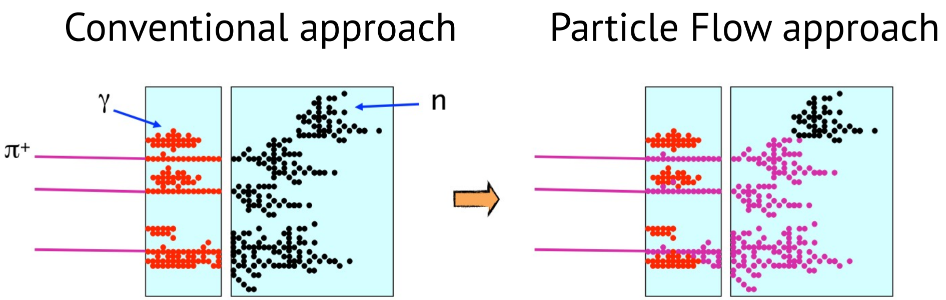
MC performance studies

- Ongoing performance studies using new readout segmentations
- Both **sliding window** and **topological clustering** are implemented
- Working towards **MVA calibration** and Particle Flow Algorithm



Particle Flow Calorimetry

- **In a typical jet:**
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \to \gamma\gamma$)
  - 10 % in neutral hadrons (mainly n and K_L)
- **Conventional calorimetric approach:**
  - Measure all components of jet energy in ECAL/HCAL
  - 50-70% of energy measured in HCAL: $\sigma_E/E \approx 60\% / \sqrt{E}$
- **Particle Flow Calorimetry: reconstruct individual particles**
  - Charged particle momentum measured in tracker (essentially perfectly)
  - Photon energies measured in ECAL
  - Neutral hadron energies measured in HCAL
- Particle flow calorimetry can be used to achieve the challenging jet energy resolution goals of FCC-ee →



$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

Picture taken from the link

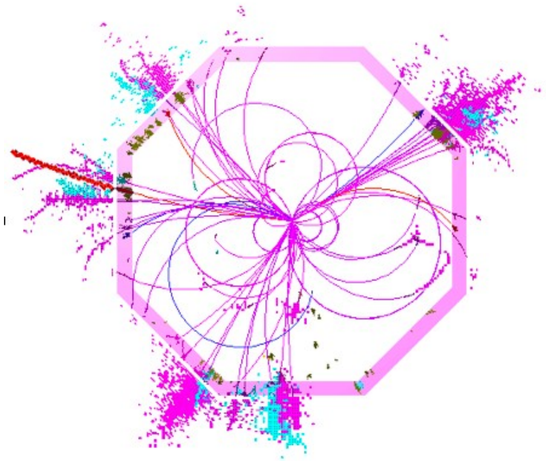
Detector geometry/readout optimization should be carried out using a particle flow algorithm

Pandora Particle Flow Algorithm

- **PandoraPFA** originally developed for the application in a future Lepton Collider experiments
  - Implemented in iLCSoft
- Widely considered as a “state of the art” in particle flow reconstruction
- Used in FCC-ee CLD detector simulation
- We aim to implement the **PandoraPFA** in **ALLEGRO detector simulation**

Multi-algorithm pattern recognition

PandoraPFA



https://github.com/PandoraPFA

https://arxiv.org/abs/0907.3577

https://arxiv.org/abs/1506.05348

PandoraPFA algorithm overview

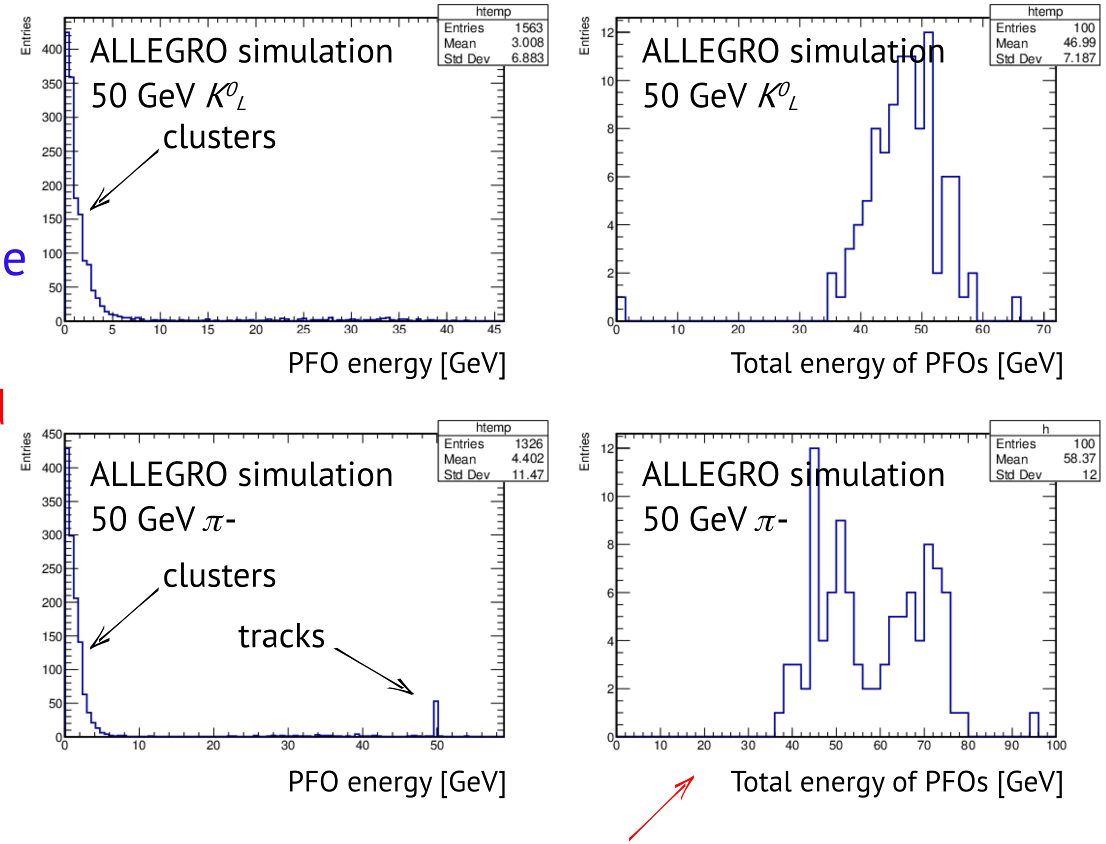
PandoraPFA in ALLEGRO simulation

- **Ongoing work to implement the PandoraPFA in ALLEGRO simulation**
- Inputs for PandoraPFA:
  - Detector information (layers, material, etc…) ← prepared for barrel ECAL and HCAL
  - Reconstructed Calorimeter (ECAL/HCAL/MUON) hits ← currently, only ECAL and HCAL hits are reconstructed
  - Tracks (at IP/FirstHit/LastHit/Calorimeter states) ← no reconstructed tracks in ALLEGRO, therefore, working with truth tracks
  - KinkVertexCollections
  - ProngVertexCollections
  - SplitVertexCollections
  - V0VertexCollections

  These are not available, therefore, the function that uses these collections is disabled
- The current state of the implementation resides in a personal GitHub repositories: https://github.com/Archil-AD/ALLEGRO_PandoraPFA
- **Anyone is welcome to join the effort**

K^0_L and π- reconstruction using PandoraPFA (work in progress)

- 100 events of 50 GeV K^0_L / π- are simulated at 60°
- PandoraPFA can reconstruct hadronic showers in the ALLEGRO detector and use charged hadron tracks
- However, too many clusters are produced
- Failed to associate the showers to the track → energy is double counted (confusion)!
- Further investigation is needed



Summary

- TileCal is the hadronic calorimeter for ALLEGRO general-purpose FCC-ee detector concept
- Ongoing work to build testbeam modules
  - First mechanical part is produced
  - Working on the SiPMs and SiPM-fibre coupling
  - Studying new scintillator materials
  - Still many open questions to resolve
- First version of the TileCal barrel and endcap is implemented in the simulation within key4hep framework
  - geometry/design should be optimized using a Particle Flow algorithm
- Ongoing work to implement PandoraPFA in ALLEGRO simulation
  - Managed to create PandoraPFA particle flow objects from truth tracks, ECAL and HCAL hits
  - Still many issues to fix

Thank you for your attention

Backup

Tracks from MCParticles in PandoraPFA

- Newly created class of DDTrackCreatorALLEGRO in DDMarlinPandora allows to feed the PandoraPFA with the tracks produced using TracksFromGenParticles
  - The default cuts are applied on d0 and z0 (50 mm)
  - Checked if a track reaches the ECAL barrel (based on the track state at Calo)
  - By default, the track is assumed to be a charged pion
- CreateTrackAssociations is disabled due to missing relevant collections
  - Attempts to identify $\gamma \to e^+e^-$, $K_S^0 \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ and $\overline{\Lambda} \to \overline{p}\pi^+$ decays
  - Attempts to identify muons from $\pi^\pm/K^\pm$ decays, and charged pions from charged Hyperon decays
  - Relates daughter tracks to the parent and produces sibling relationship →

    at the later stage, the PFO is reconstructed using the parent track, and the particle Id is assigned retrieved from the corresponding vertex

→ since this is disabled, all charged hadron tracks will be assigned the default particle Id of charged pion

Tracks for PandoraPFA

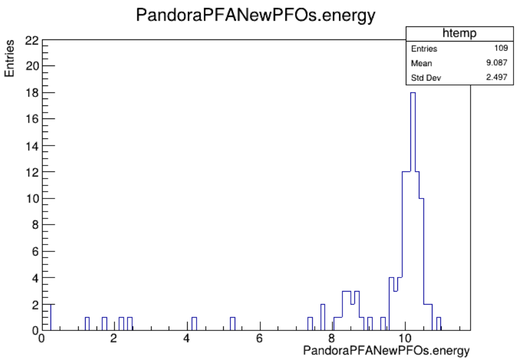
- Currently, the tracking system taken from IDEA "as is"
  - No track reconstruction performed
- Since the reconstructed track resolution is expected to be almost perfect, we can work with "truth tracks"
- TracksFromGenParticles algorithm available in k4RecTracker is modified to form the track objects with all necessary information for PandoraPFA
  - Tracks are created only from charged MCParticles
  - Track state at IP is defined at the position of MCParticle production vertex
  - Track state at FirstHit is defined using the position of the MCParticle associated lowest radius Geant4 hit in the Drift Chamber, and the extrapolated momentum from the track state at IP
  - Track state at LastHit is defined using the position of the MCParticle associated highest radius Geant4 hit in the Drift Chamber, and the extrapolated momentum from the track state at FirstHit
  - Track state at Calorimeter is defined using the position of the extrapolated track intersection point to the cylinder of the ECal barrel at inner radius (2172.8 mm), and the extrapolated momentum from the track state at LastHit
  - The algorithm can be further improved to produce kink/prong/split/V0 vertex collection

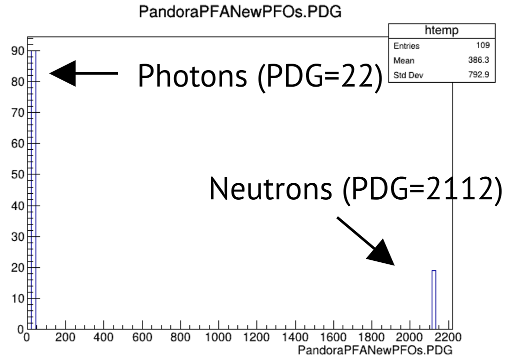
Photon reconstruction using PandoraPFA in ALLEGRO

- 100 events of 10 GeV *photons* are simulated at 60° to check if PandoraPFA can use ECAL hits for the reconstruction
- PhotonReconstruction algorithm calibration file (PandoraLikelihoodData9EBin.xml) is taken from CLDConfig
- For comparison, CLD simulation + reconstruction is also performed following this instructions

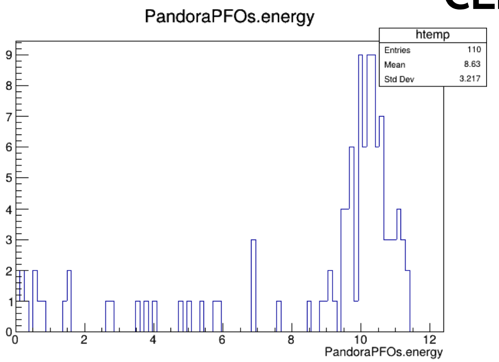
PandoraPFA can identify photons in the ALLEGRO detector!

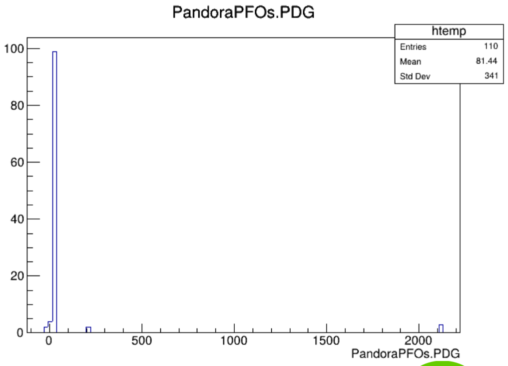
ALLEGRO





CLD

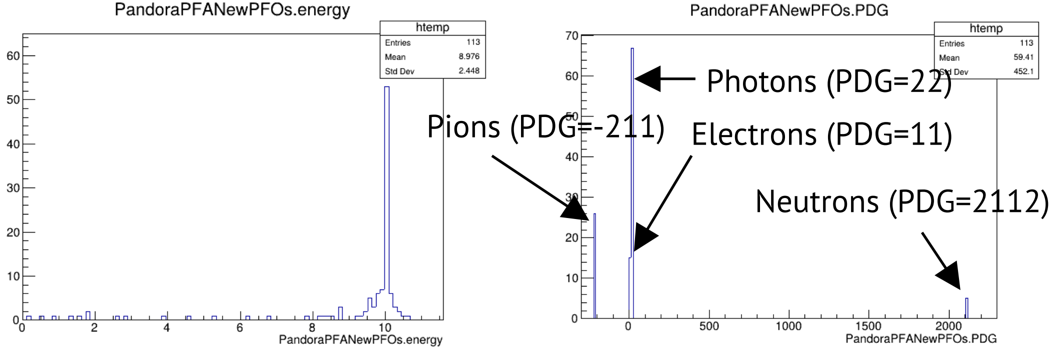




Electron reconstruction using PandoraPFA in ALLEGRO

- 100 events of 10 GeV *electrons* are simulated at 60° to check if PandoraPFA can use tracks and ECAL hits for the reconstruction
- For comparison, CLD simulation + reconstruction is also performed following this instructions
- PandoraPFA can reconstruct electrons using tracks and showers in the ECAL of the ALLEGRO detector
- It can well associate the shower in ECAL to the track and use the track energy instead of Calorimeter energy
- Failed to identify the track as an electron
  - A track is identified as electron if the associated shower cluster is classified as EM shower
  - By changing the cluster RMS cut from 40mm to 70mm manged to identify ~15 tracks as electrons
  - Clearly, tuning of EM shower related parameters is necessary

ALLEGRO



CLD