

Summary of PFA discussion at the Lisbon workshop

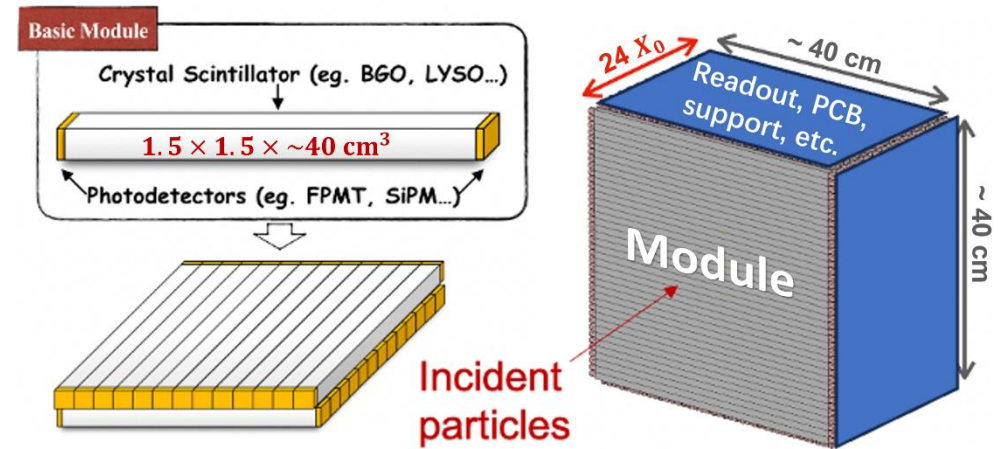
Weidong Li (IHEP)

April, 15th, 2026

CyberPFA: Crystal ECAL geometry

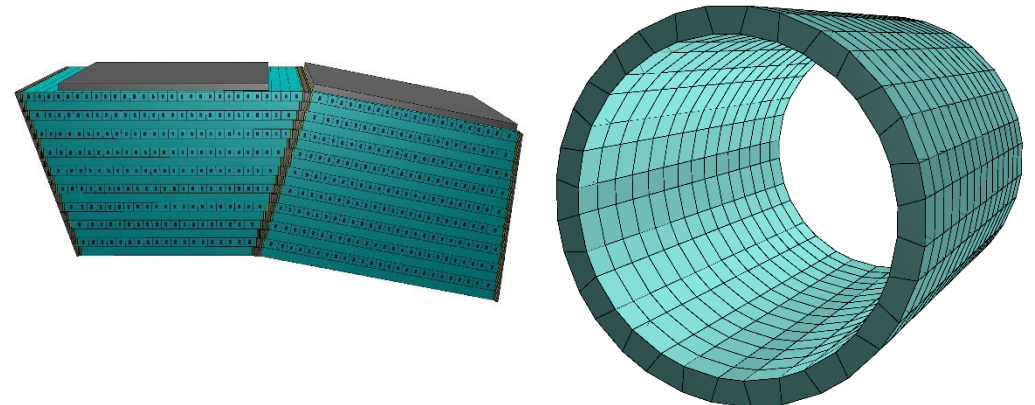
❖ BGO Crystal Units

- Long bar crystals made of BGO serve as the basic ECAL detection elements.
- Each crystal is read out by SiPMs at both ends, providing precise energy and timing measurements.
- Crystals in adjacent layers are oriented perpendicularly.
- Multiple layers form a module (see Fig. ECAL_module).
- Crystal transverse size: 15 mm, about 0.67 Molière radius of BGO (22.3 mm).
- The crisscross geometry means the ECAL does not behave like a traditional projective calorimeter.



❖ Barrel ECAL Layout

- Each module contains 18 longitudinal layers, totaling $\sim 24 X_0$.
- Modules have trapezoidal shapes (right), preventing inter-module gaps from pointing toward the interaction point.

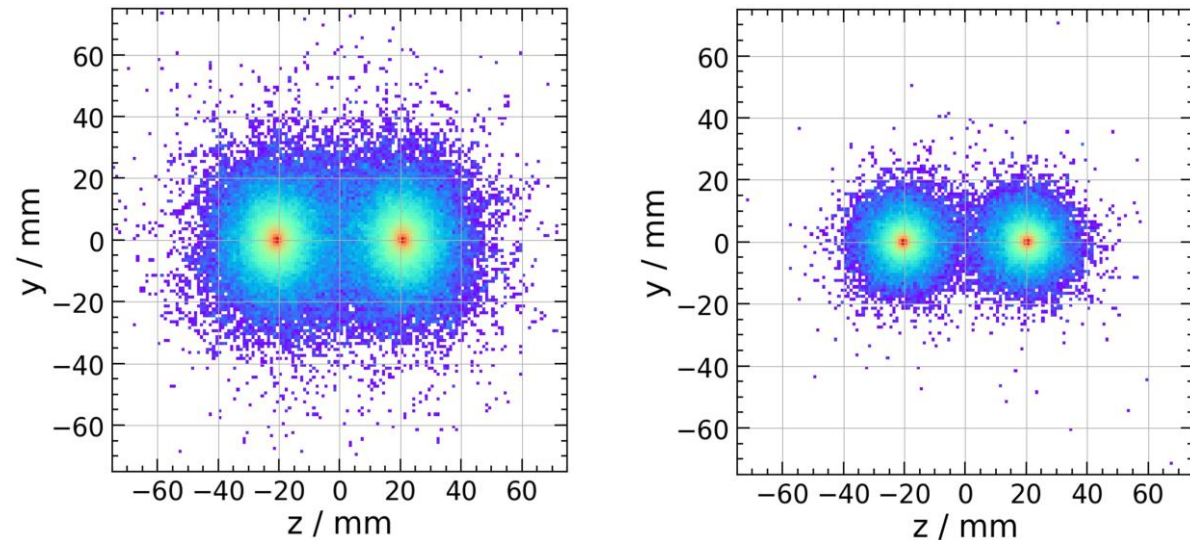


CyberPFA: Reconstruction challenges

- ❖ A larger Molière radius and a reduced λ_I/X_0 ratio result in more pronounced shower overlap within the ECAL.
- ❖ Wrong bar association leads to incorrect hit positions and can even produce ghost hits/clusters
 - The wrong bar pair yields a displaced intersection point, degrading spatial accuracy and in more severe cases producing ghost clusters that do not correspond to any real energy deposition

Larger R_M & smaller λ_I/X_0

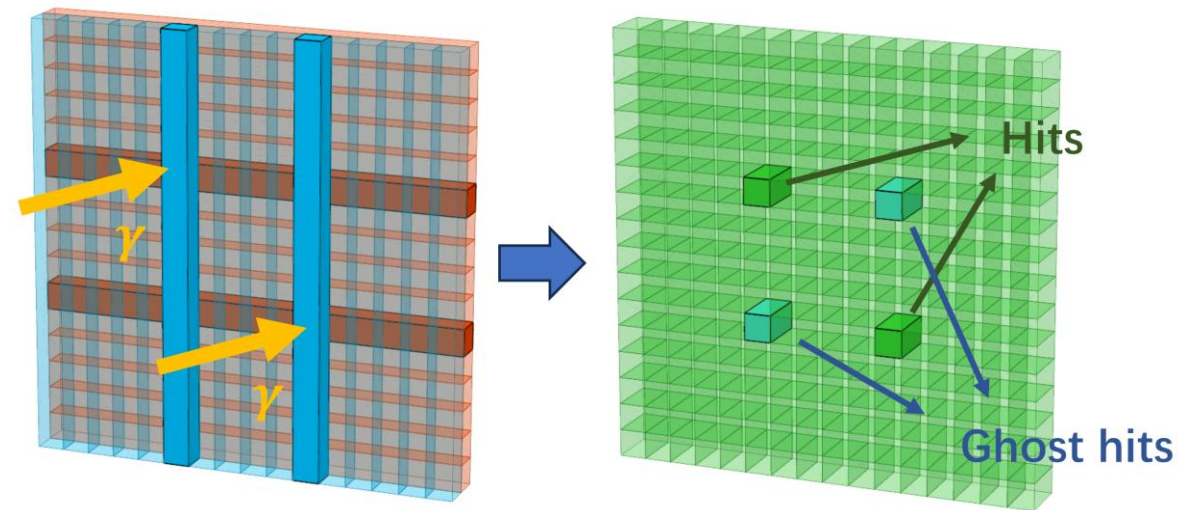
Shower overlap



Two 5 GeV EM shower in BGO crystal (left) and Tungsten (right)

Layout of orthogonally oriented bars

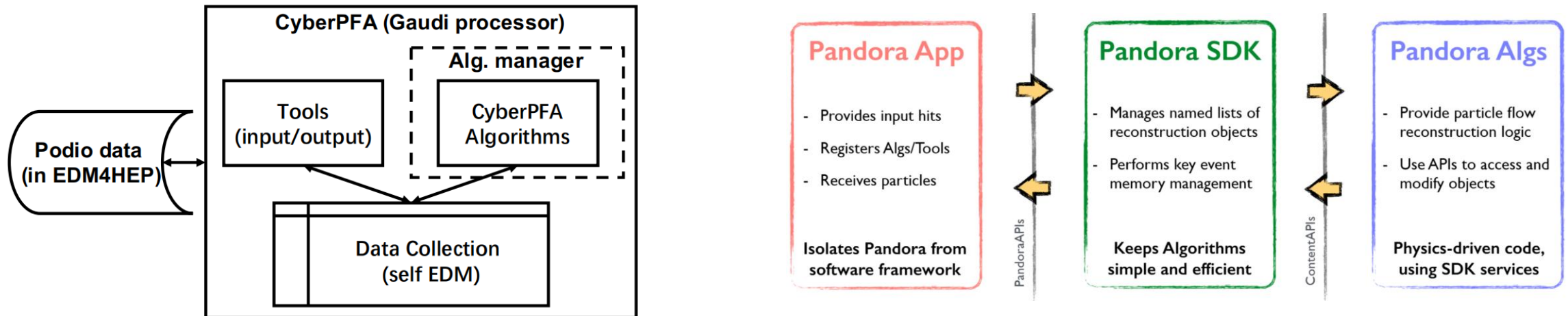
Ghost hits



Demonstration of ghost hits

CyberPFA: Software structure

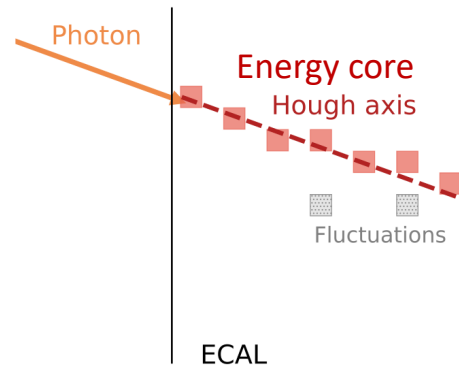
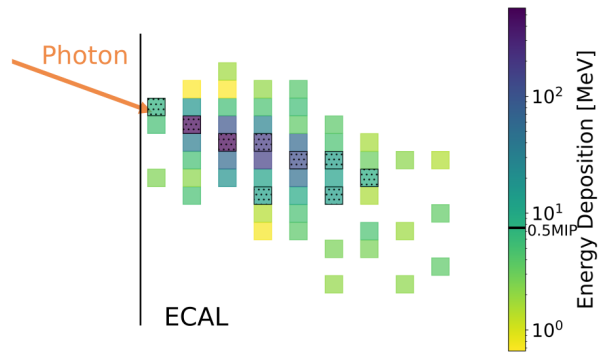
- ❖ The implementation is based on the Gaudi framework, using a modular, building-block algorithm and sub-algorithm structure comparable to PandoraSDK.
- ❖ A sub-algorithm Manager module coordinates the registration, configuration, and execution flow of all sub-algorithms.
- ❖ A dedicated Tool is implemented to perform bidirectional conversion between the CyberPFA event data model and the EDM4hep event data model.



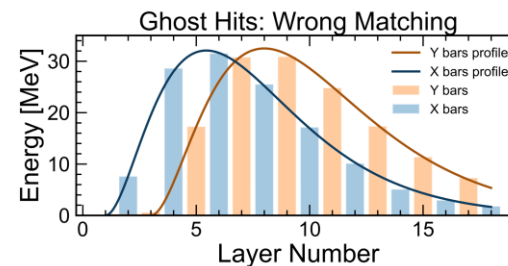
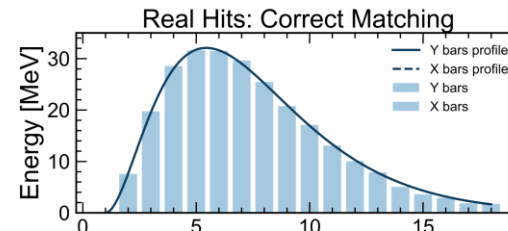
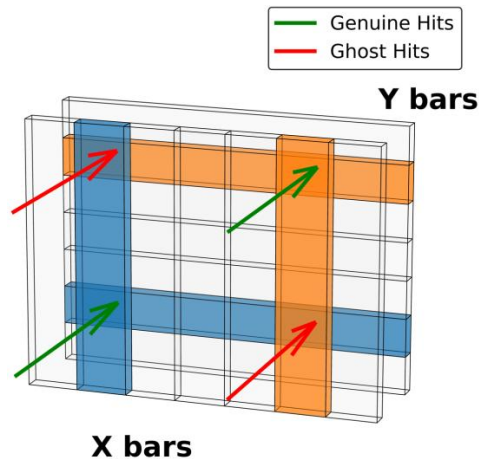
<https://github.com/PandoraPFA>

CyberPFA: Key reconstruction techniques

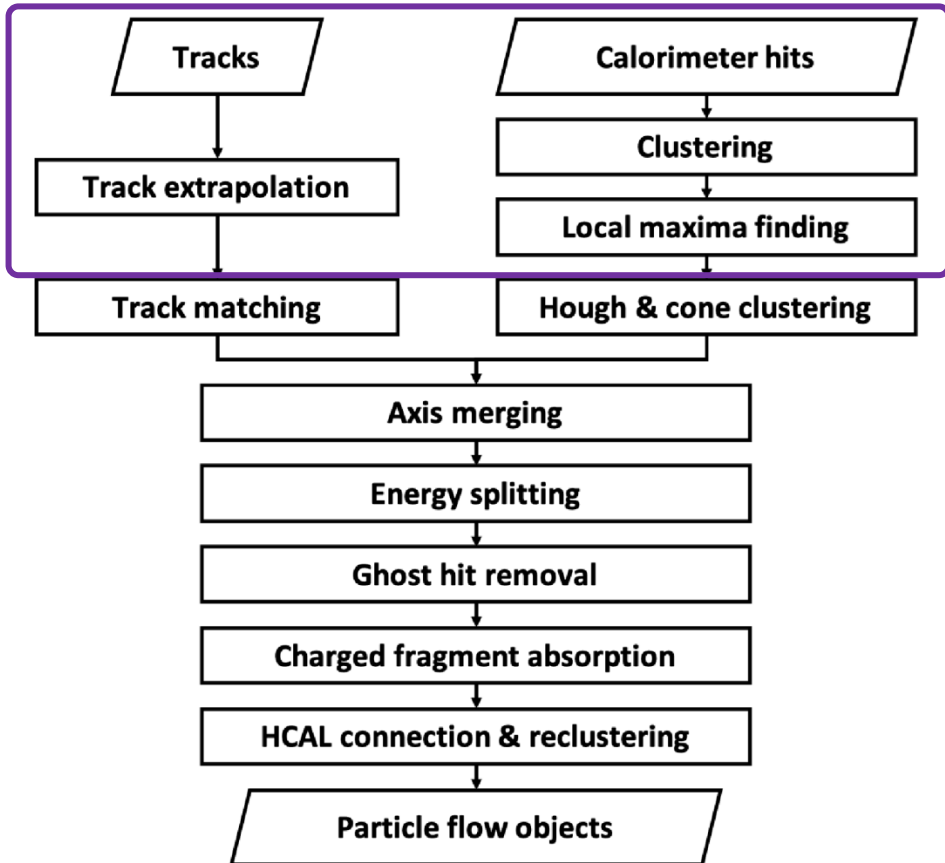
- ❖ Energy-core-based shower recognition, using controlled energy propagation to reinforce the physical shower core and improve pattern-recognition robustness in dense topologies.



- ❖ Ghost-hit suppression, combining longitudinal shower-shape information, module-level geometric constraints, and SiPM timing features to reject spurious bar intersections.

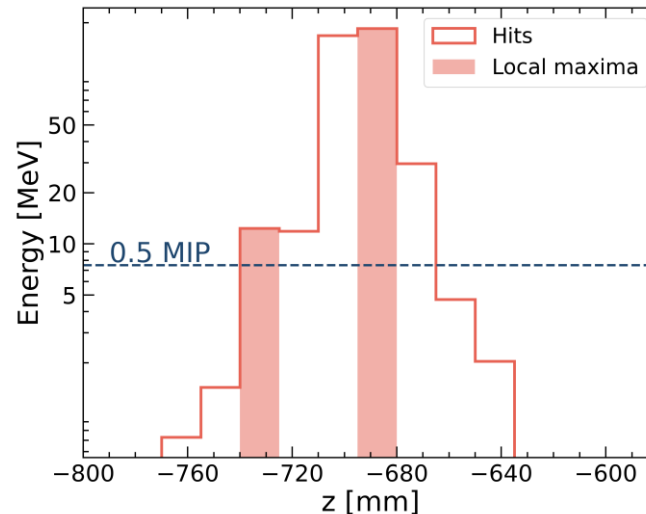


CyberPFA: Reconstruction workflow (1)

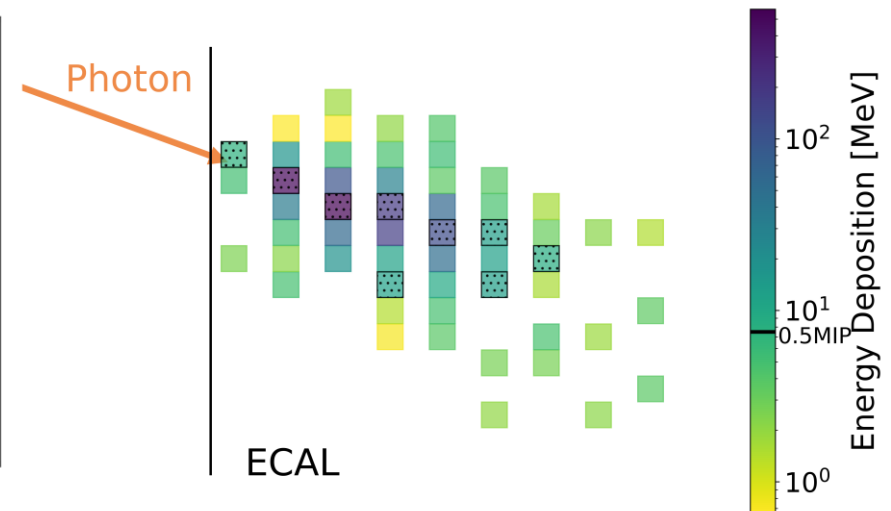


Step 1: preparation

- Track extrapolation
- Clustering: Adjacent crystals with energy deposits above a predefined threshold are grouped together
- Local Maximum finding: A local maximum is a crystal whose energy exceeds that of its two immediate neighbors in the same layer



Definition of local maximum:
 E greater than nearby crystal and
greater than 0.5 MIP

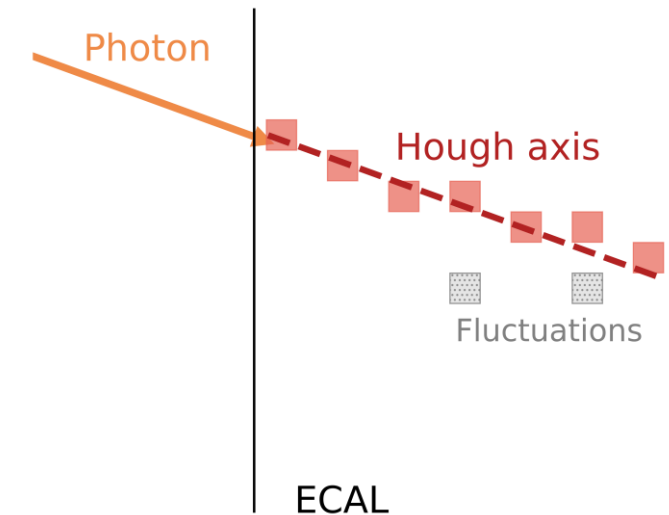
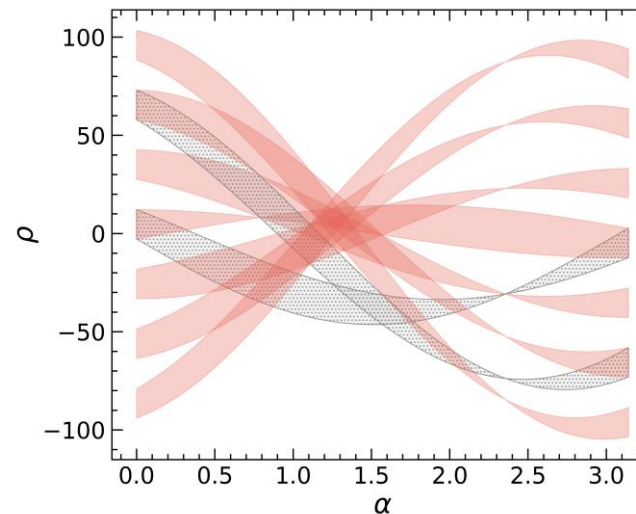


Spatial distribution of hits and local maxima of a 5 GeV EM shower

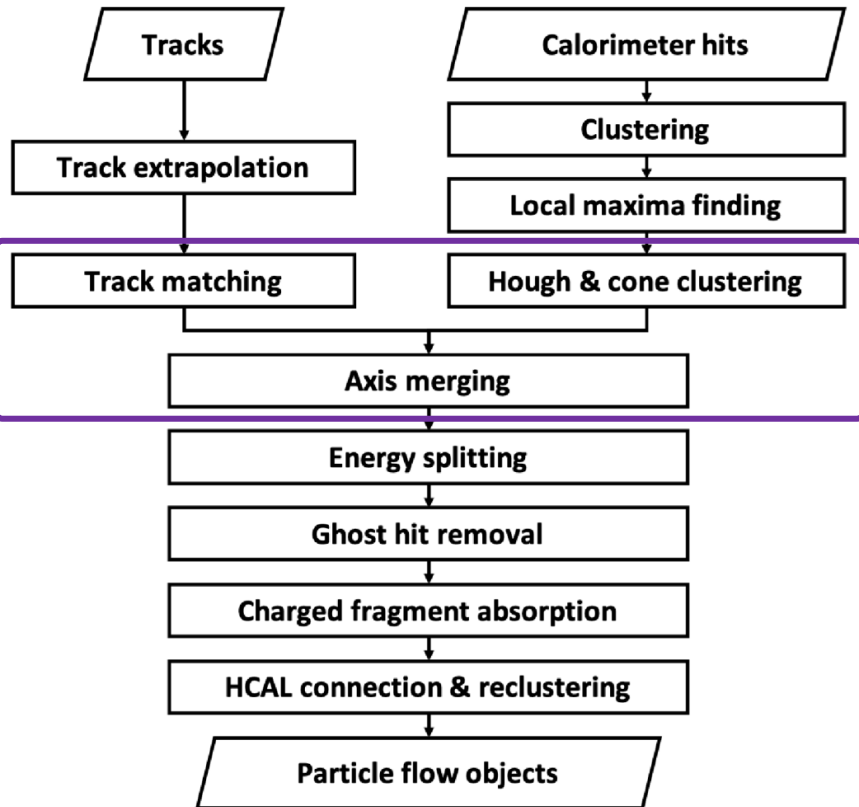
CyberPFA: Reconstruction workflow (2)

Step 2: Energy-core-based shower recognition

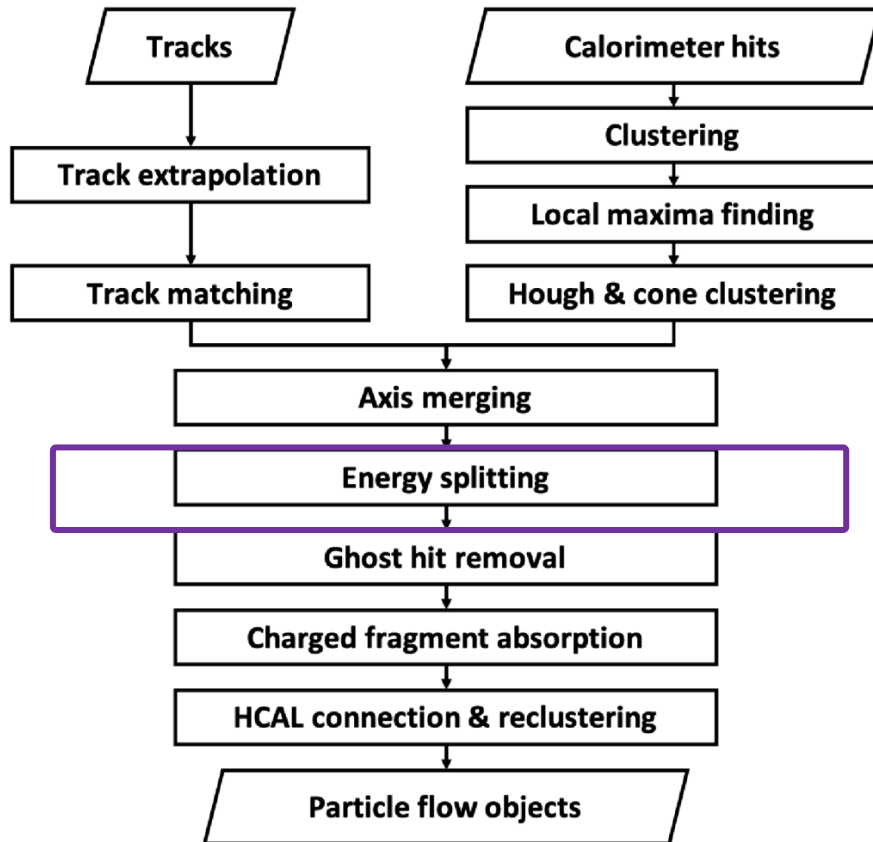
- Each local maximum is treated as a square crystal that maps to a band in Hough space
- Overlapping bands reveal aligned maxima that form a Hough axis
- A valid axis must include at least three consecutive maxima, point toward the interaction point,
- Allow low-energy sharing between nearby axes, and match with an axis in the other projection plane to be identified as a photon candidate.



Energy-core based photon recognition using Hough transform

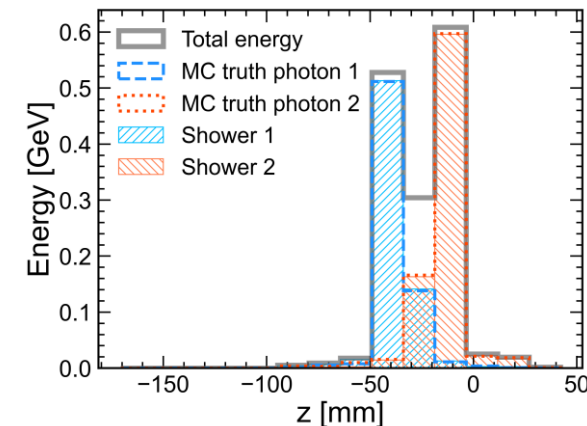


CyberPFA: Reconstruction workflow (3)



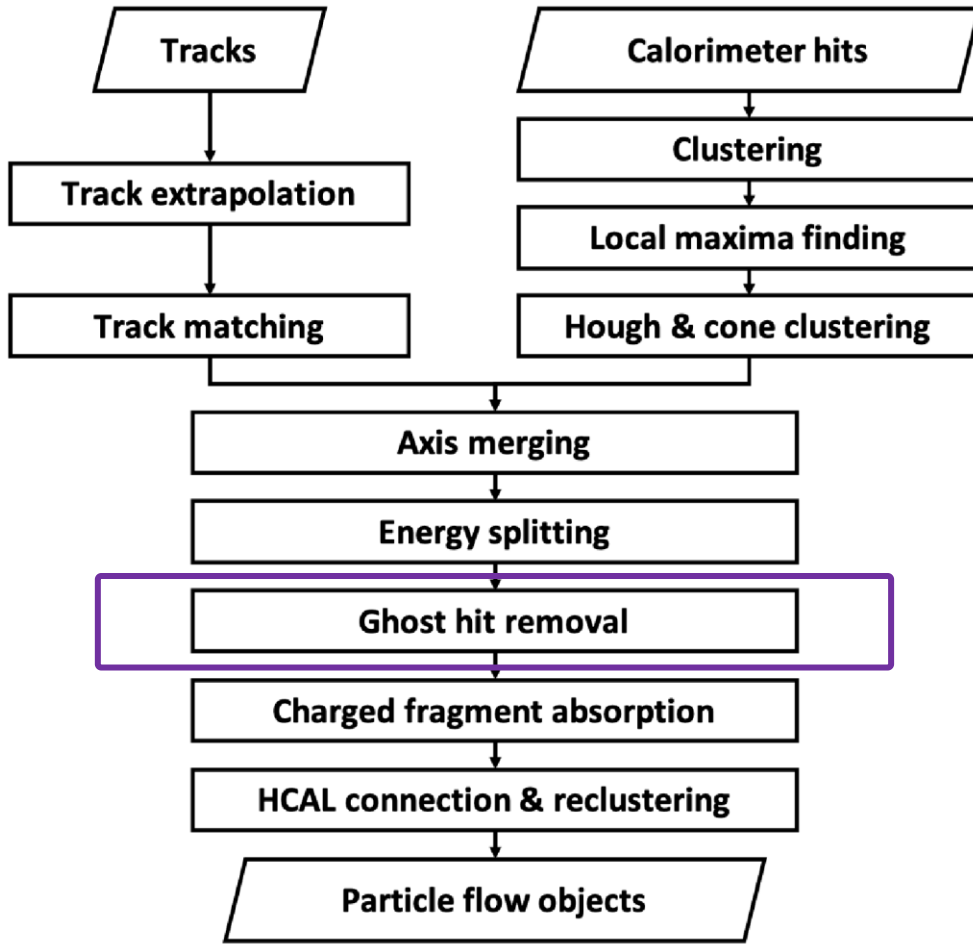
Step 3: energy splitting

- Overlapping EM showers are separated by redistributing crystal energies according to an expected shower profile.
- The shower shape is modeled with two exponentials → captures core + halo.
- For each crystal:
 - Compute each photon's expected contribution based on distance to shower center.
 - Split the measured energy proportionally among photons
- Update photon positions using an energy-weighted center
- Iterate until the solution becomes stable.



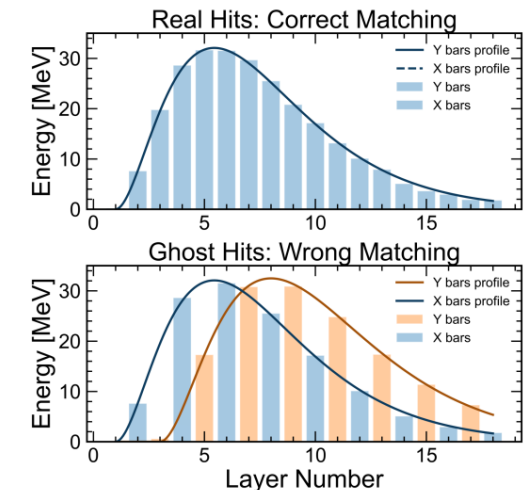
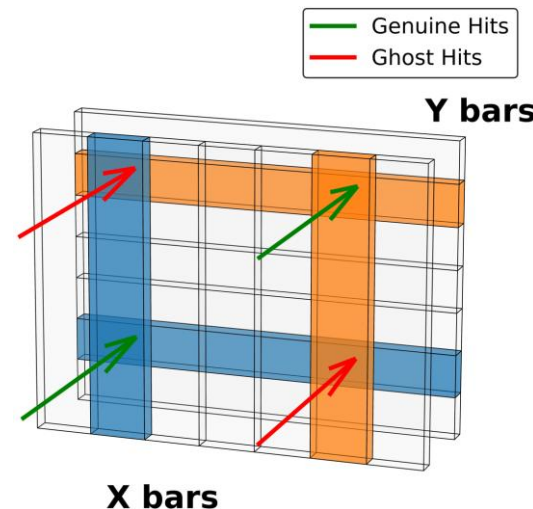
Energy splitting of two overlapping EM shower

CyberPFA: Reconstruction workflow (4)



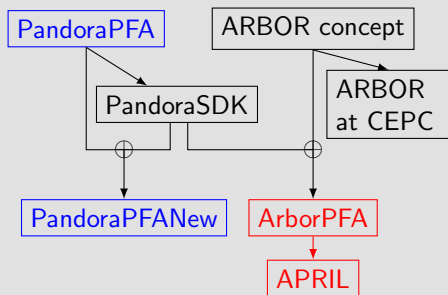
Step 4: ghost hit removal

- Orthogonal X/Y crystal bars create multiple intersection points, including fake ones (“ghost hits”).
- Real particle showers have a smooth, continuous energy profile along the detector depth.
- For each X–Y combination:
 - Compare their longitudinal energy profiles across layers.
 - True hits show matching profiles but Ghost hits show clear inconsistencies.
- Additional checks (track extrapolation, timing) further confirm the real intersections.



APRIL history

ILD PFA reconstruction



PFA strategy

Both PandoraPFA and APRIL, construct many small clusters then merge them.

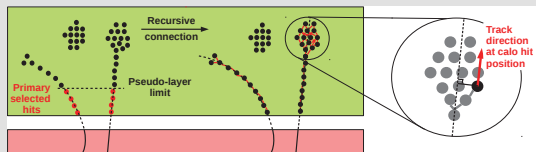
- $APRIL \simeq ARBOR \text{ concept} + PandoraSDK \text{ algorithms}$

The APRIL algorithm

APRIL : Algorithm for Particle Reconstruction at ILC from Lyon.

The clustering strategy

- 1 Start from tracks
(track driven clustering), extrapolate tracks in calorimeters \rightarrow cluster hits close to the tracks.



Clusters linked to tracks are defined as charged clusters.

- 2 Perform Arbor like clustering with all hits (parameters set to avoid making big clusters).
- 3 Some hits remain unclustered \rightarrow Nearby hits merging : remaining unclustered hits are clustered with mlpack DBSCAN (efficient Nearest Neighbour clustering)
- 4 Cluster merging : if $E_{track} > E_{cluster}$, merge nearby cluster.

Arbor like clustering

Graph theory : a shower is an oriented tree.

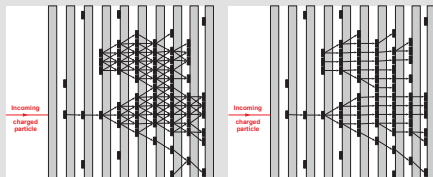
Orientation

- Rearrange hits in virtual nested cylinders (= pseudo layers)
- Count them from the inside.
- Forward direction = increase pseudo layer number.



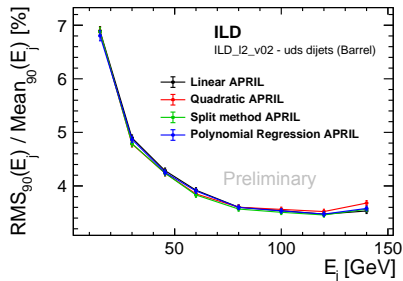
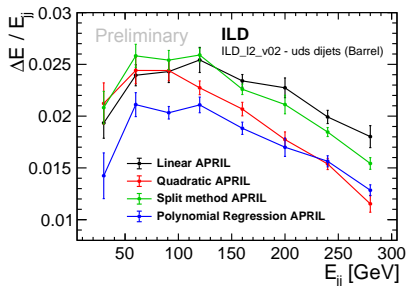
Process

- 1 Connect all neighbouring hits (use mlpack NeighborSearch).
- 2 Clean connectors = keep max one backward connection per hit.



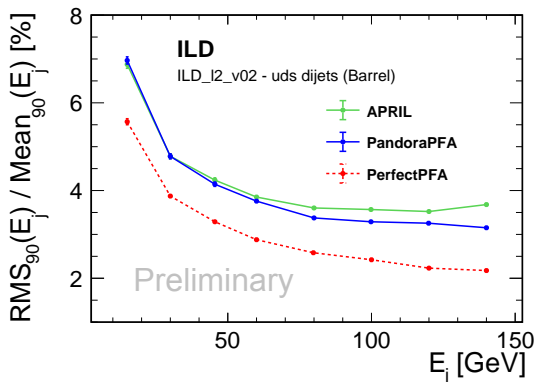
Results

- Event samples: $e^+e^- \rightarrow q\bar{q}$, where $q = u, d, s$ ($|\cos\theta_q| < 0.7$)
- With ILD option 2 large (SDHCAL, SiW ECAL), Videau geometry, iLCSoft, APRIL
- Comparison of different SDHCAL energy reconstruction formulas
- Jet energy resolution, $\text{JER} = \frac{\text{RMS}_{90}(E_j)}{\text{Mean}_{90}(E_j)} = \sqrt{2} \cdot \frac{\text{RMS}_{90}(E_{jj})}{\text{mean}_{90}(E_{jj})}$



Results (continued)

- JER at 91.2 GeV with quadratic method:
APRIL: 4.2%; Pandora: 4.1%; Perfect PFA: 3.29% (work in progress)



- APRIL slightly better than Pandora at low energies for SDHCAL
- APRIL has no reclustering → crucial to counter confusion at high energy.

Reclustering / Cluster cutting

- If $E_{cluster} > E_{track}$: need to remove energy from the cluster
 - Reclustering : Break the cluster and restart clustering with different parameters (Pandora strategy)
 - Cluster cutting : cut the cluster and remove some parts

AMSTER algorithm

- Based on graph theory with Minimum Spanning Tree (MST)
- Cut the connections with bigger weights
- Tested on simple cases → To be included in APRIL

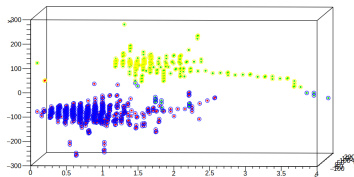


Figure: Event of a π^- (red) and a K^0 (green) in two clusters (blue and yellow)


APRIL Software inclusion and other developments

- APRIL currently being fine-tuned for ILD_I2_v02 (SDHCAL + SiW ECAL), but **versatile**
 - → **Can be applied to other detector concepts**
- SDHCALContent : Contains T-SDHCAL plugins (corrections, energy reconstruction formulas, ...) [▶ Git repo](#) → **Paper on energy-reconstruction formulas under collaboration review**
- APRILContent : Contains the APRIL algorithms [▶ Git repo](#)
- DDMarlinPandora update : Updated DDMarlinPandora able to run APRIL and SDHCALContent [▶ Git repo](#)
- All added to the Key4hep stack [▶ Git repo](#)
- **Anyone can run APRIL and/or the SDHCALContent plugins**

Commit `b028880`

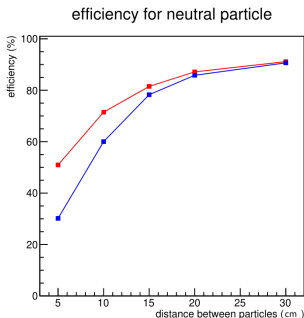
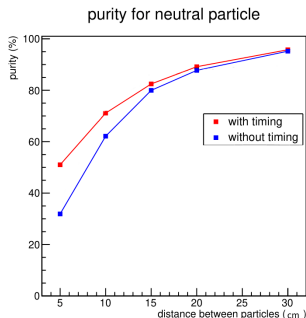
 jmcarell authored on Jun 2 · ✓ 11 / 11 · [Verified](#)

Add sdhcalcontent and aprilcontent to the stack (#754)

 [main](#) (#754)

PFA with timing

- SDHCAL should allow timing segmentation ≤ 100 ps thanks to MRPC \rightarrow T-SDHCAL (see G Grenier's talk from yesterday)
- Possibility to follow the particles in "real time"
- Previous studies : timing improves separation
- **Goal** : Add timing to APRIL



Summary

- A particle flow algorithm implementing the ARBOR approach has been developed in the PandoraSDK framework.
- Available for anyone from the Key4hep stack
- Competing with PandoraPFA at low and intermediate jet energies in SDHCAL.
- Work started for cluster cutting algorithm for APRIL is expected to improve the reconstruction at higher jet energies.
- Promising results with timing
- Next steps
 - Fully implement split cluster procedure (AMSTER)
 - Continue timing implementation/testing

Thank you for your attention !