k4Clue: the CLUE Algorithm for Future Collider Experiments

Erica Brondolin,
Felice Pantaleo, Marco Rovere

Connecting The Dots 2023, 10th October 2023

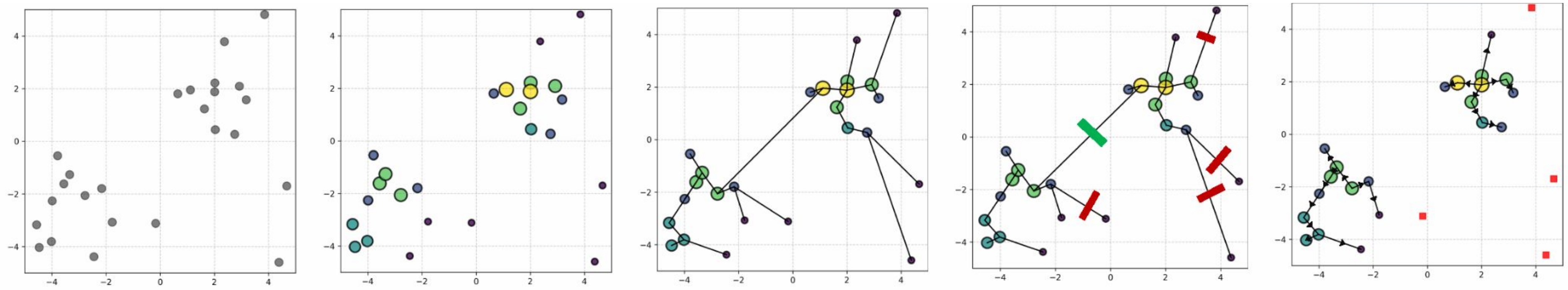
Introduction

CLUstering of Energy

- CLUE (**CLUstering of Energy**) is a fast density-based clustering algorithm for the next generation of sampling calorimeter with high granularity in HEP

  [doi: 10.3389/fdata.2020.591315](https://doi.org/10.3389/fdata.2020.591315)

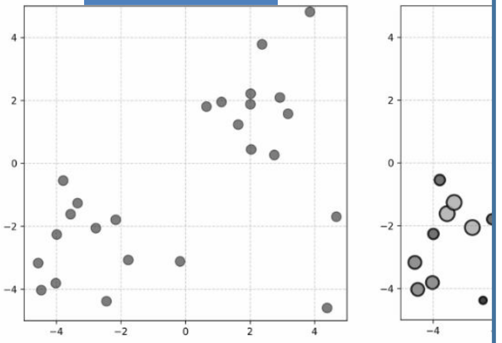
- It uses **energy density** - rather than individual cell energy - to establish **seeds, outliers, and followers** in 2D planes.
- **GPU-friendly**, i.e. suitable for the upcoming era of heterogeneous computing in HEP
- Standalone repo: CLUE - kalos gitlab.cern.ch

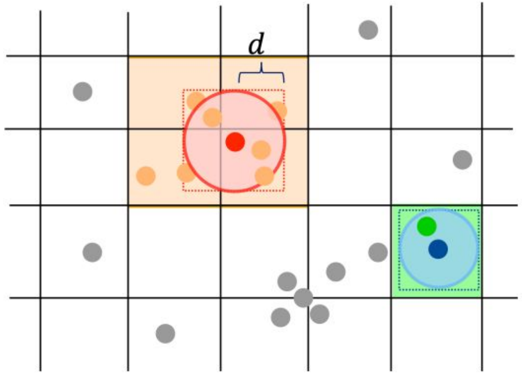


Step 1: Building Data Structure

- To enable efficient neighbor search in CLUE, a fixed-grid spatial index is constructed as a first step
- Build **Fixed-Grid Spatial Index** for hits on each layer:
  - Each tile in the grid hosts indices of hits inside it and has a fixed length of memory to store the hosted indices. It is independent by the detector granularity.
- When searching for neighbors within a specified distance d, CLUE only examines hits within the bins touched by a window of size $(x_i \pm d, y_i \pm d)$ centered on each point of interest $(N_{d,i})$

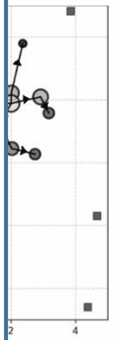
build data structure





d-searchBox:
$\Omega_d(i) = \{j : j \in$ tiles touched by square window$(x_i \pm d, y_i \pm d)\}$

d-neighborhood:
$N_d(i) = \{j : d_{ij} < d\} \subset \Omega_d(i)$



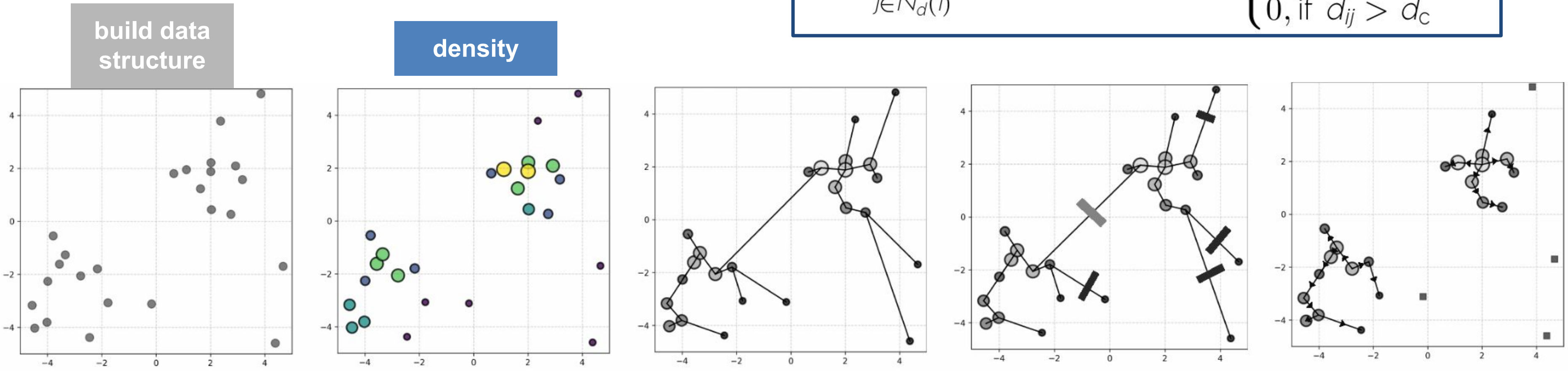
Step 2: Local energy density

- Calculate local energy density (ρ_i) in a distance (d_c)
  - Each hit *j* weighted by the deposited energy (E_j)
  - For each hit, calculate ρ_i

convolution kernel

k = 0.5

$$\rho_i = \sum_{j \in N_d(i)} E_j \times f(d_{ij})\,;\;\; f(d_{ij}) = \begin{cases} 1, \text{if } i = j \\ k, \text{if } 0 < d_{ij} \le d_c \\ 0, \text{if } d_{ij} > d_c \end{cases}$$

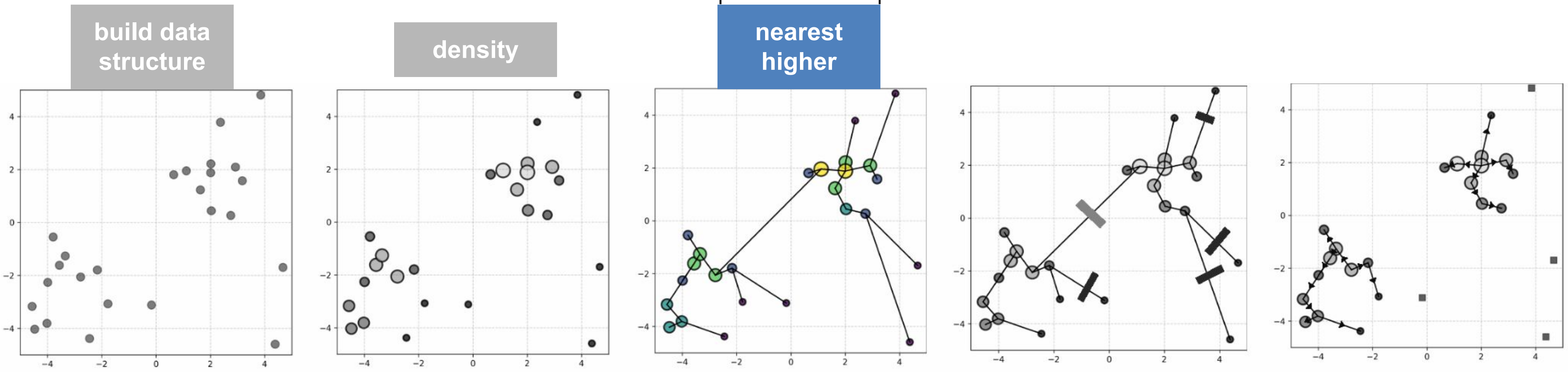


Step 3: Find "closest higher hit"

- Calculate "Nearest-Higher" hit within $N_{dm}(i)$
  - Define $d_m = o_f * d_c$
  - Find the closest hit with higher local energy density, nh_i

$$nh_i = \begin{cases} argmin_{j \in \hat{N}_{d_m}(i)} d_{ij}, \text{ if } |\hat{N}_{d_m}| \neq 0, \hat{N}_{d_m}(i) = \{j : j \in N_{d_m}(i), \rho_j > \rho_i\} \\ -1, \text{otherwise} \end{cases}$$

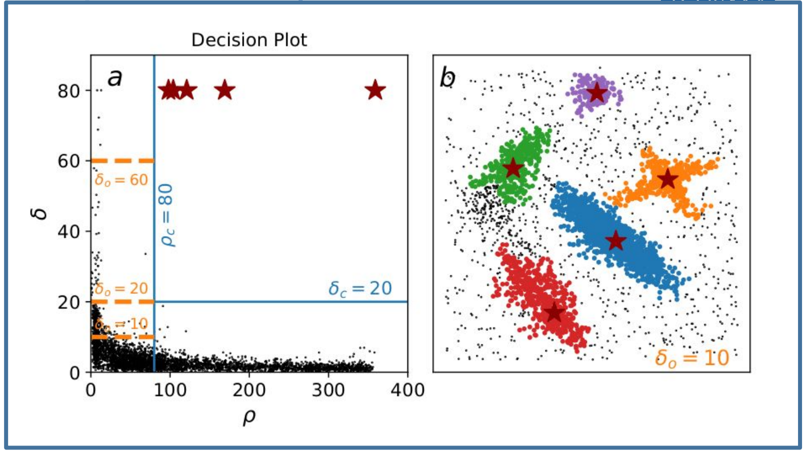
  - Calculate the separation distance $\delta_i = dist(i, nh_i)$

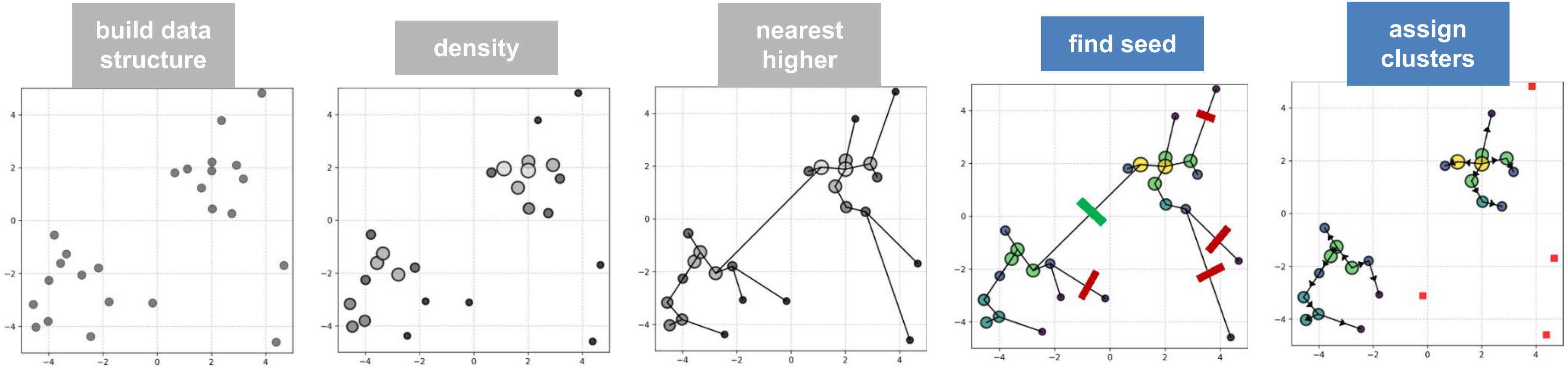


Step 4: Classify hits

- Promote as **seed** if $\rho_i > \rho_c$, $\delta_i > d_c$
- Demote as **outlier** if $\rho_i < \rho_c$, $\delta_i > o_f * d_c$
- Assign unique, progressive cluster ID to each cluster
    - **Followers** are defined and associated to their closest seed

Example of decision plot





Clustering procedure recap

Input parameters:

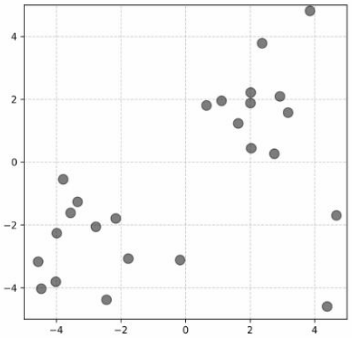
d_c : Critical Distance

o_f : Outlier Delta Factor

ρ_c: Minimum Local Density

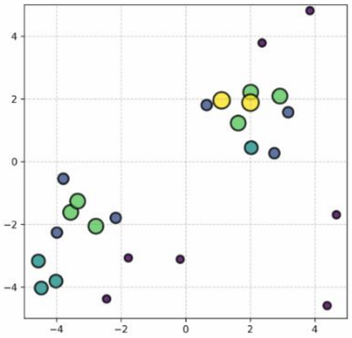
build data structure

Query the neighborhood of a point by looping over the points in N_d in the bins touched by the tiles intersected by d_c



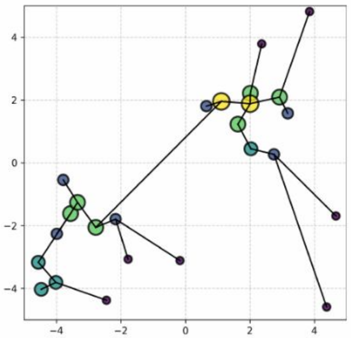
density

Hit position and energy used to calculate the hit's local energy density ρ_i and its distance δ_i to the nearest hit with higher local density



nearest higher

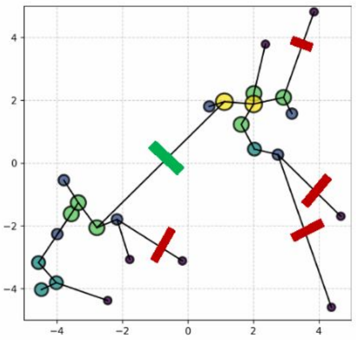
Define the nearest-higher of each hit as the hit with the local energy density higher then the hits itself and within a distance of $d_m = o_f \times d_c$



find seed

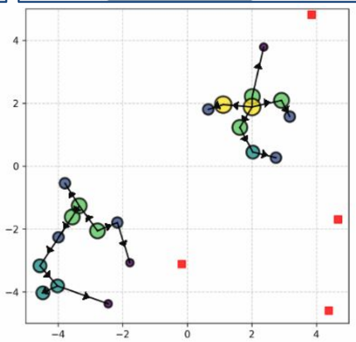
Use following criteria:

- seed: $\rho_i \geq \rho_c$ and $\delta_i \geq d_c$;
- outlier: $\rho_i < \rho_c$ and $\delta_i \geq (o_f \times d_c)$

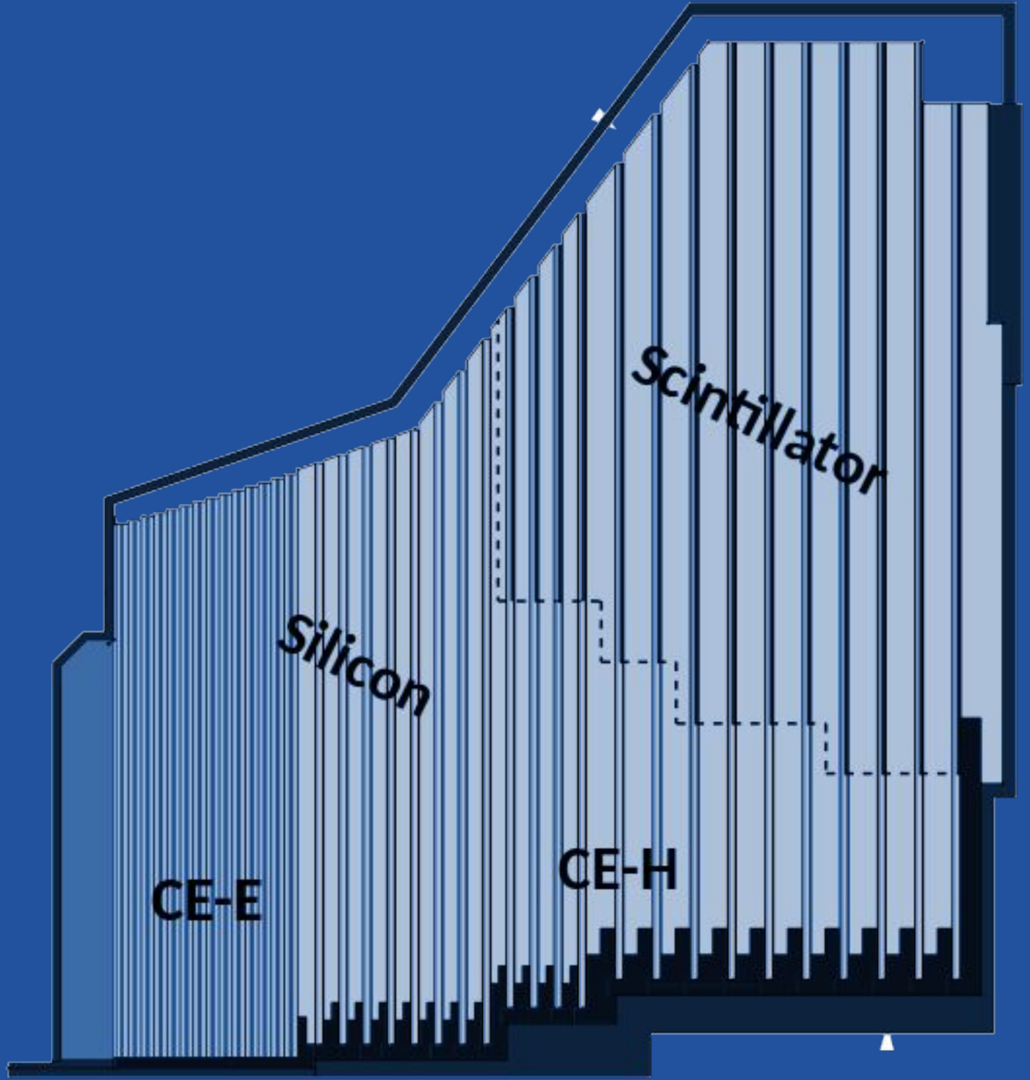


assign clusters

Register each remaining point as a follower to its nearest-higher



CLUE in the HGCAL reconstruction

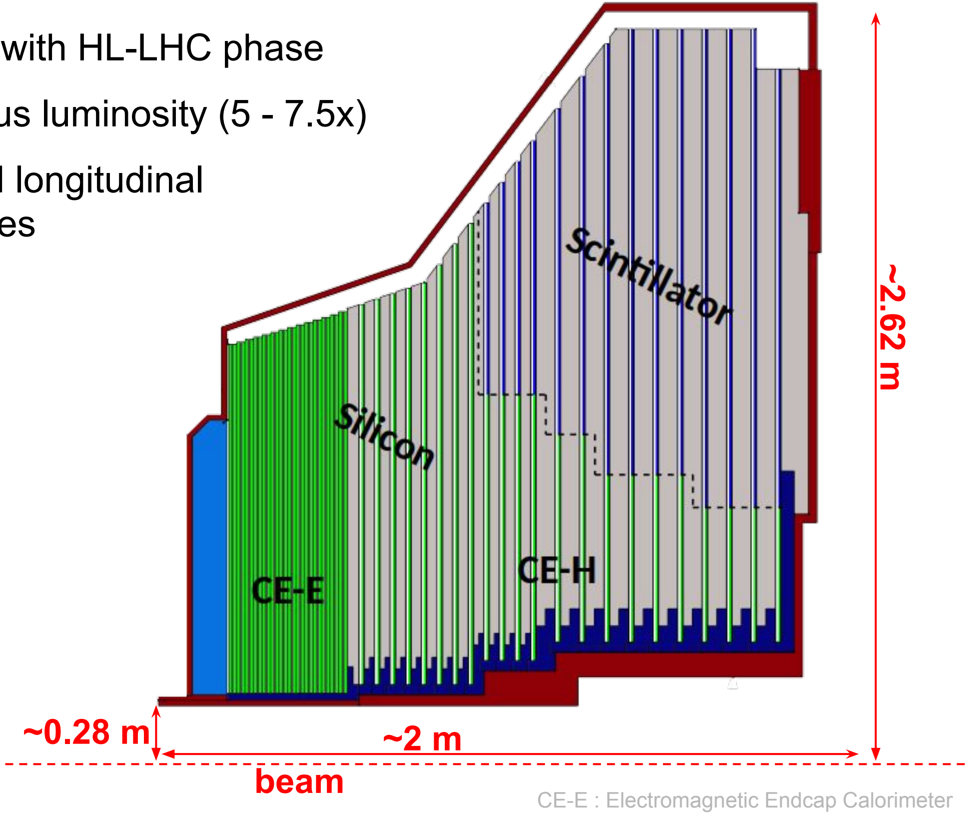


CMS High Granularity Calorimeter

- Phase-2 upgrade of CMS is needed to cope with HL-LHC phase
  - A significant increase in the instantaneous luminosity (5 - 7.5x)
- Imaging calorimeter with very fine lateral and longitudinal segmentation, and precision timing capabilities
  - Covering $1.5 < \eta < 3.0$

Both endcaps	**Silicon**	**Scintillators**
Area	**~620 m^2**	**~400 m^2**
Channel size	0.5 - 1 cm^2	4 - 30 cm^2
#Modules	~30'000	~4'000
#Channels	**~6 M**	240 k
Op. temp.	-30 °C	-30 °C

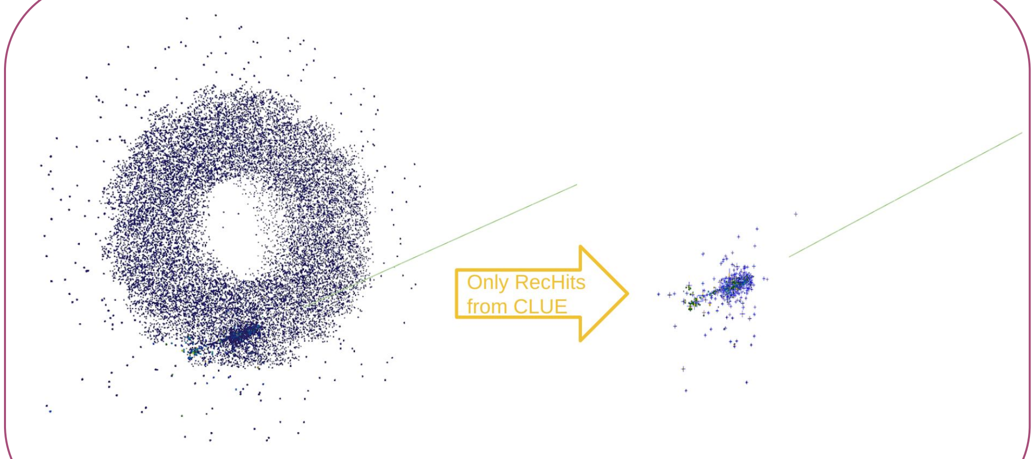
Ref.



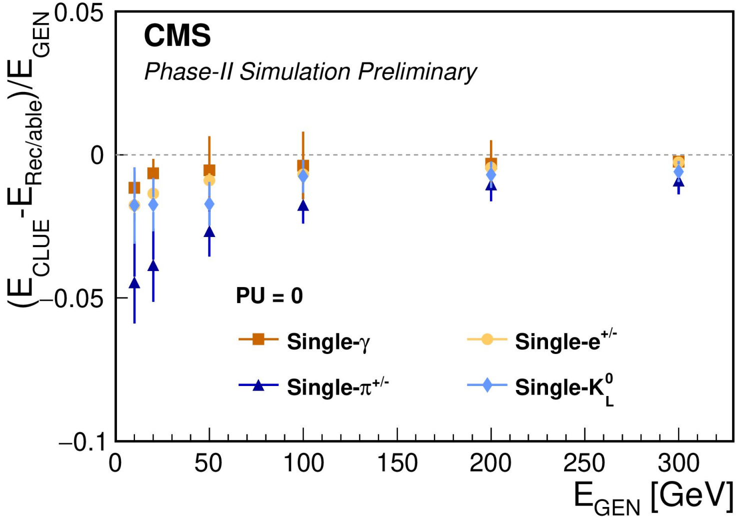
CE-E : Electromagnetic Endcap Calorimeter
CE-H : Hadronic Endcap Calorimeter

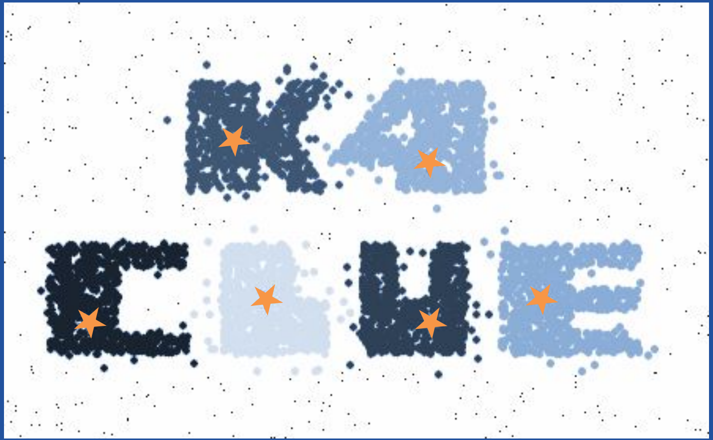
HGCAL Software Reconstruction

- The HGCAL reconstruction framework is **TICL (The Iterative Clustering)**
- It starts by calibrating deposited energy in individual cells, also called RecHits
→ an order of **10^5 RecHits** in the HGCAL detector for events @ 200 pileup
- CLUE clusters the RecHits in the same layer to produce **Layer Clusters (LCs)**



Single pion with E_{GEN} = 100 GeV with electronic noise enabled (no pileup)

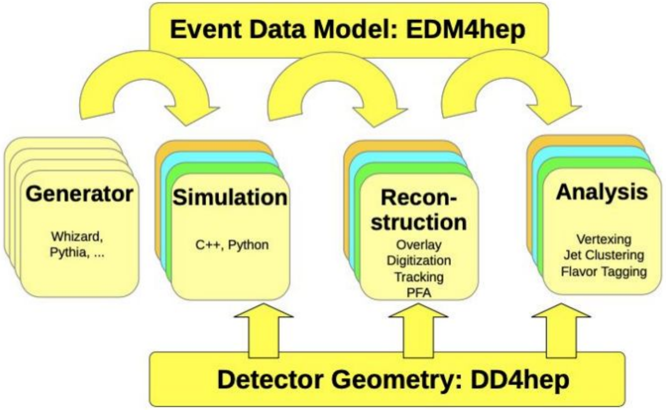


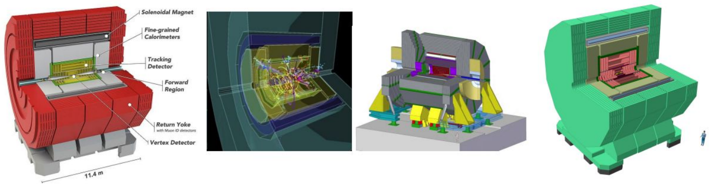
The  package

Key4hep in a nutshell

- **key4hep is a huge ecosystem of software packages**
  - It is adopted by all future collider projects
  - It implements complete workflows from generator to analysis

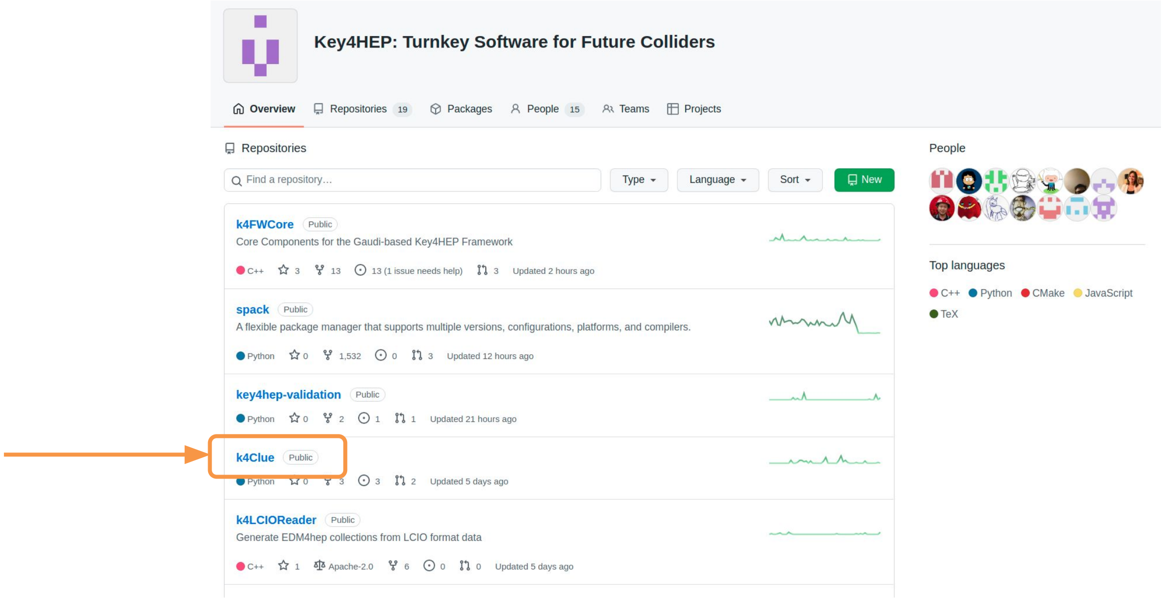
- **Main ingredients**
  - `EDM4hep` : common event data model for exchange among framework components
    - Podio used as underlying tool
  - Gaudi: software processing framework
  - DD4hep: description of geometry with ability to include CAD files
  - Spack: package manager used for building the SW stack





Integrating CLUE in Key4hep

- **k4Clue v01-00-03** (doi: [10.5281/zenodo.8256333](https://doi.org/10.5281/zenodo.8256333))
  - It's adapted to the common event data model, EDM4hep
  - It includes a wrapper class to run in the Gaudi software framework
  - It's included in the new Key4hep releases managed by Spack



Additional features w.r.t. kalos/Clue

- **Cluster hits in the entire 4π detector region**
  - Definition of the tessellated space (`LayerTile`) in the standalone version defines coordinates and searches only in the transverse plane
  - Modified basic structure of the `LayerTile` and the search algorithm to to allow for the definition of a cylindrical surface

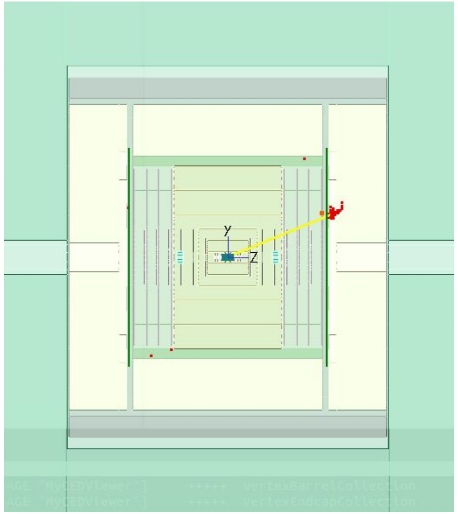
    $x \rightarrow r\Phi$ $y \rightarrow z$
- **Template CLUE algorithm classes**
  - To allow the possibility of defining several different calorimeter layouts
  - A dedicated documentation page in the package (`include/readme.md`) allows the user to follow a simple but detailed step-by-step procedure to introduce and test the preferred layout.
- **GitHub CI & EDM4hep Validation**
  - `edm4hep:CLUECalorimeterHit : CalorimeterHit` class with specific methods related to the CLUE algorithm

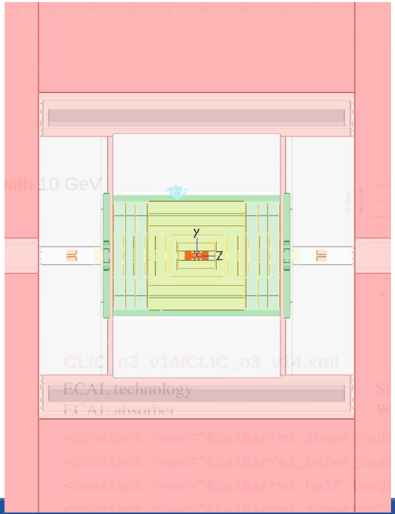
Performance

Detectors: CLD & CLICdet

ECAL of CLICdet & CLD

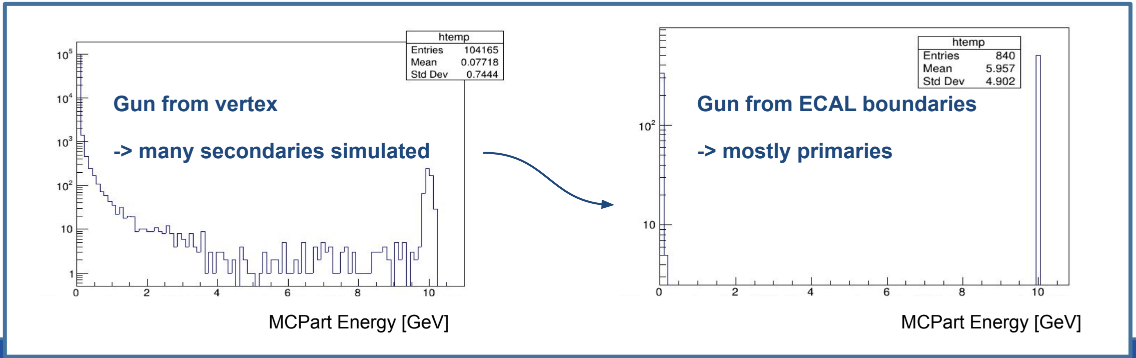
- 40 layers of 5x5 mm^2 Silicon cells & W
- The main difference between the two calorimeters lies in the layout parameters → To compensate for a lower detector solenoid field, the CLD design starts from a larger radius both in the barrel and in the endcap region w.r.t. CLICdet.
  - Further details in backup

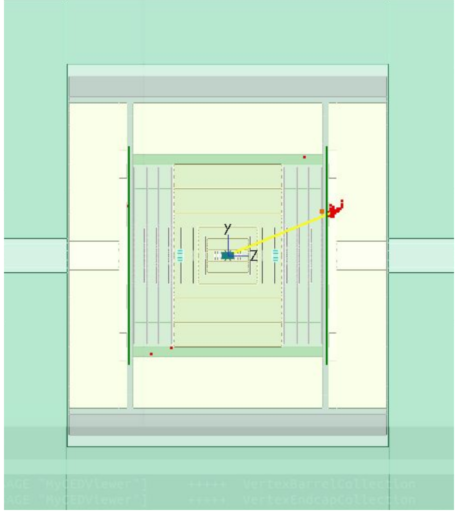


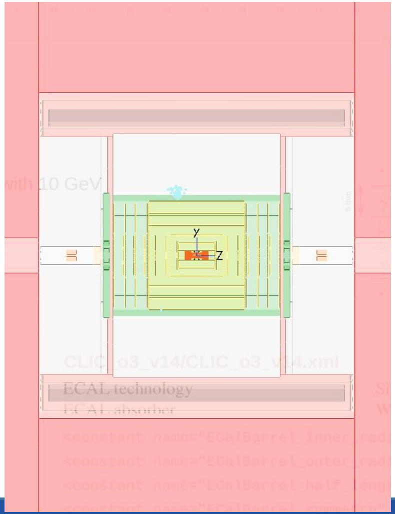


ECAL of CLICdet & CLD

- 40 layers of 5x5 mm^2 Silicon cells & W
- The main difference between the two calorimeters lies in the layout parameters → To compensate for a lower detector solenoid field, the CLD design starts from a larger radius both in the barrel and in the endcap region w.r.t. CLICdet.
  - Further details in backup
- 500 events of single gamma at 10 GeV generated perpendicular to the surface with Geant4 General Particle Source
  - Main reason: no conversion in the tracker volume

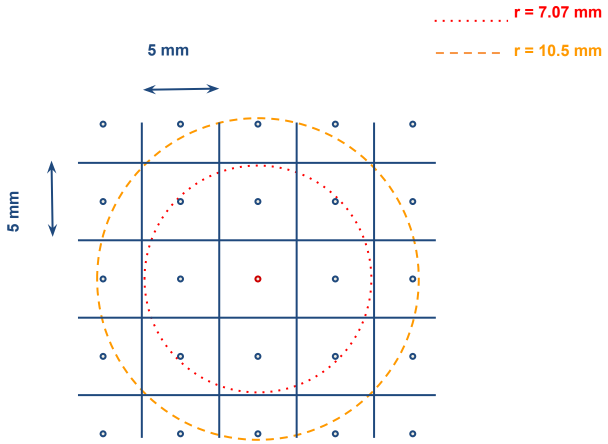






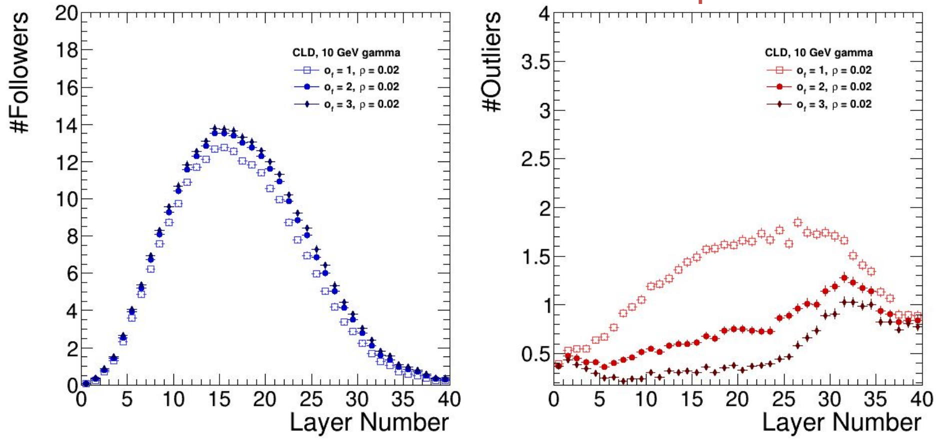
Parameters tuning

- Input parameters tuned for CLD
- Same ones tested also for CLICdet **(similar geometry, same granularity)**
- Critical Distance (d_c) is established by geometry granularity to contain (minimum) the close neighbors cells:
  - d_c = 15 mm

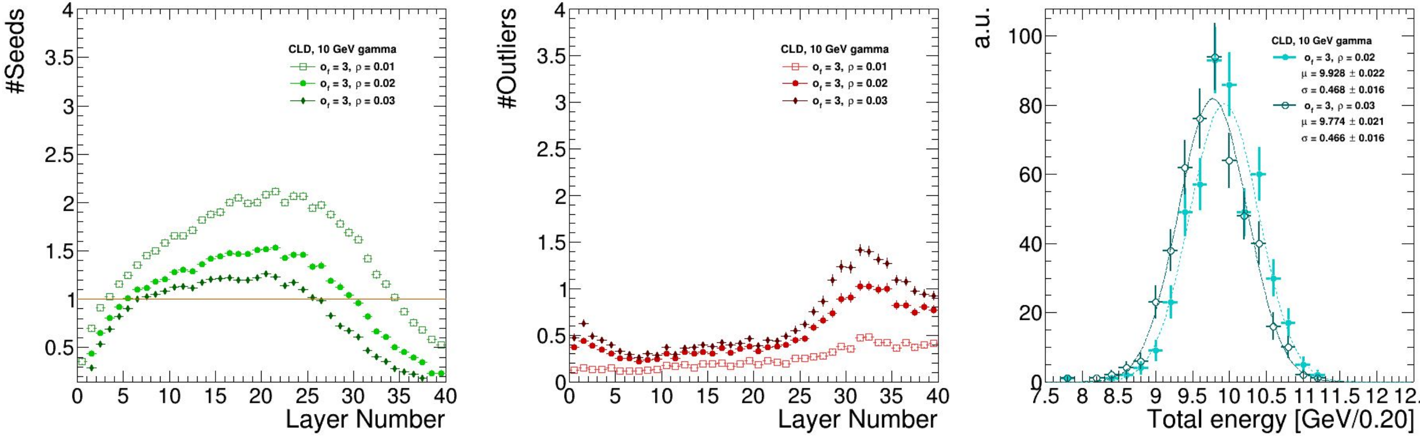


Parameters tuning

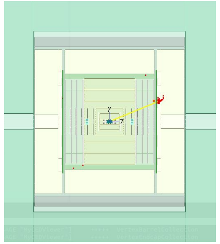
Varying the outlier factor (o_f)



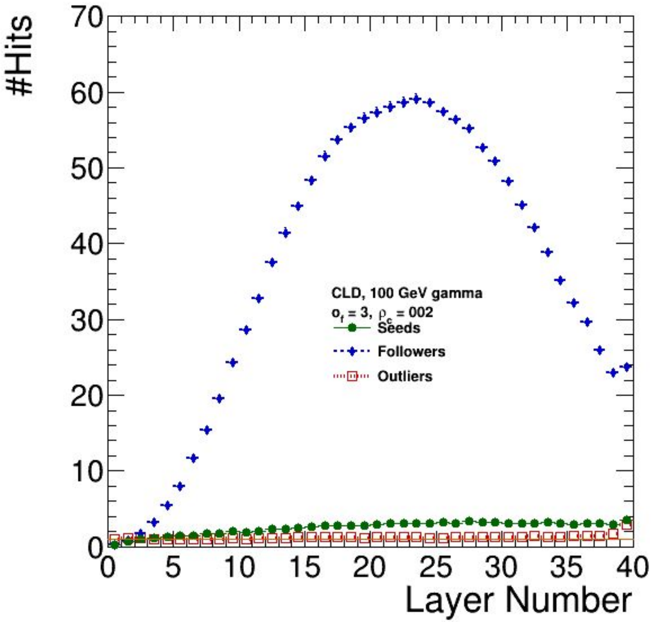
Varying the minimum local density (ρ_c)

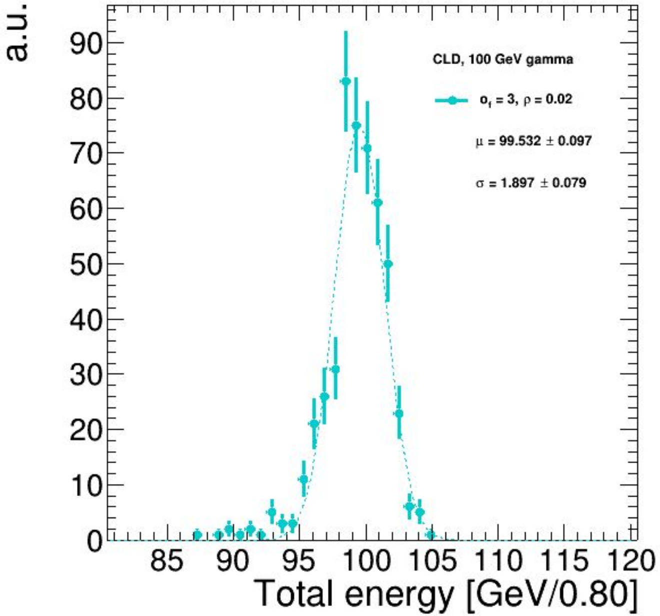


Higher energies



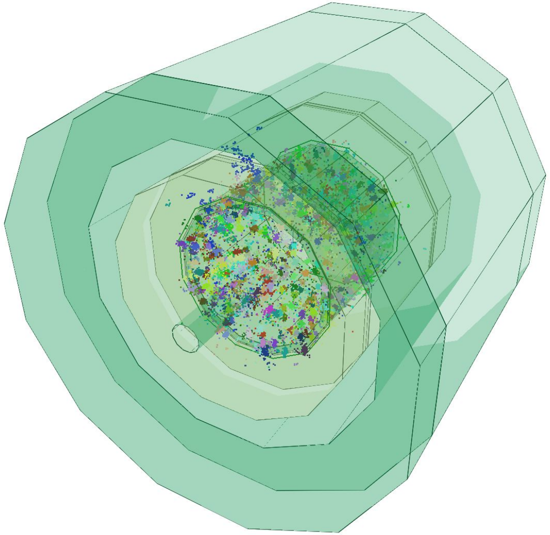
- 500 events with single gamma (from ECAL surface) at 100 GeV
- **d_c = 15.00, ρ_c = 0.02, o_f = 3.0**

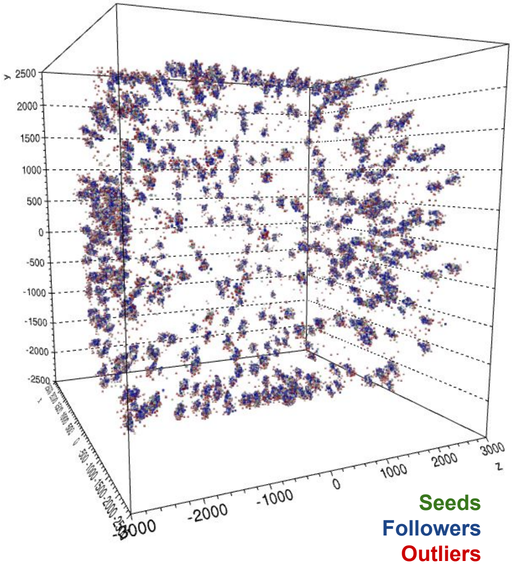


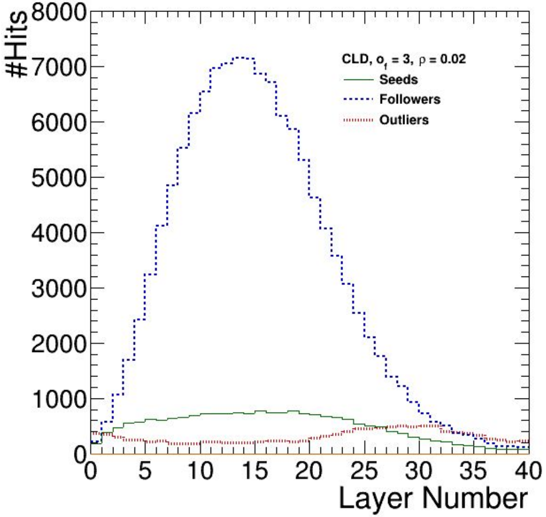


Multiple gamma event

- Produced with normal gun, i.e. particles generated from vertex
- 1 event with 500 single gammas each produced with 10 GeV
  Only simulated calorimeter hits are shown

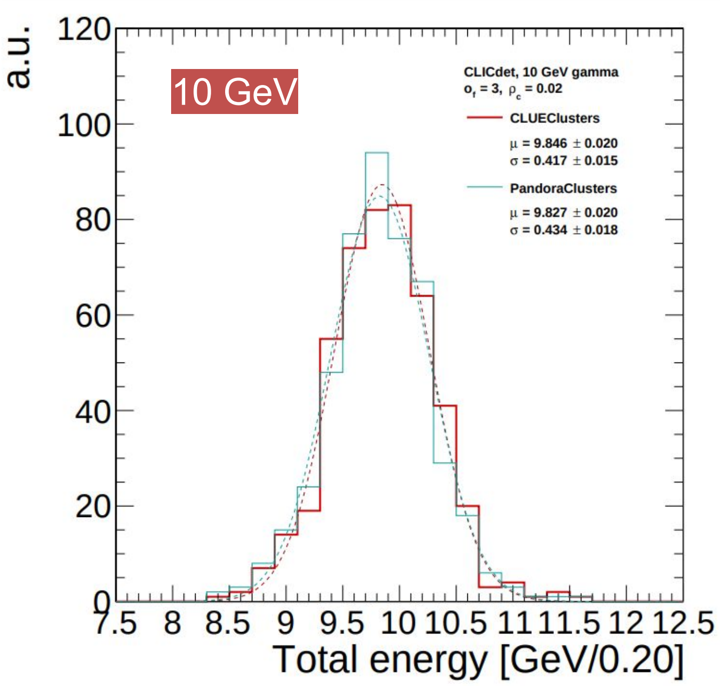


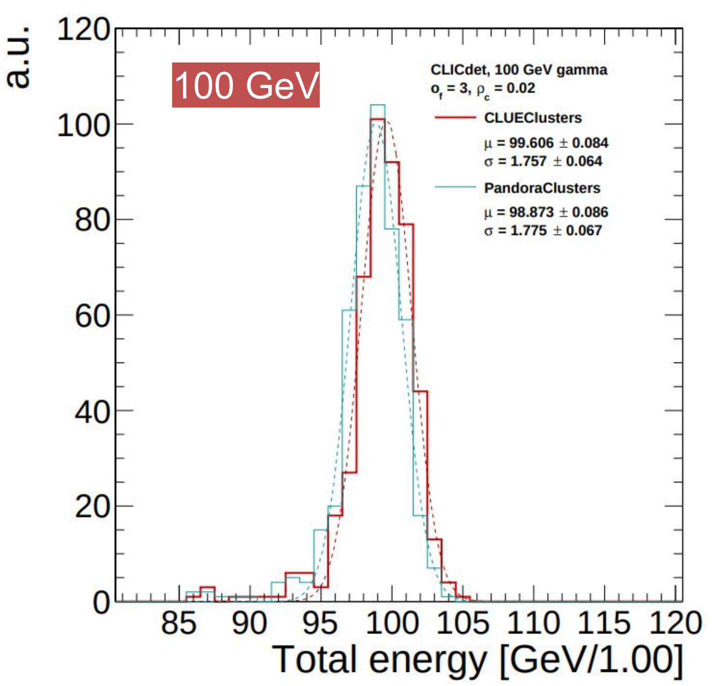




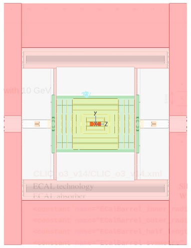
CLICdet results

- Using same input parameters selected for CLD





Comparison with **Pandora Clusters** not completely equitable comparison (it includes a dedicated calibration procedure), but comparable results in terms of energy linearity and resolution



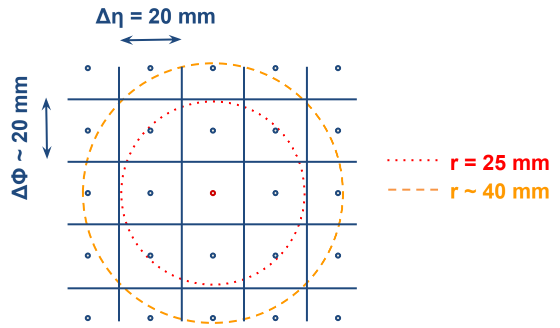
Performance

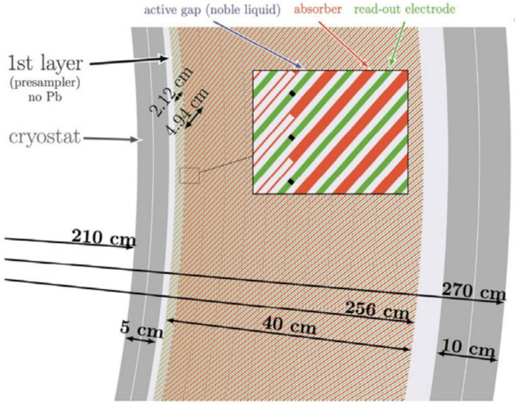
Detector: Noble Liquid Calorimeter

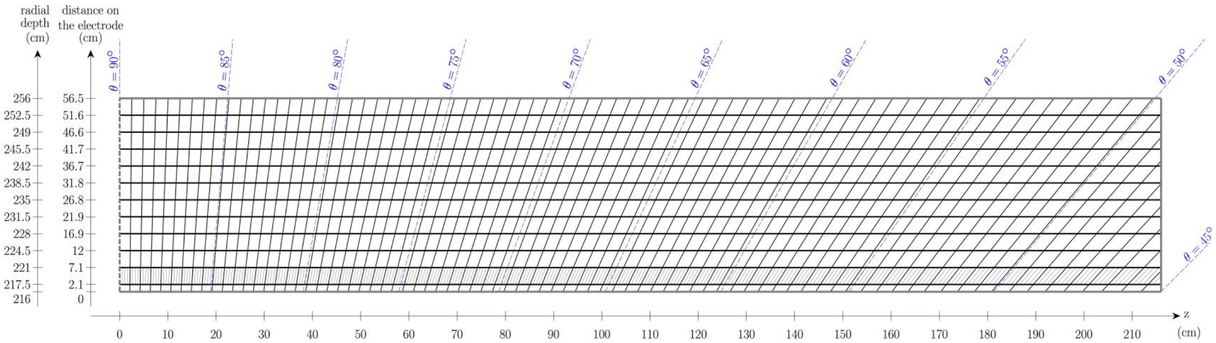
Noble Liquid ECAL for FCC-ee

- 12 layers, only barrel considered
  - cell size in Φ: 17.9 mm - 20.7 mm
  - cell size in η: ~ 20 mm
- Sample (if not stated otherwise):
  - 500 single gamma at 10 GeV
  - $\theta_{[min, max]}$ = [50, 130]

Critical distance choice: d_c = 40 mm

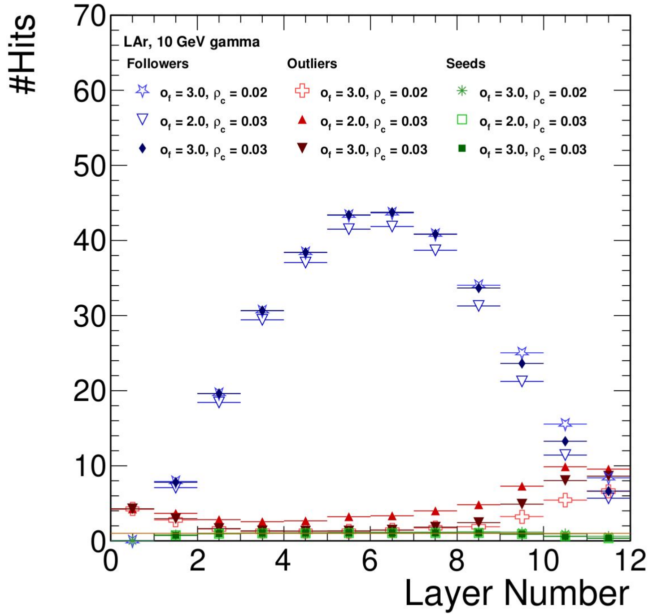


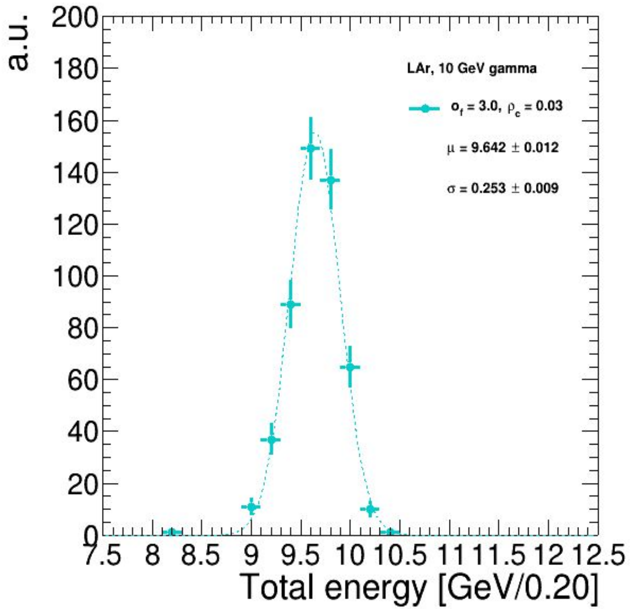




Parameters tuning

- 500 events with single gamma (from vertex) at **10 GeV**
- **d_c = 40.00, ρ_c = 0.03, o_f = 3.0**

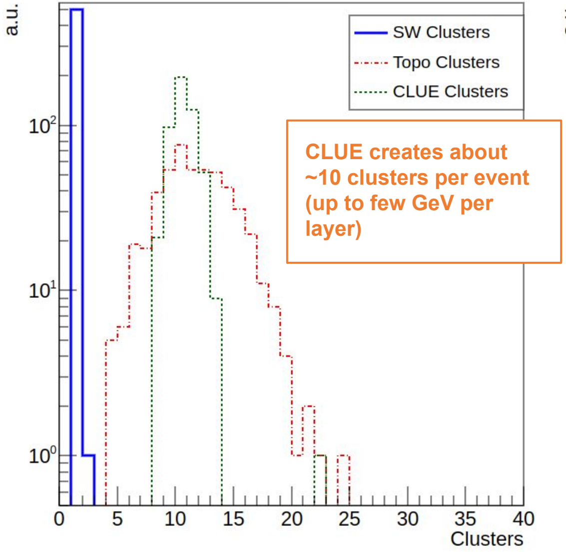


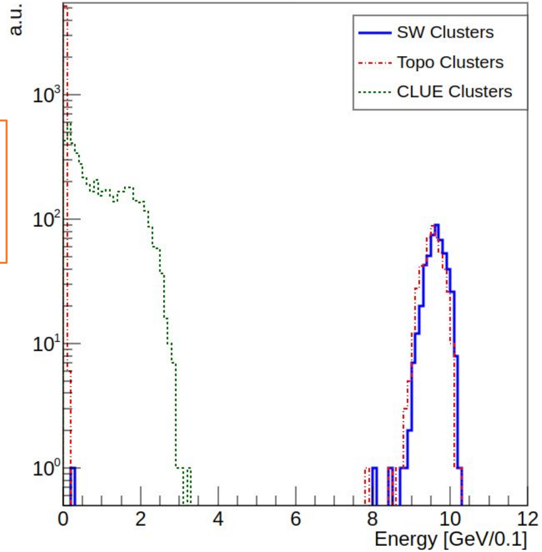


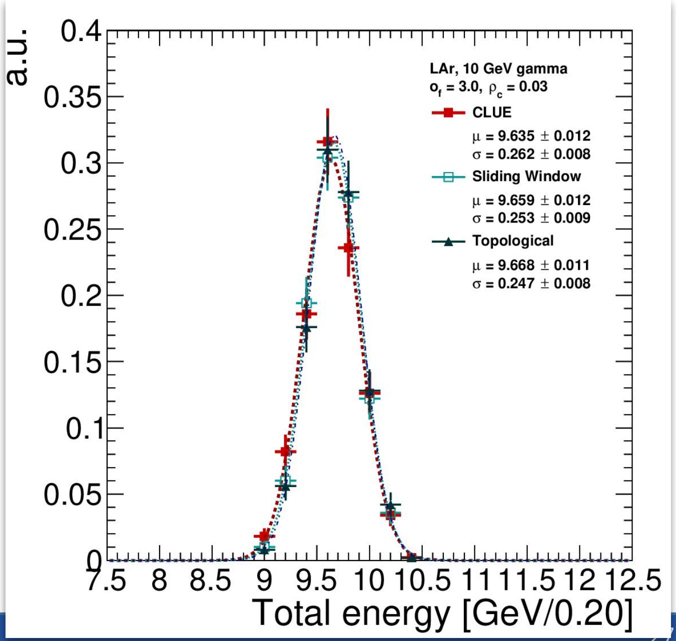
Comparison with other cluster algorithms

Calorimeters for the FCC-hh, Dec 2019

- **Sliding window**: It considers the calorimeter as a two-dimensional grid in η-ϕ space, neglecting the longitudinal segmentation of the calorimeter.
- **Topological clustering**: It starts with a seed cell and then adds topologically connected calorimeter cells







Noise in Liquid Argon Calorimeter

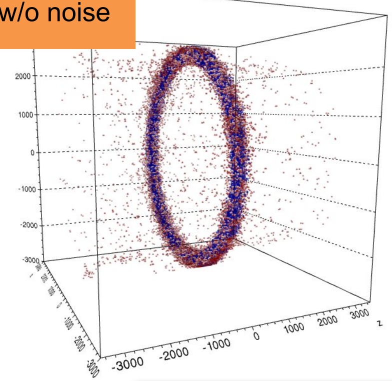
- High level of noise in the detector
- In the topoclustering, there is no filter directly at the beginning for the noise, but this is done using cuts in the algorithm itself
- The main observable is the cell significance ξ_{cell} which is defined as the absolute value of the ratio of the cell signal to the expected noise in this cell

$$\xi_{\text{cell}} = \left| \frac{E_{\text{cell}}}{\sigma_{\text{cell}}^{\text{noise}}} \right|$$

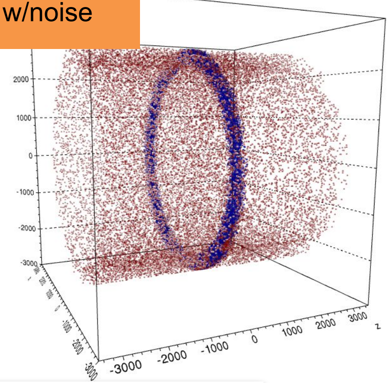
- CLUE hits w/noise **selected with filter of > $2\sigma_{noise}$**

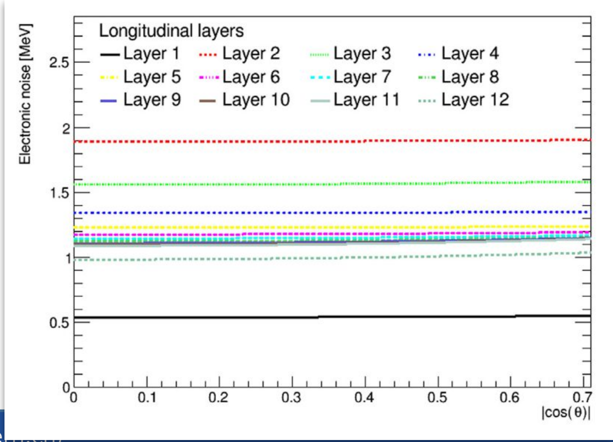
Signal produced only with θ ~ 90.25°

w/o noise



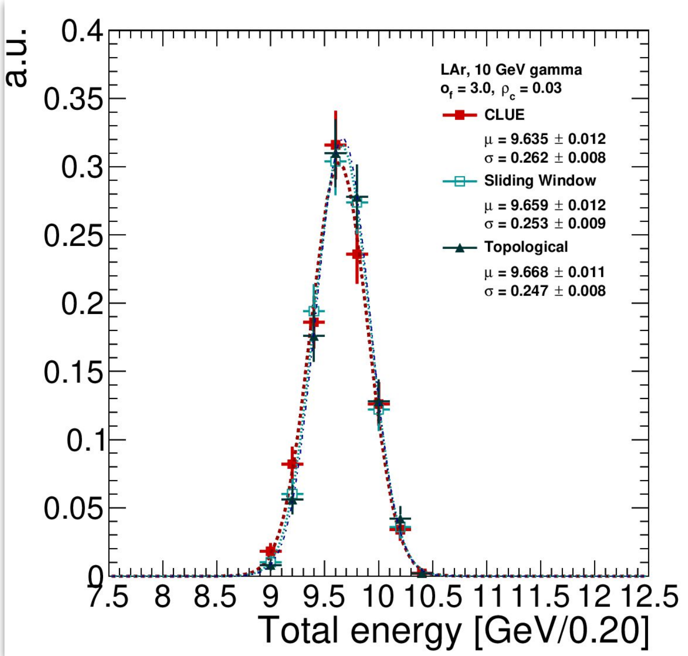
w/noise



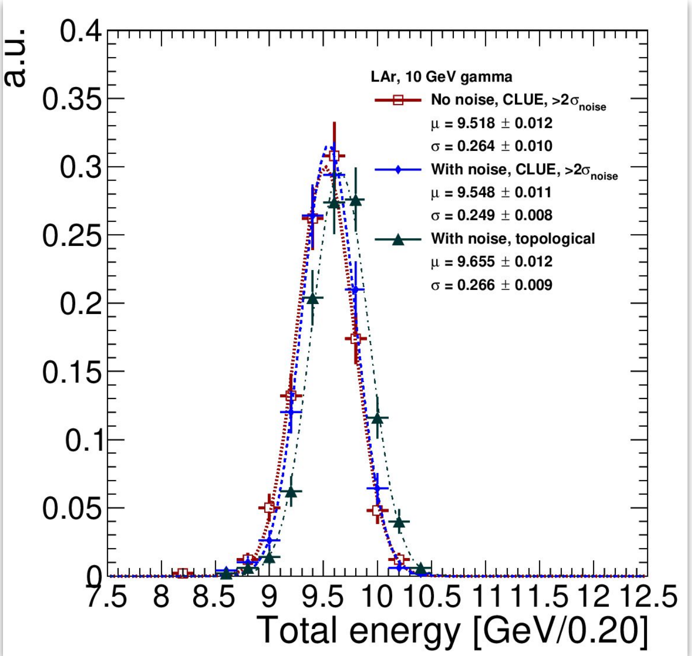


Comparison with other cluster algorithms

No noise

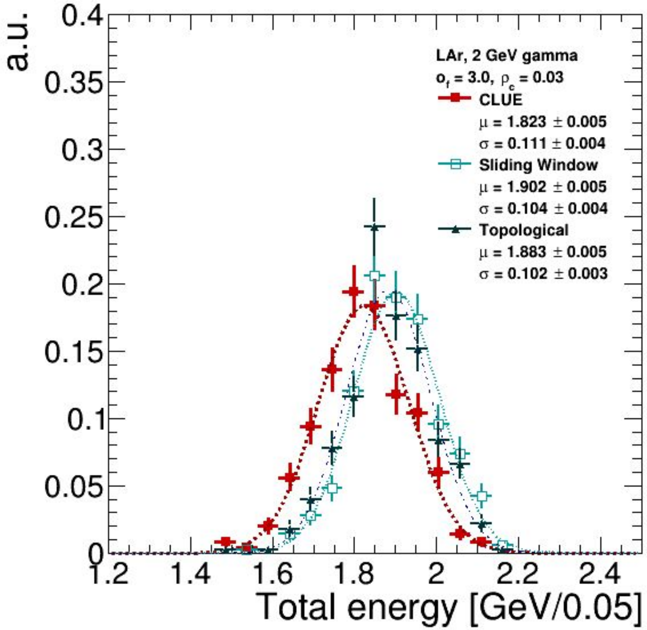


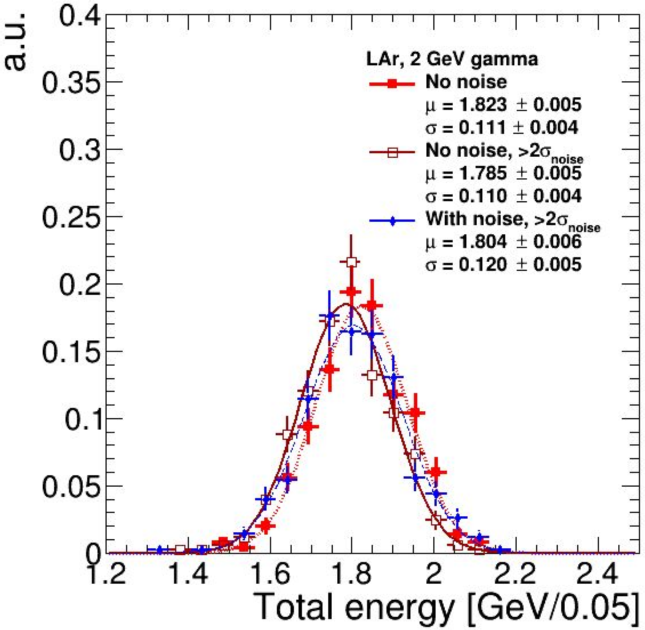
Including noise



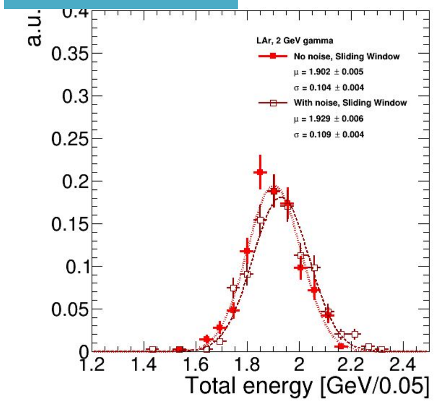
Low(er) energy

- 500 events with single gamma (from vertex) at **2 GeV**
  Motivated by flavor physics searches at Z peak

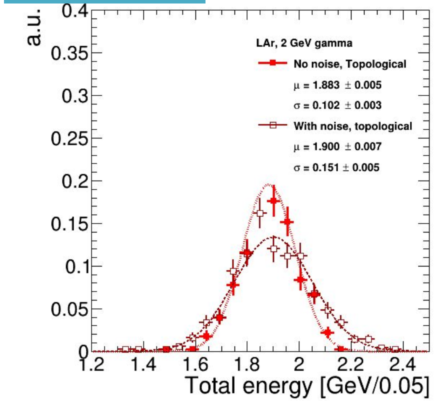




Sliding Window
cluster energy > 1GeV

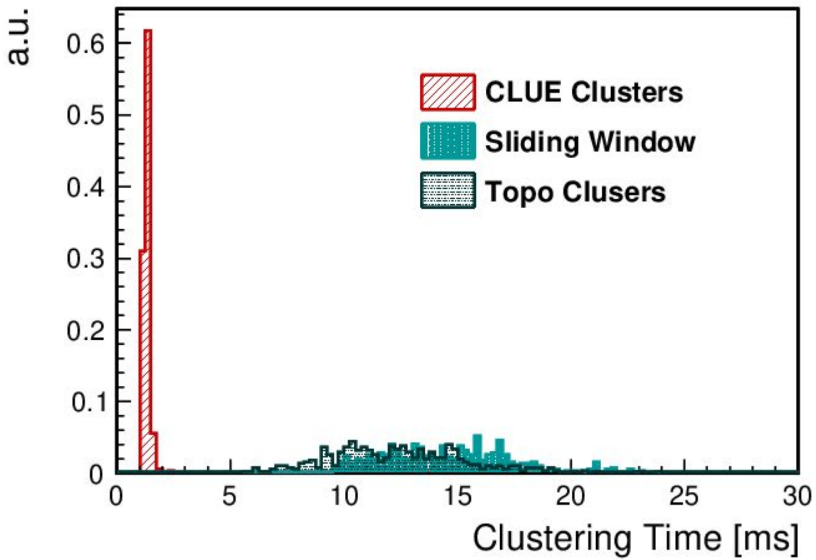


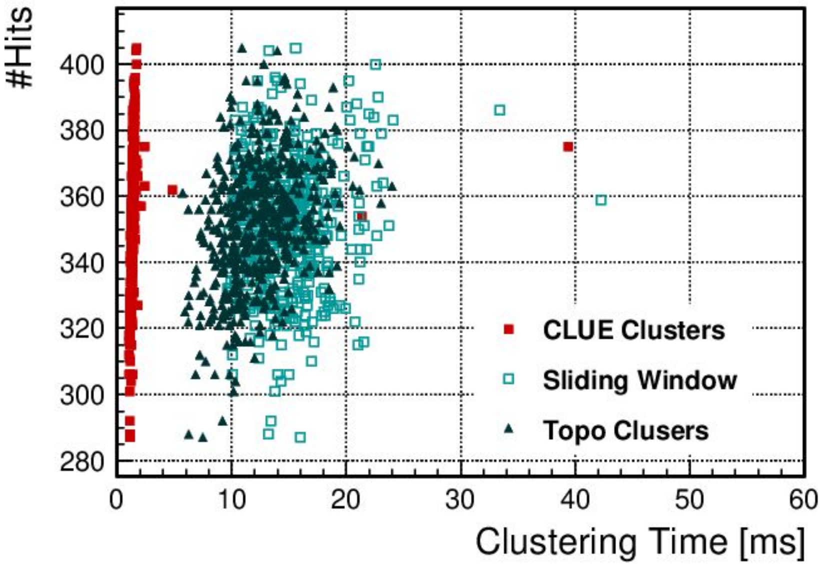
Topological



Execution Time

- CLUE demonstrates impressive timing capabilities, outperforming the other algorithms by completing the task in about a tenth of the time, regardless of the number of input hits
- Currently only CPU version is used





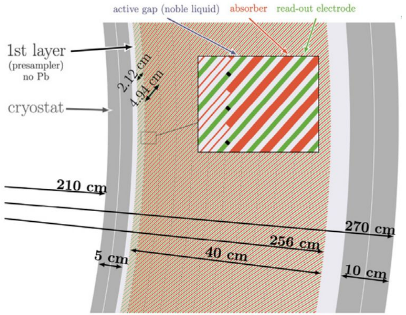
Outlook & Conclusions

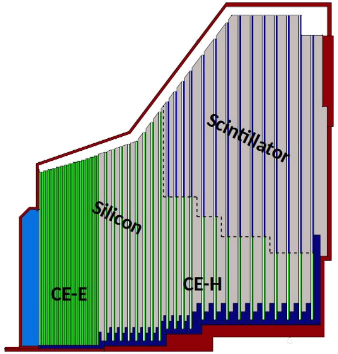
Summary

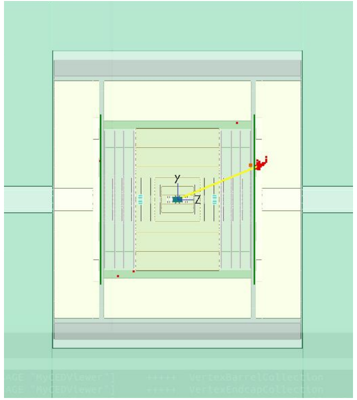
- k4Clue package ([v01-00-03]) has improved upon the standalone CLUE
  - Run on the full detector (**barrel** & endcap)
  - Adapted for **different types** of calorimeters
- Analysis on three different future calorimeters has demonstrated the good performance for single gamma events
  - Good performance even in the **presence of noise**
  - Similar performance w.r.t. **other baseline algorithms**
  - **Clear advantage in terms of timing performance**

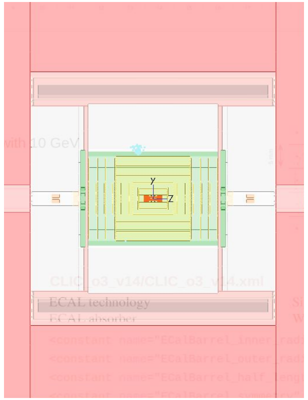
Next steps

- Bringing improvements in original repo
- Implement 3D algorithm for full pattern reco (CLUE3D)





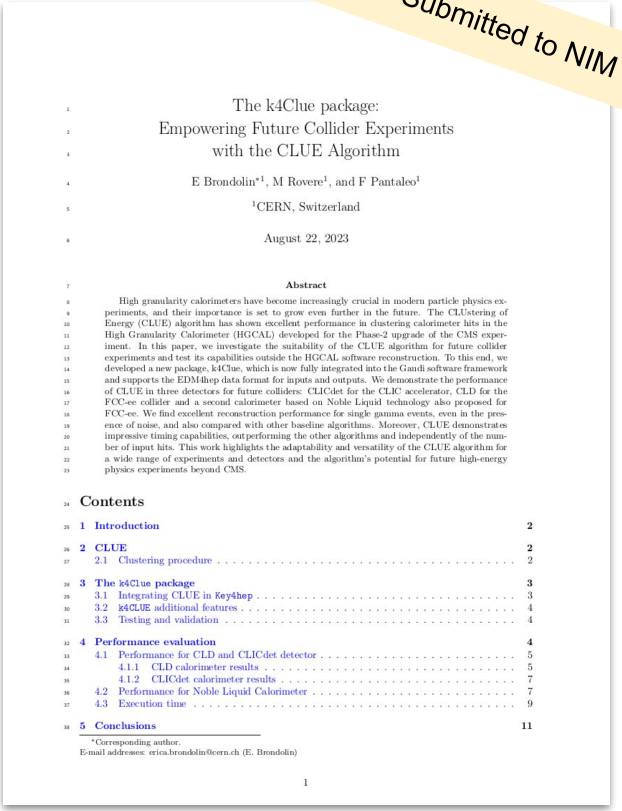




Conclusions

- This work highlights the adaptability and versatility of the CLUE algorithm for a wide range of experiments and detectors, as well as its potential for future high-energy physics experiments beyond CMS
  - Improvements from k4clue also under discussion for CMS Phase-2 barrel region
- This research was supported by the CERN Strategic R&D Programme on Technologies for Future Experiments
- Special thanks go to the Key4hep team and the FCC-ee liquid calorimeter software experts for the support

Submitted to NIM



The k4Clue package:
Empowering Future Collider Experiments
with the CLUE Algorithm

E Brondolin*[1], M Rovere[1], and F Pantaleo[1]

[1]CERN, Switzerland

August 22, 2023

Abstract

High granularity calorimeters have become increasingly crucial in modern particle physics experiments, and their importance is set to grow even further in the future. The CLUstering of Energy (CLUE) algorithm has shown excellent performance in clustering calorimeter hits in the High Granularity Calorimeter (HGCAL) developed for the Phase-2 upgrade of the CMS experiment. In this paper, we investigate the suitability of the CLUE algorithm for future collider experiments and test its capabilities outside the HGCAL software reconstruction. To this end, we developed a new package, k4Clue, which is now fully integrated into the Gaudi software framework and supports the EDM4hep data format for inputs and outputs. We demonstrate the performance of CLUE in three detectors for future colliders: CLICdet for the CLIC accelerator, CLD for the FCC-ee collider and a second calorimeter based on Noble Liquid technology also proposed for FCC-ee. We find excellent reconstruction performance for single gamma events, even in the presence of noise, and also compared with other baseline algorithms. Moreover, CLUE demonstrates impressive timing capabilities, outperforming the other algorithms and independently of the number of input hits. This work highlights the adaptability and versatility of the CLUE algorithm for a wide range of experiments and detectors and the algorithm's potential for future high-energy physics experiments beyond CMS.

Contents

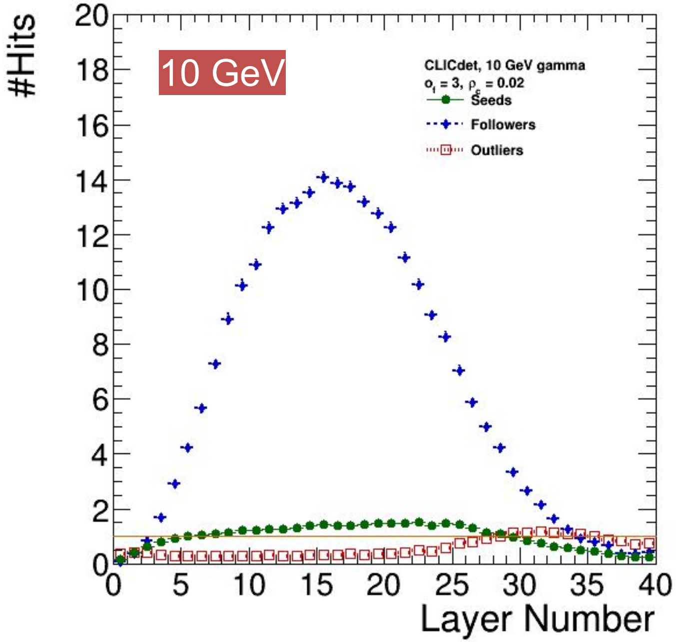
*Corresponding author.
E-mail addresses: erica.brondolin@cern.ch (E. Brondolin)

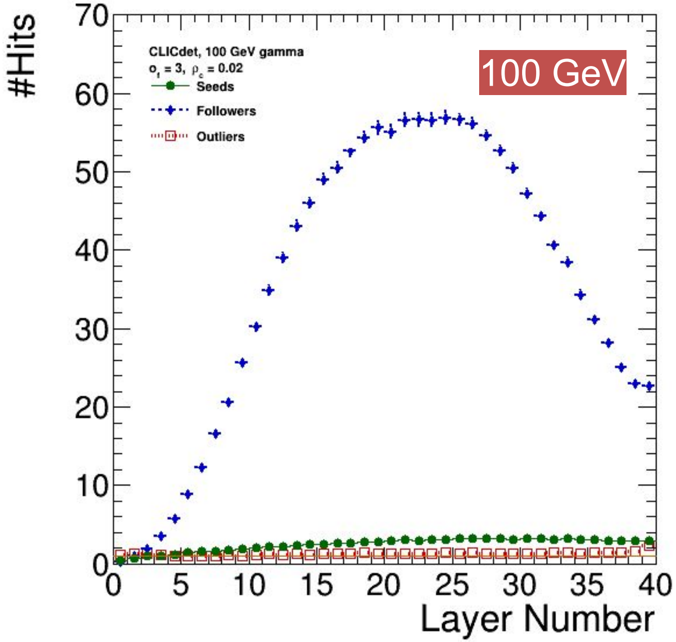
1

Backup

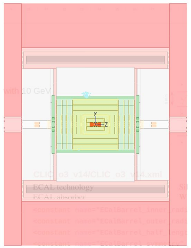
CLICdet results

- Using same input parameters selected for CLD





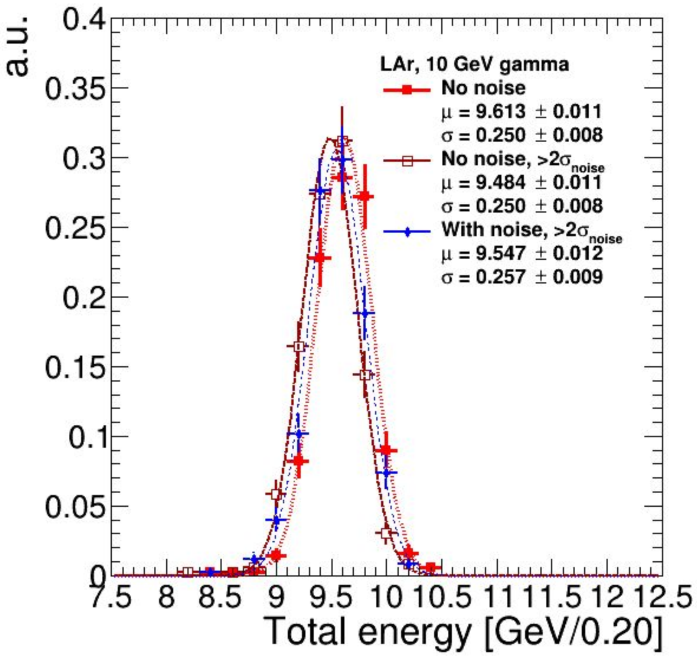
Comparison with **Pandora Clusters** not completely equitable comparison (it includes a dedicated calibration procedure), but comparable results in terms of energy linearity and resolution

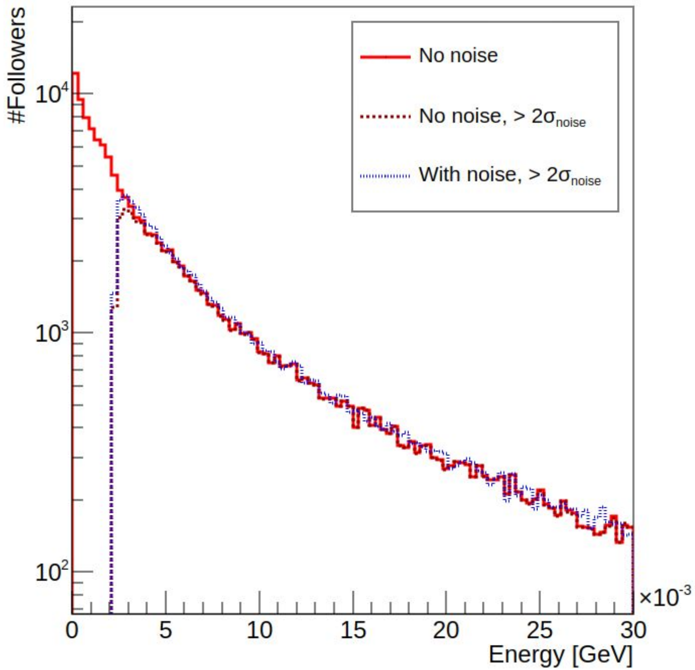


Noble Liquid Calo

Pre-filtering

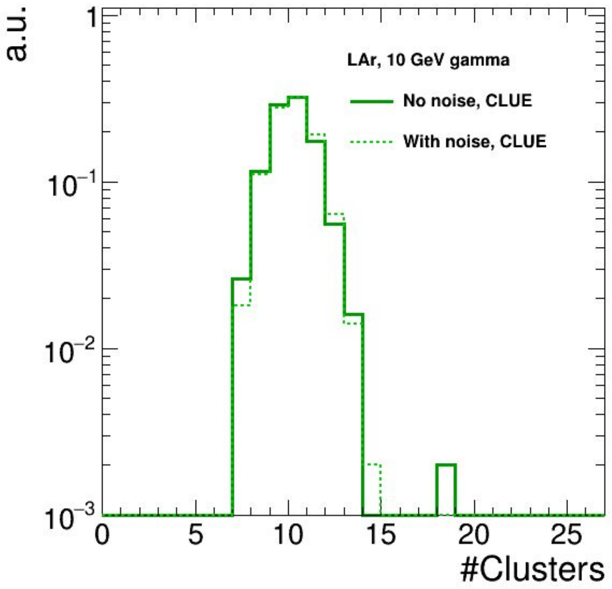
- CLUE hits w/noise selected with filter of $> 2\sigma_{noise}$



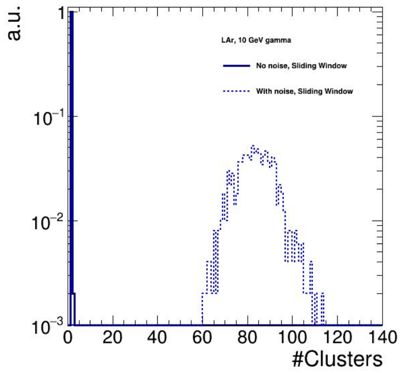


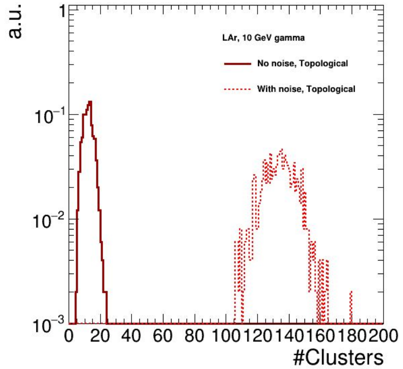
Noble Liquid Calo

Comparison with other cluster algorithms

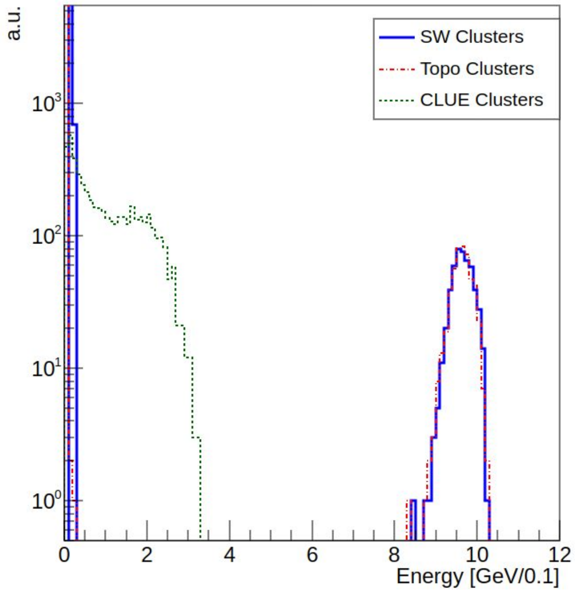


No significant effect on CLUE clusters - about ~10 per event (one per layer)





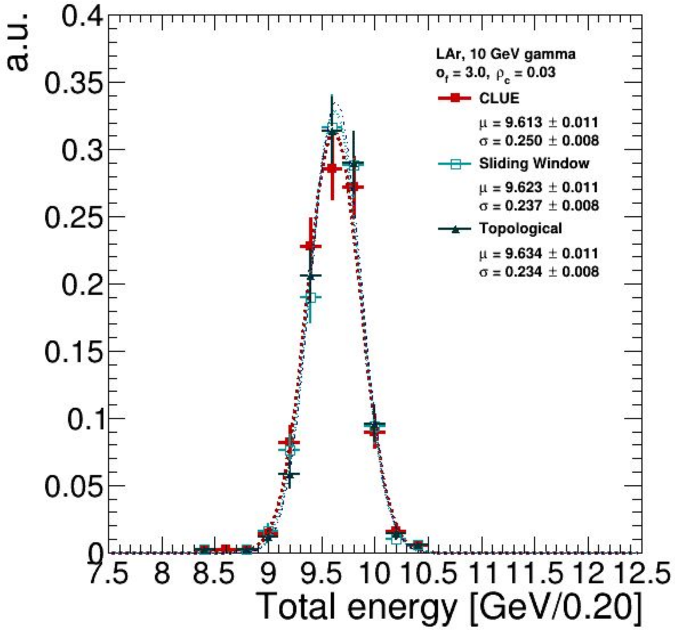
w/noise

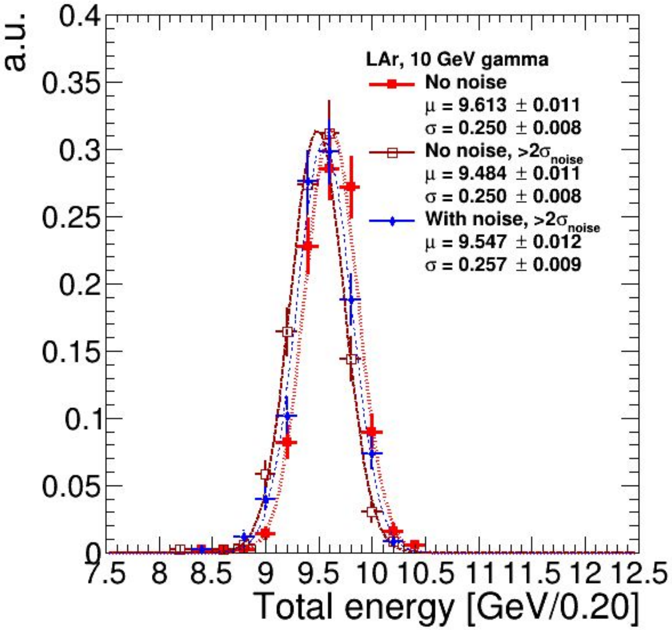


More than one SW and Topo cluster per event, but most of them with low energy

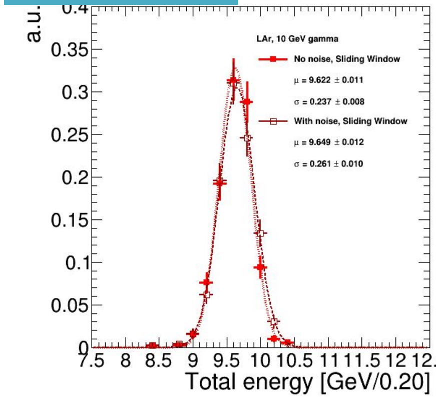
Noble Liquid Calo

Summary for 10 GeV gammas





Sliding Window cluster energy > 1GeV



Topological