中国科学院高能物理研究所
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CEPC

# Progress of reconstruction for crystal bar ECAL


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# Outline

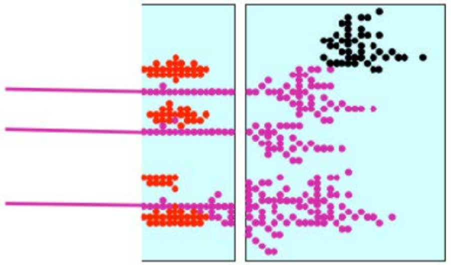
- Introduction
- Simulation and Digitization
- Reconstruction Algorithm
- Summary

# Introduction

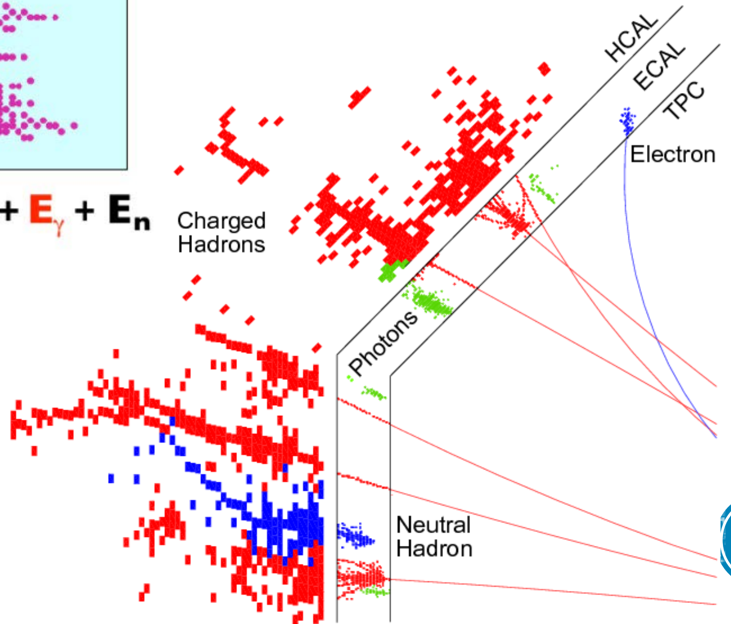
- CEPC, A high precision H/Z factory
  - Heavy bosons separation and precise Higgs measurements require excellent jet energy resolution 3~4%.
  - Fine $\gamma/\pi^0$ reconstruction for flavor physics.

| Physics process | Measurands | Detector subsystem | Performance requirement |
|---|---|---|---|
| $ZH, Z \to e^+e^-, \mu^+\mu^-$<br>$H \to \mu^+\mu^-$ | $m_H, \sigma(ZH)$<br>$\mathrm{BR}(H \to \mu^+\mu^-)$ | Tracker | $\Delta(1/p_T) =$<br>$2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$ |
| $H \to b\bar{b}/c\bar{c}/gg$ | $\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$ | Vertex | $\sigma_{r\phi} =$<br>$5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta}(\mu\mathrm{m})$ |
| $H \to q\bar{q}, WW^*, ZZ^*$ | $\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$ | ECAL<br>HCAL | $\sigma_E^{\mathrm{jet}}/E =$<br>$3 \sim 4\%$ at 100 GeV |
| $H \to \gamma\gamma$ | $\mathrm{BR}(H \to \gamma\gamma)$ | ECAL | $\Delta E/E =$<br>$\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$ |

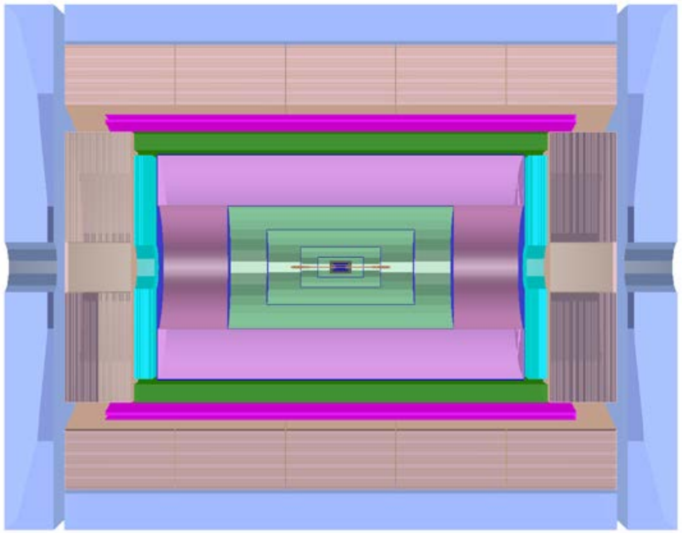
- Particle flow Approach
  - Identification of energy deposits from each individual particle.
  - $\sigma_{jet} = \sqrt{\sigma_{Track}^2 + \sigma_{EM}^2 + \sigma_{Had}^2 + \sigma_{Confusion}^2}$
  - Imaging calorimeter + Topological analysis



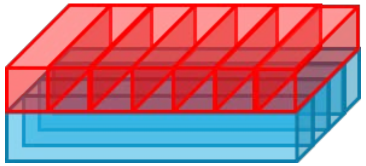
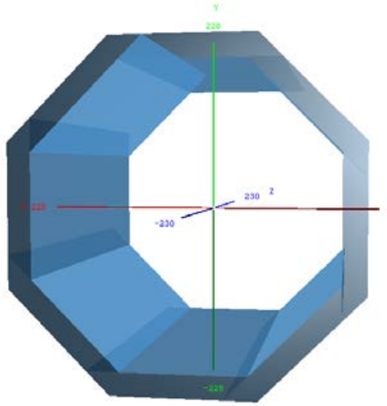
$E_{JET} = E_{TRACK} + E_{\gamma} + E_n$



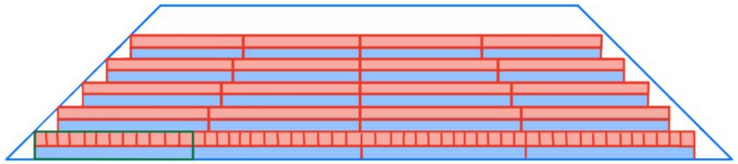
# Introduction



- Long crystal bar ECAL
  - Homogeneous structure ➔ Optimal energy resolution $(\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%)$
  - Significant reduction of number of channels
  - Time measurement at both ends to determine shower position along the bar.

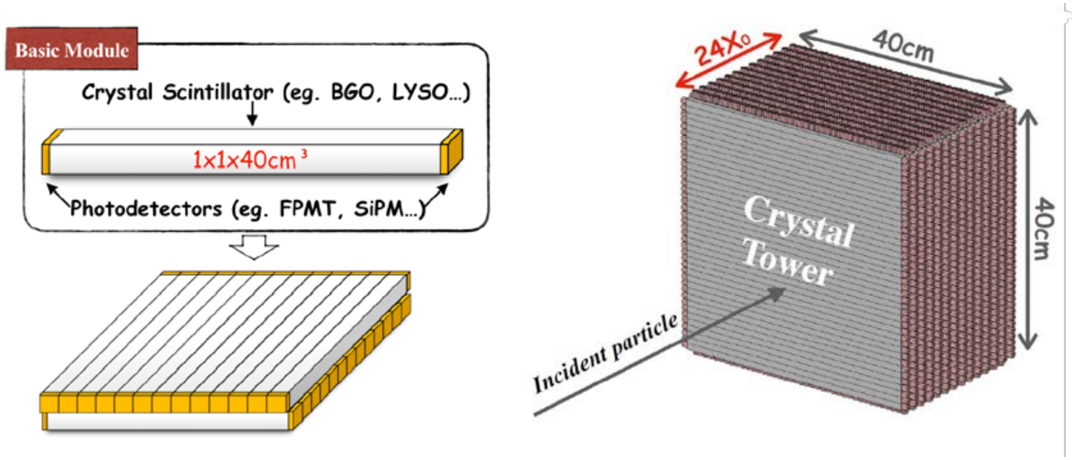
- Challenges:
  - Ambiguity caused by matching of horizontal and vertical bars.
  - Identification of energy deposits from each individual particle.
    - Larger $R_M$ and smaller $\lambda_I/X_0$ increase probability of shower overlap.

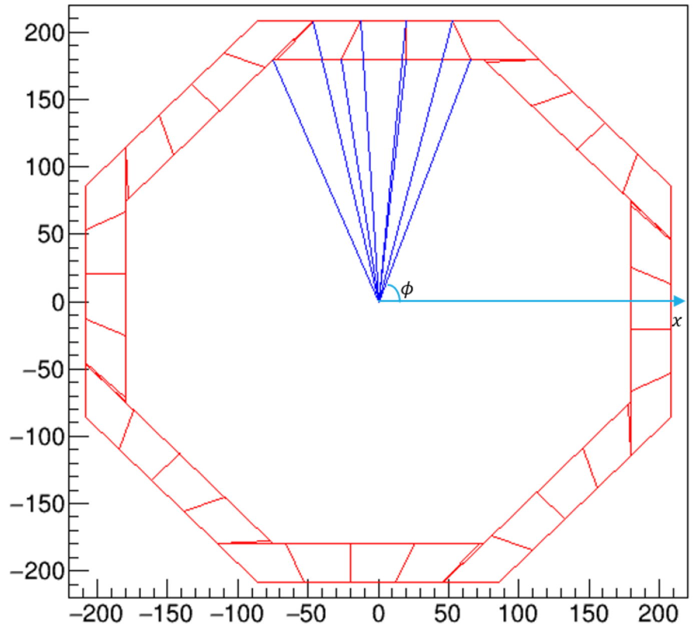


- High performance reconstruction algorithm is required!

# Design Concept of Long Crystal Bar ECAL

- Crystal bar
  - BGO: $X_0 = 1.12$ cm, $R_M = 2.23$ cm, $\lambda_I = 22.7$ cm
  - Size in simulation: $1 \times 1 \times 40{\sim}60\ \mathrm{cm}^3$
  - Readout at both ends
- Basic Detection Unit: Super Cell
  - 2 layers of perpendicular crossing bars
- Tower
  - $\sim 40 \times \sim 60 \times 24X_0\ \mathrm{cm}^3$
- Detector:
  - $R = 1.86\ \mathrm{m}, L = 6.6\ \mathrm{m}, H = 28\ \mathrm{cm}$
  - 8 same trapezoidal staves
  - Avoid gaps point to IP

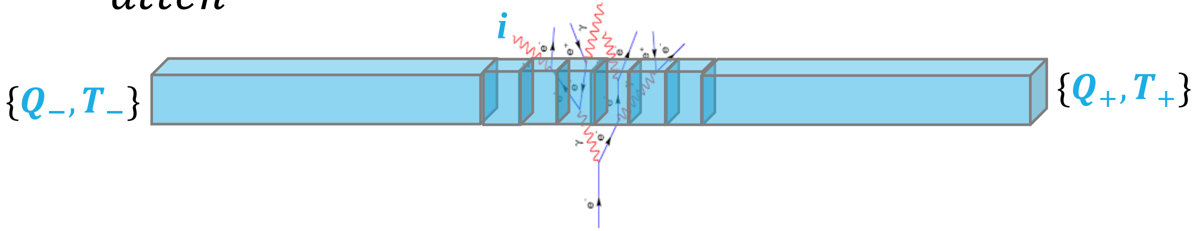


# Simulation and Digitization

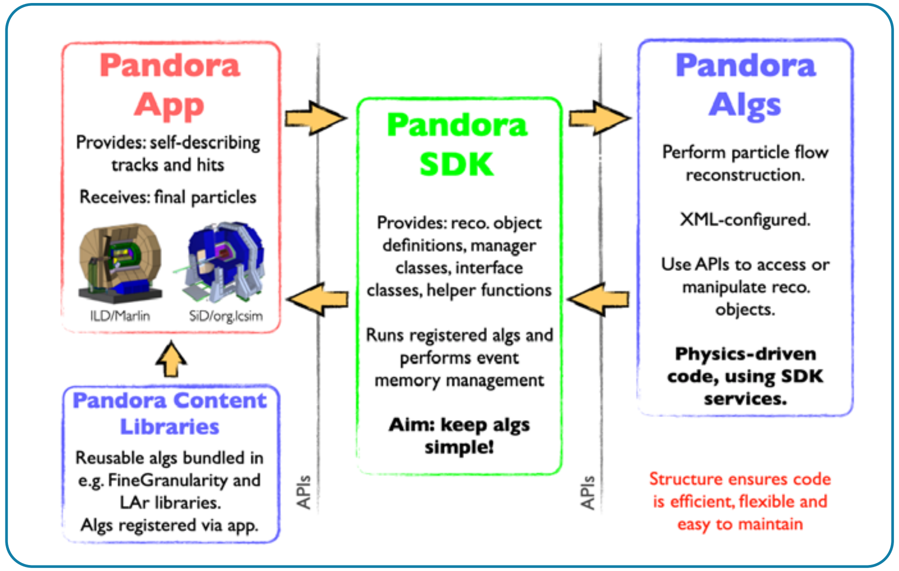
- Geant4-based simulation in CEPCSW
  - DD4Hep is used for geometry construction.
    - Focusing on software performance, ignoring dead area, supporting and cooling mechanics, etc.
  - Electromagnetic & hadronic interaction
- Digitization for each crystal bar:
  - For step $i$: $Q_{\pm}^{i} = E_0 \cdot e^{-\frac{L/2 \pm z_i}{L_{Atten}}}$ $T_{\pm}^{i} = T_0 + Gaus(z_{\pm}^{i}/v, \sigma_T)$
  - For each bar: $Q_{\pm} = \sum_{step} Q_{\pm}^{i}$ $T_{\pm} = T_{\pm}^{k} \mid (\sum_{i=1}^{k} Q_{\pm}^{i} > thres)$

*Simplified conditions:* $L_{atten} = \infty$

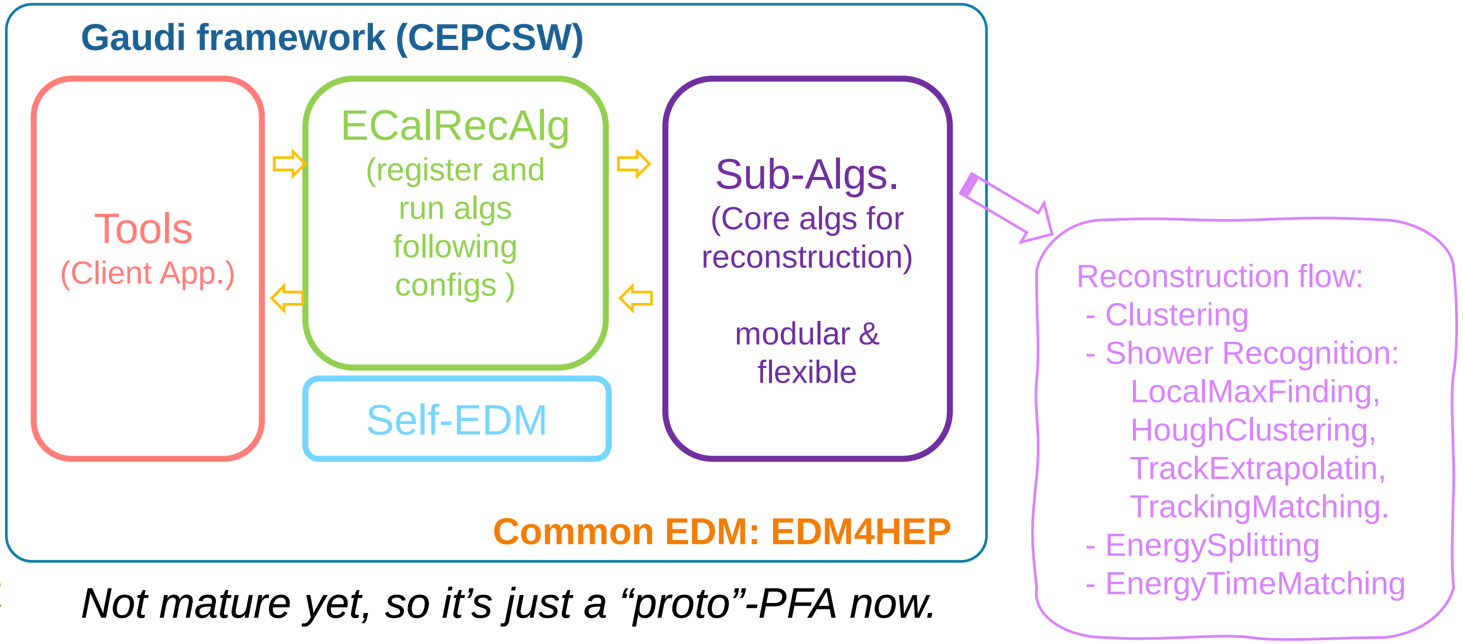


# Design of Reconstruction Software

- Design the reconstruction software as a proto-PFA:
  - Follow the idea of PandoraSDK: flexible, reusable, modular. (Many thanks!)
  - Develop within CEPCSW: based on the common HEP software stack Key4HEP.



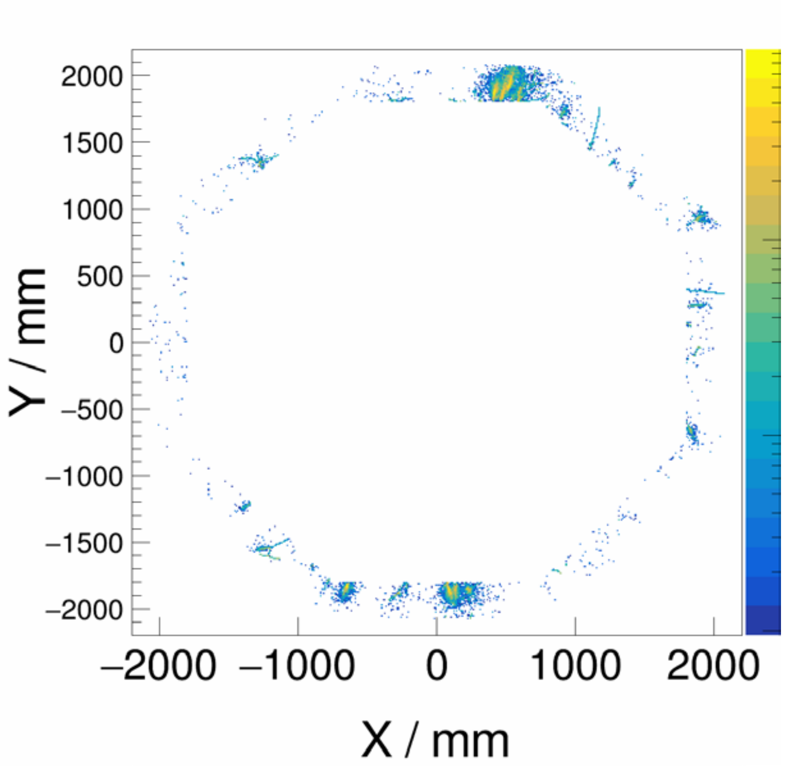

J.S.Marshall, CHEF 2013




*Not mature yet, so it's just a "proto"-PFA now.*

# Reconstruction Algorithm

- Clustering
  - Neighbor clustering
- Shower Recognition:
  - Local maximum and seed candidate $E_i > E_{th}^{seed}$
  - EM showers → Hough transformation
  - Charged particle → track extrapolating & matching
- Energy splitting and Energy/time matching
  - Correctly assign the energy deposits to correct particle.
  - Efficient ghost hit removal.
- Energy Assignment

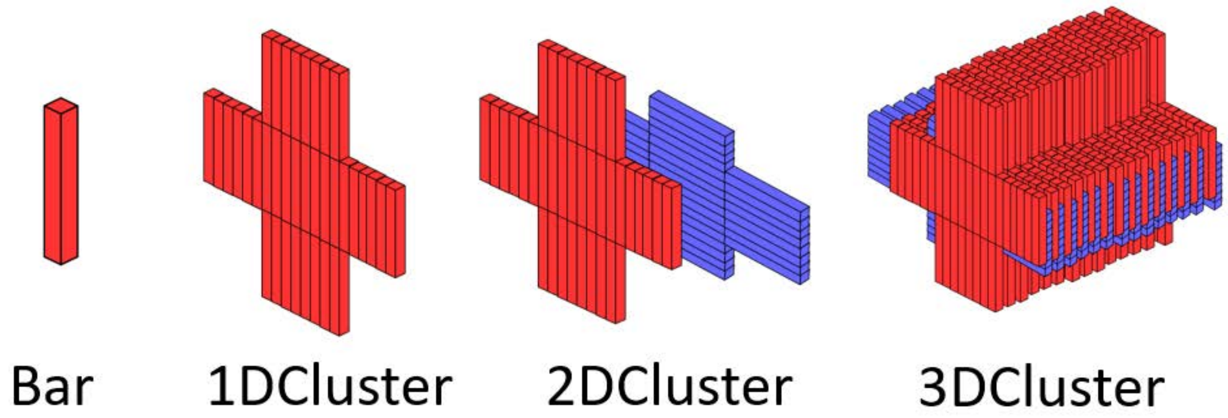


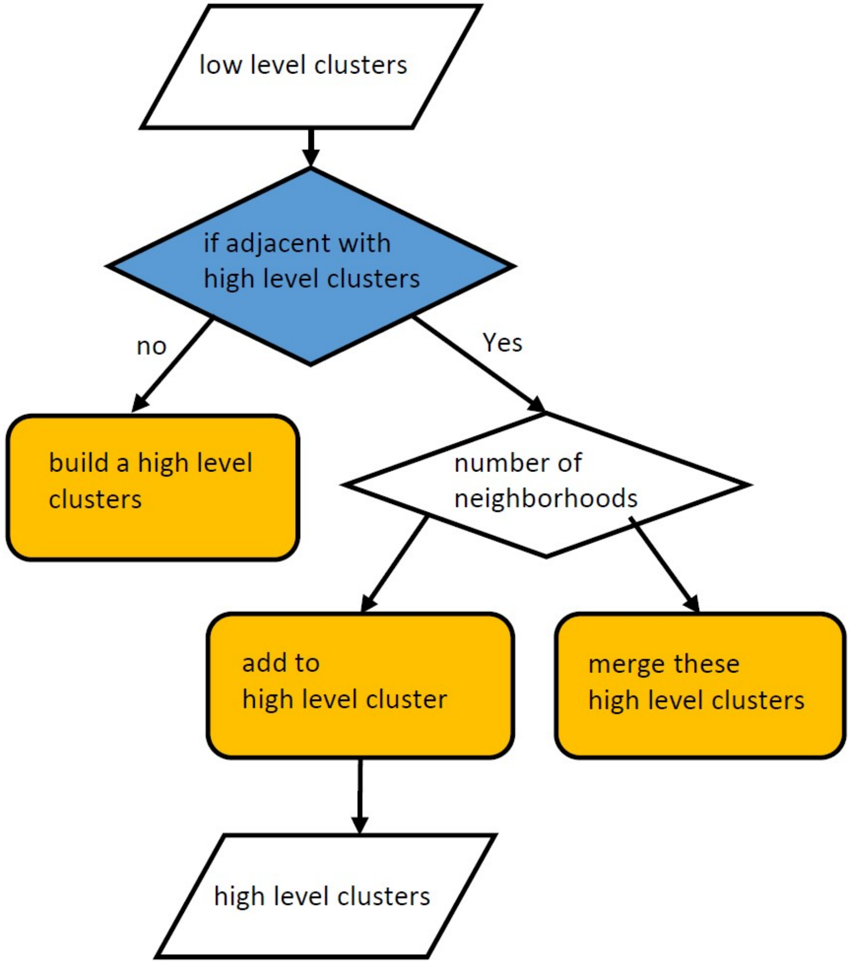

Energy deposits in ECAL of $e^+e^- -> ZH -> \nu\nu gg$

# Clustering

- Cluster:
  - A group of adjacent fired crystals whose energy are greater than threshold

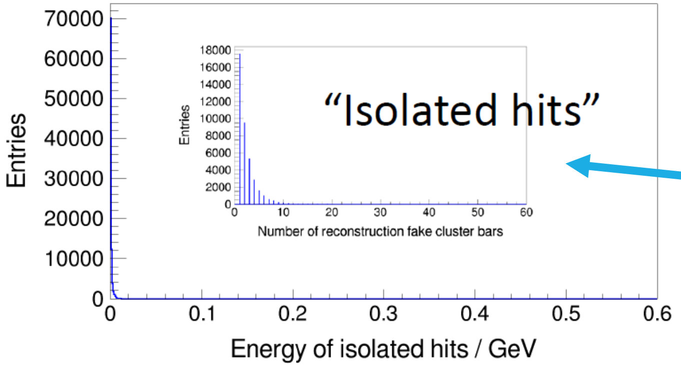
- Process of clustering algorithm:
  - bar → 1D Cluster → 2D Cluster → 3D Cluster

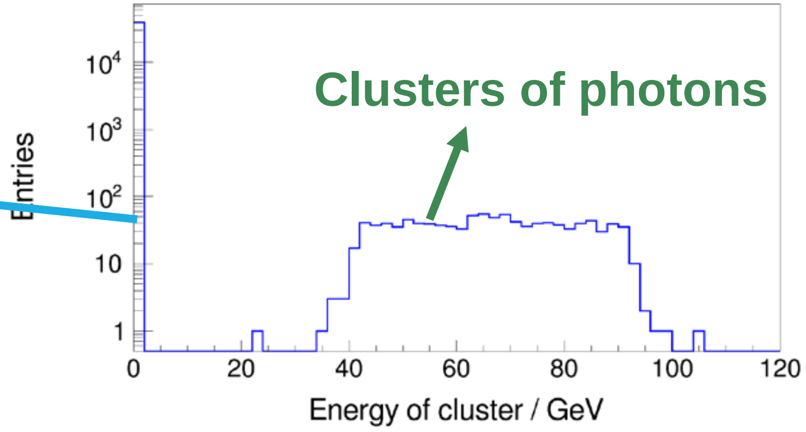


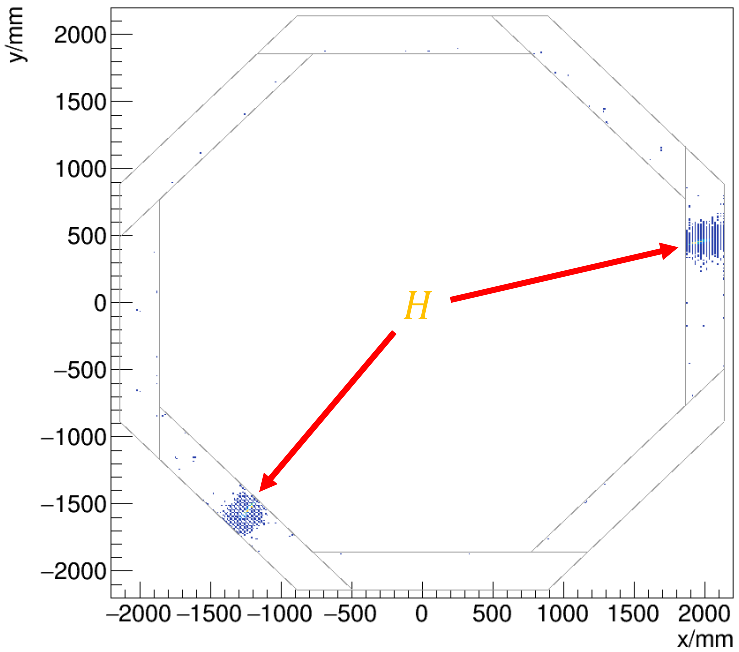



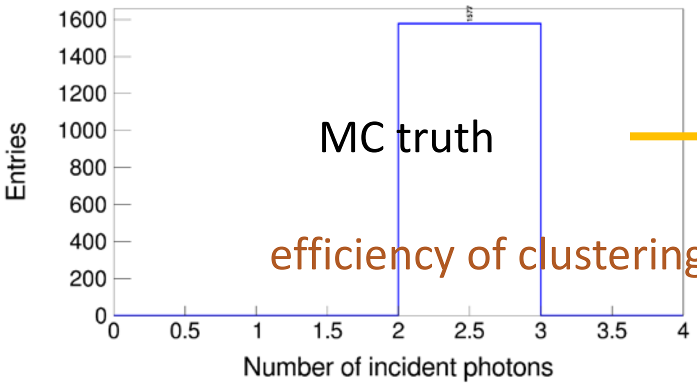
# Performance Check for Clustering Algorithm

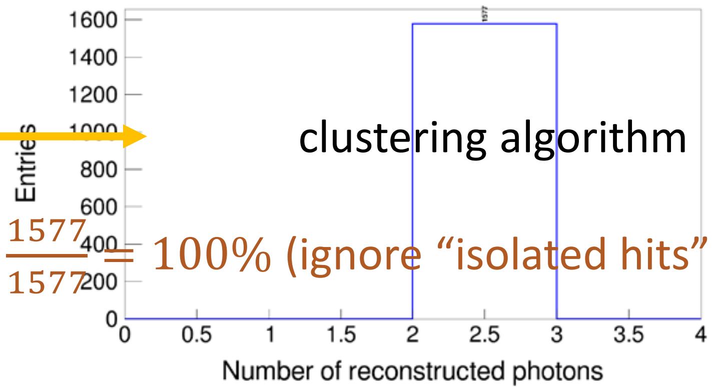
- MC research on $e^+e^- \rightarrow ZH \rightarrow \nu\nu\gamma\gamma$ process at $\sqrt{s} = 240\ \mathrm{GeV}$ to check the performance of Clustering Algorithm
- 2 high energy clusters + many low energy clusters (isolated hit)



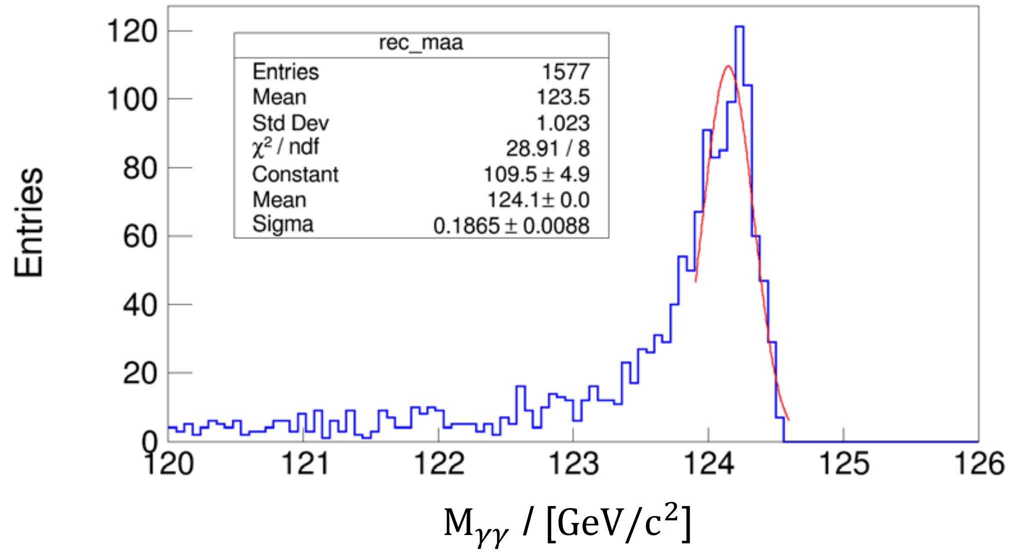



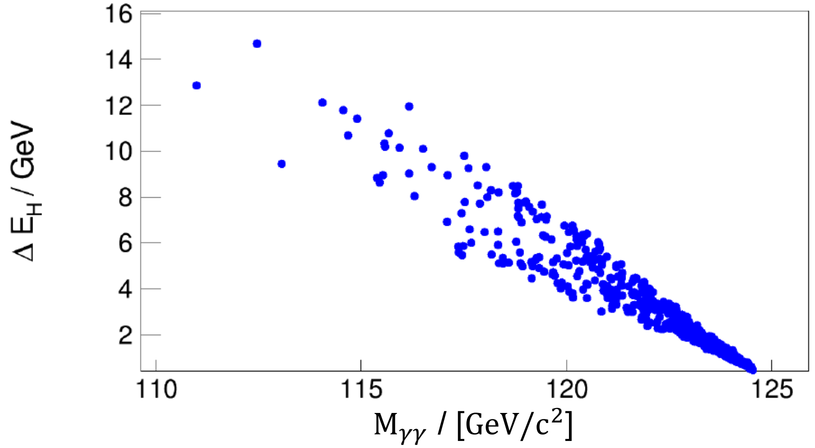

efficiency of clustering :$\varepsilon = \frac{1577}{1577} = 100\%$ (ignore “isolated hits”)

# Performance Check for Clustering Algorithm

- Invariant mass of $\gamma\gamma$: $M_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-cos\theta_{\gamma_1\gamma_2})}$
  - Fit with Gaussian
  - $M_{mean} = 124.148 \pm 0.011\ GeV/c^2$
  - Position reconstruction algorithm used to evaluate photon position
  - Without effect of dead area , attenuation…

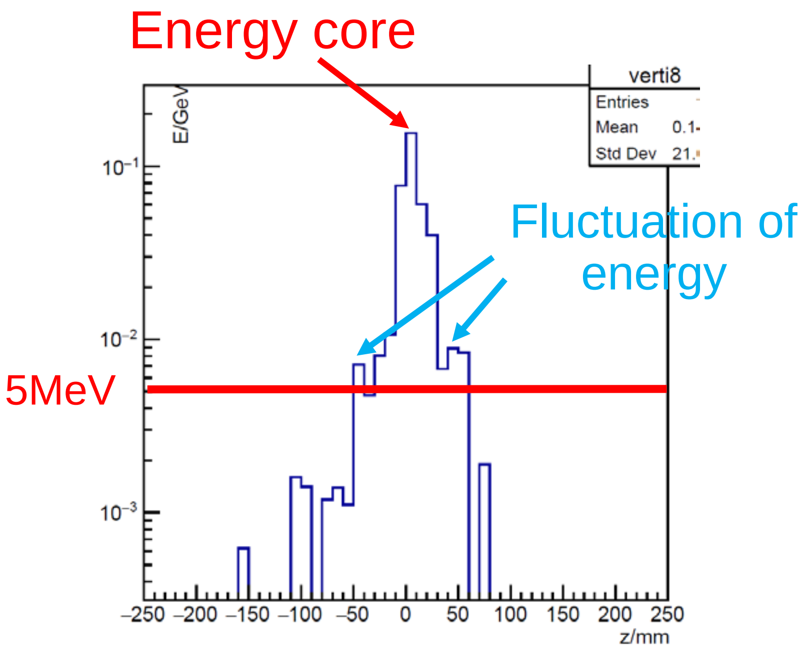


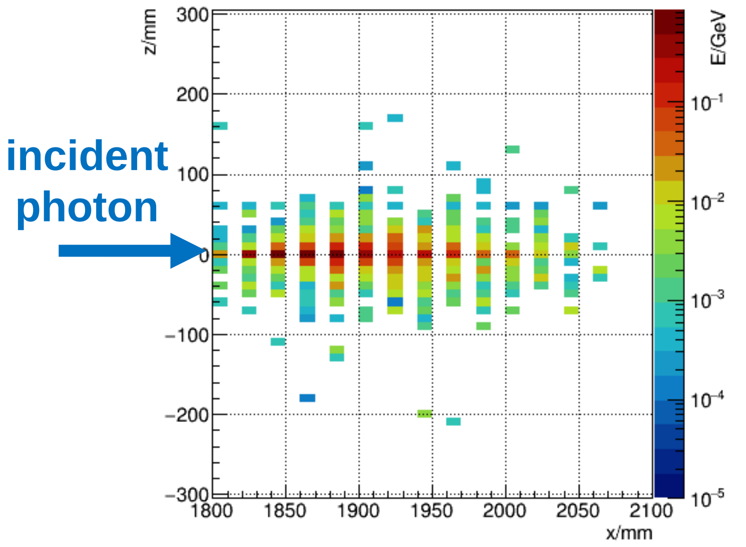

- "Tail" and shift of MPV caused by longitudinal energy leakage
  - Will be corrected based on longitudinal profile



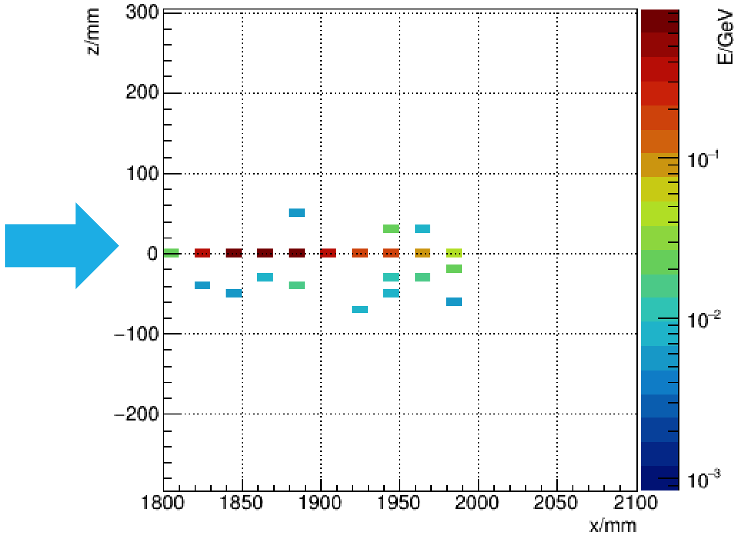
# Shower Recognition: Local Maxima

- In each layer / 1D-cluster : local maximum
  - Real: core of energy deposition ➔ real cluster
- Cluster recognition ➔ Energy "Core" recognition
  - Reduce the negative effects due to wider longitudinal and lateral developments of clusters.



Energy deposits in crystals



Local Maximum Distribution

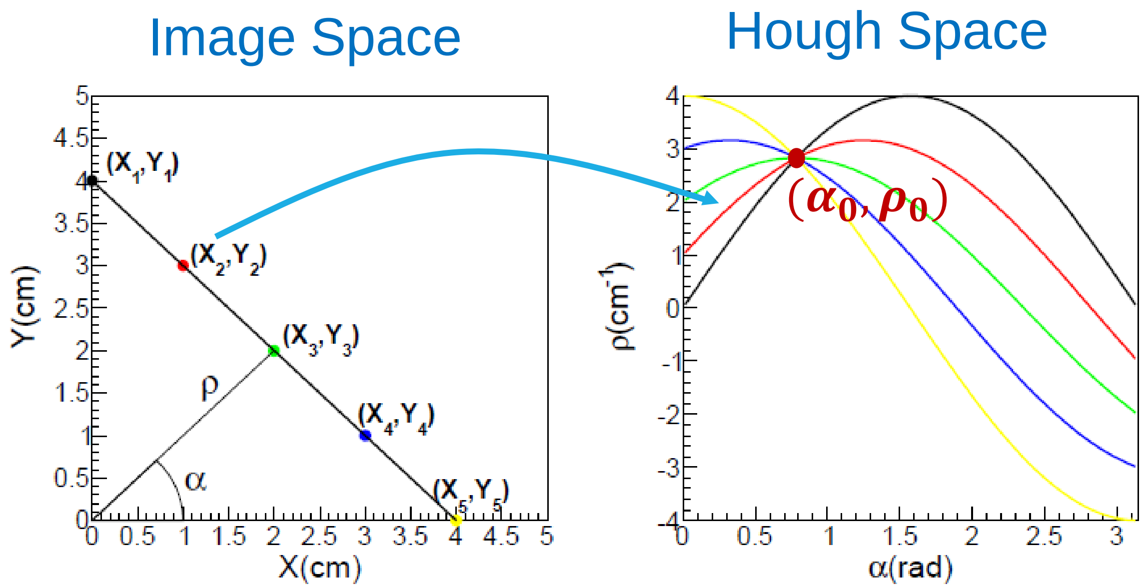
# Principle of Hough Transformation

- A feature extraction method for detecting simple shapes (e.g. lines) in an image.

- For straight lines:

$$\rho = x\cos\alpha + y\sin\alpha$$

  - Each point $(x, y)$ in image space is transformed to a curve in Hough space.
  - If several points $(x_i, y_i)$ are collinear, their curves intersect at a point $(\alpha_0, \rho_0)$ in Hough space.
  - $\alpha_0$ and $\rho_0$ are parameters of the straight line that pass through these points $(x_i, y_i)$




$(x_i, y_i) \Rightarrow \rho = x_i\cos\alpha + y_i\sin\alpha$

Series of Points — Series of Curves

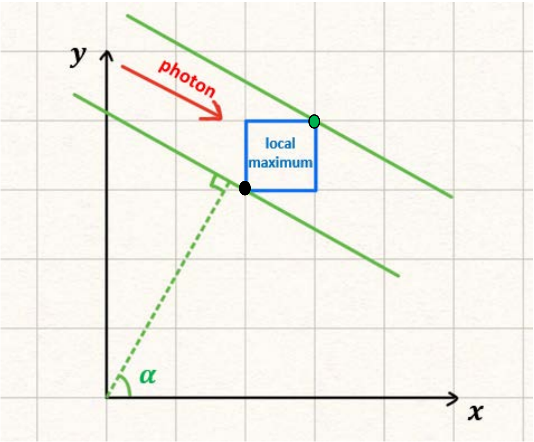
$\Downarrow$

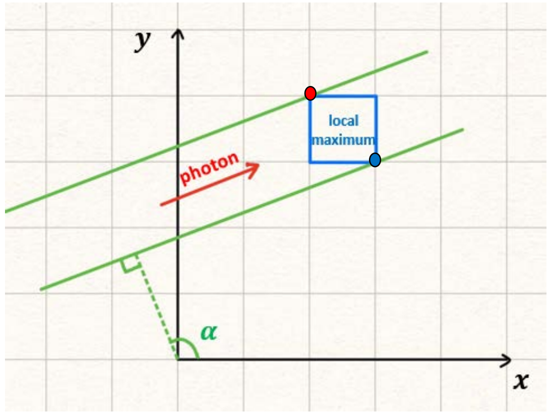
$\rho_0 = x\cos\alpha_0 + y\sin\alpha_0 \Leftarrow (\alpha_0, \rho_0)$

Line — Point

# Hough Transformation in ECAL

- Each crystal in image space is transformed to a band in Hough space instead of a curve.
- Cluster recognition in horizontal and vertical projection spaces respectively.
- Each point/peak (overlap region of band) in Hough space is chosen as a cluster candidate.



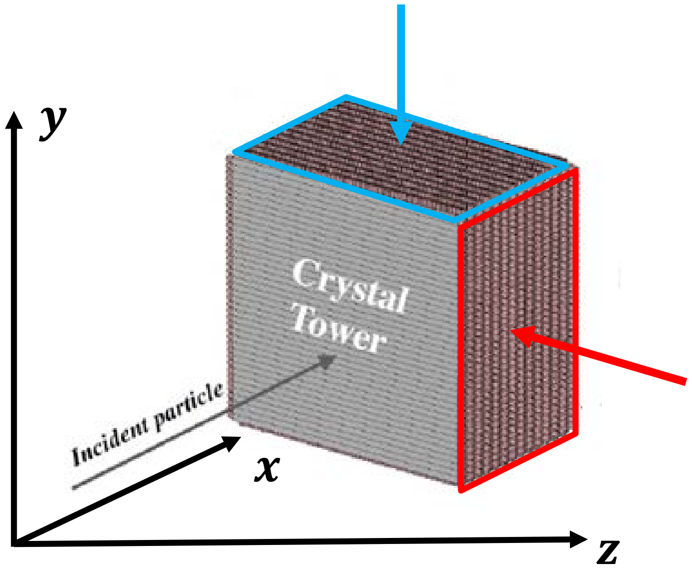
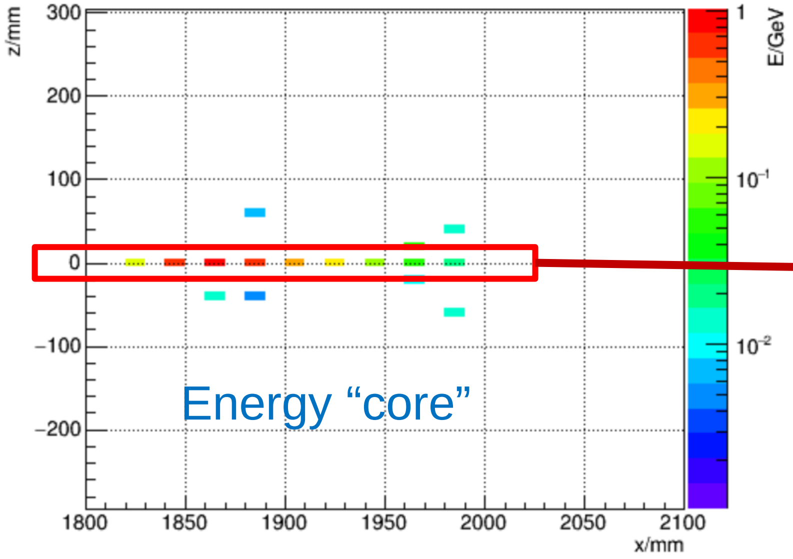
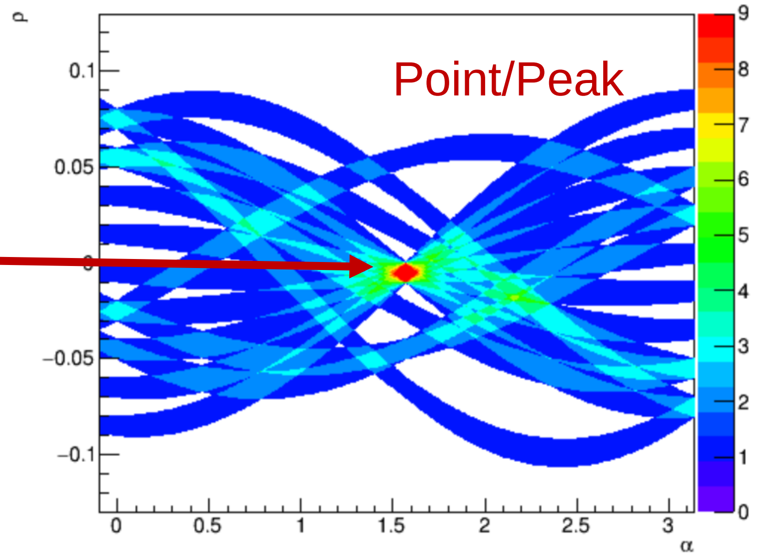



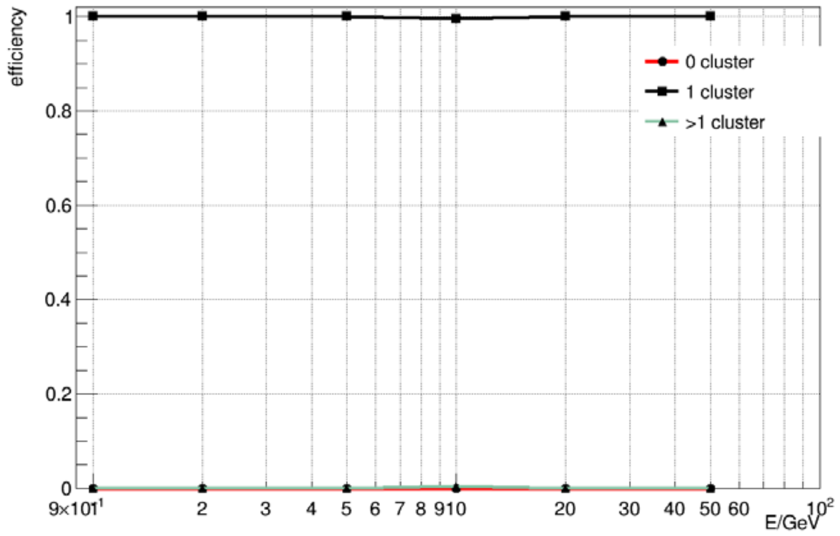

Image Space



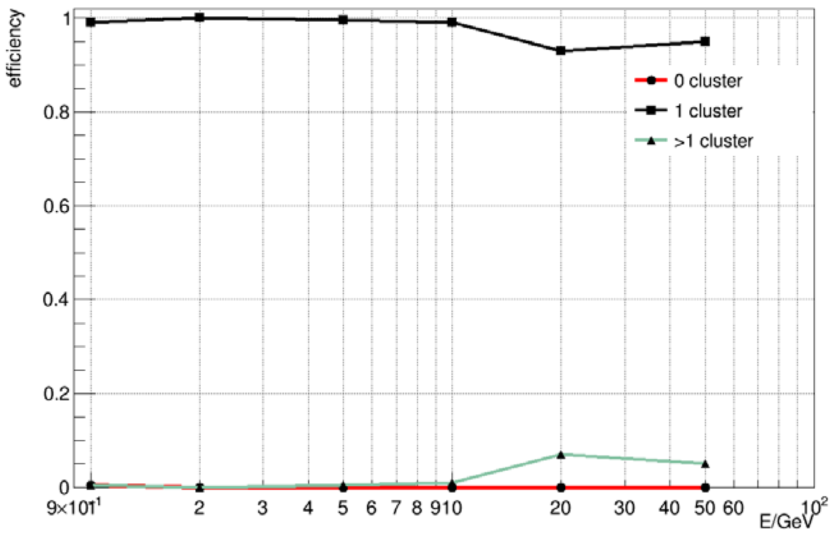

Hough Space



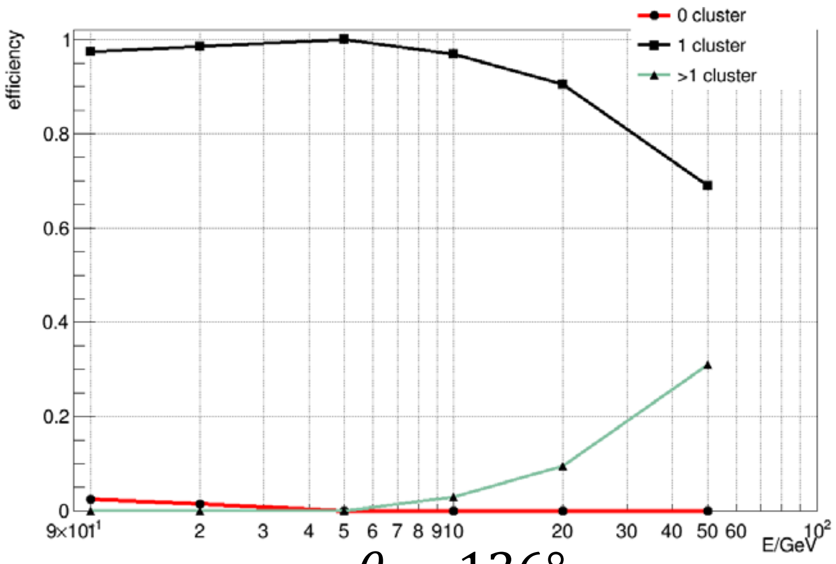
# Efficiency and Fake Rate of Single Photon




$\theta = 90°$



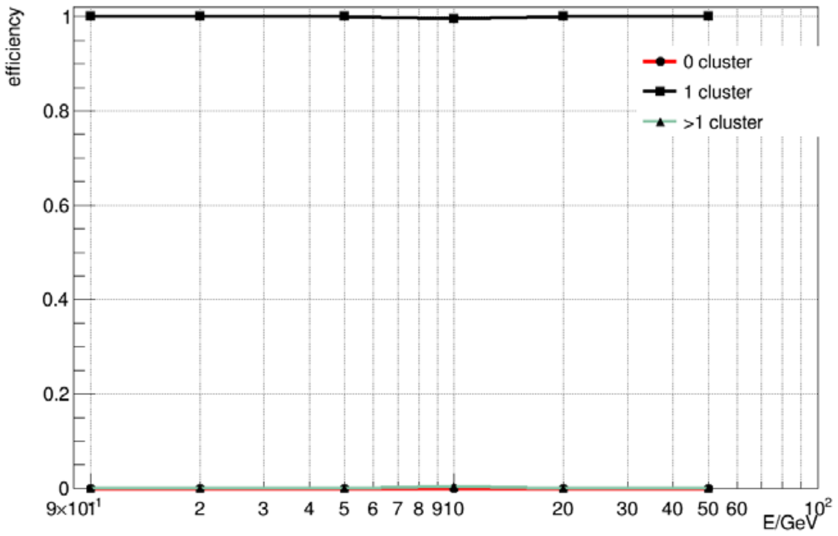

$\theta = 120°$



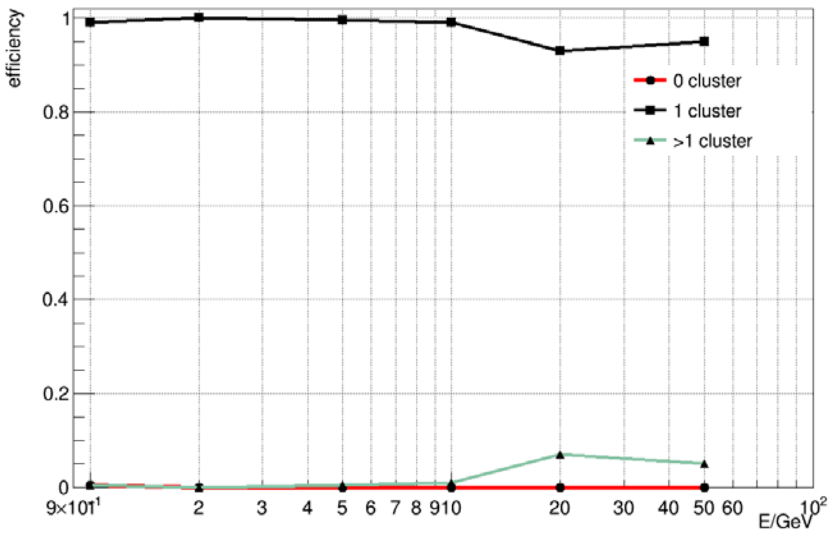

$\theta = 136°$

- Low energy or small $|\cos\theta|$: One & only one cluster
- High energy and large $|\cos\theta|$: >1 clusters
  - Fluctuations of energy deposits increase fake shower

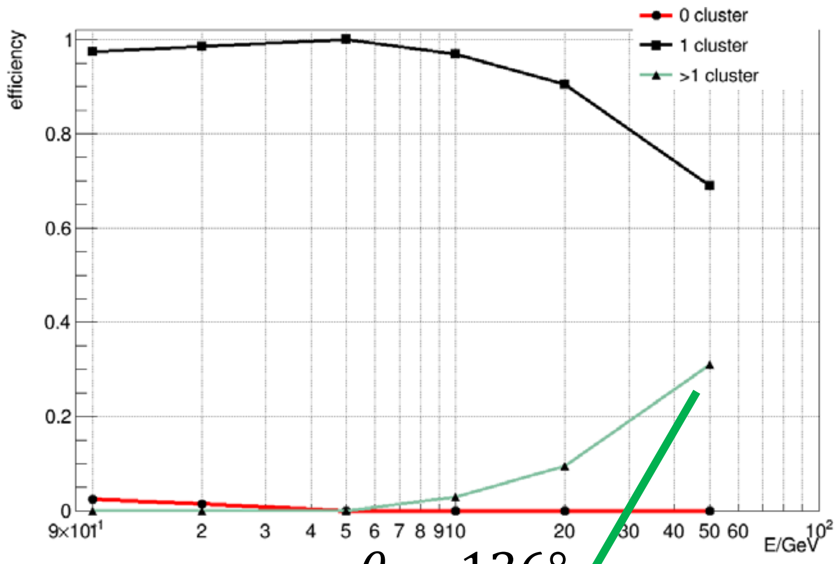
# Efficiency and Fake Rate of Single Photon




$\theta = 90°$

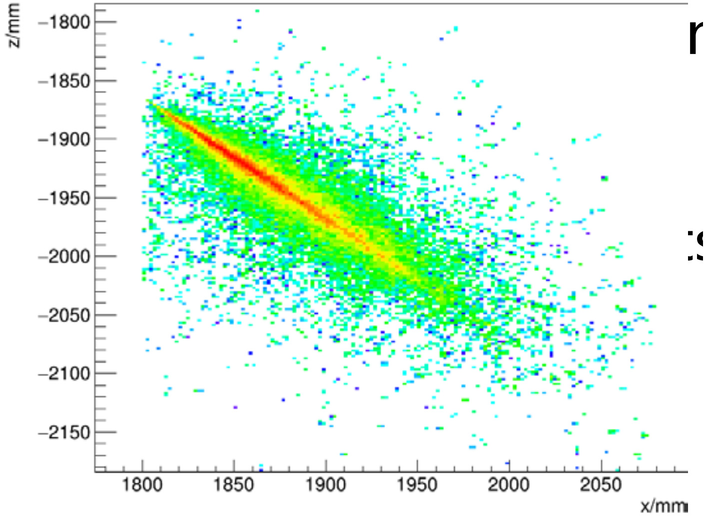


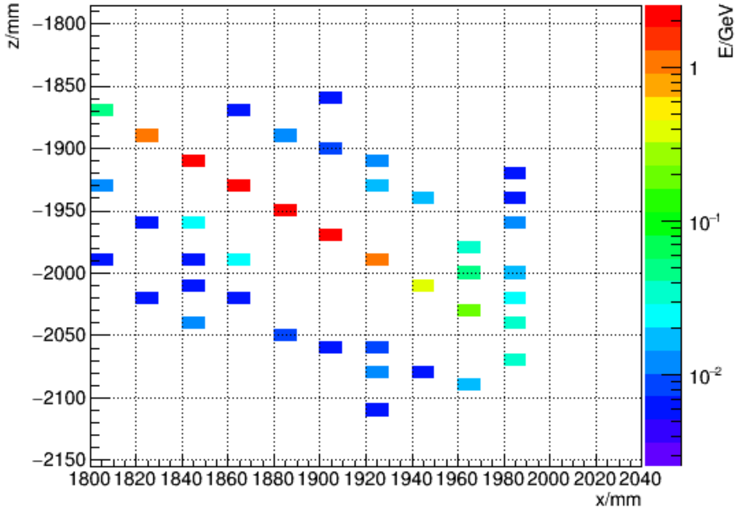

$\theta = 120°$

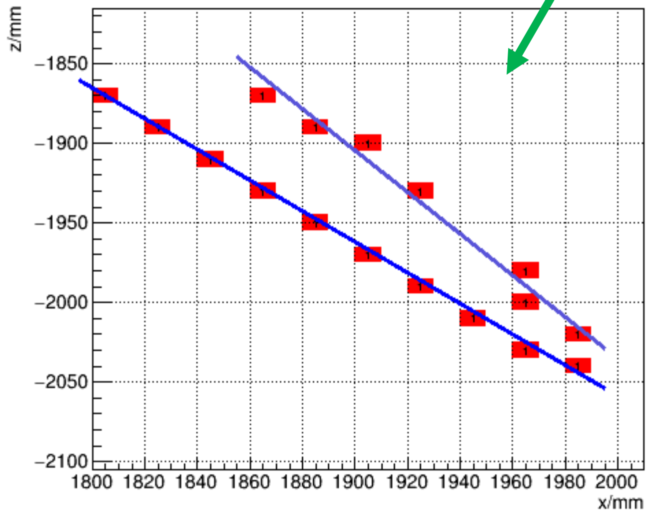



$\theta = 136°$

- Low
- High
  - Flu



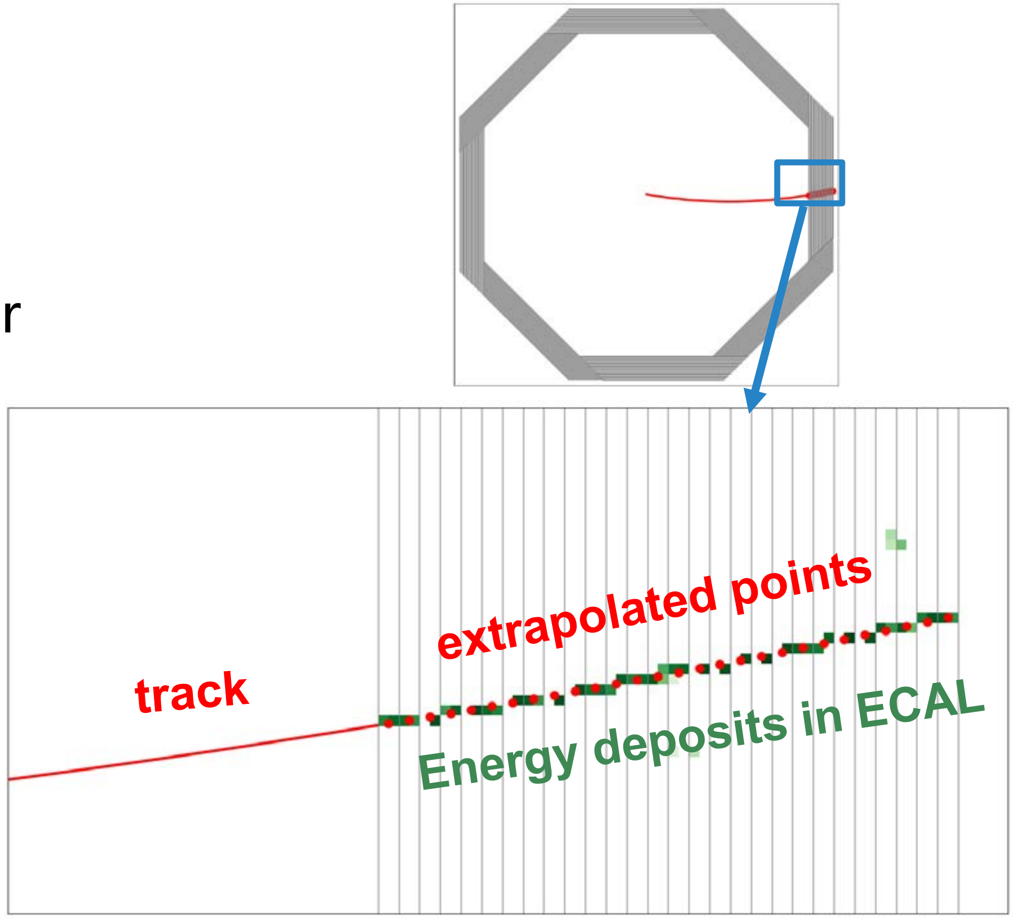



# Recognition of Charged Particles

- Track **extrapolation** and **matching** algorithm are used to identify the energy deposit of charged particle in ECAL

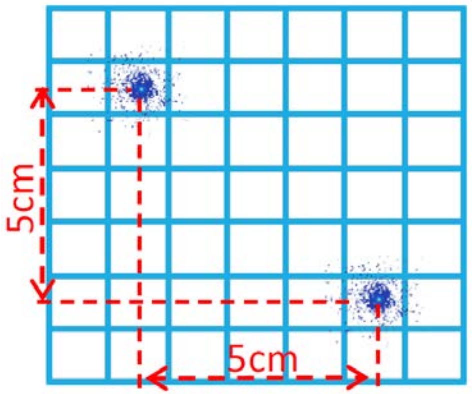
- Track extrapolation algorithm
  - Using track information of charged particles in tracker
    - reference point, parameters of helical track
  - Evaluate the expected points in each layer of ECAL

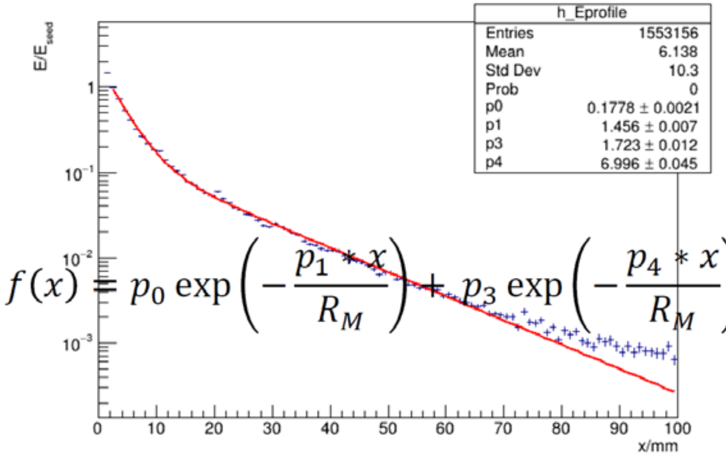
- Track matching algorithm (under development)
  - Match extrapolated points with clusters



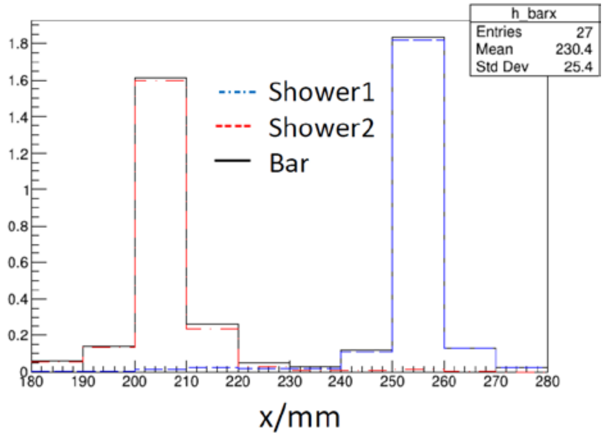
# Energy Splitting

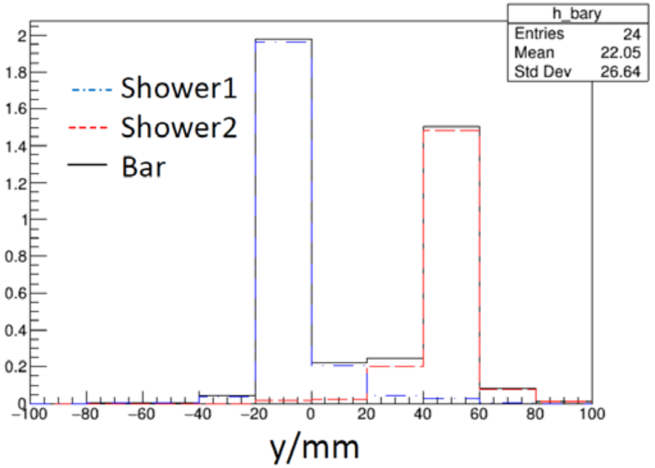
- Showers from different particles may overlap, i.e. multiple energy axis in one cluster
  - Energy of shower $\mu$ deposited in bar $i$ : $E_{i\mu}^{exp} = E_{\mu}^{seed} \times f(|x_i - x_c|)$
  - Energy splitting: $E_{i\mu} = w_{i\mu} \times E_{mea}^{i} = \frac{E_{i\mu}^{exp}}{\sum_{\mu} E_{i\mu}^{exp}} \times E_{mea}^{i}$
  - Iteration until convergence



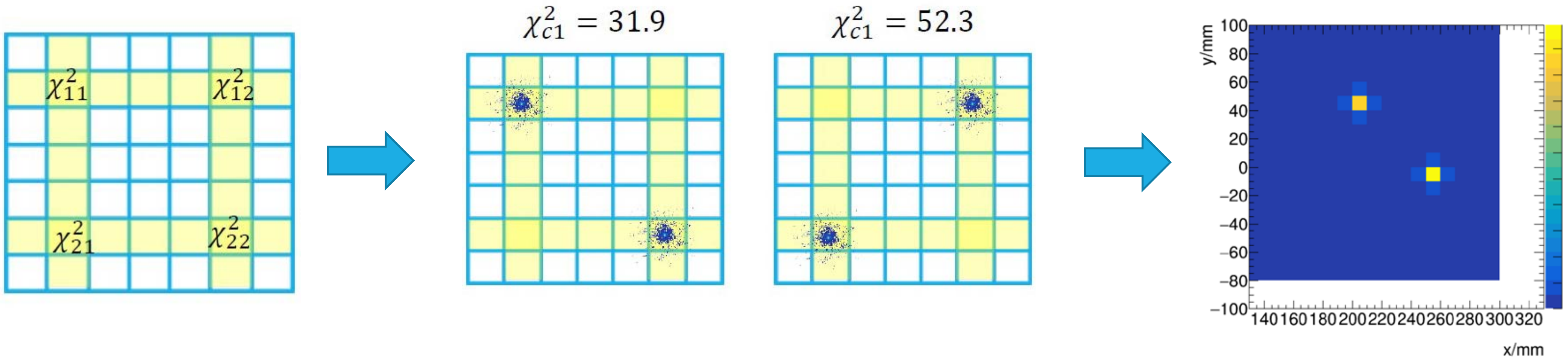

$$f(x) = p_0 \exp\left(-\frac{p_1 * x}{R_M}\right) + p_3 \exp\left(-\frac{p_4 * x}{R_M}\right)$$



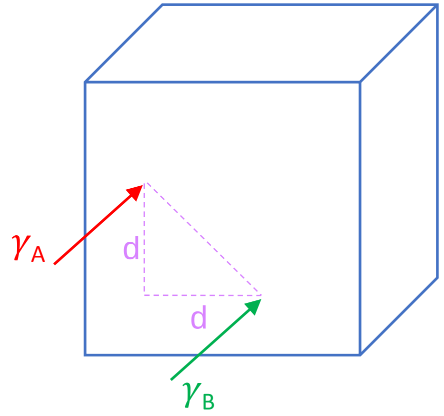
# Energy/Time Matching

- Perpendicular arrangement of crystal bars in adjacent layers may cause ambiguity problem for multiple particles in one tower
  - Define $\chi_E^2$ for energy matching: $\chi_E^2 = \frac{(E_X - E_Y)^2}{\sigma_E^2}$
  - Define $\chi_T^2$ for time matching: $\chi_T^2 = \frac{(Z_T - Z_Y)^2}{\sigma_{bar}^2 + \sigma_{Z(t)}^2}$
  - Define $\chi_{point}^2 = \chi_E^2 + \frac{1}{2}(\chi_{Tx}^2 + \chi_{Ty}^2)$
  - Totally $N!$ combinations: $\chi_c^2 = \sum_{i=1}^{N} \chi_{point}^2$

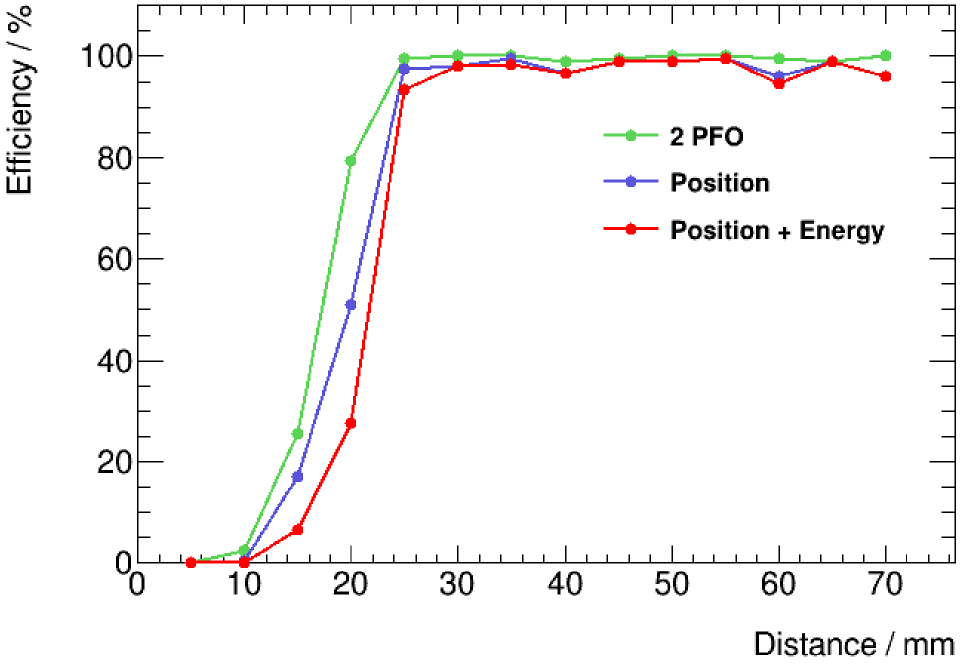


# Preliminary Performance

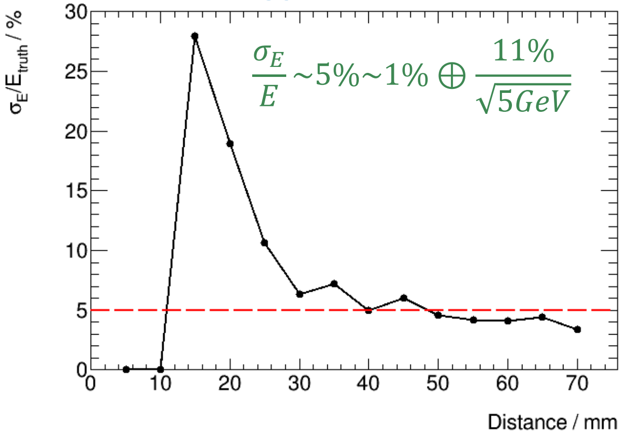
- Gamma/gamma matching:
  - Particle gun events simulation for two 5GeV photons in parallel.
  - Scan the distance between photons, check the successful reconstruction efficiency and energy resolution.



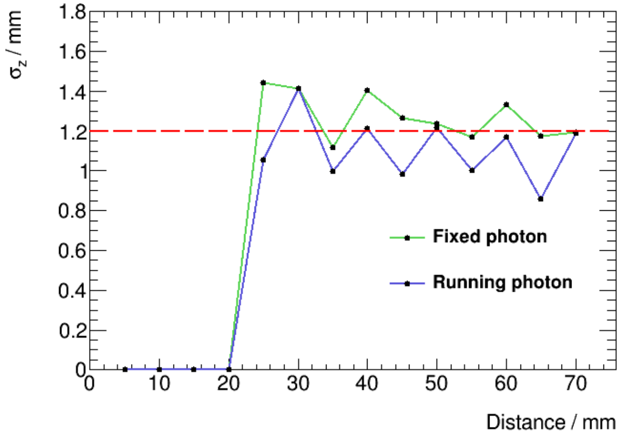

Separation efficiency




Energy resolution




Position resolution



# Summary

- Long crystal bar is a promising solution for ECAL, it is challenging for hardware and software to obtain a maximal exploitation of precise measurements.
- Simulation and digitization of barrel part of long bar crystal ECAL have been simplified for reconstruction algorithm without electronics, supporting, etc.
- Software development of reconstruction algorithms, which makes full use of 5D information (x, y, z, E, T), is in processing.
- Basic functions of clustering, shower recognition, energy splitting and energy/time matching has been implemented.
- Emphasis on clusters separation of charged and neutral particles in ECAL is in the plan.
- Simulation and reconstruction of ECAL combined with HCAL will be performed for jet energy measurement.