Reconstruction Algorithm for Long Crystal Bar ECAL

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on behalf of CEPC ECAL software group

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Outline

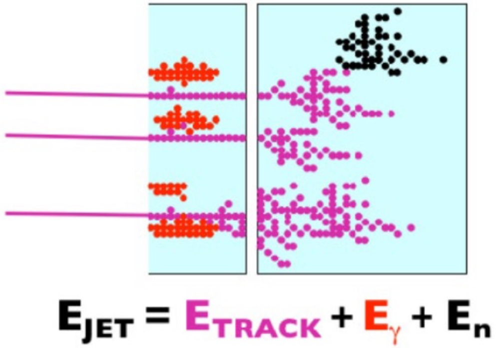
- Introduction
- Simulation and digitization
- Reconstruction algorithm and performance check
- Summary

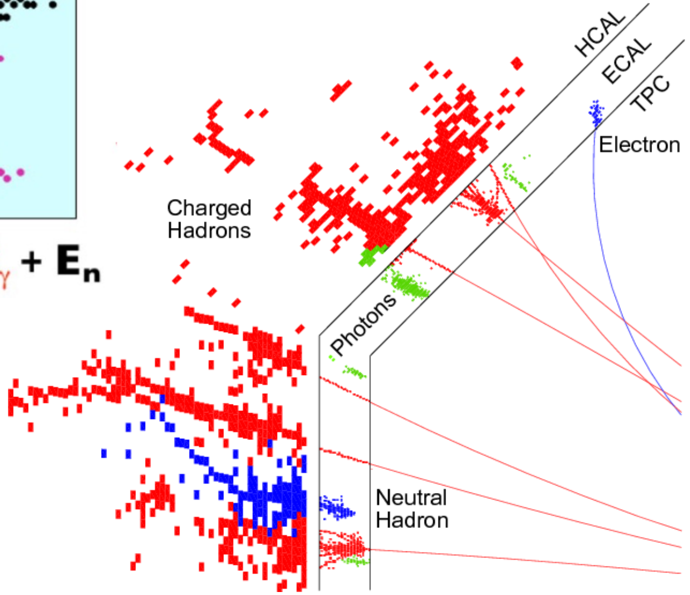
Introduction: PFA Calorimeter

- High precision Higgs / Z factory:
  - Heavy bosons separation and precise Higgs measurements require excellent jet energy resolution 3~4%.
  - Fine γ / π^0 reconstruction for flavor physics.

- Particle Flow Approach (PFA):
  - 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

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

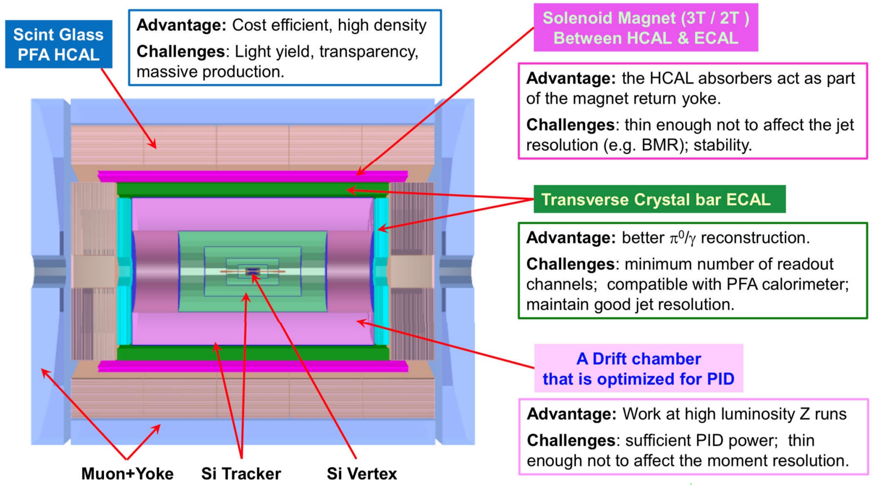


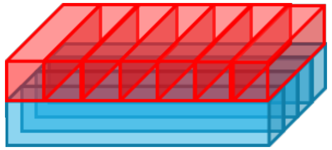


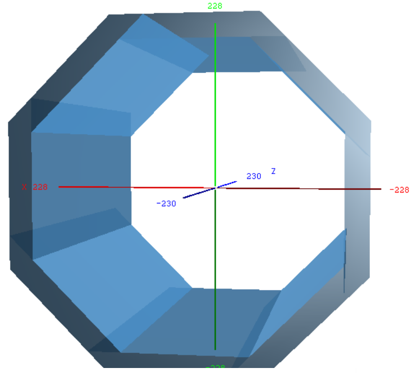
Long Crystal Bar ECAL

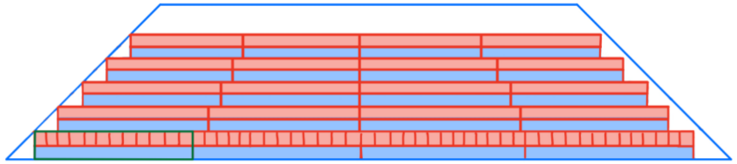
- Long crystal bar ECAL:
  - Homogeneous structure ➔ Optimal energy resolution $\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%$
  - Significant reduction of number readout channels
  - Larger Moliere radius R_M ➔ increase probability of shower overlap
  - Smaller λ_I / X_0 ➔ increase probability of hadronic shower in ECAL
- Key issues:
  - Ambiguity caused by matching of horizontal and vertical bars.
  - Identification of energy deposits from each individual particle.

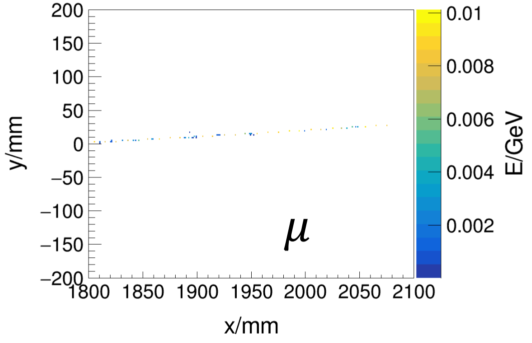
Reconstruction is big challenge!

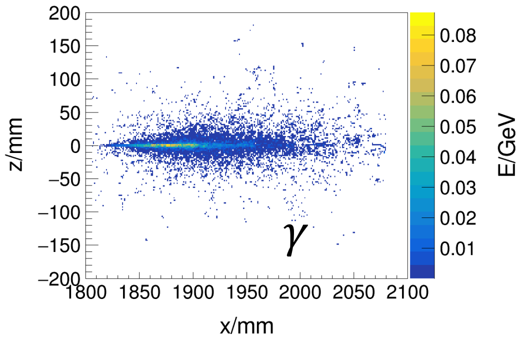


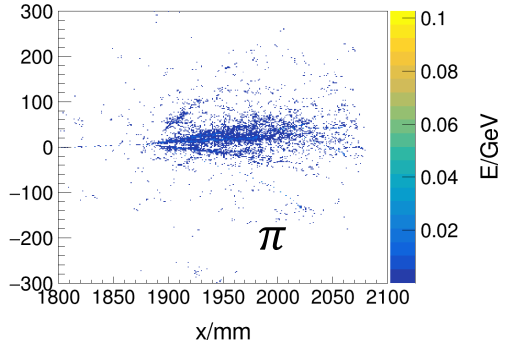












Design Concept of Long Crystal Bar ECAL

A BGO crystal barrel ECAL

Crystal Bar:

- BGO： $X_0 = 1.12cm, R_M = 2.23cm$
- Size: $1\times1\times40\sim60\ cm^3$
- Time measurements at both ends readout for position along bar

Basic Detection Unit — Super Cell:

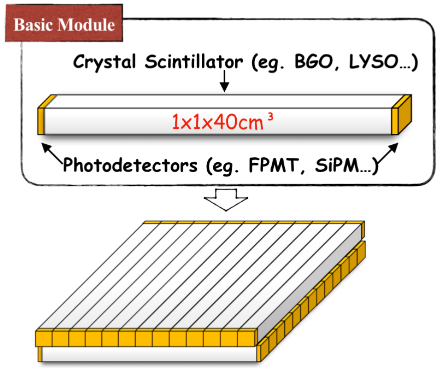
- 2 layers of perpendicularly crossing bars
- Size: $\sim40\times\sim60\times2\ cm^3$

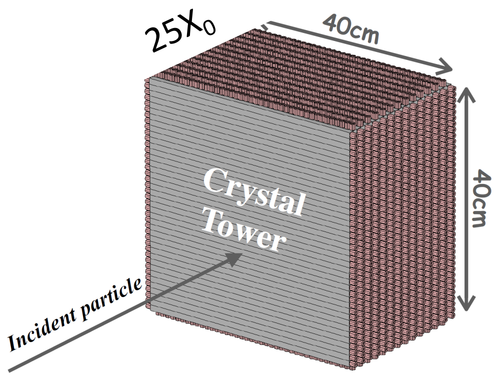
Detector:

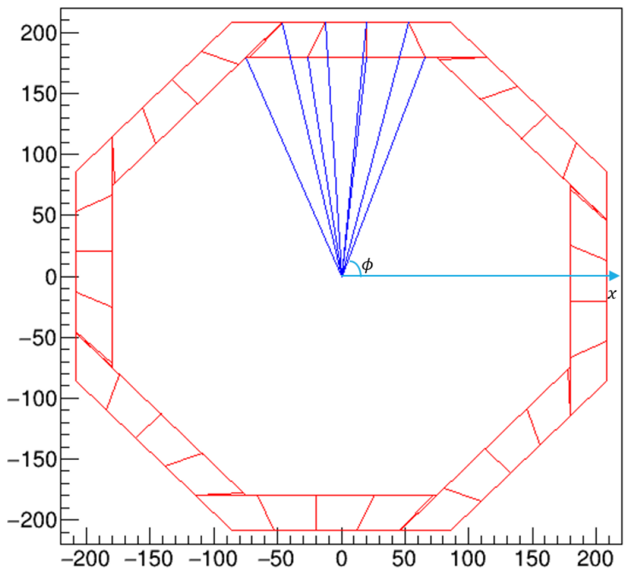
- $R = 1.9m, L = 6.6m, H = 28cm$
- 8 same trapezoidal staves
- Avoid gaps point to IP

DD4Hep is used for geometry construction

Focusing on software performance, ignoring dead area, supporting and cooling mechanics, etc







Simulation and Digitization

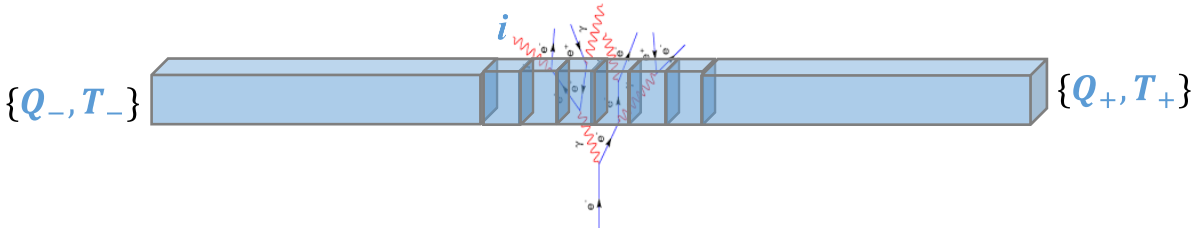
- Simulation is performed using GEANT4:
  - Electromagnetic interactions
  - Hadronic interactions
- Digitization for one long crystal bar:
  - Contribution of each G4step ***i***

$$Q_{\pm}^{i} = E_0 \cdot e^{-\frac{L/2 \pm z_i}{L_{Atten}}}, \qquad T_{\pm}^{i} = T_0 + Gaus(z_{\pm}^{i}/v,\ \sigma_T)$$

  - Readout at both ends: $\boldsymbol{Q}_{\pm}$ and $\boldsymbol{T}_{\pm}$

$$\boldsymbol{Q}_{\pm} = \sum_{step} Q_{\pm}^{i}, \quad \boldsymbol{T}_{\pm} = T_{\pm}^{k} \mid \left(\sum_{i=1}^{k} Q_{\pm}^{i} > thres\right)$$

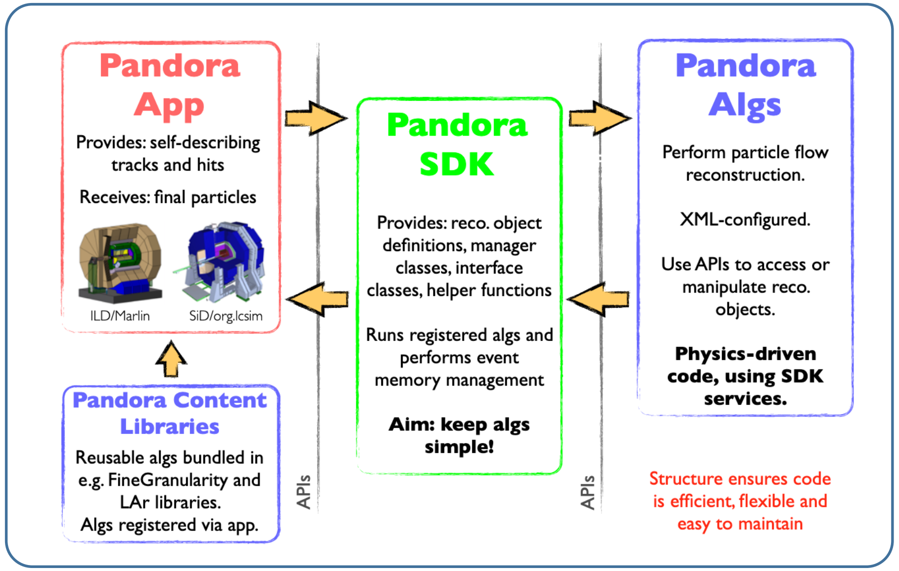
Simplified Conditions: $L_{Atten} = \infty$



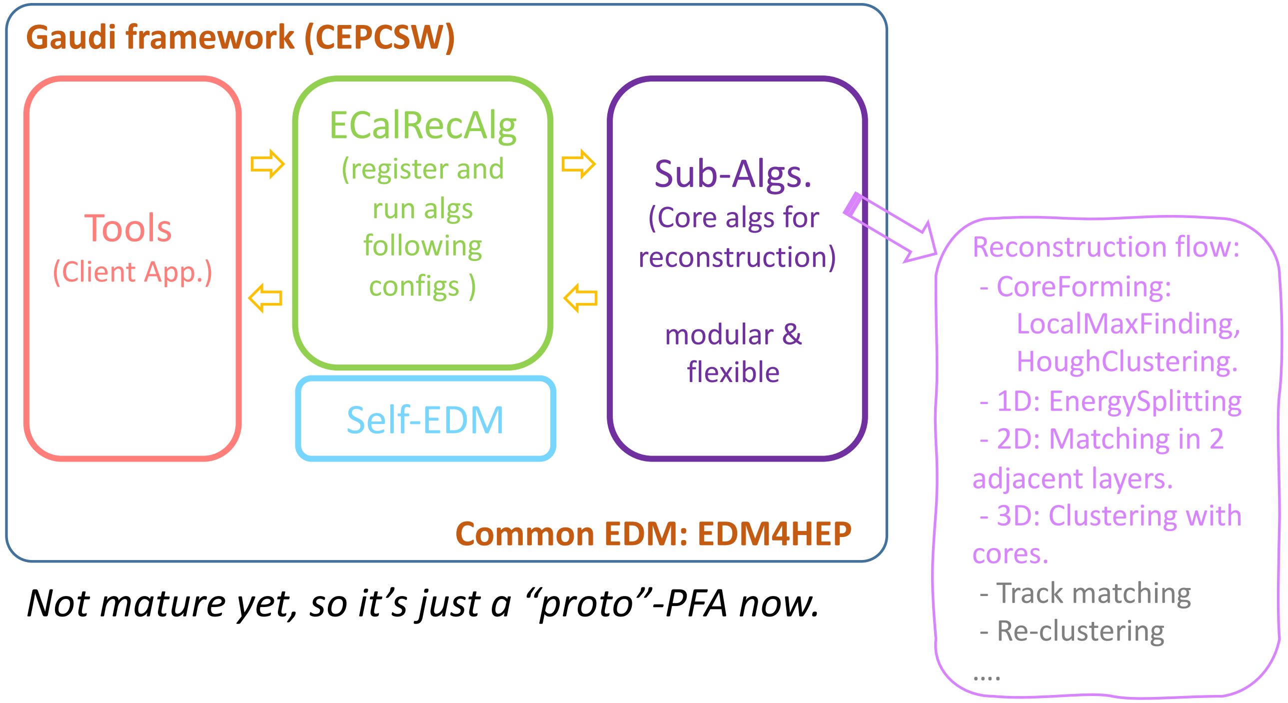
Design of Reconstruction Software

Design the reconstruction software as a proto-PFA:

- Follow the idea of PandoraSDK: flexible, reusable, modular. (*Many thanks!*)
- Develop in CEPCSW: based on the common HEP software stack Key4HEP.



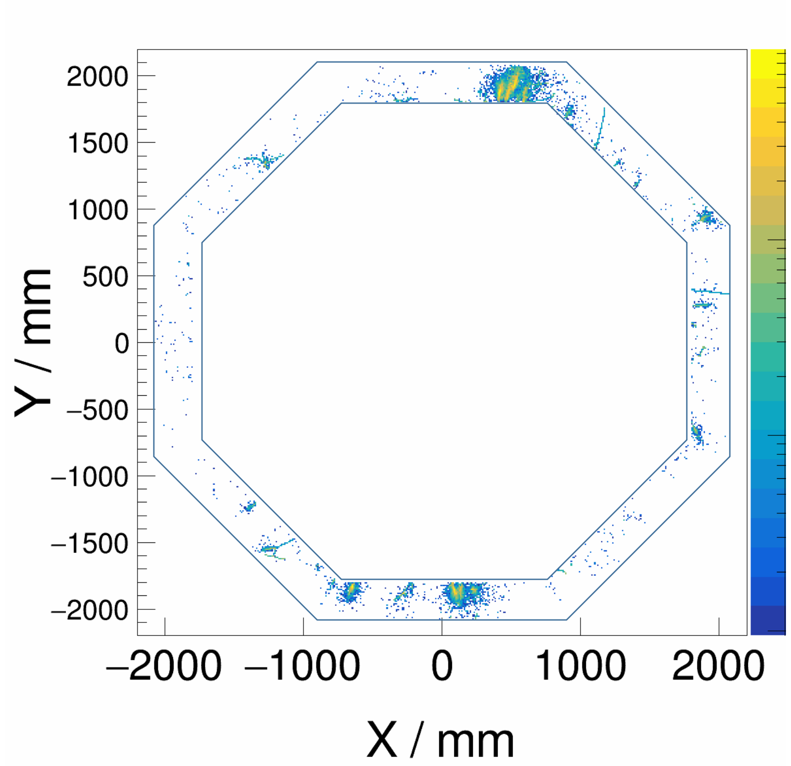
J.S.Marshall, CHEF 2013



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

Reconstruction Algorithm

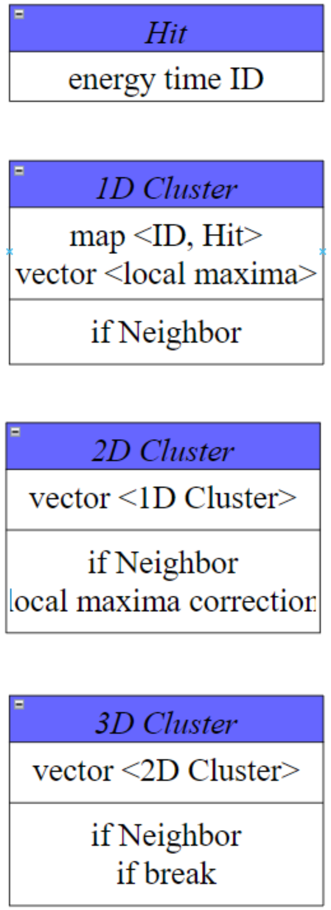
- Cluster Finding:
  - Neighbor clustering
- Cluster/Particle Recognition:
  - Local maximum and seed candidate $E_i > E_{th}^{seed}$
  - Hough transformation for EM showers
  - Match of extrapolated charged track and cluster
- Energy Splitting:
  - Efficient ghost hit removal
  - Correctly assigned the energy deposits to correct particle

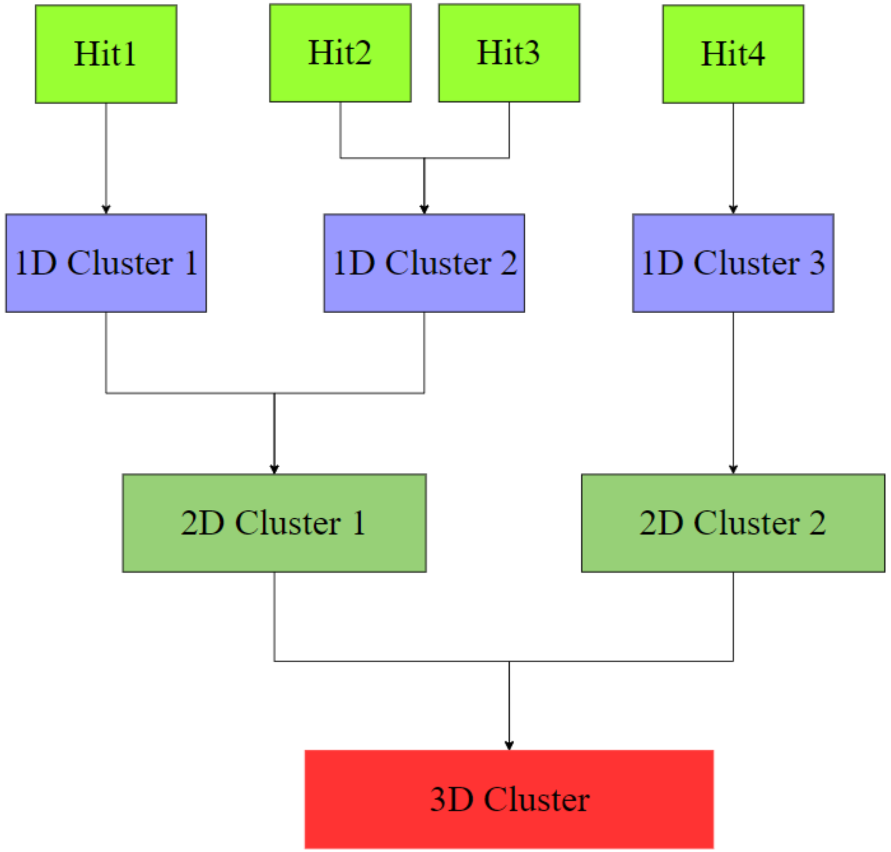


Energy deposits in ECAL of $e^+e^- -> ZH -> \upsilon\upsilon gg$

Cluster Finding

- Cluster:
  - a group of adjacent fired crystals whose energy is greater than threshold
- Each crystal bar has 3-dimentional labels
- Event data model (EDM):
  - ✓Single layer (1D)
  - ✓Bi-layer (2D)
  - ✓Multi-layer (3D)
- Algorithm:
  - if objects are neighbor in pairs, they are merged



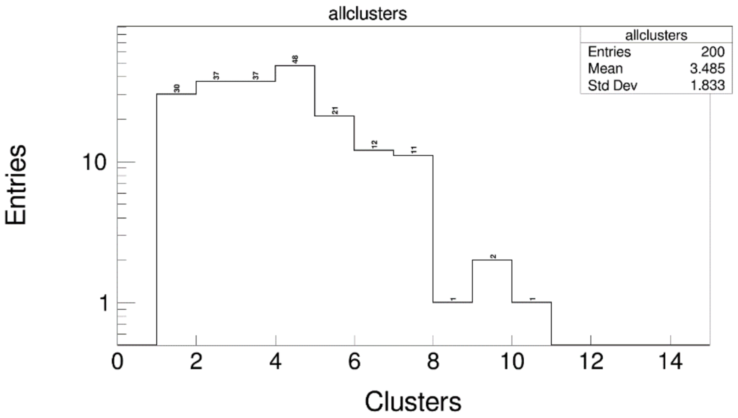


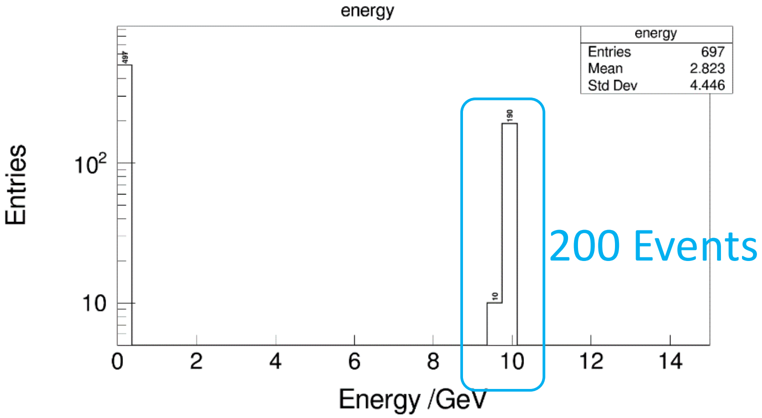
Performance Check of Cluster Finding

Single Photon: 200 events

$E_\gamma = 10GeV \quad \phi_\gamma = 0^\circ \quad \theta_\gamma = 90^\circ$

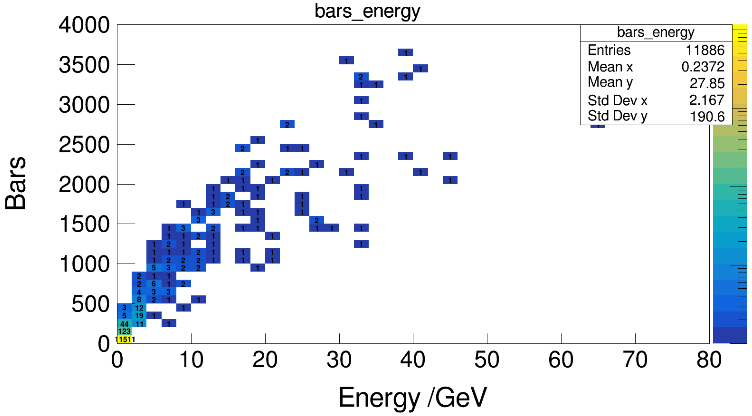
- Much more than 1 cluster/event in most cases. 200 clusters $E_\gamma \sim 10GeV$
  and $\times 2.5$ clusters with small energy
- “Isolated hits” is planned to be absorbed into clusters nearby

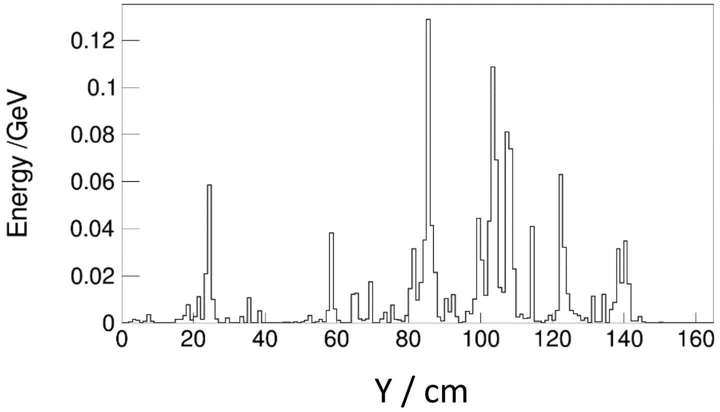




Jet: 240GeV $e^+e^- -> ZH -> \upsilon\upsilon gg$

- There are lots of “isolated hits” same as photon
- Typical lateral development of jet event will bring challenge for cluster recognition and energy splitting

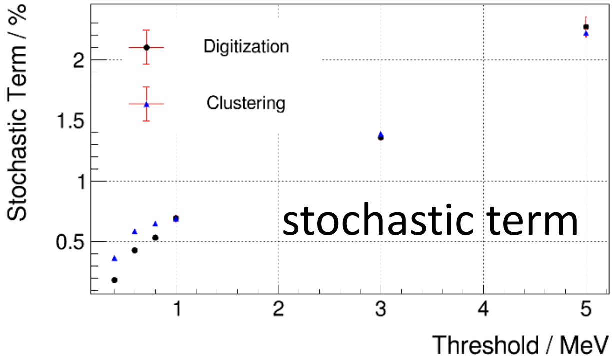


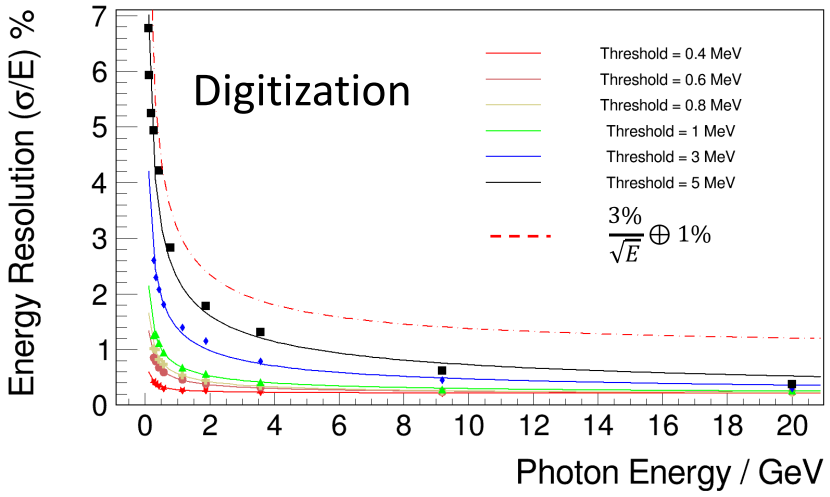


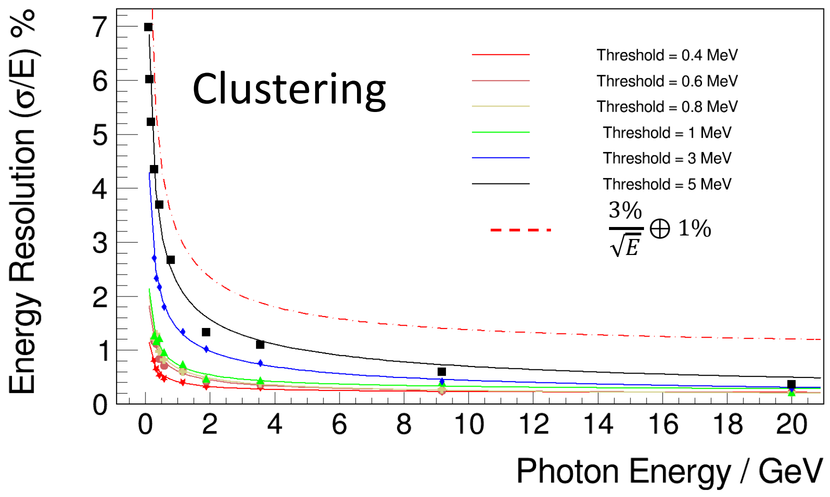
Impact of Threshold on Energy Resolution

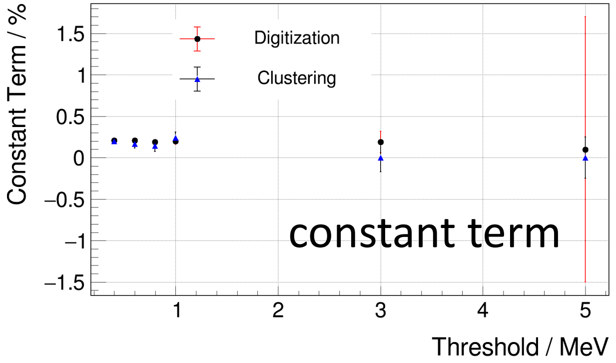
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b$$

- Impact of thresholds on energy resolution is studied using single photon simulation samples with different energies.
- Comparison of all fired crystals (single photon + isolated hits, Digitization) and energetic cluster (single photon) shows slightly differences in stochastic term with threshold<1MeV.



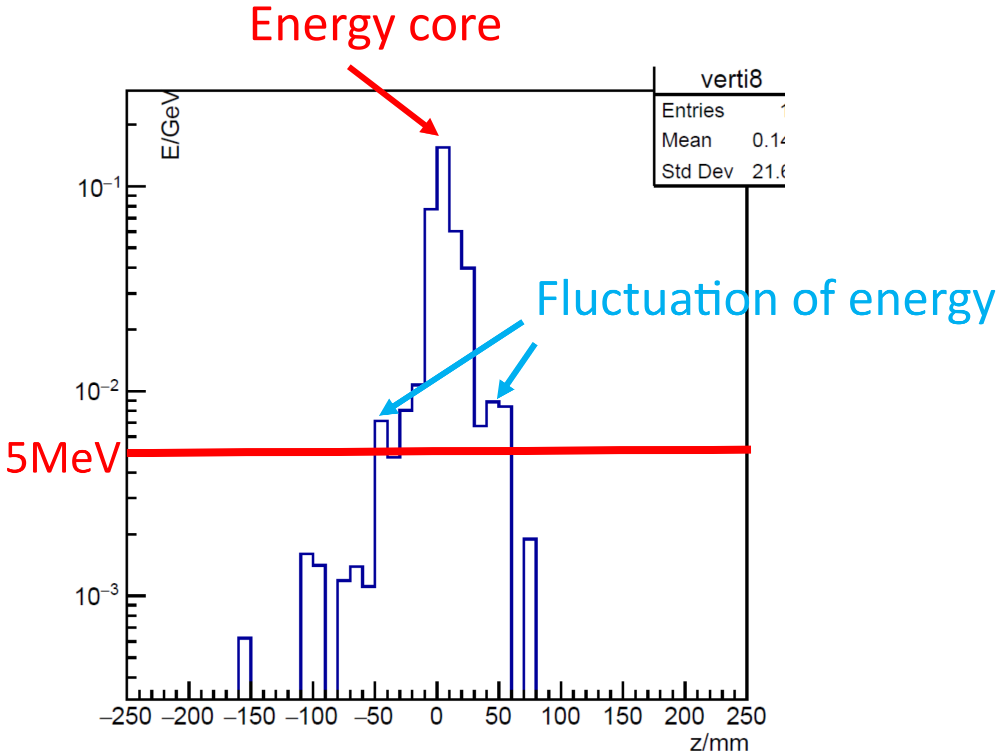


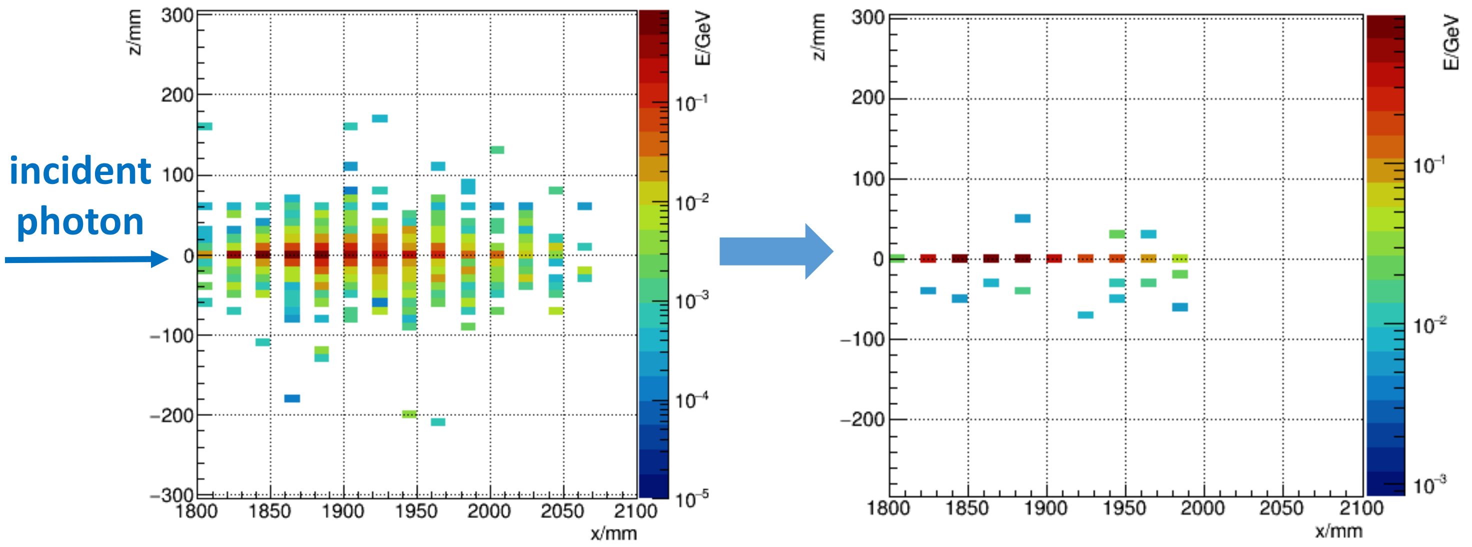




Cluster / Particle Recognition — Local Maximum

- Larger R_M enhance probability of lateral overlap of showers.
- In each layer / 1D : 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

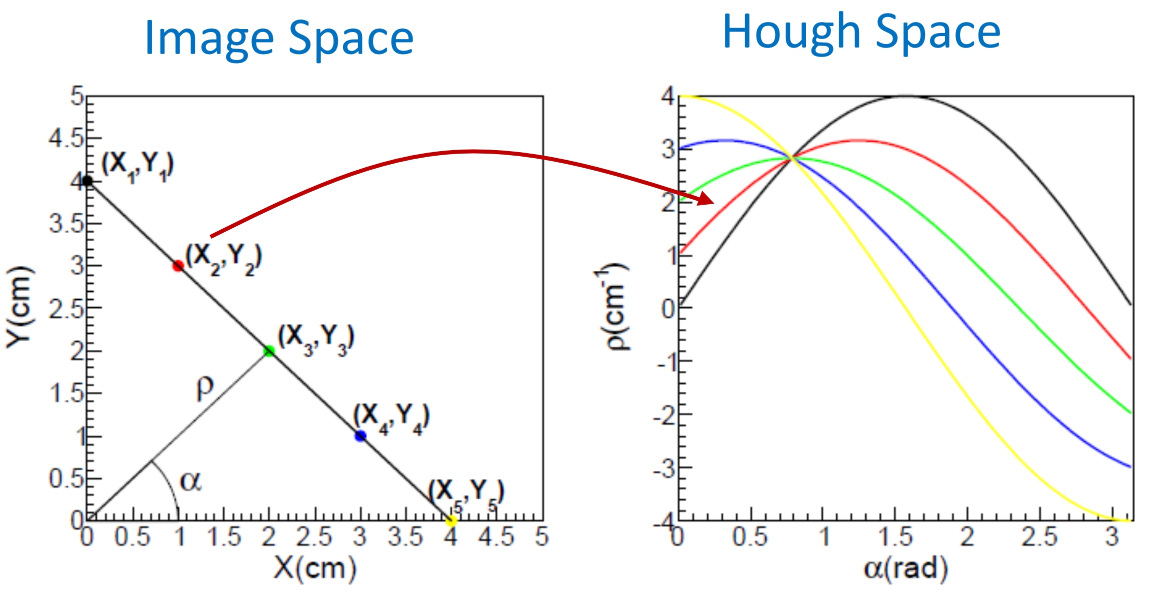
Local Maximum Distribution

Principle of Hough Transformation

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

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

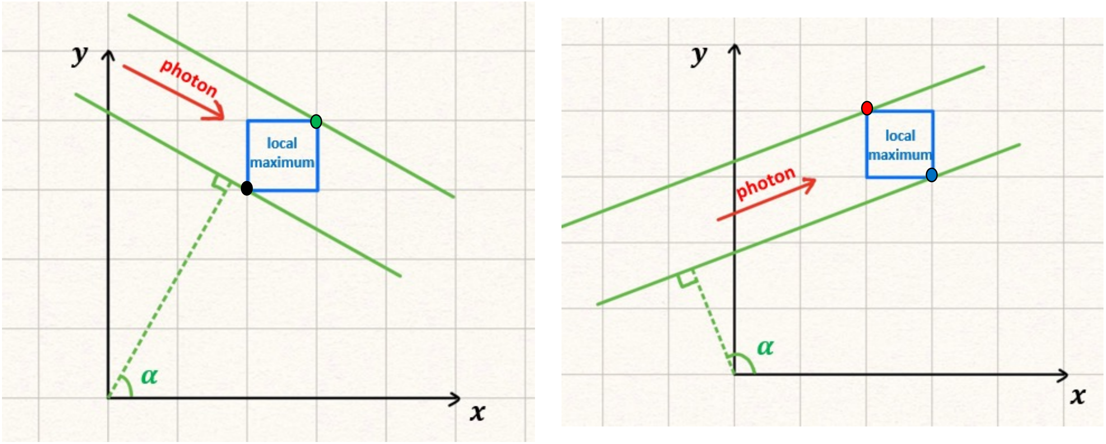
  - Each point (x, y) in image space is transformed to a curve in Hough space.
  - If several points (x_i, y_i) are collinear, their curves intersect at a point (α, ρ) in Hough space.
  - α and ρ are parameters of the straight line that pass through these points (x, y)

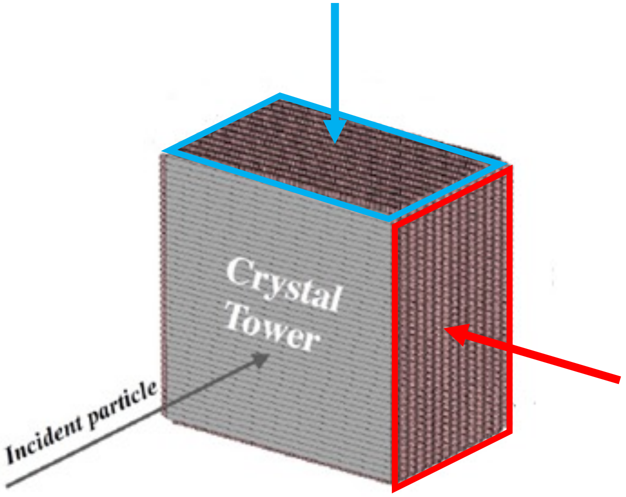


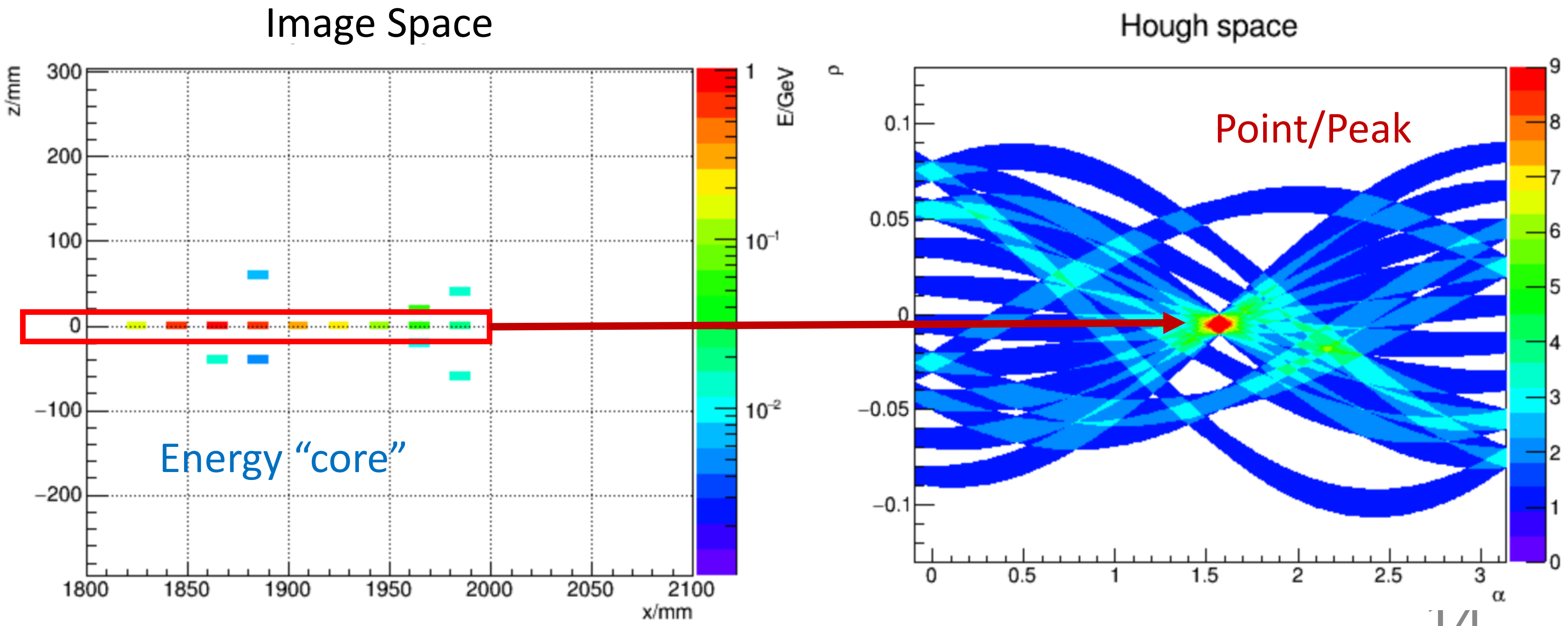
(x, y) A Point	→	$\rho = x\cos\alpha + y\sin\alpha$ A Curve
(x_i, y_i) A series of Points	→	$\rho = x_i\cos\alpha + y_i\sin\alpha$ A Series of Curves
$\rho = x\cos\alpha + y\sin\alpha$ A Line	→	(α, ρ) A Point

Crystal Granularity Hough Transformation

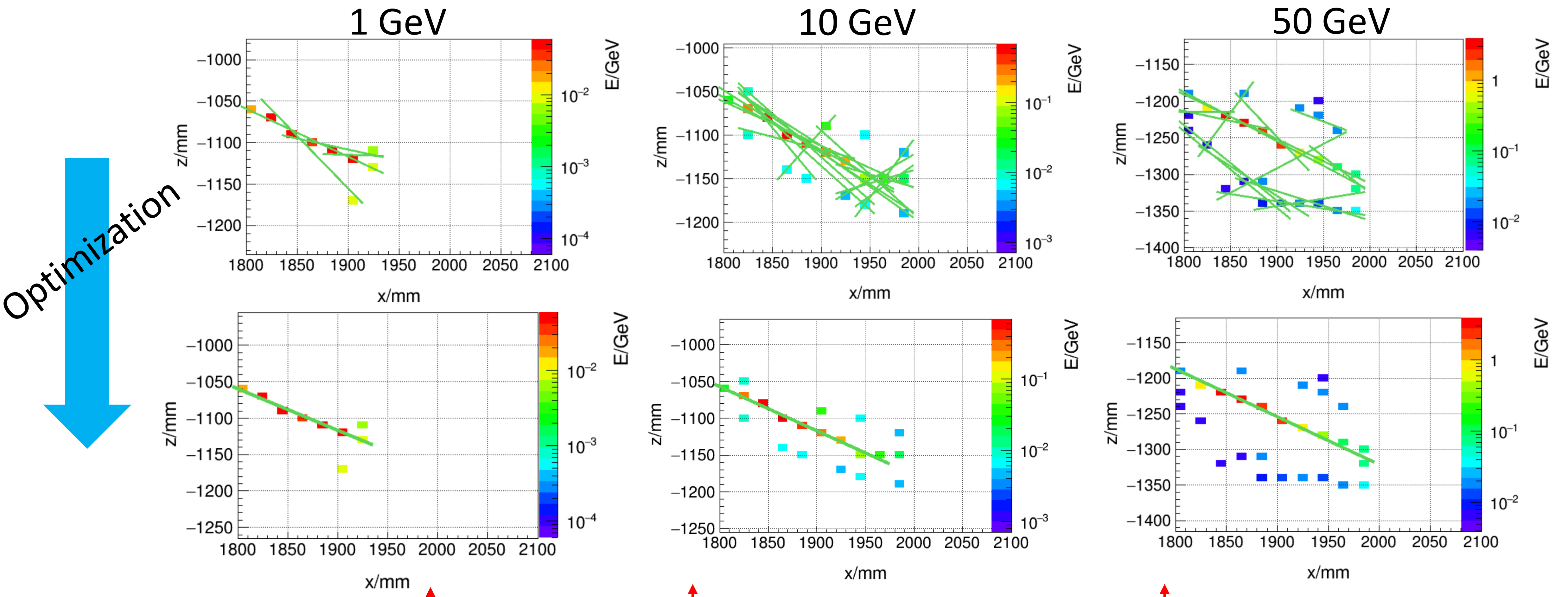
- Each crystal in image space is transformed to a band in Hough space instead of a curve
- Cluster recognition in horizontal and vertical projection spaces respectively
- Each point/peak (overlap region of band) in Hough space is chosen as a cluster candidate







Performance Check of EM Shower Recognition



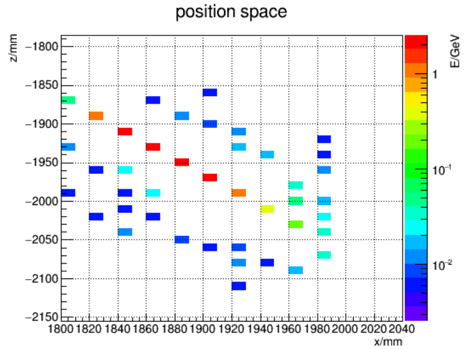
- Energy of shower ↑ → fluctuation ↑ → number of fake clusters ↑
- Further optimization improve performance: number of continuous local maxima, usage of common points, ……

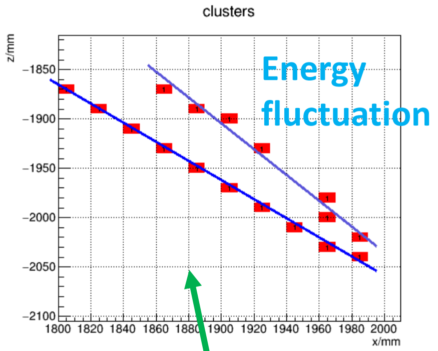
Efficiency and Fake Rate of Single Photon

- Low energy or small $|\cos\theta|$: One & only one cluster
- High energy and large $|\cos\theta|$: >1 clusters

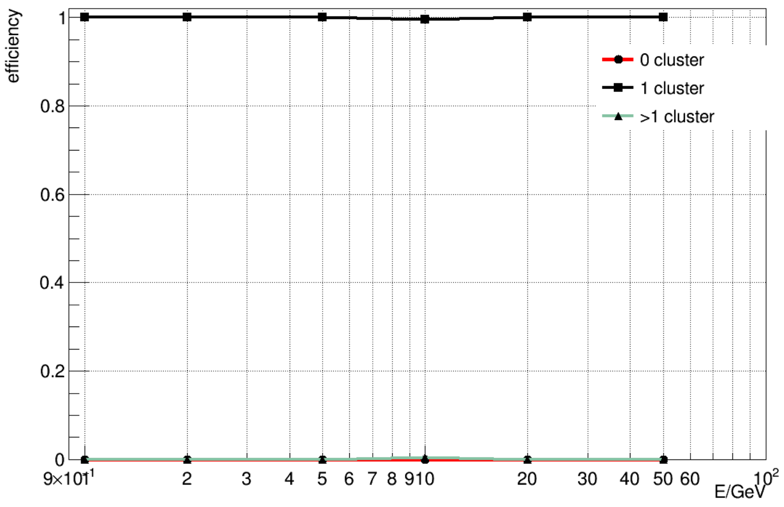
  —Fluctuations of energy deposits increase fake shower

Meet the requirement of EM showers recognition in jet reconstruction in most cases

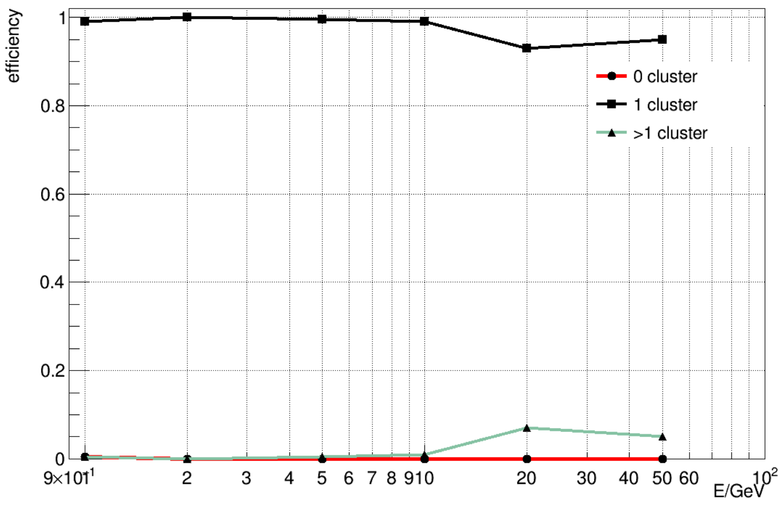




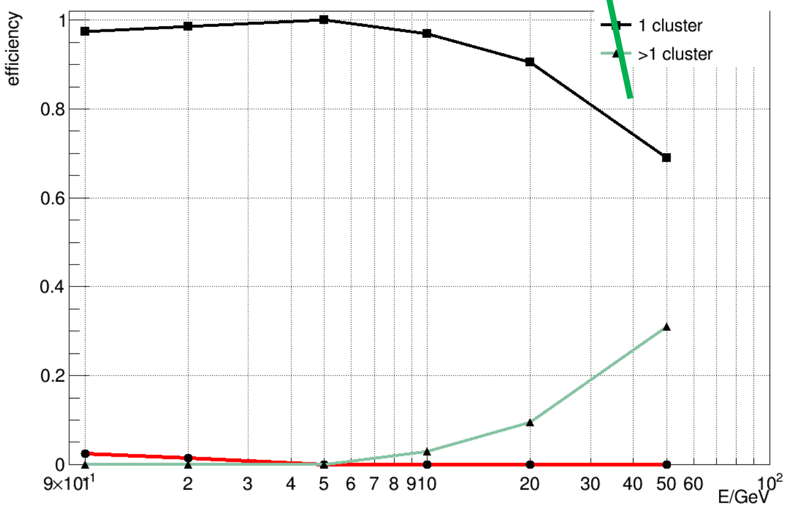
$\theta = 90^{\circ}$



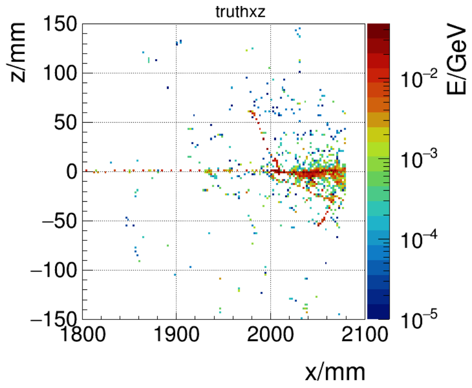
$\theta = 120^{\circ}$

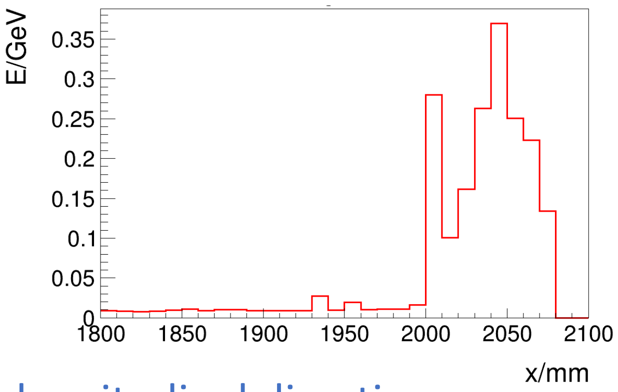


$\theta = 136^{\circ}$

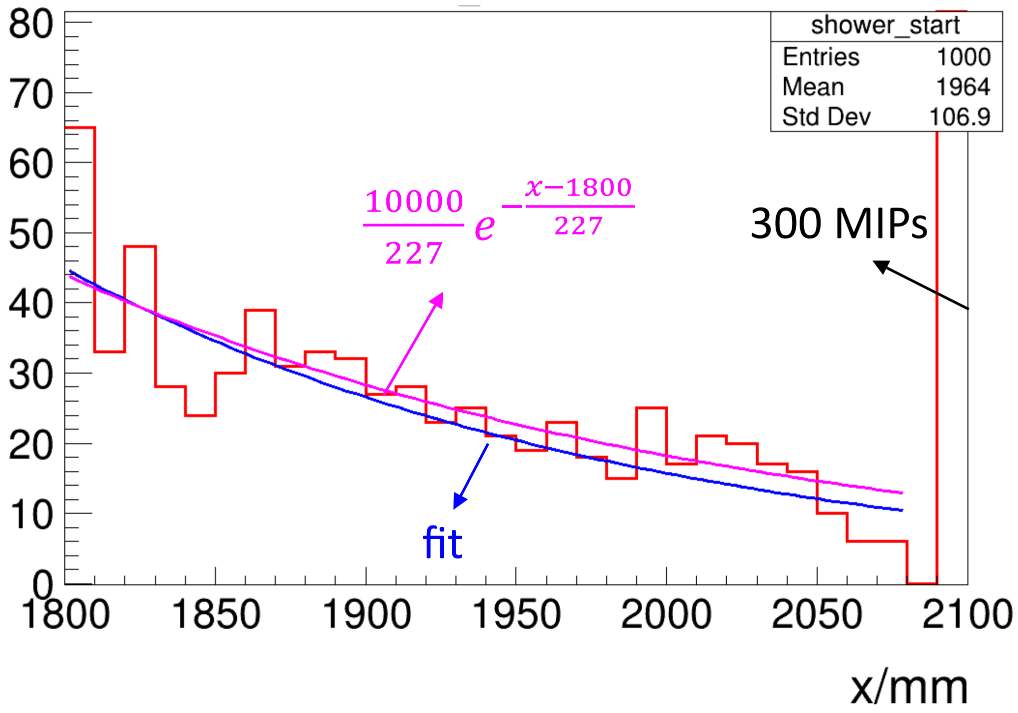


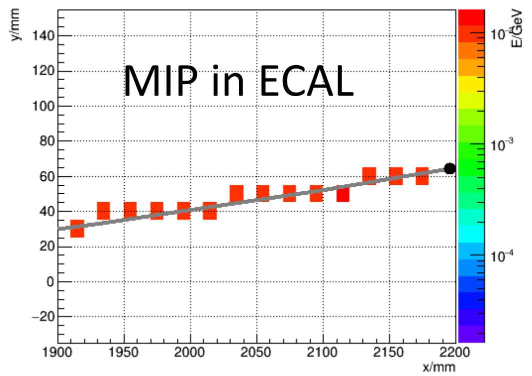
Charged Hadron

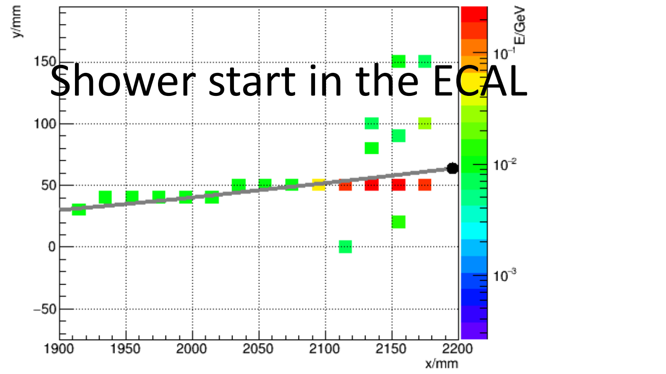


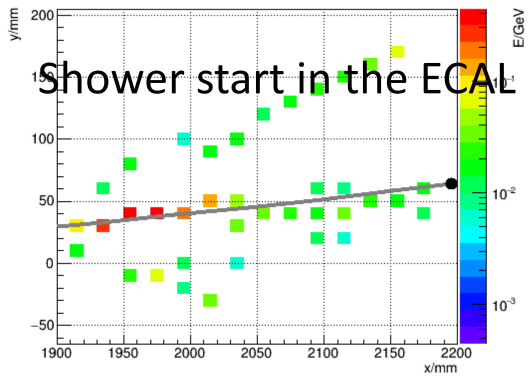


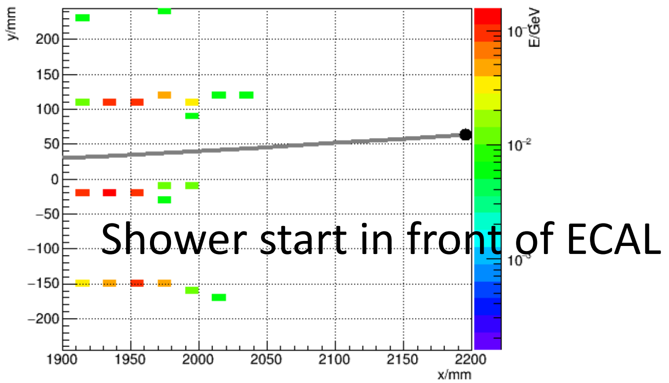
Energy deposition in longitudinal direction







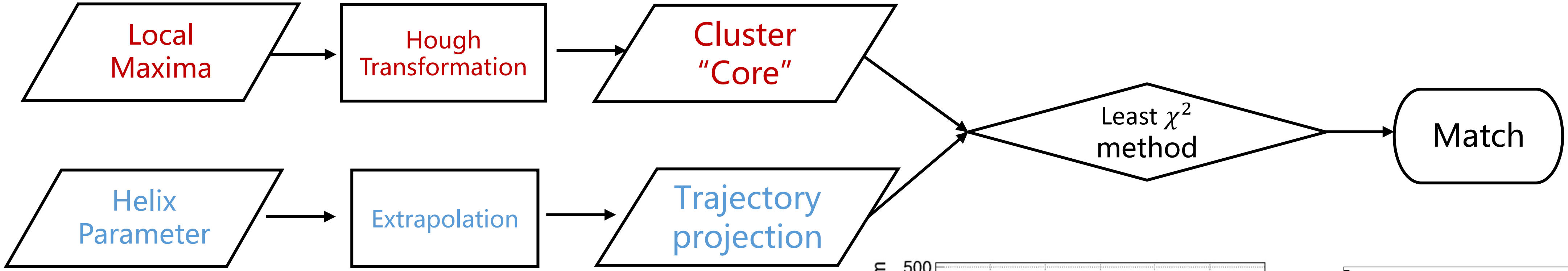




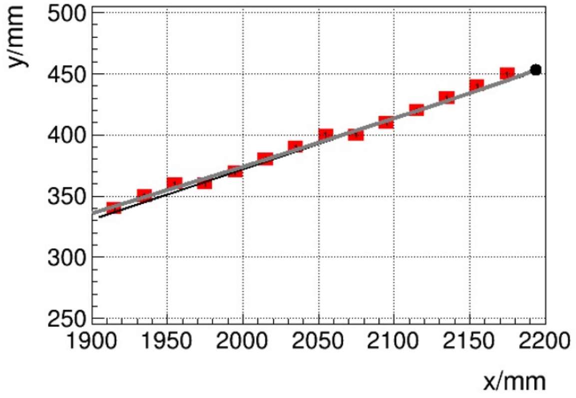
π^-, 1000 events, E=10GeV

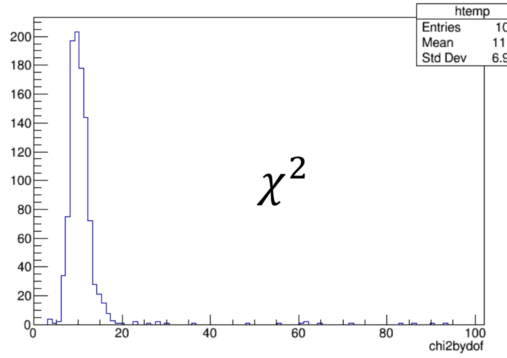
Prob of hadronic shower: $\frac{1}{\lambda_i}\int_{1800}^{2080} e^{-\frac{x-1800}{\lambda_i}}\,dx \approx 71\%$

Match of Extrapolated Charged Track and Cluster



- Matching the extrapolated trajectory of charged track with the energy "core" of cluster in ECAL.
- A χ^2 is defined to describe the consistency between the trajectory and local maxima.
- Hadronic shower "generation point" recognition is crucial to obtain an accuracy result.





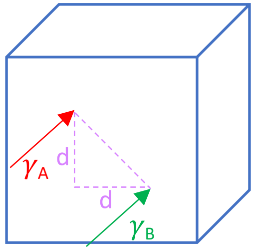
Local maxima and Trajectory projection

$$\chi^2/n_{dof} = \sum_{i=1}^{n} \left[\frac{y_i - g(x_i)}{\sigma_i}\right]^2 /n$$

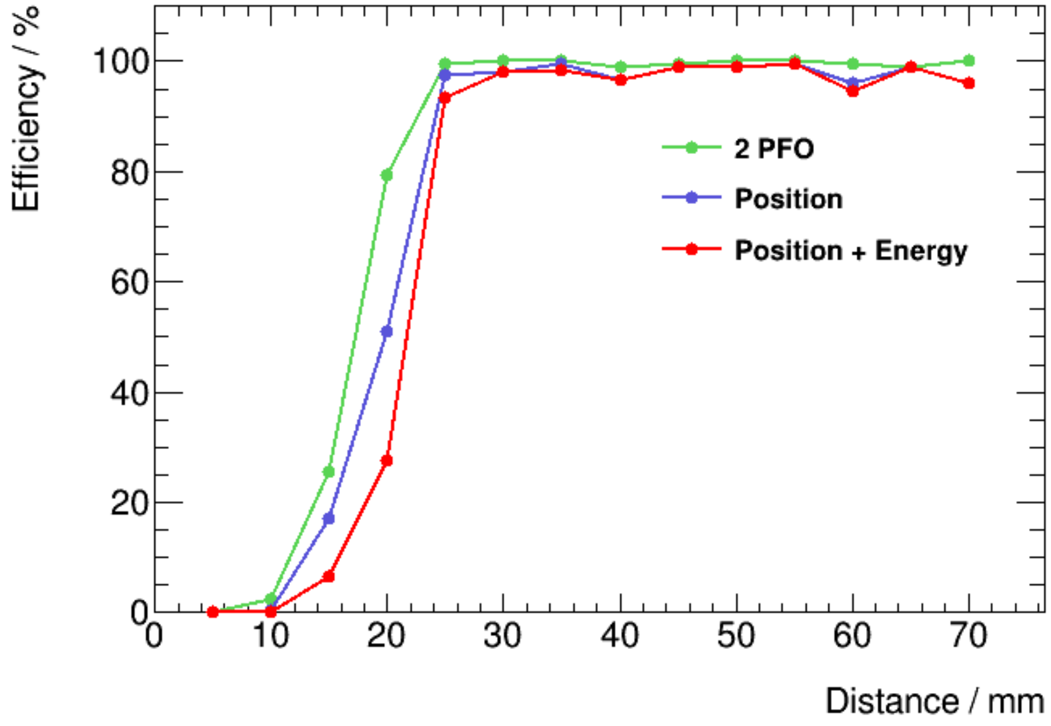
Ambiguity Removal

Update the performance with cluster recognition:

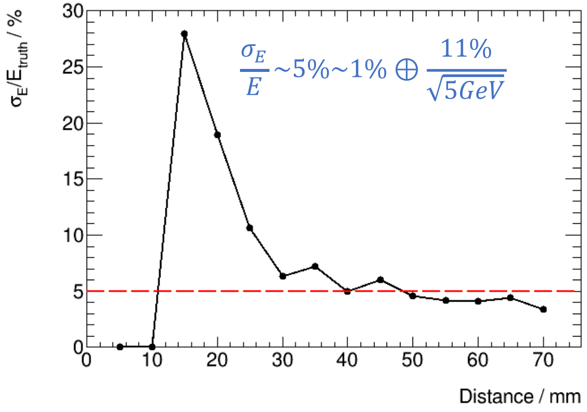
- Solve the ghost hit problem with energy-time χ^2 matching [Ref].
- Particle gun events simulation for two 5GeV photons in parallel.
- Scan the distance between photons, check the successful reconstruction efficiency and energy resolution.



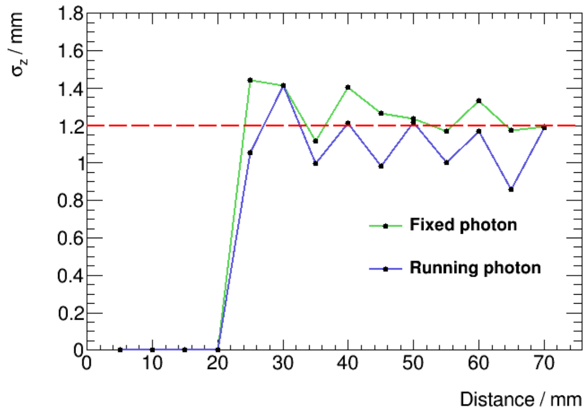
Separation efficiency



Energy resolution



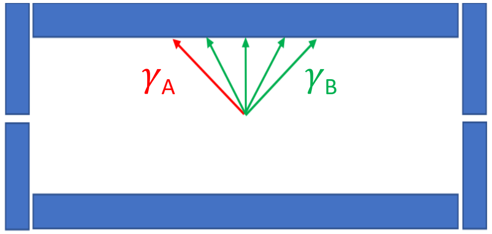
Position resolution



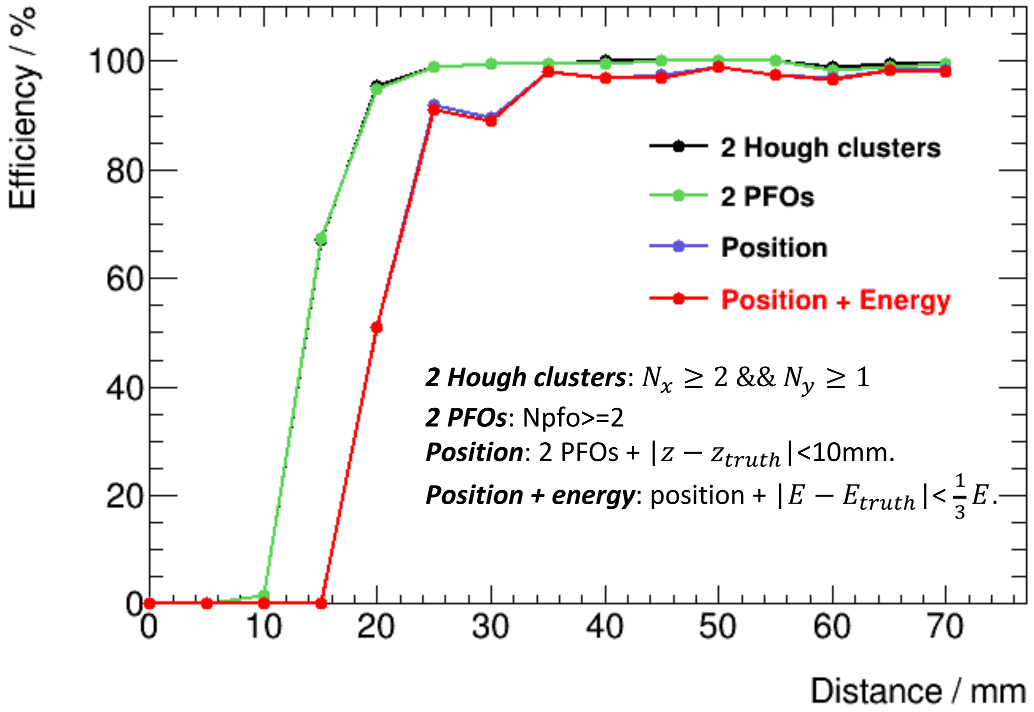
Performance Check of Energy Splitting

Gamma / gamma Separation:

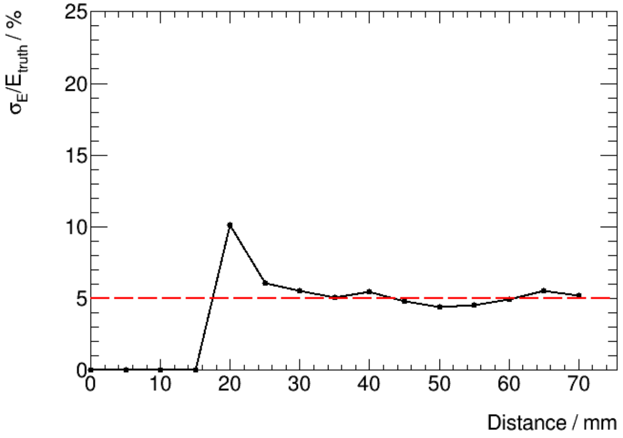
- Particle gun event of two 5GeV photons.
- Scan the angle(distance) between two photons, check the successful reconstruction efficiency and energy / position resolution.



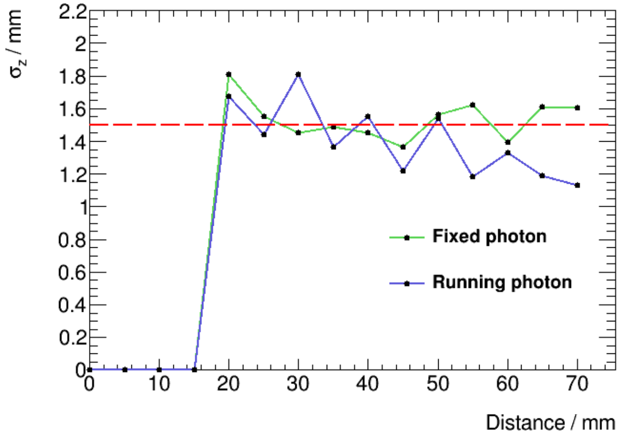
Separation efficiency



$$\frac{\sigma_E}{E} \sim 5\% \sim 1\% \oplus \frac{11\%}{\sqrt{5GeV}}$$



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 is in processing, basic functions of cluster finding, particle recognition and energy splitting has been implemented.
- Performance checks provide positive feedback of EM showers and MIPs, continue to improve for utmost precision.
- Next to do:
- Emphasis on clusters separation of charged and neutral particles in ECAL.
- Simulation and reconstruction of endcap ECAL and HCAL for jet energy measurement.

Thank you!