Institute of High Energy Physics
Chinese Academy of Sciences

Progress of Reconstruction of Crystal Bar ECAL

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on behalf of CEPC ECAL software group

IAS Program – High Energy Physics (2023)

Mini-Workshop in Experiment and Detector

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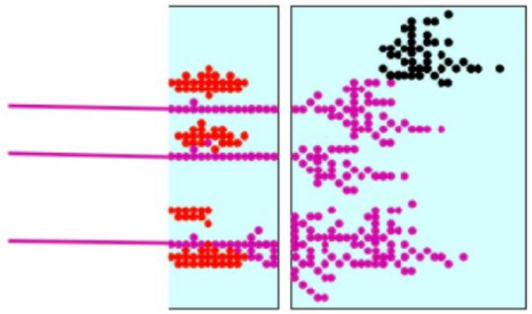
Introduction

- CEPC physics program
  - Precision Higgs, EW, flavor physics & QCD measurements
  - BSM physics
- Calorimeter for future e^+e^- collider
  - Jet energy resolution of 3~4%@100GeV
  - Fine γ/π^0 separation for flavor physics study
- Particle Flow Approach (PFA)
  - Jets = 60% charged tracks + 30% γ + 10% h^0
  - ✓ Hardware: Resolve energy deposits from different particles
  - ✓ Software: Identify energy deposits from each individual particle

Particle Flow Calorimeter = HARDWARE + SOFTWARE

Key Requirement on CEPC Detector

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	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

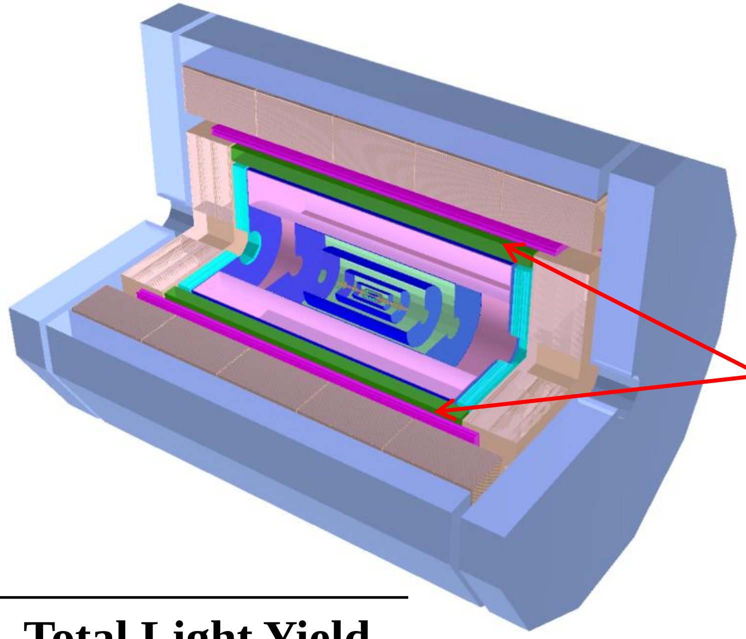


$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

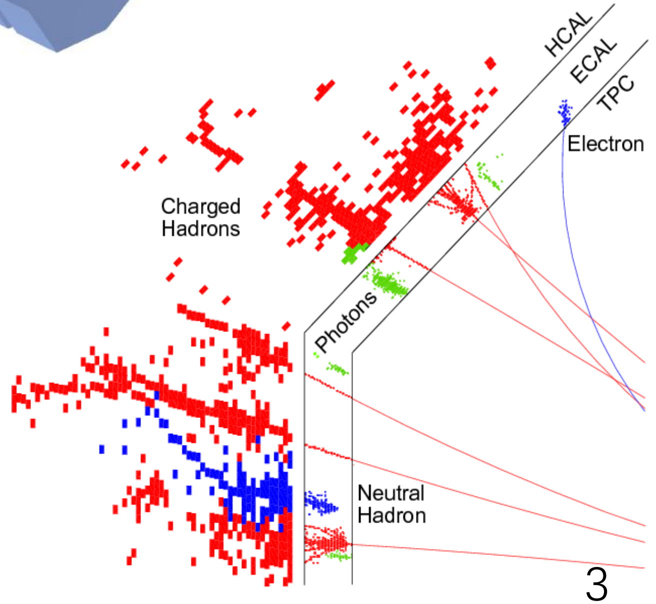
$$\sigma_{Jet} = \sqrt{\sigma_{Track}^2 + \sigma_{EM}^2 + \sigma_{Had}^2 + \sigma_{Confusion}^2}$$

Introduction: Crystal ECAL

- The 4[th] conceptual detector design
- Crystal ECAL
  - ✓ Homogenous structure
  - ✓ Optimal energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - – Incompact EM showers — X_0 & R_M
  - – EM / Hadronic showers separation — λ_I / X_0

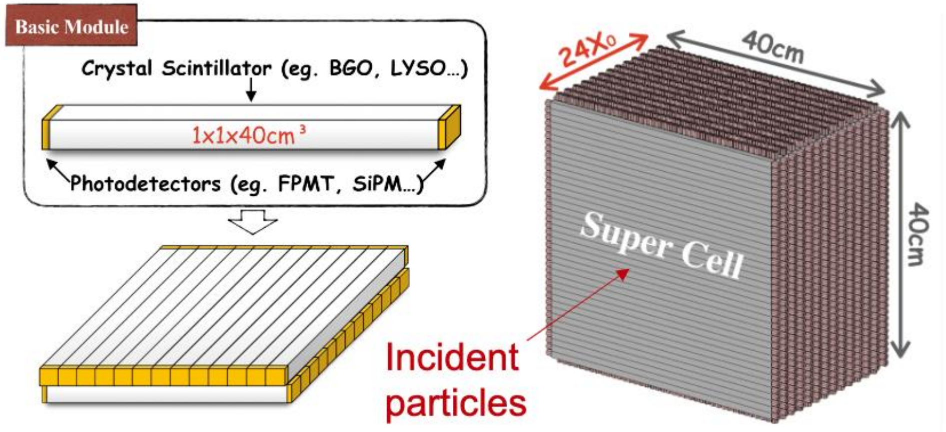


Material	X_0 / cm	R_M / cm	λ_I / cm	λ_I / X_0	Total Light Yield (ph/MeV)
$PbWO_4$	**0.89**	**2.00**	**20.7**	**23.3**	**130**
LYSO:Ce	**1.14**	**2.07**	**20.9**	**18.3**	**30’000**
CsI:Tl	**1.86**	**3.57**	**39.3**	**21.1**	**58’000**
BGO	**1.12**	**2.23**	**22.7**	**20.3**	**7’400**
W (absorber)	**0.35**	**0.93**	**9.6**	**27.4**	
BGO/W	**3.2**	**2.4**	**2.4**	**0.74**	

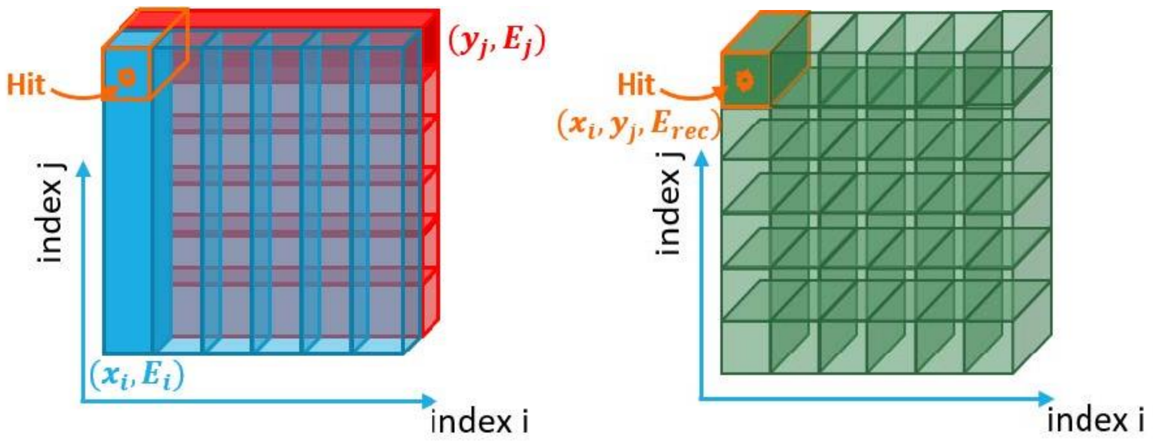


Introduction: Crystal Bar ECAL

- Crystal bar array with cross point architecture
  - Homogeneous BGO crystal
  - Energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Long crystal bar: Charge/Time measurements at double-side readouts
  - Crossed arrangement of in adjacent layers
  - Significant reduction of number of readout channels



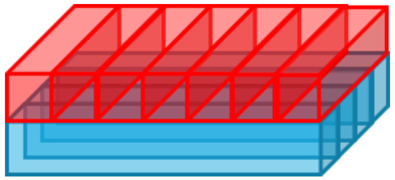
- Challenges for Reconstruction
  - Ambiguity caused by 2-dimension measurement (ghost hit)
  - Identification of energy deposits from individual particles

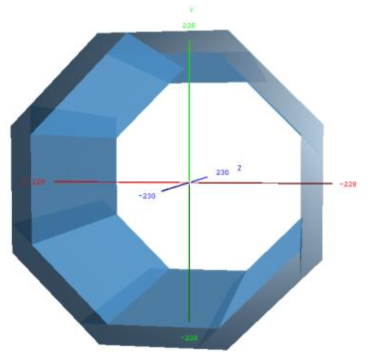


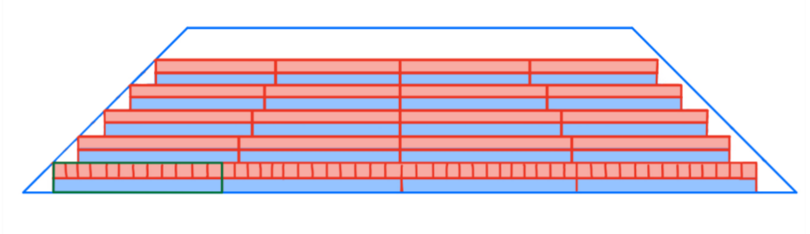
Simulation and Digitization

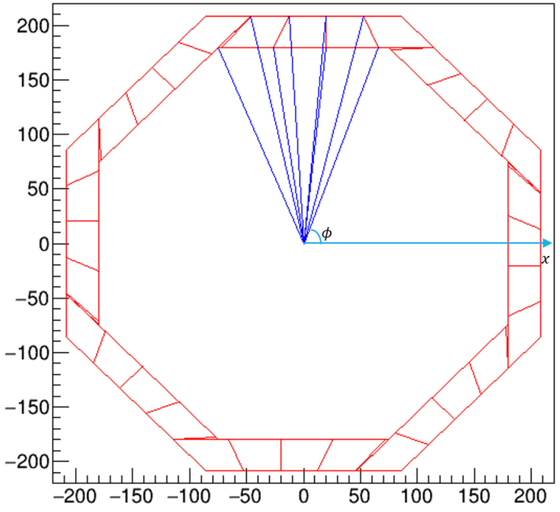
- Crystal Bar
  - Size: $1 \times 1 \times 40{\sim}60\ cm^3$
  - Double-end readout
- Super Cell
  - Adjacent layers of perpendicularly crossing bars
  - Size: $\sim 40 \times \sim 60 \times 28\ cm^3$
- Detector
  - $R = 1.9m,\ L = 6.6m,\ H = 28cm$
  - 8 same trapezoidal modules
  - Avoid gaps point to IP
- DD4Hep is used for geometry construction

Ignoring dead area, mechanics of supporting or cooling, etc



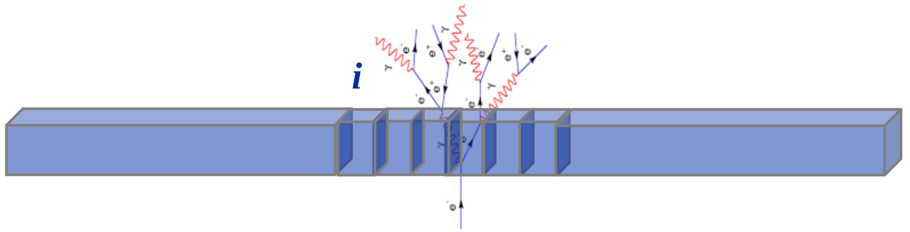






Simulation and Digitization

- A standalone full simulation for extraction of time resolution
  - Optical photon processes: scintillation, Cherenkov, absorption, refraction/reflection at boundaries
- Geant4-based simulation in CEPCSW
  - Electromagnetic & hadronic showers
- Simplified digitization for one crystal bar



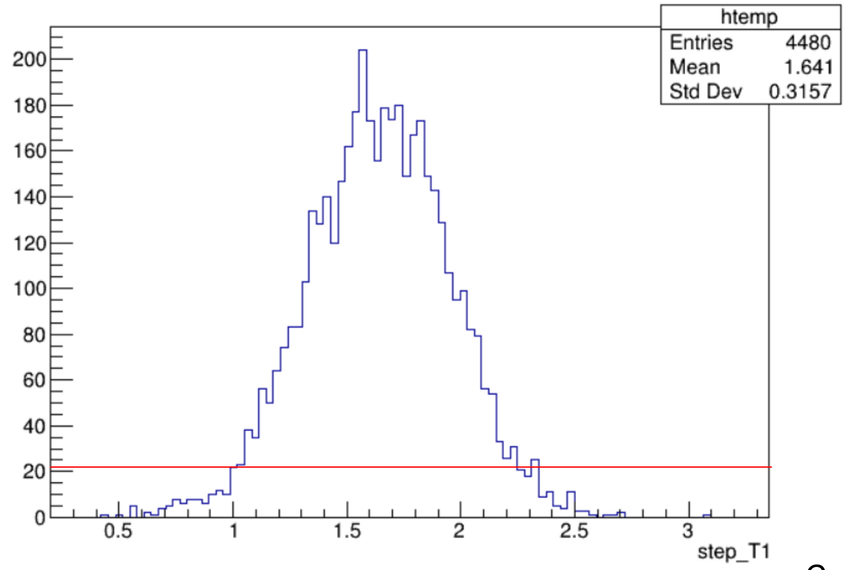
  - Contribution from G4step $\boldsymbol{i}$:

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

  - Readout at both ends: Q and T

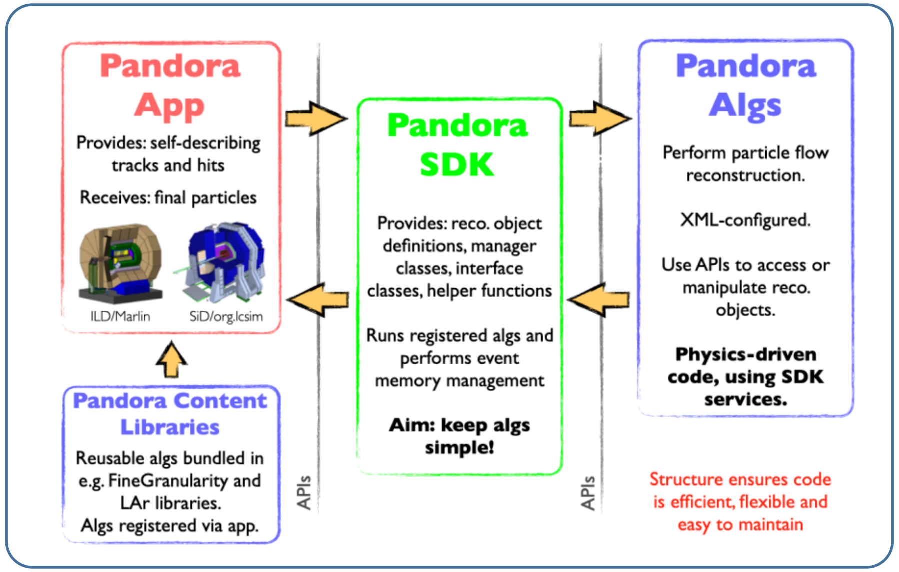
$$Q_{\pm} = \sum_{step} Q_{\pm}^{i}\,,\ T_{\pm} = T_{\pm}^{k} \mid \left(\sum_{i=1}^{k} Q_{\pm}^{i} > thres\right)$$

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

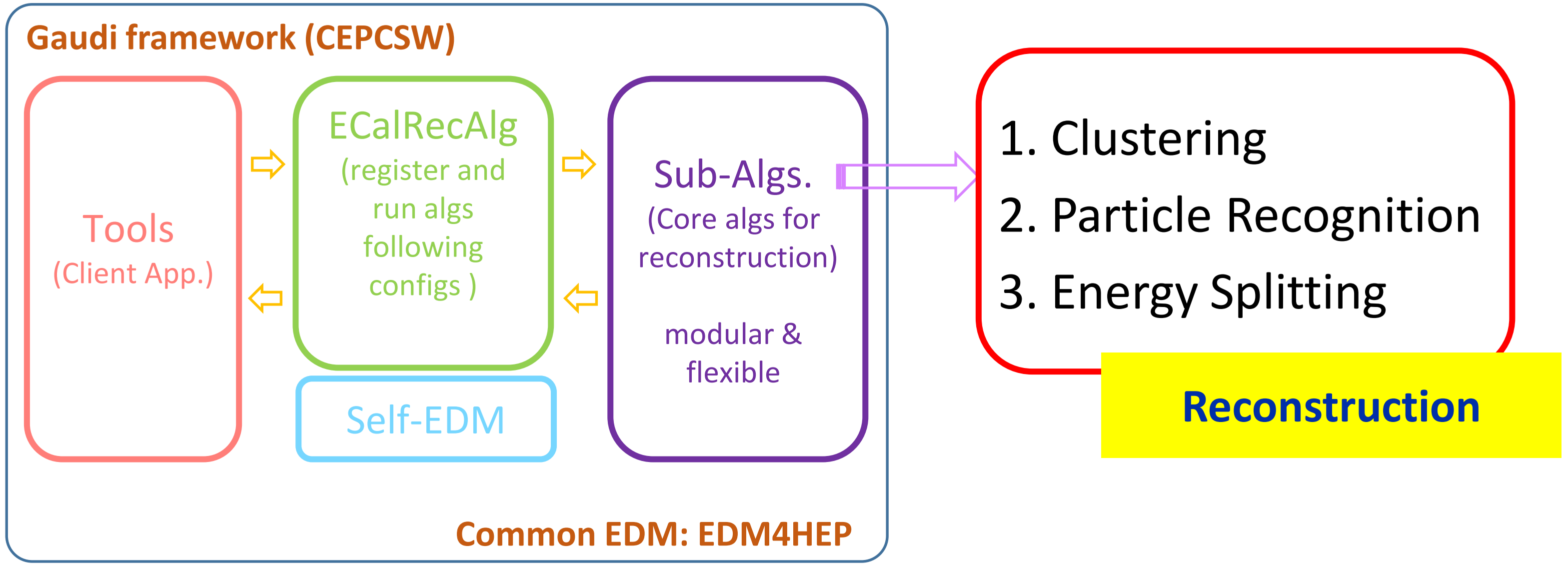


Framework for Particle Flow Reconstruction

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

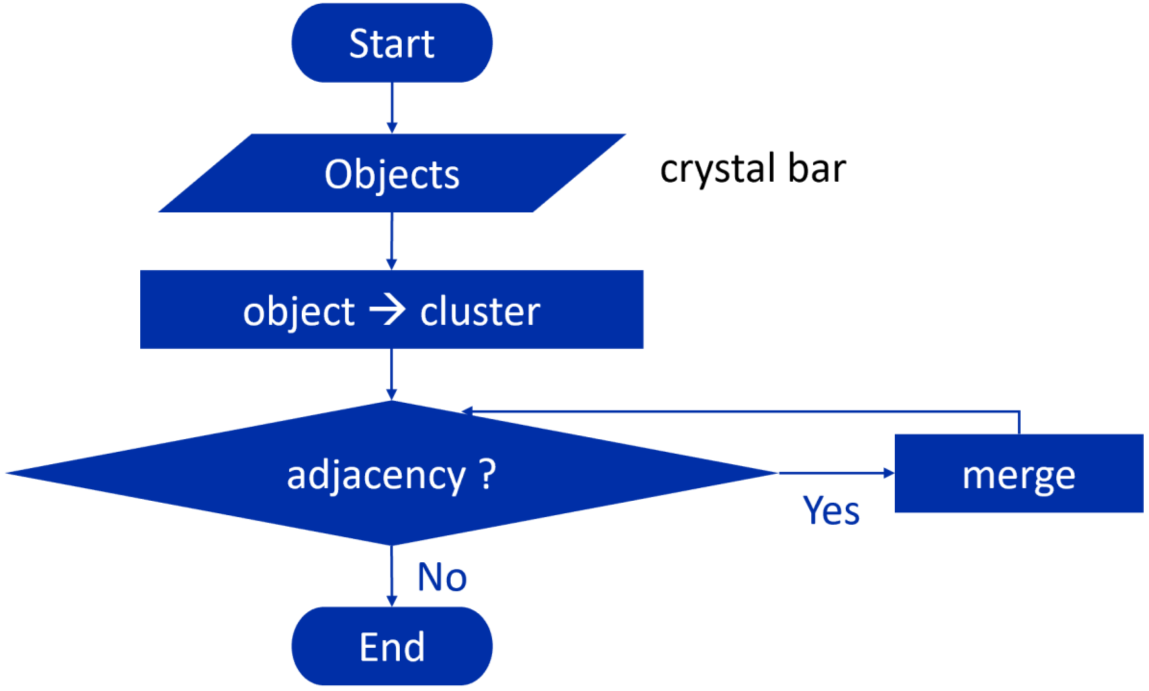


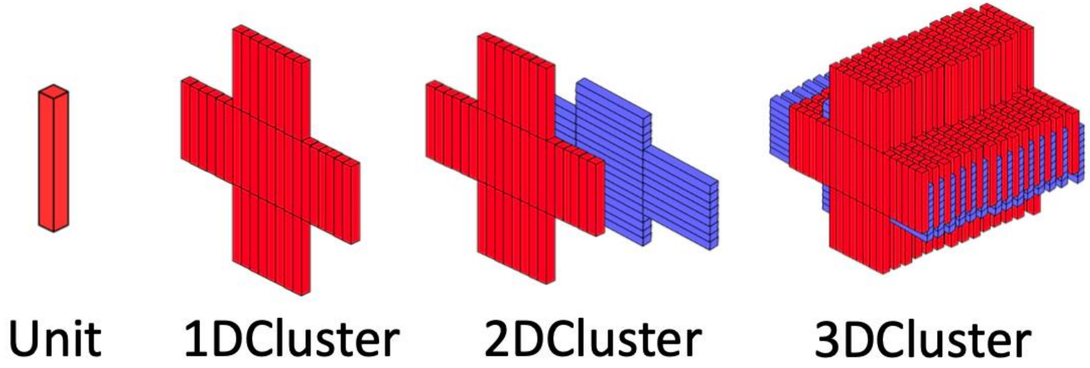
J.S.Marshall, CHEF 2013

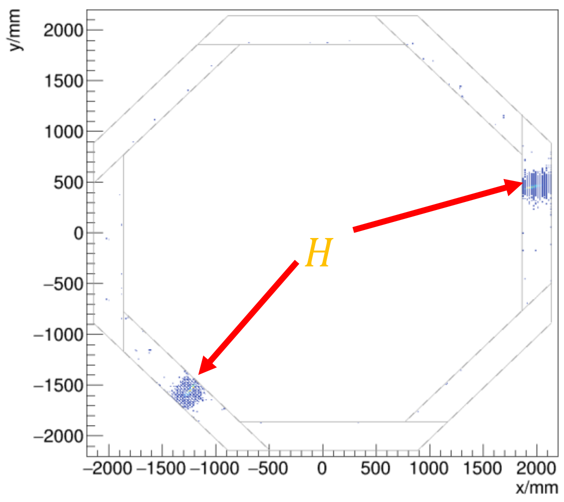


Clustering

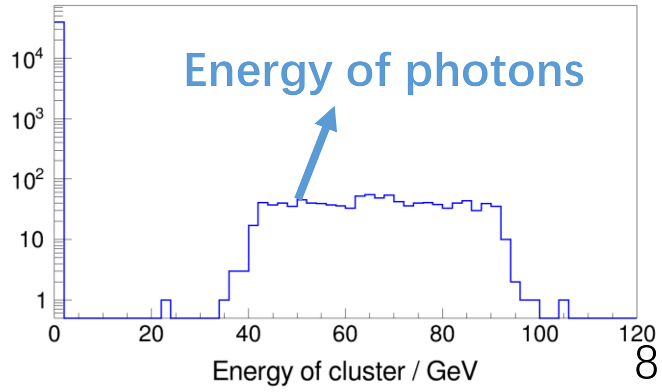
- A cluster: a group of adjacent detection units whose energy is greater than threshold
- Clustering is based on identification of adjacency or not



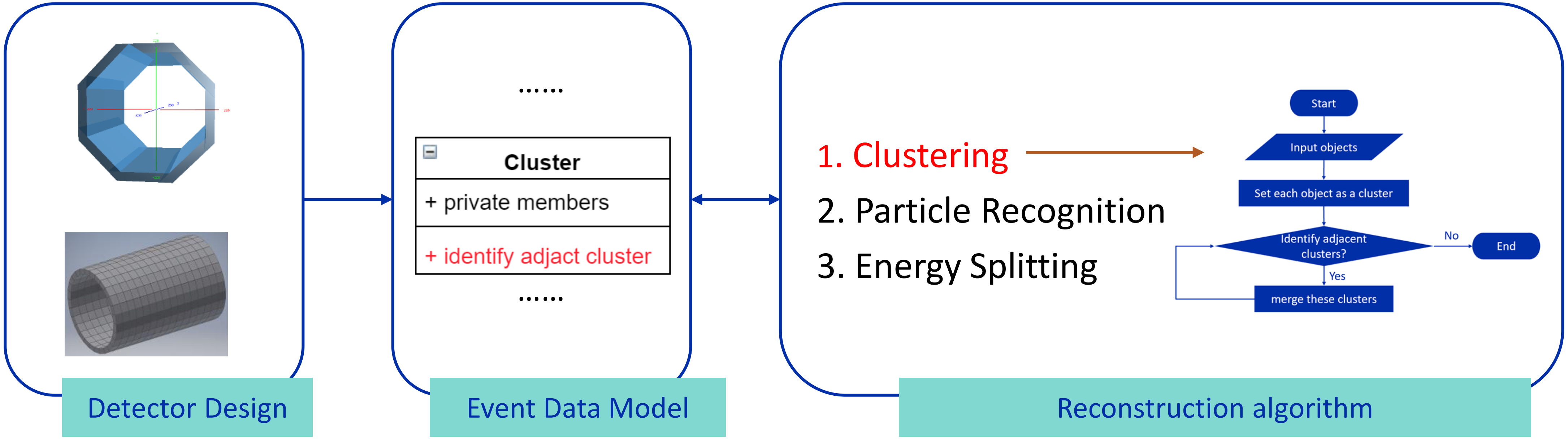




$H -> \gamma\gamma$



Clustering



Abstract concept

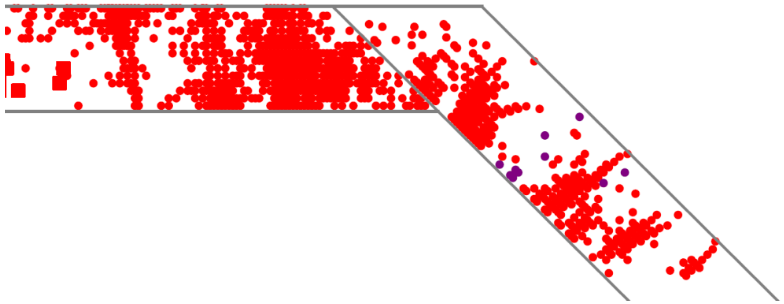
- clustering function template is used from units to 3D cluster

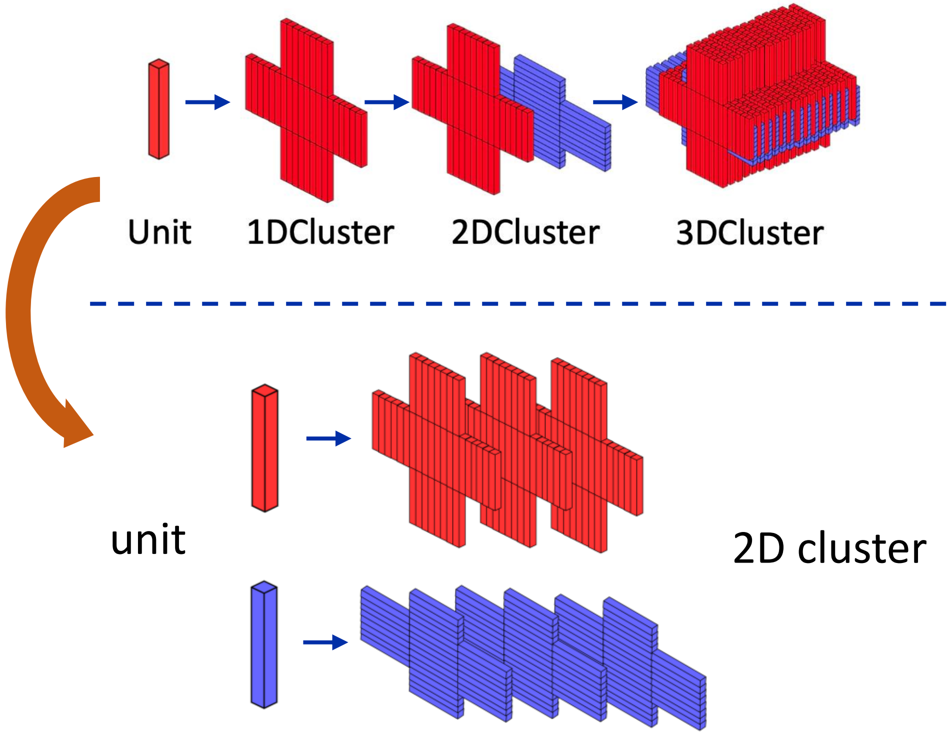
Modularization

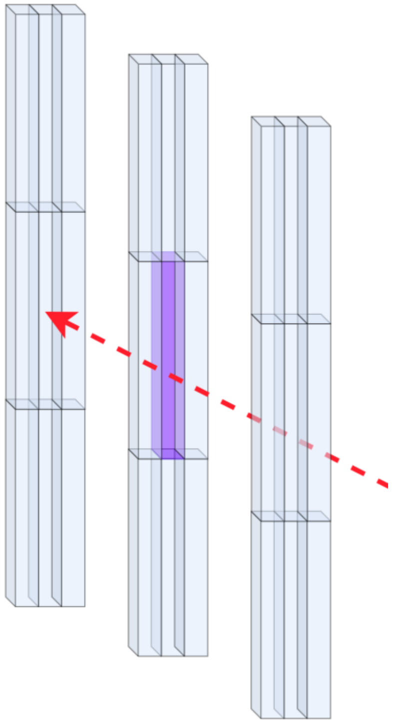
- easy to migrate, adapted to different detector design, such as endcap ECAL and HCAL

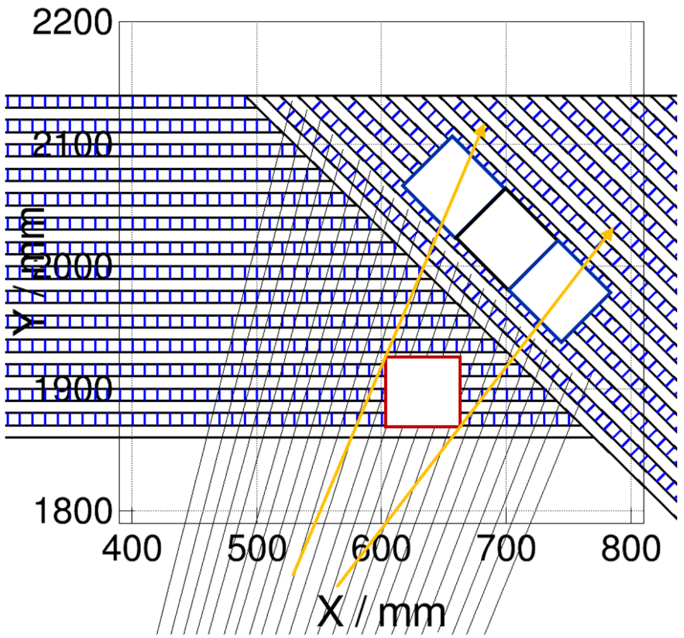
Optimization of Clustering

- Vertical and horizontal units are clustered respectively
- More strict criteria for adjacency
- Adjacent area of two modules: dictionary lookup method

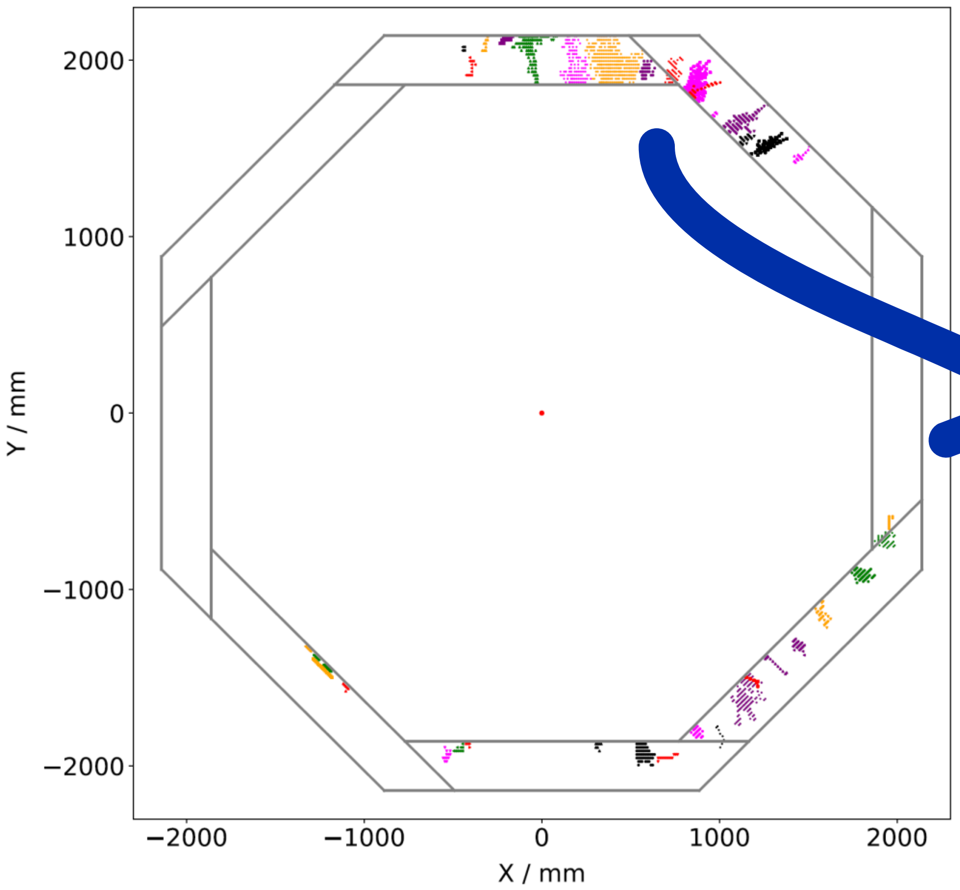




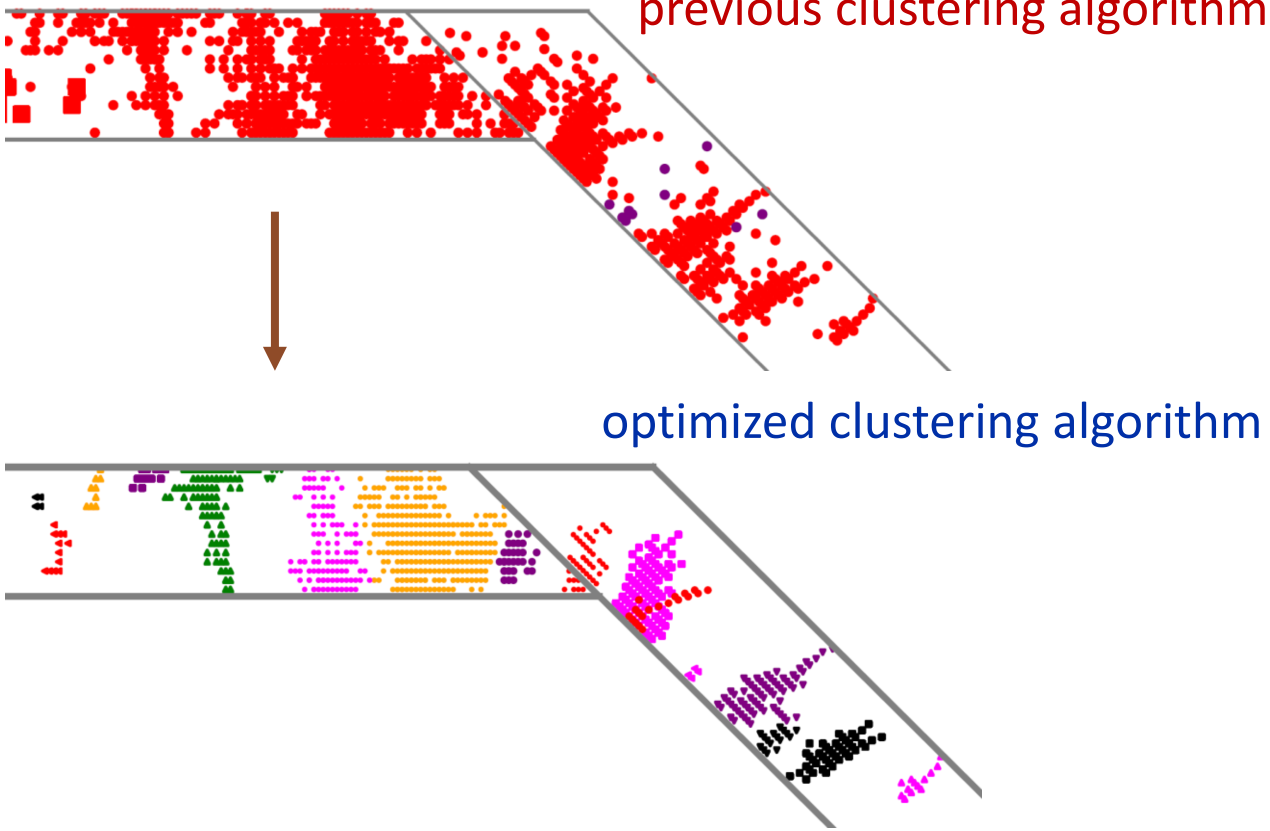




Performance check using $H \rightarrow gg$ event



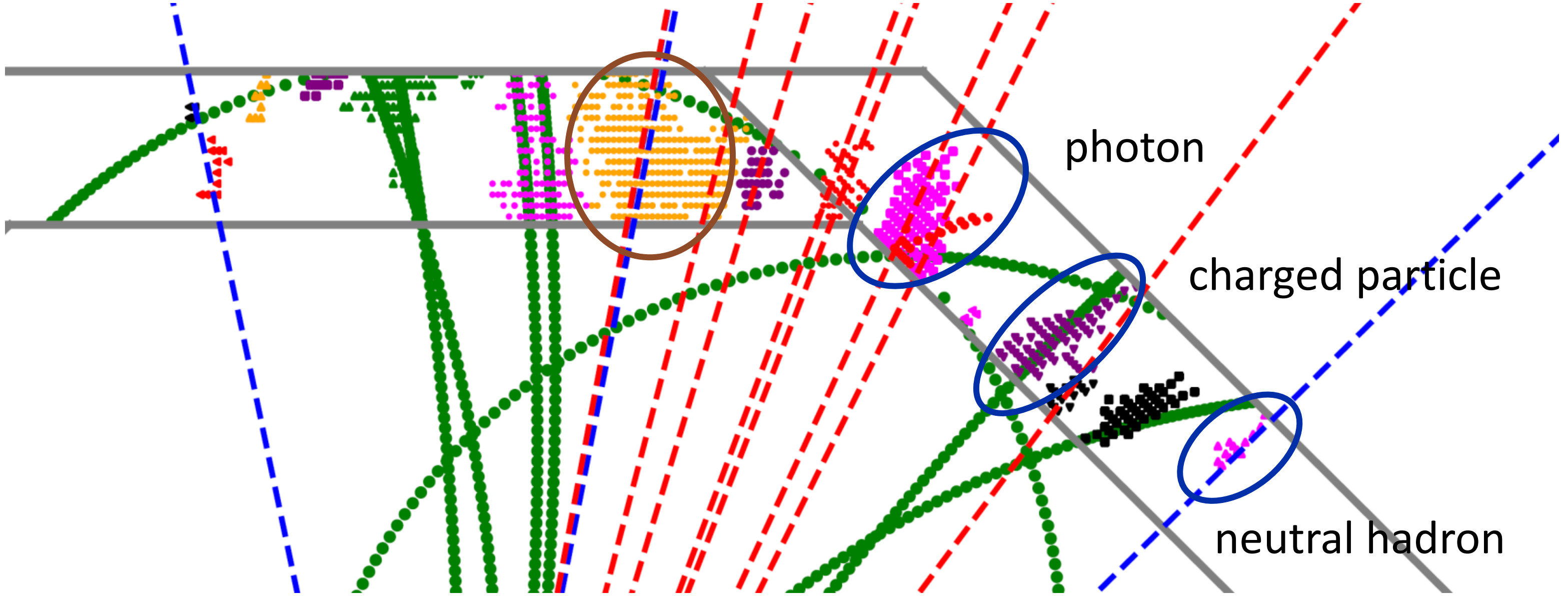
Each Color represent one Cluster



Separation power is improved significantly

Crystal bar ECAL in two projections imaging calorimeter

Validation using MC Truth



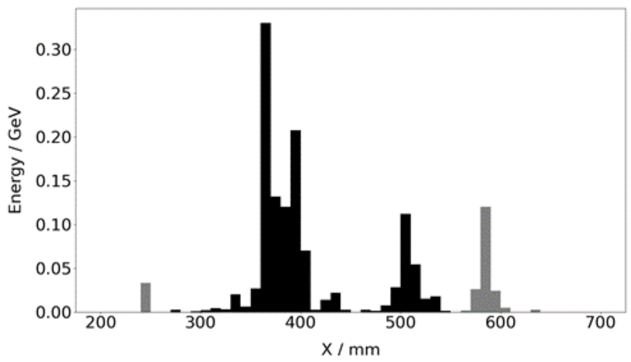
MC Truth Information

Green circle points: charged particles

Red dashed lines: photons

blue dashed line: neutral hadrons

A clear relationship between individual cluster and single particle



Principle of Hough Transformation

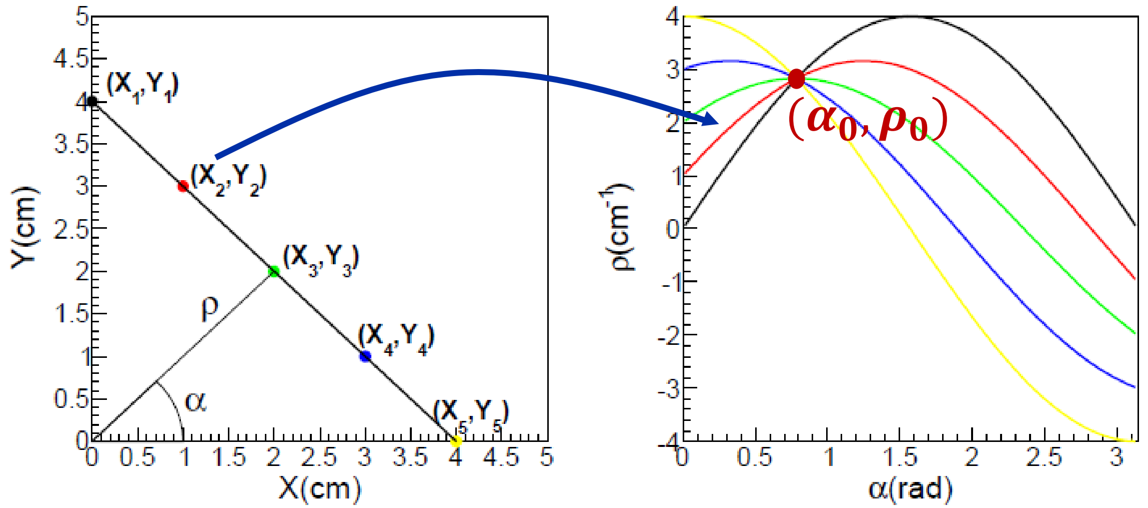
- A feature extraction method for detection simple shapes (e.g. lines) in image space
- For straight lines:

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

  - Each point (x, y) in image space ⬌ a curve in Hough space
  - If several points (x_i, y_i) are collinear, their curves intersect at a point (α_0, ρ_0) in Hough space
  - α_0 and ρ_0 are parameters of the straight line that pass through these points (x_i, y_i)

Image Space

Hough Space



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

Series of Points

Series of Curves

⬇

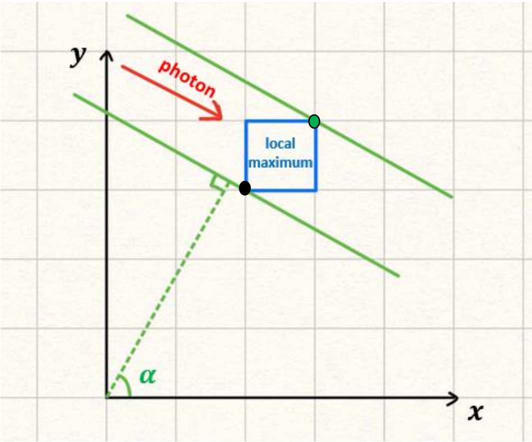
$\rho_0 = x\cos\alpha_0 + y\sin\alpha_0$ ⬅ (α_0, ρ_0)

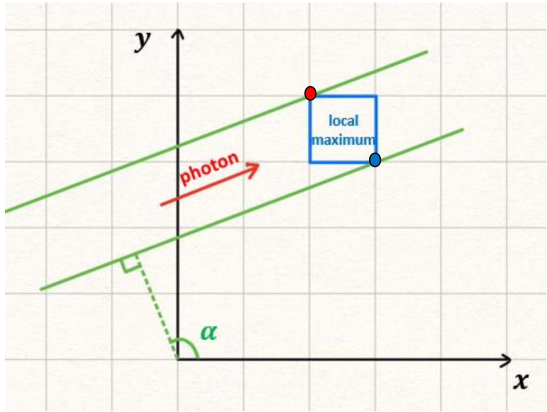
Line

Point

Hough Transformation for ECAL

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





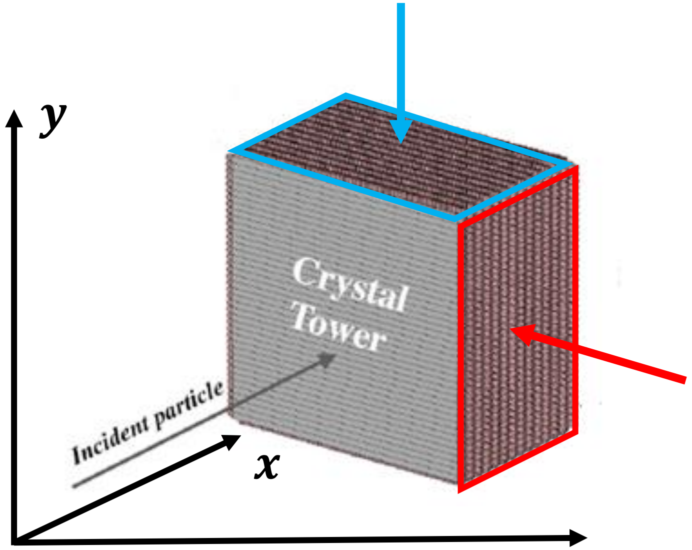
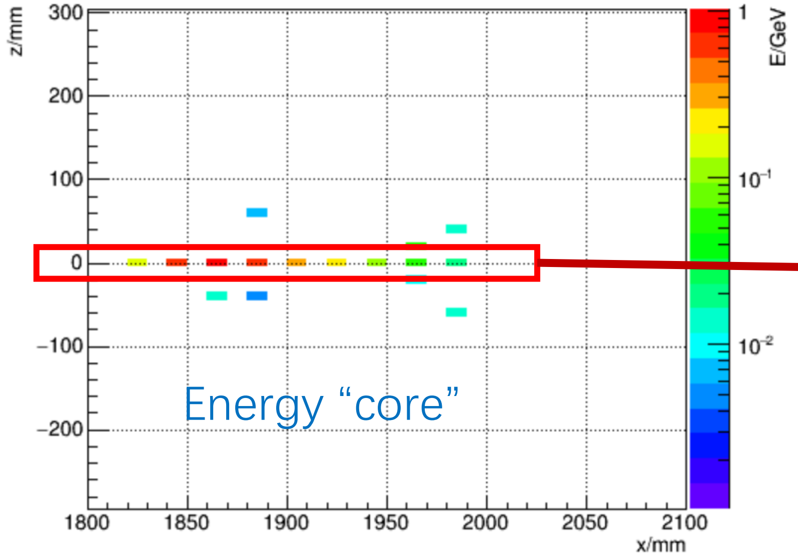
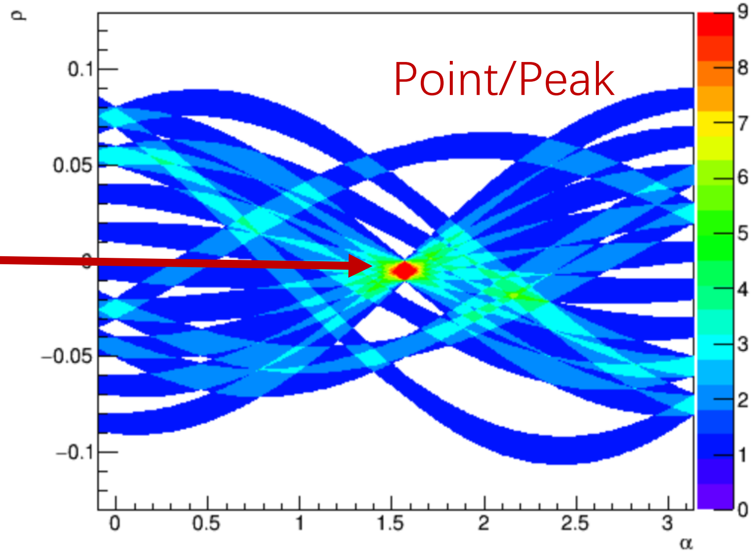


Image Space

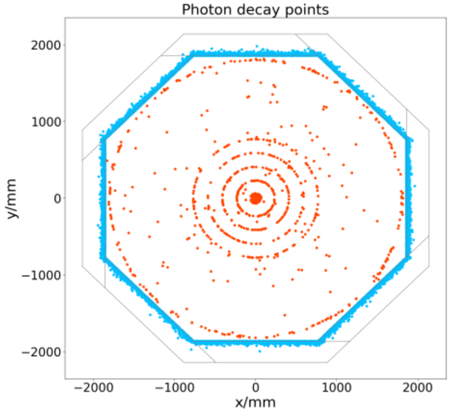


Hough Space

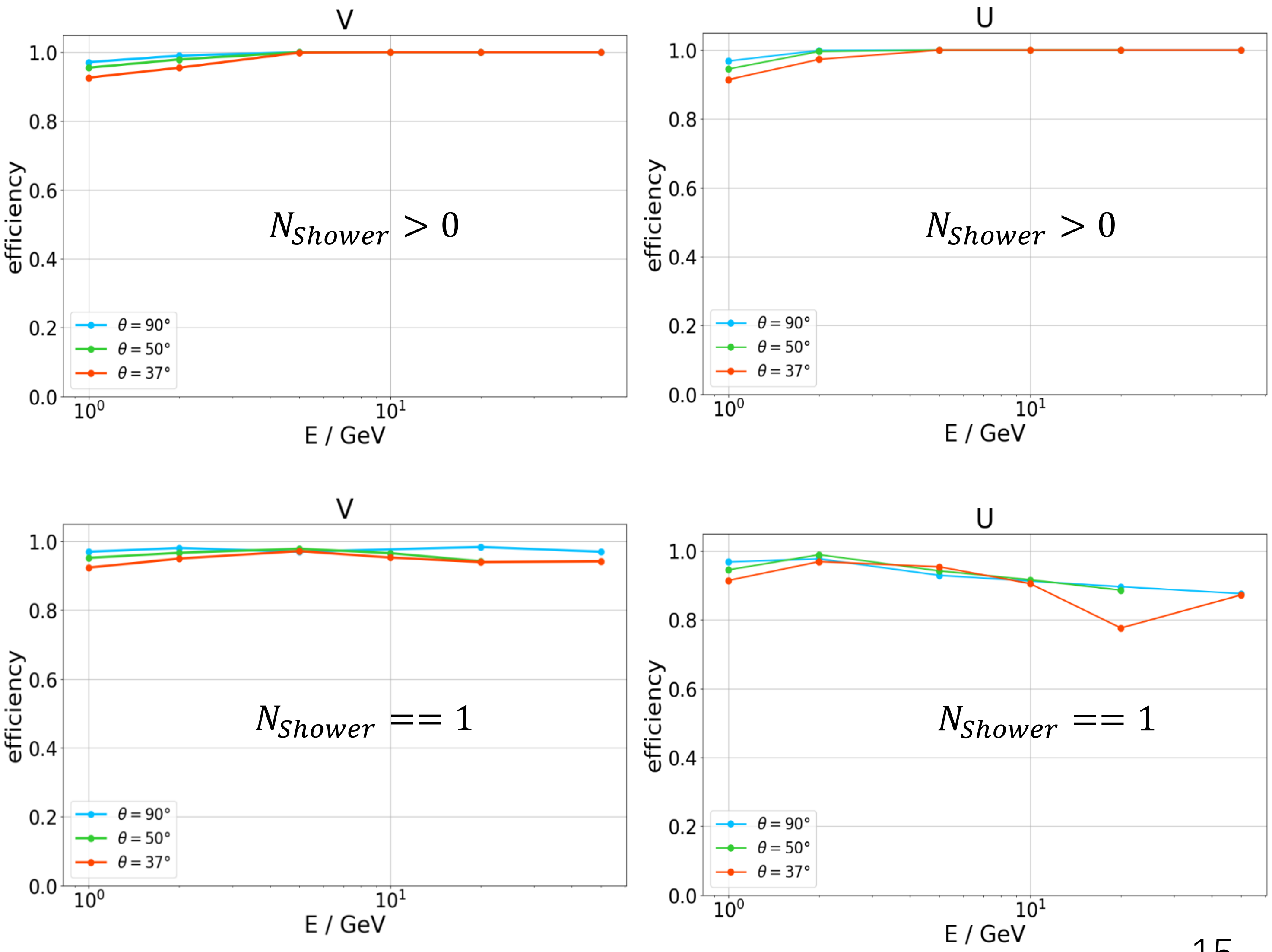


Performance of Single Photon MC Samples

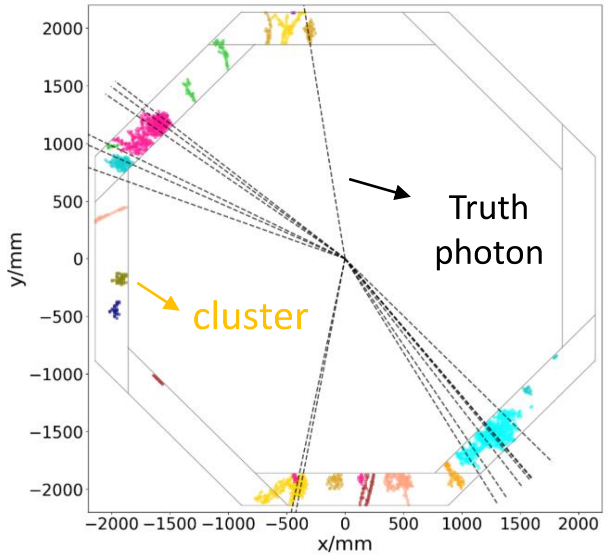
- A series of single photon MC samples are generated with differential energies and directions
- Inefficiency in low energy range since short longitudinal developments
- Number of fake showers raises in large energy and angle ranges
- Events with interactions between photon and material are included



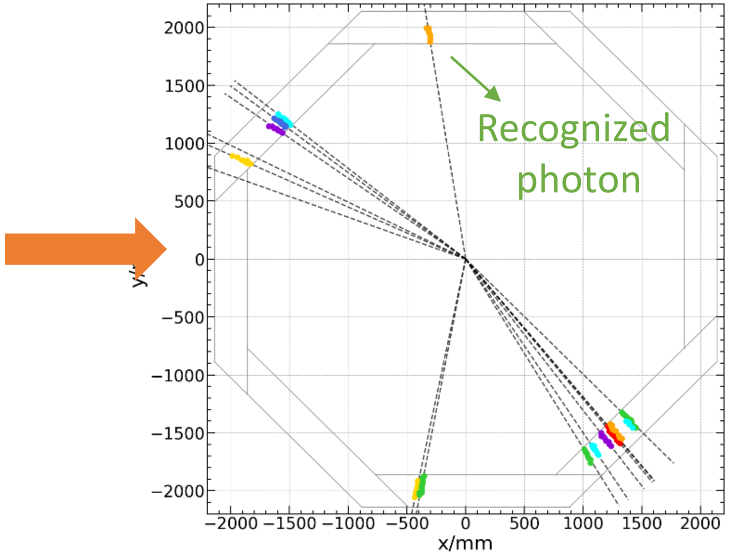
50GeV γ



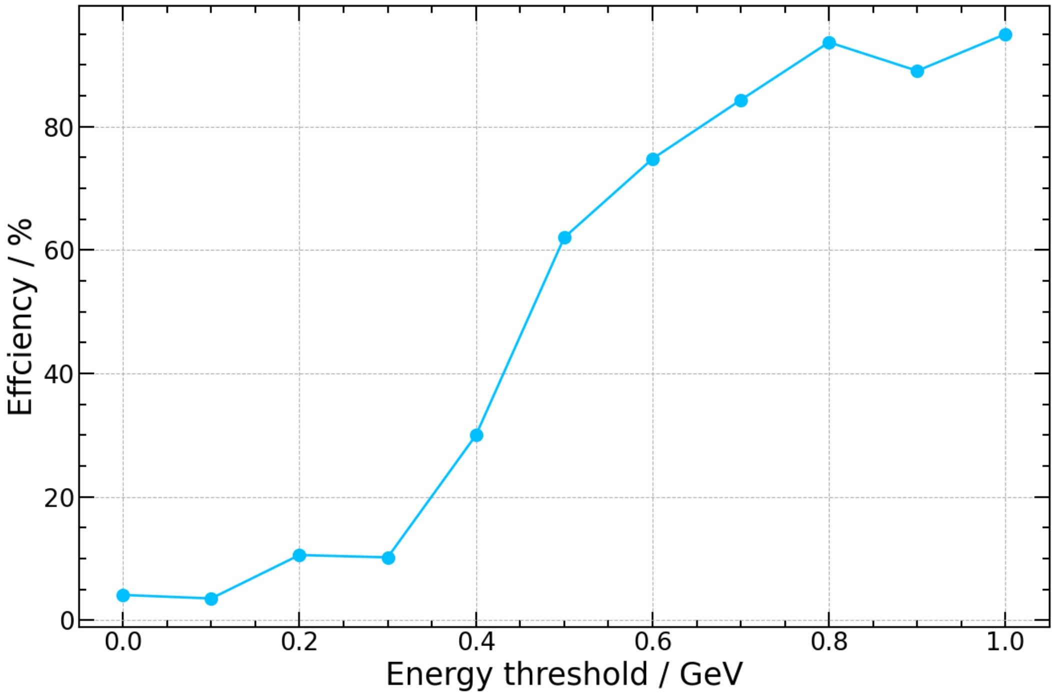
Photon Recognition in $H \to gg$ events

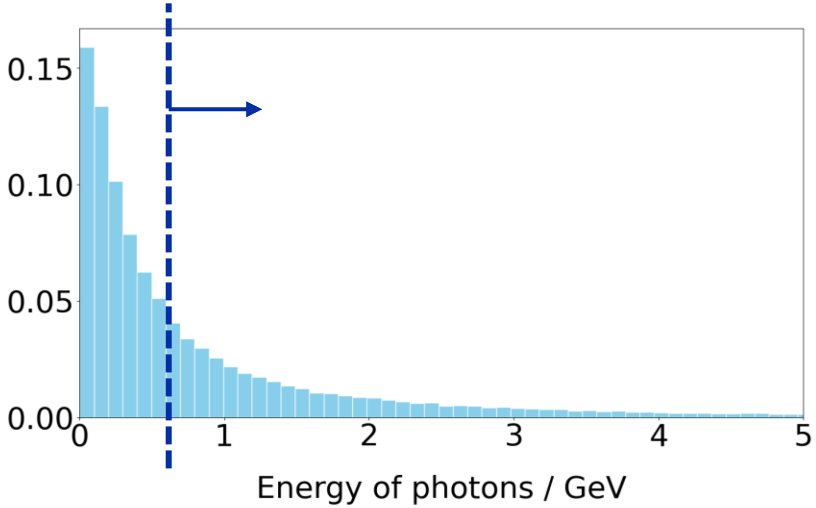


Clustering



Photon recognition

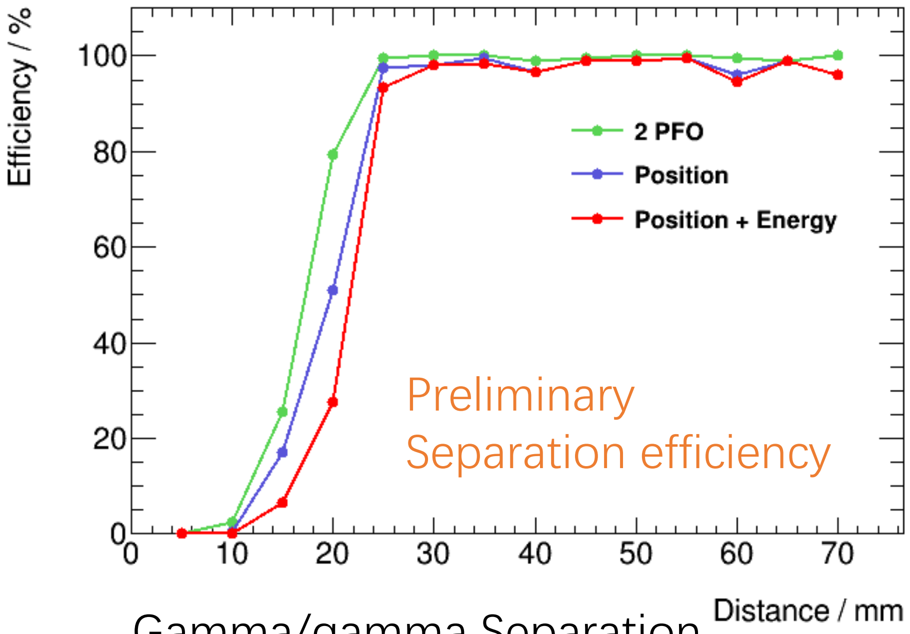




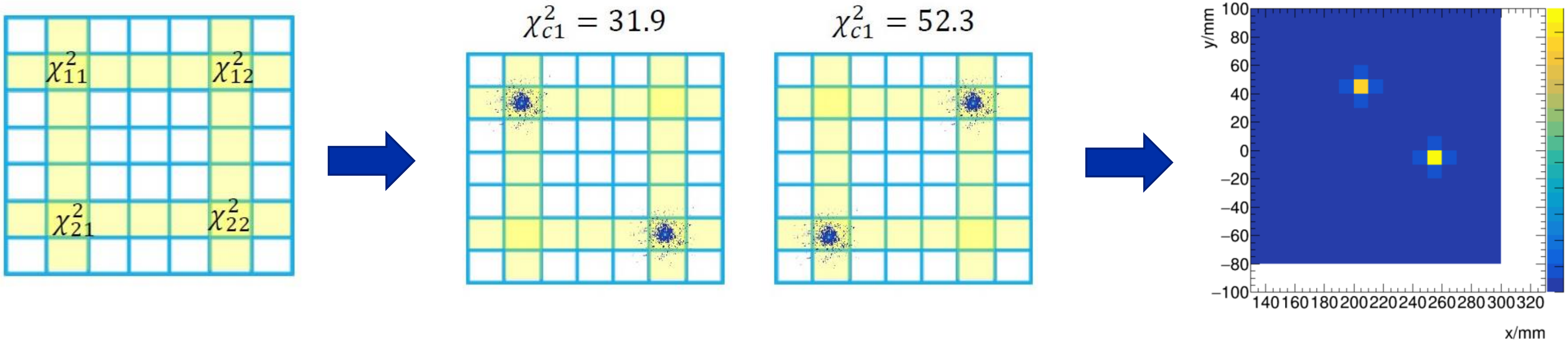
- Recognition efficiency for photons in jet with E>0.8 GeV is >95% (Gamma conversion)
- Photons with lower energy will be recognized using other method

Elimination of Ambiguity

- Perpendicular arrangement of crystal bars in adjacent layers may cause ambiguity problem for multiple particles in one super cell
  - Define χ_E^2 for energy matching: $\chi_E^2 = \frac{(E_X - E_y)^2}{\sigma_E^2}$
  - Define χ_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: $\chi_c^2 = \sum_{i=1}^{N} \chi_{point}^2$

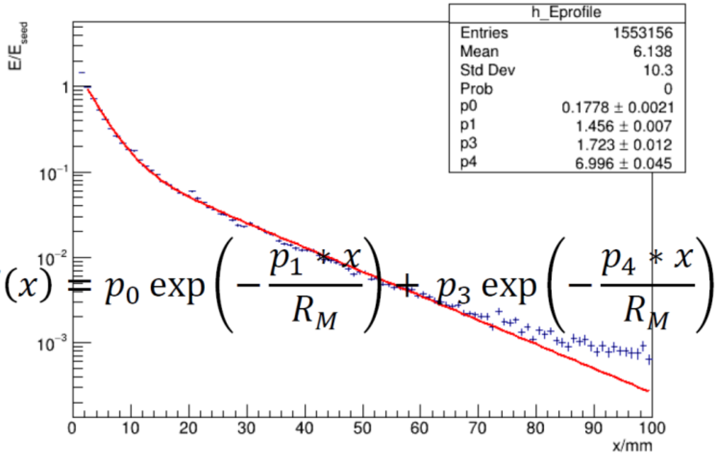


Gamma/gamma Separation

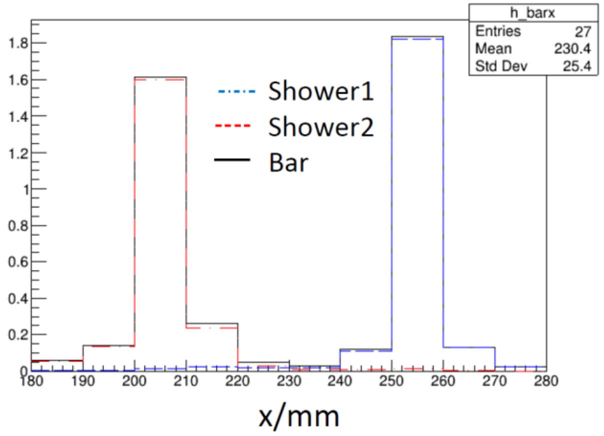


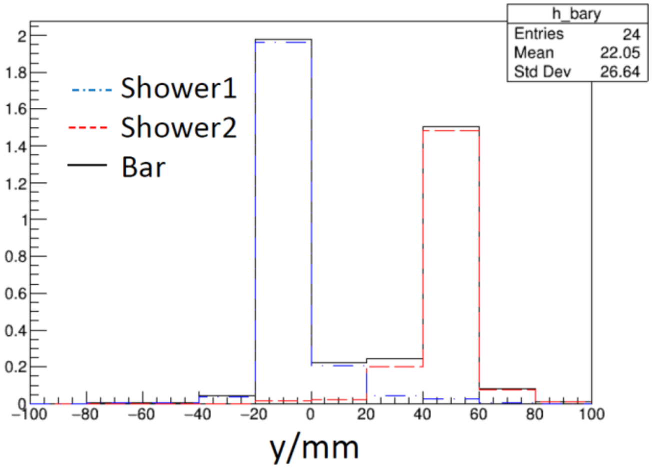
Energy Splitting

- Showers from different particles may overlap
  - EM shower development description: $E_{i\mu}^{exp} = E_{\mu}^{seed} \times f(|x_i - x_c|)$
  - 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



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





Summary

- Optimal energy resolution of crystal calorimeter enhance physics discovery potential
- Crystal bar array with cross point architecture provides a promising solution for ECAL, challenges for hardware and software to achieve a maximal exploitation of precise measurements
- Basic functions of clustering, photon recognition, elimination of ambiguity and energy splitting have been implemented and demonstrated
- More efforts are expected to complete feasibility study of cross point crystal ECAL

Thank you!