Status of Horizontal Crystal Bar ECAL Software

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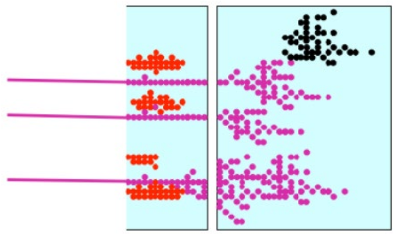
Introduction: PFA Calorimeter

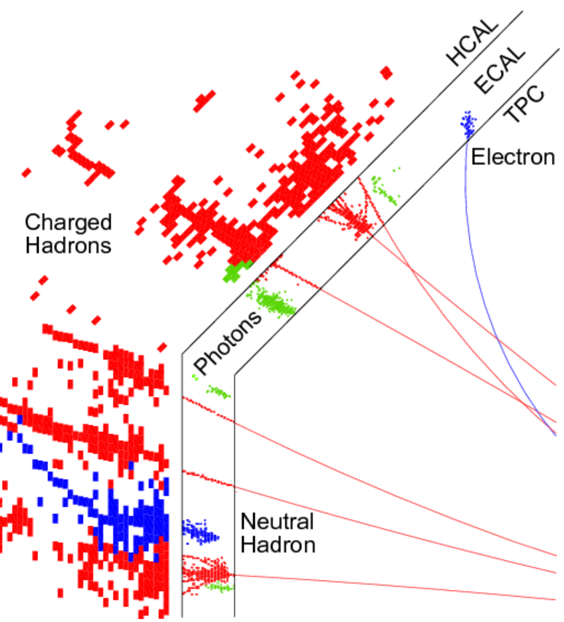
- A high precision Higgs / Z factory
  - Significance of heavy bosons depends on mass resolution, and separation also require jet energy resolution 3~4%
  - Fine γ/π^0 reconstruction.
- Reconstruction of every single particle in the event
  - Charged particle momentum measured in tracker.
  - Photon energies measured in ECAL.
  - Neutral hadron energies measured in HCAL.
- Particle flow approach (PFA) and Imaging Calorimeters
  - Identification of energy deposits from each individual particle.
  - Combination of the information of tracker and calorimeters.
  - Hardware + Software

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



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



Weekly group meetings https://indico.ihep.ac.cn/category/748/
Wider participation/collaboration are welcome!

Introduction: Crystal ECAL vs Si-W ECAL

Crystal ECAL: BGO

- Optimal energy resolution $\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%$
  - Better jet energy resolution $0.17\sqrt{E_J}$
- Larger R_M ➔ larger lateral width of a shower
  - Increase probability of showers' overlap
- Larger λ_I / X_0 ➔ longitudinal development is determined by λ_I
  - Increase probability of hadronic shower in ECAL

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

Confusion is the limiting factor in PFA. Correctly assign calorimeter energy deposits to the correct reconstructed particle.

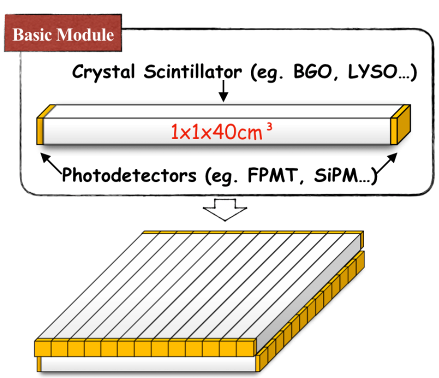
Material	X_0 /cm	R_M /cm	λ_I /cm	λ_I / X_0
W	**0.35**	**0.93**	**9.6**	**27.4**
BGO	**1.12**	**2.23**	**22.8**	**20.3**
Ratio	3.2	2.4	2.4	0.74

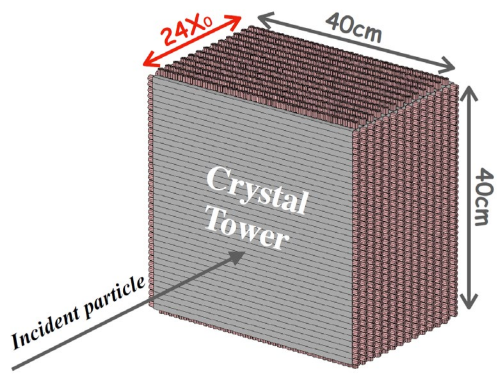
Component	Detector	Energy Fraction	Energy Resolution	Jet Energy Resolution
Charged Particles ($X^{\pm}$)	Tracker	$\sim 0.6\ E_J$	—	—
Photons (γ)	ECAL	$\sim 0.3\ E_J$	$\mathbf{0.15}\sqrt{E_\gamma}$	$\mathbf{0.08}\sqrt{E_J}$
			$\mathbf{0.03}\sqrt{E_\gamma}$	$\mathbf{0.016}\sqrt{E_J}$
Neutral Hadrons (h^0)	HCAL	$\sim 0.1\ E_J$	$0.15\sqrt{E_{h^0}}$	$0.17\sqrt{E_J}$

Horizontal Crystal Bar Solution for ECAL

ECAL design

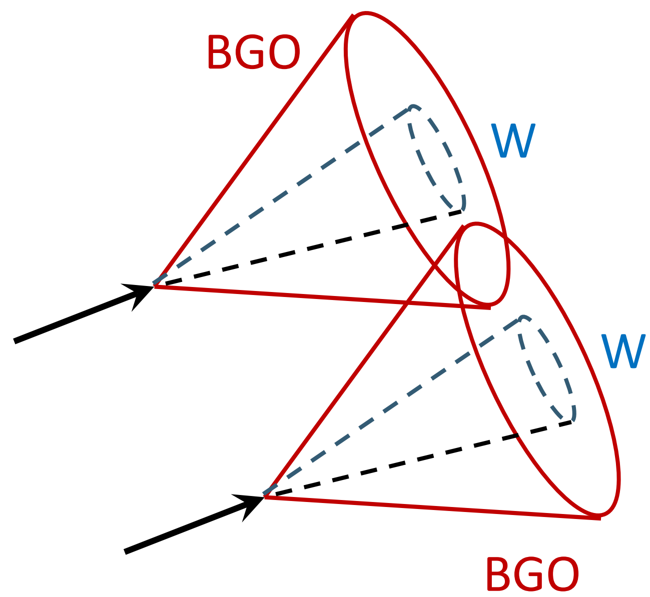
- Material: BGO
- Optimal energy resolution $\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%$
- Long bar size: $1 \times 1 \times \sim 40cm^3$
- Time measurement at both ends for position along bar.
- Crossed arrangement in adjacent layers
- Super Cell: two adjacent layers
- Cube: $\sim 40 \times \sim 40 \times 24X_0 cm^3$
- Significant reduction of number of channels





Key Issues

- Ambiguity caused by 2D measurements
- Separate energy deposits from different particles



Reconstruction is a big challenge

Geometry Construction

A BGO crystal barrel ECAL

Crystal Bar:

- BGO： $X_0 = 1.12cm, R_M = 2.23cm$
- Size: $1 \times 1 \times \sim 40\ cm^3$
- Both ends readout

Basic Detection Unit — Super Cell

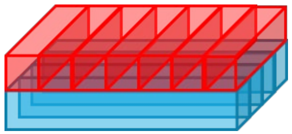
- 2 layers of perpendicularly crossing bars
- Size: $\sim 40 \times \sim 40 \times 2\ cm^3$

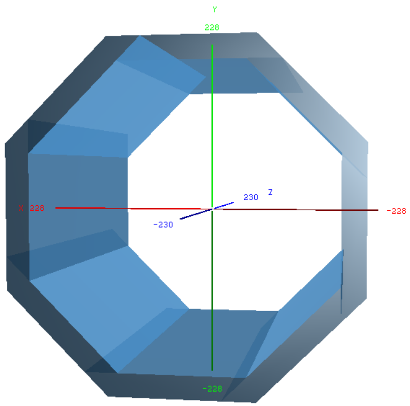
Detector

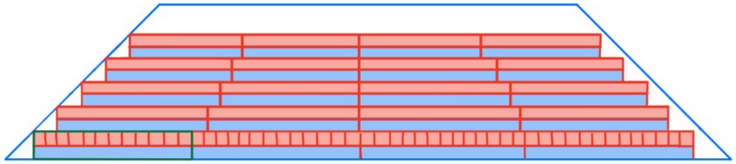
- $R = 1.8m, L = 4.6m, H = 28cm$
- 8 same trapezoidal staves
- Avoid gaps point to IP

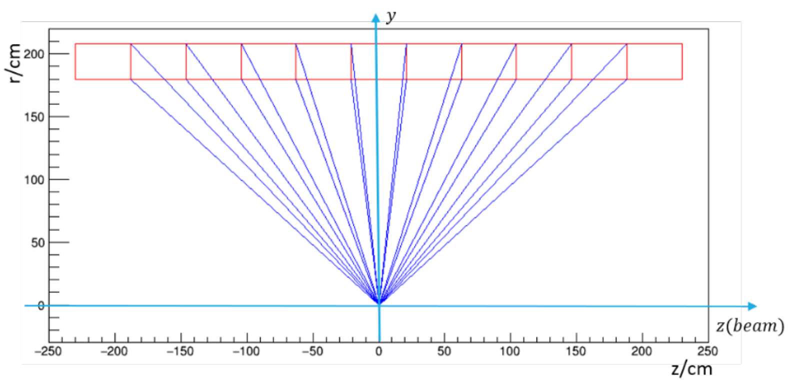
Ideal detector without electronics, supporting, etc.

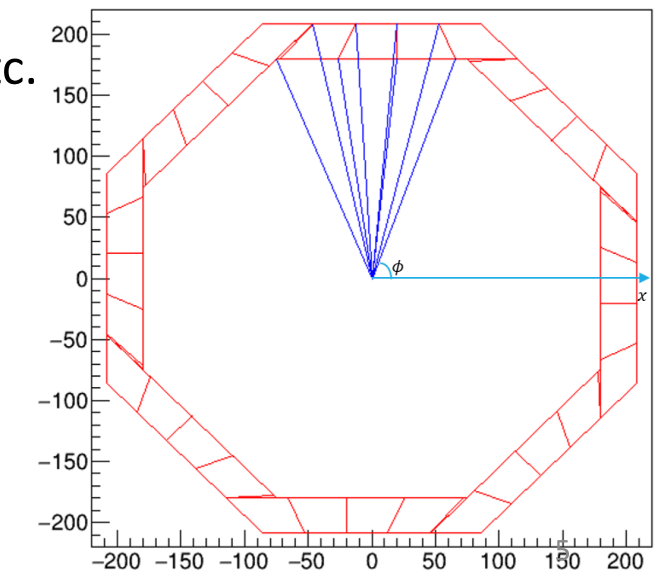
DD4Hep is used for geometry construction











Simulation and Digitization

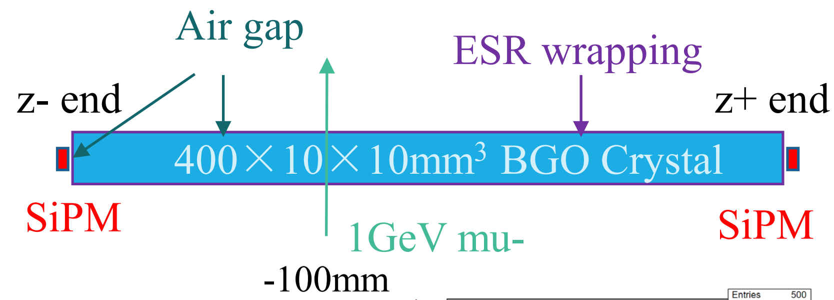
- A full simulation for extraction of time resolution
- Simulation is performed using GEANT4
  - Electromagnetic interactions
- Digitization for one long crystal bar
  - Contribution of each G4step $\boldsymbol{i}$

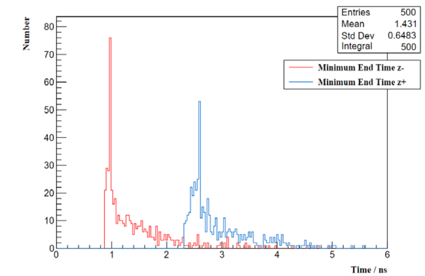
$$Q_{\pm}^{i} = E_0 \cdot e^{-\frac{L/2 \pm z_i}{L_{Atten}}}, \qquad T_{\pm}^{i} = T_0 + Gaus(z_{\pm}^{i}/v,\ \sigma_T)$$

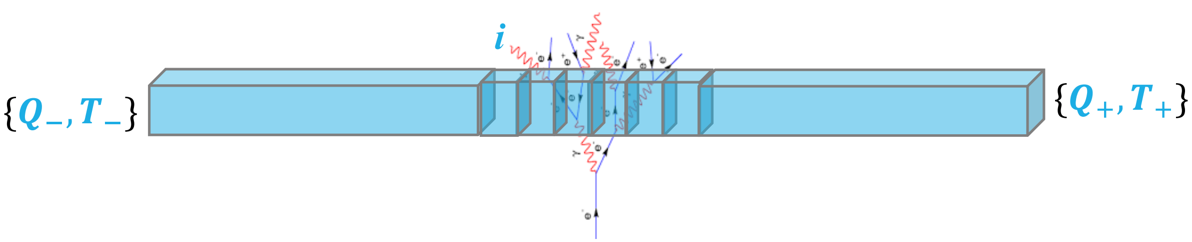
  - Readout at both ends: $\boldsymbol{Q_{\pm}}$ and $\boldsymbol{T_{\pm}}$

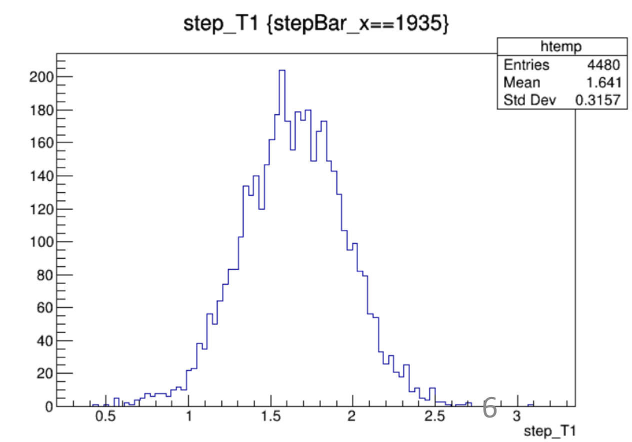
$$\boldsymbol{Q_{\pm}} = \sum\nolimits_{step} Q_{\pm}^{i}\,, \quad \boldsymbol{T_{\pm}} = T_{\pm}^{k} \mid \left(\sum\nolimits_{i=1}^{k} Q_{\pm}^{i} > thres\right)$$

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

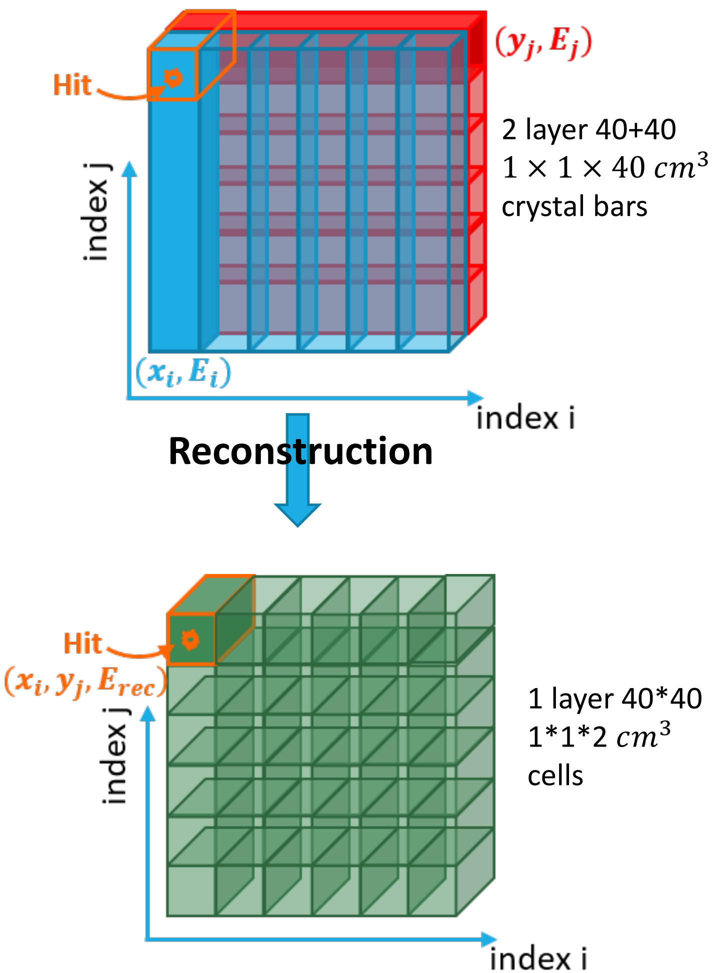








Hit Reconstruction

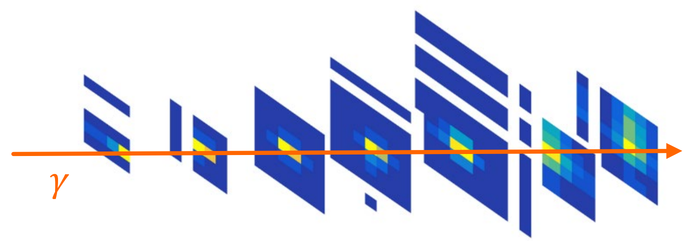


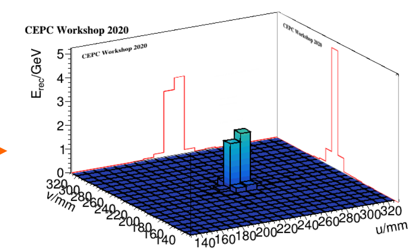
In a super cell

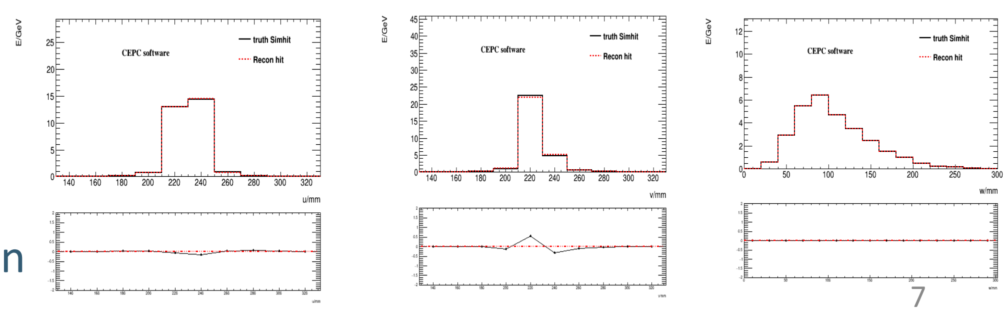
- Position: $(x_i, y_j, \frac{z_i+z_j}{2})$
- Energy: use energy distribution in adjacent layer as fractions

$$E_{rec}^{hit_{ij}} = E_i \times f_i + E_j \times f_j,$$

$$f_i = \frac{E_j}{\Sigma E_j}, \qquad f_j = \frac{E_i}{\Sigma E_i}$$



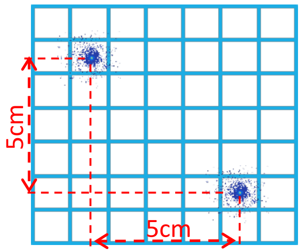




2D measurements provide 3D information

Reconstruction: Clustering and Splitting

In each layer / 1D reconstruction:

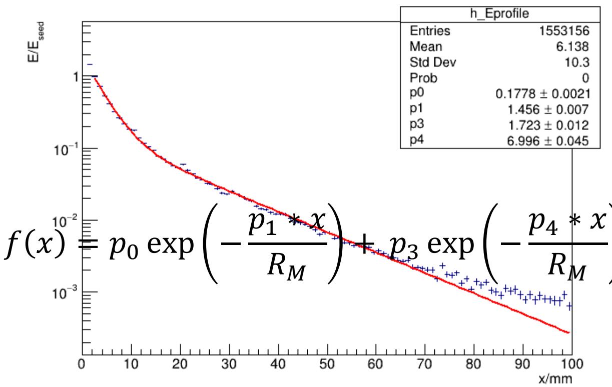


Clustering / Seed Finding

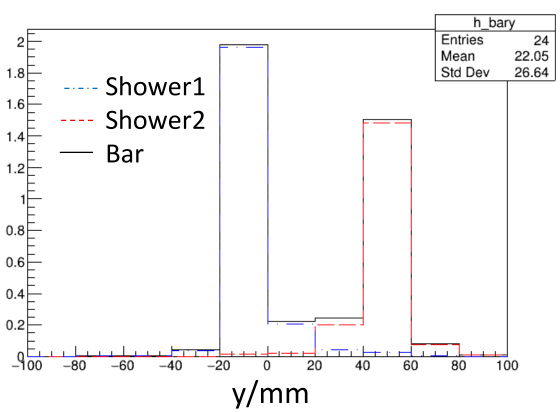
- Neighbor clustering
- Local maximum and seed candidate $E_i > E_{th}^{seed}$

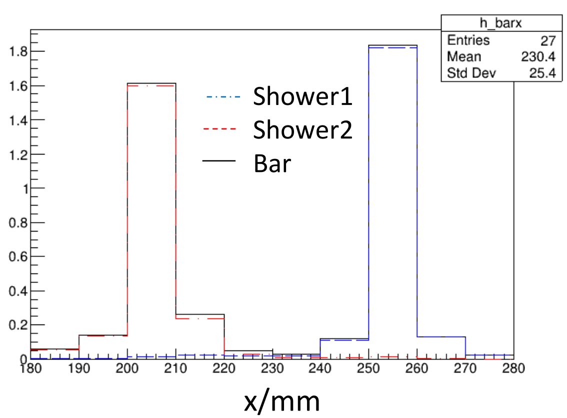
Energy Splitting

- $N_{seed} \geq 2$ && second moment $S > S_{th}(0\ now)$
- Energy of shower μ deposited in bar i: $E_{i\mu}^{exp} = E_{\mu}^{seed} \times f(|x_i - x_c|)$
- Energy splitting: $E_{i\mu} = w_{i\mu} \times E_{mea}^{i} = \frac{E_{i\mu}^{exp}}{\sum_{\mu} E_{i\mu}^{exp}} \times E_{mea}^{i}$



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





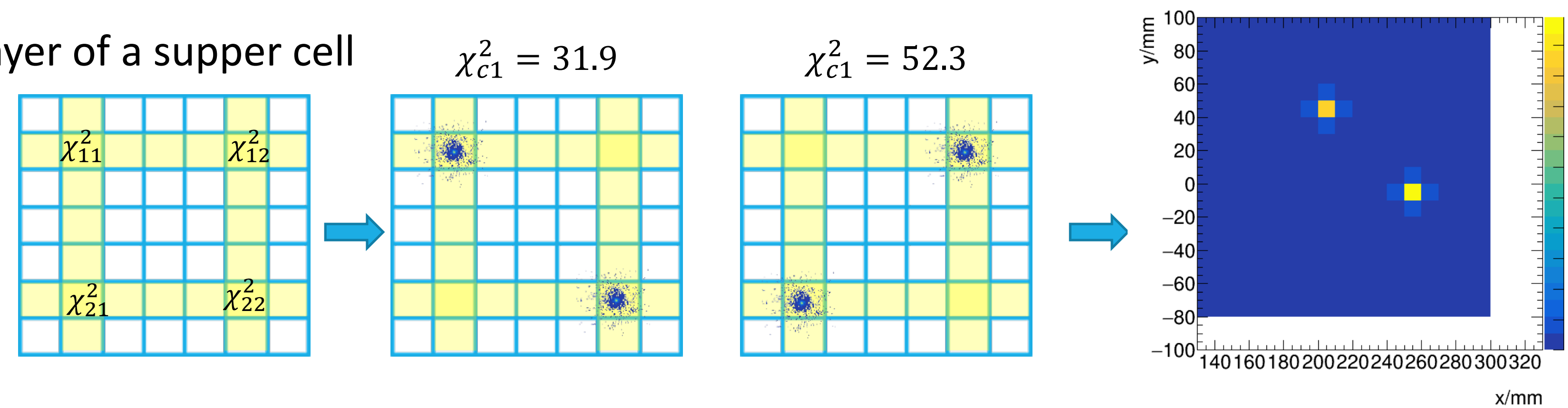
Reconstruction: Energy / Time Matching

Showers in perpendicular X/Y bars of one super cell come from one particle

In one super cell (2 layers)

- 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: $\chi_T^2 = \frac{(z_T - z_Y)^2}{\sigma_S^2 + \sigma_{z(t)}^2}$
- Define $\chi_{point}^2 = \chi_E^2 + \frac{1}{2}(\chi_{Tx}^2 + \chi_{Ty}^2)$
- Totally N! combinations: $\chi_c^2 = \sum_{i=1}^{N} \chi_{point}^2$

one layer of a supper cell

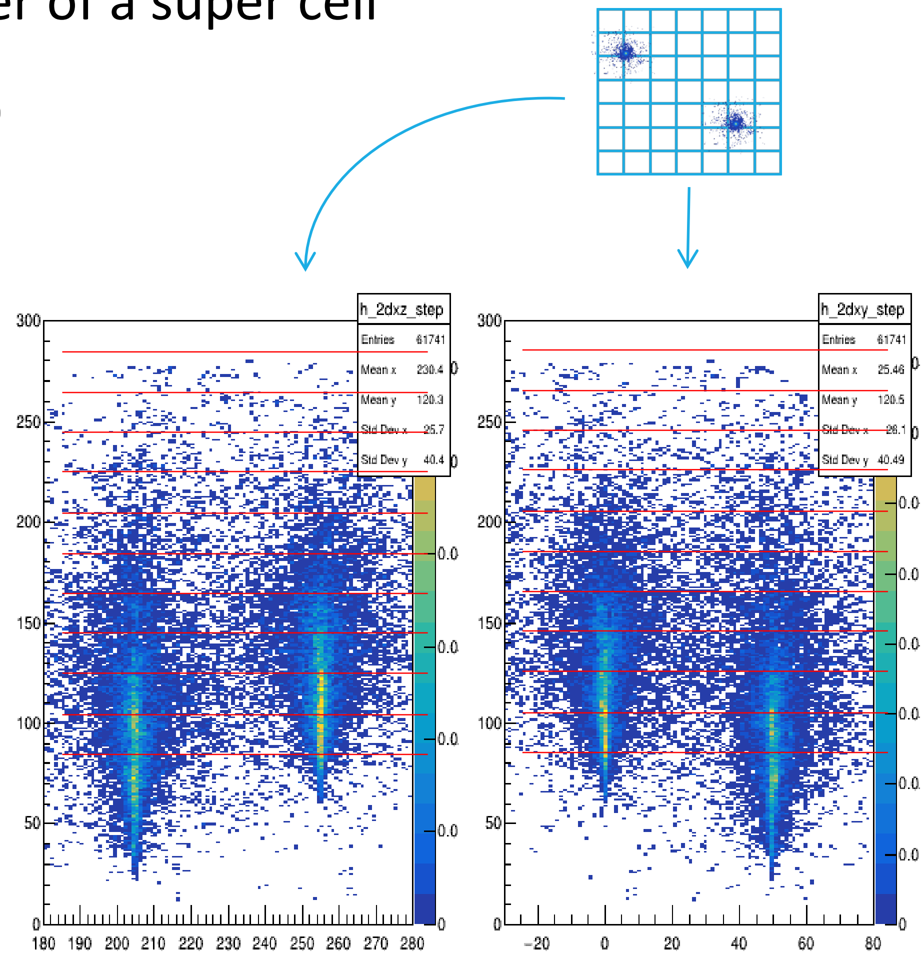


Reconstruction: Energy / Time Matching

Energy and time matching in one layer of a super cell

$$\chi^2_{point} = \chi^2_E + \frac{1}{2}(\chi^2_{Tx} + \chi^2_{Ty})$$

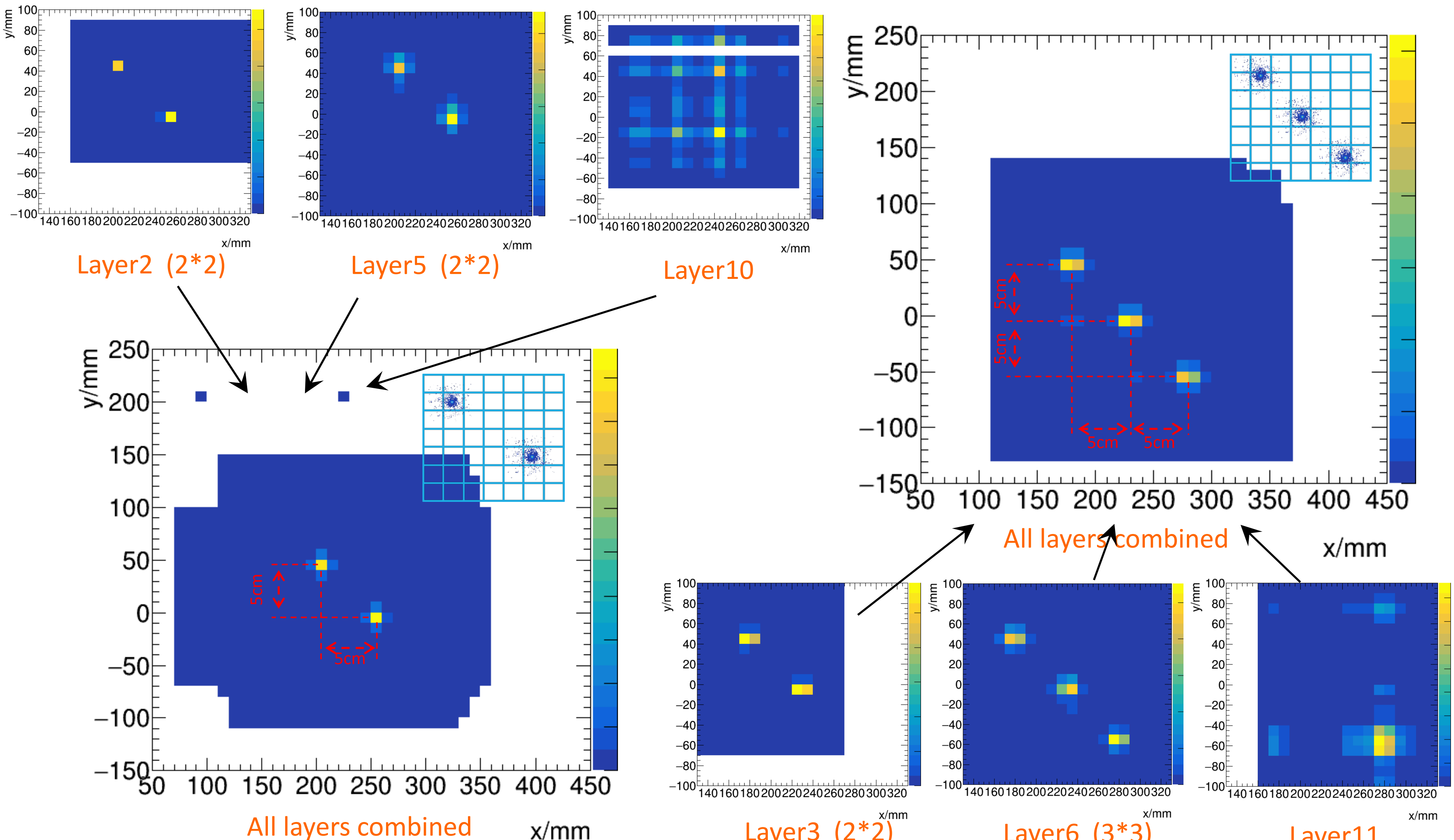
Depth/mm	Nshower	Eshower1	Eshower2
20	1	0.051	
40	1	0.527	
60	2	1.378	0.135
80	2	1.781	1.313
100	2	2.138	2.192
120	2	1.507	2.252
140	2	0.715	2.070
160	2	0.547	1.171
180	2	0.314	0.540
200	2	0.218	0.346
220	1		0.275
240	1		0.146
260	1		0.067



Energy and time matching provide a solution of ambiguity / ghost hits!

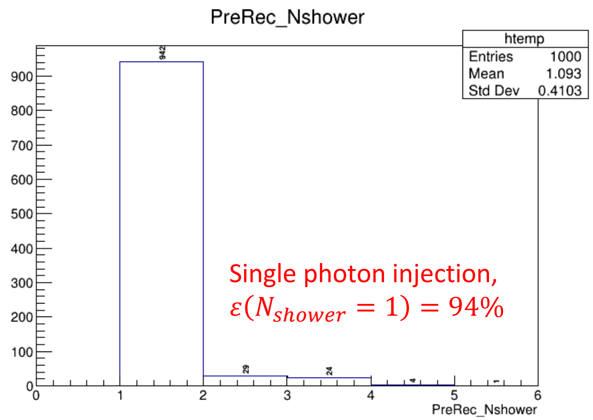
Better performance is expected with further optimization.

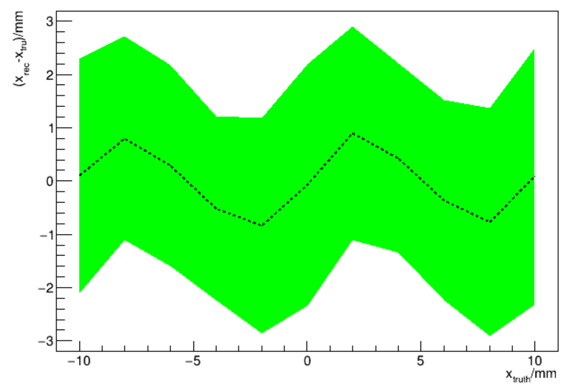
Some Validations



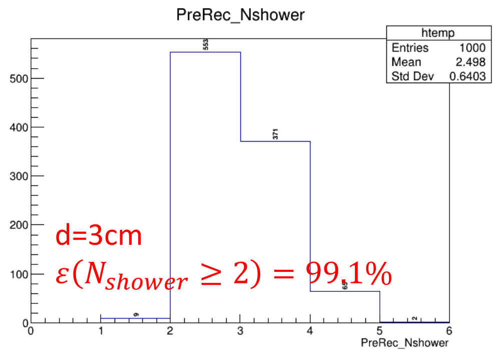
Performance Checks

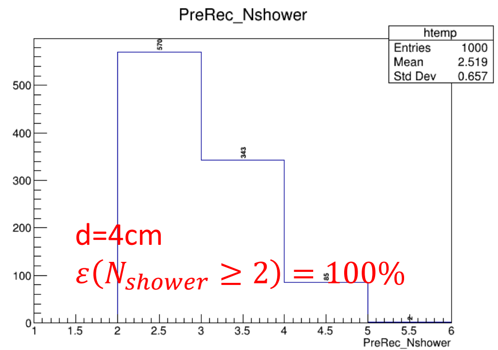
Performance check with photon events: correct rate, position resolution

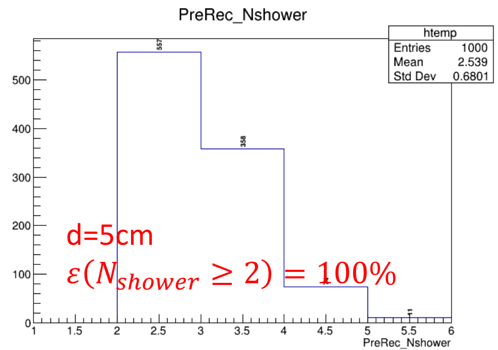




x residual and resolution.
Scan the inject position from -1cm~1cm.
Need position correction.

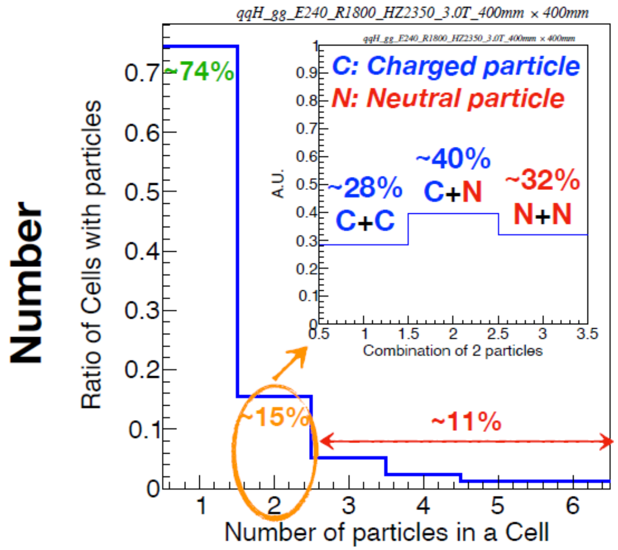


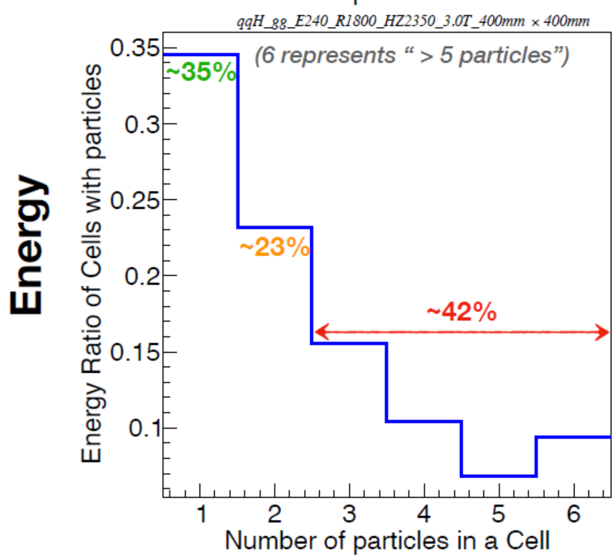




More seeds / showers are found in latter half of the cluster development.
Possible introduce more *confusions*, Optimization is expected.

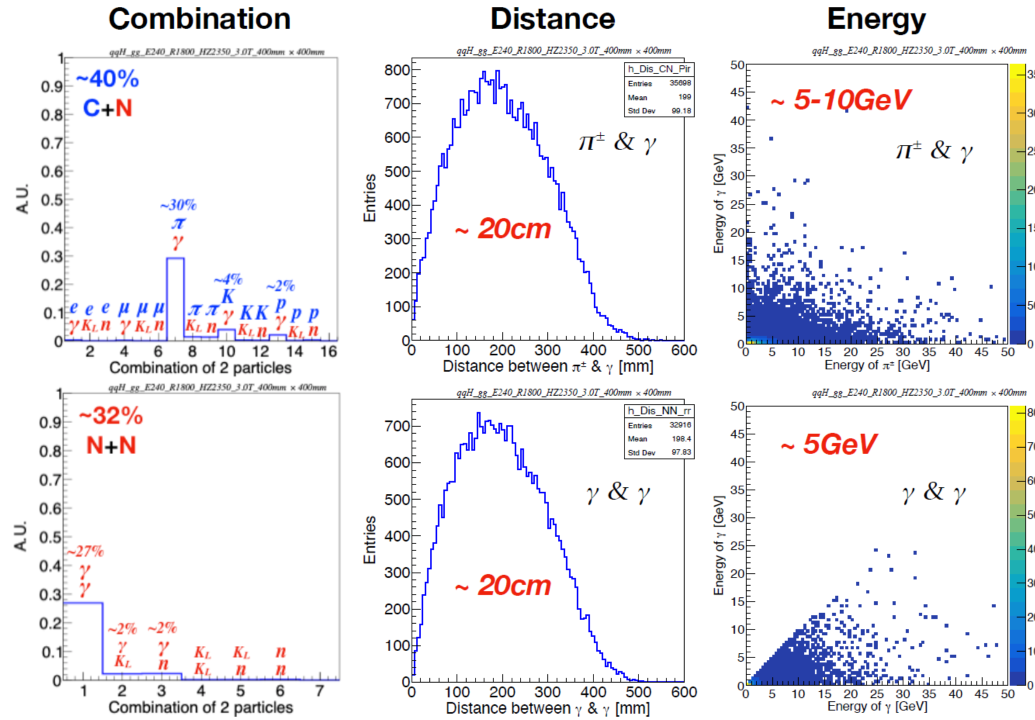
Discussions: Multiplicity





Multiplicity in a $40cm \times 40cm$ cube

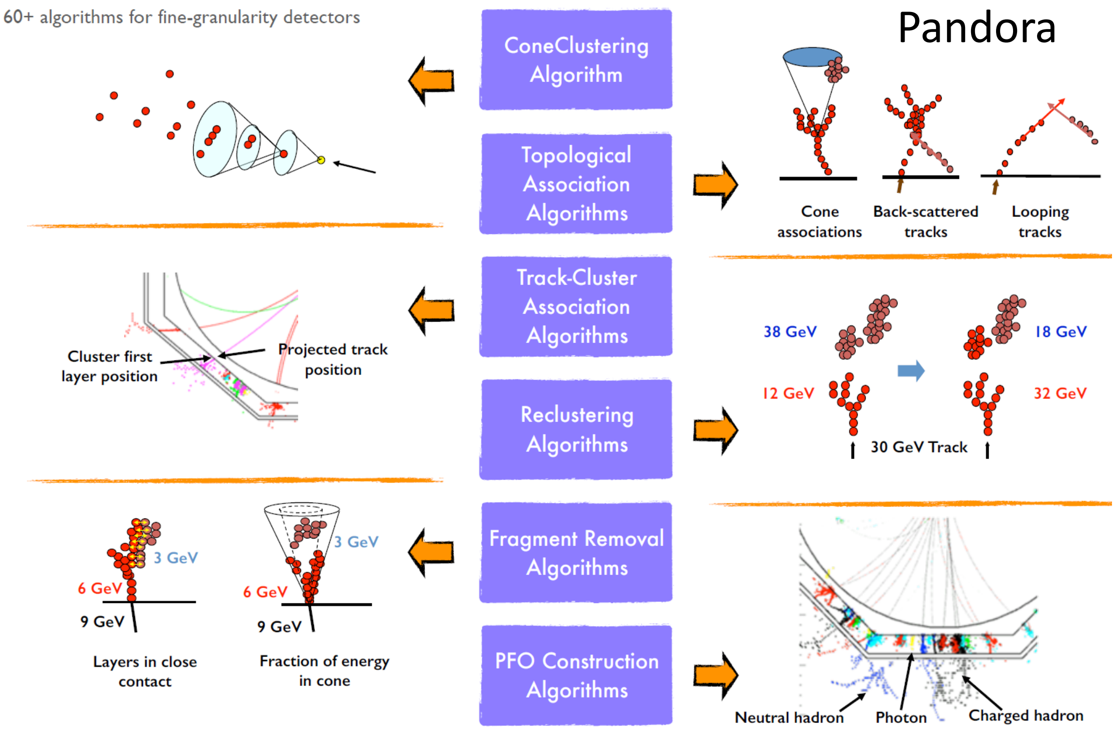
Wang Yuexin, *et. al.*, Crystal ECAL Workshop 2020



Cube with 2 particles: distance and energy distribution

- 11% Cubes with >2 particles, 42% energy of 4-jet event with >2 particle
- Average distance between 2 particles in one cube is ~20cm.

Discussion: Clustering



Arbor

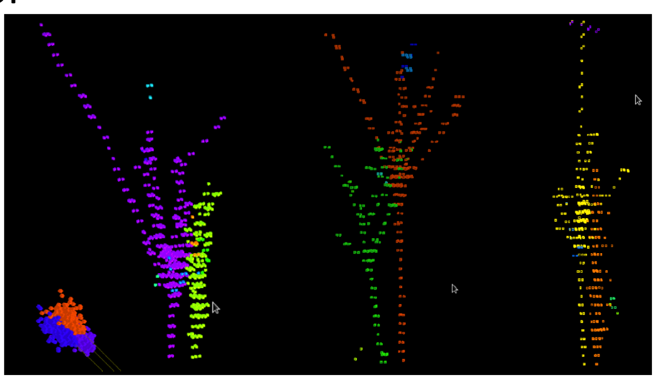
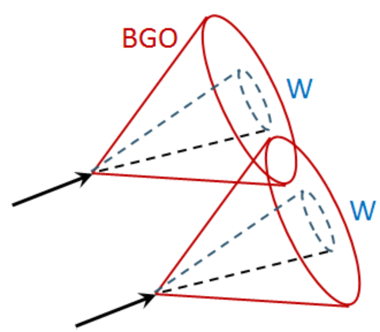


Figure 7: Nearby showers reconstructed by Arbor. The display at left corner shows three nearby photon clusters, while the other three display shows nearby hadron showers



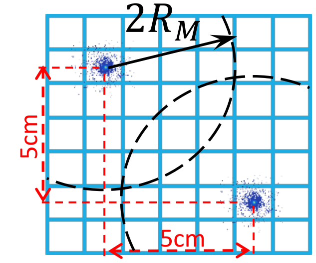
Crystal Showers

- Highly granular sampling calorimeter: e.g. Si-W
  - Best separation for narrow showers
  - W: $X_0 \sim 3mm$, $R_M \sim 9mm$
  - Active elements: $\sim 0.5cm^3$ segmentation
  - Each ECAL hit associate with one particle, no sharing.
- Crystal calorimeter: e.g. BGO
  - BGO: $X_0 \sim 1cm$, $R_M \sim 2cm$
  - Larger lateral development require a high performance energy splitting algorithm
  - R&D of a new PFA software for dedicated crystal ECAL

Plan and Summary

- Particle Flow ECAL requires an efficient separation of showers from charged hadrons, photons and neutral hadrons, the *confusion* term dominate the jet energy resolution.
- Crystal has better energy resolution, larger X_0/R_M and shorter λ_I, to foresee more overlap.
- *Ambiguity* of perpendicular crystal bars is promising to be removed with established software solution.
- Enormous potential for advanced reconstruction techniques dedicated for crystal ECAL making full use of the 5D information (x,y,z,E,t).

Thank you for your attention!


$2R_M$
5cm
5cm