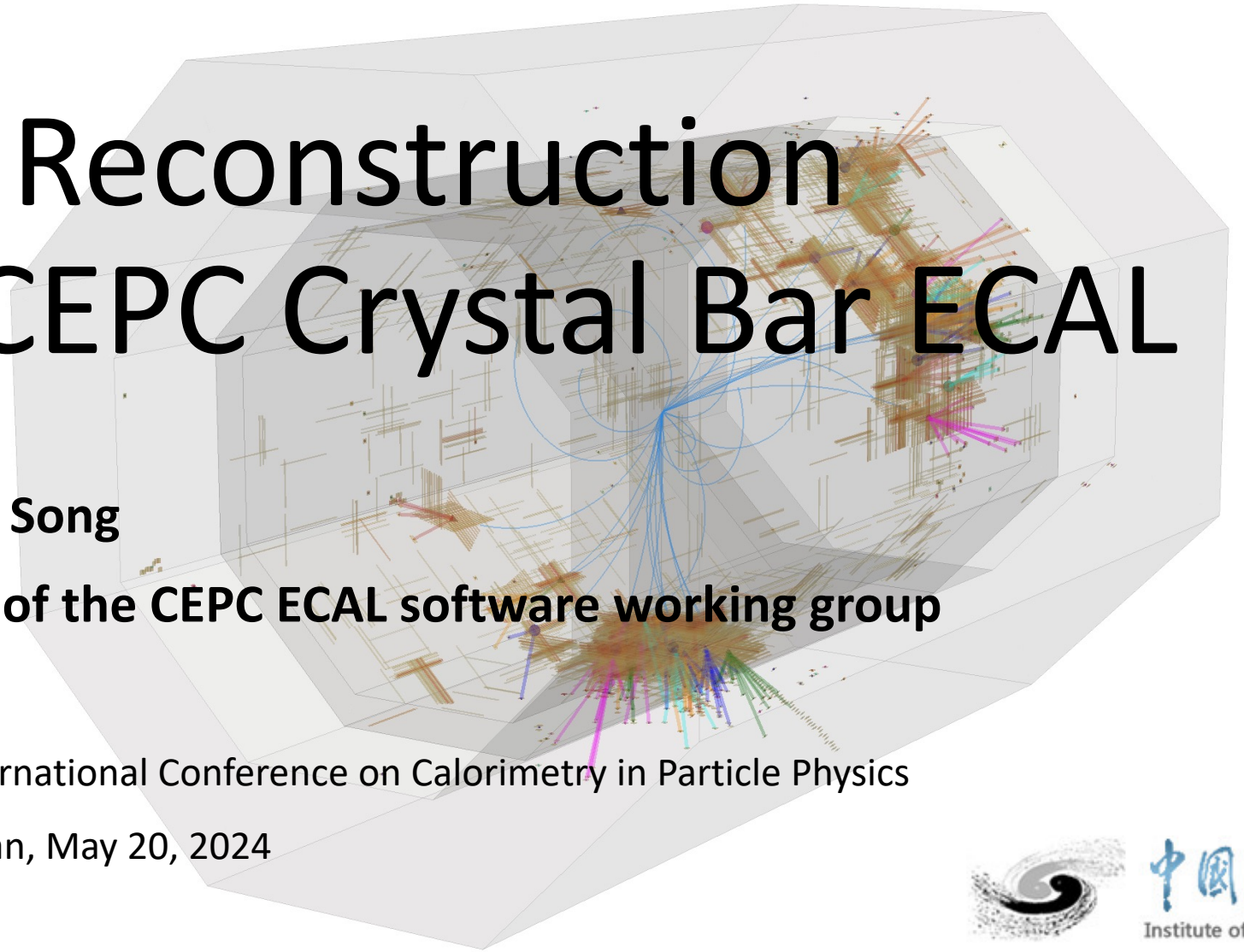


PFA Reconstruction for CEPC Crystal Bar ECAL

Weizheng Song

on behalf of the CEPC ECAL software working group

IHEP, CAS

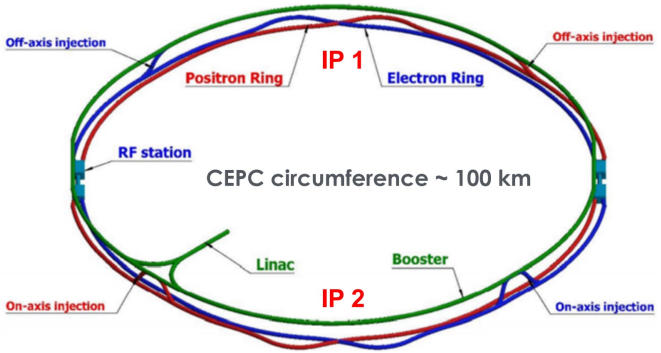
The 20th International Conference on Calorimetry in Particle Physics

Tsukuba, Japan, May 20, 2024

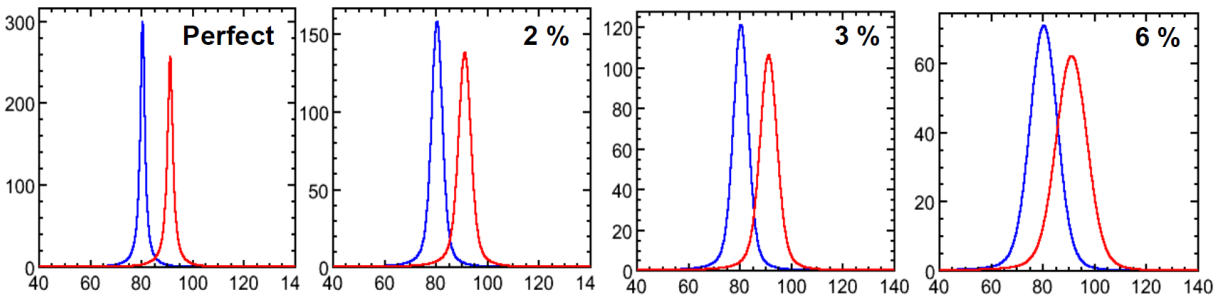
中國科學院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

CEPC and Detector Requirements

- CEPC (Circular Electron Positron Collider)
  - High precision Higgs, EW, flavor physics and QCD studies.
  - Probe for physics BSM.
- Detector Requirements
  - Jet energy resolution $< 30\%/\sqrt{E}$.
  - BMR (Boson Mass Resolution) $< 4\%$:
    - Clean separation between hadronic decayed Higgs/Z/W.

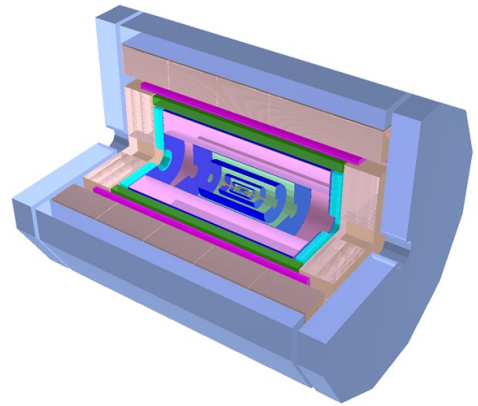


CEPC Operation mode		ZH	Z	W^+W^-	ttbar
		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	-
CDR (30MW)	$\mathcal{L}$ / IP [$\times 10^{34}$ $cm^{-2}s^{-1}$]	3	32	10	-
	[ab^{-1}, 2 IPs]	5.6	16	2.6	-
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	-
Run time [years]		10	2	1	5
Latest (50MW)	$\mathcal{L}$ / IP [$\times 10^{34}$ $cm^{-2}s^{-1}$]	8.3	192	27	0.83
	[ab^{-1}, 2 IPs]	20	96	7	1
	Event yields [2 IPs]	4×10^6	4×10^{12}	5×10^7	5×10^5



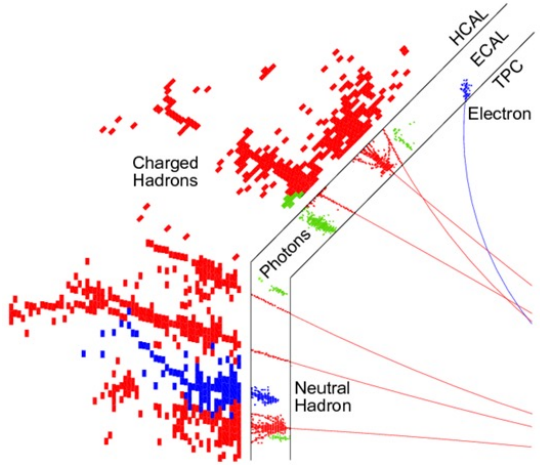
Jet E res.	W/Z sep
Perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

from Pandora LC reconstruction



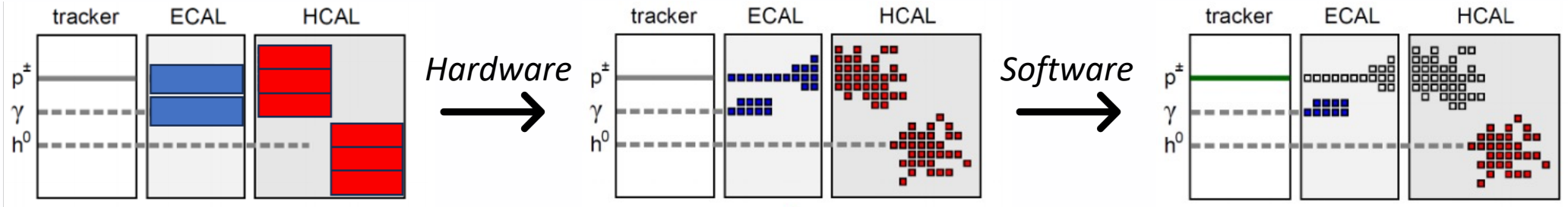
Particle Flow Approach

- Particle Flow Approach
  - Promising approach to achieve an unprecedented jet energy resolution.
  - Measure the jet by its components: $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$.
    - Charged particle momentum: tracker.
    - Photon energies: ECAL.
    - Neutral hadron energies: HCAL.
  - Hardware and Software.



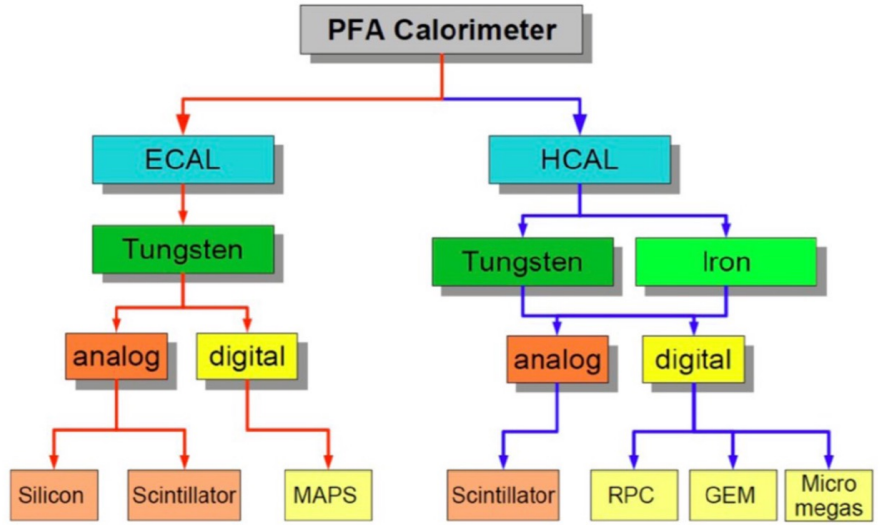
Hardware: separate clusters from different particles.
--- High granularity.
--- Compact shower structure.

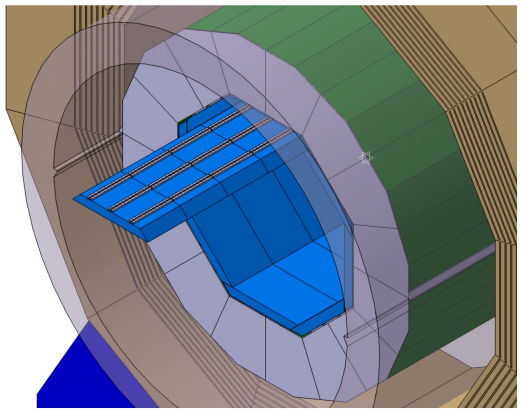
Software: correctly assign calorimeter energy deposits to the particles.
--- Clustering.
--- Pattern recognition.



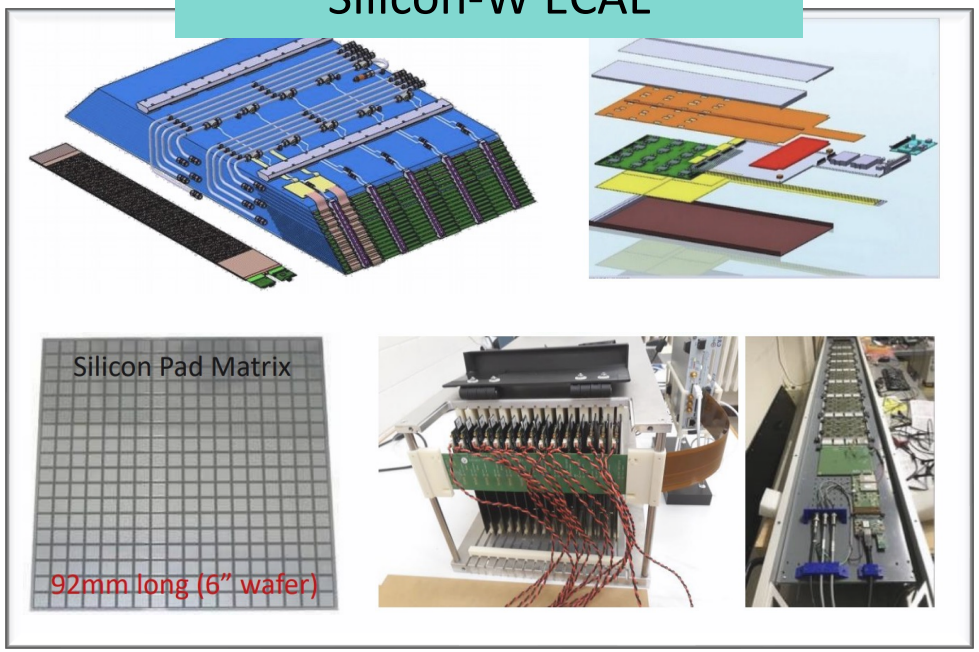
PFA-oriented Calorimetry

- Hardware: sampling calorimetry
  - ECAL: Si/Sci + W.
  - HCAL: Sci/RPC + W/Iron.
  - High granularity.
- Software: PFA reconstruction
  - PandoraPFA.
  - ArborPFA.

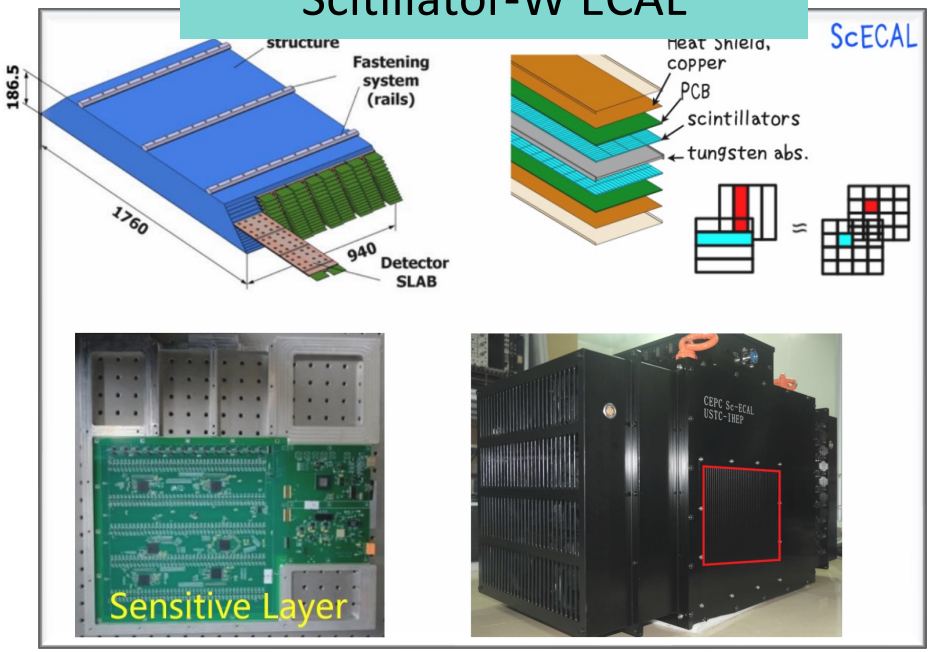




Silicon-W ECAL

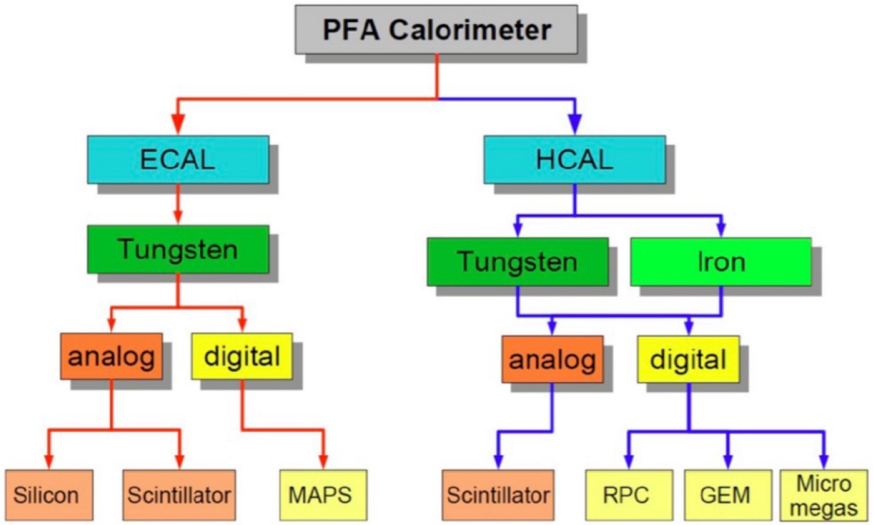


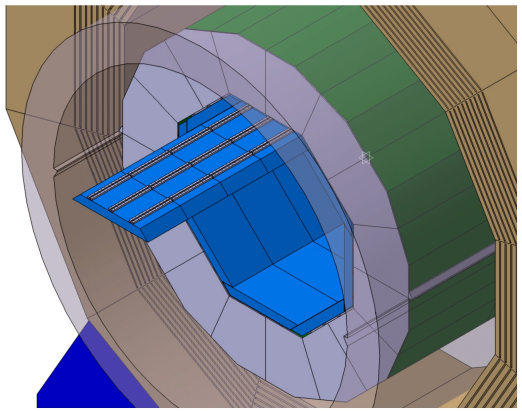
Scitillator-W ECAL



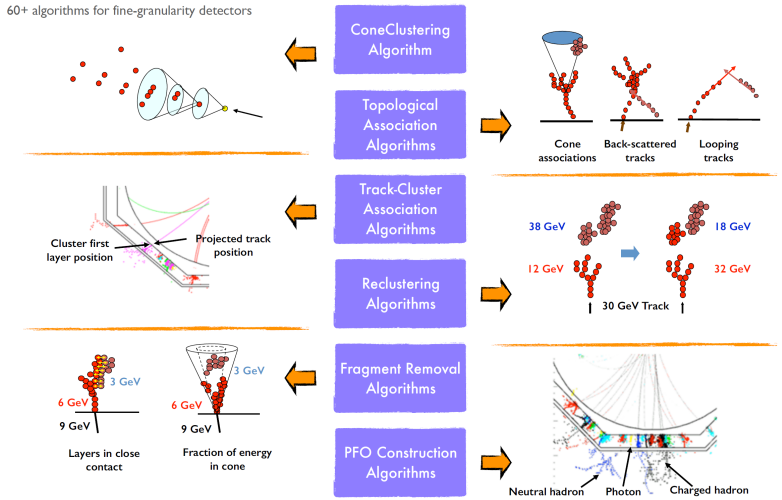
PFA-oriented Calorimetry

- Hardware: sampling calorimetry
  - ECAL: Si/Sci + W.
  - HCAL: Sci/RPC + W/Iron.
  - High granularity.
- Software: PFA reconstruction
  - PandoraPFA.
  - ArborPFA.

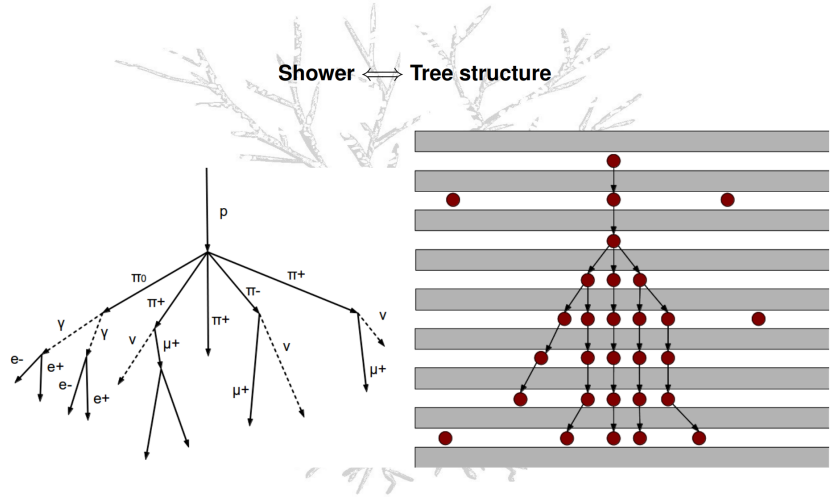




PandoraPFA

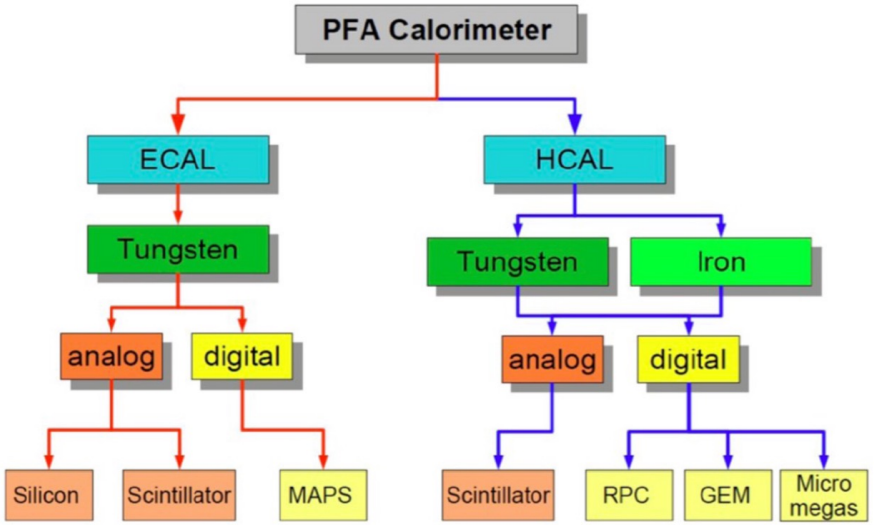


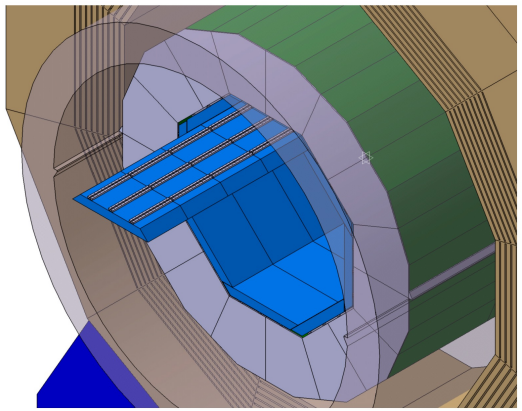
ArborPFA

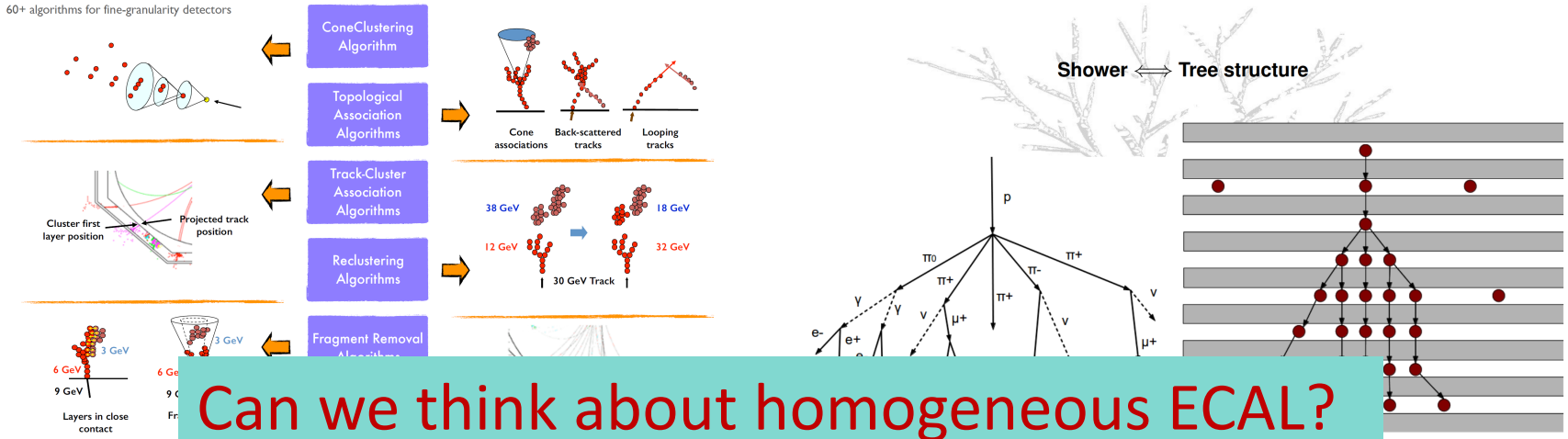


PFA-oriented Calorimetry

- Hardware: sampling calorimetry
  - ECAL: Si/Sci + W.
  - HCAL: Sci/RPC + W/Iron.
  - High granularity.
- Software: PFA reconstruction
  - PandoraPFA.
  - ArborPFA.





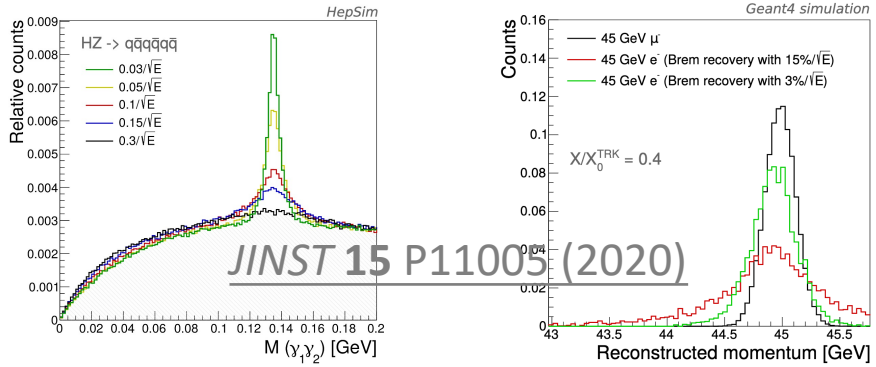


Can we think about homogeneous ECAL?

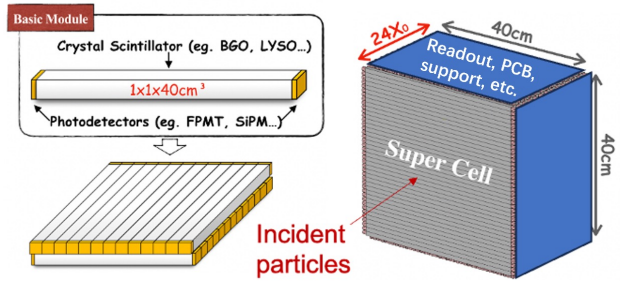
CEPC Homogeneous Crystal ECAL

- Homogeneous crystal ECAL for CEPC
  - Better EM resolution: $\sigma_E/E < 3\%/\sqrt{E}$
    - Photon recovery from bremsstrahlung.
    - π^0 reconstruction.
- A novel concept: orthogonal arranged crystal bars
  - Basic module:
    - BGO crystal bar.
    - Double-end readout with SiPM (Q, T).
    - Cross-location by bars: 2D measurements to get 3D high granularity.
  - Compared with high granularity sampling ECAL:
    - O(10) less readout channels.

Compatible with PFA?



JINST **15** P11005 (2020)



Parameter	BGO
R_M (cm)	2.23
X_0 (cm)	1.12
λ_I (cm)	22.7
Light yield (ph/MeV)	7400
Decay time (ns)	300

PFA Reconstruction Issues

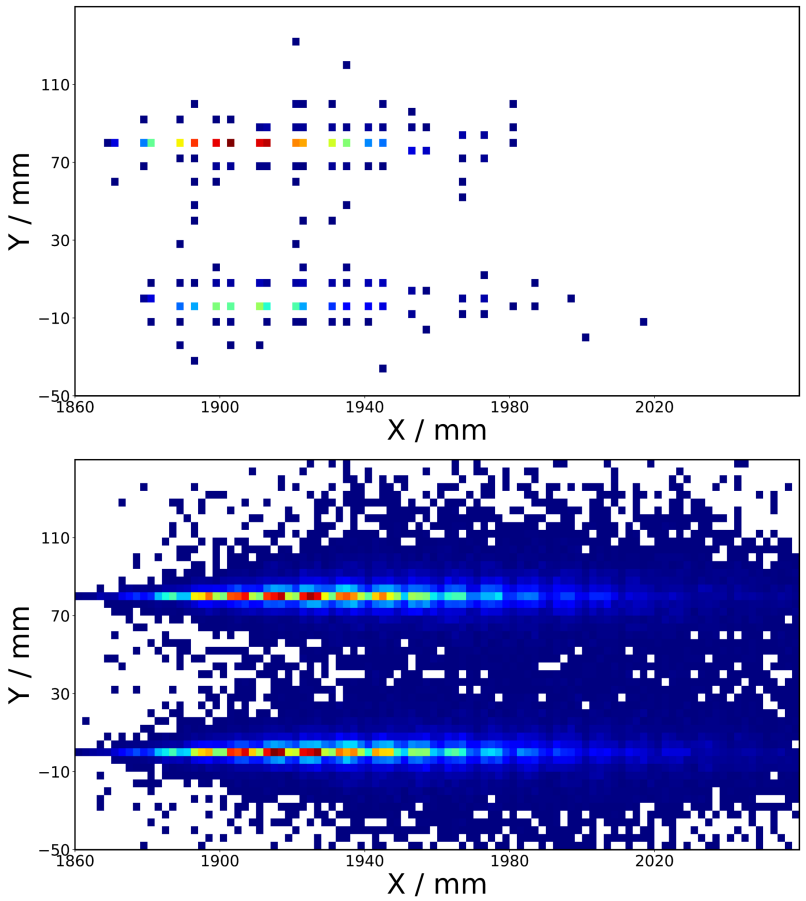
Hardware

- More shower overlap with larger crystal R_M and X_0/λ_I

Sampling SiW ECAL (with threshold)

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

Homogeneous BGO ECAL



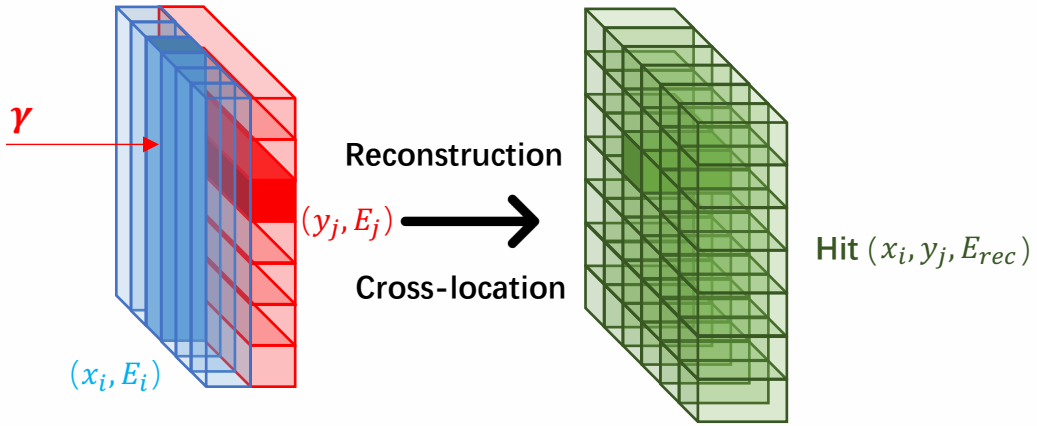
Software

- Clustering
- Pattern recognition
- + Energy splitting

PFA Reconstruction Issues

Hardware

- More shower overlap with larger crystal R_M and X_0/λ_I
- There are ghost hits (ambiguity) when getting cross location from 2D to 3D



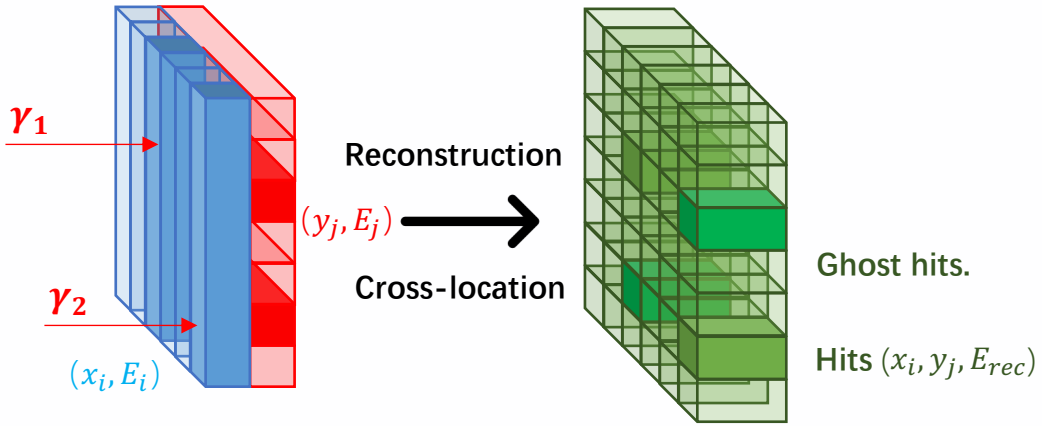
Software

- Clustering
- Pattern recognition
- + Energy splitting

PFA Reconstruction Issues

Hardware

- More shower overlap with larger crystal R_M and X_0/λ_I
- There are ghost hits (ambiguity) when getting cross location from 2D to 3D



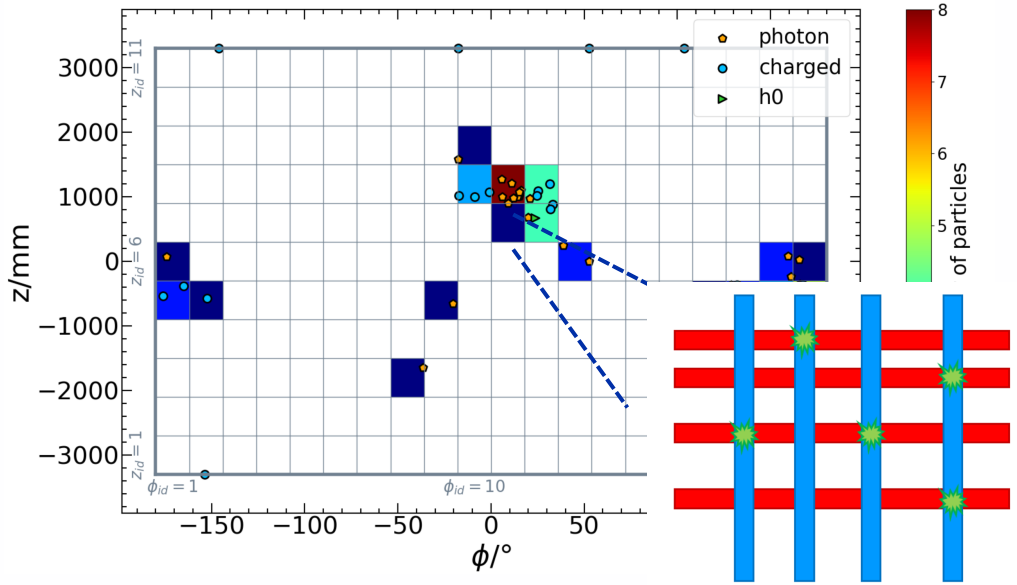
Software

- Clustering
- Pattern recognition
- + Energy splitting

PFA Reconstruction Issues

Hardware

- More shower overlap with larger crystal R_M and X_0/λ_I
- There are ghost hits (ambiguity) when getting cross location from 2D to 3D
- Multi-particle ambiguity in jet events



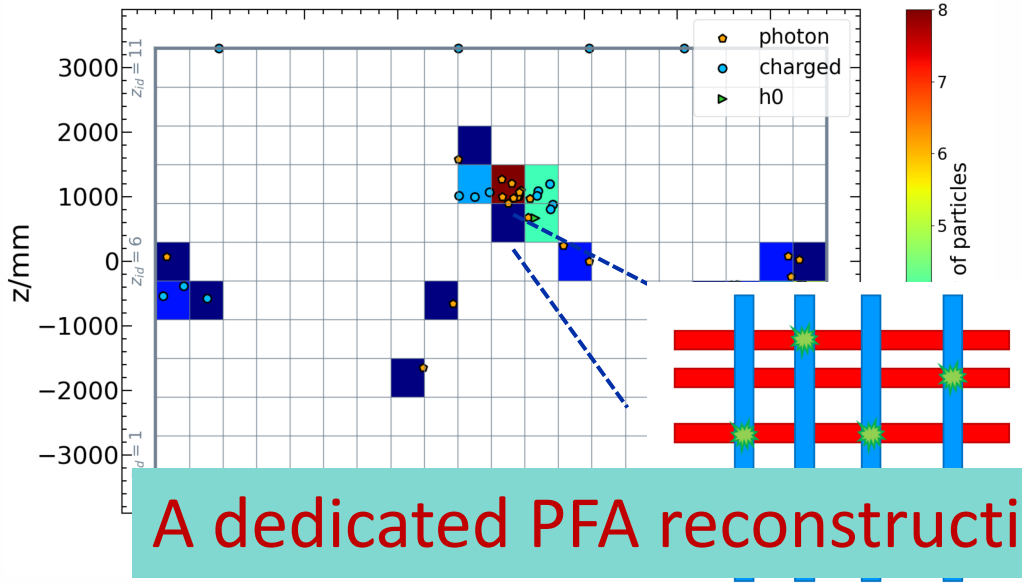
Software

- Clustering
- Pattern recognition
- + Energy splitting
- + Ambiguity removal

PFA Reconstruction Issues

Hardware

- More shower overlap with larger crystal R_M and X_0/λ_I
- There are ghost hits (ambiguity) when getting cross location from 2D to 3D
- Multi-particle ambiguity in jet events



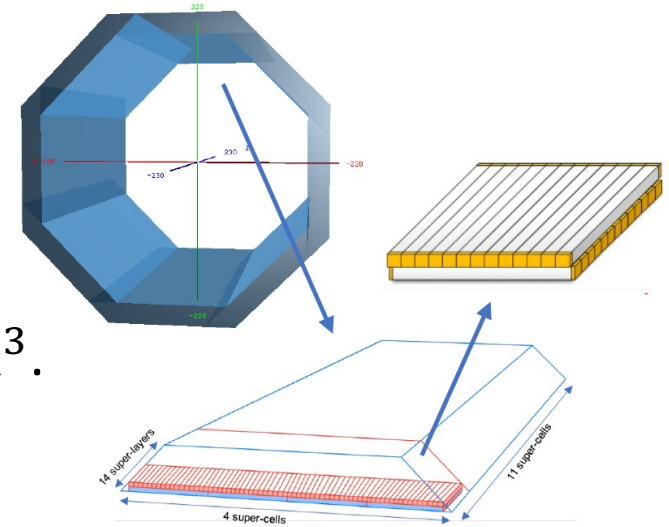
Software

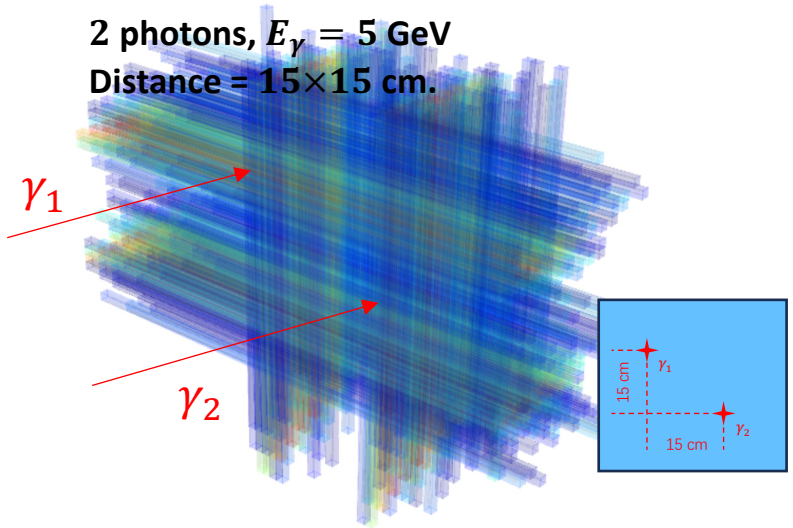
- Clustering
- Pattern recognition
- + Energy splitting
- + Ambiguity removal

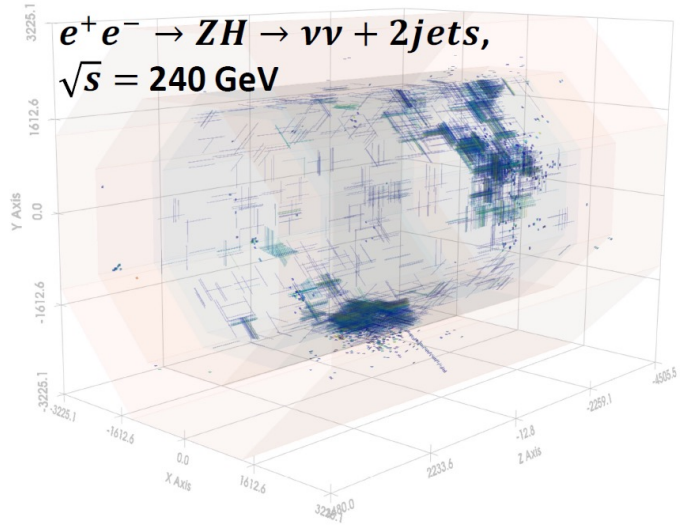
A dedicated PFA reconstruction is needed for crystal bar ECAL!

Simulation

- Detector geometry
  - Global: octagonal ECAL, $R = 1.86$ m, $L = 6.6$ m, $H = 28$ cm.
  - Crystal Bar(BGO): $1\times1\times40\sim60$ cm^3.
  - Super Cell: 2 layers of perpendicular crossing bars $\sim40\times\sim60\times2$ cm^3.
  - Ideal geometry: no wrapping, electronics, cooling, mechanics, etc.
- Ideal digitization for energy and time
- Event display

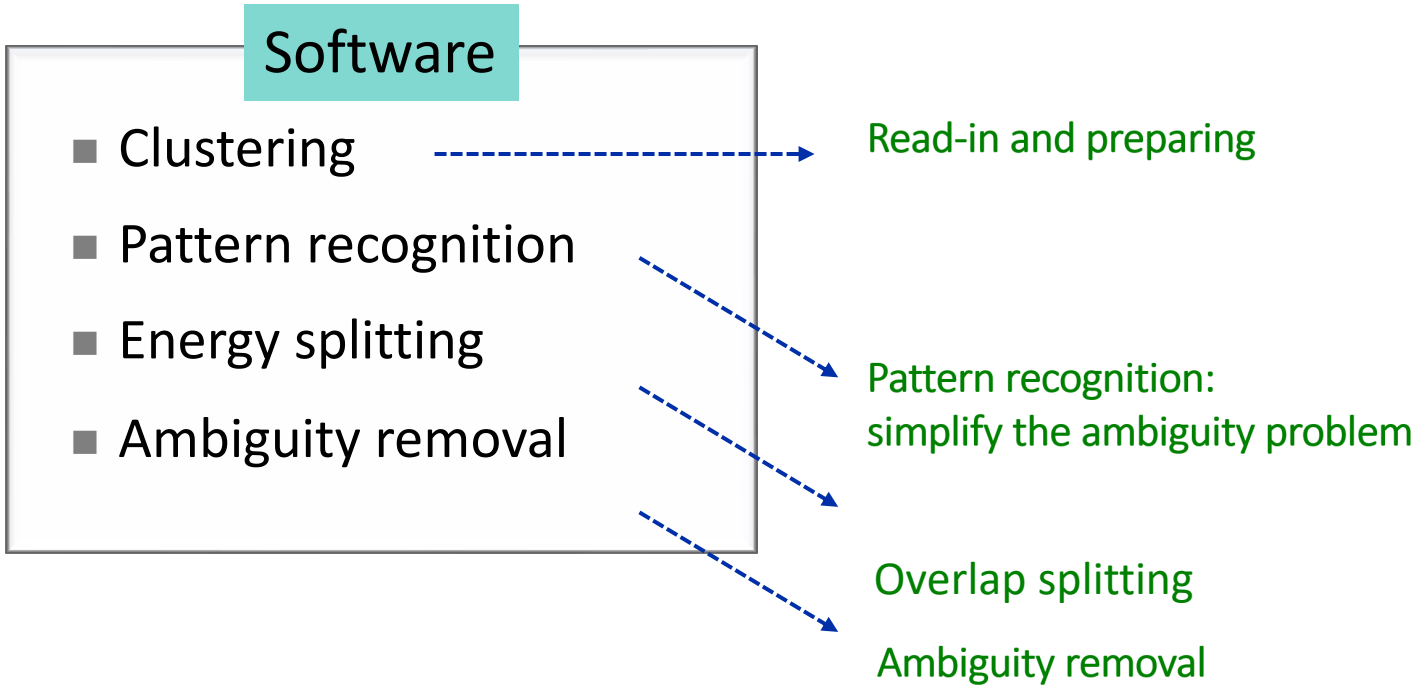


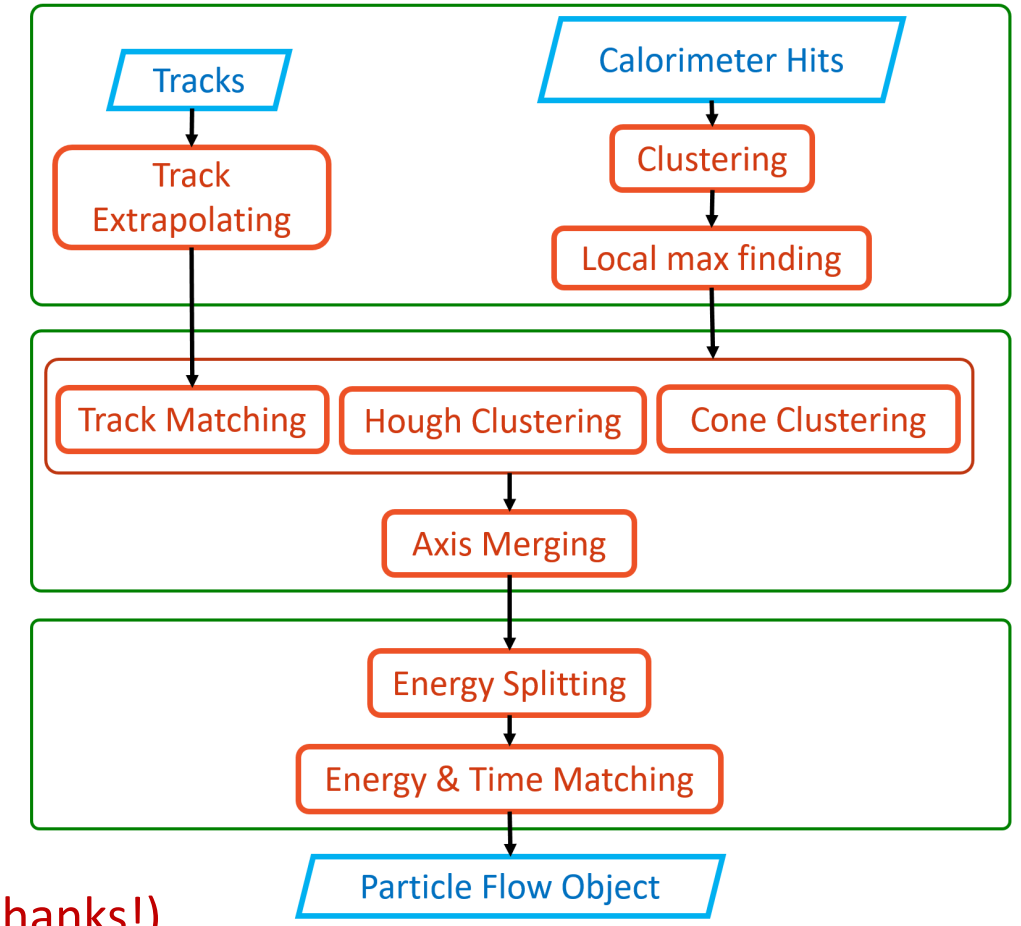




Reconstruction algorithm

- Dedicated PFA reconstruction for CEPC crystal bar ECAL



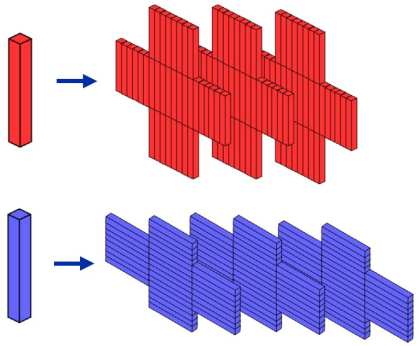


*Follow the idea of PandoraSDK: flexible, reusable, modular. (Many thanks!)

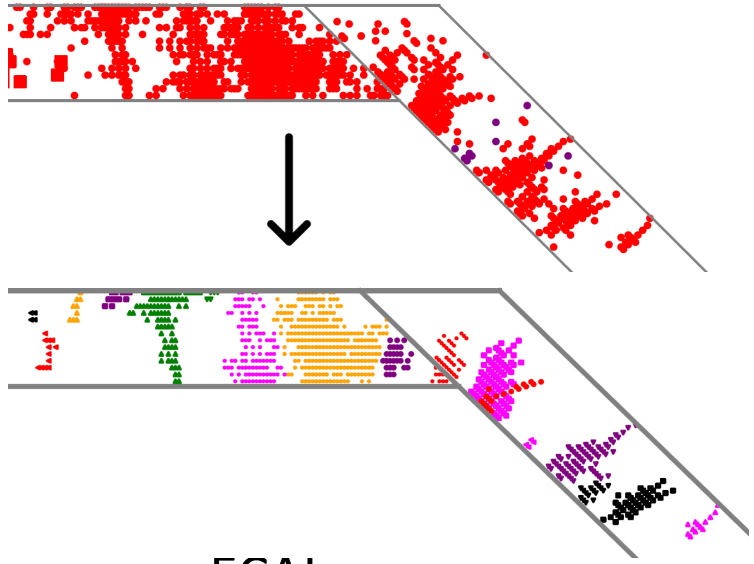
Clustering and recognition

- Global neighbor clustering for pre-processing

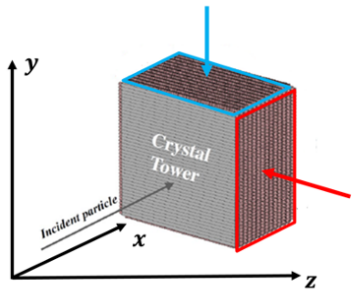
Crystal bars

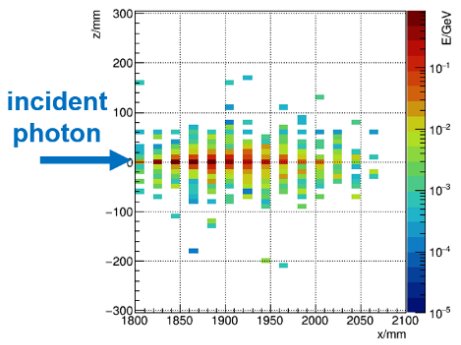


Cluster in 2 directions.

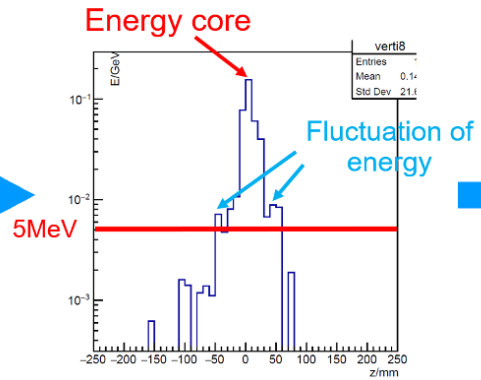


- Shower recognition
  - Use the local maximum to simplify the pattern in homogeneous ECAL

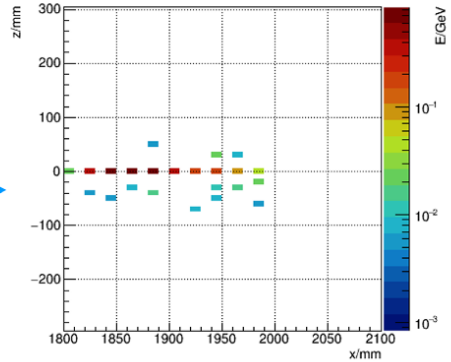




Energy deposits in crystals



Picking out local-max in each layer

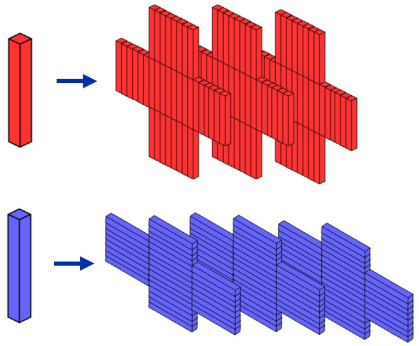


Local Maximum Distribution

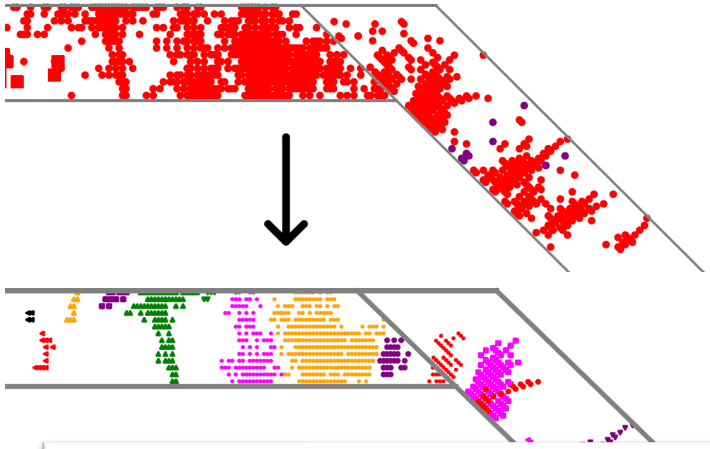
Clustering and recognition

- Global neighbor clustering for pre-processing

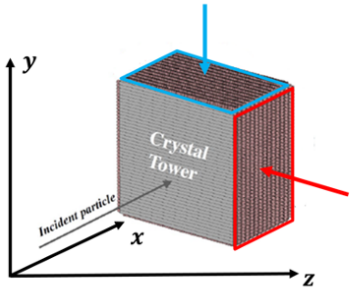
Crystal bars

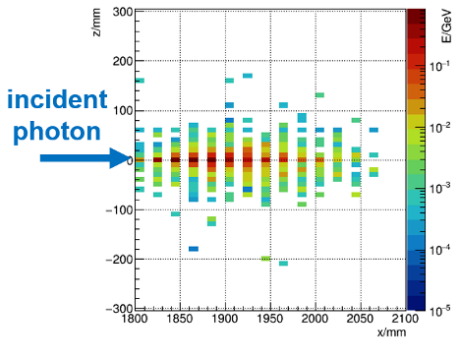


Cluster in 2 directions.

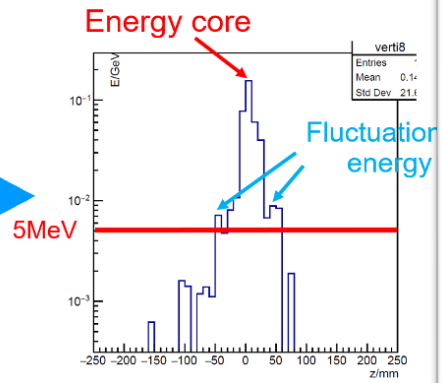


- Shower recognition
  - Use the local maximum to simplify the pattern in homoge

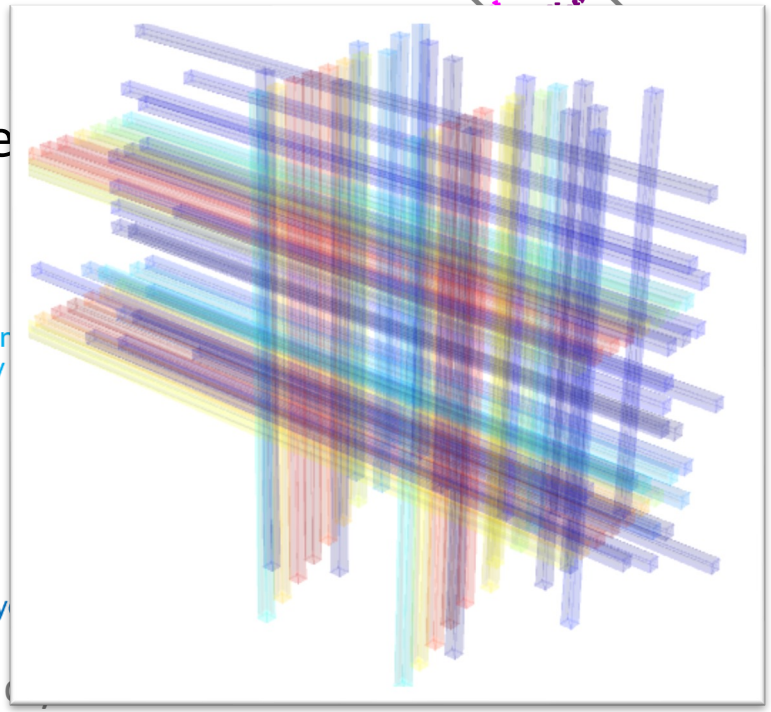




Energy deposits in crystals

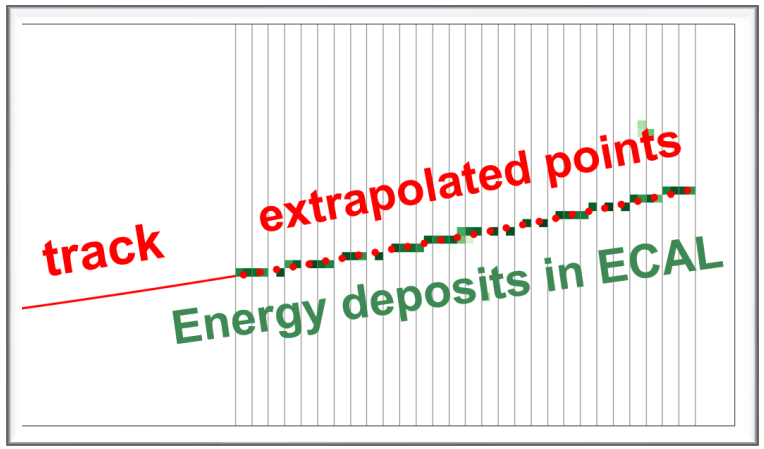


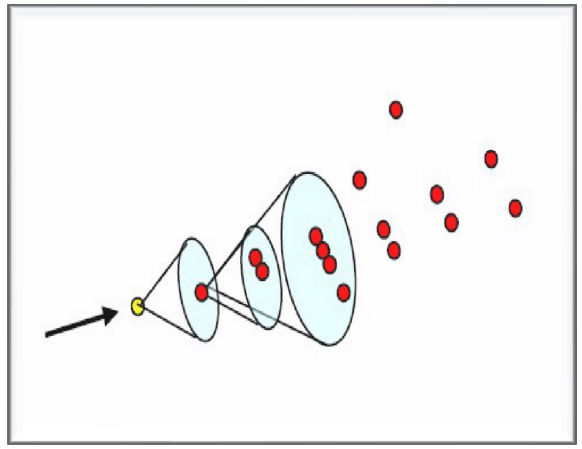
Picking out local-max in each lay

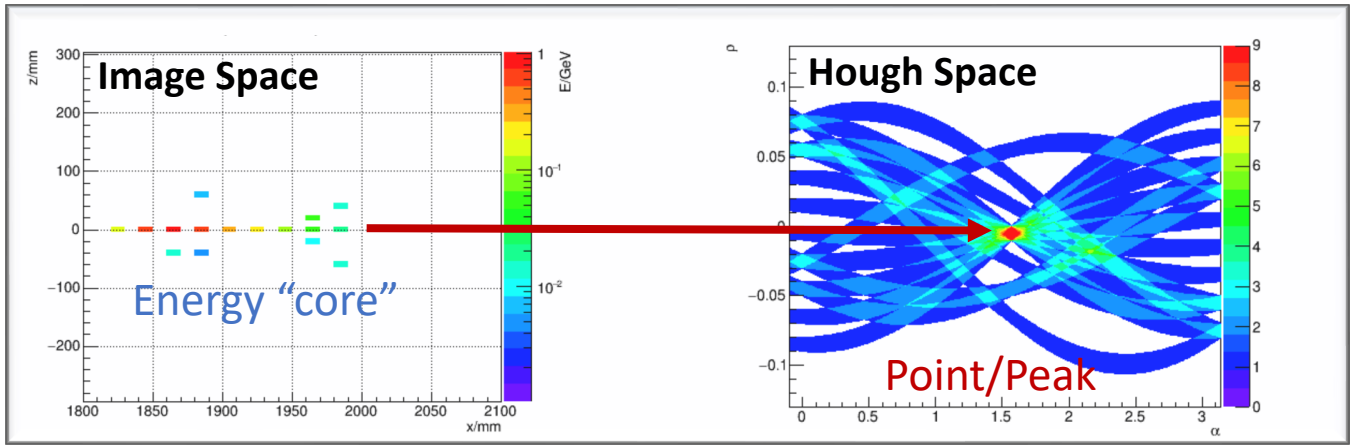


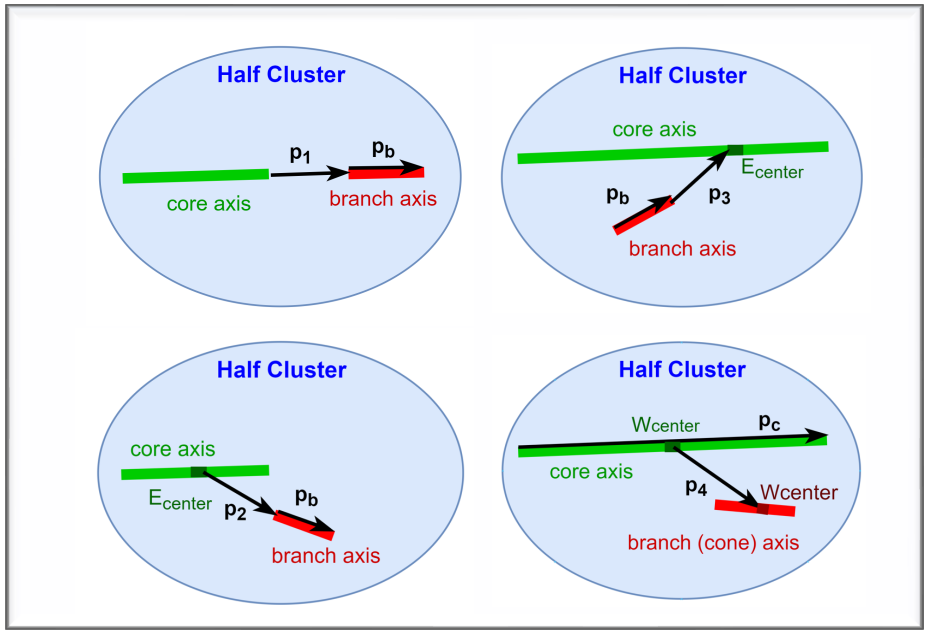
Clustering and recognition

- Shower recognition:
  - 3 individual algorithms for different types: track-match, Hough-transformation, Cone-clustering.
  - A set of topological cluster merging.



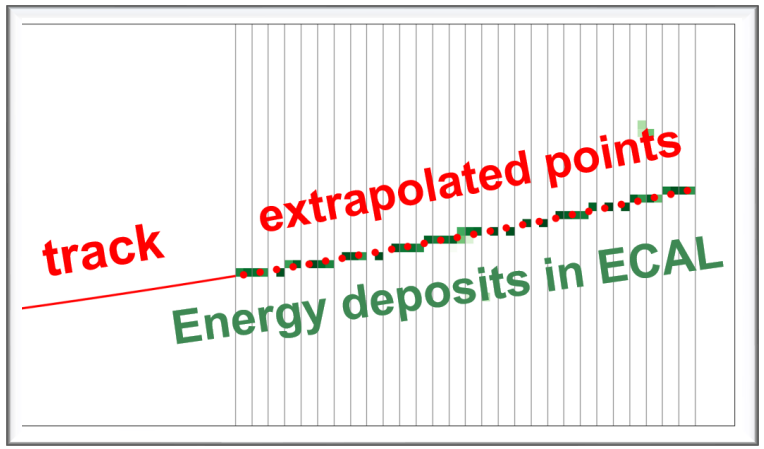


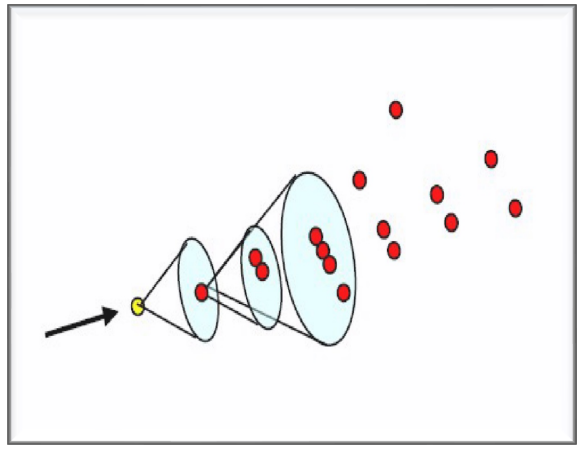


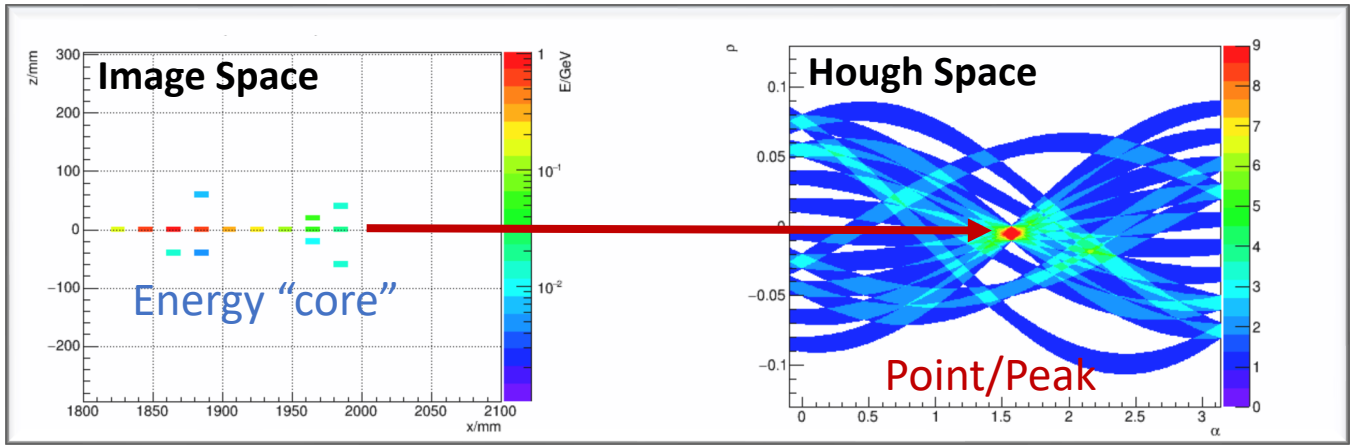


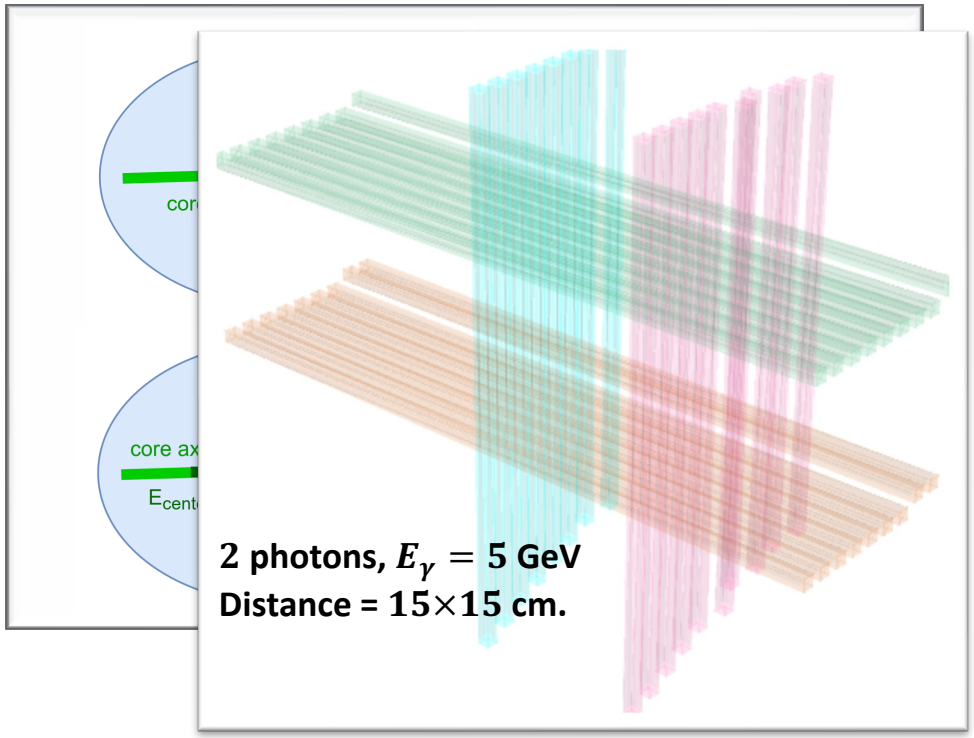
Clustering and recognition

- Shower recognition:
  - 3 individual algorithms for different types: track-match, Hough-transformation, Cone-clustering.
  - A set of topological cluster merging.







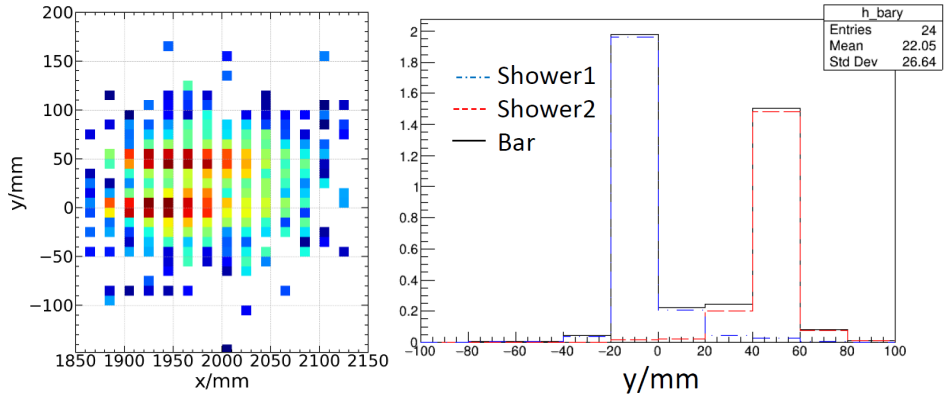


Energy splitting and matching

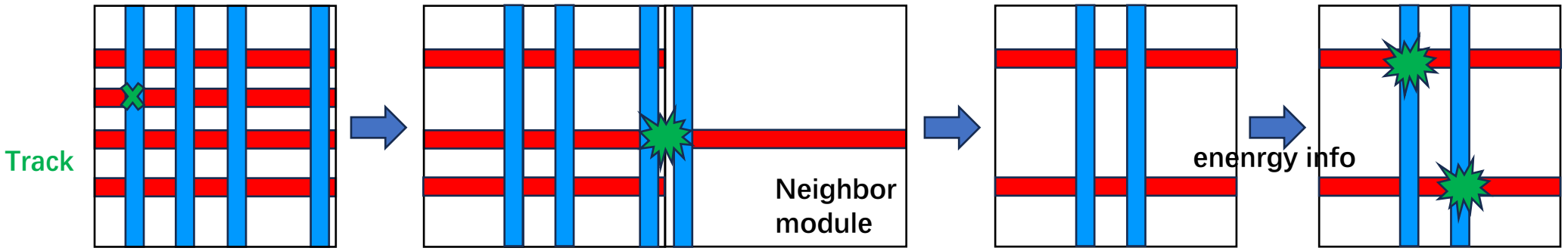
- Splitting for the overlapped shower:
  - Calculate the expected energy deposition from EM profile.

Expected energy : $E_{i\mu}^{exp} = E_{\mu}^{seed} \times f(|x_i - x_c|)$

Assigned weight: $w_{i\mu} = \frac{E_{i\mu}^{exp}}{\sum_{\mu} E_{i\mu}^{exp}}$



- Ambiguity removal:
  - Information from: track, neighbor tower, energy.



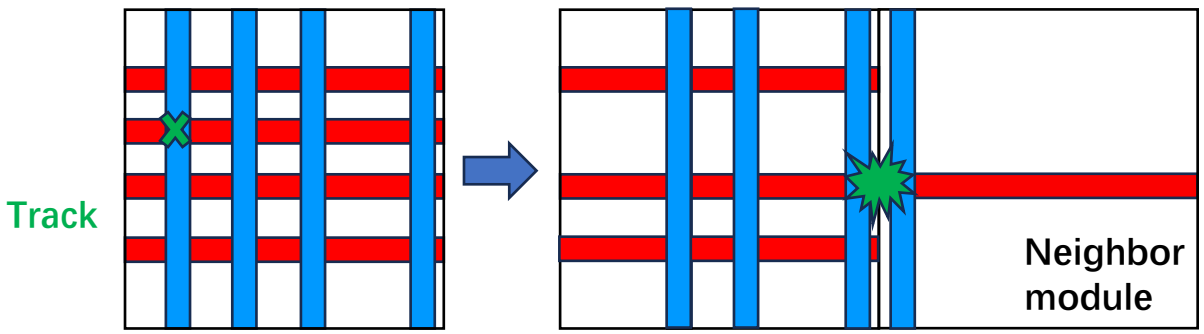
Energy splitting and matching

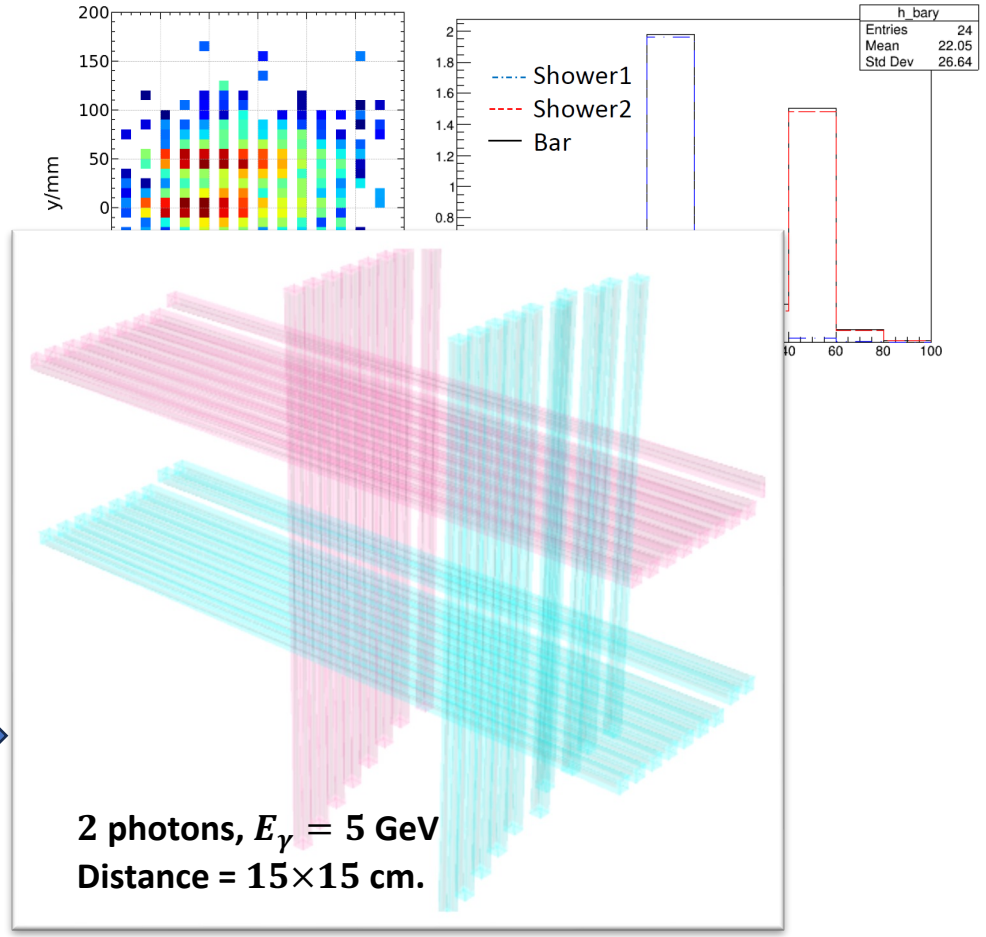
- Splitting for the overlapped shower:
  - Calculate the expected energy deposition from EM profile.

Expected energy : $E_{i\mu}^{exp} = E_{\mu}^{seed} \times f(|x_i - x_c|)$

Assigned weight: $w_{i\mu} = \frac{E_{i\mu}^{exp}}{\sum_{\mu} E_{i\mu}^{exp}}$

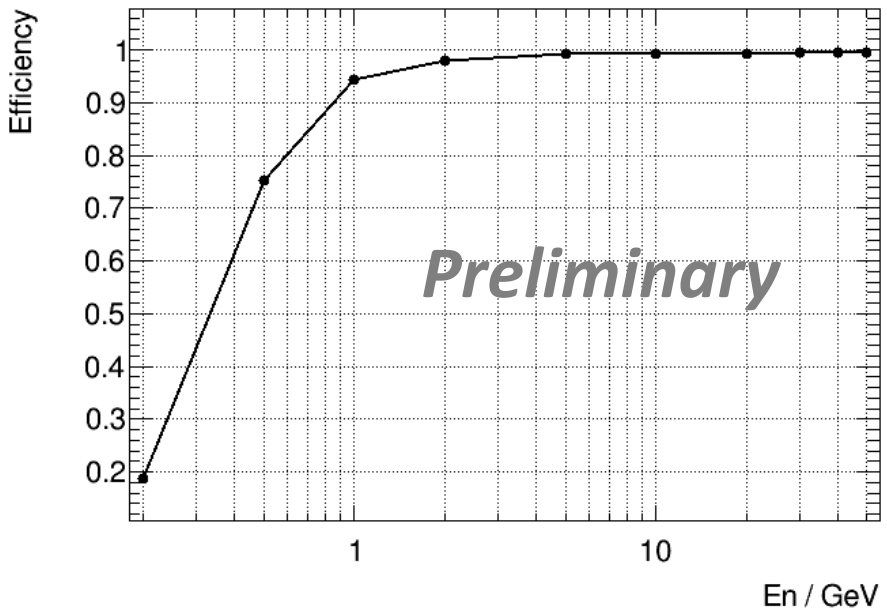
- Ambiguity removal:
  - Information from: track, neighbor tower, energy.

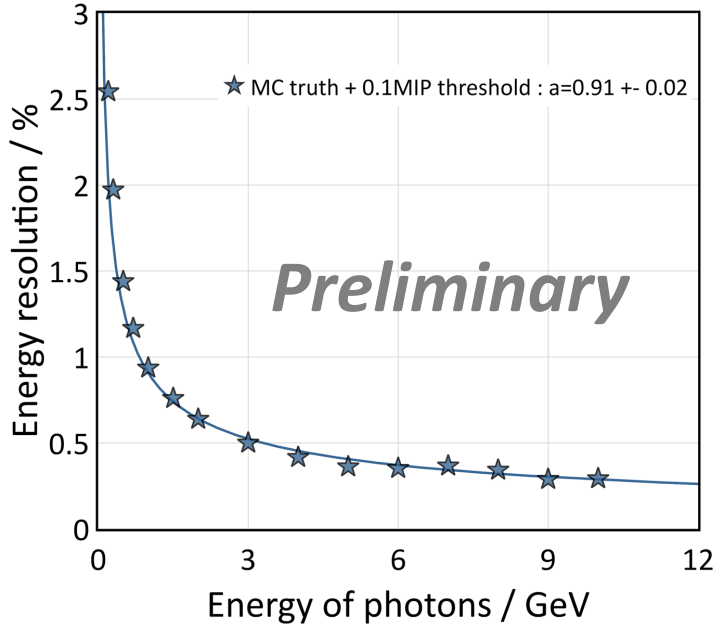




Performance

- Single photon reconstruction:
  - EM shower recognition efficiency: ~100% for >1 GeV photons.
  - Energy resolution: stochastic term = 0.91% +- 0.02%





*Without realistic digitization model.

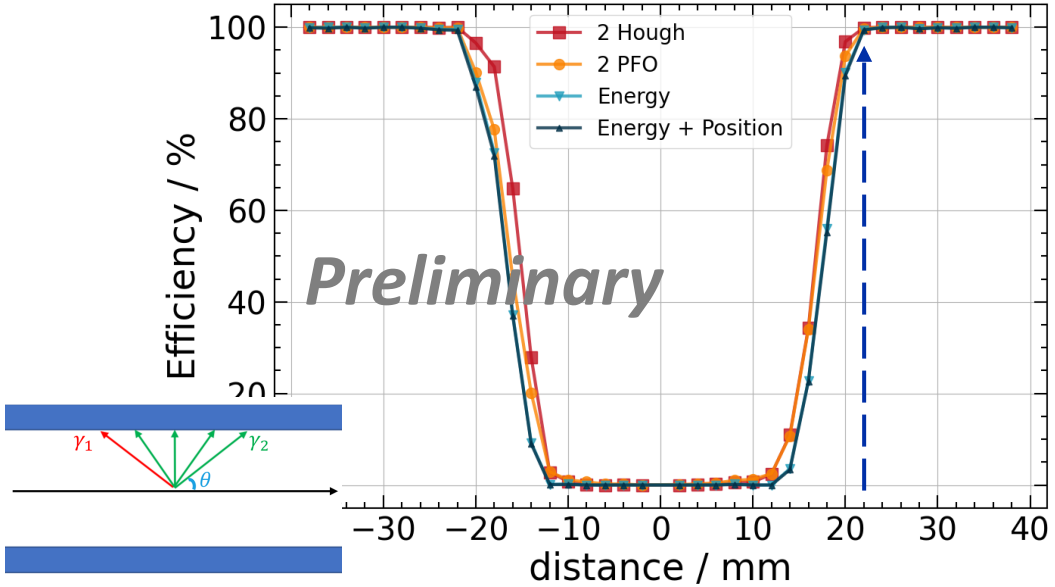
*Without wrapping, electronics, cooling, mechanics in geometry.

Performance

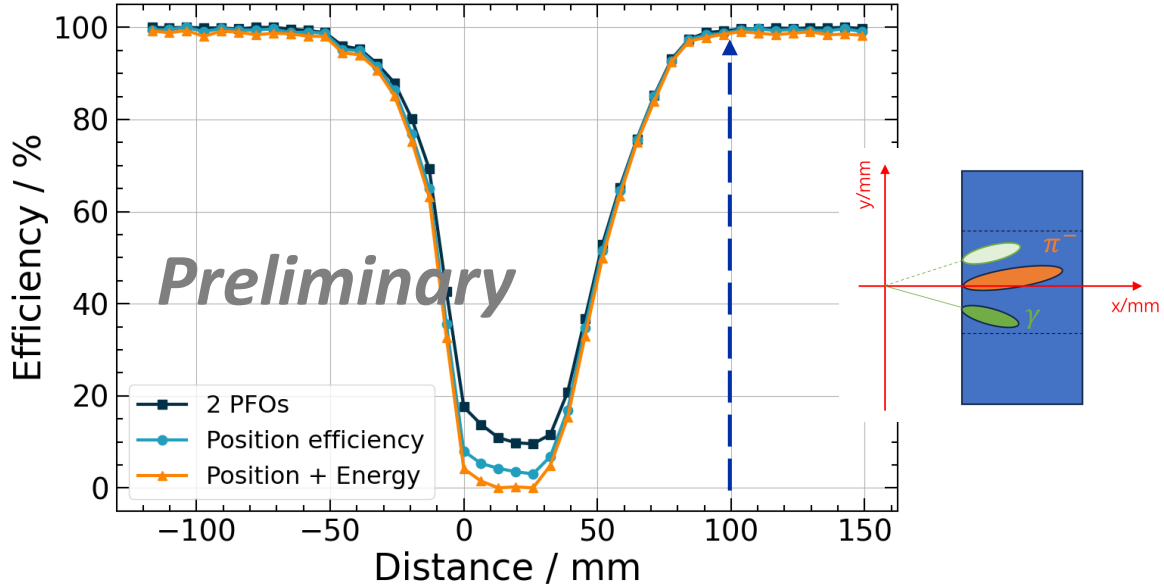
- Nearby particle separation:
  - Key performance in PFA reconstruction.
  - $\gamma - \gamma$ separation : ~20 mm @ 100% efficiency.
  - $\gamma - \pi$ separation : 50 ~ 100 mm @ 100% efficiency.

*Asymmetry is due to exist of magnetic field.

$\gamma - \gamma$ separation for 5 GeV photons

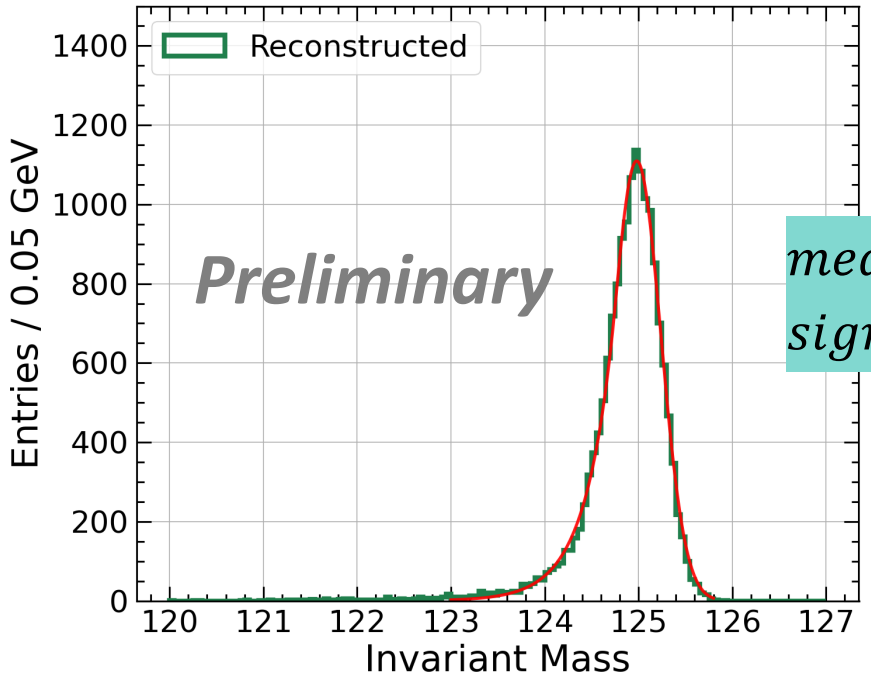


$\gamma - \pi$ separation for 5 GeV γ and π^-



Performance

- Physics performance: $H \rightarrow \gamma\gamma$
  - Pure channel for ECAL performance, a benchmark channel for physics.
  - An energy correction for longitudinal leakage is applied.



$mean = 124.9814 \pm 0.0028\ GeV/c^2$

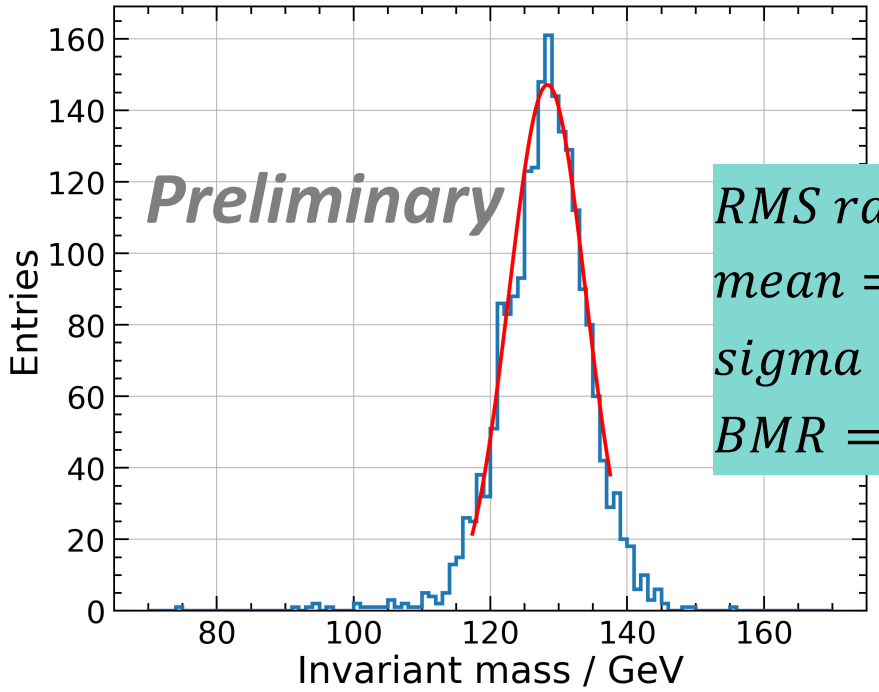
$sigma = 0.2570 \pm 0.0031\ GeV/c^2$

*No lateral leakage without considering cracks between modules.

*Ideal detector geometry and digitization

Performance

- Physics performance: $e^+e^- \rightarrow ZH \rightarrow \nu\nu gg$
  - Boson mass resolution (BMR) of di-jet event is essential for CEPC detector.
  - $m_{Higgs} = \sqrt{\left(p_{mc\ charged\ particles} + p_{reconsrtucted\ neutral\ PFO}\right)^2}$



$RMS\ range$: $117.37 \sim 137.53\ GeV/c^2$

$mean = 128.33 \pm 0.16\ GeV/c^2$

$sigma = 5.59 \pm 0.17\ GeV/c^2$

$BMR = 4.36 \pm 0.13\ \%$

*Reconstructed neutral PFO includes ECAL and HCAL, ECAL clusters are obtained by PFA reconstruction above, HCAL(steel – scintillator HCAL) clusters are based on track-matching and re-clustering.

Ongoing and Next Step

- Next step: a full PFA with
  - Optimized 32-side ECAL geometry with fine geometry and material description.
  - Realistic digitization model.
  - Energy correction for the cracks between modules.
  - Full simulation and reconstruction of tracker.
  - For better understanding: decouple the contributions in current BMR / JER.

Summary

- A novel crystal ECAL design for CEPC reference detector
  - Optimal EM resolution, excellent low energy sensitivity, lower cost.
  - R&D progresses in hardware are introduced in Baohua's talk.
- A dedicated PFA reconstruction for crystal bar ECAL
  - Main challenges are the shower overlapping and ambiguity.
  - Promising separation power and a preliminary BMR are derived.
- Feasibility analysis of crystal bar ECAL is very promising
  - Will broaden detector options and reconstruction methods for future electron-positron collider experiments.

Thank you!