CyberPFA: CrYstal Bar ECAL Reconstruction in CEPC

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26 Oct. 2024

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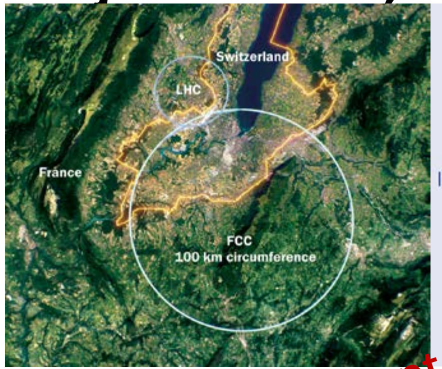
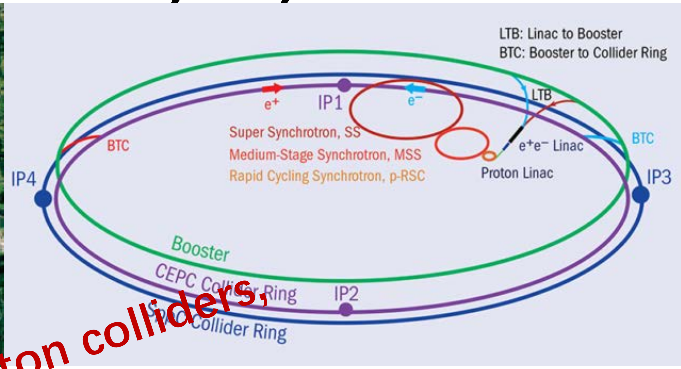
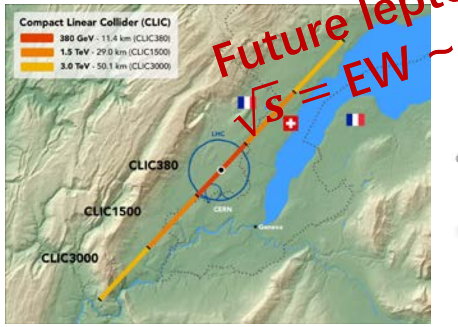
Future lepton collider

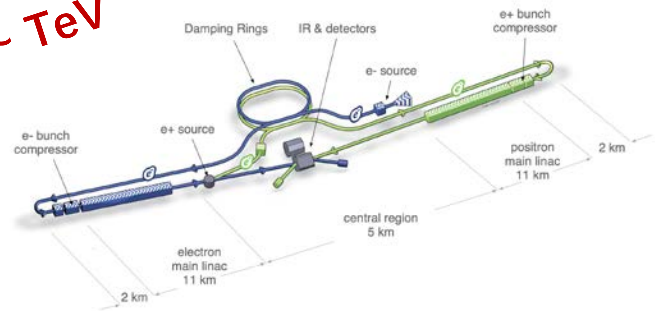
- **Physics after Higgs discovery:**
  - Precise measurement of Higgs, EW, top, flavor, QCD…
  - BSM physics (dark matter, EW phase transition, SUSY, LLP…)

- **Projects: CEPC, FCC-ee, ILC, CLIC.**

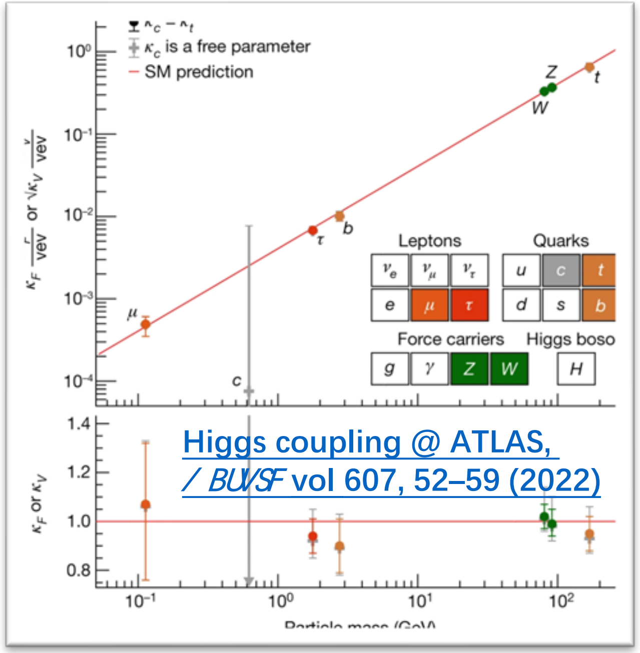




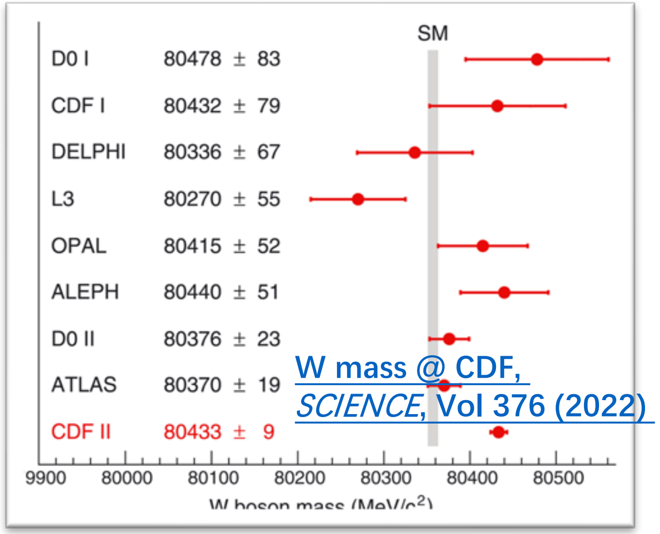




Future lepton colliders,
$\sqrt{s}$ = EW ~ TeV



Higgs coupling @ ATLAS, *NATURE* vol 607, 52–59 (2022)

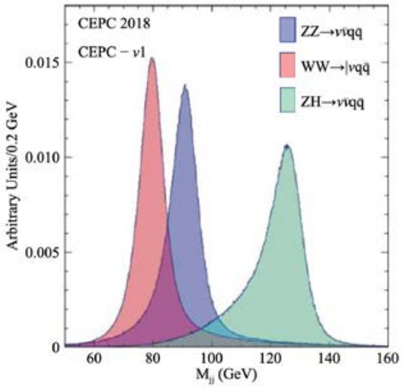


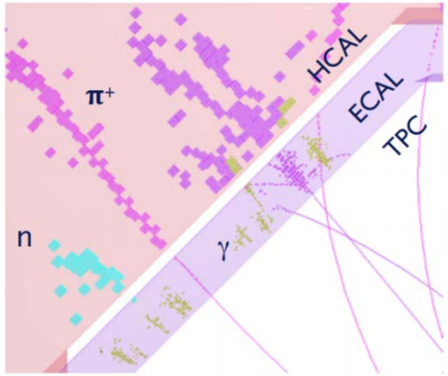
W mass @ CDF, *SCIENCE*, Vol 376 (2022)

Future lepton collider

- **Detector requirement:**
  - For hadronic final states $W^{\pm}/Z/H \to q\bar{q}$: BMR<4%
  - For flavor: precise PID in heavy quark decay

    K/π separation, jet tagging, jet charge, etc.

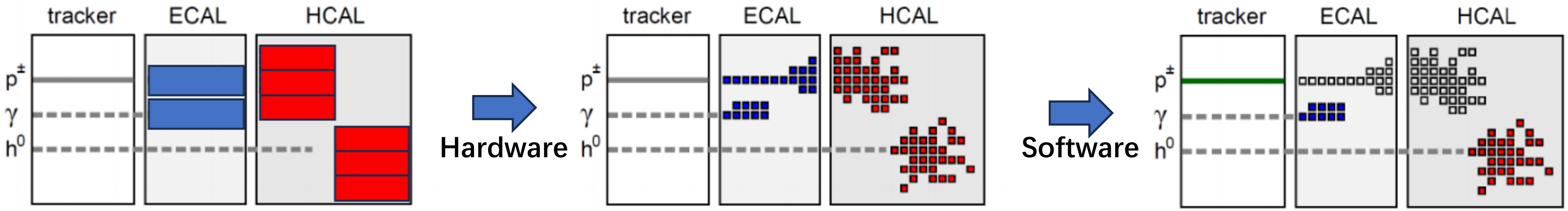




- **Particle Flow Approach:**
  - Measure the jet by its components: $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$
  - Hardware + Software:

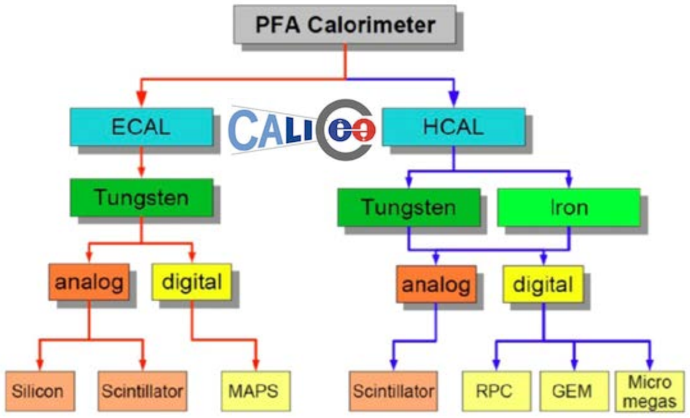
Hardware: separate clusters from different particles.
- High granularity.
- Compact sampling structure.

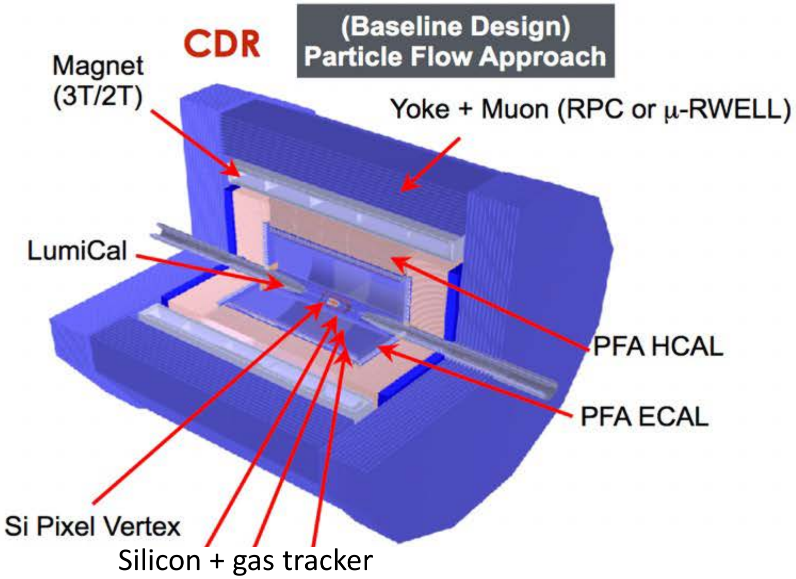
Software: correctly assign calorimeter energy deposits to the particles.
- Clustering
- Pattern recognition.

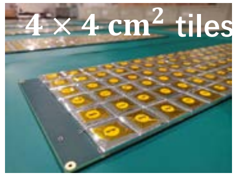


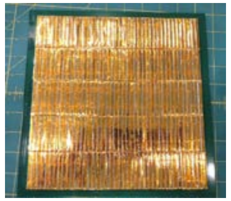
Calorimetry in CALICE

- **CALICE concept: high granularity sampling calorimeter**
  - **Hardware**: sampling and compact calorimeter.
  - **Software**: fantastic pattern recognition, PandoraPFA / ArborPFA.
- **Also is CEPC CDR design: enormous efforts from team**
  - **ECAL prototype**: scintillator strip + SiPM + CuW (ScW)
  - **HCAL prototype**: scintillator tile + SiPM + steel (AHCAL)
  - From 2016 to now: Technical R&D, prototype development, beam test activities…

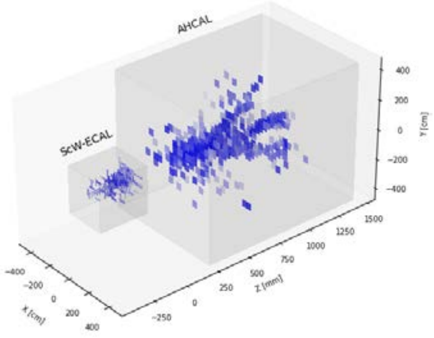








$5 \times 45\ \mathrm{mm}^2$ strips

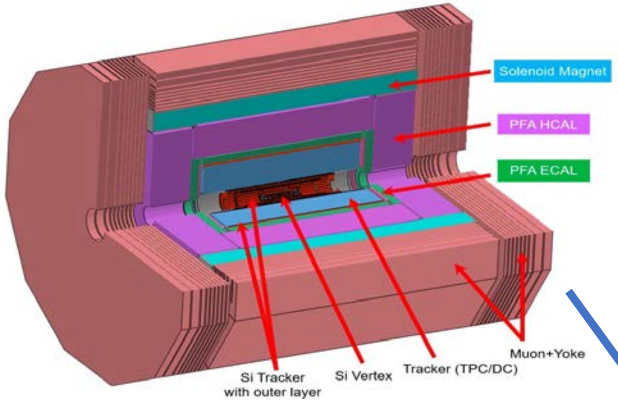


Homogeneous ECAL in CEPC Ref-TDR

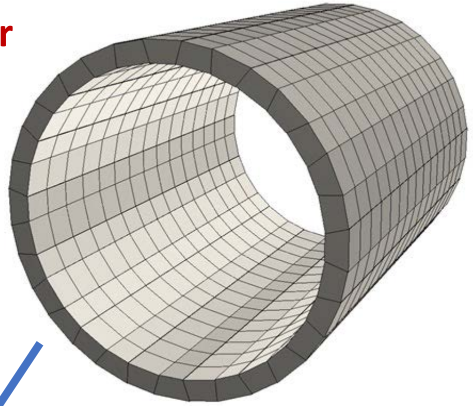
- **Why crystal calorimeter**
  - A long history in particle physics precise measurement:
    L3@LEP, BESIII@BEPC, CMS@LHC, HERD, Panda…
  - Optimal intrinsic EM resolution: $\sigma_E/E < 3\%/\sqrt{E}$
    - Photon recovery from bremsstrahlung,
    - π^0 reconstruction.
  - Fast response:
    - Introduce timing in PFA.

	CsI	BGO	$PbWO_4$	LYSO
R_M (cm)	3.57	2.23	2.00	2.07
X_0 (cm)	1.86	1.12	0.89	1.14
λ_I (cm)	39.3	22.7	20.7	20.9
Light yield (ph/MeV)	58000	7400	130	30000
Decay time (ns)	1220	300	30	40

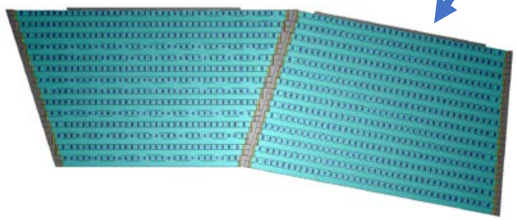
  - BGO for a balance performance & cost.



Reference detector



Barrel ECAL

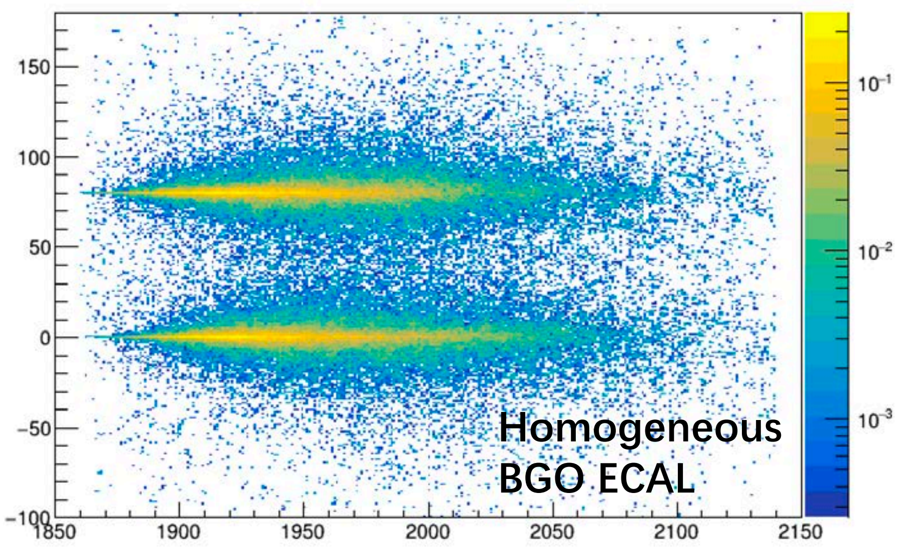


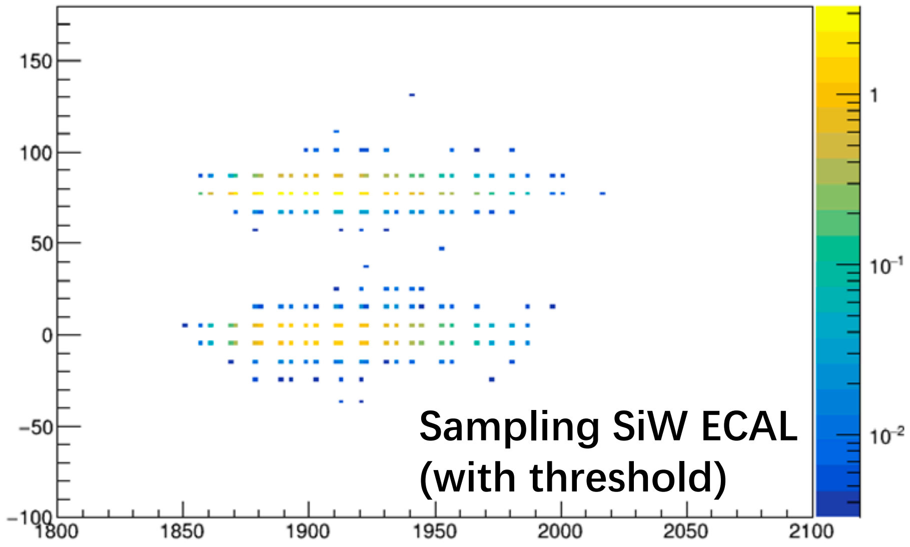
Invert trapezoid module

Homogeneous ECAL

- **New concept of crystal ECAL:**
  - Advantage:
    - Optimal energy resolution.
    - Better EM sensitivity for flavor physics.
  - But at what cost:
    - Larger R_M & smaller λ_I/X_0 ⇨ more shower overlap.
    - Not self-supporting ⇨ Need supporting mechanics (dead material).

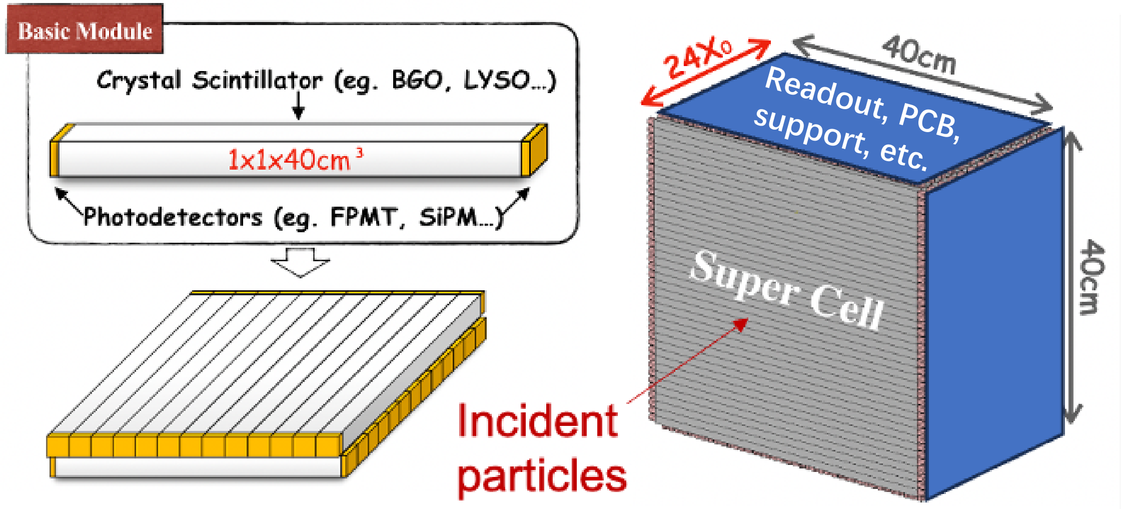
Software task:
* Clustering
* Pattern recognition.
+ Overlap: energy splitting.

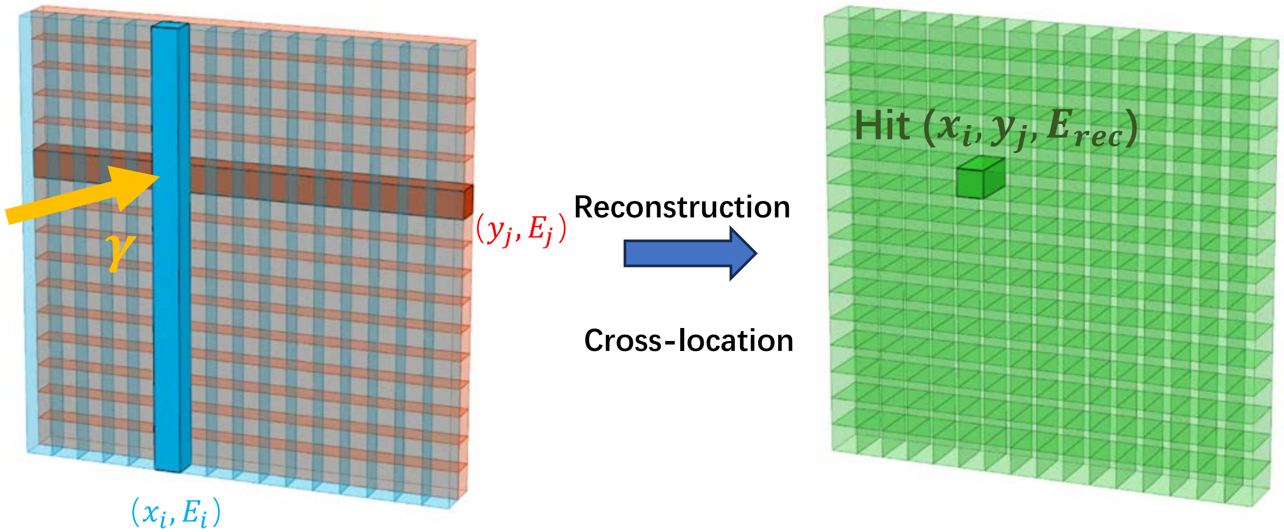




Homogeneous ECAL

- **New concept of crystal ECAL: orthogonal arranged crystal bars.**
  - Double-end readout with SiPM (Q, T).
  - Cross-location by bars.
  - Less readout channels, lower cost.





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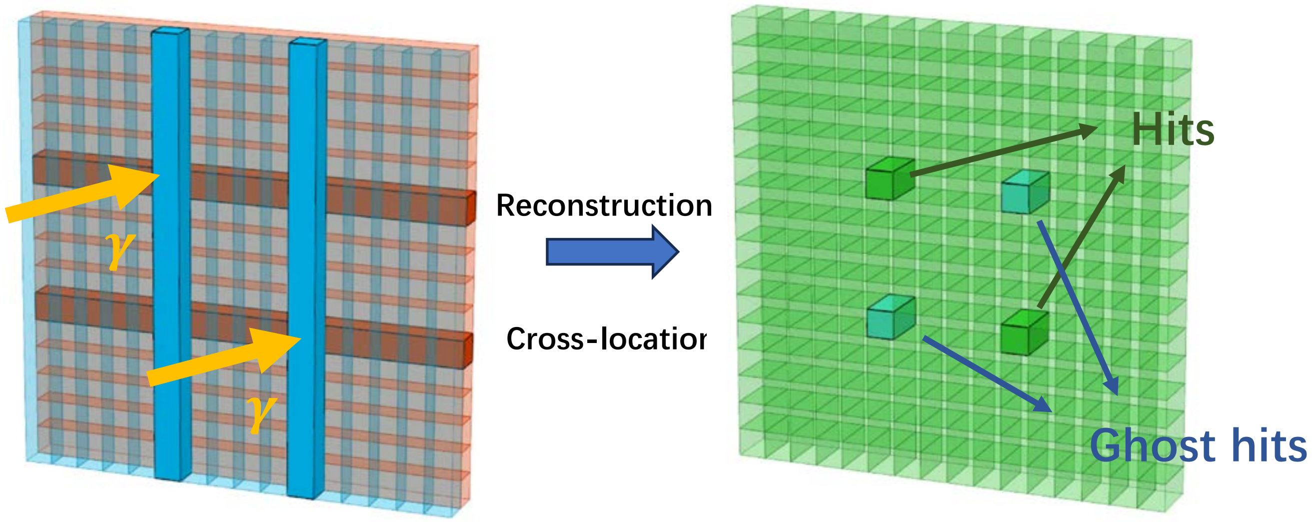
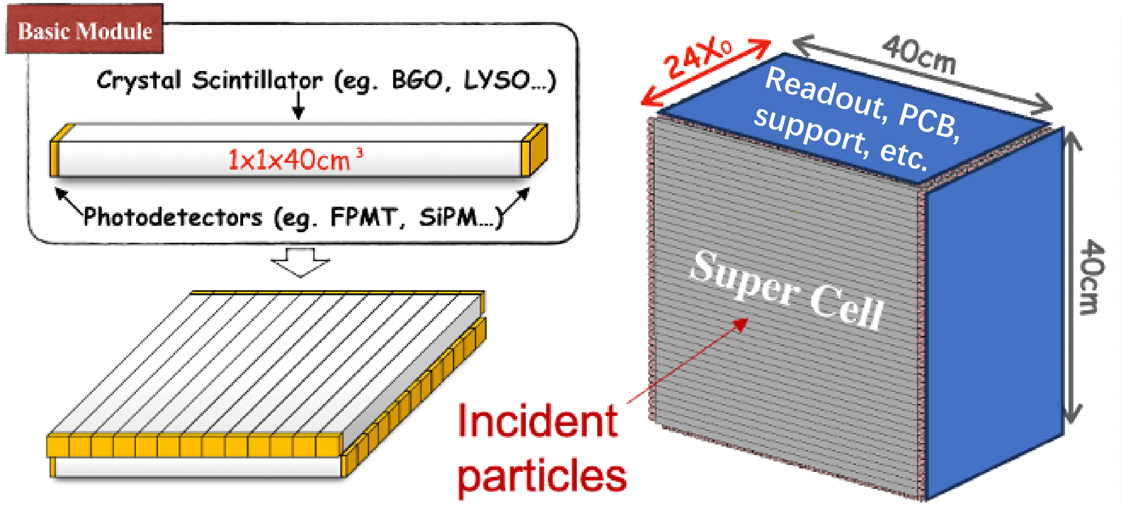
    New challenge: multi-particle ambiguity.





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- + Ambiguity removal

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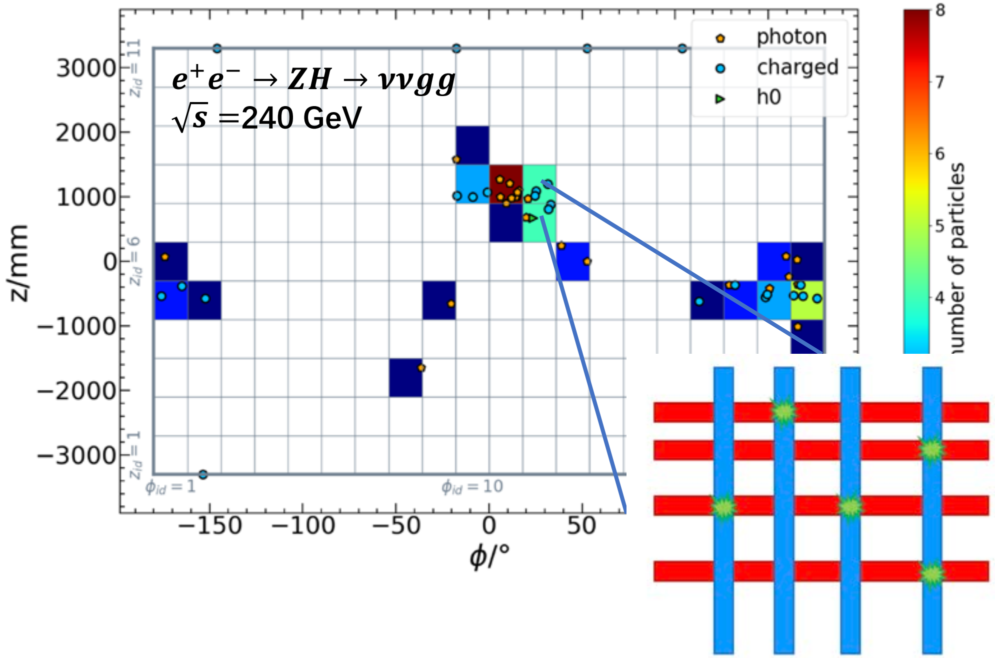

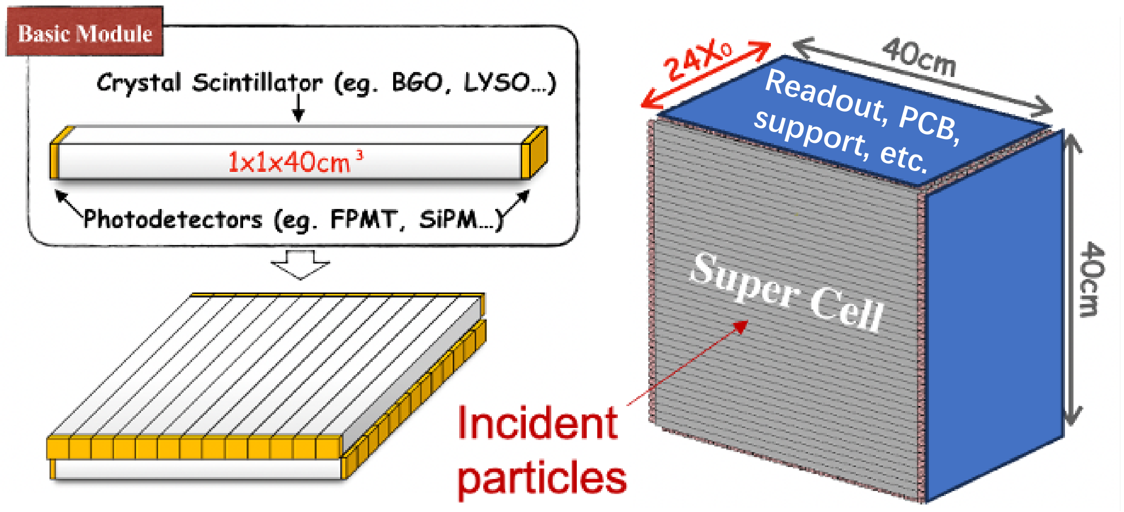

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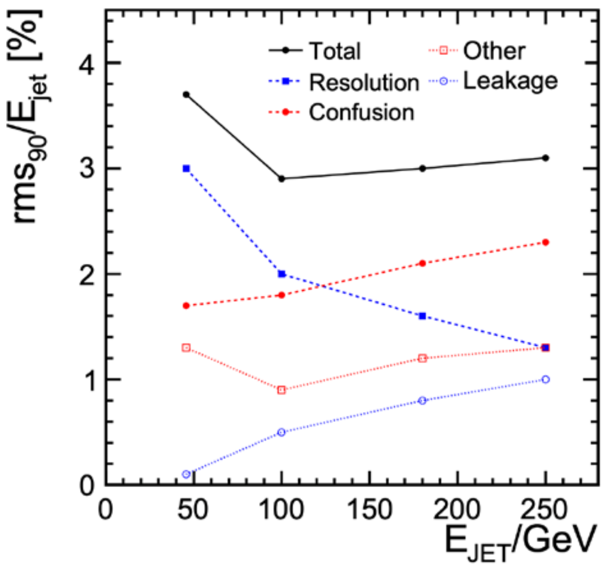
Particle flow algorithm

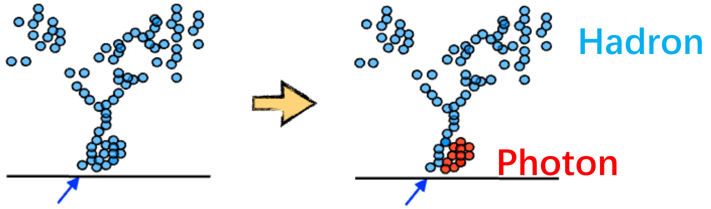
- **PF performance decoupling**
  - $\sigma_{jet} \sim \sigma_{trk} \oplus \sigma_{EM} \oplus \sigma_{Had} \oplus \sigma_{confusion}$. **Confusion is an important limitation factor.**

Contribution	Jet Energy Resolution $rms_{90}(E_j)/E_j$			
	E_j=45 GeV	E_j=100 GeV	E_j=180 GeV	E_j=250 GeV
Total	3.7 %	2.9 %	3.0 %	3.1 %
Resolution	3.0 %	2.0 %	1.6 %	1.3 %
Tracking	1.2 %	0.7 %	0.8 %	0.8 %
Leakage	0.1 %	0.5 %	0.8 %	1.0 %
Other	0.6 %	0.5 %	0.9 %	1.0 %
Confusion	1.7 %	1.8 %	2.1 %	2.3 %
i) Confusion (photons)	0.8 %	1.0 %	1.1 %	1.3 %
ii) Confusion (neutral hadrons)	0.9 %	1.3 %	1.7 %	1.8 %
iii) Confusion (charged hadrons)	1.2 %	0.7 %	0.5 %	0.2 %



PandoraPFA, Nim.A Vol 611, Issue 1, 2009

- Confusion mainly comes from the imperfect pattern recognition.



e.g. Perfect photon reconstruction

Particle flow algorithm

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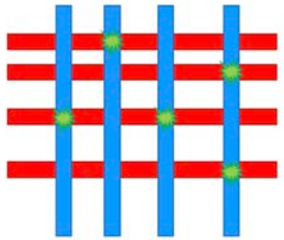
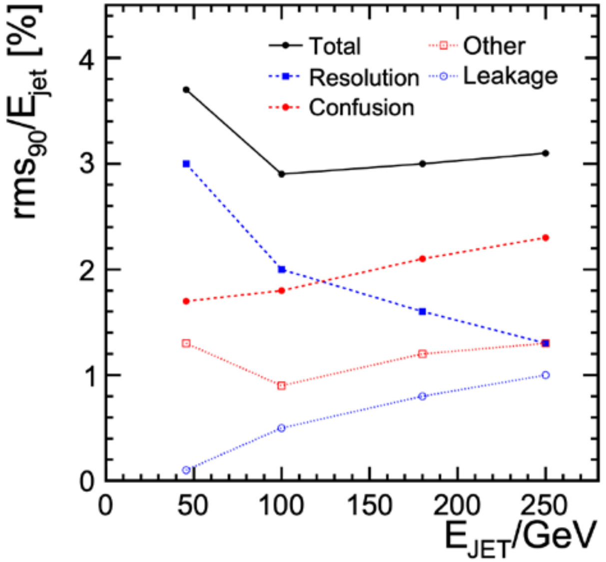
Crystal ECAL improves the intrinsic resolution

iv) Confusion (ambiguity)





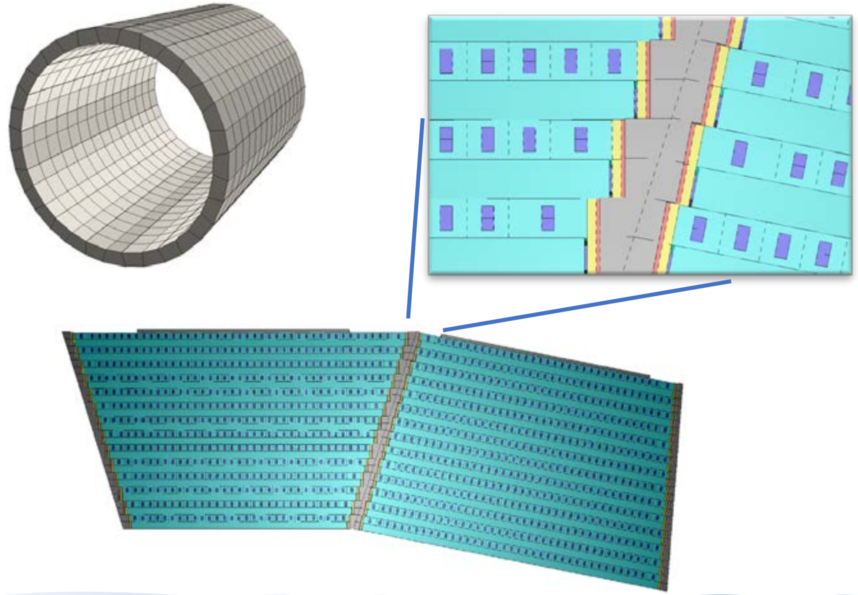
PandoraPFA, Nim.A Vol 611, Issue 1, 2009

Software task:
- * Clustering
- * Pattern recognition.
  - + Improve the performance.
- * Overlap: energy splitting.
- * Ambiguity problem.
  - + Minimize the impact.

CyberPFA was proposed to address these issues.

Detector Simulation

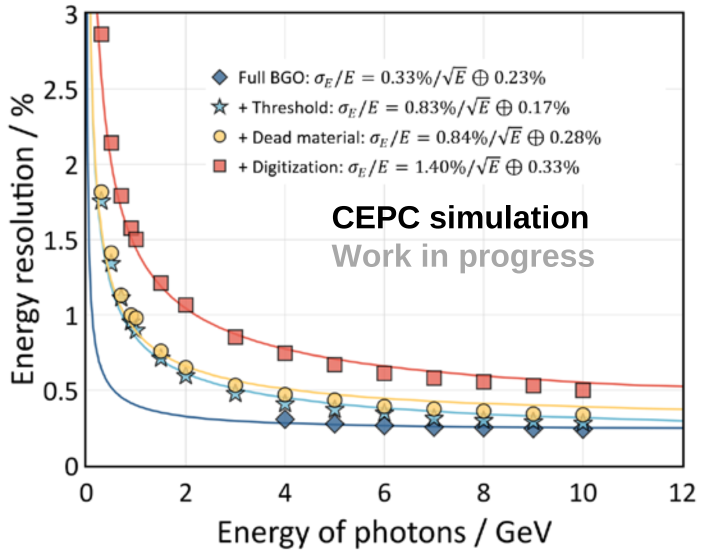
A realistic detector description implemented in CEPCSW with DD4HEP
- Inner R = 1830 mm, depth 300 mm (24 X_0), 28 layers.
- $1 \times 1 \times \sim 40\ cm^3$ BGO bars with ESR wrapping
- 32-side polygon, invert trapezoid modules.
- Dead material between modules:
  - SiPM, PCB, FE and BE electronic boards (~3 mm)
  - Copper plate cooling (1 mm)
  - Carbon fiber supporting (5 mm/side)
- An energy correction for the crack leakage.



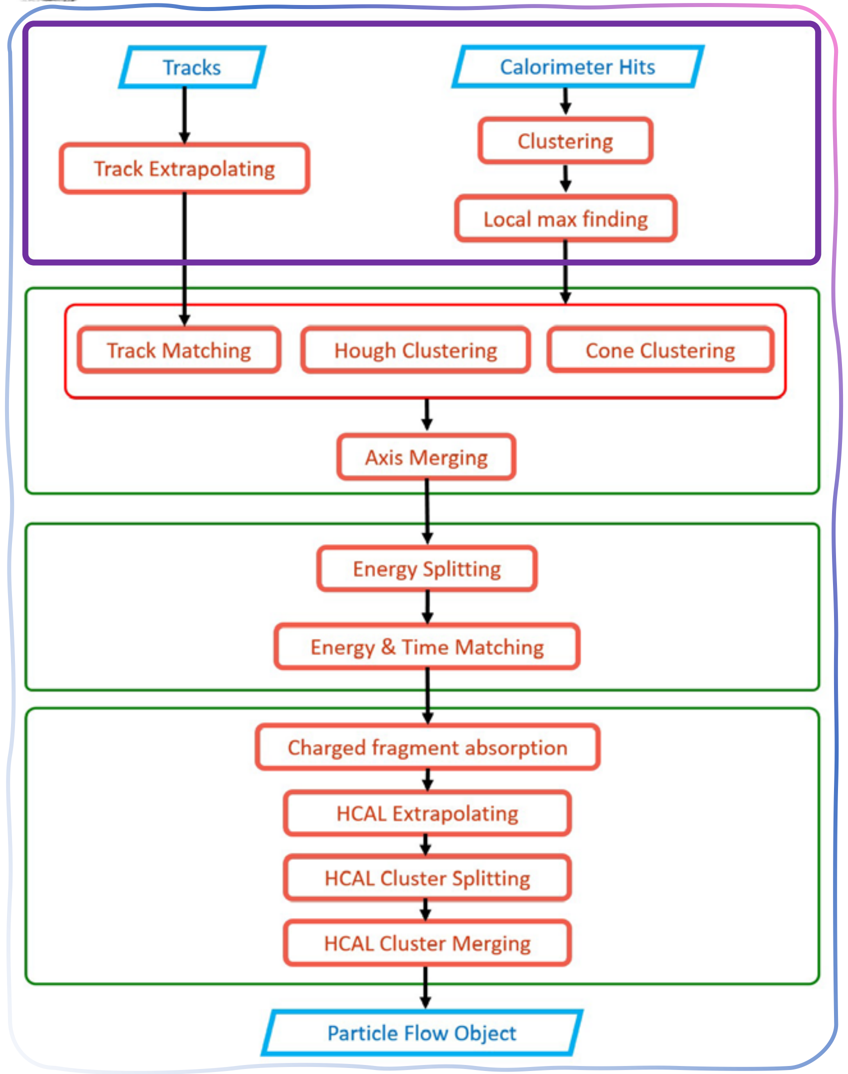
Digitization model: from beam test
- Crystal scintillation: 100 p.e./MIP (single end detected)
- SiPM gain calibration: 1 p.e. = 5 ADC, with noise
- Electronics: 12 bits ADC with precision 0.2%, 3 gain modes
- Threshold: 0.1 MIP.

Energy resolution with full digi: $\sigma_E/E = 1.4\%/\sqrt{E} \oplus 0.3\%$ (in module center)

Geant4 hits: Energy deposition → Crystal-SiPM: detected photons → SiPM: p.e. to ADC → ASIC: ADC in Gain modes → ADC digits



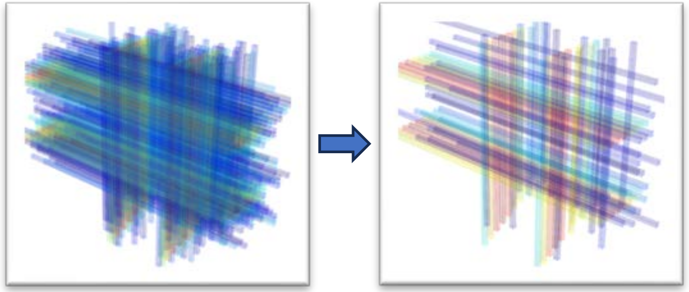
CyberPFA



Step 1: preparation

- Global neighbor clustering in full detector.
- Find the local maximum: 1st pattern recognition

Event display: 2 photons, $E_\gamma = 5$ GeV, distance = 15×15 cm.

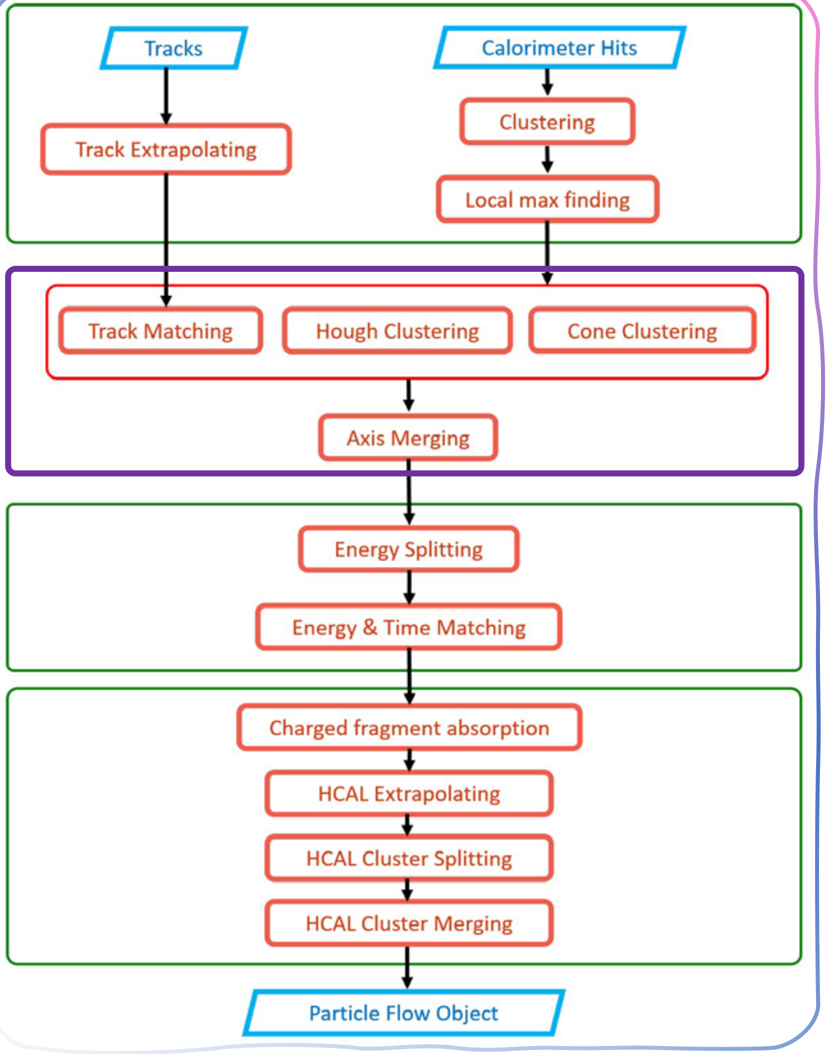


Task list in PFA reconstruction:

✓ Clustering

* Pattern recognition.
* Shower splitting for overlap
* Ambiguity removal

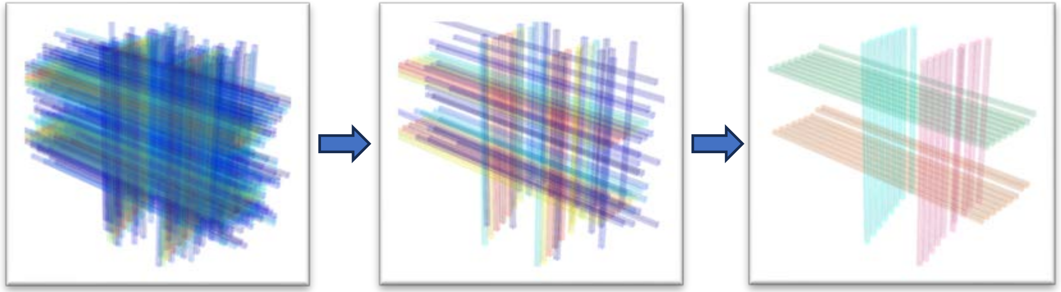
CyberPFA



Step 2: shower recognition

- Tracking in ECAL: find patterns with 3 individual algorithms.
- A set of topological cluster merging

Event display: 2 photons, $E_\gamma = 5$ GeV, distance = 15×15 cm.



Task list in PFA reconstruction:

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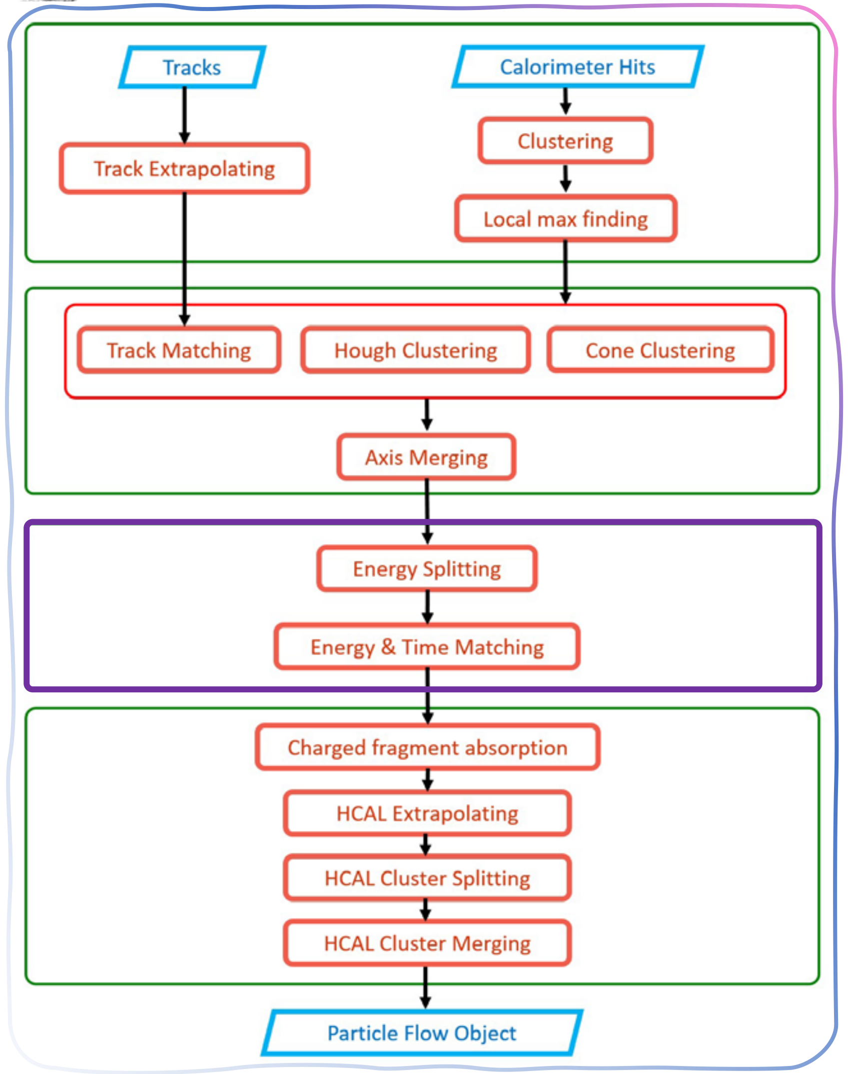
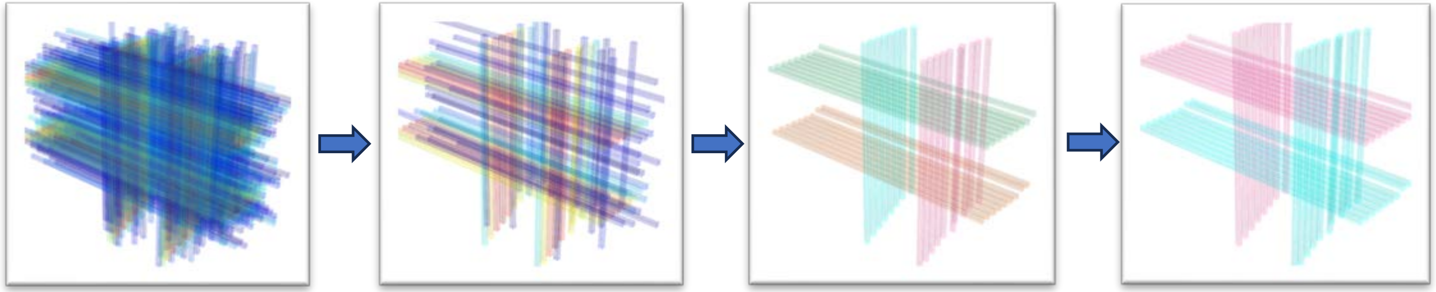


Step 3: energy splitting & ambiguity removal

- Split the energy with EM profile.
- Remove ambiguity from track + neighbor module + time.

Event display: 2 photons, $E_\gamma = 5$ GeV, distance = 15×15 cm.



Task list in PFA reconstruction:

- ✓ Clustering
- ✓ Pattern recognition.
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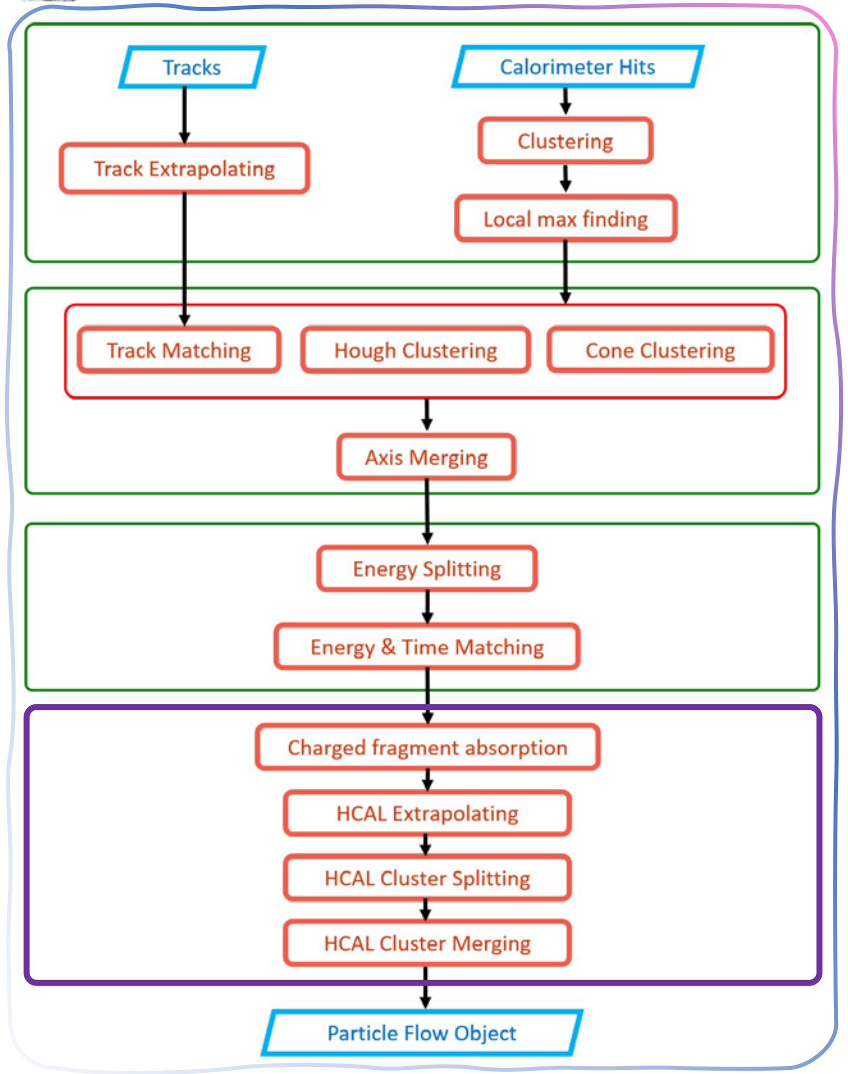
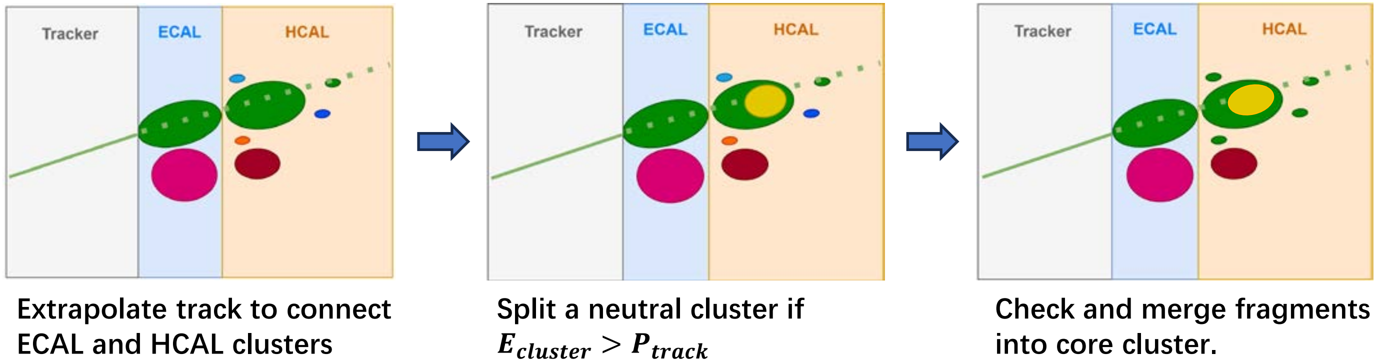
- ✓ Ambiguity removal

CyberPFA



Step 4: clustering and reclustering

- Traditional PFA idea: $E_{cluster} \sim P_{track}$ match.



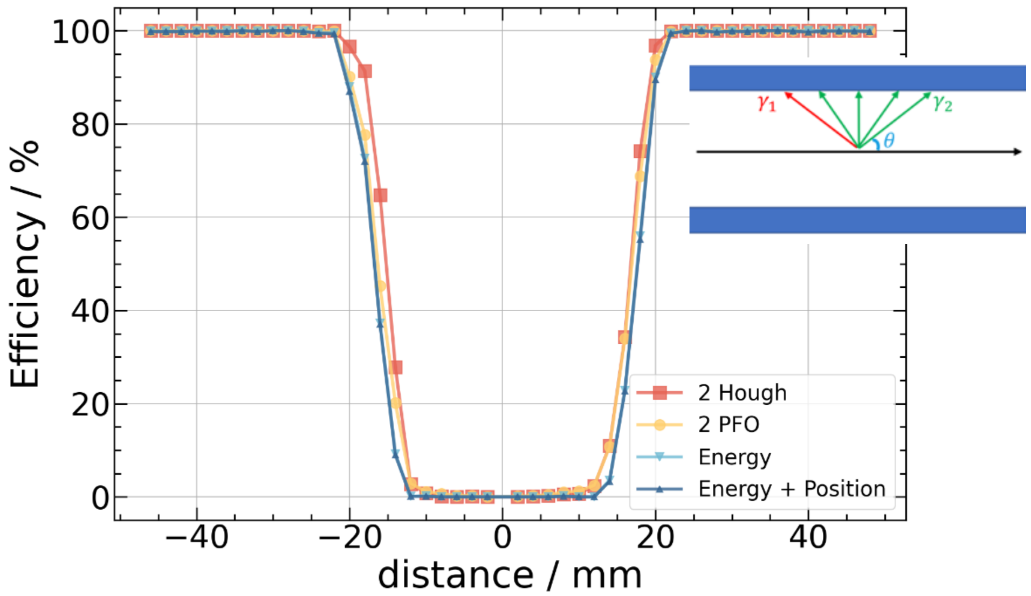
Task list in PFA reconstruction:

- ✓ Clustering
- ✓ Pattern recognition.
- ✓ Shower splitting for overlap
- ✓ Ambiguity removal
- ✓ Full PFA

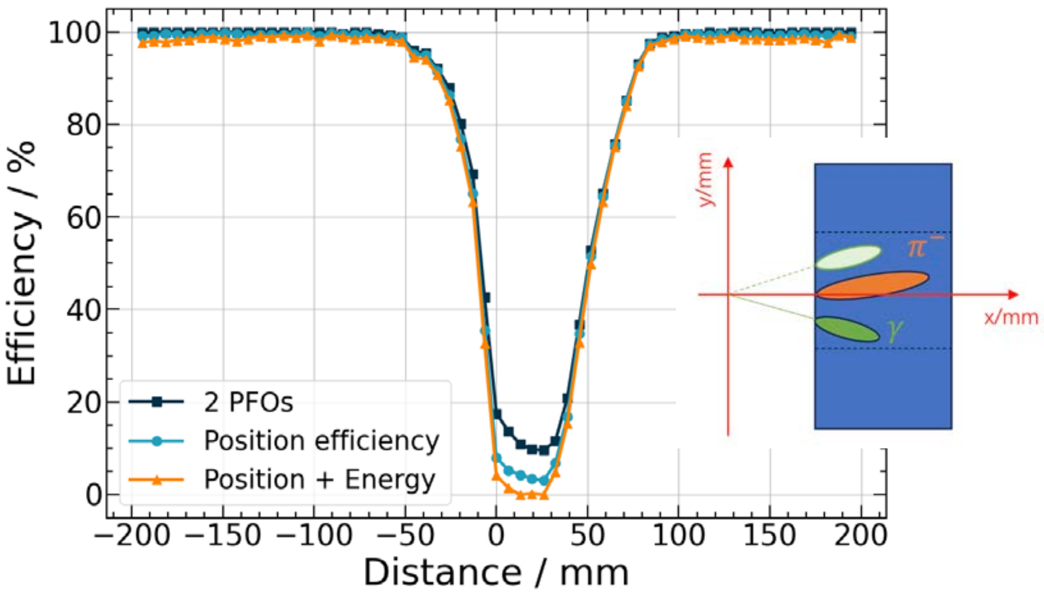
Separation performance

- **Close-by particle separation**
  - Key performance in PFA reconstruction.
  - $\gamma - \gamma$ separation: 2.2 cm @ 100% efficiency.
  - $\gamma - \pi$ separation: 10 cm @ 100% efficiency.

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

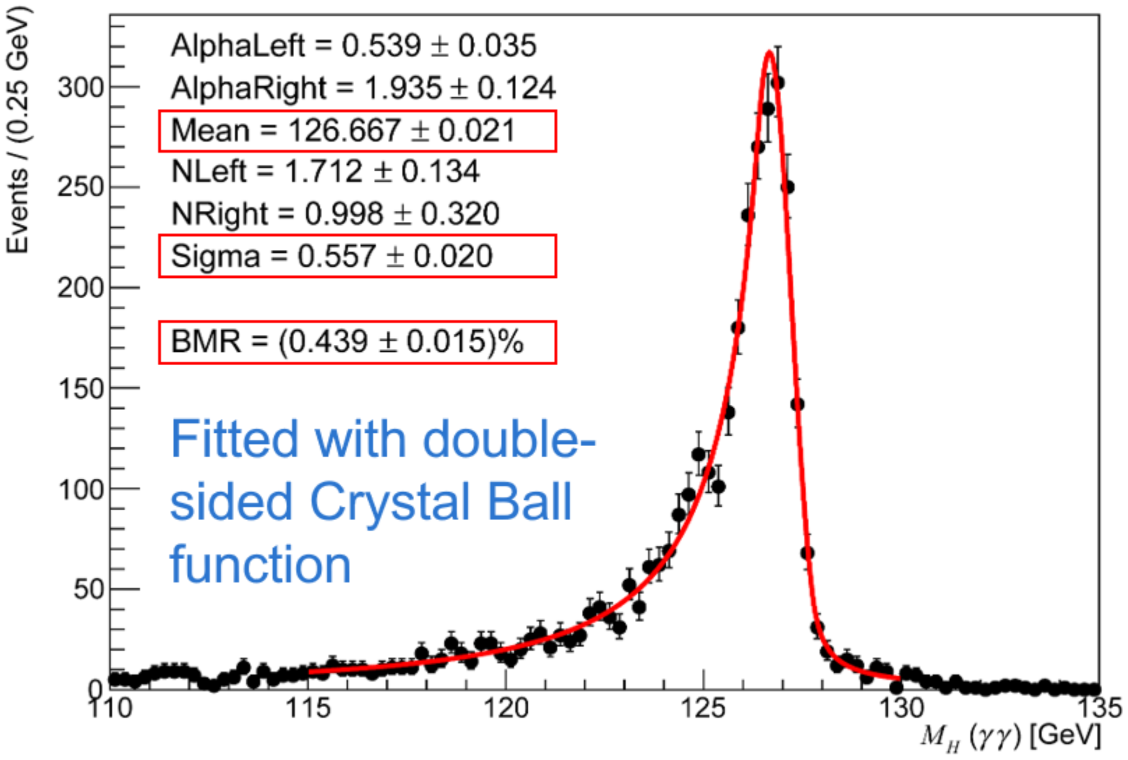


$\gamma - \pi$ separation for 5 GeV γ and π^-



Physics performance: $H \to \gamma\gamma$

- **Physics process: $ee \to ZH \to \nu\nu\gamma\gamma$ in $\sqrt{s} = 240$ GeV**
  - Full simulation and digitization. Energy correction in crack region has been applied.



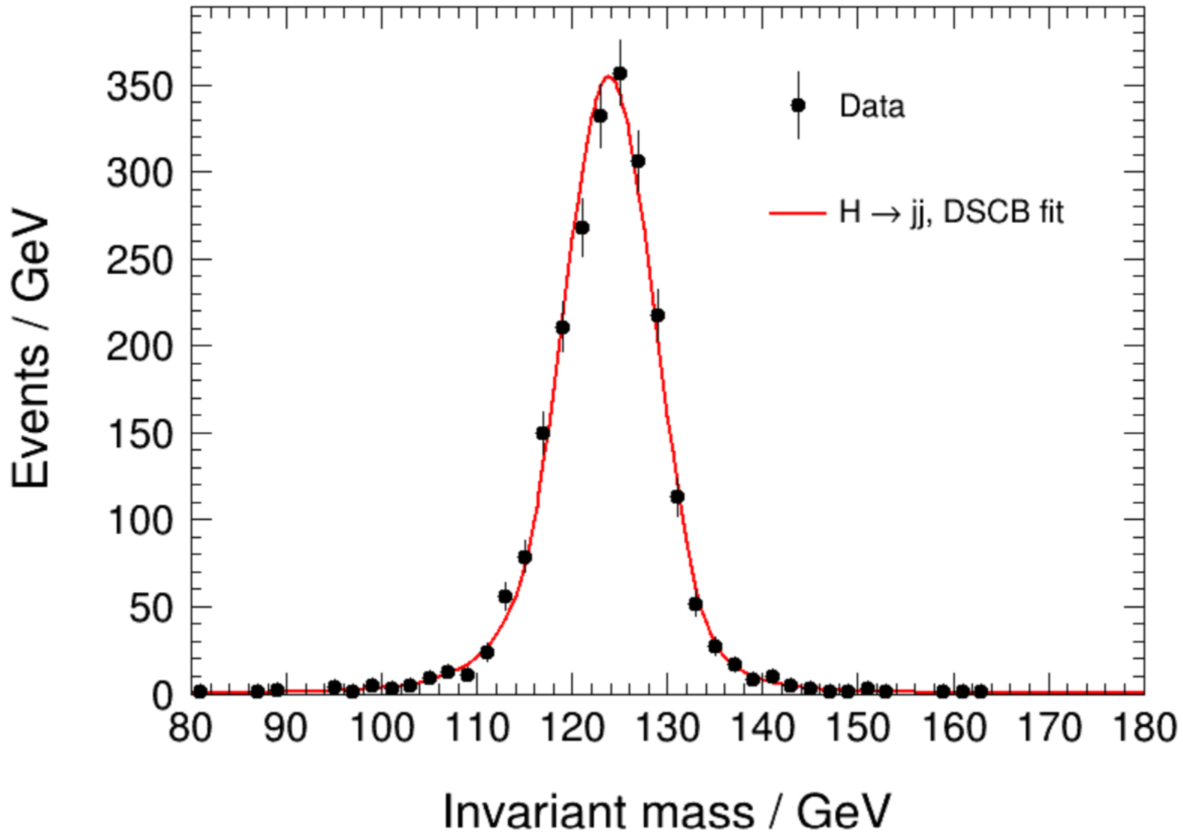
Double-side CB fit, $\sigma(m_{\gamma\gamma})$ = 0.56 GeV

Long tile & biased peak from:
- longitudinal energy leakage.
- Imperfect energy correction.

Can be fixed with better photon energy correction in the future.

Physics performance: $H \rightarrow gg$

- **Physics process:** $ee \rightarrow ZH \rightarrow \nu\nu gg$ **in** $\sqrt{s} = 240$ **GeV**
  - Full reconstruction in CEPC detector: Silicon + TPC tracker, crystal ECAL, glass tile HCAL.



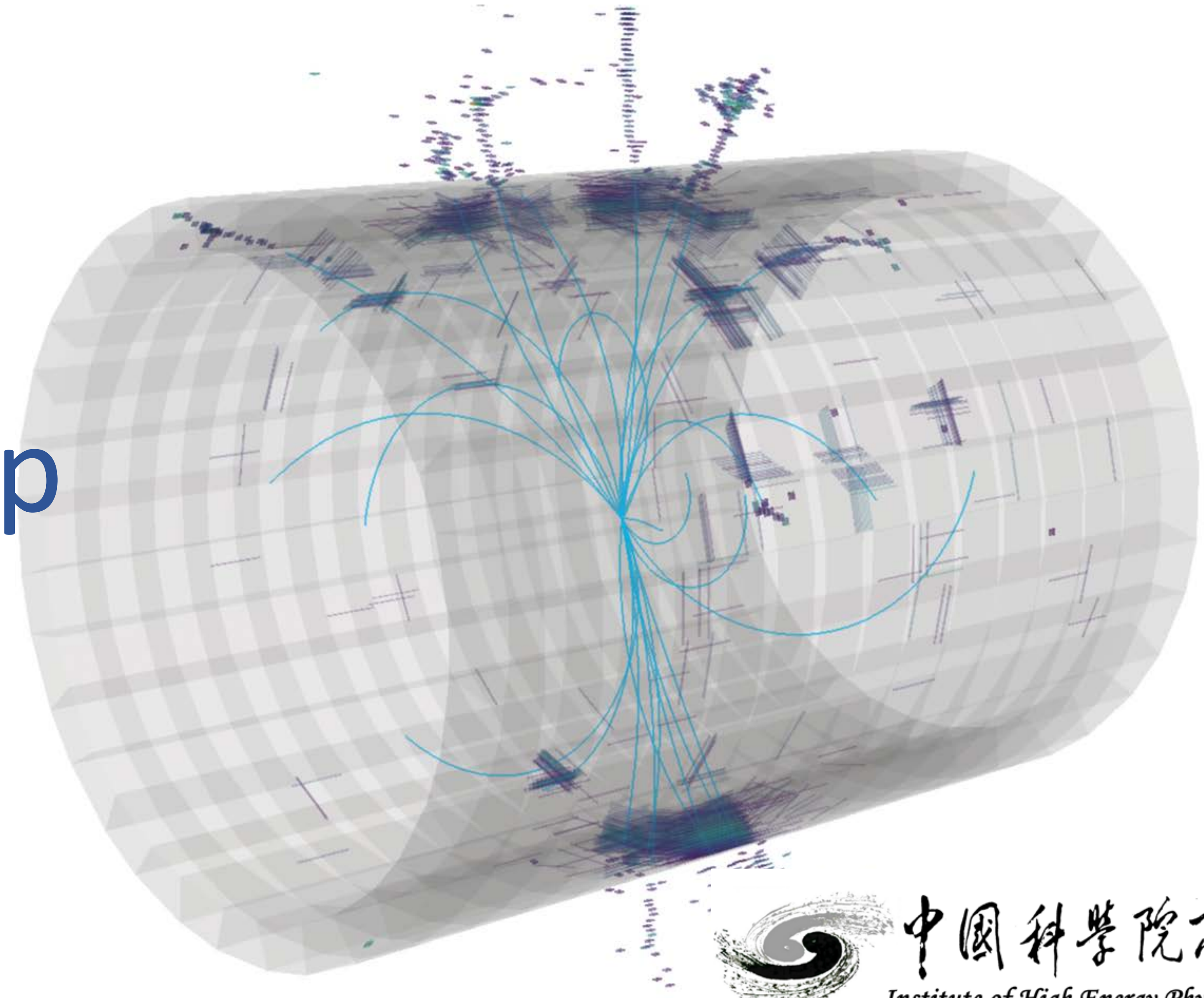
$m_{jj} = 123.81 \pm 0.13$ GeV,
$\sigma(m_{jj}) = 4.89 \pm 0.12$ GeV
Boson mass resolution (BMR) $3.95 \pm 0.10\%$.
With truth track: BMR ~3.7%.

Summary and outlook

- **A novel crystal ECAL design for CEPC detector**
  - Following PFA concept.
  - Satisfy the jet energy resolution requirement in future lepton collider.
  - Optimal EM resolution for flavor physics.
- **CyberPFA for the new design:**
  - Main challenges: overlapping & ambiguity.
  - Series of algorithms are developed and show promising results.
  - Boson Mass Resolution (BMR) ~3.95%.
- **Future plan: CEPC reference detector TDR in 2025**
  - Optimization of PFA performance: cluster ID, energy correction, advanced pattern recognition, …

Thank you for your attention!

Backup



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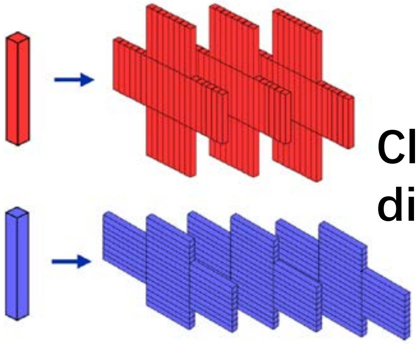
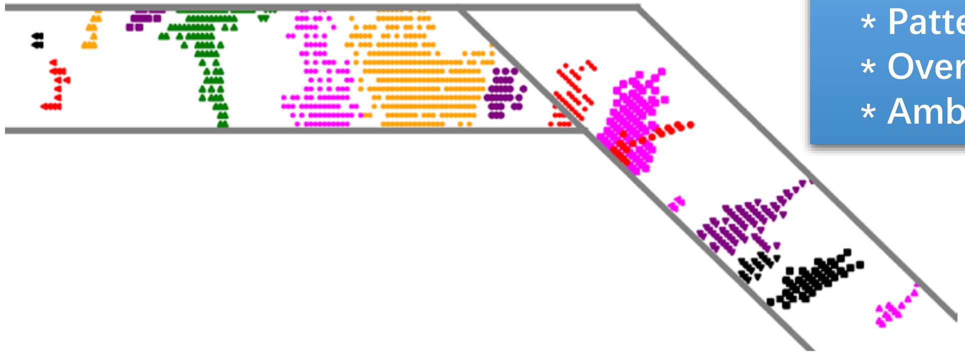
Clustering & recognition

- **Global neighbor clustering for pre-processing.**

Crystal bars

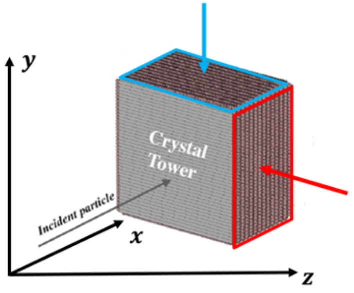


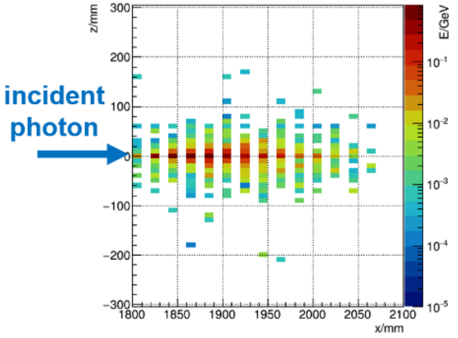
Cluster in 2 directions.



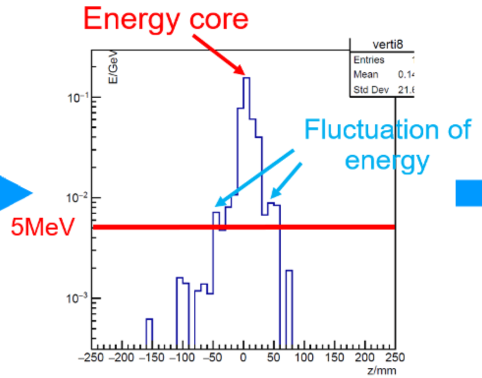
Software task:
✔ * Clustering
* Pattern recognition.
* Overlap: energy splitting.
* Ambiguity problem.

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

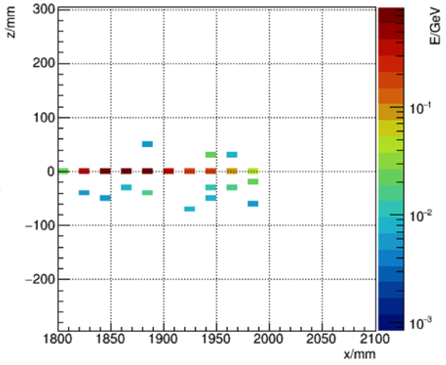




Energy deposits in crystals



Picking out local-max in each layer

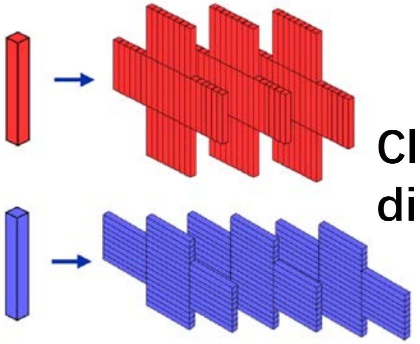


Local Maximum Distribution

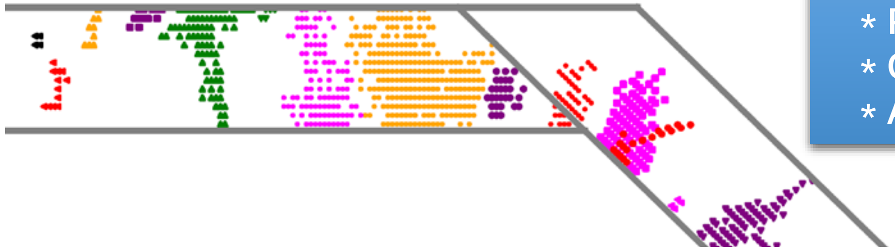
Clustering & recognition

- **Global neighbor clustering for pre-processing.**

Crystal bars

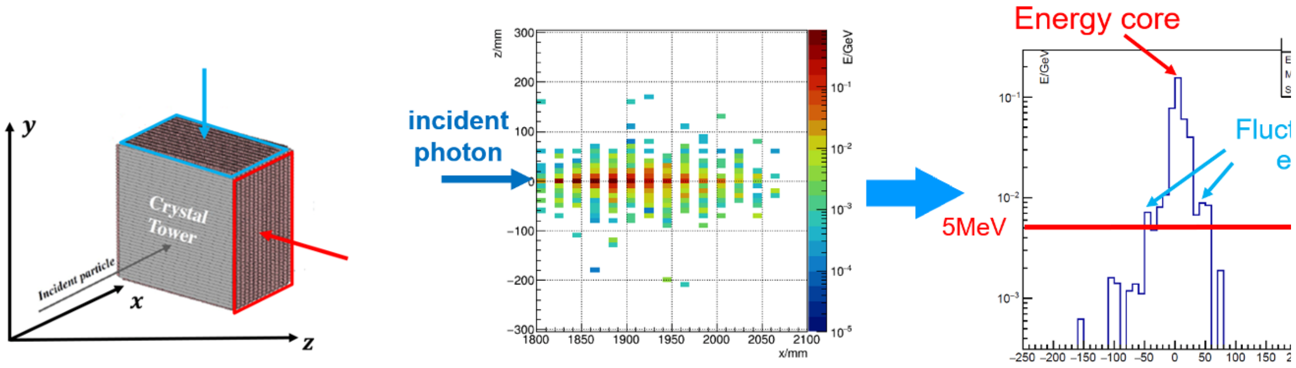


Cluster in 2 directions.



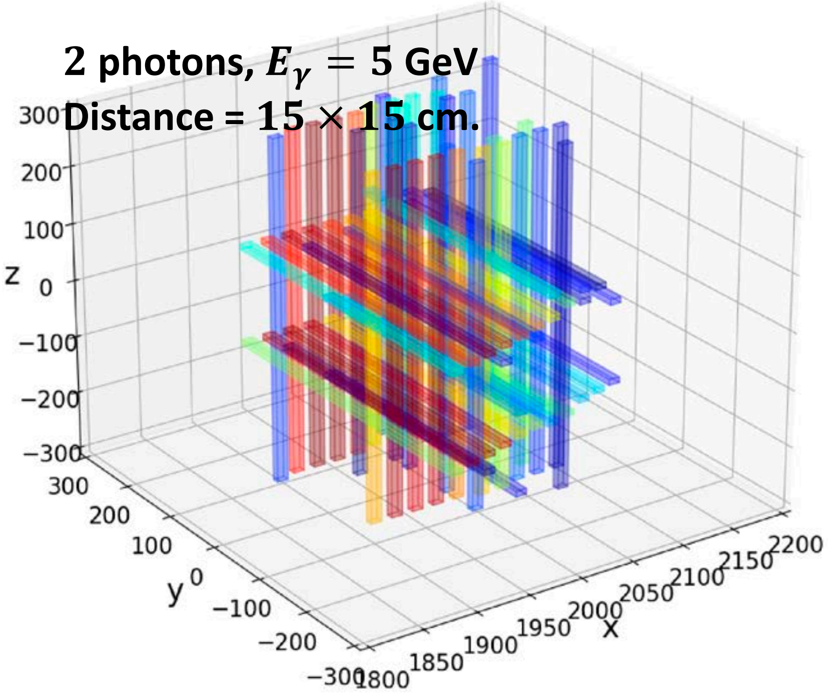
Software task:
- ✔ * Clustering
- * Pattern recognition.
- * Overlap: energy splitting.
- * Ambiguity problem.

- **Shower recognition:**
  - Use the local maximum to simplify the pattern in homogen



Energy deposits in crystals

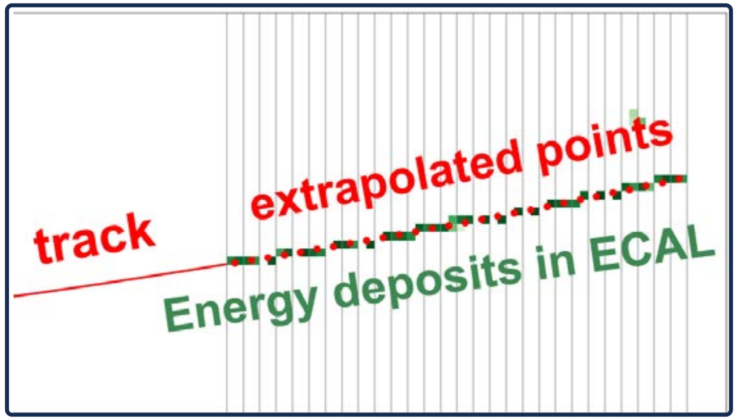
Picking out local-max in ea

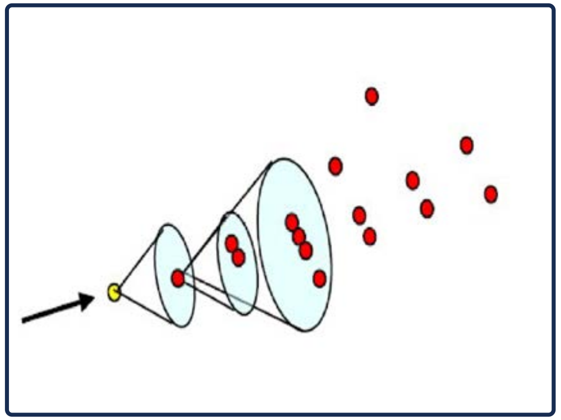


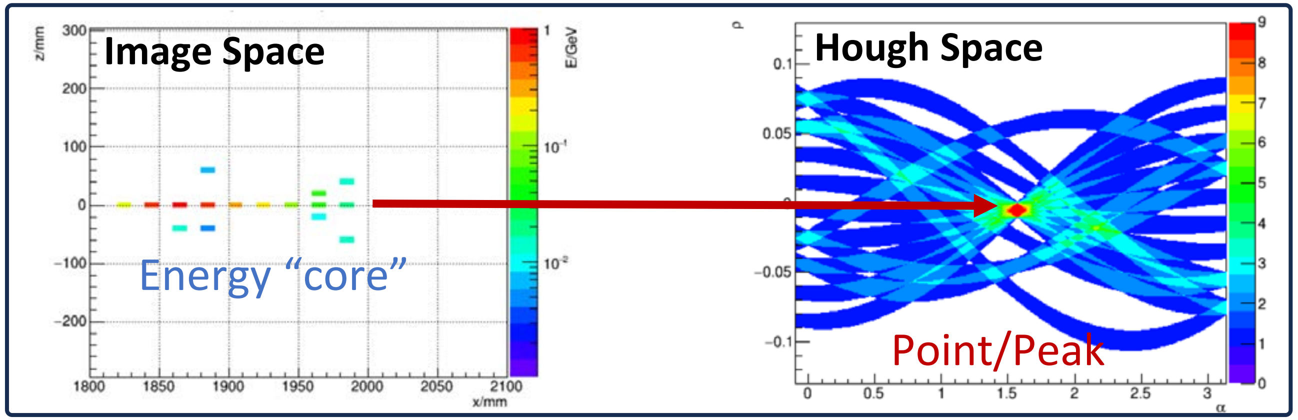
Clustering & recognition

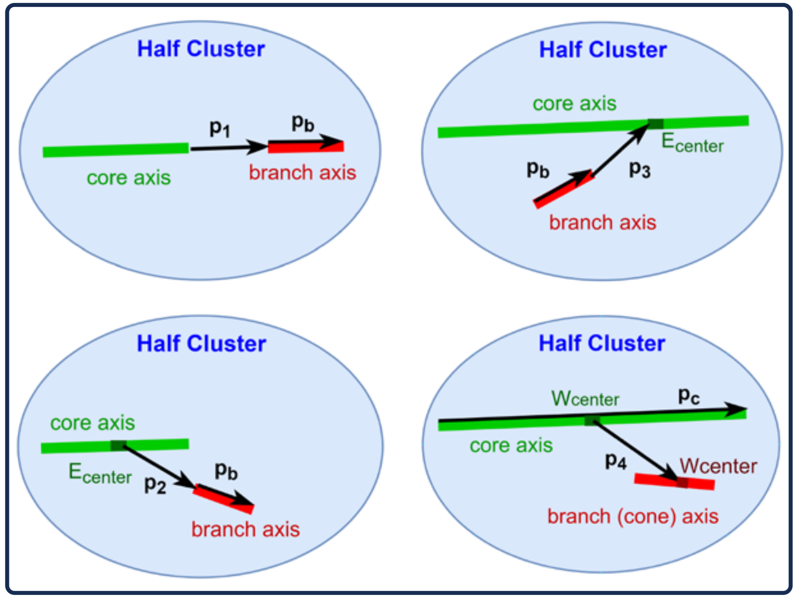
- **Shower recognition:**
  - 3 individual algorithms for different type: track-match, Hough, Cone-clustering.
  - A set of topological cluster merging.

Software task:
✔ * Clustering
✔ * Pattern recognition.
* Overlap: energy splitting.
* Ambiguity problem.









Clustering & recognition

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

Software task:
✔ * Clustering
✔ * Pattern recognition.
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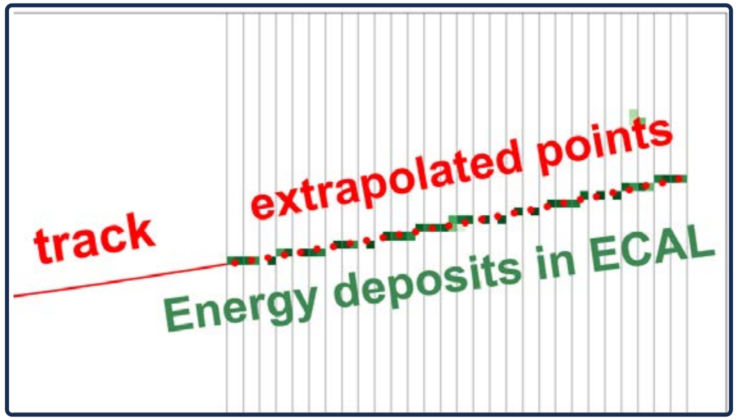
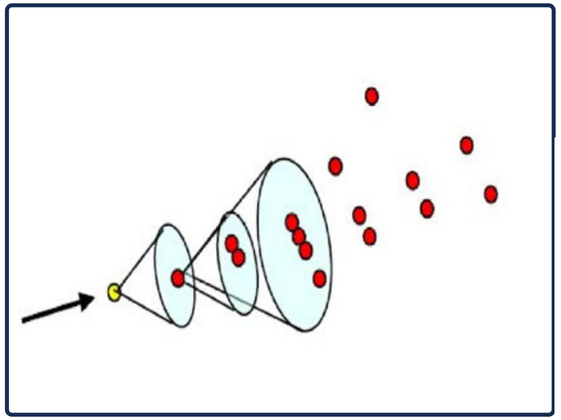
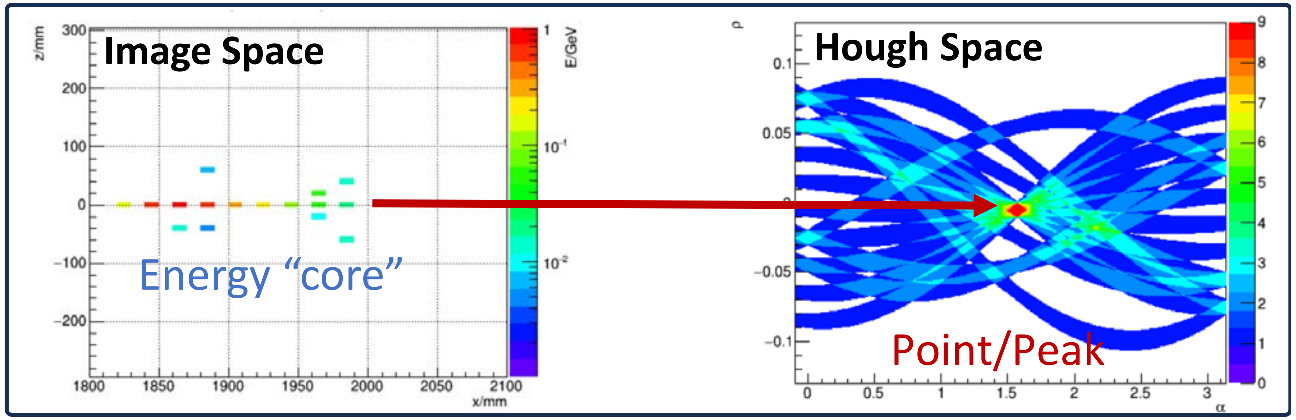
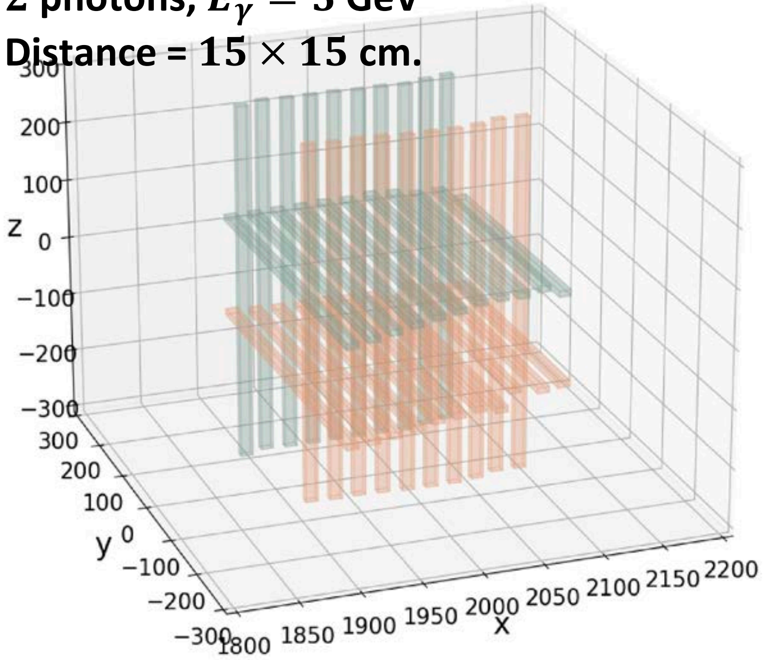






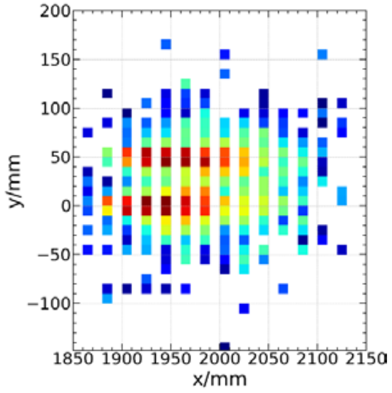
2 photons, $E_\gamma = 5$ GeV
Distance = 15×15 cm.

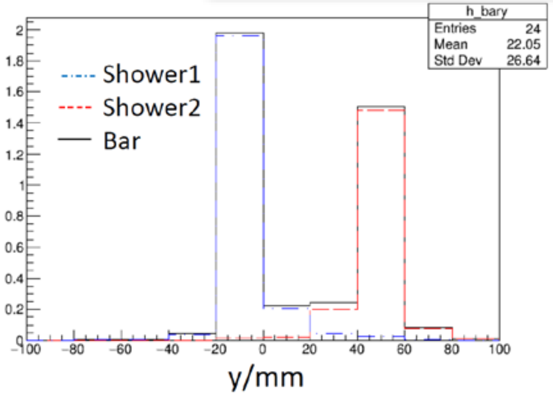


Energy splitting and matching

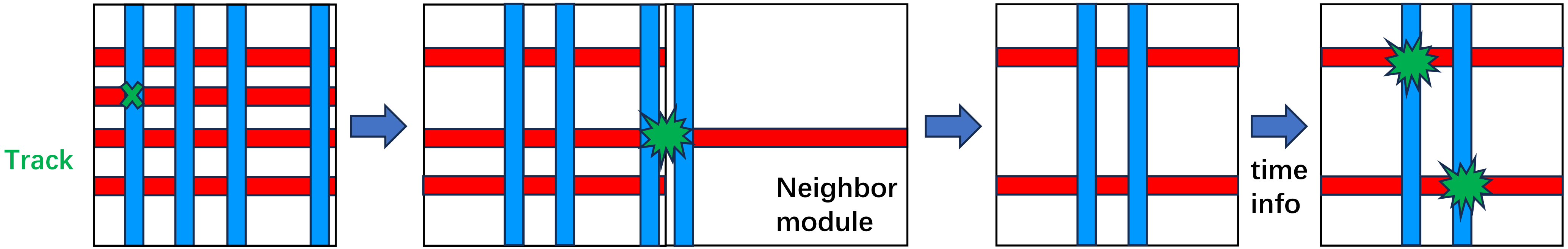
Software task:
✔ * Clustering
✔ * Pattern recognition.
✔ * Overlap: energy splitting.
✔ * Ambiguity problem.

- **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: $w_{i\mu} = \frac{E_{i\mu}^{exp}}{\sum_{\mu} E_{i\mu}^{exp}}$



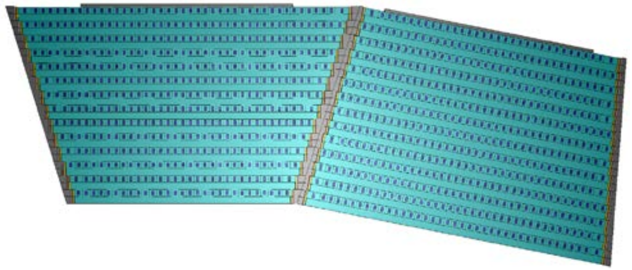


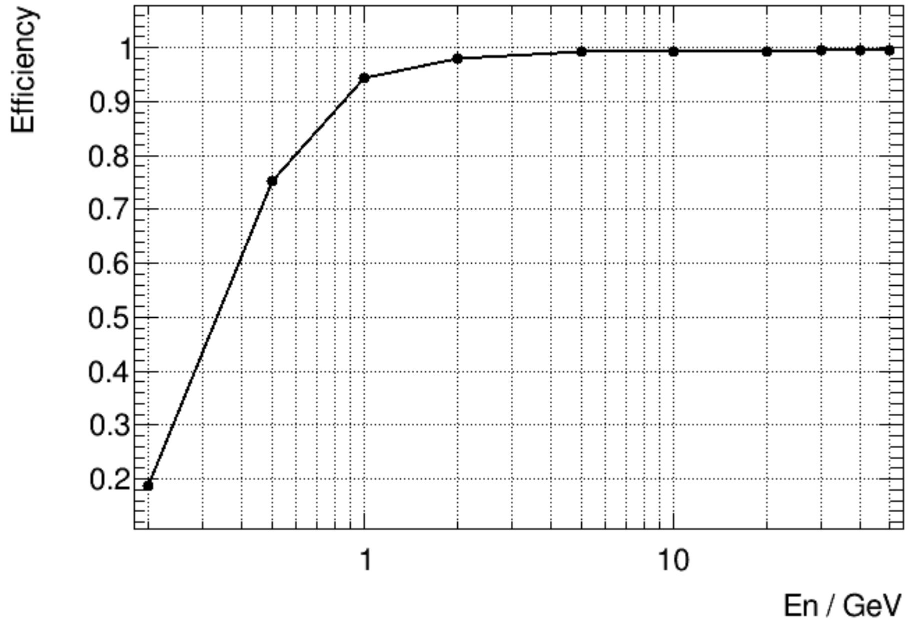
- **Ambiguity removal:**
  - Information from: track, neighbor tower, time.

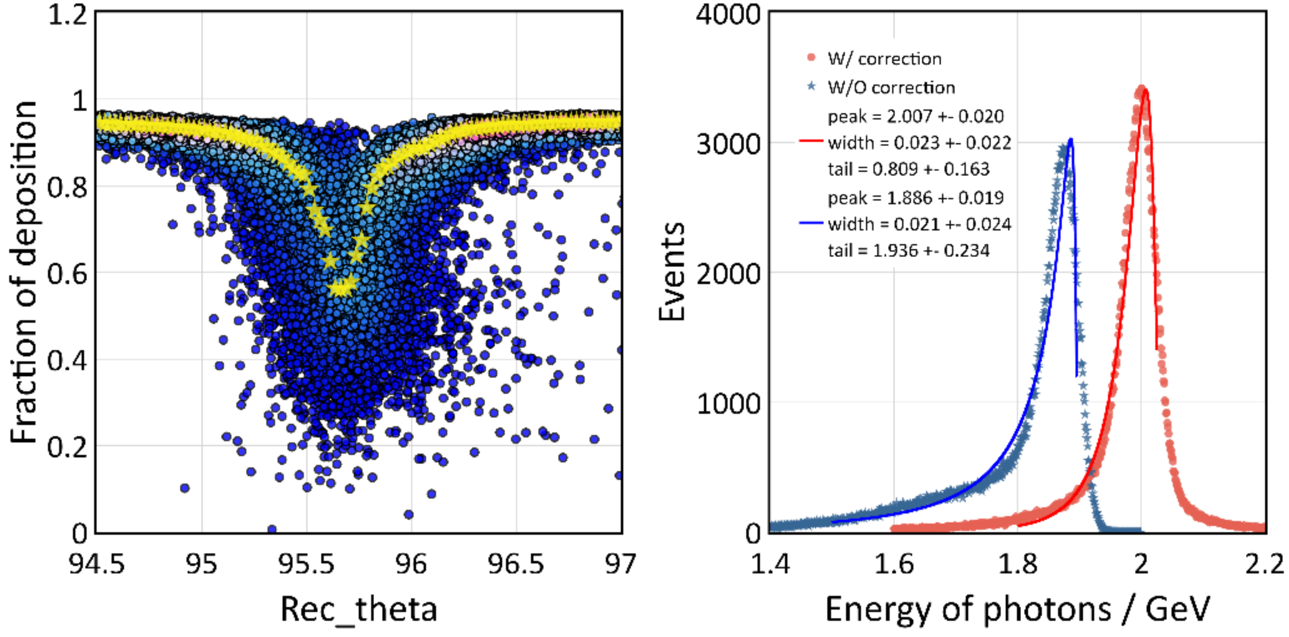


Physics performance: single photon

- **Single photon reconstruction efficiency:**
  - Efficiency: ~100% for >1 GeV photons.
- **Energy correction from simulation:**
  - For the cracks: $E_{corr} = \frac{E'_{truth}}{E'_{deposition}} \times E_{dep}^{mean}$

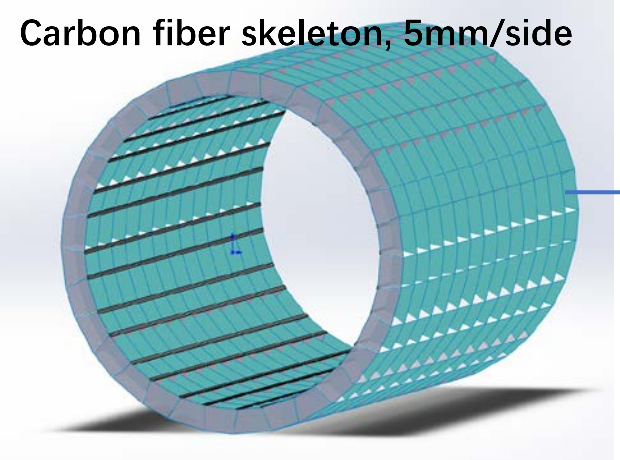


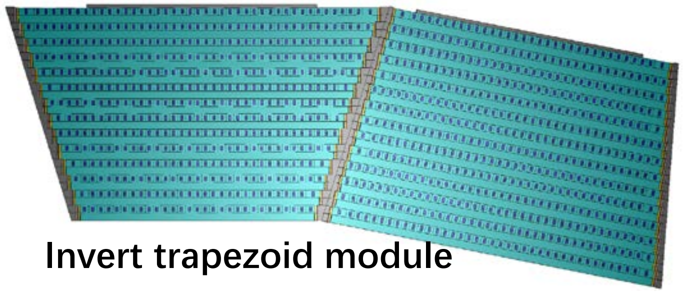


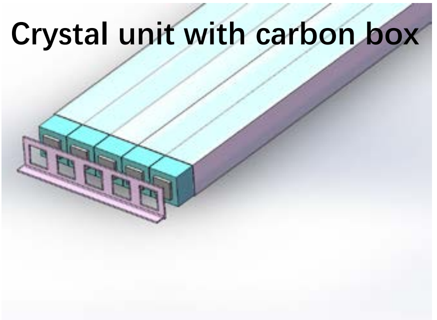


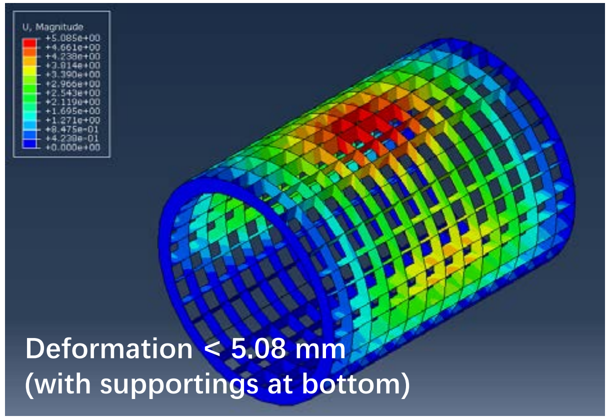
Mechanics design

- **Carbon fiber skeleton and unit strength**

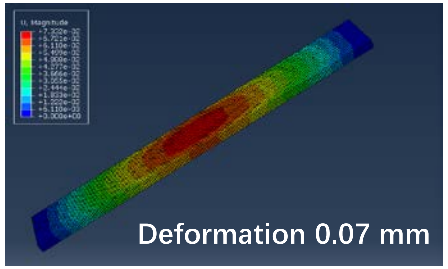

Carbon fiber skeleton, 5mm/side


Invert trapezoid module


Crystal unit with carbon box

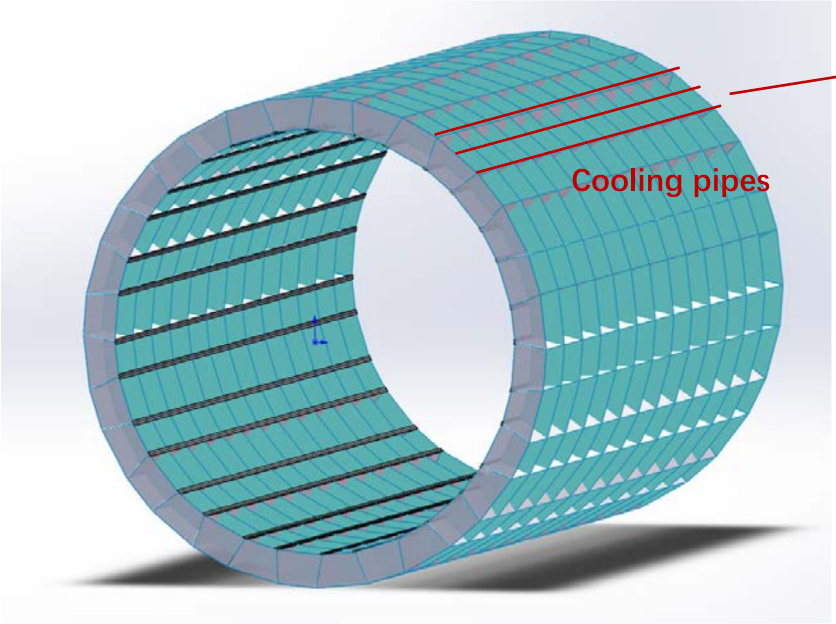


Deformation < 5.08 mm
(with supportings at bottom)

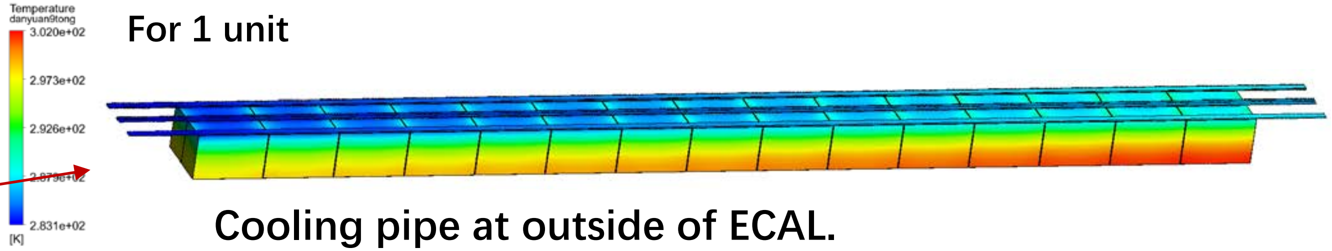

Deformation 0.07 mm

Cooling design

- **Copper plate + aluminum water pipe cooling**

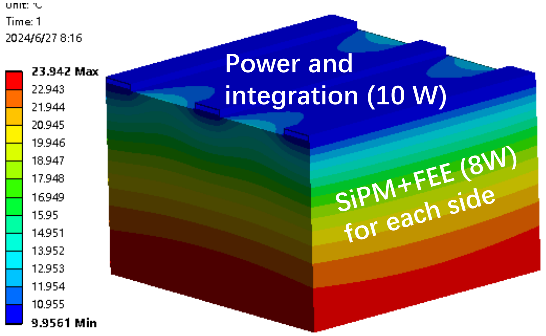


For 1 unit



Cooling pipe at outside of ECAL.
Heat from electronics: (10W + 4*8W) / module.
Stable but large temperature gradient (~15℃).
Working in progress.

For 1 module



Energy resolution