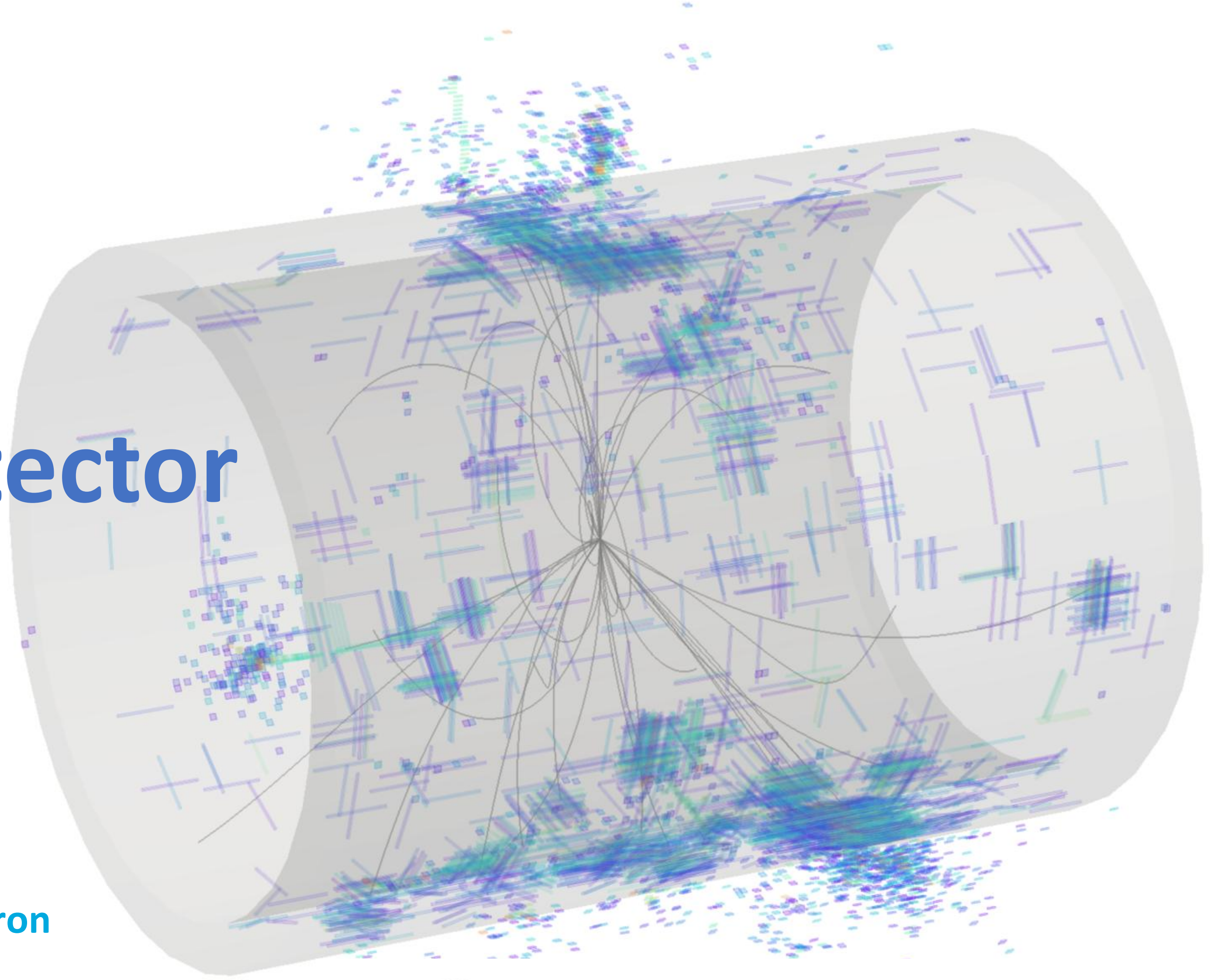
CyberPFA for the CEPC reference detector



SUN Shengsen

Institute of High Energy Physics

International Workshop on the Circular Electron Positron Collider 2025 European Edition

Barcelona, 17 June 2025

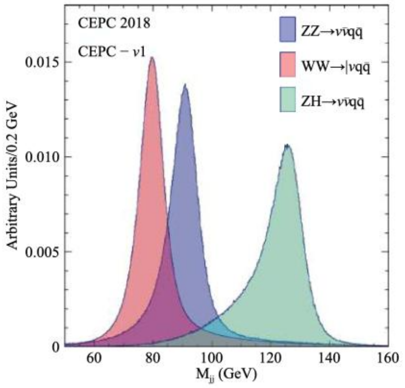
中国科学院高能物理研究所

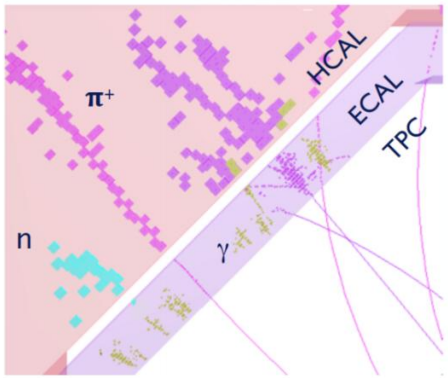
Institute of High Energy Physics, Chinese Academy of Sciences

Future e+e- collider

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

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

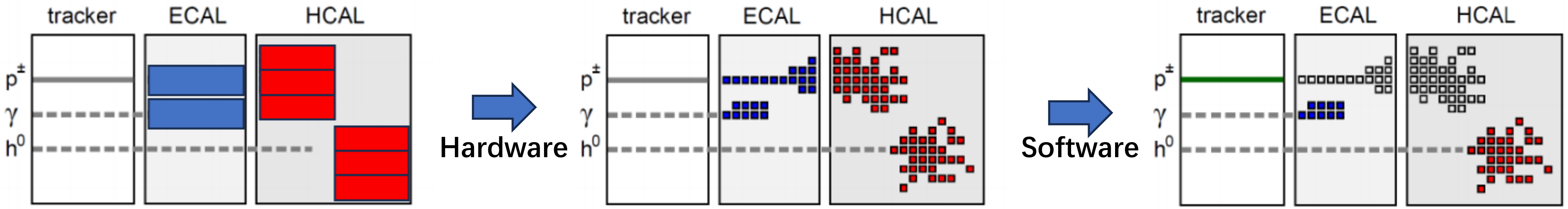




- **Particle Flow Approach:**
  - Measure the jet by its components: $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$
  - Hardware + Software:

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

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

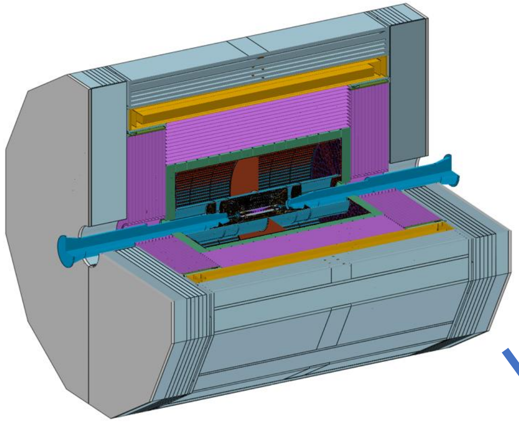


ECAL in CEPC reference detector

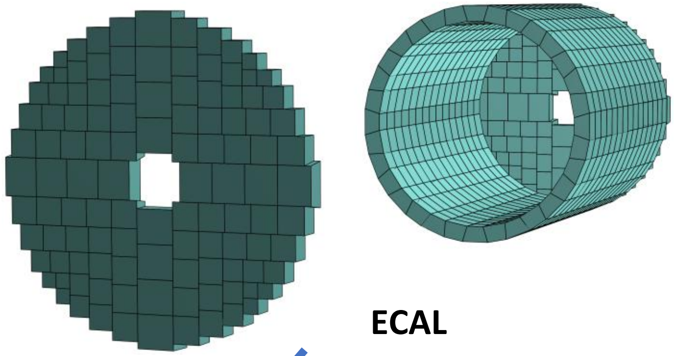
- **Why crystal calorimeter**
  - A long history in particle physics precise measurement:
    L3@LEP, BESIII@BEPC, CMS@LHC, HERD, Panda…
  - Optimal intrinsic EM resolution: $\sigma_E/E < 3\%/\sqrt{E}$
    - Photon recovery from bremsstrahlung,
    - π^0 reconstruction.
  - Fast response:
    - Introduce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

	CsI	BGO	$\mathrm{PbWO_4}$	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

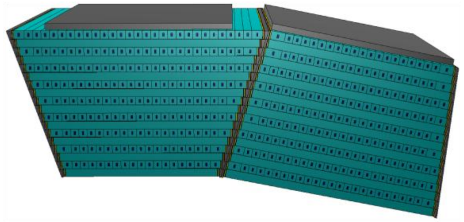
  - BGO for a balance performance & cost.



Reference detector



ECAL

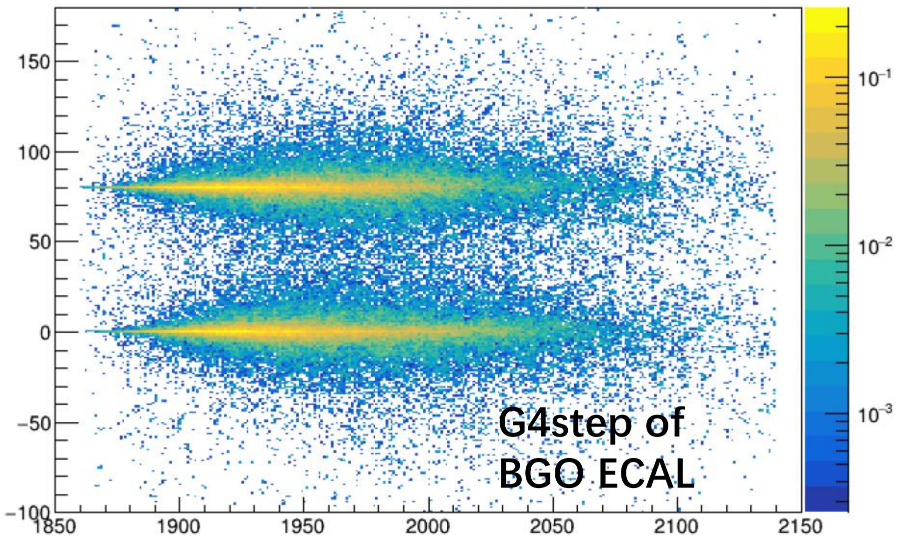


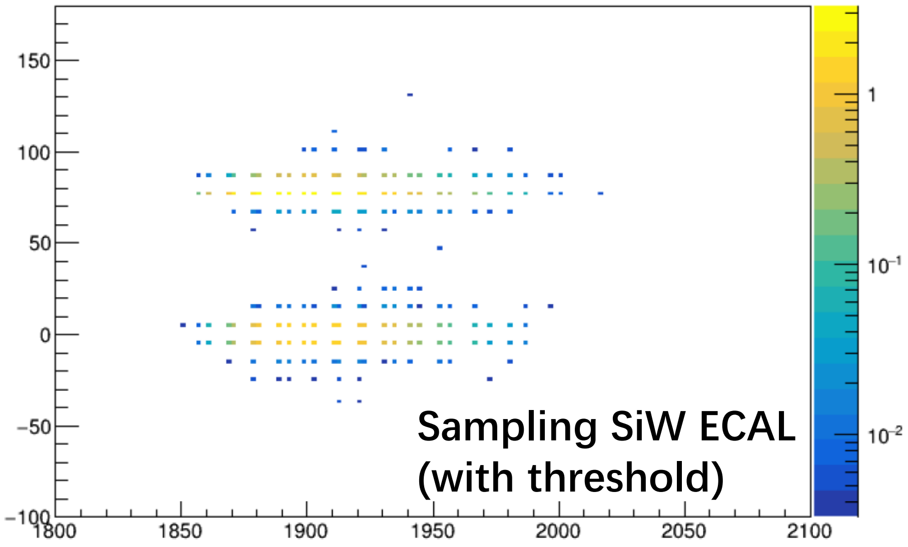
Invert trapezoid module

Crystal 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).

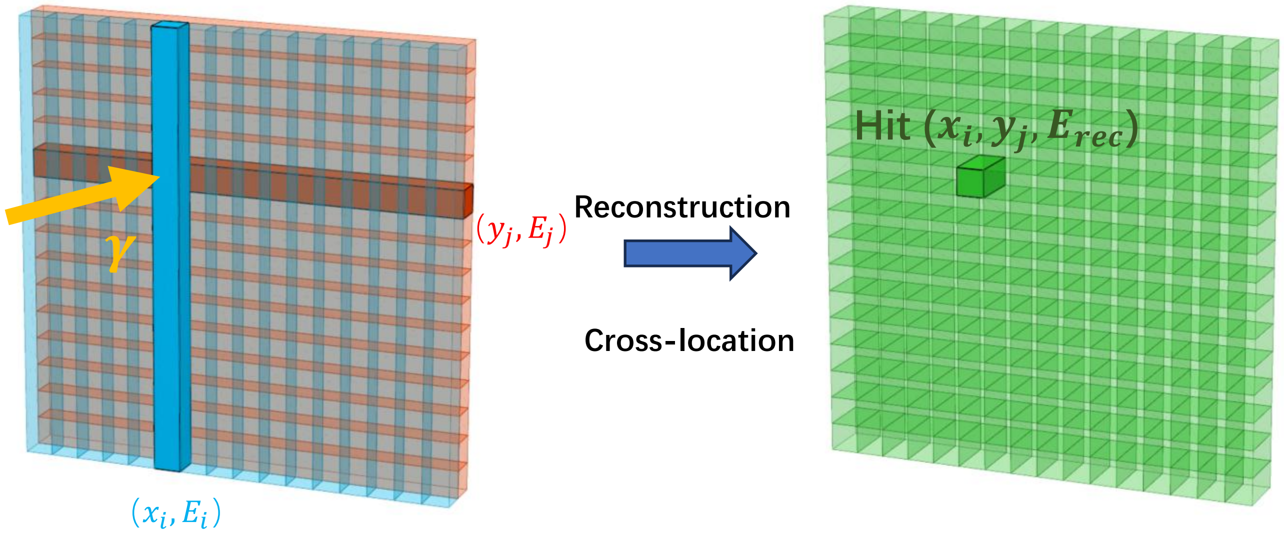
Software task:
* Clustering
* Pattern recognition.
+ Overlap: energy splitting.

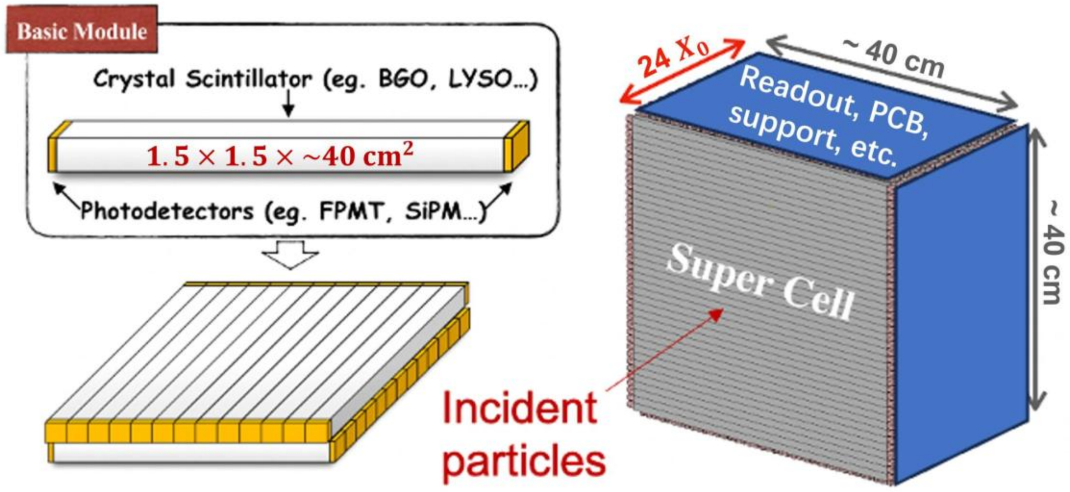




Crystal ECAL

- **Orthogonal arranged crystal bars.**
  - Double-end readout with SiPM (Q, T).
  - Cross-location by bars.
  - Less readout channels, cost effective.





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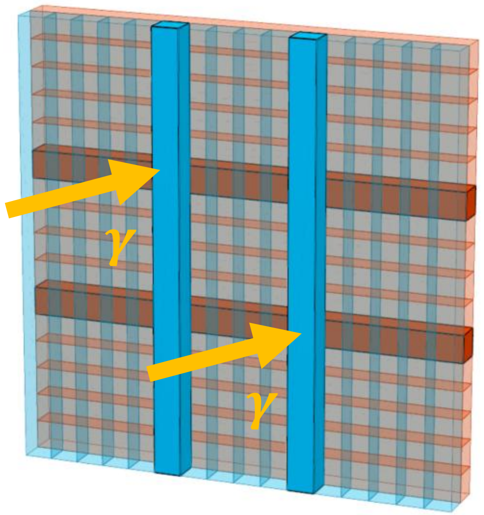
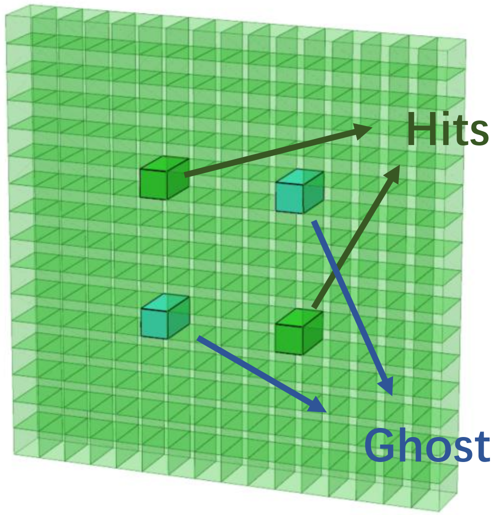
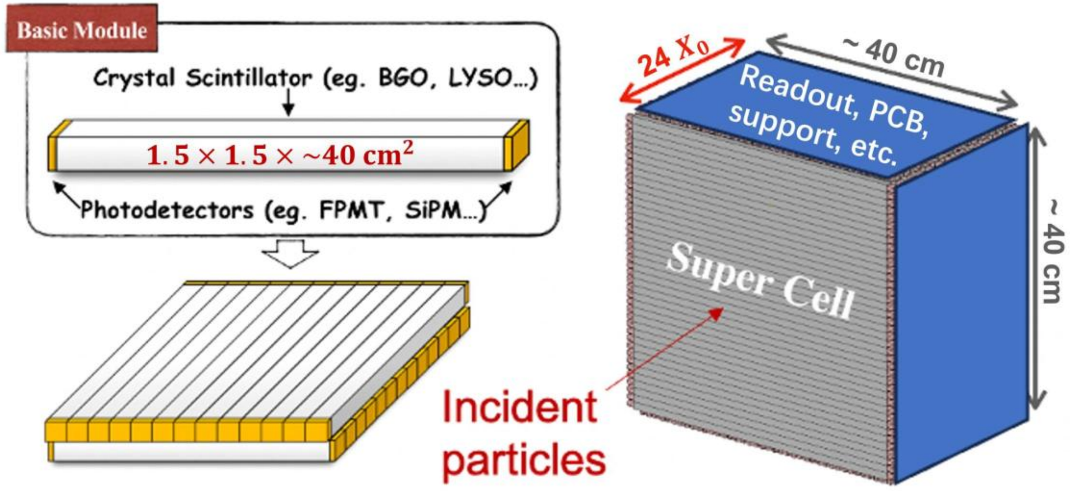
    New challenge: multi-particle ambiguity.



Reconstruction

Cross-location





Software task:
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- \+ Ambiguity removal

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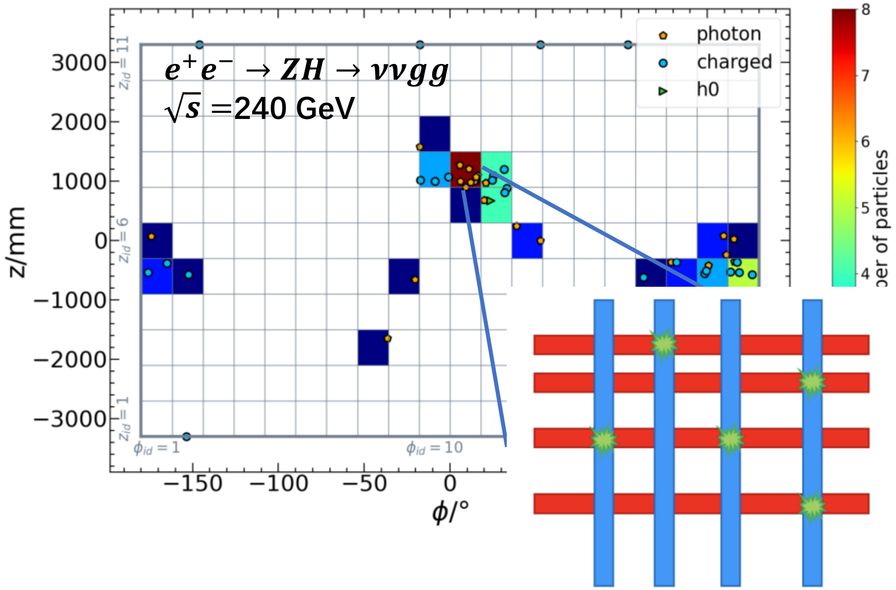

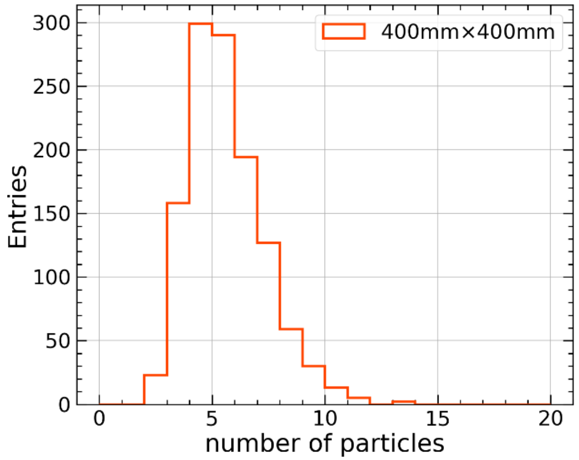

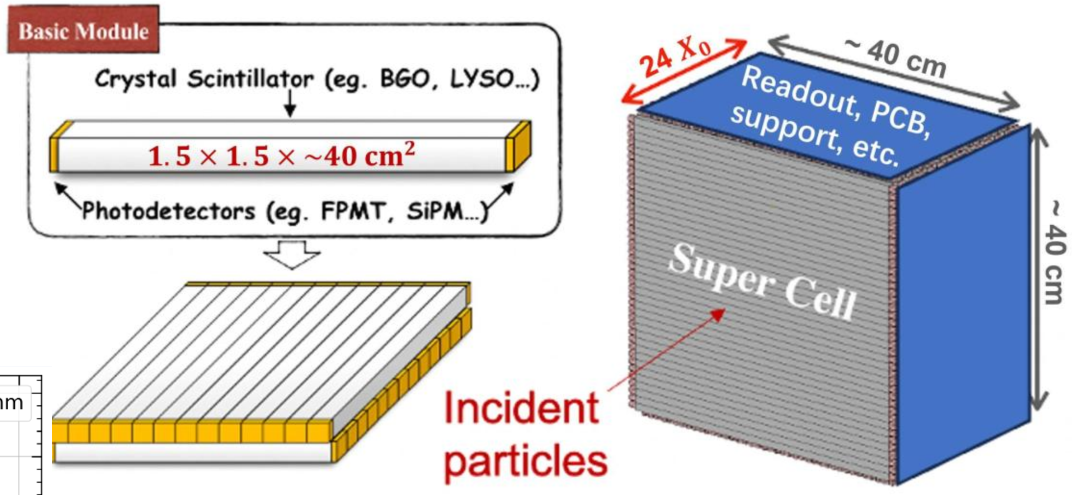

Software task:
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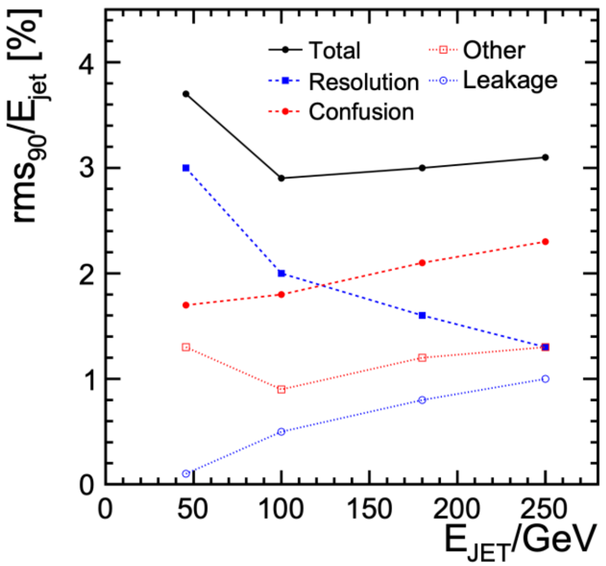
Particle flow algorithm

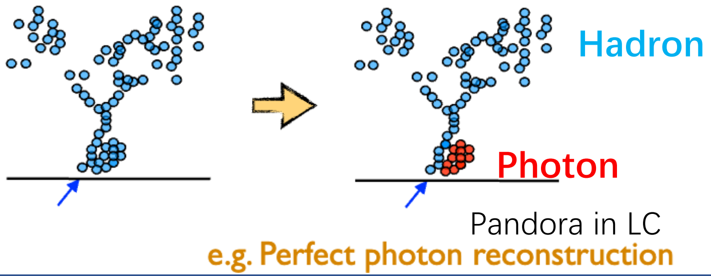
- **PF performance decoupling**
  - $\sigma_{jet} \sim \sigma_{trk} \oplus \sigma_{EM} \oplus \sigma_{Had} \oplus \sigma_{confusion}$. **Confusion is an important limitation factor.**

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.



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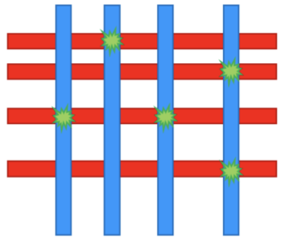
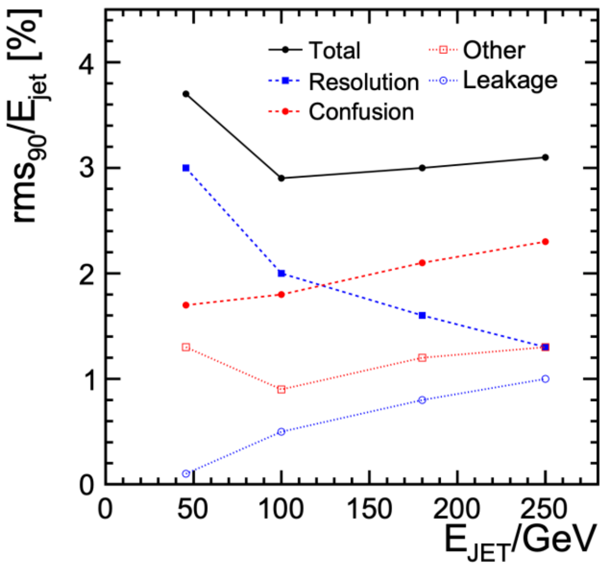
Crystal ECAL improves the intrinsic resolution

iv) Confusion (ambiguity)





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

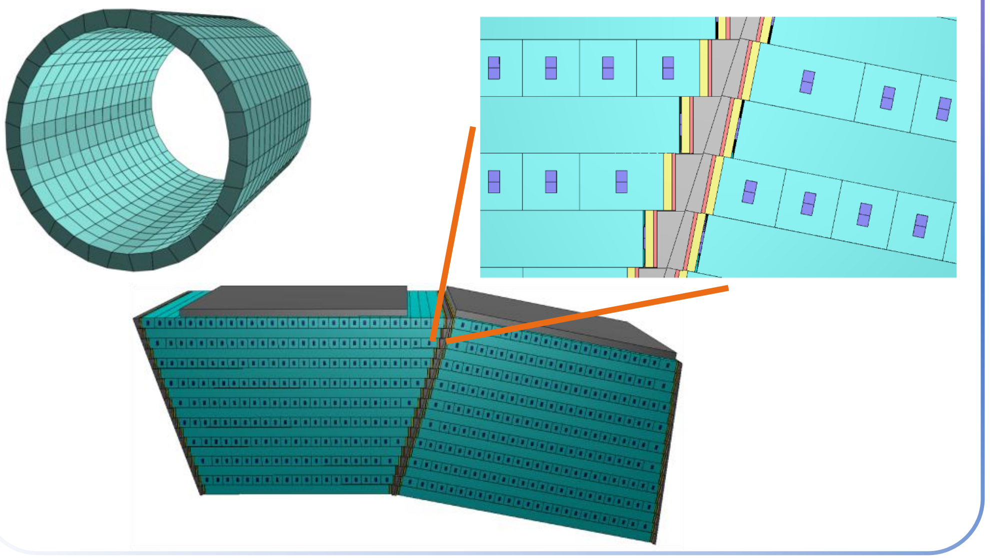
Software task:
- ⁎ Clustering
- ⁎ Pattern recognition.
  - \+ Improve the performance.
- ⁎ Overlap: energy splitting.
- ⁎ Ambiguity problem.
  - \+ Minimize the impact.

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), 18 layers.
- $1.5 \times 1.5 \times {\sim}40\ cm^3$ 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.

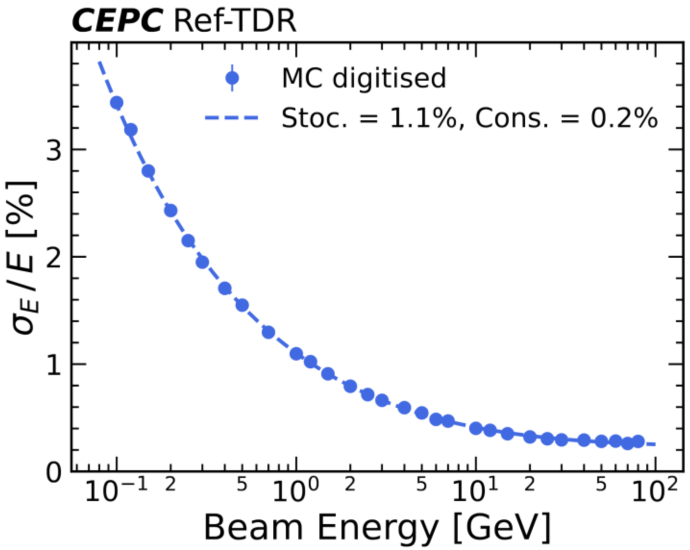


Digitization model: from beam test

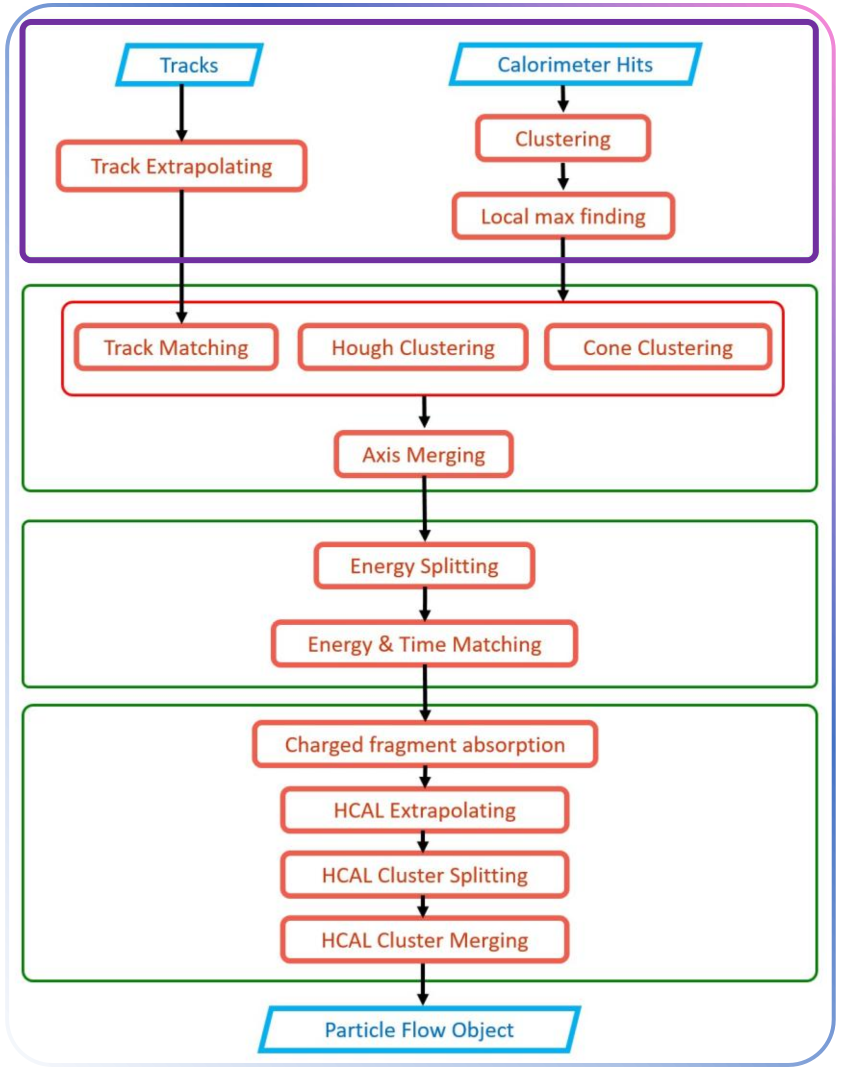
- MIP response: 300 p.e./MIP
- Energy threshold: 0.1 MIP.
- SiPM gain calibration: 1 p.e. = 5 ADC, with noise
- Electronics: 12 bits ADC with precision 0.2‰, 3 gain modes

Energy resolution with full digitization: $\sigma_E/E = 1.1\%/\sqrt{E} \oplus 0.2\%$ (in module center)

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



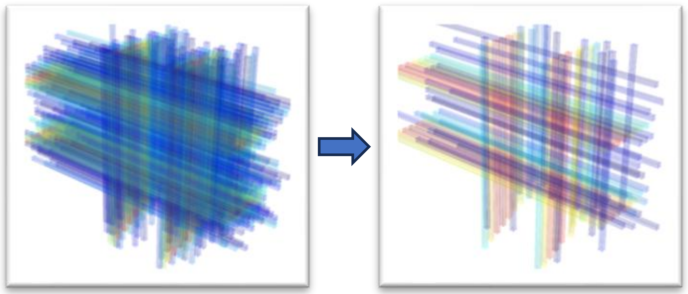
CyberPFA



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.

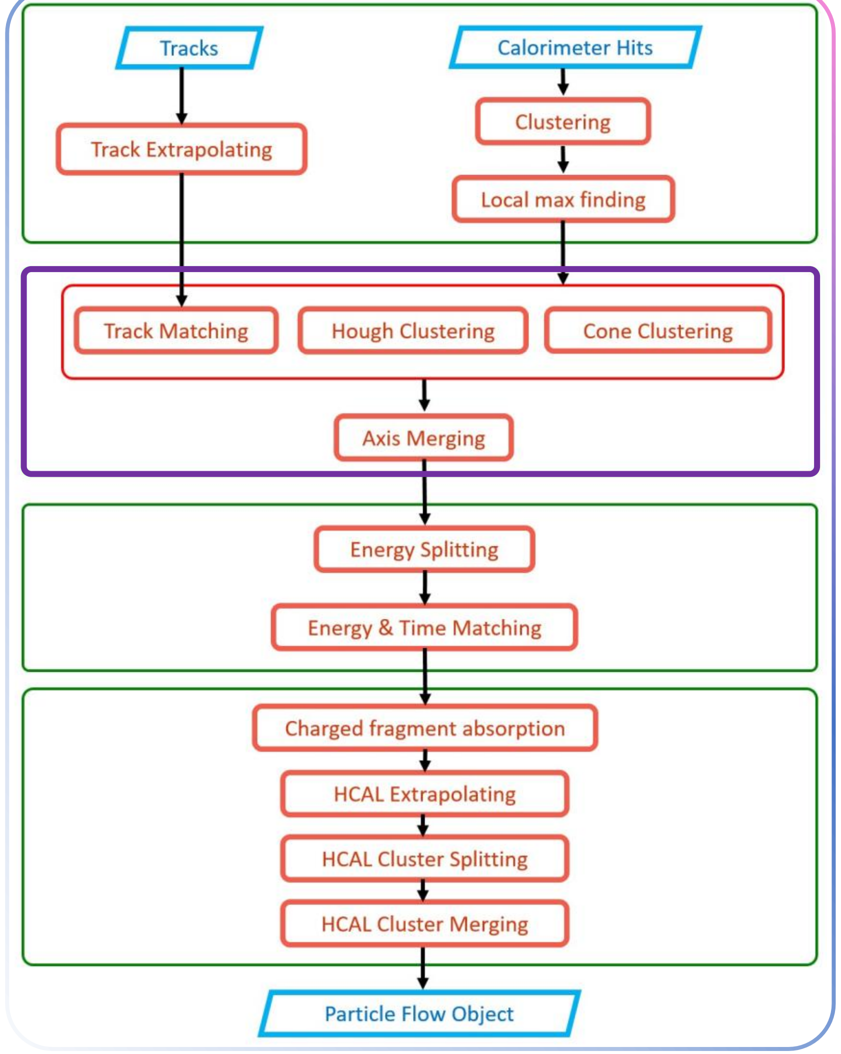


Task list in PFA reconstruction:

✓ Clustering

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

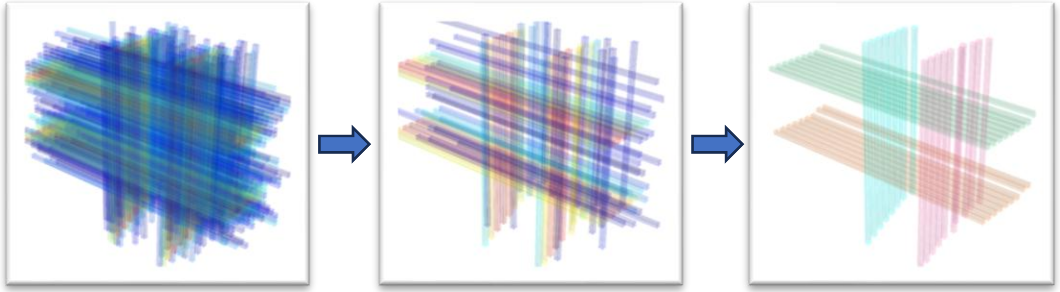
CyberPFA



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 $= 15 \times 15$ cm.



Task list in PFA reconstruction:

✓ Clustering

✓ Pattern recognition.

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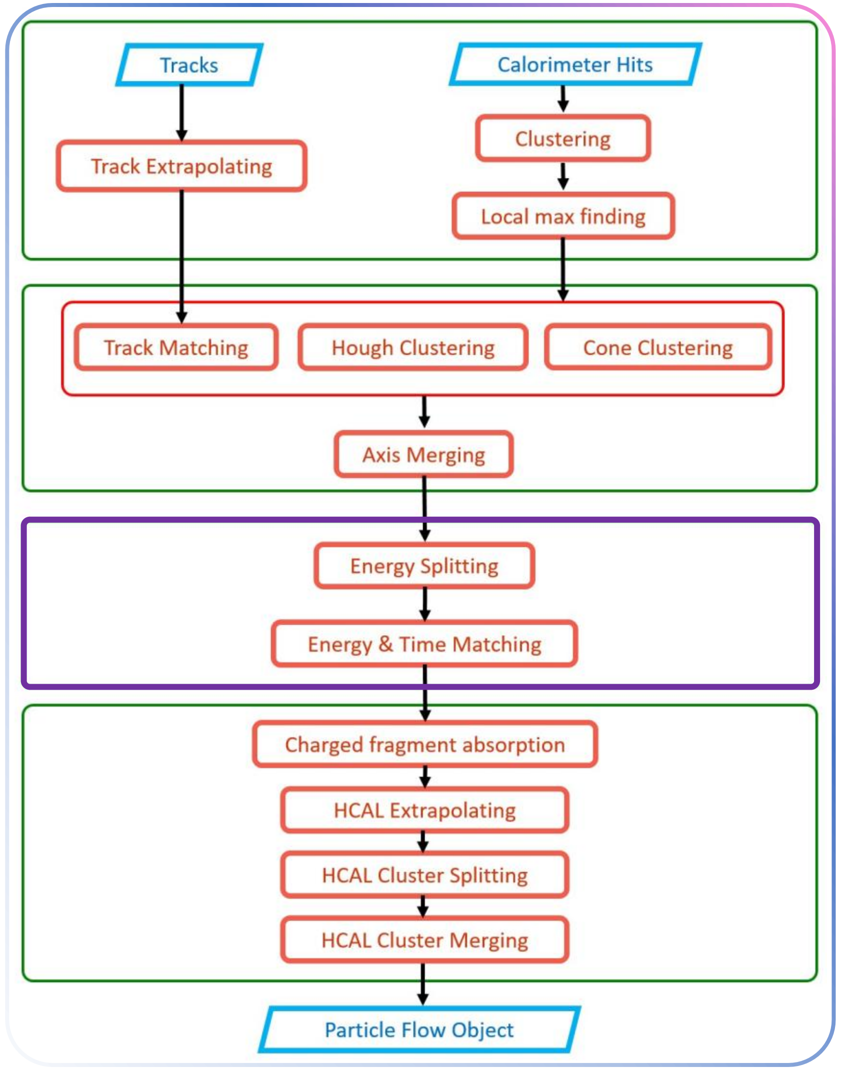
* Ambiguity removal

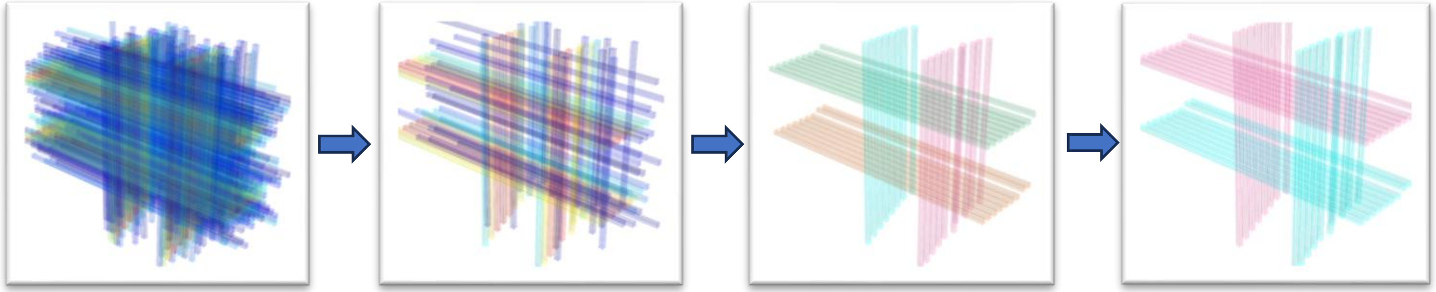
CyberPFA



Step 3: energy splitting & ambiguity removal

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

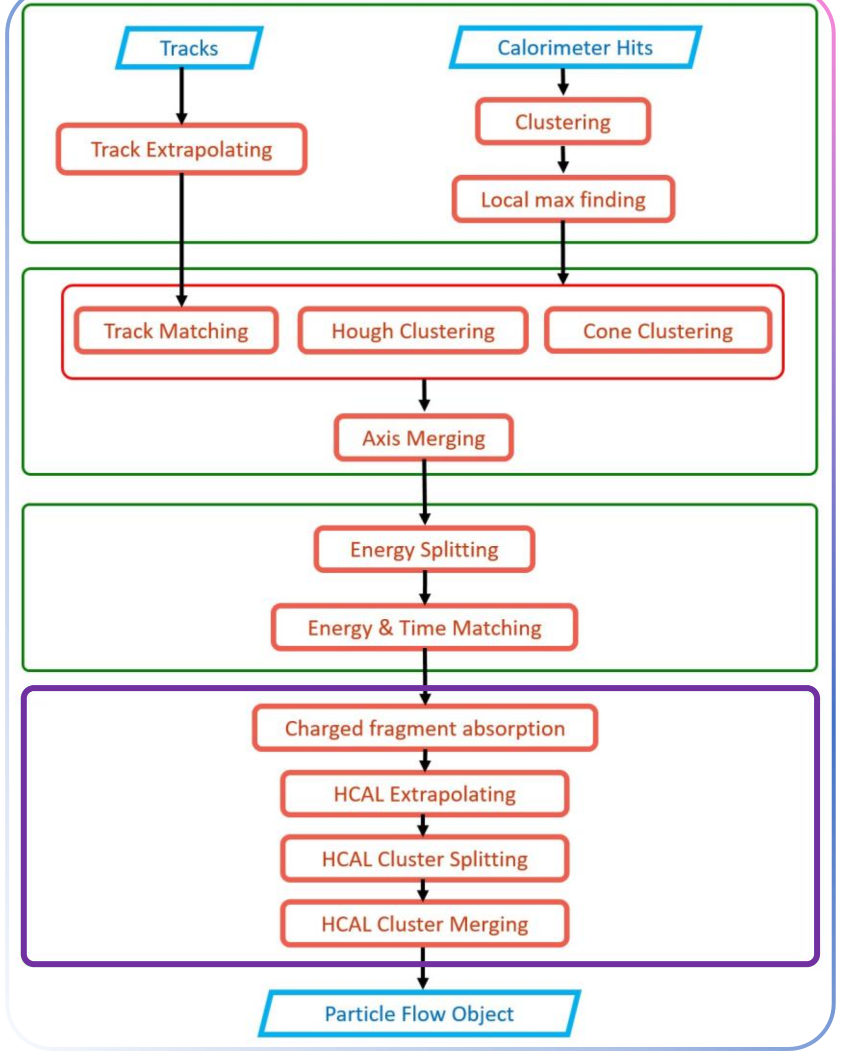
Event display: 2 photons, $E_\gamma = 5$ GeV, distance = 15×15 cm.



Task list in PFA reconstruction:

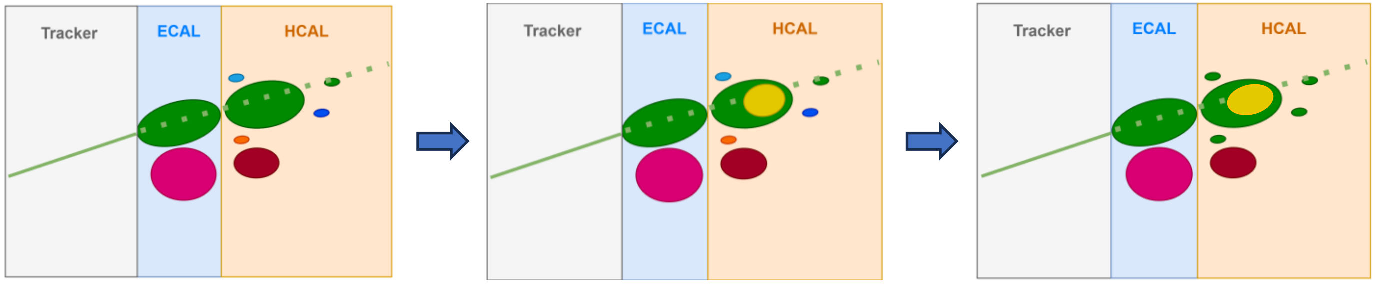
- ✓ Clustering
- ✓ Pattern recognition.
- ✓ Shower splitting for overlap
- ✓ Ambiguity removal

CyberPFA



Step 4: clustering and reclustering

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



Extrapolate track to connect ECAL and HCAL clusters

Split a neutral cluster if $E_{cluster} > P_{track}$

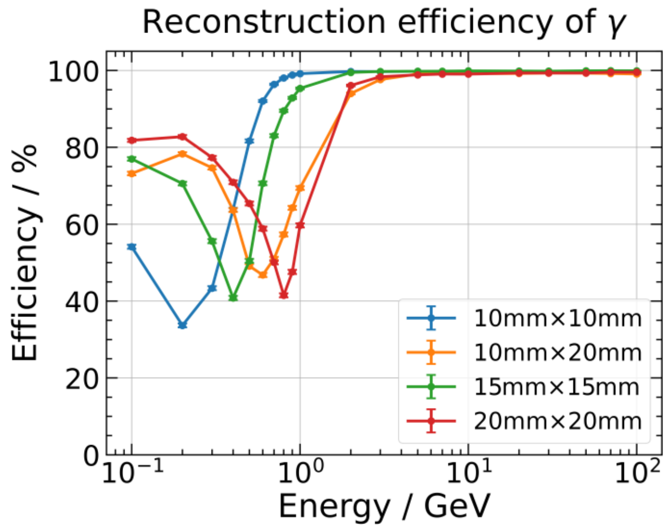
Check and merge fragments into core cluster.

Task list in PFA reconstruction:

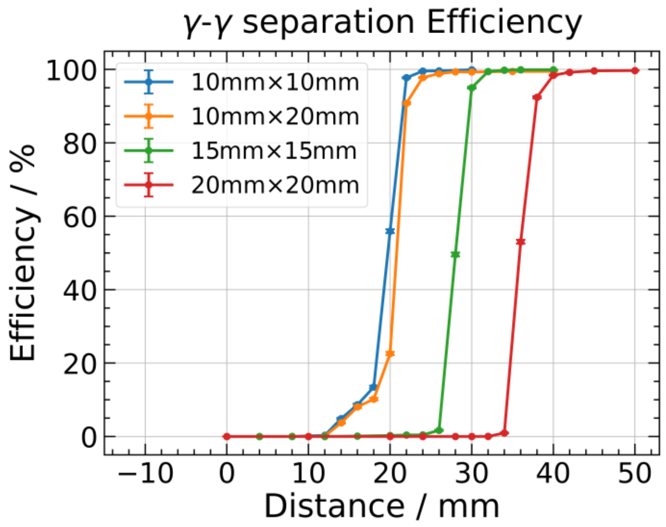
- ✓ Clustering
- ✓ Pattern recognition.
- ✓ Shower splitting for overlap
- ✓ Ambiguity removal
- ✓ Full PFA

Granularity optimization

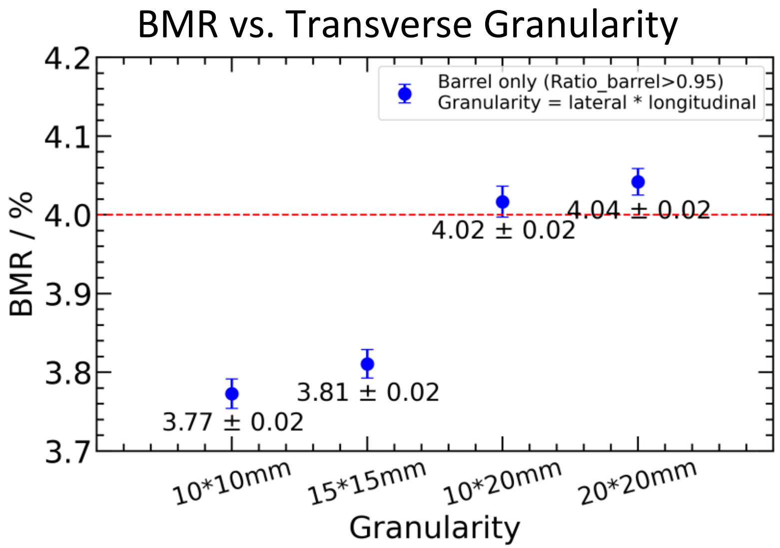
- **Four typical scenarios of transverse granularity investigated**
  - 10×10mm, 10×20mm, 15×15mm and 20×20mm
- **Figures of merit**
  - Single photon reconstruction, separation power and jet performance



Major impact from ECAL longitudinal segmentation



Separation efficiency dominated by ECAL transverse granularity



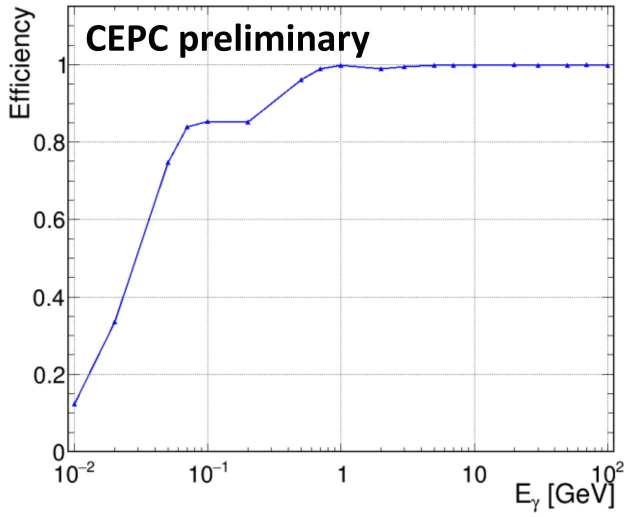
10x10mm and 15x15mm can meet physics requirement of BMR <4%

Conclusion: ECAL granularity of $\mathbf{15 \times 15\ mm^2}$ selected for the baseline design

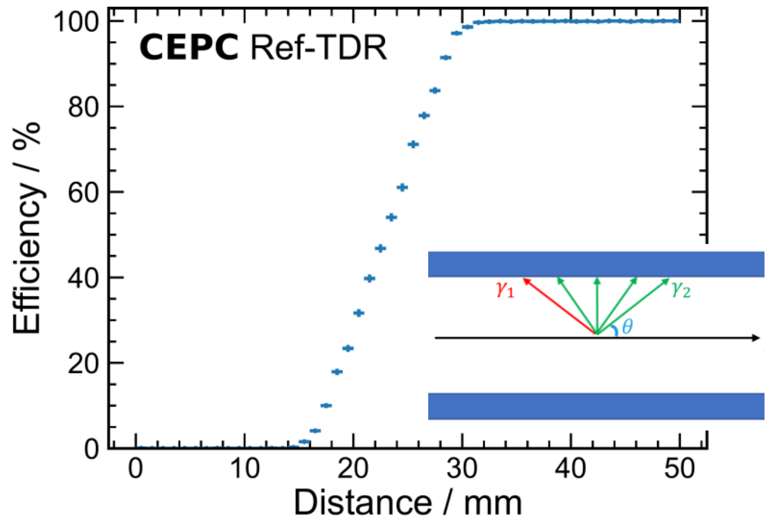
Photon reconstruction performance

- **Core ECAL mission: precise measurement of photons**
- **Essential and fundamental constituent in jet and other process**

- **Performance result**
  - γ reconstruction: ~100% efficiency for $E_\gamma > 1\text{GeV}$
  - γ-γ separation: ~100% efficiency for distance$> 30\text{mm}$



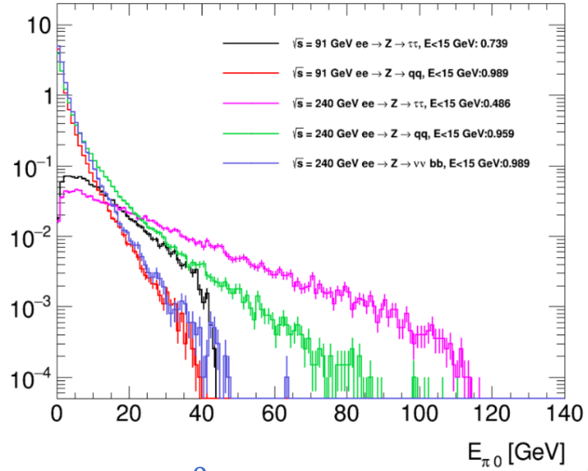
Single γ reconstruction



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

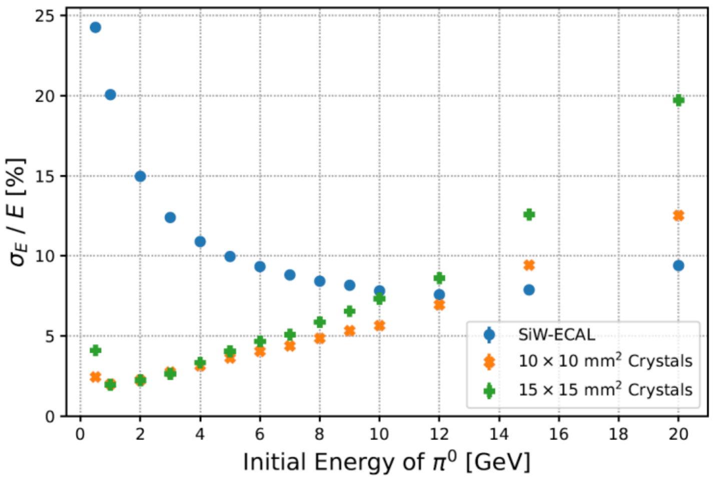
Physics performance: $\pi^0 \to \gamma\gamma$

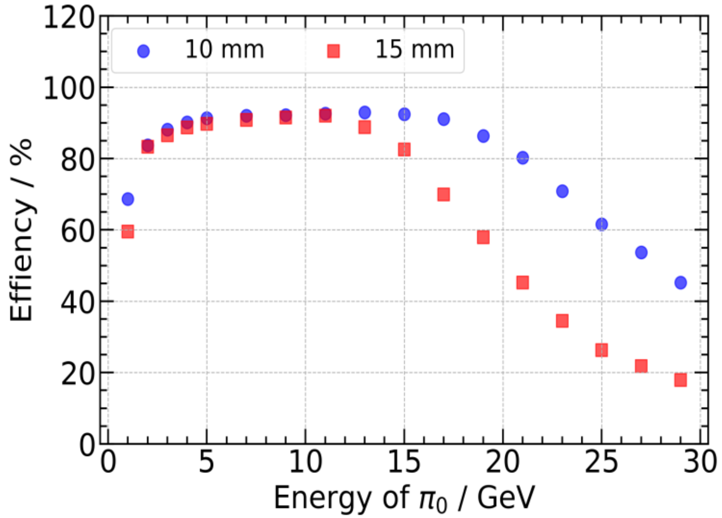
- **π^0: essential EM object in flavor studies in Tera-Z factory**
  - $B^0/B_s^0 \to \pi^0\pi^0/\eta\eta$ and CP asymmetry
  - τ hadronic decay for $H \to \tau\tau$ and $Z \to \tau\tau$
- **Preliminary study with single π^0**
  - Much better mass resolution than sampling calorimeter in low energy
  - Higher efficiency in high energy region from shower splitting
  - Second momentum further improves high-energy π^0 efficiency

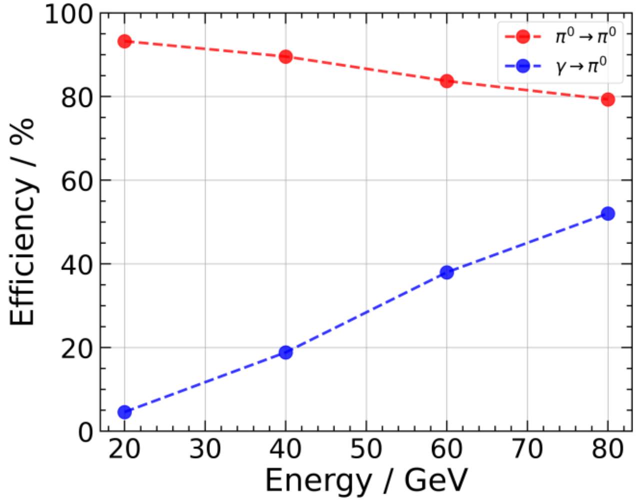


Energy of π^0 in τ and jets from H/Z

Mass Resolution of π^0

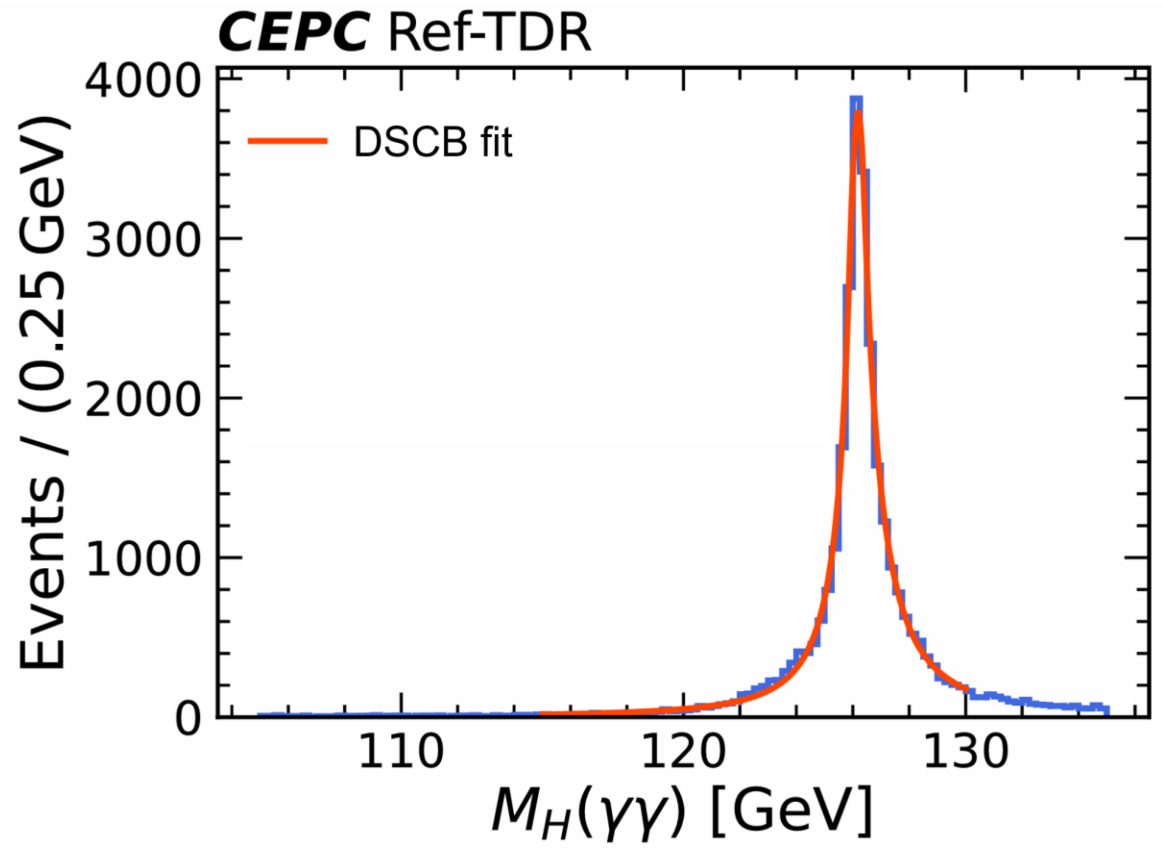






Physics performance: $H \to \gamma\gamma$

- **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.



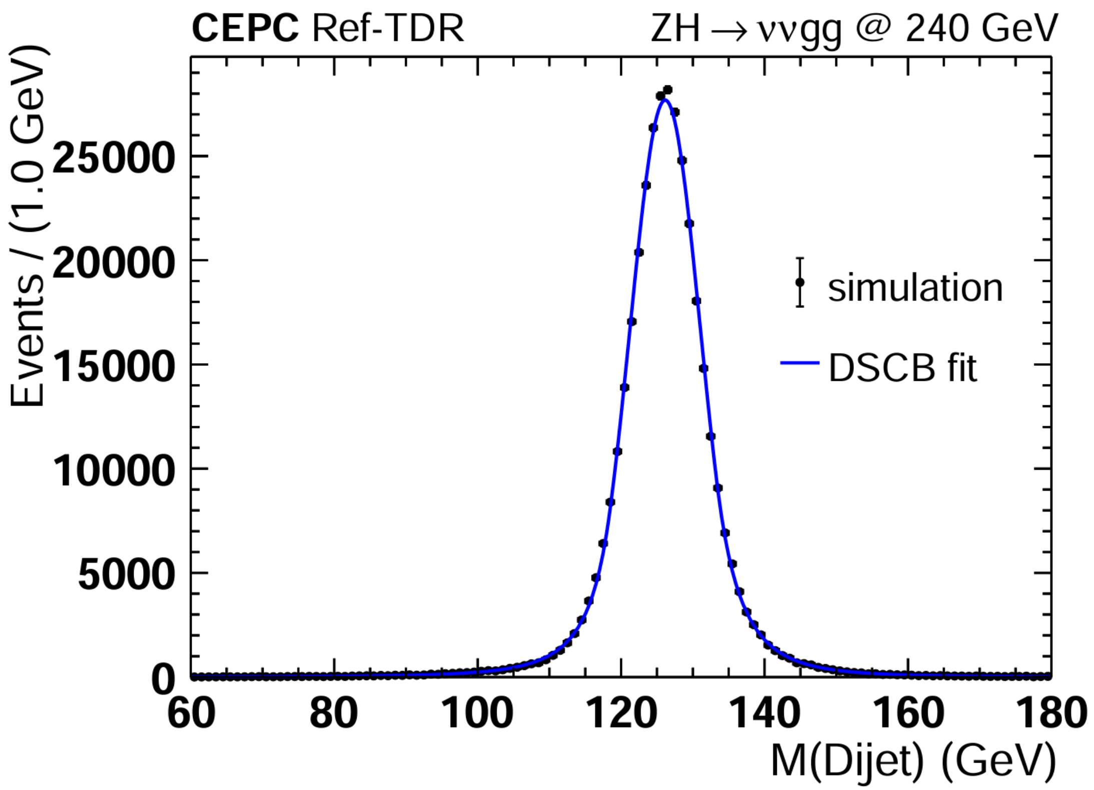
Fit with double-sided crystal ball function

$mean = 126.185 \pm 0.005$ GeV,
$\sigma = 0.397 \pm 0.006$ GeV

Boson mass resolution (BMR): $0.31 \pm 0.10\%$.

Physics performance: $H \to gg$

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



Reconstruction for $|\cos\theta_{jet}| < 0.85$
Fit with double-sided crystal ball function

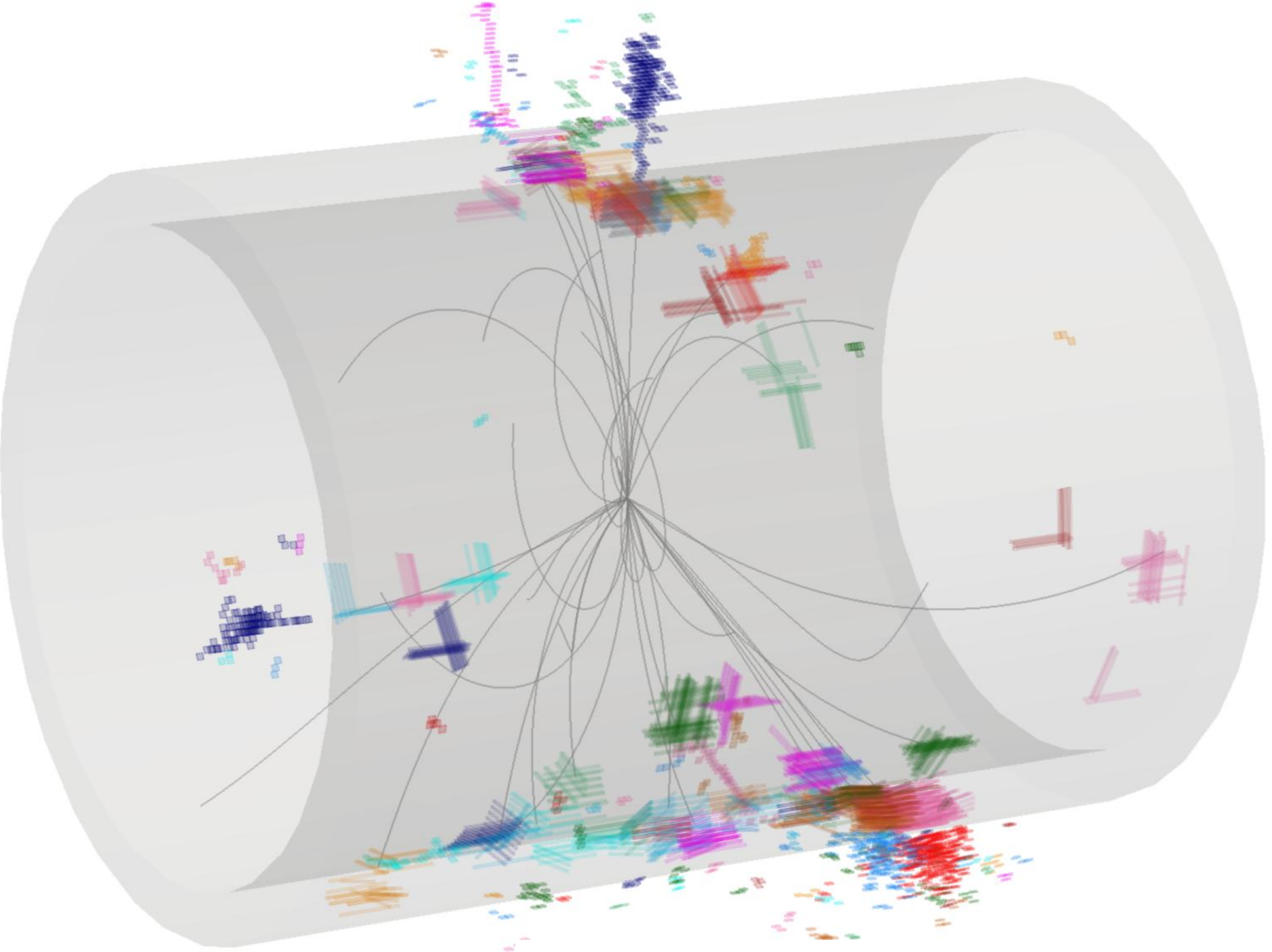
$m_{jj} = 126.14 \pm 0.01$ GeV,
$\sigma_{jj} = 4.89 \pm 0.01$ GeV
Boson mass resolution (BMR) $3.87 \pm 0.10\%$.

Summary and outlook

- **Crystal ECAL for CEPC reference detector**
  - Following PFA concept.
  - Satisfy the jet energy resolution requirement in future lepton collider.
  - Optimal EM resolution for flavor physics.
  - Transverse granularity optimized to $15 \times 15\text{mm}^2$
- **CyberPFA for the crystal ECAL:**
  - Main challenges: overlapping & ambiguity.
  - Series of algorithms are developed and show promising results.
  - Boson Mass Resolution (BMR) ~3.87%.
- **Future plan:**
  - Optimization of PFA performance: cluster ID, energy correction, advanced pattern recognition, …

Thank you for your attention!

Backup



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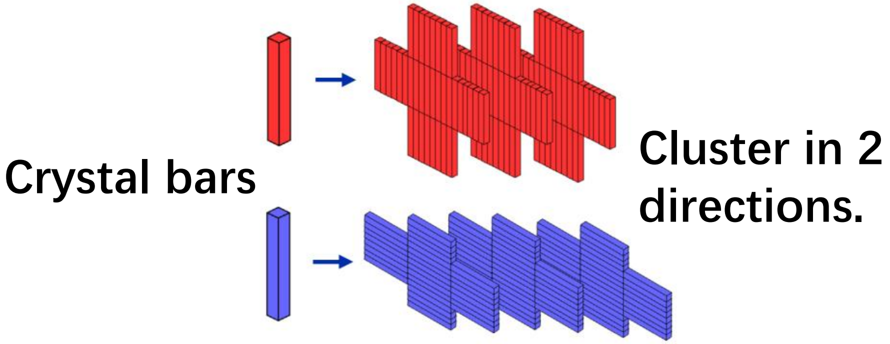
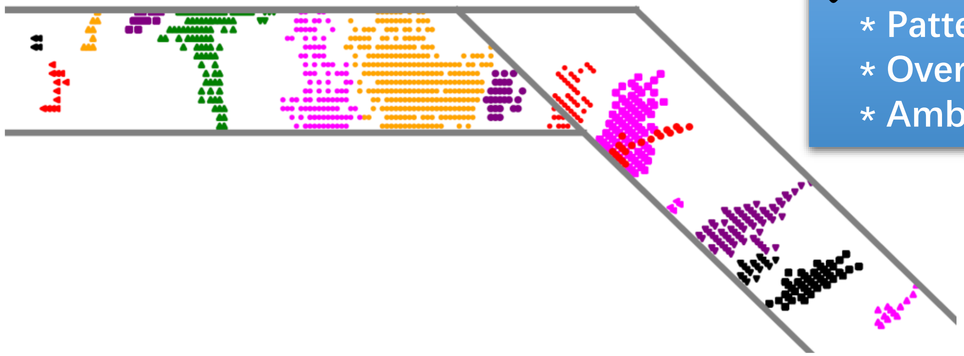
Institute of High Energy Physics, Chinese Academy of Sciences

Clustering & recognition

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





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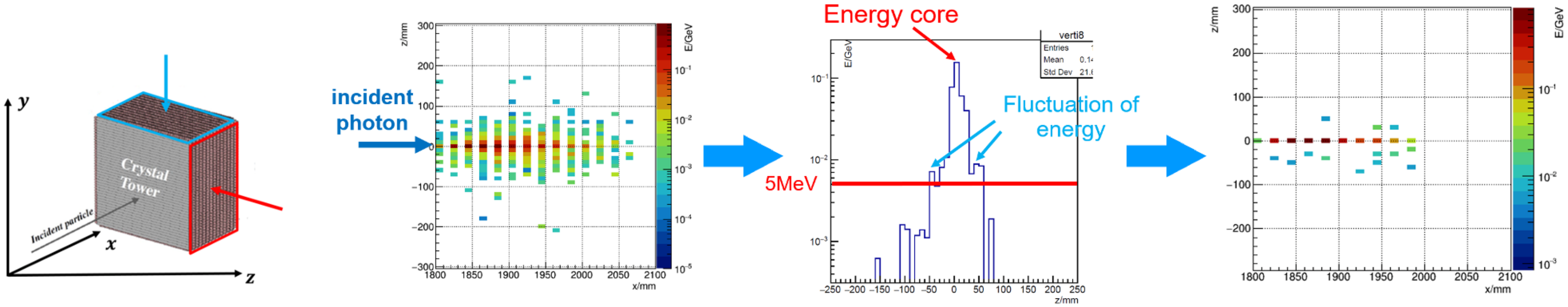
- * Pattern recognition.
- * Overlap: energy splitting.
- * Ambiguity problem.

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



Energy deposits in crystals

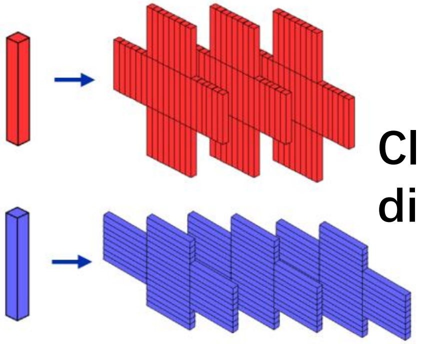
Picking out local-max in each layer

Local Maximum Distribution

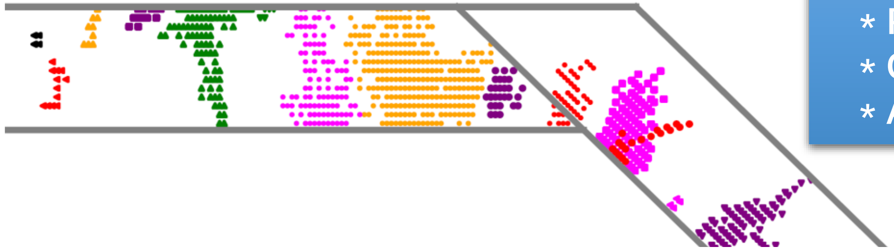
Clustering & recognition

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

Crystal bars

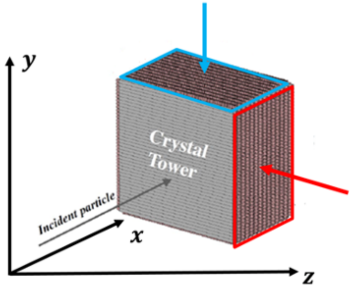


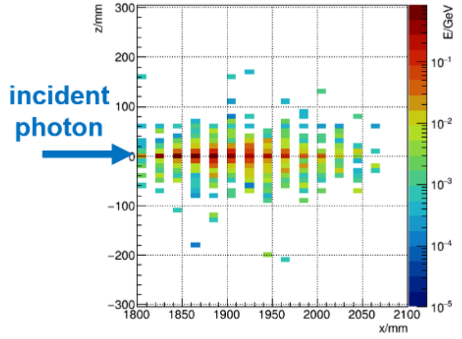
Cluster in 2 directions.



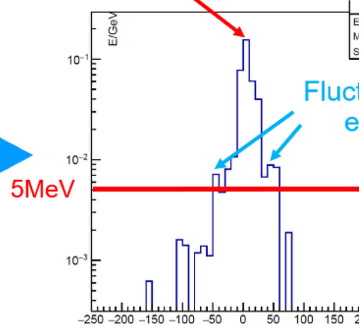
Software task:
- * Clustering
- * Pattern recognition.
- * Overlap: energy splitting.
- * Ambiguity problem.

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

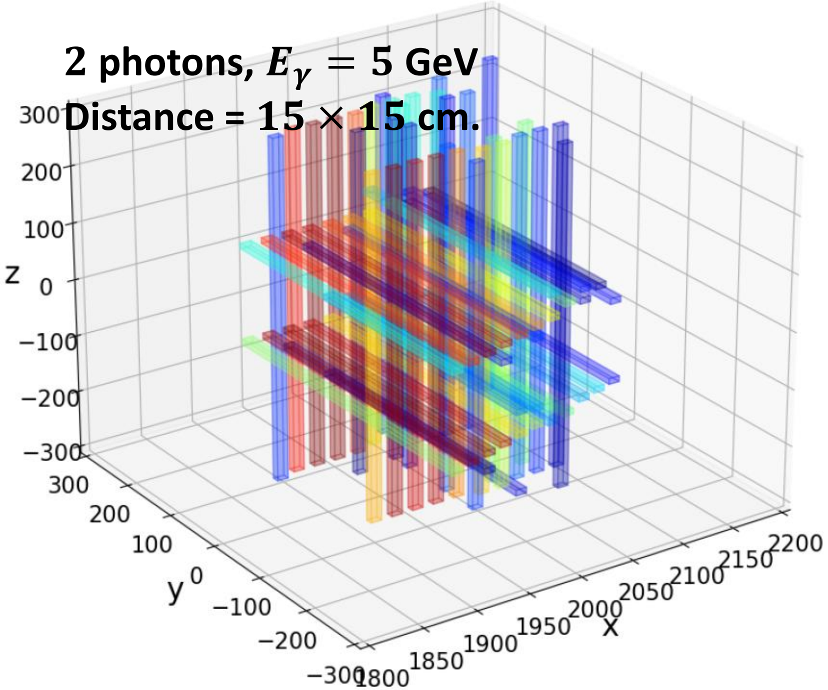




Energy deposits in crystals

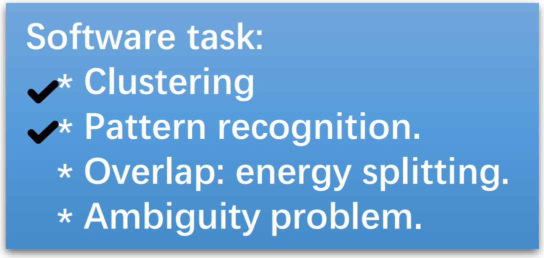


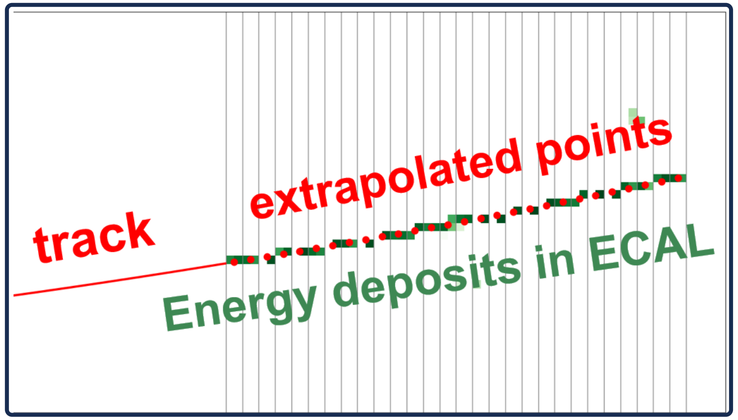
Picking out local-max in ea

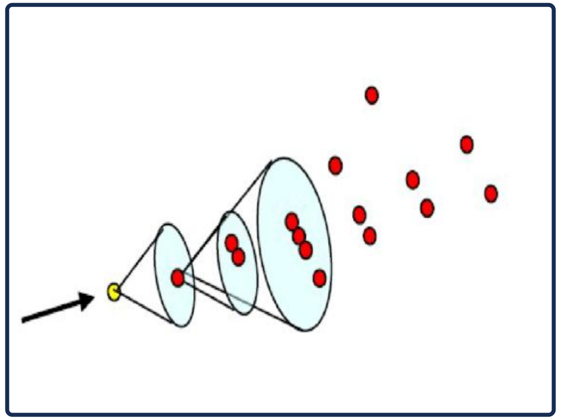


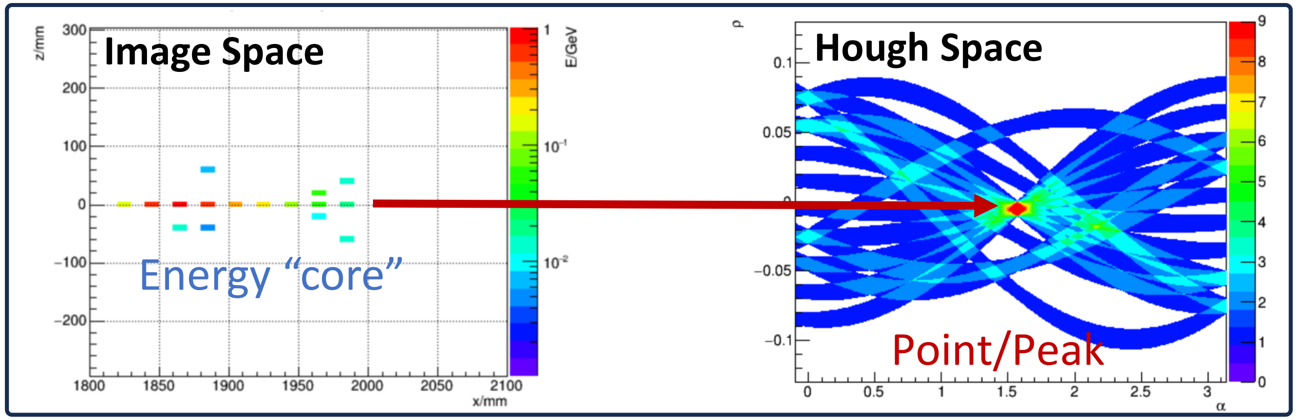
Clustering & recognition

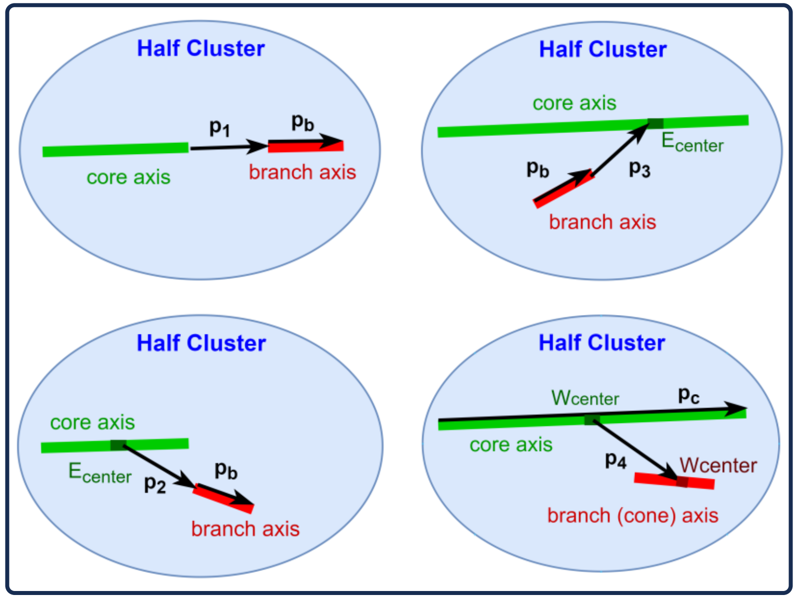
- **Shower recognition:**
  - 3 individual algorithms for different type: track-match, Hough, Cone-clustering.
  - A set of topological cluster merging.











Clustering & recognition

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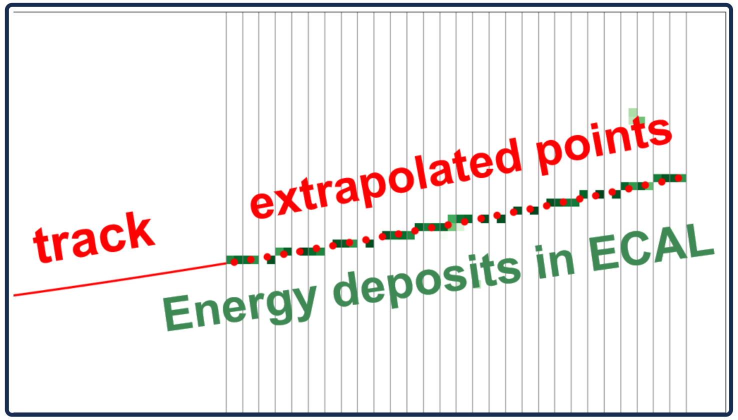
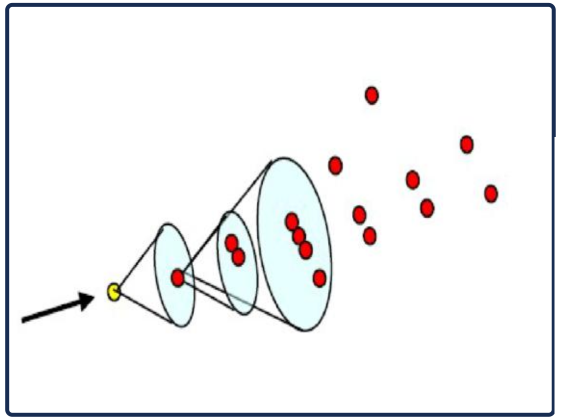
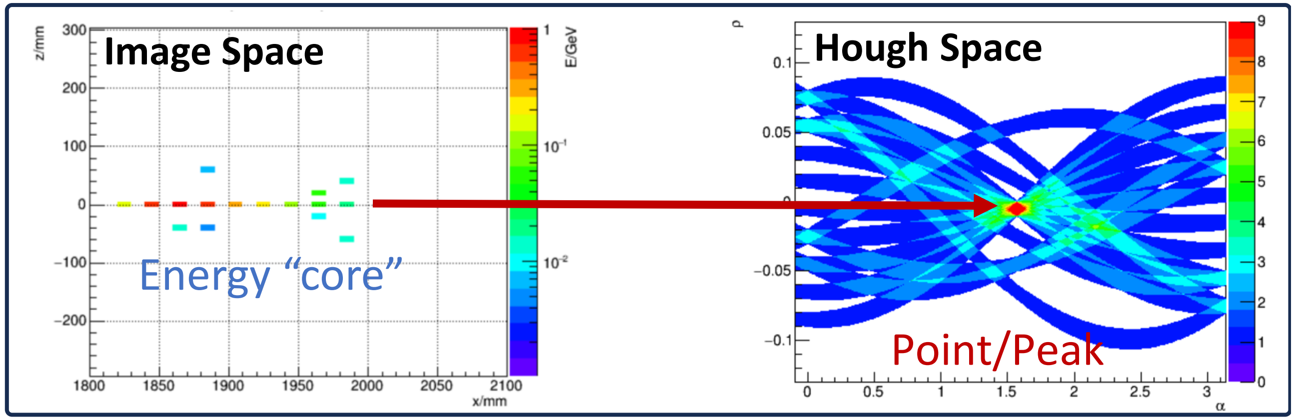
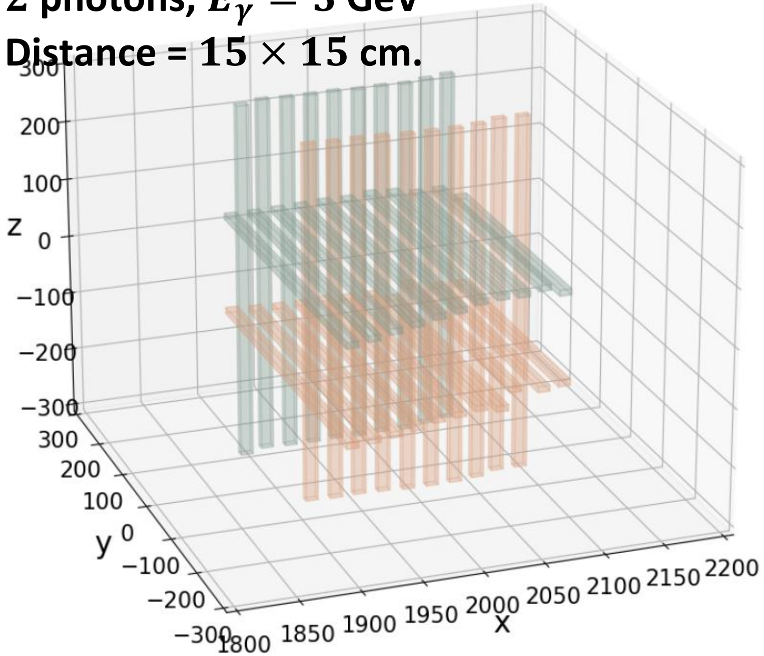






Software task:
- ✔ * Clustering
- ✔ * Pattern recognition.
- * Overlap: energy splitting.

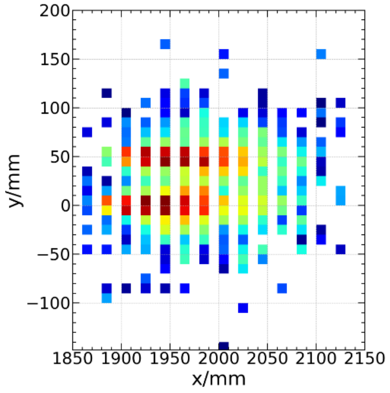
2 photons, $E_\gamma = 5$ GeV
Distance = 15×15 cm.

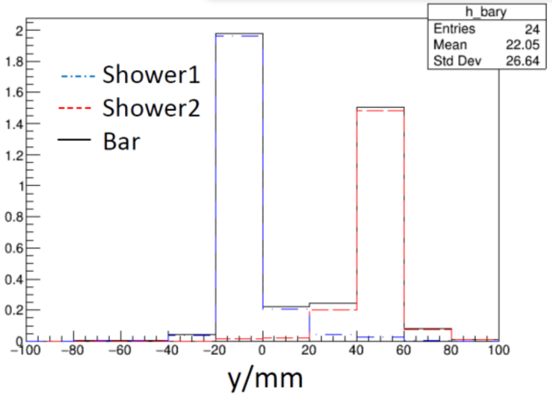


Energy splitting and matching

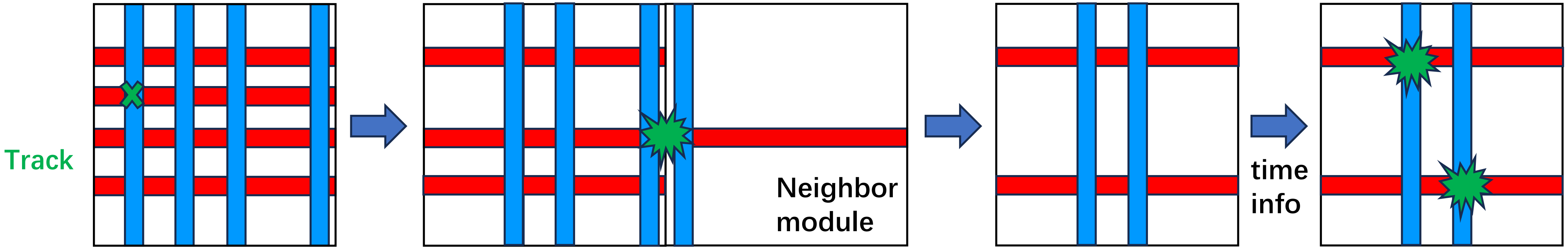
- **Splitting for the overlapped shower:**
  - Calculate the expected energy deposition from EM profile.
    - Expected energy : $E_{i\mu}^{exp} = E_{\mu}^{seed} \times f(|x_i - x_c|)$
    - Assigned weight: $w_{i\mu} = \frac{E_{i\mu}^{exp}}{\sum_{\mu} E_{i\mu}^{exp}}$

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



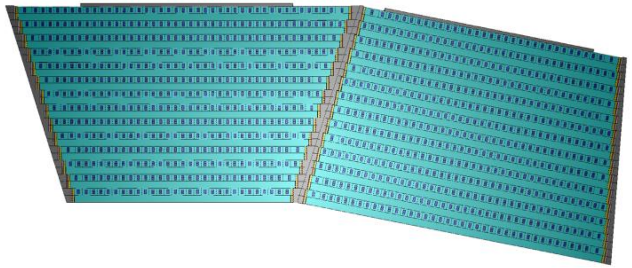


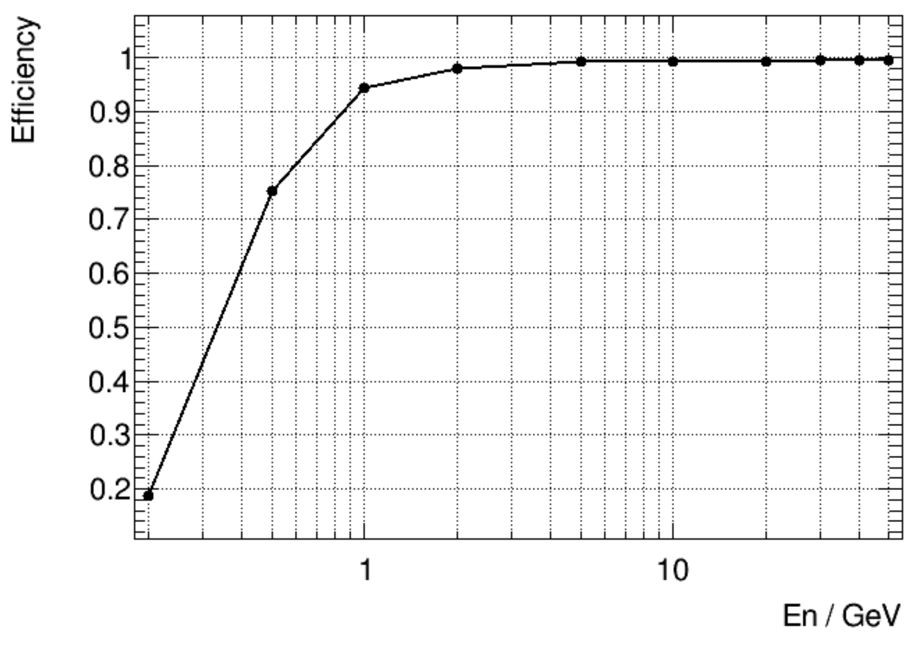
- **Ambiguity removal:**
  - Information from: track, neighbor tower, time.

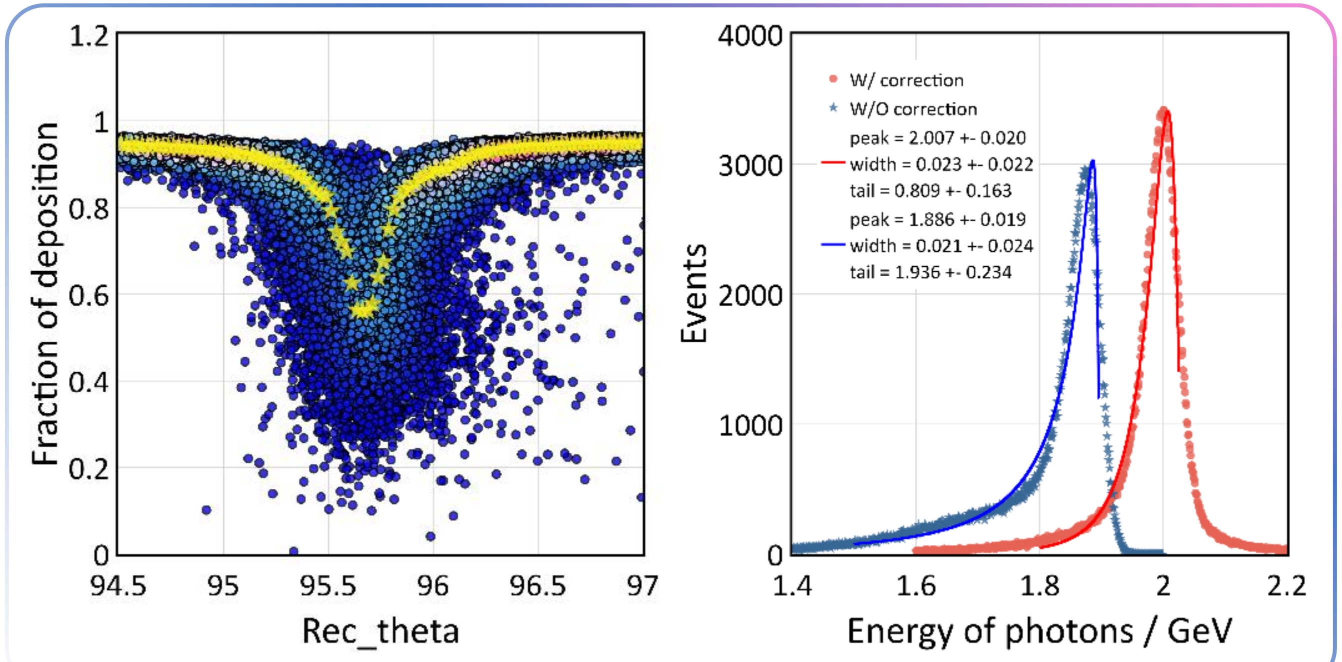


Physics performance: single photon

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

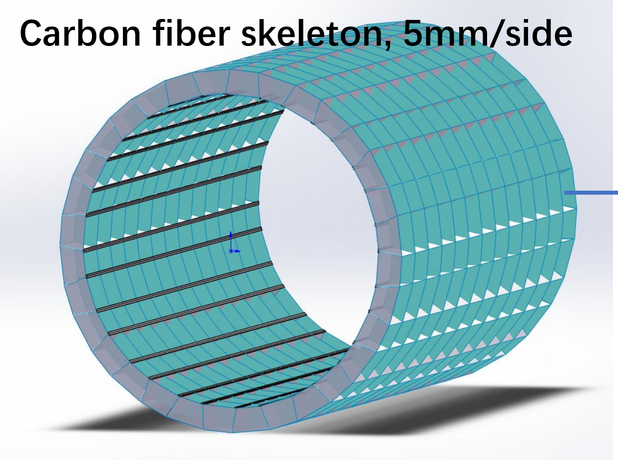


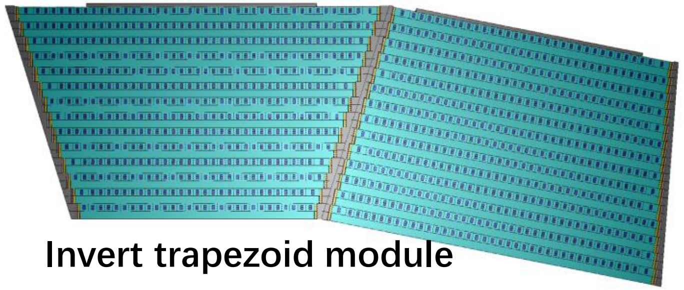


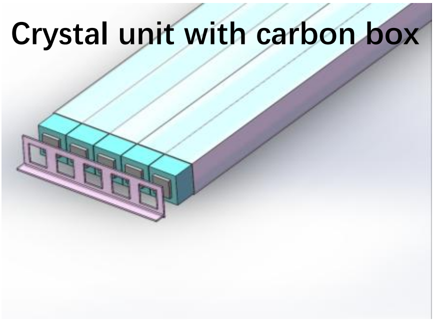


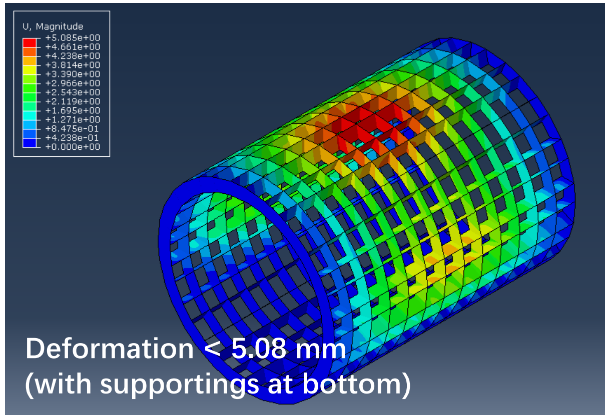
Mechanics design

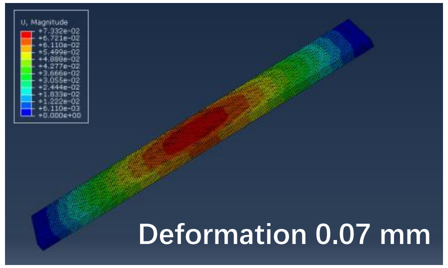
- **Carbon fiber skeleton and unit strength**





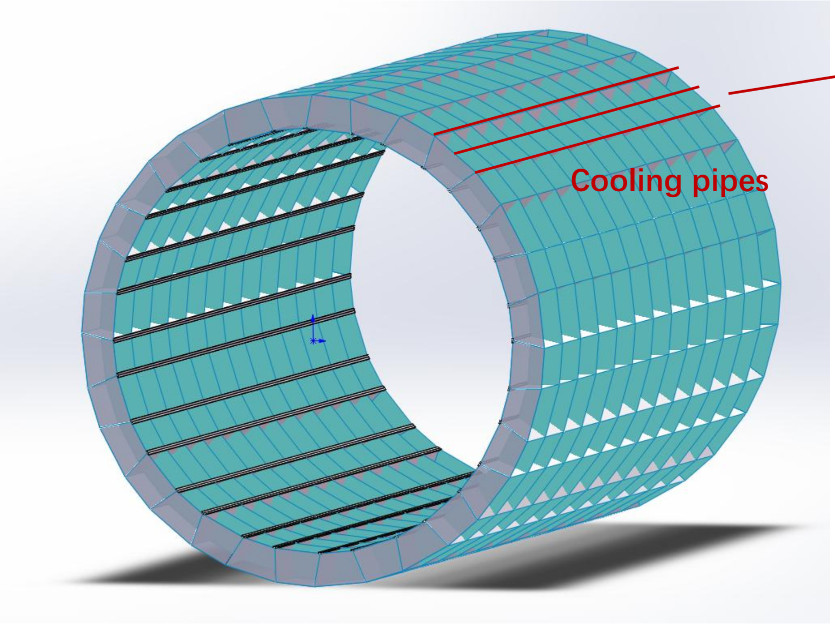




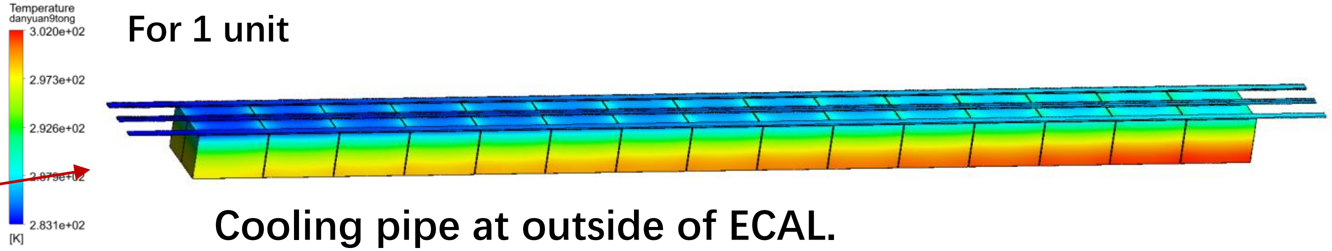


Cooling design

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

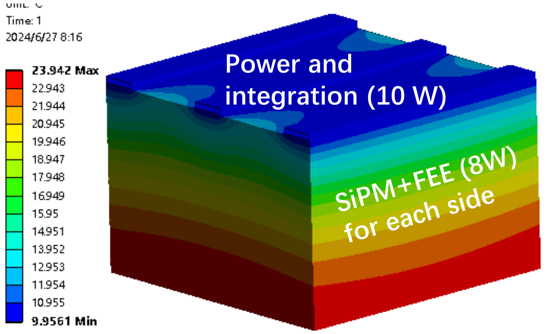


For 1 unit



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