PFA reconstruction for the crystal bar ECAL in future lepton colliders

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IHEP, CAS

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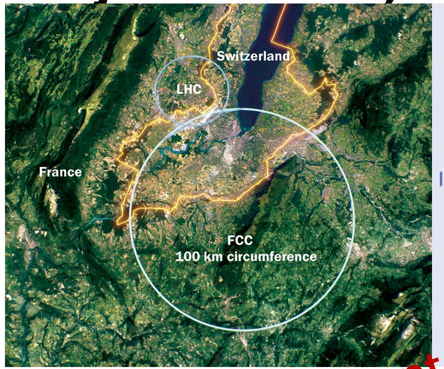
CTICC CAPE TOWN SOUTH AFRICA

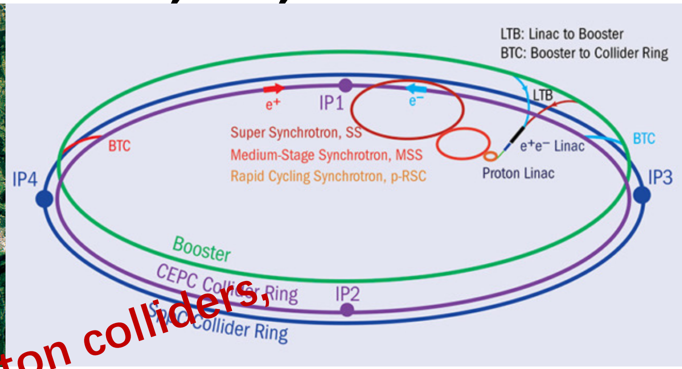
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

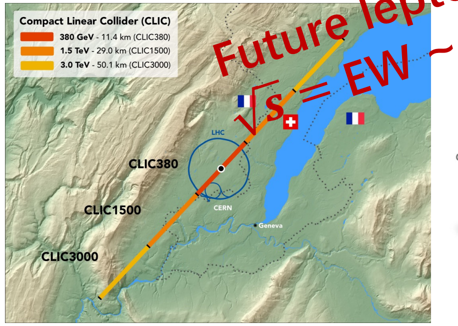
Future lepton collider

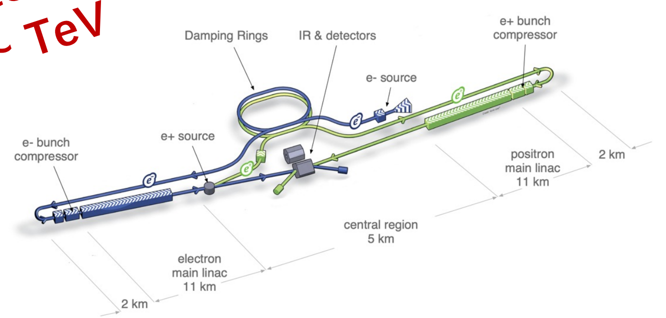
- **Physics after Higgs discovery:**
  - Precise measurement of Higgs, EW, top, flavor, QCD…
  - BSM physics (dark matter, EW phase transition, SUSY, LLP…)

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

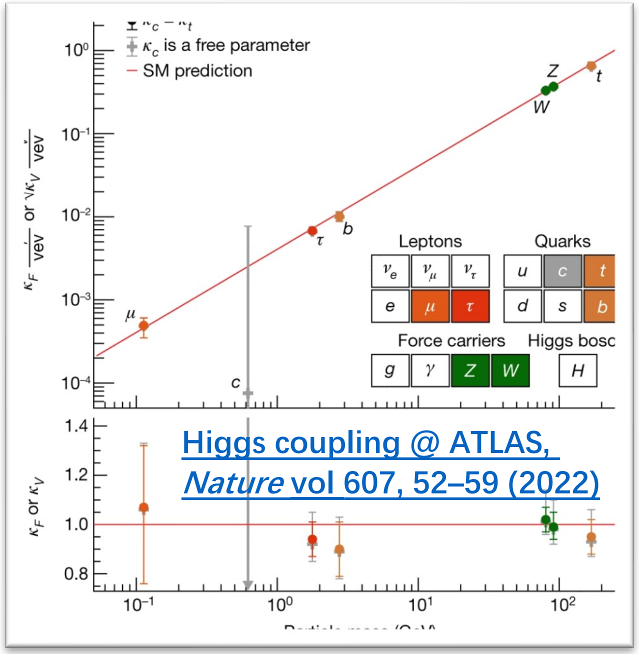




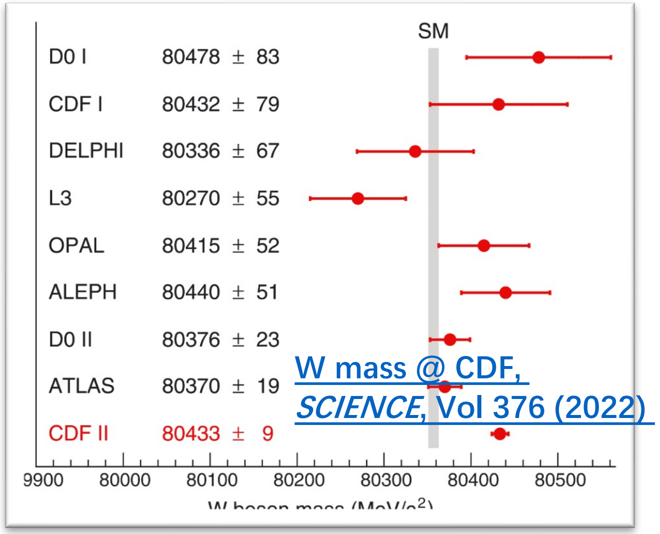




Future lepton colliders, $\sqrt{s}$ = EW ~ TeV



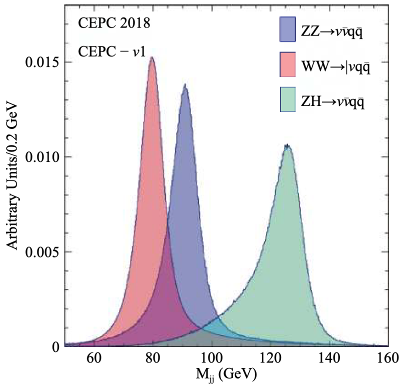
[Higgs coupling @ ATLAS, *Nature* vol 607, 52–59 (2022)]

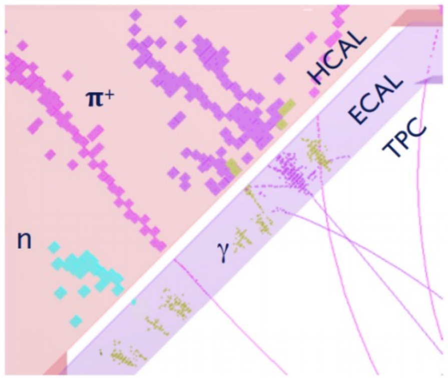


[W mass @ CDF, *SCIENCE*, Vol 376 (2022)]

Future lepton collider

- **Detector requirement:**
  - For hadronic final states $W^{\pm}/Z/H \rightarrow q\bar{q}$: BMR<4%
  - For flavor: precise PID in heavy quark decay
    K/π separation, jet tagging, jet charge, etc.

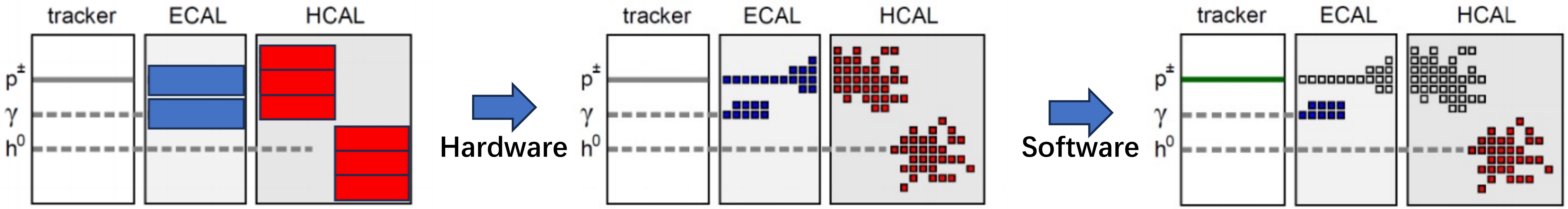




- **Particle Flow Approach:**
  - Measure the jet by its components: $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$
  - Hardware + Software:

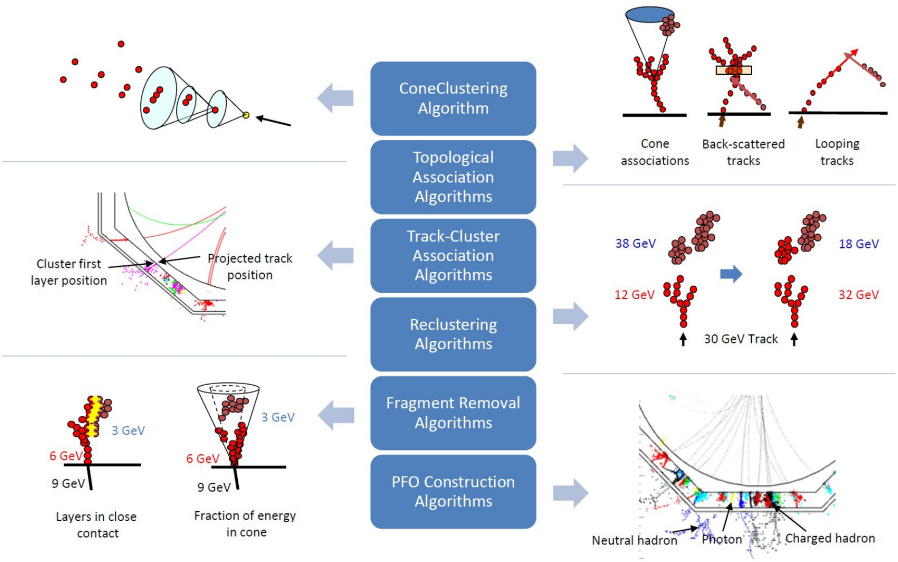
Hardware: separate clusters from different particles.
- High granularity.
- Compact sampling structure.

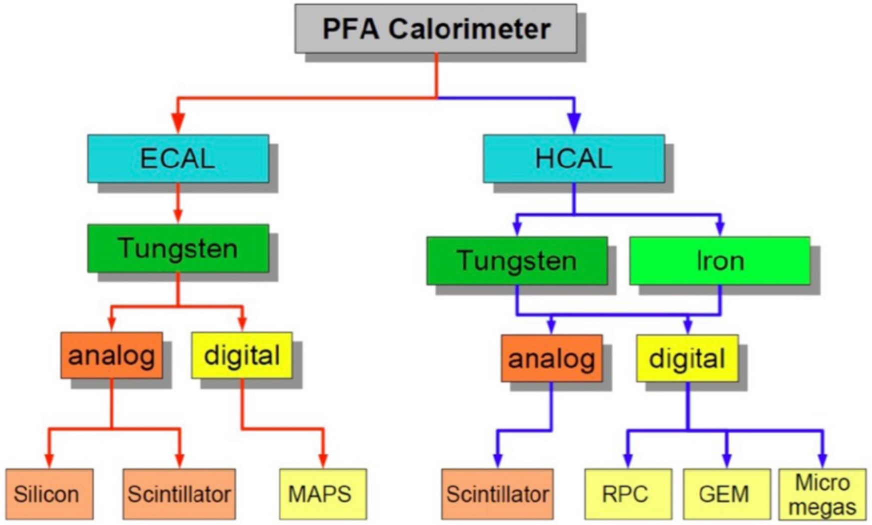
Software: correctly assign calorimeter energy deposits to the particles.
- Clustering
- Pattern recognition.

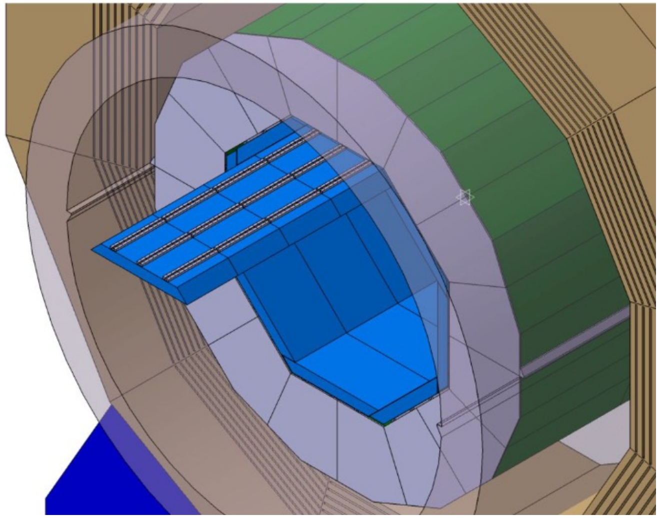


Calorimetry and PFA

- **CALICE concept: sampling calorimeter.**
  - ECAL: Si/Sci + W
  - HCAL: Sci/RPC + W/Iron
  - High granularity.
  - PFA reconstruction: PandoraPFA.







Can we think about a homogeneous ECAL?

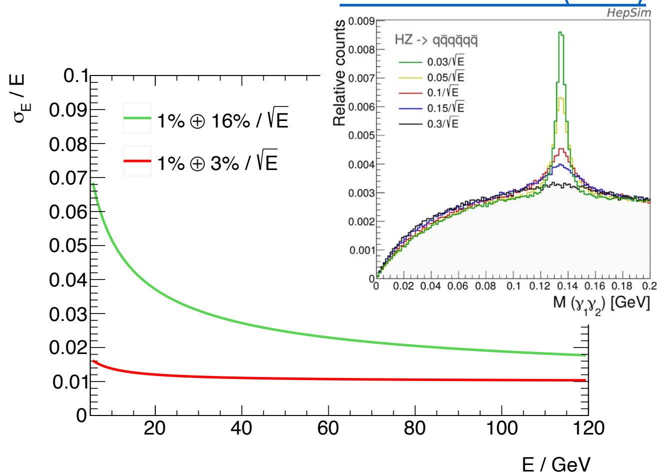
Homogeneous ECAL

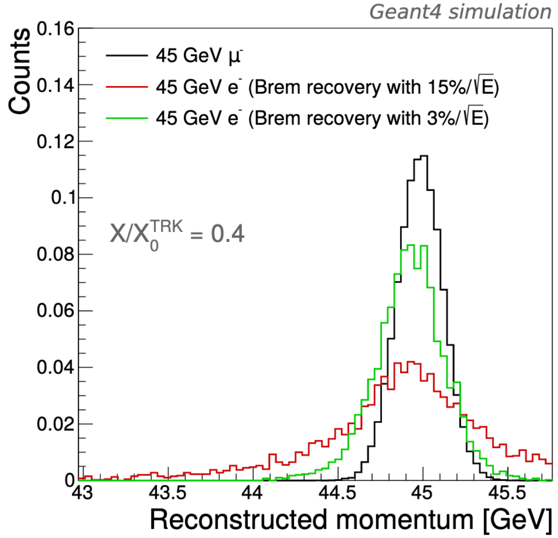
- **Why crystal calorimeter**
  - A long history in particle physics precise measurement:
    L3@LEP, BESIII@BEPC, CMS@LHC, HERD, Panda…
  - Bright light: $\sigma_E/E \sim 3\%/\sqrt{E}$
    - Photon recovery from bremsstrahlung,
    - π^0 reconstruction.
  - Fast response:
    - Introduce timing in PFA.

	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.

JINST **15** P11005 (2020)

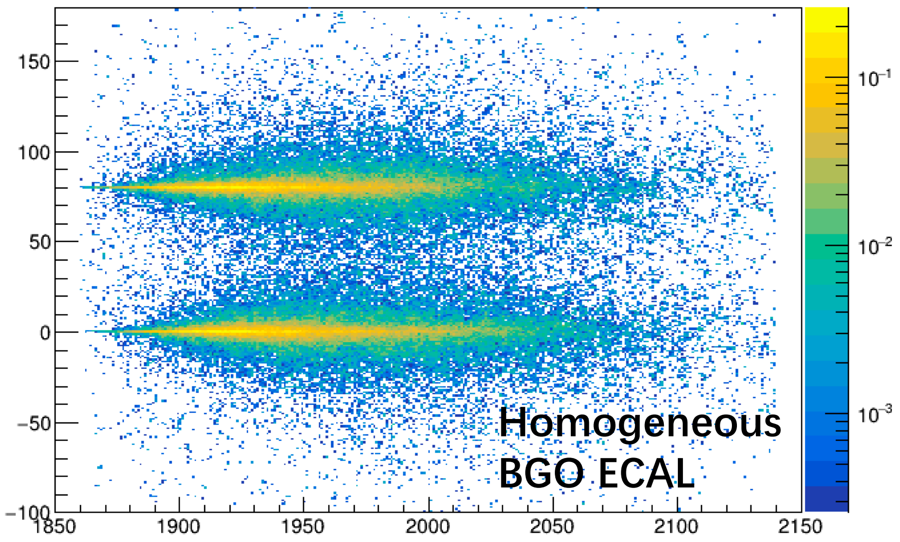


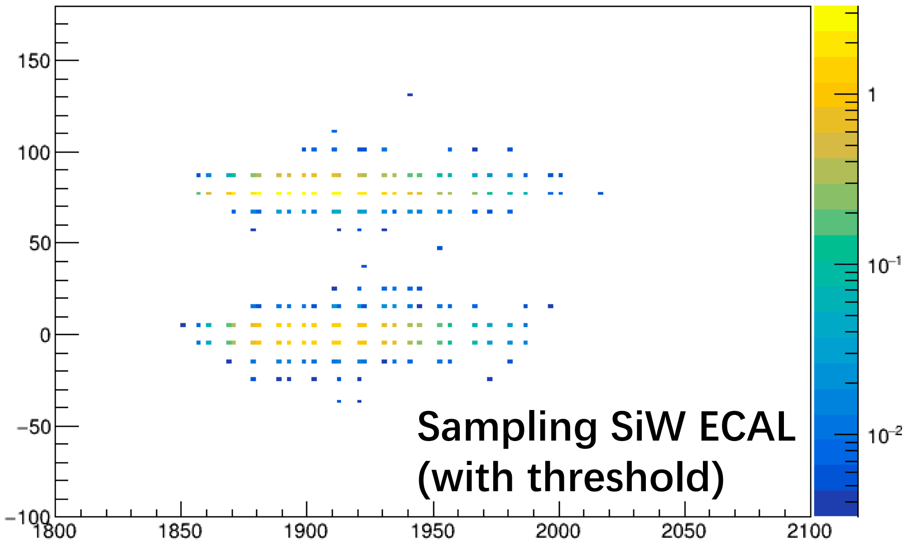


Homogeneous ECAL

- **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).

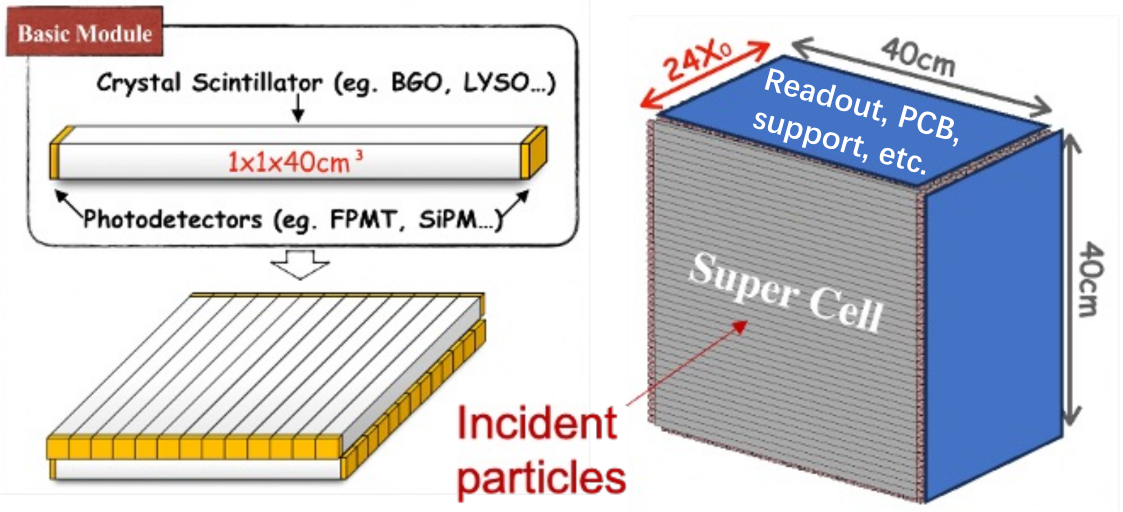
Software task:
* Clustering
* Pattern recognition.
+ Overlap: energy splitting.

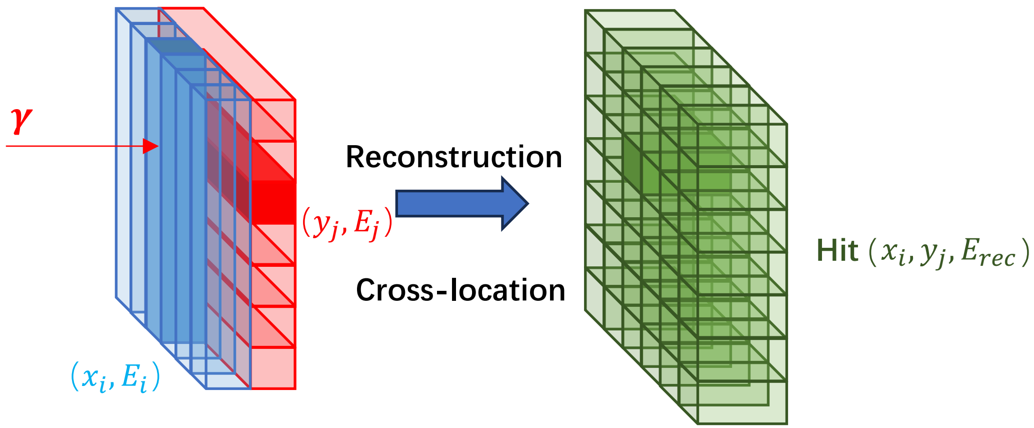




Homogeneous ECAL

- **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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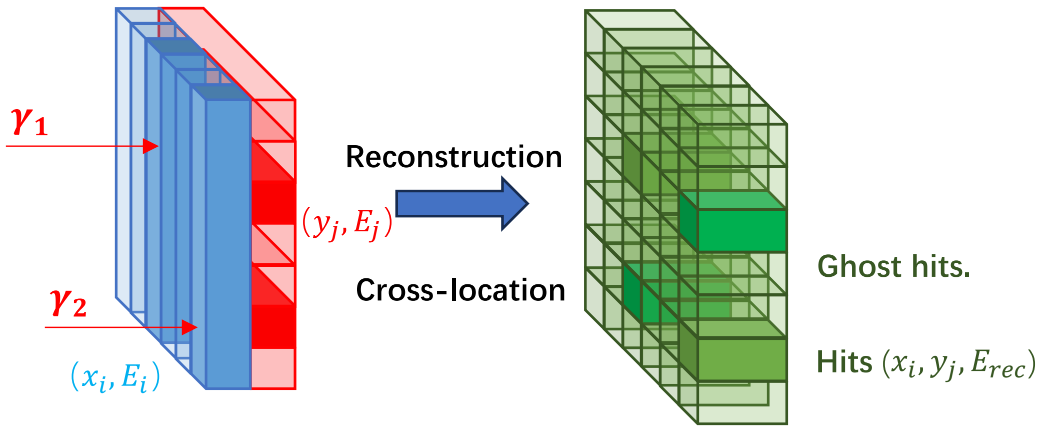

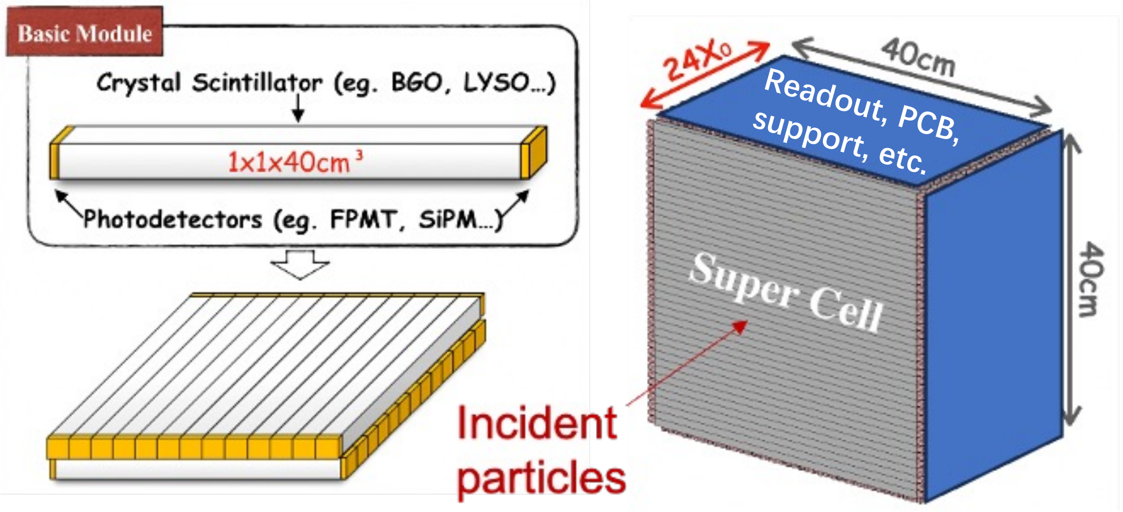

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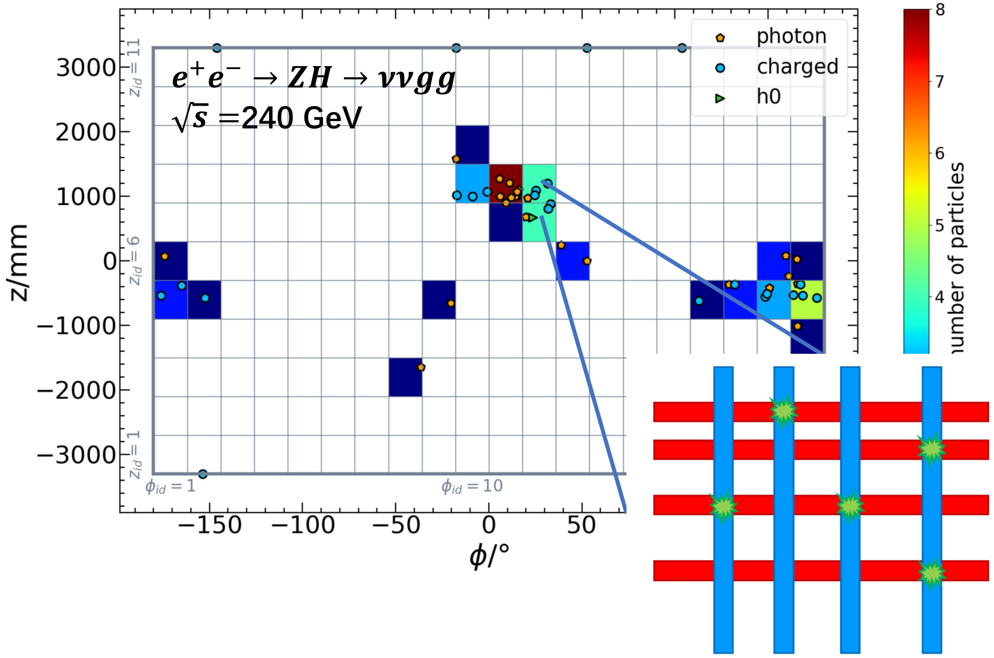

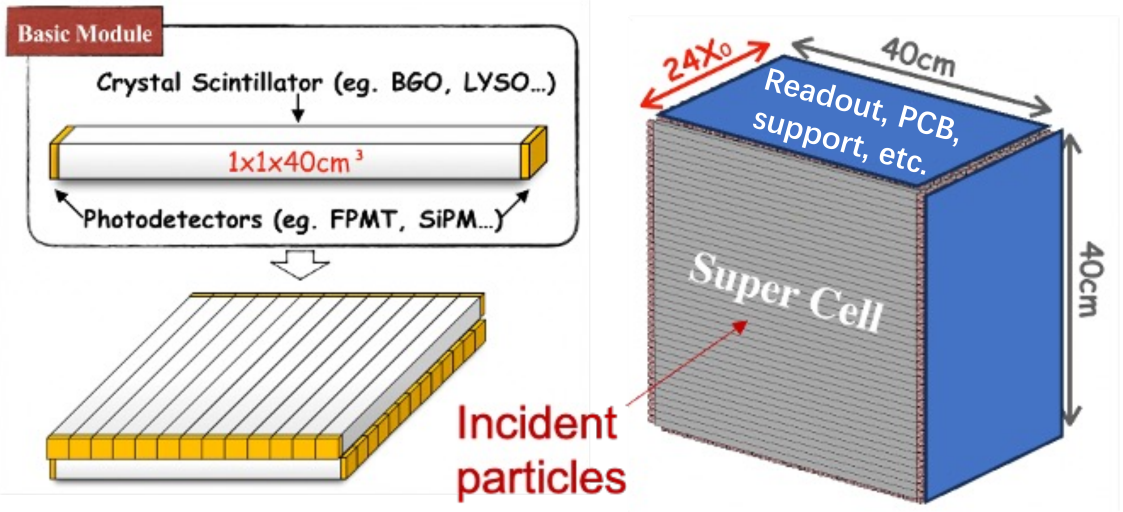

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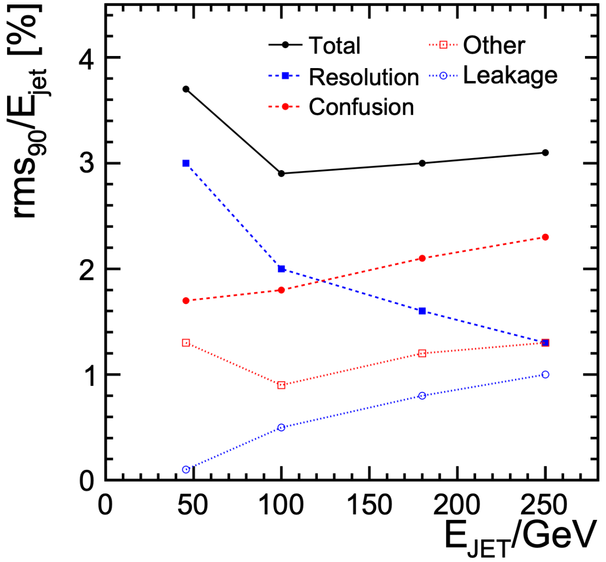
Particle flow algorithm

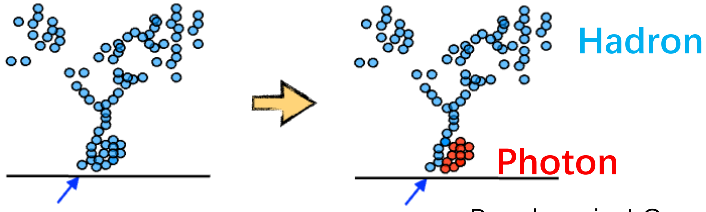
- **PF performance decoupling**
  - $\sigma_{jet} \sim \sigma_{trk} \oplus \sigma_{EM} \oplus \sigma_{Had} \oplus \sigma_{confusion}$. **Confusion is an important limitation factor.**

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.



Pandora in LC

e.g. Perfect photon reconstruction

Particle flow algorithm

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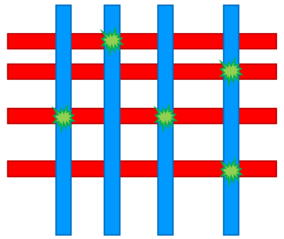
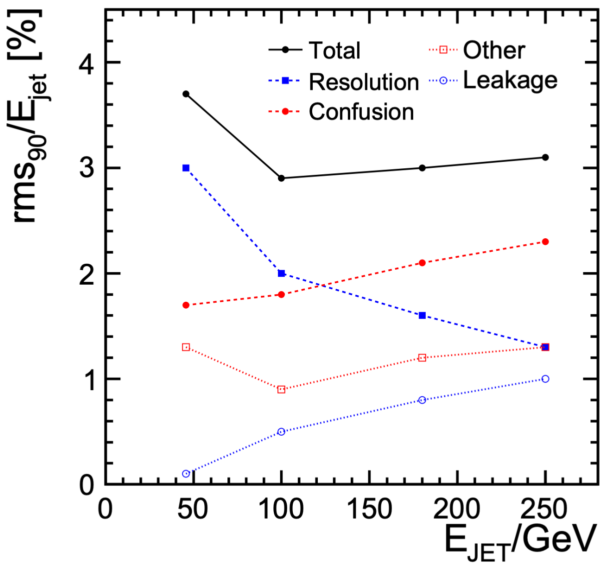
Crystal ECAL improves the intrinsic resolution

iv) Confusion (ambiguity)



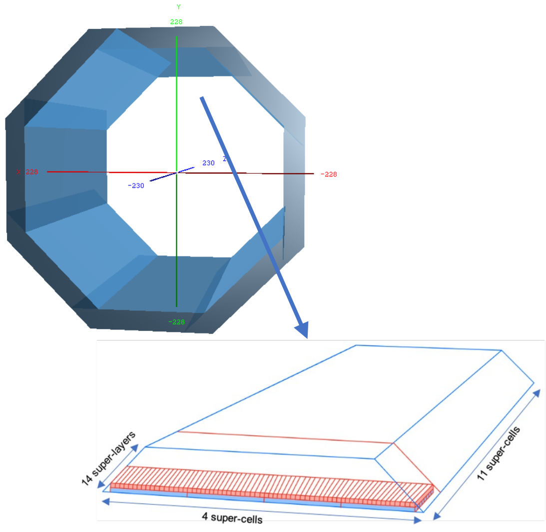


PandoraPFA, Nim.A Vol 611, Issue 1, 2009

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

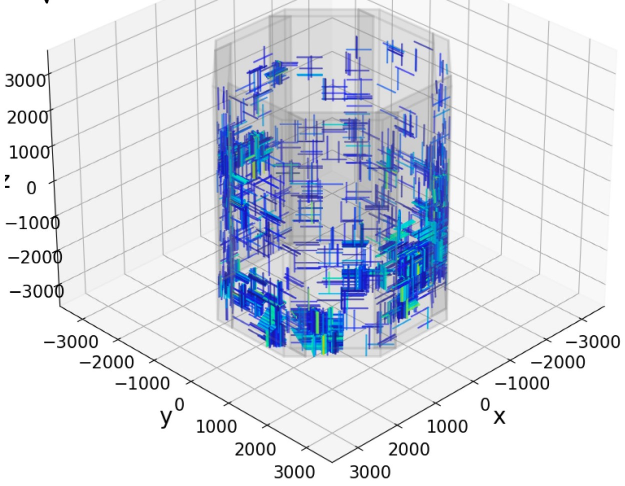
Simulation

- **Detector geometry**
  - Global: octagonal ECAL, $R = 1.86\ \text{m}, L = 6.6\ \text{m}, H = 28\ \text{cm}$
  - Crystal Bar: $1\times1\times40\sim60\ \text{cm}^3$
  - Super Cell: 2 layers of perpendicular crossing bars $\sim40\times\sim60\times2\ \text{cm}^3$
  - Ideal digitization: no dead area, supporting, mechanics, etc.

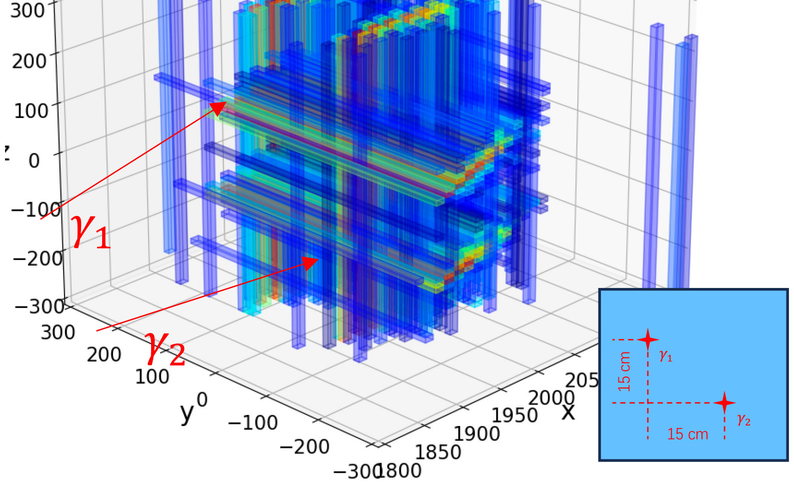


- **How events look like**

$e^+e^- \to ZH \to \nu\nu + 2jets,$
$\sqrt{s} = 240$ GeV

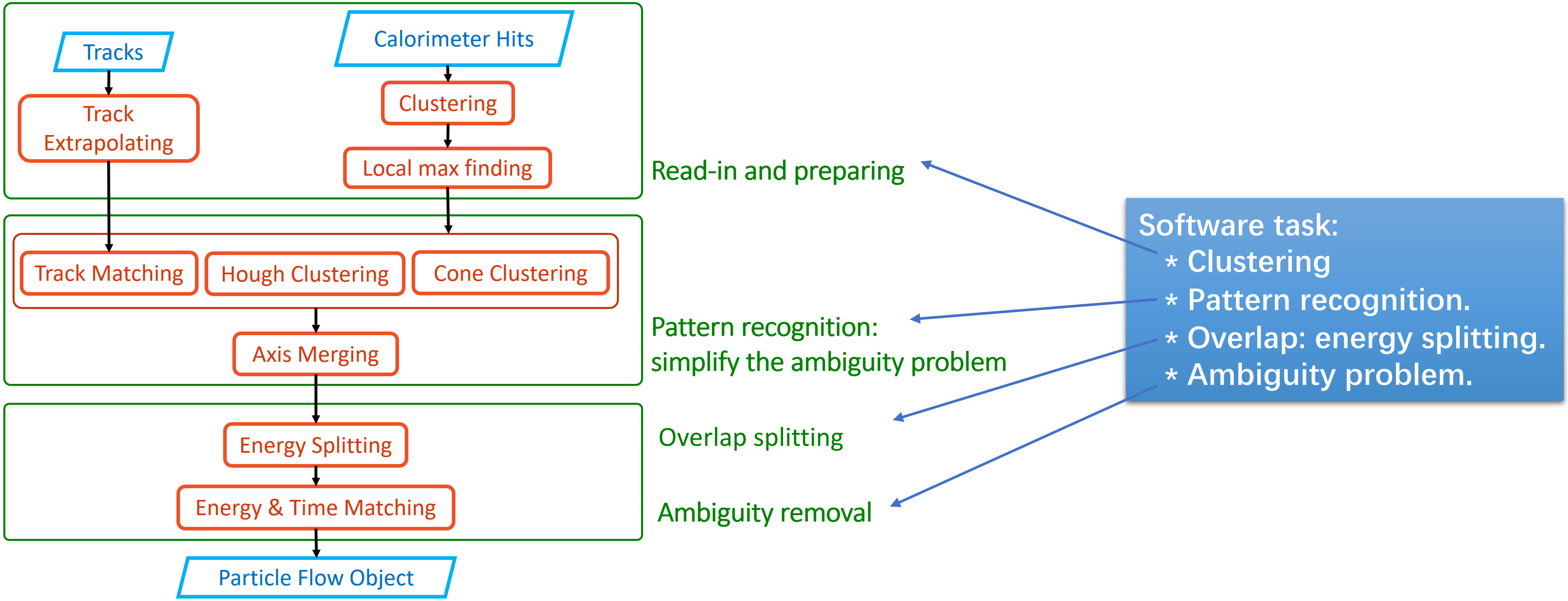


2 photons, $E_\gamma = 5$ GeV
Distance = 15×15 cm.



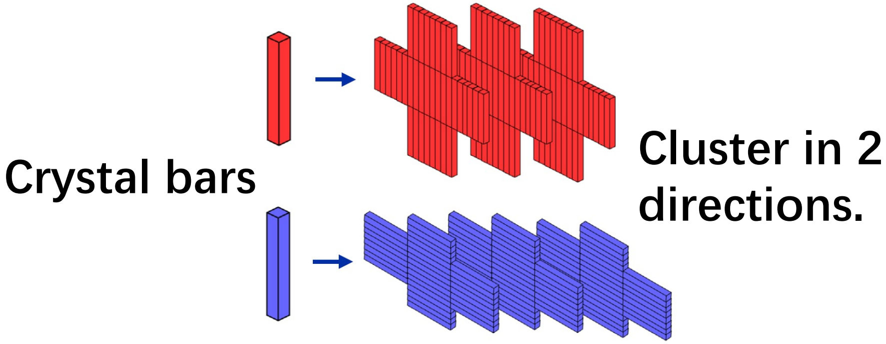
Reconstruction algorithm

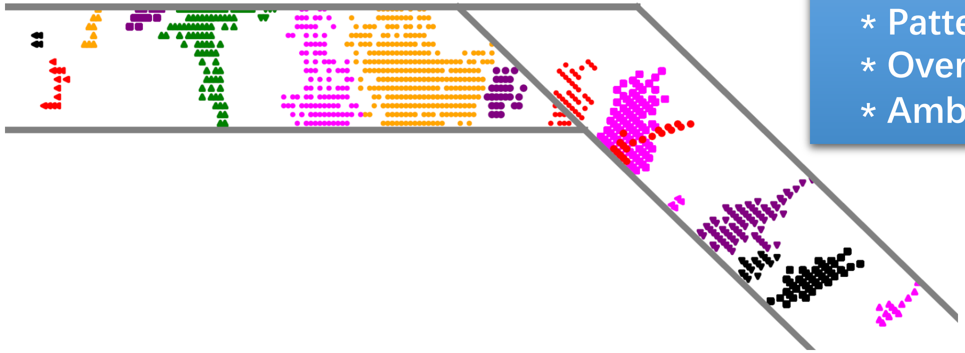
- **A pattern recognition PFA**



Clustering & recognition

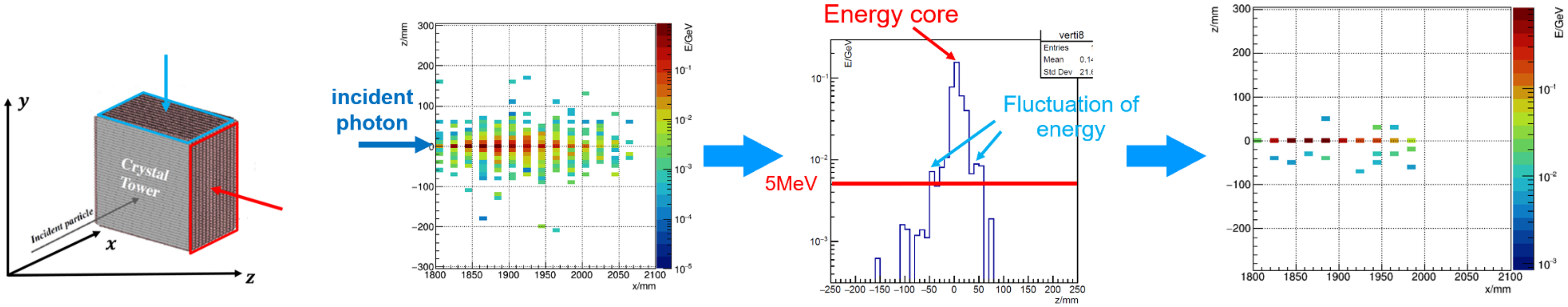
- **Global neighbor clustering for pre-processing.**





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

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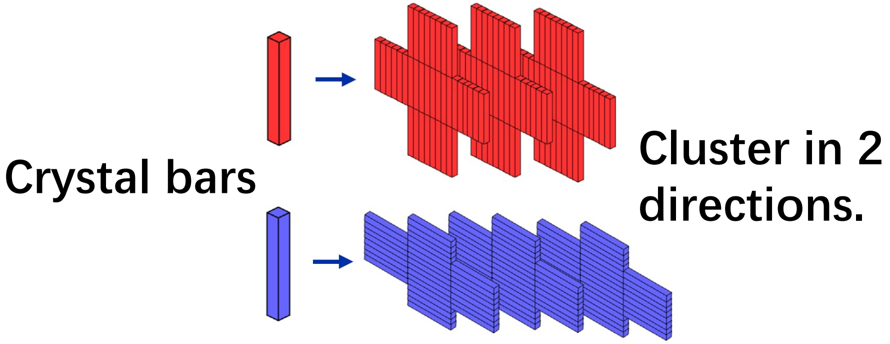

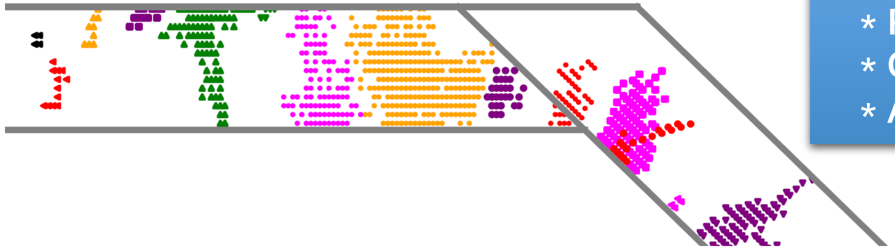

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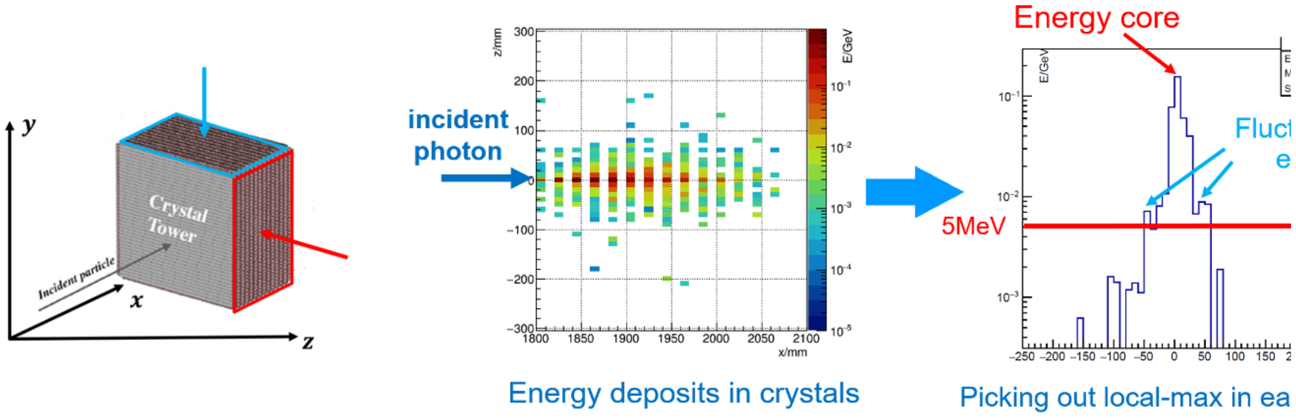

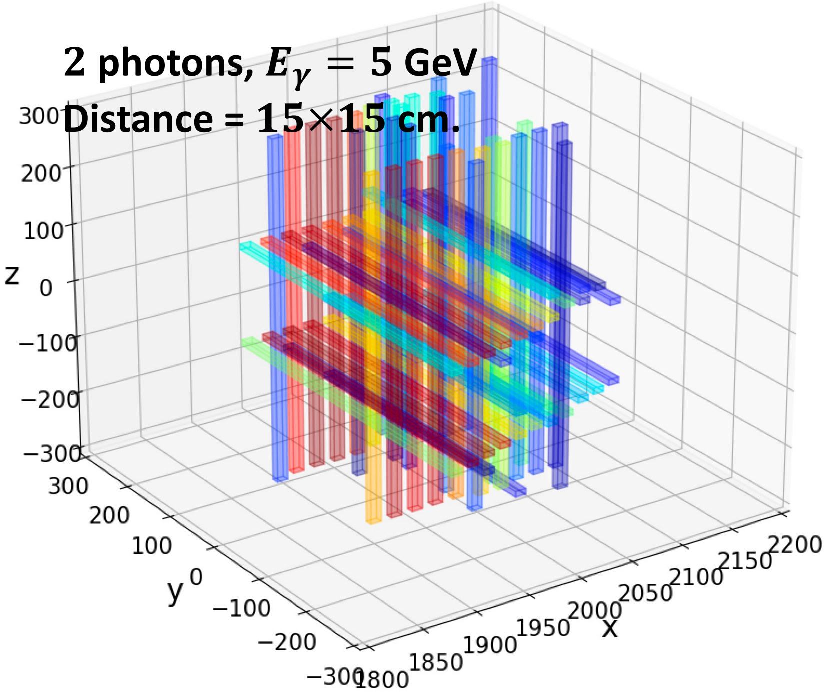

Clustering & recognition

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

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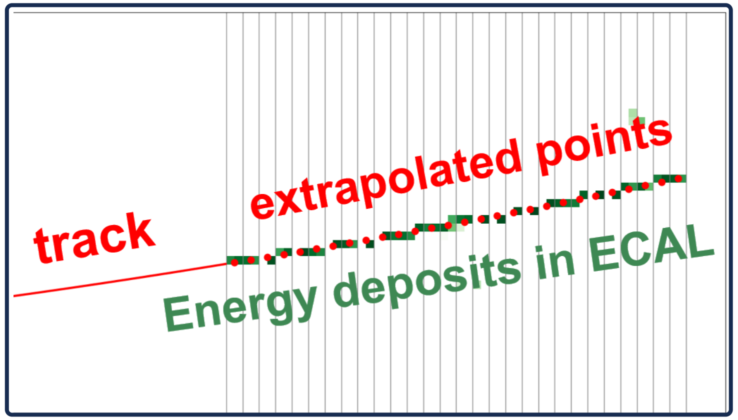

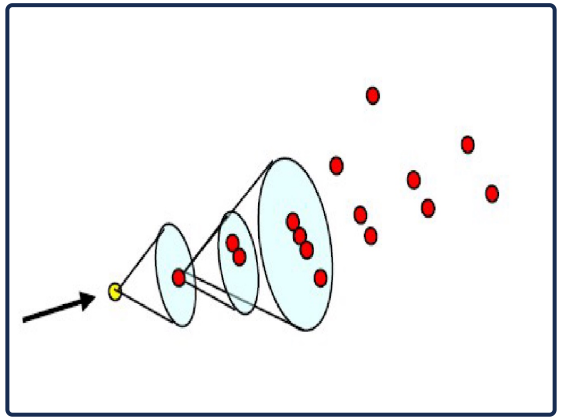

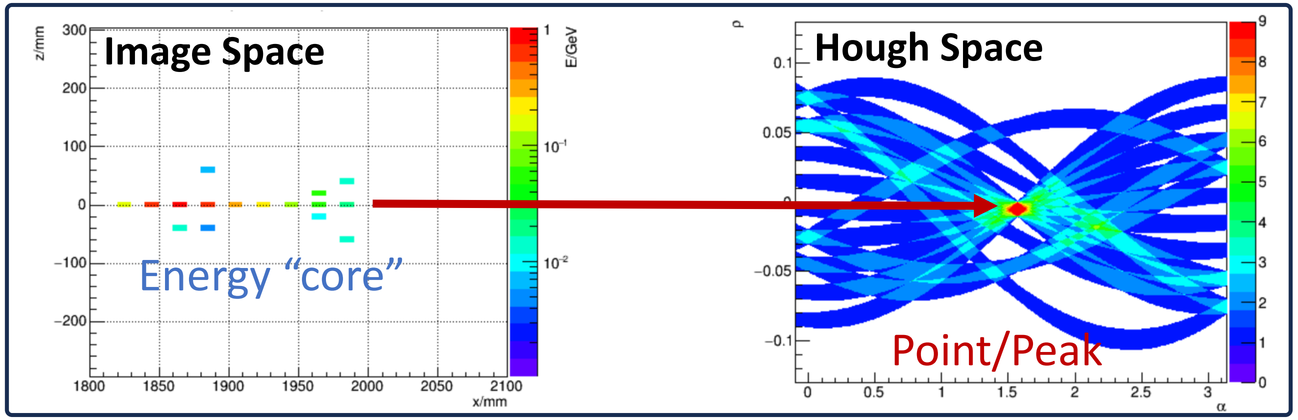

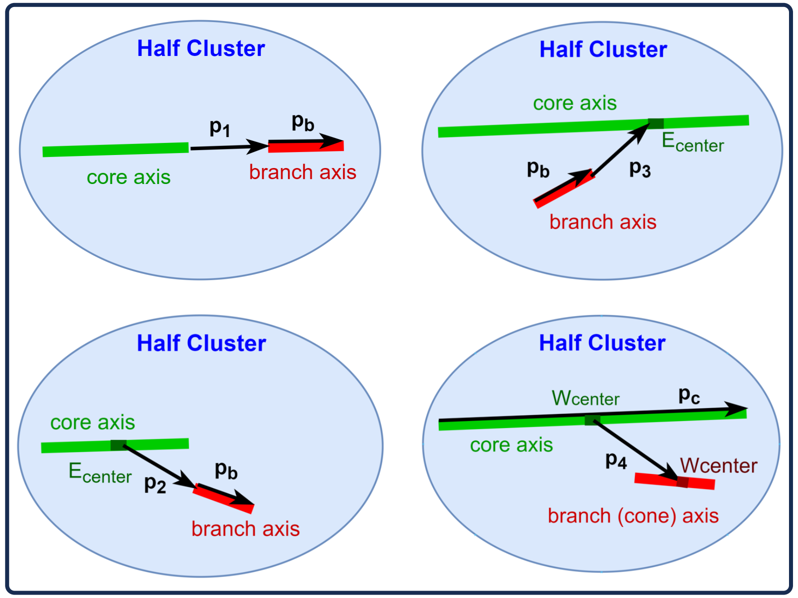

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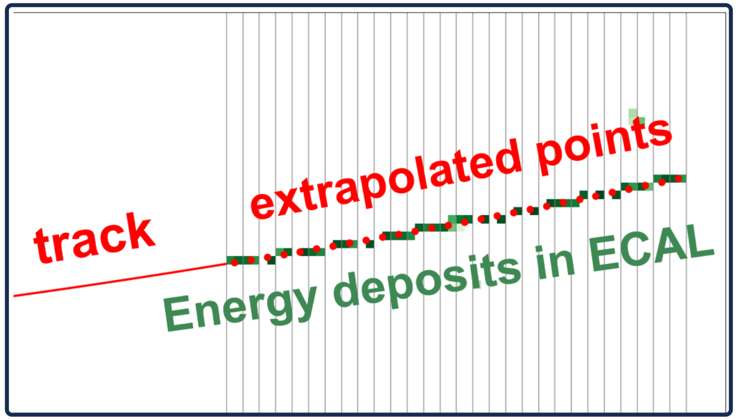

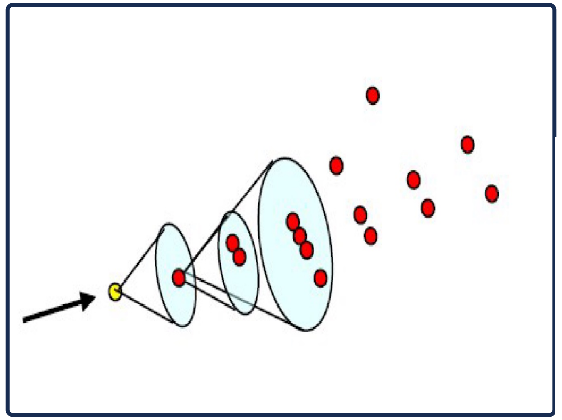

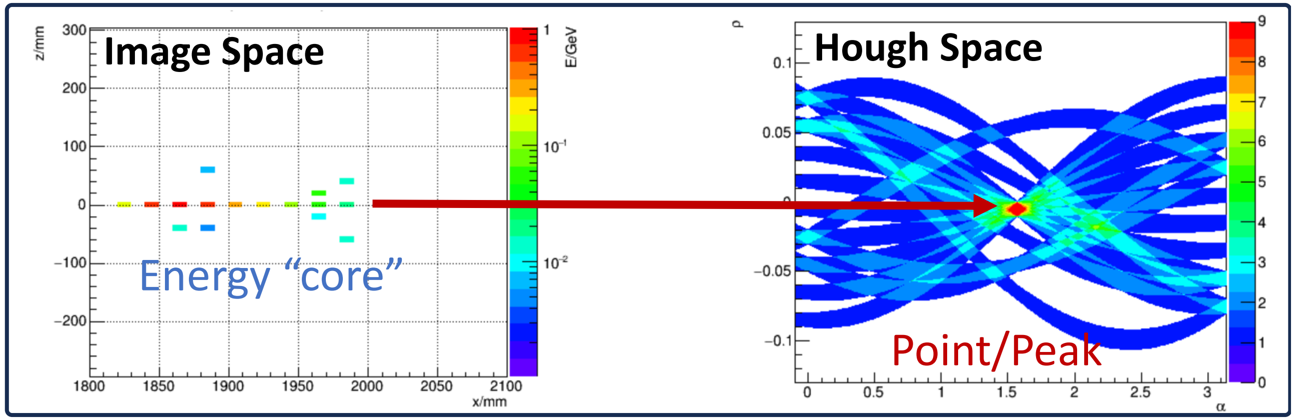

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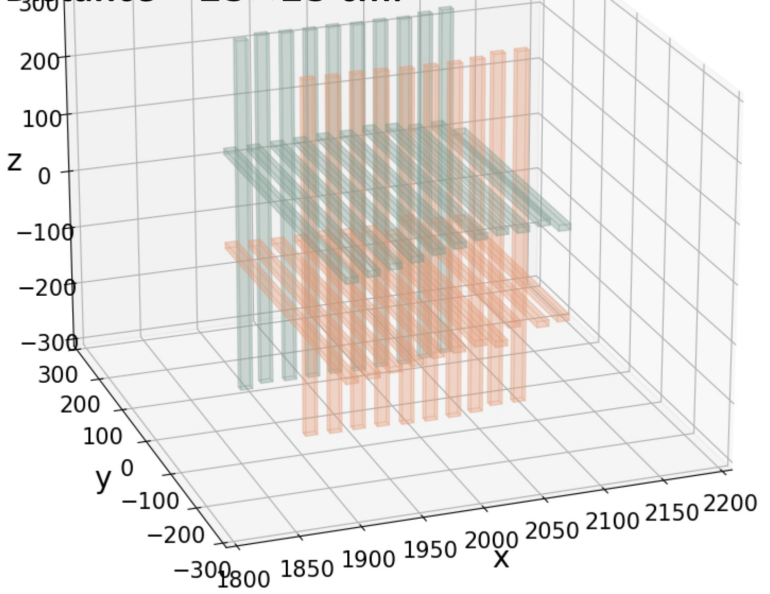

Energy splitting and matching

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

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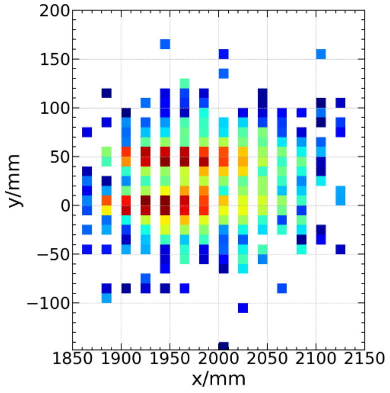
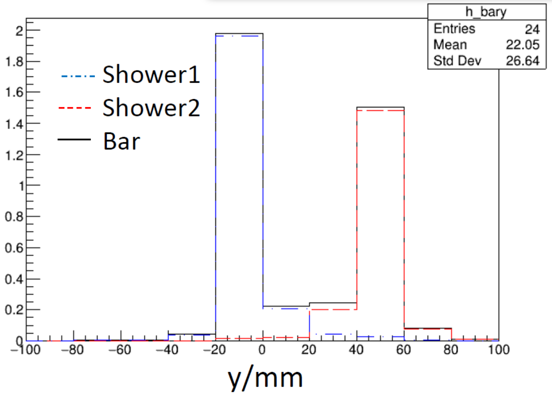
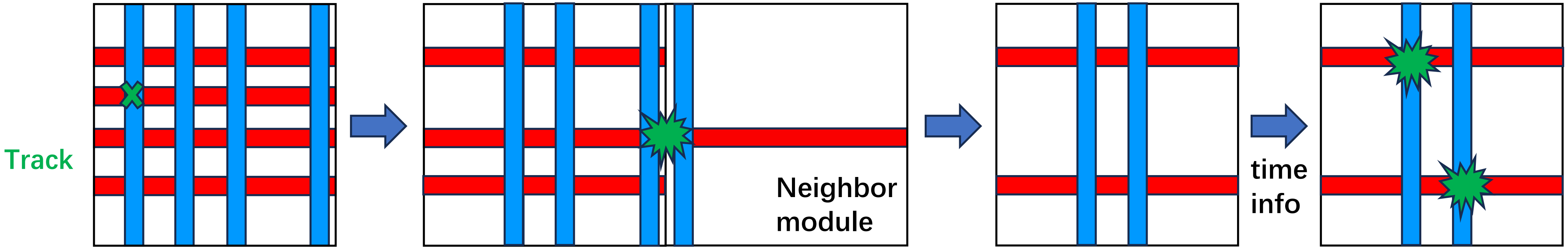
✓ * Overlap: energy splitting.
✓ * Ambiguity problem.



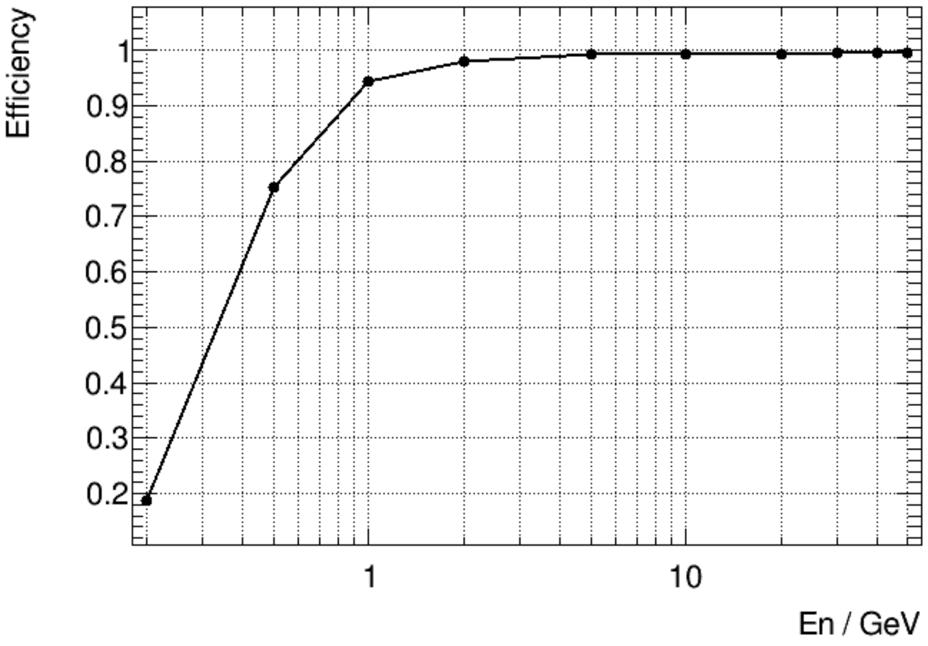


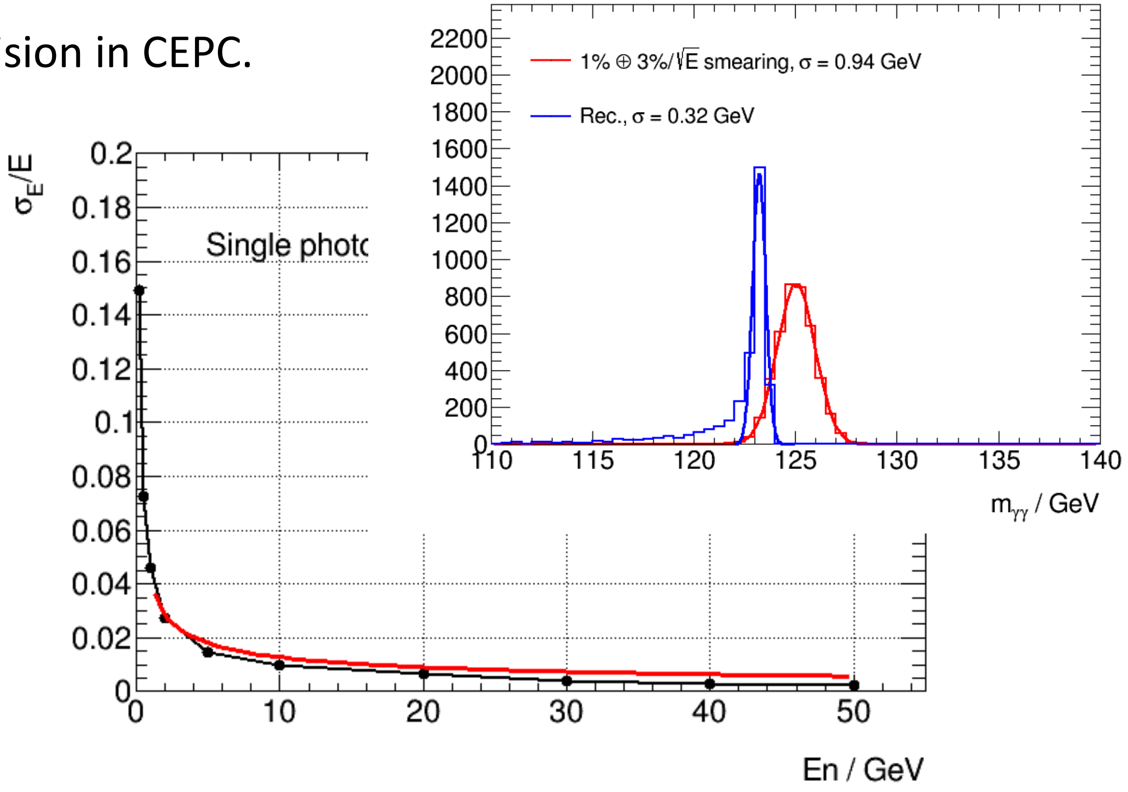
- **Ambiguity removal:**
  - Information from: track, neighbor tower, time.



Algorithm performance

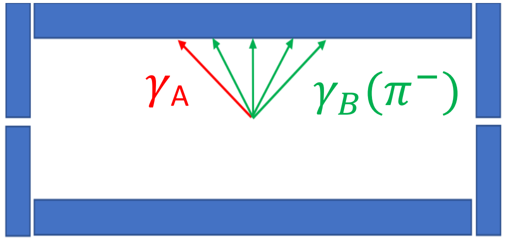
- **Photon reconstruction**
  - Recognition efficiency ~100% for γ with $E > 1GeV$
  - $H \to \gamma\gamma$ reconstruction: $\sigma(m_{\gamma\gamma})$~0.32 GeV.
    - Can improve the $H \to \gamma\gamma$ measurement precision in CEPC.



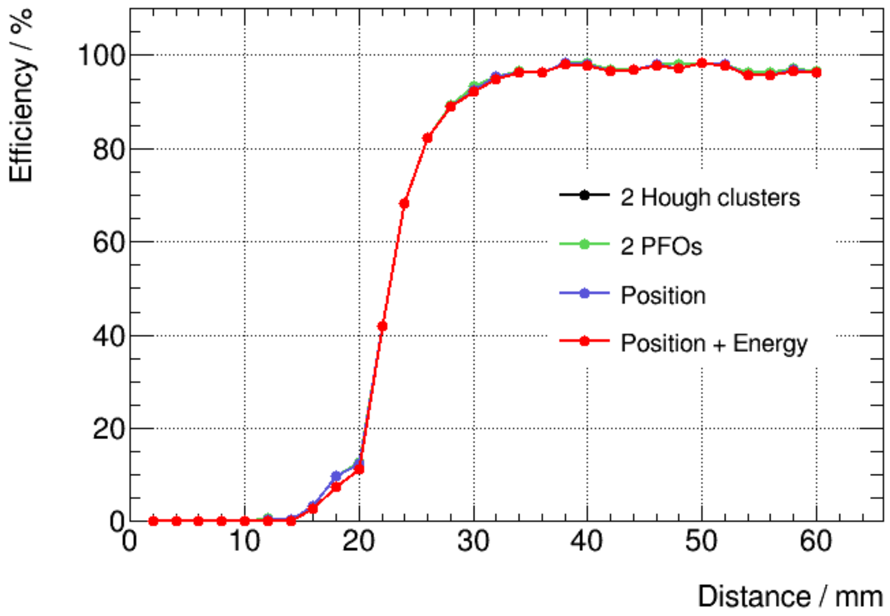


Algorithm performance

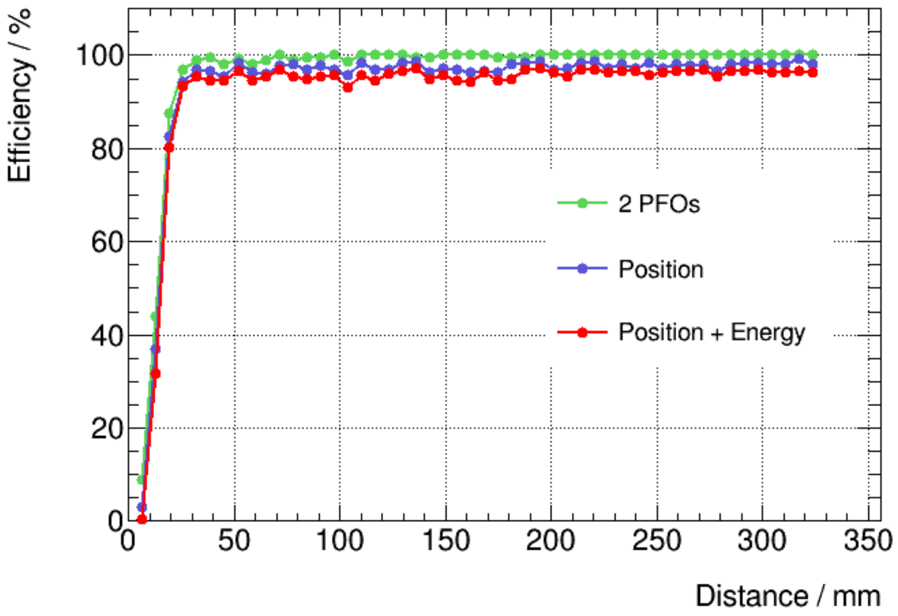
- $\gamma-\gamma, \gamma-\pi$ **separation**
  - Separation efficiency ~95% with distance > 30mm.



$\gamma-\gamma$ **separation efficiency**



$\gamma-\pi$ **separation efficiency**



Summary and outlook

- **A novel design of crystal ECAL for the future lepton colliders**
  - New homogeneous ECAL design, better energy resolution, less readout channels.
  - Can be compatible with Particle Flow and match the physics requirement.
  - Module construction and test will be presented in This talk.
- **A new pattern recognition PFA for this new design:**
  - Main challenges in the software are the overlapping and ambiguity.
  - Series of algorithms are developed and show promising results.
  - Final reconstruction of jets and Boson Mass Resolution (BMR) is under developing.
- **Look into the future:**
  - Time information from SiPM can be further used in PFA.
  - Deep learning approach: graph neural network, self-attention, etc.
    - AI is always very promising in pattern recognition.

Thank you for your attention!

Backup