Long Crystal Bar ECAL Software

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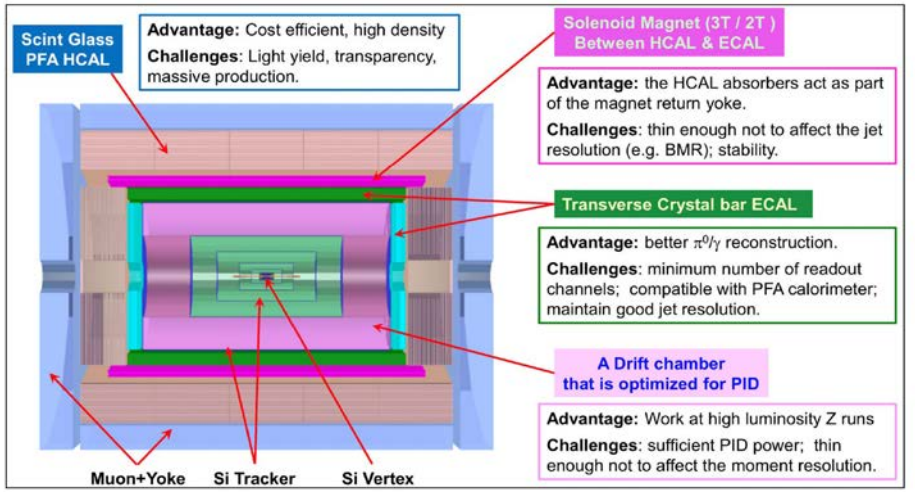
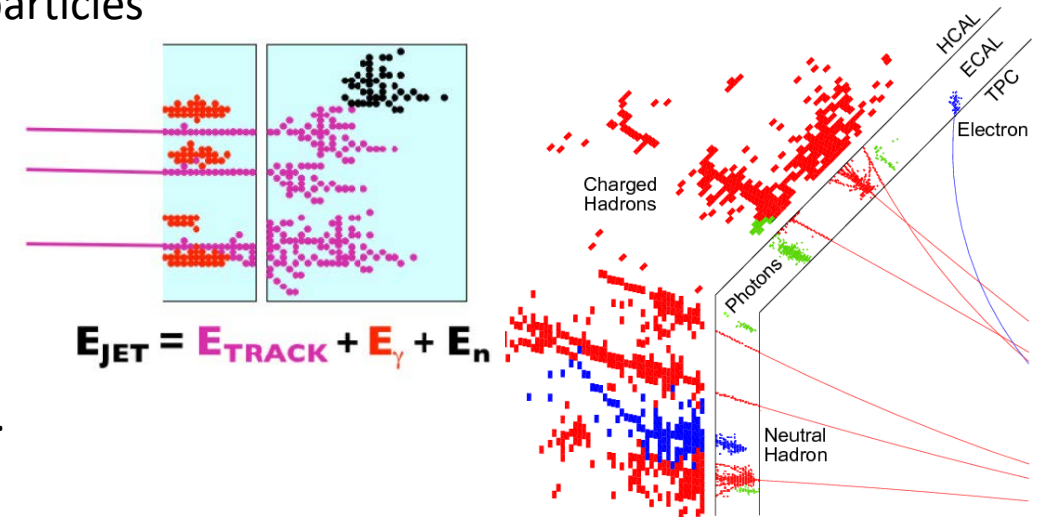
Introduction

- CEPC, a high precision H/Z factory
  - Heavy bosons separation and precise Higgs measurements require excellent jet energy resolution $3\sim4\%$.
  - Fine γ/π^0 reconstruction for flavor physics.
- Particle flow Approach
  - Requires the reconstruction of the four-momentum of all visible particles
    - charged particle momentum measured in tracker
    - photon energies measured in ECAL
    - Neutral hadron energies measured in HCAL
  - "Confusion" is the limiting factor
    - Identification of energy deposits from each individual particle.





Hardware + Software

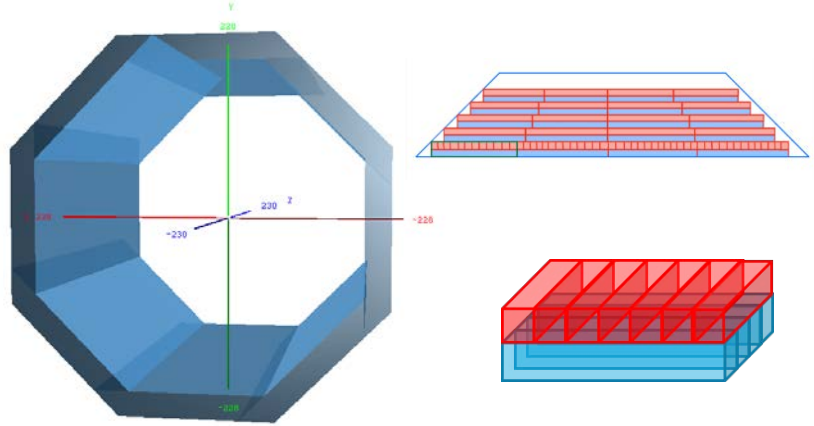
Natural Idea: High granularity & Compact EM shower

$$\sigma_{jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{EM} + \sigma^2_{Had} + \sigma^2_{Confusion}}$$

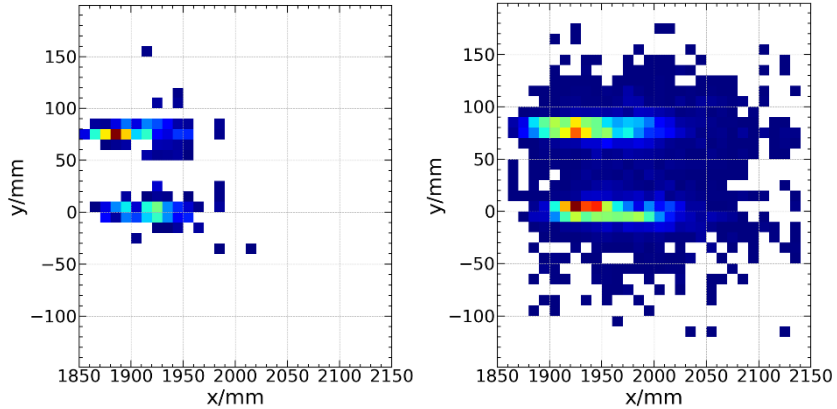
Introduction

- Long crystal bar electromagnetic calorimeter detector design
  - ✓ Optimal energy resolution ($\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%$), better γ/π^0 reconstruction
  - ✓ Significant reduction of number of readout channels
  - ✓ Time measurement to determine shower position along the bar
  - Larger R_m
  - Smaller λ_I/X_0

  } increase probability of shower overlap



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

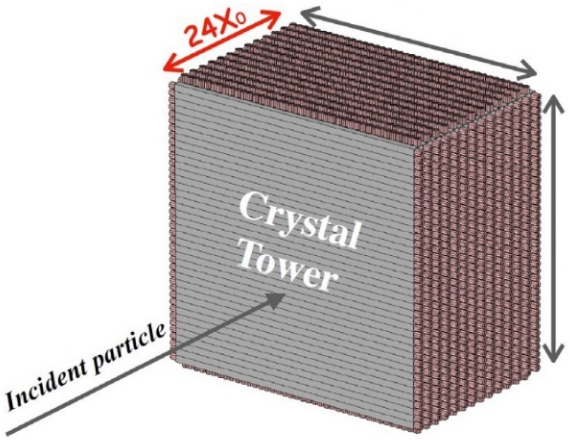


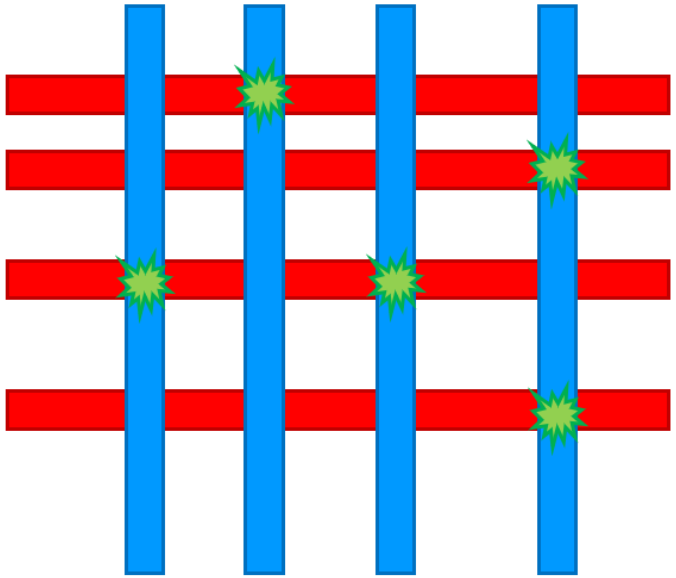
EM showers in SiW(left) and BGO(right)

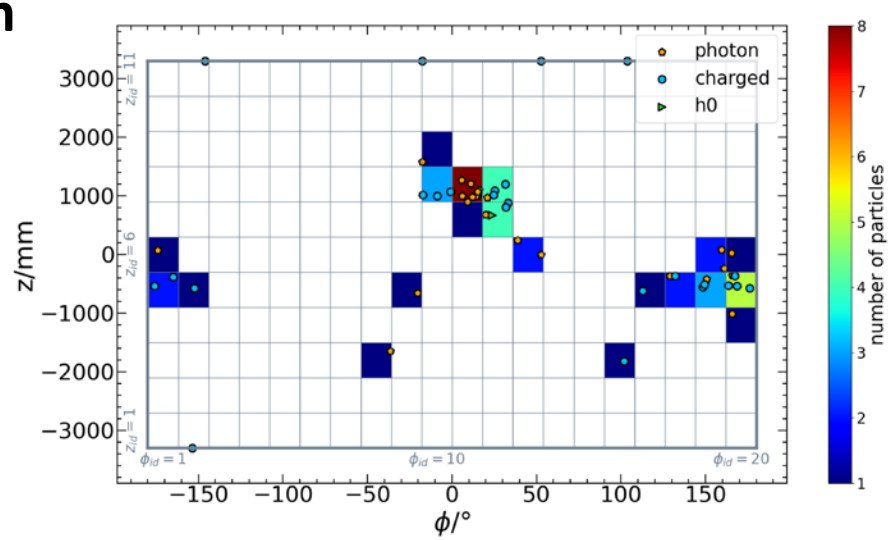
- Challenges for reconstruction algorithm:
  - Identification of energy deposits from each individual particle.
  - Ambiguity caused by matching of horizontal and vertical bars.

The Ambiguity Problem

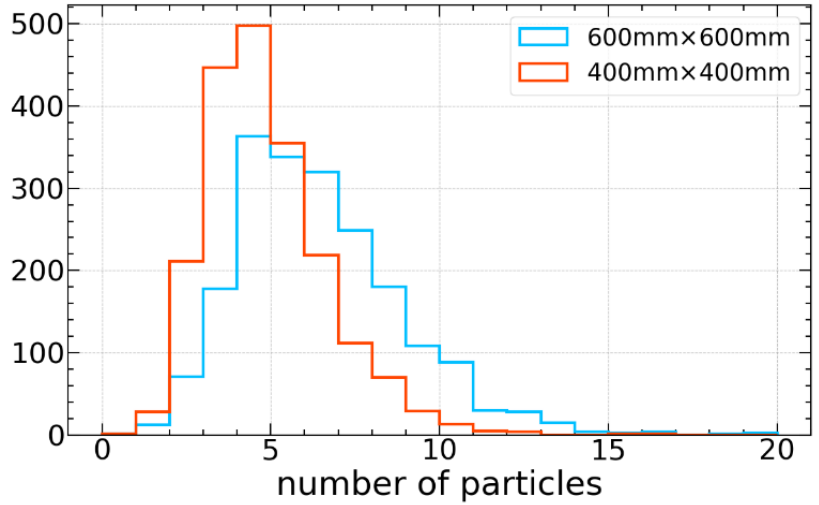
- Perpendicular arrangement of crystal bars → **ambiguity problem**
  - ~5 particles in the hottest tower in jet events







hit map of a jet event



Hottest tower for jet events

The Ambiguity Problem

- Fast simulation to estimate contributions of different effects on BMR
  - $e^+e^- \to \nu\bar{\nu}H, H \to gg$

Term	Effect	
Intrinsic	Acceptance	$\lvert\cos\theta\rvert < 0.99$
	Threshold	$E_\gamma > 0.2\ GeV$, $E_{h^0} > 2GeV$, $p_{T\ charged} > 0.2GeV$
	Energy resolution	Smear E_γ, E_{h^0}
	Position resolution	Smear direction of $\vec{p}$
Confusion	**Shower overlap**	Smear energy of overlapped showers
	Neutral fragment	Sampling based on performance
	ambiguity	Smear $\vec{p}_\gamma, \vec{p}_{h^0}$, ghost particle

Yuexin, IHEP

https://indico.ihep.ac.cn/event/9960/

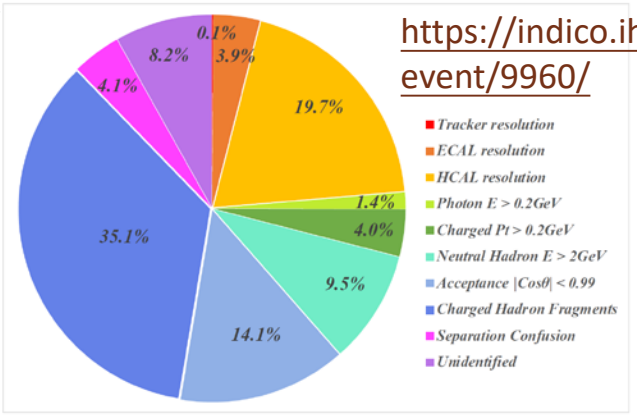
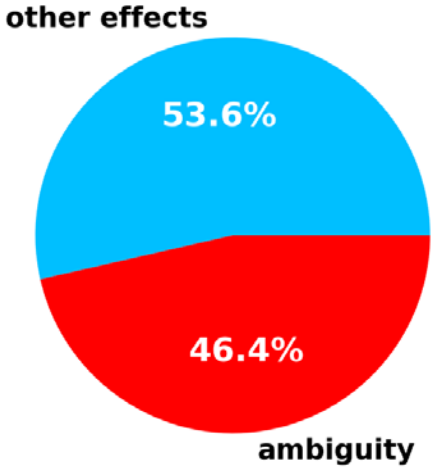


图 4-7 不同效应对 BMR 影响的贡献占比图。

Figure 4-7 Contributions of different effects to BMR.

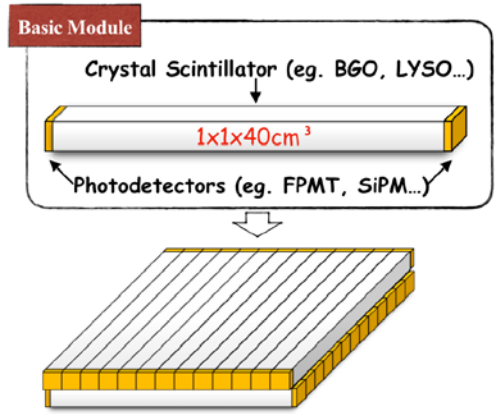


Contributions of ambiguity on BMR

- **Our main challenge is the ambiguity problem**

Detector description and digitization

- A BGO crystal barrel ECAL:
  - Crystal Bar: $1 \times 1 \times 40{\sim}60\ \mathrm{cm}^3$
  - Super Cell: 2 layers of perpendicular crossing bars $\sim 40 \times \sim 60 \times 2\ \mathrm{cm}^3$
  - Detector:$R = 1.86\ \mathrm{m}, L = 6.6\ \mathrm{m}, H = 28\ \mathrm{cm}$, 8 same trapezoidal staves, avoid gaps point to IP

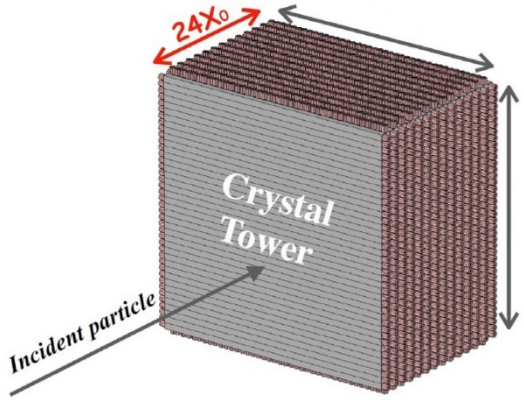


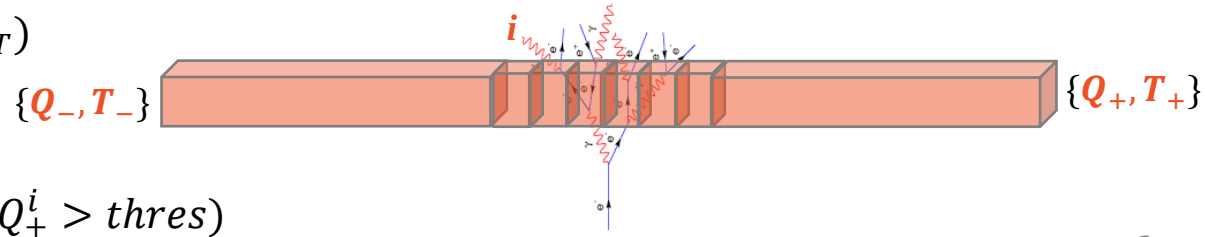
- Focusing on software performance, ignoring dead area, supporting and cooling mechanics, etc
- Simulation is performed using GEANT4: electromagnetic and hadronic interactions
- Simplified digitization for one long crystal bar:
  - contribution of each G4step i:

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

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

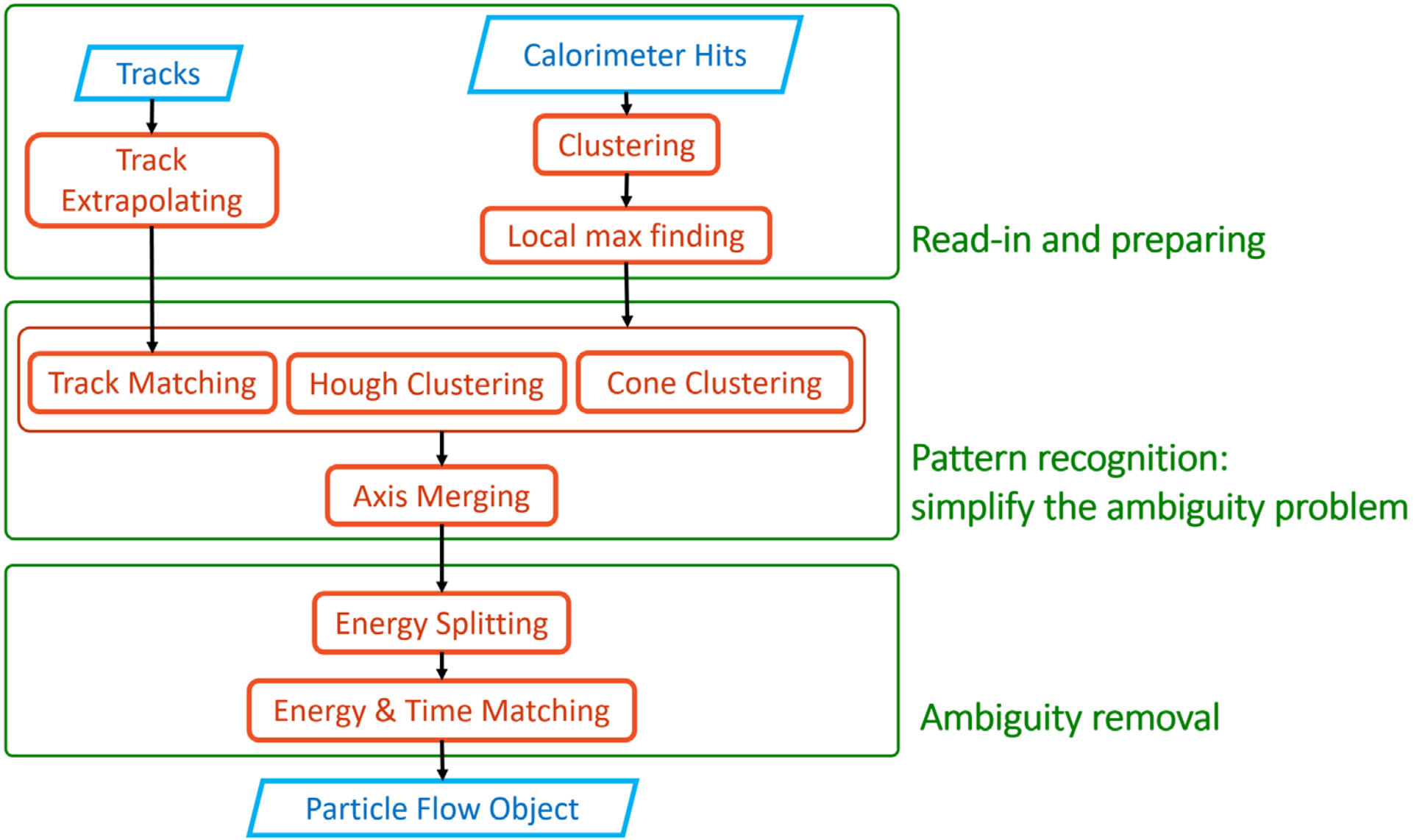
$$Q_{\pm} = \sum_{step} Q_{\pm}^{i} \qquad T_{\pm} = T_{\pm}^{k} \mid (\sum_{i=1}^{k} Q_{\pm}^{i} > thres)$$





Introduction on Algorithm

- A set of algorithms are developed to address the challenge.

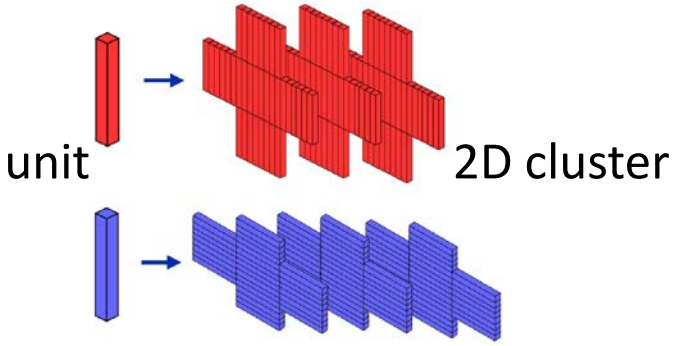


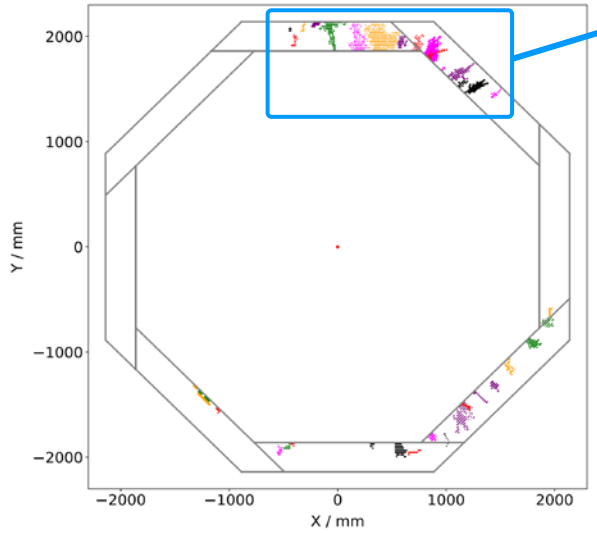
Clustering

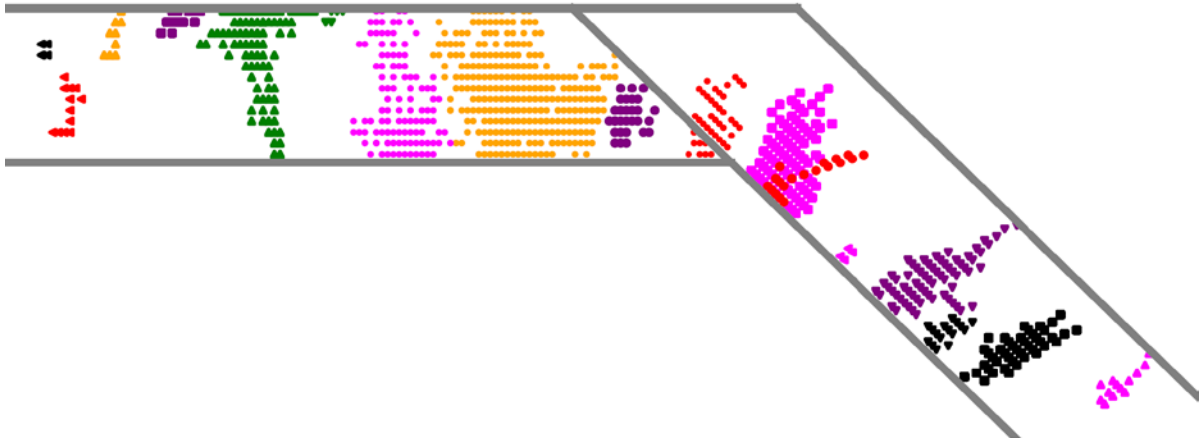
- Global Clustering
  - Cluster: a group of adjacent units whose energy is greater than noise threshold
  - Vertical and horizontal units are clustered respectively

PFA needs an imaging calorimeter

Projection of vertical and horizontal units make it possible!

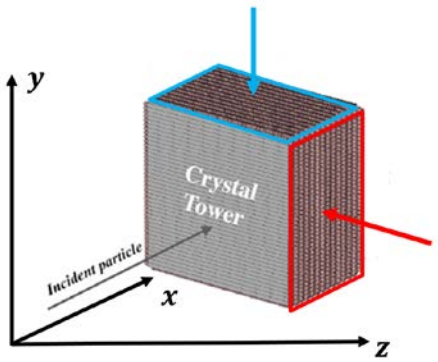


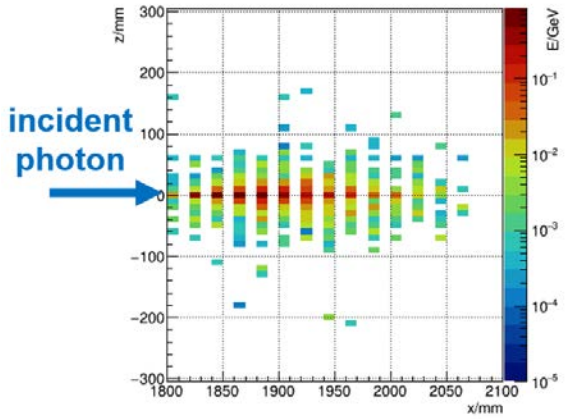




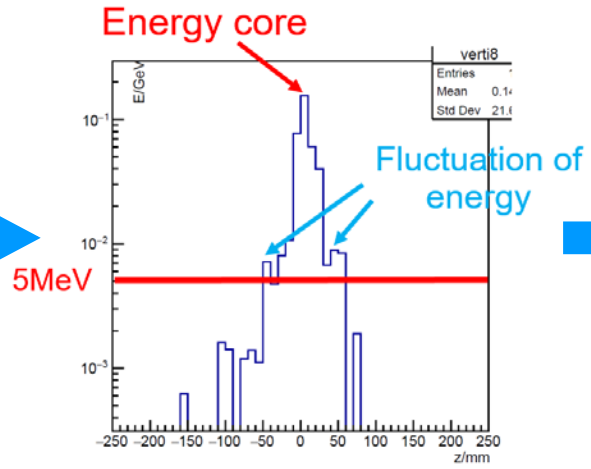
Local Max Finding

- Local Max Finding
  - In each layer / 1D-cluster : local maximum
  - Core of energy deposition ➔ real cluster

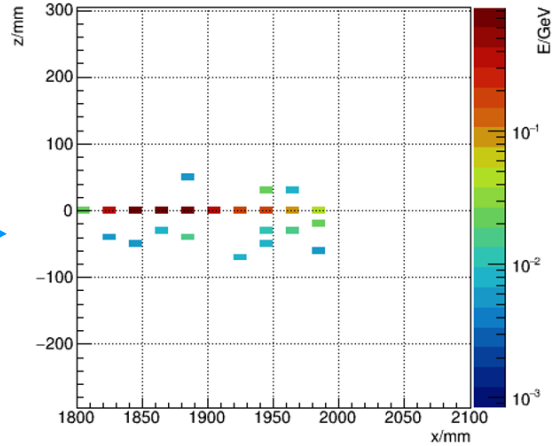




Energy deposits in crystals



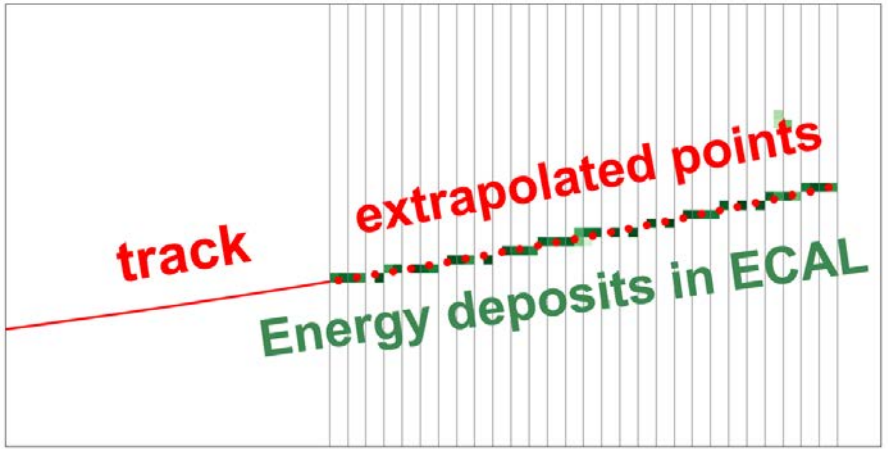
Picking out local-max in each layer

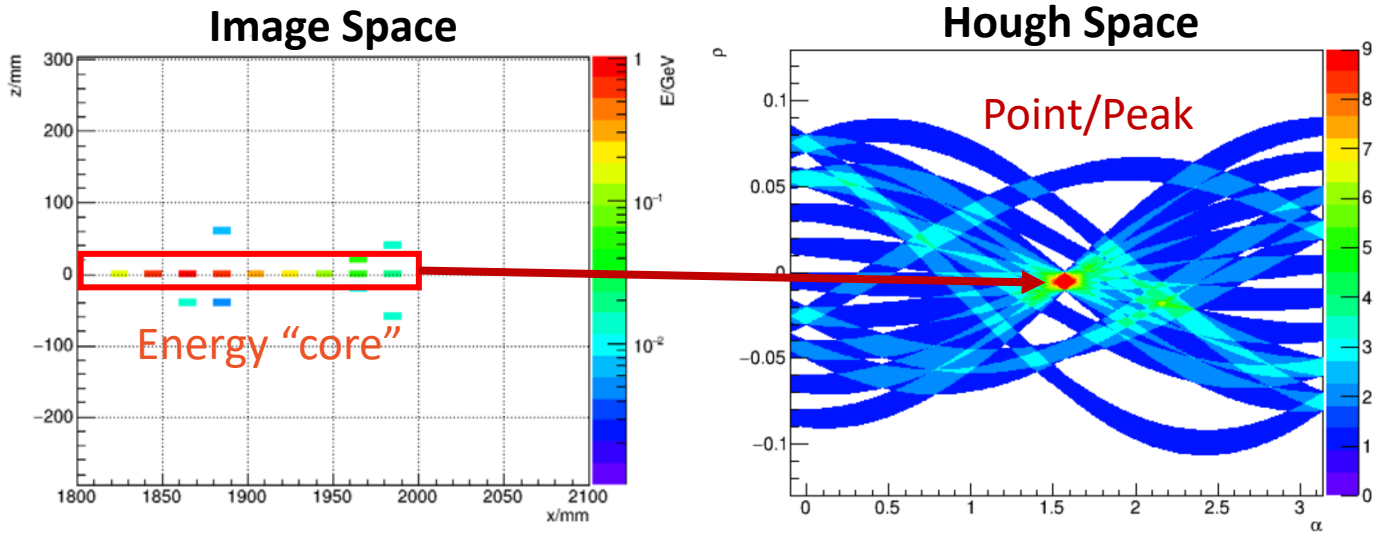


Local Maximum Distribution

Shower Recognition

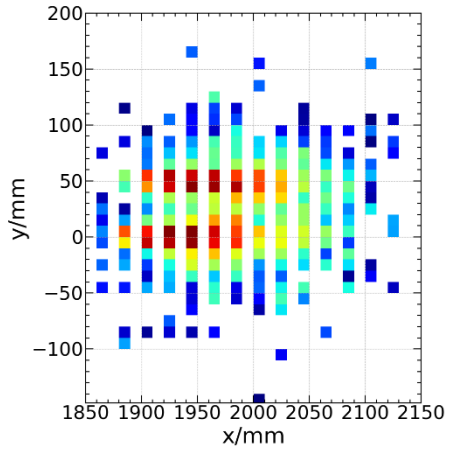
- Multiple algorithm for shower recognition:
  - Charged particle: track-matching.
  - EM shower: Hough transformation.
  - Fragment: cone-clustering.

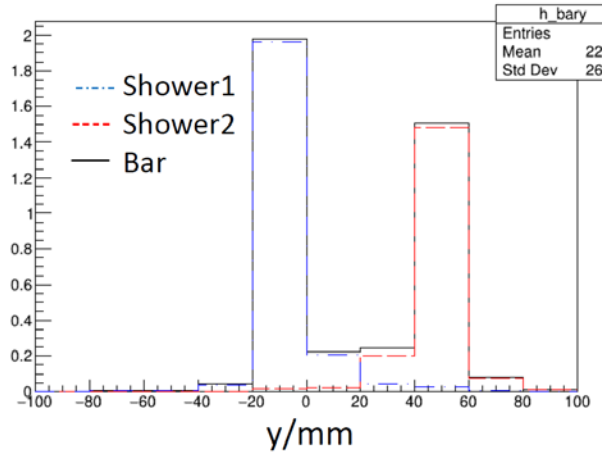




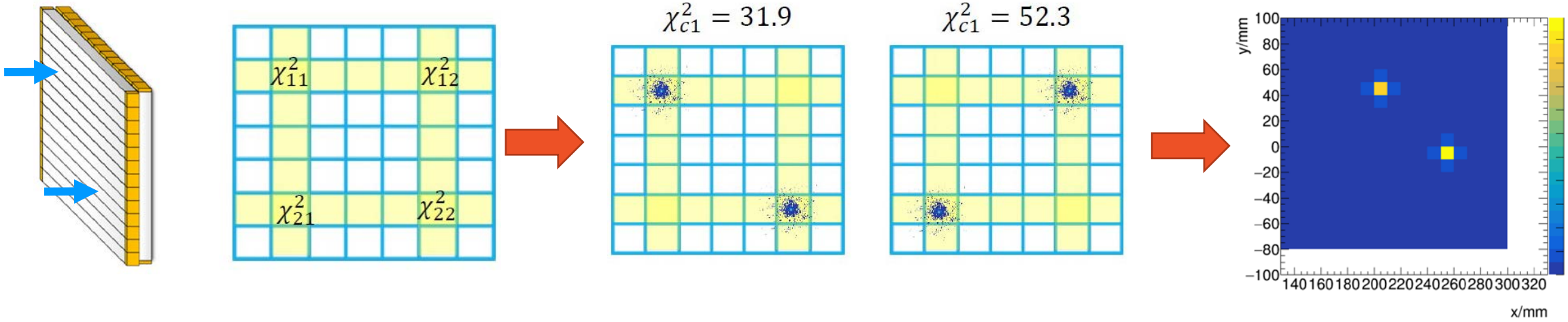
Energy Splitting & Energy-Time Matching

- Larger R_M for crystal ➔ several shower overlap ➔ Energy splitting
  - 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: $w_{i\mu} = \frac{E_{i\mu}^{exp}}{\sum_{\mu} E_{i\mu}^{exp}}$



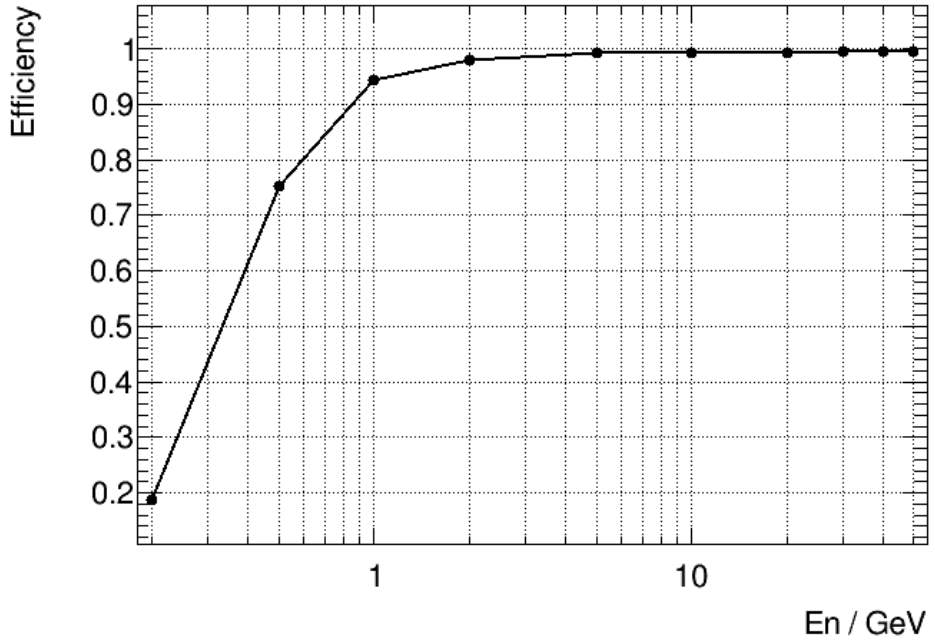


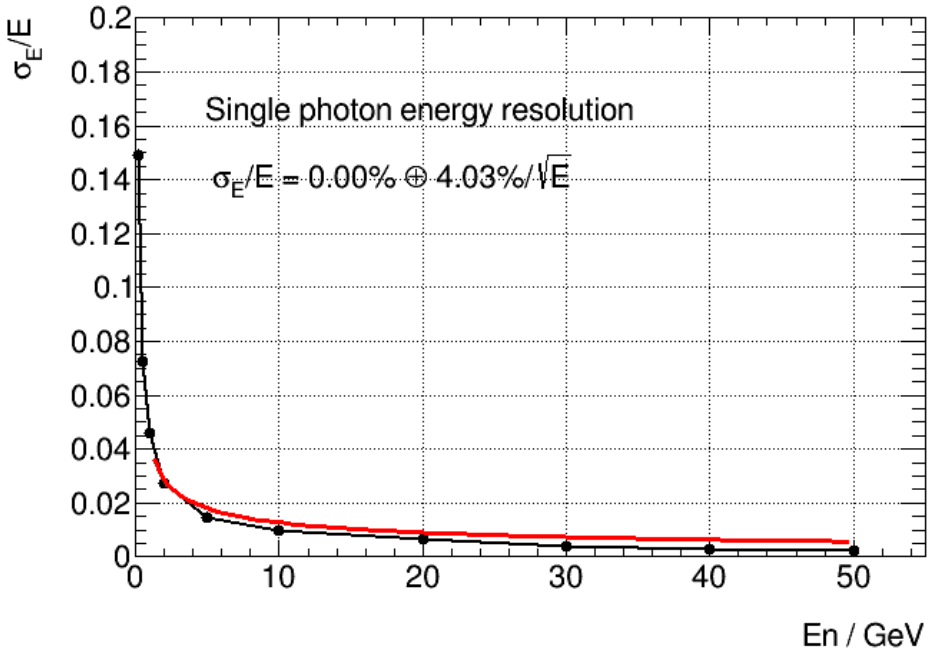
- The ambiguity problem ➔ Energy-Time Matching
  - Define χ^2 with energy and time info to get the correct combination



Performance

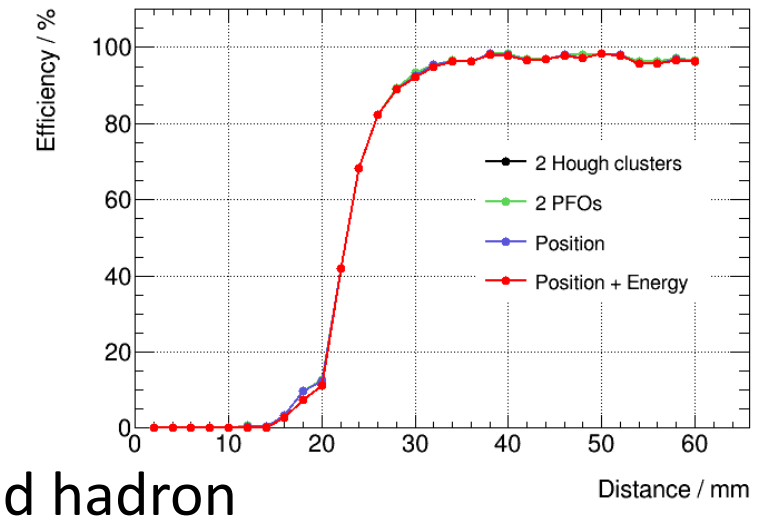
- Single photon recognition
  - Recognition efficiency ~100% for γ with $E > 1GeV$
  - $\frac{\sigma_E}{E} = \frac{4.03\%}{\sqrt{E}} + 0\%$

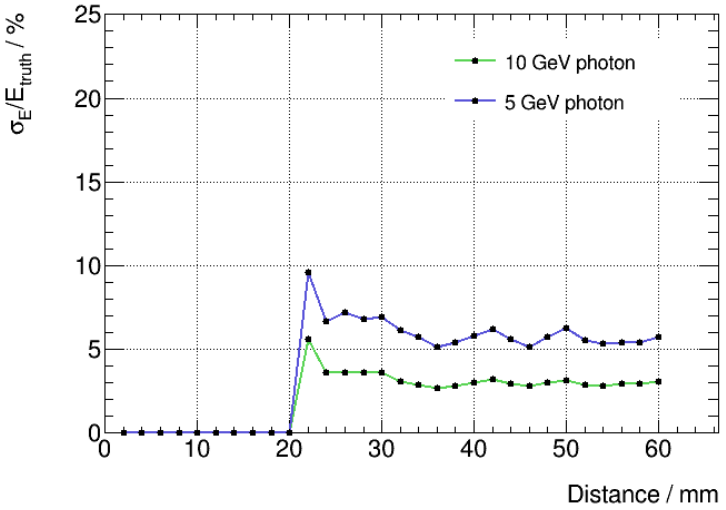




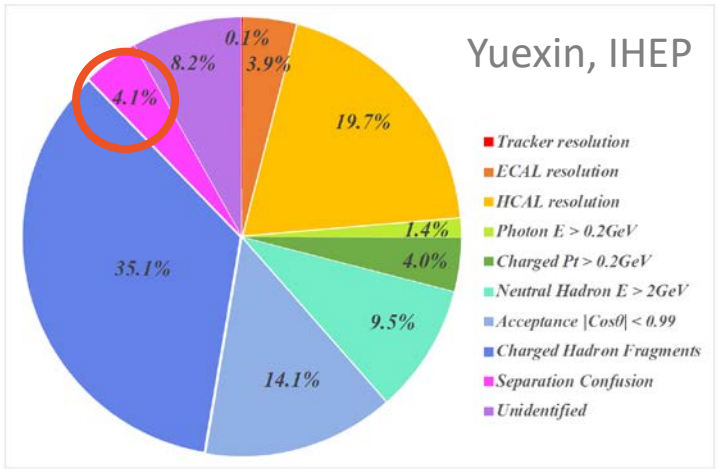
Performance

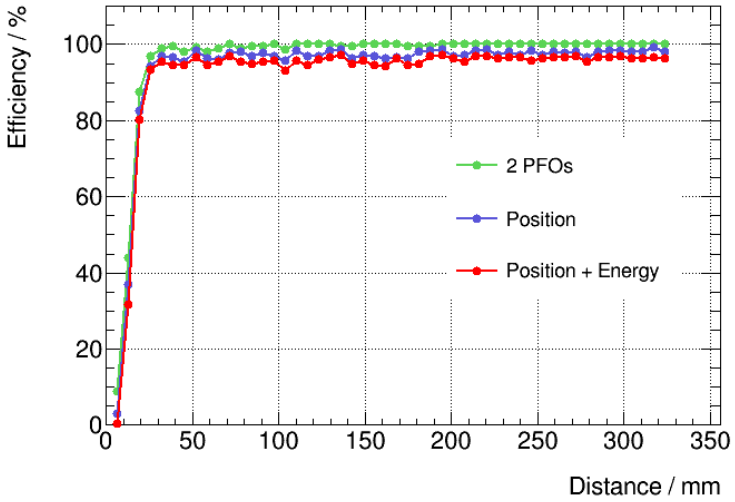
- Separation of di-photon
  - Separation efficiency ~95% with distance > 30mm

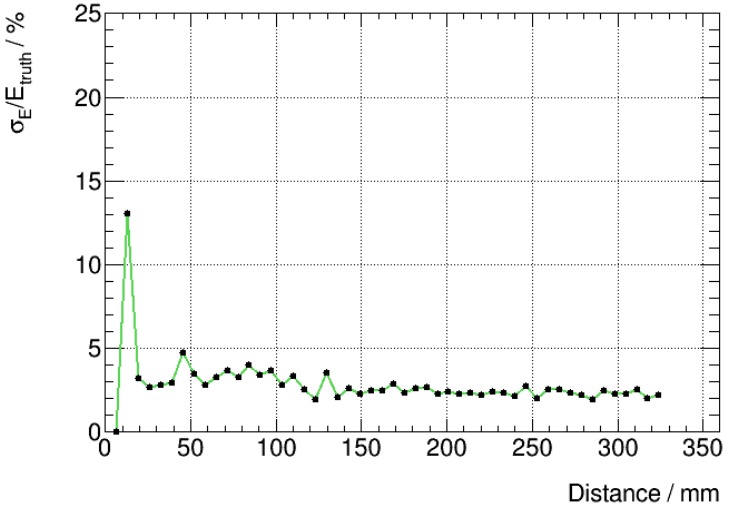




- Separation of photon and charged hadron
  - Separation efficiency ~95% with distance > 30mm

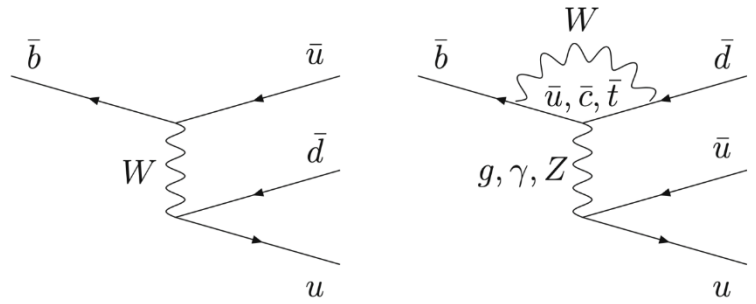


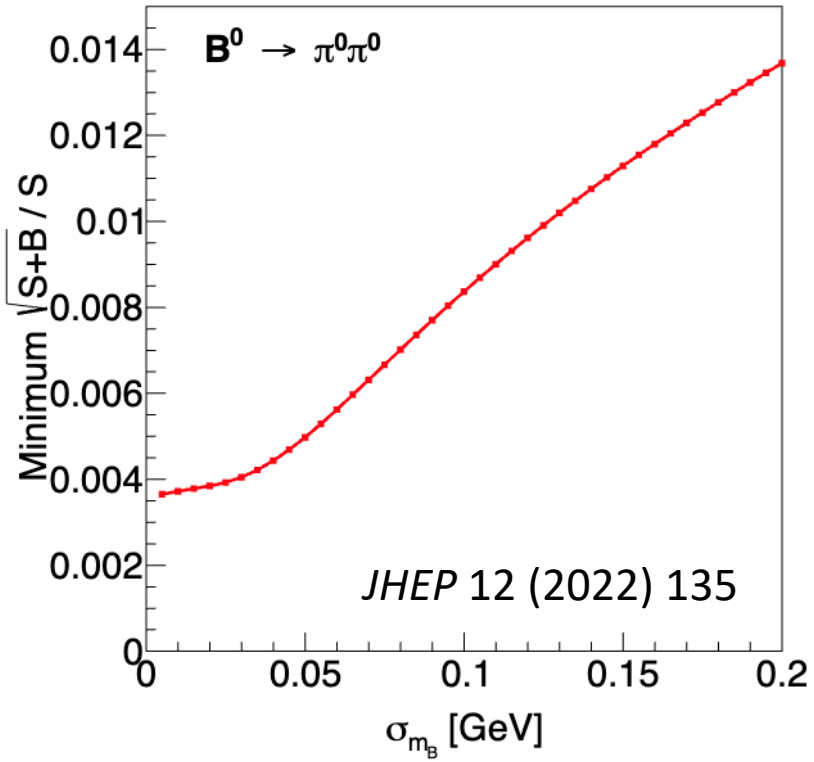


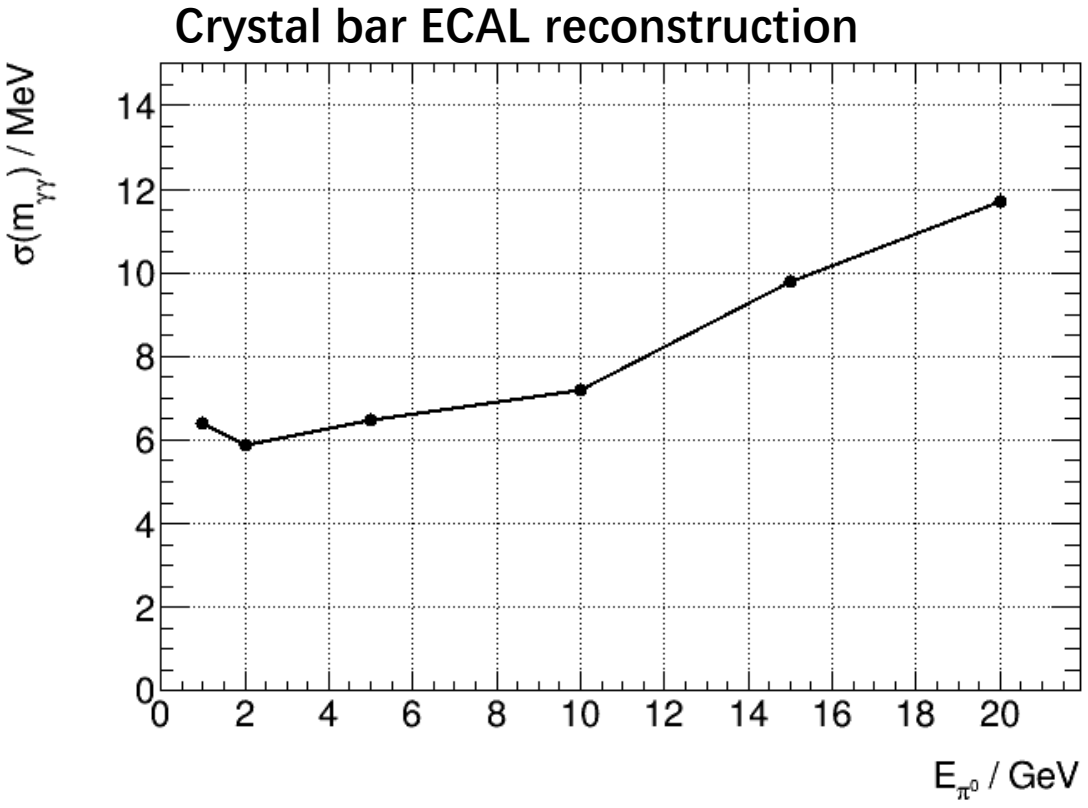


Performance

- Flavor physics in $B^0 \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ channel
  - Key for CKM α angle study.
  - Can be complementary to B-factory in CEPC Tera-Z phase.
  - Highly depending on the π^0 reconstruction.

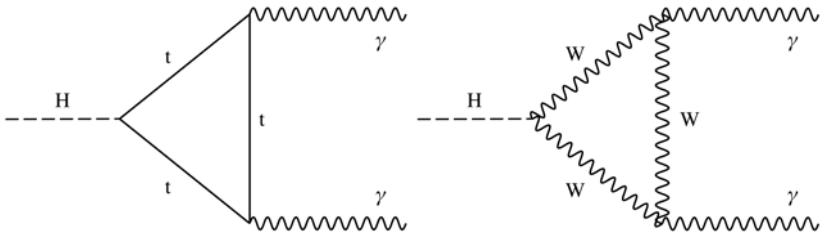


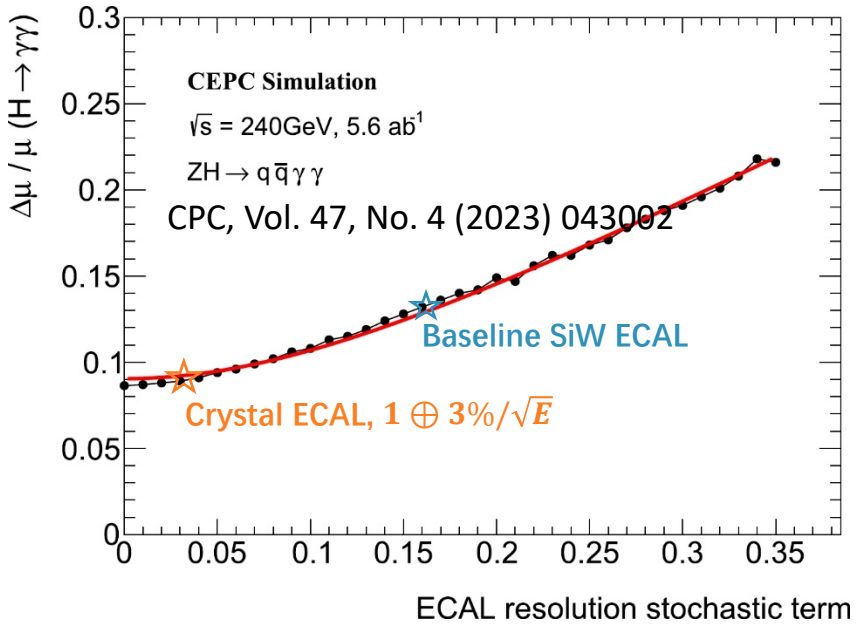


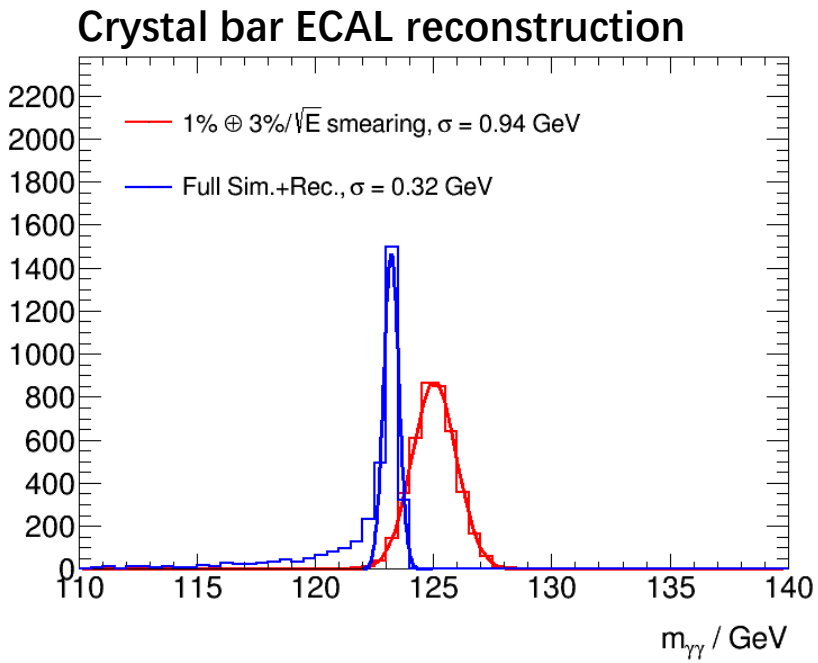


Performance

- $H \to \gamma\gamma$ in CEPC:
  - Low branching ratio but simple topology.
  - Important channel for Higgs measurement and new physics search.
  - Expected precision: $\Delta\left(\sigma_{ZH} \cdot BR(H \to \gamma\gamma)\right) = 7.9\%$ @ $5.6\ \mathrm{ab}^{-1}$
  - Impact from ECAL resolution: $m_{\gamma\gamma}$ width
    - ~30% improvement from new ECAL.





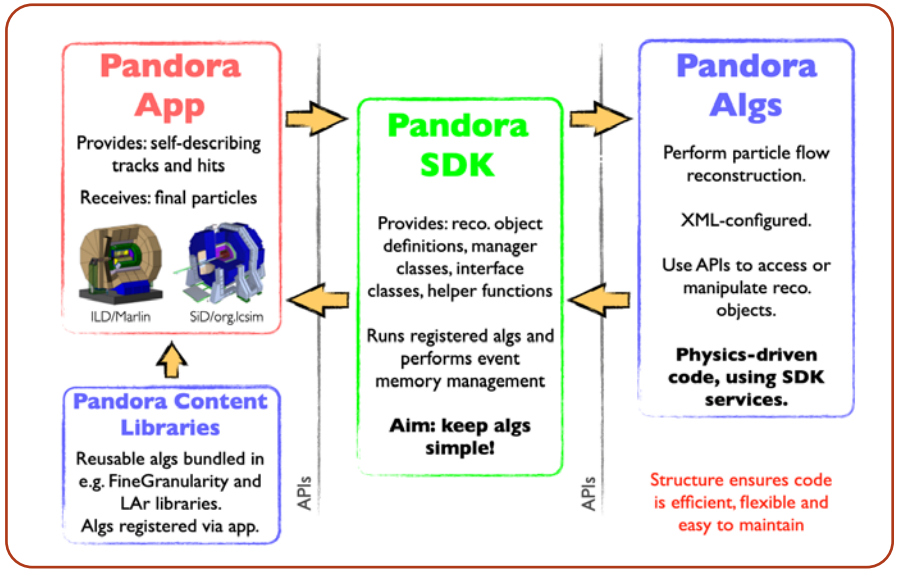


Summary

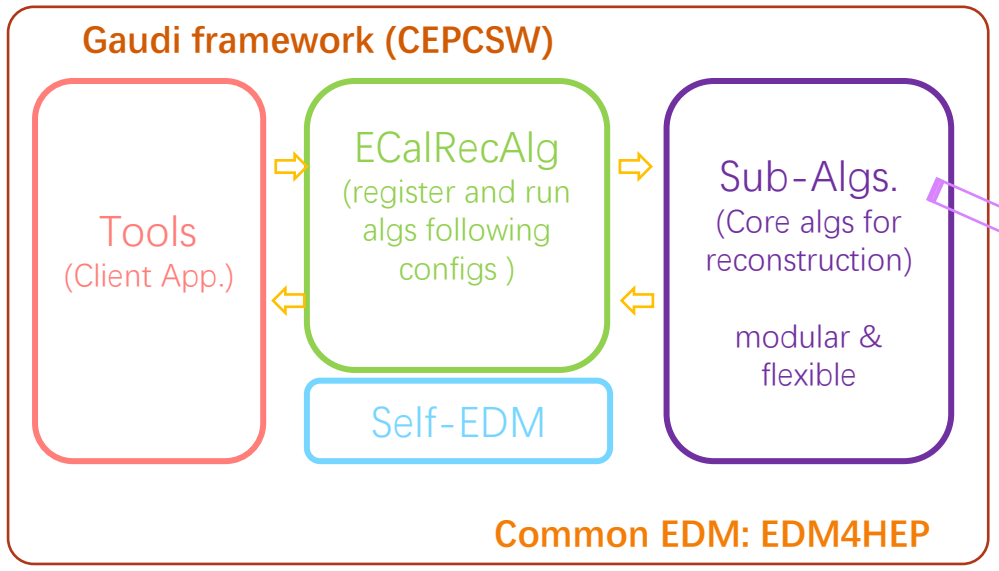
- Crystal bar ECAL is a novel and challenging ECAL design
  - ✓ Better energy resolution; Less readout channel.
  - Ambiguity is the main challenge
- Reconstruction algorithm development has reached an advanced stage
  - Preliminary performance has shown promising results.
- Future optimization: ambiguity problem and BMR

Backup

- Design the reconstruction software as a proto-PFA:
  - Follow the idea of PandoraSDK: flexible, reusable, modular. (Many thanks!)
  - Develop within CEPCSW: based on the common HEP software stack Key4HEP.

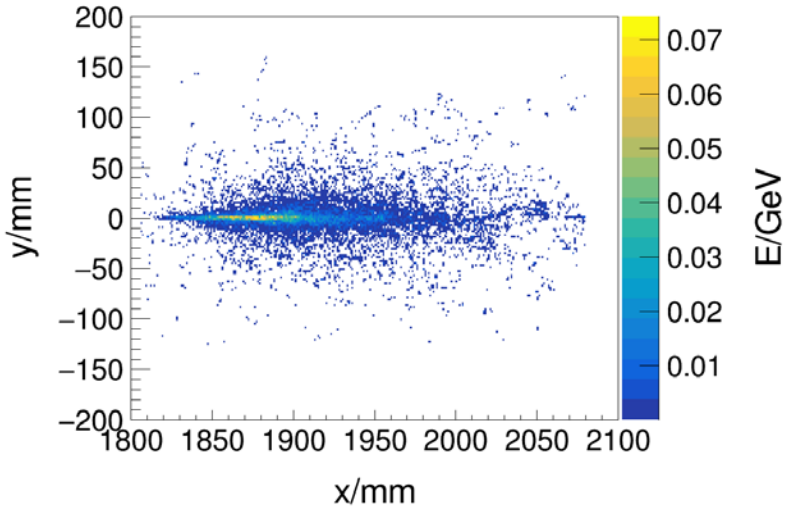


J.S.Marshall, CHEF 2013



Not mature yet, so it's just a "proto"-PFA now.

Backup


y/mm
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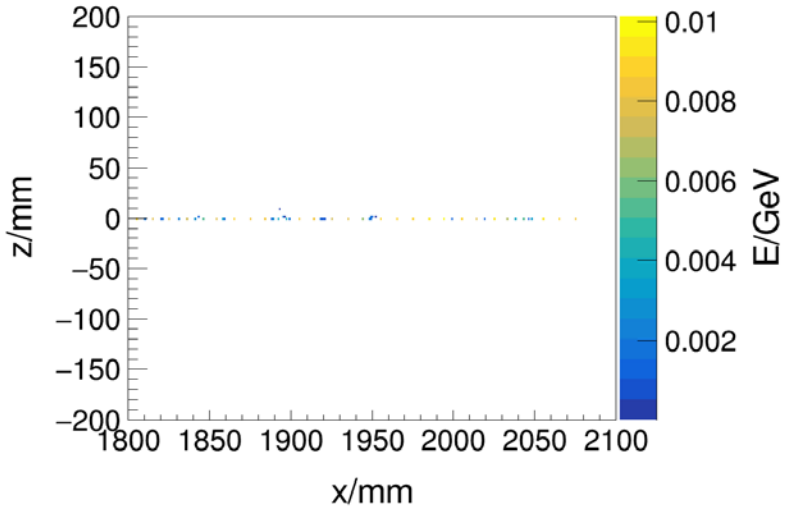
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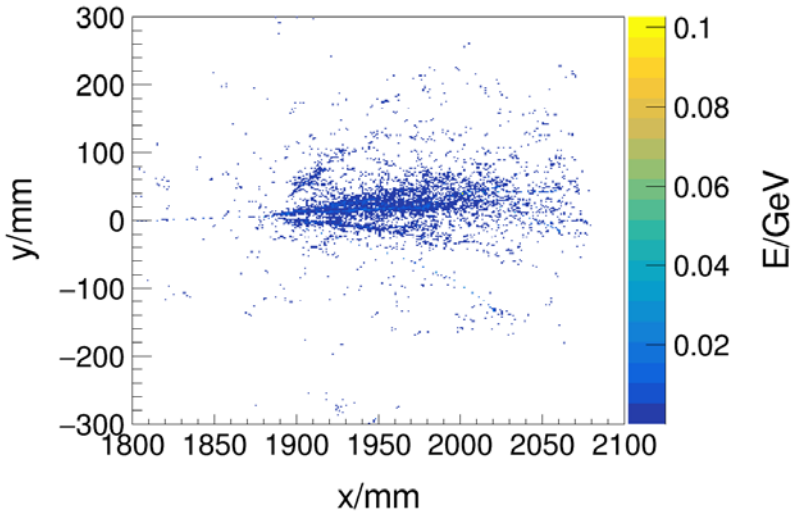
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