

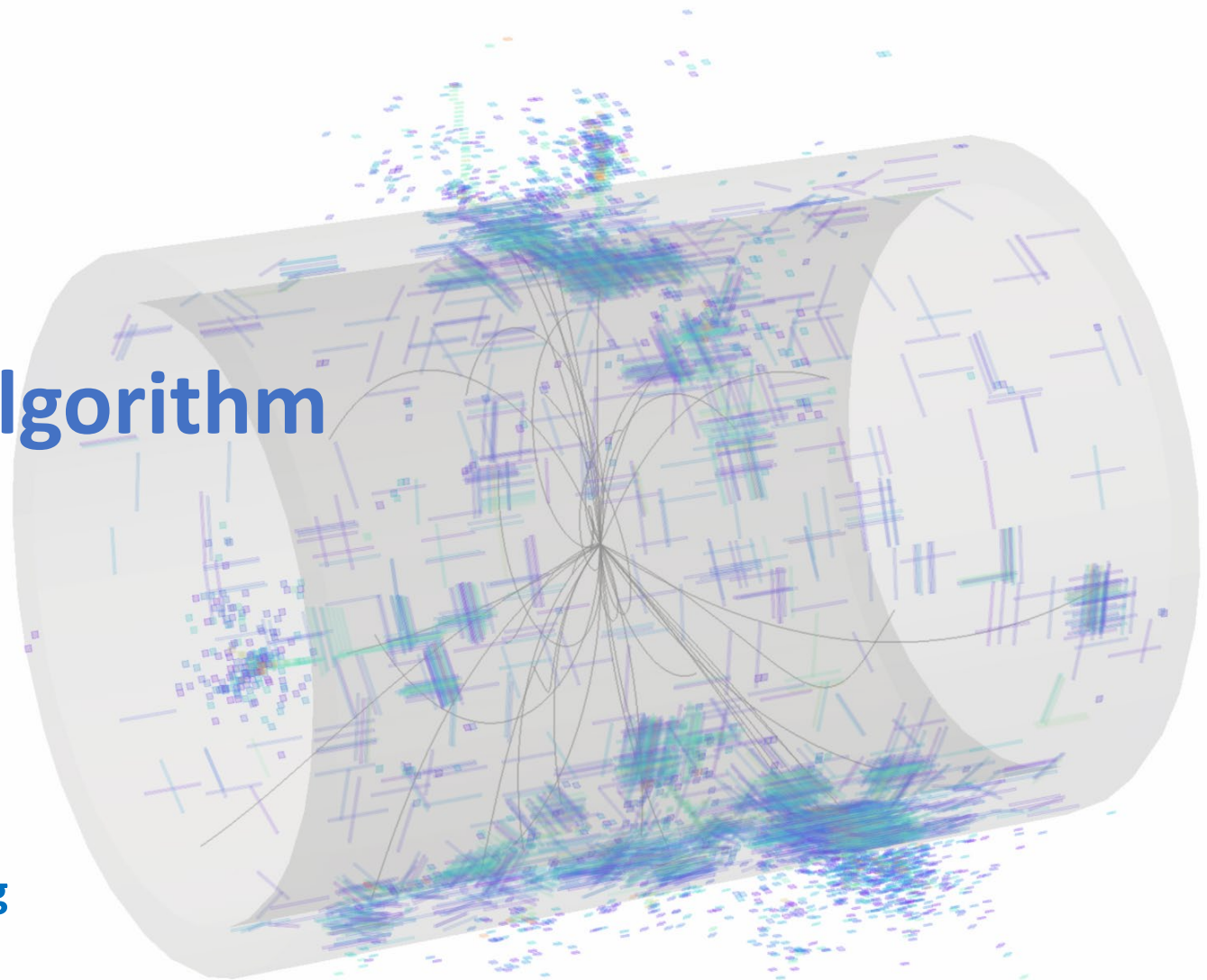


CyberPFA: Particle flow algorithm for crystal bar ECAL

SUN Shengsen

CEPC Physics and Detector Plenary Meeting

March 4, 2026



中国科学院高能物理研究所

Institute of High Energy Physics Chinese Academy of Sciences

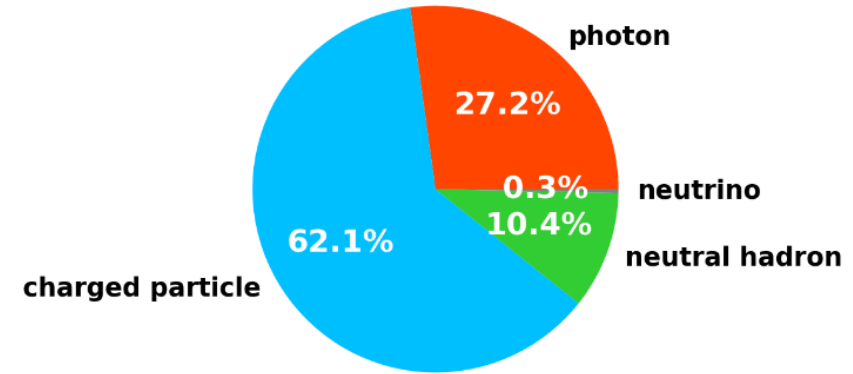
Particle Flow Approach

- **Detector requirement**

- Separate hadronic final states $W^\pm/Z/H \rightarrow q\bar{q}$
 - **Boson mass resolution (BMR) < 4%**
 - **Jet energy resolution (JER) < $\frac{30\%}{\sqrt{E}} \oplus 4\%$**

- **Particle Flow Approach**

- Measure the jet by its component: $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$
- Hardware + Software



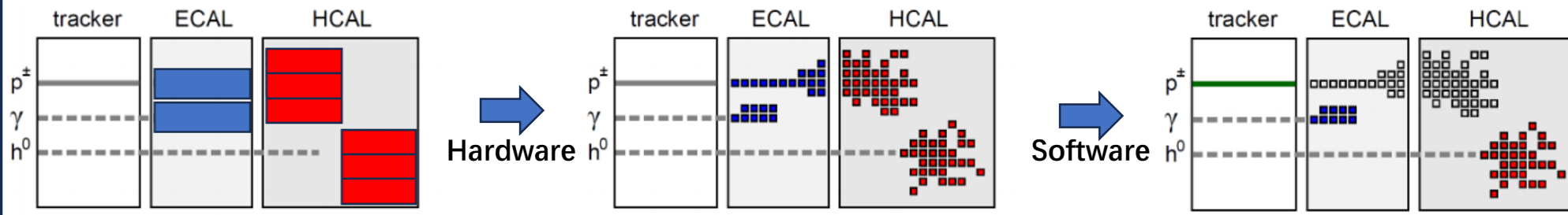
Energy ratio of particles in jet

Hardware: separate clusters from different particles.

- High granularity.
- Compact sampling structure.

Software: correctly assign calorimeter energy deposits to the particles.

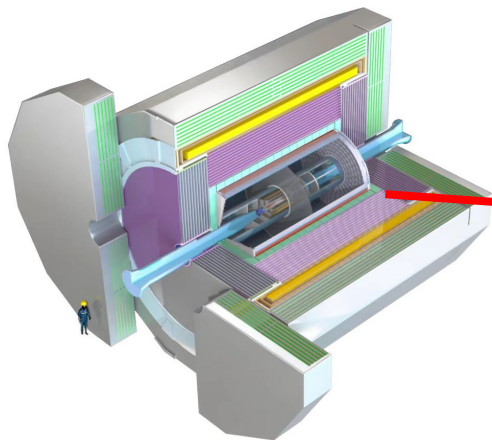
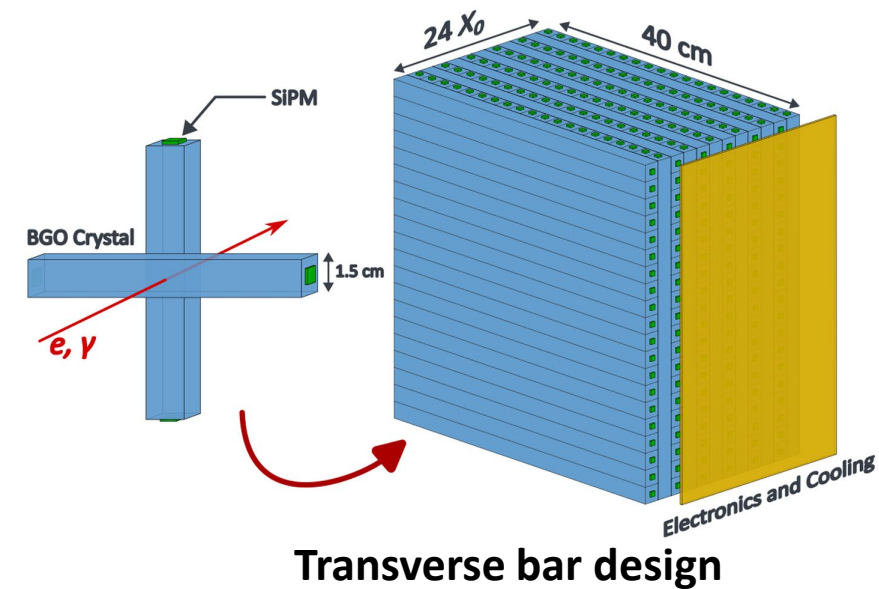
- Clustering
- Pattern recognition.



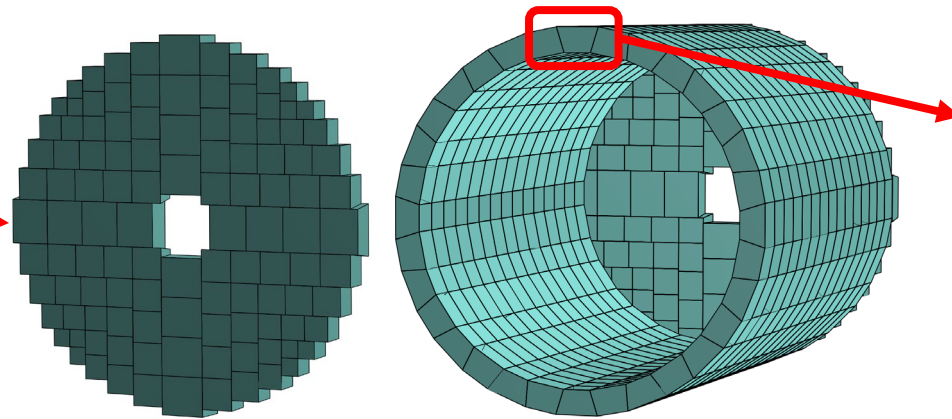
ECAL in CEPC reference detector

- **Homogeneous crystal bar ECAL**

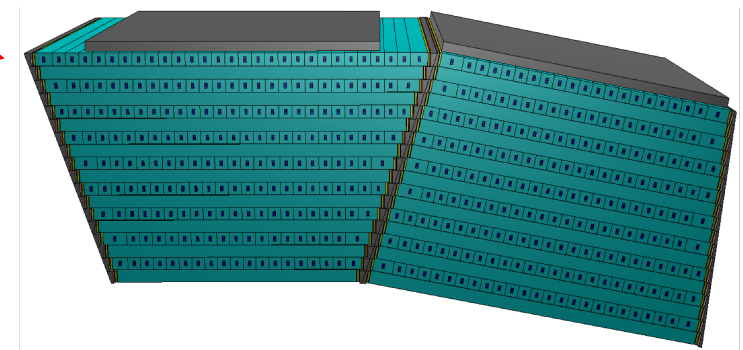
- Optimal intrinsic EM resolution:
 - $\sigma_E/E < 2\%/\sqrt{E}$,
 - Much better than $\sim 15\%/\sqrt{E}$ of SiW ECAL
- Less readout channels / Cost effective
- Compatible with PFA
 - No conventional PFA support crystal bar ECAL design
 - Only choice is to develop a dedicated PFA algorithm



Reference detector



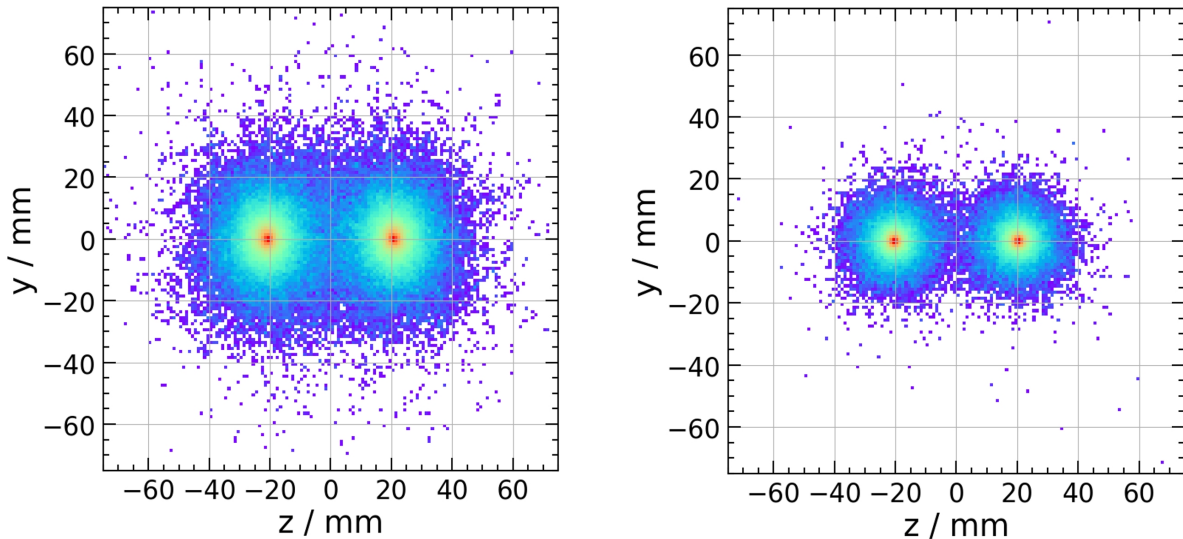
ECAL



Challenges of PF algorithm

Larger R_M & smaller λ_I/X_0

↓
Shower overlap

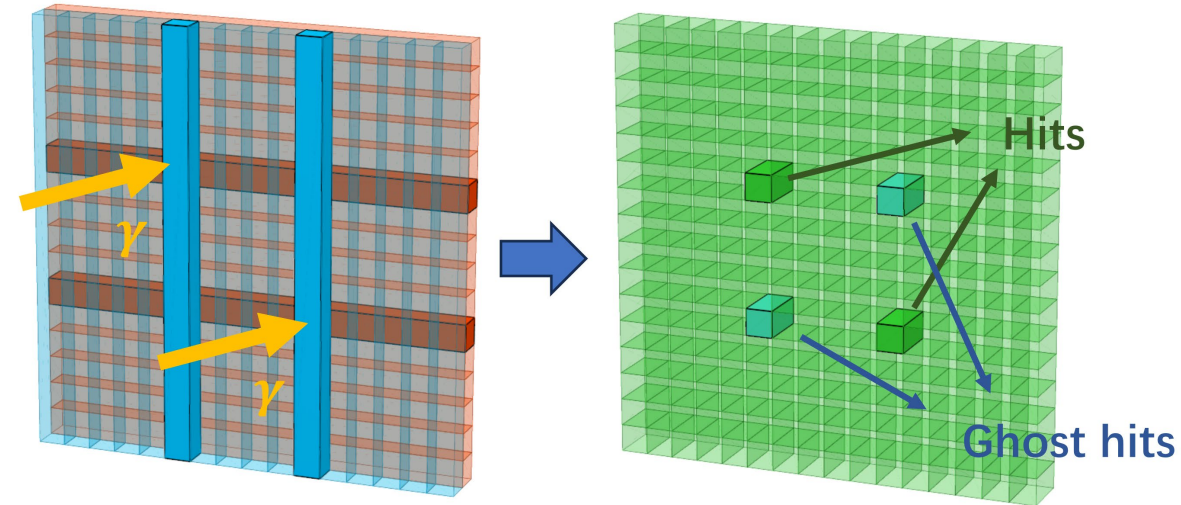


Two 5 GeV EM shower in
BGO crystal (left) and Tungsten (right)

CyberPFA developed for crystal bar ECAL

Arrangement of transverse bar

↓
Ghost hit



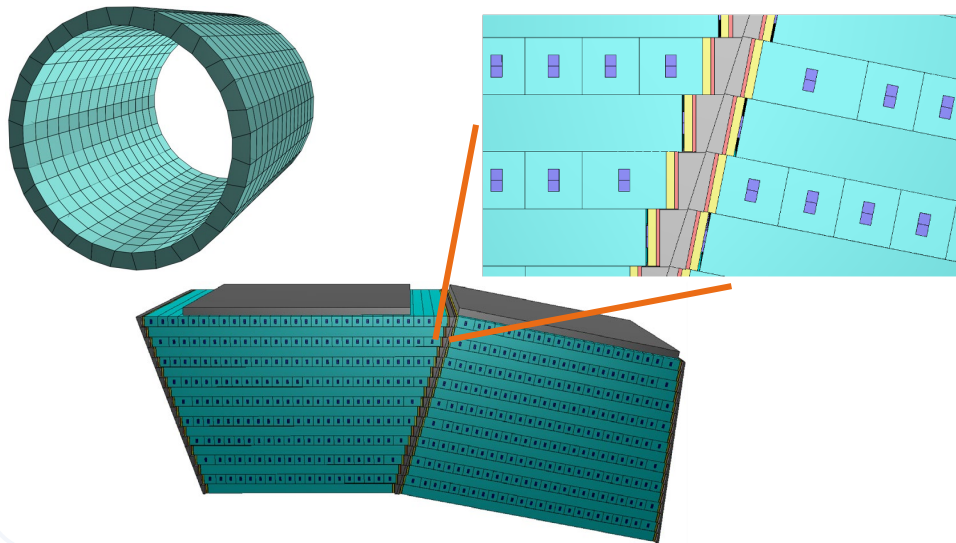
Software task:

- * Clustering
- * Pattern recognition.
- + Energy splitting.
- + Ghost hit removal

Detector Simulation

A realistic detector description implemented in CEPCSW with DD4HEP

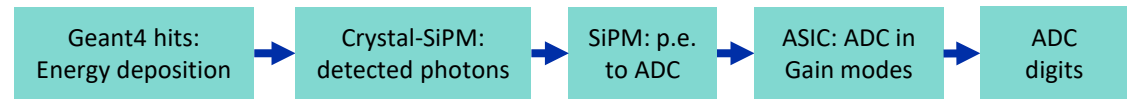
- Inner R = 1830 mm, depth 300 mm (24 X_0), 18 layers.
- $1.5 \times 1.5 \times \sim 40 \text{ cm}^3$ BGO bars with ESR wrapping
- 32-side polygon, invert trapezoid modules.
- **Dead material between modules:**
 - SiPM, PCB, FE and BE electronic boards ($\sim 3 \text{ mm}$)
 - Copper plate cooling (1 mm)
 - Carbon fiber supporting (5 mm/side)
- An energy correction for the crack leakage.



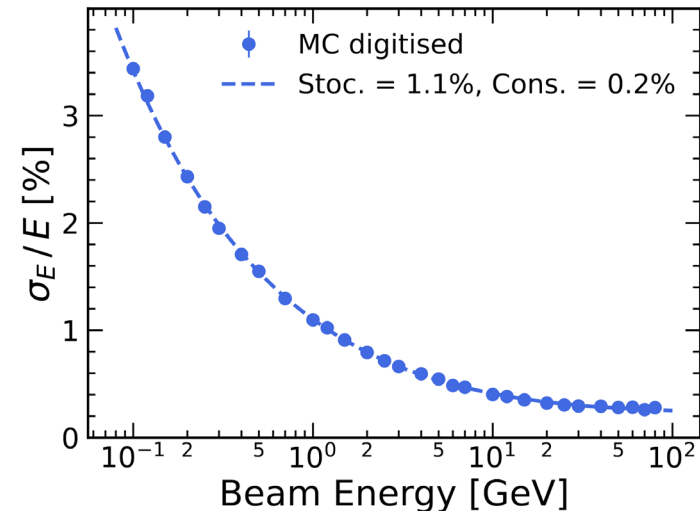
Digitization model: from beam test

- 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

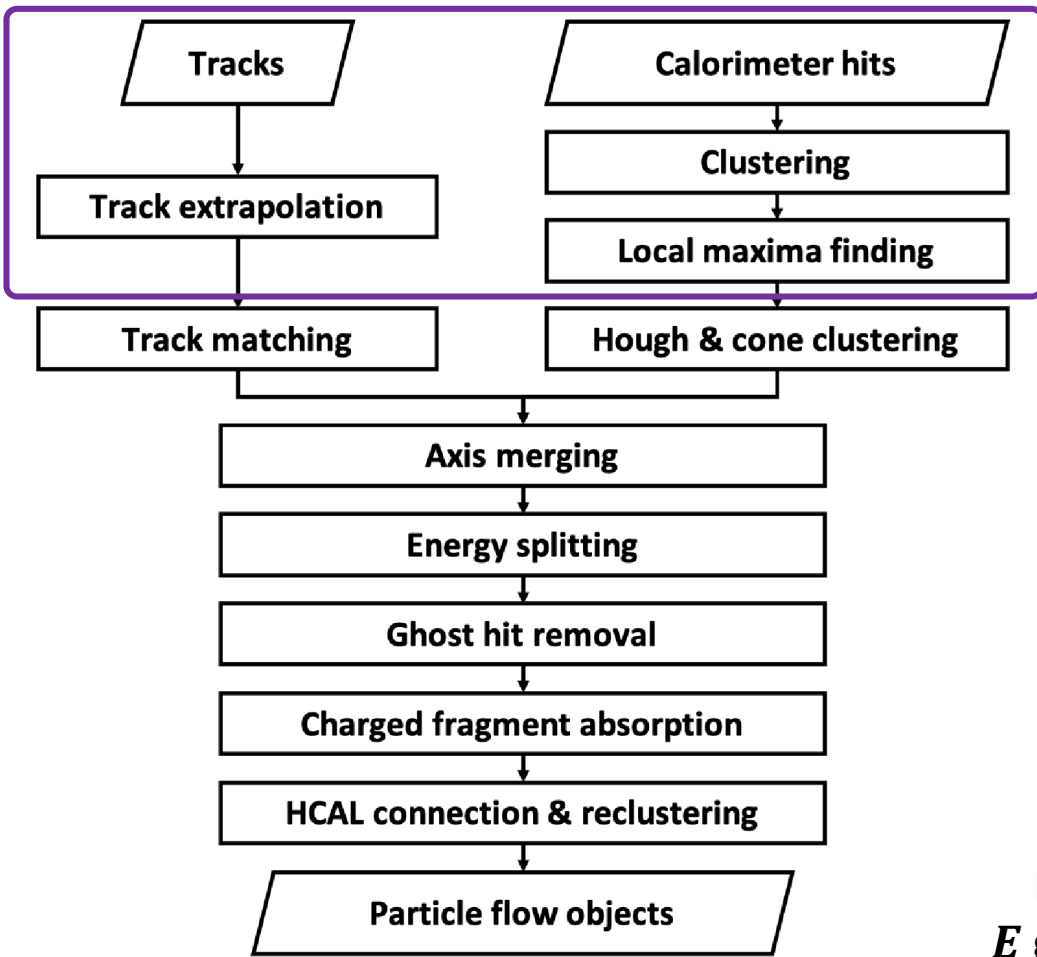
Energy resolution with full digitization: $\sigma_E/E = 1.1\%/\sqrt{E} \oplus 0.2\%$
(in module center)



CEPC Ref-TDR

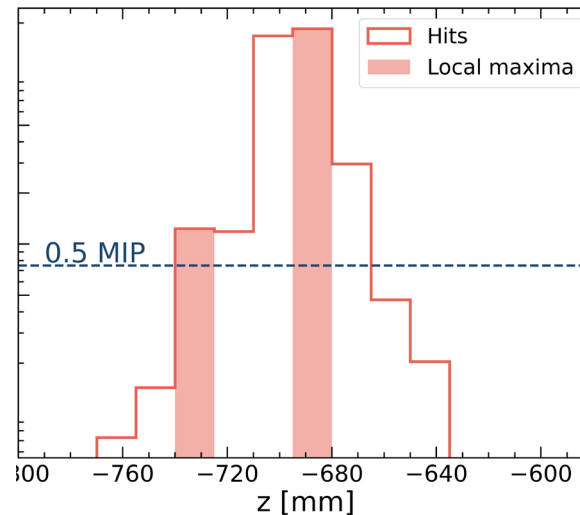


CyberPFA: PFA for crystal bar ECAL

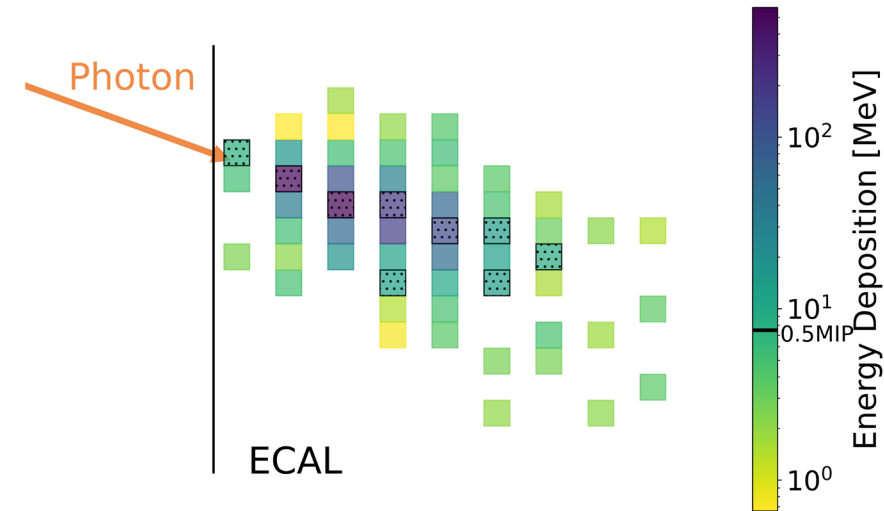


Step 1: preparation

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

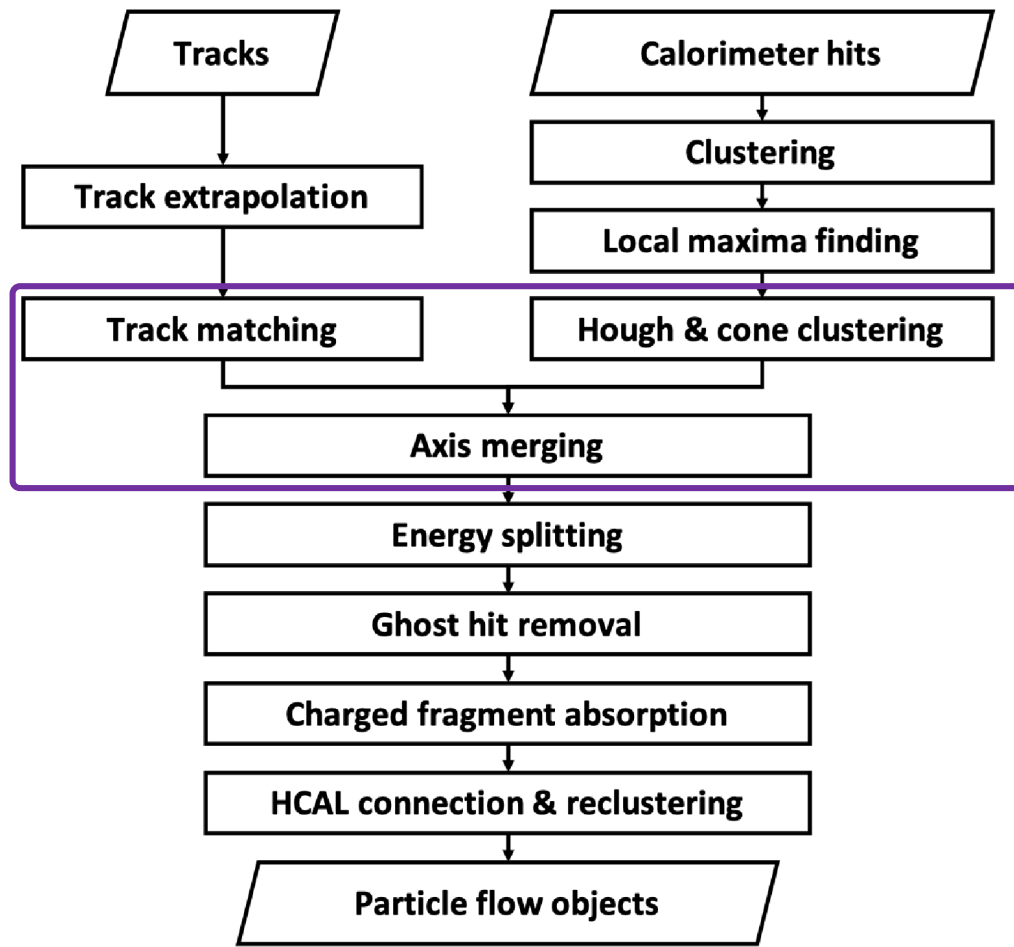


Definition of local maximum:
 E greater than nearby crystal and
greater than 0.5 MIP



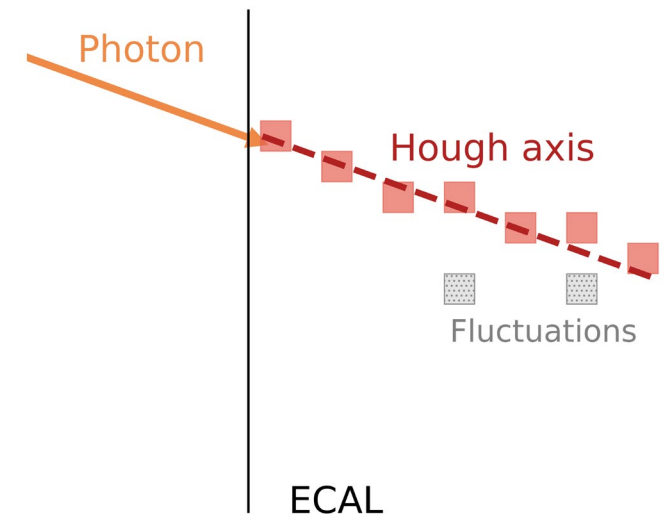
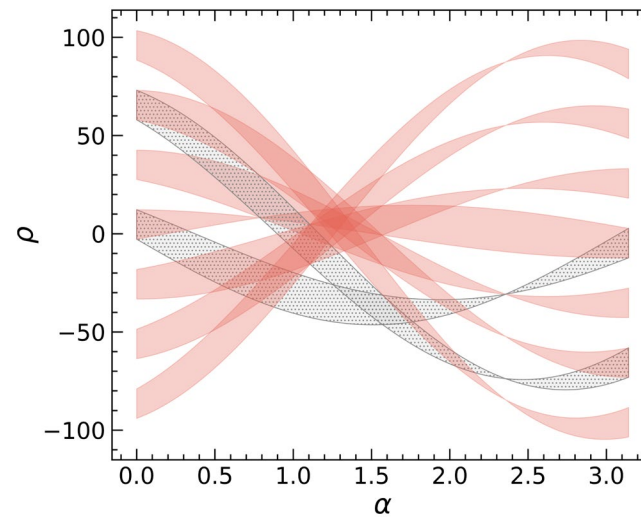
Spatial distribution of hits and local maxima of a 5 GeV EM shower
[Yang Zhang et.al, arxiv 2508.20728](https://arxiv.org/abs/2508.20728)

CyberPFA: PFA for crystal bar ECAL



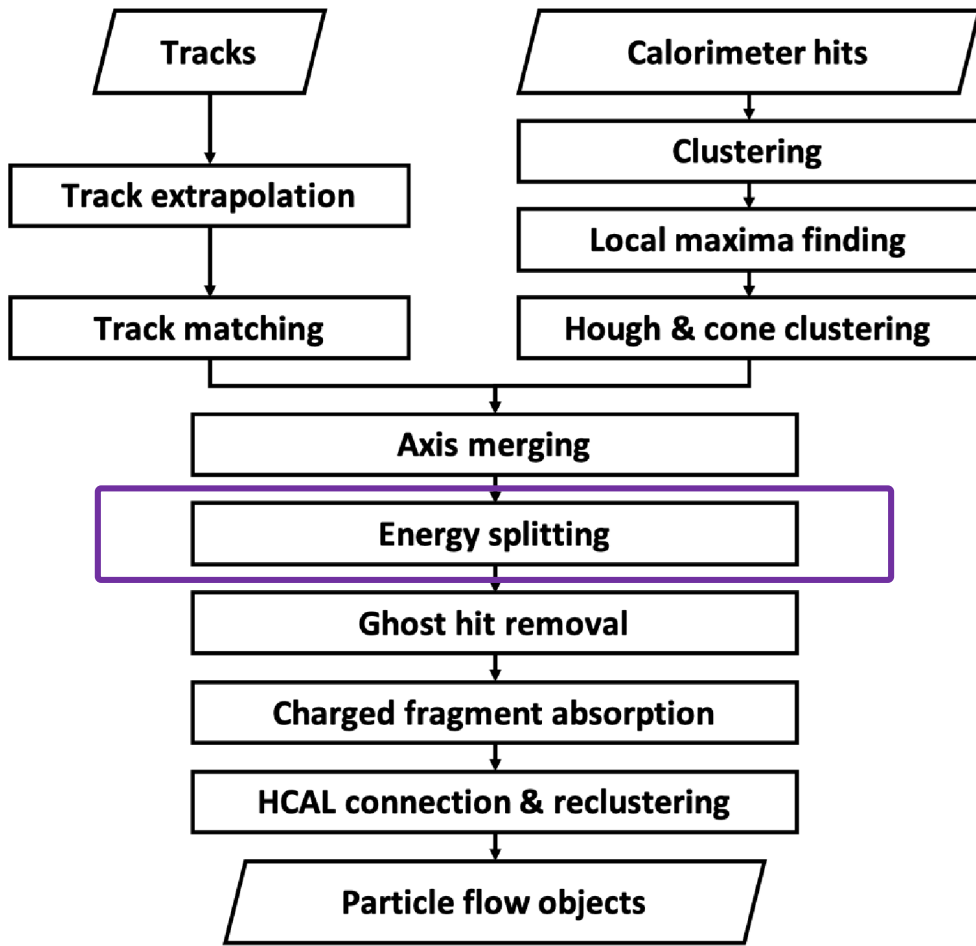
Step 2: Energy-core-based shower recognition

- 3 individual algorithms for different types of particles
- A set of topological cluster merging



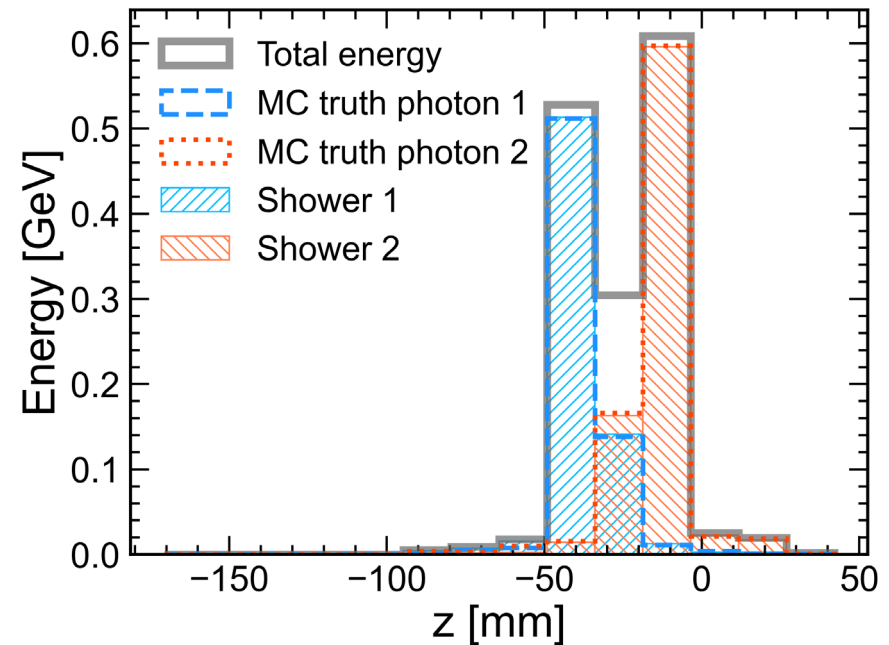
Energy-core based photon recognition using Hough transform

CyberPFA: PFA for crystal bar ECAL



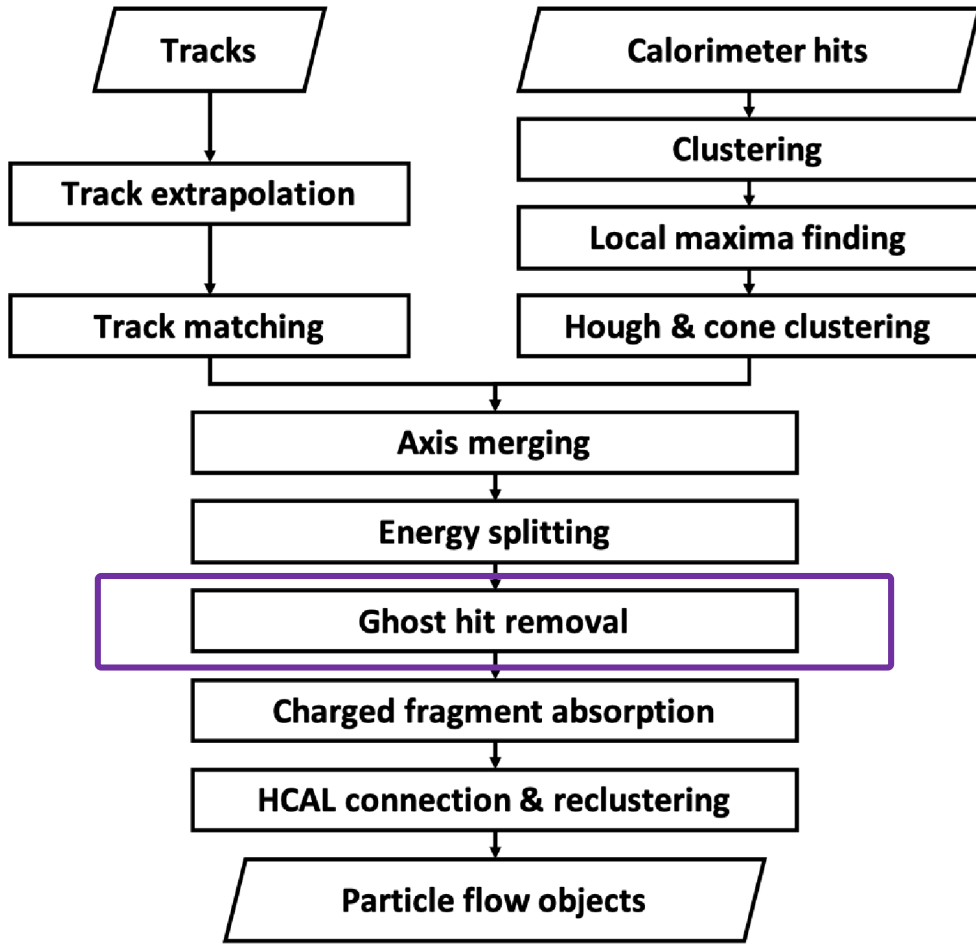
Step 3: energy splitting

- Split the energy with lateral shower profile.



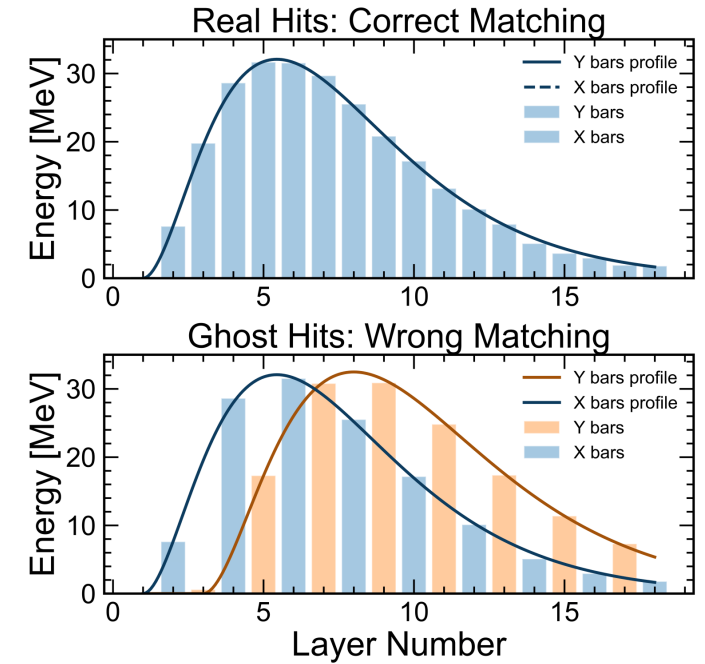
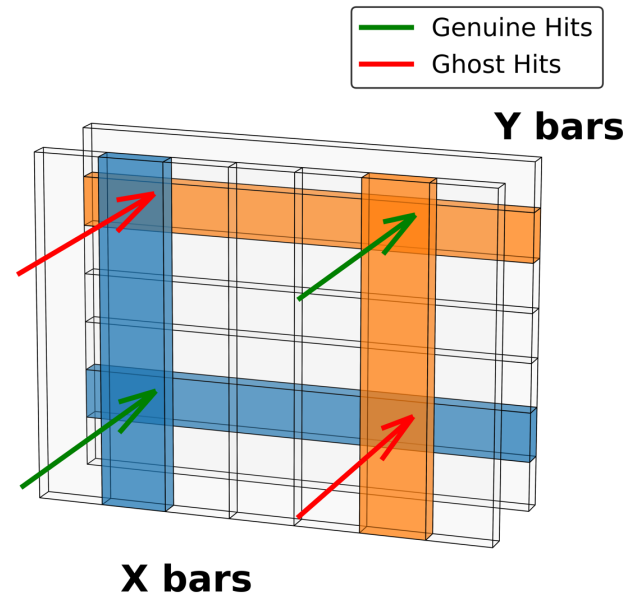
Energy splitting of two overlapping EM shower

CyberPFA: PFA for crystal bar ECAL

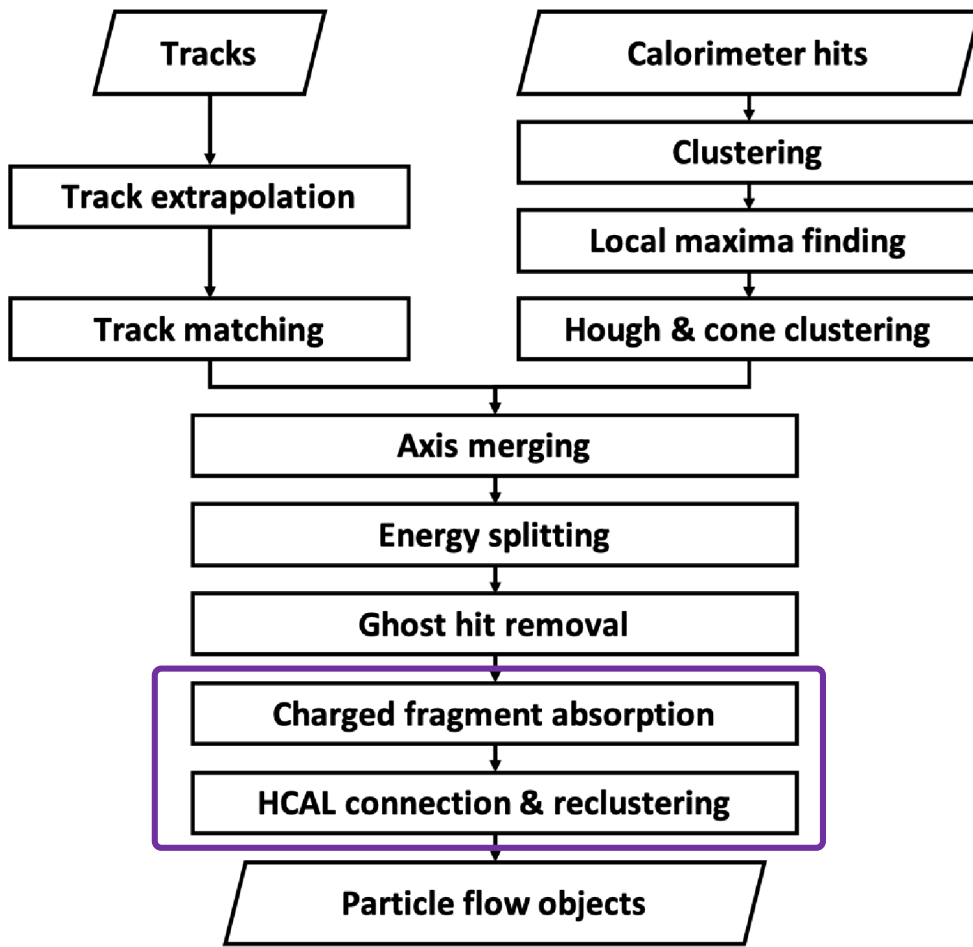


Step 4: ghost hit removal

- Remove ghost hit with track + neighbor module + energy + ...

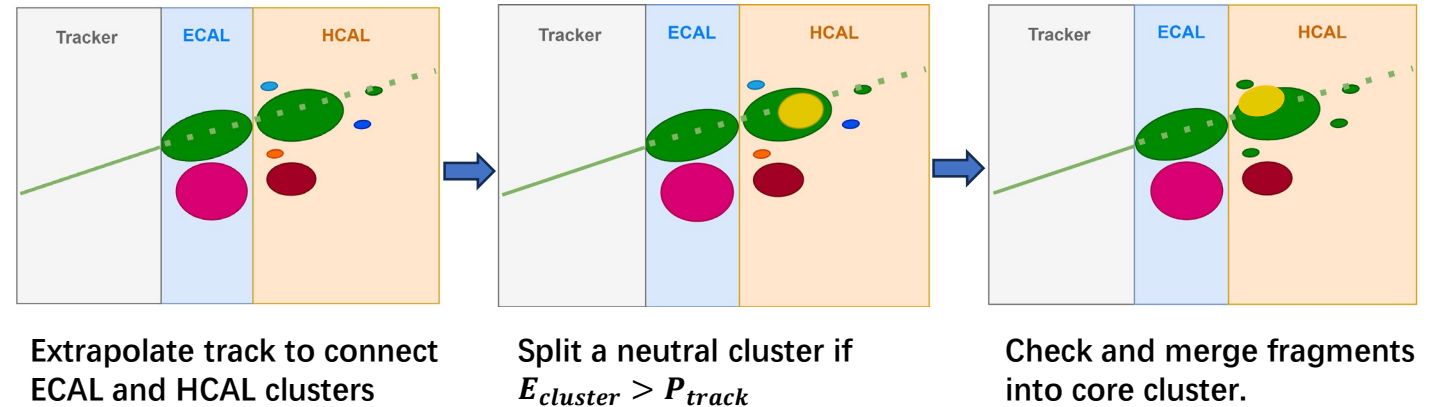


CyberPFA: PFA for crystal bar ECAL



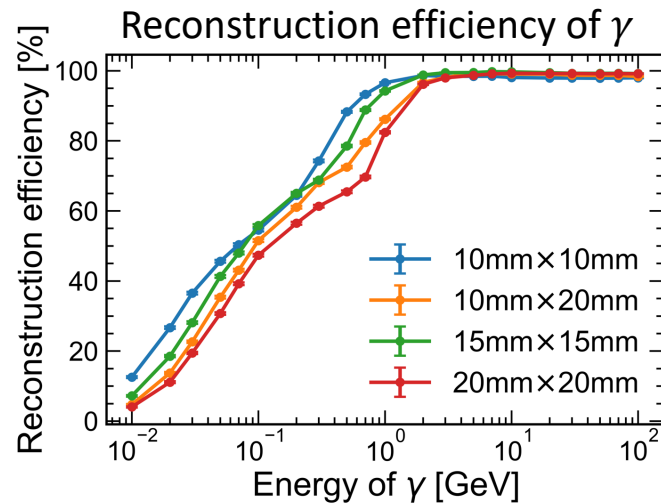
Step 5: clustering and re-clustering

- Match ECAL & HCAL clusters.
- Traditional PFA idea: $E_{cluster} \sim P_{track}$ match.

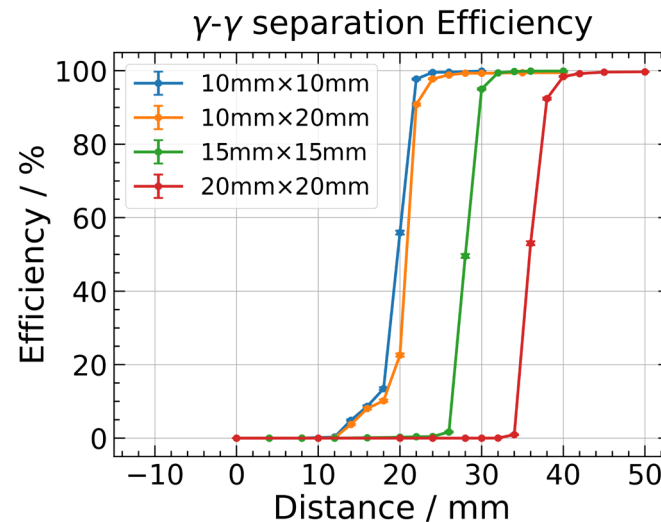


Granularity optimization

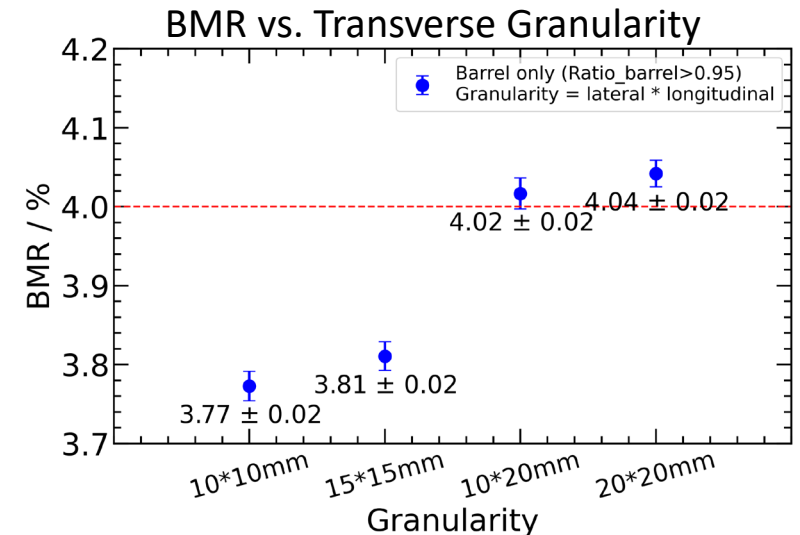
- Four typical scenarios of transverse granularity investigated
 - 10×10 mm, 10×20 mm, 15×15 mm and 20×20 mm
- Figures of merit
 - Single photon reconstruction, separation power and jet performance



Major impact from ECAL longitudinal segmentation



Separation efficiency dominated by ECAL transverse granularity



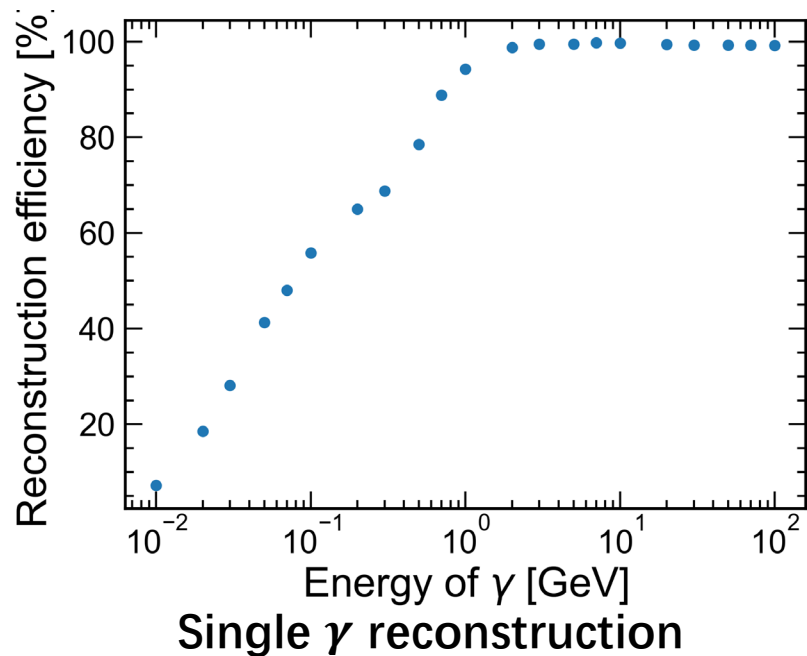
10x10mm and 15x15mm can meet physics requirement of BMR <4%

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

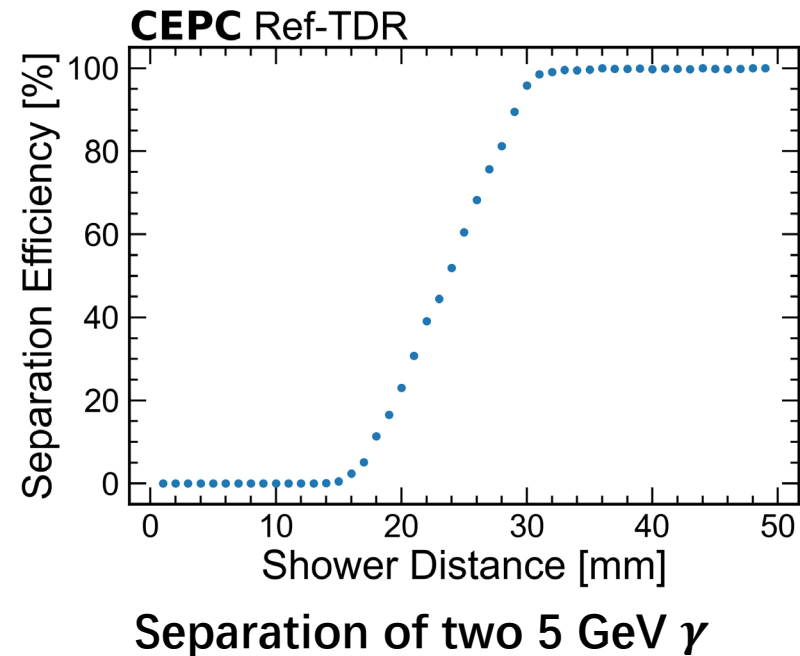
Performance: Photon



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



~100% efficiency for $E_\gamma > 2$ GeV

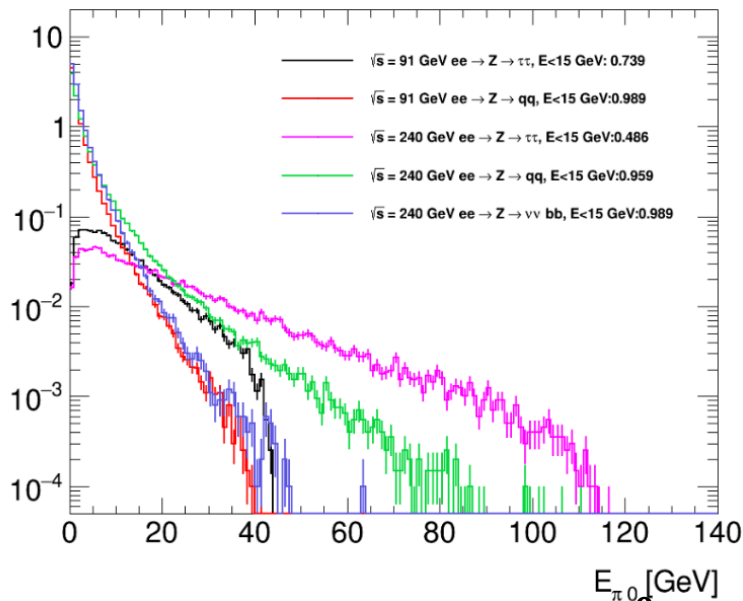


~100% efficiency for distance > 30 mm

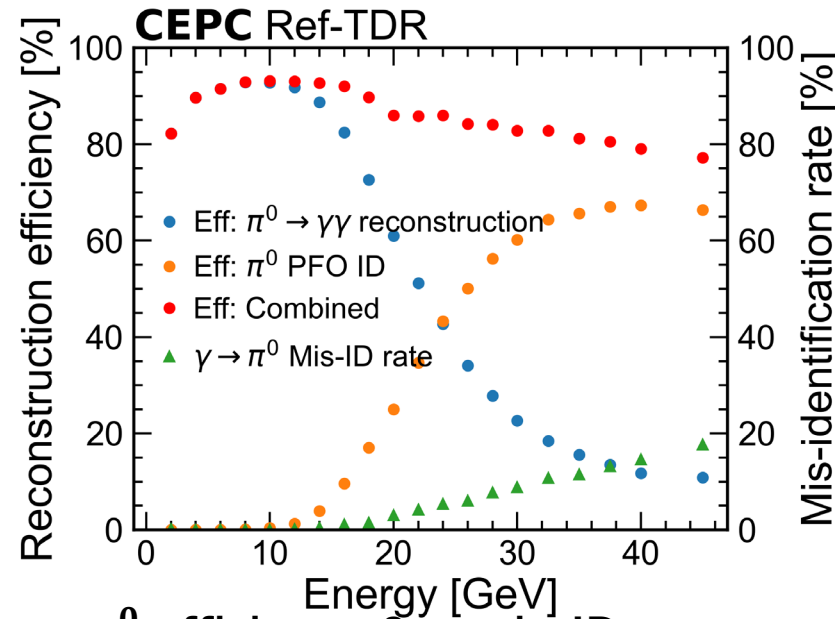
Performance: $\pi^0 \rightarrow \gamma\gamma$



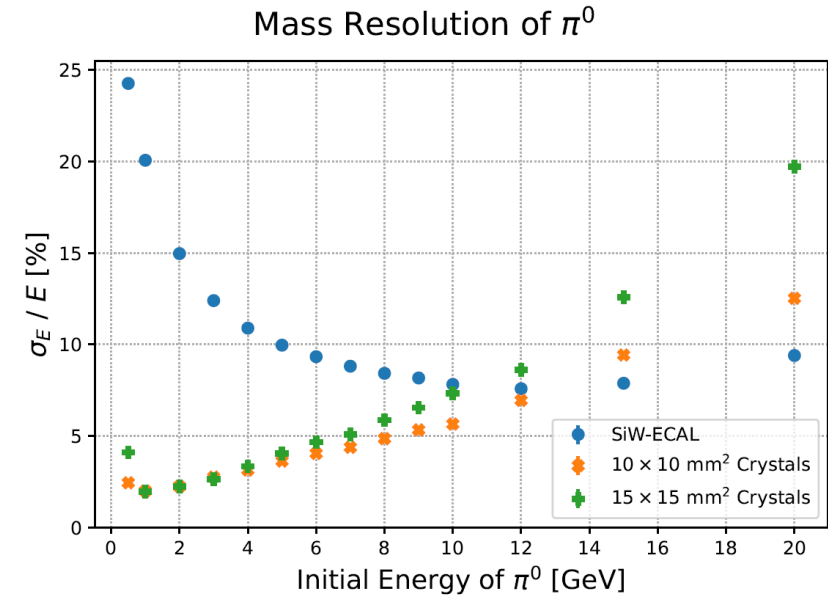
- π^0 : essential EM object in flavor studies in Tera-Z factory
 - $B^0/B_s^0 \rightarrow \pi^0\pi^0/\eta\eta$ and CP asymmetry
 - τ hadronic decay for $H \rightarrow \tau\tau$ and $Z \rightarrow \tau\tau$



Energy distribution of π^0
in different processes



π^0 efficiency & γ mis-ID rate
with CyberPFA + second moment



π^0 mass resolution
in SiW-ECAL & crystal ECAL

Efficiency > 90% @ ~10 GeV; >75% up to 45 GeV

Enhanced mass resolution (<10 GeV) over sampling ECAL

Performance: $H \rightarrow \gamma\gamma$



$e^+e^- \rightarrow ZH \rightarrow \nu\nu\gamma\gamma$ @ $\sqrt{s} = 240$ GeV

Full simulation and digitization.

Energy correction in crack region applied.

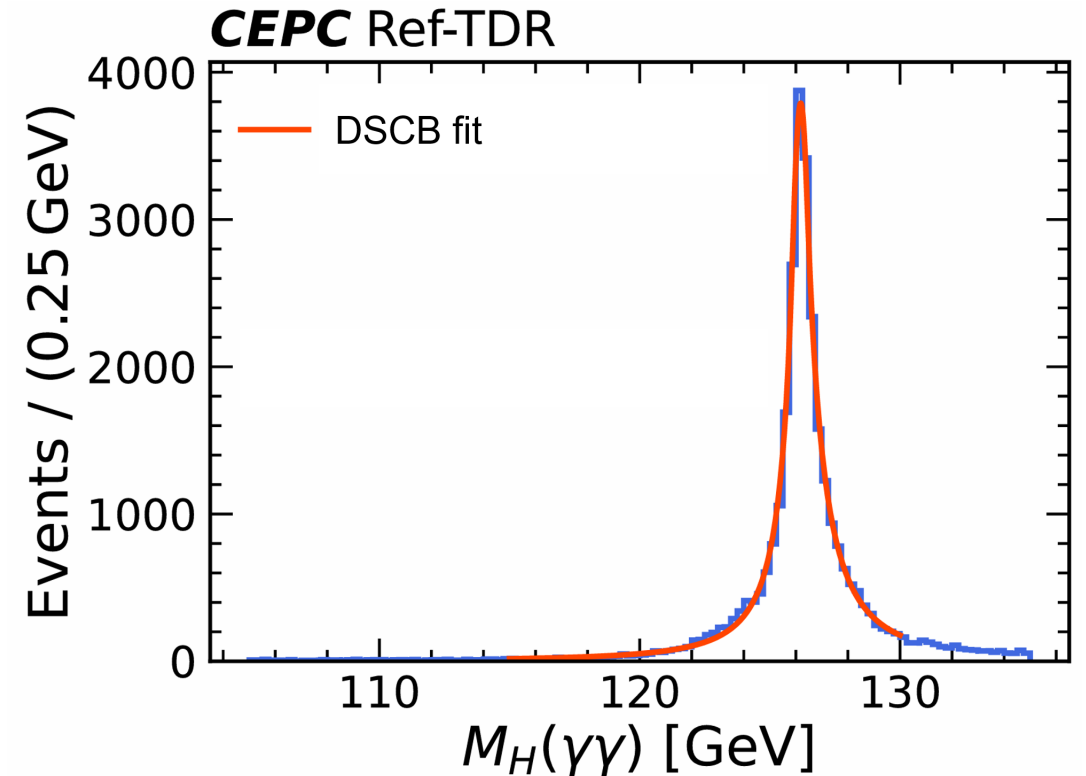
$mean = 126.185 \pm 0.005$ GeV,

$\sigma = 0.397 \pm 0.006$ GeV

Mass resolution: $0.31 \pm 0.10\%$.

Measurement precision of $\sigma(e^+e^- \rightarrow ZH) \times Br(H \rightarrow \gamma\gamma)$

increased by $\sim 20\%$ compare to CEPC CDR detector, benefit from ECAL resolution

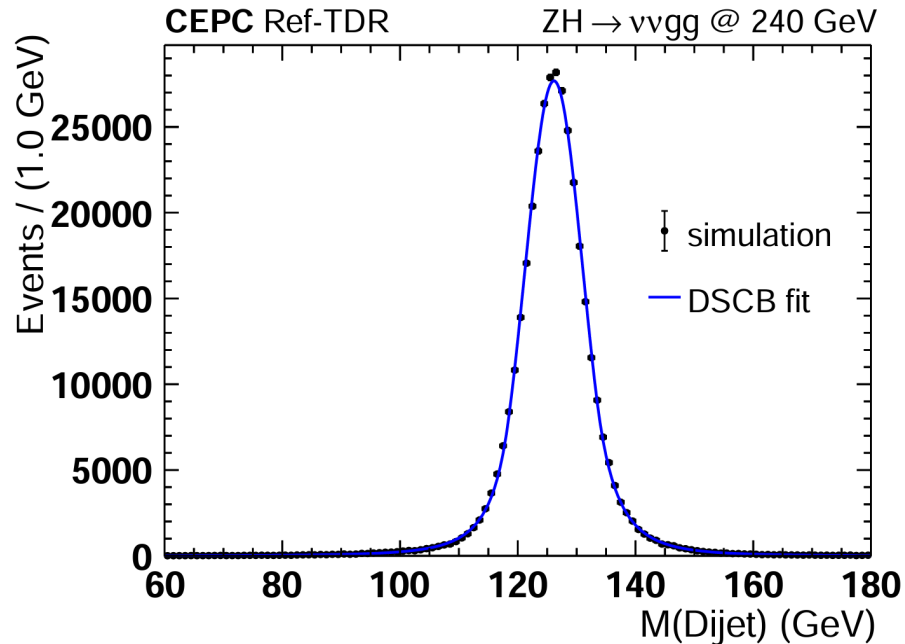


Talk by Reda: [Measurement of the Higgs decaying into two photons with the CEPC reference detector](#)

Performance: Jet reconstruction



$e^+e^- \rightarrow ZH \rightarrow \nu\nu gg @ \sqrt{s} = 240 \text{ GeV}$



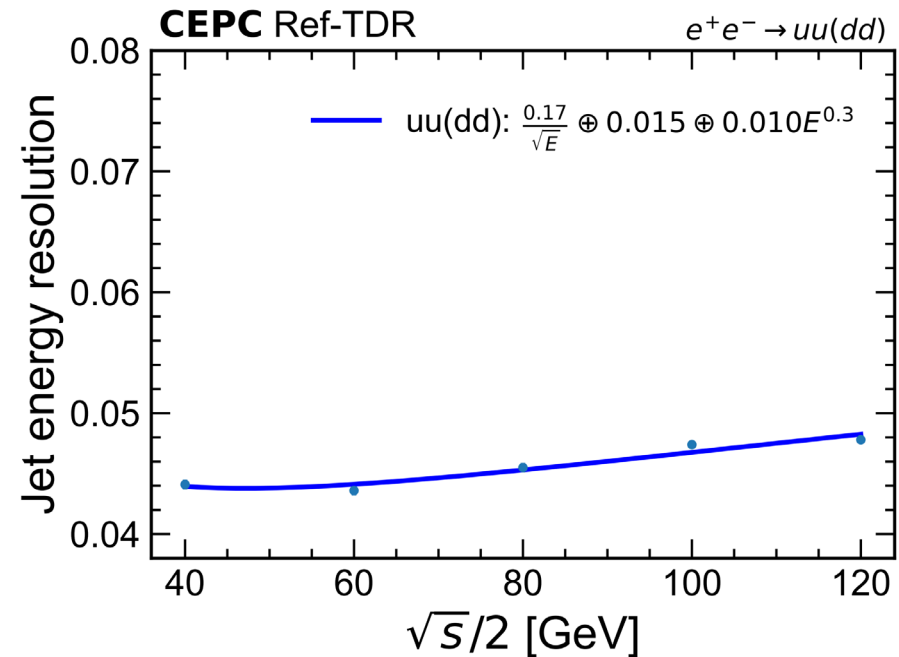
$$|\cos \theta_{jet}| < 0.85$$

$$m_{jj} = 126.14 \pm 0.01$$

$$\sigma_{jj} = 4.89 \pm 0.01$$

$$\text{BMR} = 3.87 \pm 0.10\%$$

$e^+e^- \rightarrow uu(dd)$



$$|\cos \theta_{jet}| < 0.85$$

$$\text{JER} = \frac{0.17}{\sqrt{E_{Gen}}} \oplus 0.015 \oplus 0.01E^{0.3}$$

Jet reconstruction satisfy physics requirement in CEPC

Summary and outlook

- **Crystal ECAL for CEPC reference detector**
 - Precision resolution for both energy and position
 - First homogenous ECAL compatible with PFA
- **CyberPFA for the crystal ECAL:**
 - Overlap addressed by energy-core-based shower recognition & energy splitting
 - Ghost hit removed by multi-variate information (tracking, energy...)
 - BMR $\sim 3.87\%$, comparable with traditional PFA
- **Future plan:**
 - Optimization of PFA performance: cluster ID, energy correction, advanced pattern recognition, ...

Thank you for your attention!



Backup

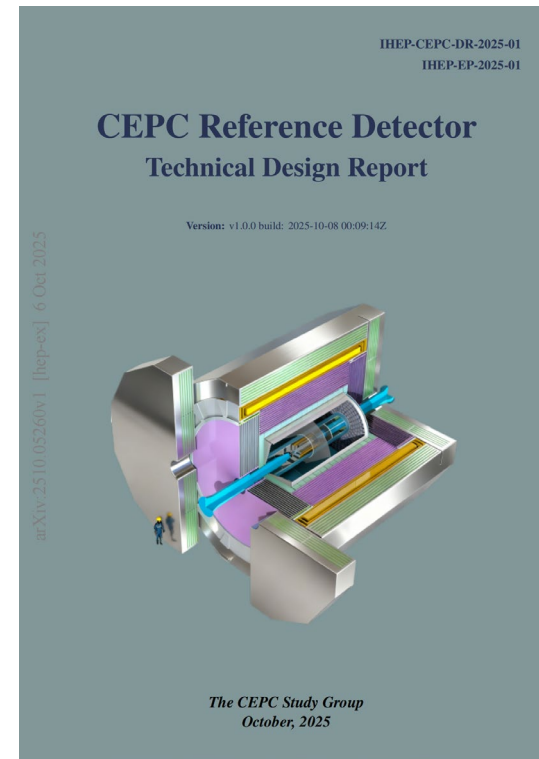
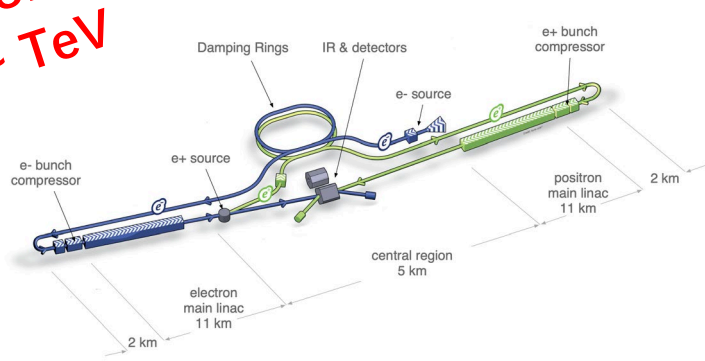
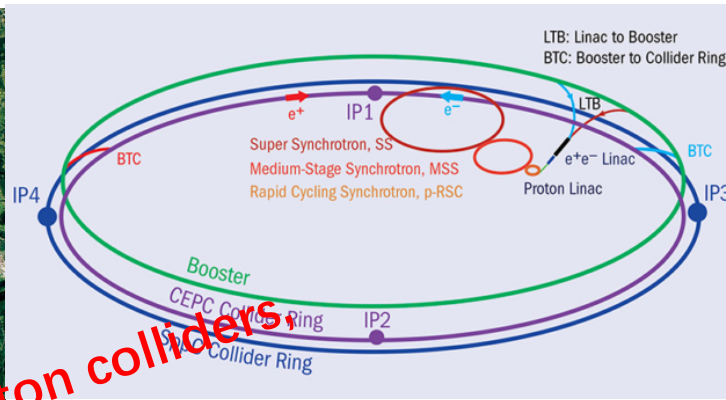
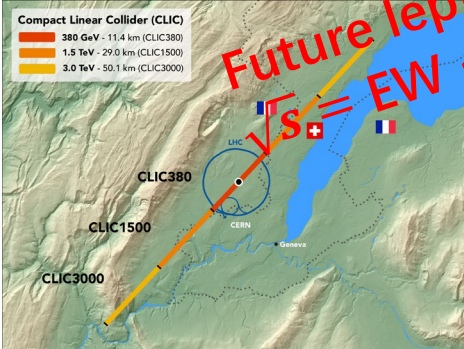
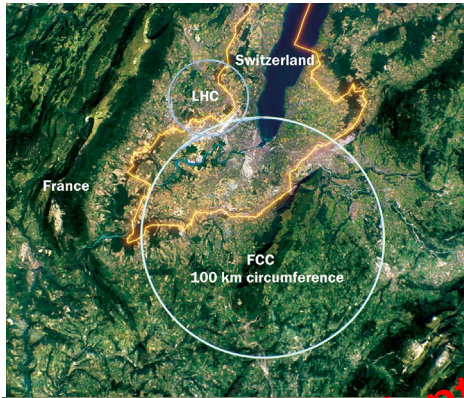


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Future lepton collider

- **Physics after Higgs discovery:**

- Precise measurement of Higgs, EW, top, flavor, QCD...
- BSM physics (dark matter, EW phase transition, SUSY, LLP...)



arXiv:[2510.05260](https://arxiv.org/abs/2510.05260)

arXiv:[2312.14363](https://arxiv.org/abs/2312.14363)

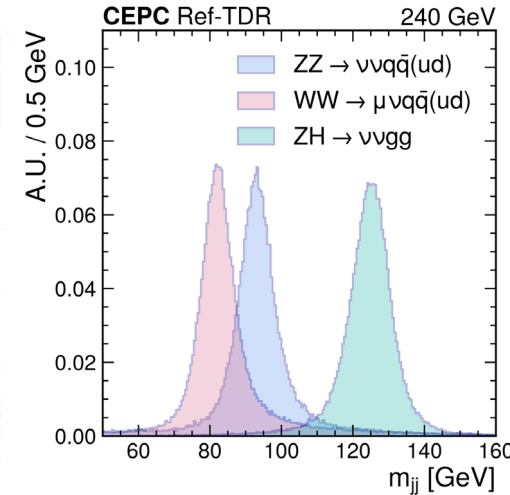
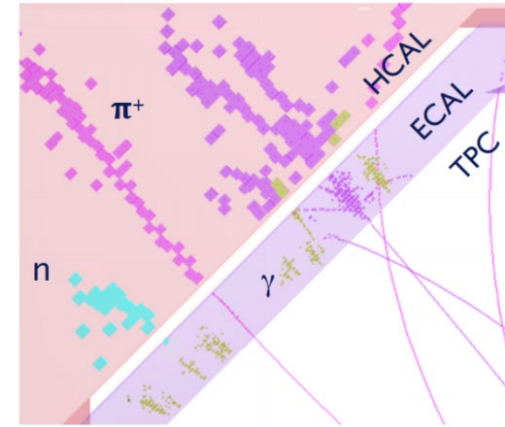
Future lepton collider

- **Detector requirement**

- Separate hadronic final states $W^\pm/Z/H \rightarrow q\bar{q}$
 - **Boson mass resolution (BMR) < 4%**
 - **Jet energy resolution (JER) < $\frac{30\%}{\sqrt{E}} \oplus 4\%$**

- **Particle Flow Approach**

- Measure the jet by its component: $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$
- Hardware + Software

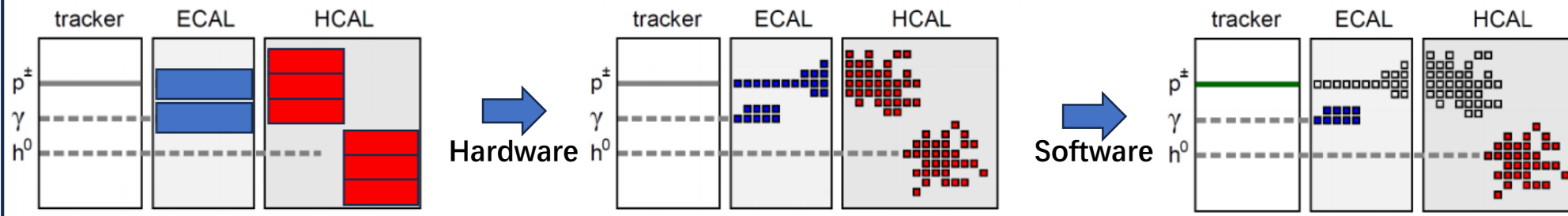


Hardware: separate clusters from different particles.

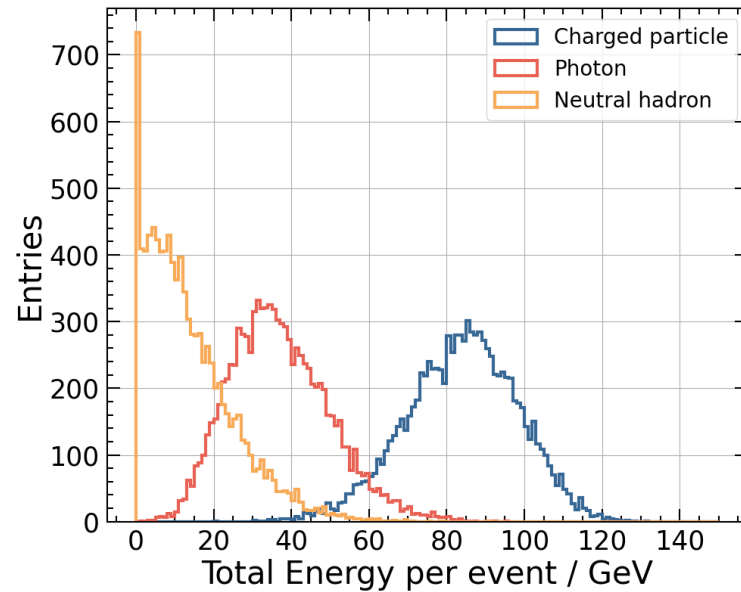
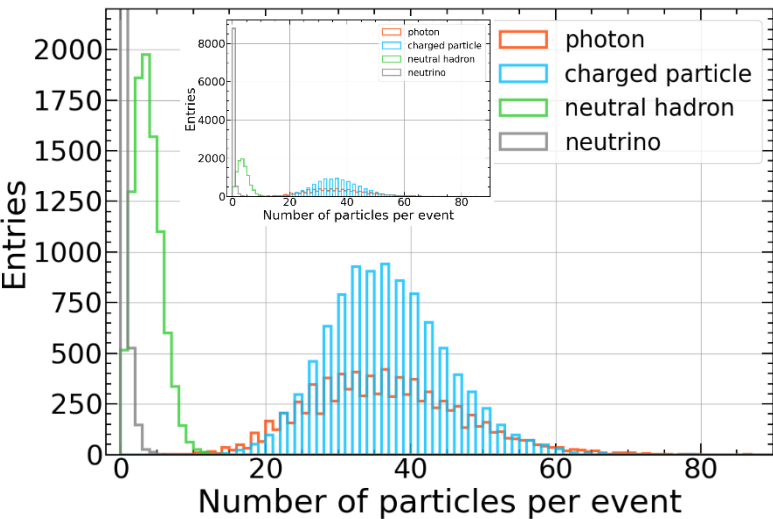
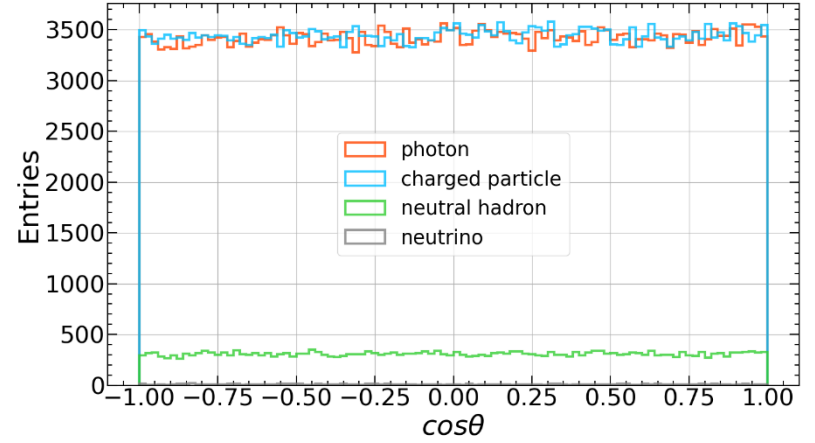
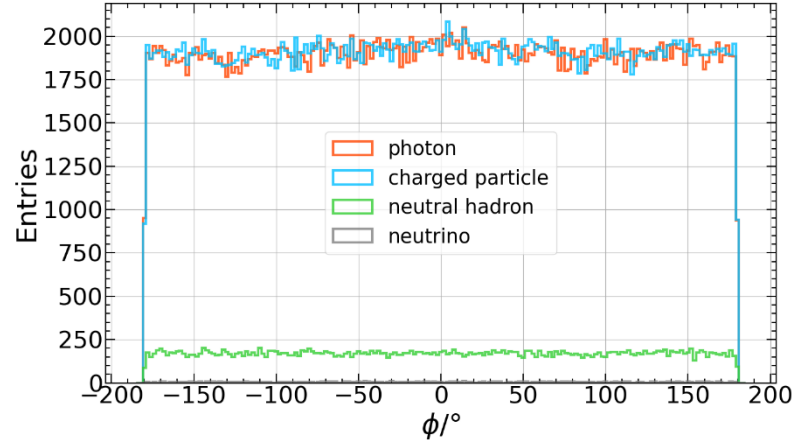
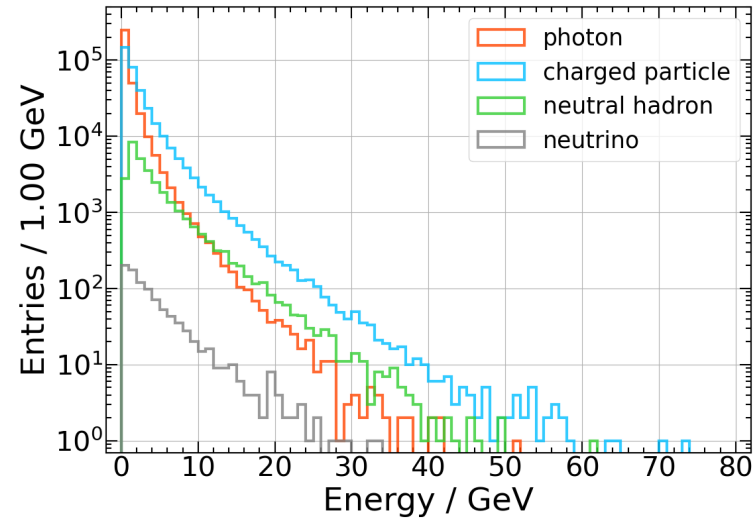
- High granularity.
- Compact sampling structure.

Software: correctly assign calorimeter energy deposits to the particles.

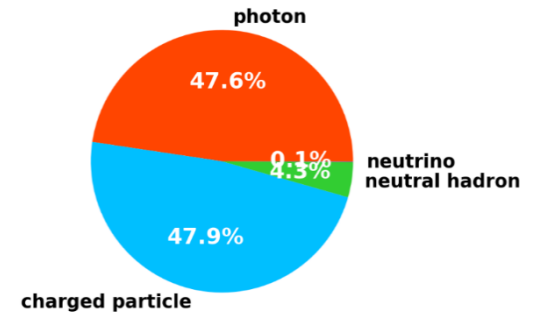
- Clustering
- Pattern recognition.



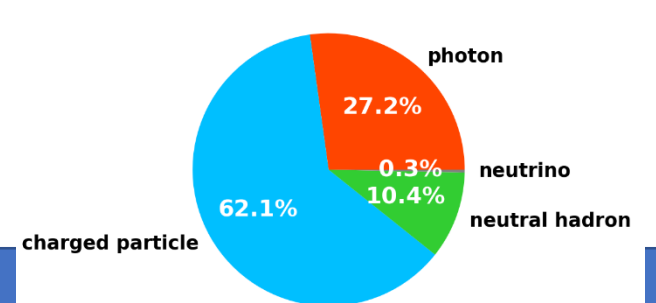
$H \rightarrow aa$ MC information



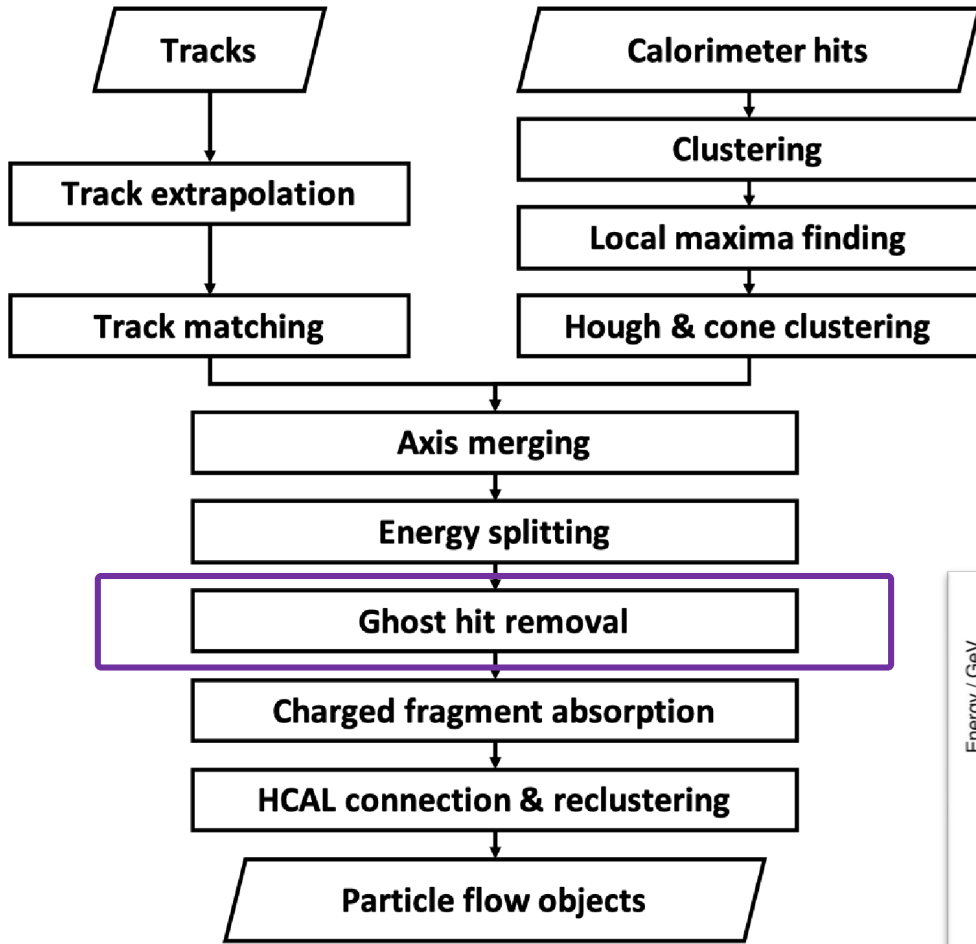
Number of particles



Energy of particles

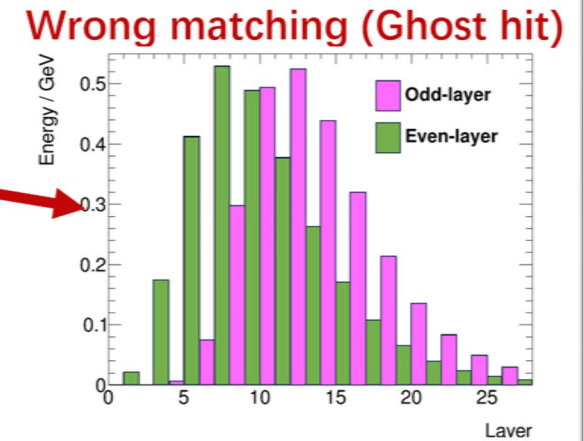
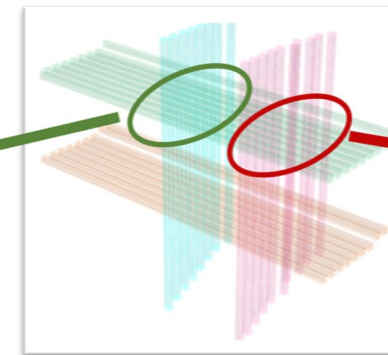
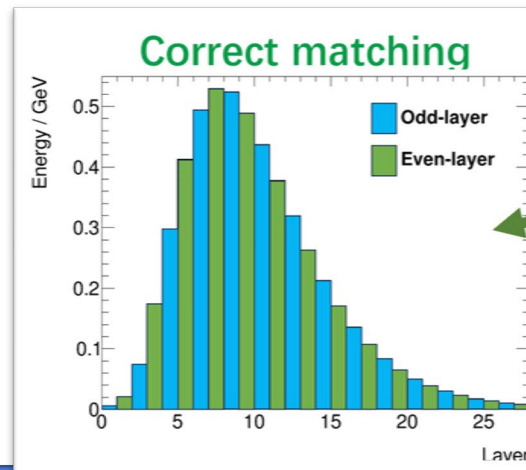
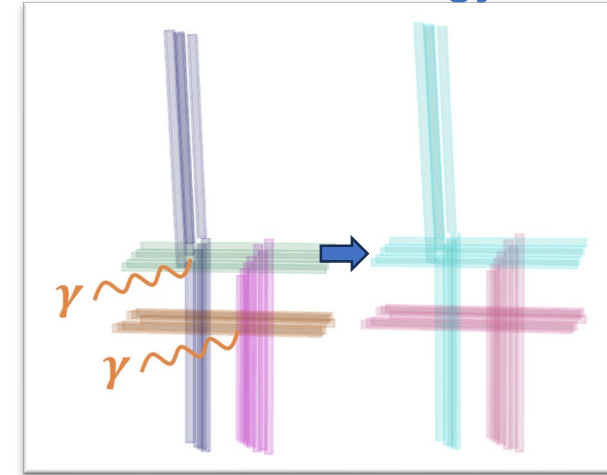
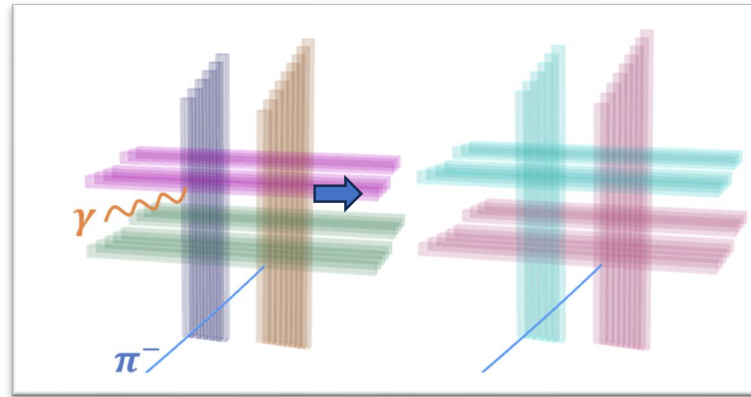


CyberPFA: PFA for crystal bar ECAL



Step 4: ghost hit removal

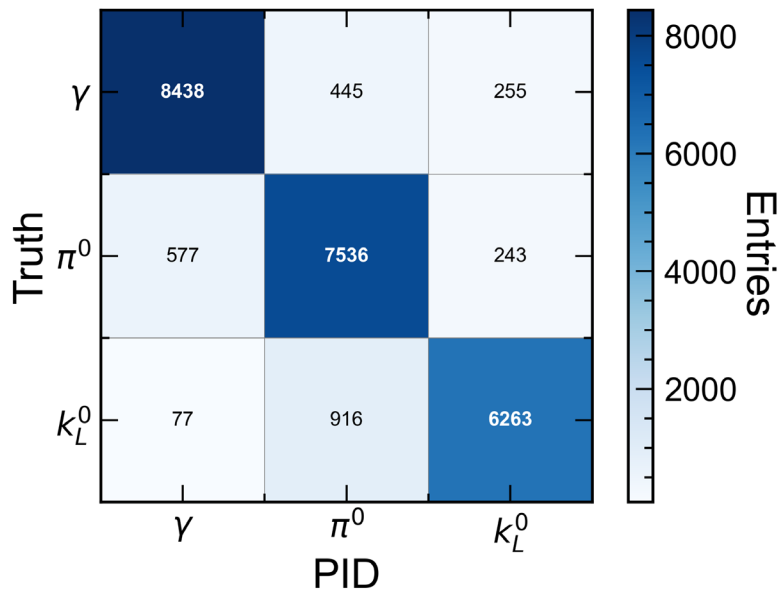
- Remove ghost hit with track + neighbor module + energy + ...



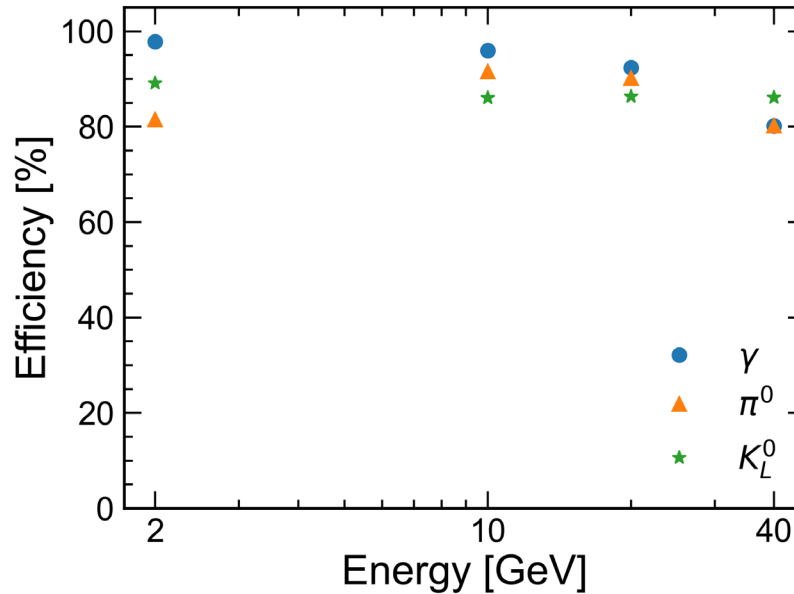
Performance: $\gamma/\pi^0/K_L^0$ PID



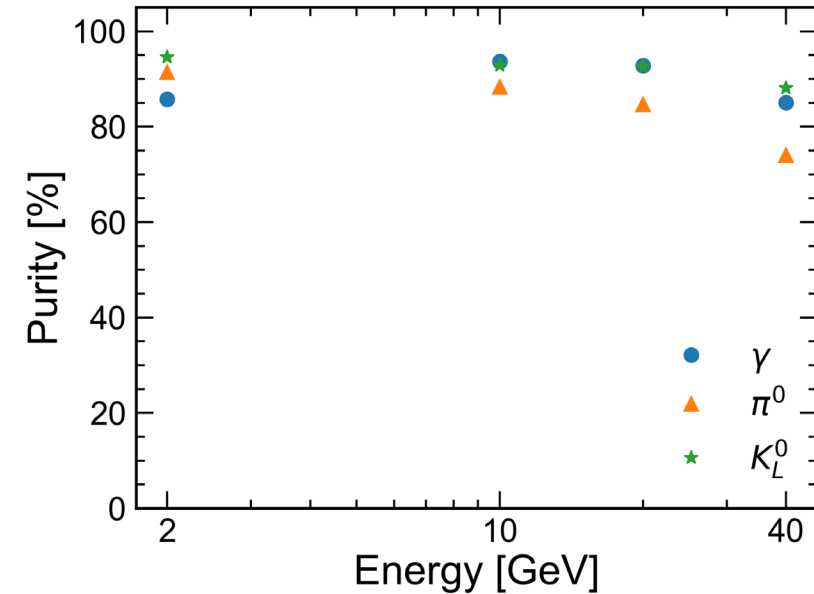
- $\gamma/\pi^0/K_L^0$ showers in ECAL and HCAL
- PID with second moment + energy ratio between ECAL & HCAL



Confusion matrix of $\gamma/\pi^0/K_L^0$ PID @ 20 GeV



Identification efficiency & purity vs true energy



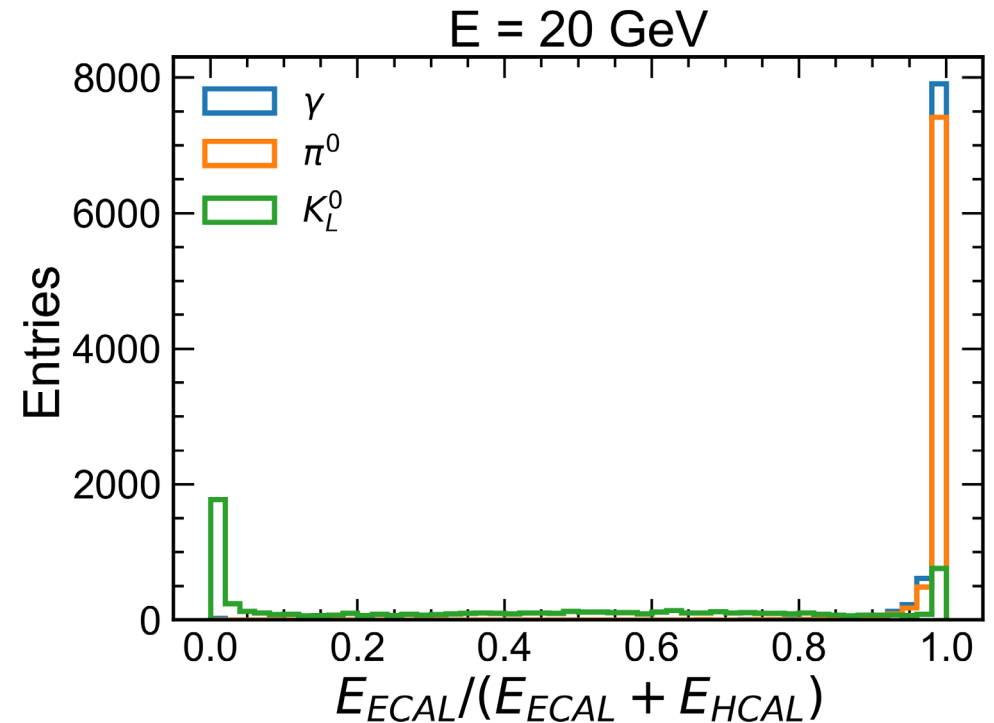
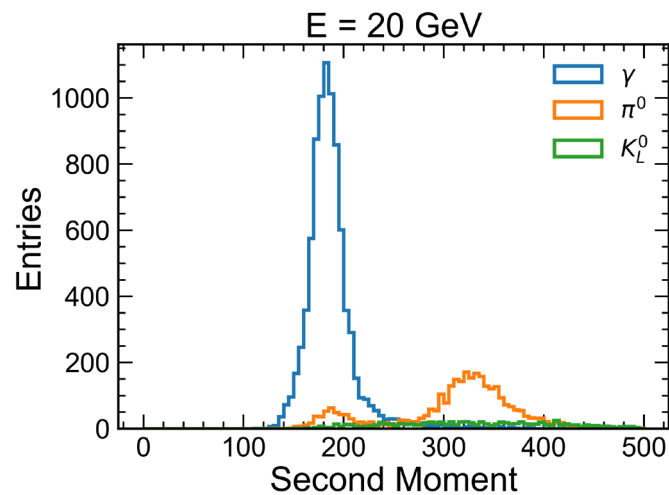
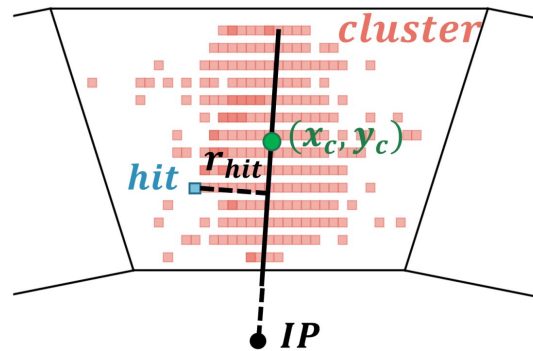
Second moment & Energy ratio



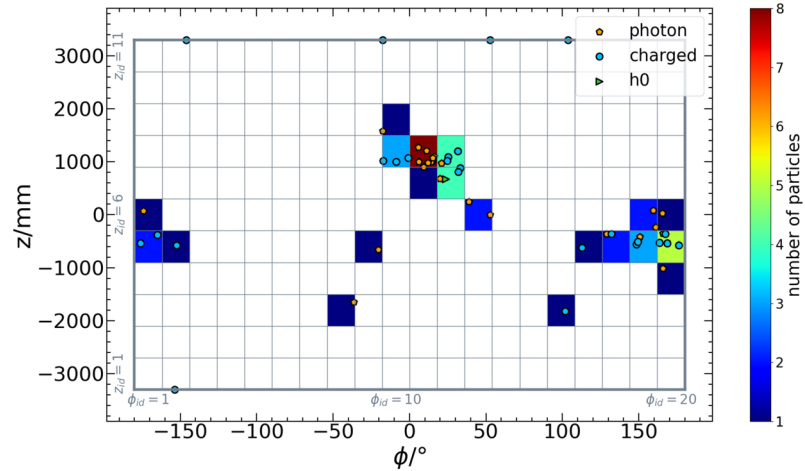
Second moment: $S = \frac{\sum(E_{hit}r_{hit}^2)}{\sum E_{hit}}$

Quantifies the lateral spread of a cluster

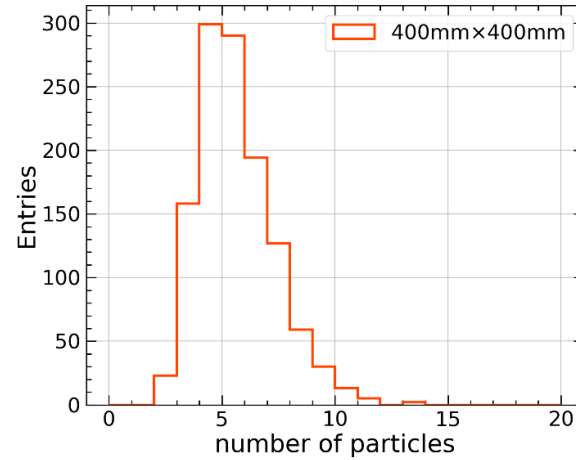
Energy ratio in ECAL & HCAL: $R = \frac{E_{ECAL}}{E_{ECAL} + E_{HCAL}}$



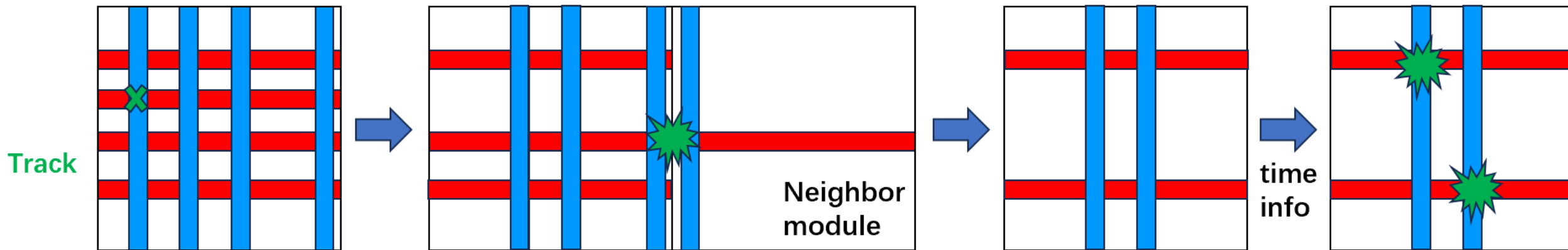
Ghost hit removal



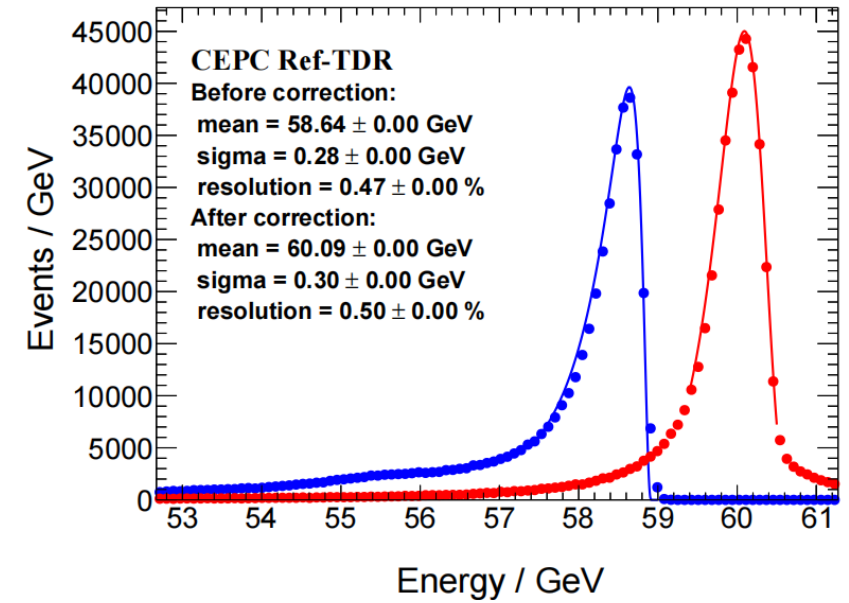
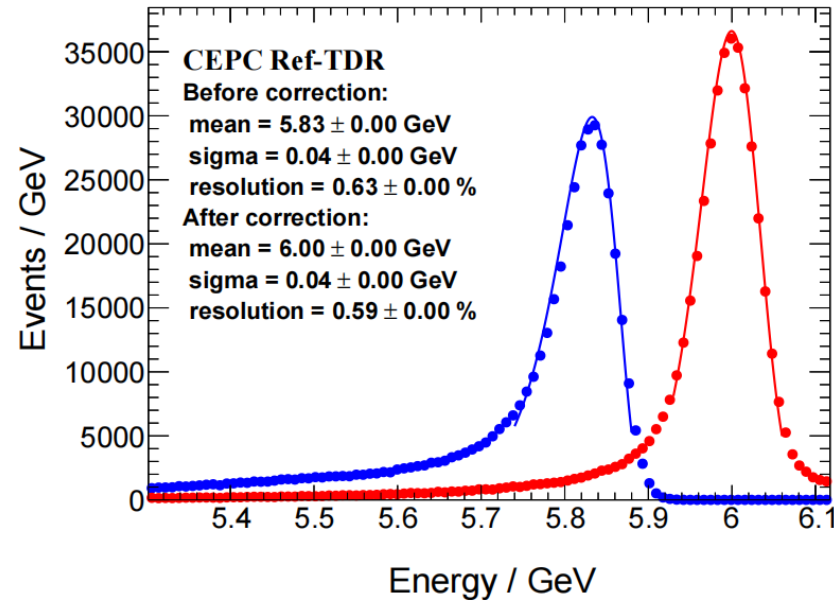
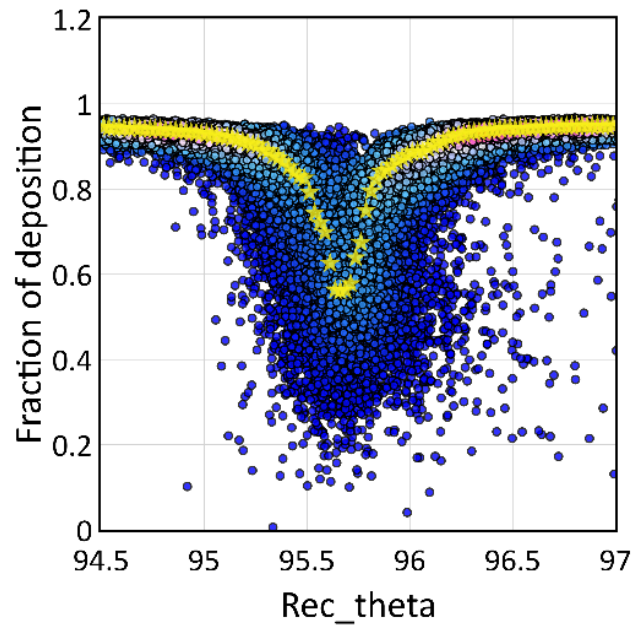
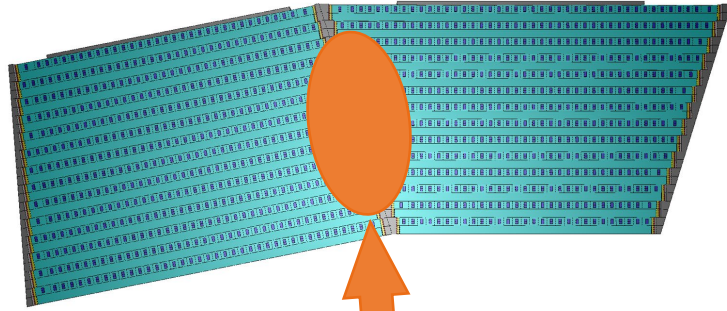
ECAL hit map of a jet event



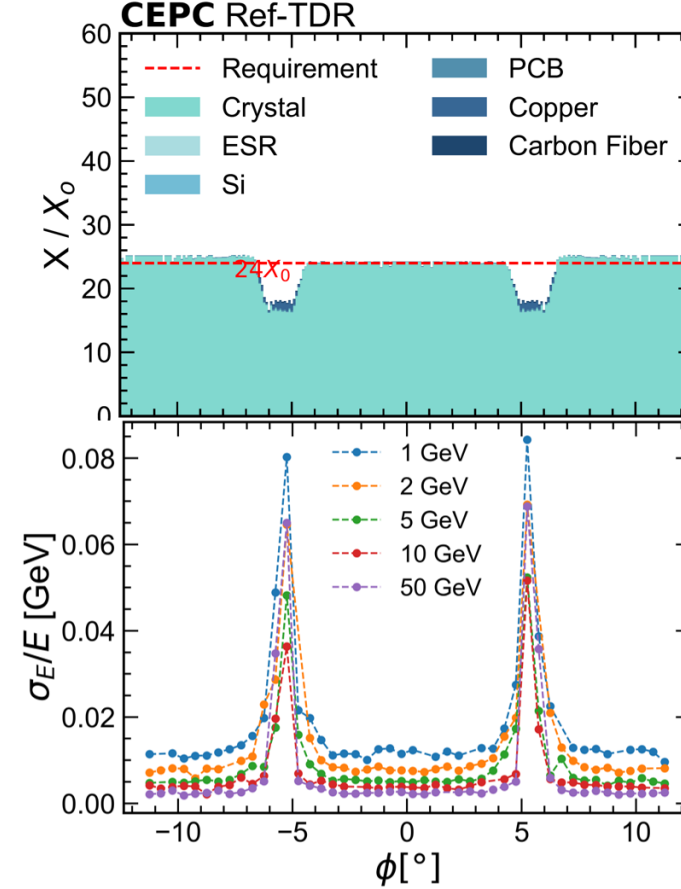
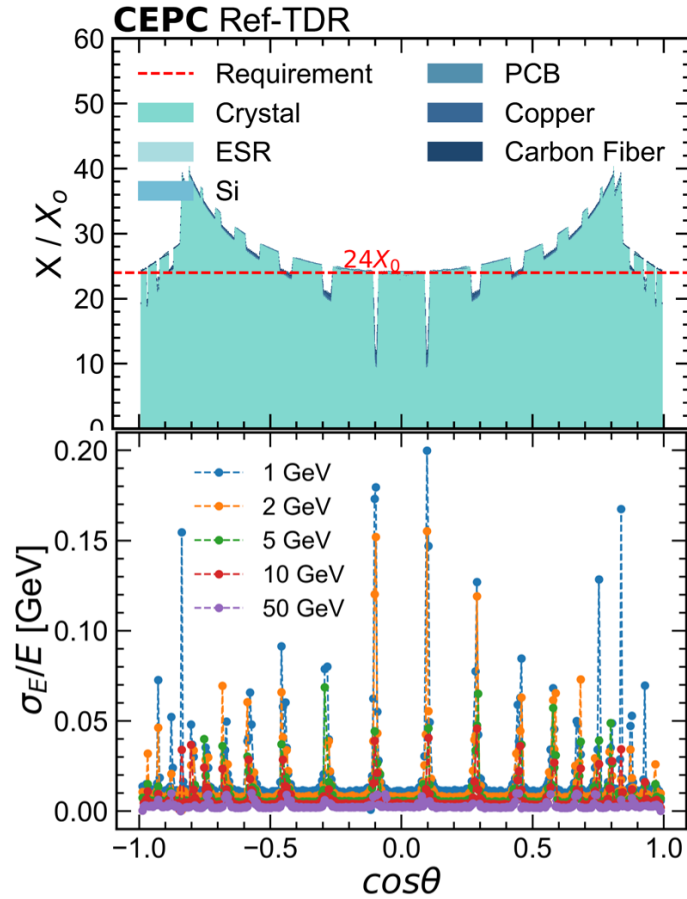
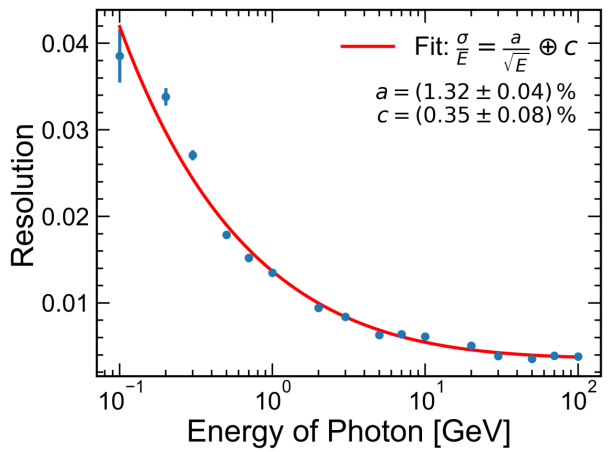
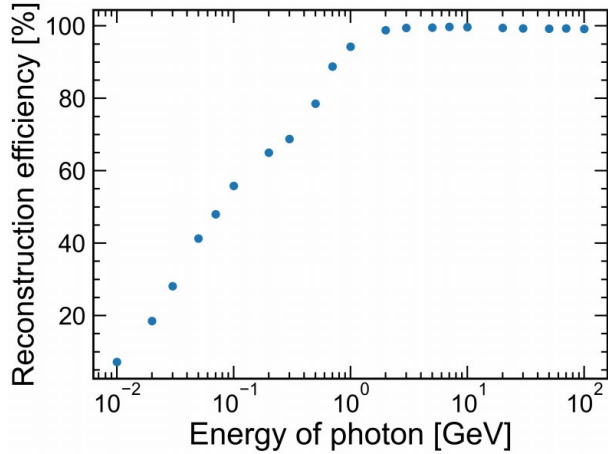
~5 particles in one module in a jet



Energy correction



Photon reconstruction performance



JER

