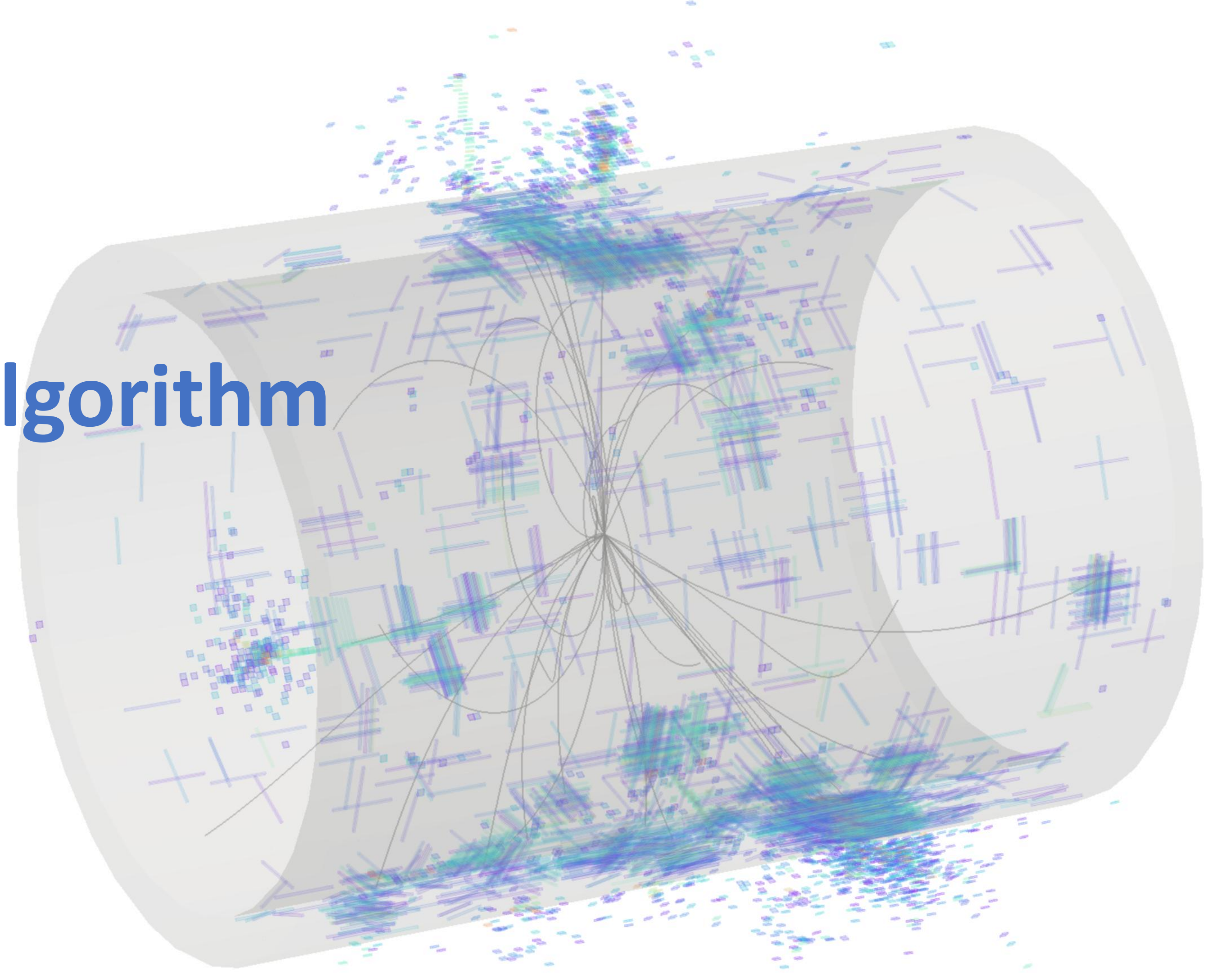
CyberPFA: Particle flow algorithm for crystal bar ECAL



Yang Zhang

Institute of High Energy Physics

CEPC workshop 2025

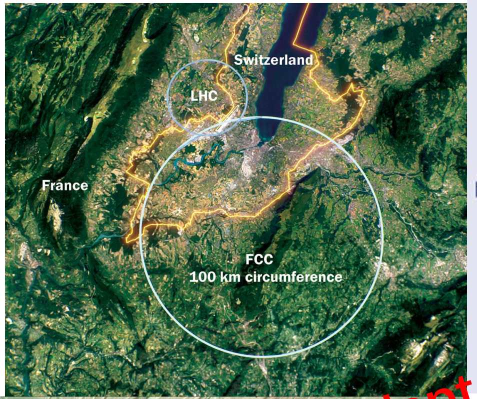
Guangzhou, 10 Nov. 2025

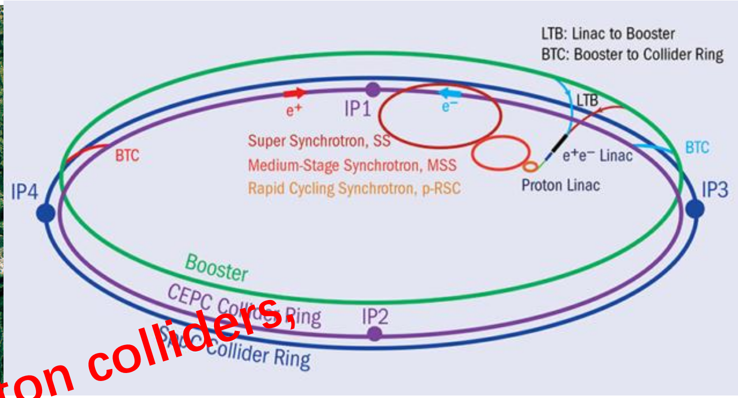
中国科学院高能物理研究所

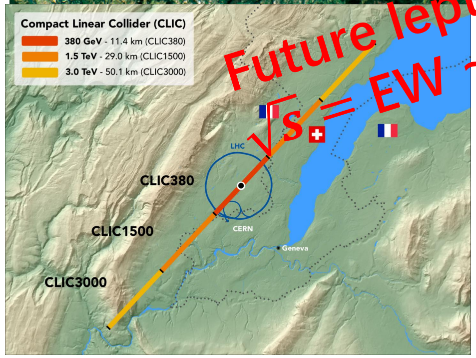
Institute of High Energy Physics Chinese Academy of Sciences

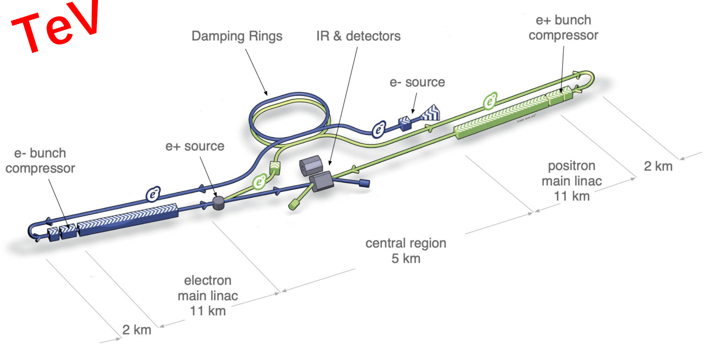
Future lepton collider

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

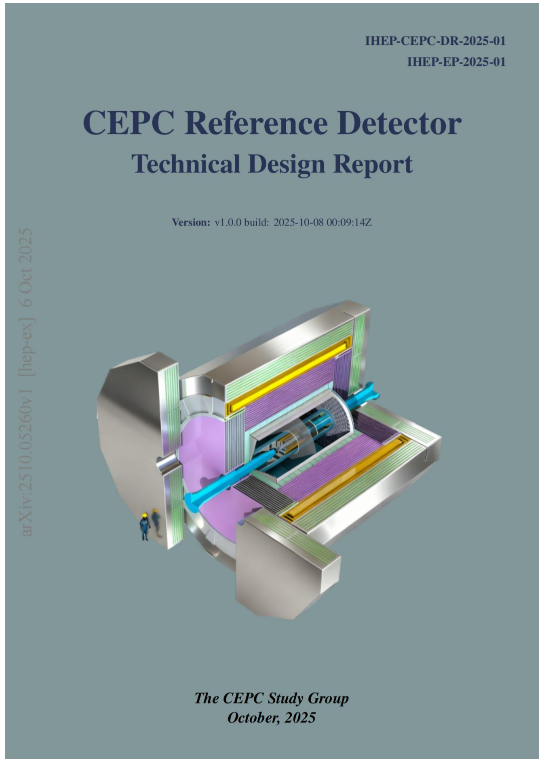








Future lepton colliders, $\sqrt{s}$ = EW ~ TeV

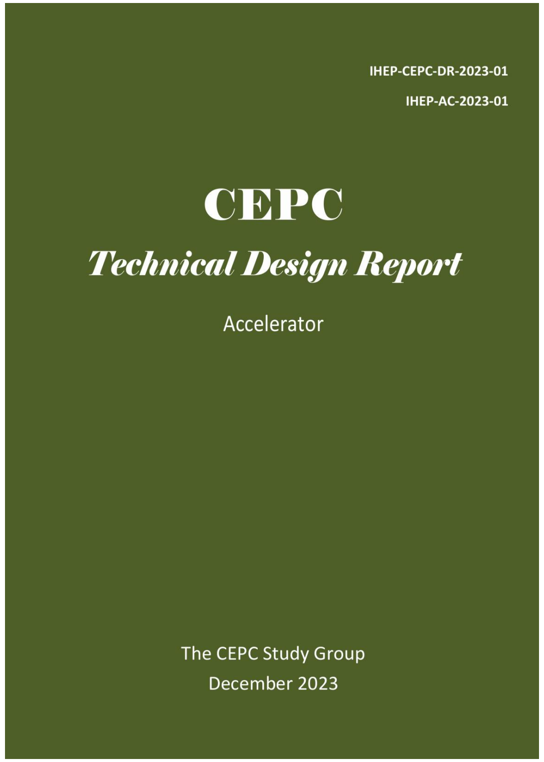

IHEP-CEPC-DR-2025-01
IHEP-EP-2025-01

CEPC Reference Detector
Technical Design Report

Version: v1.0.0 build: 2025-10-08 00:09:14Z

The CEPC Study Group
October, 2025

arXiv:2510.05260


IHEP-CEPC-DR-2023-01
IHEP-AC-2023-01

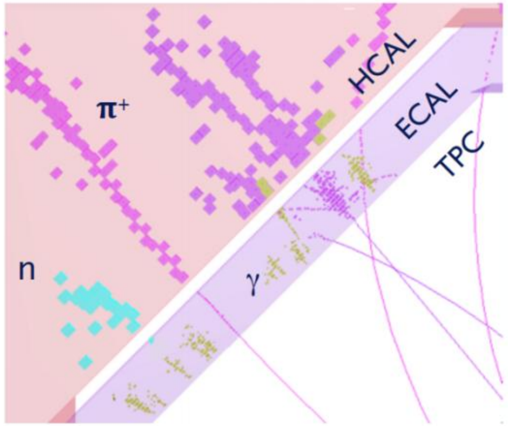
CEPC
Technical Design Report
Accelerator

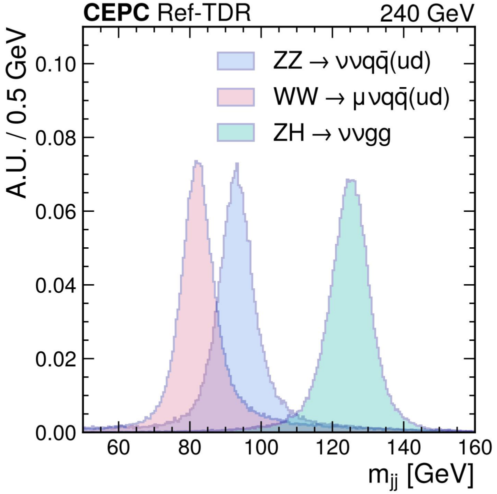
The CEPC Study Group
December 2023

arXiv:2312.14363

Future lepton collider

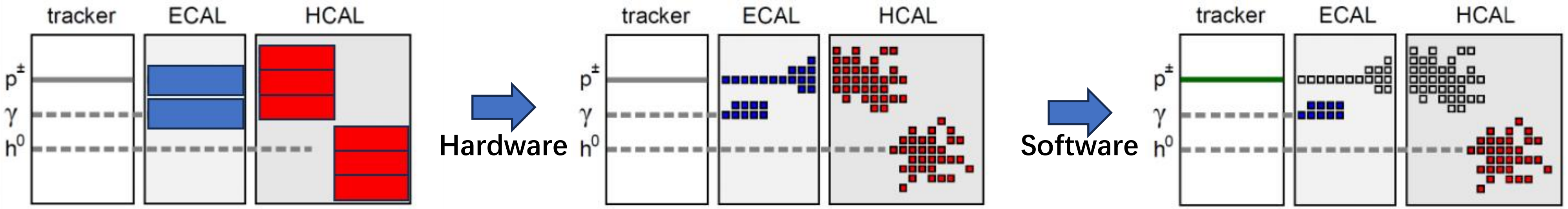
- **Detector requirement**
  - Separate hadronic final states $W^{\pm}/Z/H \to q\bar{q}$
    - **Boson mass resolution (BMR)<4%**
    - **Jet energy resolution (JER)**$< \frac{30\%}{\sqrt{E}} \oplus 4\%$
- **Particle Flow Approach**
  - Measure the jet by its component: $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$
  - Hardware + Software





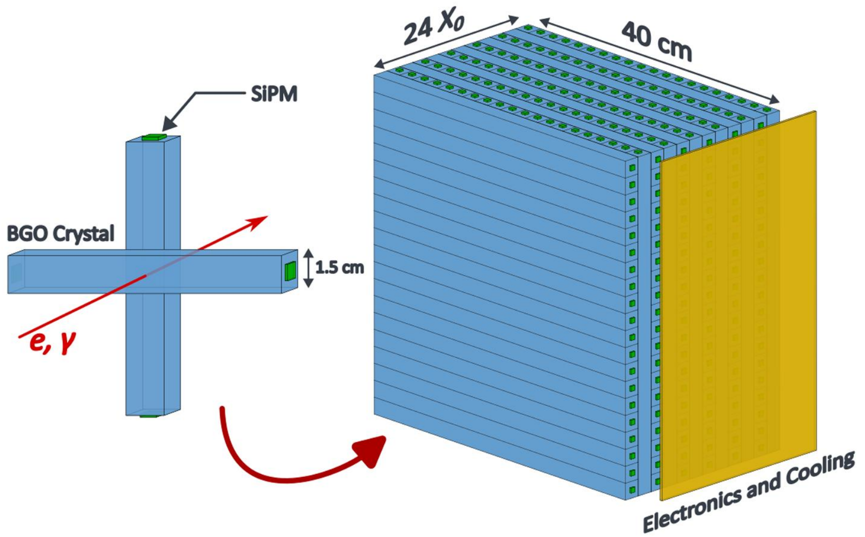
Hardware: separate clusters from different particles.
- High granularity.
- Compact sampling structure.

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

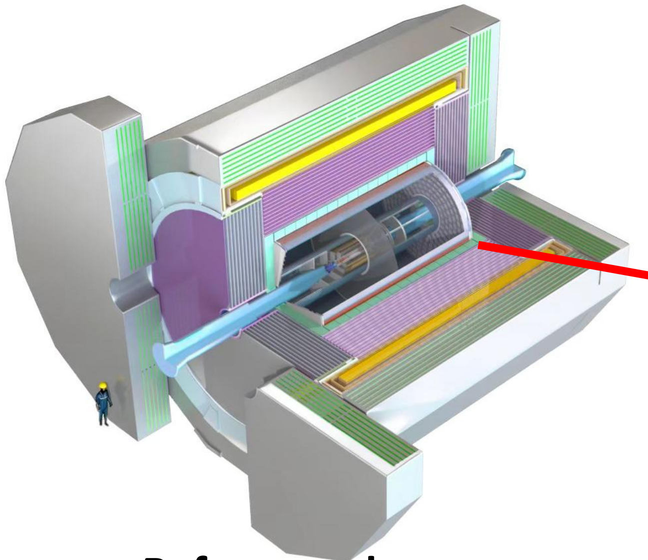


ECAL in CEPC reference detector

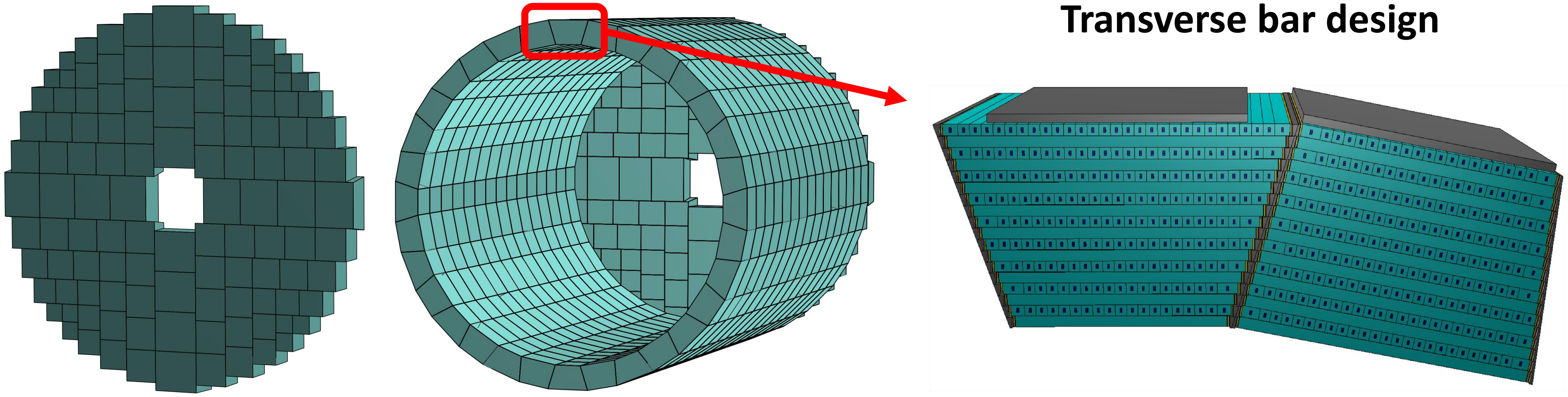
- **Homogeneous crystal bar ECAL**
  - Optimal intrinsic EM resolution:
    - $\sigma_E/E < 2\%/\sqrt{E}$
  - Compatible with PFA
    - Fine transverse and longitudinal segmentation
    - Precise shower position measurement
  - Less readout channels



Transverse bar design



Reference detector

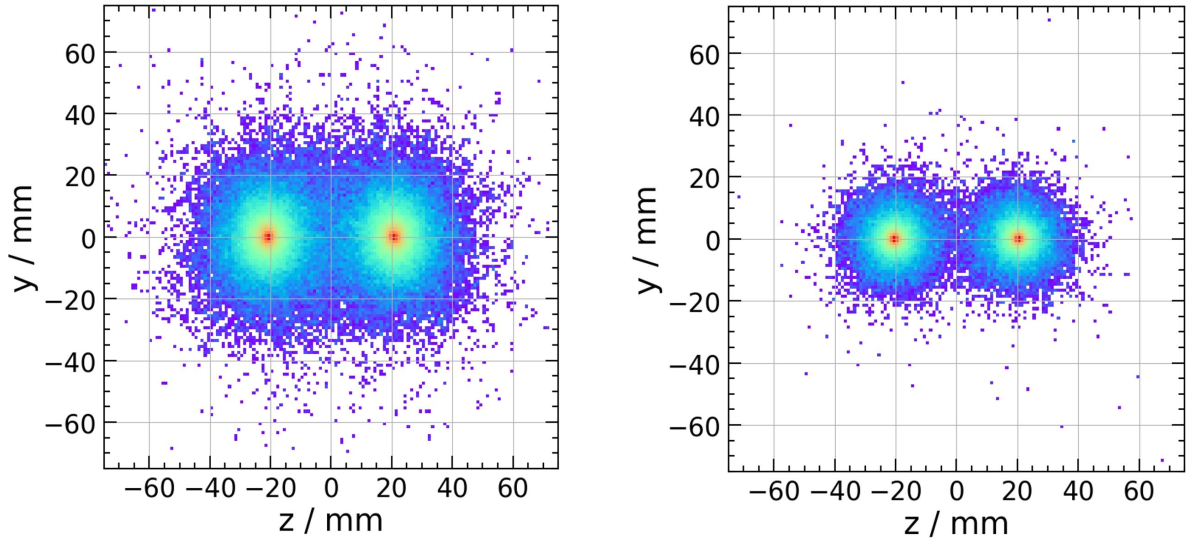


ECAL

Challenges of PF algorithm

Larger R_M & smaller λ_I/X_0

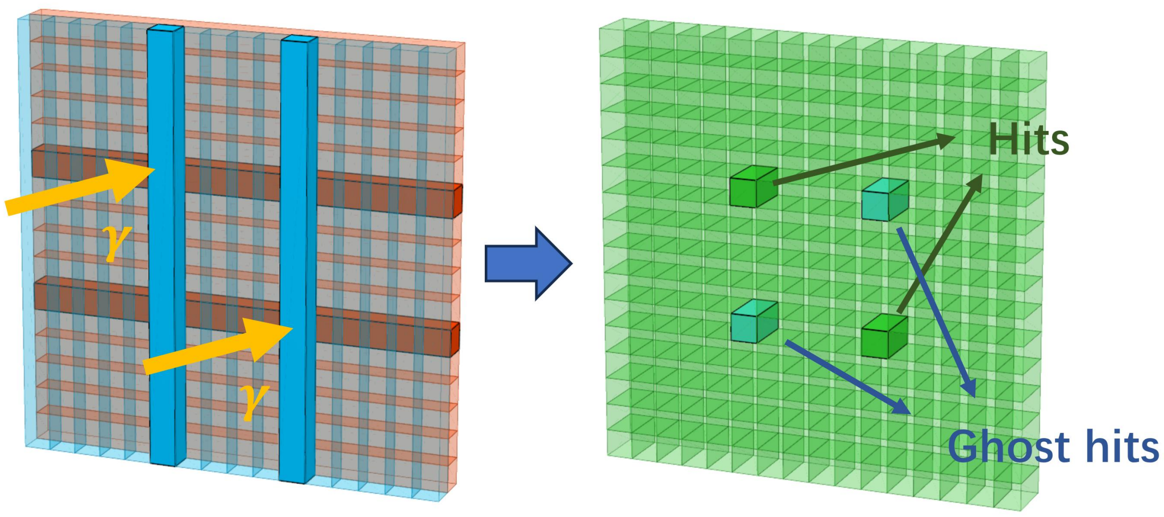
Shower overlap



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

Arrangement of transverse bar

Ghost hit

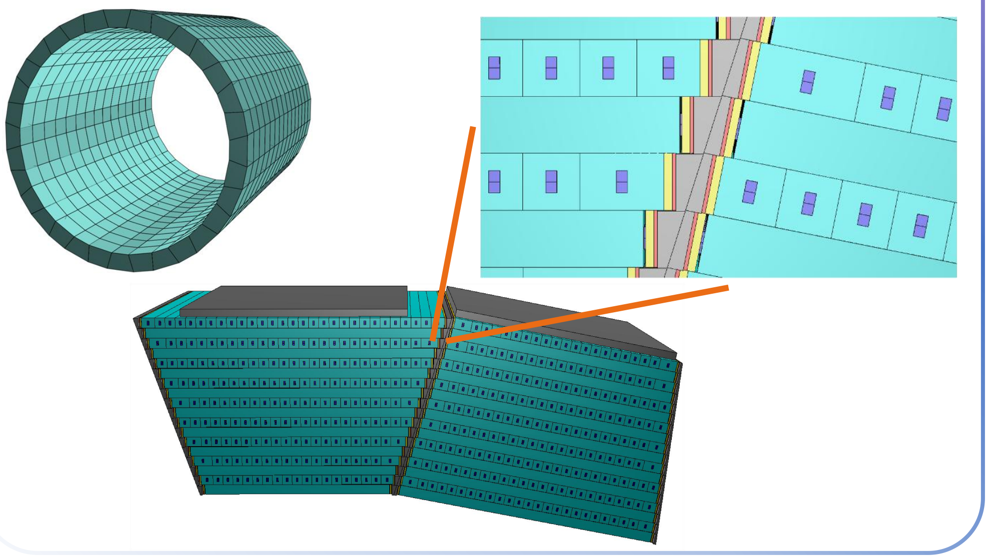


Software task:
- * Clustering
- * Pattern recognition.
- + Energy splitting.
- + Ghost hit removal

CyberPFA developed for crystal bar ECAL

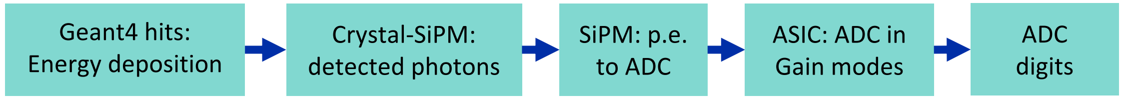
Detector Simulation

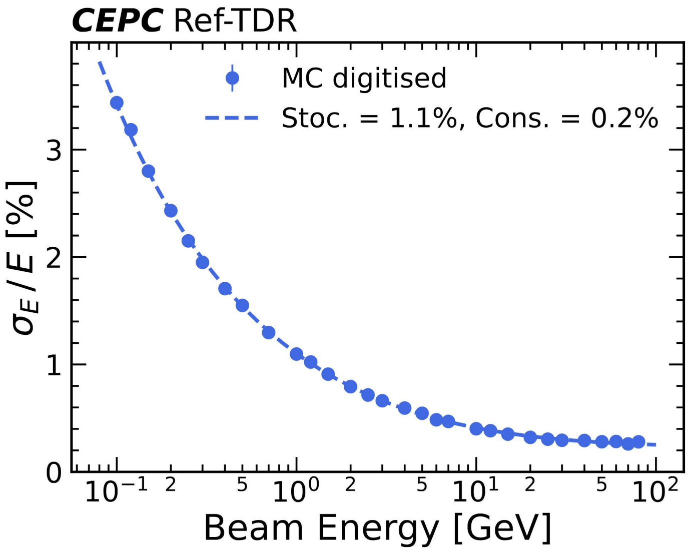
A realistic detector description implemented in CEPCSW with DD4HEP
- Inner R = 1830 mm, depth 300 mm (24 X_0), 18 layers.
- $1.5 \times 1.5 \times \sim 40\ cm^3$ BGO bars with ESR wrapping
- 32-side polygon, invert trapezoid modules.
- Dead material between modules:
  - SiPM, PCB, FE and BE electronic boards (~3 mm)
  - Copper plate cooling (1 mm)
  - Carbon fiber supporting (5 mm/side)
- An energy correction for the crack leakage.



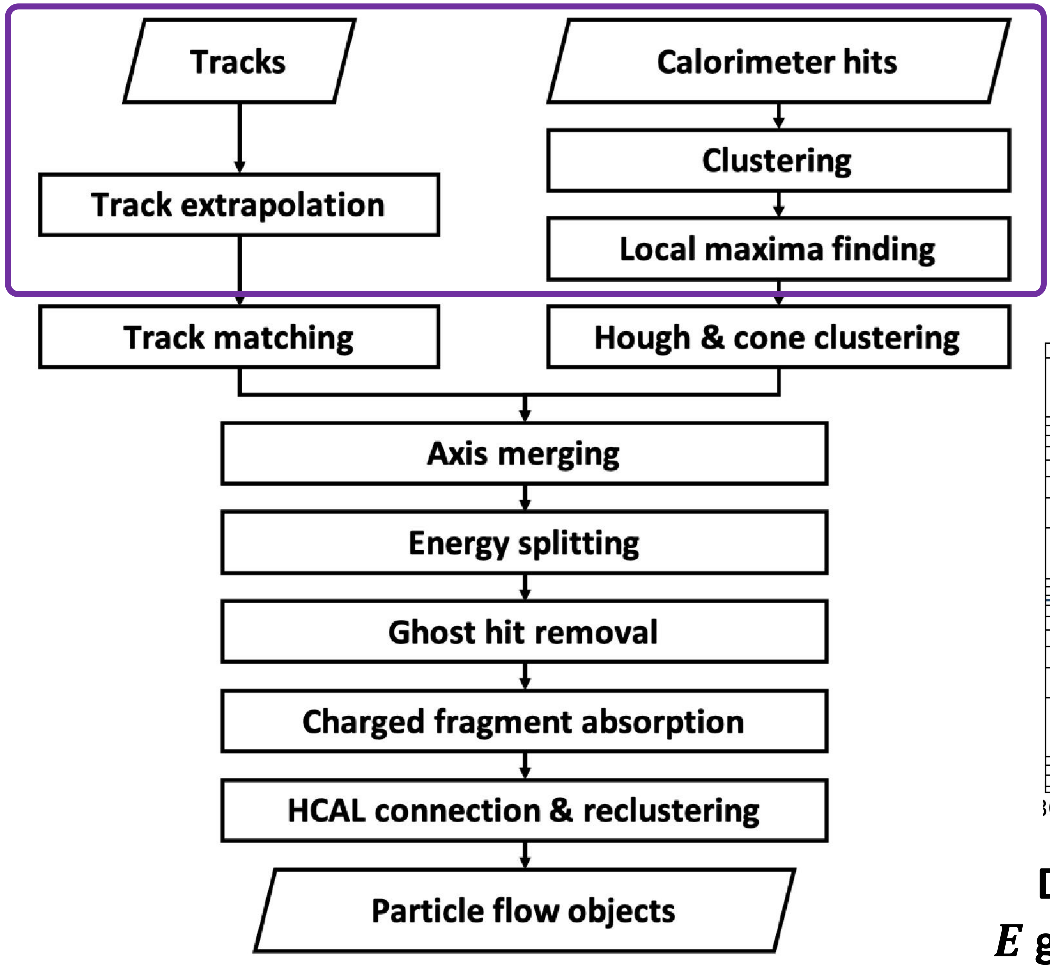
Digitization model: from beam test
- MIP response: 300 p.e./MIP
- Energy threshold: 0.1 MIP.
- SiPM gain calibration: 1 p.e. = 5 ADC, with noise
- Electronics: 12 bits ADC with precision 0.2%, 3 gain modes

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



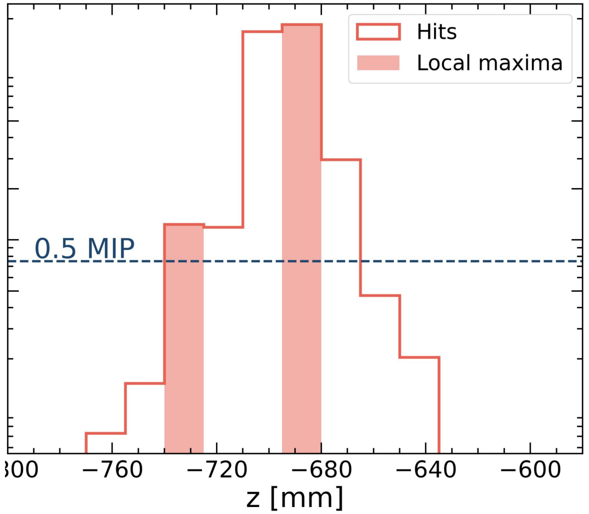


CyberPFA: PFA for crystal bar ECAL

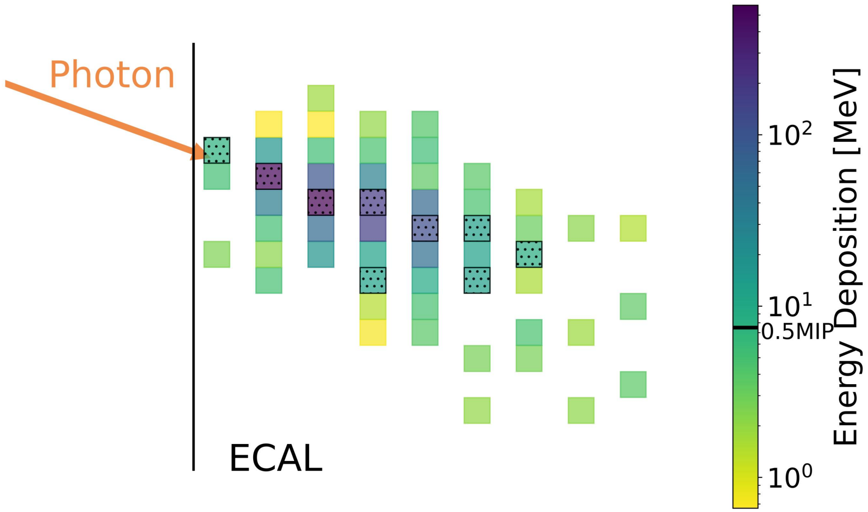


Step 1: preparation

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



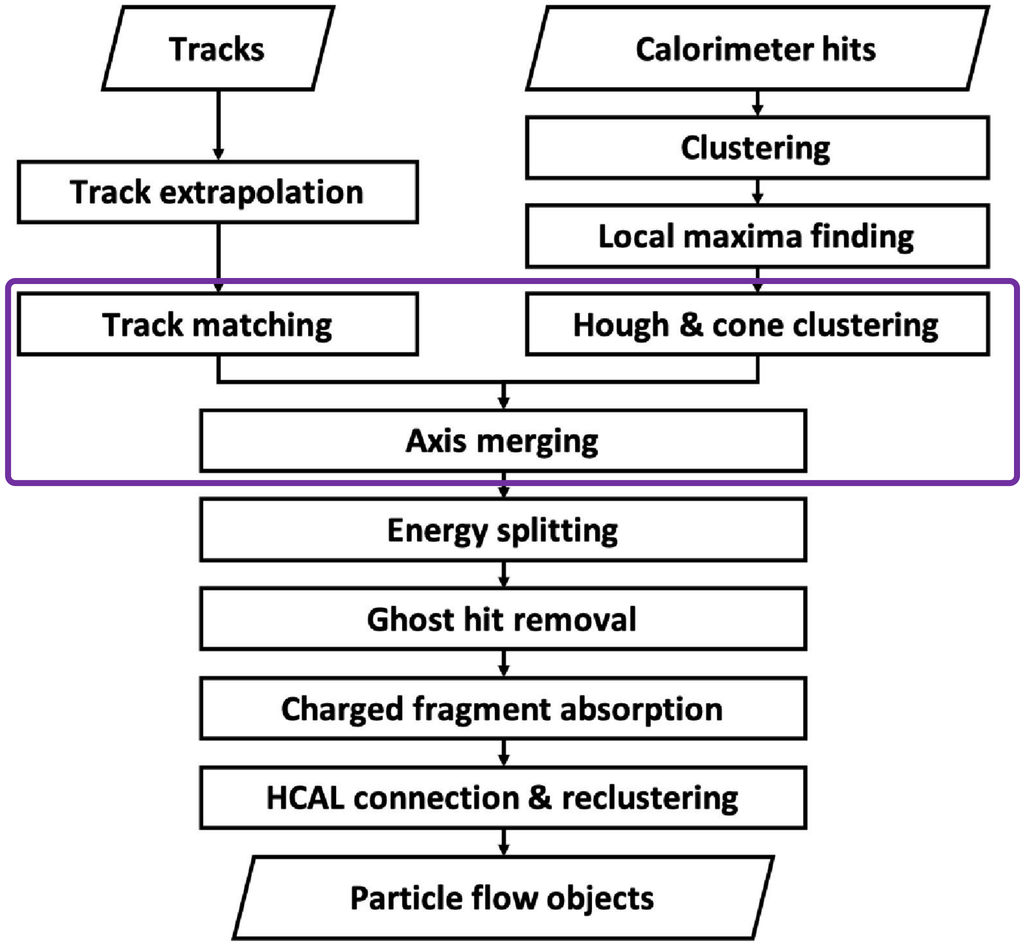
Definition of local maximum:
E greater than nearby crystal and greater than 0.5 MIP



Spatial distribution of hits and local maxima of a 5 GeV EM shower

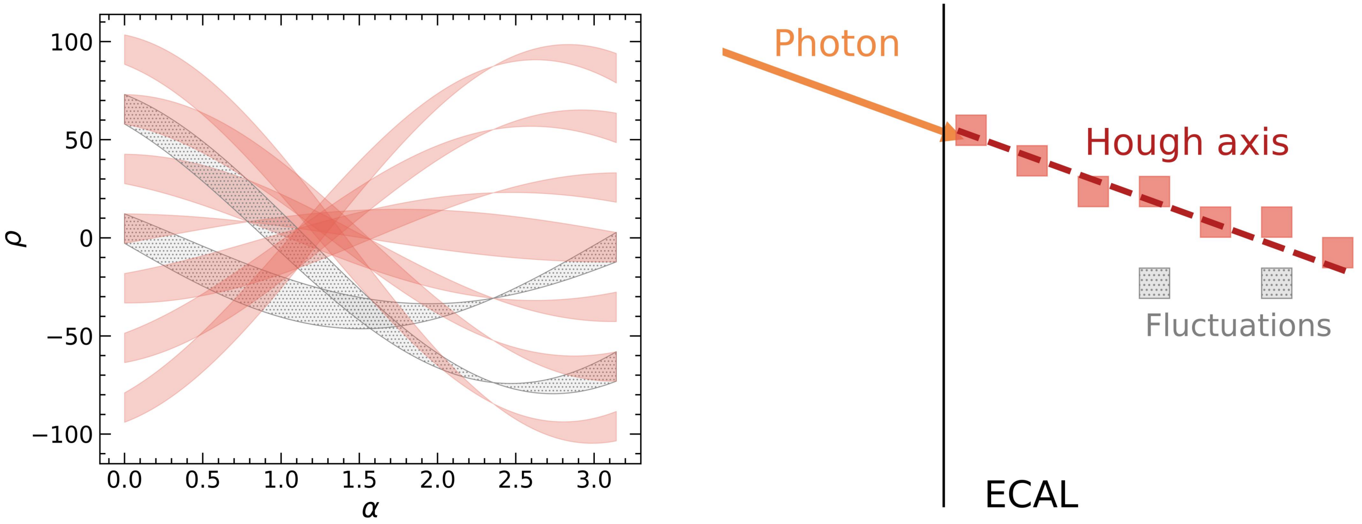
Yang Zhang et.al, arxiv 2508.20728

CyberPFA: PFA for crystal bar ECAL



Step 2: Energy-core-based shower recognition

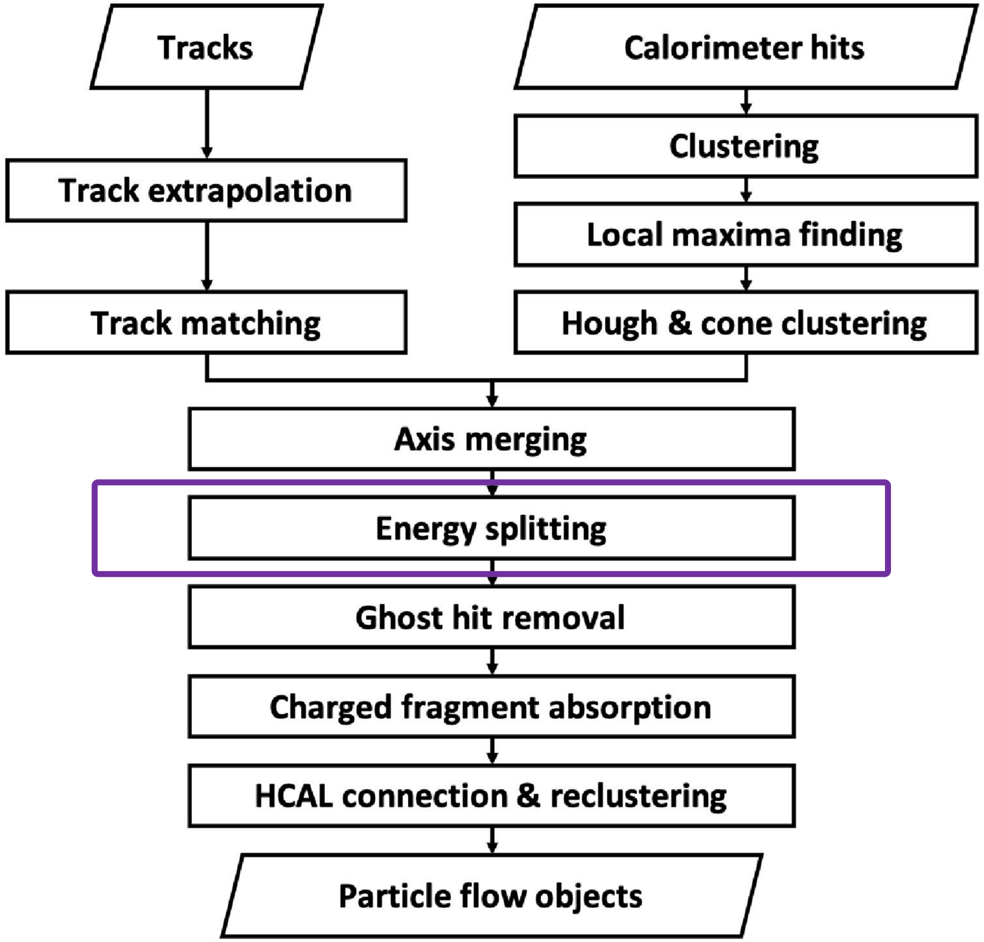
- 3 individual algorithms for different types of particles
- A set of topological cluster merging



Energy-core based photon recognition using Hough transform

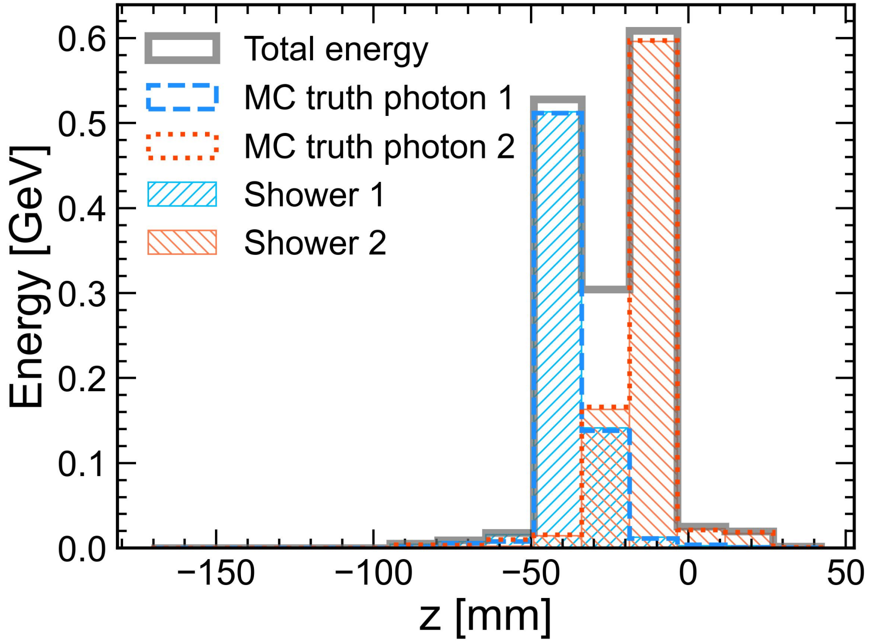
Yang Zhang et.al, arxiv 2508.20728

CyberPFA: PFA for crystal bar ECAL



Step 3: energy splitting

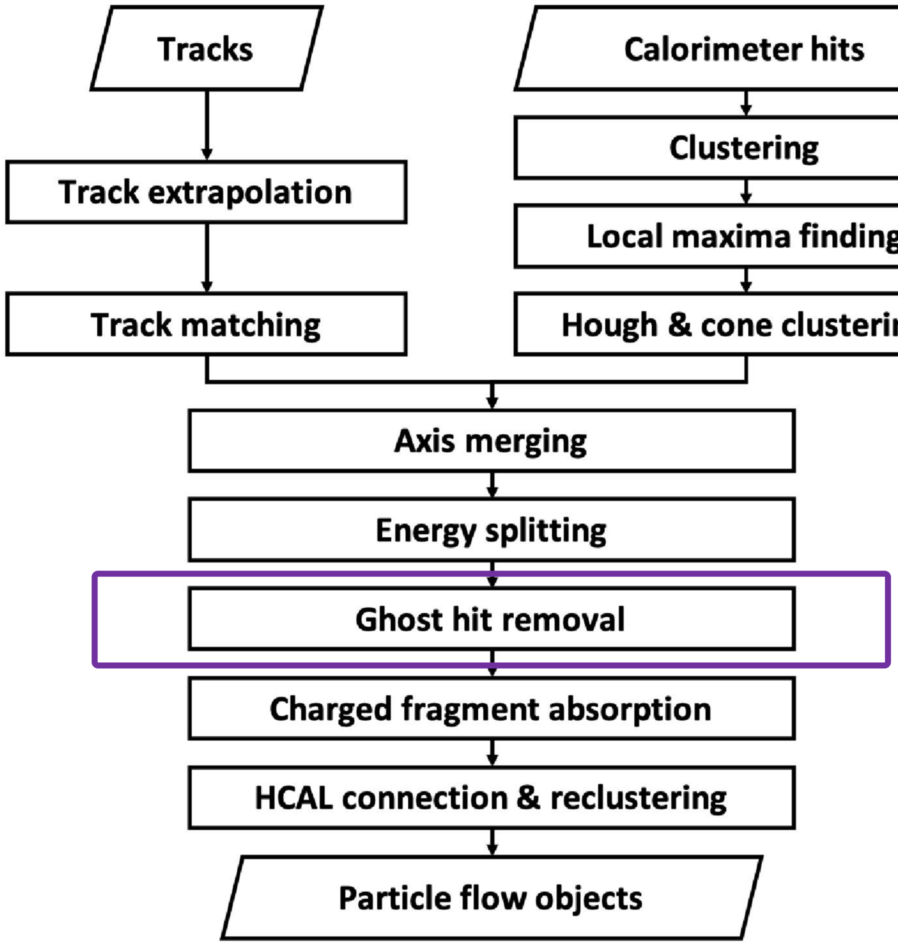
- Split the energy with lateral shower profile.



Energy splitting of two overlapping EM shower

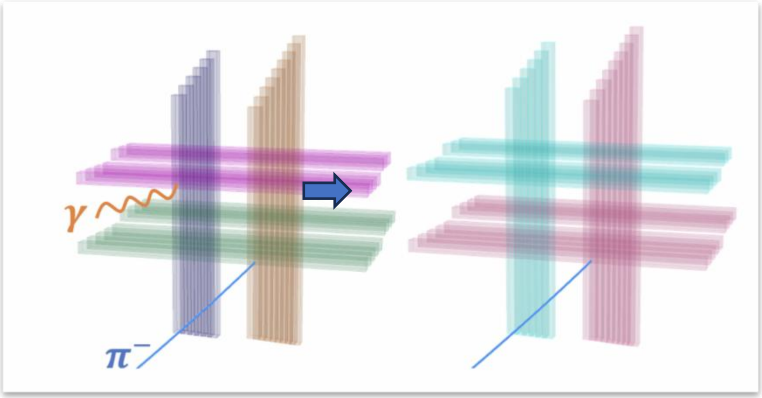
Yang Zhang et.al, arxiv 2508.20728

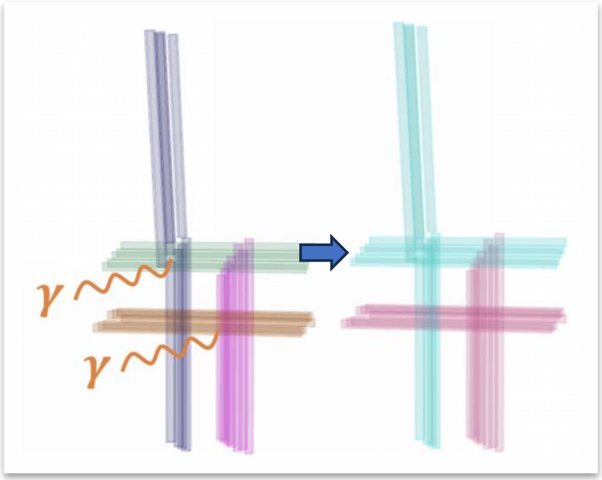
CyberPFA: PFA for crystal bar ECAL

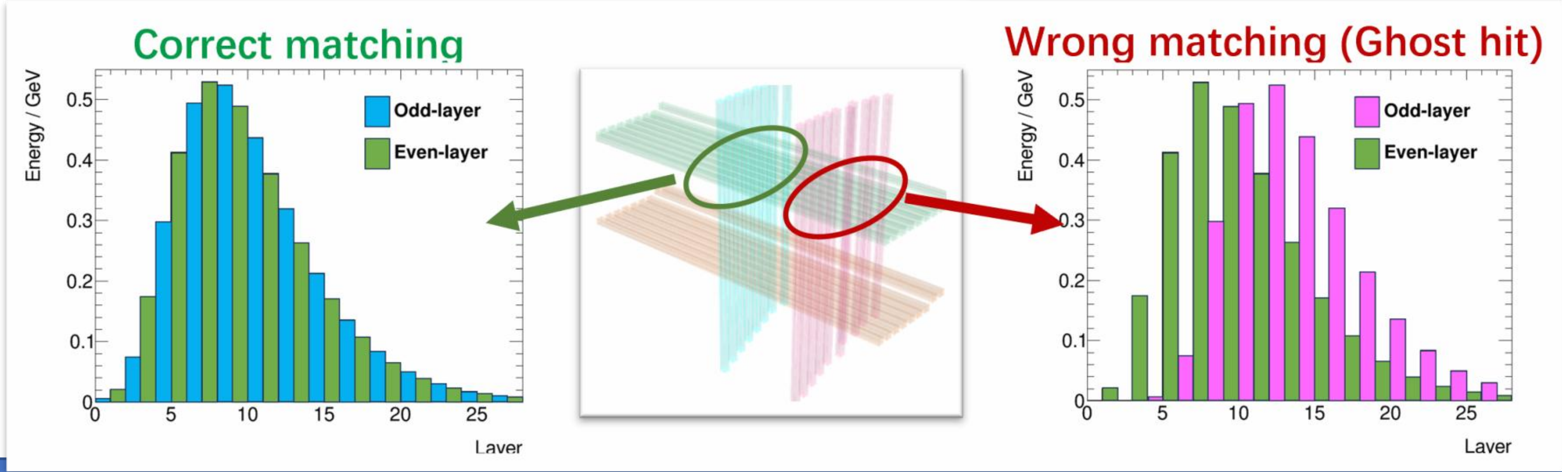


Step 4: ghost hit removal

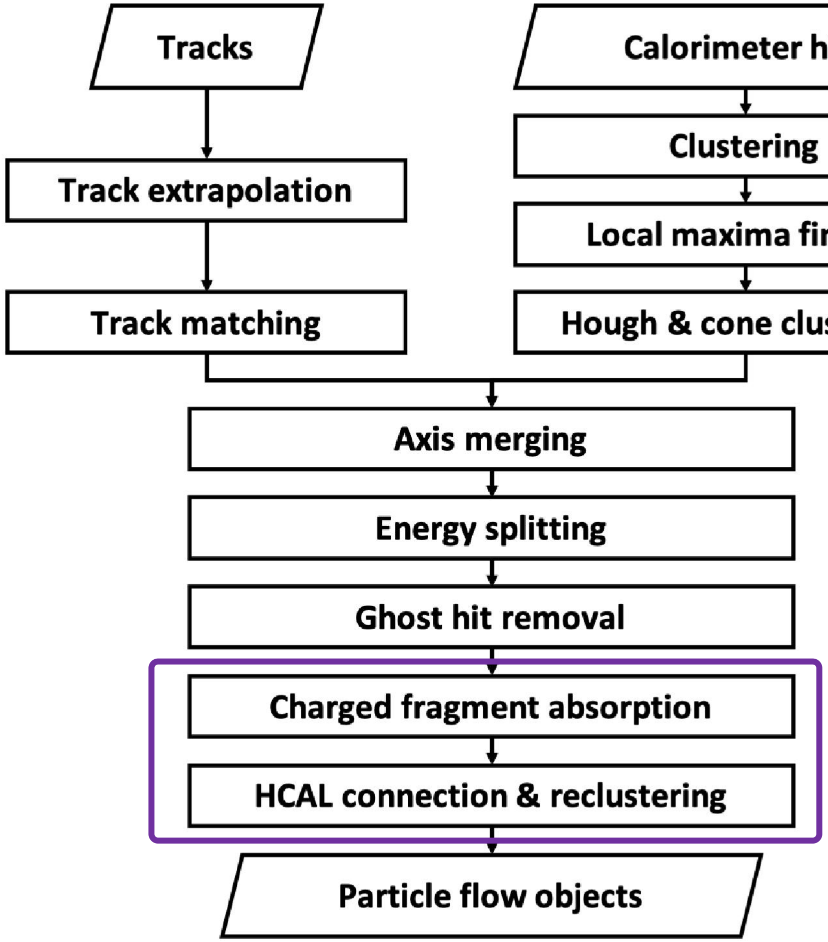
- Remove ghost hit with track + neighbor module + energy + …





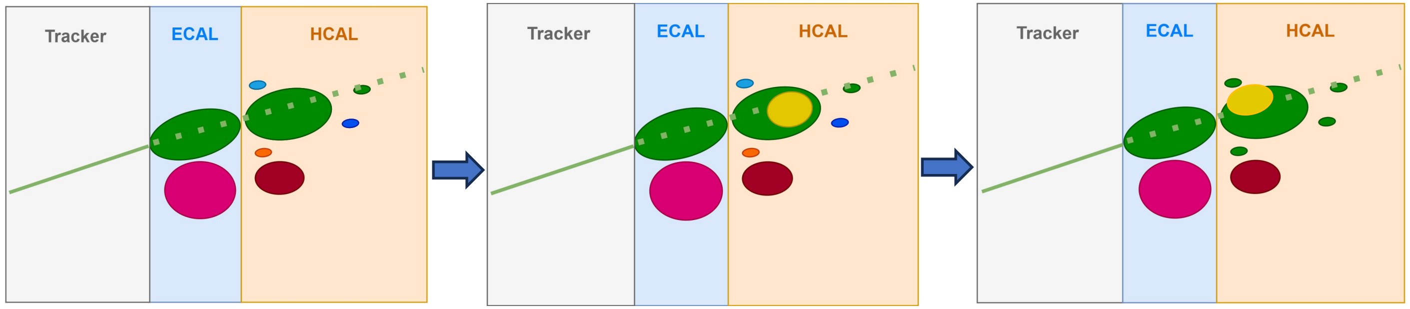


CyberPFA: PFA for crystal bar ECAL



Step 5: clustering and re-clustering

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



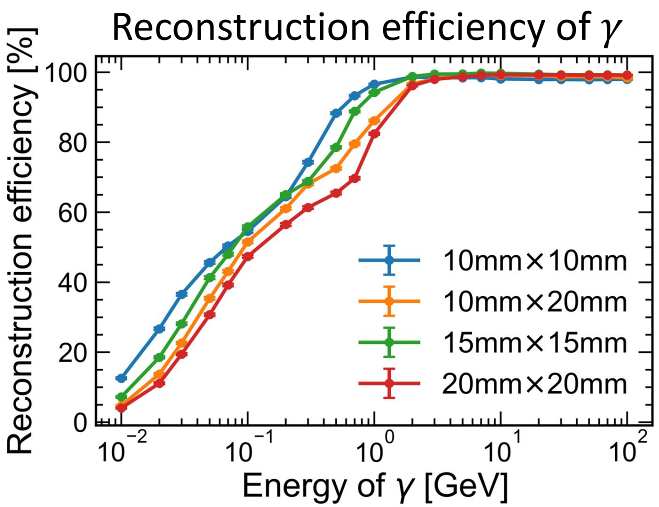
Extrapolate track to connect ECAL and HCAL clusters

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

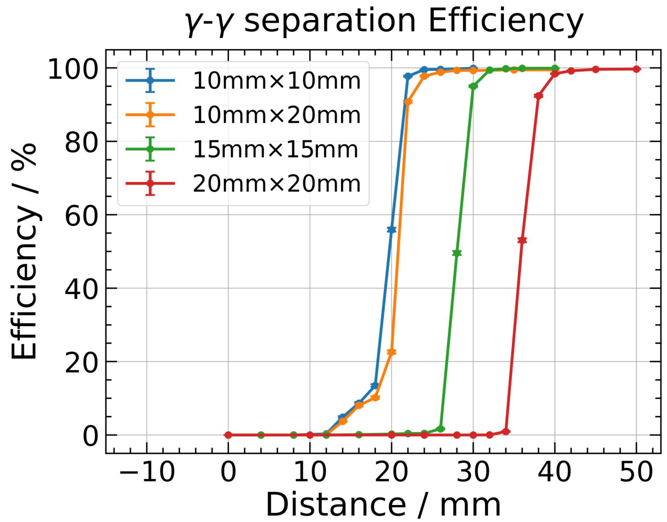
Check and merge fragments into core cluster.

Granularity optimization

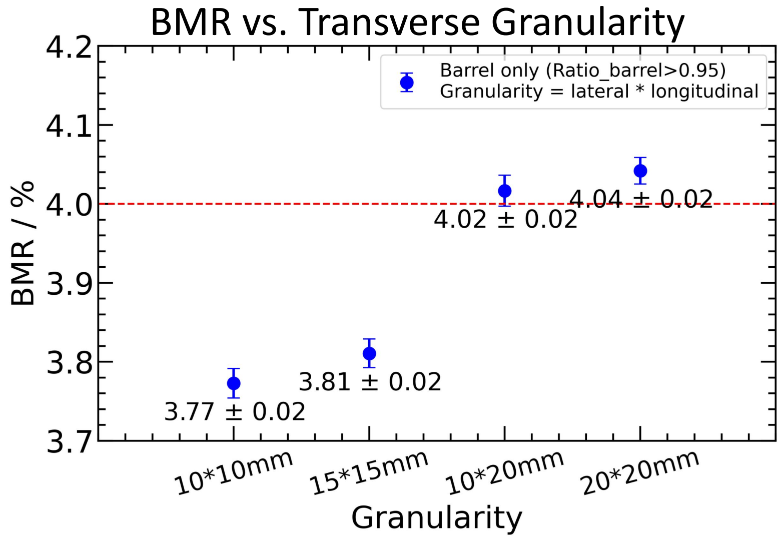
- **Four typical scenarios of transverse granularity investigated**
  - 10×10 mm, 10×20 mm, 15×15 mm and 20×20 mm
- **Figures of merit**
  - Single photon reconstruction, separation power and jet performance



Major impact from ECAL longitudinal segmentation



Separation efficiency dominated by ECAL transverse granularity

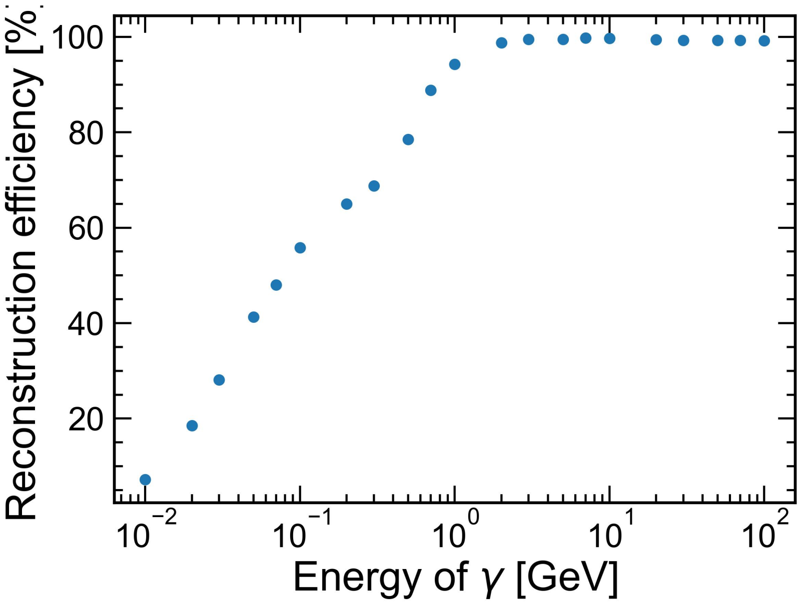


10x10mm and 15x15mm can meet physics requirement of BMR <4%

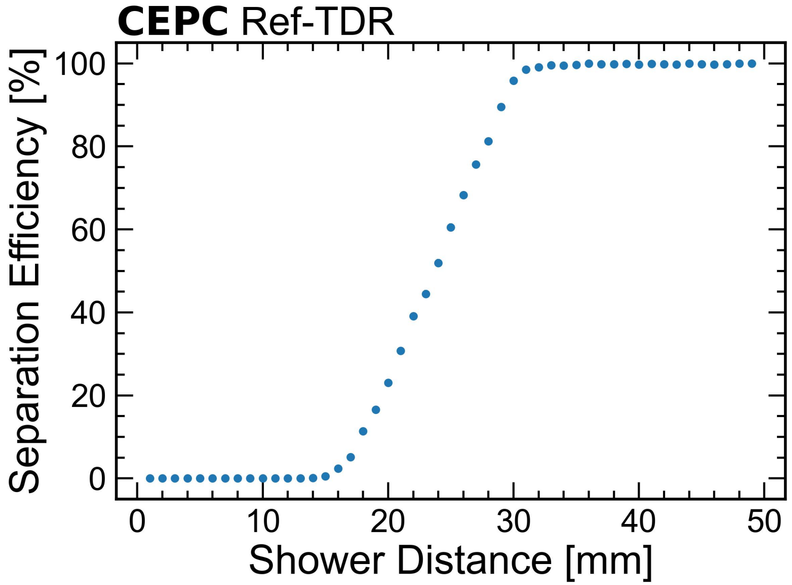
ECAL granularity of $15 \times 15\ \mathrm{mm}^2$ selected for the baseline design

Performance: Photon

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



Single γ reconstruction



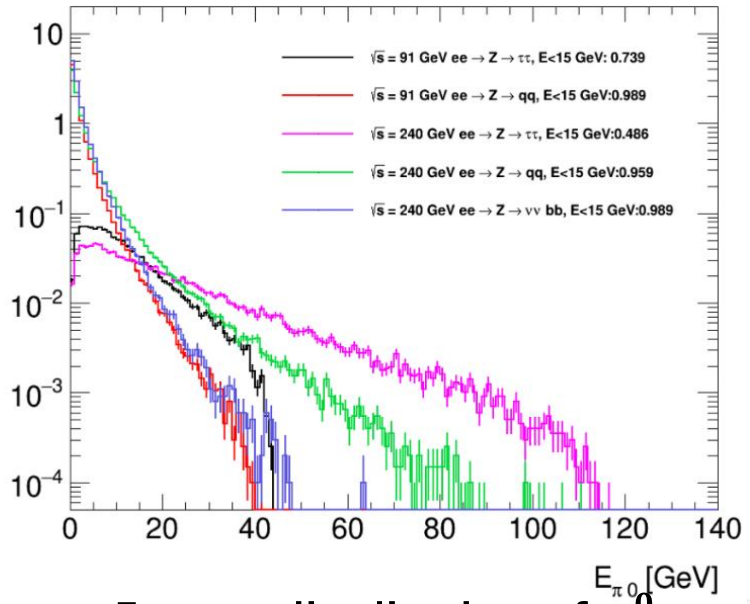
Separation of two 5 GeV γ

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

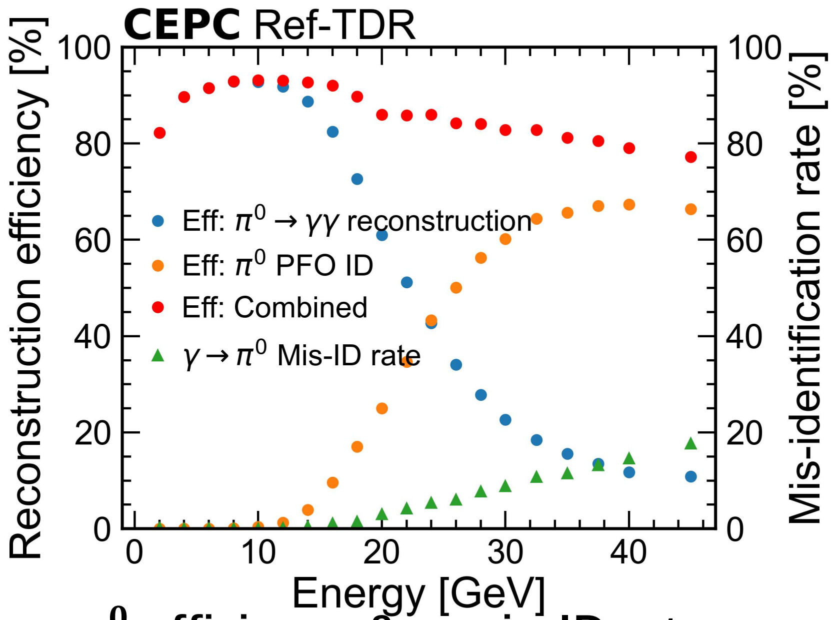
~100% efficiency for distance> 30mm

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

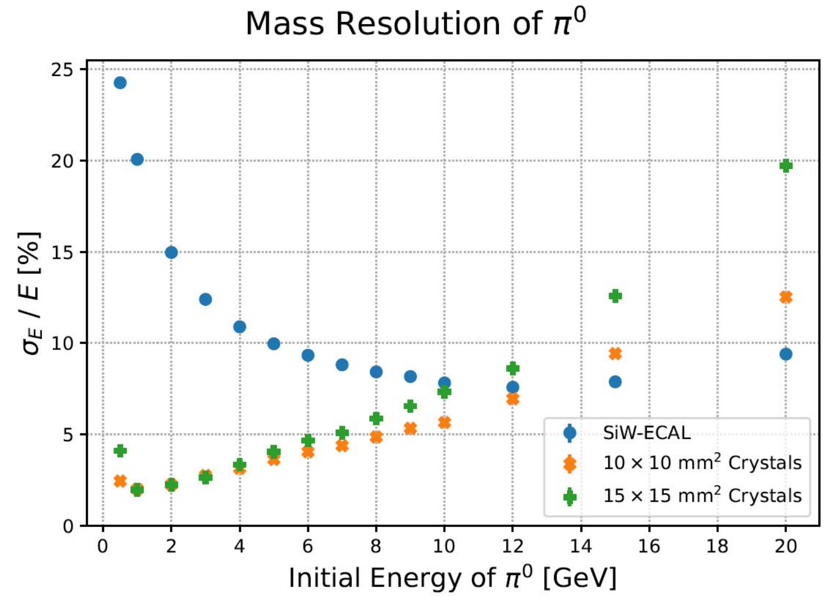
- **π^0: essential EM object in flavor studies in Tera-Z factory**
  - $B^0/B_s^0 \to \pi^0\pi^0/\eta\eta$ and CP asymmetry
  - τ hadronic decay for $H \to \tau\tau$ and $Z \to \tau\tau$



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

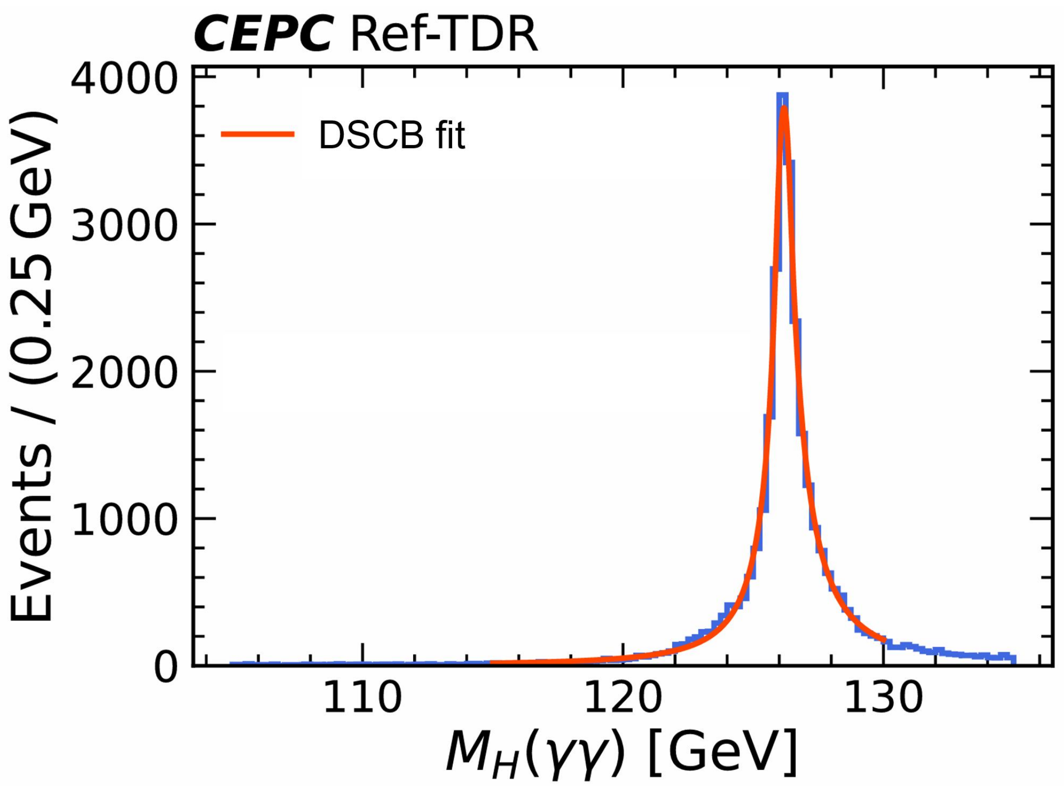
Enhanced mass resolution (<10 GeV) over sampling ECAL

Performance: $H \to \gamma\gamma$

$e^+e^- \to ZH \to \nu\nu\gamma\gamma$ @ $\sqrt{s} = 240$ **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: $0.31 \pm 0.10\%$.

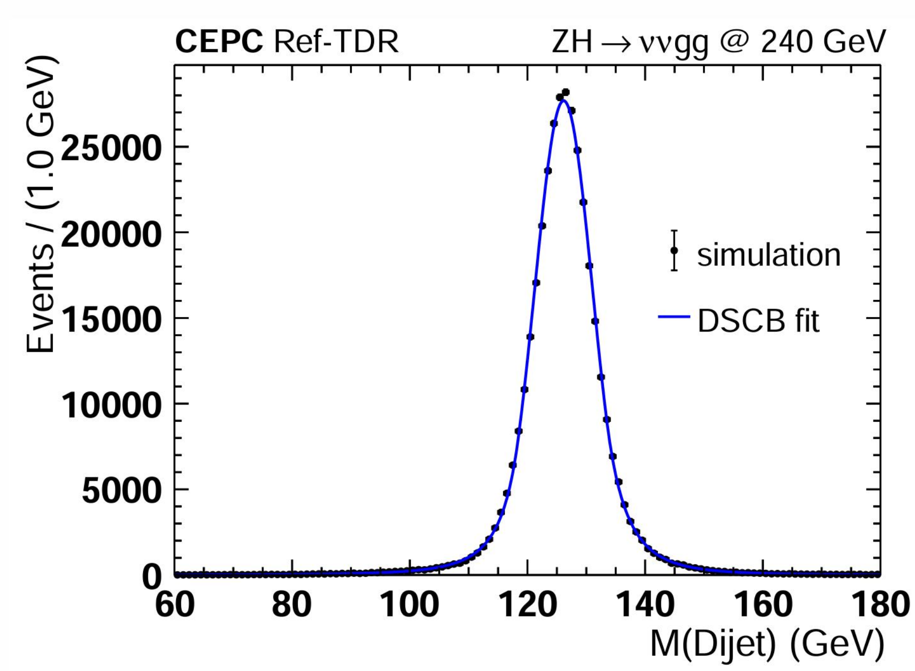


Measurement precision of $\sigma(e^+e^- \to ZH) \times Br(H \to \gamma\gamma)$
increased by ~20% compare to CEPC CDR detector, benefit from ECAL resolution

Talk by Reda: Measurement of the Higgs decaying into two photons with the CEPC reference detector

Performance: Jet reconstruction

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



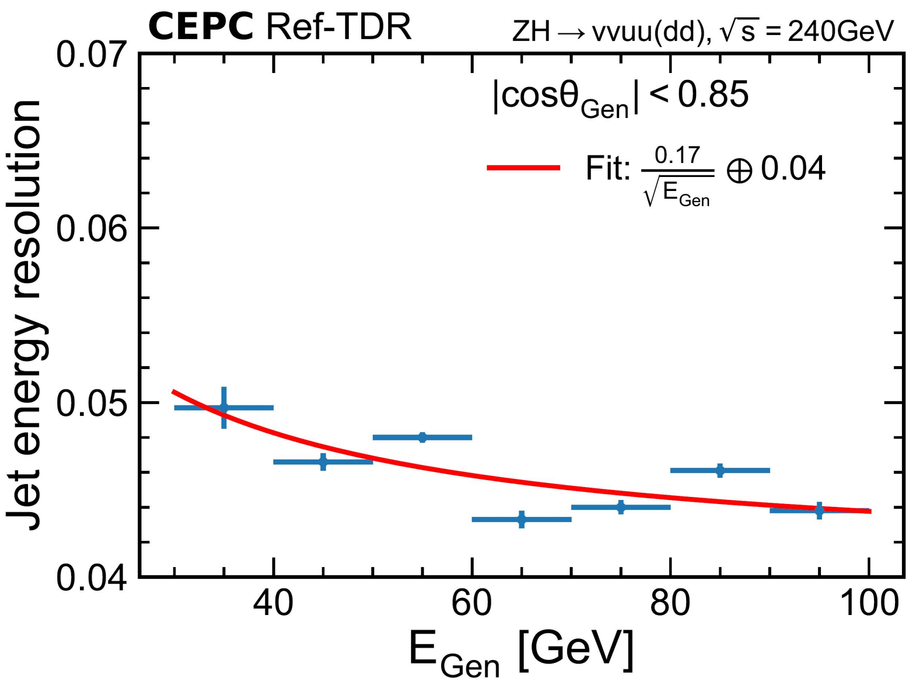
$|\cos\theta_{jet}| < 0.85$

$m_{jj} = 126.14 \pm 0.01$

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

BMR = $3.87 \pm 0.10\%$

$e^+e^- \to ZH \to \nu\nu uu(dd)$ @ $\sqrt{s} = 240$ GeV



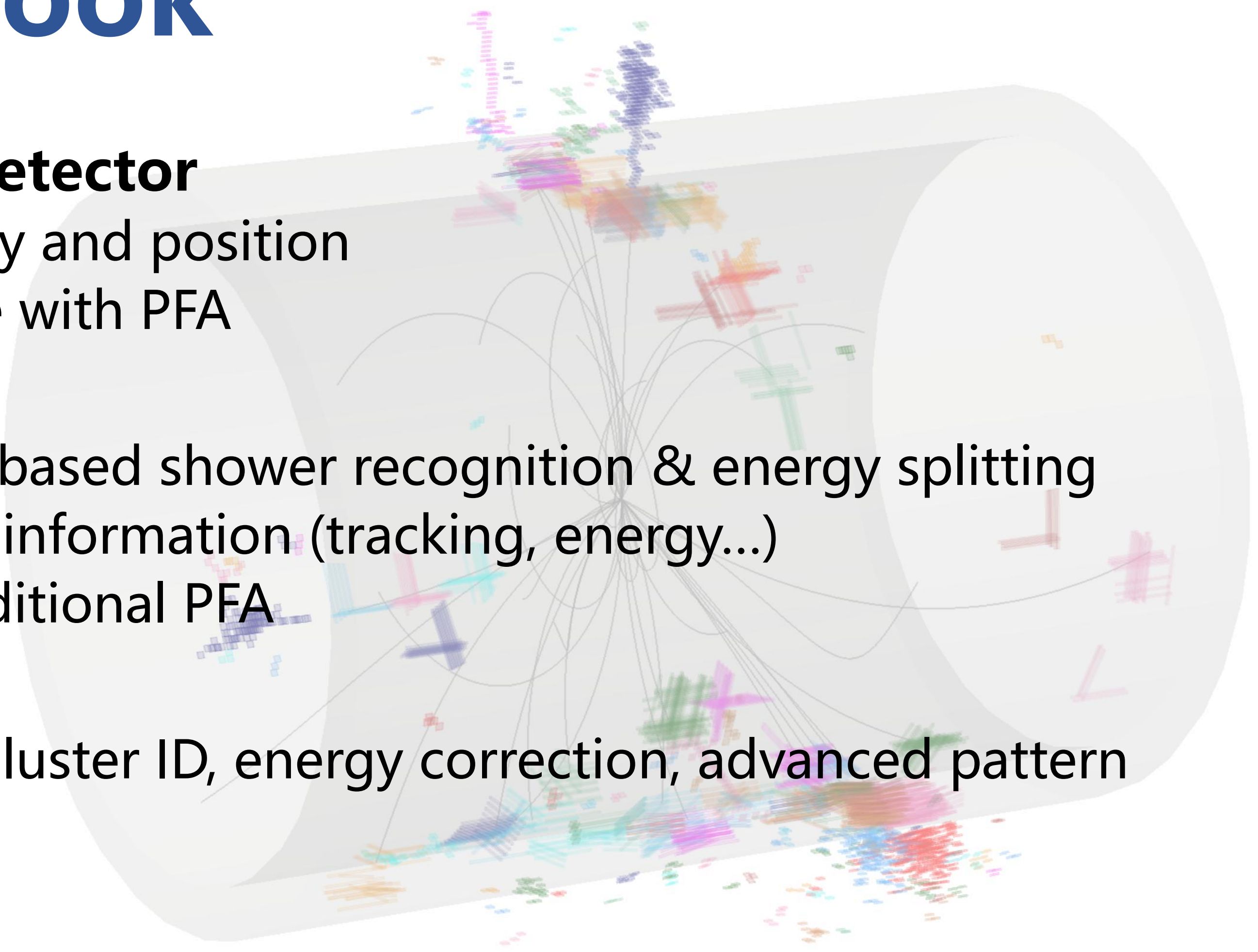
$|\cos\theta_{jet}| < 0.85$

JER = $\frac{0.17}{\sqrt{E_{Gen}}} \oplus 0.04$

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 ~ 3.87%, comparable with traditional PFA
- **Future plan:**
  - Optimization of PFA performance: cluster ID, energy correction, advanced pattern recognition, …

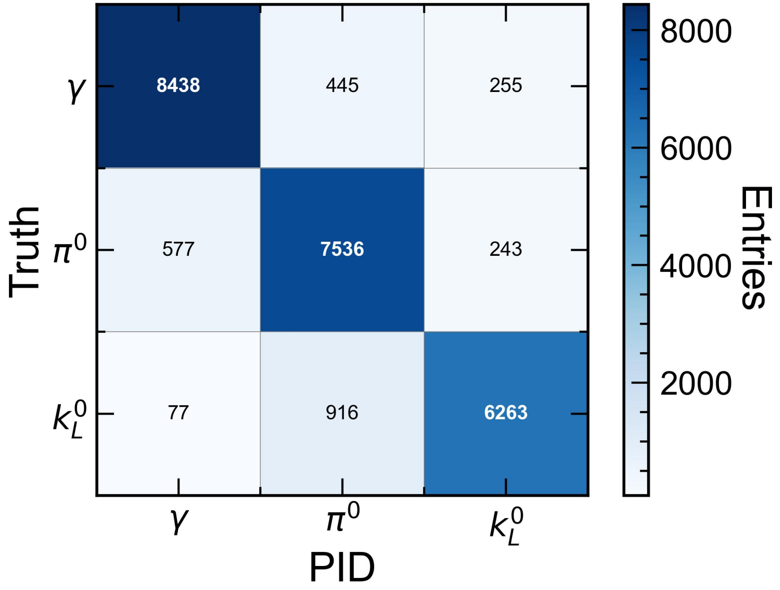


Thank you for your attention!

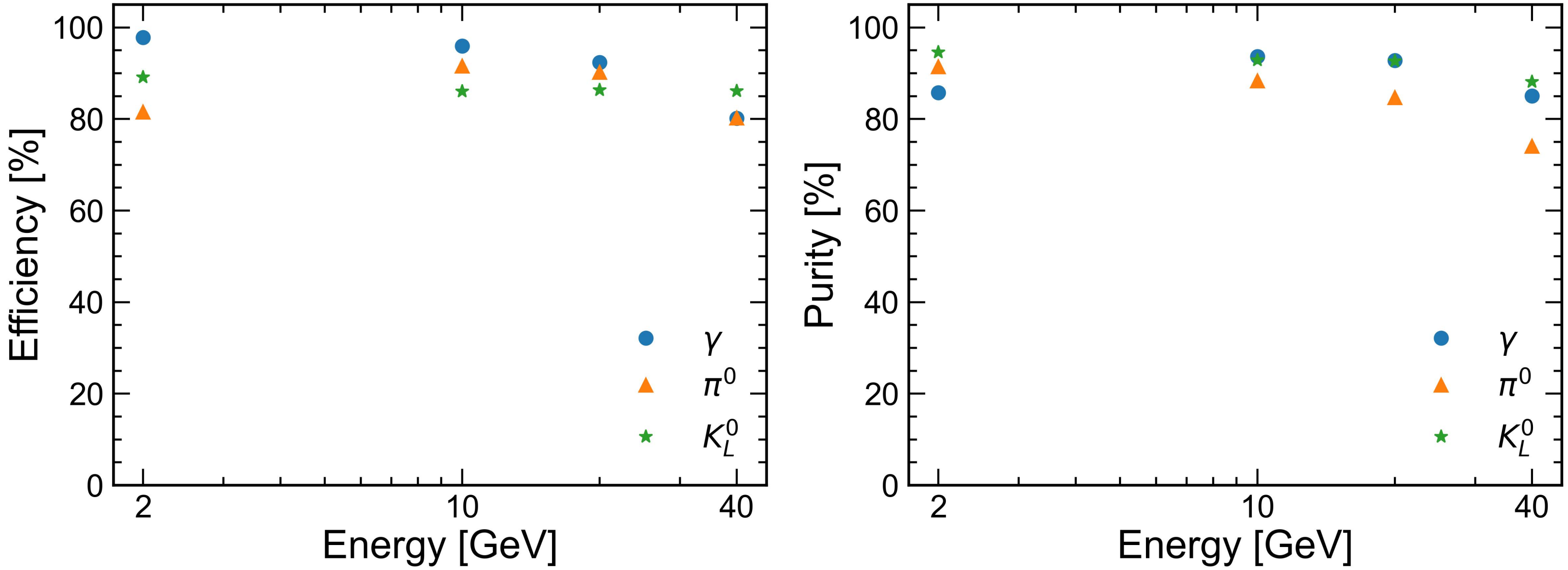
Backup

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

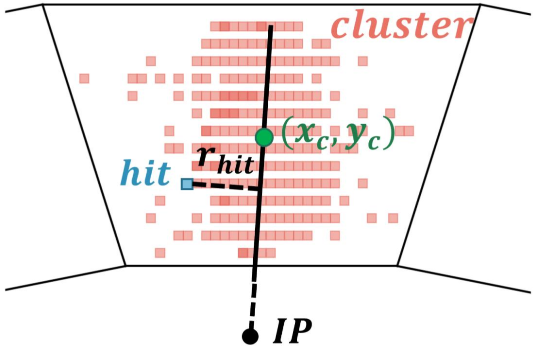


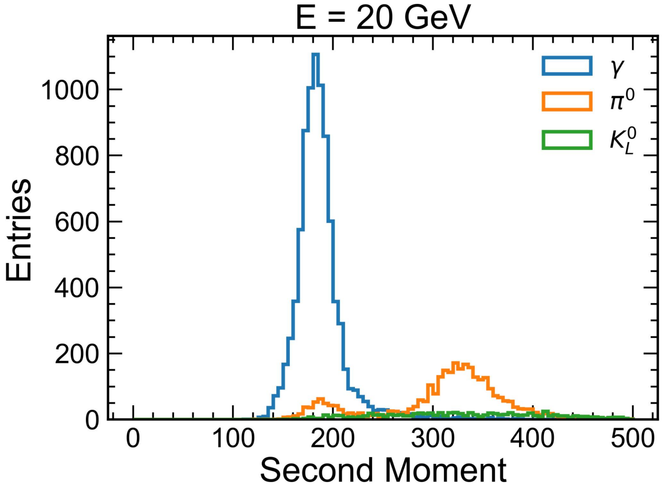
Identification efficiency & purity vs true energy

Second moment & Energy ratio

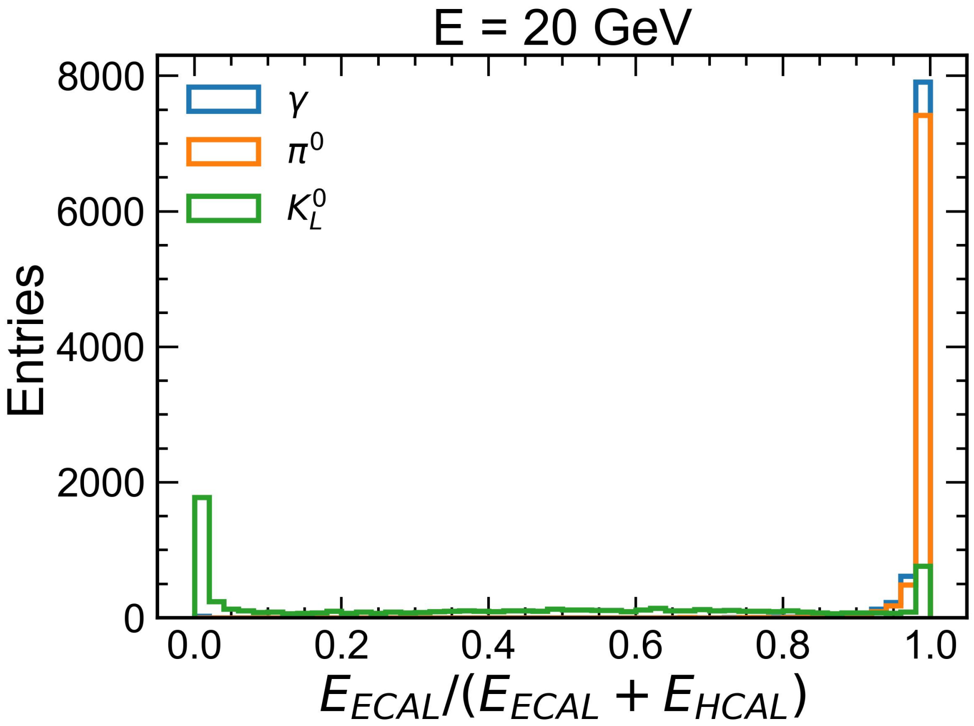
Second moment: $S = \frac{\sum(E_{hit} r_{hit}^2)}{\sum E_{hit}}$

Quantifies the lateral spread of a cluster

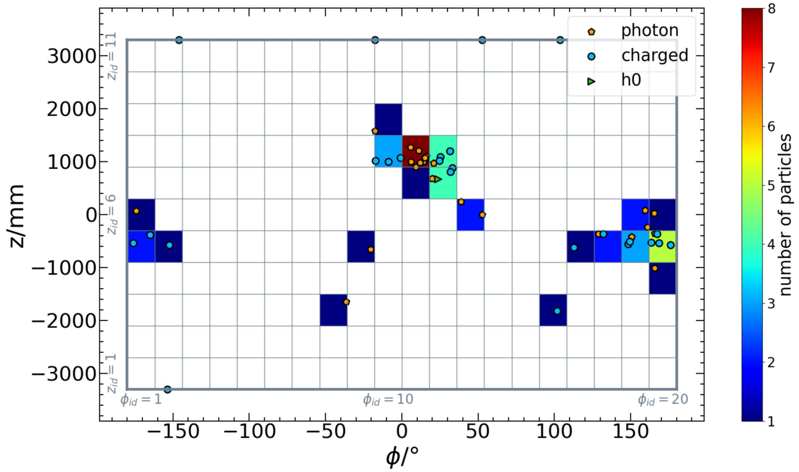




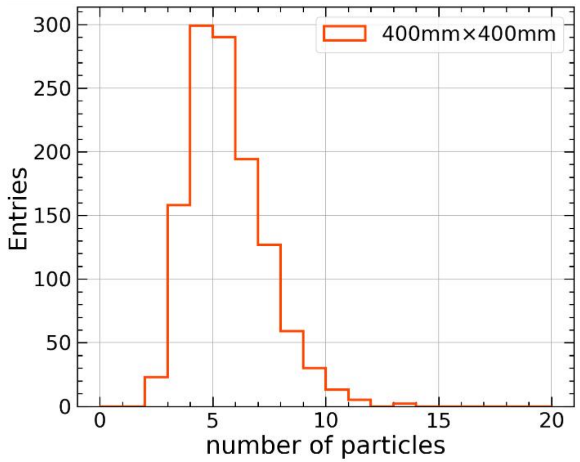
Energy ratio in ECAL & HCAL: $R = \frac{E_{ECAL}}{E_{ECAL}+E_{HCAL}}$



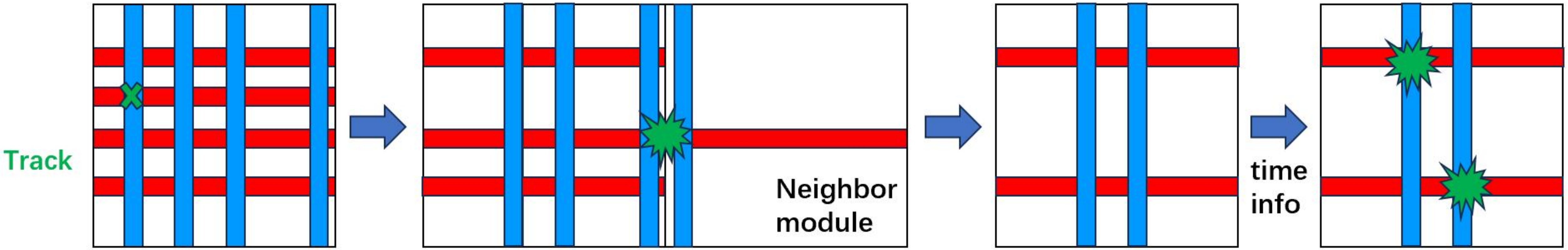
Ghost hit removal



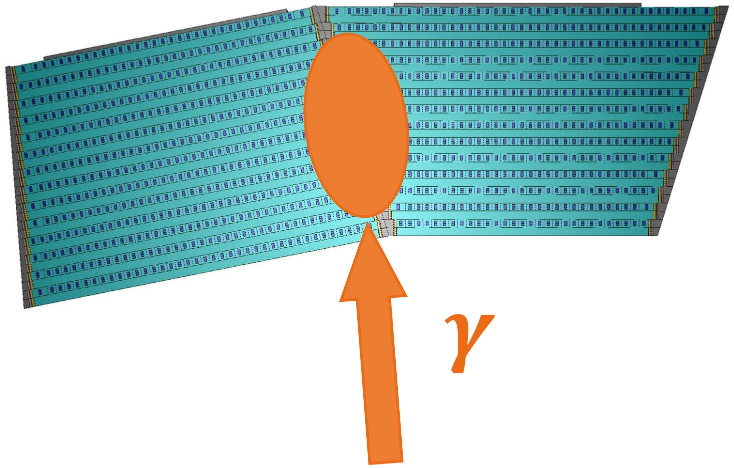
ECAL hit map of a jet event

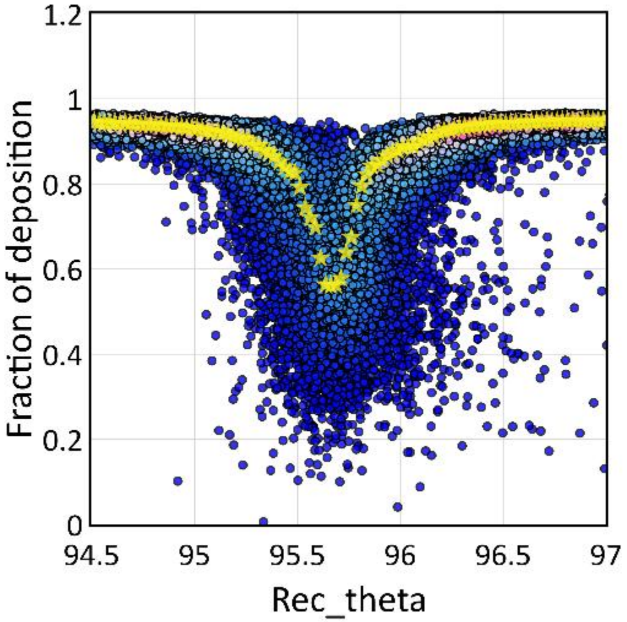


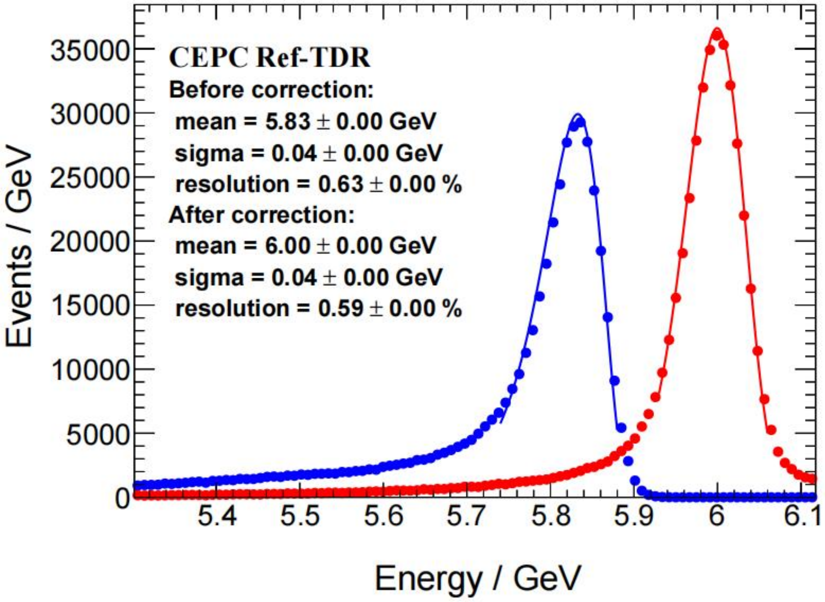
~5 particles in one module in a jet

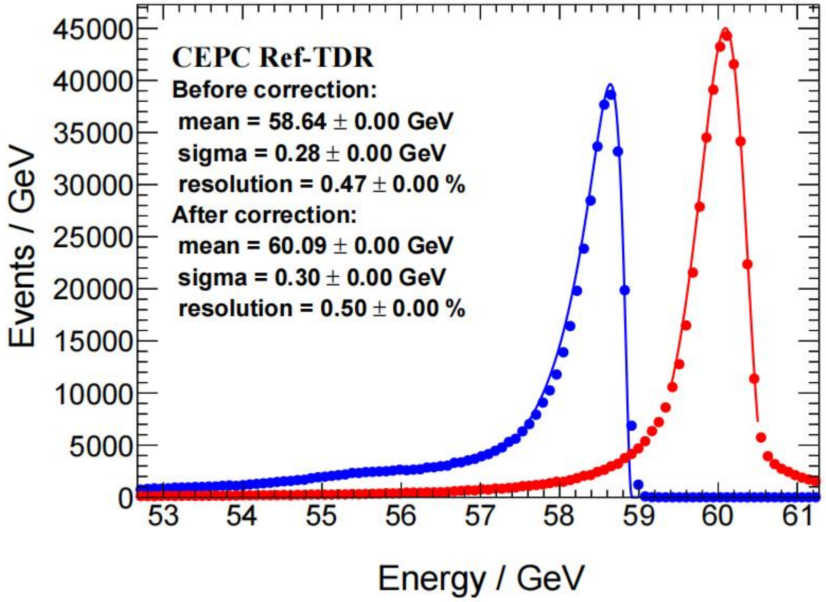


Energy correction

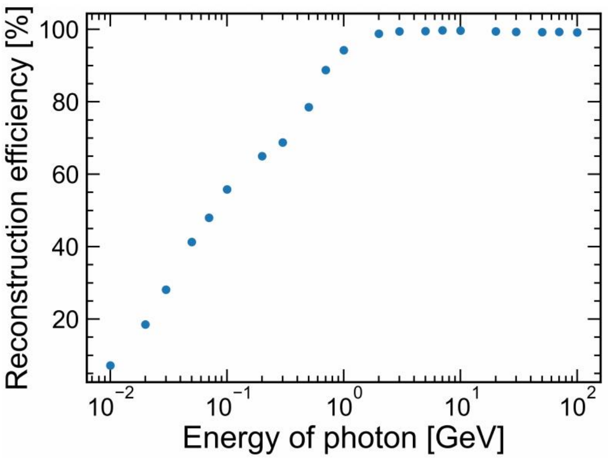


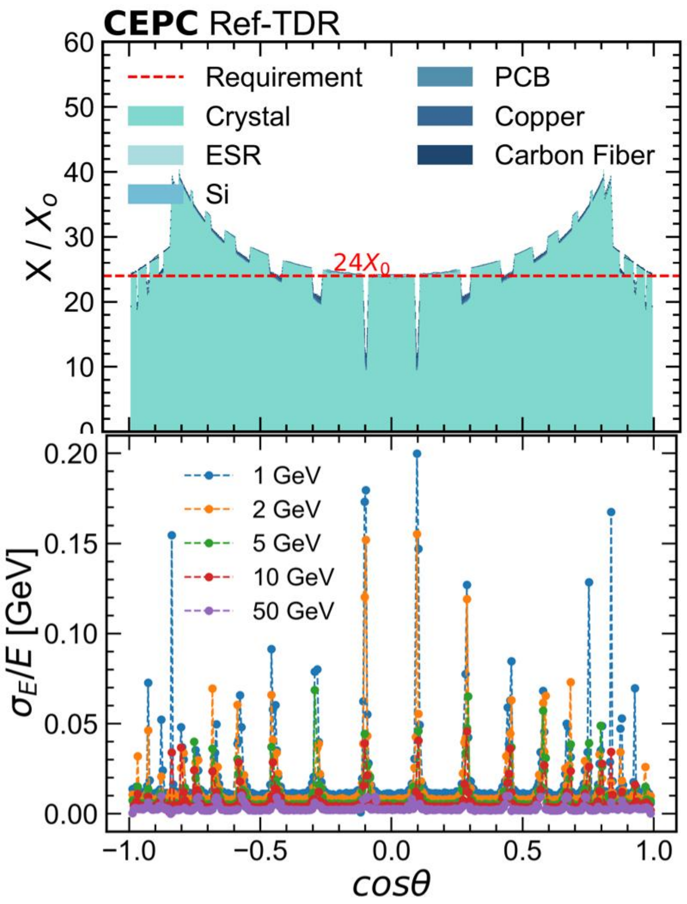


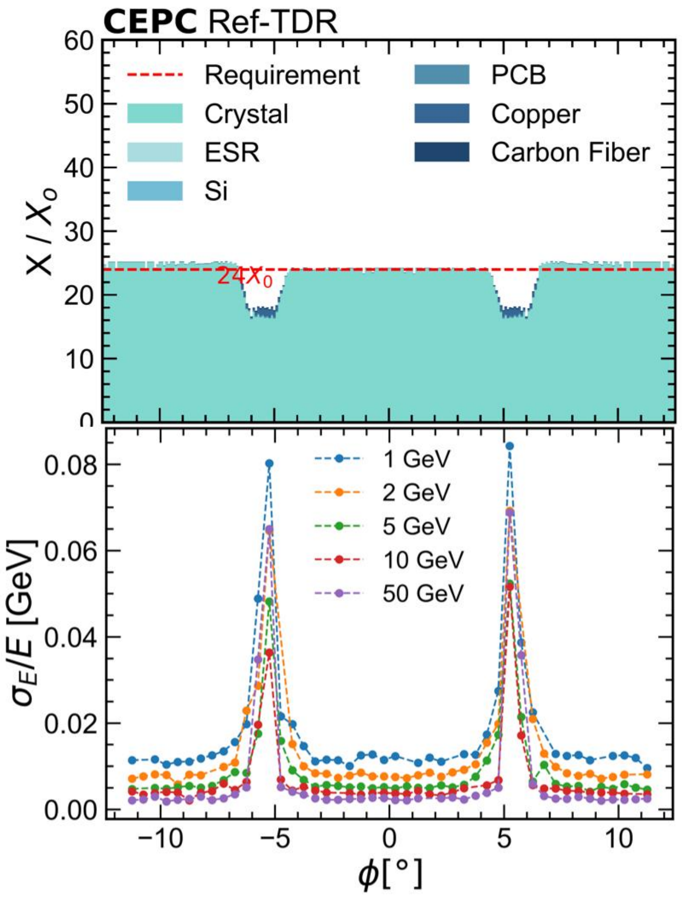


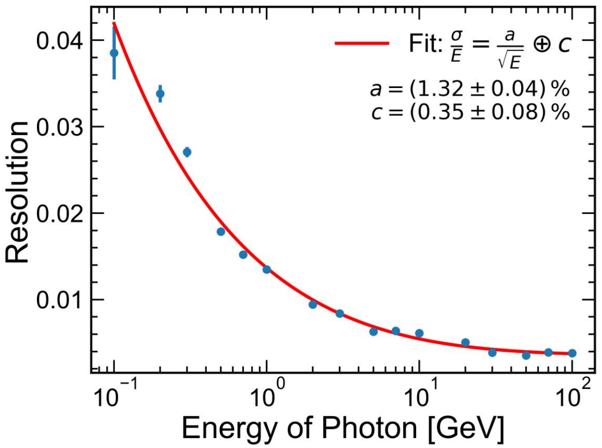


Photon reconstruction performance

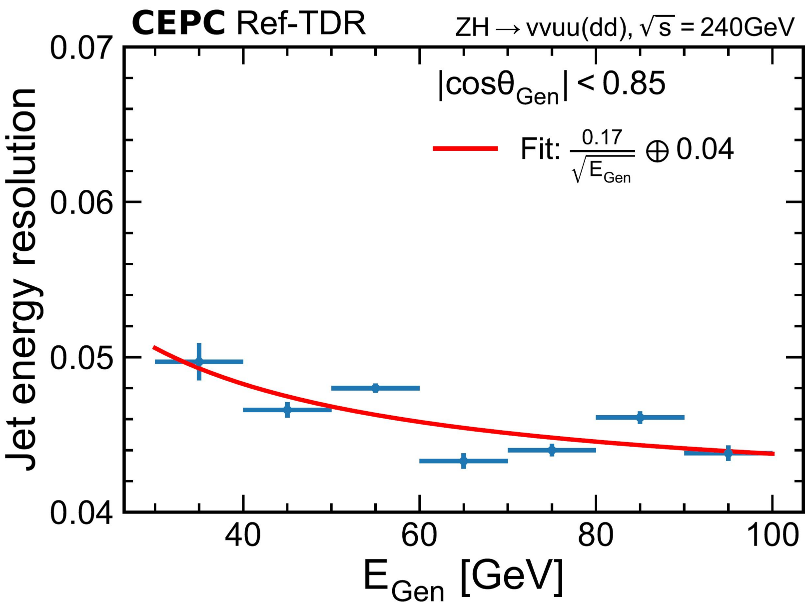


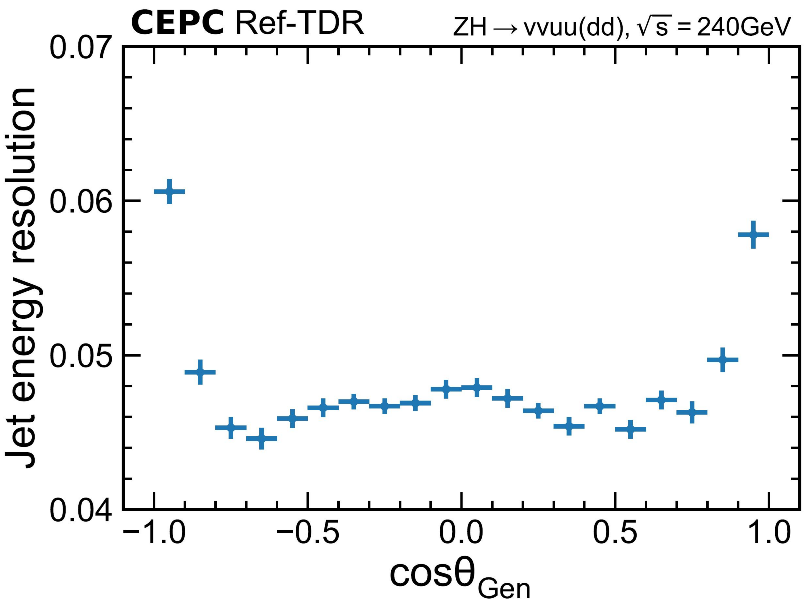


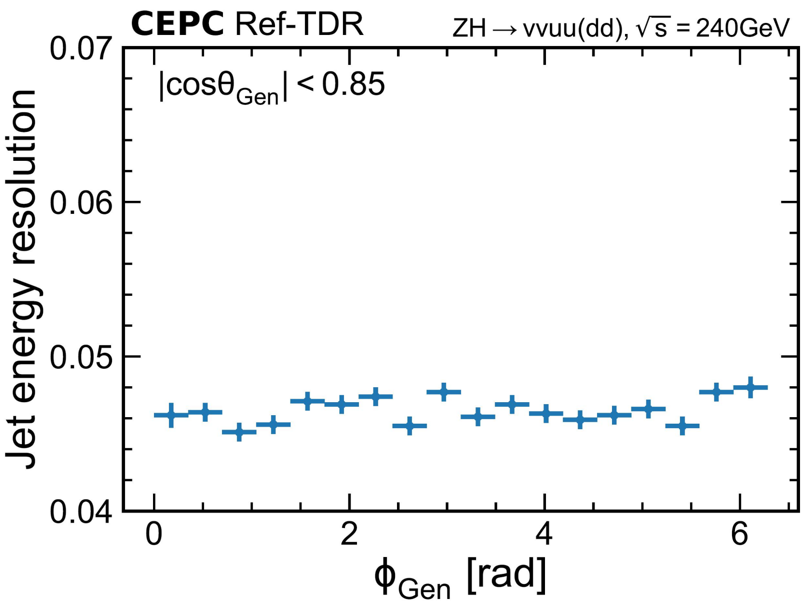




JER


CEPC Ref-TDR
ZH → vvuu(dd), √s = 240GeV
|cosθGen| < 0.85
Fit: 0.17/√EGen ⊕ 0.04
Jet energy resolution
EGen [GeV]
0.07
0.06
0.05
0.04
40
60
80
100


CEPC Ref-TDR
ZH → vvuu(dd), √s = 240GeV
Jet energy resolution
cosθGen
0.07
0.06
0.05
0.04
−1.0
−0.5
0.0
0.5
1.0


CEPC Ref-TDR
ZH → vvuu(dd), √s = 240GeV
|cosθGen| < 0.85
Jet energy resolution
ϕGen [rad]
0.07
0.06
0.05
0.04
0
2
4
6