High-Granularity Crystal Electromagnetic Calorimeter

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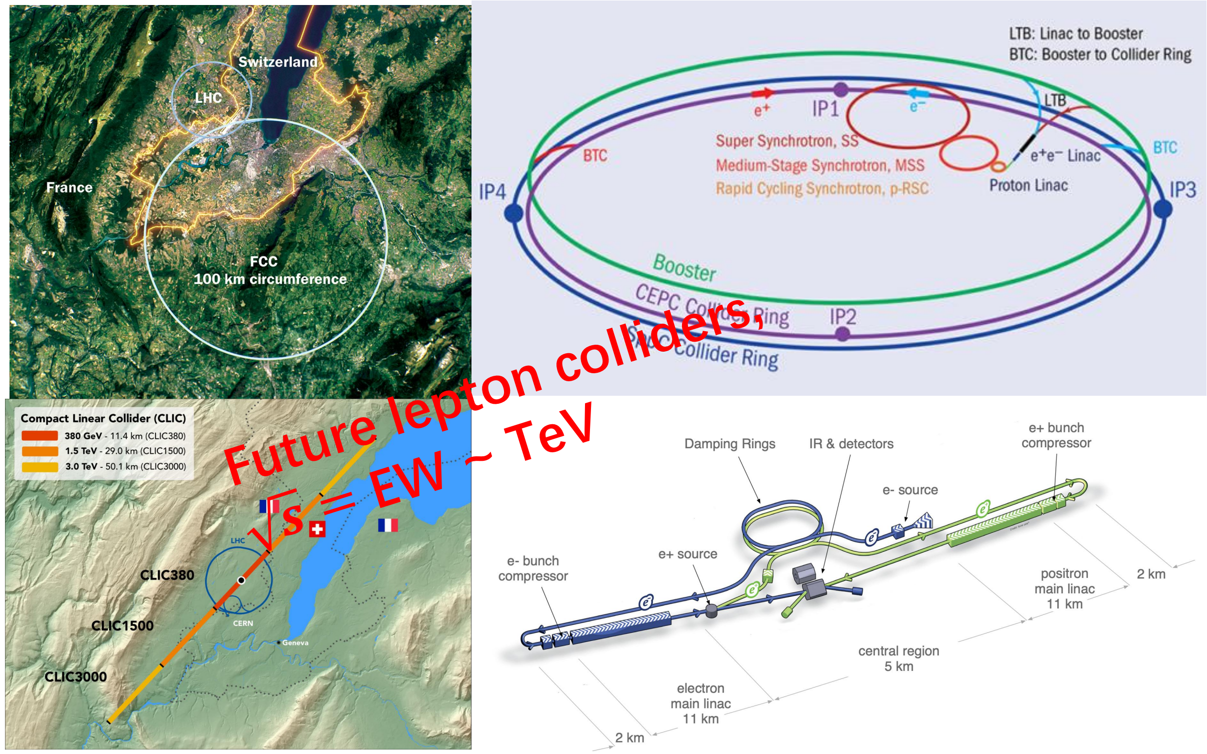
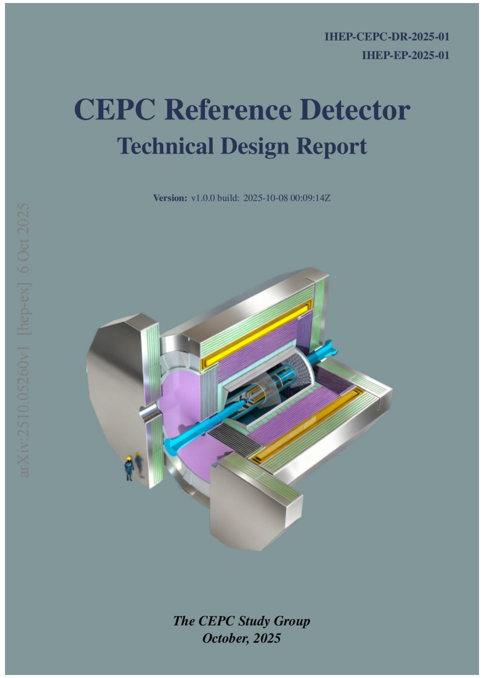
Future lepton collider

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



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



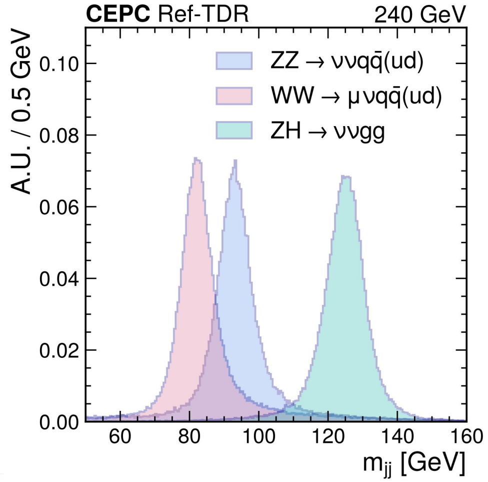
arXiv:2510.05260

AGORA
ADVANCED GLASS OPTIMIZED RESEARCH APPARATUS

Agora as a reference detector for CEPC

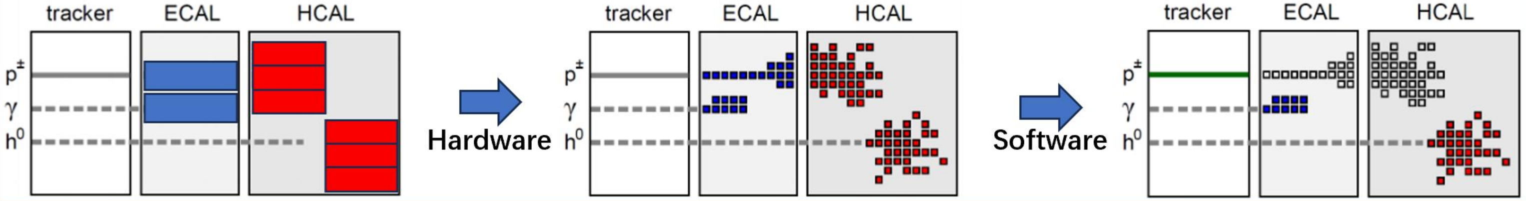
Calorimeter requirements

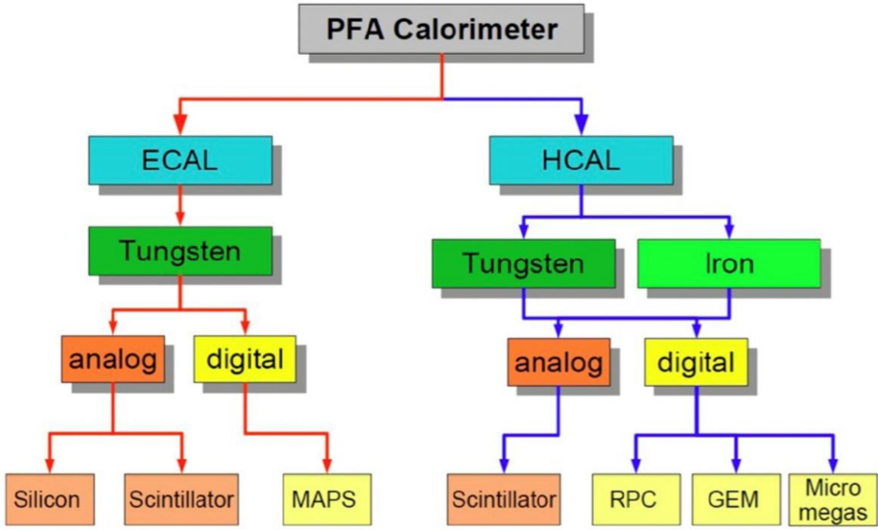
- **Precise jet reconstruction:** **Boson mass resolution (BMR)<4%**
  - Separate hadronic final states $W^{\pm}/Z/H \rightarrow q\bar{q}$
- Optimal EM resolution: $\sigma_E/E < 3\%/\sqrt{E(GeV)} \oplus 1\%$
  - Higgs Physics ($H \rightarrow \gamma\gamma$)
  - Flavor physics ($B^0_{(s)} \rightarrow \pi^0\pi^0$)
  - BSM ($ALP \rightarrow \gamma\gamma$)
- 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.

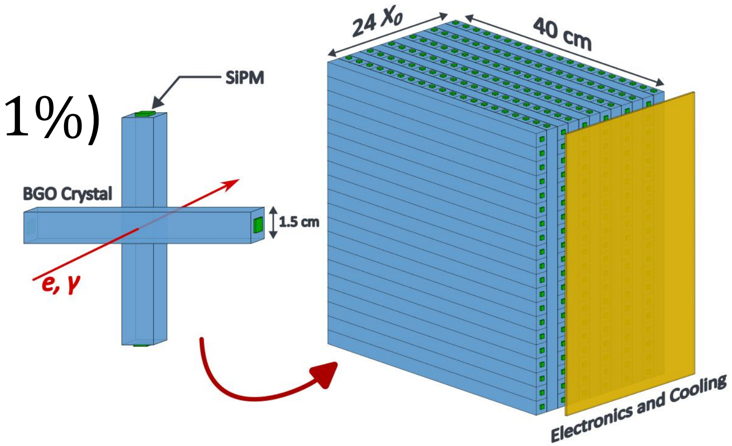




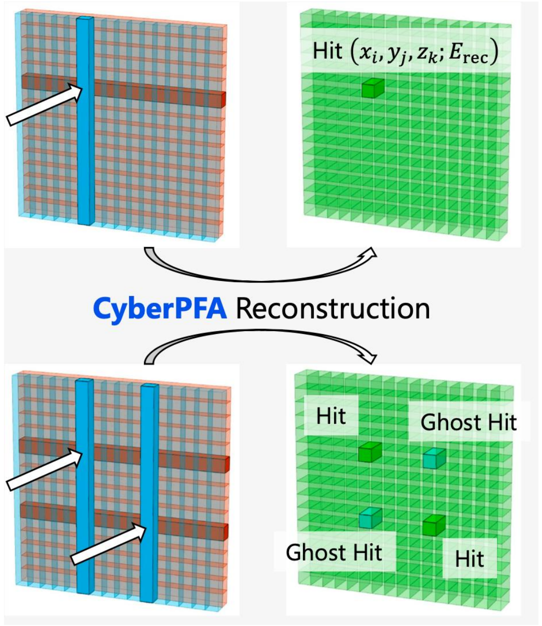
PF calorimetry options explored in CALICE/DRD-Calo collaborations

High-granularity crystal calorimeter (HGCCAL)

- **HGCCAL**: The **first** electromagnetic calorimeter of this type
  - Homogeneous: optimal EM performance ($< 3\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$)
  - Imaging capability: compatible with PFA for jet measurement



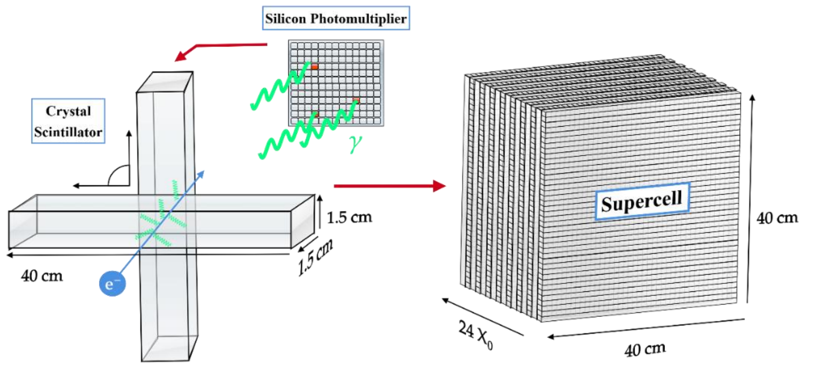
- Long crystal bars in orthogonal arrangement
  - Significant reduction of readout channels
  - Minimum dead materials between layers
  - 3D positioning with cross-point



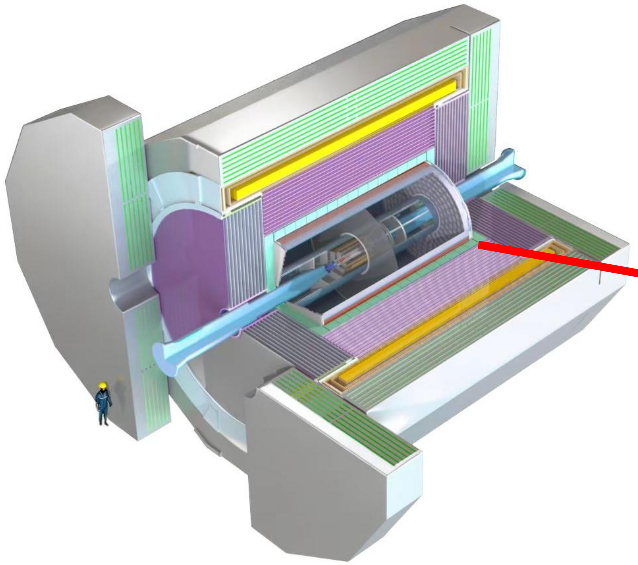
- Challenges
  - Integration: light-weighted mechanics, cooling, readout
  - Pattern recognition: to resolve ambiguities & overlap
  - Readout: A large dynamic range for SiPM + ASIC

HGCCAL: overview

- ECAL design features: high granularity, modularity and hermeticity
  - Nominal crystal bar dimensions: $15 \times 15 \times\sim 40\ \mathrm{mm}^3$
  - Transverse (effective) granularity: $15 \times 15\ \mathrm{mm}^2$
  - Total depth of $24X_0$ with 18 longitudinal layers
- Barrel: 480 modules (411k channels, ~17.9 m^3 crystals)
- Endcaps: 224 modules (160k channels, ~6.3 m^3 crystals)



Module schematics



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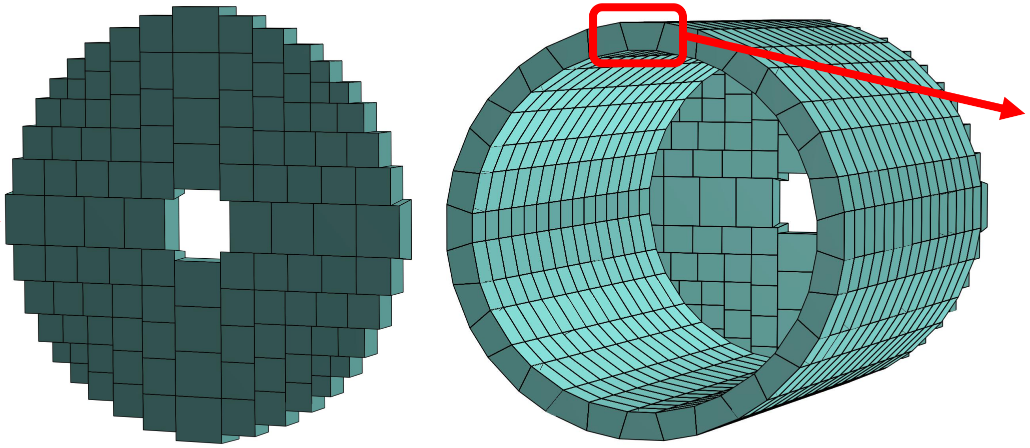
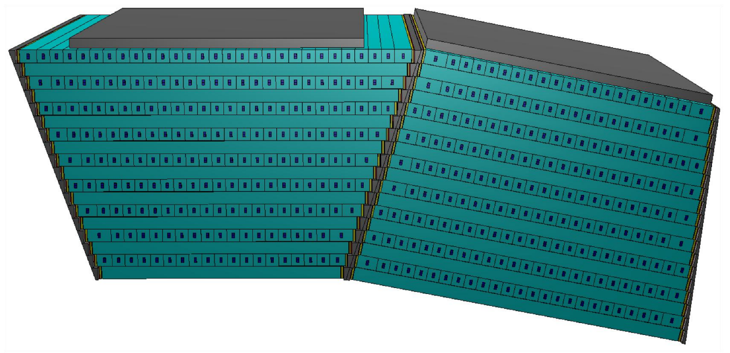


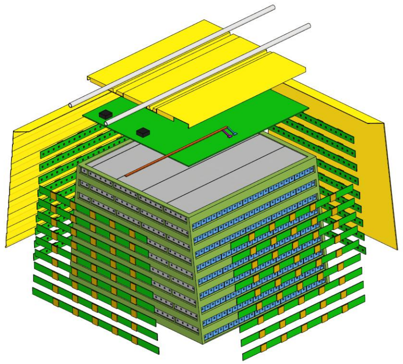
HGCCAL

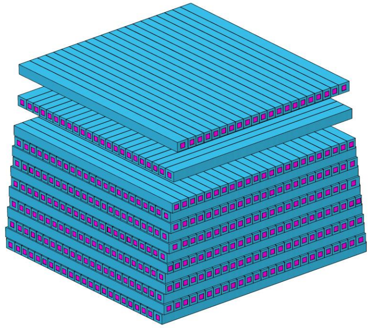


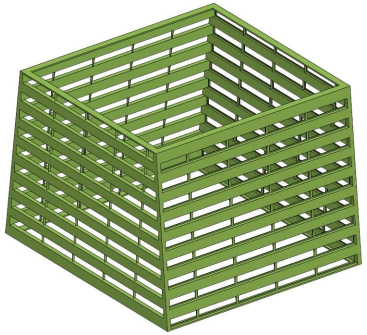
Modules

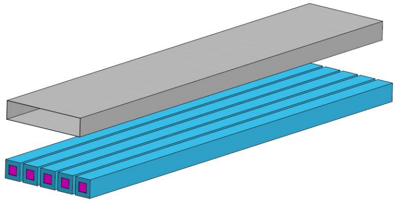
HGCCAL: Module design

- Module boundary optimised: to avoid projectile gaps (i.e. not pointing to Interaction Point)
- Aim for feasibility of **mass production** and **system integration** (within limited space)
- **Integration** of crystals, readout boards, cabling, cooling plates/pipes and mechanics

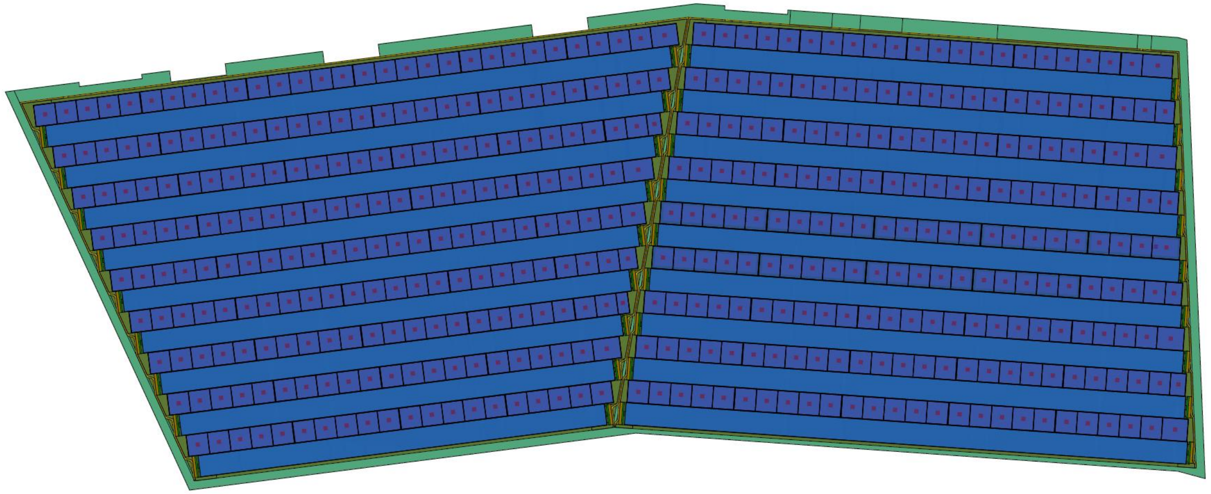

(a)


(b)


(c)


(d)

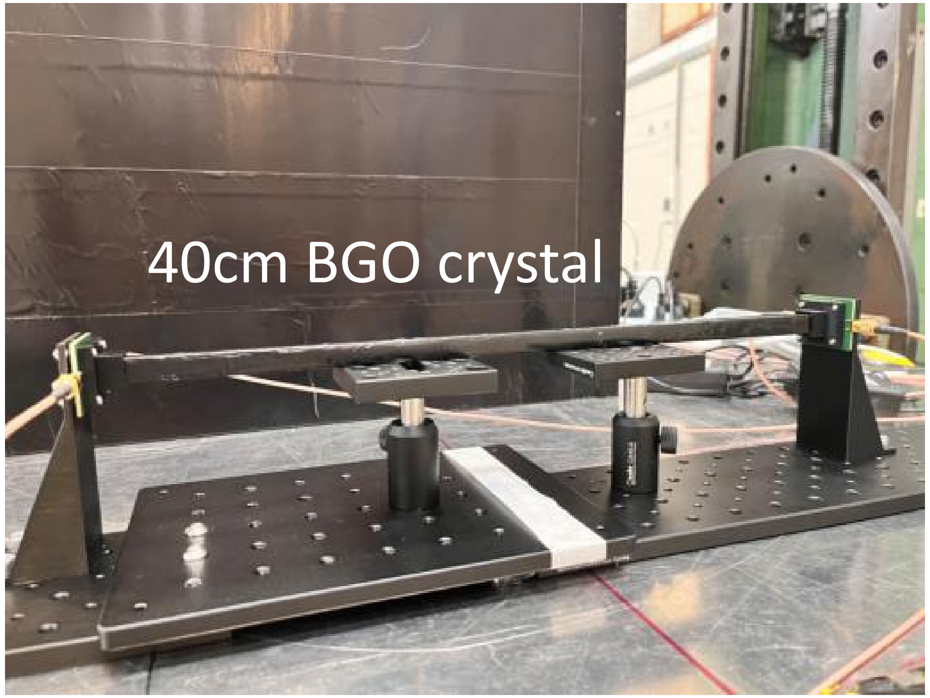
- Mechanics structure based on carbon-fibres
  - Mechanical strength and stability for dense crystals
  - Light-weight: minimum material budget

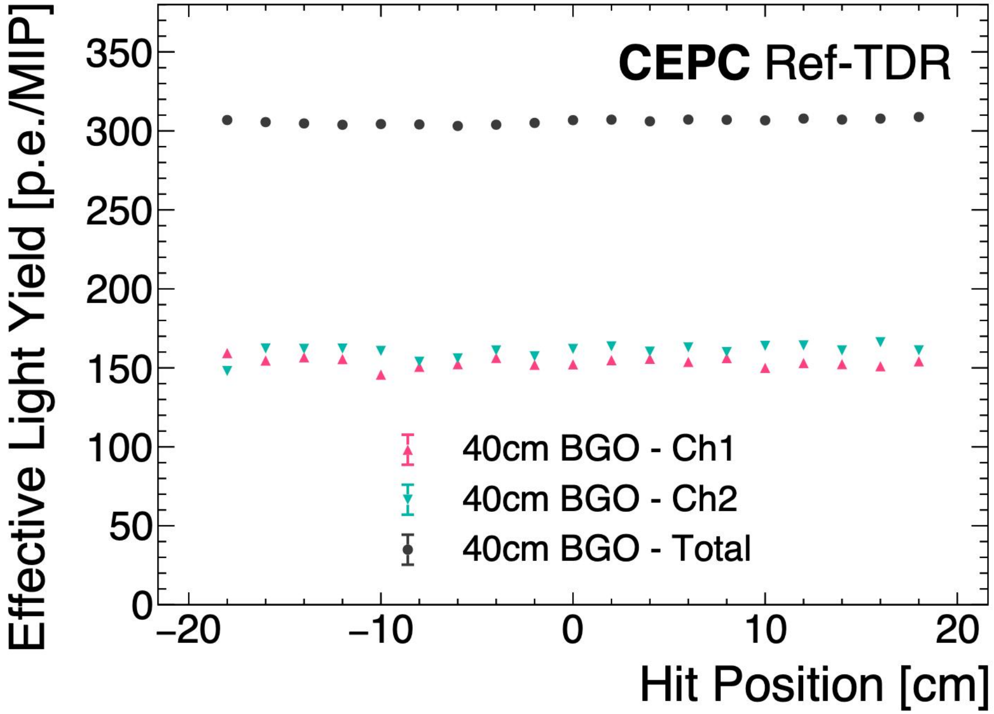


BGO response uniformity

- 40cm BGO crystal bar tested at CERN
  - Using 10 GeV pion beams
  - MIP response uniformity and timing resolution
- Response uniformity: 0.4% (standard deviation)

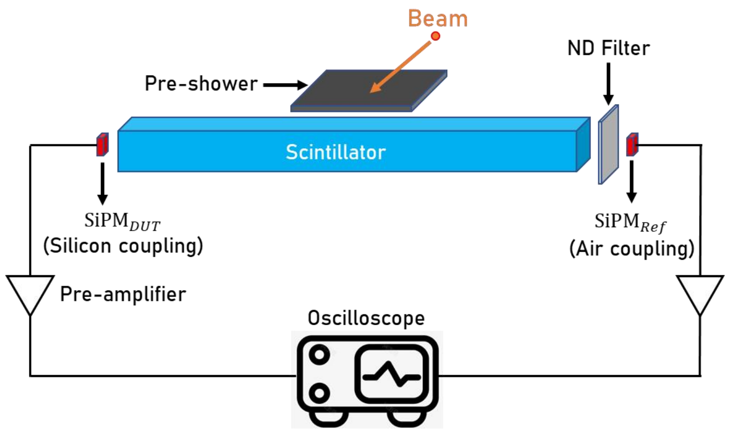
Talk at DRD-Calo Ancona (2025)
Talk (Zhiyu Zhao) at CEPC workshop EU (2026)



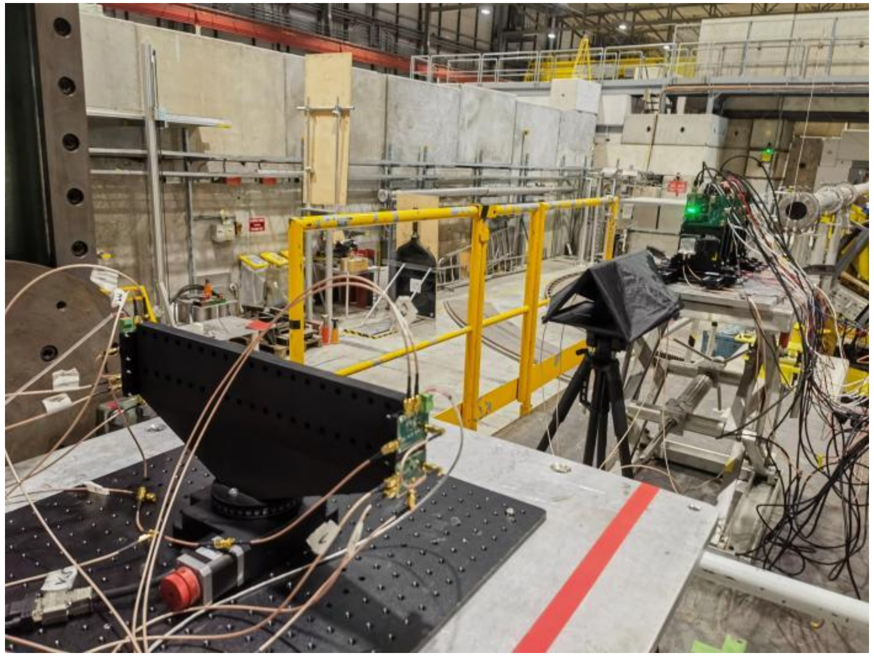


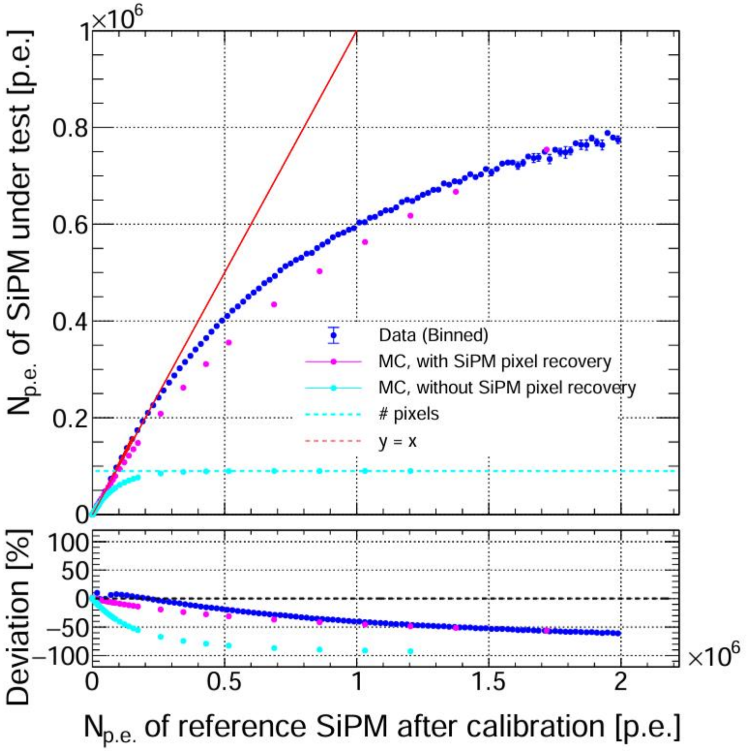
BGO-SiPM response tested with beams

- 40cm BGO tested with SiPMs to study response in a wide dynamic range
  - Tested with electron beam up to 300 GeV (SPS-H2)
  - Used tungsten plate to induce showers and large energy depositions
  - First quantitative studies on impact of SiPM pixel recovery during BGO scintillation time



BGO-SiPM response simulation includes SiPM pixel recovery, PDE, crosstalk, BGO scintillation and photon propagation, etc.

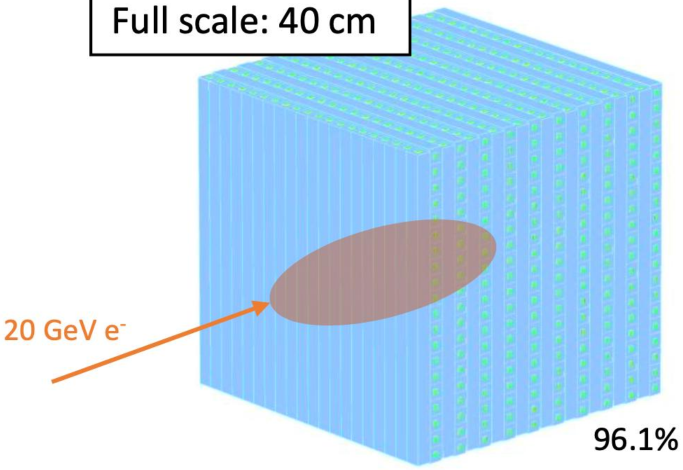




Prototype dimensions: simulation studies

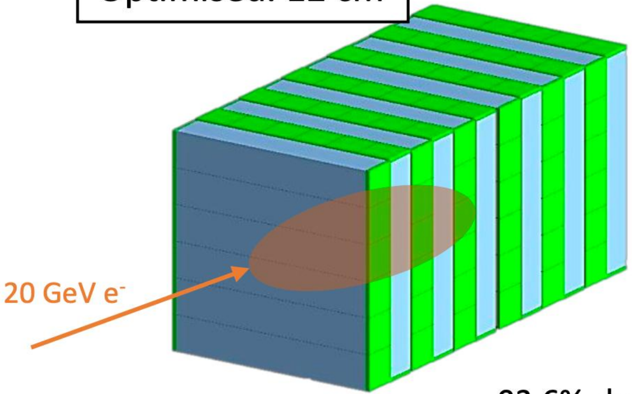
- Major focus of the first prototype
  - **Key performance** validation: linearity, energy resolution
  - System integration: crystals, readout and mechanics
- Prototype dimensions: Geant4 simulation studies
  - Benefit from compact EM shower profiles in nature
  - $12 \times 12 \times 24\ \mathrm{cm}^3$ can reasonably contain EM showers

Full scale: 40 cm

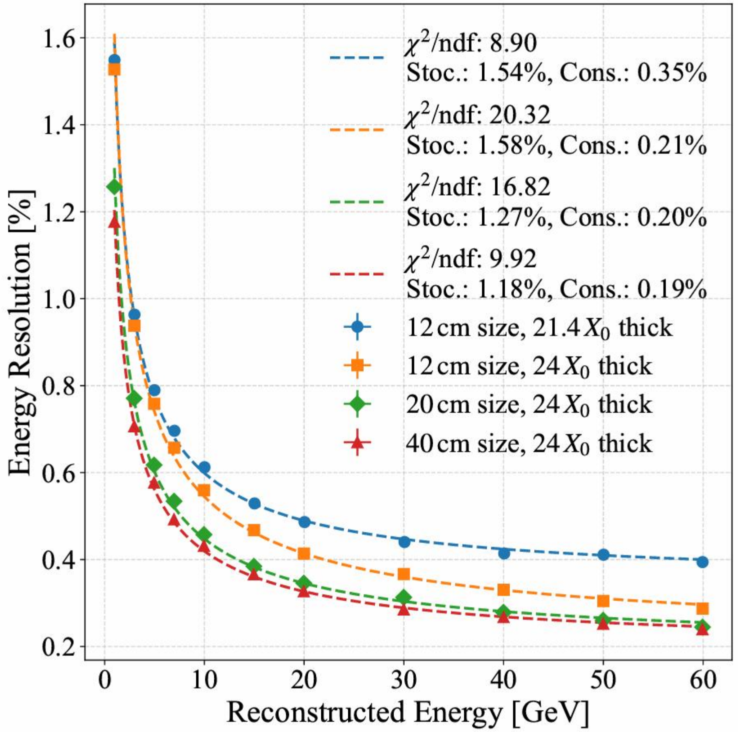


96.1% shower energy contained

Optimised: 12 cm



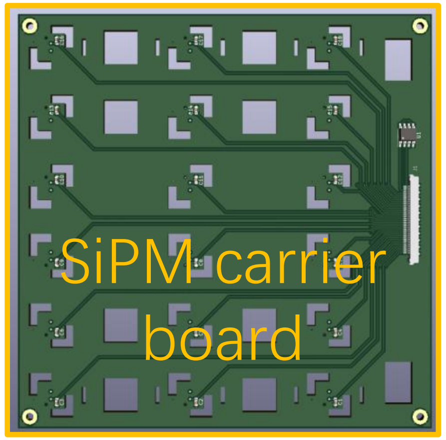
93.6% shower energy contained

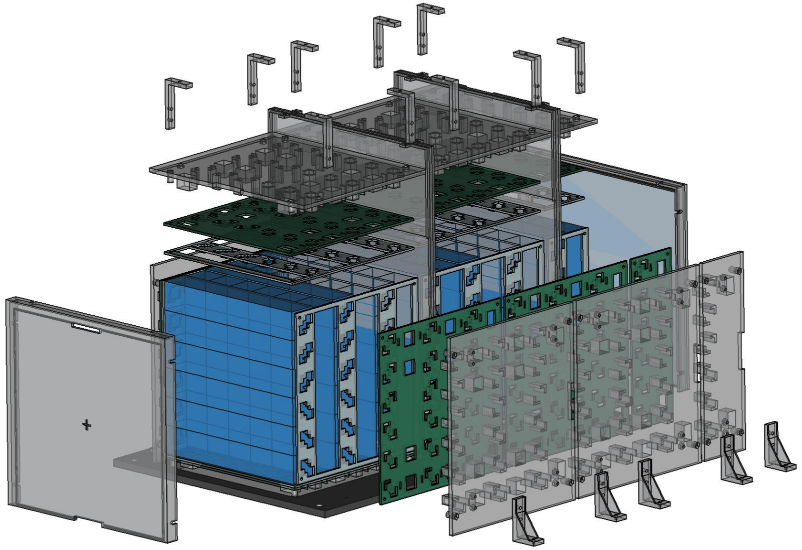


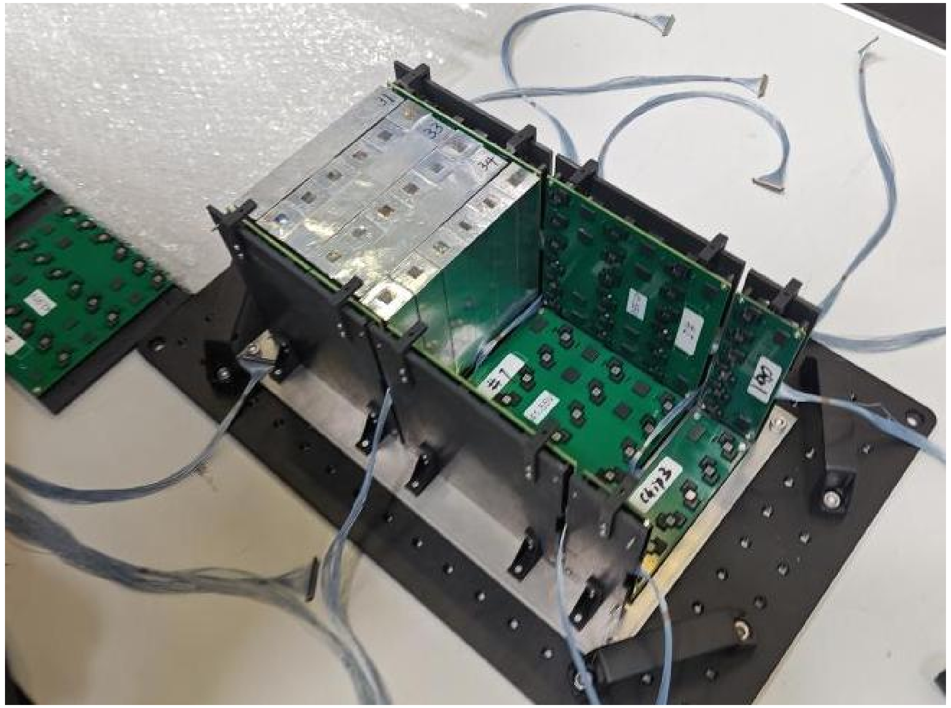
EM energy resolution with different prototype dimensions

Prototype: system integration

- SiPM-carrier board: custom-designed
  - Bias voltage, SiPM signals, temperature
- Light-weight mechanics for crystals
  - To minimise material budget
- Micro-coaxial cables: high pin-count
  - Reliable connection of SiPMs and ASICs





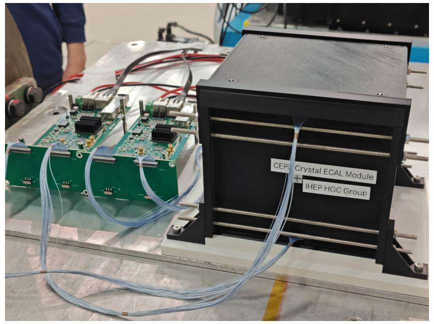


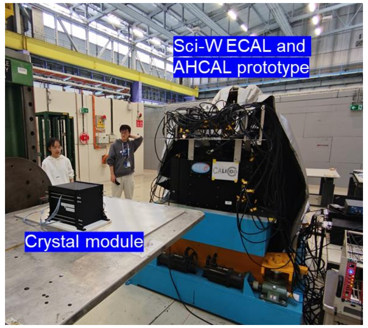
Prototype development and beam tests

- Prototype with 2×2×12 cm^3 BGO crystal bars: to evaluate EM performance

Module test

- **Successful** commissioning
- **MIP signals** in all channels





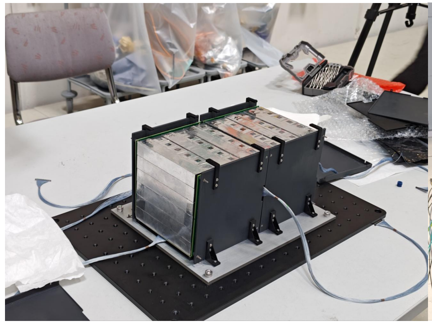
HGCCAL module

- Dimensions: 12×12×12 cm^3
- 36 BGO bars (10.7 X_0)
- 72 readout channels

First prototype beam test

- **Validated** digitisation
- **Consistency** for data/MC
- Beam momentum spread

(due to *Beam Instrumentation*)



First HGCCAL Prototype

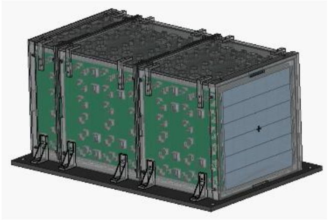
- Dimensions: 12×12×24 cm^3
- 72 BGO bars (21.4 X_0)
- 144 readout channels
- Active cooling

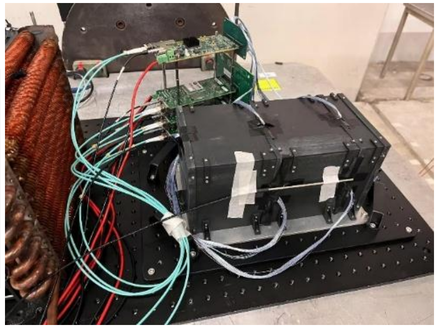
Improved beam test in 2025

- **Minimum upstream materials**

in the beamline: removed all *BI*

- **Prototype depth >24X_0**: to study shower leakage effects

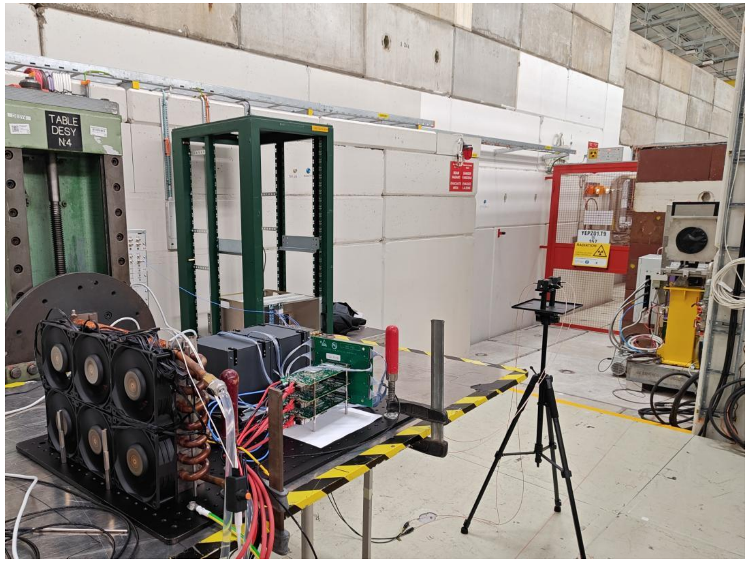


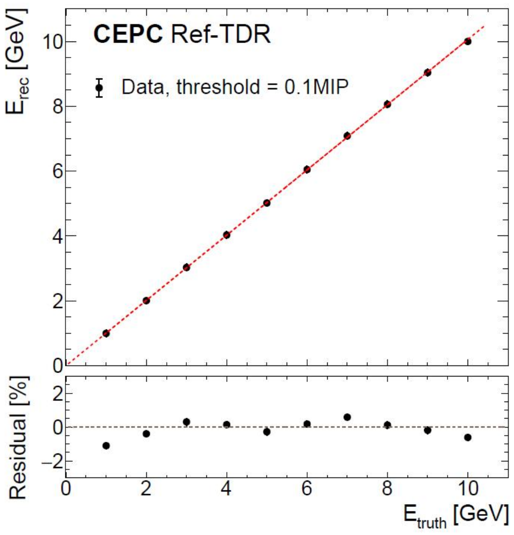


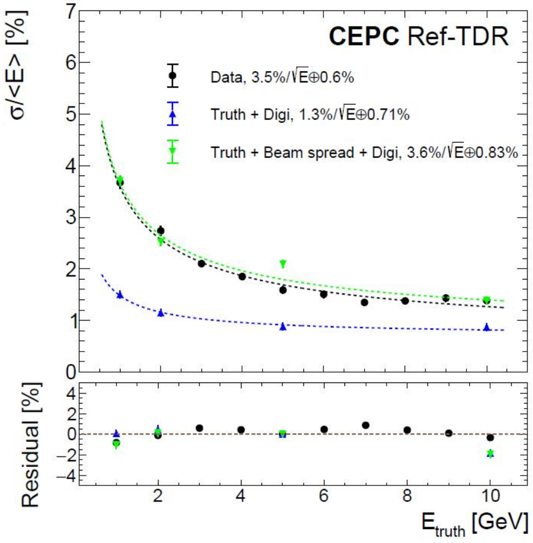
HGCCAL Prototype in 2025

- Dimensions: 12×12×28 cm^3
- 72 BGO + 12 BSO bars (24.9 X_0)
- 168 readout channels
- Active cooling

HGCCAL prototype: beam test in 2024



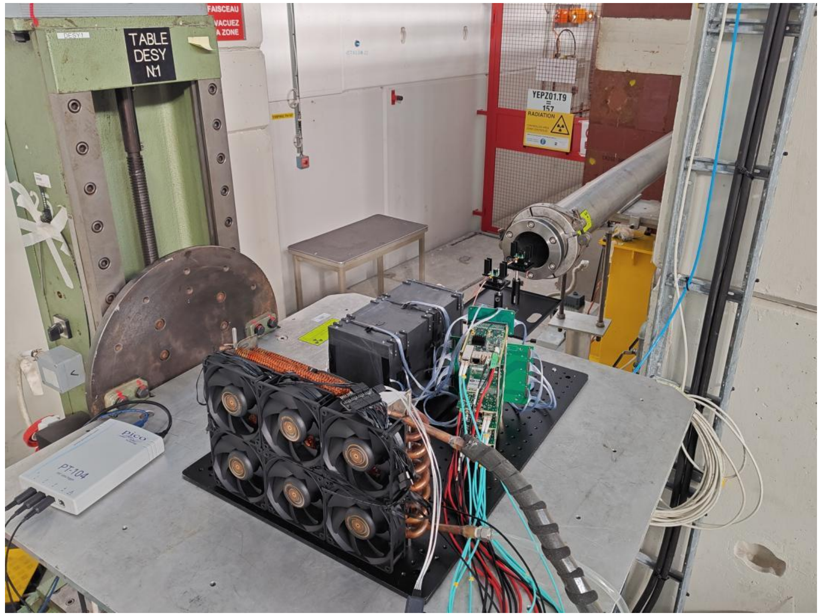


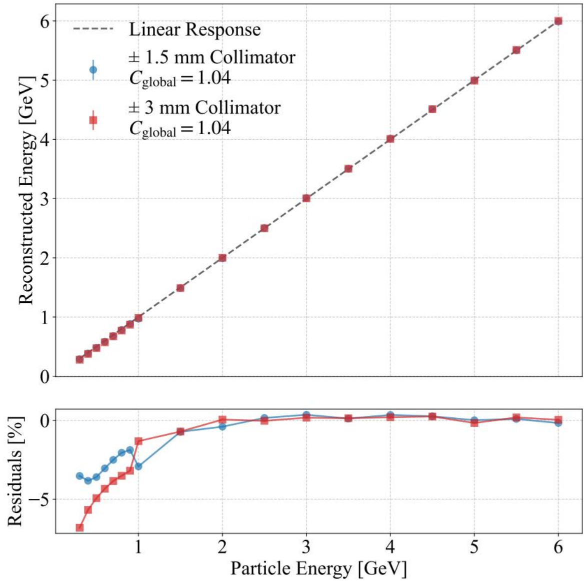


- Studies based on electron beam data in 1 – 10 GeV
  - Beam data taken with *Beam Instrumentation* in upstream
  - Beamline simulation: to quantify momentum spread
- EM response linearity within $\pm 1\%$
- EM energy resolution
  - Including beam momentum spread
    - $\sigma_E/E = 3.6\%/\sqrt{E(GeV)} \oplus 0.3\%$
  - Excluding momentum spread
    - Using beamline simulation as input
    - $\sigma_E/E < 2\%/\sqrt{E(GeV)} \oplus 1\%$

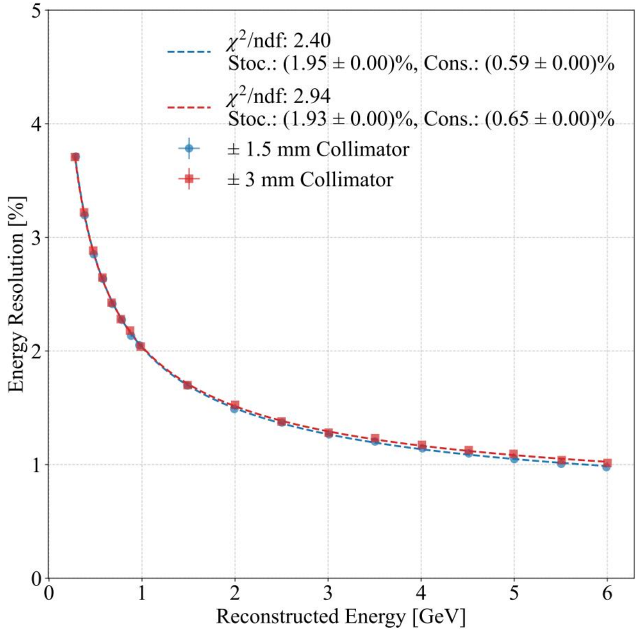
HGCCAL prototype: beam test in 2025

- **Preliminary results**: using electron data at CERN PS-T9
  - **Removed** all Beam Instrumentation components → **confirmed less momentum spread**
  - EM response linearity within $\pm 1\%$
  - EM energy resolution: $\sigma_E/E = 1.95\%/\sqrt{E(GeV)} \oplus 0.6\%$ (**including beam momentum spread**)
- Evaluated key performance: EM resolution achieved $\sigma_E/E < 2\%/\sqrt{E(GeV)} \oplus 1\%$
  - Even in the presence of beam momentum spread





EM response linearity (data)



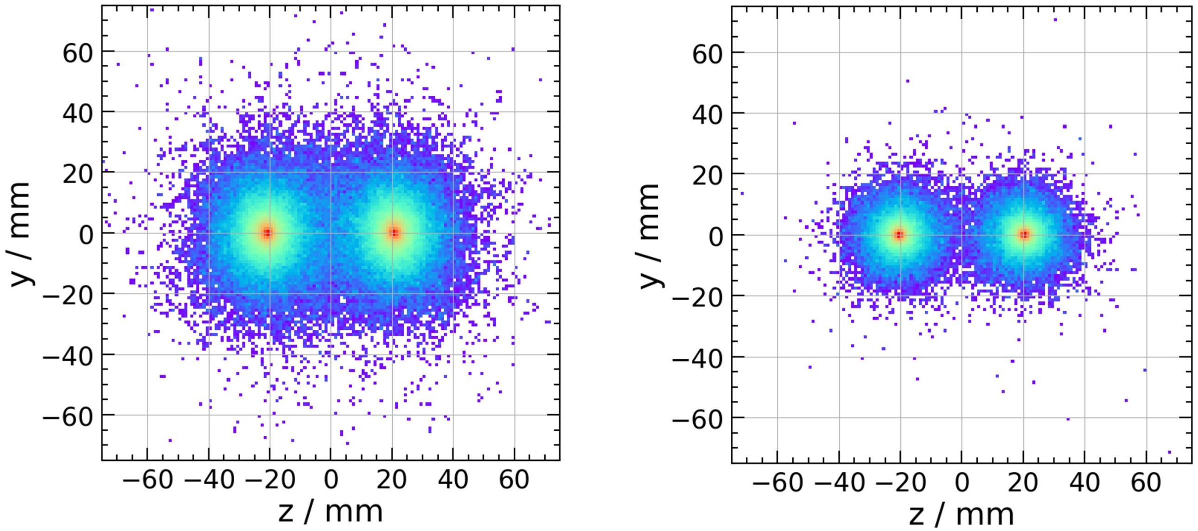
EM energy resolution (data)

Particle flow Algorithm

- Excellent energy resolution, but new challenges for reconstruction arise from the **crystal properties** and **bar design**.

Large R_M & small λ_I/X_0

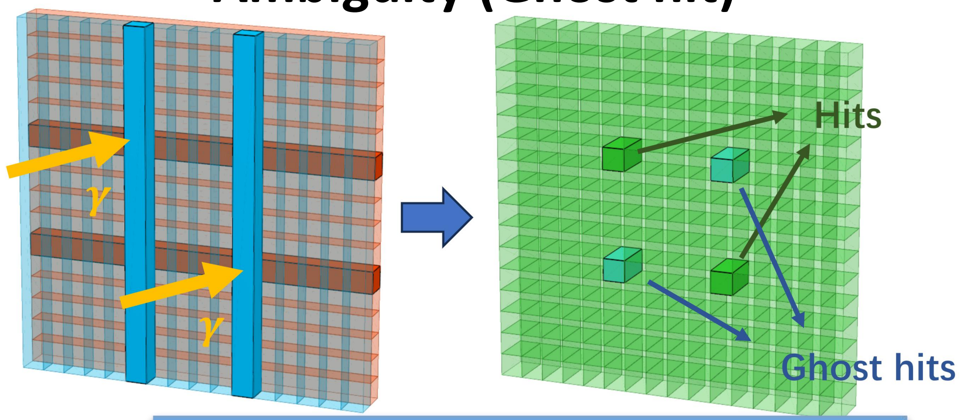
Shower overlap



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

Arrangement of transverse bar

Ambiguity (Ghost hit)



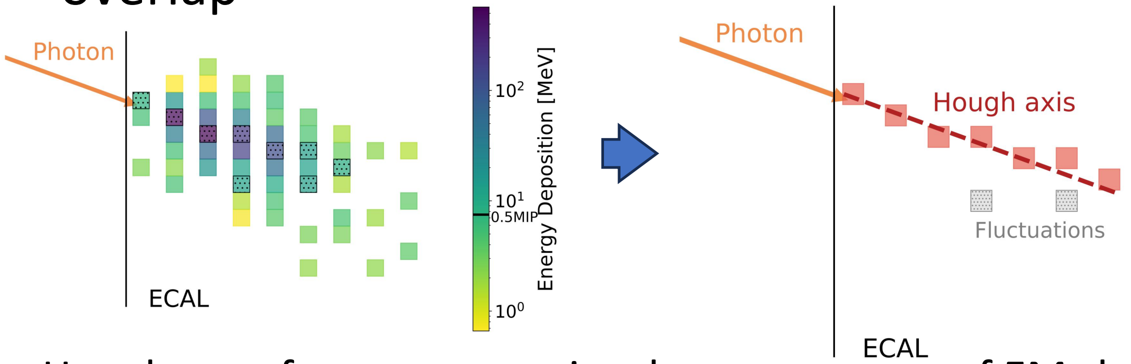
Software task:
* Clustering
* Pattern recognition.
+ Energy splitting.
+ Ghost hit removal

CyberPFA developed for crystal bar ECAL

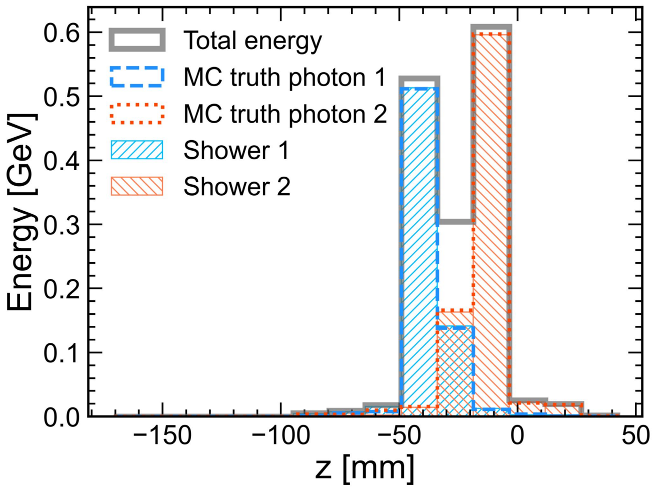
CyberPFA: Crystal Bar Ecal Reconstruction PFA

- **Energy-core shower recognition**

  \+ **energy splitting** to address shower overlap

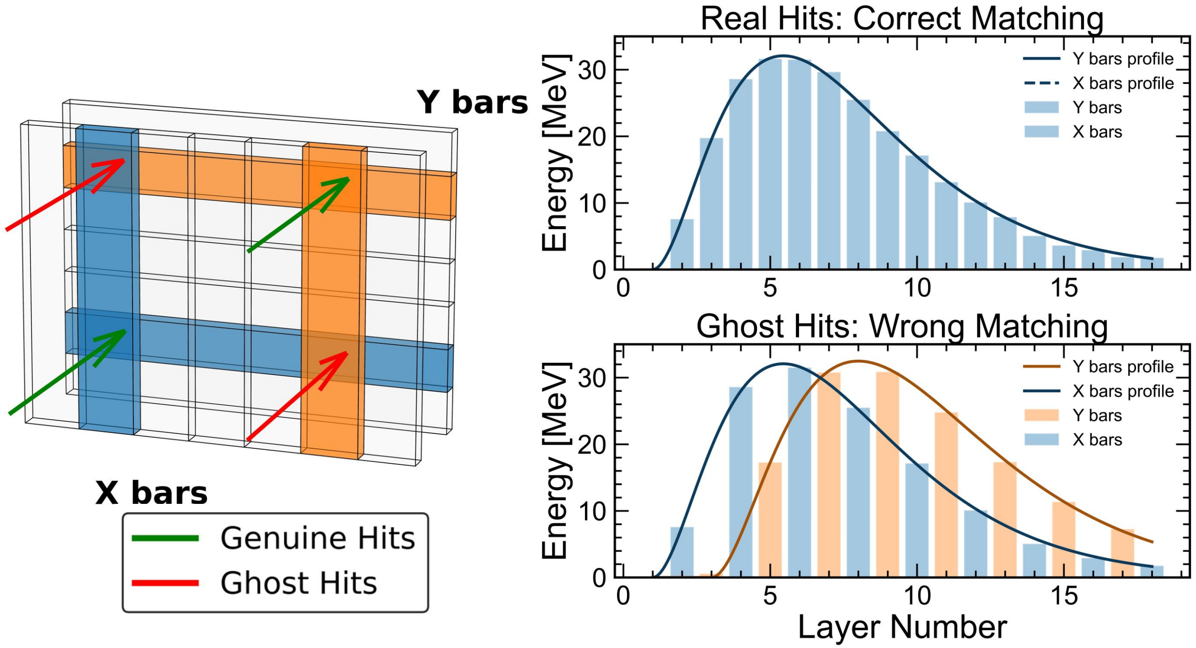


Hough transform to recognize the energy-core of EM shower



Iterative energy splitting based on lateral shower profile

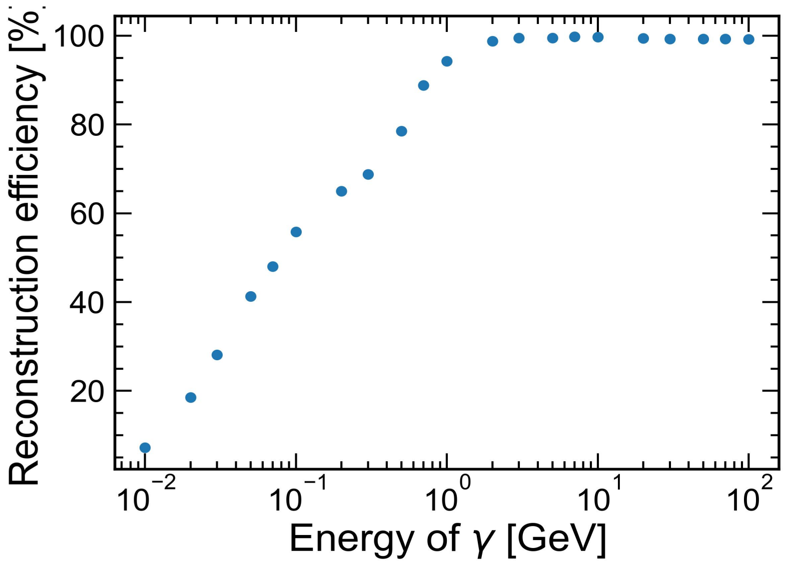
- Ghost-hit (Ambiguity) suppression by exploiting **longitudinal shower-profile consistency**



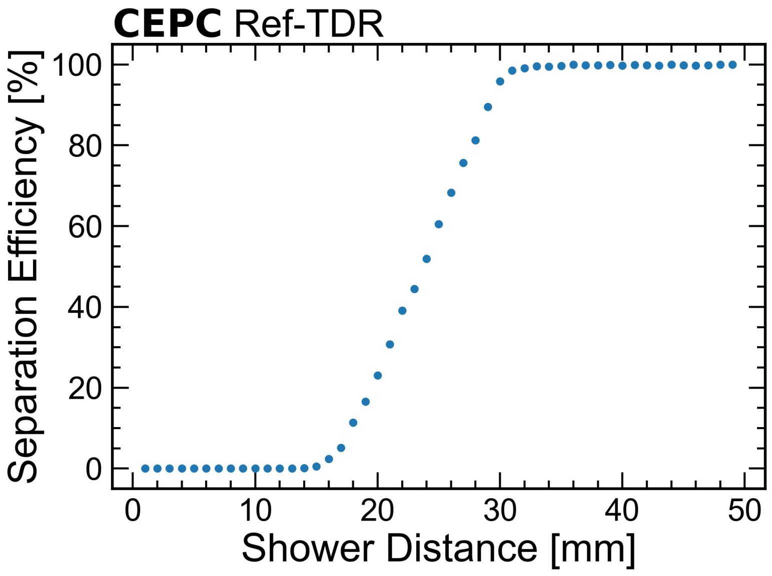
Ghost-hit suppression

Performance

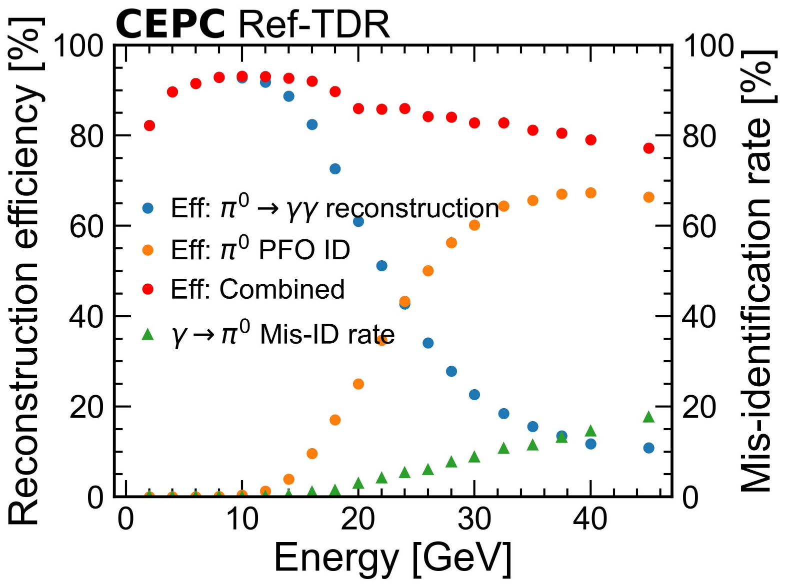
- Single photon reconstruction efficiency
  - Optimization for low-energy photons: good efficiency in sub-GeV region
- Two-photon separation efficiency: reach limitation of transverse granularity
- Neutral pion reconstruction efficiency and mis-identification rate
  - Promising performance in the wide energy range of 2 – 40 GeV



Single γ reconstruction



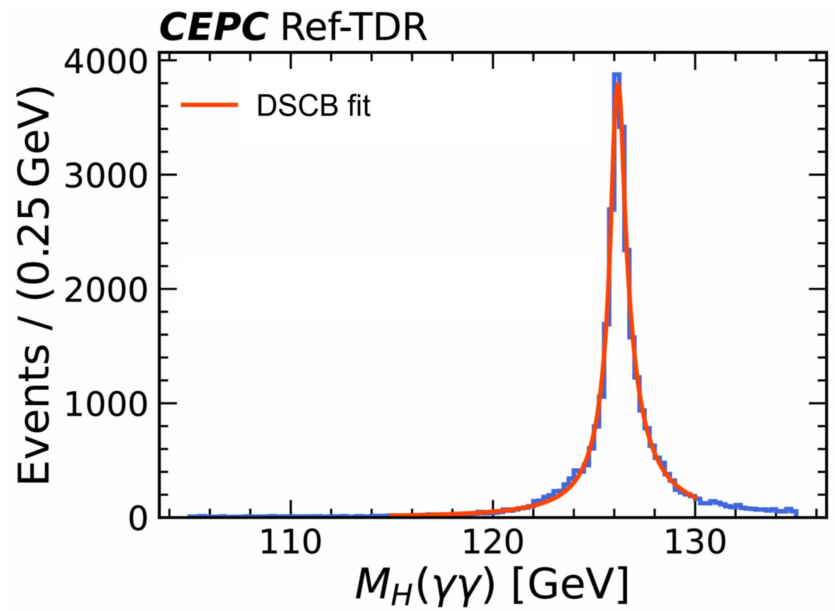
Separation of two 5 GeV γ

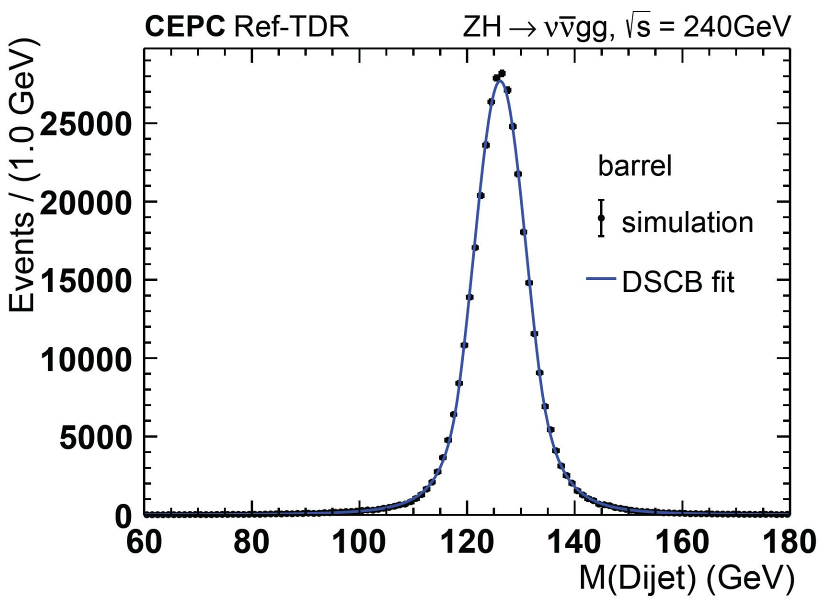


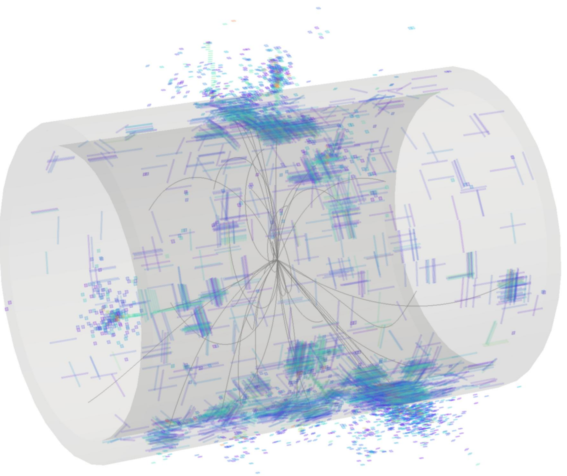
π^0 rec. efficiency & purity

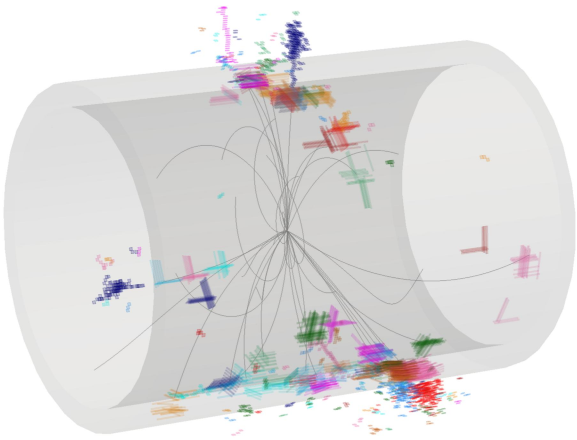
Performance

- Higgs benchmark studies at 240 GeV
  - $e^+e^- \to \nu\nu H \to \nu\nu\gamma\gamma\ (gg)$ @ $\sqrt{s} = 240$ GeV









$H \to \gamma\gamma$

$mean = 126.185 \pm 0.005$ GeV,
$\sigma = 0.397 \pm 0.006$ GeV
Mass resolution: $0.31 \pm 0.10\%$.

$H \to gg$

$m_{jj} = 126.14 \pm 0.01$
$\sigma_{jj} = 4.89 \pm 0.01$
BMR = $3.87 \pm 0.10\%$

Meet the requirement of BMR<4%

HGCCAL R&D plan

- Follow-up studies on the outlook of IDRC final report
  - **QA/QC** for crystals and SiPMs
  - **Calibration procedures** with beam backgrounds
  - **Fast timing** and other technological advancements
  - **CyberPFA** optimizations
- High-granularity crystal calorimeter prototype
  - **EM performance and shower profiles** using electron beam data in a wide energy range of 0.1 – 100 GeV
  - **Calorimetry-based PID** techniques using all test-beam data
  - **First hadronic interaction in ECAL** using pion beam data
  - Joint efforts: test-beam data migration to **Key4Hep software** framework (for particle-flow studies)
- New ECAL design and developments
  - **ECAL based on new scintillators**: BSO, scintillating glass
  - Joint efforts: **SiPM common R&D** (focusing on a high dynamic range for ECAL) and **SiPM-readout ASIC**

Summary

- A new PFA-oriented ECAL option for future Higgs factories
  - **Homogeneous imaging** calorimetry based on technology evolutions (e.g. SiPM, ASIC)
  - Design featuring **high granularity**, **modularity** and **hermeticity**
    - Crystals and SiPMs fully integrated in mechanics, cooling and readout electronics

- First prototype successfully developed and tested in high-energy beams
  - EM resolution achieved $\sigma_E/E < 2\%/\sqrt{E(GeV)} \oplus 1\%$

- A new PFA for crystal ECAL design (CyberPFA):
  - demonstration of BMR$< 4\%$ for jets

- Teams actively involved in international collaborations
  - Members of **CALICE** and **DRD-Calo** collaborations
  - Welcome more collaborators and joint effort

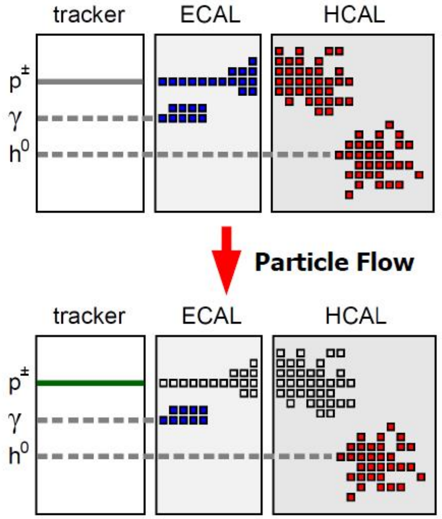
Backup

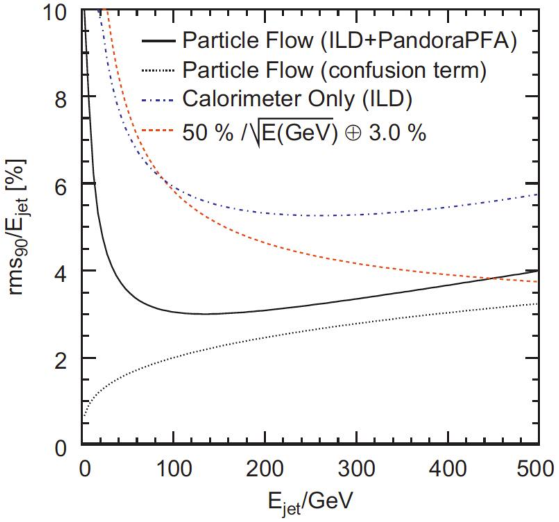
Particle-flow paradigm

Components in jets	Sub-Detectors	Energy fraction (average) within a jet	Detector Resolution
charged particles ($X^{\pm}$)	Tracker	$60\%\ E_j$	$10^{-4}E^2{}_X$
photons (γ)	ECAL	$30\%\ E_j$	$0.15\sqrt{E_\gamma}$
neutral hadrons (h)	ECAL+HCAL	$10\%\ E_j$	$0.55\sqrt{E_h}$

- Particle-Flow
  - To achieve unprecedented jet energy resolution of $\sim 30\%/\sqrt{\mathrm{E_{jet}}}$
  - **Choose a sub-detector best suited for each particle type**
  - Charged particles measured in tracker
  - **Photons** in ECAL and **neutral hadrons** in HCAL
- Separation of close-by particles in the calorimeters
  - **Matching** of charged tracks and clusters; **merging** neutral clusters
- PFA-oriented calorimeters: **high granularity** (1-10 million channels)

Multiple particles in a jet





https://doi.org/10.1016/j.nima.2009.09.009

Beam Induced Background

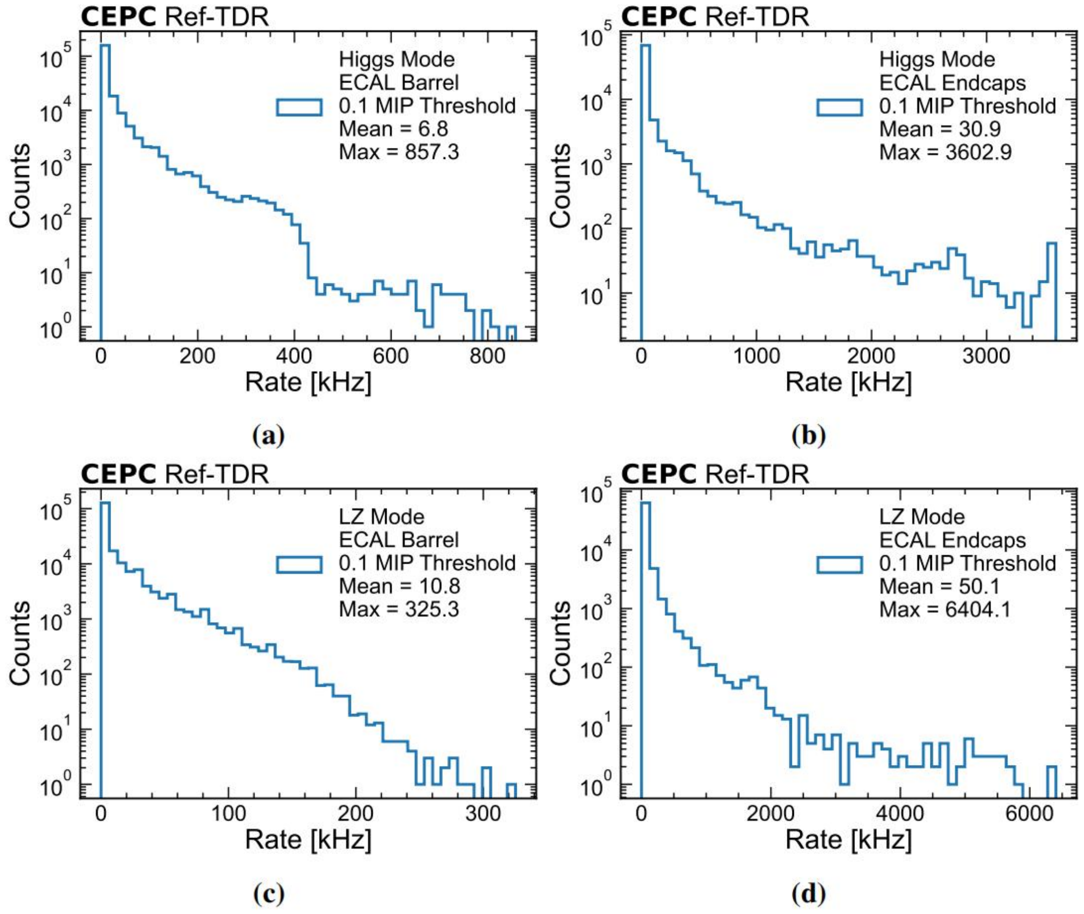


Figure 7.35: BIB hit rate distributions of crystals in the barrel (a) and endcaps (b) in the Higgs mode, and in the barrel (c) and endcaps (d) in the Low-Luminosity Z mode.

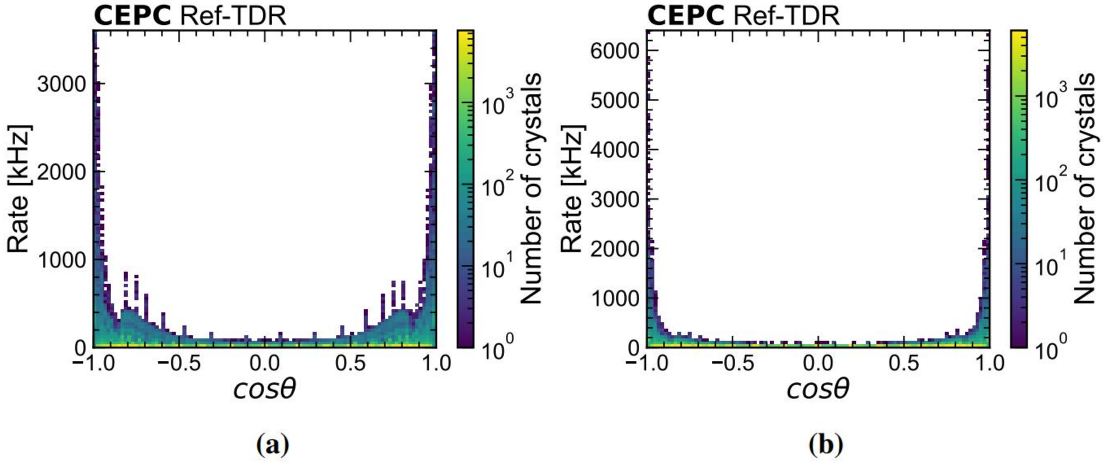


Figure 7.36: BIB hit rate distributions in the Higgs mode (a) and the Low-Luminosity Z mode (b) along with $\cos\theta$, where θ denotes the polar angle. The color scale represents the number of crystals associated with a specific BIB rate at a given polar angle.

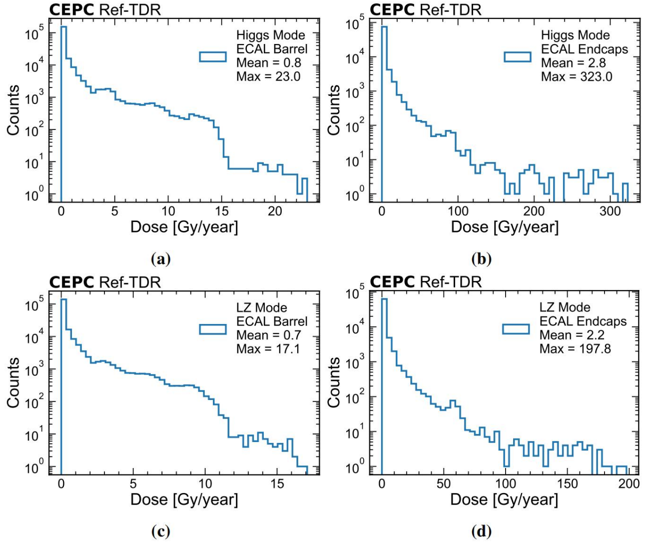
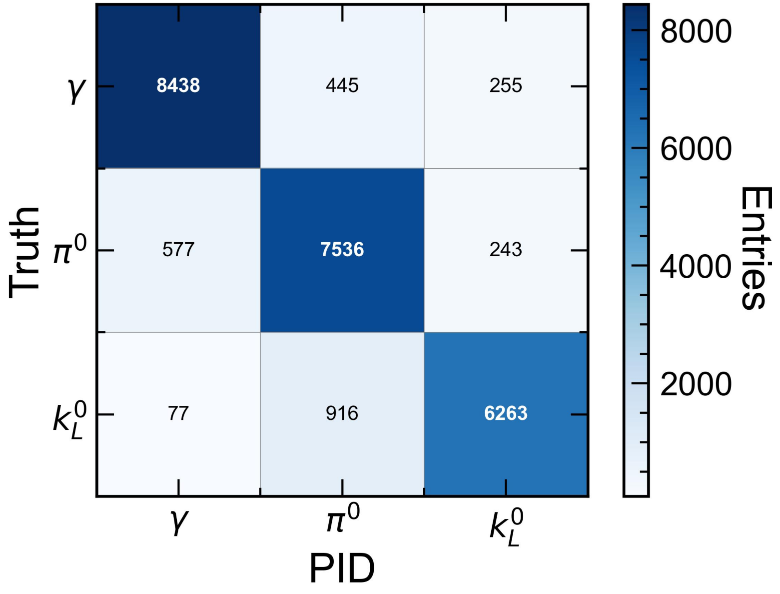


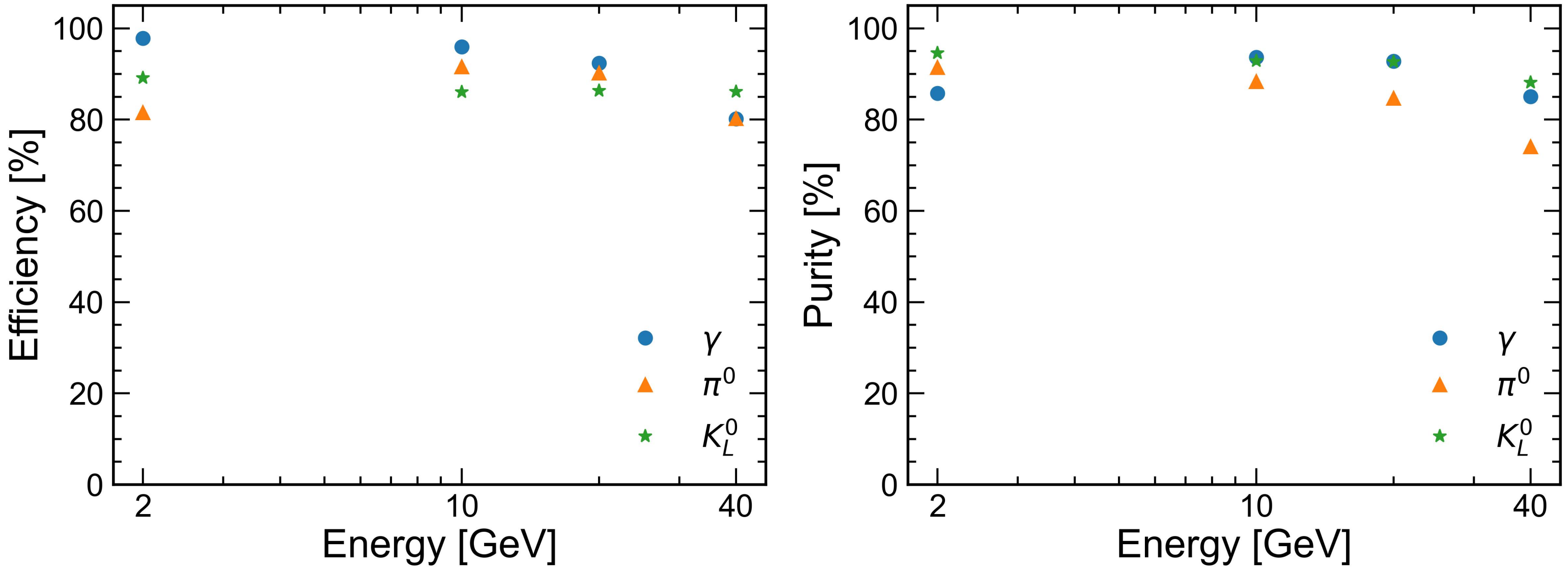
Figure 7.37: TID distributions of crystals in the ECAL: in the barrel (a) and endcaps (b) in the Higgs mode, and in the barrel (c) and endcaps (d) in the Low-Luminosity Z mode.

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

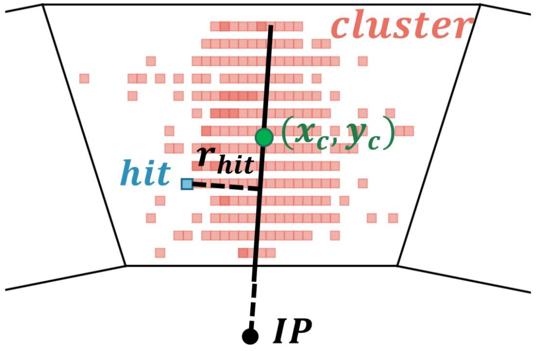


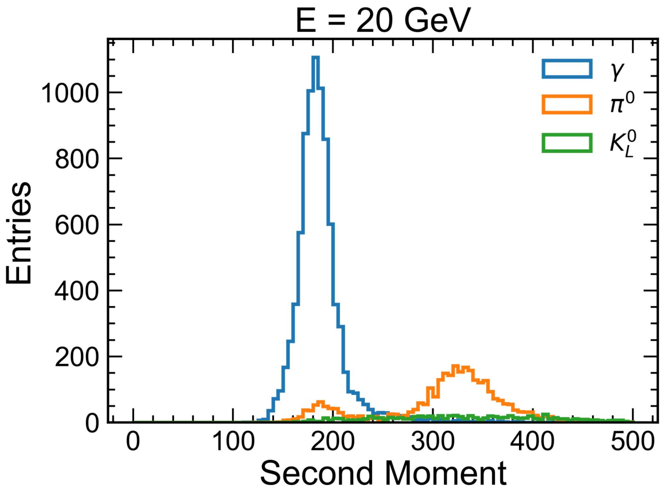
Identification efficiency & purity vs true energy

Second moment & Energy ratio

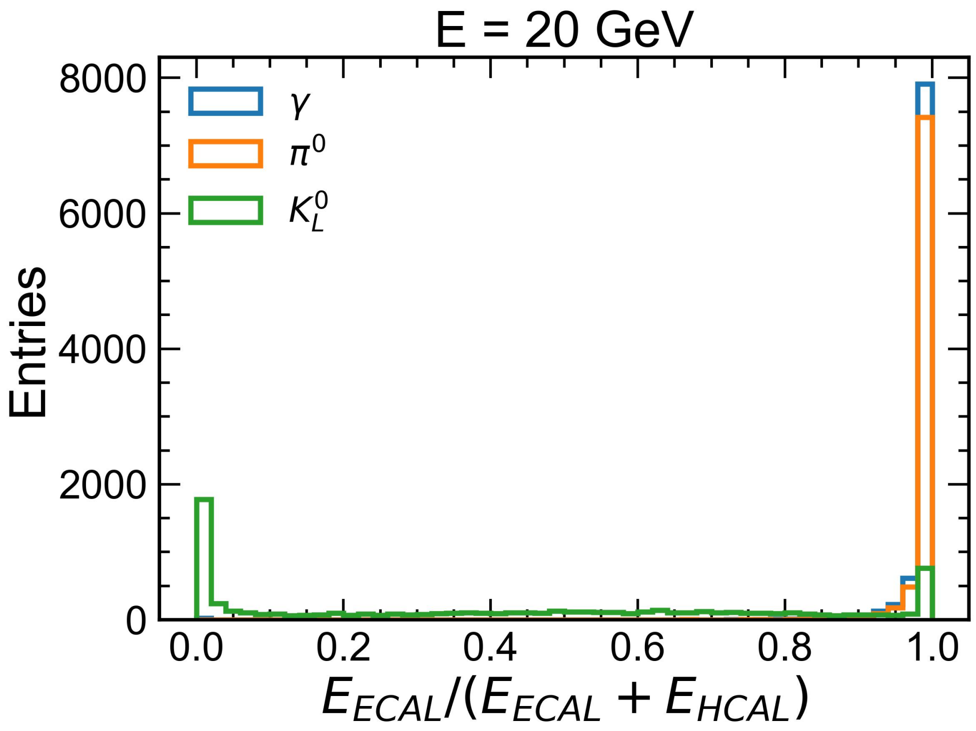
Second moment: $S = \frac{\sum(E_{hit} r_{hit}^2)}{\sum E_{hit}}$

Quantifies the lateral spread of a cluster

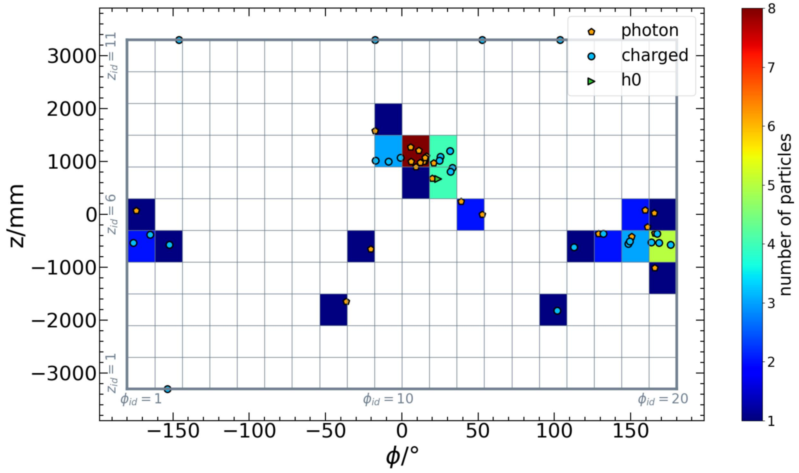




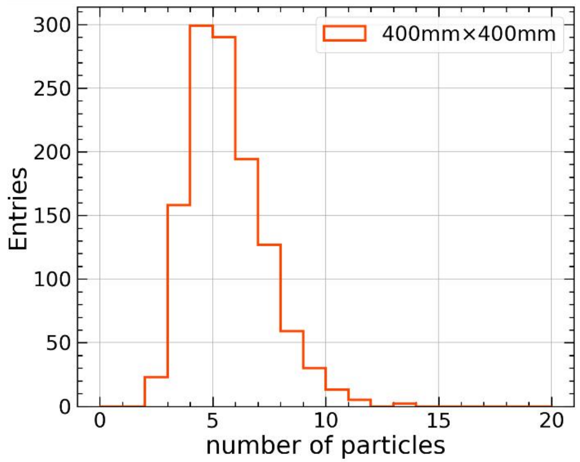
Energy ratio in ECAL & HCAL: $R = \frac{E_{ECAL}}{E_{ECAL}+E_{HCAL}}$



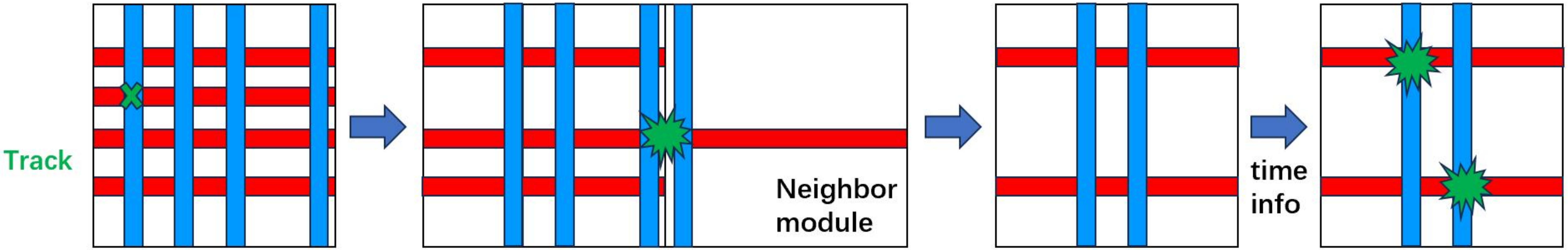
Ghost hit removal



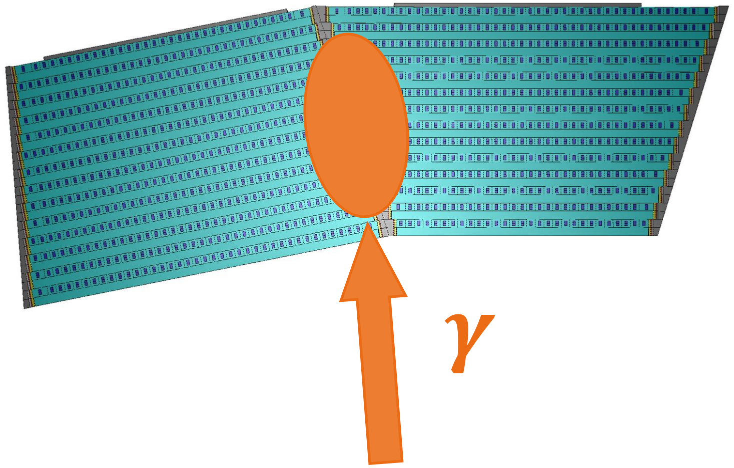
ECAL hit map of a jet event

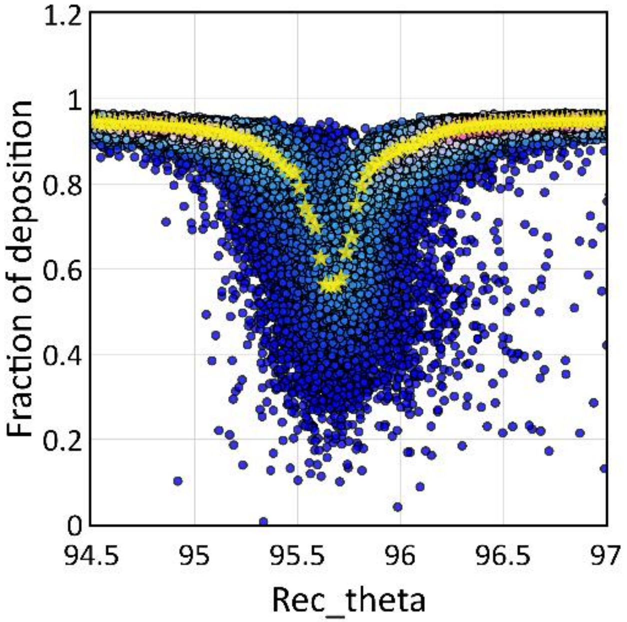


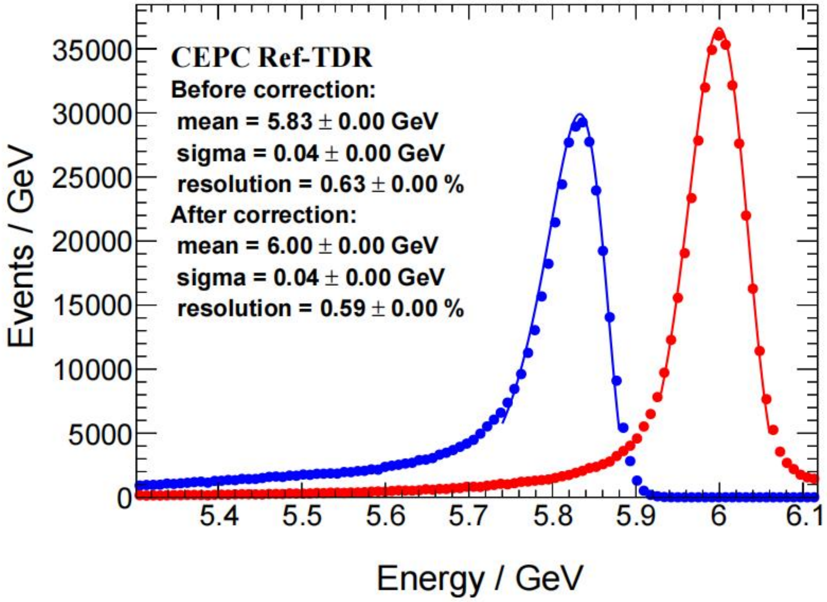
~5 particles in one module in a jet

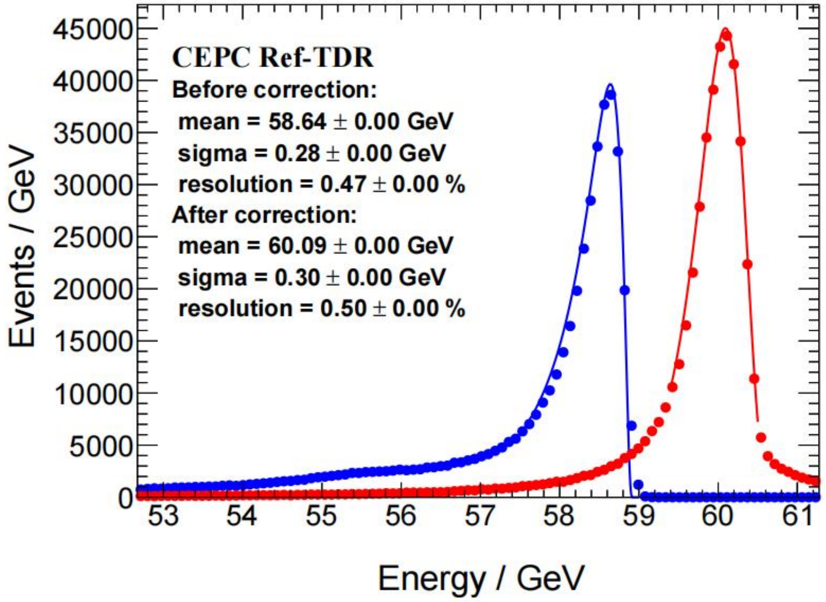


Energy correction

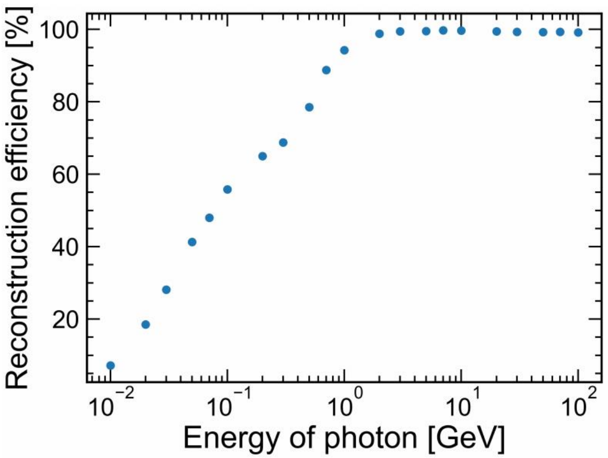


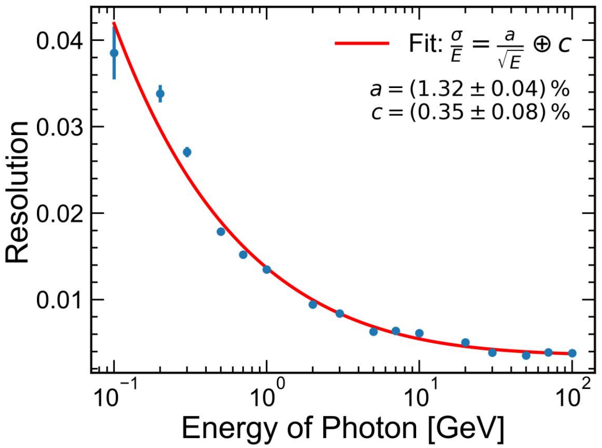


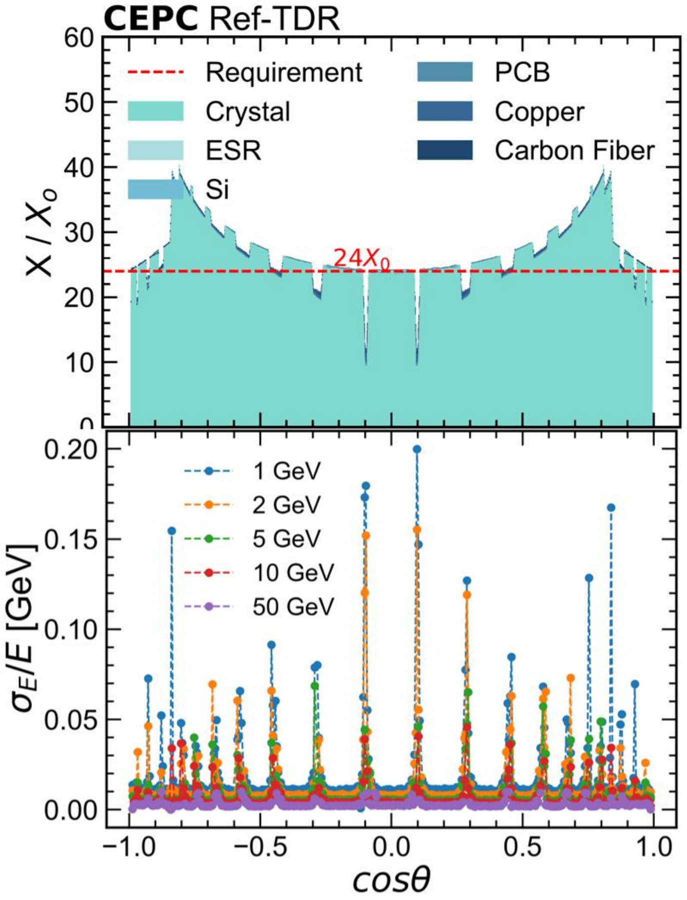


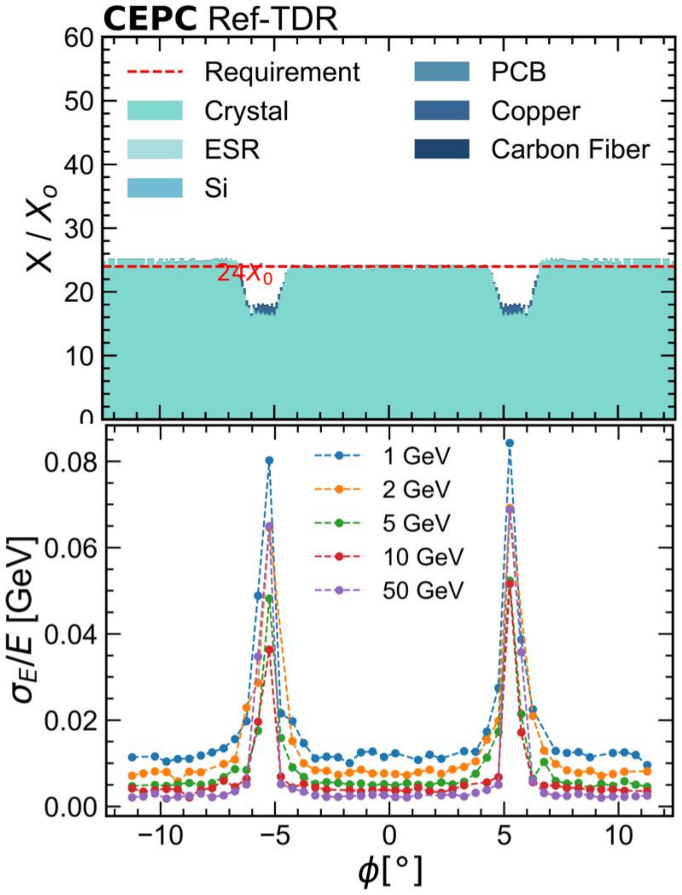


Photon reconstruction performance

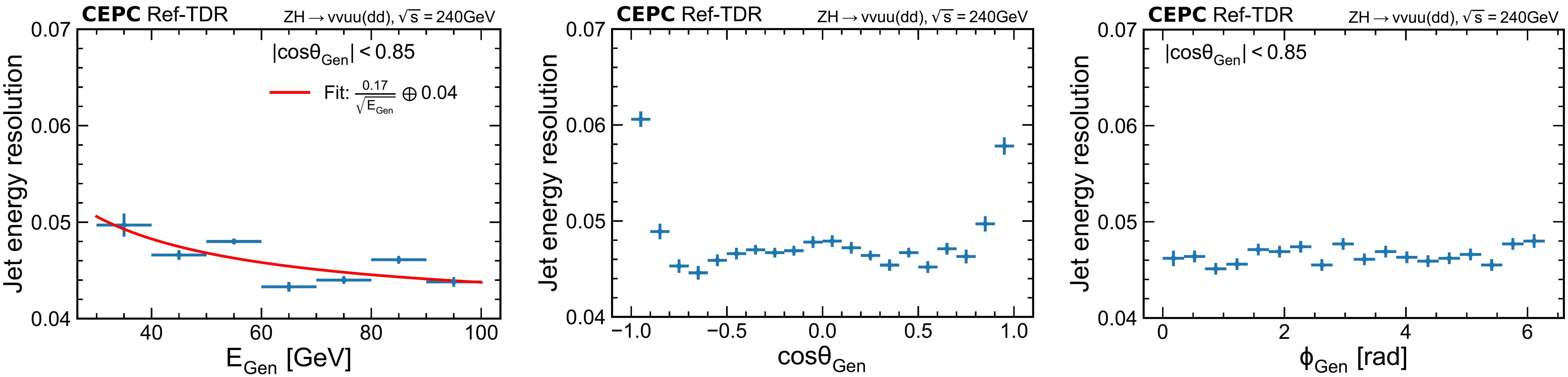








JER


CEPC Ref-TDR
ZH → vvuu(dd), √s = 240GeV
|cosθGen| < 0.85
Fit: 0.17/√EGen ⊕ 0.04
Jet energy resolution
EGen [GeV]
cosθGen
ϕGen [rad]