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

TIPP2023
TECHNOLOGY AND INSTRUMENTATION & PARTICLE PHYSICS CONFERENCE
4 - 8 SEPTEMBER 2023

Cape Town International Convention Centre (CTICC)

Development of a novel high granularity crystal electromagnetic calorimeter

Baohua Qi
On behalf of CEPC Calorimeter Working Group

TIPP2023
CTICC Cape Town South Africa
September 4 – 8, 2023

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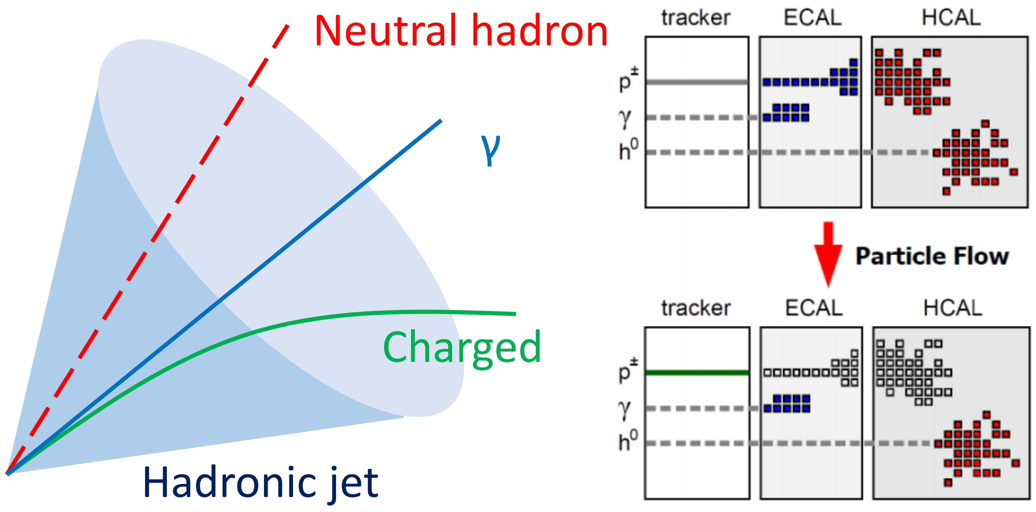
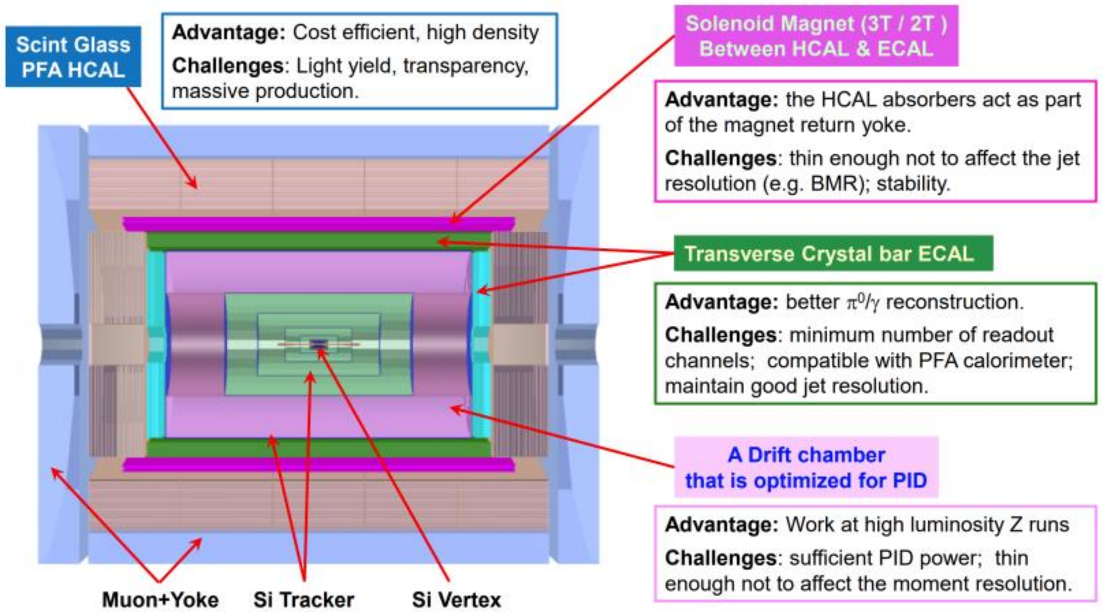
Motivations: new detector for CEPC

- CEPC: future lepton collider
  - Higgs/Z/W bosons, BSM searches, etc.
  - Precision jet measurement
  - Particle-Flow Algorithm (PFA)
    - Different final state particles -> different detectors
    - High-granularity calorimeter: separation of showers



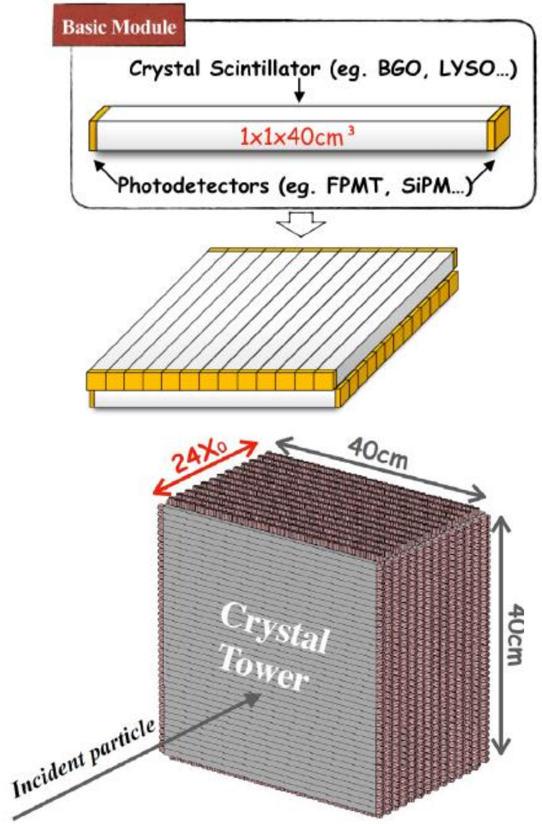
- New "CEPC 4th concept" detector design
  - High-granularity crystal ECAL ★
    - 5D detector: spatial + energy + time
    - Intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Scintillating glass HCAL
    - High density for better boson mass resolution

TIPP2023 talks:
Glass Scintillator HCAL at future e+e– Higgs factory
Development of highly granular hadronic calorimetry with glass scintillator tiles



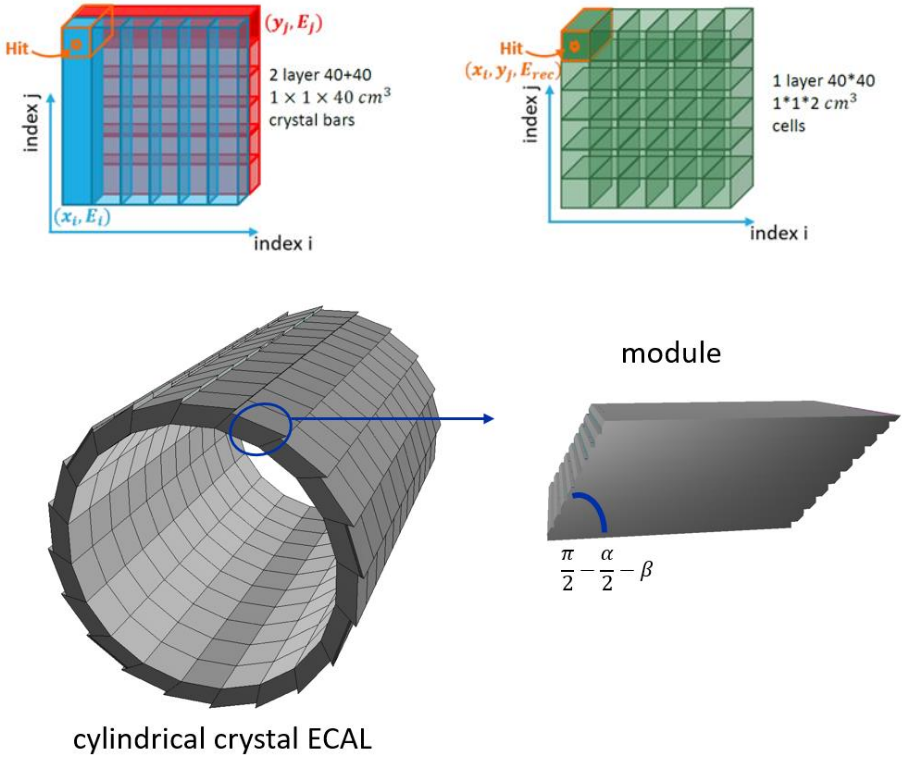
Crystal ECAL R&D: overview

➢ Design concept



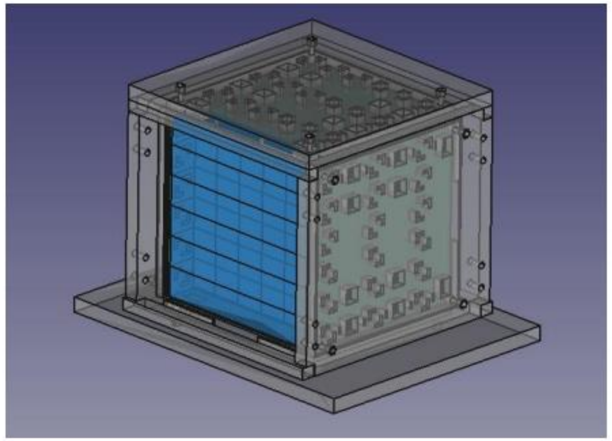
- Crystals arranged to be orthogonal between layers
- Readout from two sides

➢ Optimization and validation



- Dedicated new reconstruction software
- Performance evaluation and optimization

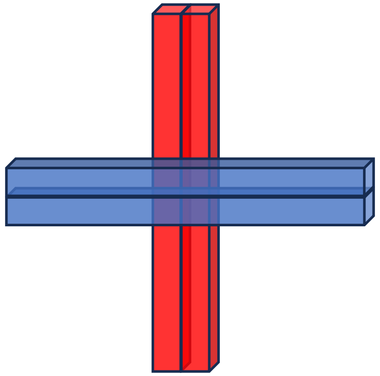
➢ Hardware development

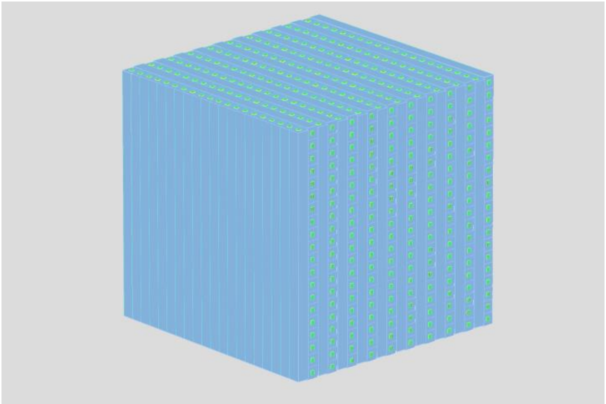


- Development of crystal module(s) for beam tests

Design concept of high-granularity crystal ECAL

- General design concept

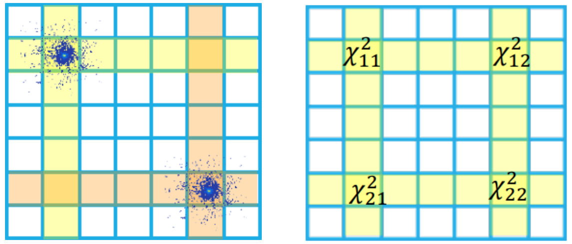




- ➢ Long crystal bar with 2 SiPMs
- ➢ Crisscrossed arrangement between layers
- ➢ Supercell of the crystal ECAL

- Key points
  - Long crystal bars instead of small crystal cubes
    - Save #channels and minimize dead materials
    - Achieve high-granularity with information from adjacent layers
  - Double-sided readout
    - Positioning potentials with timing at two sides

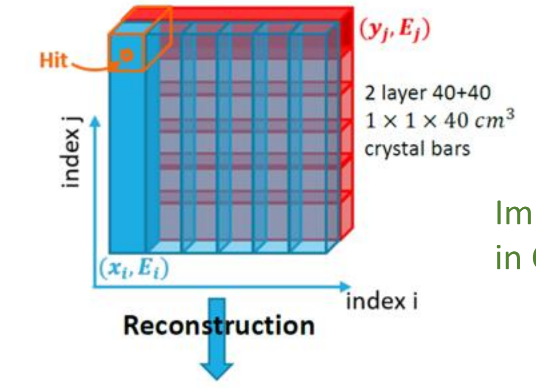
- Challenges
  - Difficulties in the mechanical/geometry design
  - Impact from ghost hits



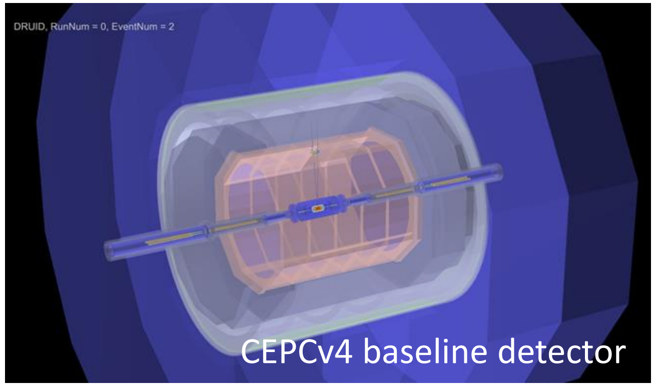
➢ Ghost hits case when 2 or more particles hit on one supercell

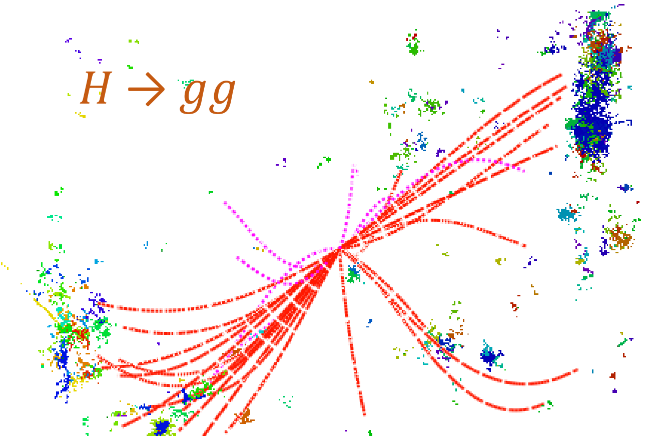
Workflow of preliminary performance evaluation

- Geometry adapted from the CEPC baseline detector (SiW ECAL)
- Application and optimization of “Arbor-PFA” under CEPC Software

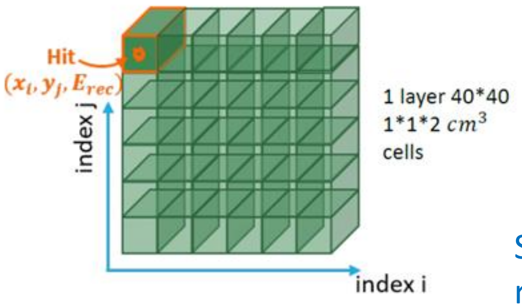


Implementation in CEPC detector

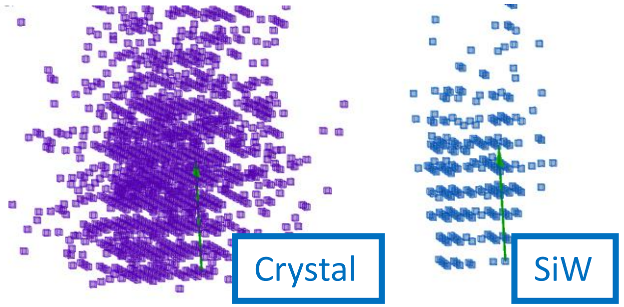




Performance studies with Higgs events



Simulation and reconstruction



Arbor-PFA: necessary to be optimized for crystal ECAL design

Crossed long bar design:
$1 \times 1 \times 2\ cm^3$ granularity
after reconstruction

Crystal compared to SiW:
significant increase of #hit

Dedicated reconstruction software is also under development

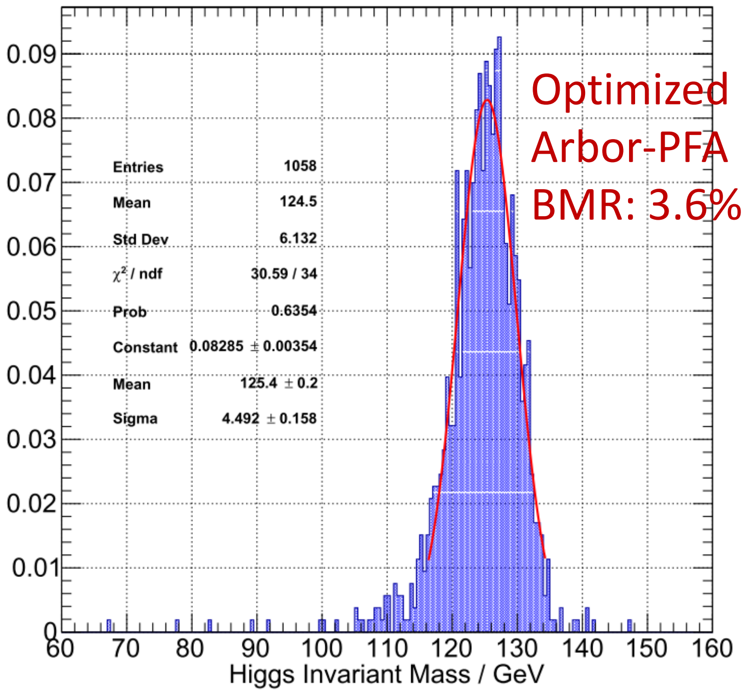
PFA performance: Higgs benchmark

CEPC Software v0.1.1

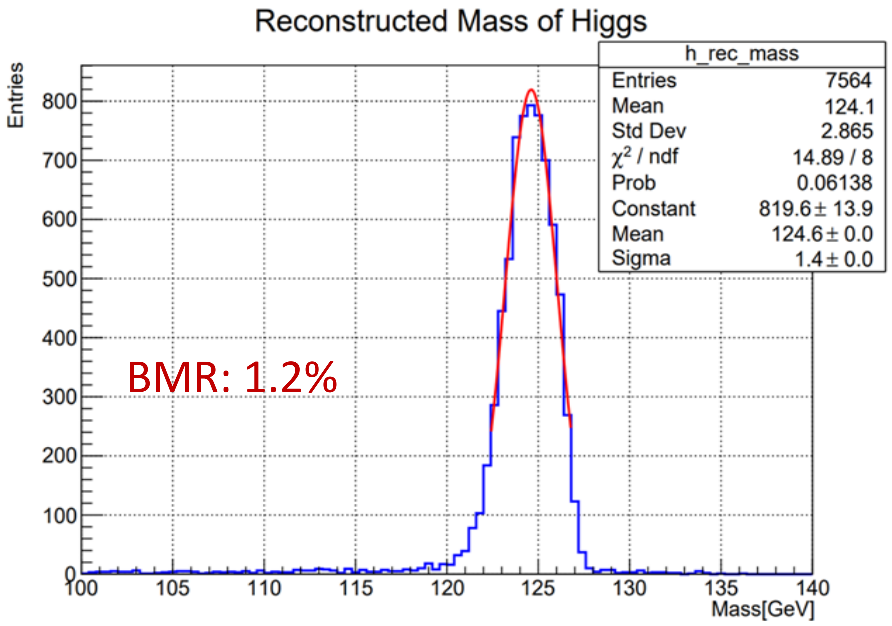
Baohua Qi (IHEP), Zhiyu Zhao (TDLI/SJTU)

- Physics performance: Boson mass resolution (BMR)
- Studied with 1 cm^3 crystal cubes

BMR ($H \to gg$)



BMR ($H \to \gamma\gamma$)

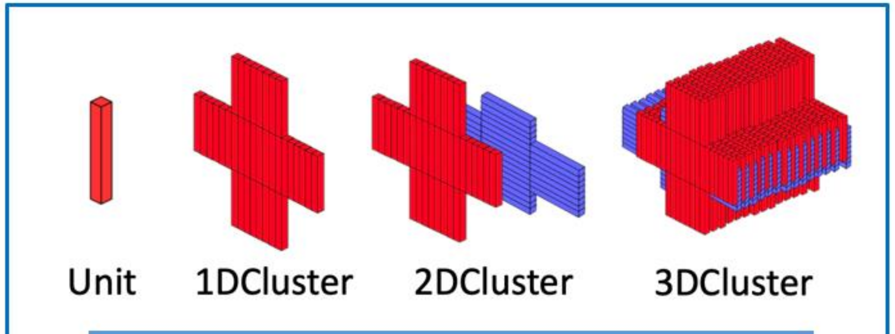


- Good performance with Arbor-PFA algorithm

Reconstruction algorithm dedicated to long crystal bar ECAL

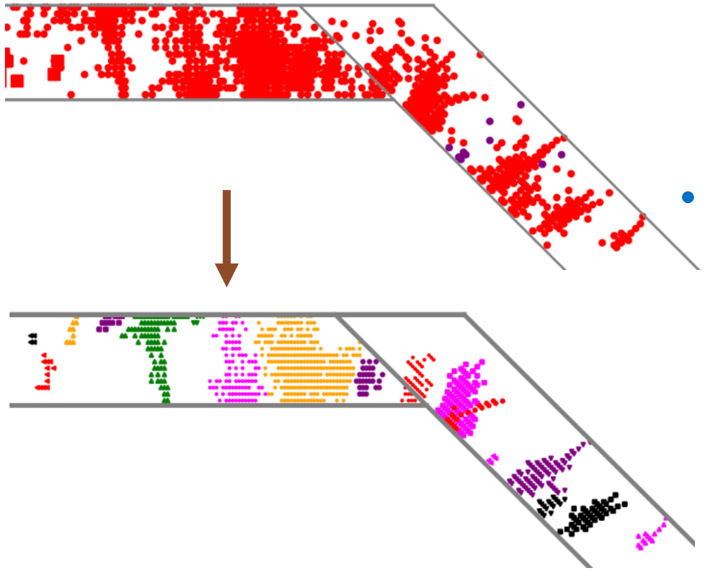
- Particle reconstruction for long bar crystal ECAL

Weizheng Song, Yang Zhang (IHEP)

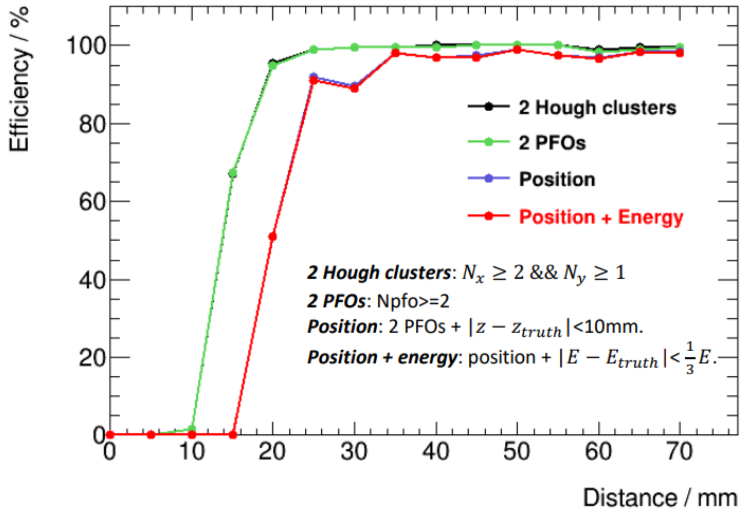


Clustering from crystal bars to 3D cluster

Cluster inputs → shower identification →
- Photon: Hough transformation
- Charged (MIP-like): track matching
- Neutral hadron: cone clustering



- Clustering algorithm test with $H \to gg$ events



- Performance study: di-photon recognition efficiency

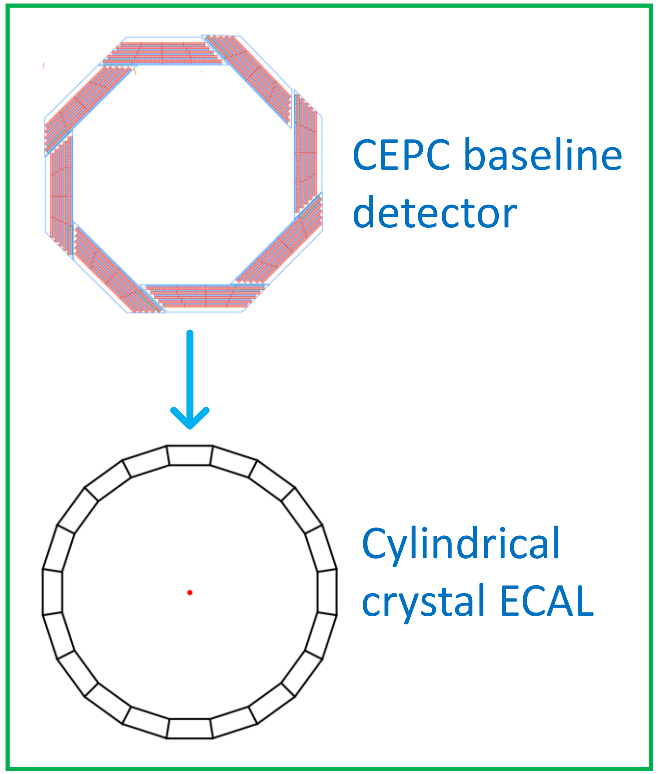
Talk by Yang Zhang, 2022 CEPC Workshop

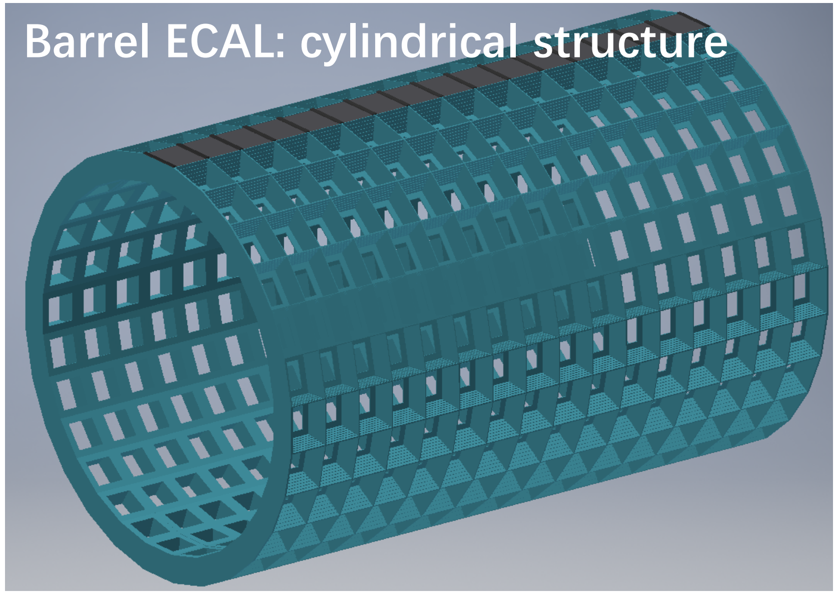
- Reconstruction flow has already been built
- Key issues: sophisticated software

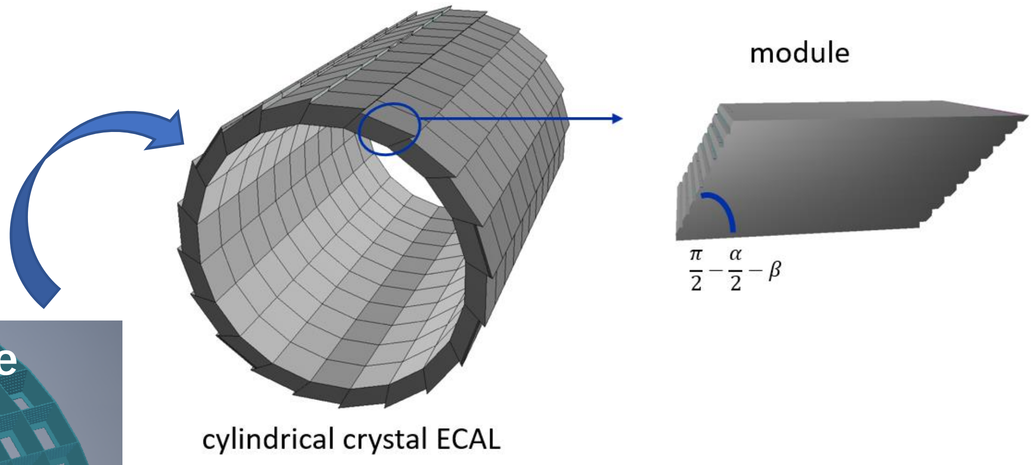
Detector optimization: barrel ECAL geometry

Quan Ji, Chang Shu (IHEP)

- CEPC crystal ECAL barrel geometry design
  - Finer segmentation of towers
  - Decrease outer radius for lower cost of the outer detectors
  - 28 towers per ring, 17 rings along beam direction
  - ~25 radiation length: 28 layers





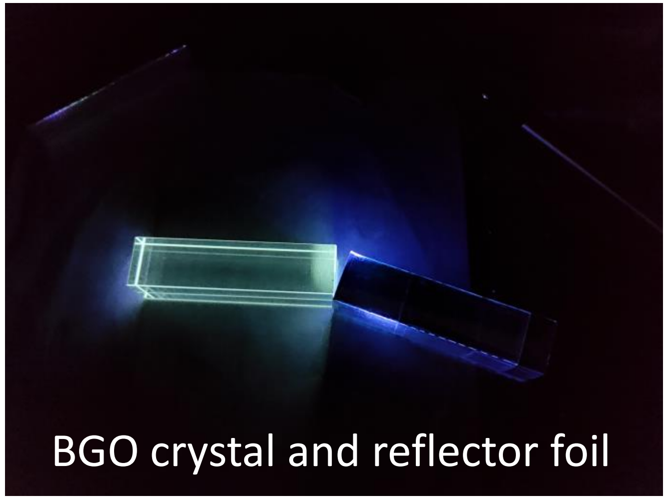


- First optimization: implement an extra angle to avoid energy leakage

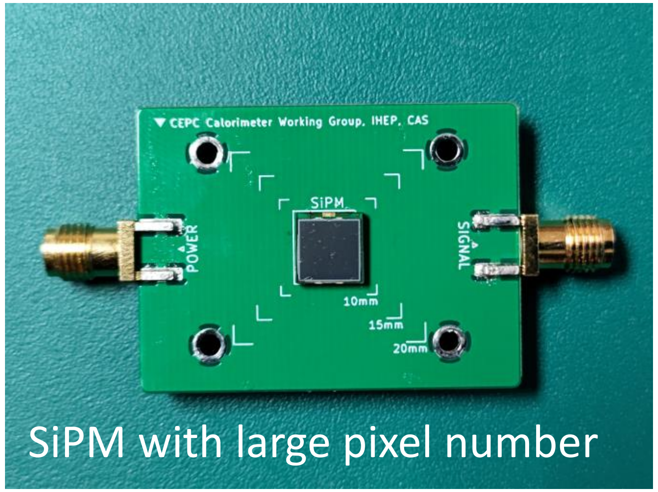
Key questions
- Space for electronics and cooling
- Assembly method

Hardware design of high-granularity crystal ECAL

- Requirements of hardware development
  - Crystal candidates: e.g. BGO (~8000 p.e./MeV, 300ns decay time)
  - SiPM candidates: large dynamic range, low cross-talk…
  - Electronics: large dynamic range, good time resolution…
- Key issues
  - Single photon resolution is incompatible with large dynamic range
    - Requirements: 0.1~10^3 MIPs dynamic range, ~200 detected p.e./MIP
  - Radiation hardness, temperature stability, mechanical tolerance…


BGO crystal and reflector foil

+



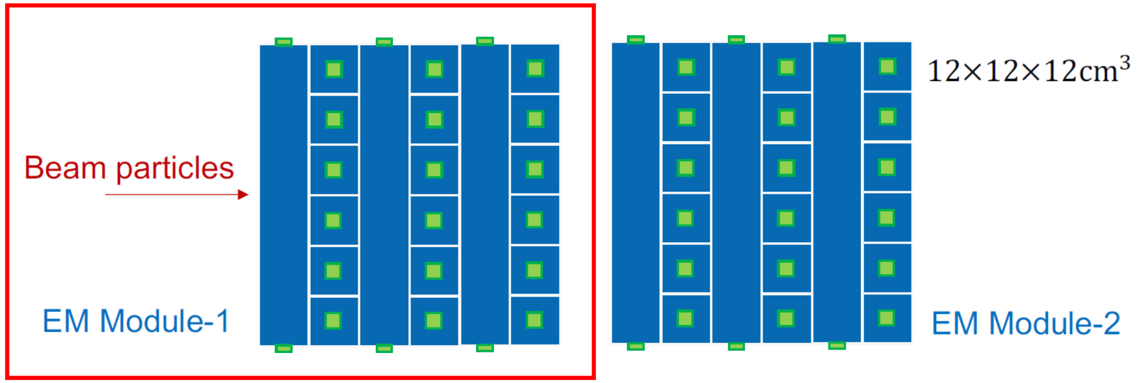
SiPM with large pixel number

+

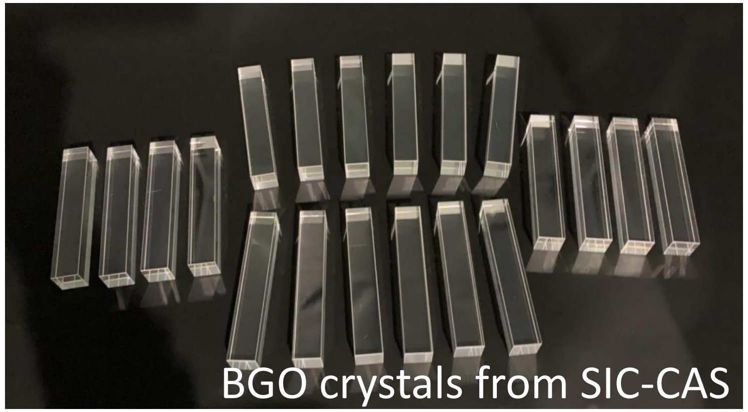

Readout electronics

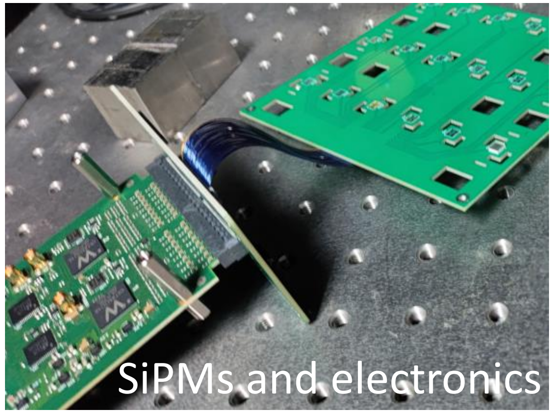
Introduction to the first small-scale crystal module

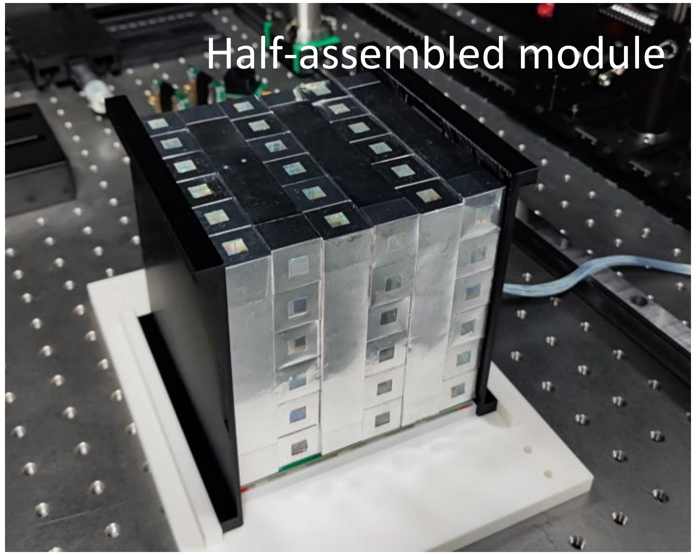
- First $12\times12\times12$ cm^3 BGO modules development
- Motivations
  - Identify critical questions/issues on system level
    - Mechanical design, PCB and electronics…
  - Evaluate performance with TB data
  - Validation of simulation and digitization
- Beam test at CERN T9 beamline
  - Muon, electron and pion data
  - Future plan: 2 modules serial arrangement



Beam test for the first module: 72 channels, double-sided readout


BGO crystals from SIC-CAS


SiPMs and electronics

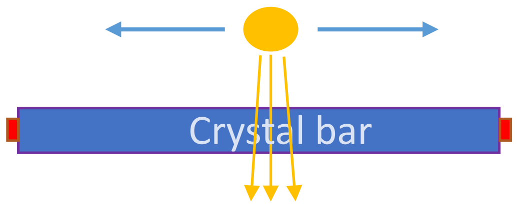

Half-assembled module

- 36 crystals wrapped with ESR and Al foil
- 3D printed support structure

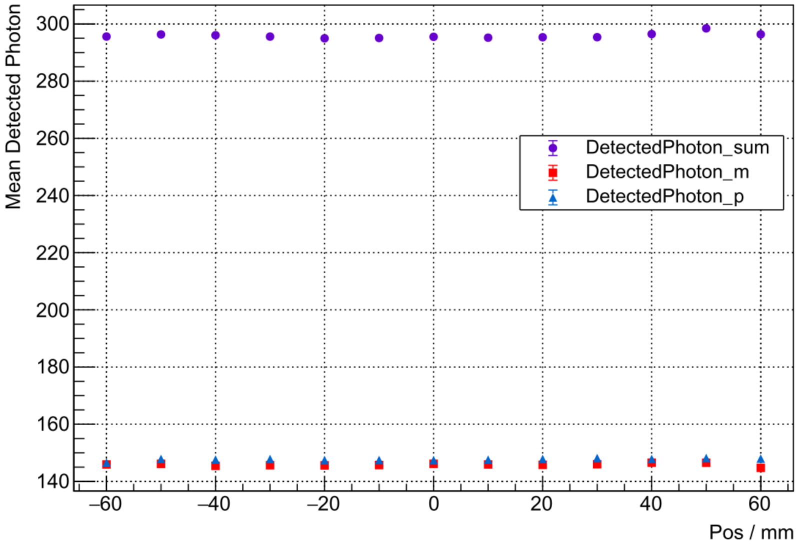
Uniformity scan of BGO crystal bars

Zhikai Chen (USC)

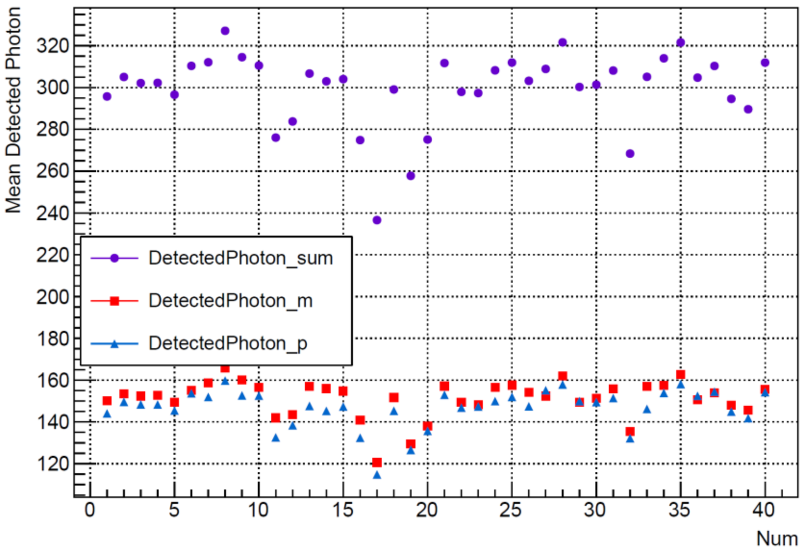
- Batch test of SIC-CAS BGO crystal bars
  - 40 crystals with ESR and Al foil wrapping
  - Scan with Cs-137 radioactive source

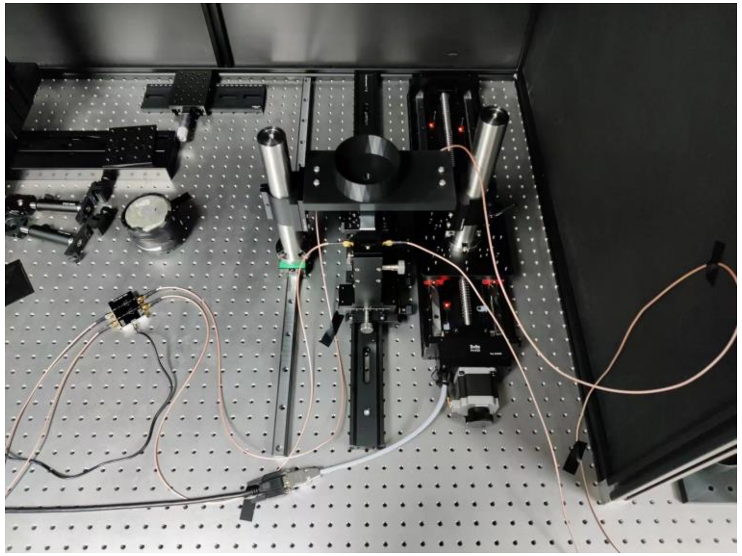


Response uniformity along bar



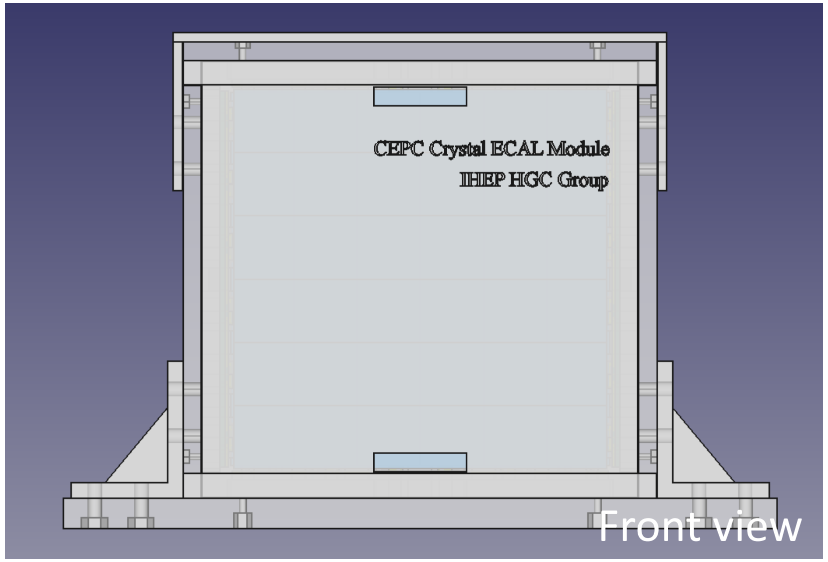
Comparison of 40 crystal bars

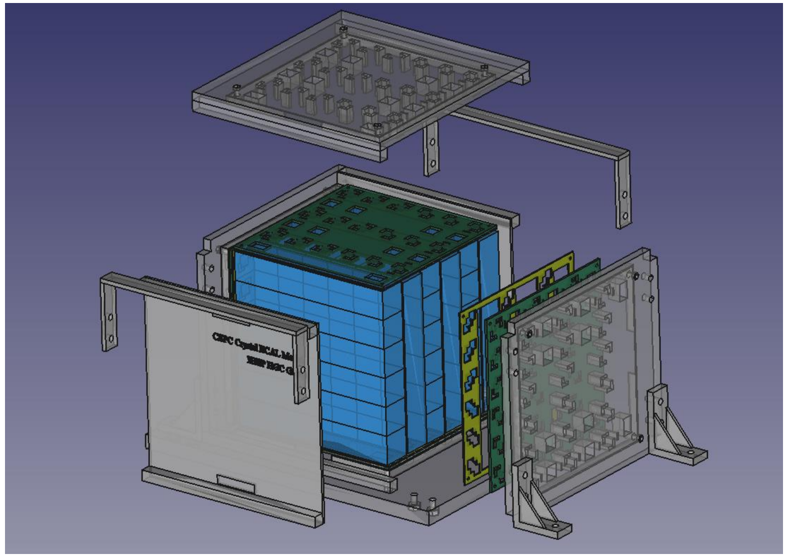


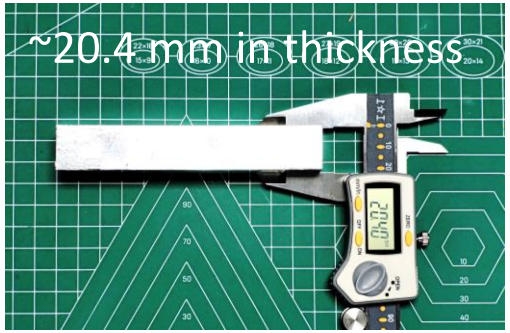


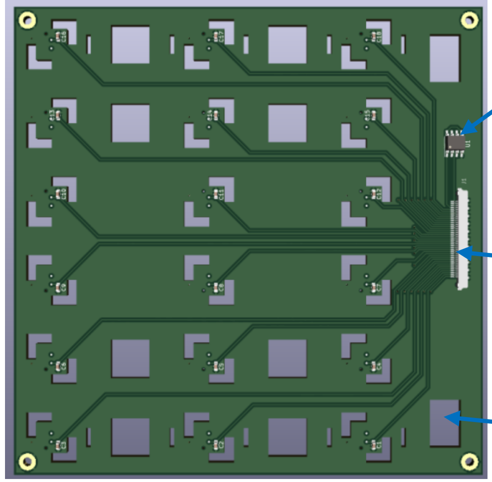
- Generally good uniformity along a single bar
- Response varies among bars, 36 crystals were selected for beam tests

Mechanical and PCB design





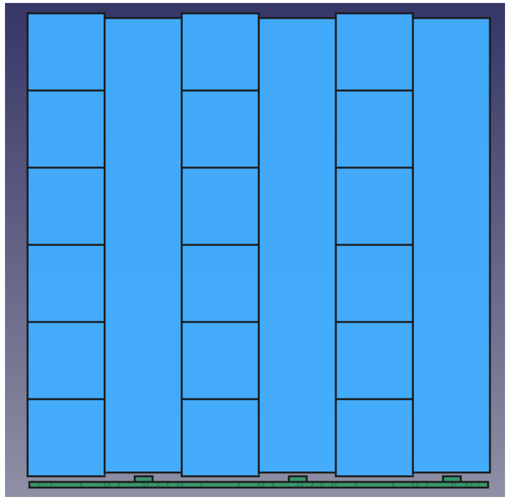




Temperature sensor

Micro-coaxial connector

Holes for crystal support

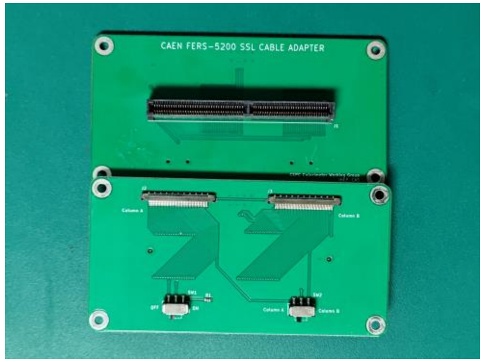


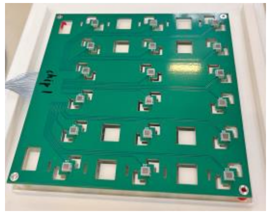
- Difficulties with module development
  - Mechanical design is unusual
  - PCB is non-load-bearing and should be decoupled
  - Module assembly

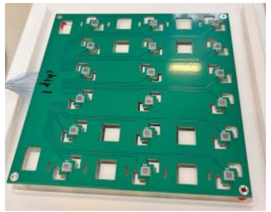
Electronics and trigger scheme

- Electronics: CAEN A5202 units with Citiroc-1A chips

36/64 channels used



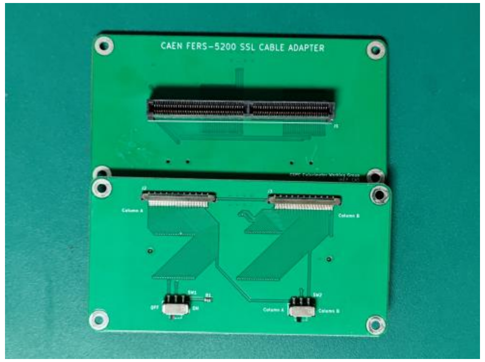


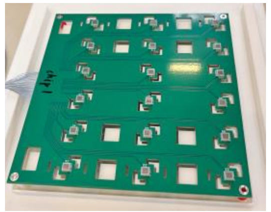


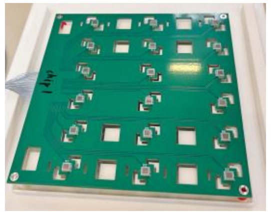
Micro-coaxial cables

Daisy chained trigger distribution

36/64 channels used







CAEN A5202 unit
Built-in HV power supply

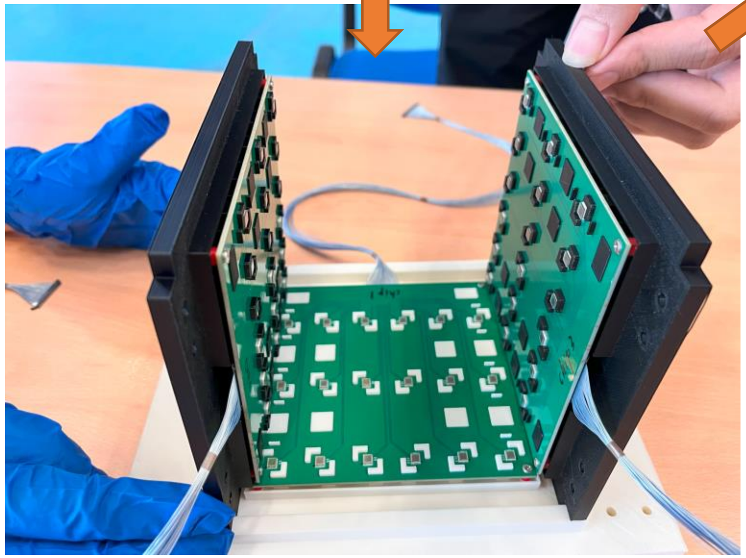
Self-designed adapter board

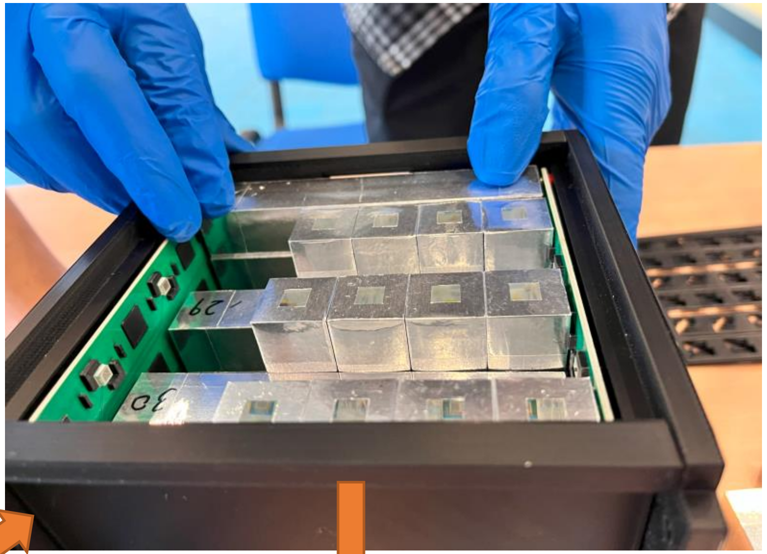
4 PCBs with 18 SiPM channels (HPK S14160-3010PS)

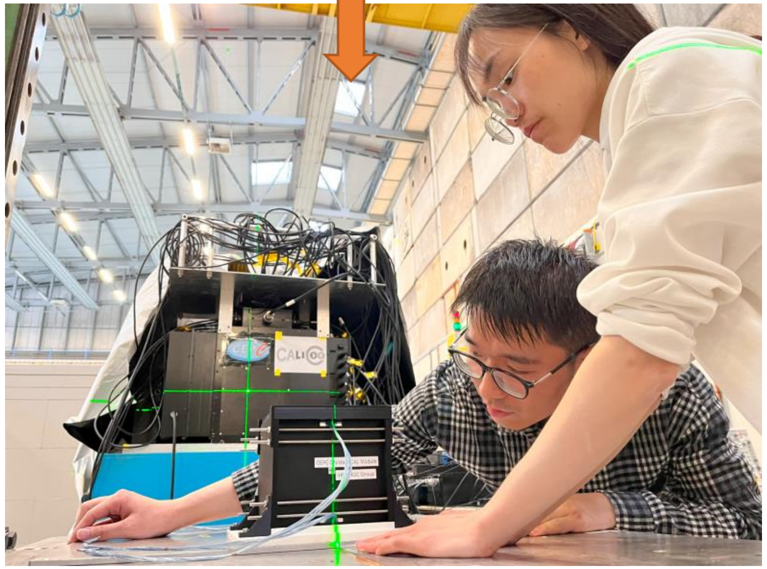
External triggers from plastic scintillators

Beam test: installation of module

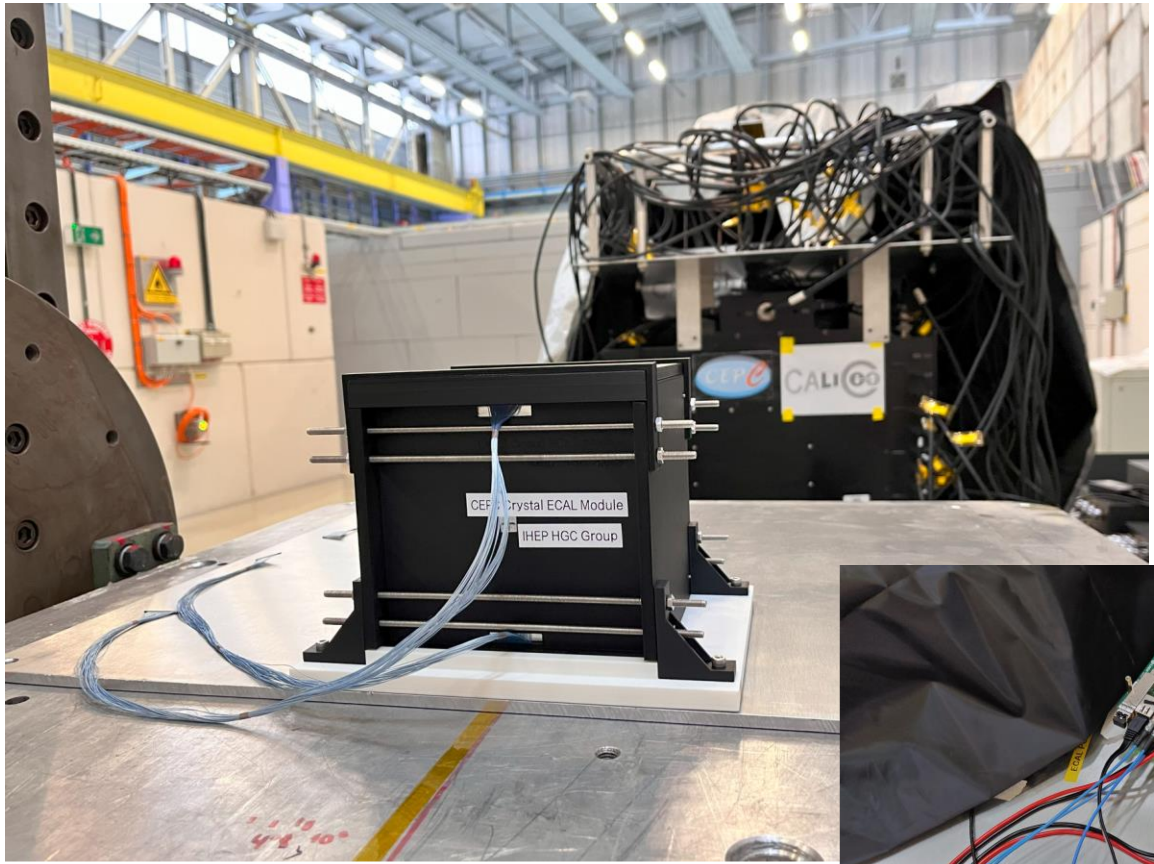
Box with crystals, glass tiles and accessories (75kg)

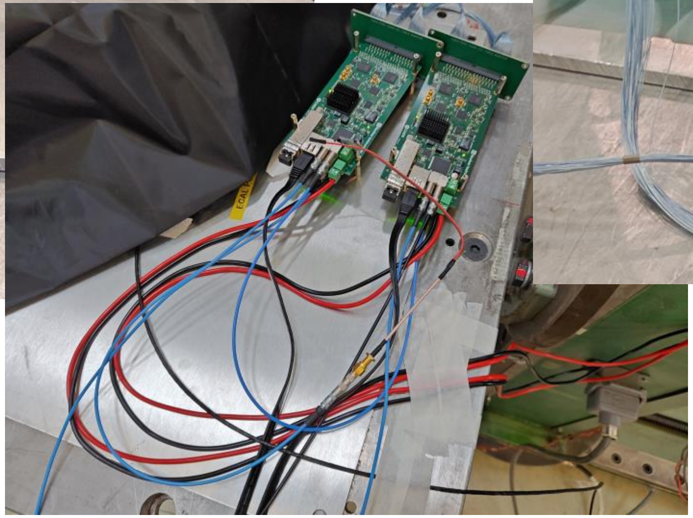


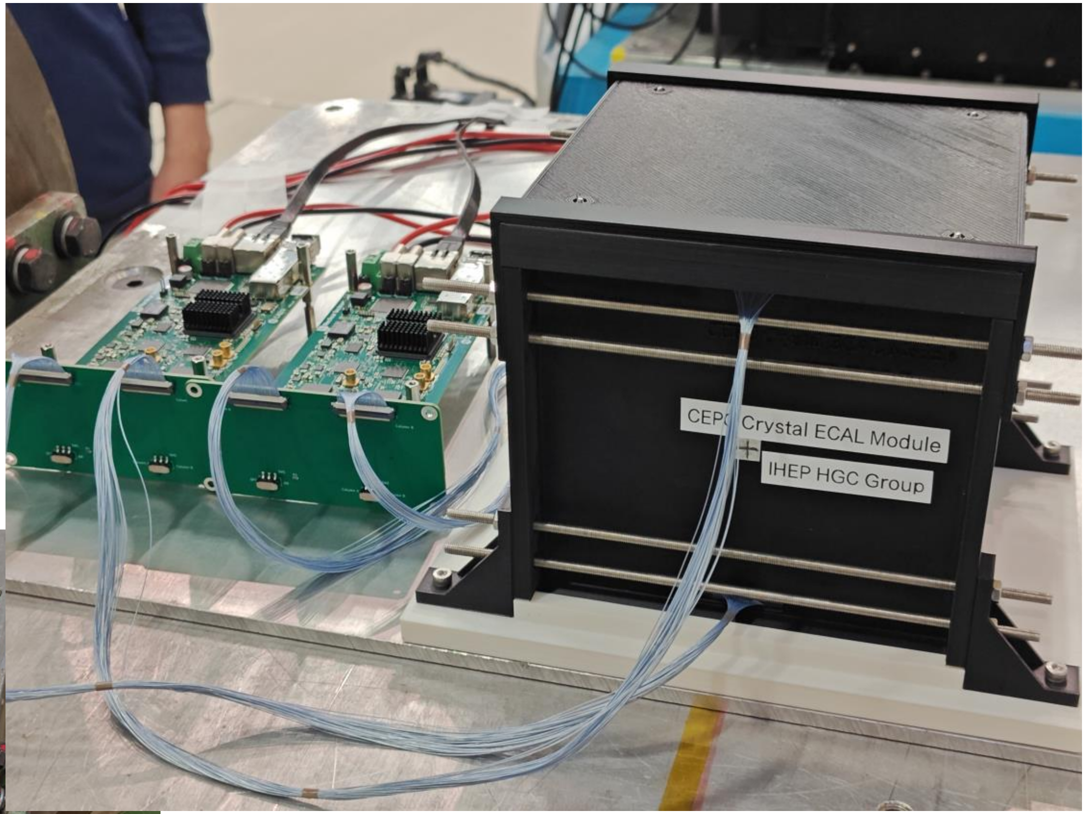




Beam test: installation of module



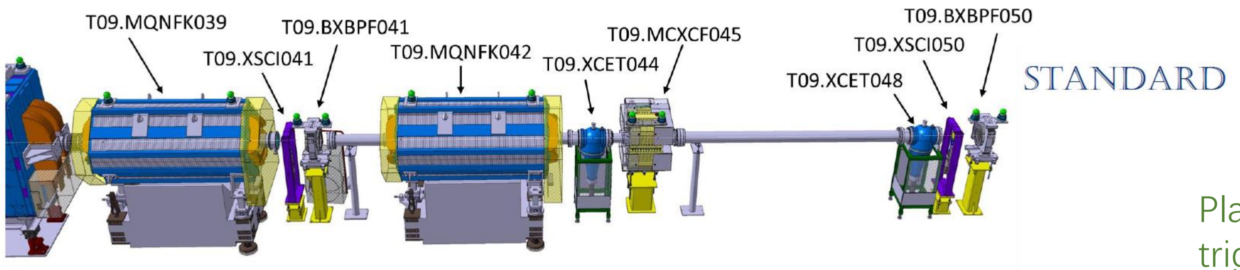


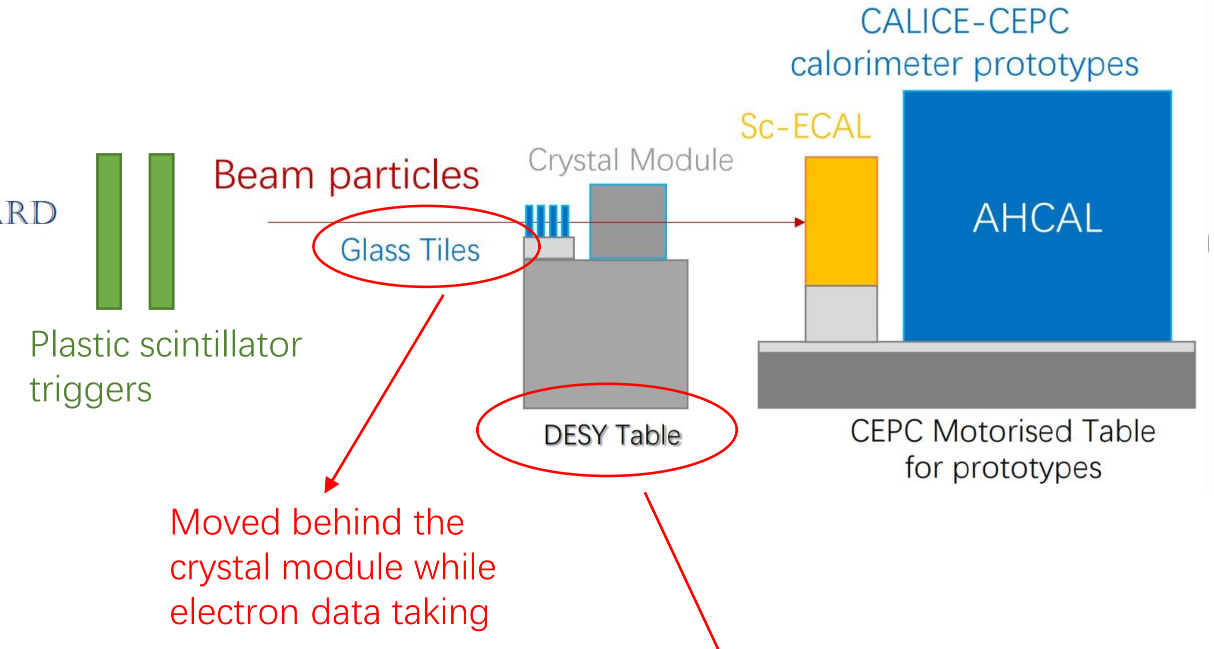


Parasitic runs with CEPC calorimeter prototypes

Beam test setup in CERN T9 beamline

- Setup of the beamline





- Parasitic runs with CEPC calorimeter prototypes
  - Muon data: taken along with glass tiles and CEPC calorimeter prototypes
  - Electron data: taken independently
- Self-trigger runs when the crystal module is moved out from the beamline

➢ **Move IN/OUT of beamline: coordination with testing of CEPC calorimeter prototypes**

Beam test data summary

- 10 GeV/c muon- beam: MIP response
  - High/low gain, Hold-Delay time, shaping time scans
  - ~5.5M events acquired

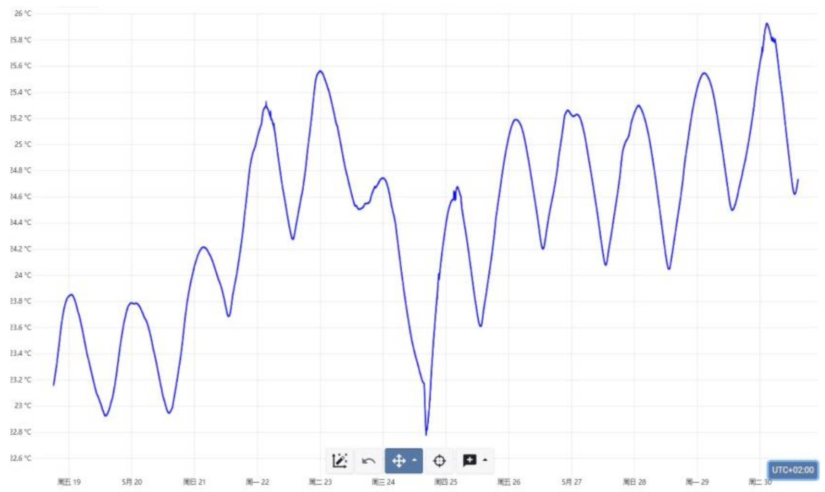
- Verification of the system
- Parameter scans

- 0.5~5 GeV/c electron beam: energy response
  - ~980k events acquired

- Severe energy leakage is expected
- Preliminary reference for energy resolution

- Other data
  - Pion- data for high fluence test
    - > 80% trigger loss at ~20k events per beam spill
  - Self-trigger of "leaked particles" from upstream
    - Muon events can be clearly observed
  - Temperature monitoring data

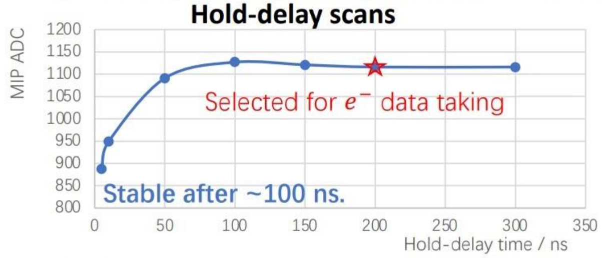
➢ ~2℃ temperature change during the beam test



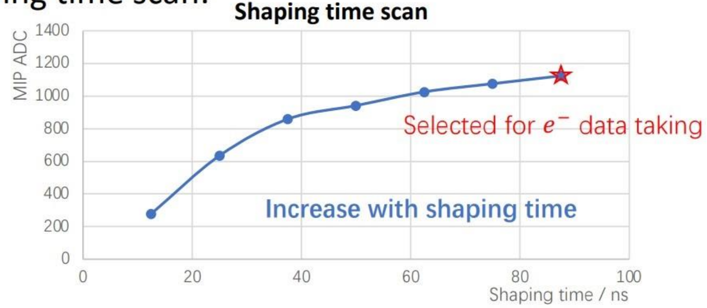
Muon data for parameter scans and calibration

- 10 GeV/c muon- beam: MIP response
  - High-gain and Low-gain scans
  - Hold-Delay / Shaping time scans
  - Channel-by-channel calibration

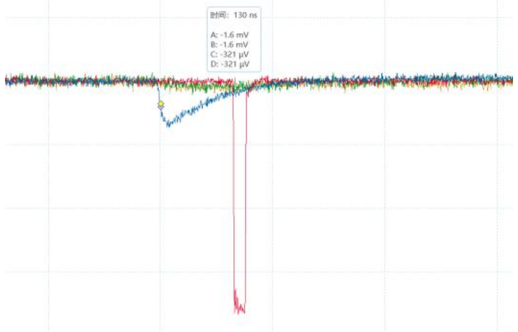
- Hold-delay time scan:
  - 10 GeV muon, HG 59, LG 63, scan from 5 ns to 300 ns.

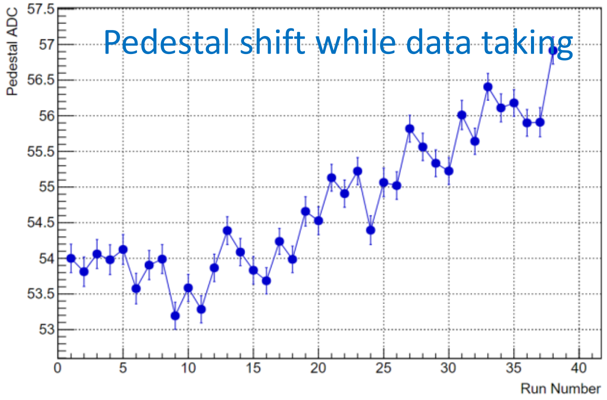


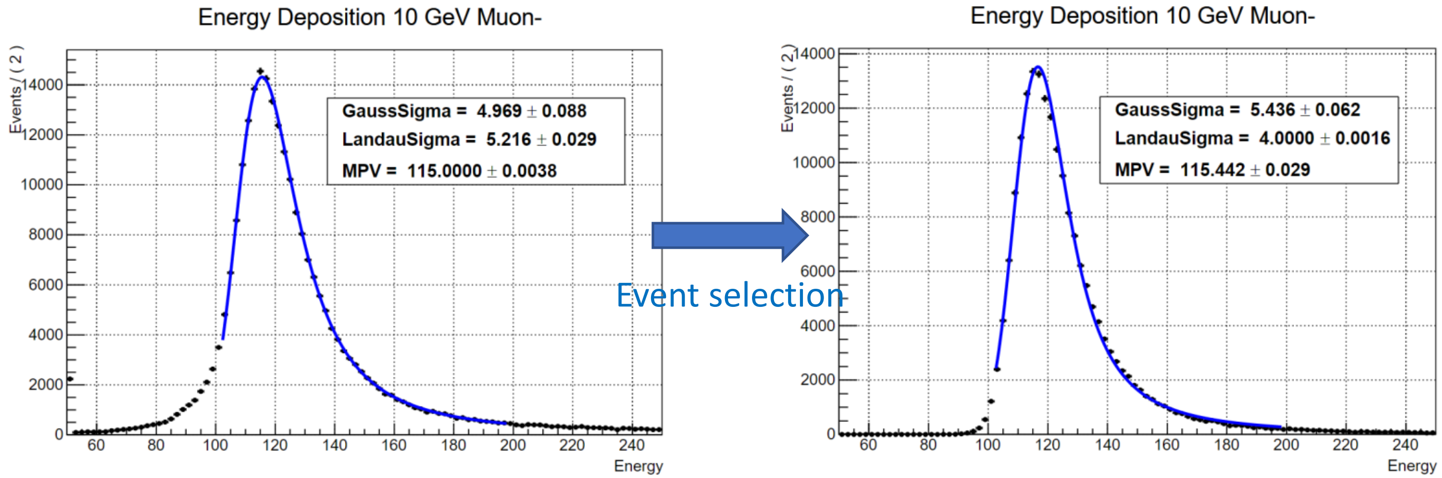
- Shaping time scan:



Delay of external trigger: ~130 ns



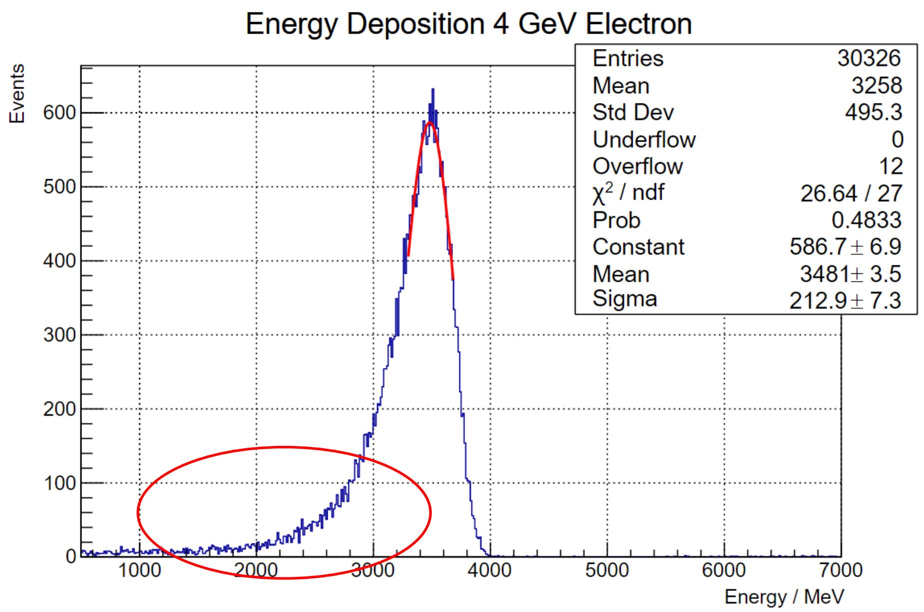


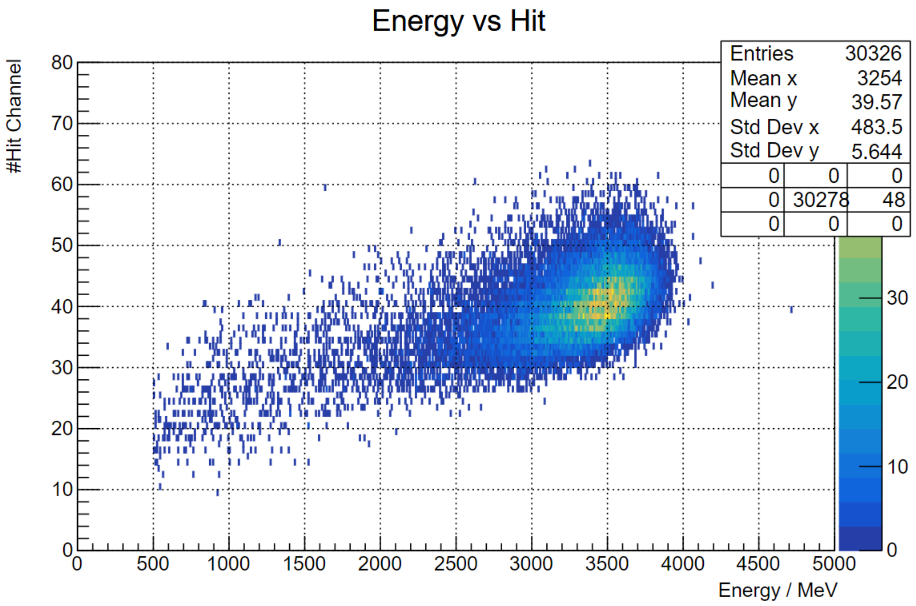


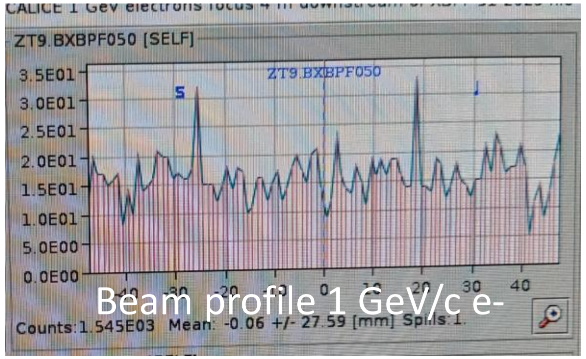
- Successfully acquired muon data with good quality
- Selected parameters for electron data taking
- Channel-by-channel calibration completed

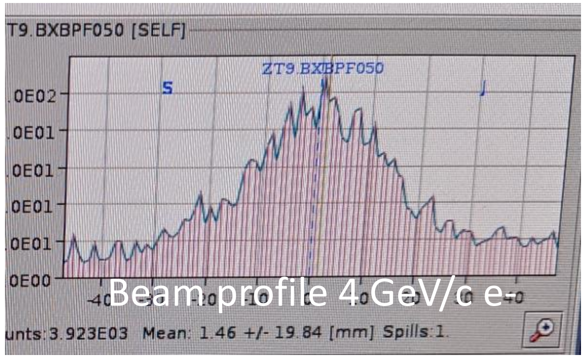
Electron data: energy response

- Data: calibrated channel-by-channel with muon events, 0.5MIP threshold
- Event selection: hitting at the center of the module







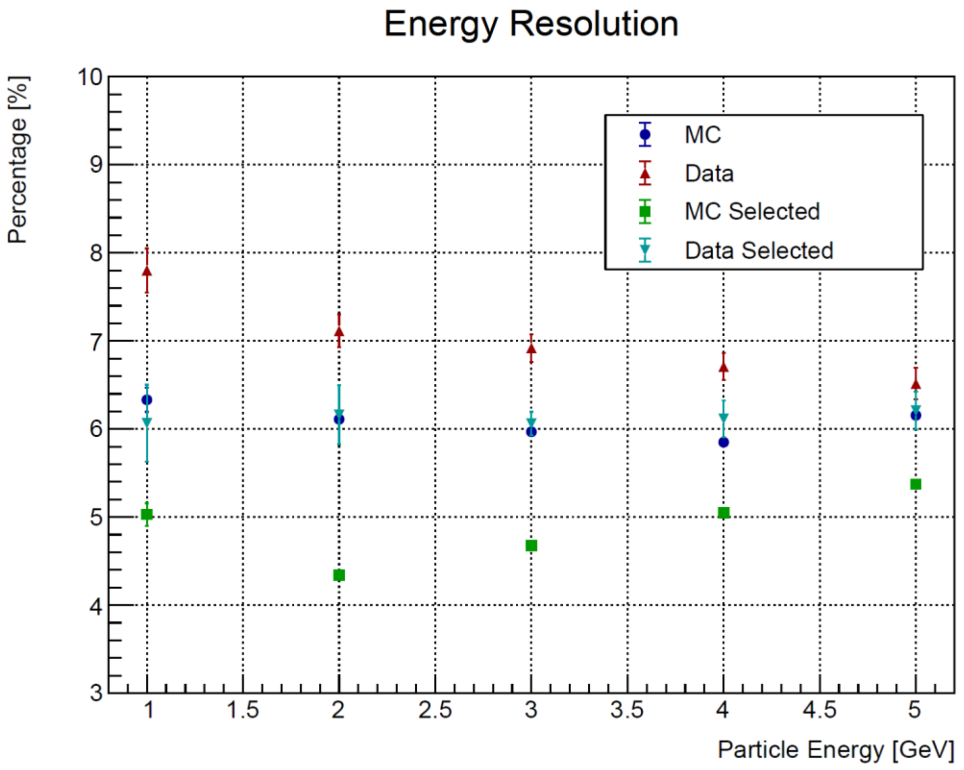


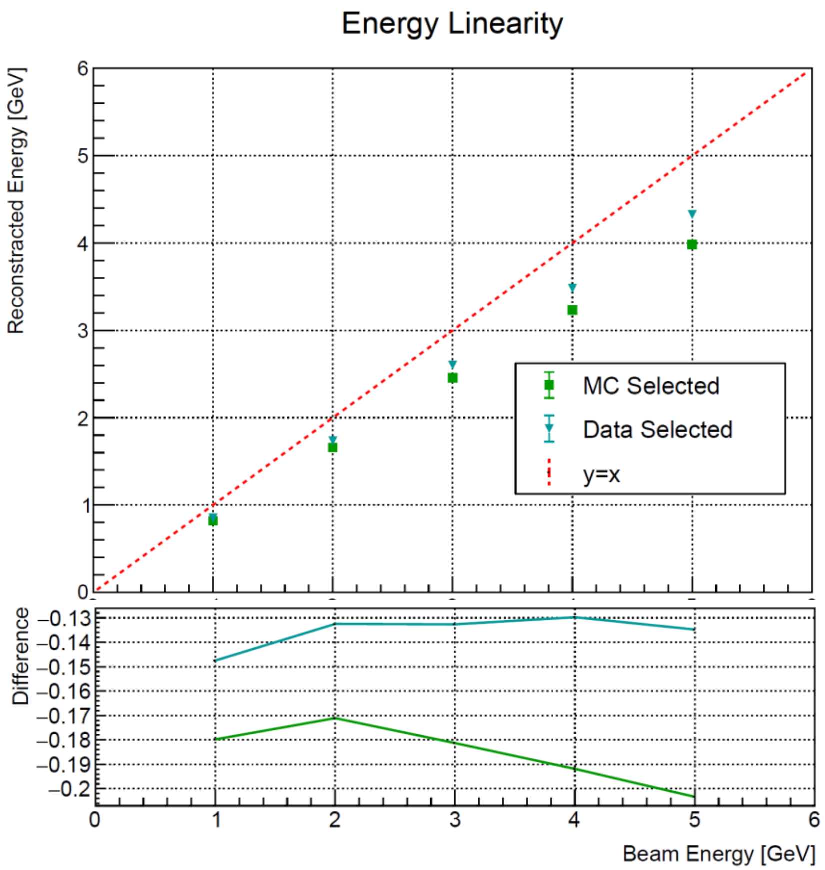
- Beam profile: severe changes in the spatial distribution of the beam spot

- Still significant energy leakage after event selection

Electron data: energy resolution

- Simulation of beam test experiments: electron events
  - Realistic module geometry
  - Upstream material, beam profile, momentum uncertainty…



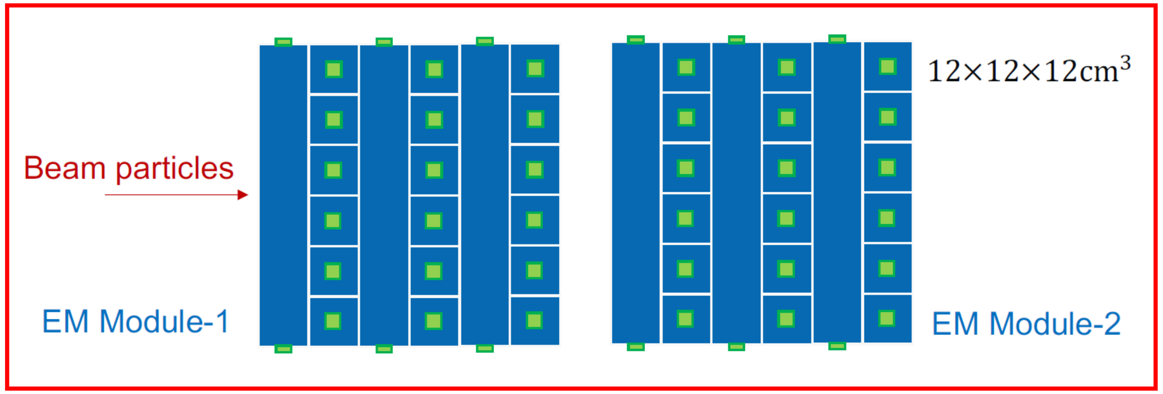


- Energy resolution of Data is worse than MC
- Data shows better energy linearity and larger mean value of energy
- Further check and improvements on data:
  - Studies on crosstalk, temperature calibration…

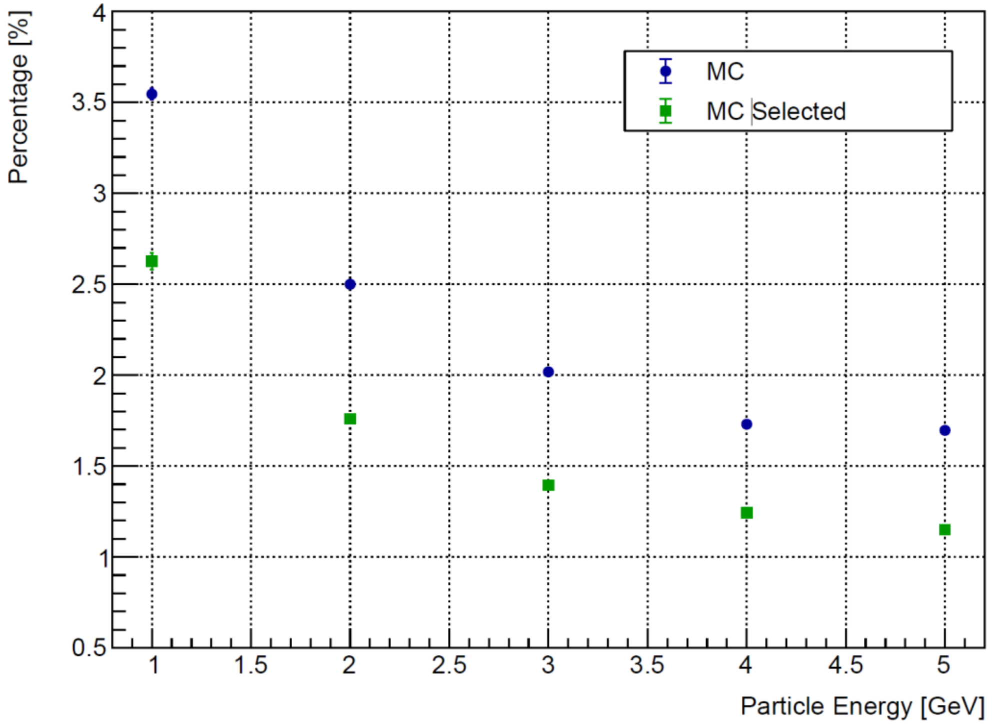
Plan of the second beam test at DESY

DESY beam test in October:

- Prepare 2 modules in serial
- Support structure for two modules
- Shielding…



Expected Energy Resolution of two modules

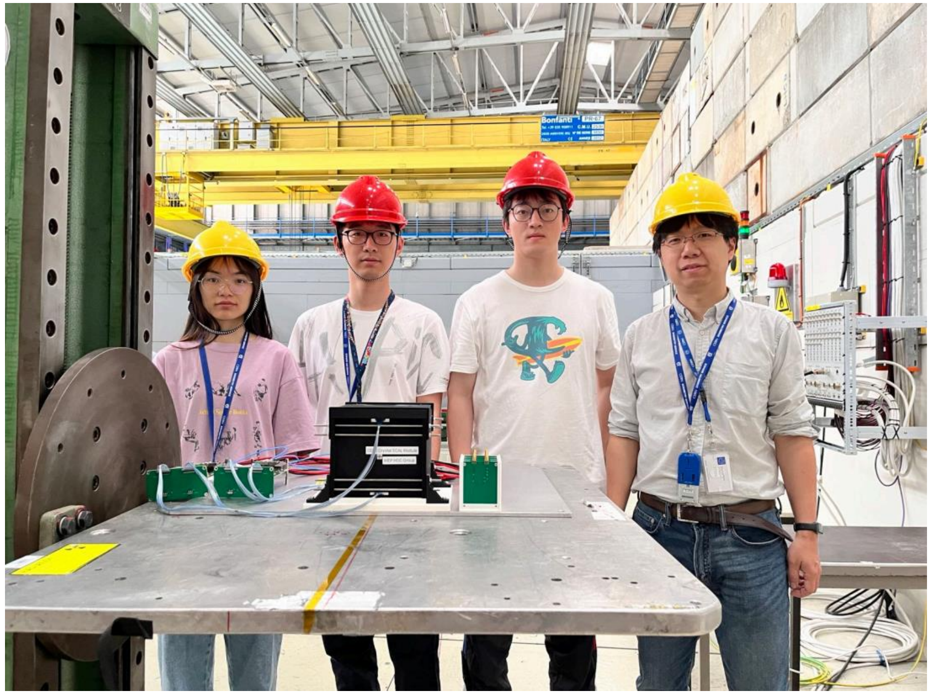


- EM Energy resolution is expected to < 3% at 1 GeV
  - Improve collimation of the beam spot
  - Re-examine the PCB design to reduce noise
  - Improve coupling of SiPMs
- Further beam test targets
  - Time resolution of the 40/60 cm long crystal bars

Summary and prospects

- Introduction of high-granularity crystal ECAL R&D status
- First small-scale crystal module was developed, and the first beam test of has been successfully completed
- Preliminary performance study has been done

- Further analysis of beam data
- The second module is in production and another beam test is scheduled
  - Energy measurement with two modules
  - Time resolution study with long crystal bars



Thanks to every teammate for their contribution!

Backup

Crystal ECAL: specifications

Key Parameters	Value/Range	Remarks
MIP light yield	~200 p.e./MIP	~8.9 MeV/MIP in 1 cm BGO
Dynamic range	0.1~10^3 MIPs	Energy range from ~1 MeV to ~10 GeV
Energy threshold	0.1 MIP	Equivalent to ~1 MeV energy deposition
Timing resolution	~400 ps	Limits from G4 simulation (validation needed)
Crystal non-uniformity	< 1%	After calibration
Temperature stability	Stable at ~0.05 Celsius	Reference of CMS ECAL
Gap tolerance	~100 μm	TBD via module development

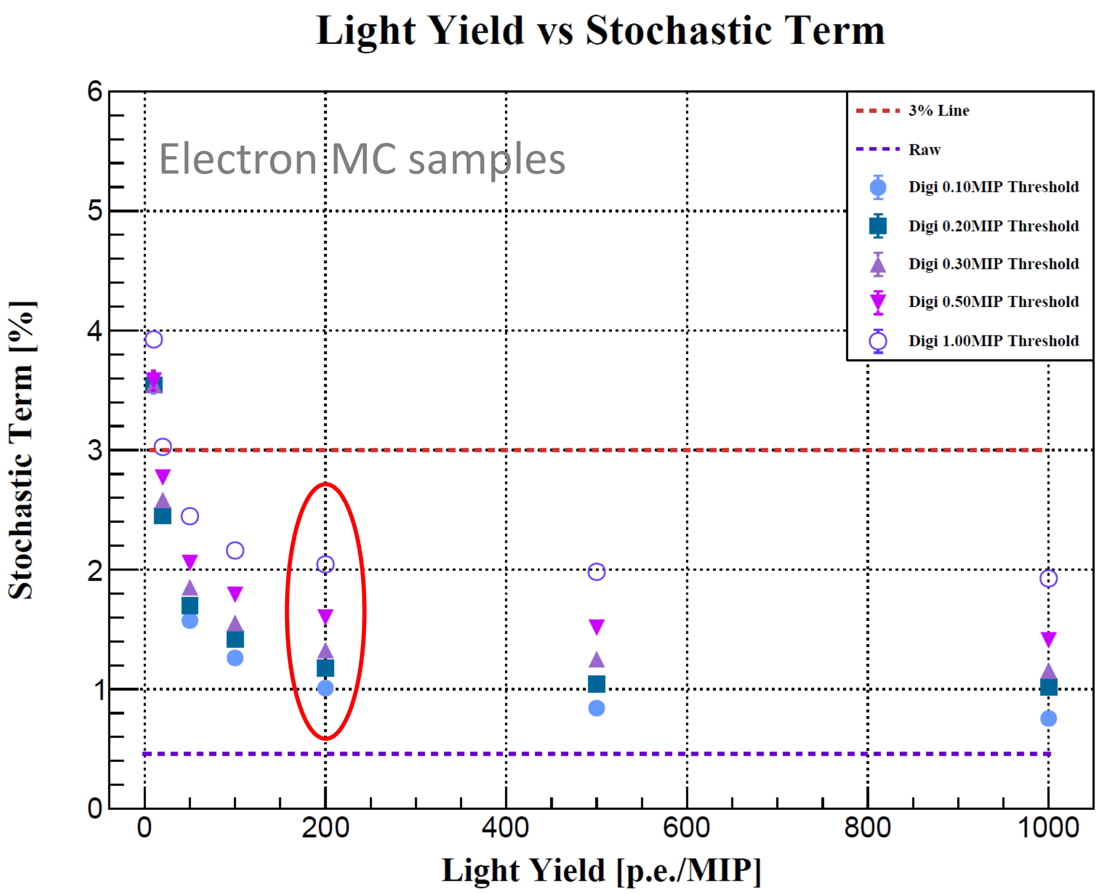
Challenges/issues…

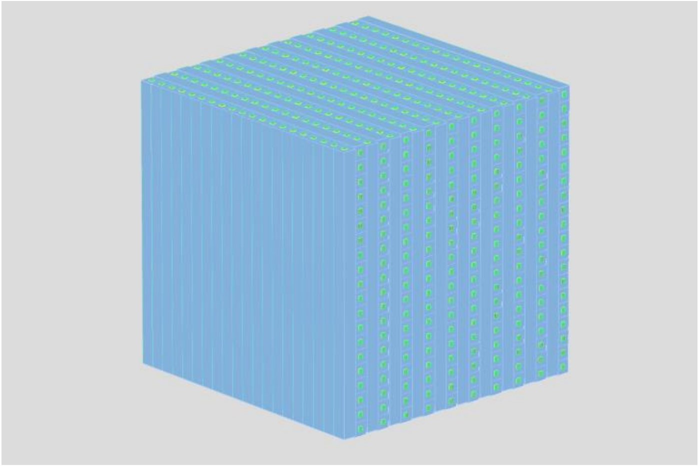
- Crystal size optimization, as well as realistic ECAL geometry design
- Sophisticated software for long bar crystal ECAL
- New BGO crystal with lower light output and faster decay time (collaboration with SIC-CAS)
- Limitation from SiPM dynamic range
- Radiation damage

EM energy resolution: light yield requirements

Geant4 Simulation (v11.0)

- Light yields: number of detected photons per MIP
- Energy resolution: need stochastic term < 3%





Simulation: 40×40×28 supercell, BGO long bars, gaps, 1~40 GeV electrons
Digitization: photon statistics, gain uncertainty, ADC error,…

- Good resolution requires
  - Moderately high light yield → dynamic range
  - Low energy threshold → noise level

Key requirements

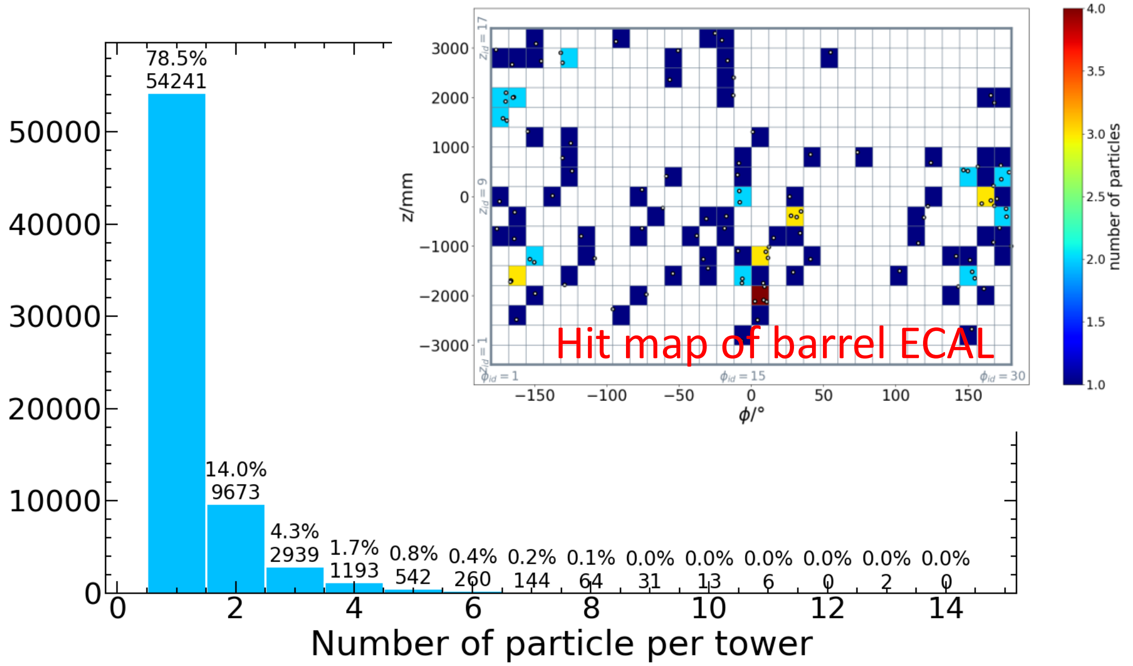
- Light yield required for one crystal: ~200 p.e./MIP (1 cm BGO)

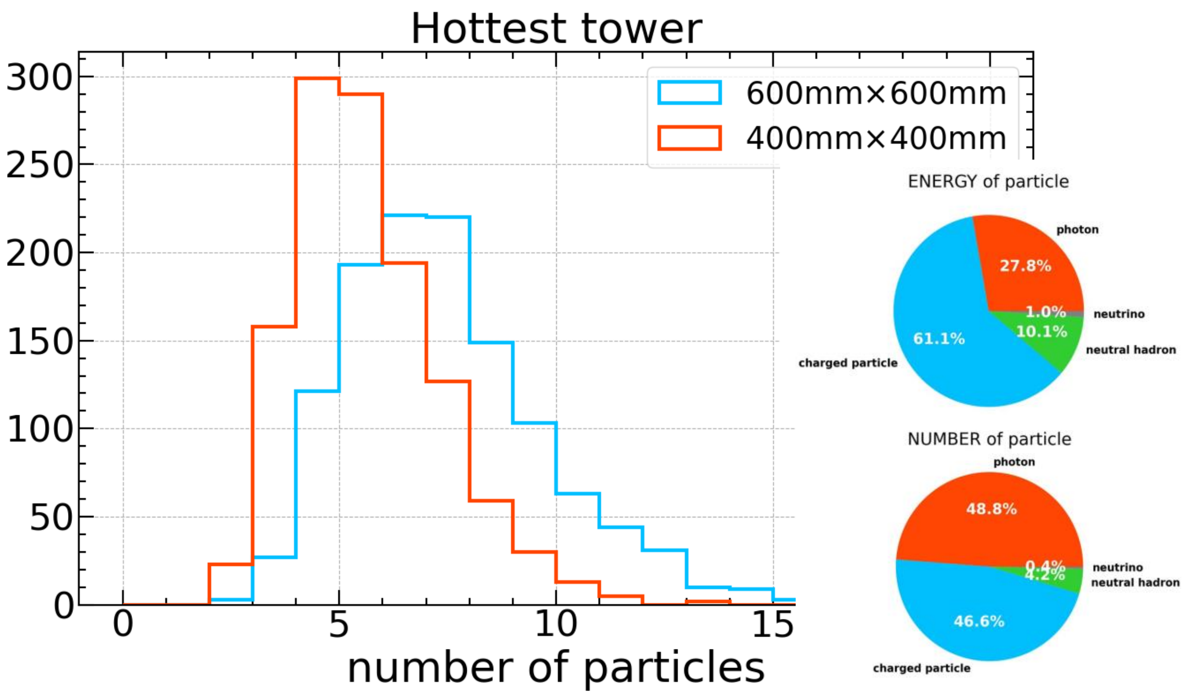
Reconstruction algorithm dedicated to long crystal bar ECAL

- Occupancy of ECAL towers: challenges on reconstruction
- Hottest tower: the tower with the largest number of particles hitting on
- 4 jets event: $e^+e^- \rightarrow ZH, Z \rightarrow q\bar{q}, H \rightarrow gg$

Yang Zhang (IHEP)

Key issues
- Sophisticated software





- Most towers have 0~1 particle hitting on
- Occupancy of these towers can be ignored

- Always have multiple particles hitting on one tower
- Need to deal with the occupancy by algorithm improvement
- Potential performance degradation needs to be understood