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

R&D Progress of the CEPC High-Granularity Crystal ECAL

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On behalf of CEPC Calorimeter Working Group

NED'2023

August 9 – 11, 2023

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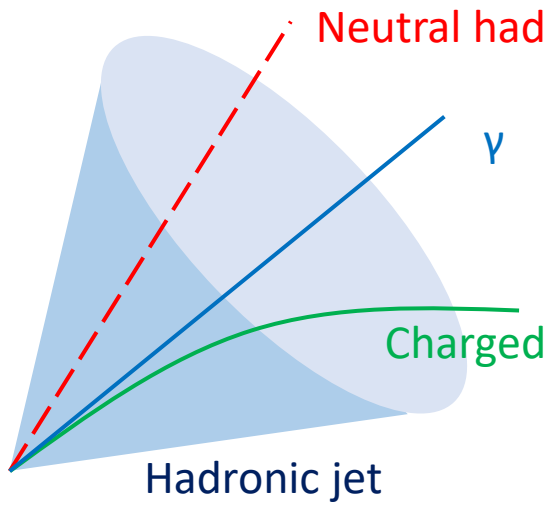
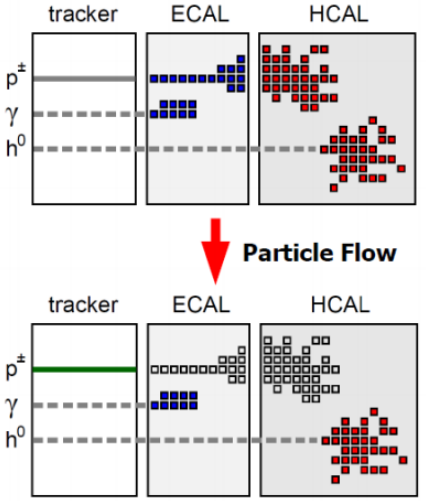
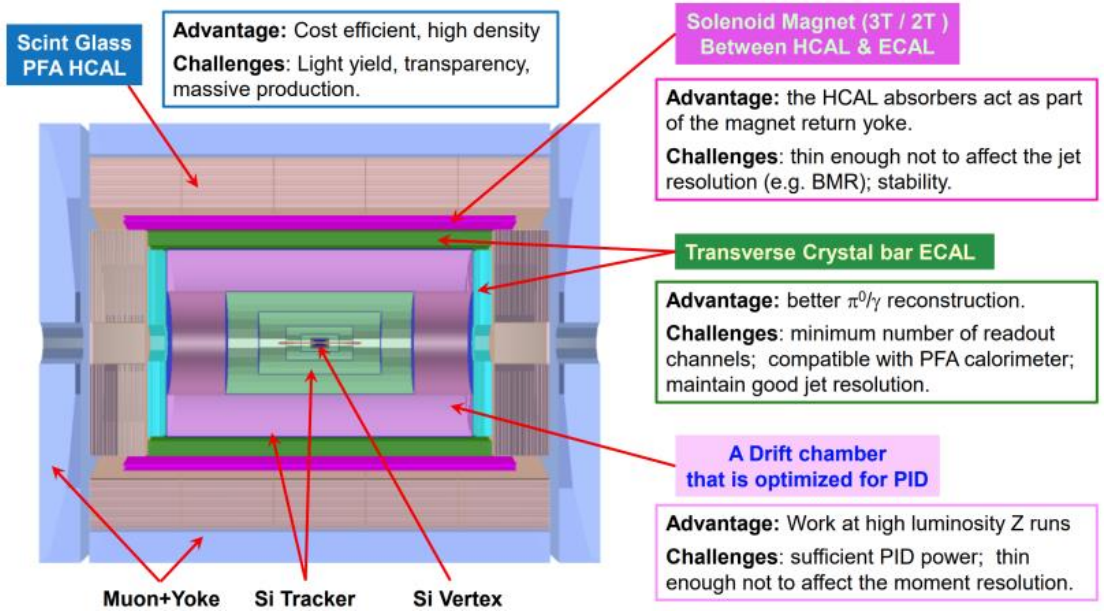
Motivations: new detector for CEPC

- 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

NED'2023: 高颗粒度闪烁玻璃强子量能器的研发进展

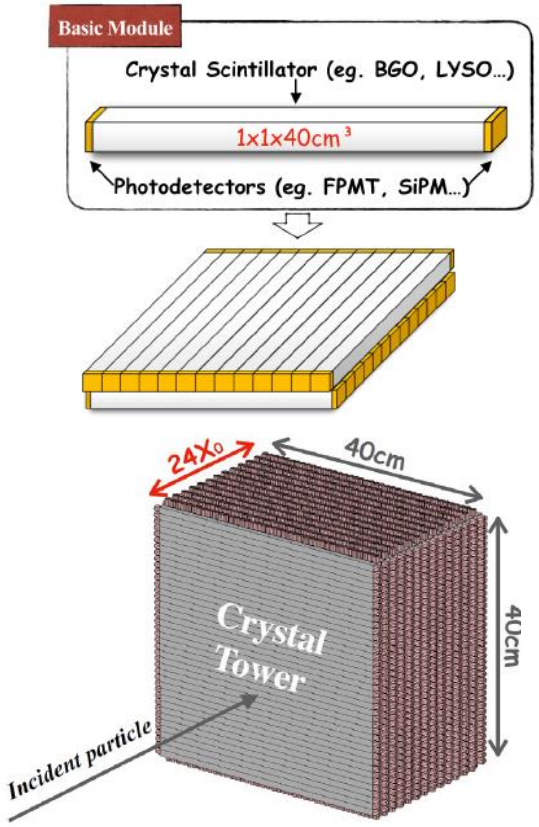






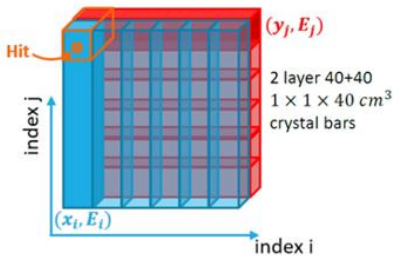
Crystal ECAL R&D: overview

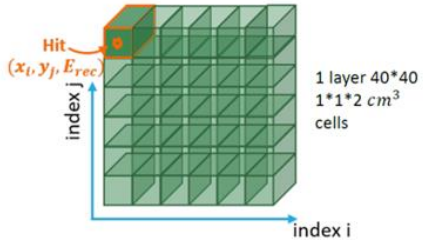
➢ Design concept

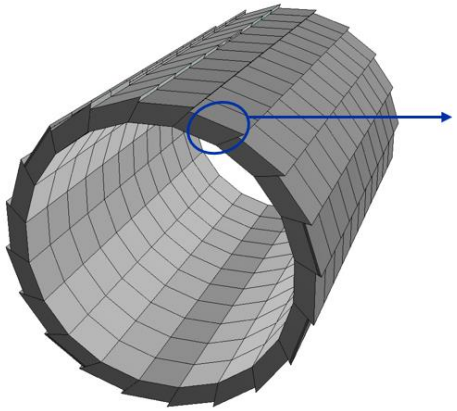


- Crystals arranged to be orthogonal between layers
- Readout from two sides

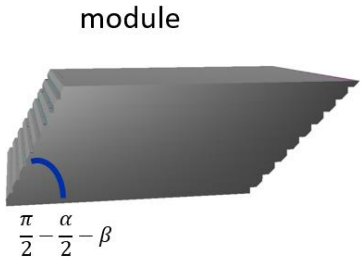
➢ Optimization and validation





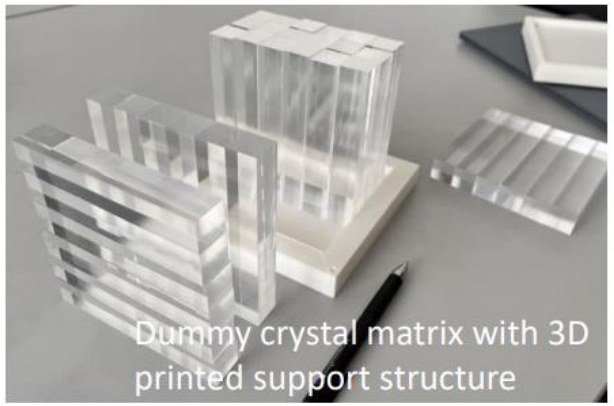


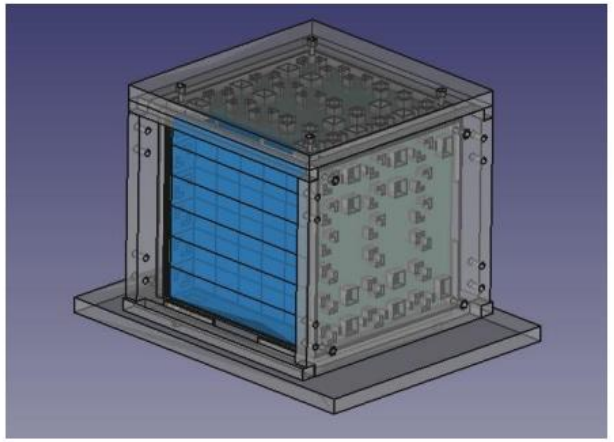
cylindrical crystal ECAL



- Dedicated new reconstruction software
- Performance evaluation and optimization

➢ Hardware development

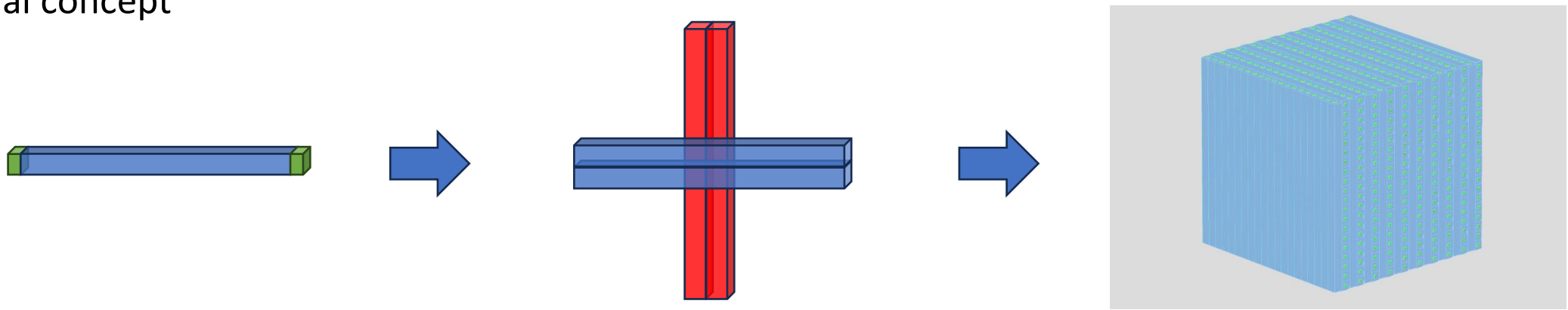




- Development of crystal module(s) for beam tests

Design concept of high-granularity crystal ECAL

- General concept



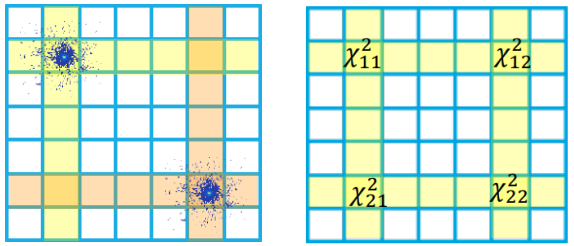
➢ Long crystal bar with 2 SiPMs

➢ Crisscrossed arrangement between layers

➢ A 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

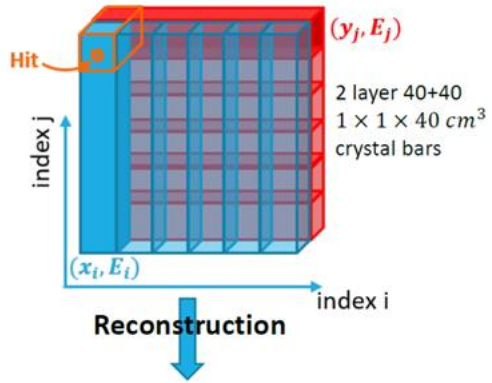
- Challenges
  - Difficulties in the mechanical/geometry design
  - Impact from ghost hits



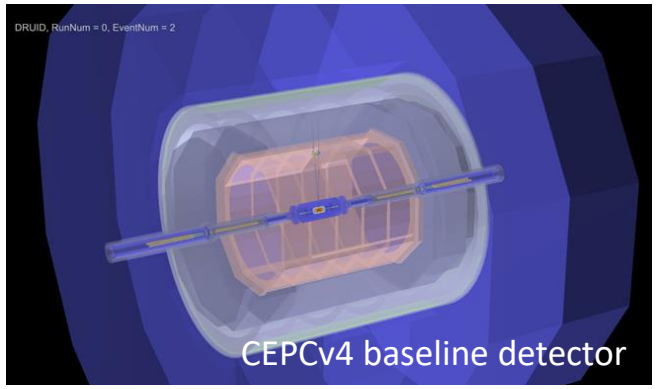
➢ Ghost hits case when 2 or more particles hit on one supercell

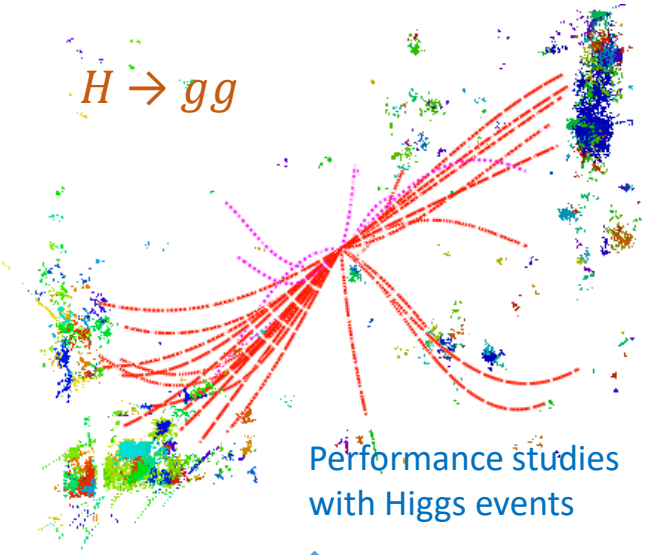
Workflow of preliminary performance evaluation

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



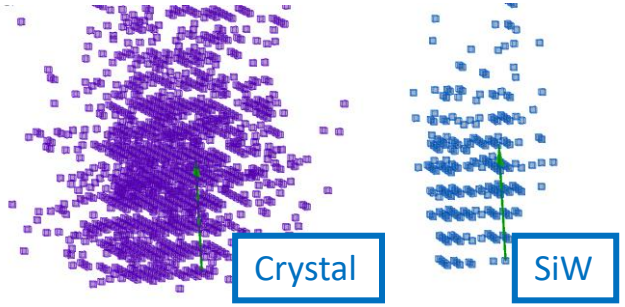
Material replacement





Performance studies with Higgs events

Simulation and reconstruction



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

Crystal compared to SiW:
significant increase of #hit

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

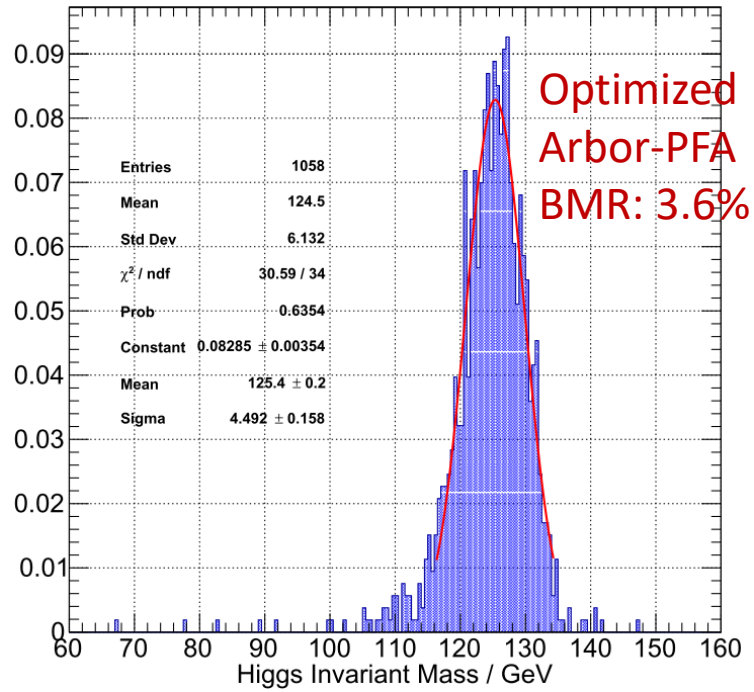
Dedicated reconstruction software is also under development

PFA performance: Higgs benchmark

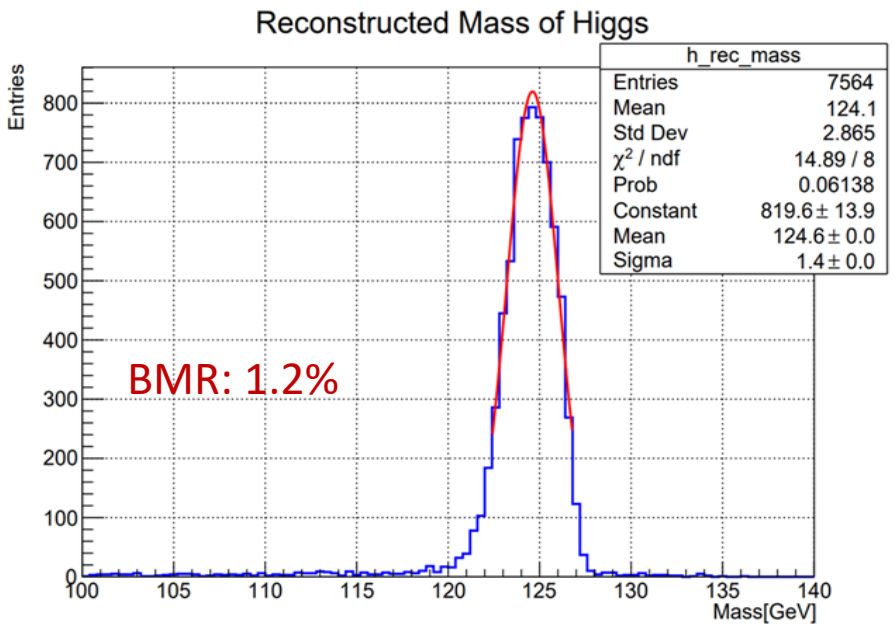
Baohua Qi (IHEP), Zhiyu Zhao (TDLI/SJTU)

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

BMR ($H \to gg$)



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

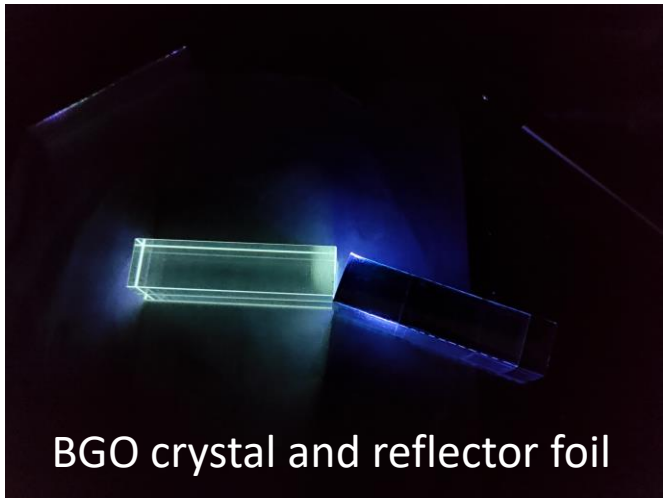


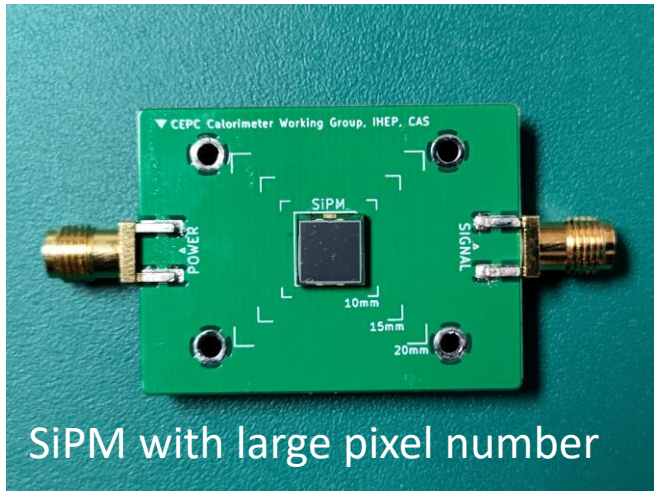
- Good performance with Arbor-PFA algorithm

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, ~200 p.e./MIP
  - Radiation hardness, temperature stability, mechanical tolerance…

NED'2023: 大动态范围SiPM的响应刻度


BGO crystal and reflector foil

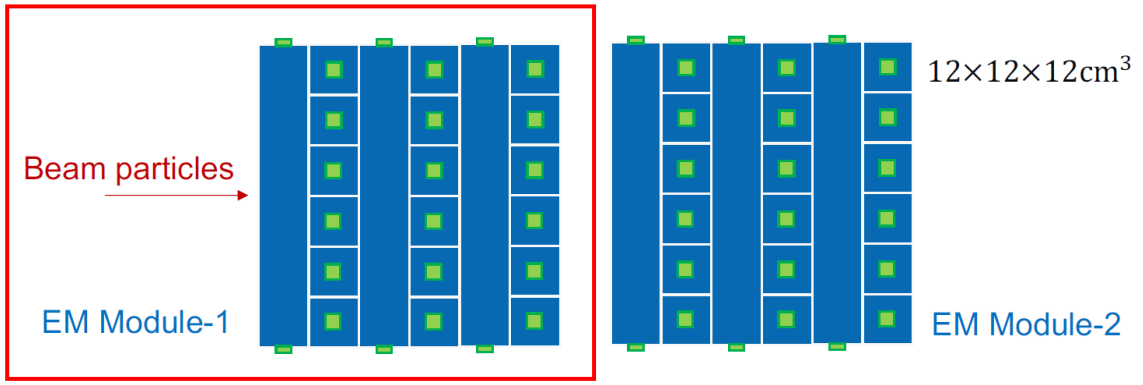


SiPM with large pixel number

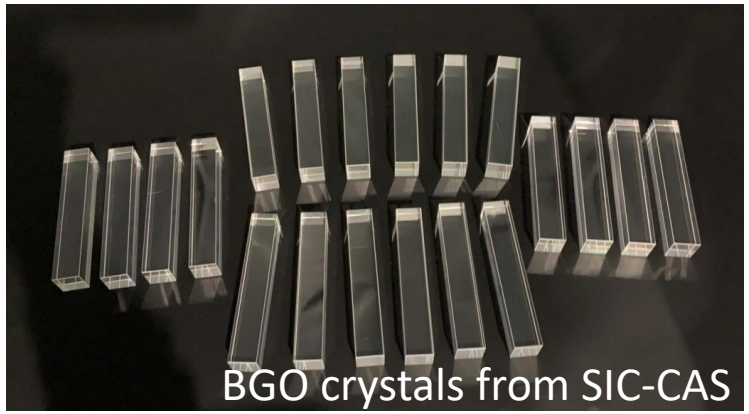

Readout electronics

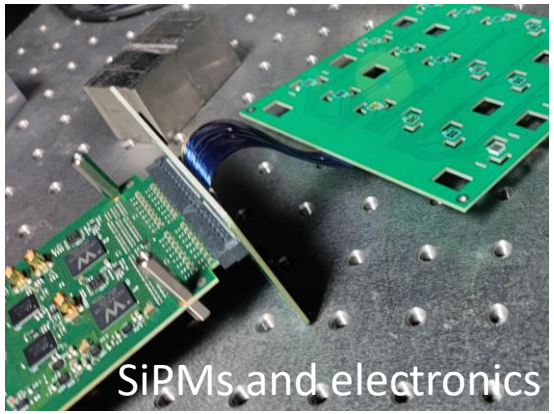
Introduction to the first small-scale crystal module

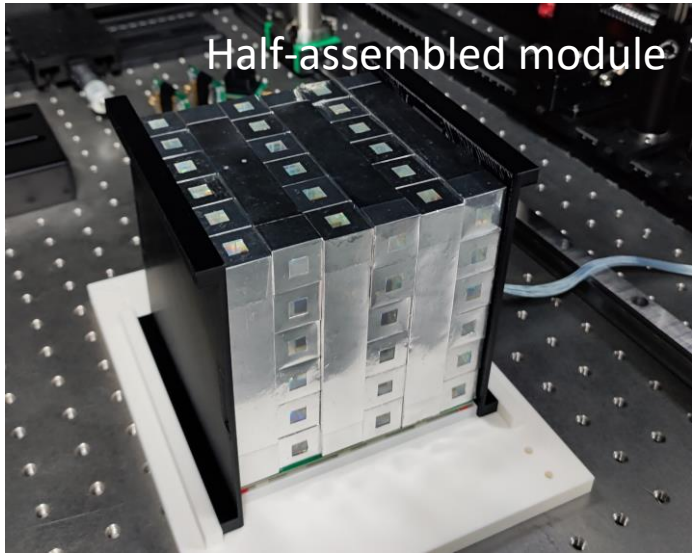
- Motivations
  - Identify critical questions/issues on system level
    - Mechanical design, PCB and electronics…
  - Evaluate performance with TB data
  - Validation of simulation and digitization
- First 12 × 12 × 12 cm^3 BGO modules development
- Beam test at CERN T9 beamline
  - Muon, electron and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



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

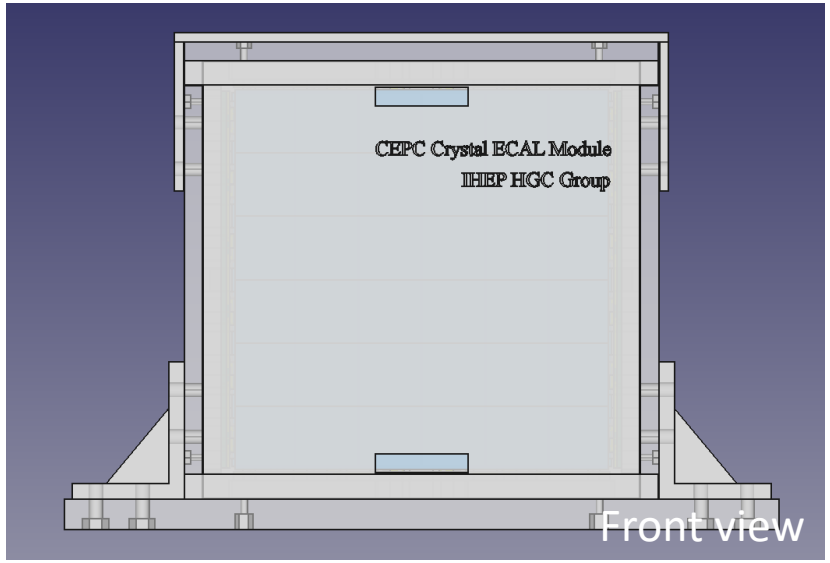


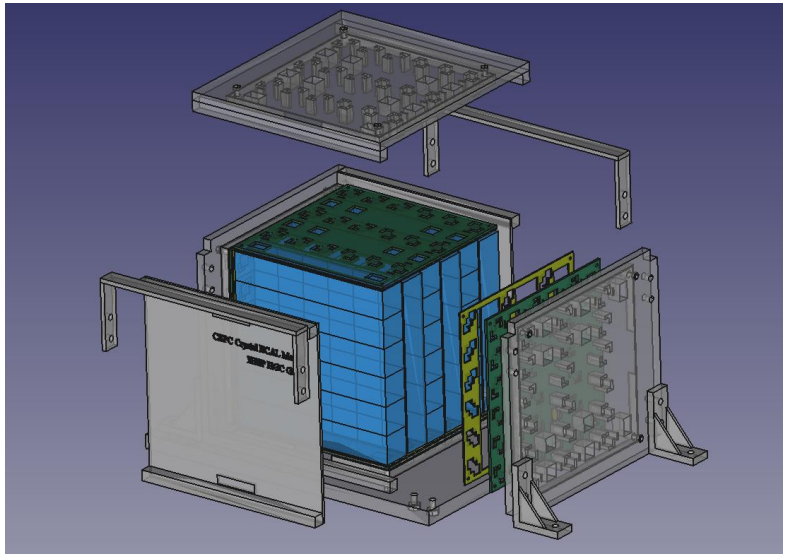


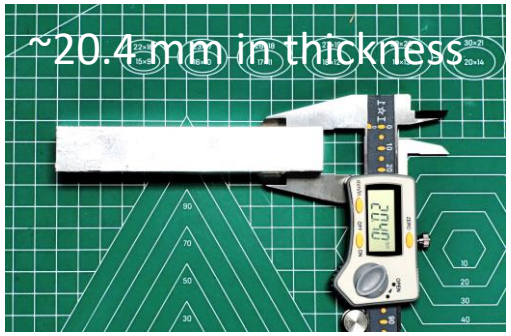


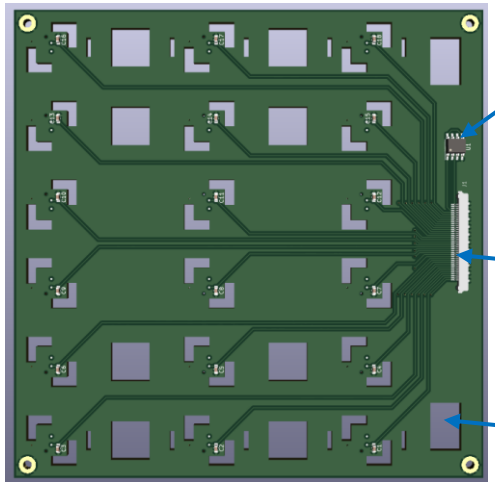
- 36 crystals wrapped with ESR and Al foil
- 3D printed support structure

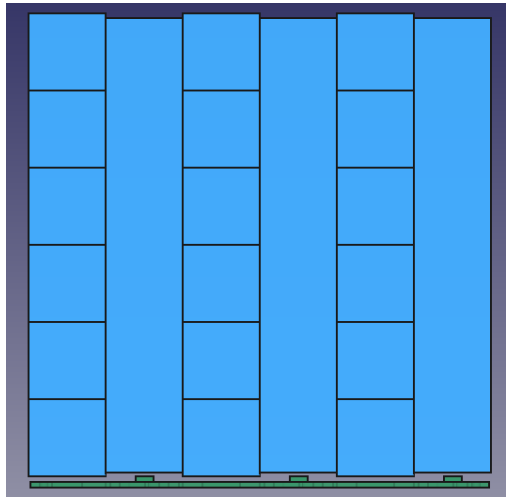
Mechanical and PCB design









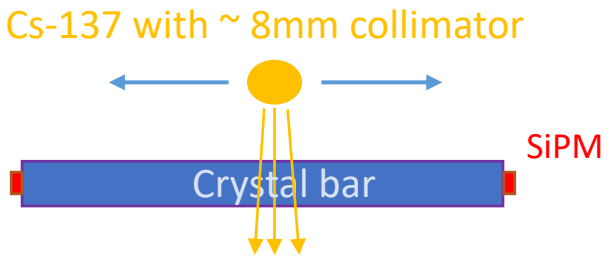


- Difficulties with module development
  - Mechanical design is unusual
  - PCB is non-load-bearing and should be decoupled
  - Module assembly is difficult

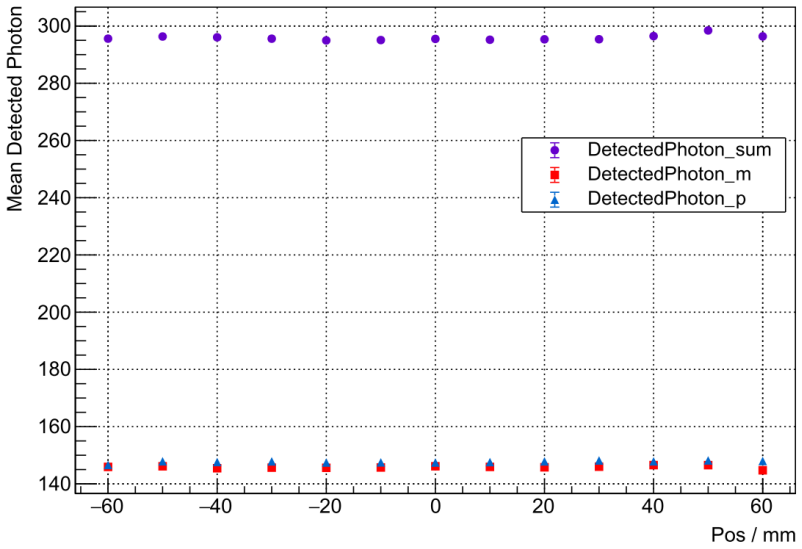
Uniformity scan of BGO crystal bars

Zhikai Chen (USC)

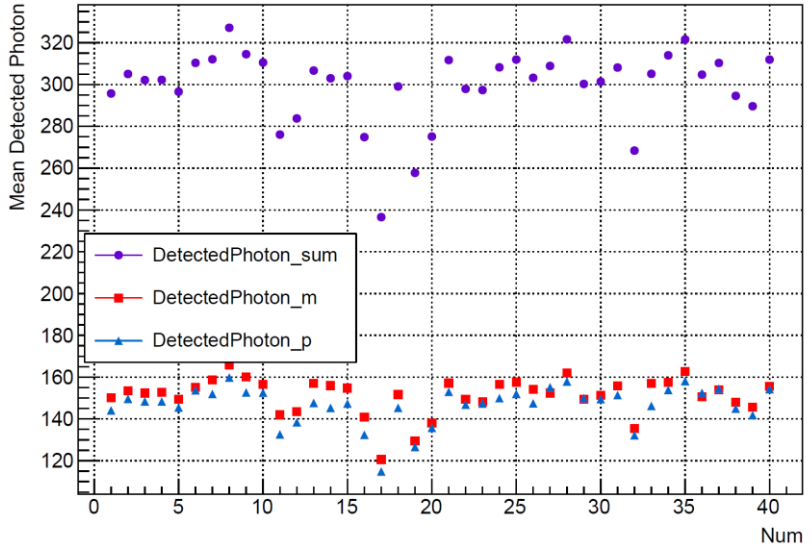
- Batch test of SIC-CAS BGO crystal bars
  - 40 crystals with ESR and Al foil wrapping
  - Scan with Cs-137 radioactive source

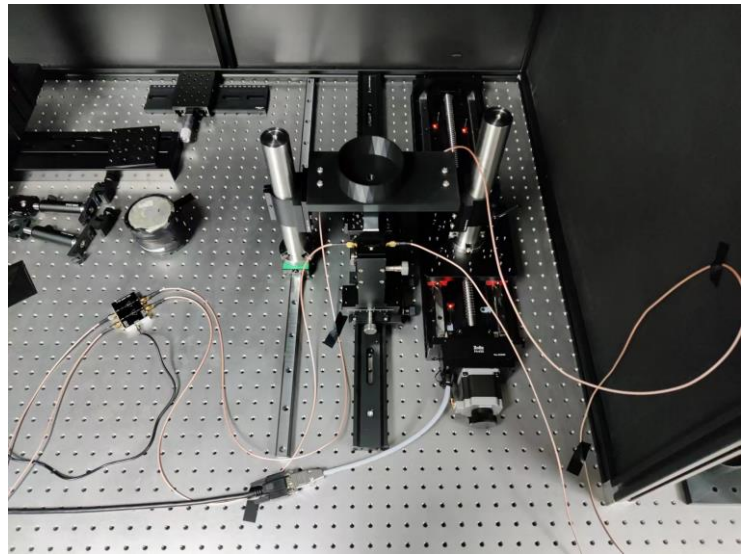


Response uniformity along bar



Comparison of 40 crystal bars





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

Electronics and trigger scheme

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

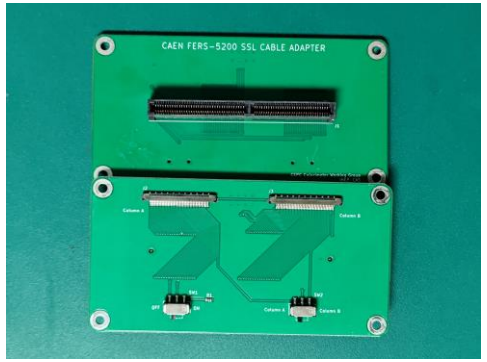
36/64 channels used

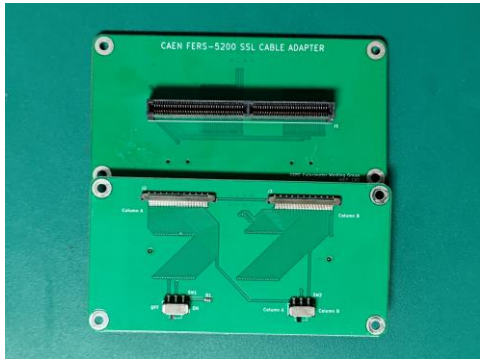
36/64 channels used

Daisy chained
trigger distribution

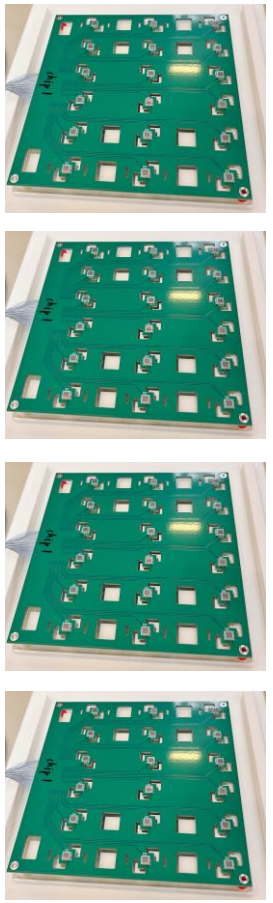
A5202 unit
Built-in HV power supply

External trigger



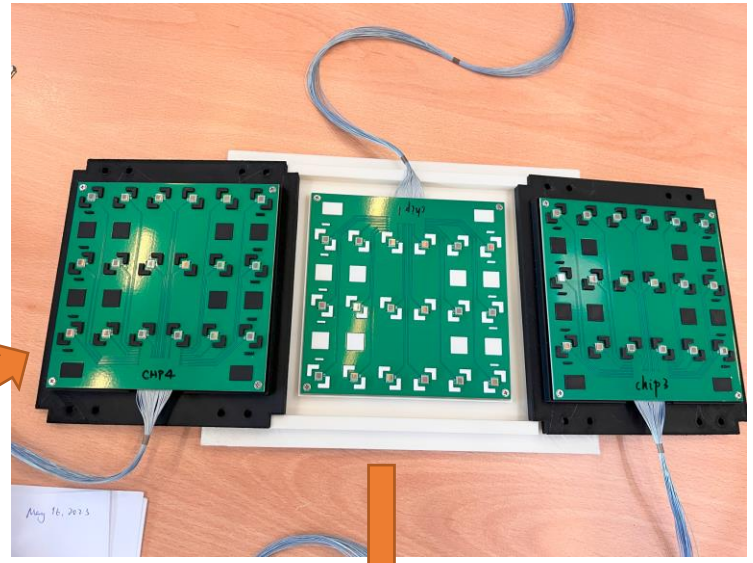


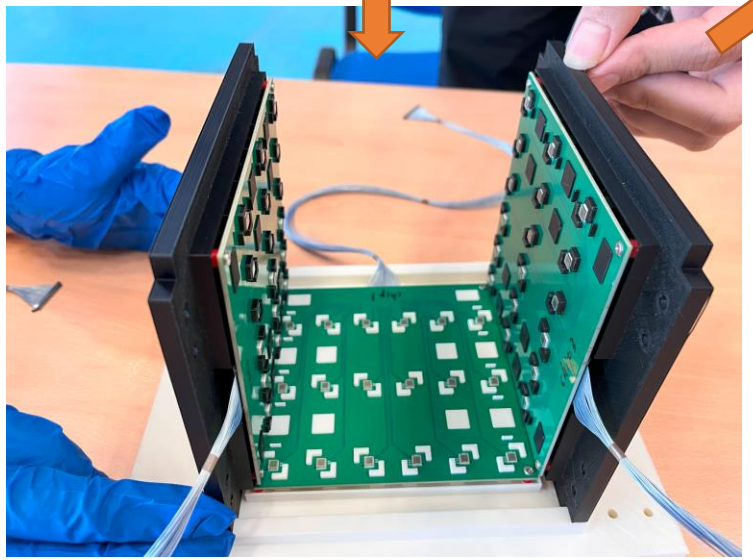
Self-designed
adapter board

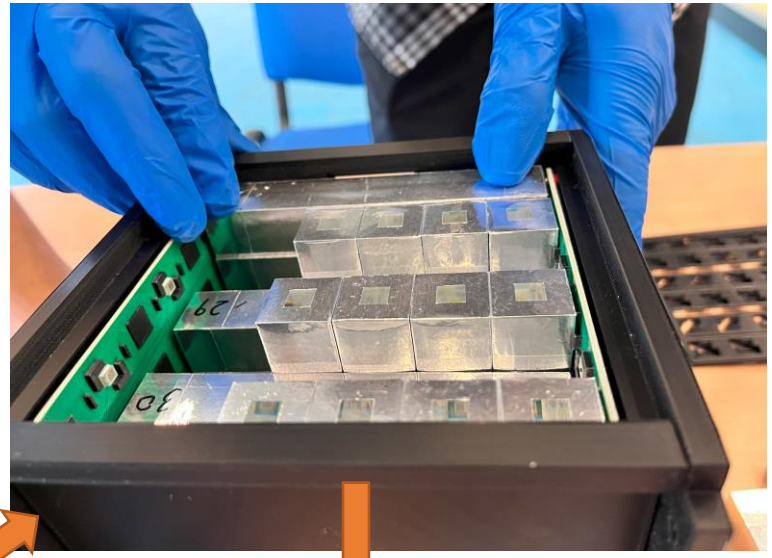


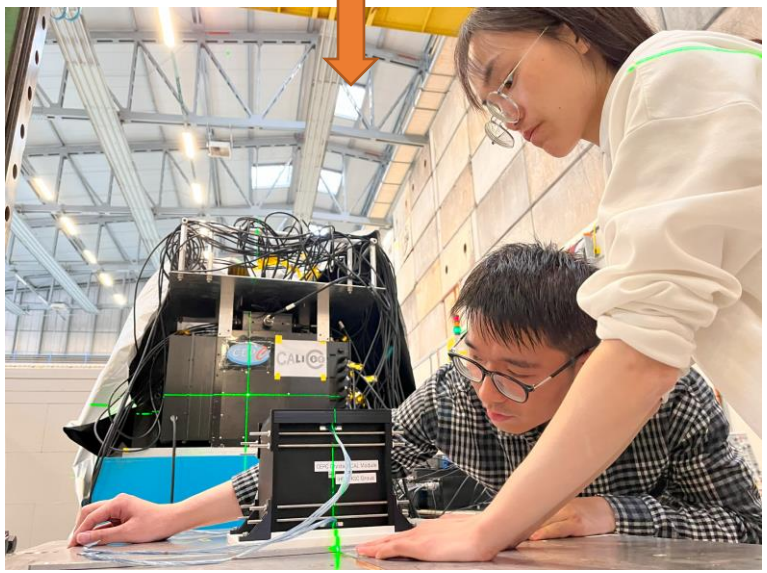
18 SiPM channels per PCB

Beam test: installation of module

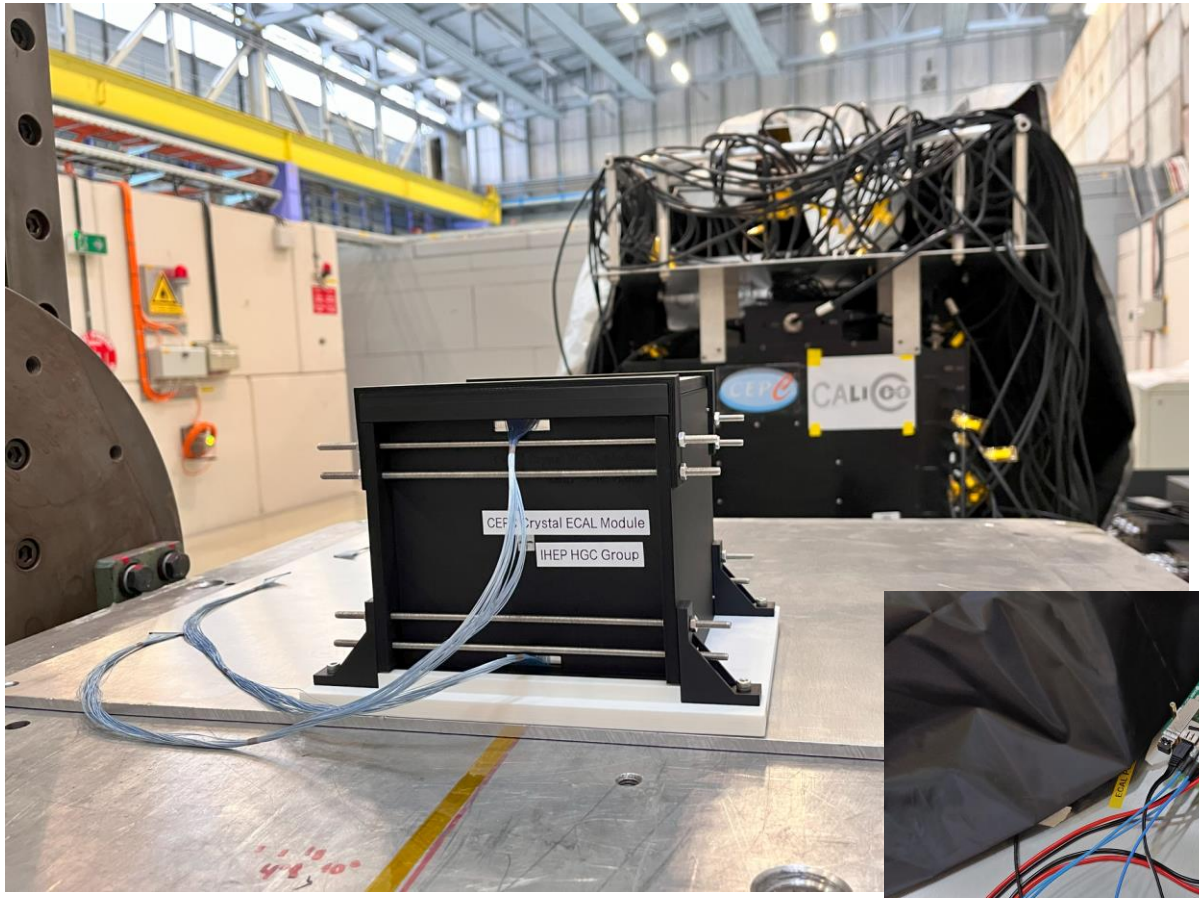


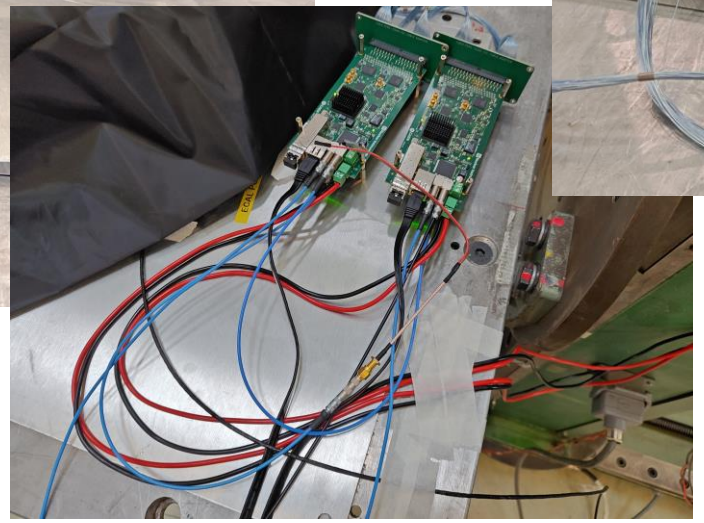


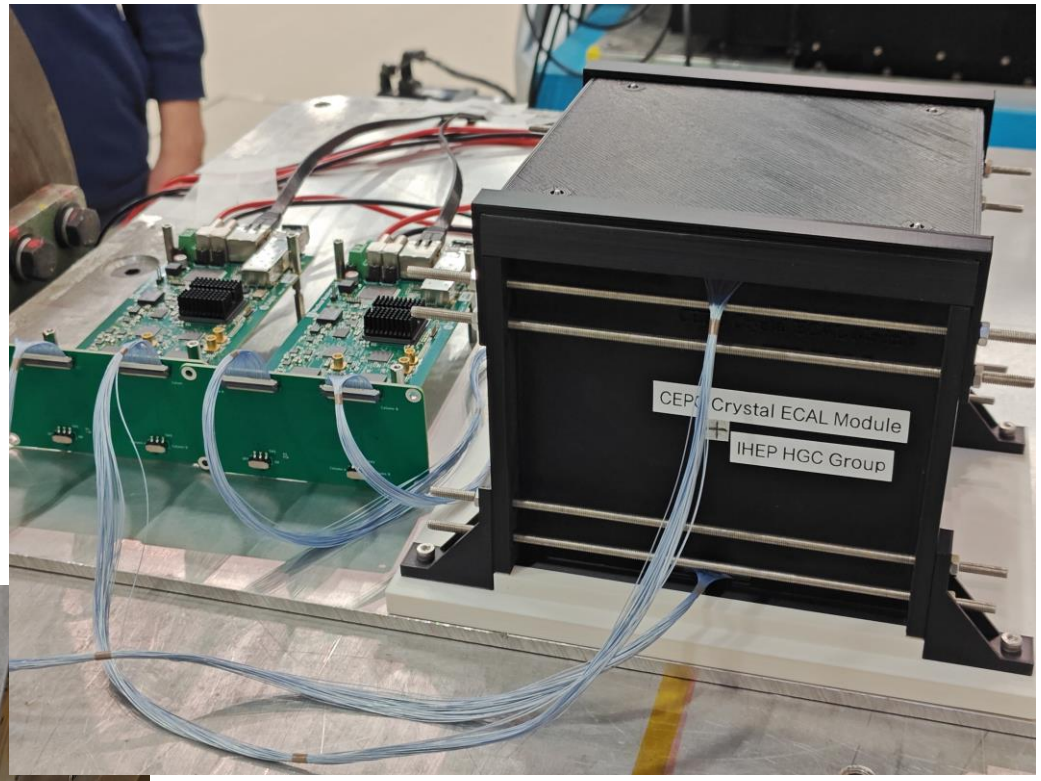




Beam test: installation of module





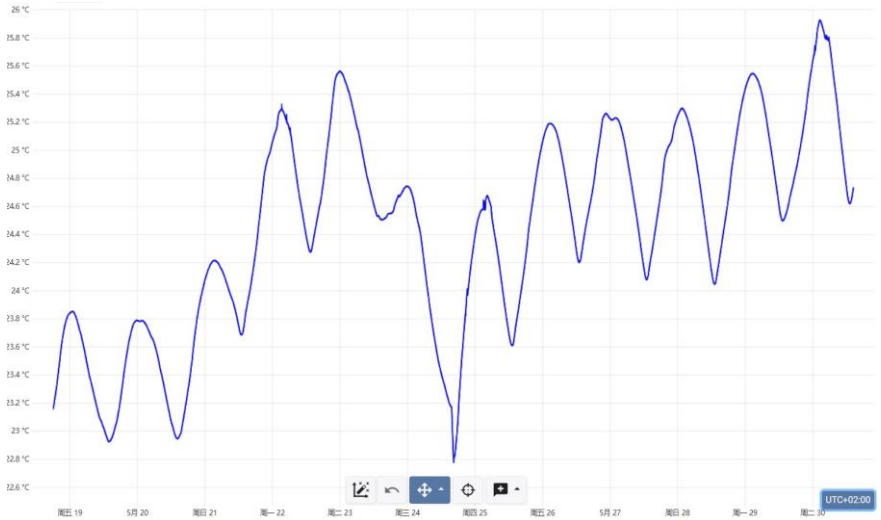


NED'2023: CERN beamtests of CALICE scintillator-based calorimeter prototypes

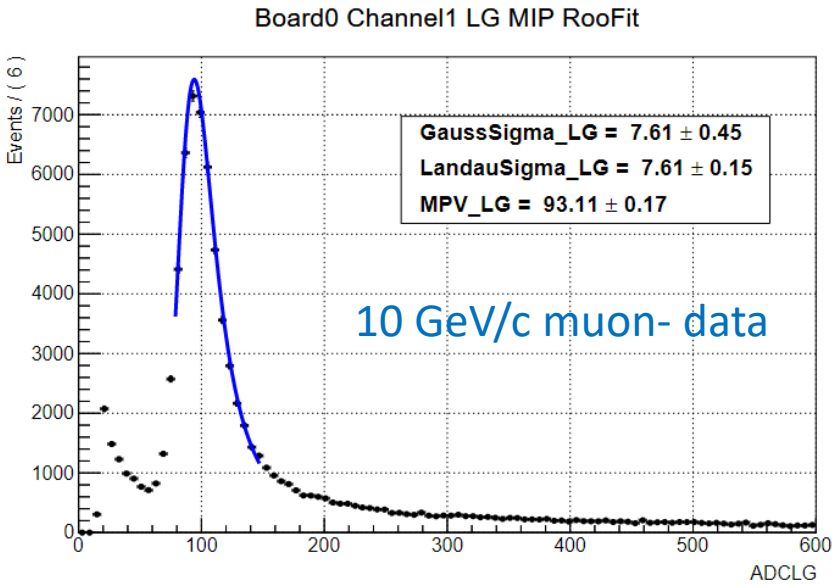
Thanks to the efforts of Yong, Dejing, Baohua, Zhiyu and Lijun!

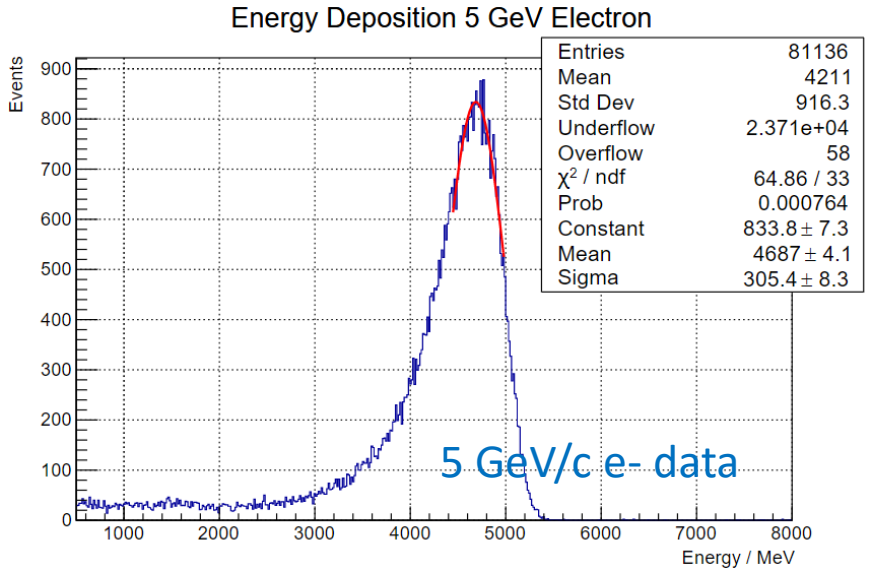
Beam test data summary

- 10 GeV/c muon- beam: MIP response
  - High/low gain, Hold-Delay time, shaping time scans
  - ~5.5M events acquired
- 0.5~5 GeV/c electron beam: energy response
  - ~980k events
- Other data
  - Pion- data for high fluence test
  - Self-trigger of “leaked particles” form upstream
  - Temperature monitoring data



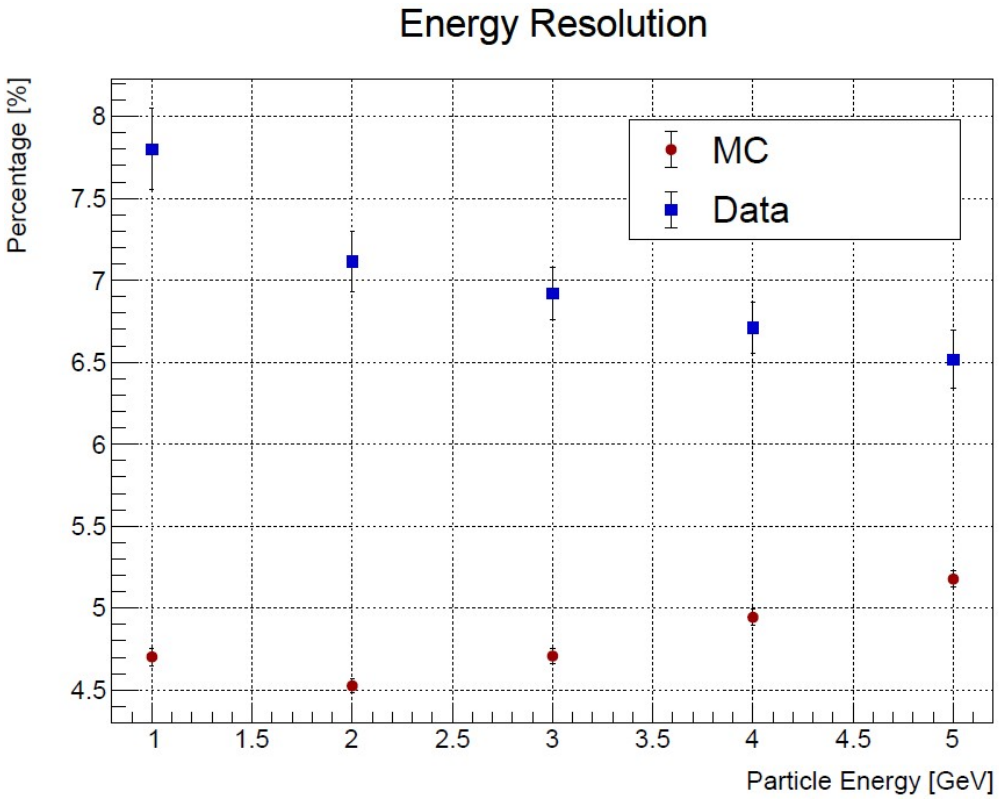
➢ ~2℃ temperature change during the beam test

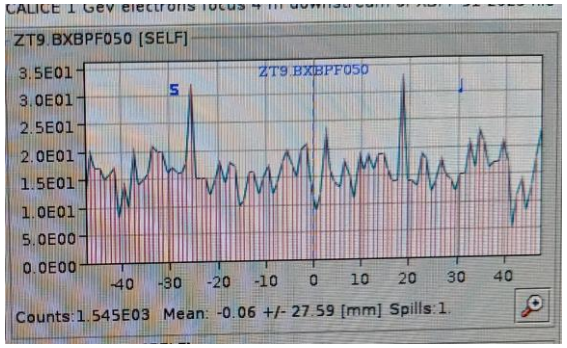




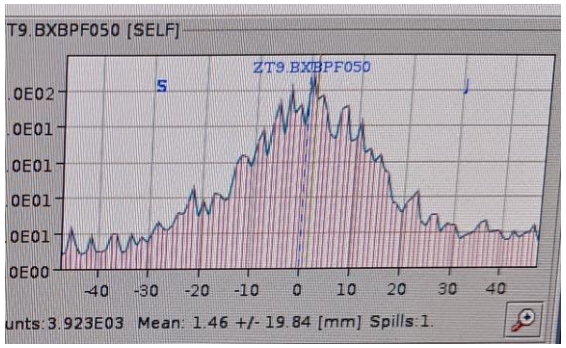
Beam test: preliminary results

- Simulation of beam test experiments: electron events
  - Realistic module geometry
  - Upstream material, beam profile, momentum uncertainty…
- Data: calibrated channel by channel with muon- events





Beam profile 1 GeV/c e-



Beam profile 4 GeV/c e-

Generally Data energy resolution is worse than MC

- MC: effect of energy leakage is significant
  - Further improvements in digitization and beam profile description…
- Data: energy calibration should be checked
  - Studies on crosstalk among channels, temperature calibration…

Summary and prospects

- First small-scale crystal module was developed, and the beam test of the module has been successfully completed!
- Preliminary performance study has been done

- Further analysis of beam data and obtained reliable results of performance reference
- The second module is in production and another beam test is scheduled
  - Electronic crosstalk should be addressed
  - Energy measurement with two modules
  - Time resolution study with long crystal bars

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

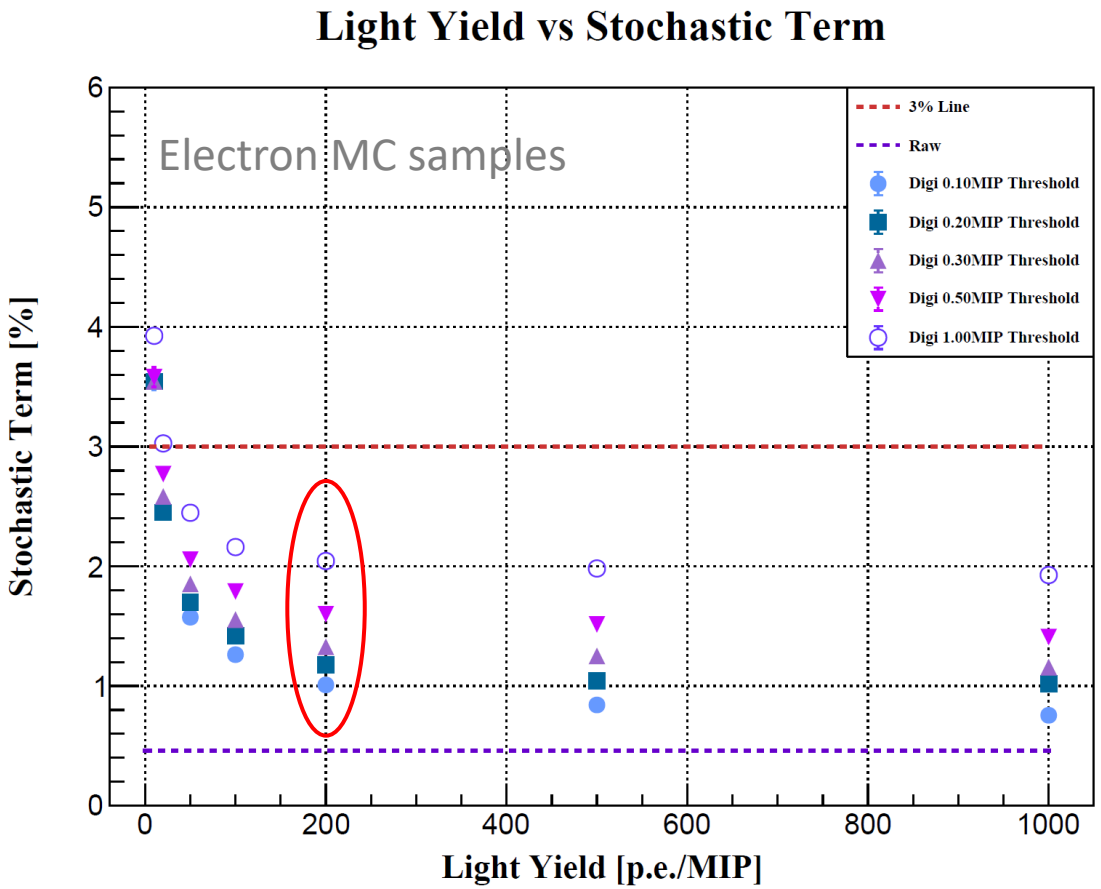
Challenges/issues…

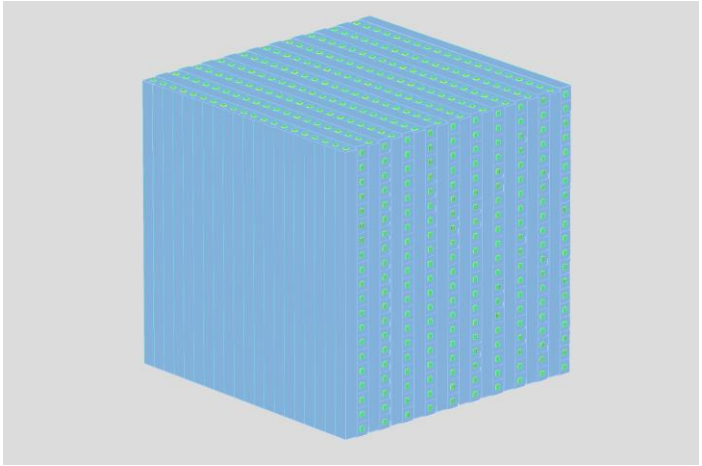
- Crystal size optimization, as well as realistic ECAL geometry design
- Sophisticated software for long bar crystal ECAL
- New BGO crystal with lower light output and faster decay time (collaboration with SIC-CAS)
- Limitation from SiPM dynamic range
- Radiation damage

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,…

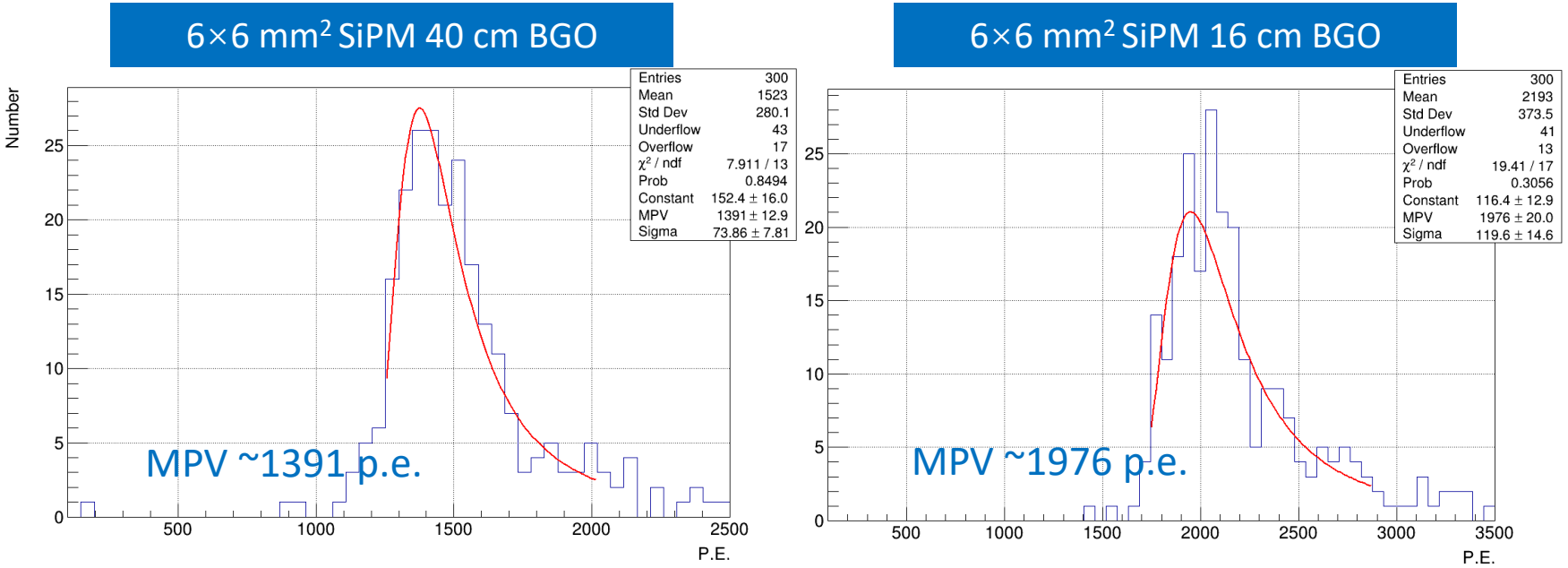
- Good resolution requires
  - Moderately high light yield → dynamic range
  - Low energy threshold → noise level

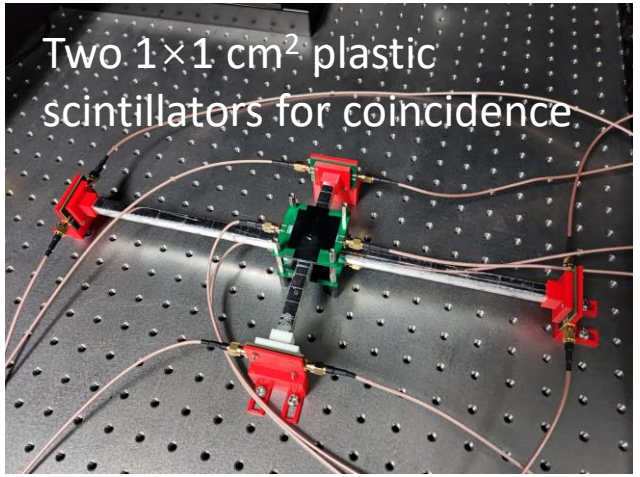
Key requirements

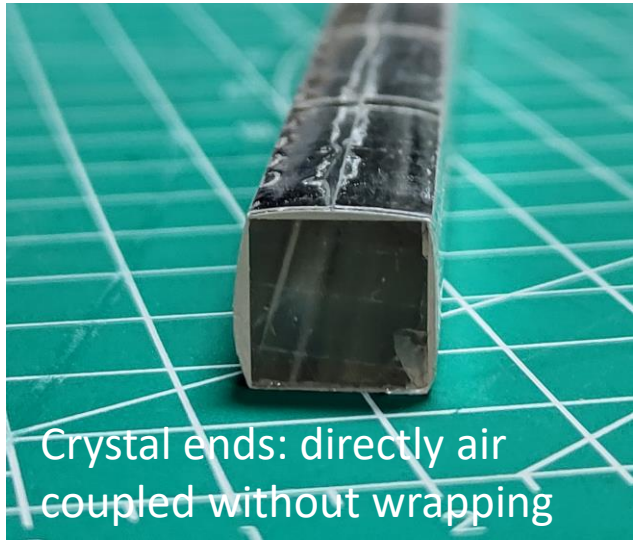
- Light yield required for one crystal: ~200 p.e./MIP (1 cm BGO)

Cosmic-ray test: MIP response of BGO crystal

- Measurement of crystal-SiPM units
  - 16 and 40 cm BGO crystals, double-sided readout







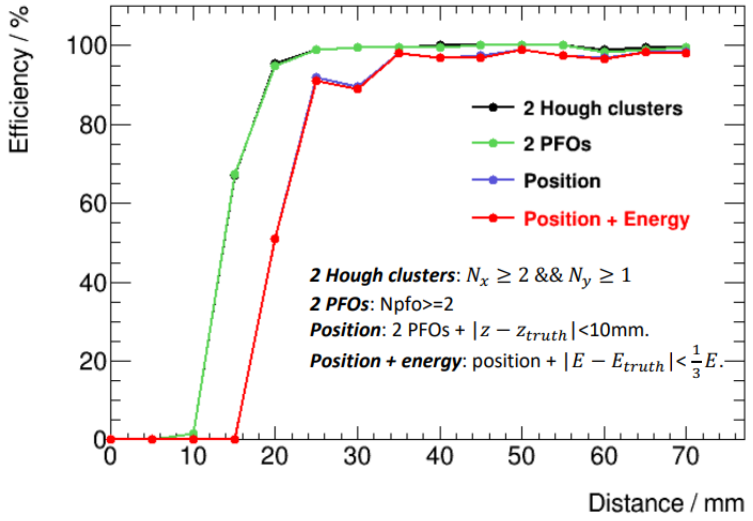
Reconstruction algorithm dedicated to long crystal bar ECAL

- Particle reconstruction for long bar crystal ECAL

Yang Zhang (IHEP)

Basic principles of reconstruction

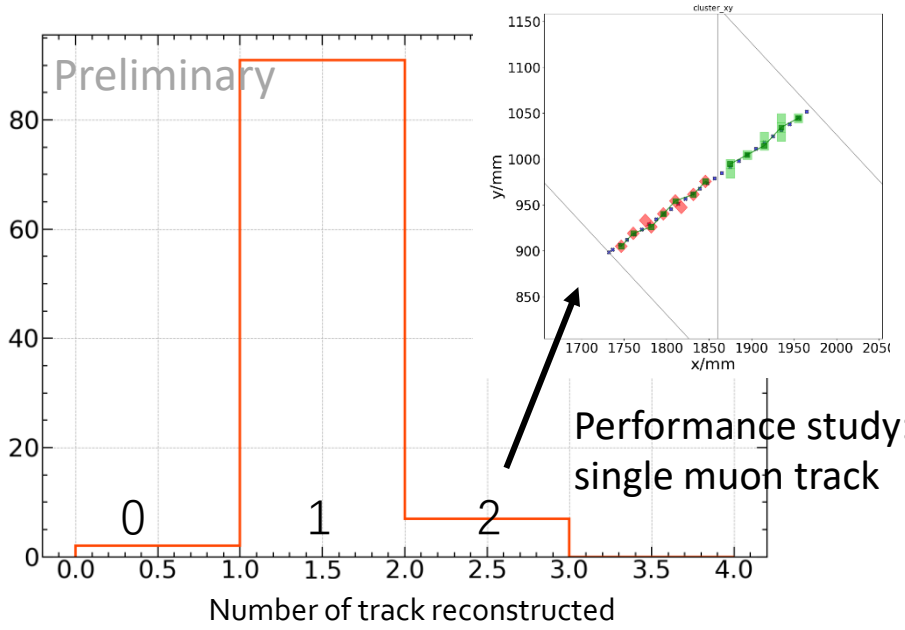
Cluster inputs → shower identification →
- Photon: Hough transformation
- Charged (MIP-like): track matching
- Neutral hadron: cone clustering



Performance study: di-photon recognition efficiency

Talk by Yang Zhang, 2022 CEPC Workshop

Photon reconstruction with Hough transformation



Performance study: single muon track

- Tracking matching algorithm for crystal ECAL
- Two tracks due to ECAL tower boundary

- Reconstruction flow has already been built
- Ongoing work on hadron…