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

High Granularity Crystal Calorimeter R&D Progress

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On behalf of CEPC Calorimeter Working Group

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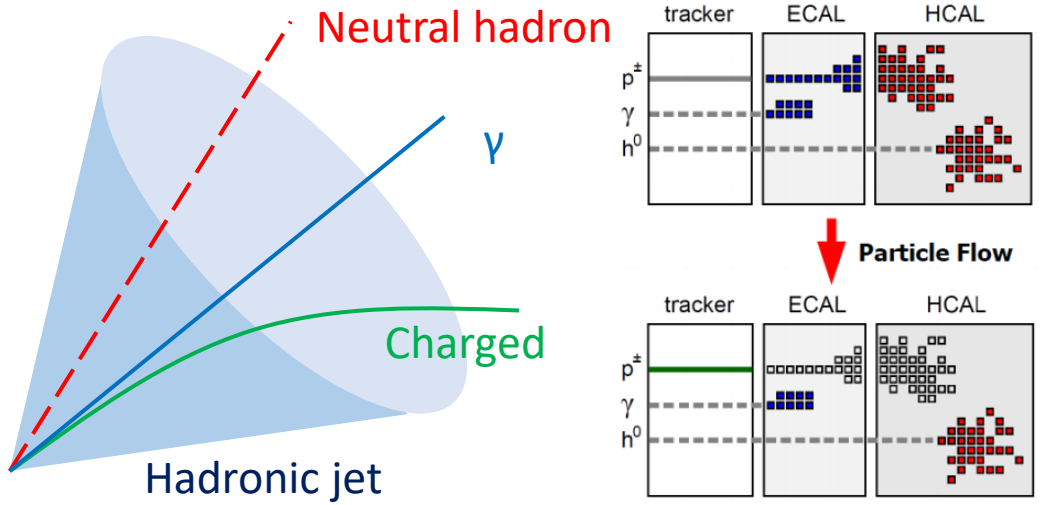
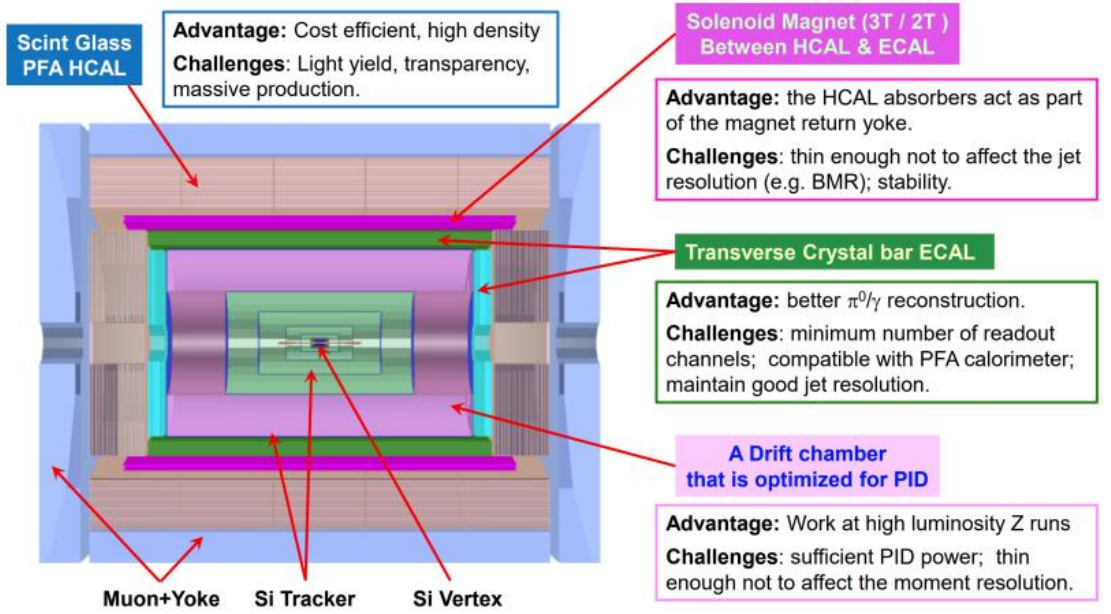
Motivations: new detector for CEPC

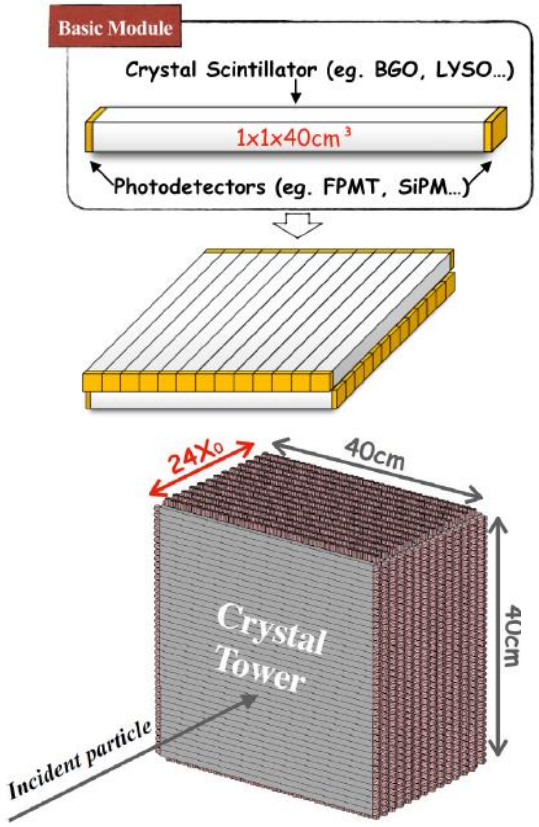
- CEPC: future lepton collider
  - Higgs/Z/W bosons, BSM searches, etc.
  - Precision jet measurement
  - Particle-Flow Algorithm (PFA)
    - Different final state particles -> different detectors
    - High-granularity calorimeter: separation of showers
- New "CEPC 4th concept" detector design
  - High-granularity 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





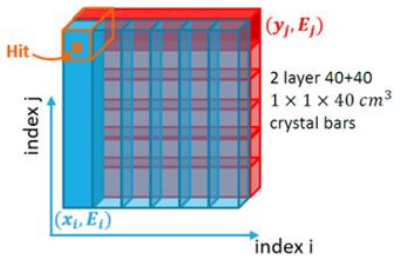
Crystal ECAL R&D: overview

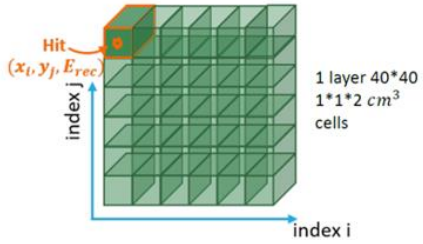
➢ Design concept

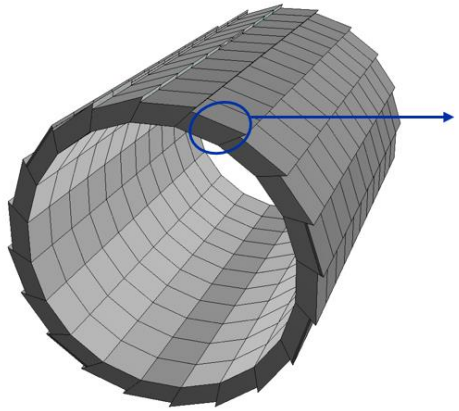


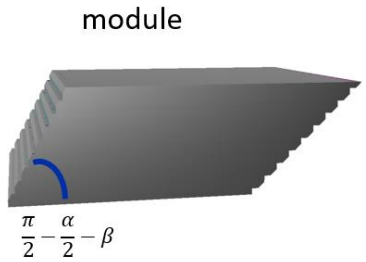
- Crystals arranged to be orthogonal between layers
- Readout from two sides

➢ Optimization and validation



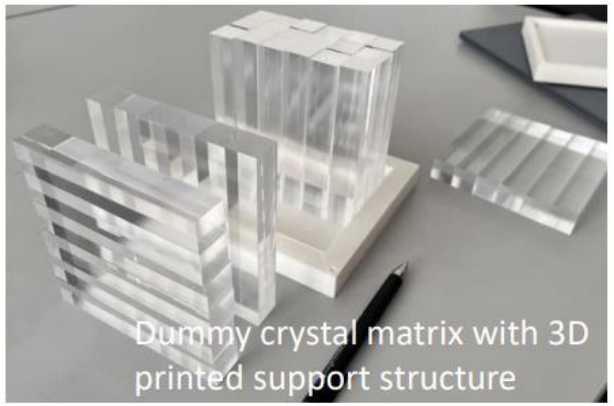


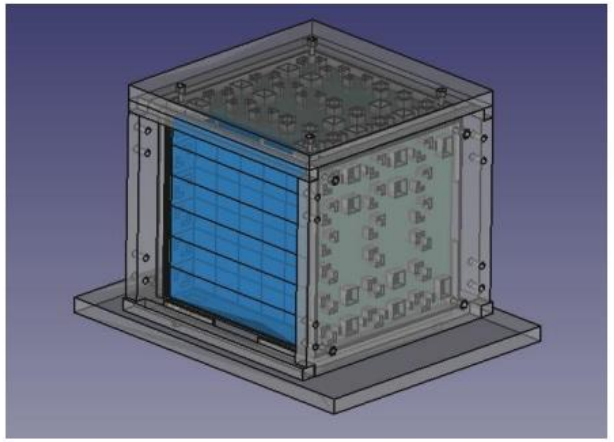




- Dedicated new reconstruction software
- Performance evaluation and optimization

➢ Hardware development

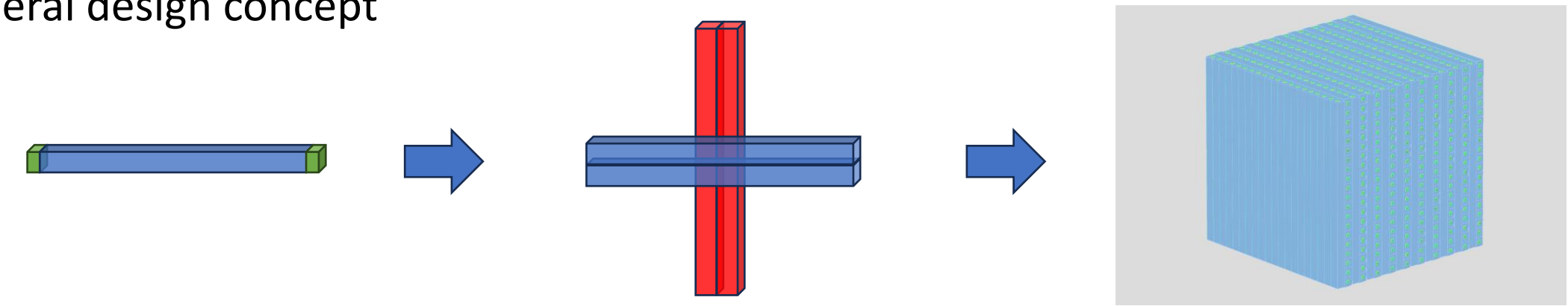




- Development of crystal module(s) for beamtests

Design concept of high-granularity crystal ECAL

- General design concept



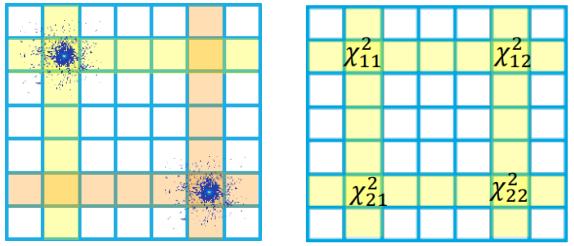
➢ Long crystal bar with 2 SiPMs

➢ Crisscrossed arrangement between layers

➢ Supercell (tower) 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

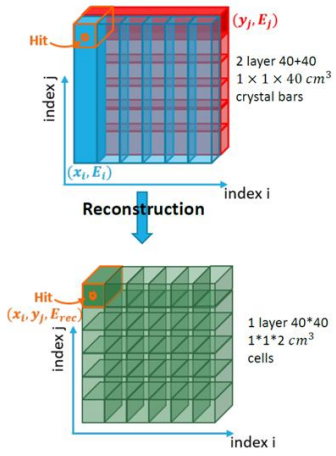
- Challenges
  - Difficulties in the mechanical/geometry design
  - Impact from ghost hits



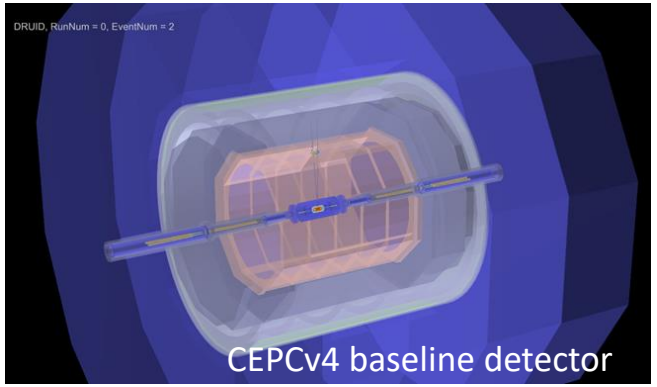
➢ Ghost hits case when 2 or more particles hit on one supercell

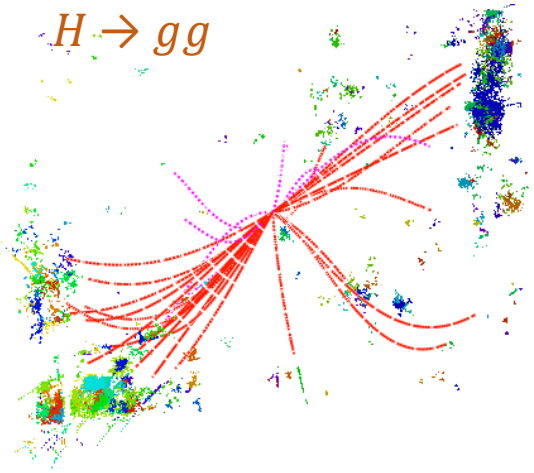
PFA performance with Arbor

- Application and optimization of “Arbor-PFA” under CEPC Software
- Physics performance: Boson mass resolution (BMR)
- Studied with 1 cm^3 crystal cubes



Implementation in CEPC detector **Si-W -> BGO**

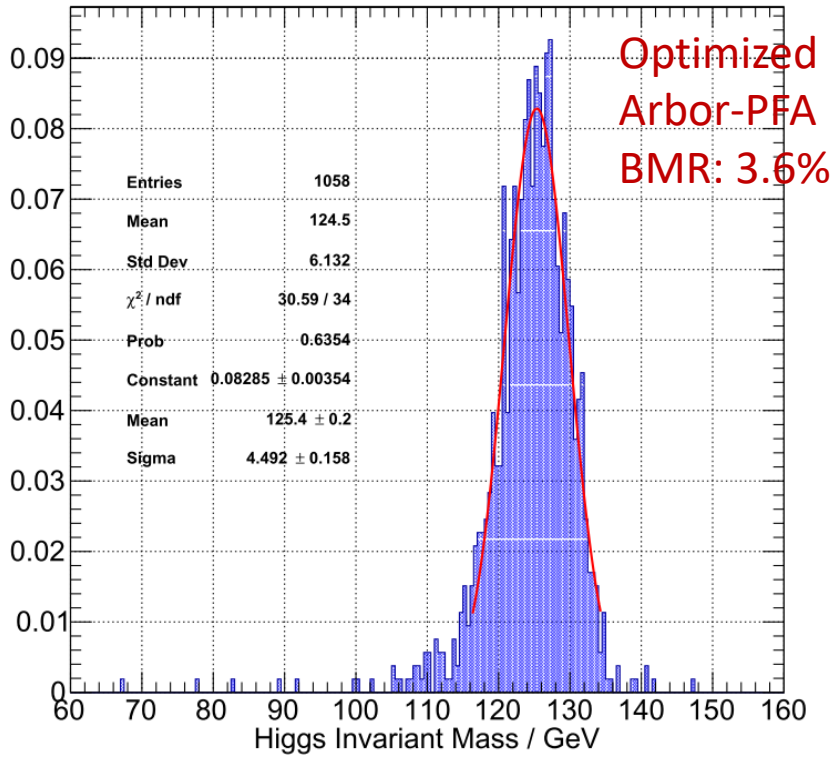




Performance studies with Higgs events

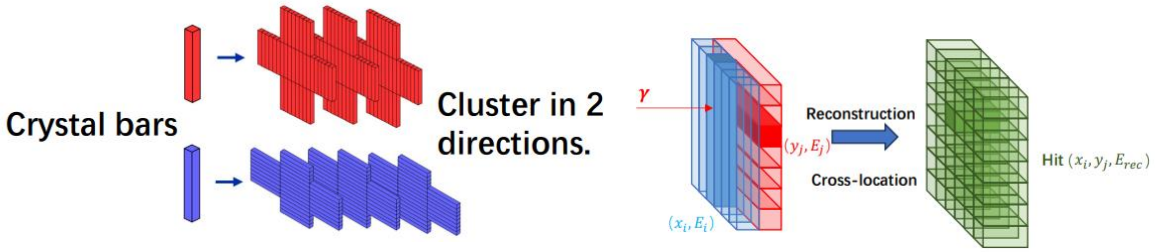
Arbor-PFA: optimized for crystal ECAL design

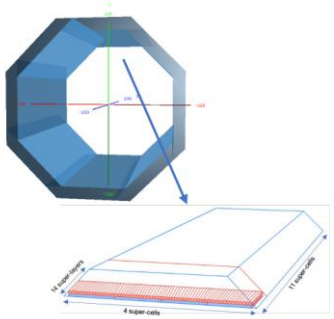
BMR ($H \rightarrow gg$)



Dedicated reconstruction software for crystal ECAL

- New reconstruction software under CEPSW
- Particle reconstruction for long bar crystal ECAL
  - Global clustering





Preliminary geometry

Software task:
- ∗ Clustering
- ∗ Pattern recognition.
  - + Improve the performance.
- ∗ Overlap: energy splitting.
- ∗ Ambiguity problem.
  - + Minimize the impact.

  - Shower recognition

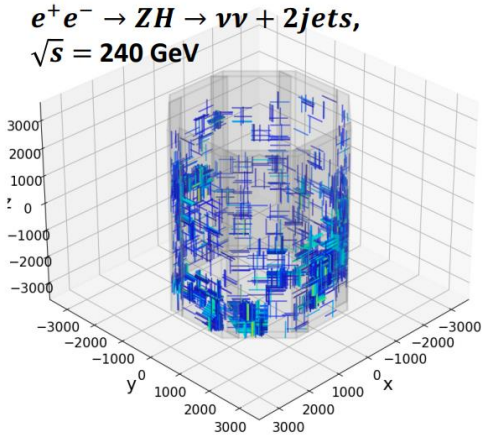
Track matching	Hough Clustering	Cone Clustering
Charged	Photon	Neutron Hadron

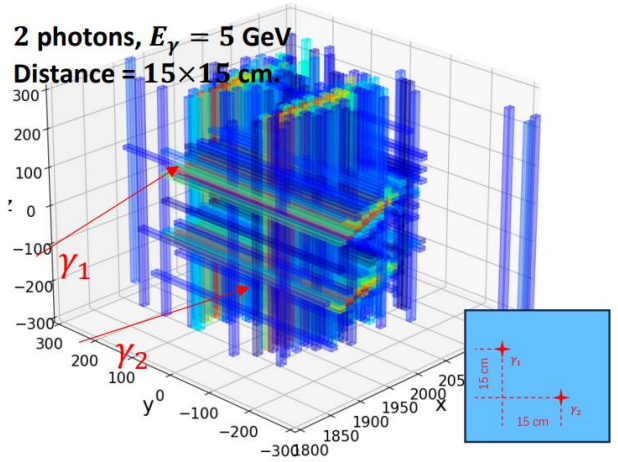
  - Energy splitting

$$\text{Expected energy}: E_{i\mu}^{exp} = E_{\mu}^{seed} \times f(|x_i - x_c|)$$

$$\text{Assigned weight}: w_{i\mu} = \frac{E_{i\mu}^{exp}}{\sum_{\mu} E_{i\mu}^{exp}}$$

Calculate from EM profile



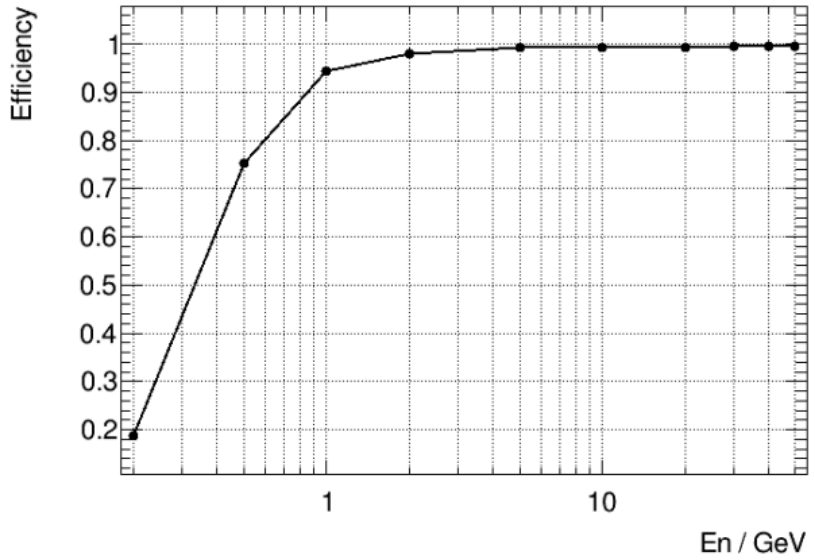


Challenge: ambiguity removal
- Information from track, neighbor tower, time

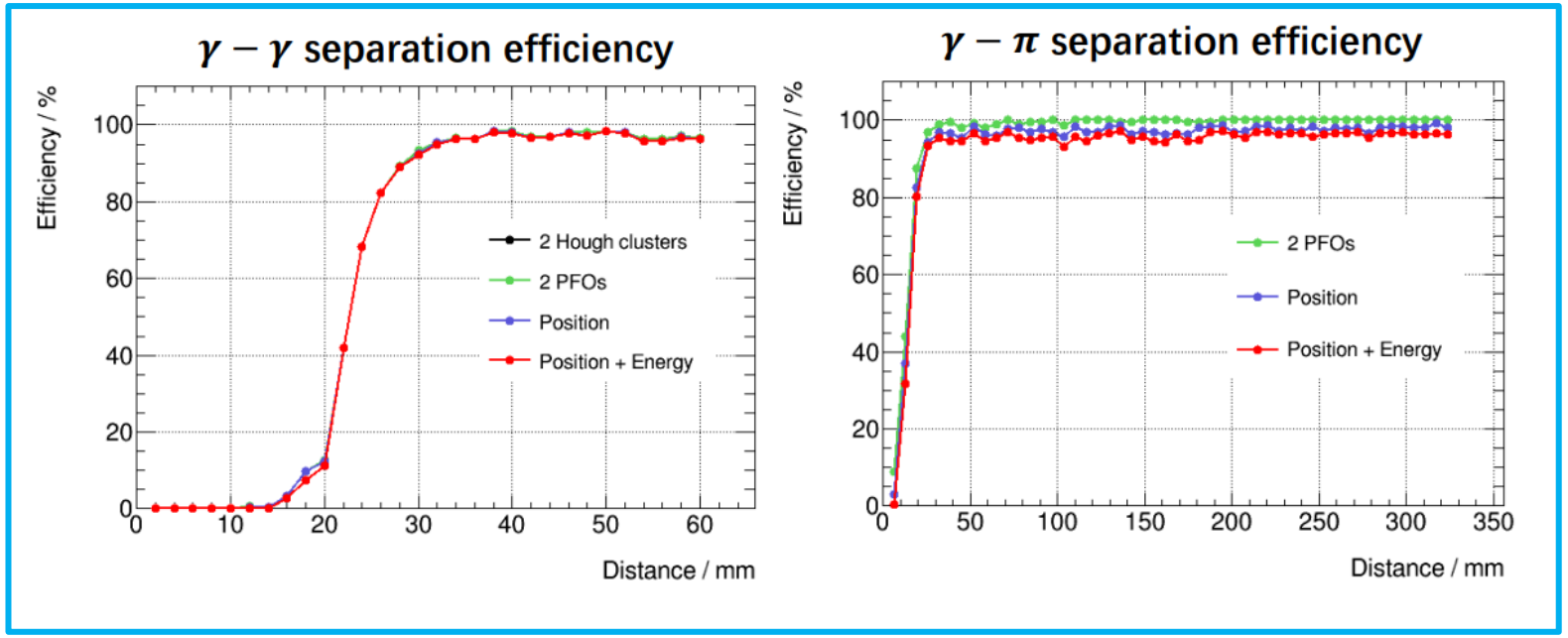
Dedicated reconstruction software for crystal ECAL

- New reconstruction software under CEPSW
- Particle reconstruction for long bar crystal ECAL
- Global clustering -> shower recognition -> energy splitting (ambiguity removal)

Photon reconstruction



Particle Separation

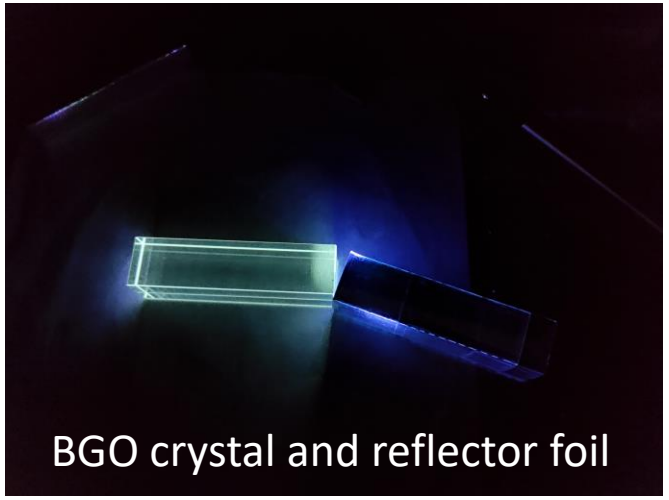


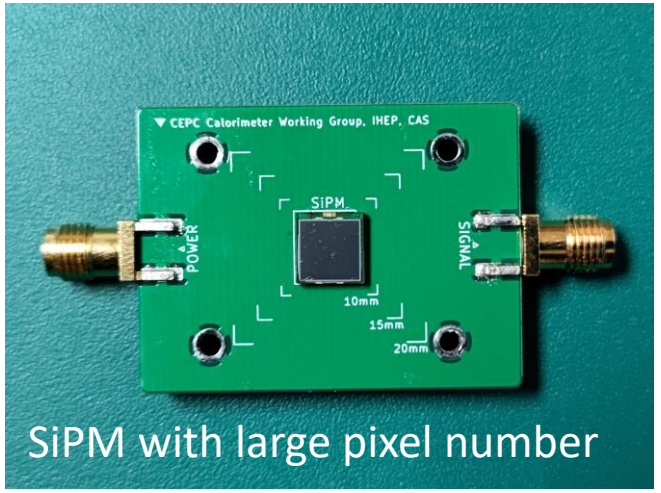
- Recognition efficiency ~100% for a photon with E > 1GeV
- Separation efficiency > 95% with distance > 30 mm

Hardware development 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…

Validation from system level: development of crystal modules


BGO crystal and reflector foil

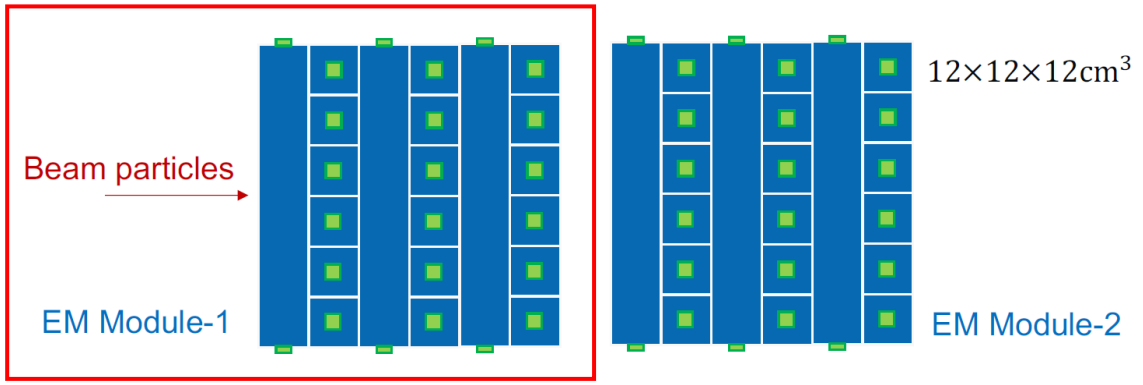


SiPM with large pixel number

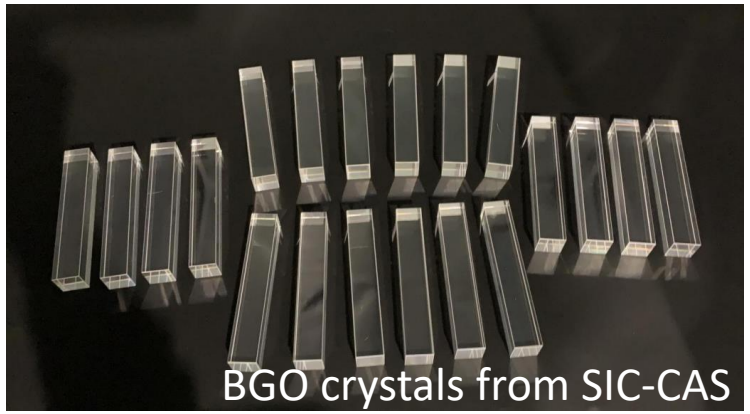

Readout electronics

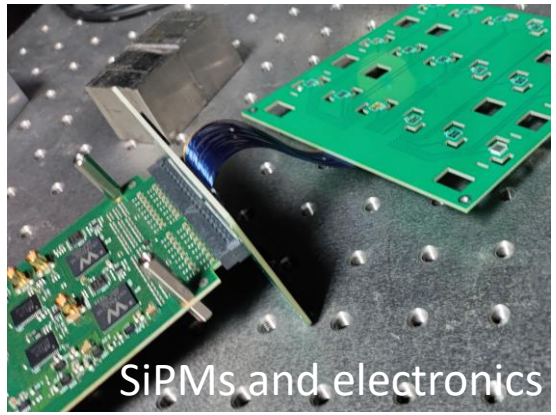
Introduction to the first small-scale crystal module

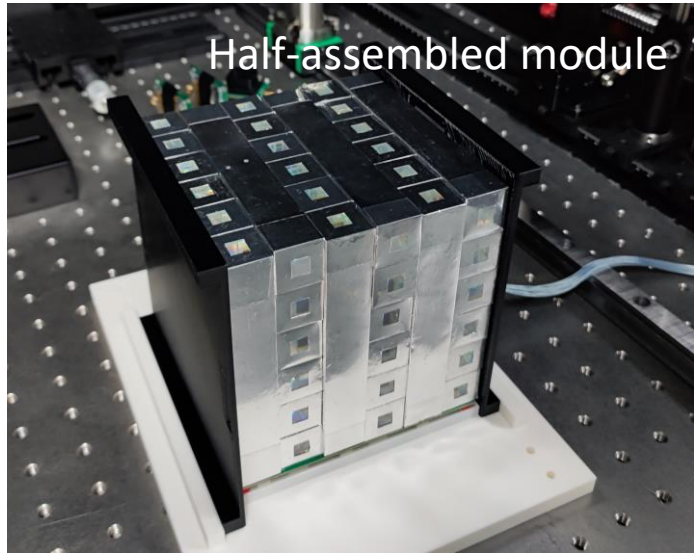
- First $12 \times 12 \times 12$ cm^3 BGO modules development
- Motivations
  - Identify critical questions/issues on system level
    - Mechanical design, PCB and electronics…
  - Evaluate performance with TB data
  - Validation of simulation and digitization
- Beamtest at CERN T9 beamline
  - First beamtest
    - ~10.7 X_0 BGO crystal + HPK S14160-3010PS SiPM
  - Muon, electron and pion data



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





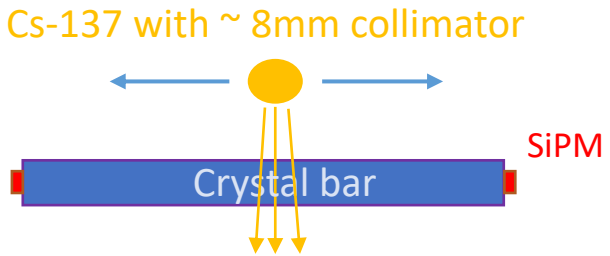


- 36 BGO crystals wrapped with ESR and Al foil
- 72 HPK S14160-3010PS SiPMs
- 3D printed support structure

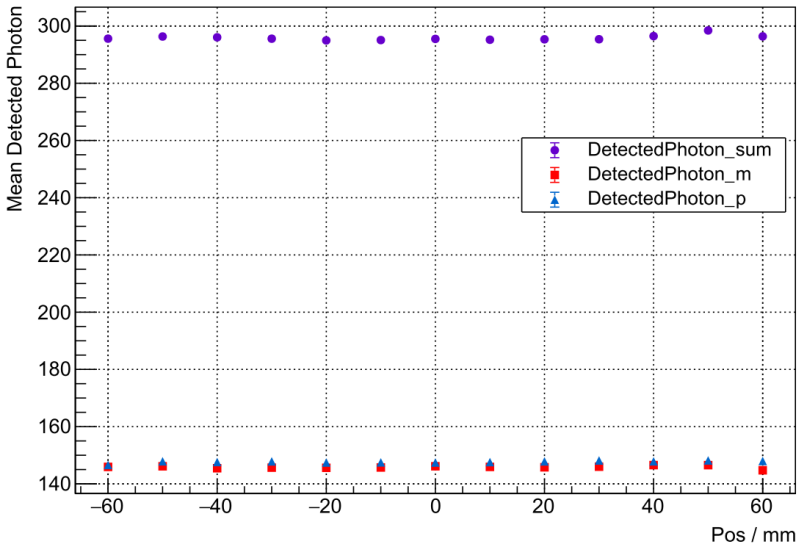
Uniformity scan of BGO crystal bars

Zhikai Chen (USC)

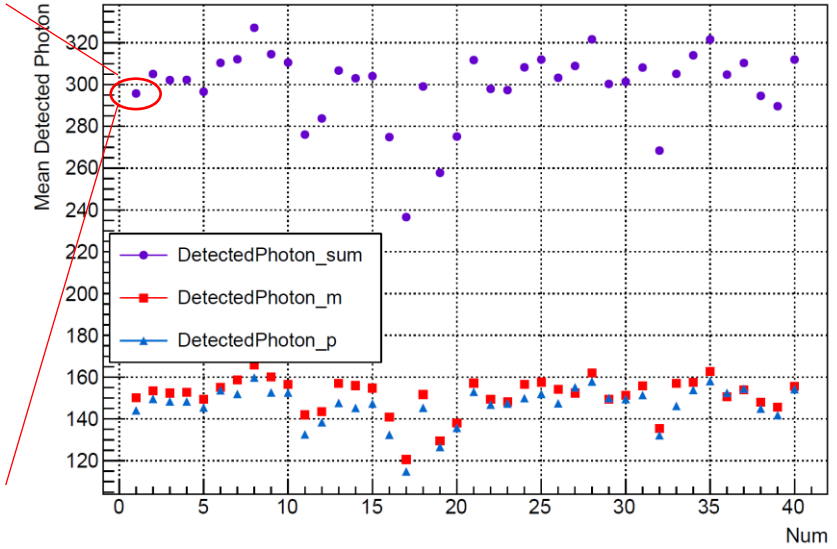
- Batch test of SIC-CAS BGO crystal bars
  - 40 crystals with ESR and Al foil wrapping
  - Scan with Cs-137 radioactive source

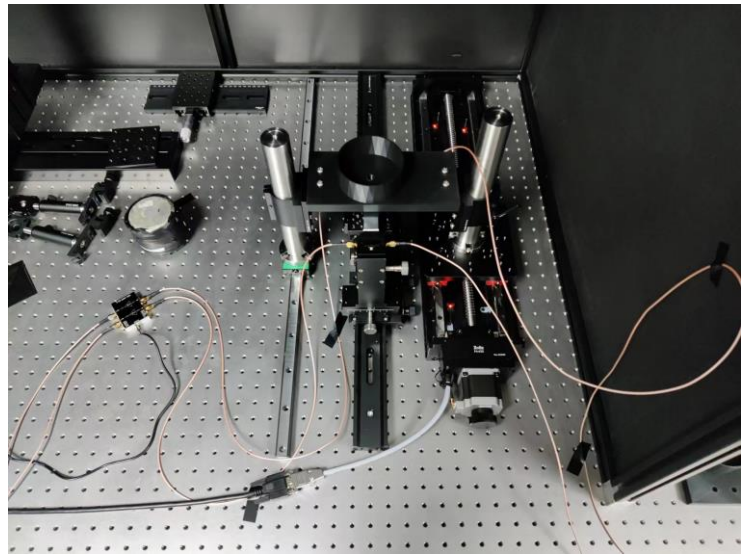


Response uniformity along #1 BGO bar



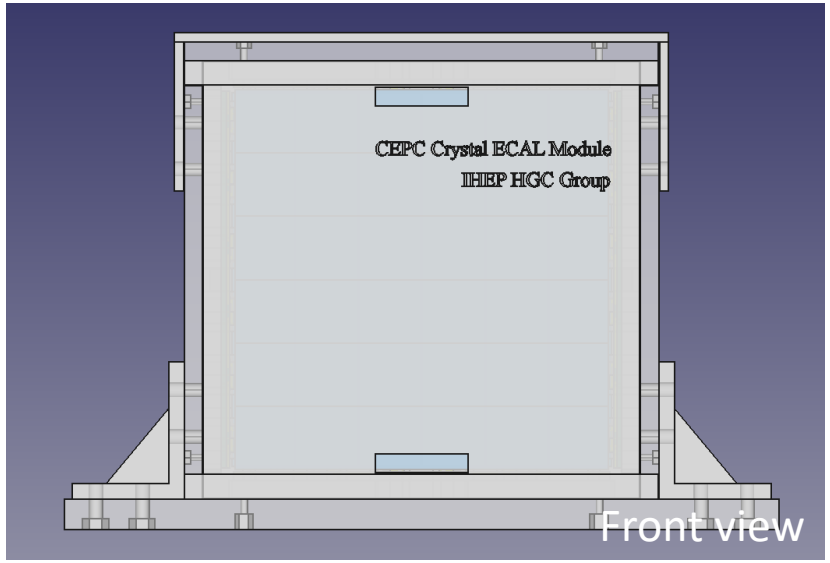
Comparison of 40 crystal bars

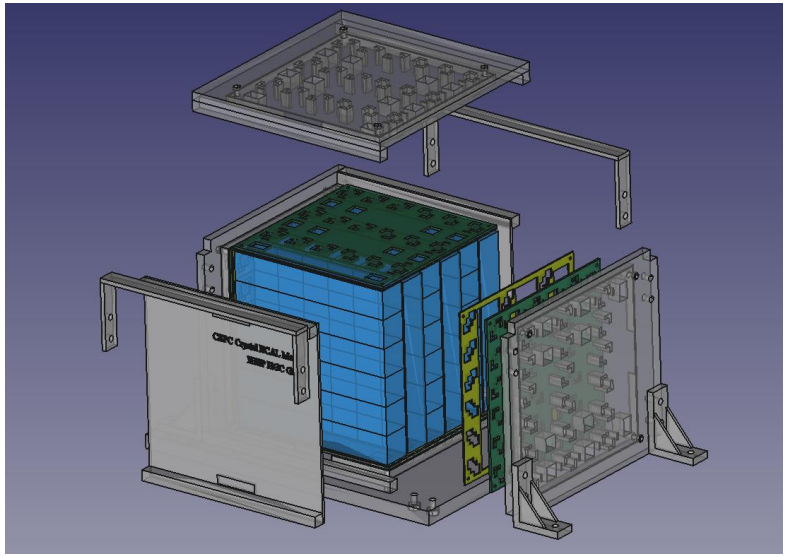


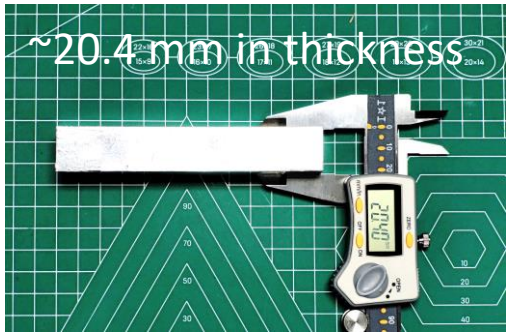


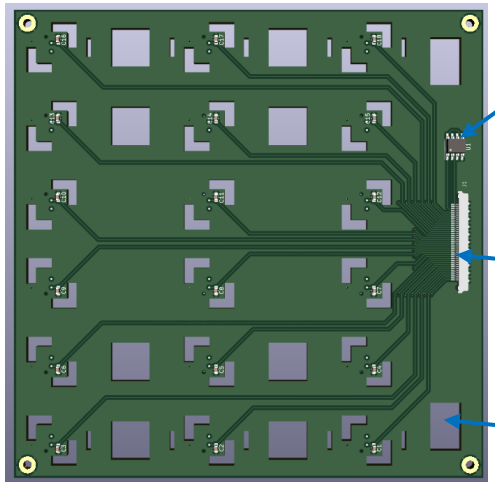
- Generally good uniformity along a single bar
- Response varies among bars, 36 crystals were selected for beamtests

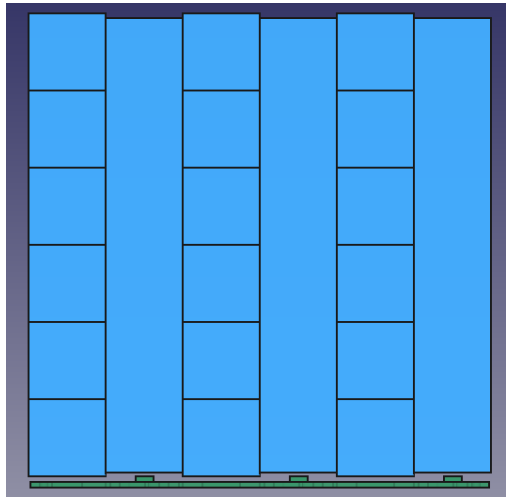
Mechanical and PCB design









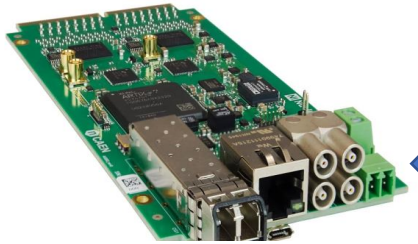


- Difficulties with module development
  - Mechanical design is unusual
  - PCB is non-load-bearing and should be decoupled
  - Module assembly

Electronics and trigger scheme

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

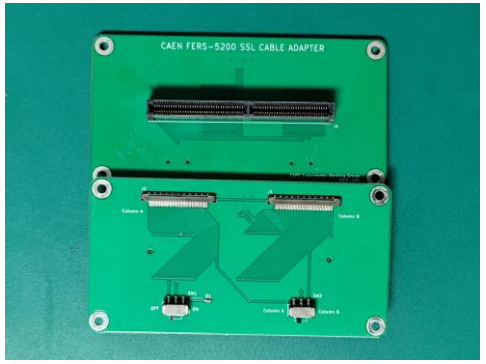
36/64 channels used

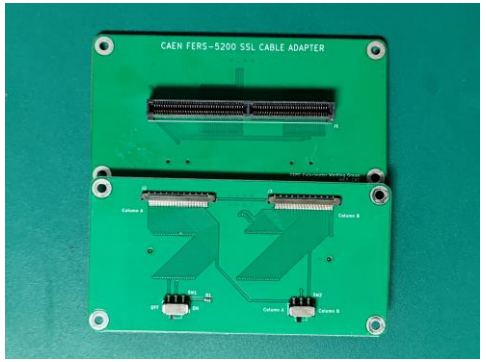


36/64 channels used

CAEN A5202 units
Built-in HV power supply

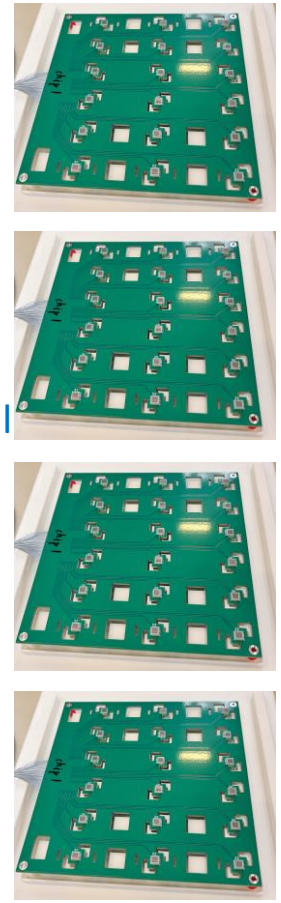
Daisy chained
trigger distribution





Self-designed
adapter boards

Micro-coaxial
cables

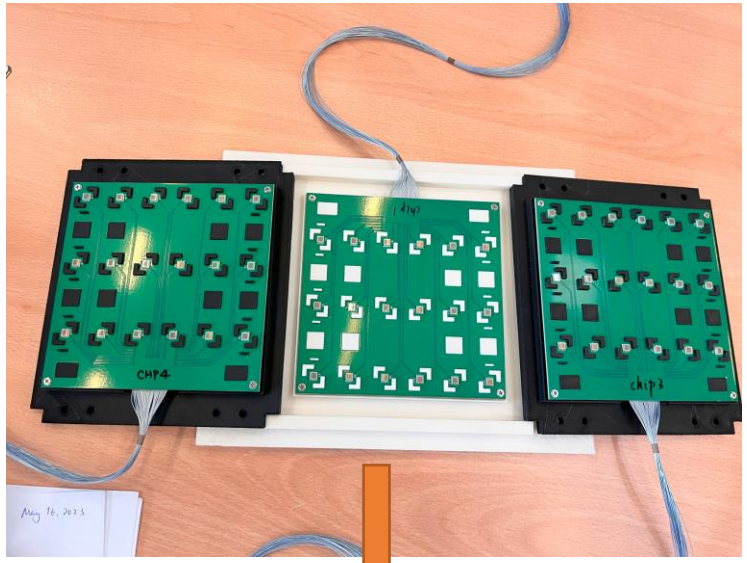


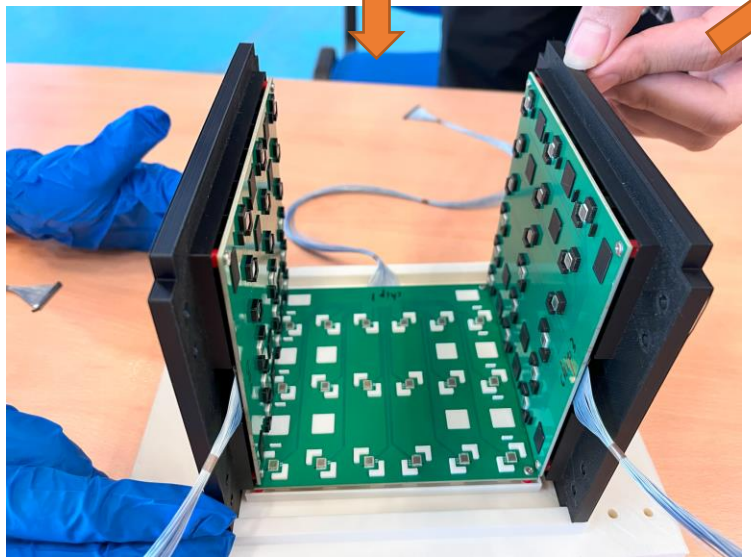
4 PCBs with 18 SiPM channels
(HPK S14160-3010PS)

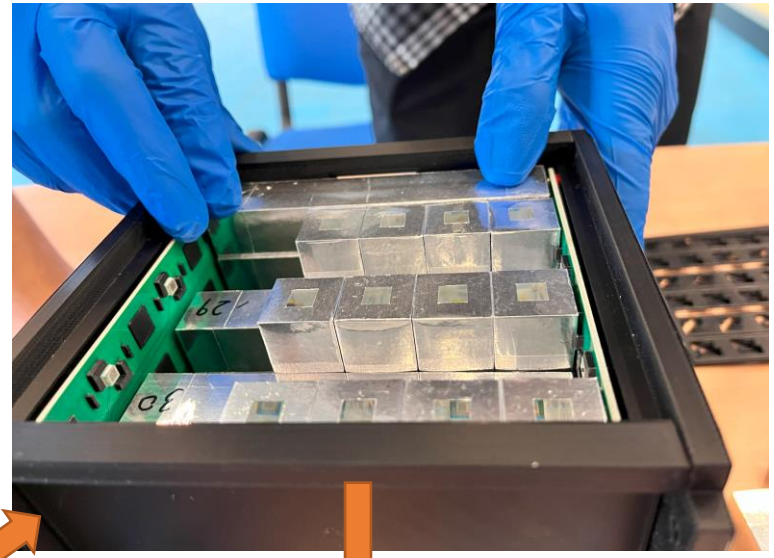
External triggers from plastic scintillators
(Event synchronization of 2 units: triggers within 20 ns)

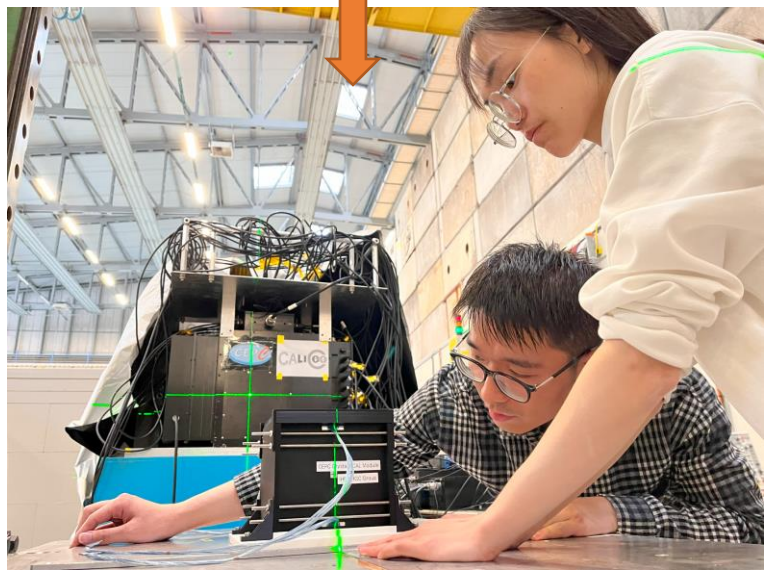
Beamtest: installation of module

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

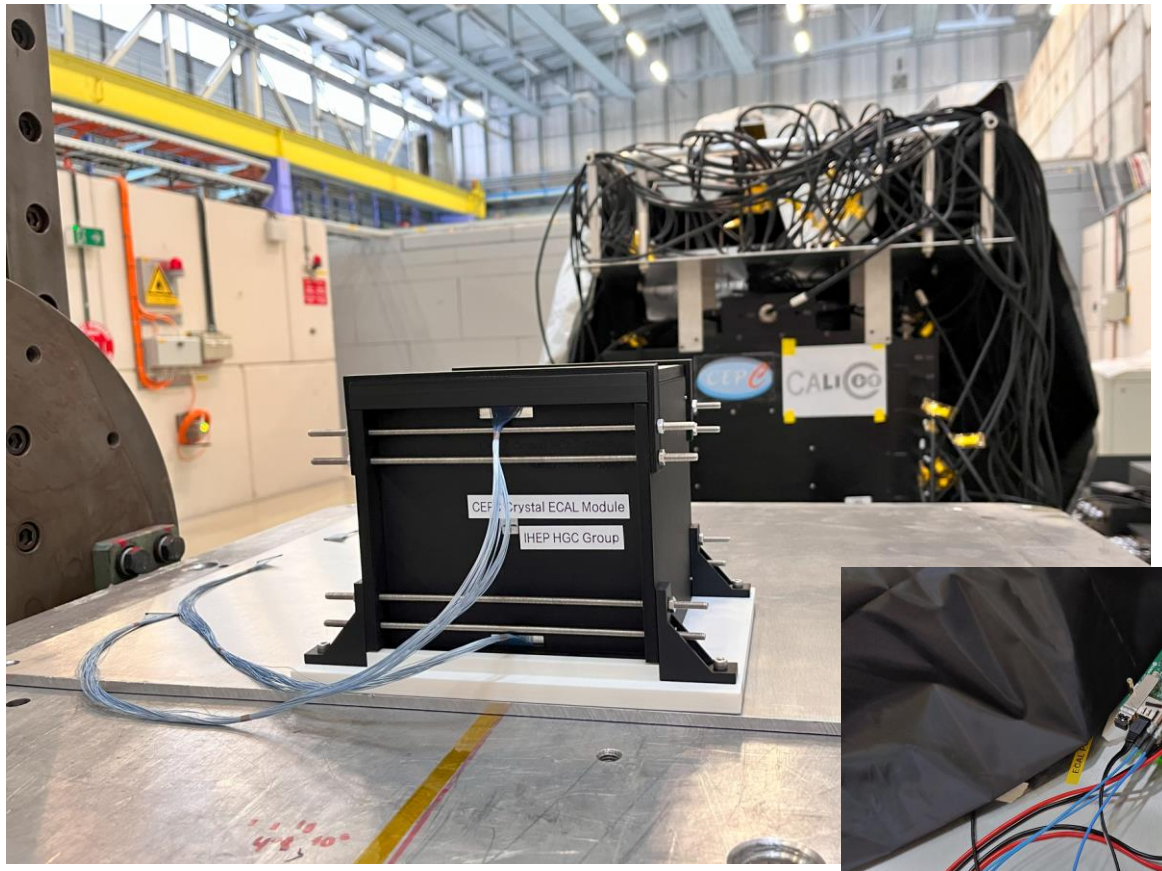


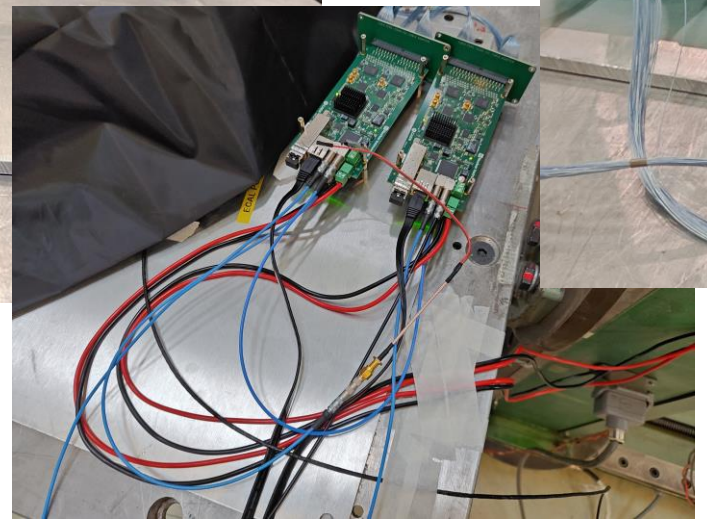


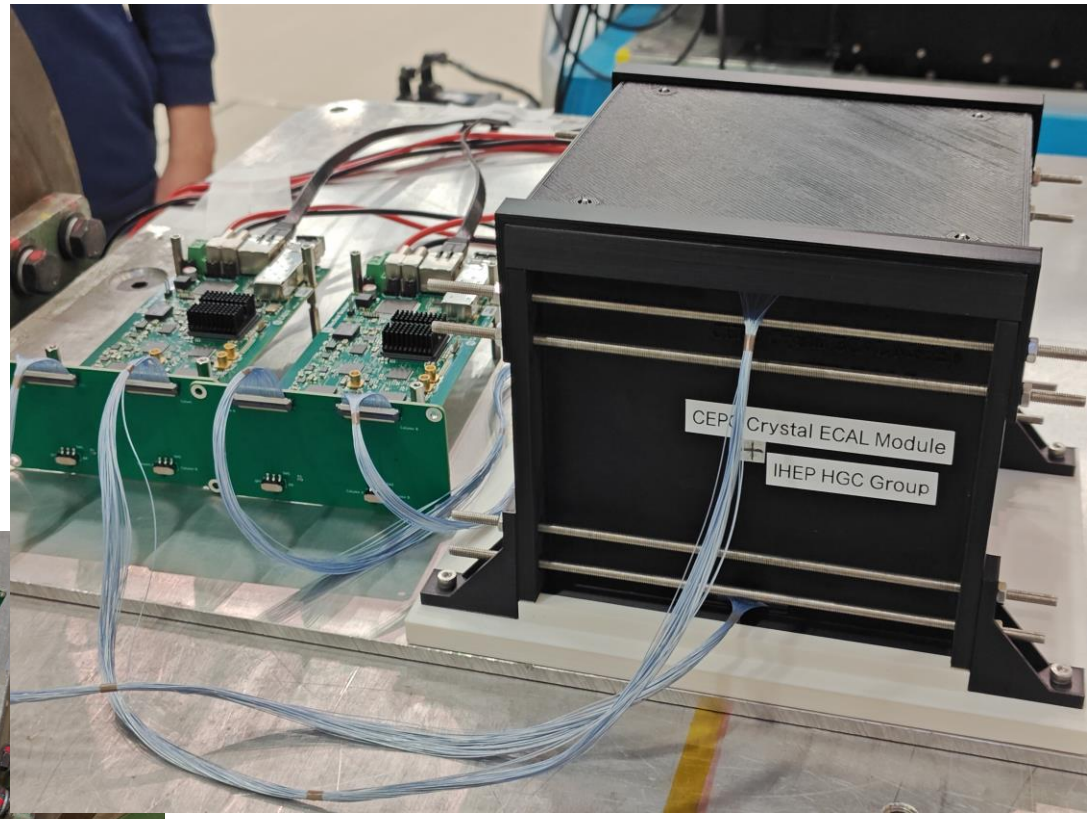




Beamtest: installation of module



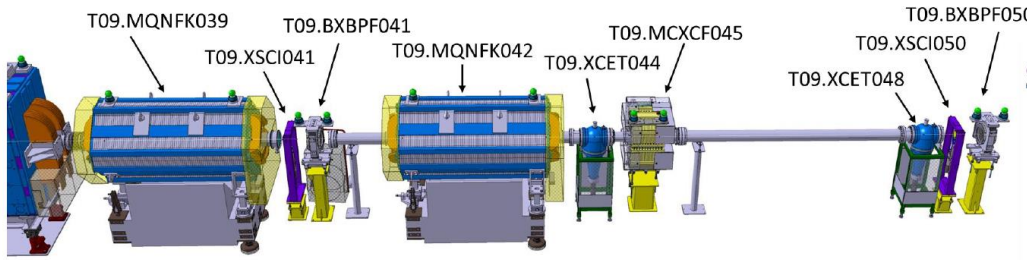


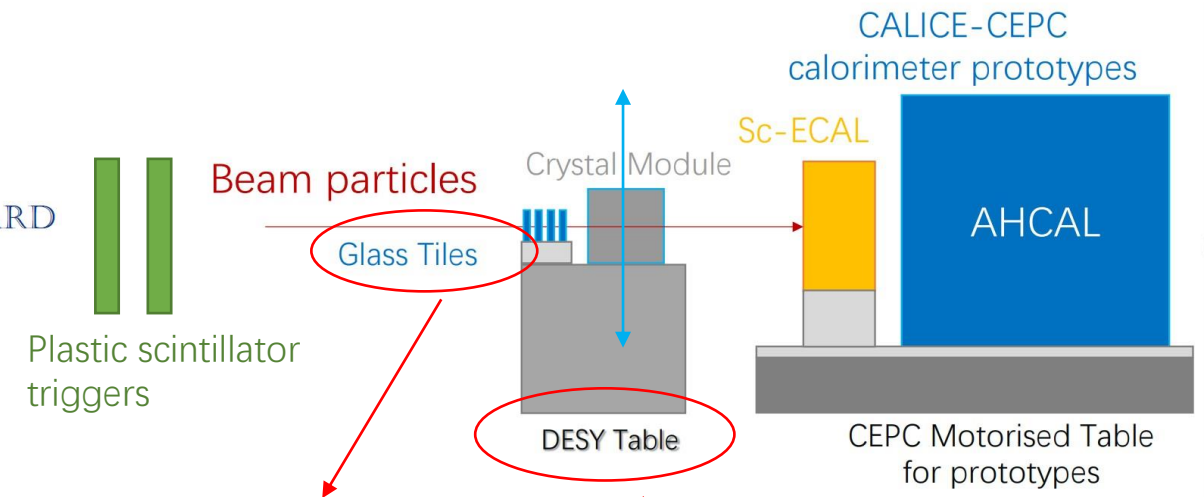


Parasitic runs with CEPC calorimeter prototypes

Beamtest 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

Beamtest 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

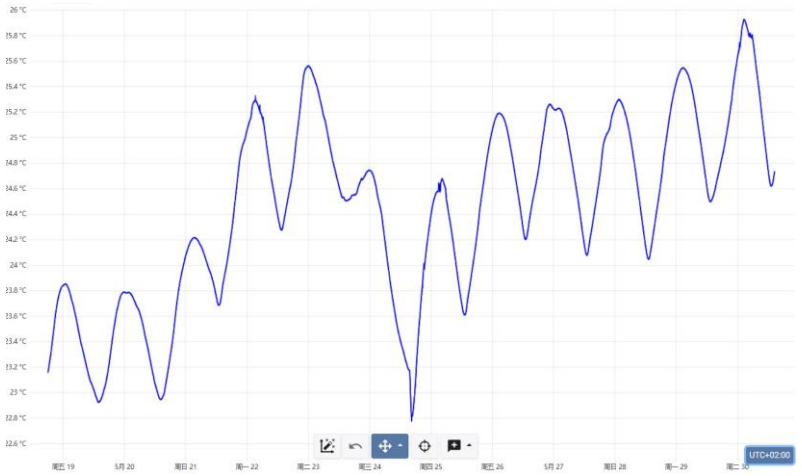
- 0.5~5 GeV/c electron beam: energy response
  - ~980k events acquired

→

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

- Other data
  - Pion- data for high fluence test
    - > 80% trigger loss at ~20 k events per beam spill
      - Performance of A5202 units: ~4-5 kHz under current beam status: dead time + event synchronization….
  - Self-trigger of “leaked particles” from upstream
    - Muon events can be clearly observed
  - Temperature monitoring data

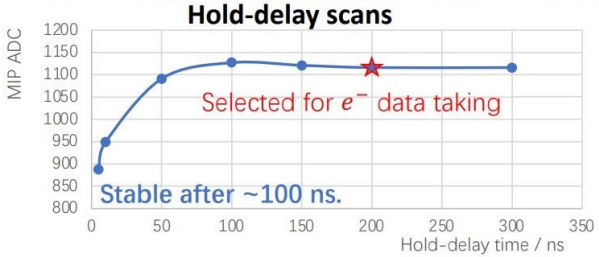
➢ ~2℃ temperature change during the beamtest



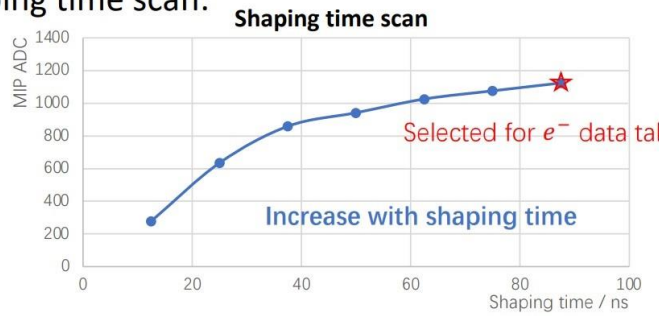
Muon data for parameter scans and calibration

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

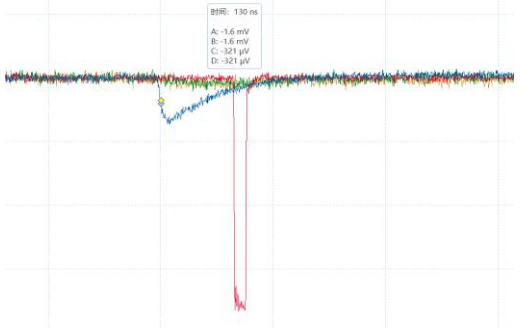
- Hold-delay time scan:
  - 10 GeV muon, HG 59, LG 63, scan from 5 ns to 300 ns.

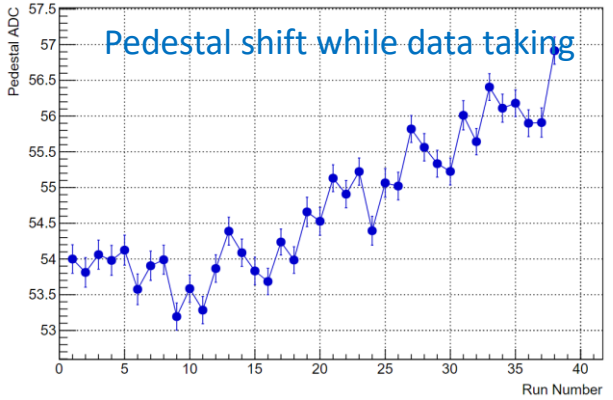


- Shaping time scan:

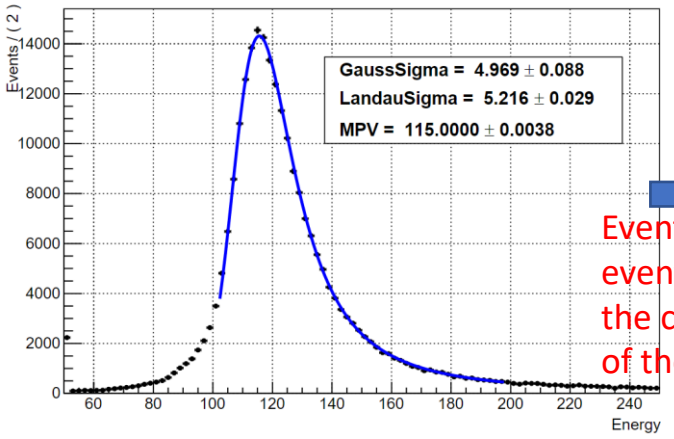


Delay of external trigger: ~130 ns



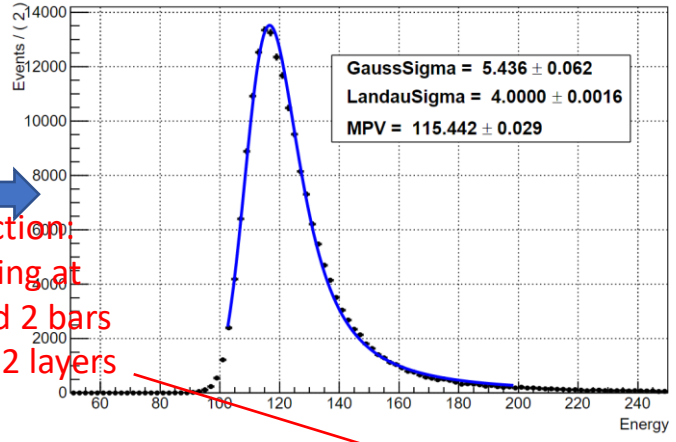


Energy Deposition 10 GeV Muon-

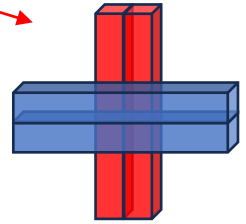


Event selection:
events hitting at
the centred 2 bars
of the first 2 layers

Energy Deposition 10 GeV Muon-



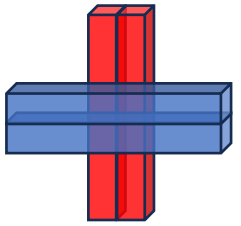
- Successfully acquired muon data with good quality
- Selected parameters for electron data taking
- Channel-by-channel calibration completed

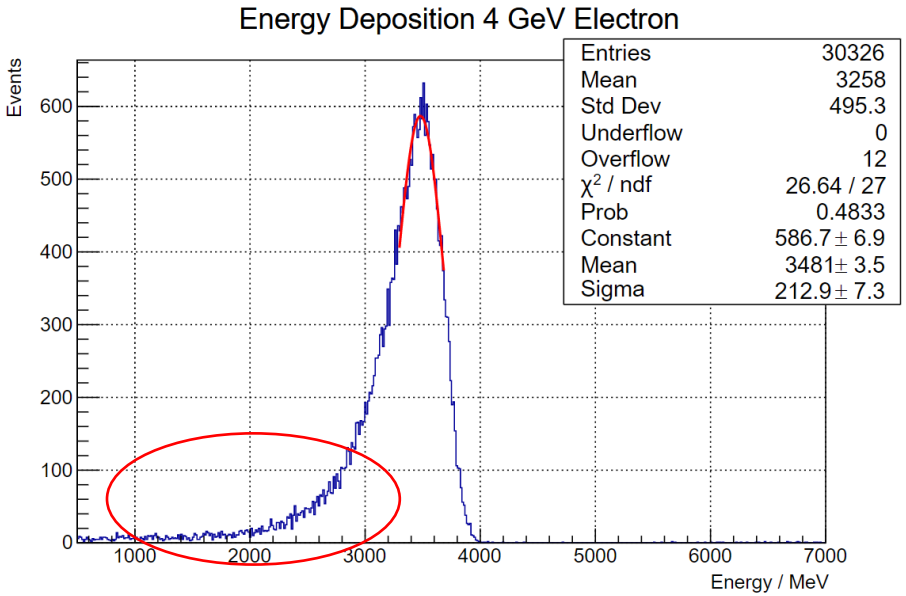


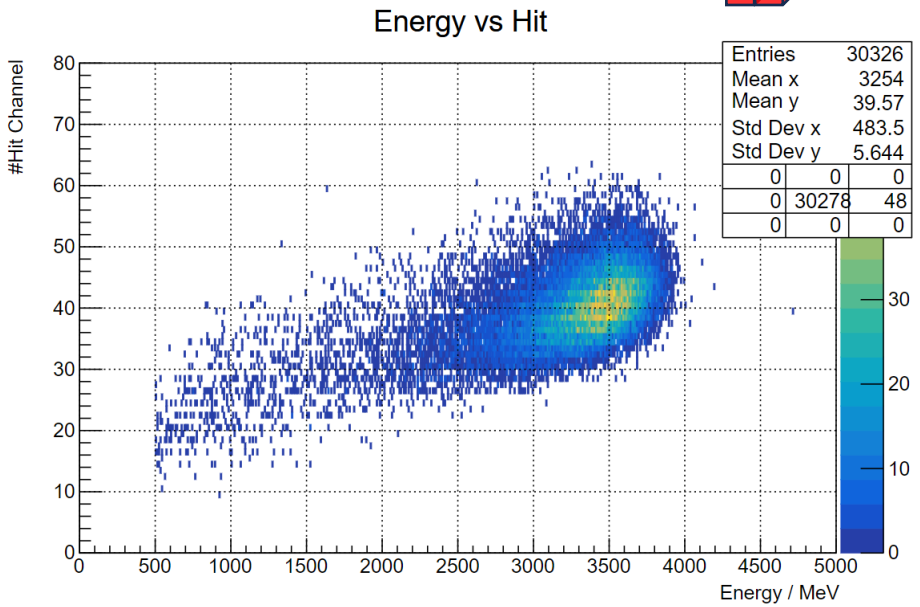
Electron data: energy response

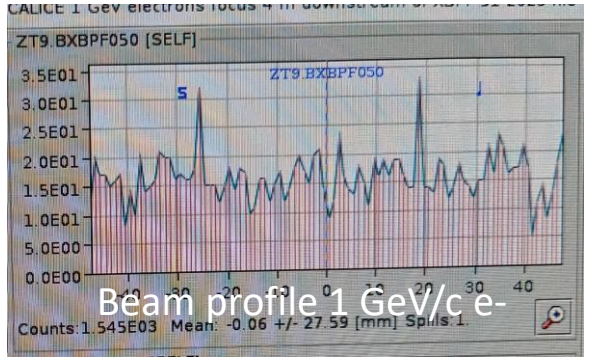
- Data: calibrated channel-by-channel with muon events, 0.5MIP threshold
- Event selection: hitting at the centre of the module

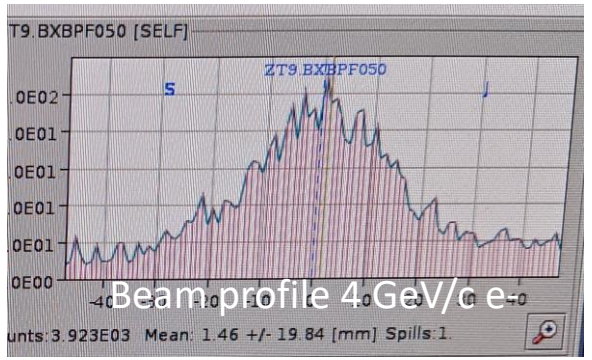
➢ Events hitting at the centred 2 bars of the first 2 layers









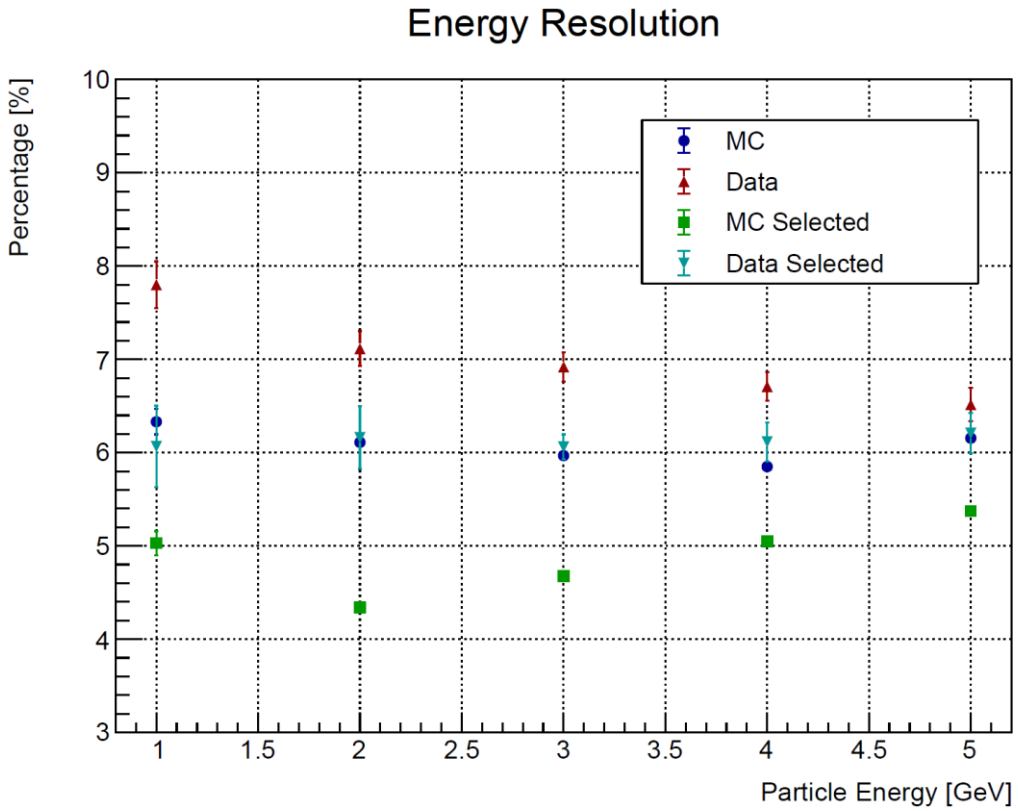


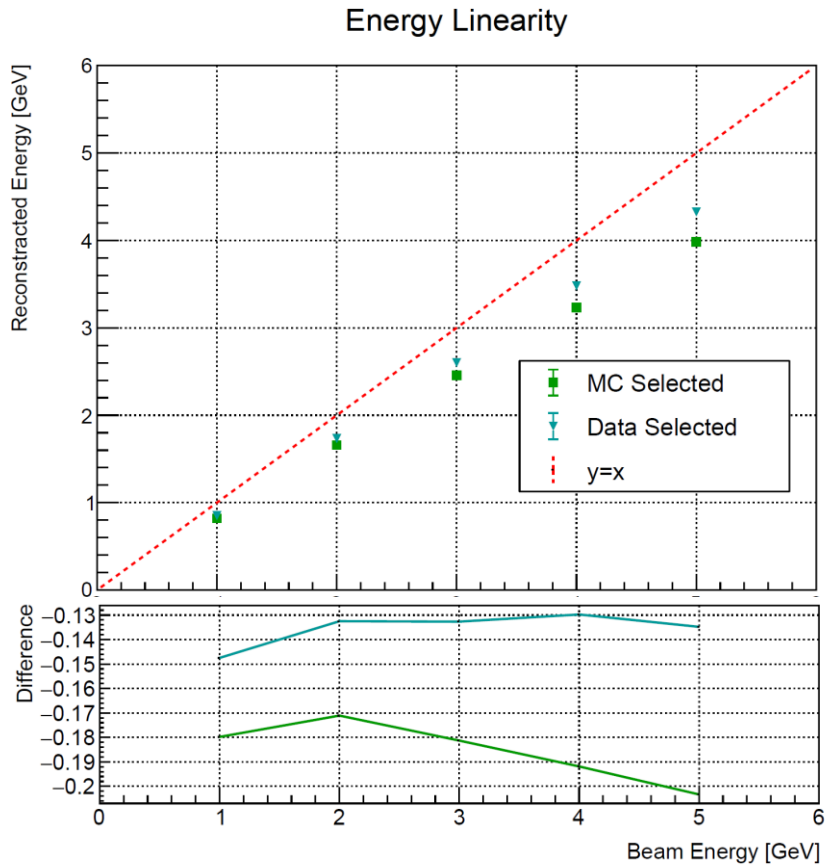
➢ Beam profile: severe changes in the spatial distribution of the beam spot

- Still significant energy leakage after event selection
- ~10.7 X_0 BGO module is not enough for energy measurements

Electron data: energy resolution

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



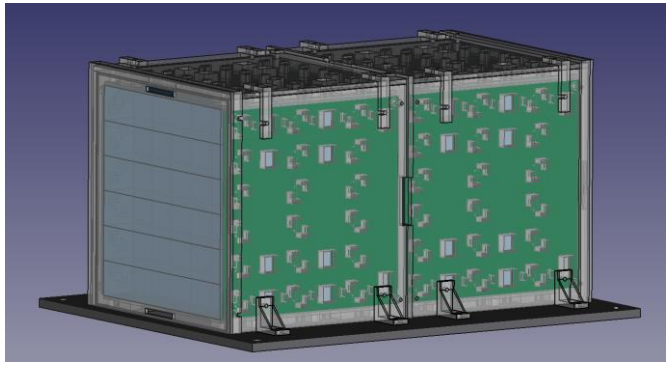


- Energy resolution of Data is worse than MC
- Data shows better energy linearity and larger mean value of energy
- Further check and improvements on data:
  - Studies on crosstalk, temperature calibration…

Plan of the second beamtest at DESY

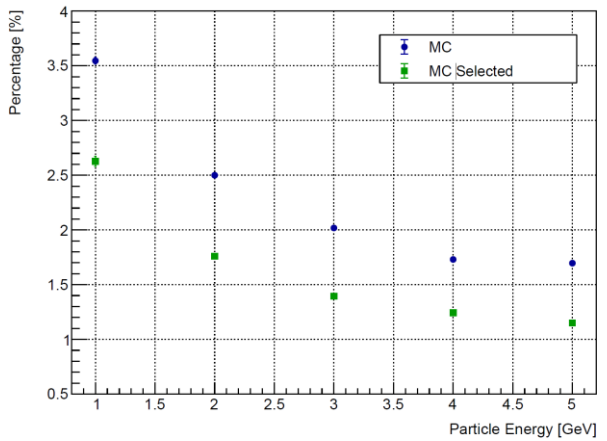
DESY TB22 CALICE-Crystal beamtest in October

- Uniformity scan of all 80 crystals (Done)
- Support structure for 2 modules (Done)
- New PCBs: reduce noise and crosstalk (Done)
- 1 cm^3 plastic scintillator: better collimation (Done)
- Final beamtest timetable (In progress)



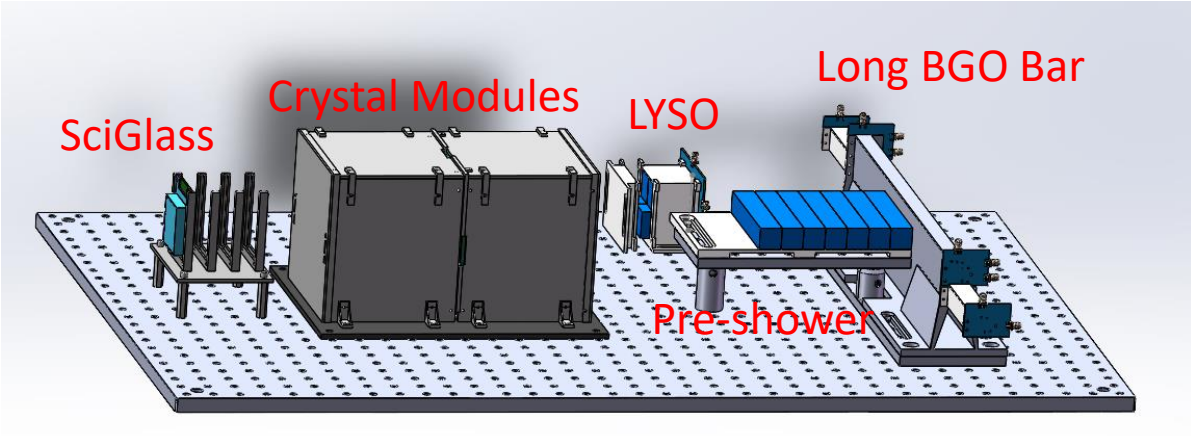
➢ 2 modules in serial

Expected energy resolution of two modules



Other targets

- Timing studies with 40/60 cm long crystal bars
  - Timing performance for MIP/shower
  - Time resolution of 2 cm BGO as reference
- Scintillating glass
- LYSO with MPT2321 electronics



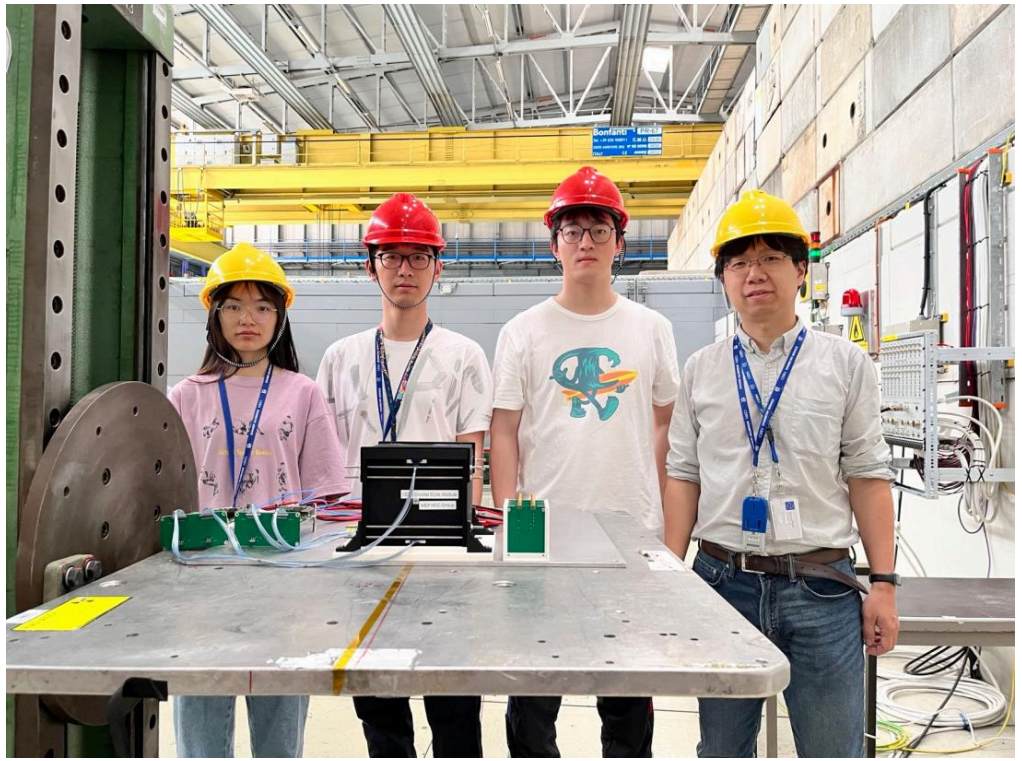
➢ Overview of the planned beamtest setup at DESY

Summary and prospects

High-granularity crystal ECAL R&D status

- Updates on dedicated reconstruction software
- A crystal module was developed, and the first beamtest was successfully completed
- Preliminary performance study has been done

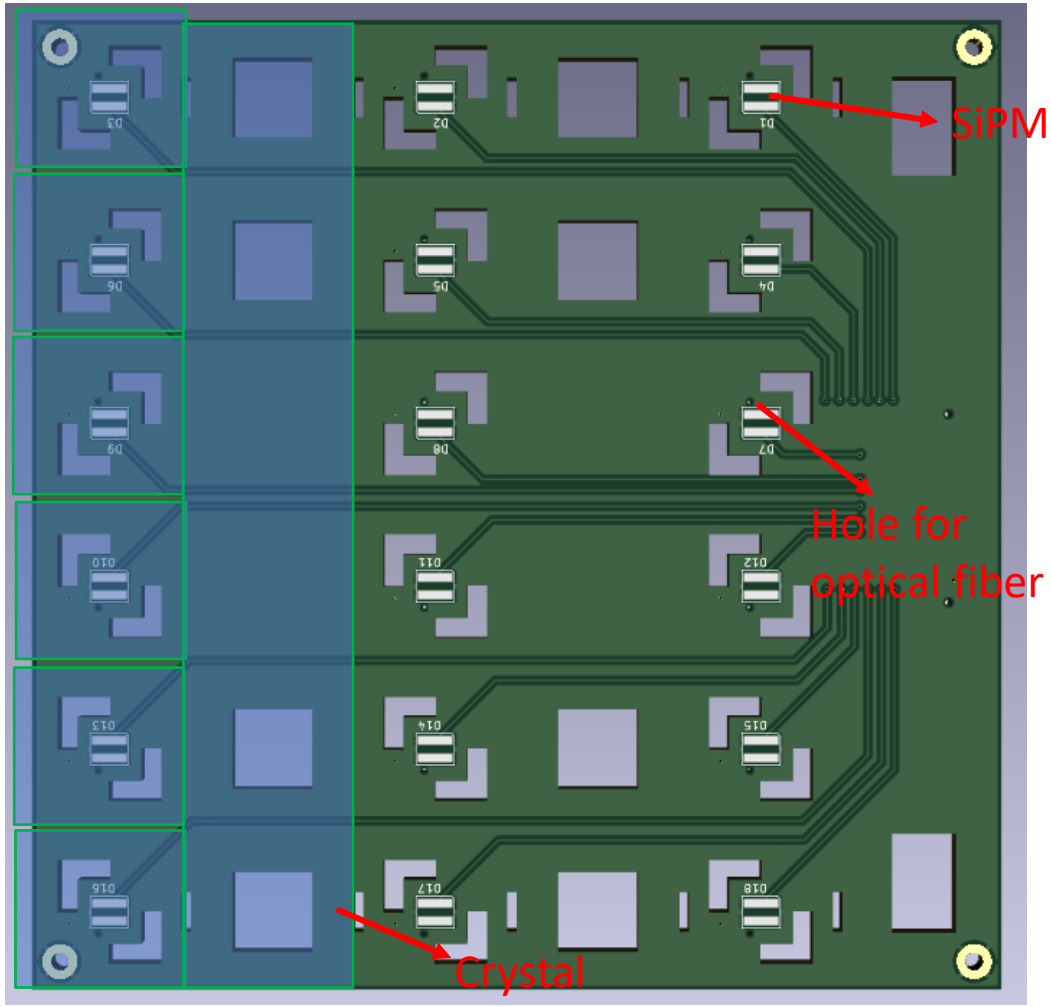
- Further analysis of beam data
- Upcoming second beamtest at DESY
  - Energy measurement with two modules
  - Time resolution study with long crystal bars
  - …



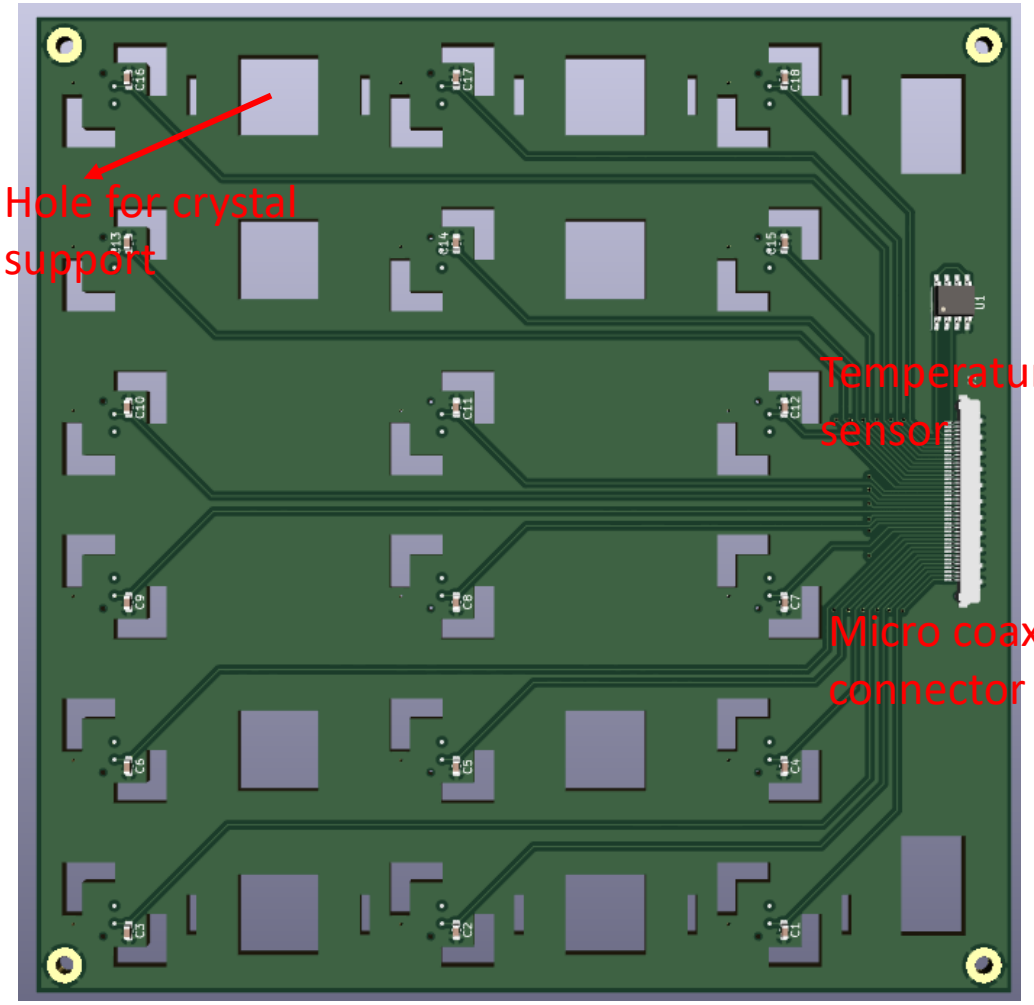
Thanks to every teammate for their contribution!

Backup

PCB layout



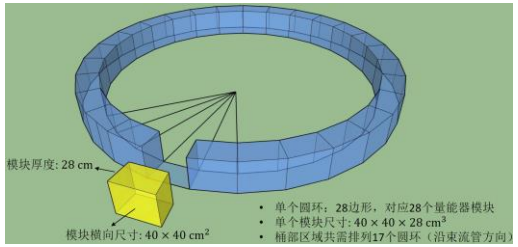
Front side



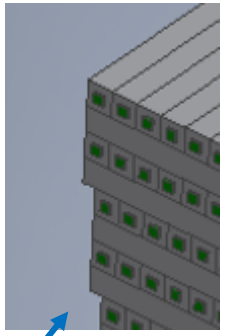
Back side

General geometry design for crystal ECAL

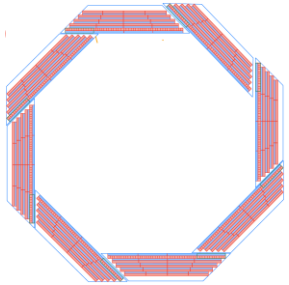
- CEPC crystal ECAL barrel geometry design
  - Finer segmentation of towers for better homogeneity
  - Decrease outer radius for lower cost of the outer detectors
  - 28 towers per ring, 17 rings along beam direction
  - ~25 radiation length: 28 layers



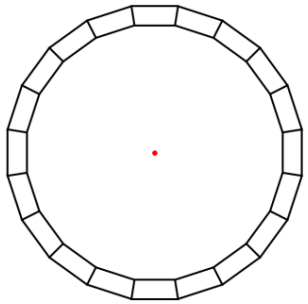
Quan Ji, Chang Shu (IHEP)



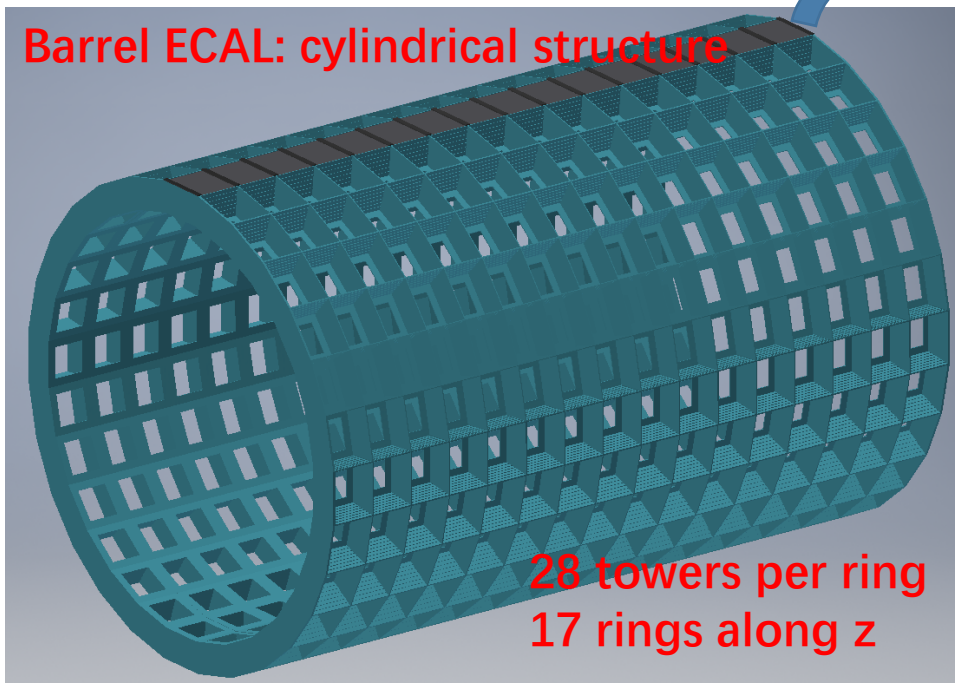
4 layers per “step” with the same transverse size

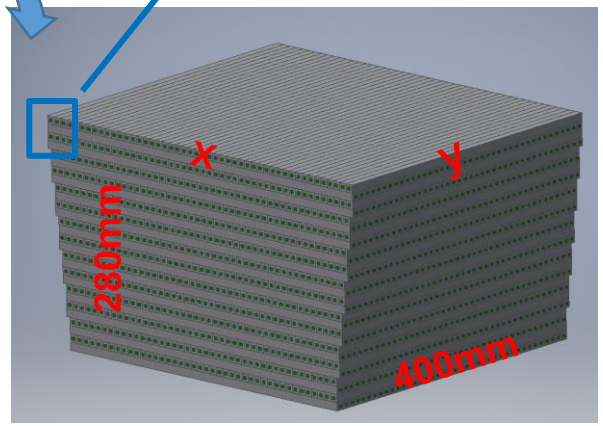


Previous design: octagonal detector



New design: cylindrical crystal ECAL





Key questions
- Space for electronics and cooling
- Assembly

General geometry design of crystal ECAL

- Mechanical assembly: PCB and crystals

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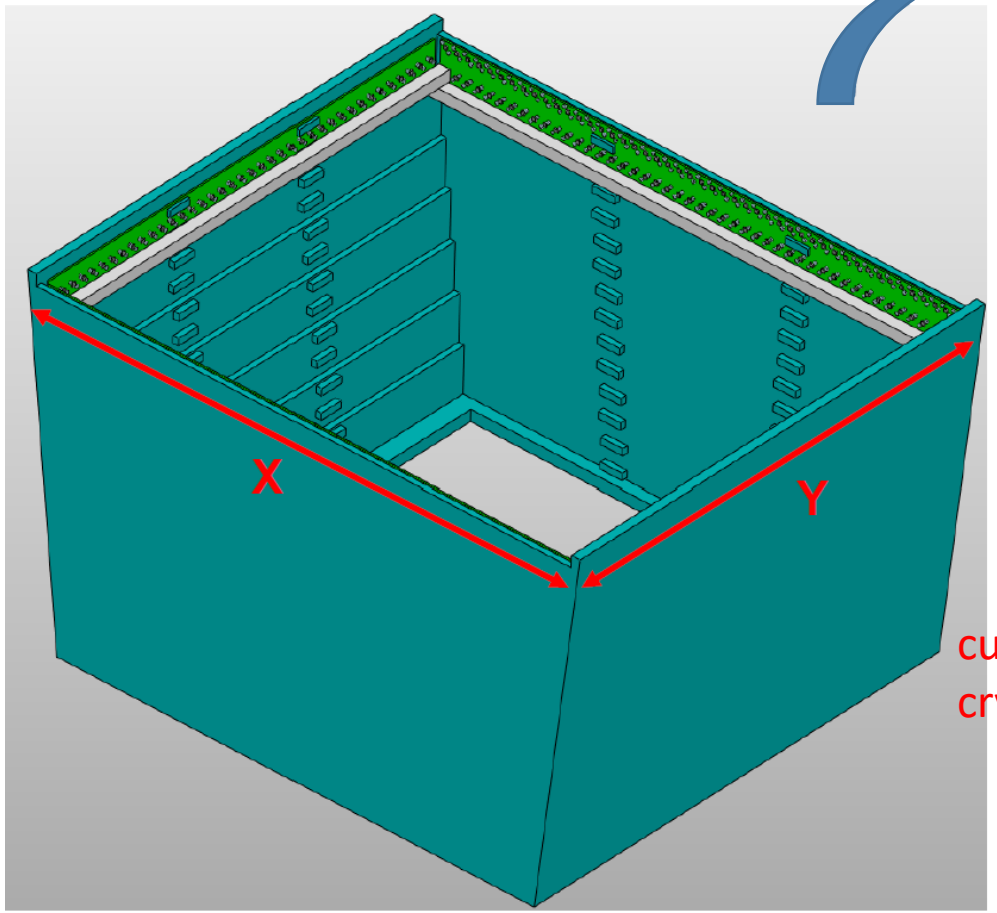
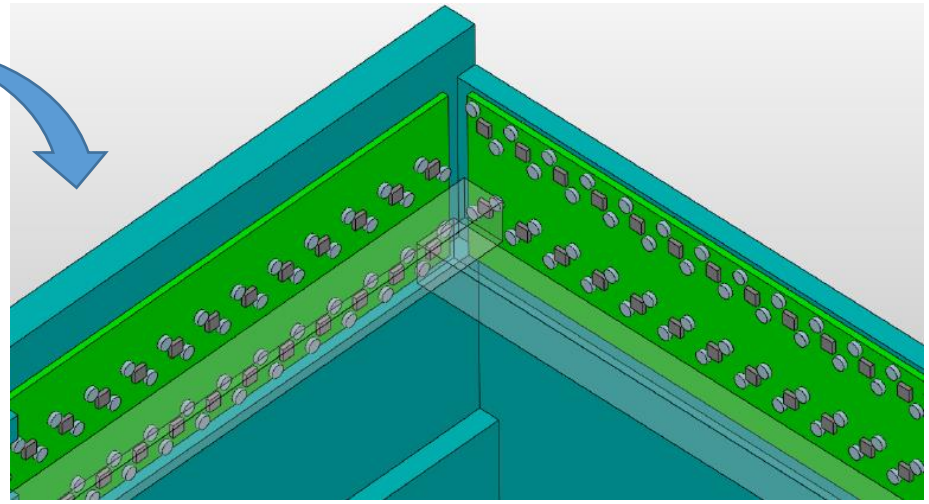
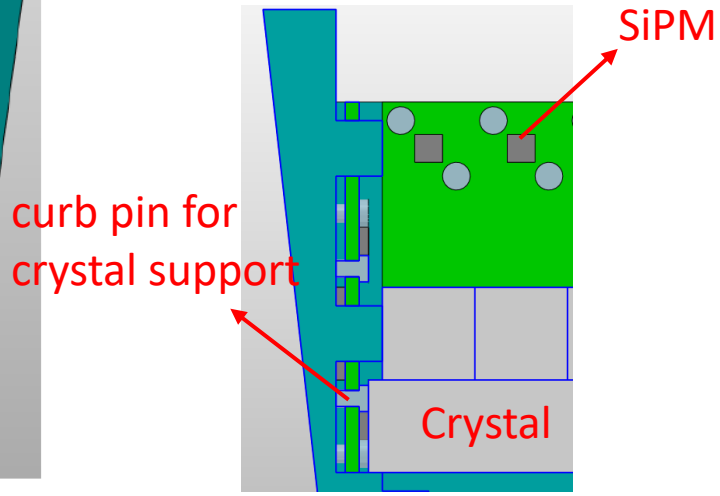






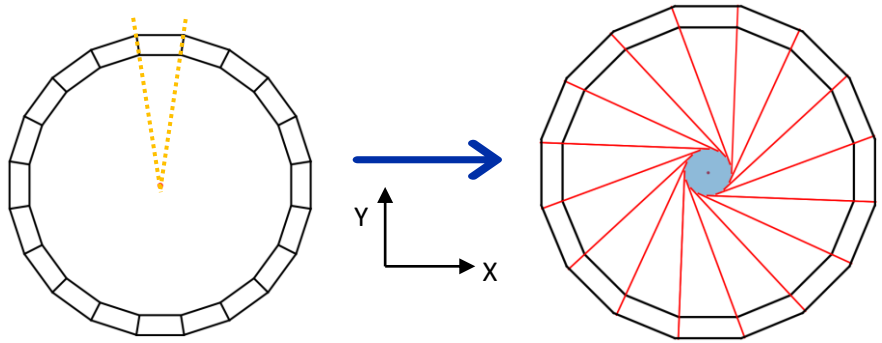
Total mass of the crystals in one tower: 380 kg

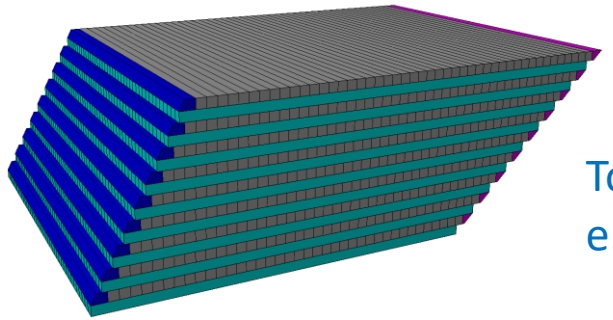
- PCB cannot bear the weight of crystals
- Holes on PCB for external support structure

General geometry design of crystal ECAL

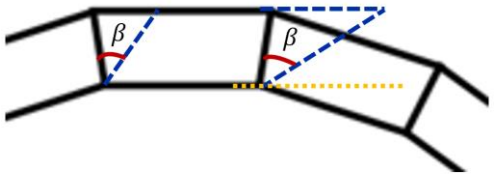
- Energy leakage study: geometry optimization
- Avoid cracks pointing to the interaction point

Weizheng Song (IHEP)

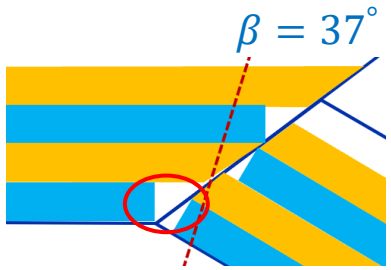


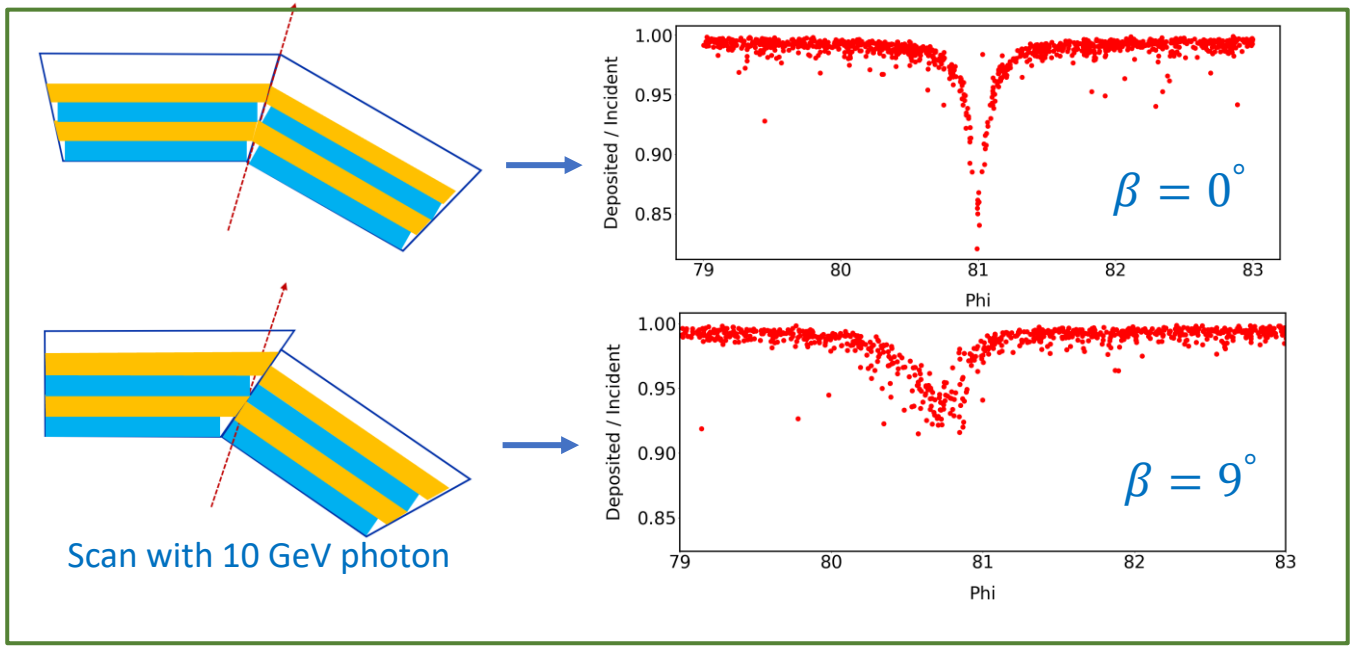


Tower geometry
e.g. $\beta = 37^{\circ}$



- Larger value of β: fewer projectile cracks, but more gaps





Scan with 10 GeV photon