R&D of High-Granularity Crystal ECAL for CEPC

Zhiyu Zhao (TDLI/SJTU)

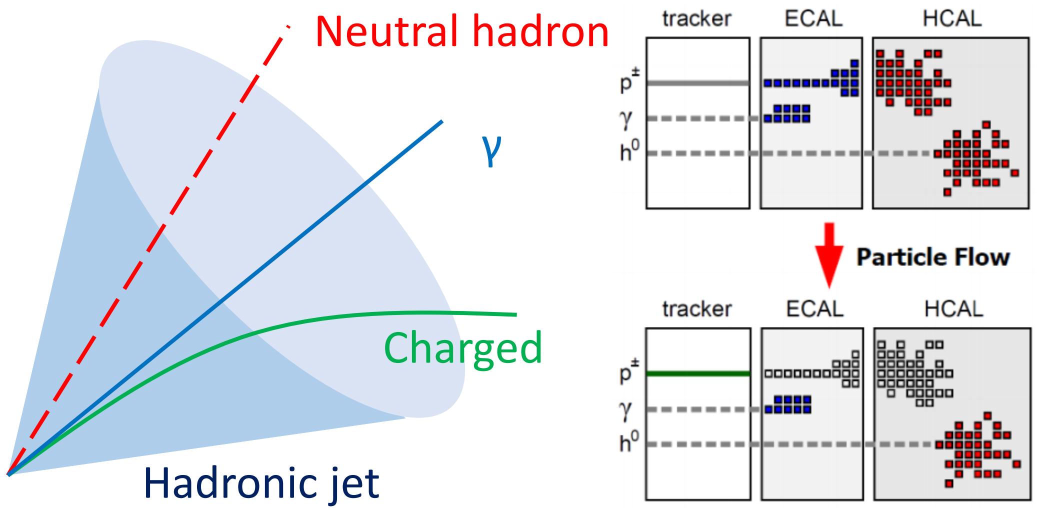
On Behalf of CEPC Calorimeter Working Group

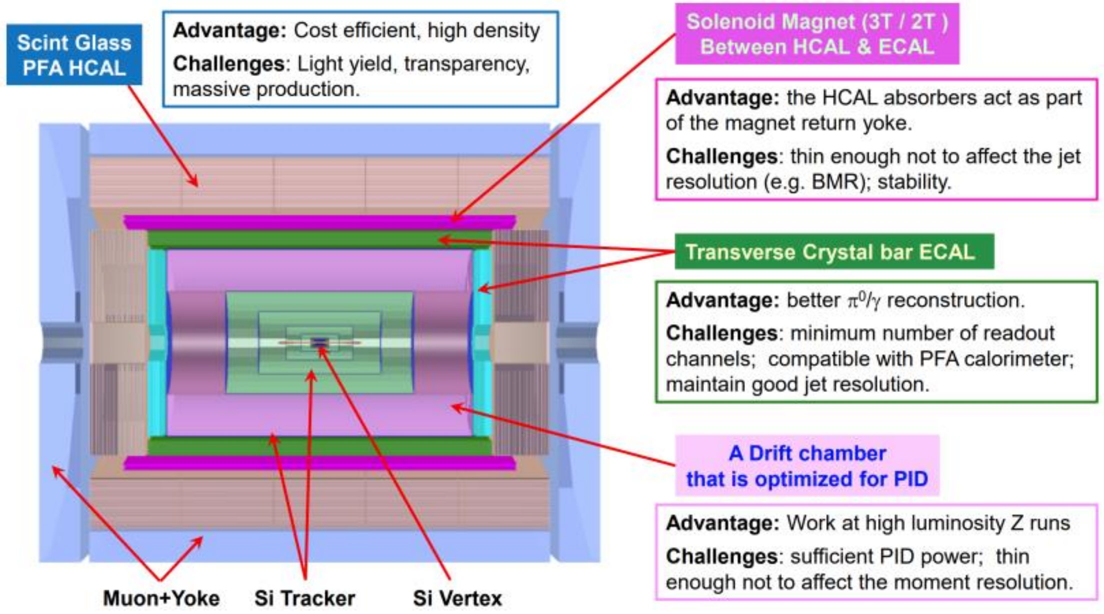
CEPC Flavor Physics/New Physics/Detector Technology Workshop

13-18 August, 2023

Motivation: New Detector for CEPC

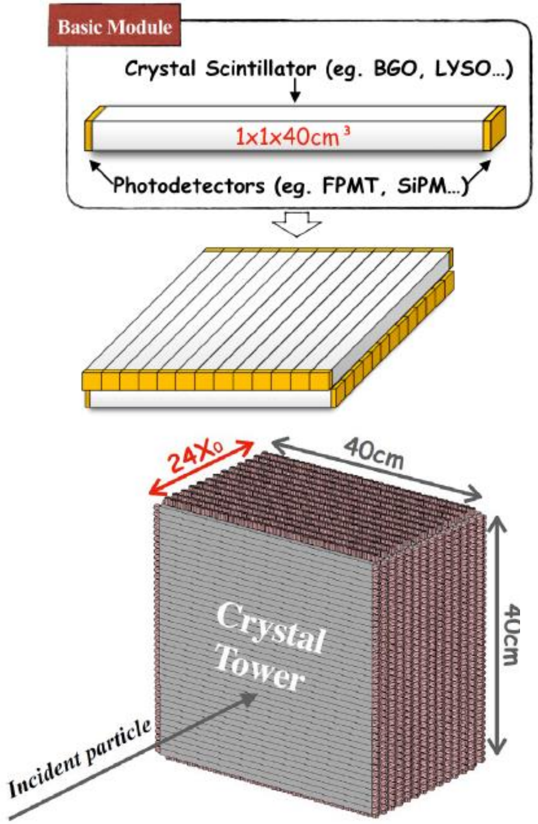
- CEPC: future lepton collider
  - Higgs/W/Z bosons, top, BSM searches, etc.
  - Precision jet measurement
  - Particle-Flow Algorithm (PFA)
    - High-granularity calorimeter: separation of showers
- New "CEPC 4th concept" detector design
  - High-granularity crystal ECAL ★
    - 5D detector: 3D spatial + energy + time
    - Intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Scintillating glass HCAL
    - High density for better boson mass resolution





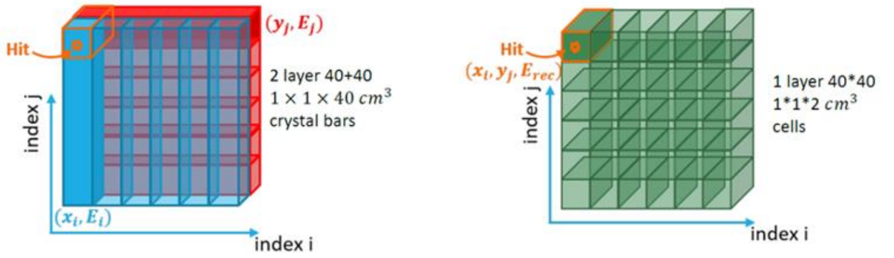
Crystal ECAL R&D: Overview

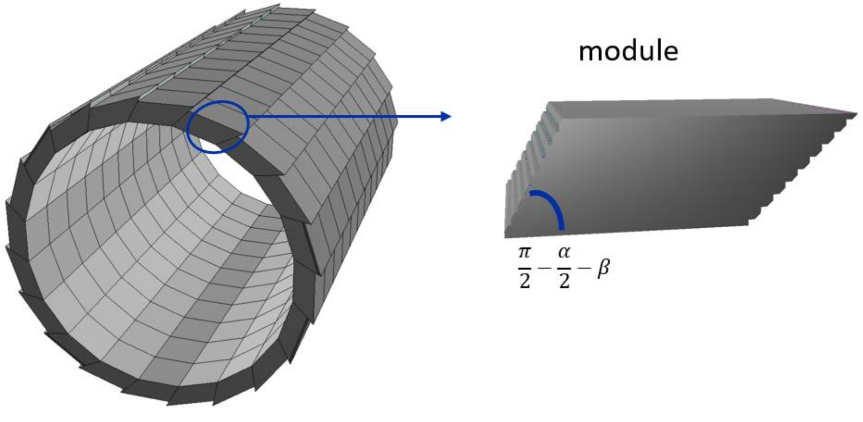
➢ Design concept



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

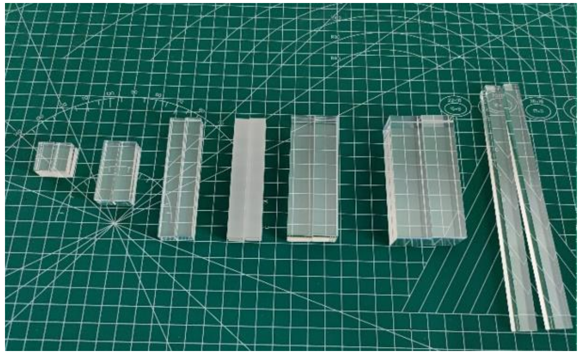
➢ Optimization and validation

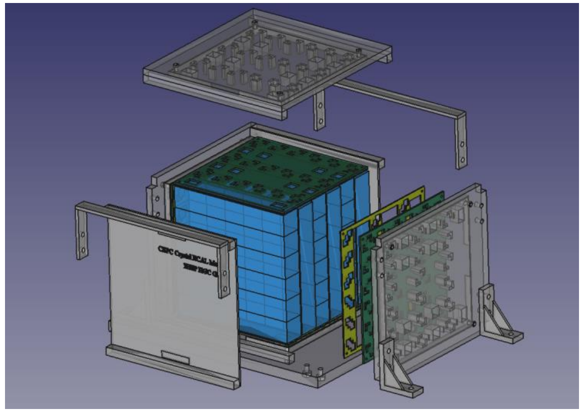




- Dedicated new reconstruction software
- Performance evaluation and optimization

➢ Hardware development



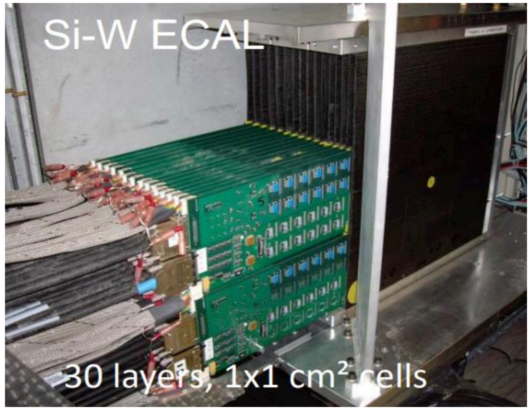


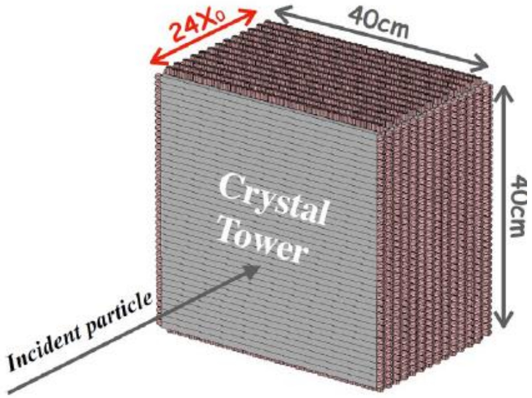
- Unit test(BGO+SiPM)
- Development of crystal module(s) for beam tests

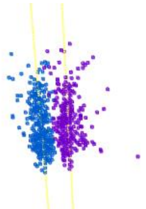
Performance Comparison: SiW vs. Crystal

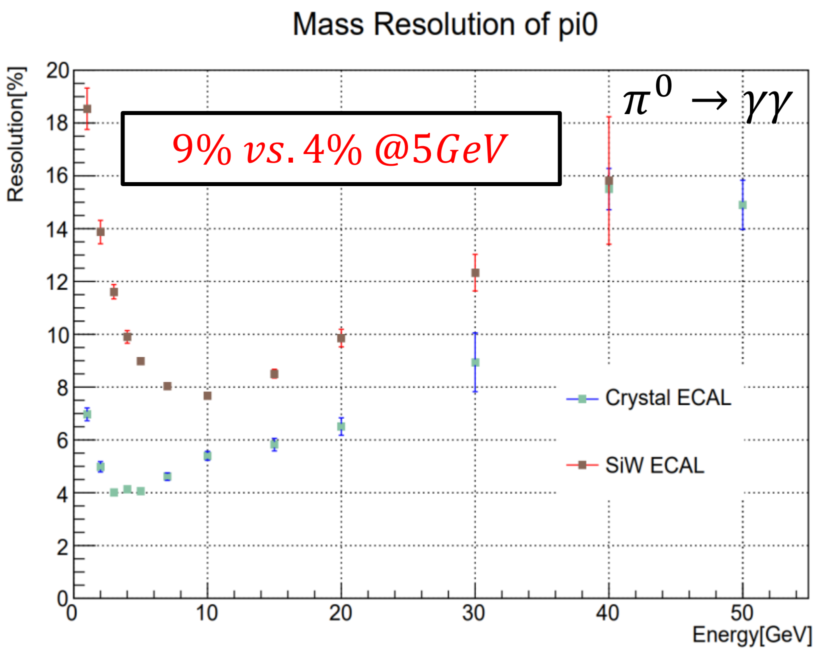
Baohua Qi(IHEP)
Zhiyu Zhao(TDLI/SJTU)

- CEPC CDR baseline SiW-ECAL
  - Sampling calorimeter, small X_0 and R_M
- CEPC 4th concept: crystal calorimeter
  - Homogenous, high energy resolution
- PFA reconstructed with “Arbor”



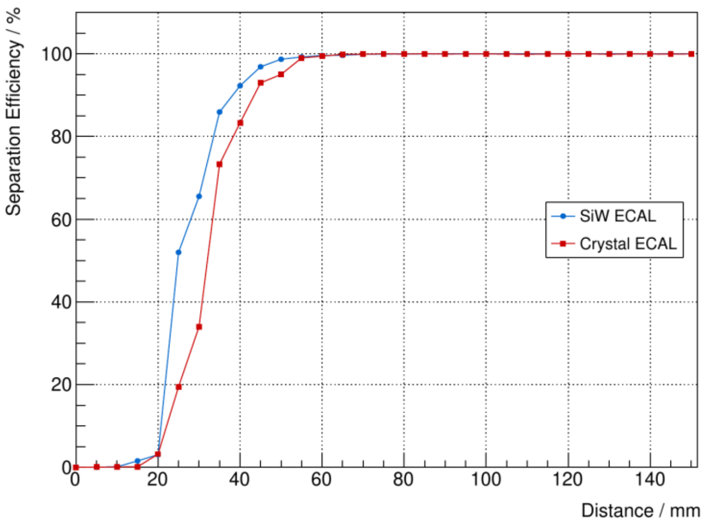




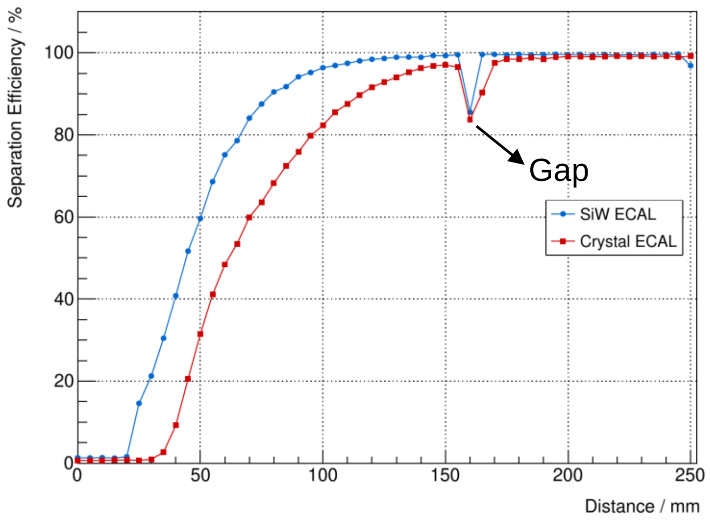


$$\frac{\delta m_0}{m_0} = \frac{\delta E_1}{2E_1} \oplus \frac{\delta E_2}{2E_2} \oplus \cot\frac{\alpha}{2}\frac{\delta\alpha}{2}$$

γ/γ separation with barrel ECAL



π^+/γ separation with barrel ECAL

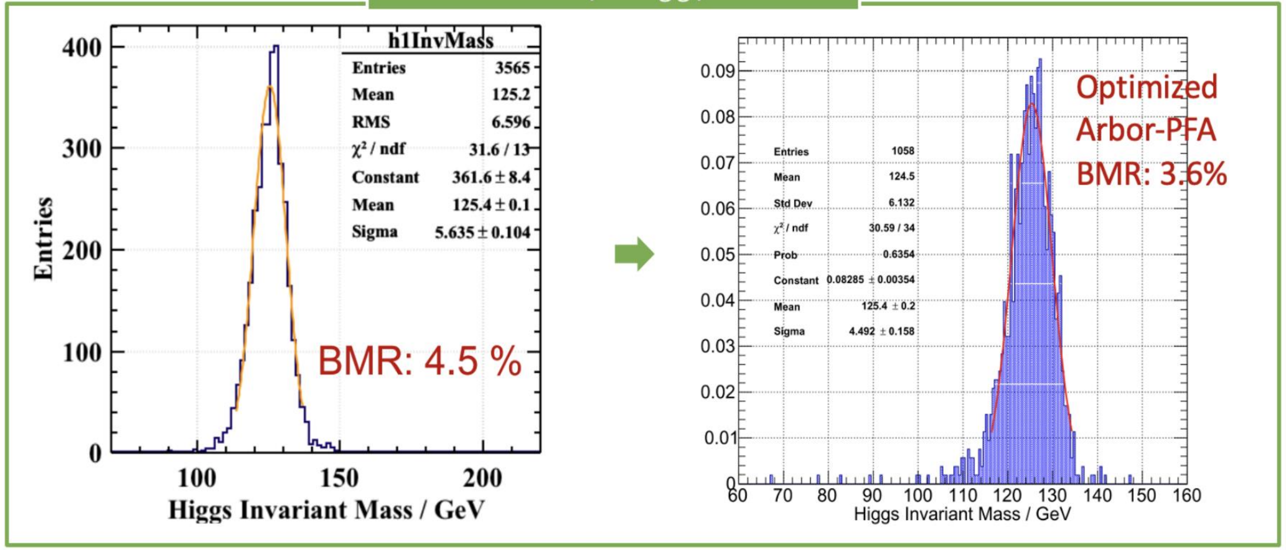


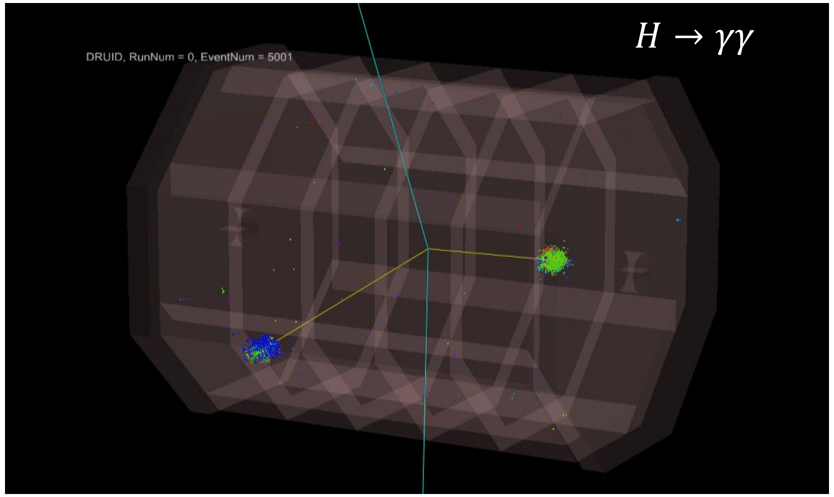
Performance comparison: SiW vs. Crystal

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

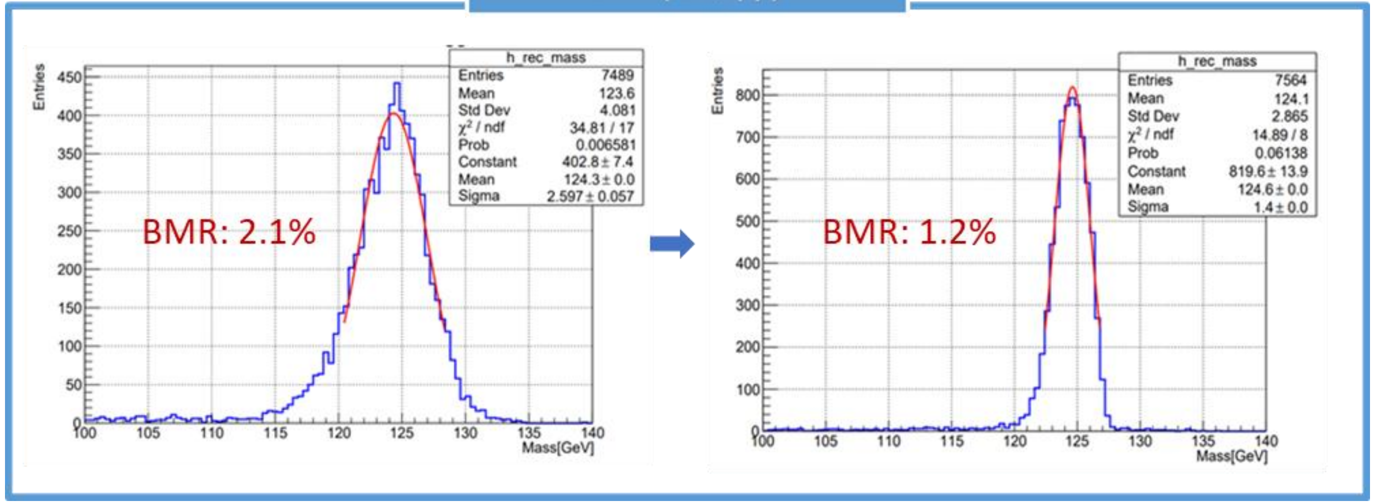
- Higgs boson mass resolution(BMR)
  - $H \to gg$: 4.5% → 3.6%
  - $H \to \gamma\gamma$: 2.1% → 1.2%

BMR ($H \to gg$)





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



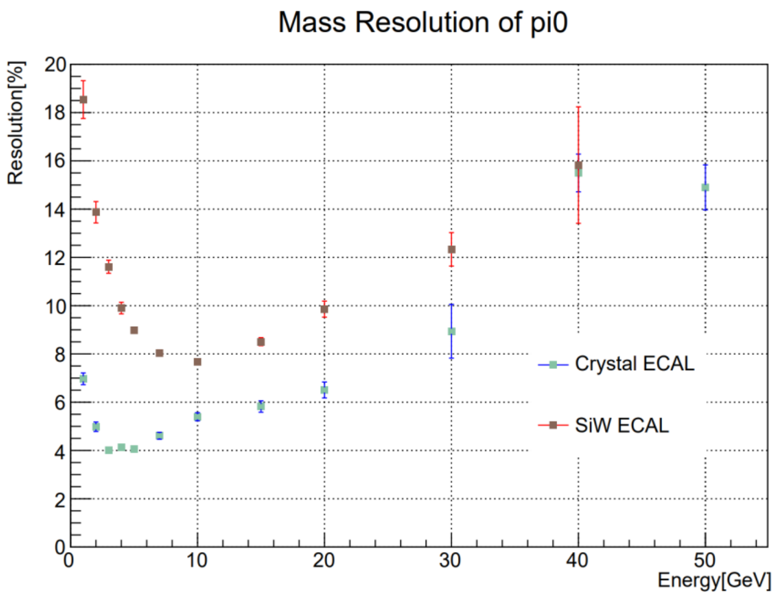
ECAL Performance: $B^0 \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$

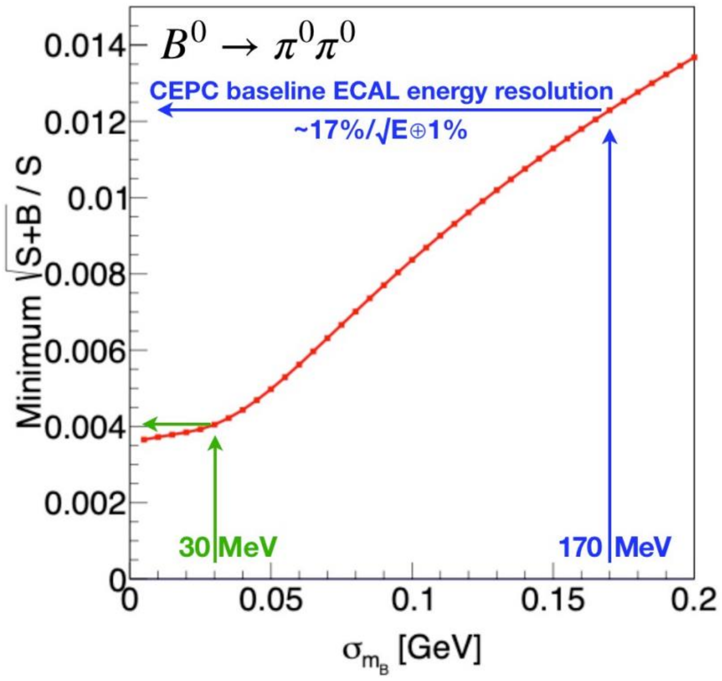
Yuexin Wang (IHEP)

- $B^0 \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ measurement
  - Necessary channel to determine CKM angle α
  - ECAL performance can be characterized by σ_{m_B}
  - Highly depending on the π^0 reconstruction

	ECAL Resolution	σ_{m_B} (MeV)	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$
SiW	$17\%/\sqrt{E}\oplus1\%$	170	~ 1.2%	~ 21%
Crystal	$3\%/\sqrt{E}\oplus0.3\%$	30	~ 0.4%	~ 4%

3 ~ 5 times improvement

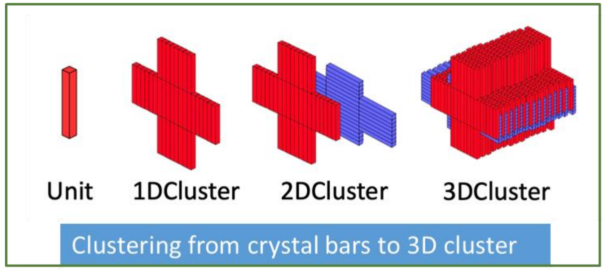


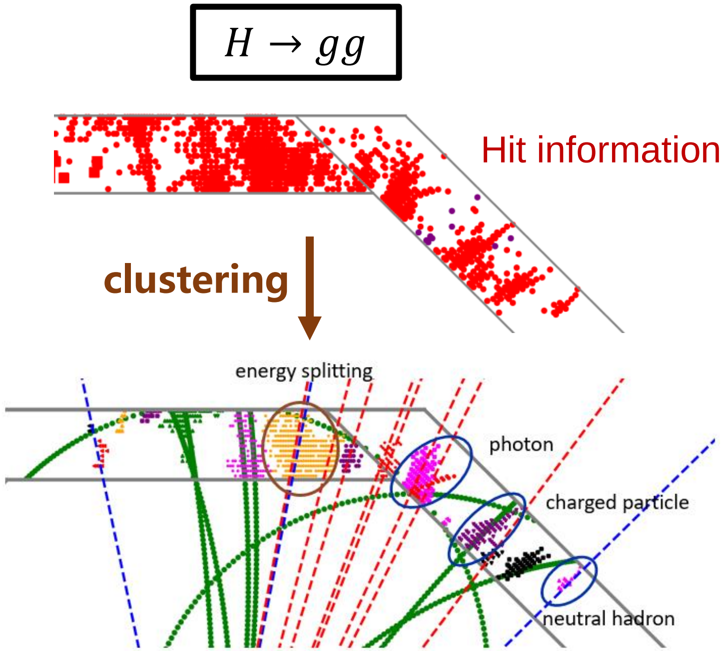


Reconstruction Algorithm Dedicated to Long Crystal Bar ECAL

Yang Zhang (IHEP)
Weizheng Song (IHEP)

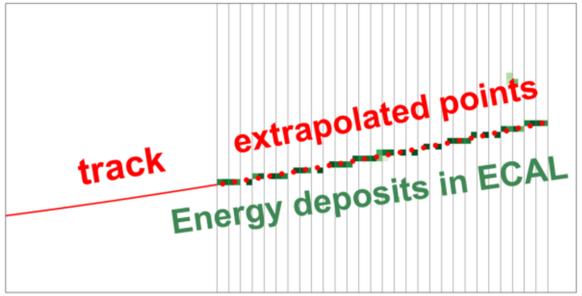
➢ Clustering

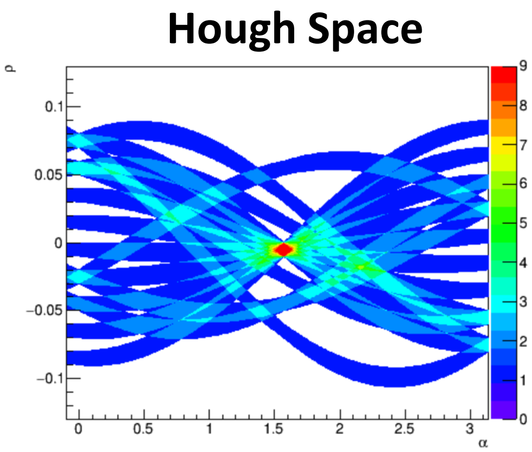




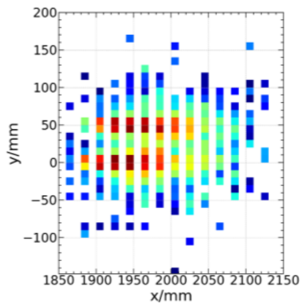
➢ Shower recognition:

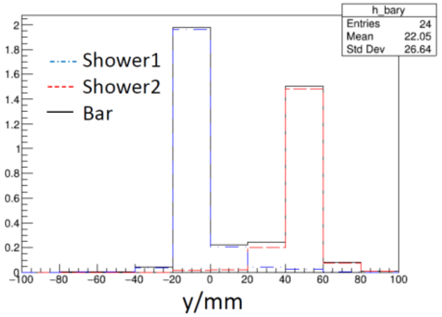
- Charged particle: track-matching.
- EM shower: Hough transformation.
- Fragment: cone-clustering.





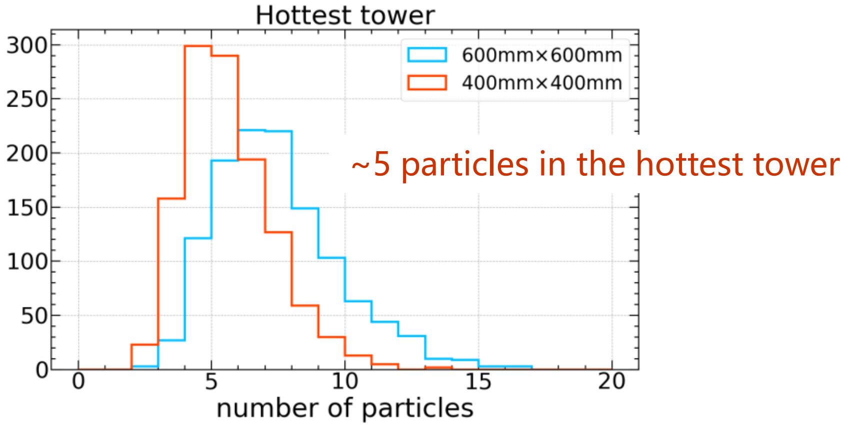
➢ Energy splitting for overlap showers





➢ Ambiguity problem

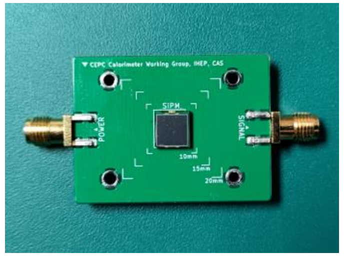
- Need more efforts on multi-hit rec

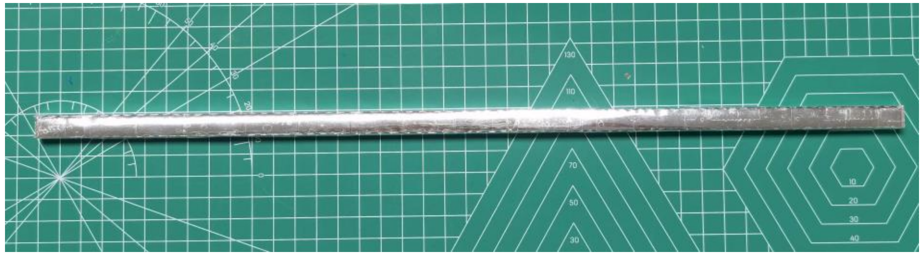


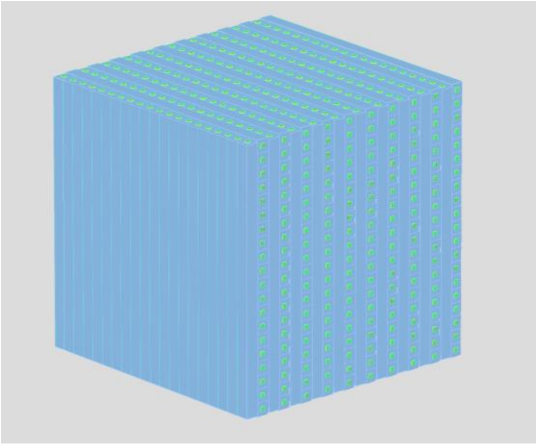
Light Yield of BGO Crystal Bar

Baohua Qi(IHEP)

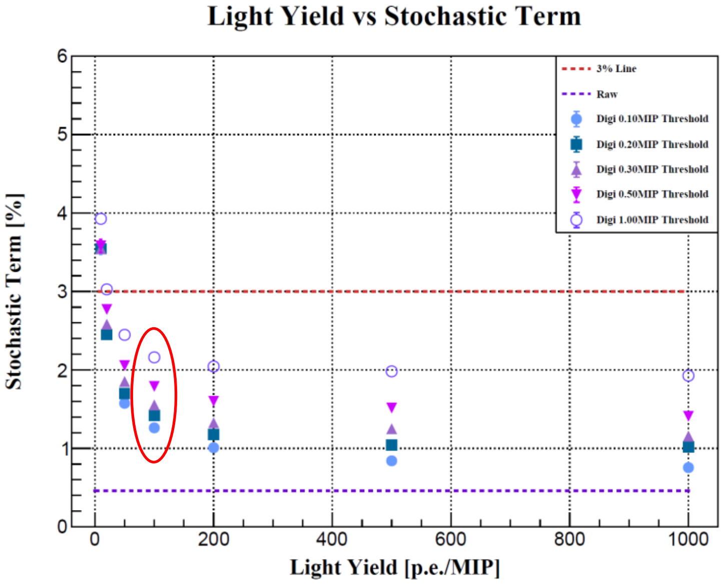
- Energy resolution: need stochastic term < 3%
- Light yields: number of detected photons per MIP
  - Experiment: >300 pe/MIP ($1 \times 1 \times 40cm^3$ BGO, ESR, NDL 6μm SiPM)
  - Standalone simulation: required >100 pe/MIP
- Able to detect low-energy particles ~600keV



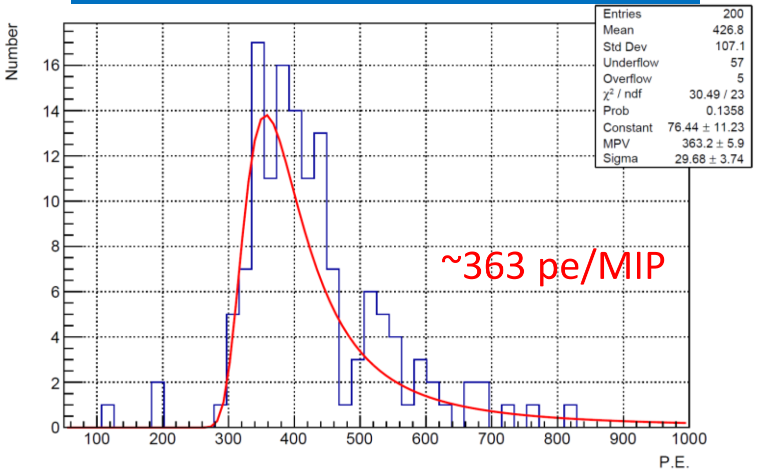




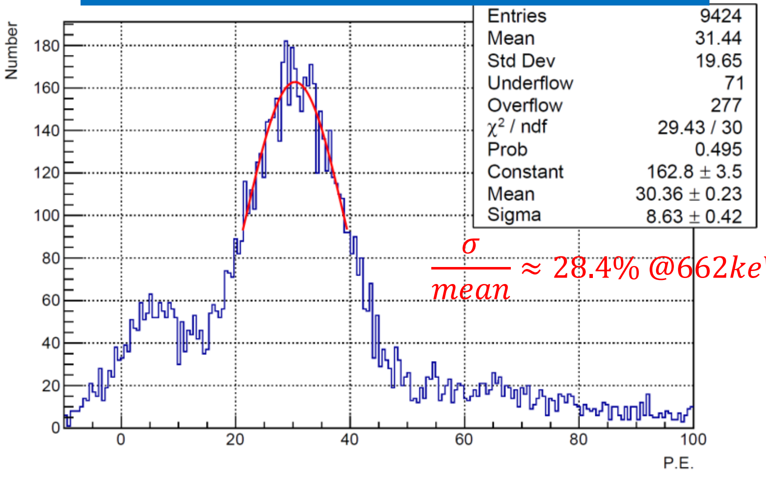
Simulation: 40×40×28 supercell, BGO long bars, gaps, 1~40 GeV electrons
Digitization: photon statistics, gain uncertainty, ADC error,…



$1 \times 1 \times 40cm^3$ BGO, Cosmic Ray



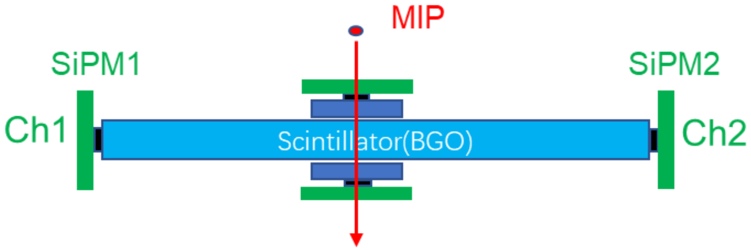
$1 \times 1 \times 40cm^3$ BGO, 662keV γ

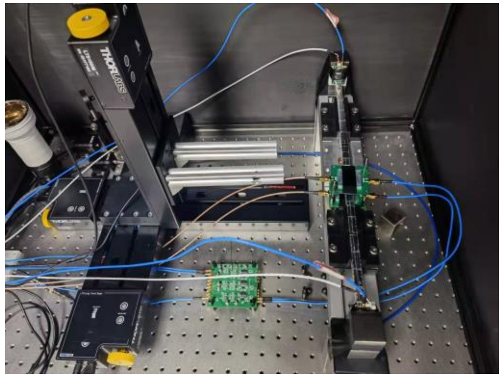


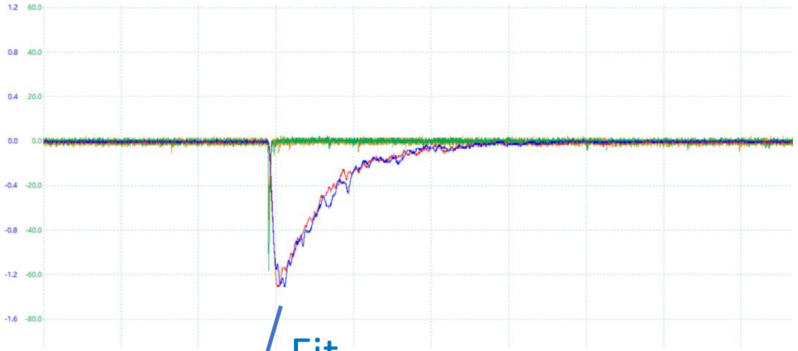
Time Resolution of BGO Crystal Bar

Zhiyu Zhao(TDLI/SJTU)

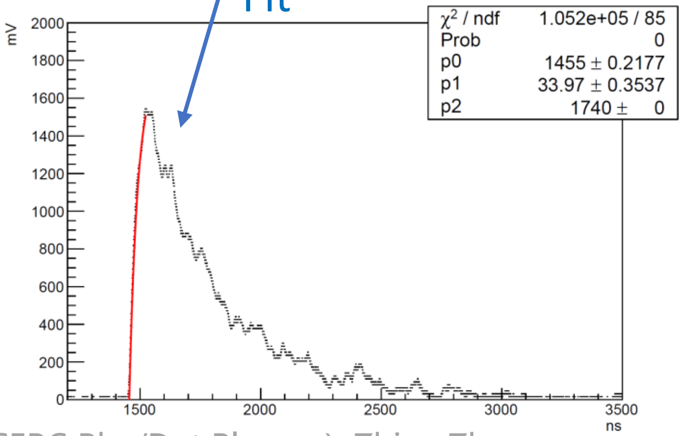
- Potential for improving shower reconstruction
- Experiment setup:
  - double-side readout
  - Fast sampling rate(1.25 GS/s)
  - Leading edge fitting + constant fraction timing
- Timing resolution ~1ns at MIP signal level



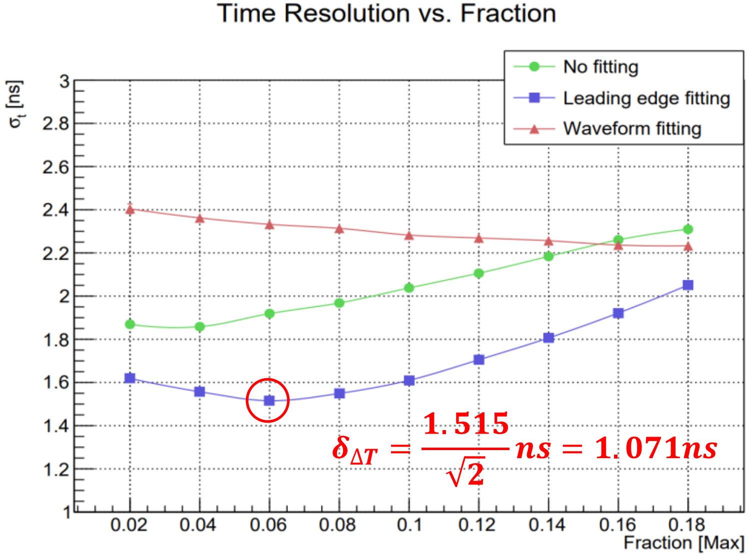




Fit



Definition of time resolution: $\sigma(t_{ch1} - t_{ch2})$

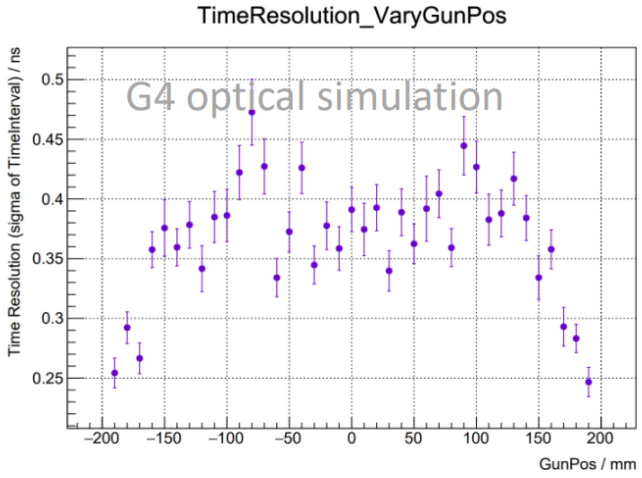


Timing Studies with a Crystal ECAL Readout Unit (CEPC Phy/Det Plenary), Zhiyu Zhao

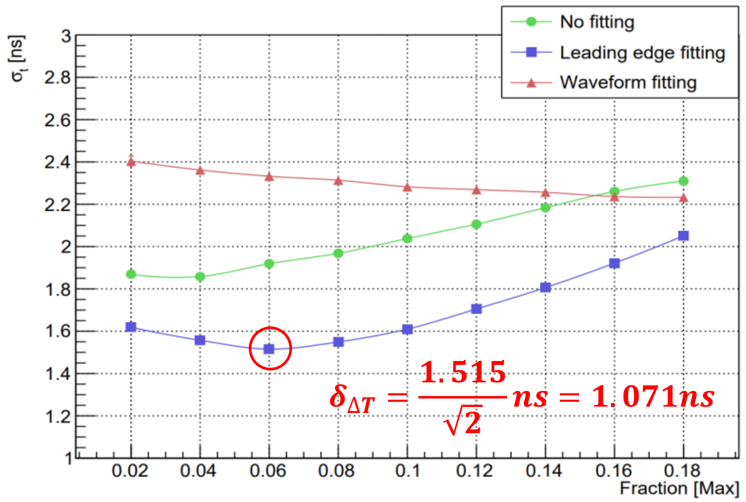
Time Resolution of BGO Crystal Bar

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

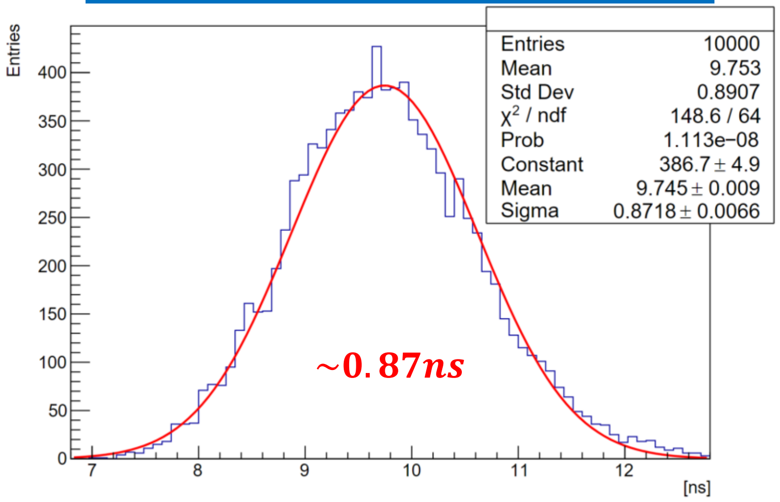
- Geant4 optical simulation
  - Ultimate performance (triggering first photons): ~0.4ns
  - Including digitization (SiPM waveform): ~0.87ns
- Experimental result: ~1ns
- Future development for time resolution test:
  - Crystals with different sizes
  - Contribution of SiPM, reflective film and electronics



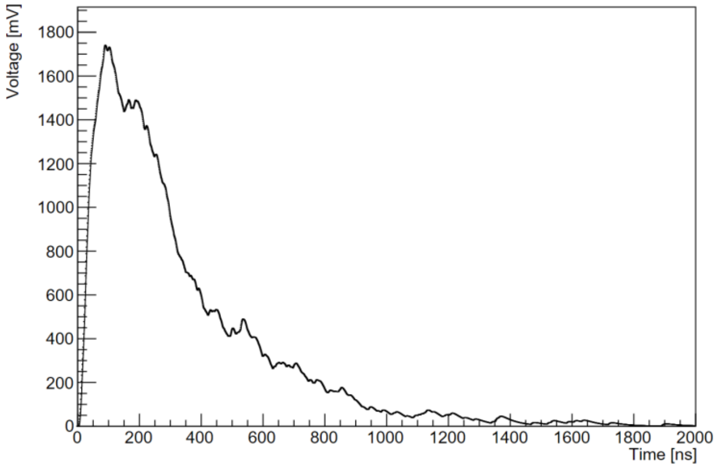
Time Resolution from Experiment



Time Resolution from Waveform Simu

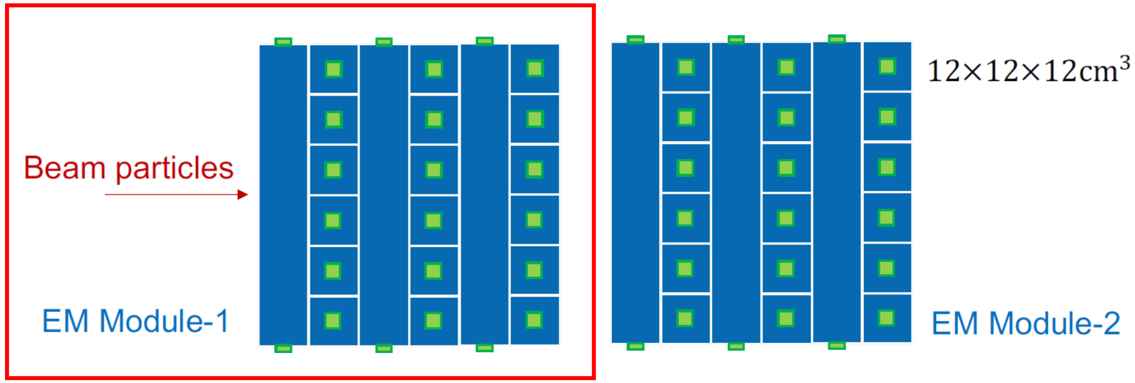


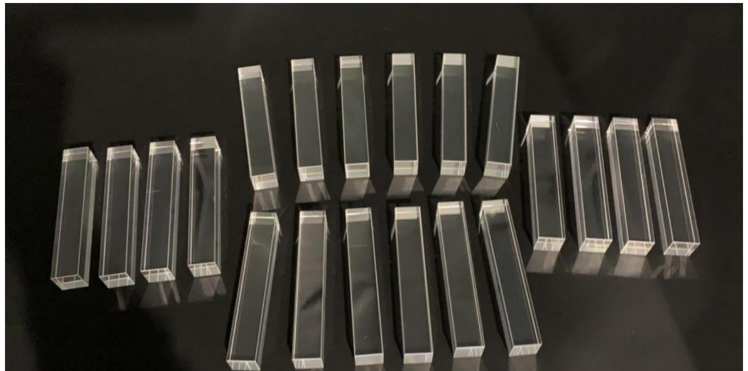
Simulated Waveform



Crystal Module Beam Test

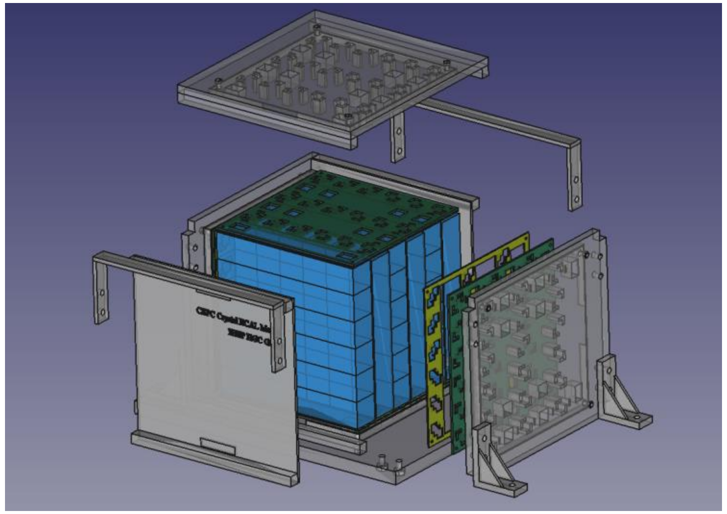
- Motivation
  - Identify critical questions/issues on system level
    - Mechanical design, PCB and electronics…
  - Evaluate performance with TB data
  - Validation of simulation and digitization
- First 12×12×12 cm^3 BGO modules development
  - 2×2×12 cm3 BGO unit, 72 channels, double-sided readout
- Beam test at CERN T9 beamline(May, 2023)
  - Muon, electron and pion beam
- Future plan: 2 modules serial arrangement





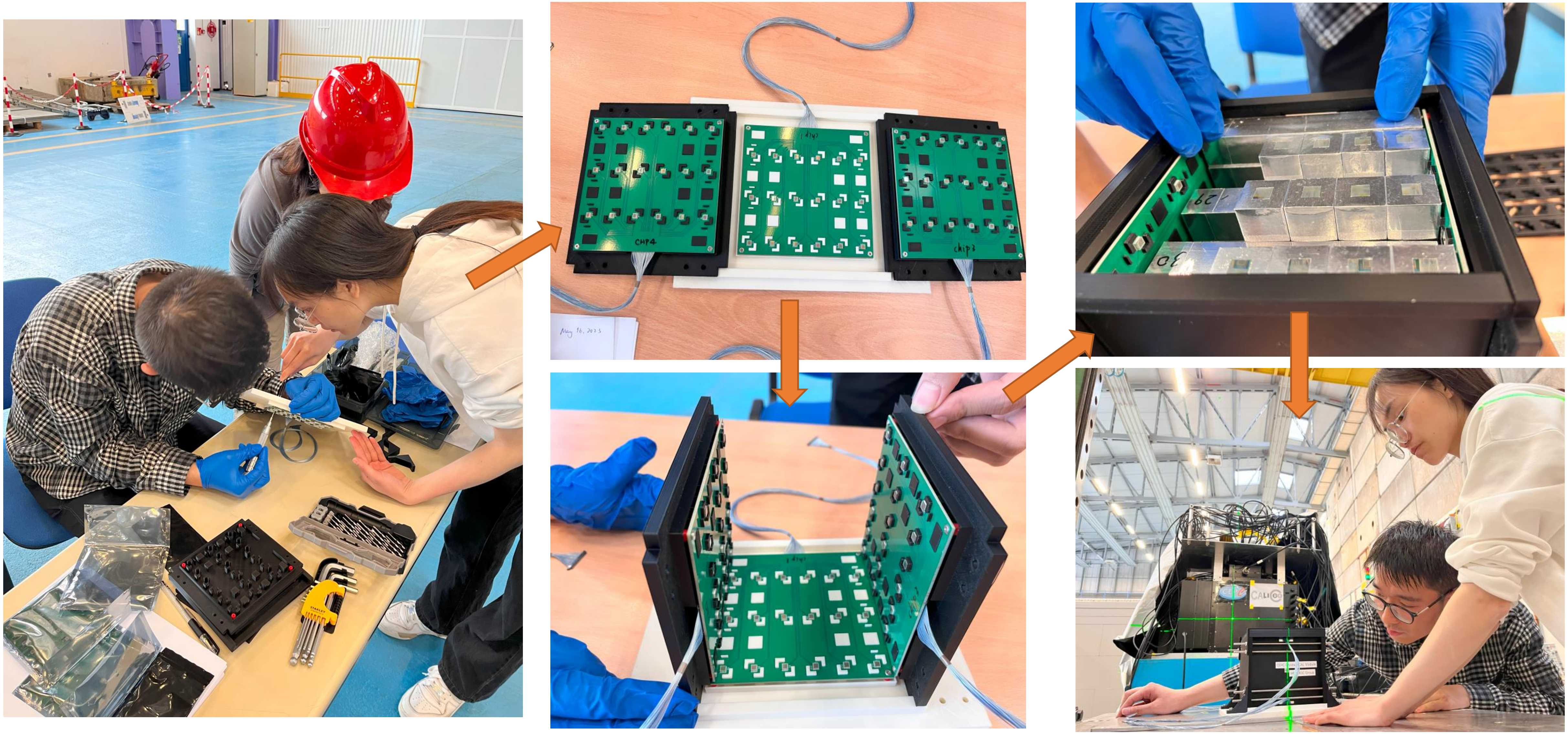
BGO crystals from SIC-CAS

CAEN A5202 with Citiroc-1A chips



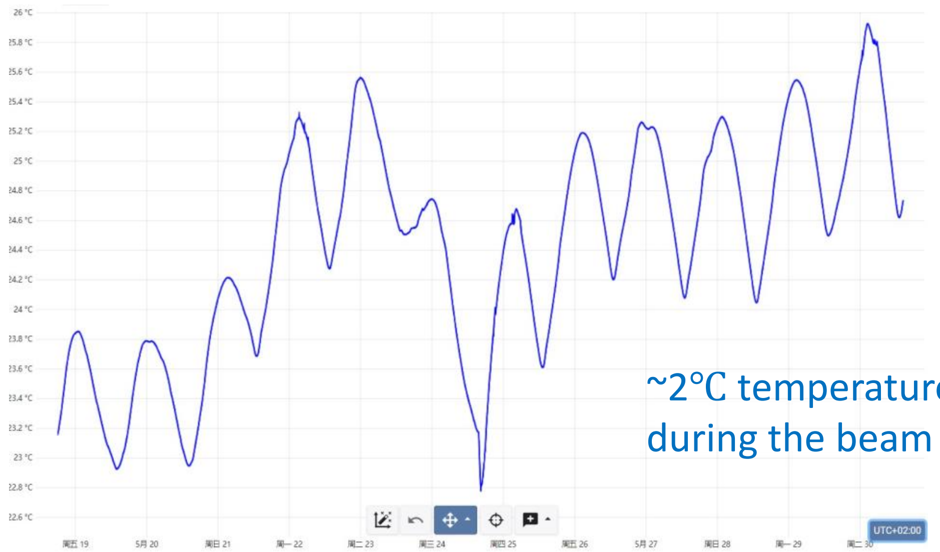
- 36 crystals wrapped with ESR and Al foil
- 4 PCB boards
- 3D printed support structure

Crystal Module Beam Test

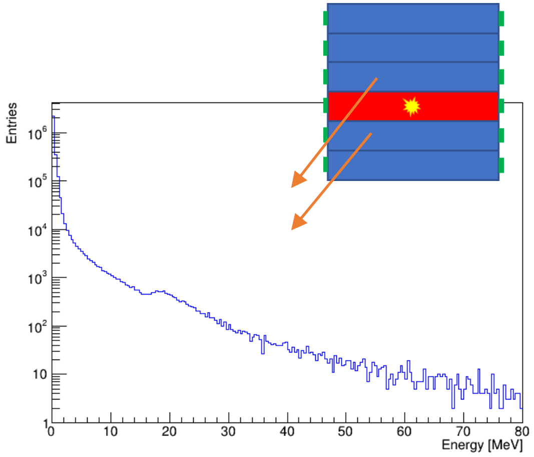


Crystal Module Beam Test

- 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

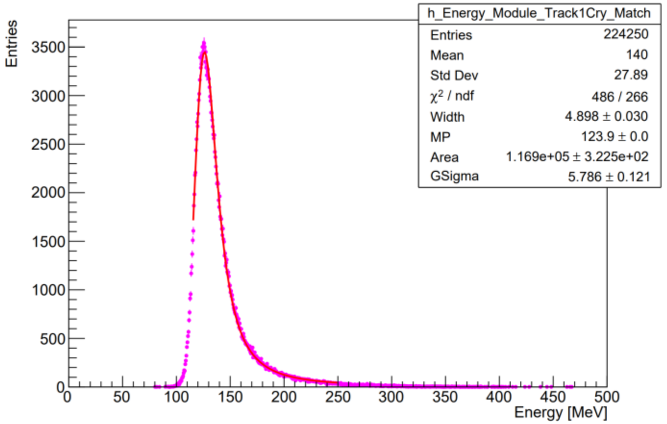


~2°C temperature change during the beam test

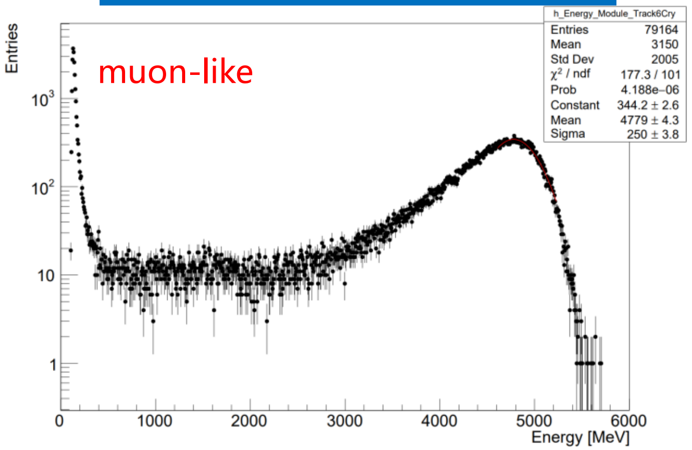


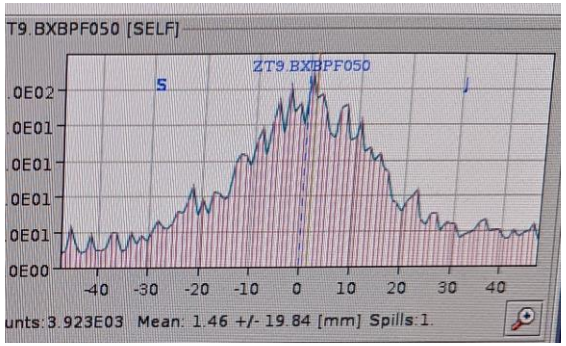
- Beam is impure
- Crosstalk

10GeV muon data



5GeV electron data





Beam Profile

Summary and Prospects

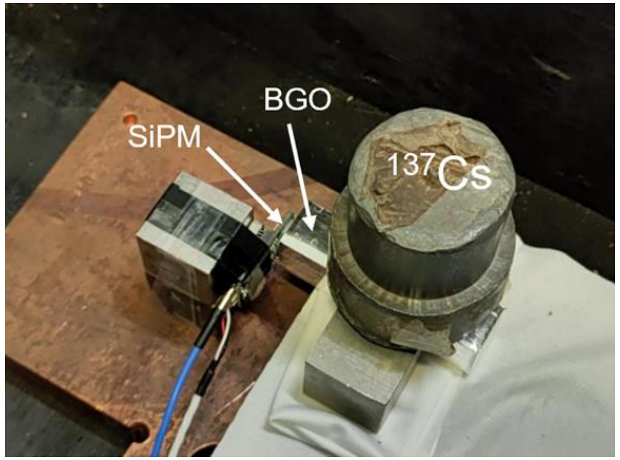
- High-granularity crystal calorimeter: a new design proposed for CEPC
  - Optimal EM energy resolution, excellent resolutions in 3D space and timing
- Crystal-SiPM lab measurements
  - Good sensitivity and resolution to low-energy photons (~600keV level)
  - MIP timing resolution ~1ns (per crystal)
- Crystal module development
  - First small-scale crystal module developed
  - Successful CERN beam test at CERN PS-T09; ongoing data analysis
  - Second crystal module in preparation + another beam test is scheduled

- Open questions for crystal calorimeter option
  - What are (significant) physics potentials for CEPC flavor physics?
  - How to best exploit the crystal ECAL option to strength the flavor physics cases?

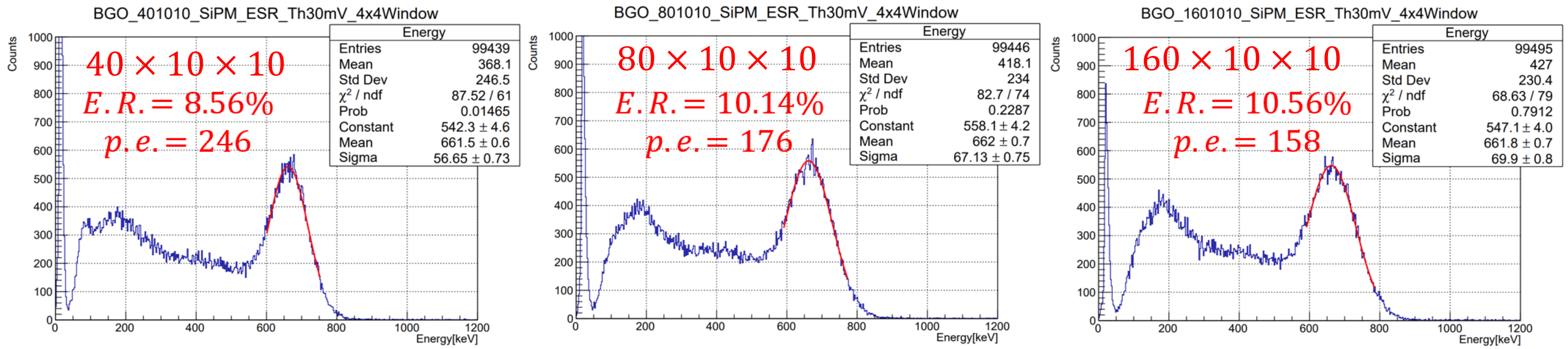
Backup

Low Energy Photon Detection of BGO

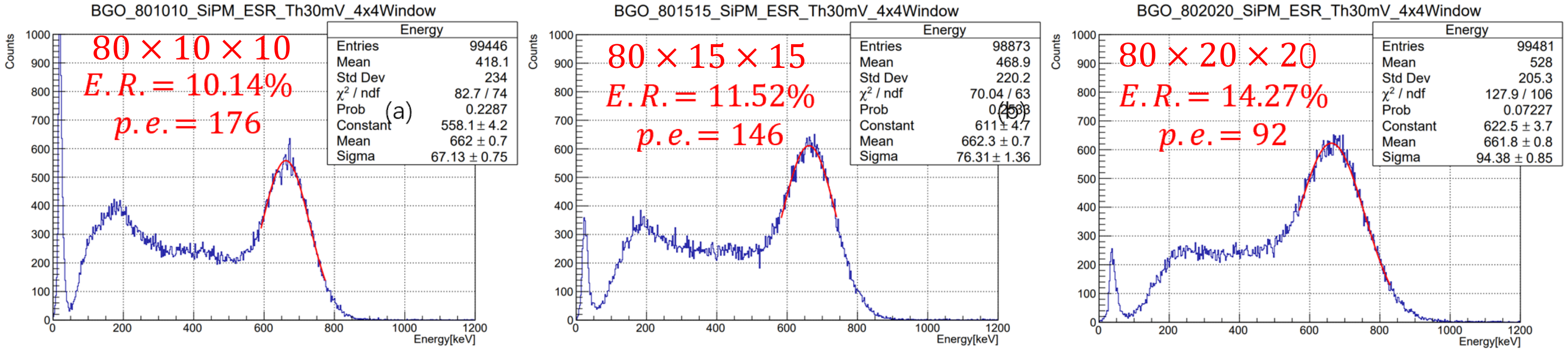
- BGO has the ability to detect low-energy photons
- SiPM: HAMAMATSU C13360-3050SA
- BGO crystals with different sizes
- Source: Cs-137, 662keV γ



Different lengths



Different cross-sectional areas

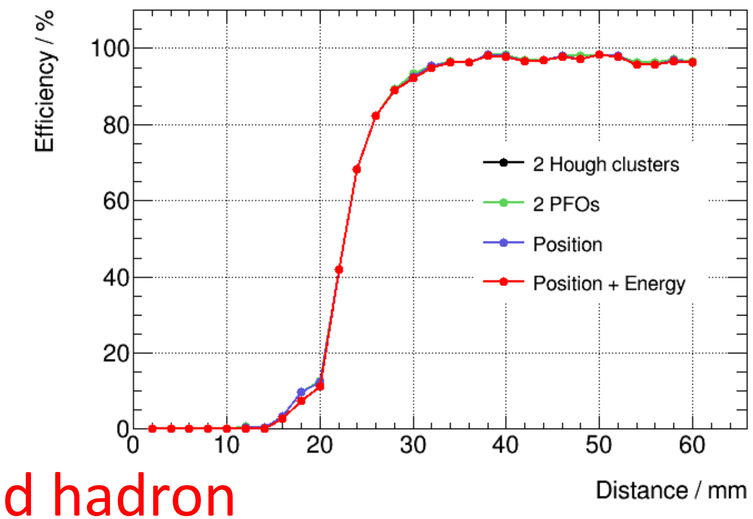


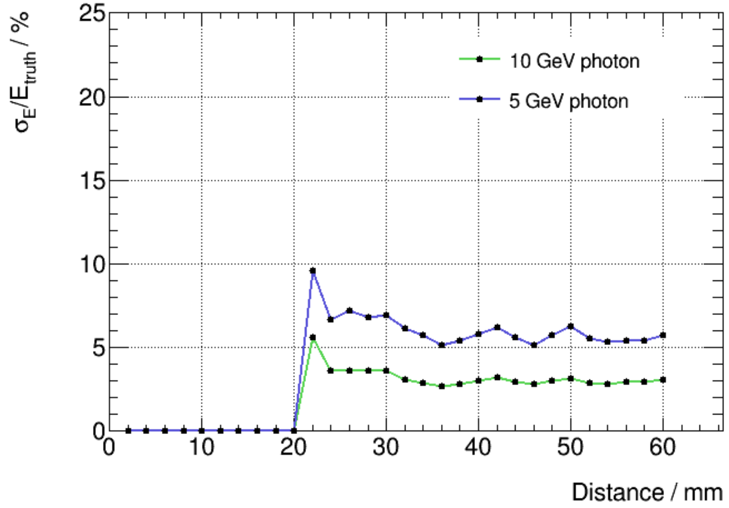
Separation of Di-Particle with Long Crystal Bar ECAL

Yang Zhang (IHEP)

➢ Separation of di-photon

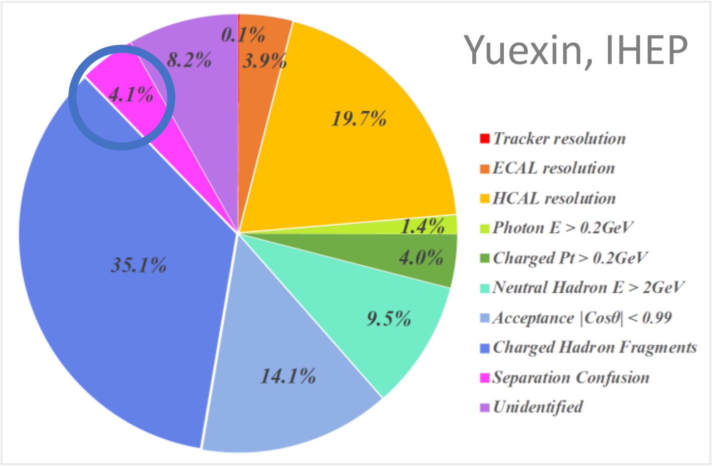
- Separation efficiency ~95% with distance > 30mm

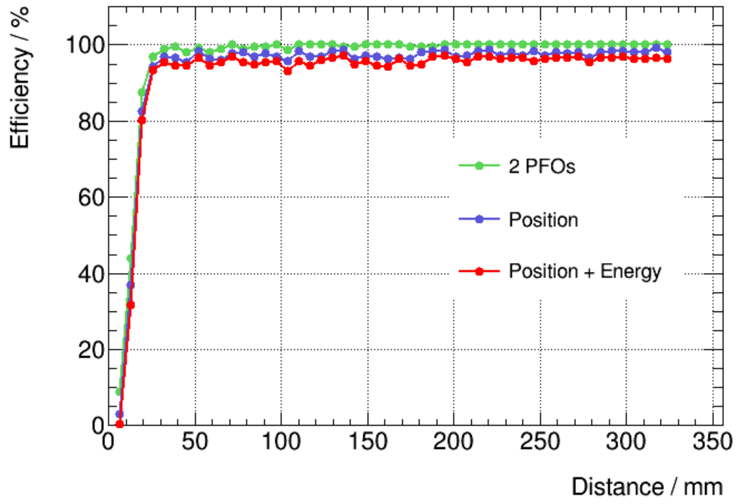


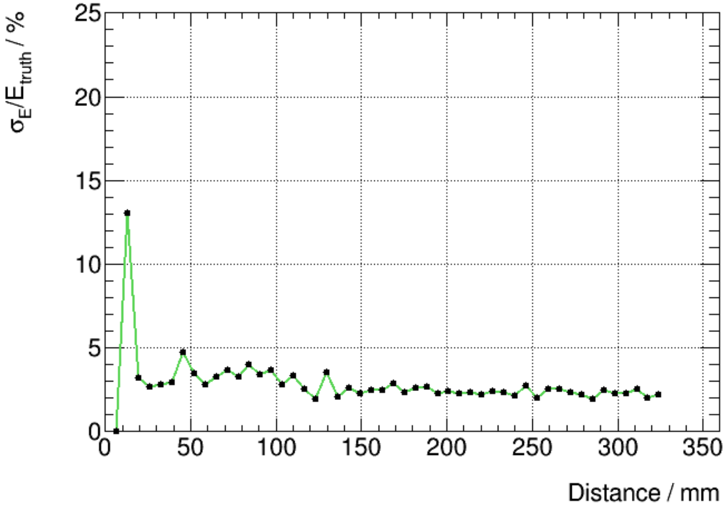


➢ Separation of photon and charged hadron

- Separation efficiency ~95% with distance > 30mm



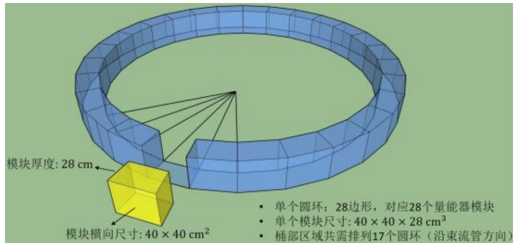




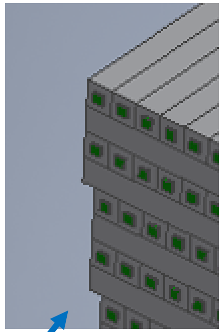
HGC crystal ECAL: software development progress and highlights(CEPC Workshop, Edinburgh, 2023), Yang Zhang

General Geometry Design for Crystal ECAL

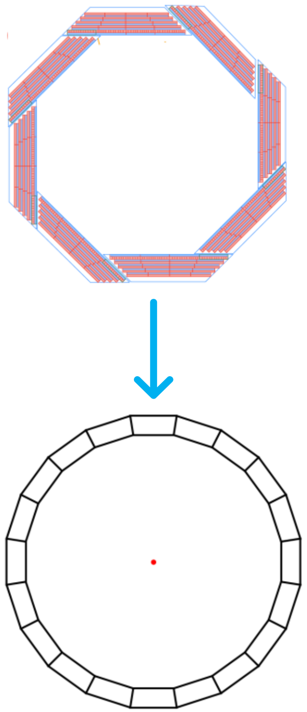
- CEPC crystal ECAL barrel geometry design
  - Finer segmentation of towers
  - Decrease outer radius for lower cost of the outer detectors
  - 28 towers per ring, 17 rings along beam direction
  - ~25 radiation length: 28 layers



Quan Ji, Chang Shu (IHEP)

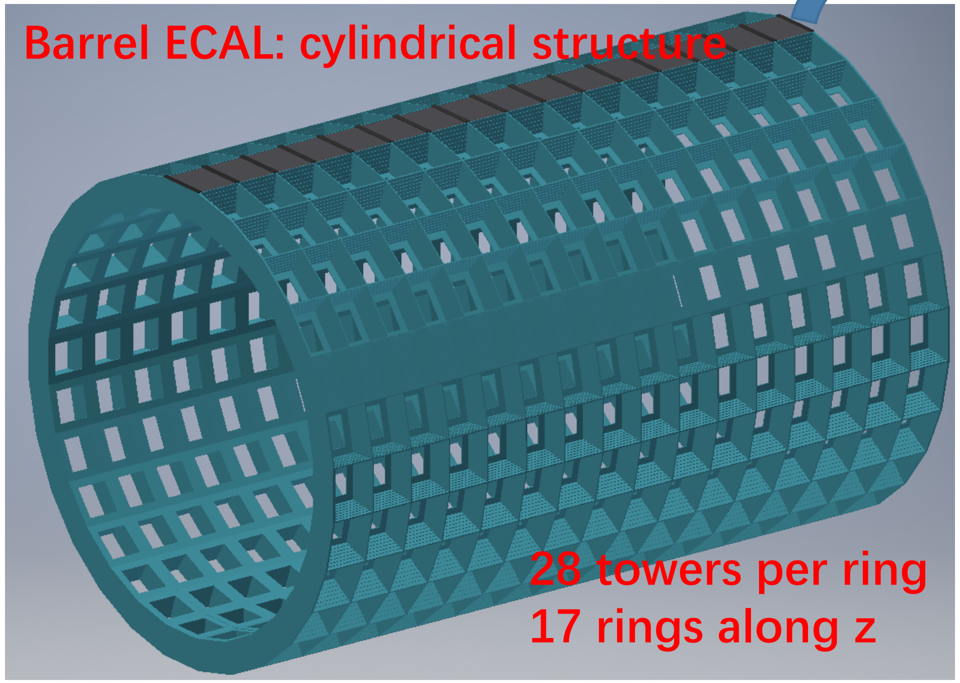


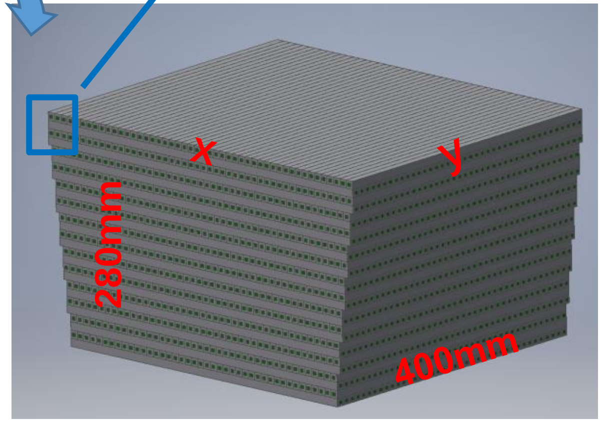
4 layers per “step” with the same transverse size



Octagonal detector

Cylindrical crystal ECAL

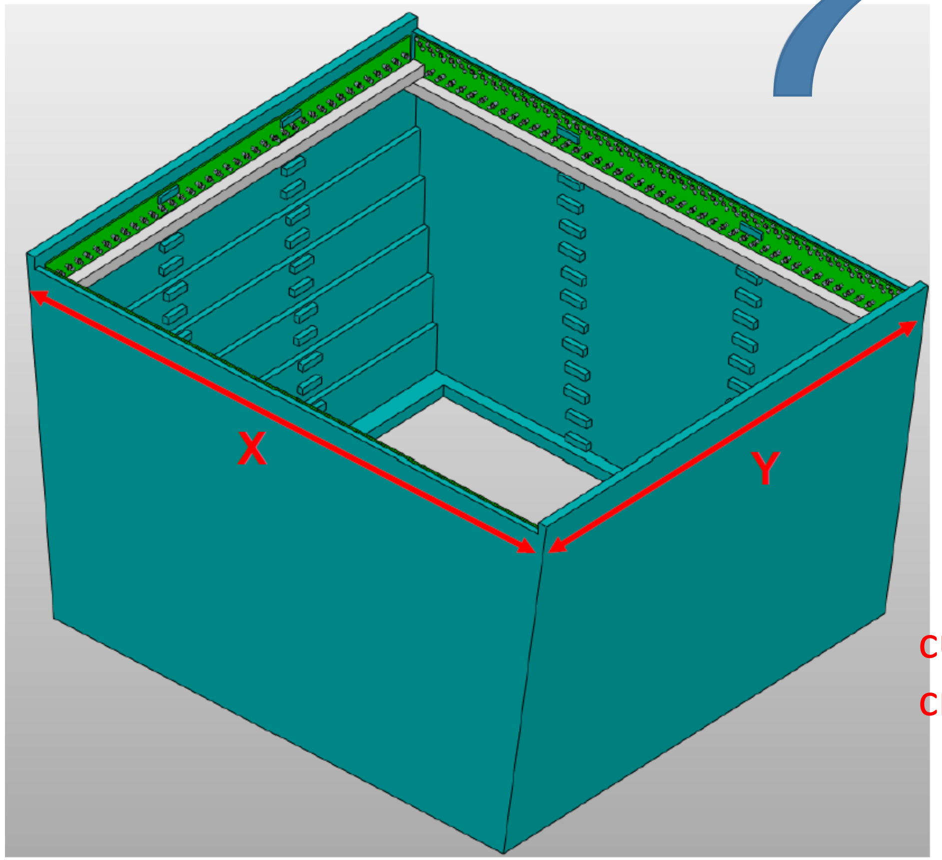


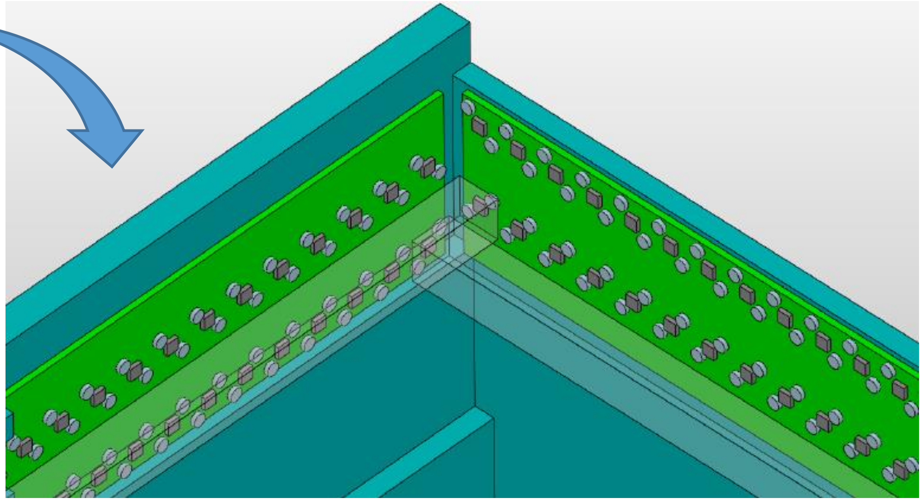


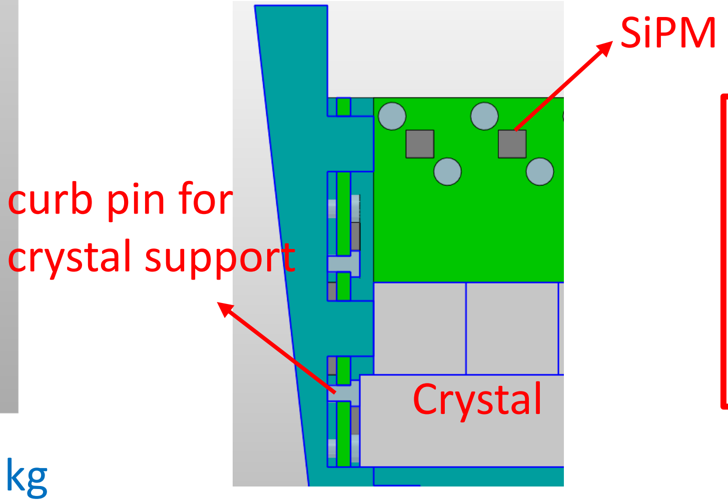
Key questions
- Space for electronics and cooling
- Assembly

Detailed Assembly of PCB and Crystal

- Mechanical assembly: crystals will be supported by curb pins through hole on PCB







Key questions
- PCB cannot bear the weight of crystals
- Holes on PCB for external support structures

- Total mass of the crystals in one tower: ~380 kg