Development of High-Granularity Crystal ECAL for CEPC

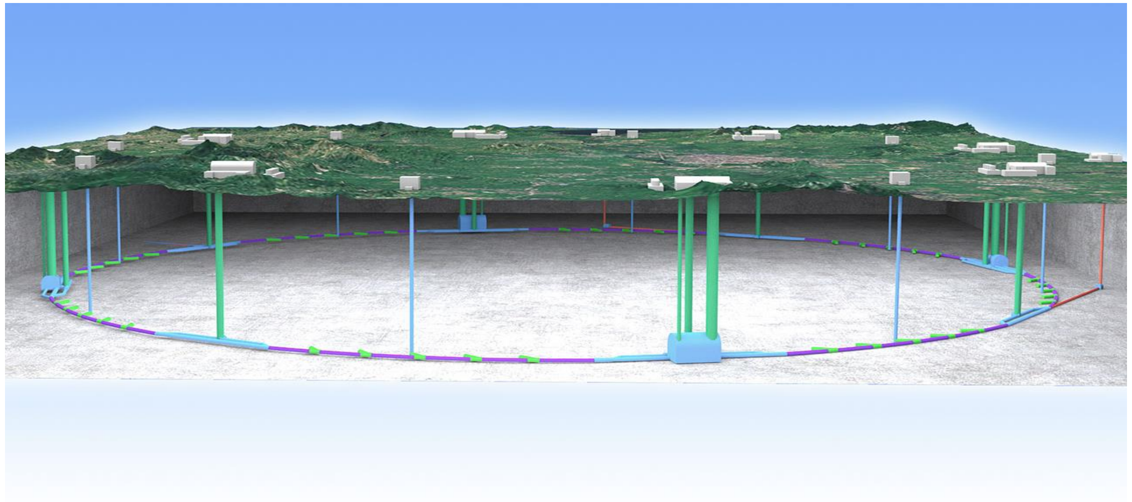
Zhiyu Zhao (TDLI/SJTU)

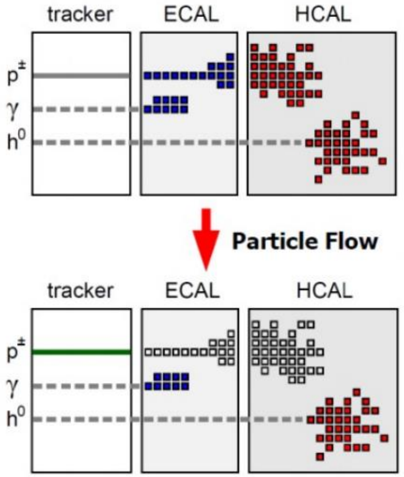
On Behalf of CEPC Calorimeter Working Group

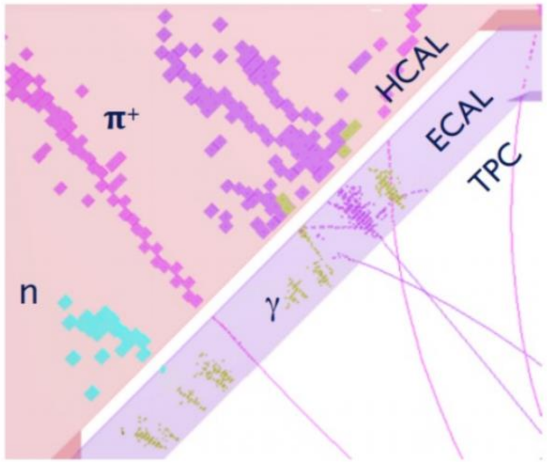
CEPC Workshop - NJU, Oct. 23-27, 2023

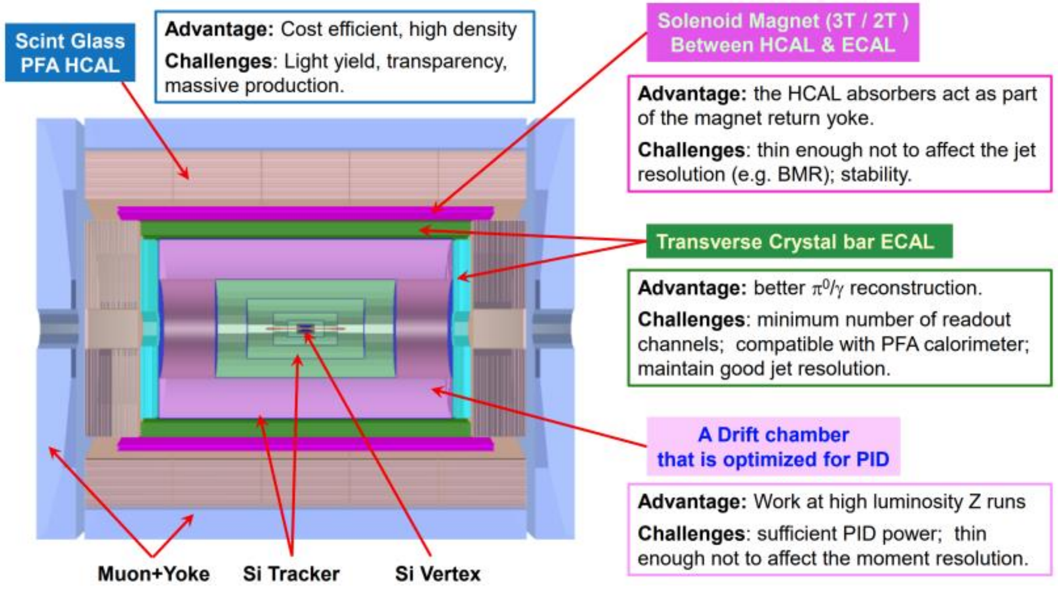
Introduction

- CEPC: future circular lepton collider
  - Higgs/W/Z bosons, top, BSM searches, etc.
  - PFA calorimeter: promising to achieve 3-4% jet resolution
- New “CEPC 4^{th} concept” detector
  - High-Granularity crystal ECAL



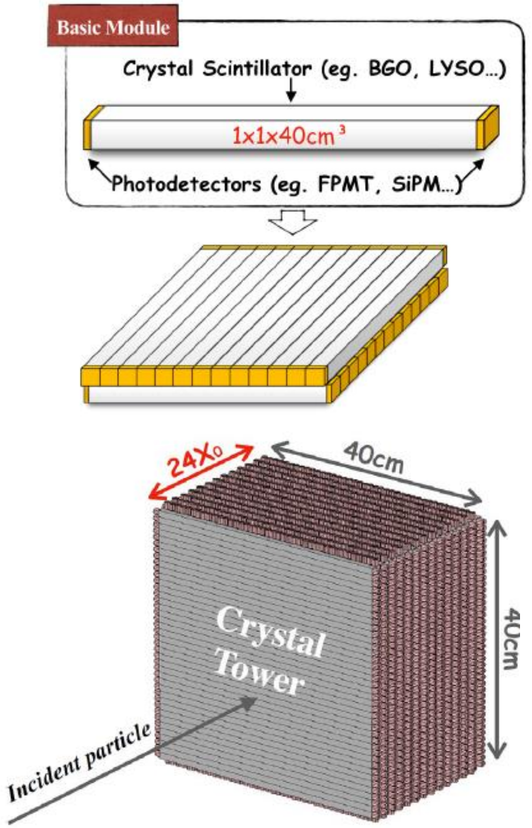






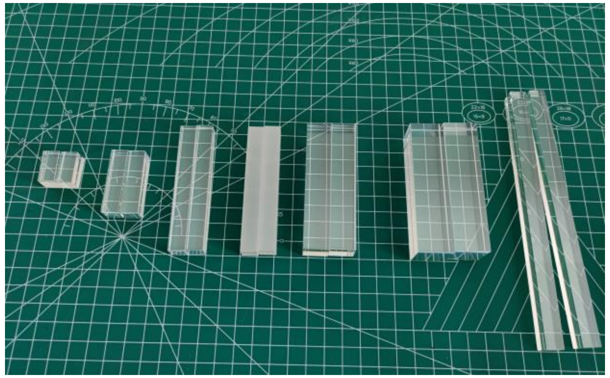
Overview of High-Granularity Crystal ECAL

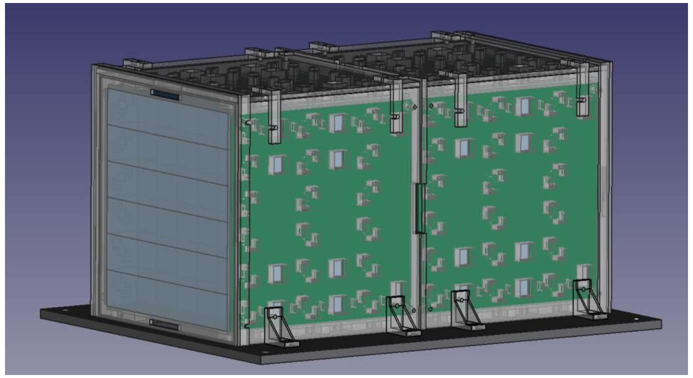
➢ Conceptual design



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

➢ Hardware development

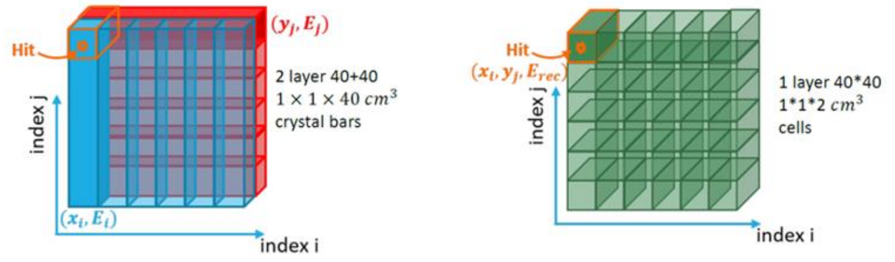


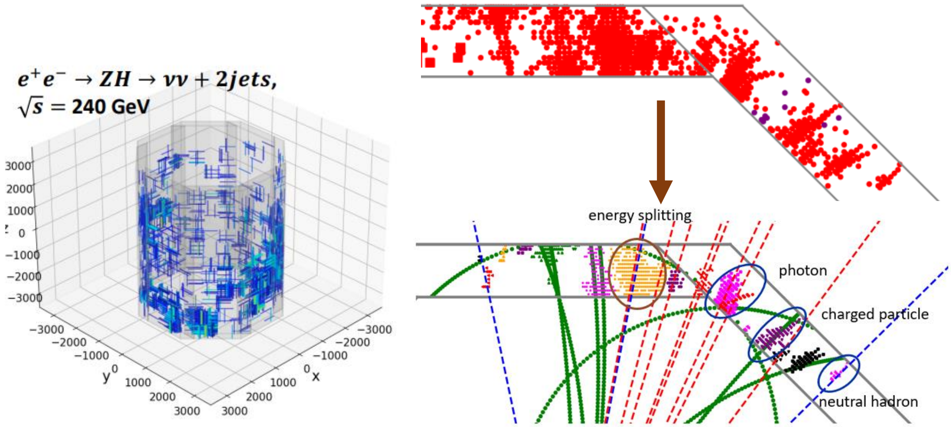


- Units test of BGO and SiPM
- Crystal modules for beamtest

Weizheng's poster

➢ Software development



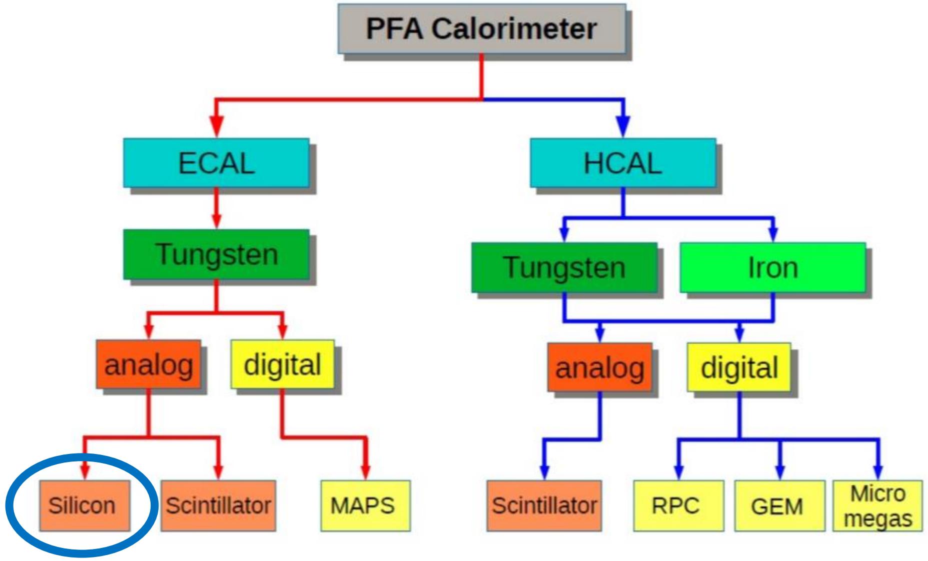


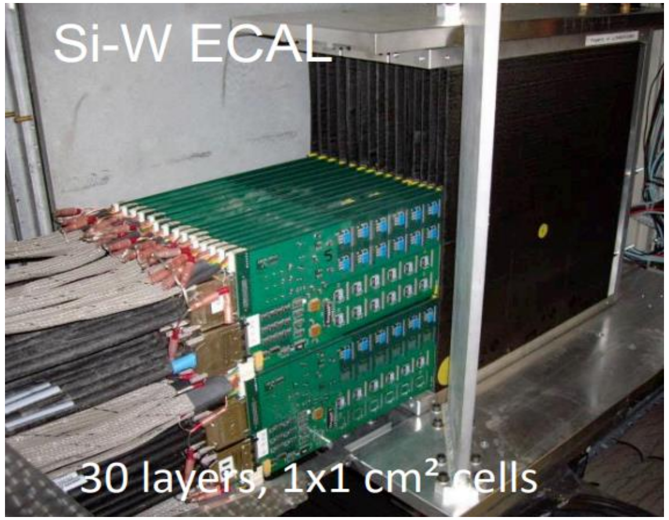
- Dedicated reconstruction software
- Performance evaluation and optimization

ECAL Designs for CEPC

Si-W ECAL

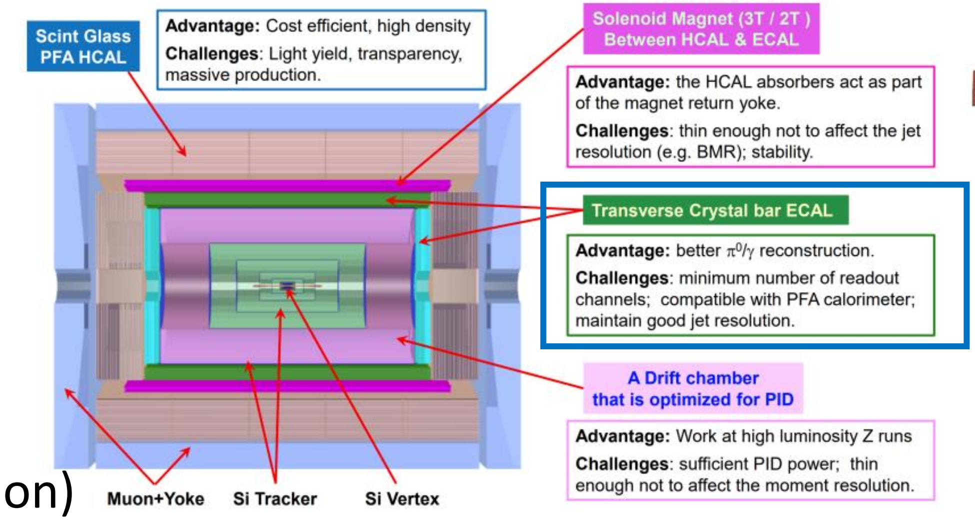
- Baseline design
- Sampling structure
- High granularity
- Strong shower separation

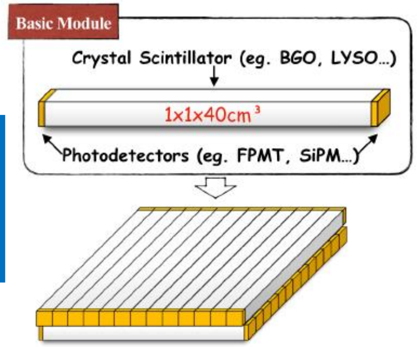


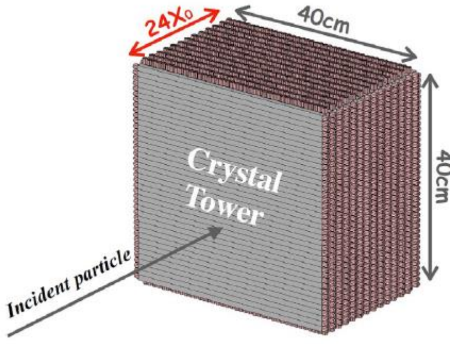


Crystal ECAL

- New design
- Homogeneous structure
- High granularity
- High energy resolution ($3\%/\sqrt{E}$ intrinsic resolution)

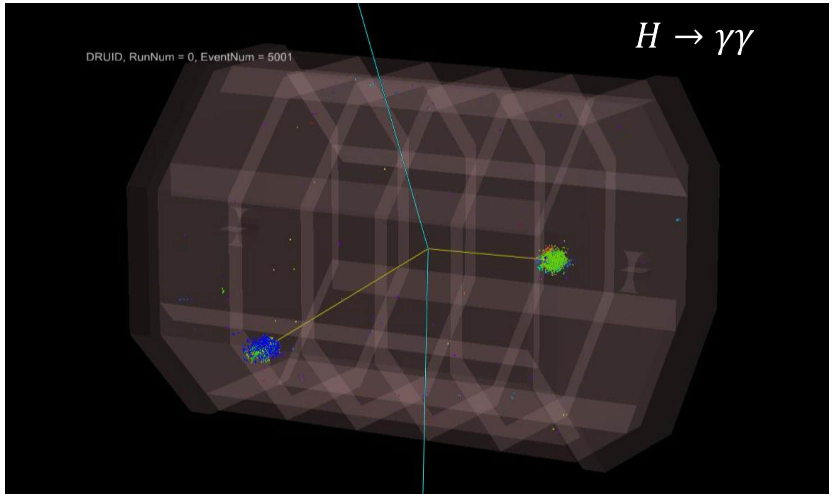


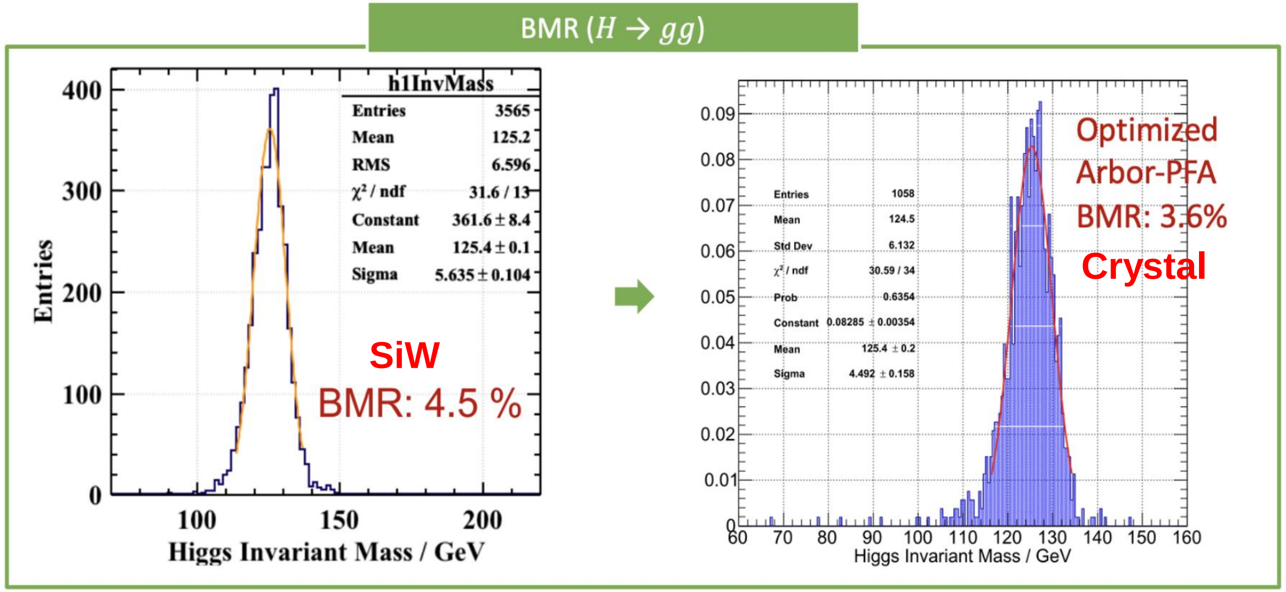


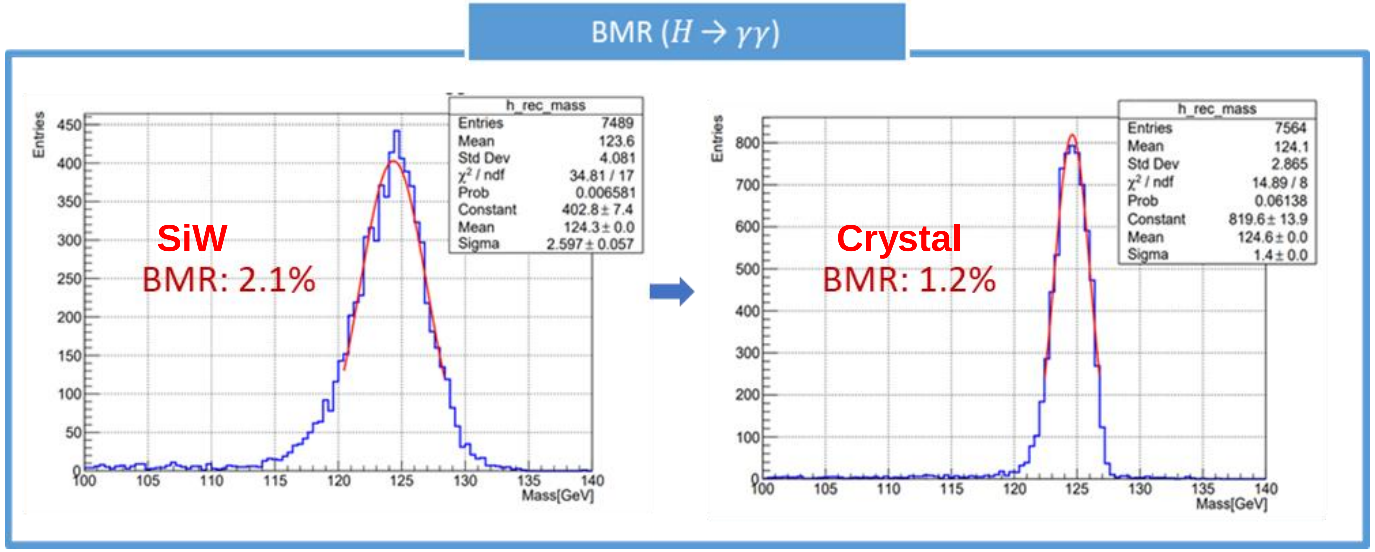


ECAL Performance Comparison: BMR

- Higgs boson mass resolution(BMR) improvement:
  - $H \rightarrow gg$: 4.5% → 3.6%
  - $H \rightarrow \gamma\gamma$: 2.1% → 1.2%
- Better BMR with crystal ECAL





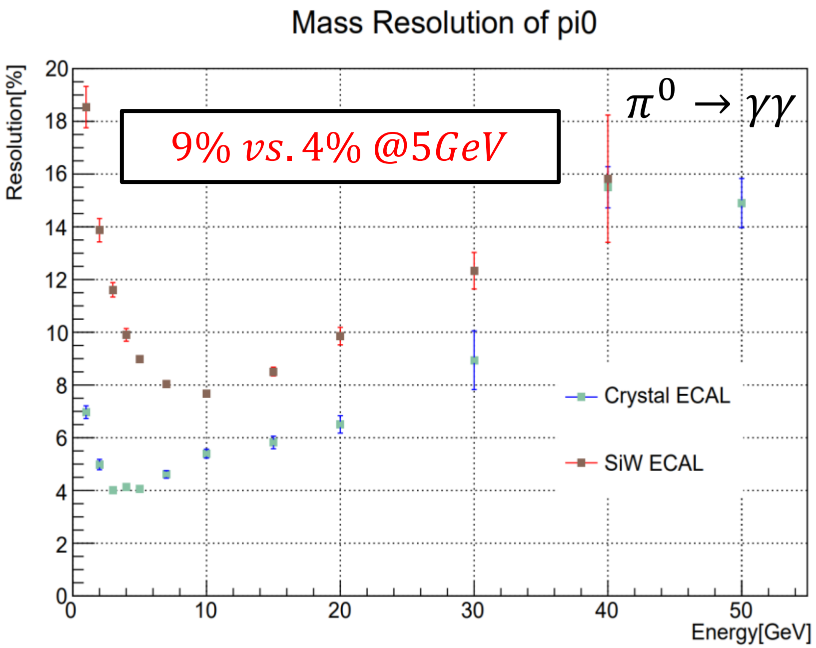


ECAL Performance Comparison : π^0/γ Reconstruction

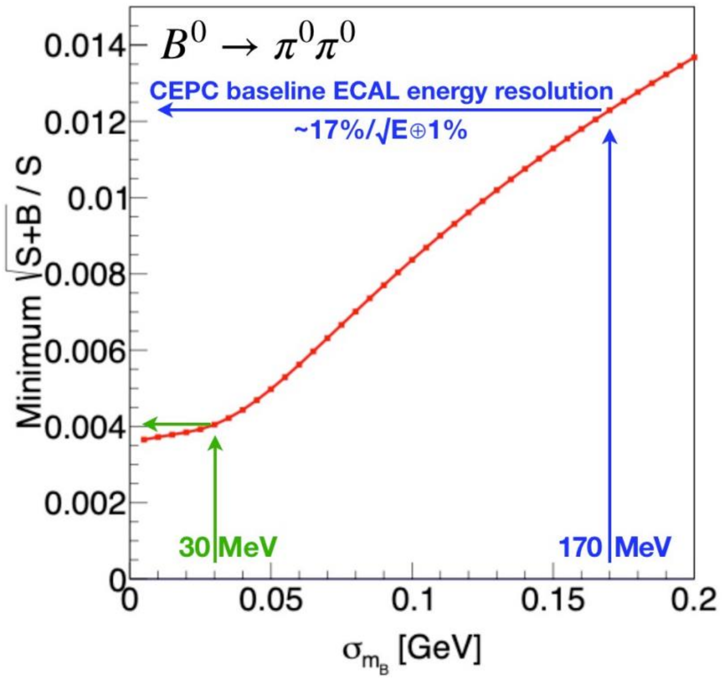
- $B^0 \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ measurement
  - Necessary channel to determine CKM angle α
  - ECAL performance can be characterized by σ_{m_B}
- Crystal ECAL: more potentials for π^0/γ reconstruction (flavor physics)

	ECAL Resolution	σ_{m_B} (MeV)	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$
SiW	$17\%/\sqrt{E} \oplus 1\%$	170	~ 1.2%	~ 21%
Crystal	$3\%/\sqrt{E} \oplus 0.3\%$	30	~ 0.4%	~ 4%

3 ~ 5 times improvement



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



Overview of Crystal ECAL Specifications

Key Parameters	Value	Notes
MIP light yield	~200 p.e./MIP	9.1 MeV/MIP in 1cm BGO
Energy threshold	0.05 MIP	Depends on S/N and light yield
Crystal non-uniformity	<1%	After calibration
Dynamic range	$5 - 10^5$ p.e.	About 500keV – 10GeV
Time resolution	~400 ps	Ideal performance (from G4 simulation)
Temperature stability	Stable at the level of 0.05℃	CMS ECAL value

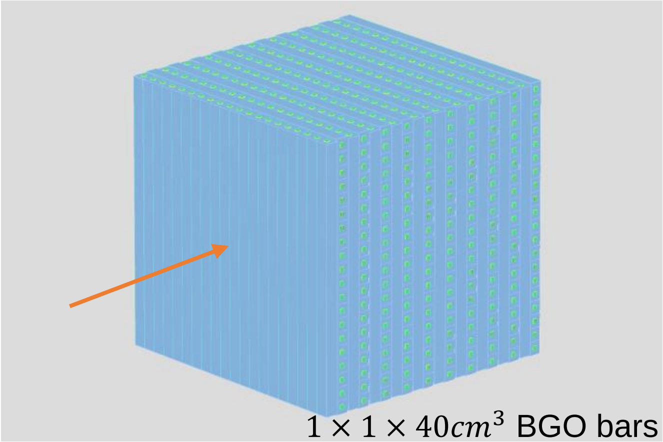
Further issues:

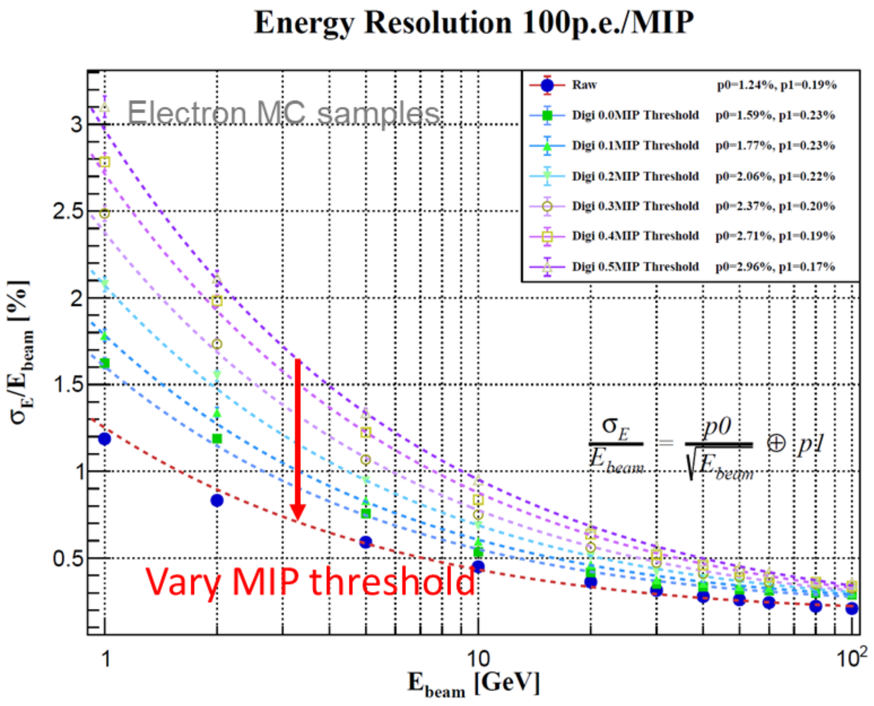
- Temperature control
  - Temperature dependent properties (SiPM, crystal)
  - Cooling system for Front-end electronics
- Calibration schemes
  - LED single photon calibration of SiPMs
  - Transmittance of crystal: radiation damage
  - Operation and maintenance: MIP calibration

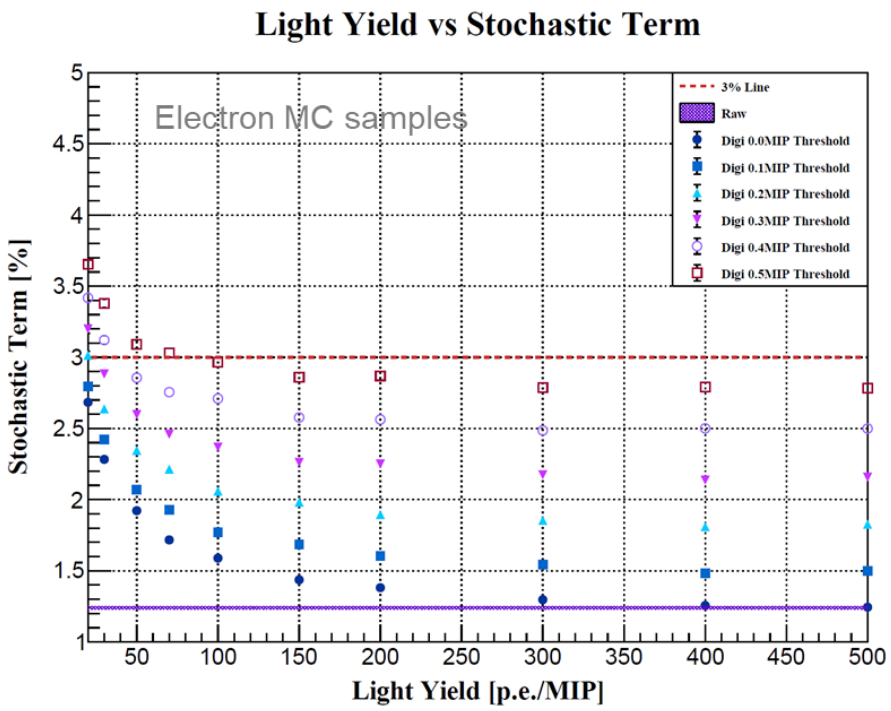
EM Energy Resolution: Threshold and Light Yield Requirements

- Impact on energy threshold and light yield
  - Digitization: photon statistics (crystal + SiPM), electronics resolution
  - ~200 p.e./MIP light yield and low threshold: promising for $\sim 1.6\%/\sqrt{E}$ energy resolution

Geant4 Simulation (v10.7)

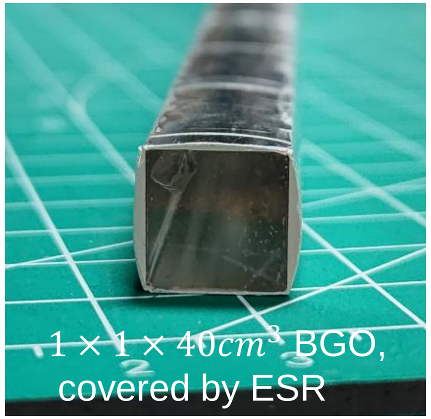


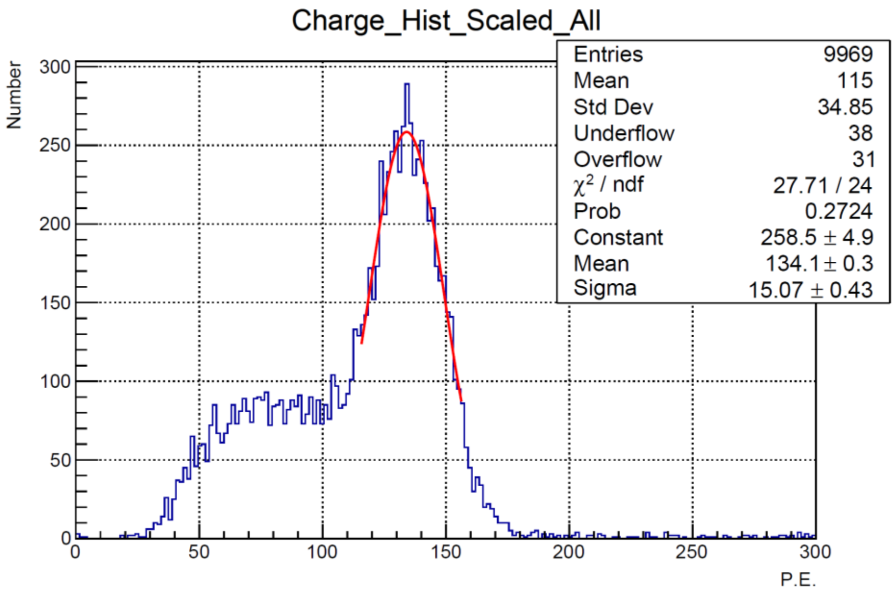




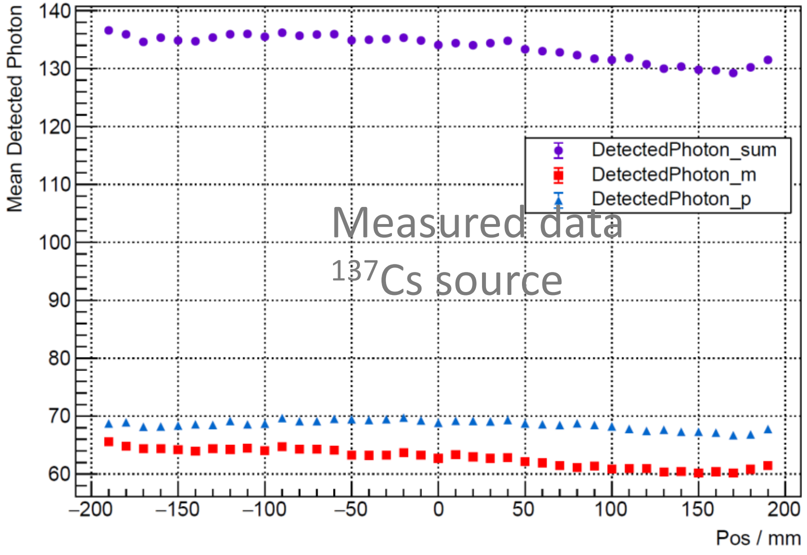
Test of Radioactive Sources for Long Crystal Bar

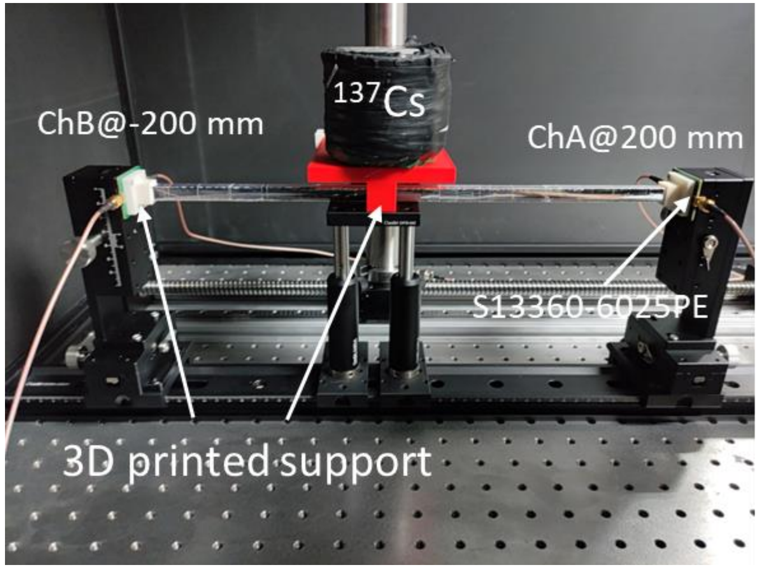
- BGO crystal bar coupled with SiPM
  - Energy resolution of : 11.2% @662keV
  - Light yield: ~200 p.e./MeV, enough for the LY requirement
  - Uniformity scan: <5% non-uniformity





Experiment: detected photon



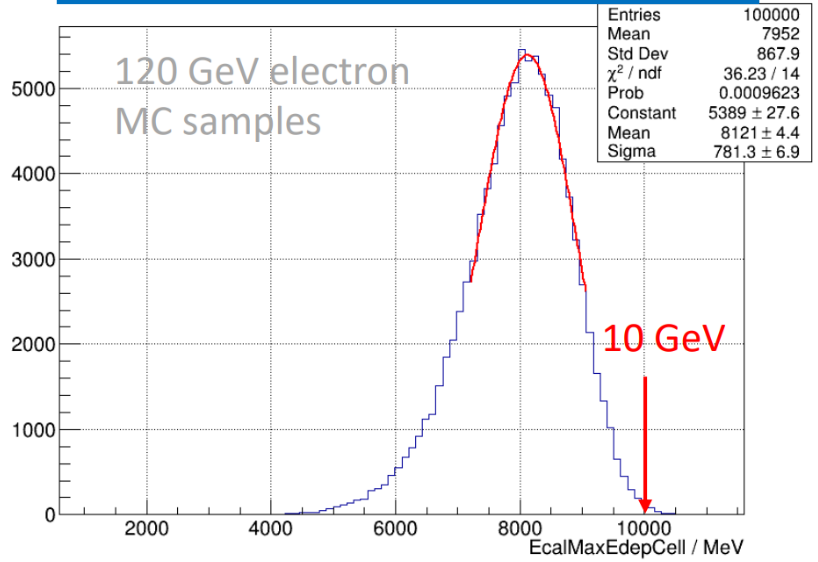


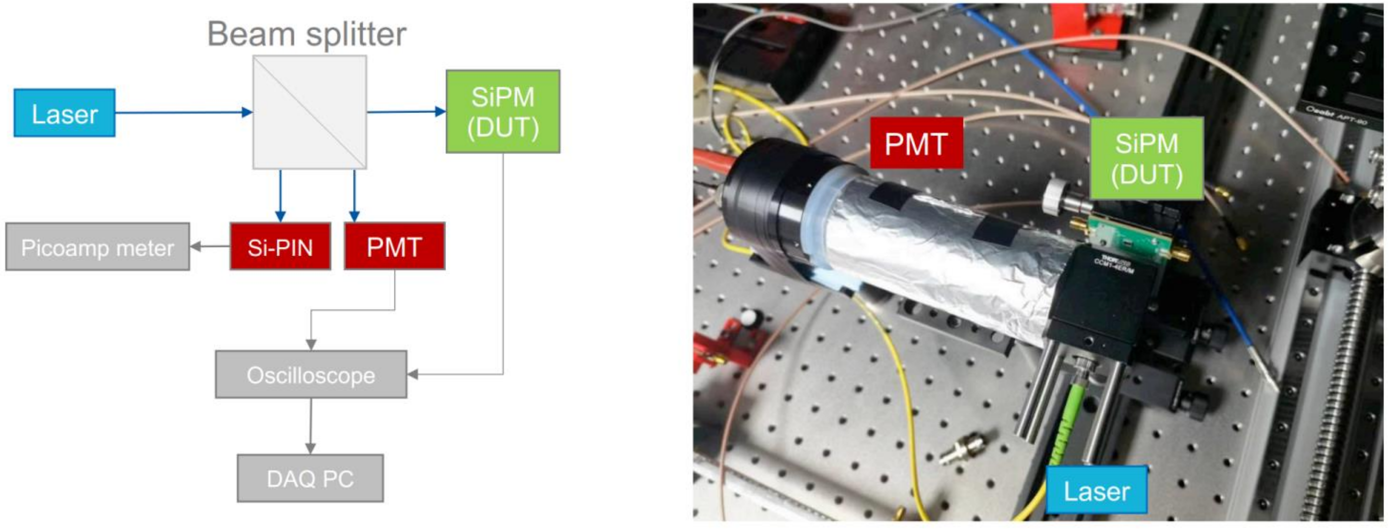
- Relatively low response near one side
- Coupling, crystal manufacture……

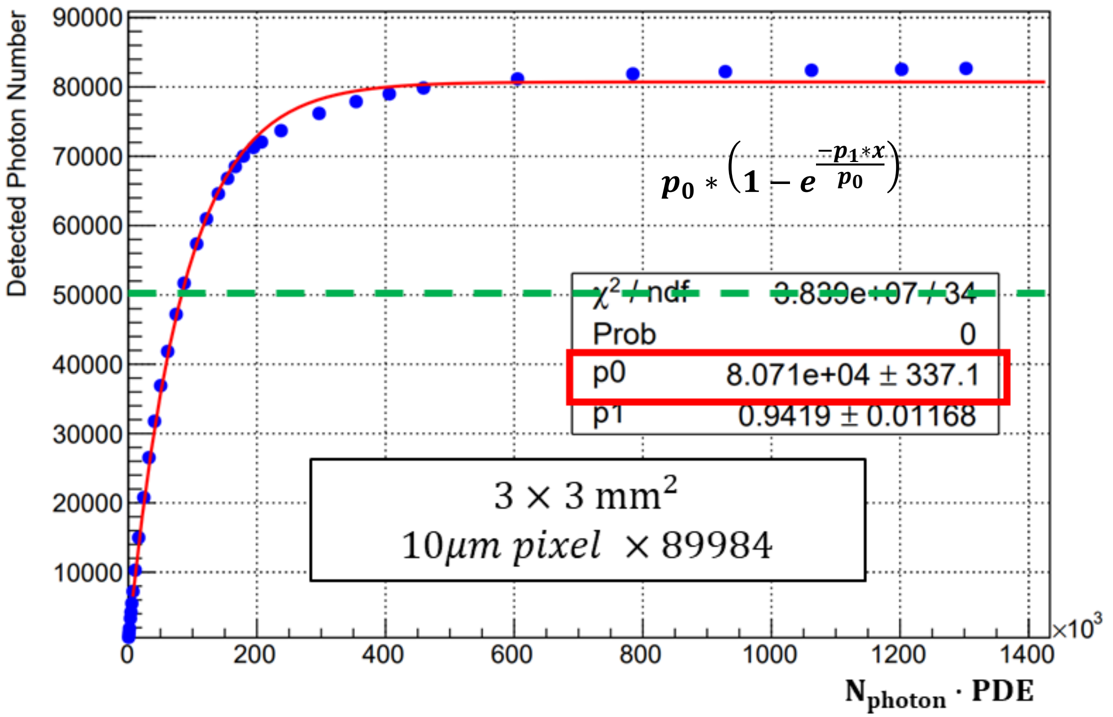
SiPM Dynamic Range Test

- Maximum energy deposition in one crystal(from Bhabha electrons): ~10GeV → ~ 5×10^4 p.e.(1 side)
- Setup
  - Pico-second laser: ~40ps pulse width, 405nm wavelength
  - Beam splitter: divide the light between SiPM and PMT
  - SiPM: HPK S14160-3010PS, 10μm pixel, 89984 pixels
  - PMT: determine the number of pe that SiPM received
  - Si-PIN: auxiliary scaler

Maximum energy deposition within a bar



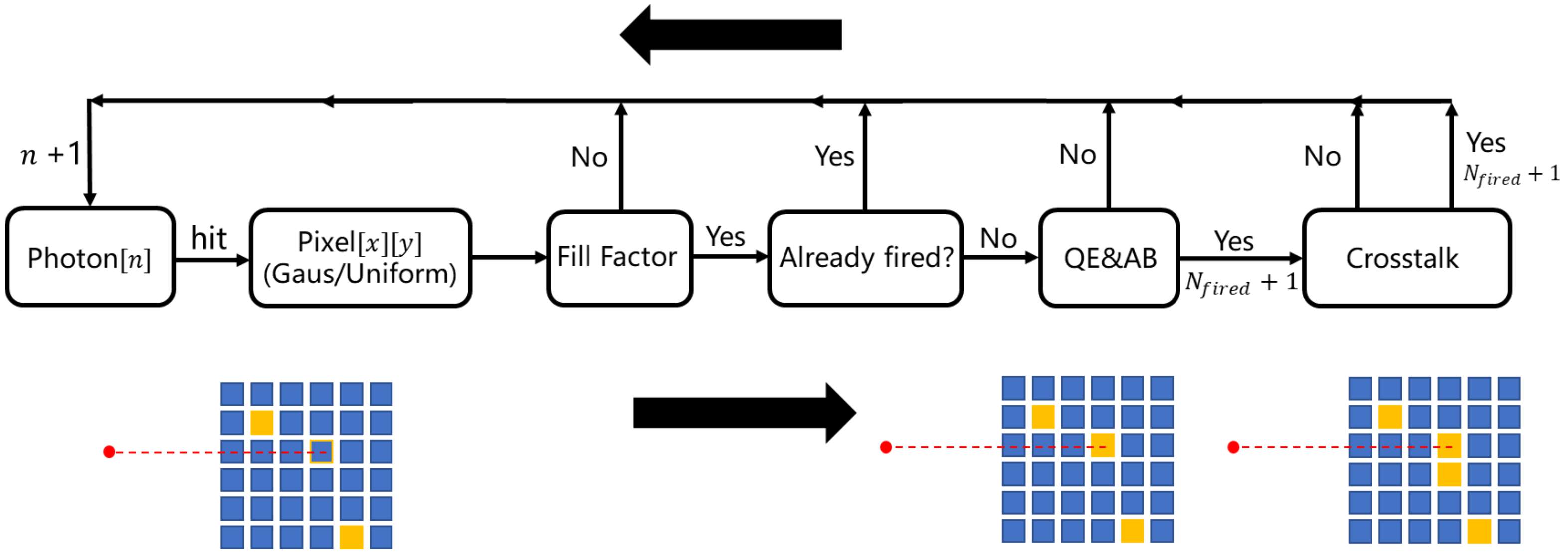




Studies on wide dynamic-range SiPMs with high pixel densities, Zhiyu Zhao – TIPP2023

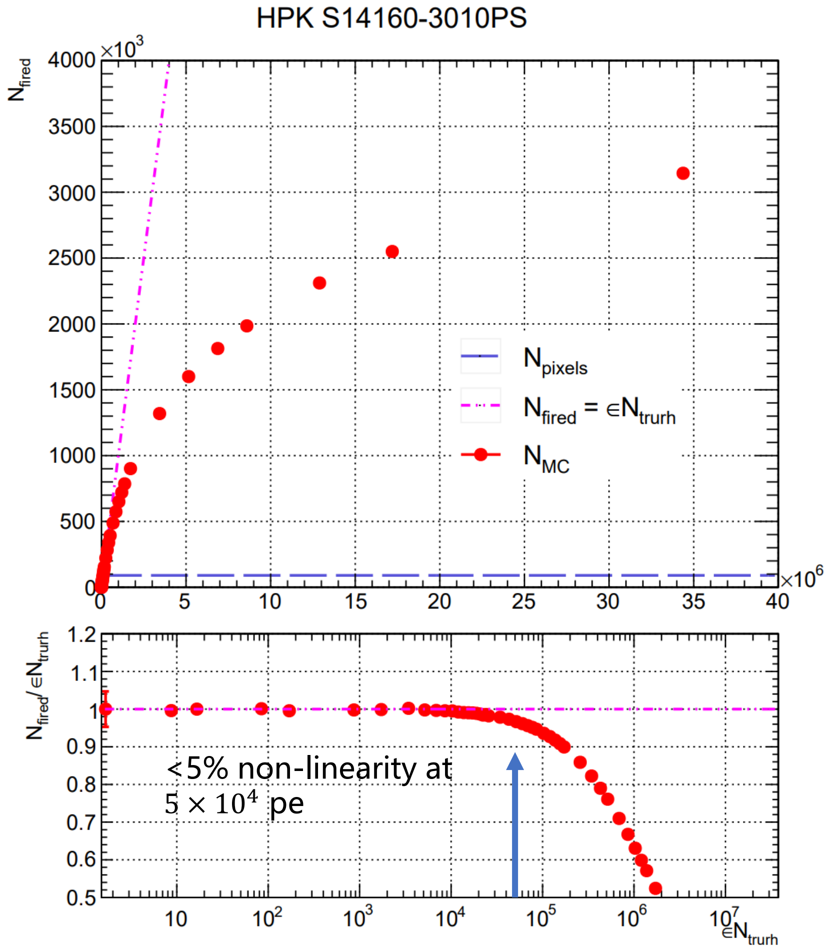
Toy Monte Carlo for SiPM Response

- MC with SiPM recovery effect:
  - Incident time of photon comes from Geant4 optical simulation of a $1 \times 1 \times 40cm^3$ BGO crystal bar
  - Uniform light spot on SiPM
  - SiPM PDE spectrum and BGO emission spectrum
- $1 \times 1 \times 40cm^3$ BGO crystal bar readout by SiPMs with $10\mu m$ pixel and $3 \times 3cm^2$ size can maintain linearity >95% at 5×10^4 pe



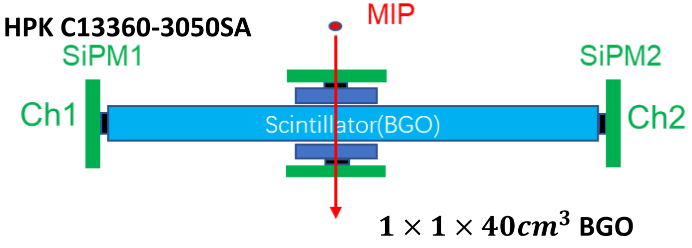
Toy Monte Carlo w/:

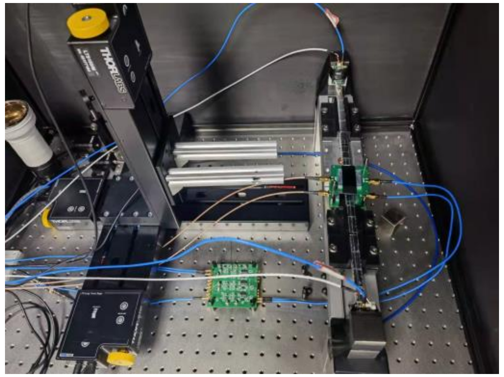
- SiPM pixel density, PDE spectrum, crosstalk, pixel recovery effect
- BGO emission spectrum, scintillation photon detected time

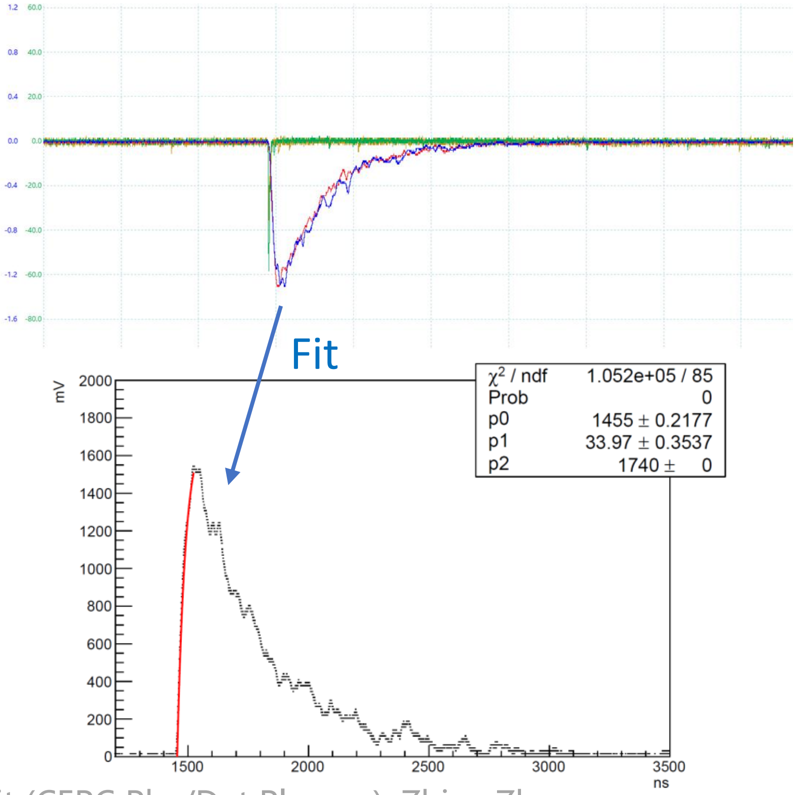


Time Resolution of BGO Crystal Bar

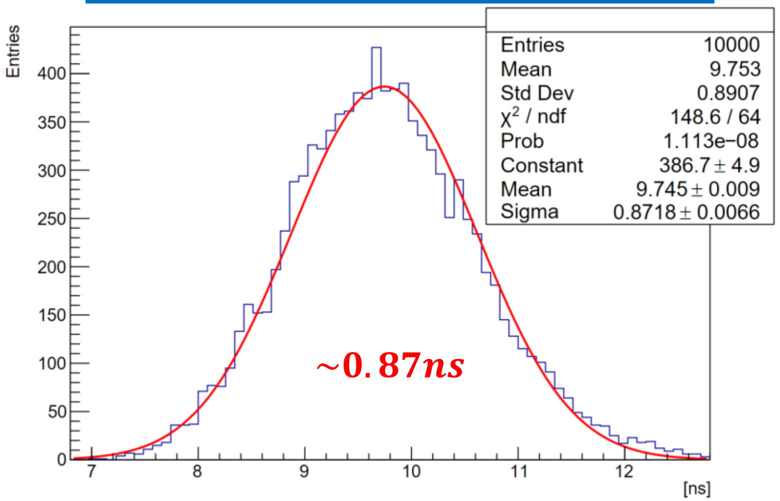
- Potential for improving shower reconstruction
- Experiment setup:
    - double-side readout
    - Fast sampling rate(1.25 GS/s)
    - Leading edge fitting + constant fraction timing
- Timing resolution ~1ns at 1-MIP signal level

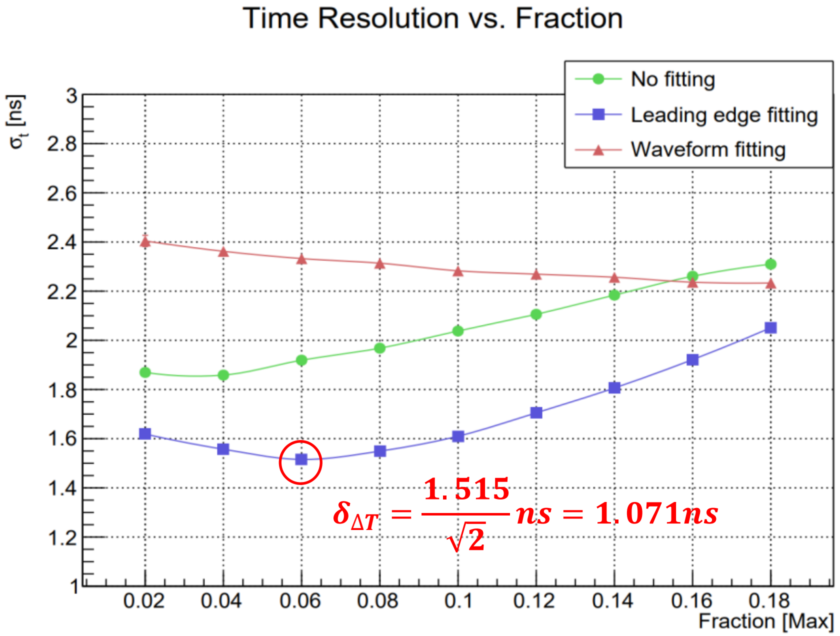






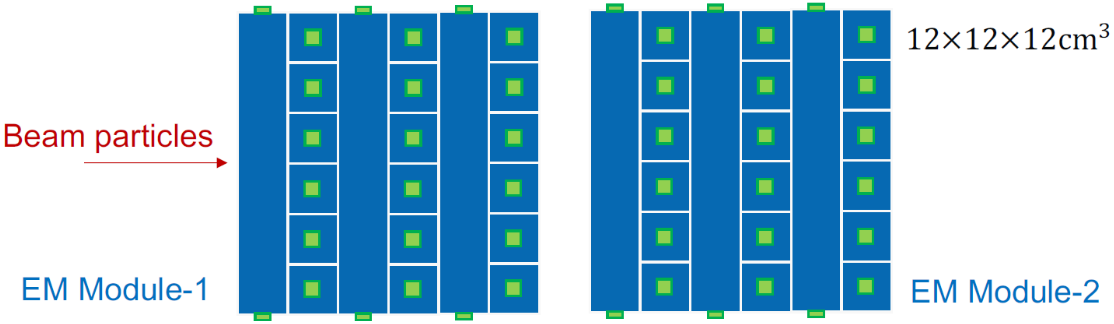
Time Resolution from Waveform Simu

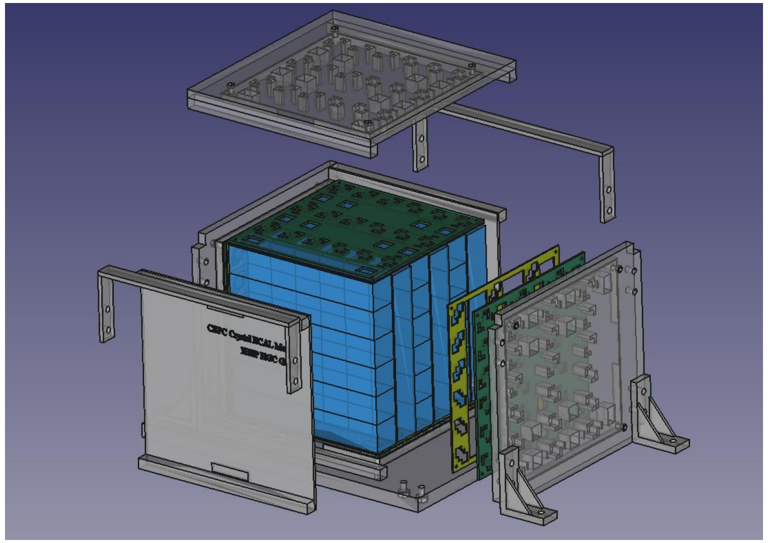


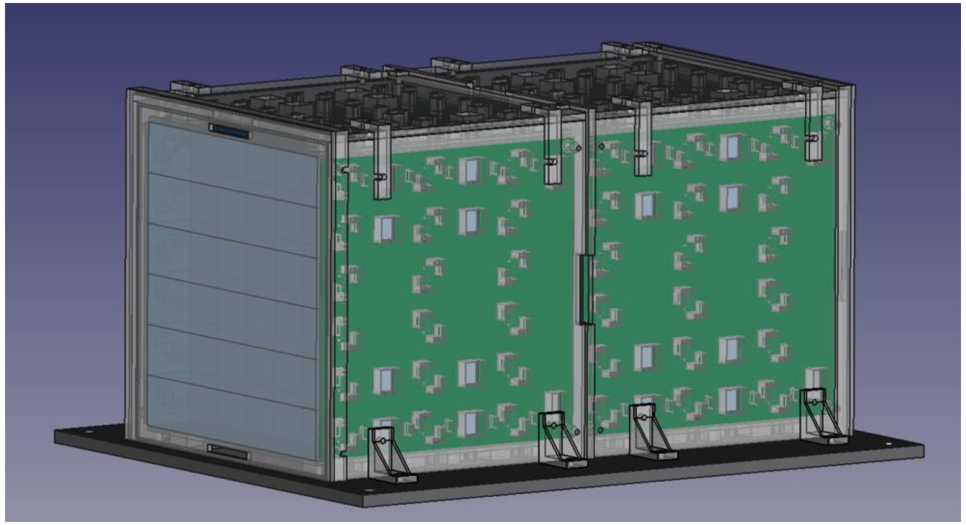


Development of Crystal Modules

- Motivations
  - Identify critical questions/issues on system level:
    - Frond-end ASIC, mechanics, integration, …
  - Evaluate key performance with TB data
  - Validation of simulation and digitization







Future

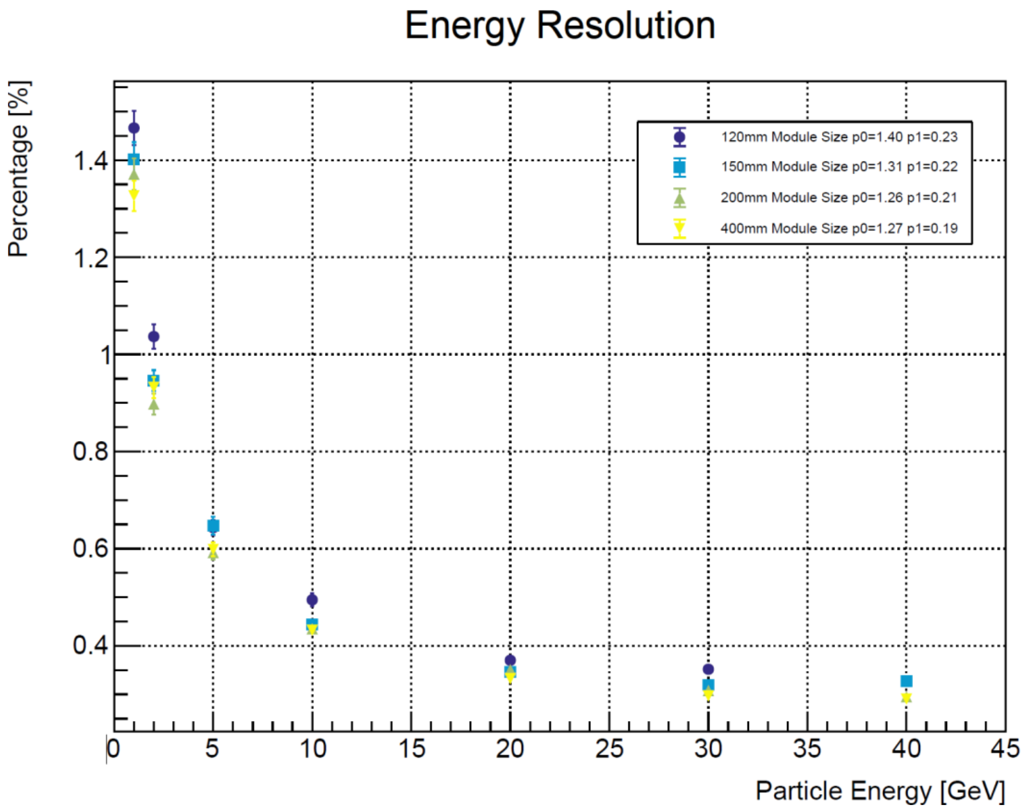
- First crystal module, 72 channels , $10.7X_0$
- First beamtest at CERN PS-T9(May, 2023)
- Main target: first module commissioning

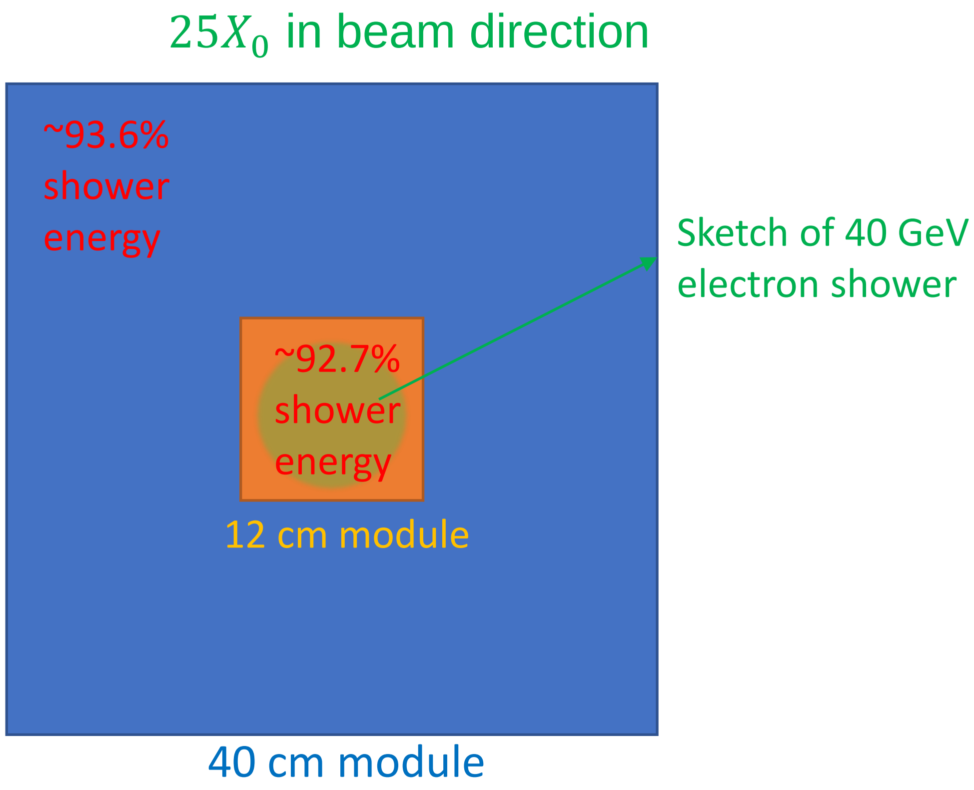
- Second module, 144 channels, $21.4X_0$
- Beamtest at DESY TB22(Oct, 2023)
- Main goals: EM performance

Large scale prototype with longer bars and more channels?

Small-Scale Crystal Module Design: Impact of Module Size

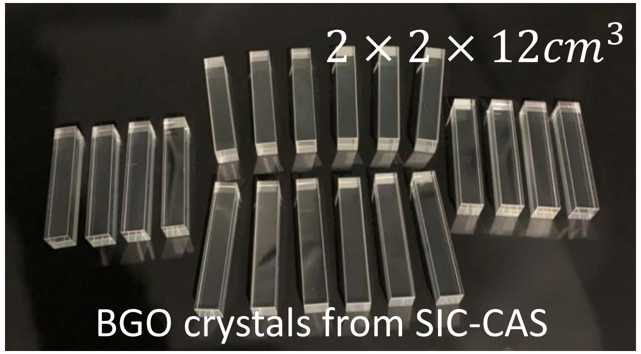
- For EM showers, 12 cm size is enough to contain most of the energy when particles hit on the center of the module
- Degradation of energy resolution: ~0.1% level

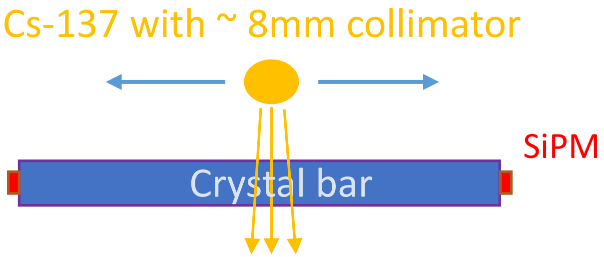




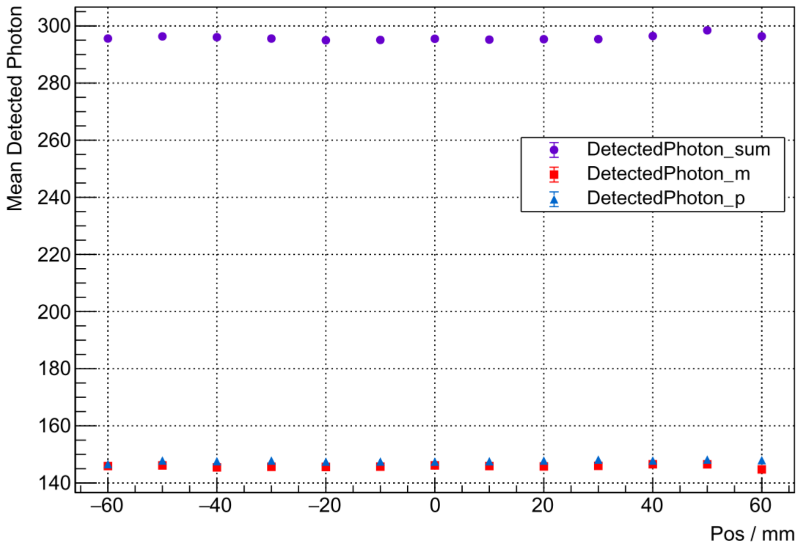
First Crystal Module: Uniformity Scan of BGO Crystal Bars

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

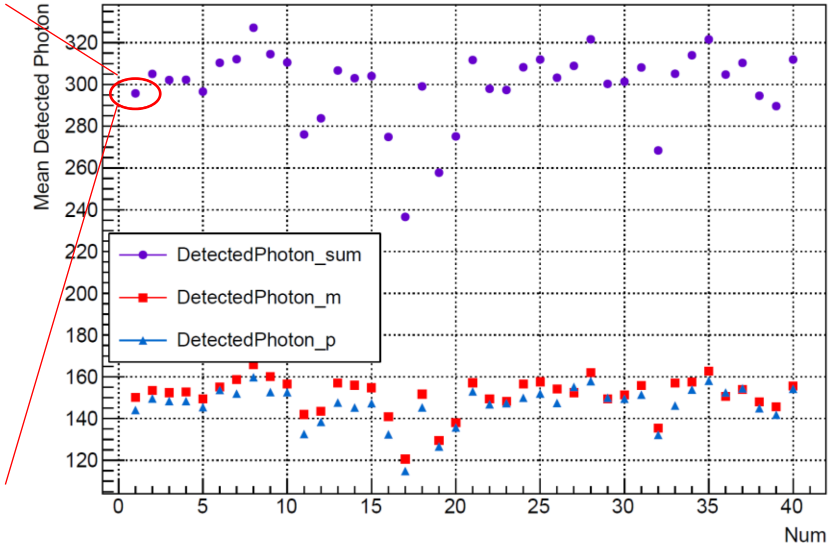


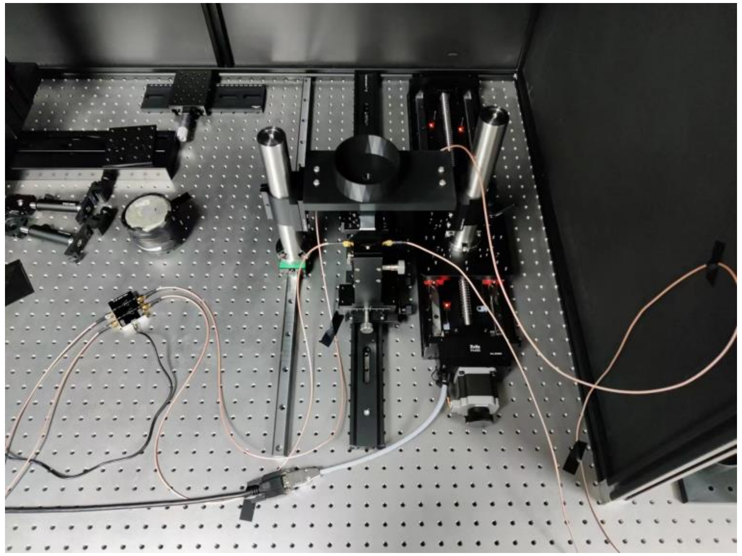


Response uniformity along #1 BGO bar



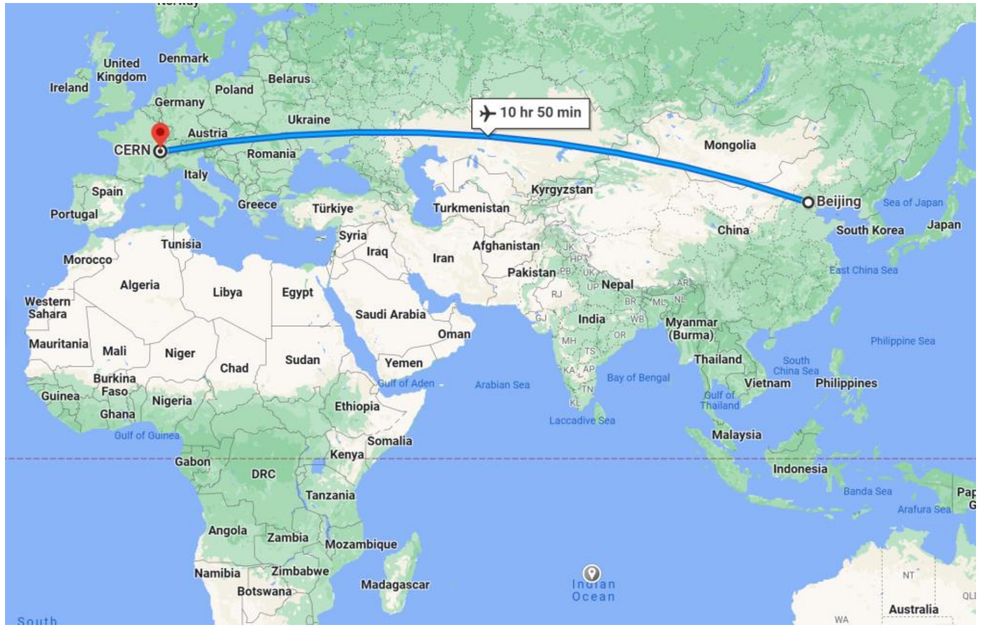
Comparison of 40 crystal bars

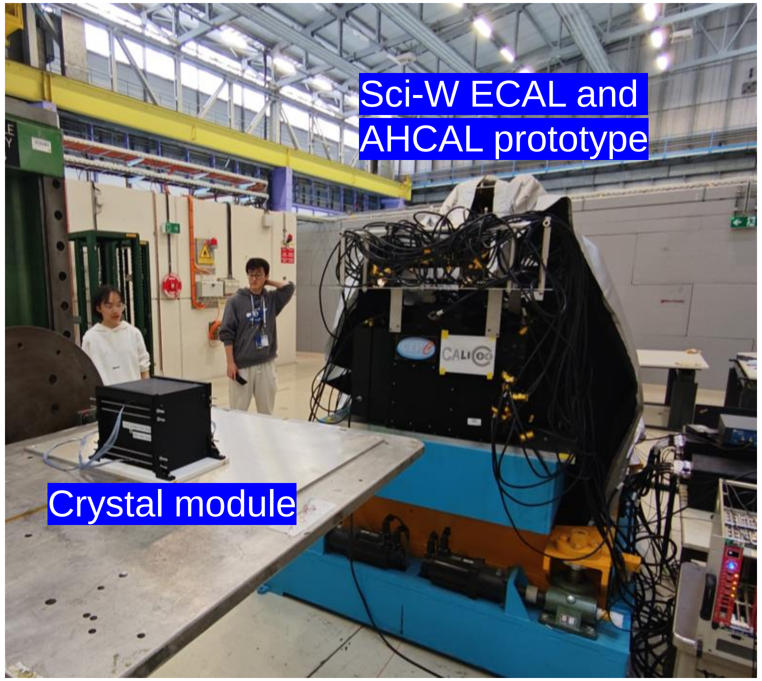




- Generally good uniformity along a single bar
- Response varies among bars, 36 crystals were selected for beamtests

First Crystal Module: Transport and Preparations



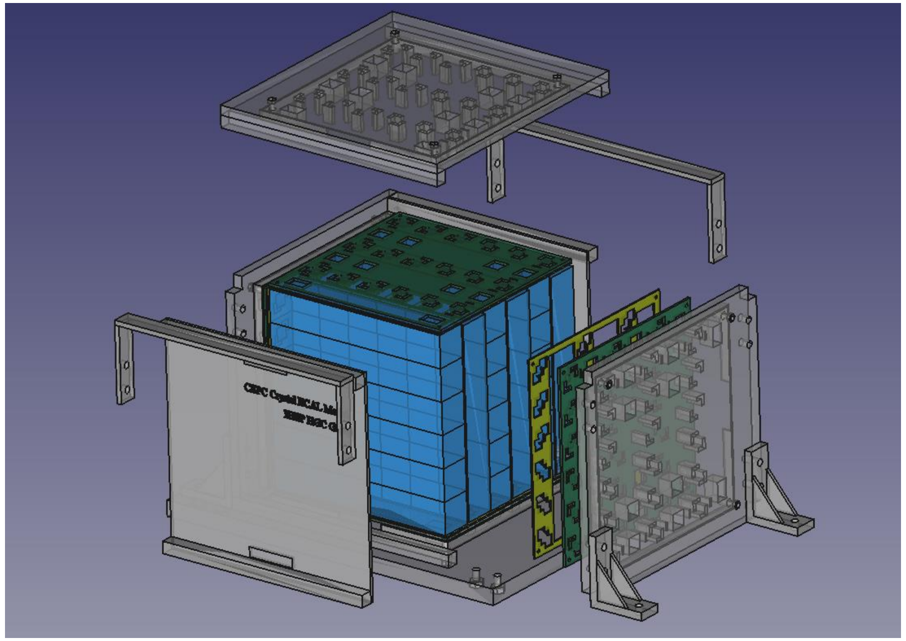


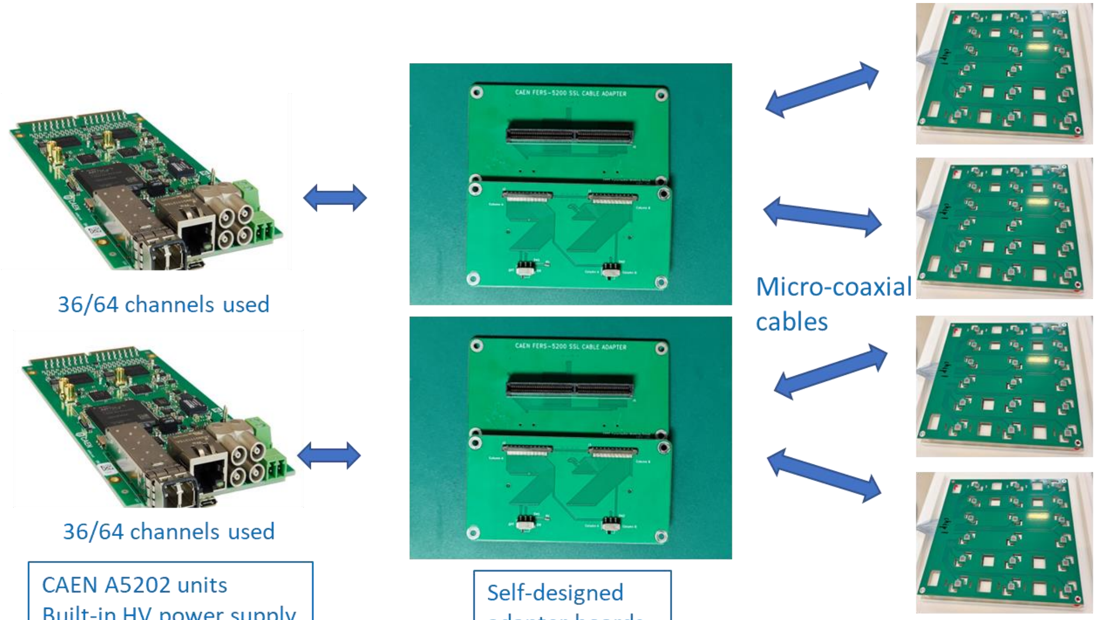
- Preparation since the end of 2022
  - Simulation, mechanical design, PCB design, crystal production…
- Successful transportation from Beijing to CERN in May. 2023
- First beamtest at CERN PS-T9, together with CEPC Sci-W ECAL and AHCAL prototype

Status of high granular sci-ECAL, Tatsuki Murata
CEPC AHCAL beam test data analysis, Siyuan Song

First Crystal Module: Mechanics and DAQ

- Mechanical structure and PCB design
  - Four readout PCBs with SiPMs and temperature sensors
  - 3D print PLA to provide support and shadowing
  - Pressure decoupled between crystal and SiPM





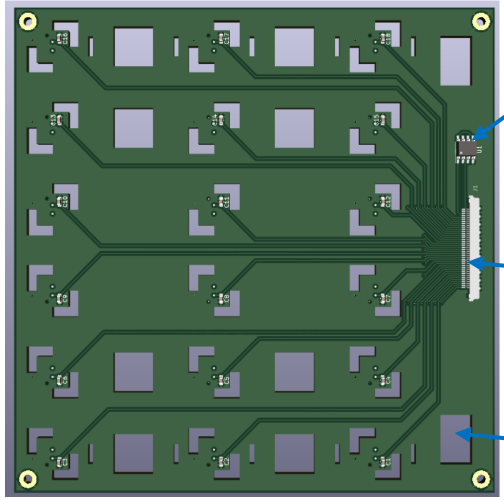
Daisy chained trigger distribution

CAEN A5202 units
Built-in HV power supply

Self-designed adapter boards

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

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

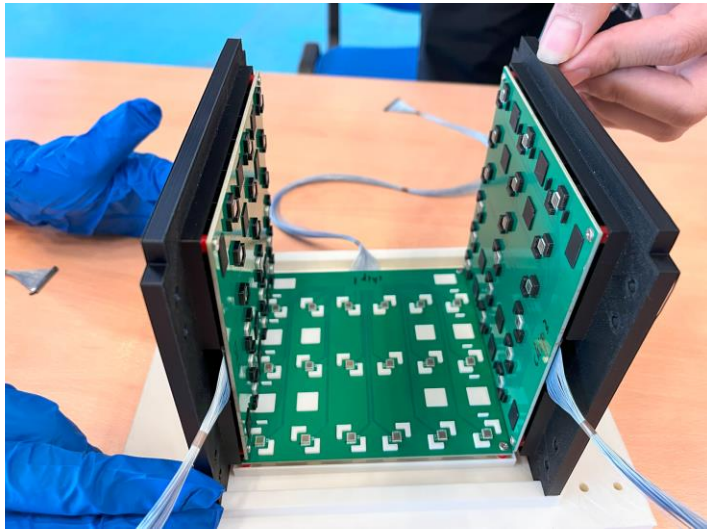


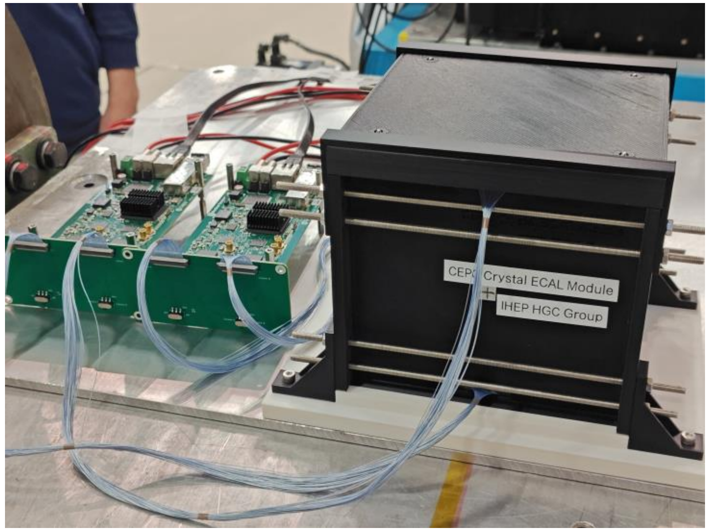
Temperature sensor

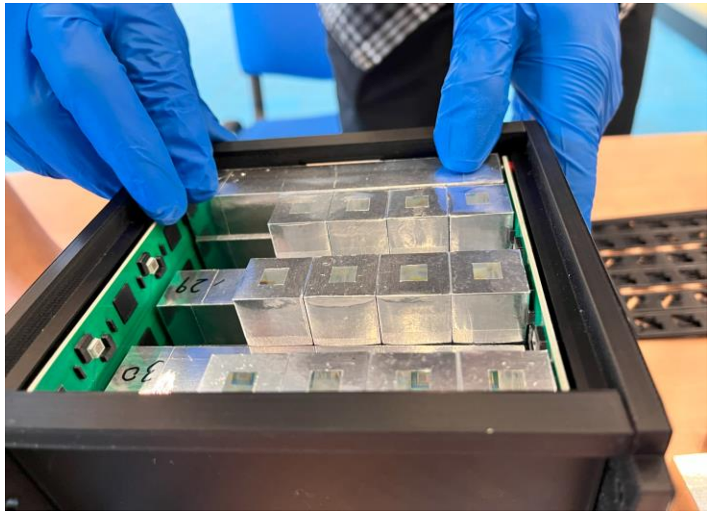
Micro-coaxial connector

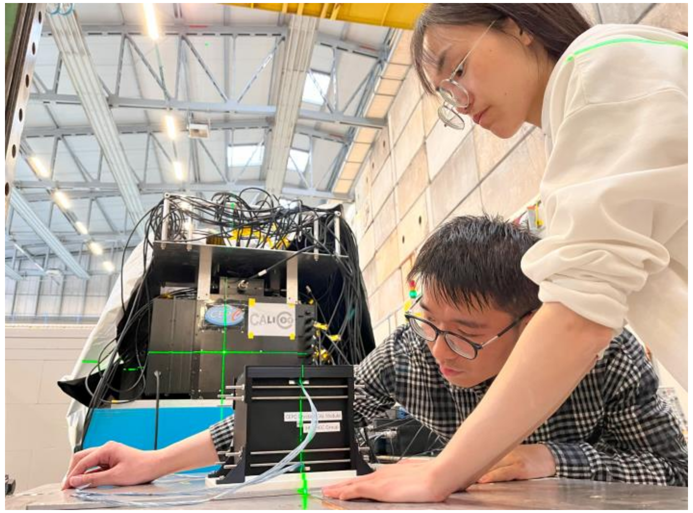
Holes for crystal support

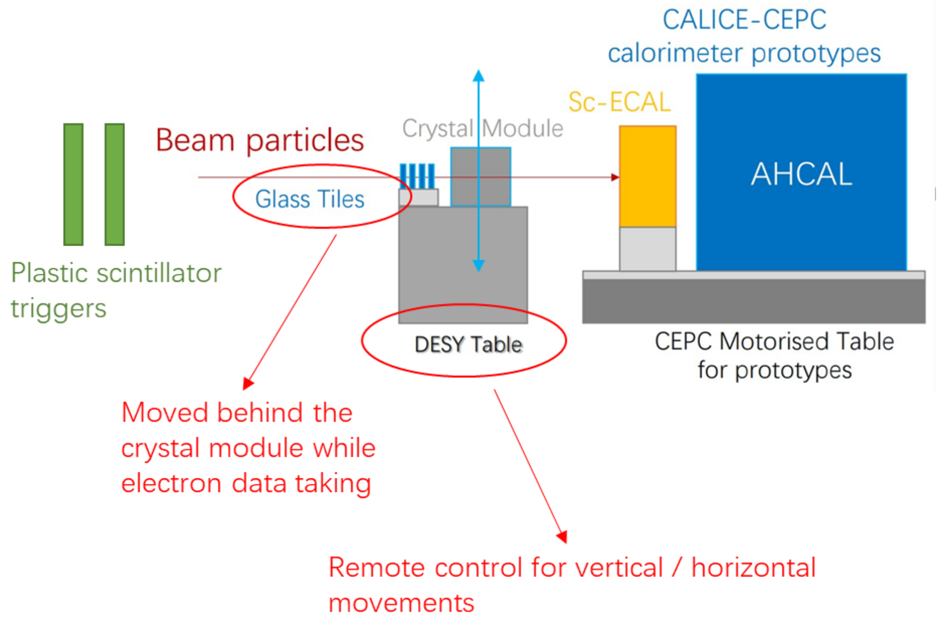
First Crystal Module: Setup for Beamtest







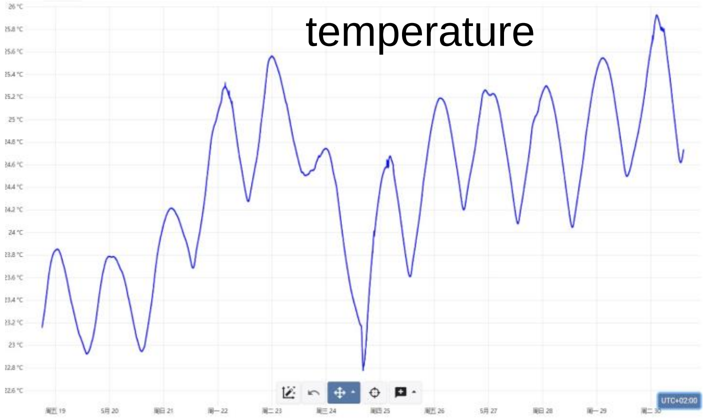


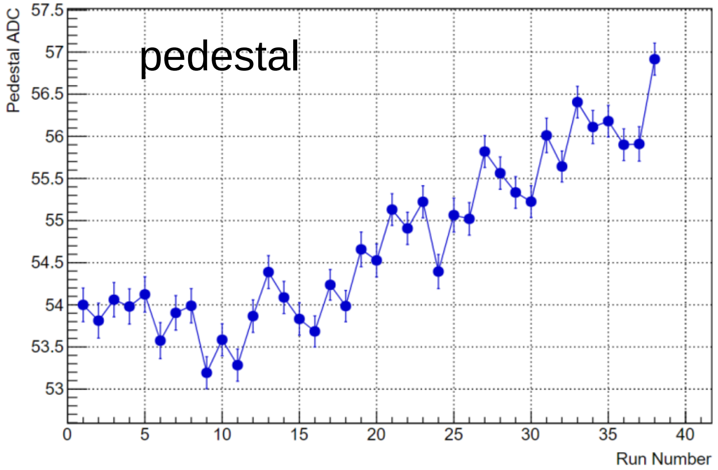


- Parasitic runs with CEPC calorimeter prototypes
  - Muon data: taken along with glass tiles and CEPC calorimeter prototypes
  - Electron data: taken independently
- Self-trigger runs when the crystal module is moved out from the beamline

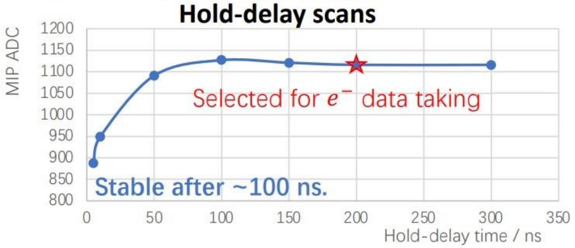
First Crystal Module: Muon Data for Parameter Scans and Calibration

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

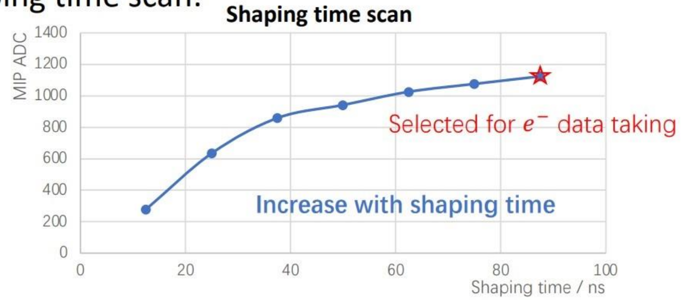


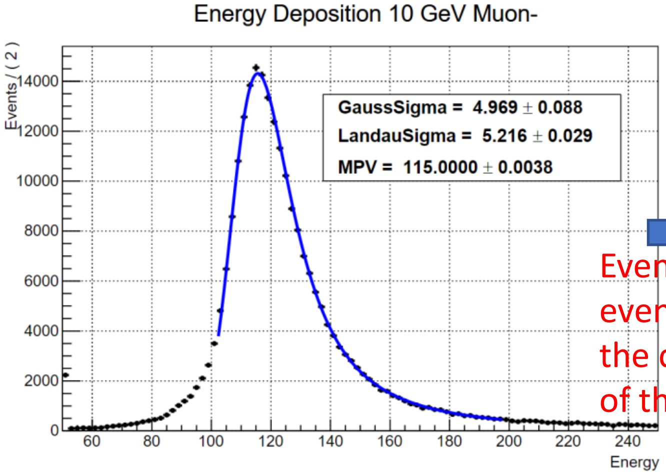


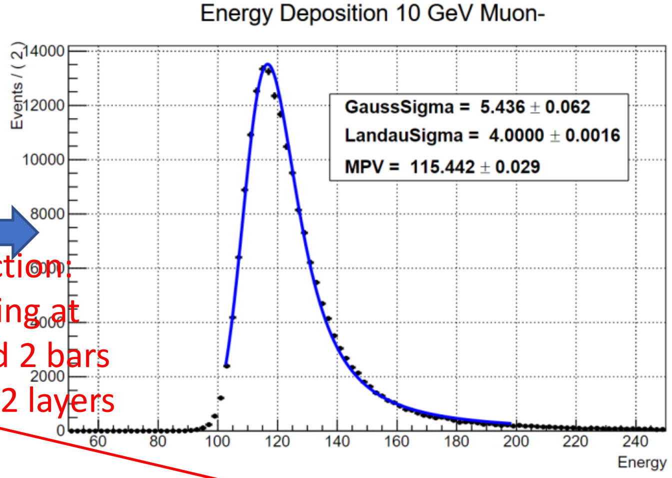
- Hold-delay time scan:
  - 10 GeV muon, HG 59, LG 63, scan from 5 ns to 300 ns.



- Shaping time scan:

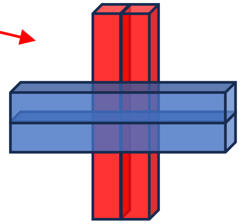






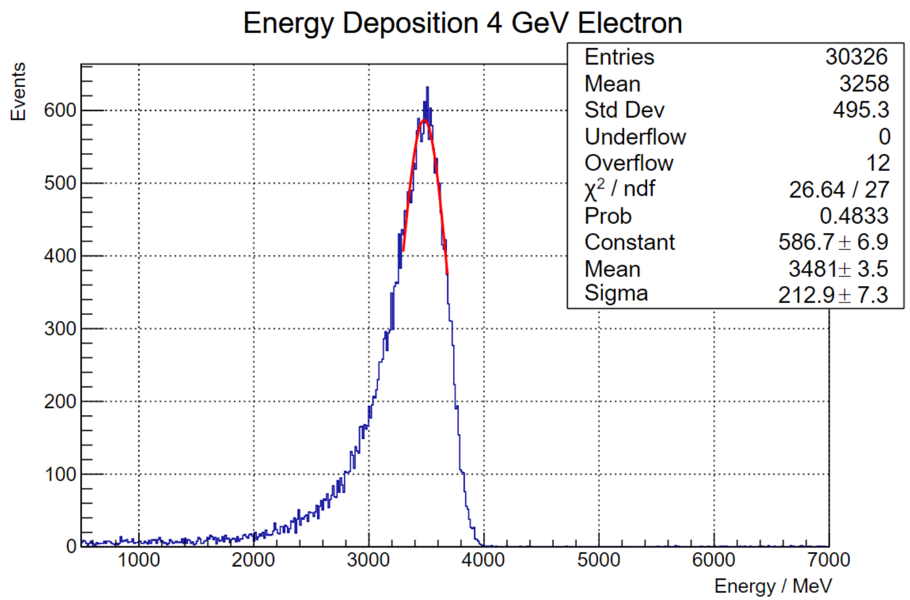
Event selection: events hitting at the centred 2 bars of the first 2 layers

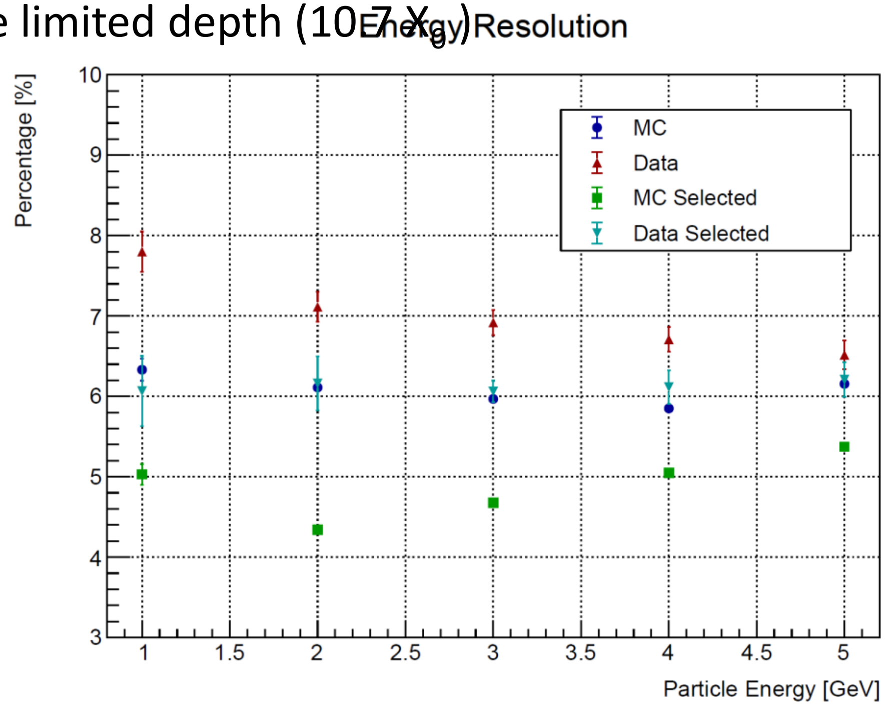
- Successfully acquired muon data with good quality
- Selected parameters for electron data taking
- Channel-by-channel calibration completed

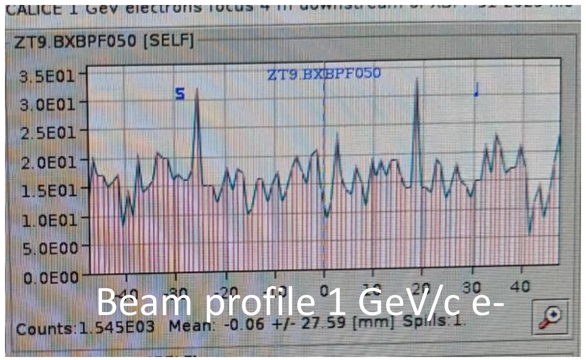


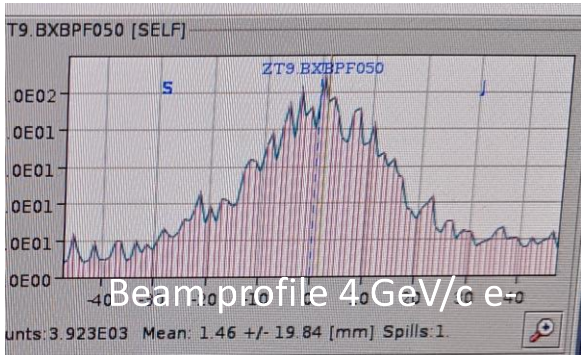
First Crystal Module: Electron Data for Energy Resolution

- MIP calibration: channel-wise calibration with muon beam
- Event selection: beam incidence at the module center (wide beam profile)
- Simulation of beamtest experiments: electron events
  - Implemented realistic module geometry, upstream material, beam profile, momentum spread…
- Significant energy leakage effects due to the limited depth (10.7 X_0)





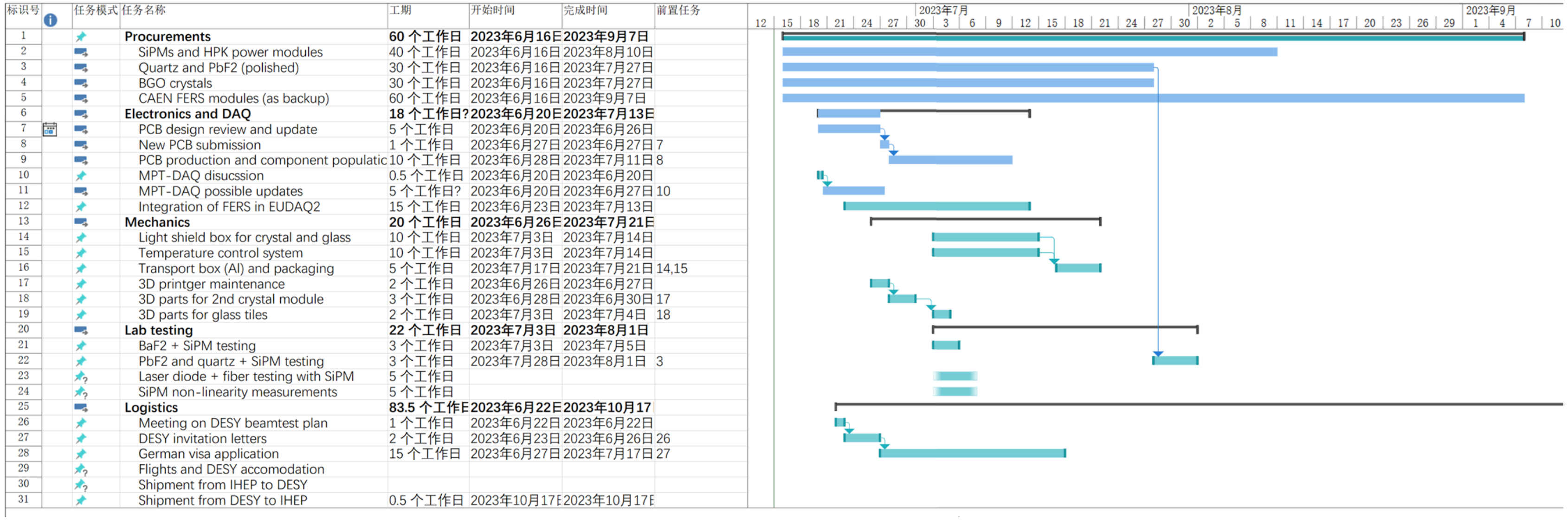




- Beam profile: severe changes in the spatial distribution of the beam spot

- Achieved major goals
  - Commissioning of the first crystal module
  - Validation of simulation+digititstaion

Second Crystal Module: Preparations and Transport



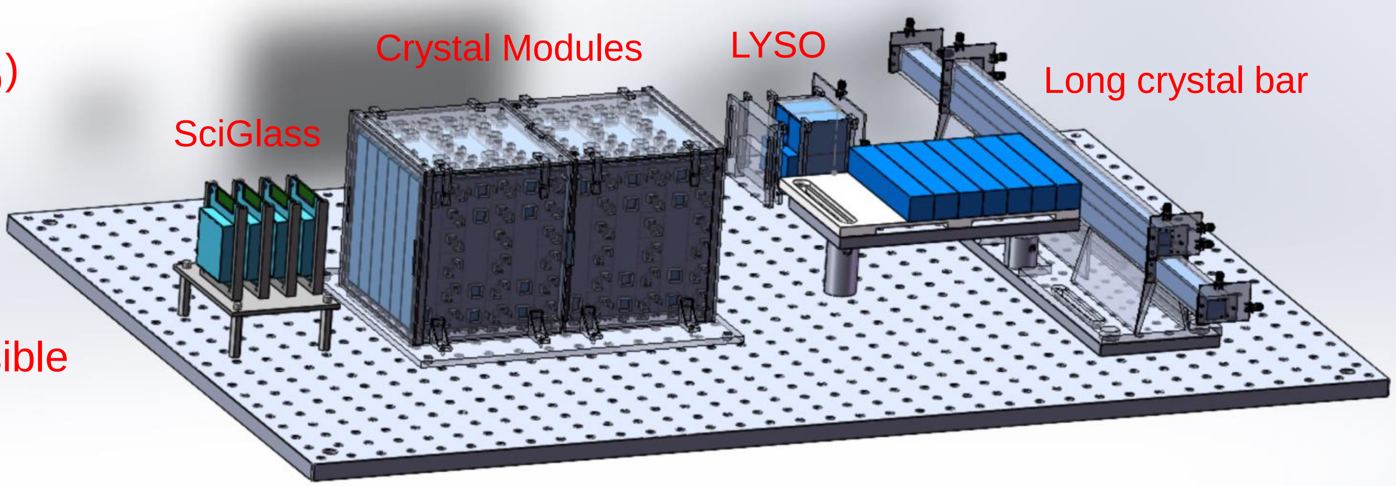
标识号	任务模式	任务名称	工期	开始时间	完成时间	前置任务
1		**Procurements**	**60 个工作日**	**2023年6月16E**	**2023年9月7日**	
2		SiPMs and HPK power modules	40 个工作日	2023年6月16日	2023年8月10日	
3		Quartz and PbF2 (polished)	30 个工作日	2023年6月16日	2023年7月27日	
4		BGO crystals	30 个工作日	2023年6月16日	2023年7月27日	
5		CAEN FERS modules (as backup)	60 个工作日	2023年6月16日	2023年9月7日	
6		**Electronics and DAQ**	**18 个工作日?**	**2023年6月20E**	**2023年7月13E**	
7		PCB design review and update	5 个工作日	2023年6月20日	2023年6月26日	
8		New PCB submission	1 个工作日	2023年6月27日	2023年6月27日	7
9		PCB production and component populatic	10 个工作日	2023年6月28日	2023年7月11日	8
10		MPT-DAQ disucssion	0.5 个工作日	2023年6月20日	2023年6月20日	
11		MPT-DAQ possible updates	5 个工作日?	2023年6月20日	2023年6月27日	10
12		Integration of FERS in EUDAQ2	15 个工作日	2023年6月23日	2023年7月13日	
13		**Mechanics**	**20 个工作日**	**2023年6月26E**	**2023年7月21E**	
14		Light shield box for crystal and glass	10 个工作日	2023年7月3日	2023年7月14日	
15		Temperature control system	10 个工作日	2023年7月3日	2023年7月14日	
16		Transport box (Al) and packaging	5 个工作日	2023年7月17日	2023年7月21日	14,15
17		3D printger maintenance	2 个工作日	2023年6月26日	2023年6月27日	
18		3D parts for 2nd crystal module	3 个工作日	2023年6月28日	2023年6月30日	17
19		3D parts for glass tiles	2 个工作日	2023年7月3日	2023年7月4日	18
20		**Lab testing**	**22 个工作日**	**2023年7月3日**	**2023年8月1日**	
21		BaF2 + SiPM testing	3 个工作日	2023年7月3日	2023年7月5日	
22		PbF2 and quartz + SiPM testing	3 个工作日	2023年7月28日	2023年8月1日	3
23		Laser diode + fiber testing with SiPM	5 个工作日			
24		SiPM non-linearity measurements	5 个工作日			
25		**Logistics**	**83.5 个工作E**	**2023年6月22E**	**2023年10月17**	
26		Meeting on DESY beamtest plan	1 个工作日	2023年6月22日	2023年6月22日	
27		DESY invitation letters	2 个工作日	2023年6月23日	2023年6月26日	26
28		German visa application	15 个工作日	2023年6月27日	2023年7月17日	27
29		Flights and DESY accomodation				
30		Shipment from IHEP to DESY				
31		Shipment from DESY to IHEP	0.5 个工作日	2023年10月17E	2023年10月17E	

- Preparation the second module since Jun. 2023
- Transportation from Beijing to DESY in Sep. 2023
- Beamtest at DESY TB22, Oct. 2 ~ Oct. 15
  - Also tested long crystal bars and new ASIC

Second Crystal Module: Setup and Tasks

Second Crystal Module: EM performancess

- More channels: 72ch – 144ch $(10.7X_0 \rightarrow 21.4X_0)$
- New mechanics structure
- New PCBs: reduce noise and crosstalk
- Dark box: light and electromagnetic shielding
- Evaluate EM performance and understand possible limitations of existing ASICs



- Long crystal bars: time resolution
  - 40/60 cm
  - Time resolution with crystal bars and position dependence
  - Time resolution at different shower depths
- New ASIC(MPT2321) for 32-ch SiPM readout
  - Large dynamic range
  - Good S/N for single photon calibration
- Scintillating glass tiles

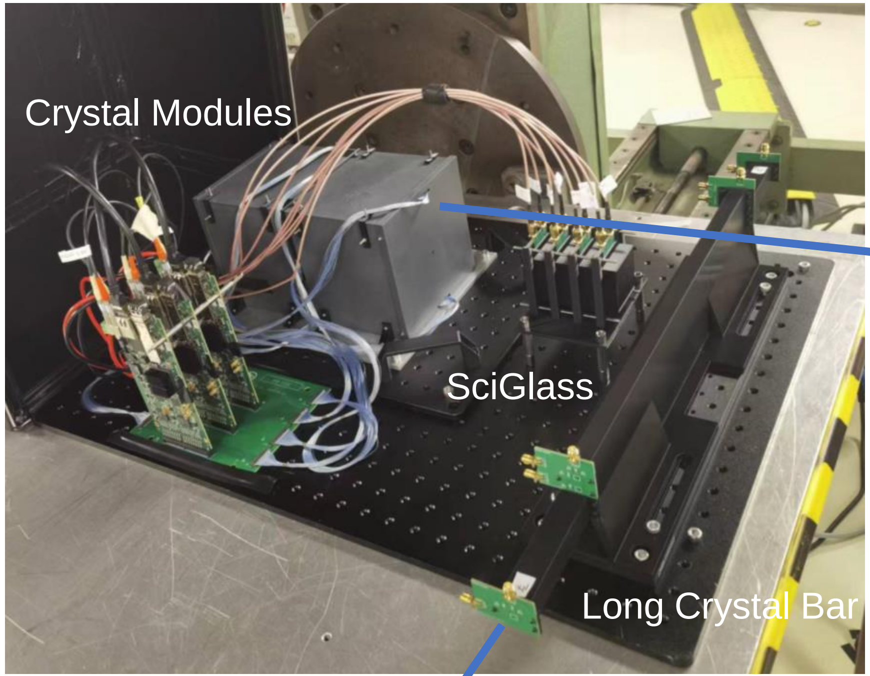
CEPC glass scintillator calorimeter simulation, Peng Hu
Glass scintillator R&D, Sen Qian

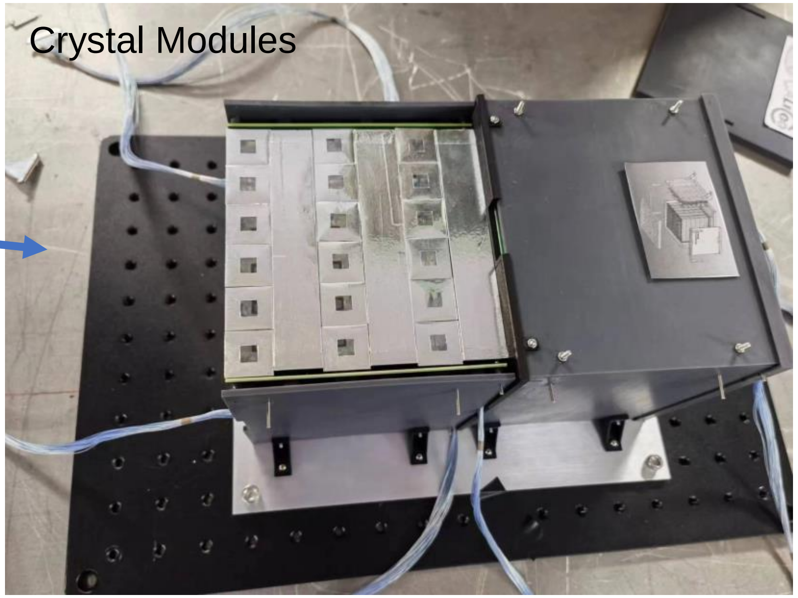
DESY TB22 beam condition

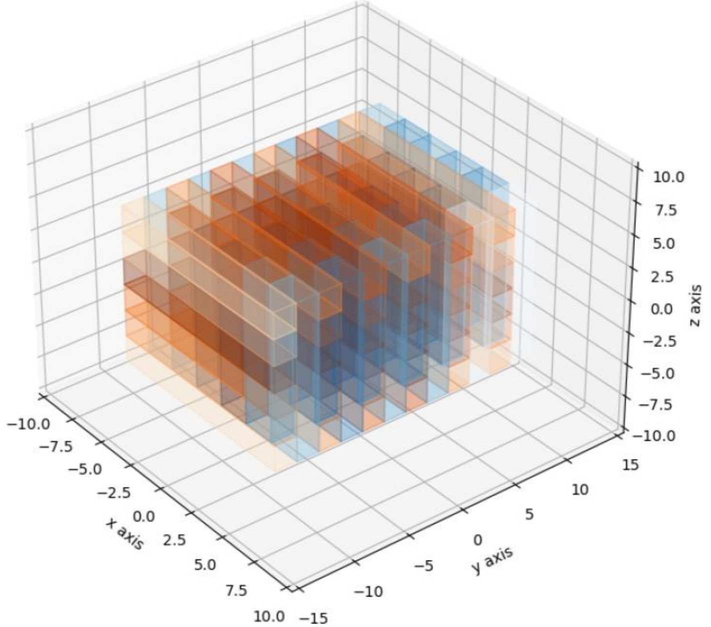
- 1~6GeV single electron beam, a few multi-particle events
- ~10kHz maximum repetition rate
- Adjustable spot size, momentum divergence

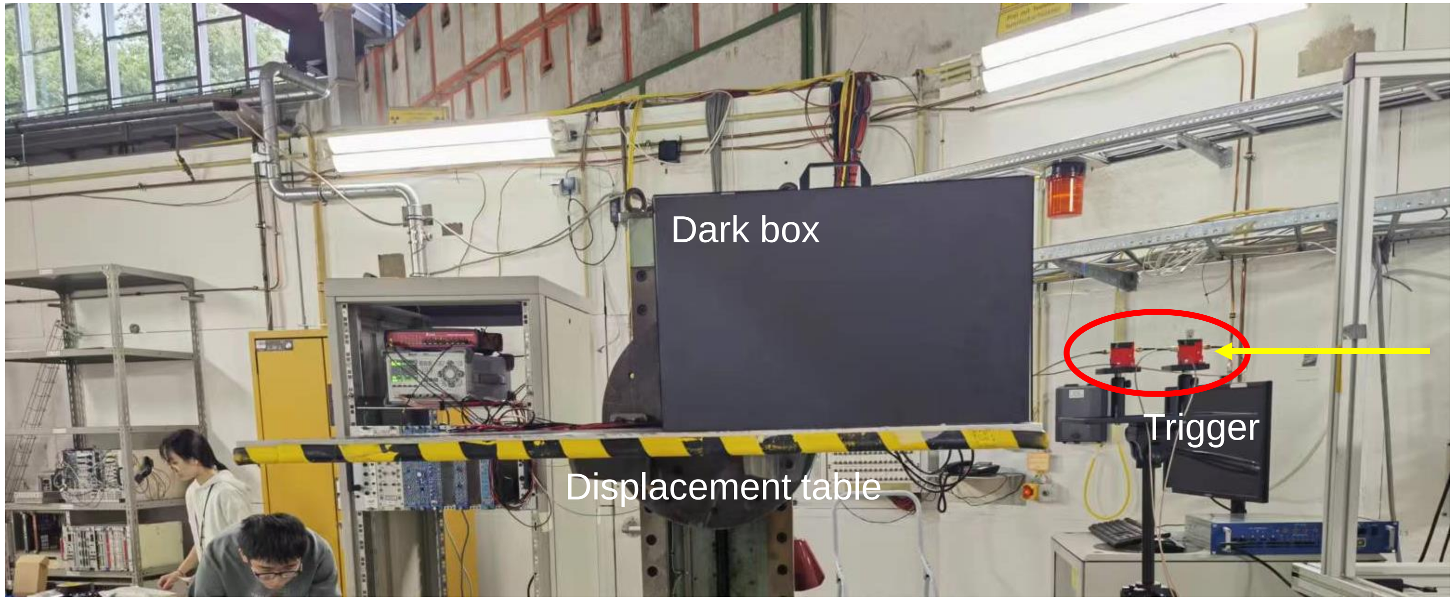
Second Crystal Module at DESY

Data analysis is ongoing…







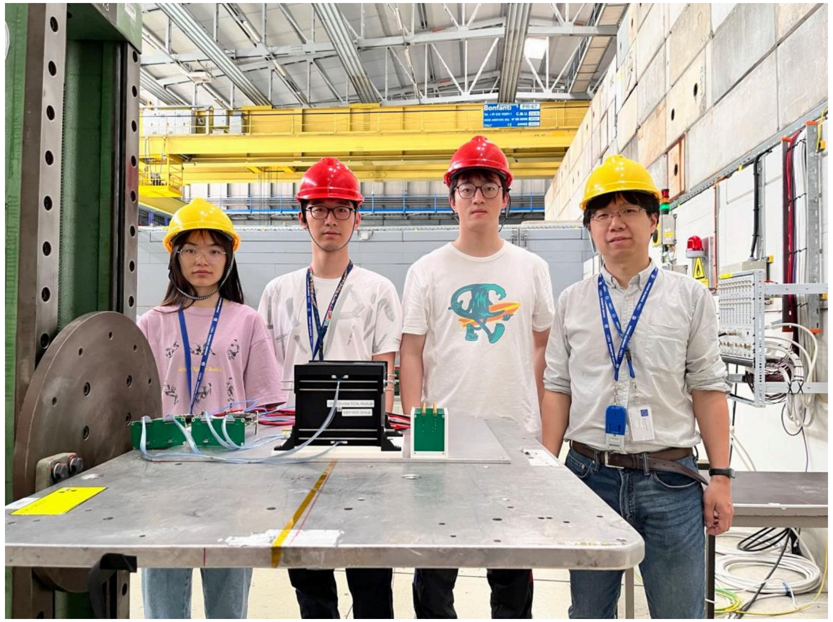


Acknowledgment

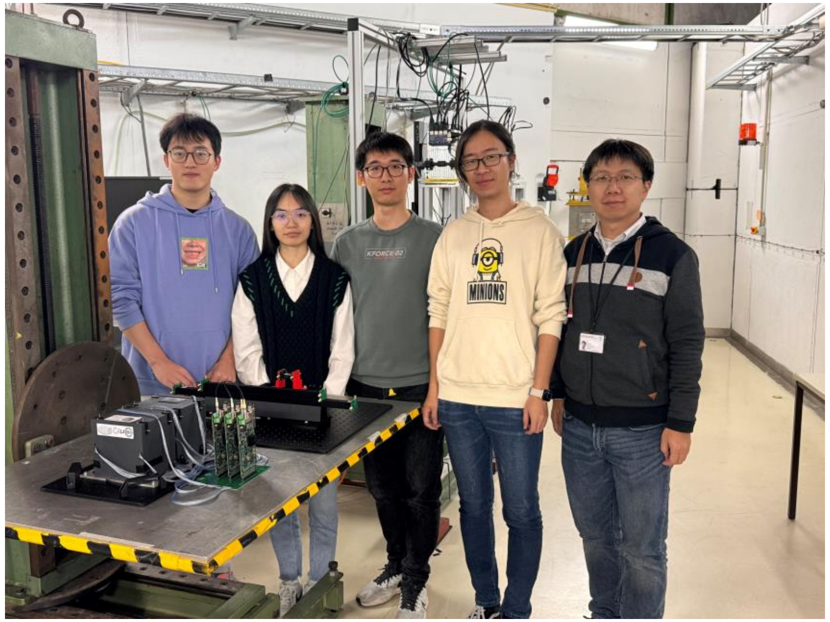
- Thank you to every one who works on the team
- Enormous and substantial support from CERN, DESY, CALICE and CEPC
- Funding support from CAS

CERN PS-T9 May. 2023

CERN PS-T9 May. 2023



DESY TB22 Oct. 2023



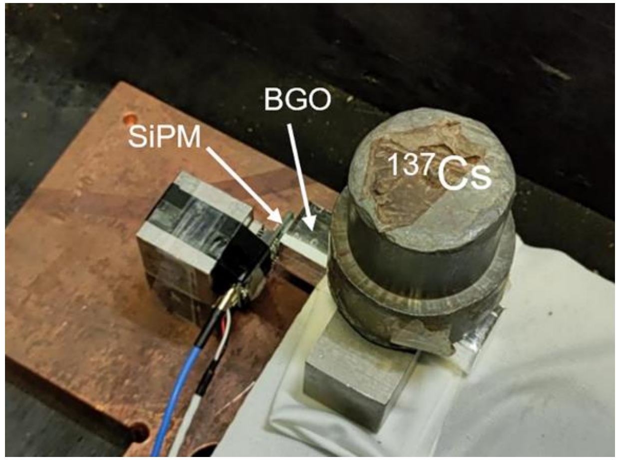
Summary and Prospects

- High-granularity crystal calorimeter
  - Optimal EM energy resolution, potential for BMR and π^0/γ reconstruction
- Crystal-SiPM lab measurements
  - Easy to meet the requirements of 100 p.e./MIP light yield
  - Dynamic range of SiPM with 10μm pixel is enough for BGO output
  - MIP time resolution ~1ns
- Crystal module development
  - Complete the first beamtest of the first module at CERN. The preliminary performance was given.
  - Complete beamtest for the second upgraded crystal module at DESY. Data analysis is ongoing.

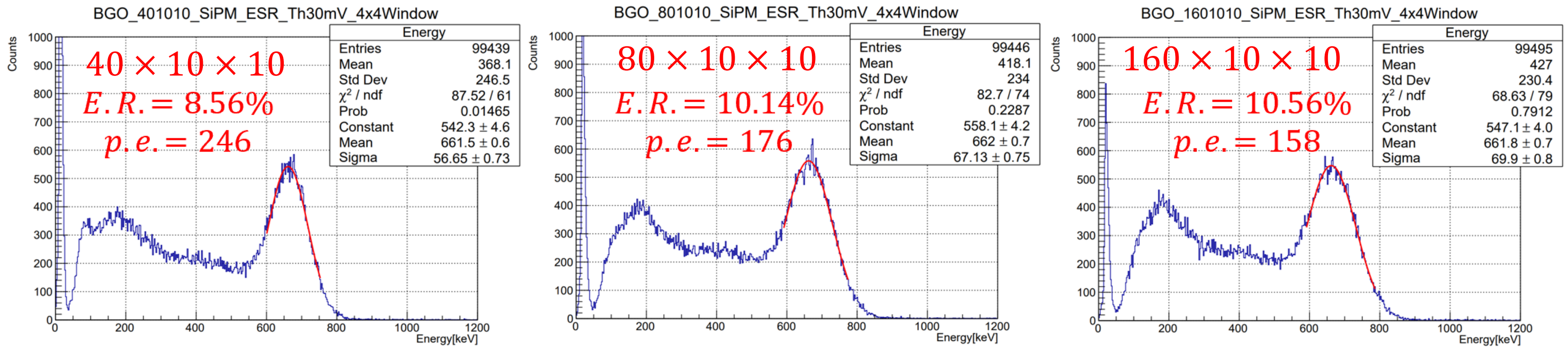
Backup

Low Energy Photon Detection of BGO

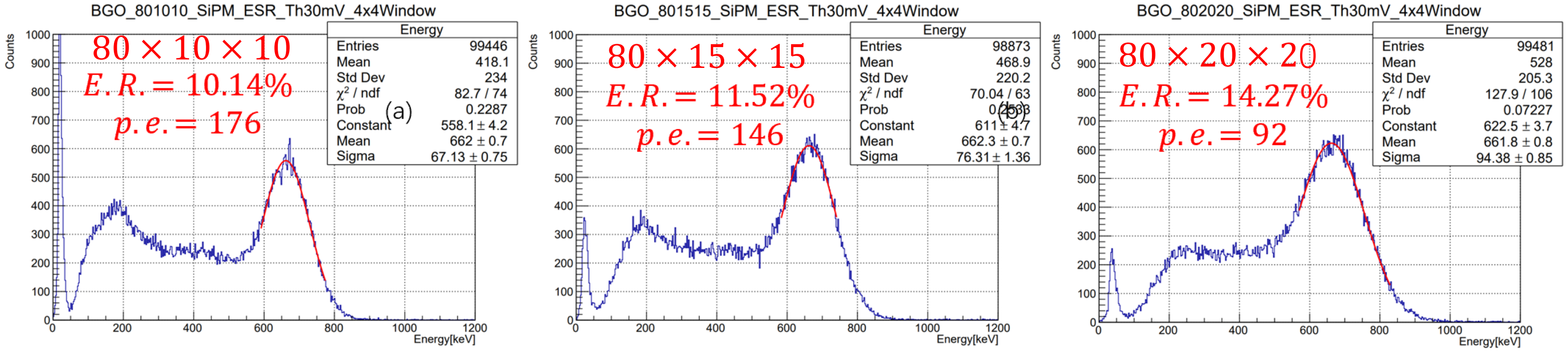
- BGO has the ability to detect low-energy photons
- SiPM: HAMAMATSU C13360-3050SA
- BGO crystals with different sizes
- Source: Cs-137, 662keV γ



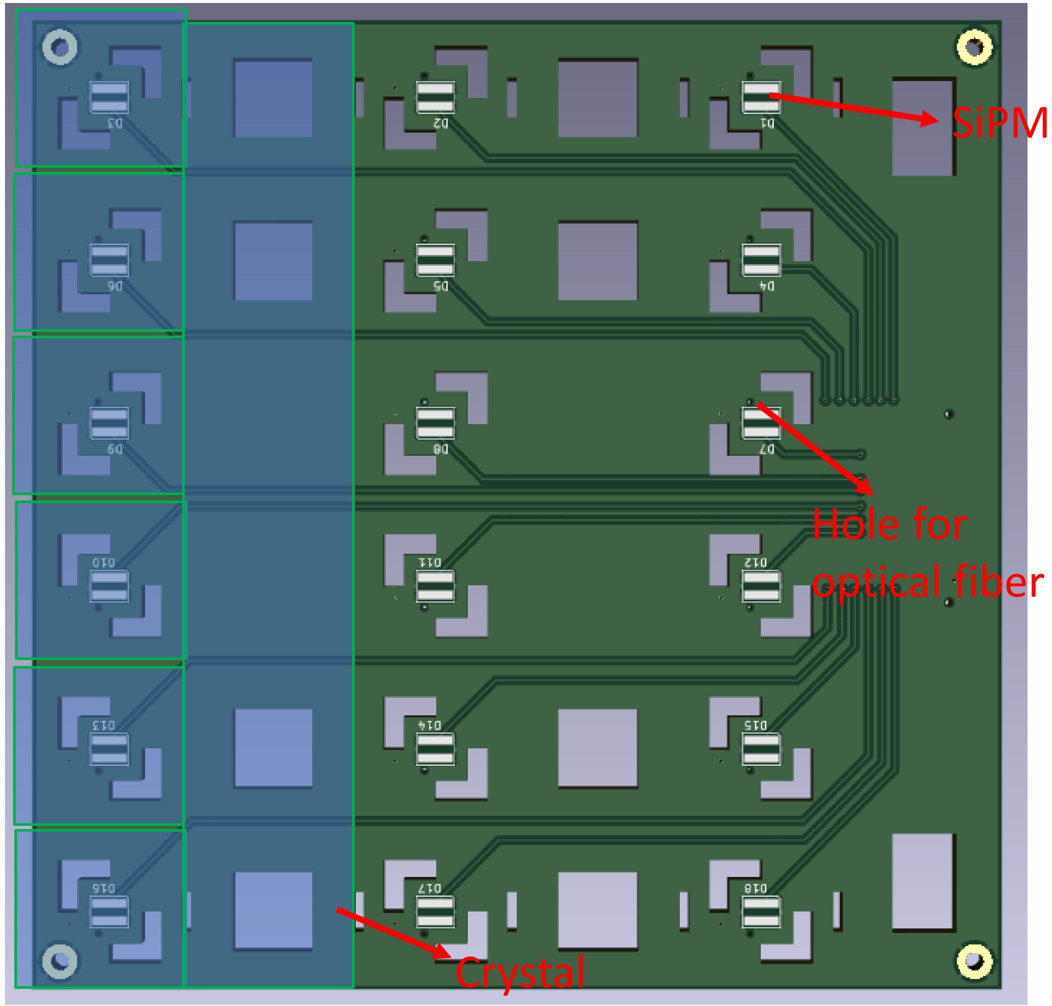
Different lengths



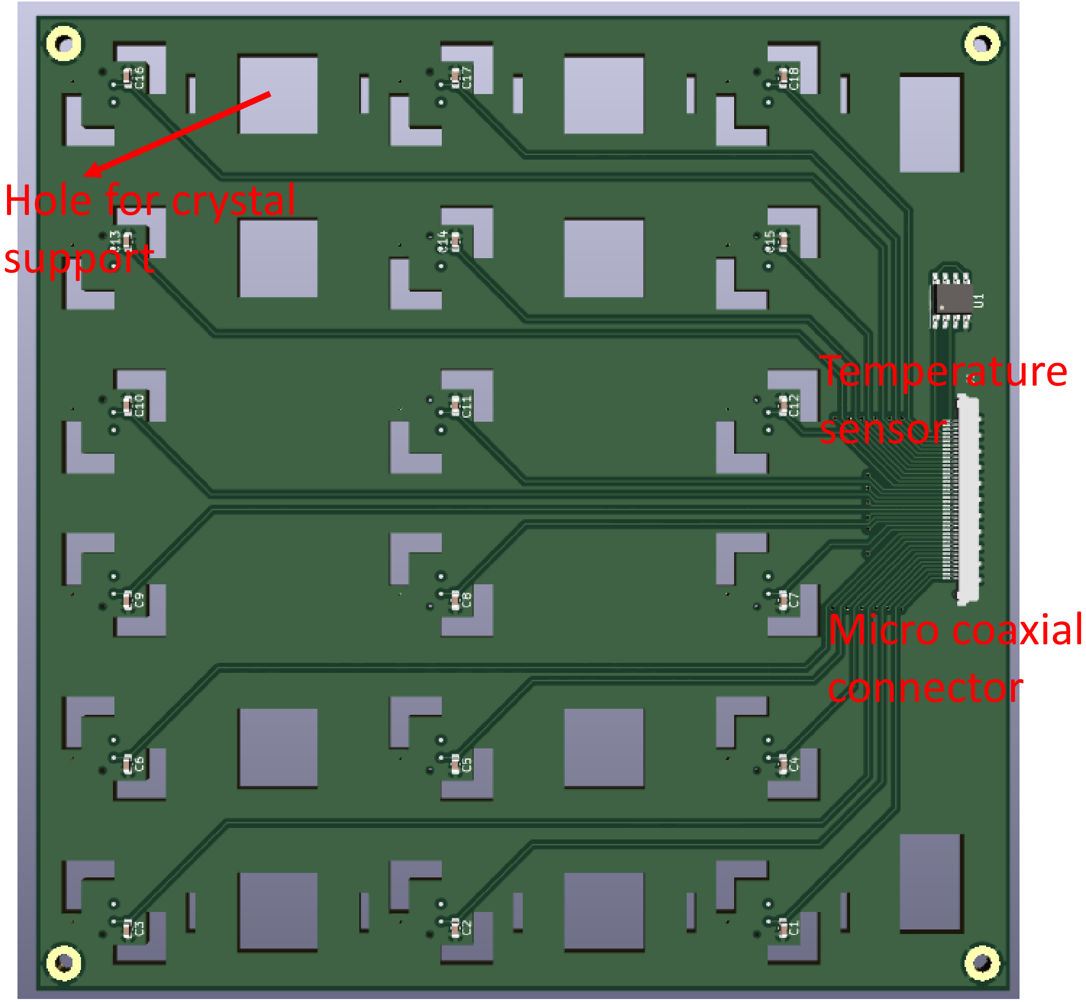
Different cross-sectional areas



PCB Layout



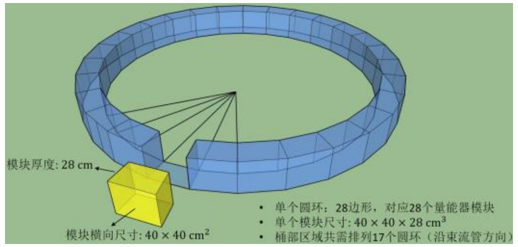
Front side



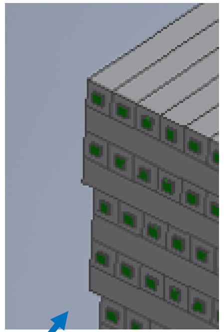
Back side

General Geometry Design for Crystal ECAL

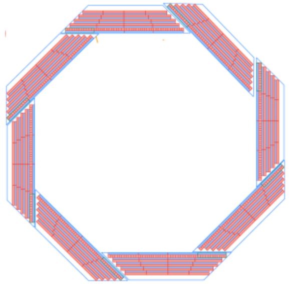
- CEPC crystal ECAL barrel geometry design
  - Finer segmentation of towers for better homogeneity
  - Decrease outer radius for lower cost of the outer detectors
  - 28 towers per ring, 17 rings along beam direction
  - ~25 radiation length: 28 layers



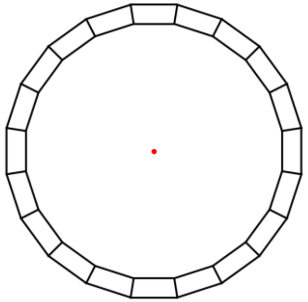
Quan Ji, Chang Shu (IHEP)



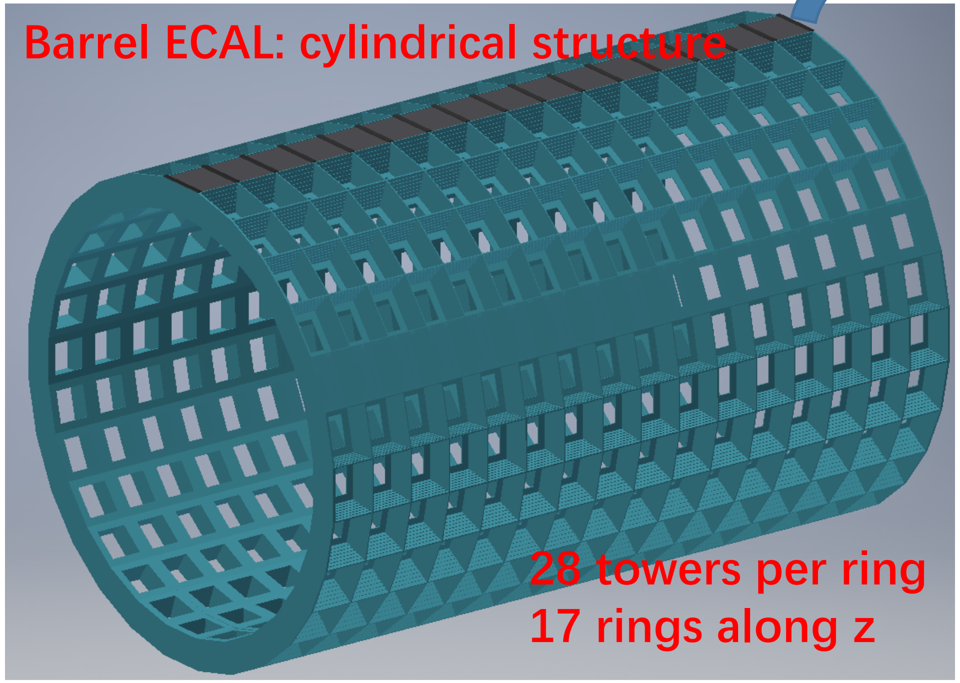
4 layers per "step" with the same transverse size

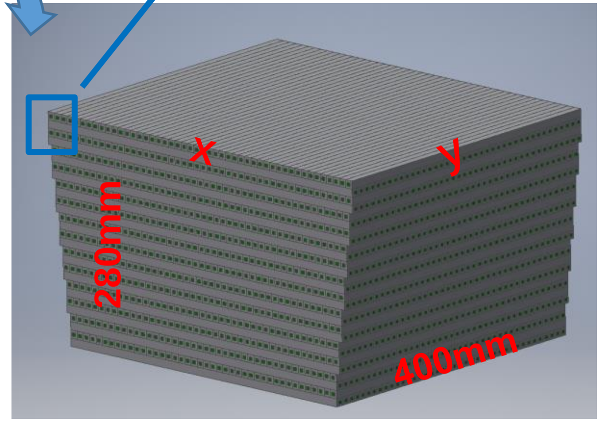


Previous design: octagonal detector



New design: cylindrical crystal ECAL



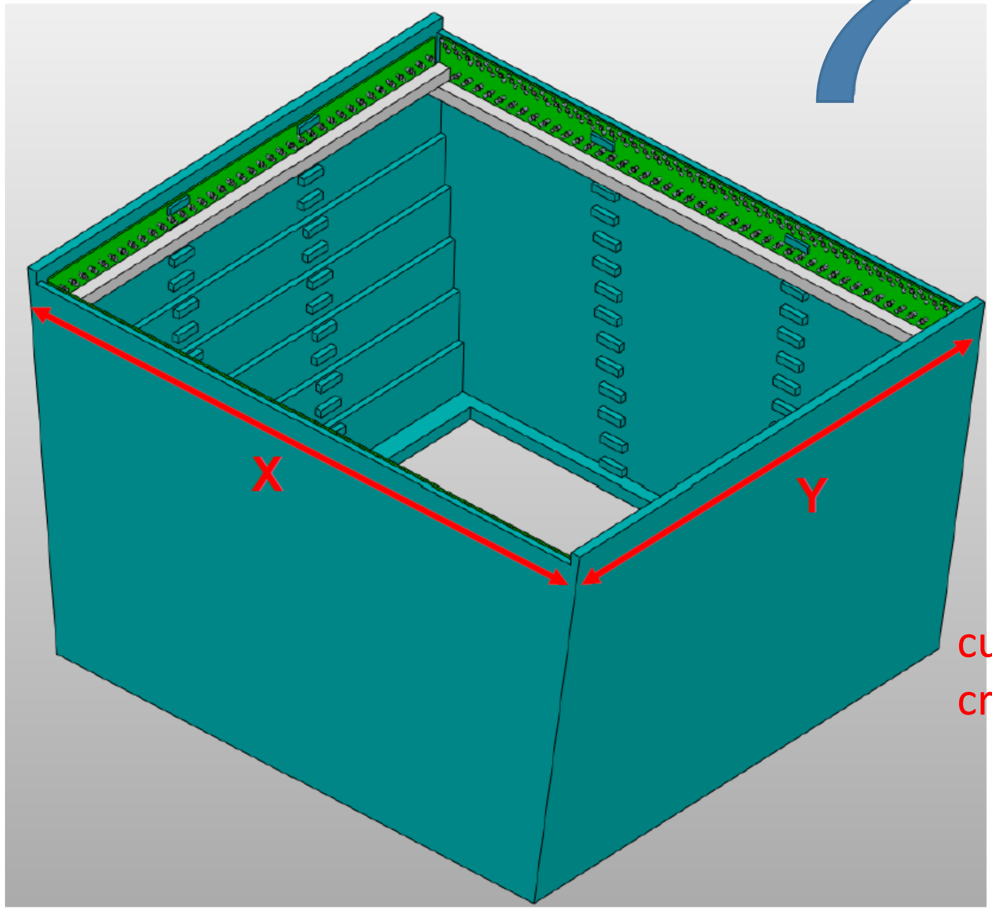


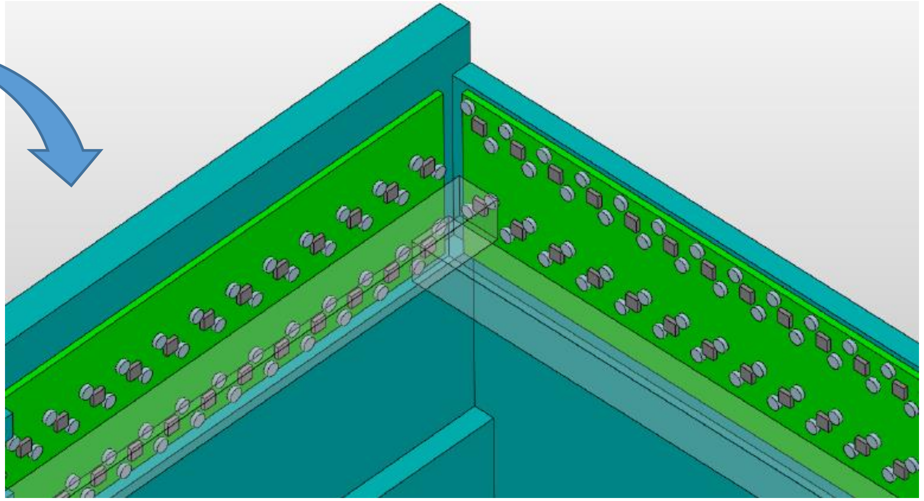
Key questions
- Space for electronics and cooling
- Assembly

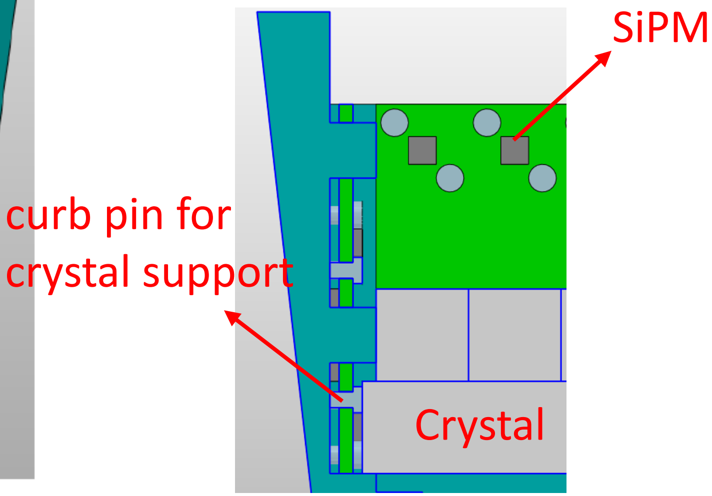
General Geometry Design for Crystal ECAL

Quan Ji, Chang Shu (IHEP)

- Mechanical assembly: PCB and crystals





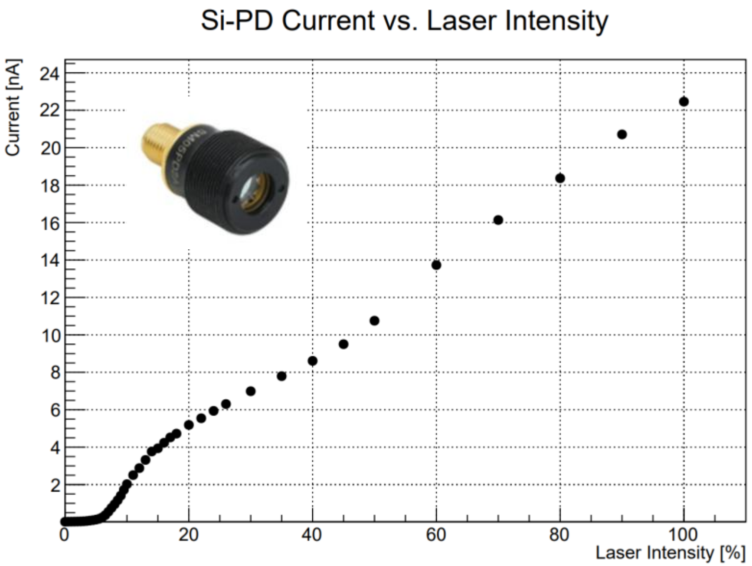


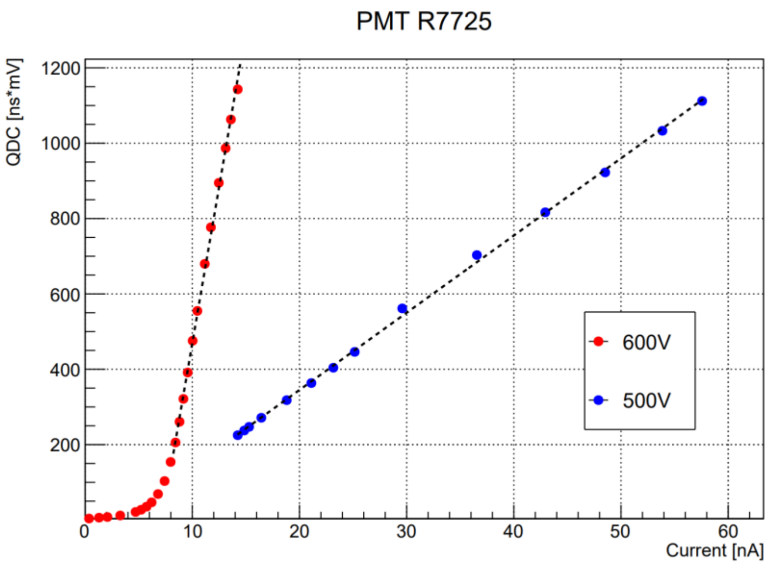
Total mass of the crystals in one tower: 380 kg

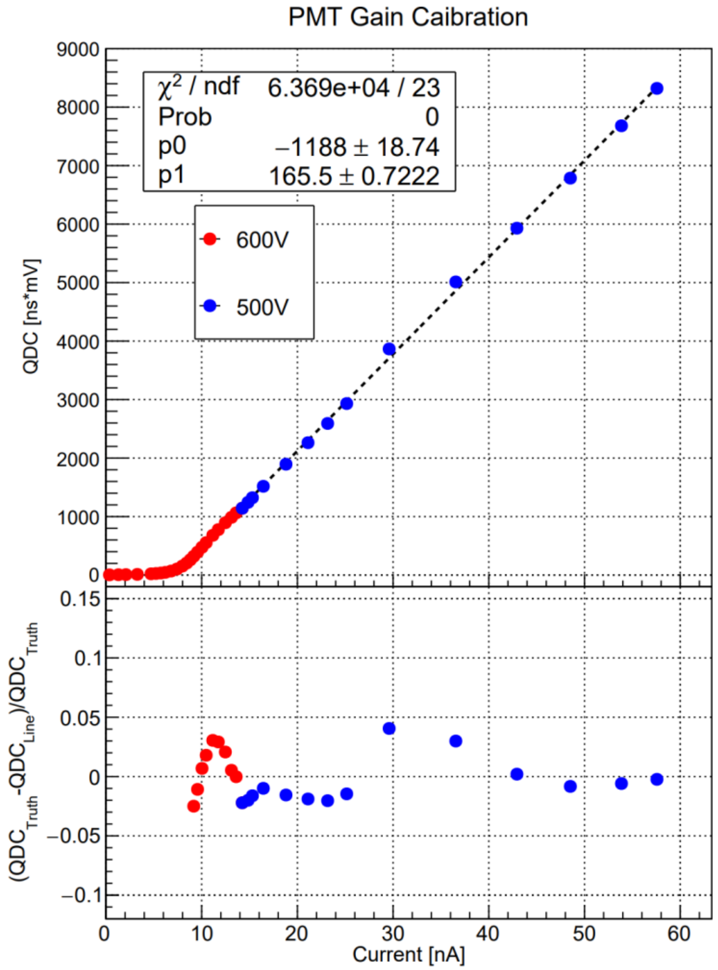
- PCB cannot bear the weight of crystals
- Holes on PCB for external support structure

Linear Region Selection for PMT

- Select the linear region of PMT with a Si-PIN at different light intensities
  - Weak light intensity → 600V
  - Strong light intensity → 500V
- Combination of discrete linear regions can keep linear within the whole light range







Number of pe Calibration

- Gain of PMT is not high enough to discriminate single pe with 600V bias voltage
- SiPM calibrates PMT in weak light intensity region