Development of High-Granularity Crystal ECAL for CEPC

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On Behalf of CEPC Calorimeter Working Group

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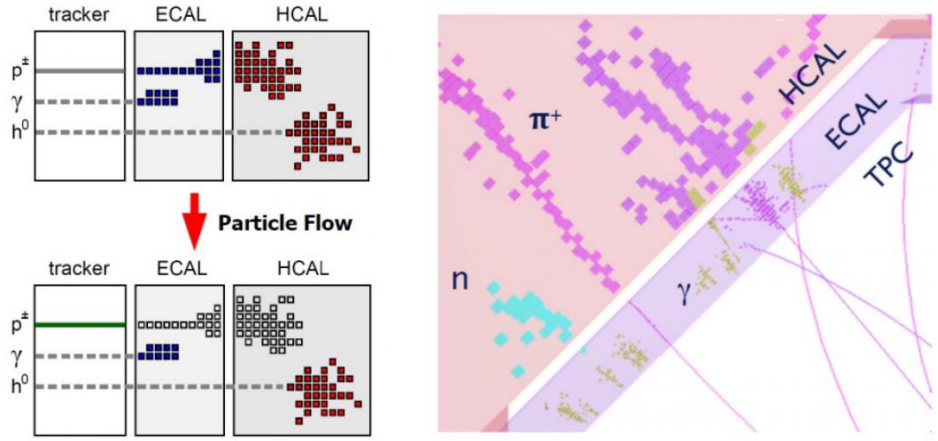
Introduction

- CEPC: future circular lepton collider
  - Higgs/W/Z bosons, top, BSM searches, etc.
  - PFA calorimeter: promising to achieve 3-4% jet resolution, and <4% boson mass resolution

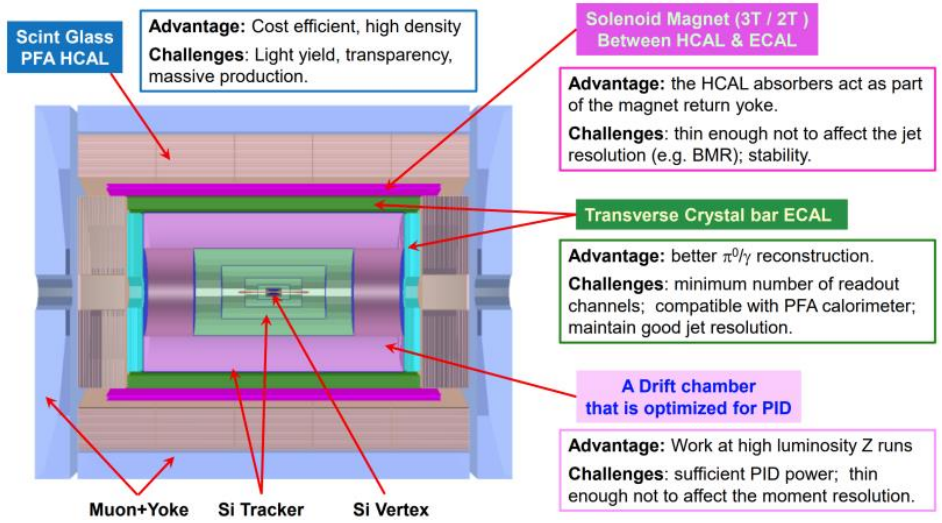
- High-granularity calorimeter with PFA
  - Electromagnetic calorimeter with crystal option
    - Expect to provide Space + Energy + Time
    - To improve EM energy resolution from $16\%/\sqrt{E}$(CEPC-CDR) to ~ $3\%/\sqrt{E}$
  - Hadronic calorimeter with glass option
    - Scintillating glass(dense and bright): in the form factor of tiles for high granularity
    - To improve hadron energy resolution from $60\%/\sqrt{E}$(CEPC-CDR) to $30\%{\sim}40\%/\sqrt{E}$

High-granularity scintillating glass HCAL R&D activities and highlights – Sen Qian

PFA-oriented calorimeter



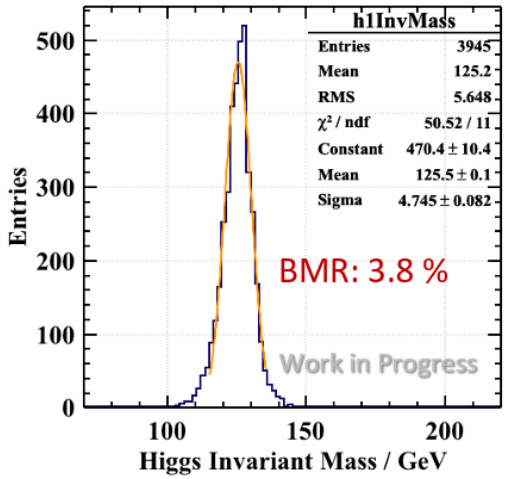
CEPC the 4th conceptual detector design



Physics Benchmarks: CEPC Detector with BGO Crystal ECAL

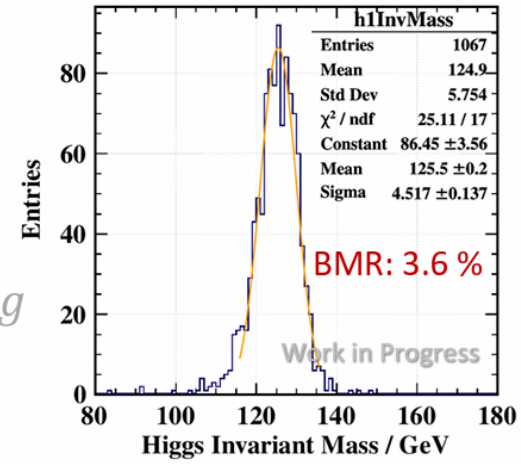
- Ideal crystal ECAL geometry with $1cm^3$ BGOs
- Higgs boson mass resolution(BMR) :
  - Jets($H \to gg$): 3.8% $\to$ 3.6%
  - Photons($H \to \gamma\gamma$): 2.1% $\to$ 1.2%

Detector with SiW-ECAL option

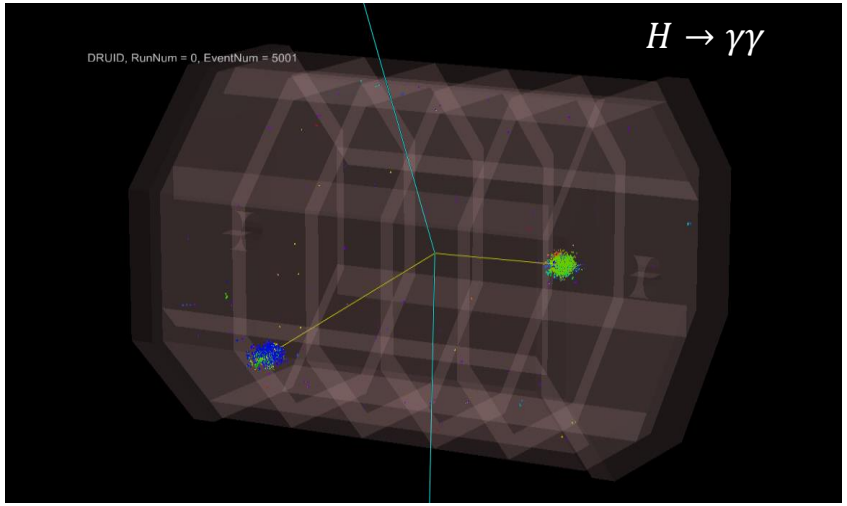


$H \to gg$

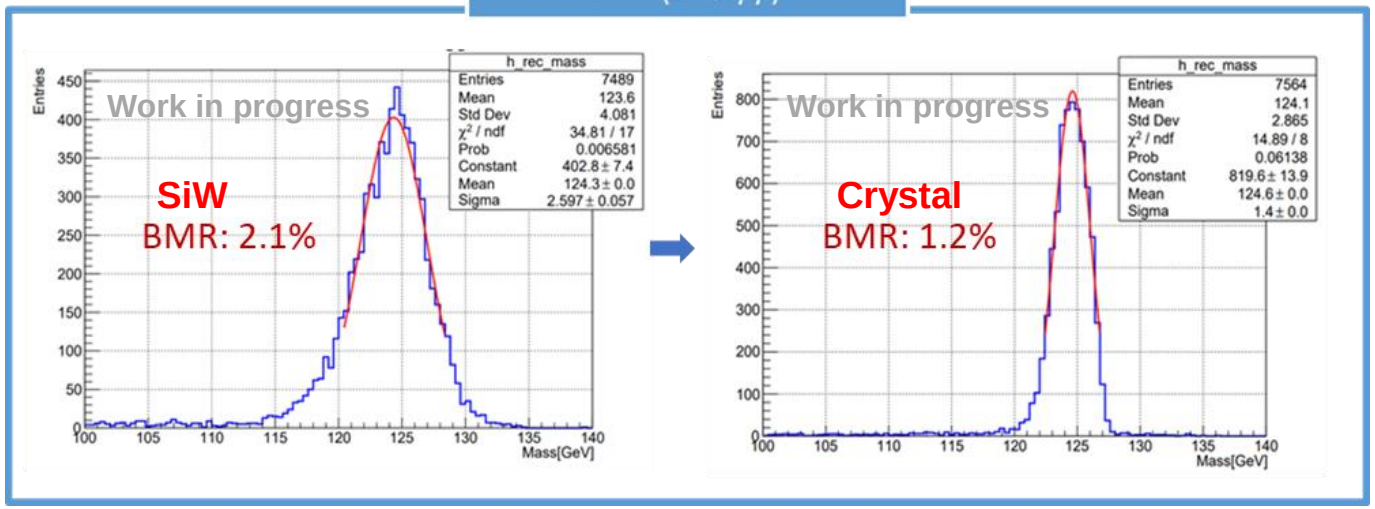
Detector with crystal ECAL option



ECAL with $1cm^3$ cubic crystals



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



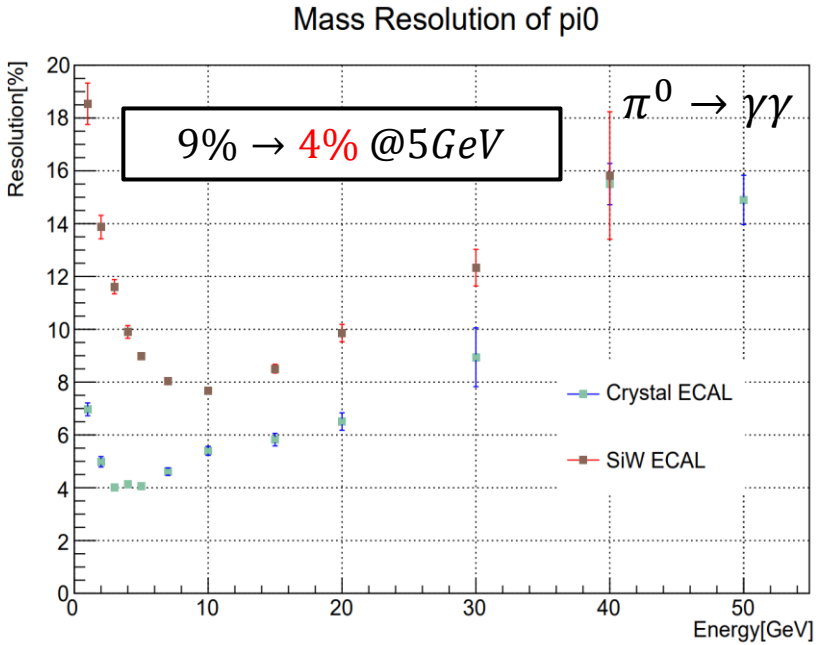
Flavor Physics Potentials

JHEP12(2022)135

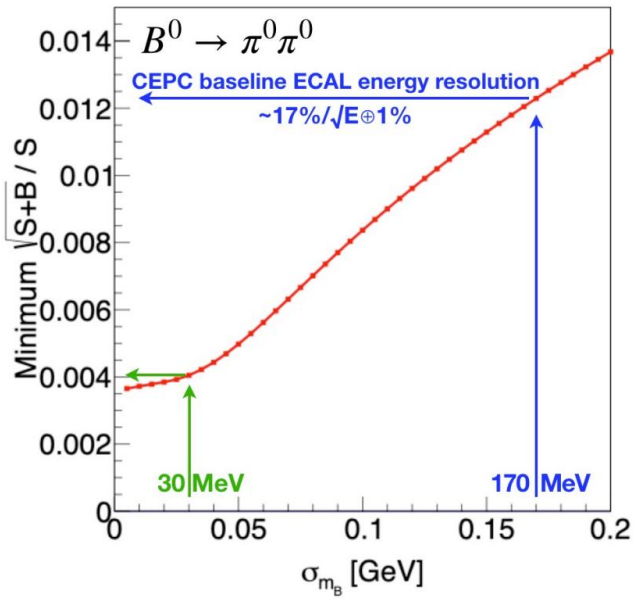
- $B^0/B_S^0 \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$
  - Necessary channel to determine CKM angle α
  - Measurement can be characterized by σ_{m_B}
- Good measurement precision on $B^0/B_S^0 \to \pi^0\pi^0$ with crystal ECAL

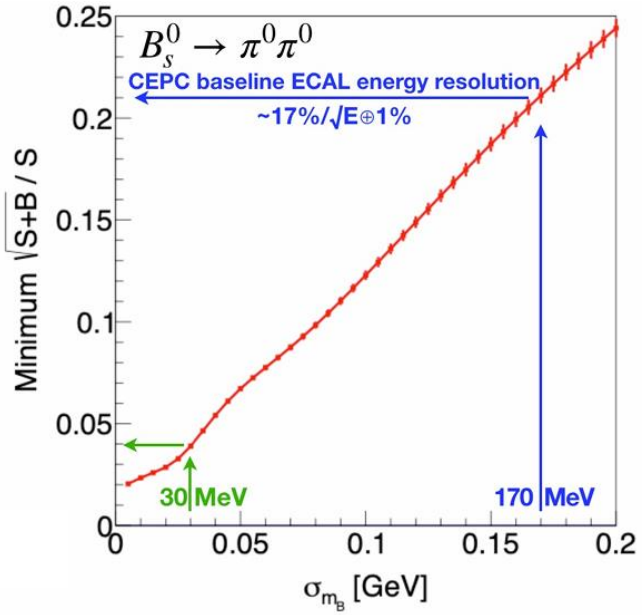
	ECAL Resolution	σ_{m_B} (MeV)	$B^0 \to \pi^0\pi^0$	$B_S^0 \to \pi^0\pi^0$
SiW	$17\%/\sqrt{E}\oplus 1\%$	170	~ 1.2%	~ 21%
Crystal	$3\%/\sqrt{E}\oplus 0.3\%$	30	~ 0.4%	~ 4%

3 ~ 5 times improvement



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

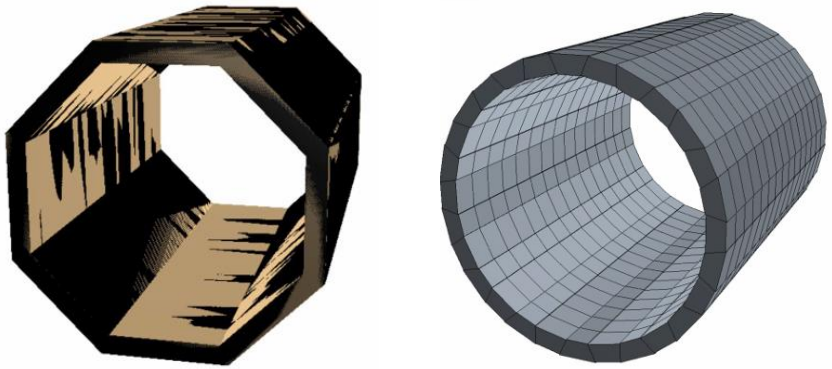




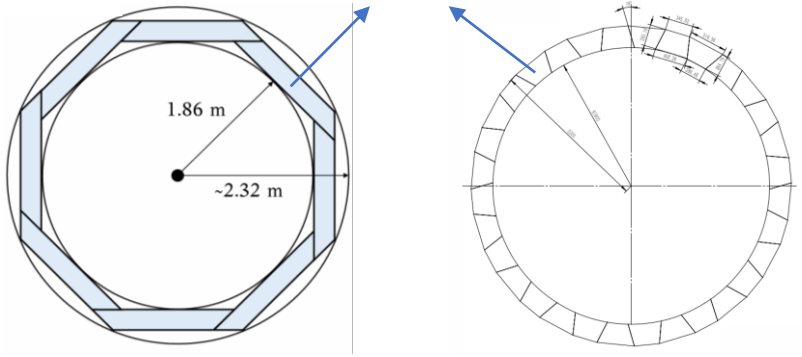
- Smaller σ_{m_B} will give a better $\sqrt{S+B}/S$

Geometry of ECAL Barrel - Polygon

Polygon Crystal ECAL



towers

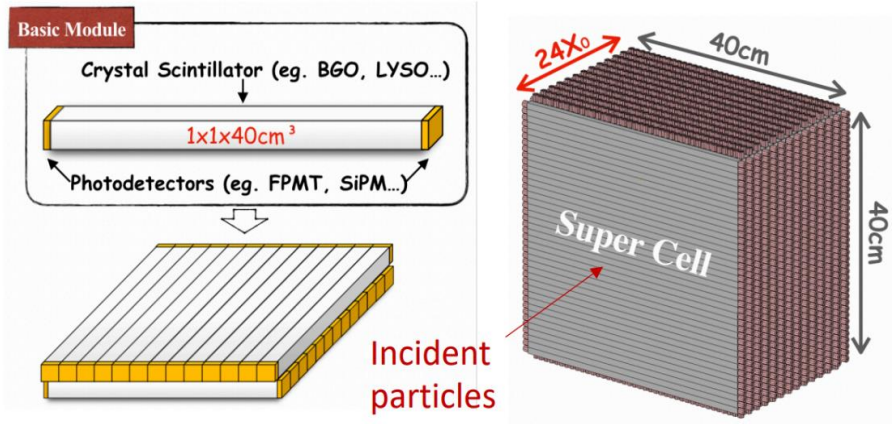


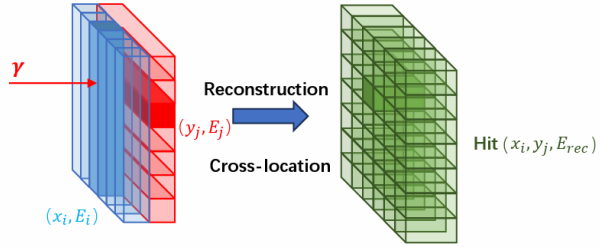
Less dead materials

Less active materials

Millions of channels

Tower structure: orthogonal long bar design



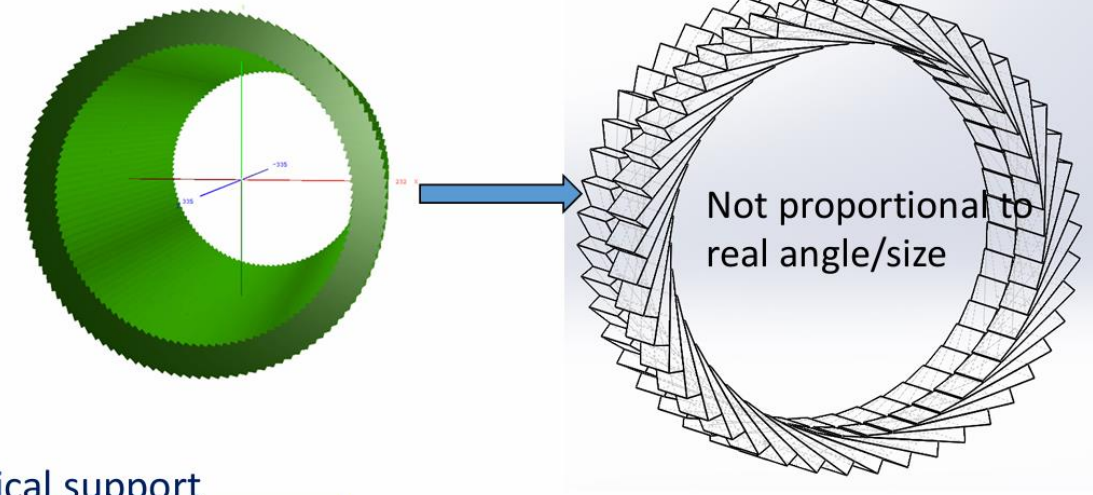


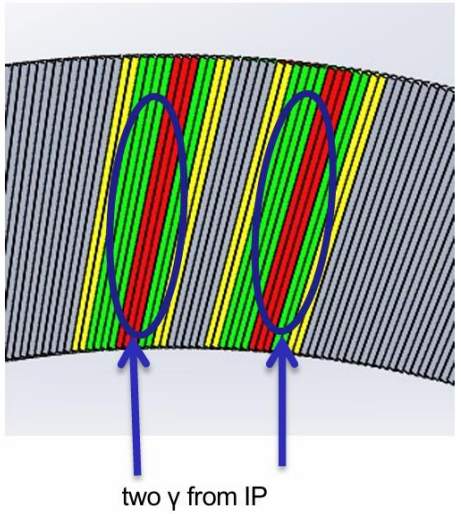
- Long bars: 1×40cm, double-side readout
  - Orthogonal arrangement in adjacent layers
- Save #ch and reduce dead materials, while keeping fine granularity
- Challenge: reconstruction algorithm

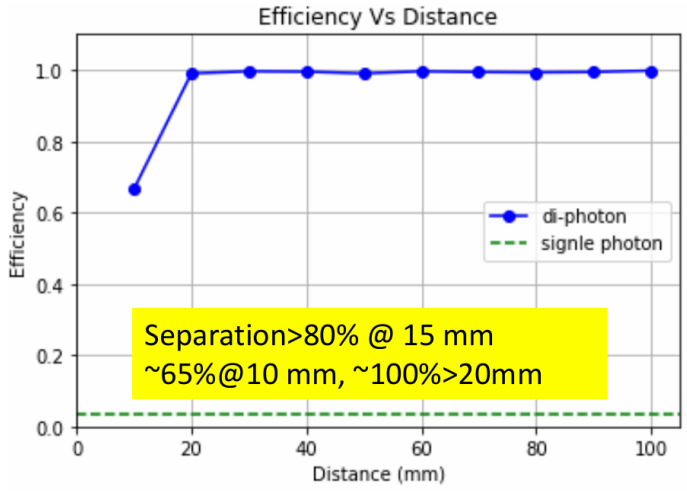
Geometry of ECAL Barrel - Stereo

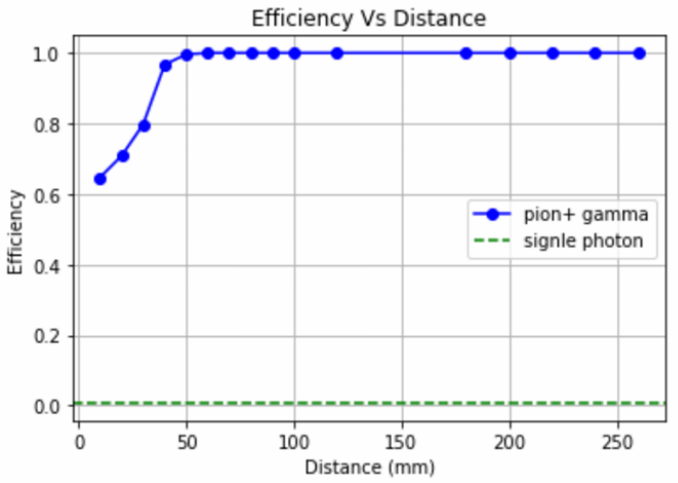
- To improve the 3D position resolution
  - Pointing angle of even layers alone Z: α
  - Pointing angle of odd layers alone Z:

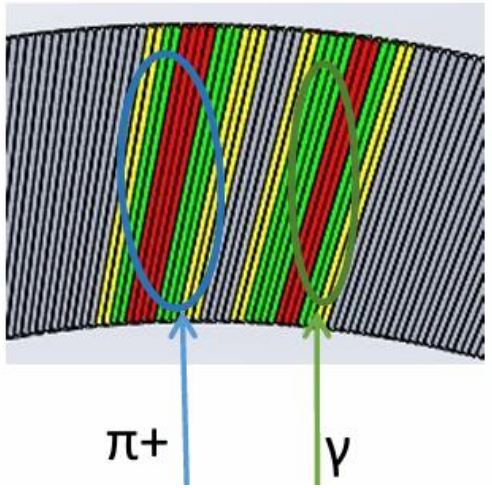
  $\alpha' = -\alpha$
- Benchmark design:
  - α=20 degrees
  - R segmentation = 10
  - Crystal: (8-8.1)*10*284 mm^3
  - Readout: SiPM (or APD/PD) + electronics
  - Cooling pipe planted into the outside of the mechanical support
  - 24X0+10mm electronics+10mm support + 10 mm contingency = 300mm







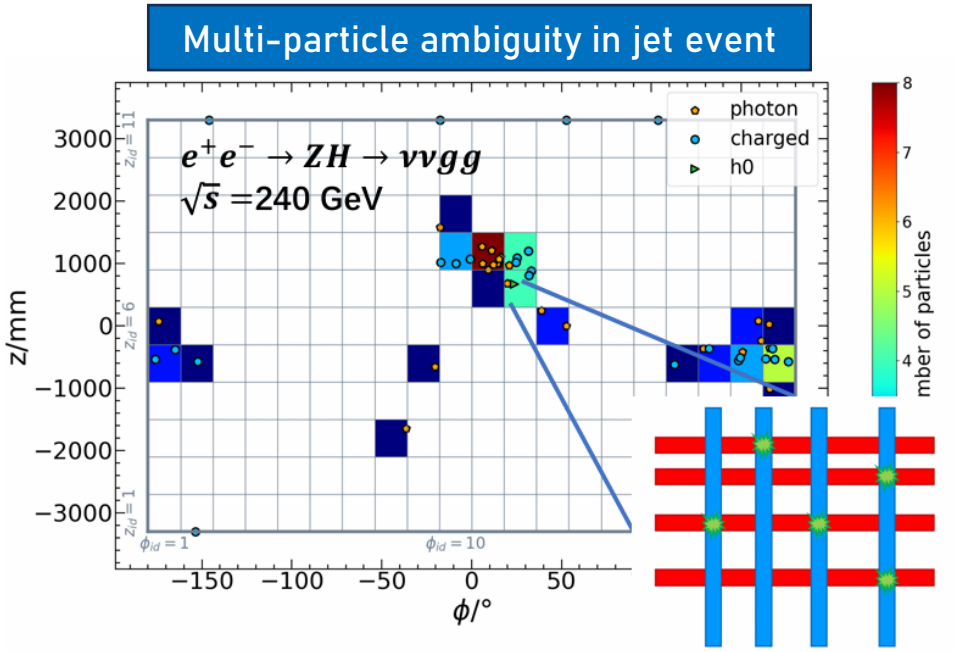




Separation and energy regression using end-to-end NN PhysRevD.108.052002

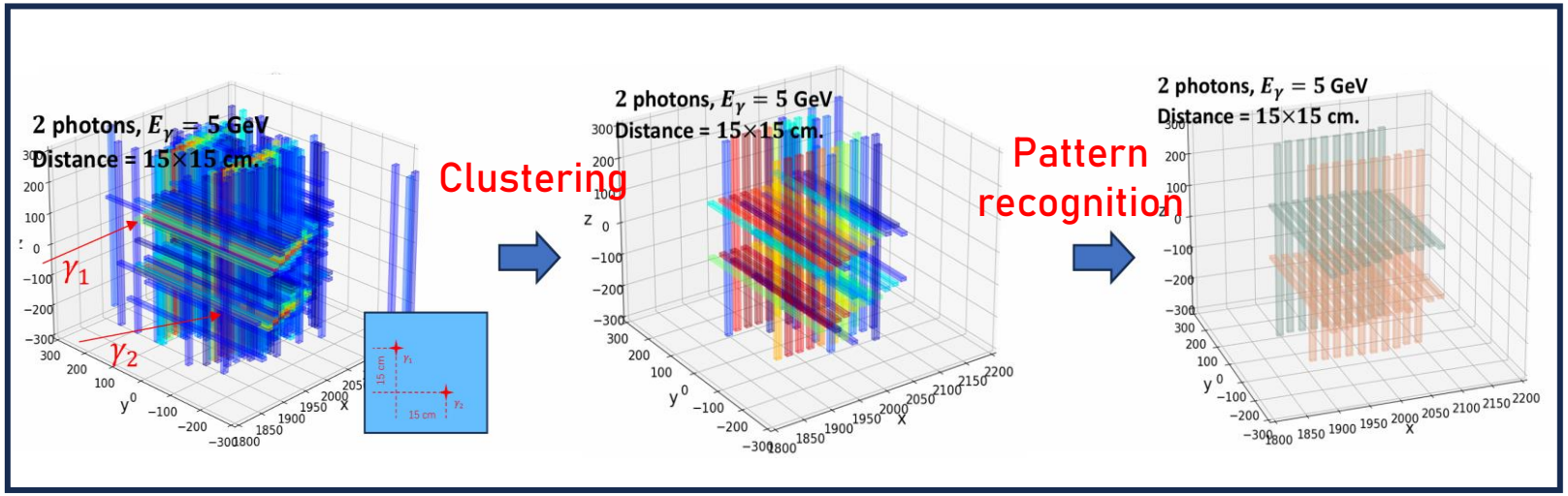
PFA Reconstruction Algorithm for Long Bar ECAL

Reconstruction algorithm development towards crystal bar ECAL – Fangyi Guo

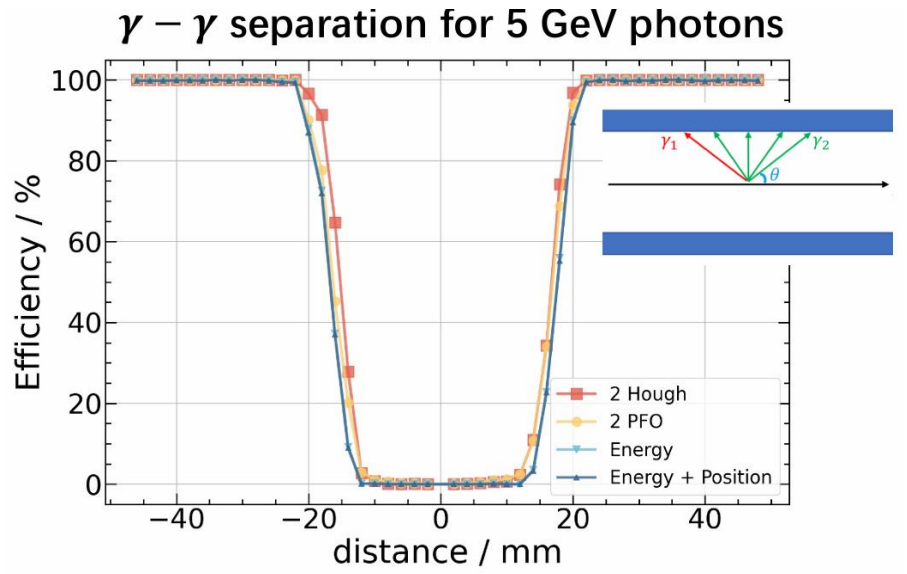


- PFA reconstruction algorithm dedicated to long bar ECAL
  - Main challenges from overlapping and ambiguity
  - Algorithms are developed and show promising results

Ambiguity removed by information from track, neighbor tower and time



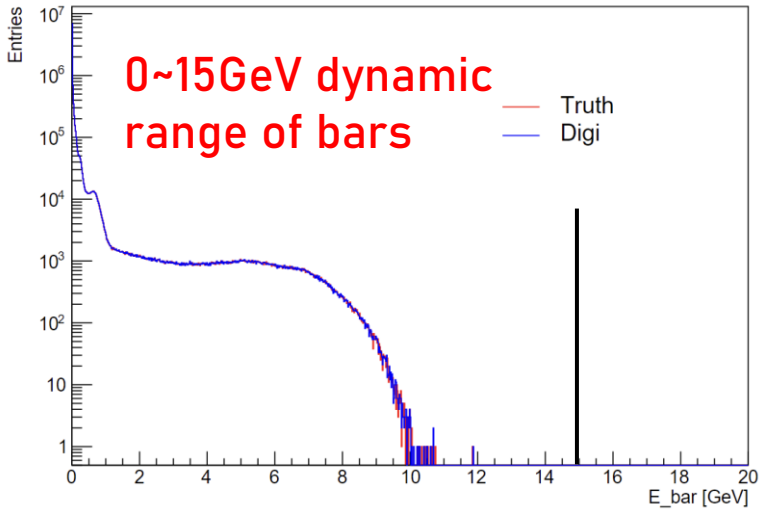
> 90% γ-γ separation efficiency @ 2cm



Digitization for Long Bar ECAL

- Realistic digitization model: scintillation ⊕ SiPM ⊕ ADC
  - Scintillation: crystal light yield and uniformity
  - SiPM response and saturation correction
  - ADC precision, noise and dynamic range(3 gains)
- SiPM resolution is the dominate term
- ADC resolution exhibits drop at switching points

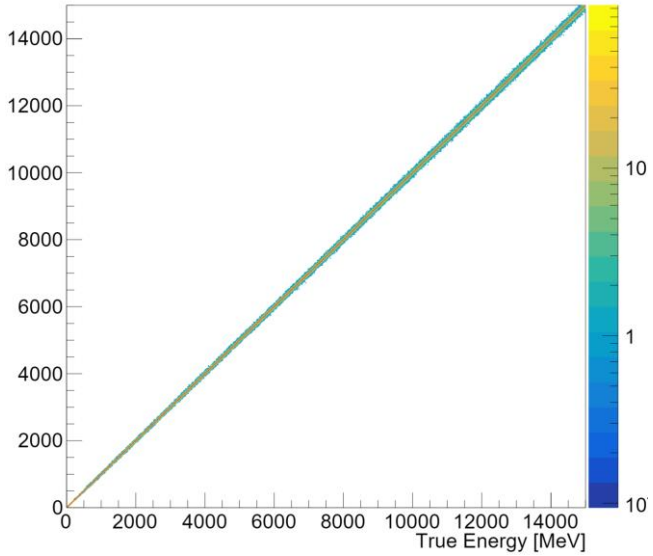
Bar energy with full simulation of 180 e-



Digitization induced resolution in 0~15GeV

		Gain-1		Gain-2			Gain-3			
		0MeV		24MeV		594MeV				1500MeV
	Energy (MeV)	5	10	50	100	500	1000	5000	10000	15000
Scintillation	σ/<E> (%)	13.18	9.35	4.20	2.96	1.32	0.94	0.42	0.30	0.24
SiPM	σ/<E> (%)	15.28	10.84	4.88	3.47	1.55	1.09	0.49	0.35	0.28
ADC	σ/<E> (%)	0.98	0.68	0.97	0.53	0.24	1.14	0.30	0.23	0.21
1⊕2⊕3	σ/<E> (%)	20.20	14.33	6.51	4.59	2.05	1.84	0.71	0.52	0.42
Total	σ/<E> (%)	19.74	14.15	6.51	4.60	2.05	1.83	0.71	0.51	0.44

Linearity after digitization



Overview of Crystal ECAL Specifications

Key Parameters	Value	Notes
MIP light yield	~200 p.e./MIP	8.9 MeV/MIP in 1cm BGO
Energy threshold	0.1 MIP	Depends on S/N and light yield
Crystal non-uniformity	<1%	Calibration precision
Dynamic range	$1 - 1.7 \times 10^5$ p.e.	Up to 15GeV per crystal bar
Time resolution	~400 ps @ 1-MIP	Ideal performance from G4 simulation
Temperature stability	Stable at the level of 0.05℃	CMS ECAL value
Gap tolerance	~100μm	-

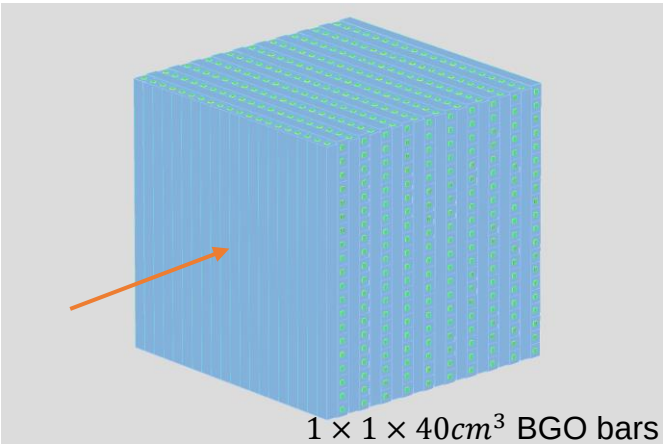
Further issues:

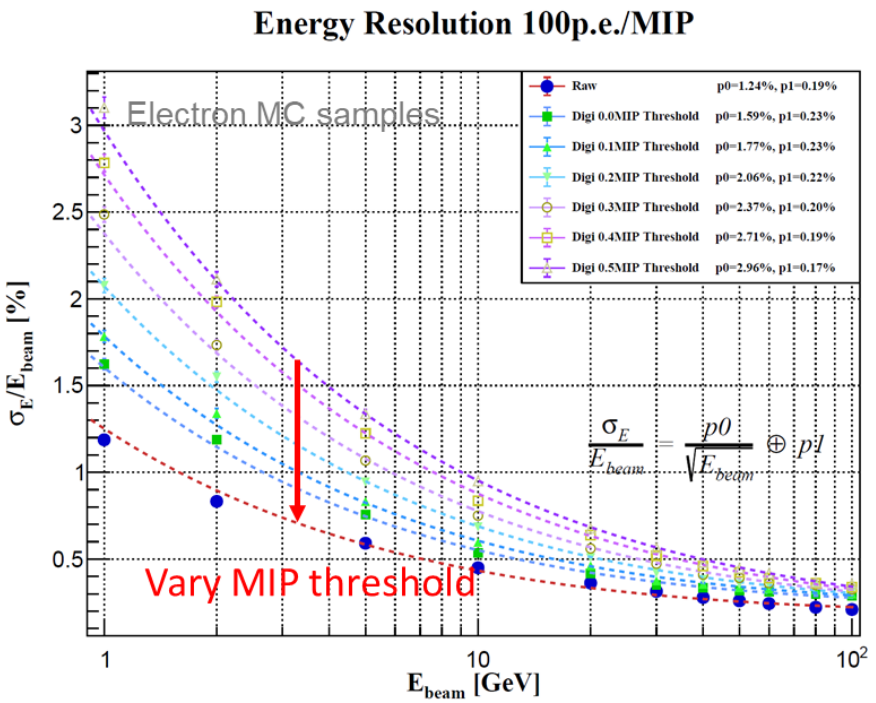
- Dynamic range of electronics and its precision
- Optimal time resolution in experiment and its impact on shower reconstruction and hit positioning
- Temperature control
- Calibration schemes
  - LED single photon calibration of SiPMs
  - Transmittance of crystal: radiation damage
  - Operation and maintenance: MIP calibration

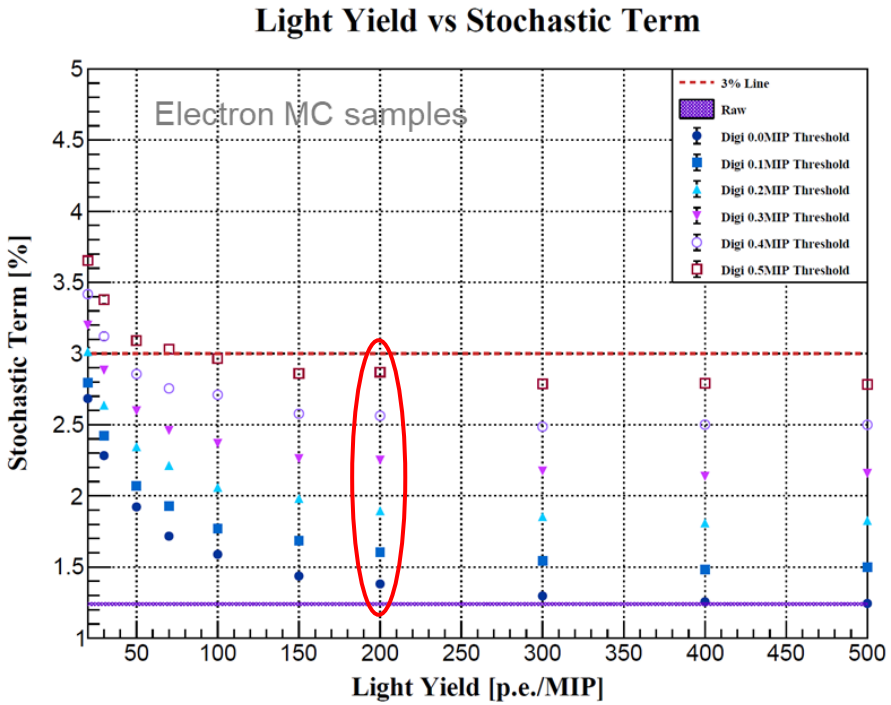
EM Energy Resolution: Threshold and Light Yield Requirements

- Impact of hit threshold and light yield
  - Digitization: photon statistics (crystal + SiPM), electronics resolution
  - 200 p.e./MIP is enough for $3\%/\sqrt{E}$, low threshold is promising for $1.6\%/\sqrt{E}$

Geant4 Simulation (v10.7)

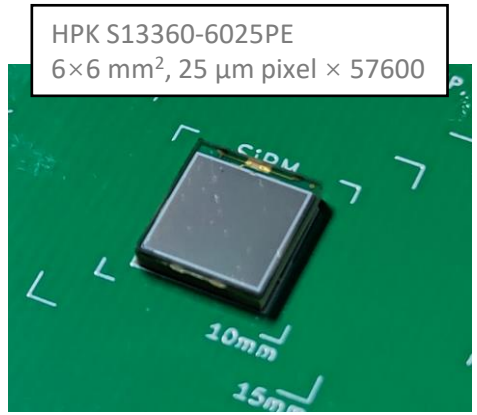


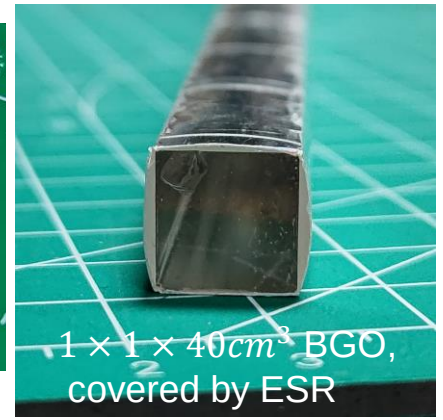


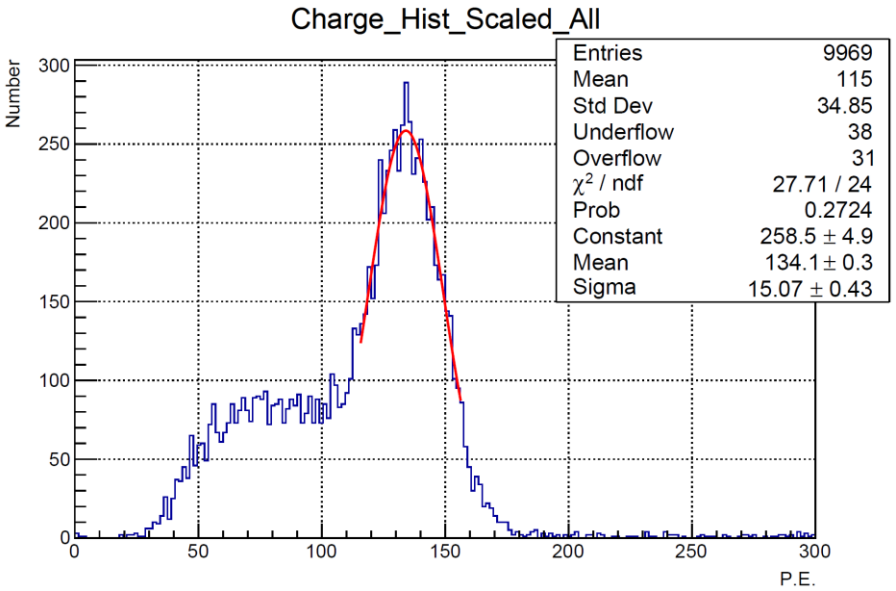


Test of Radioactive Sources for Long Crystal Bar

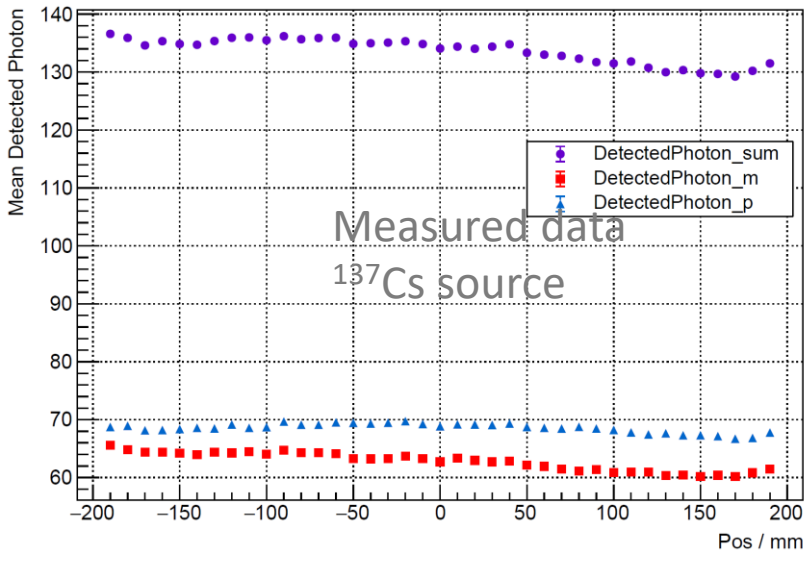
- BGO crystal bar coupled with SiPM
  - Energy resolution of : 11.2% @662keV
  - Light yield: ~200 p.e./MeV, enough for the LY requirement
  - Uniformity scan: <5% non-uniformity

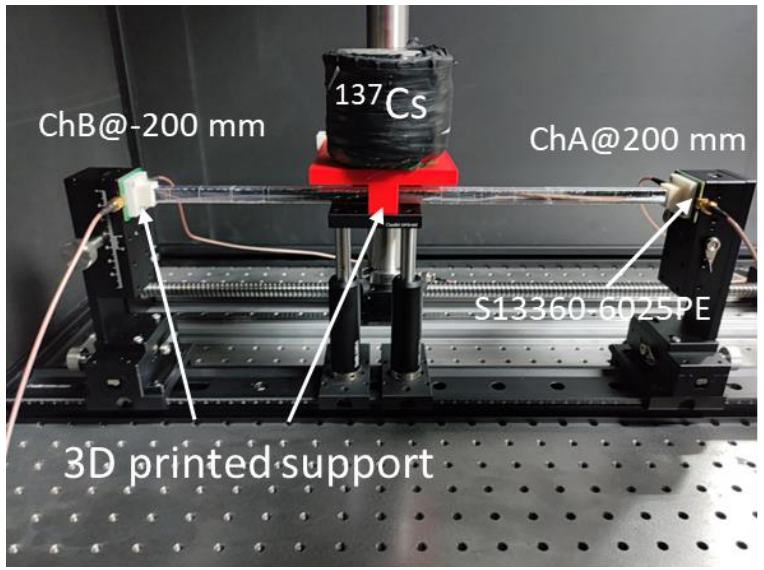






Experiment: detected photon



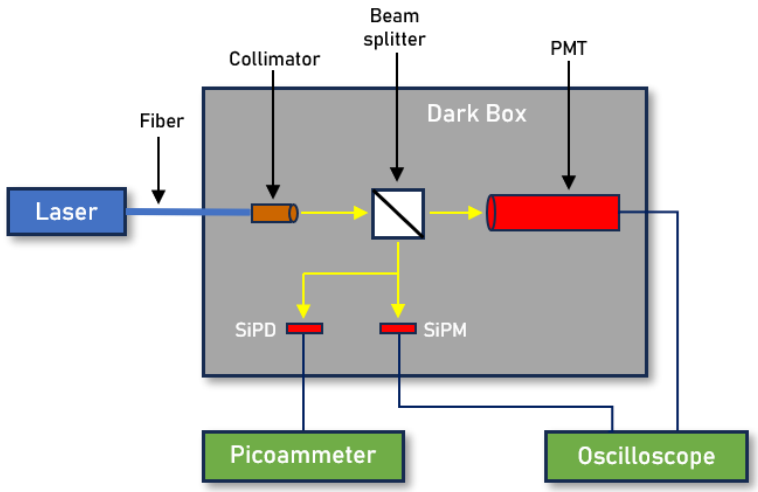


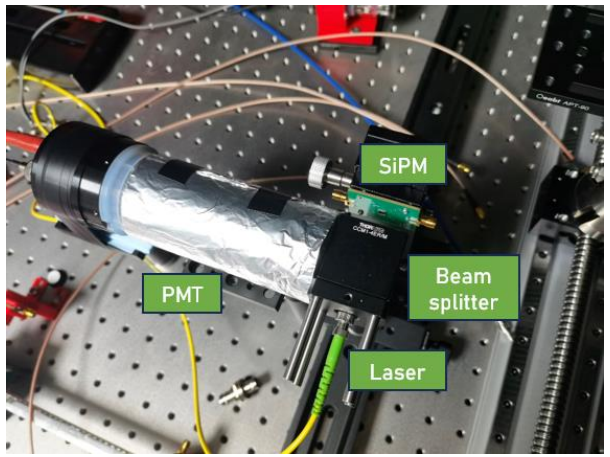
- Relatively low response near one side
- Coupling, crystal manufacture……

Intrinsic Dynamic Range of SiPM – Laser Test

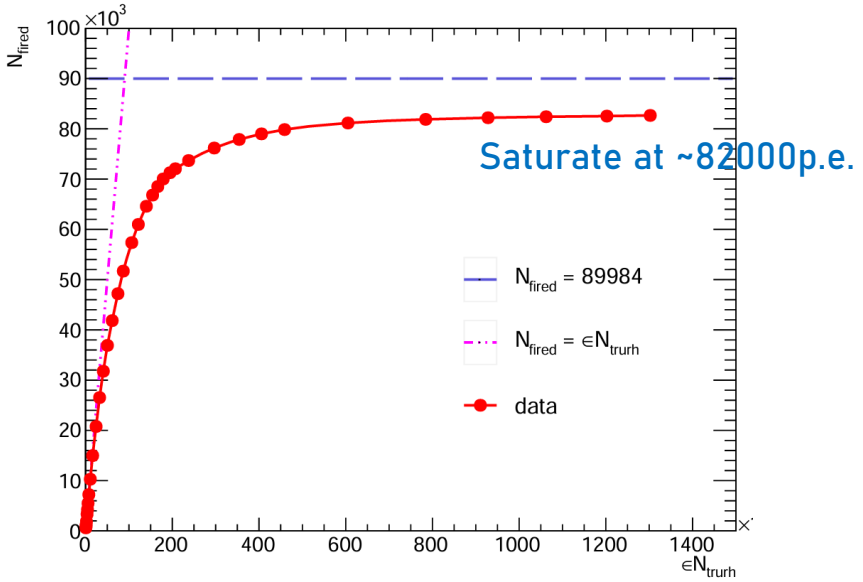
SiPM: $3 \times 3\ \mathrm{mm}^2$
$10\mu m\ pixel\ \times 89984$

- Experiment to measure the intrinsic dynamic range of SiPM with laser
  - Pico-second laser: <40ps pulse width, 405nm wavelength
  - SiPM: HPK S14160-3010PS, $10\mu m$ pixel, 89984 pixels(SiPMs with 50μm and 6μm pixel were also tested)
- Deviation from linearity becomes noticeable starting from 10^4 p.e.
- SiPM saturation value is close to but a little smaller than its pixel number

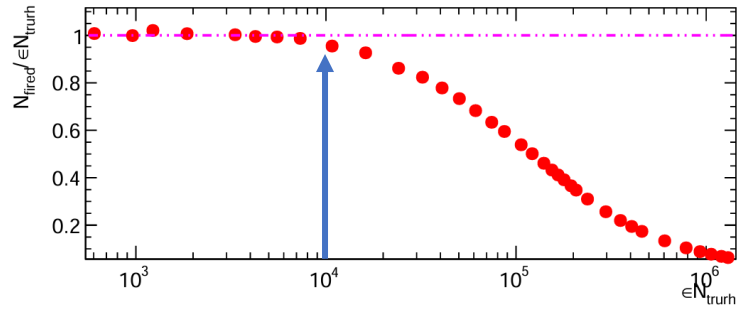




SiPM output vs. input



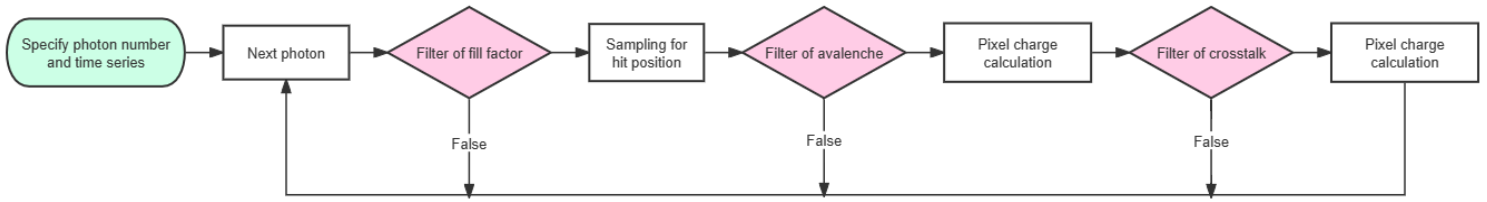
Start to deviate from linearity



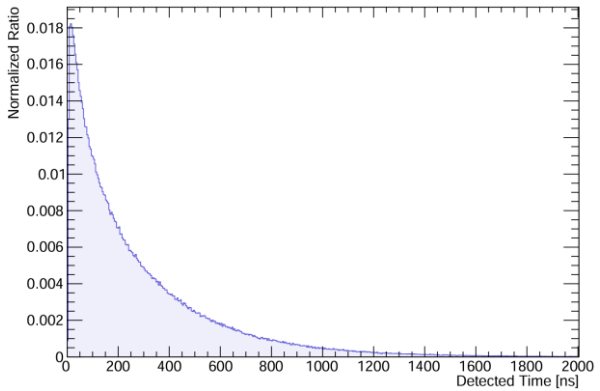
Simulation of SiPM – Scintillation Light

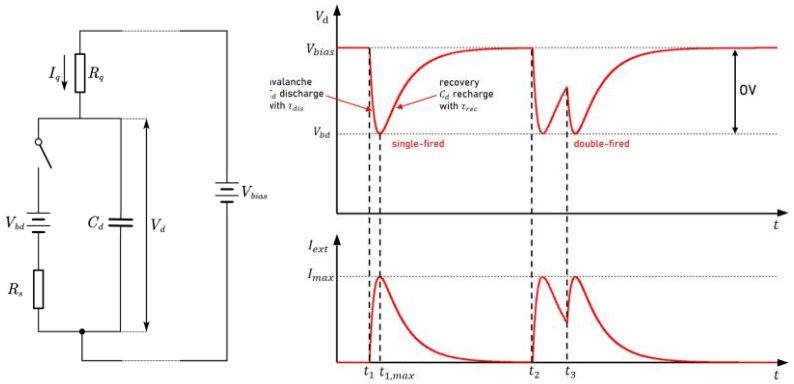
- Maximum energy deposition in one crystal(from 180GeV Bhabha electrons): ~15GeV → ~ 1.7×10^5 p.e.(1 side)
- Detailed simulation including SiPM pixel recovery effect:
  - Photon time stamps: based on Geant4 optical simulation of $1 \times 1 \times 40cm^3$ BGO crystal bar
  - Assuming uniform light profile on SiPM
  - Including SiPM PDE and BGO emission spectra
- $1 \times 1 \times 40cm^3$ BGO + $10\mu m$ SiPM with $3 \times 3cm^2$ size: 10% non-linearity at 1.7×10^5 p.e. -> can be corrected by this model

Toy Monte Carlo including
- SiPM pixel density, PDE spectrum, crosstalk, pixel multi-fired effect
- BGO emission spectrum, detected time of scintillation photon



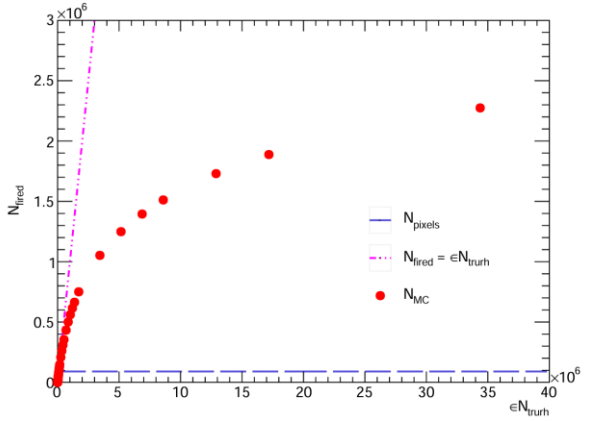
Detected time of photons (Geant4)

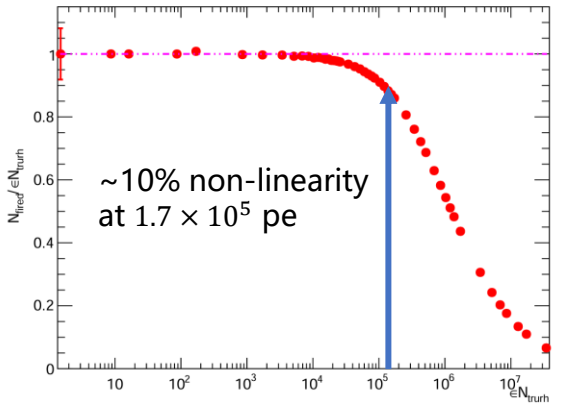




Multi-fired within one pixel

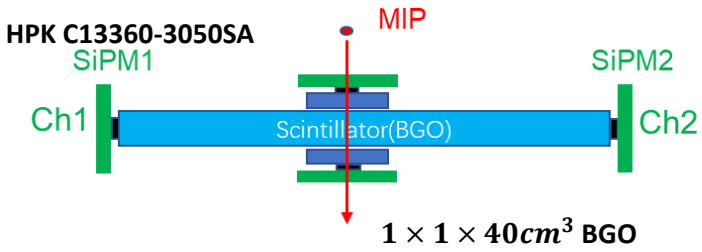
Simulated response curve of SiPM

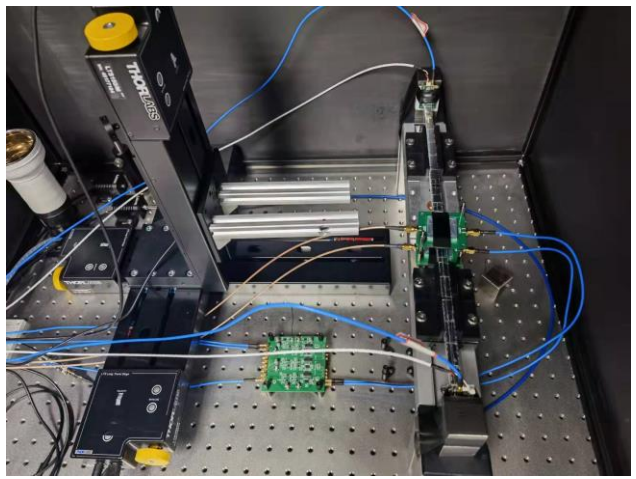


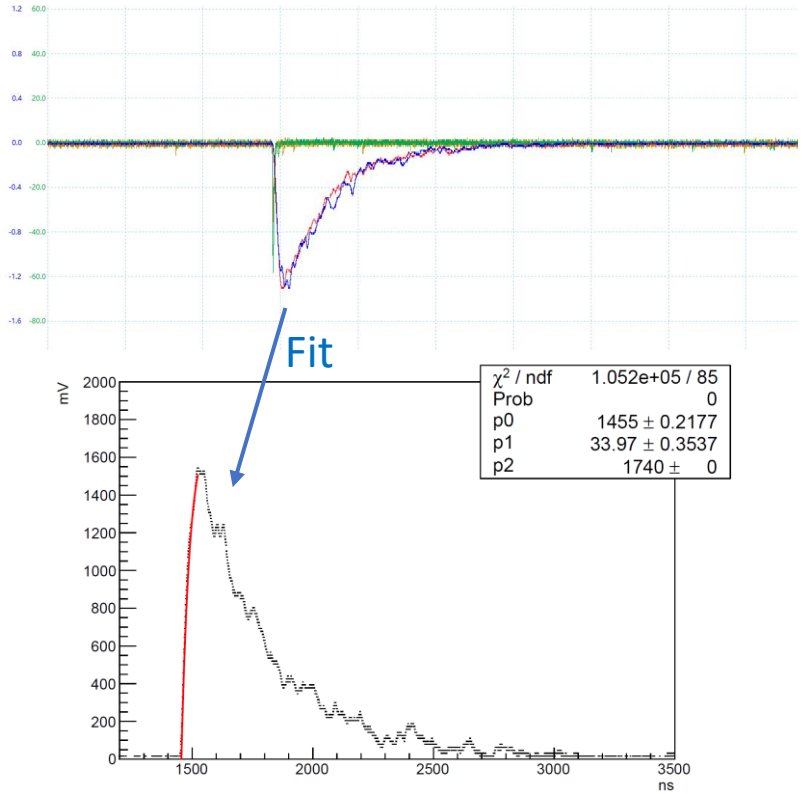


Time Resolution of BGO Crystal Bar

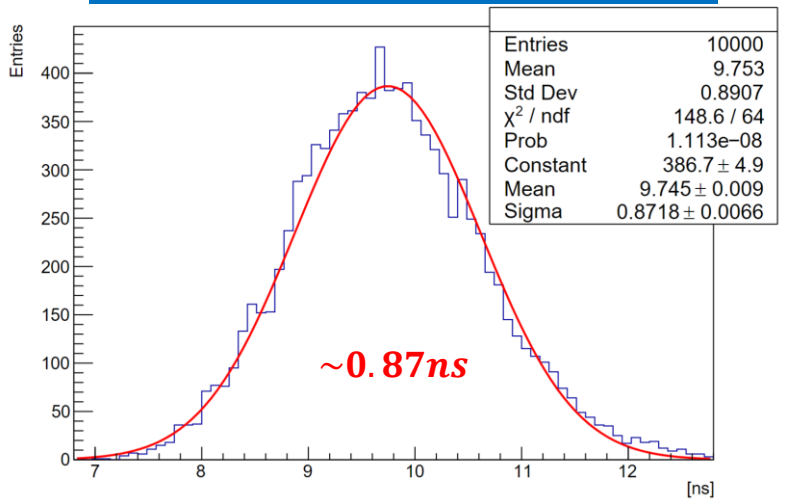
- Experiment setup:
  - Double-side readout by SiPMs
  - Oscilloscope with fast sampling rate(1.25 GS/s)
  - Leading edge fitting + constant fraction timing
- Timing resolution ~1ns at 1-MIP signal level

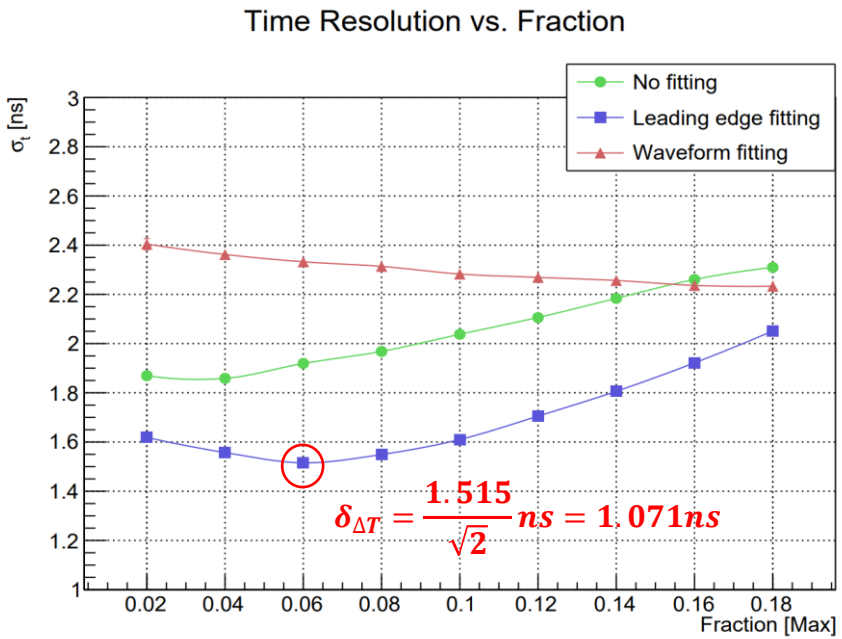






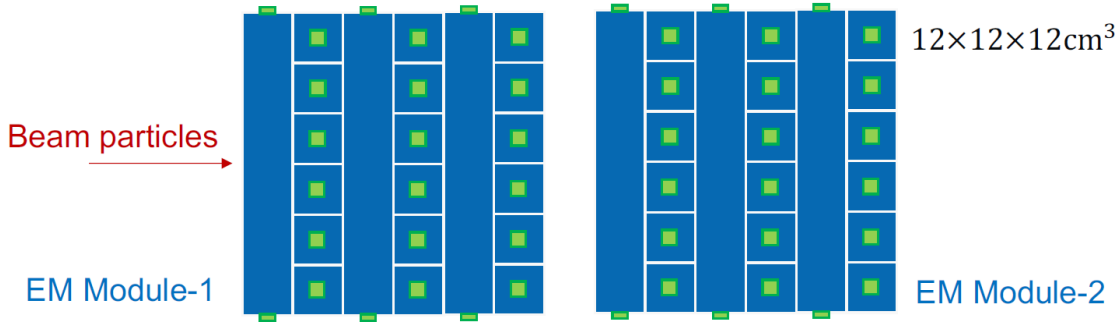
Time Resolution from Waveform Simu

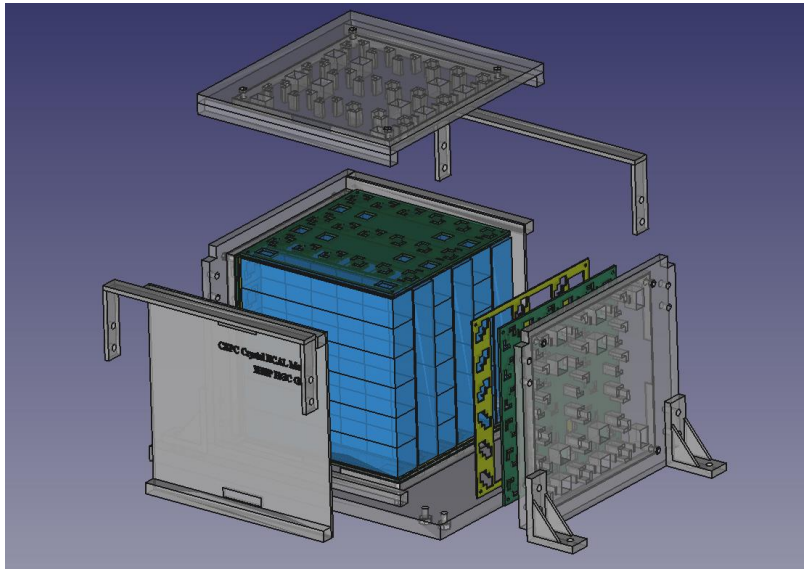




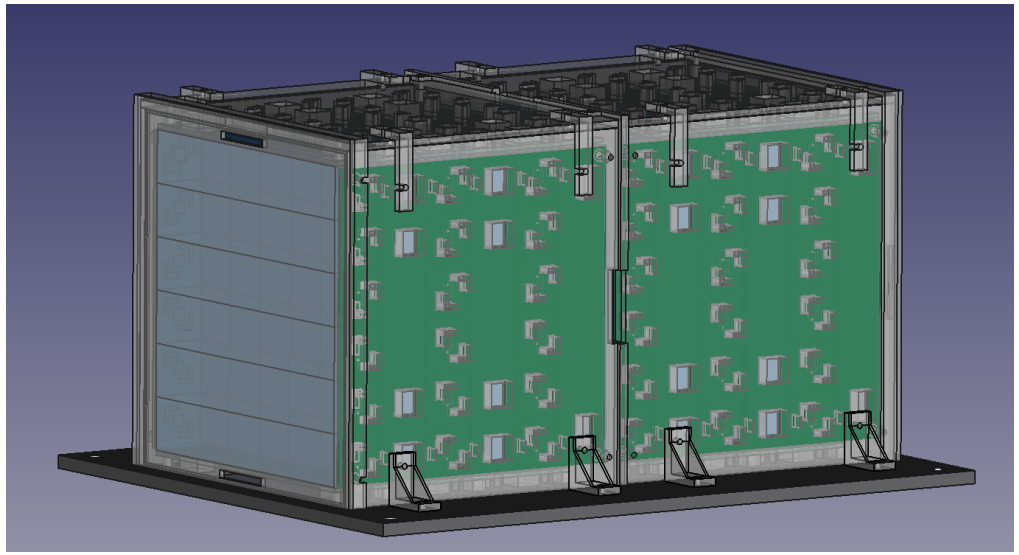
Development of Crystal Modules

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





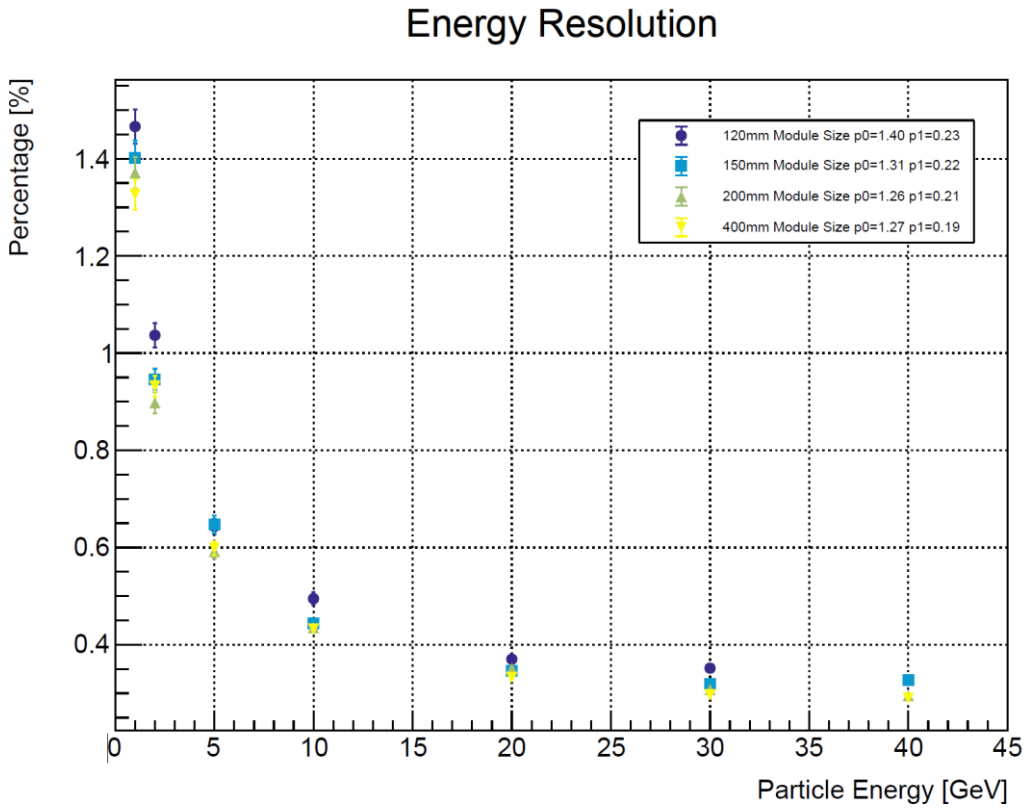
- First crystal module, 72 channels , $10.7X_0$
- First beamtest at CERN PS-T9(May, 2023)
- Main goal: first module commissioning

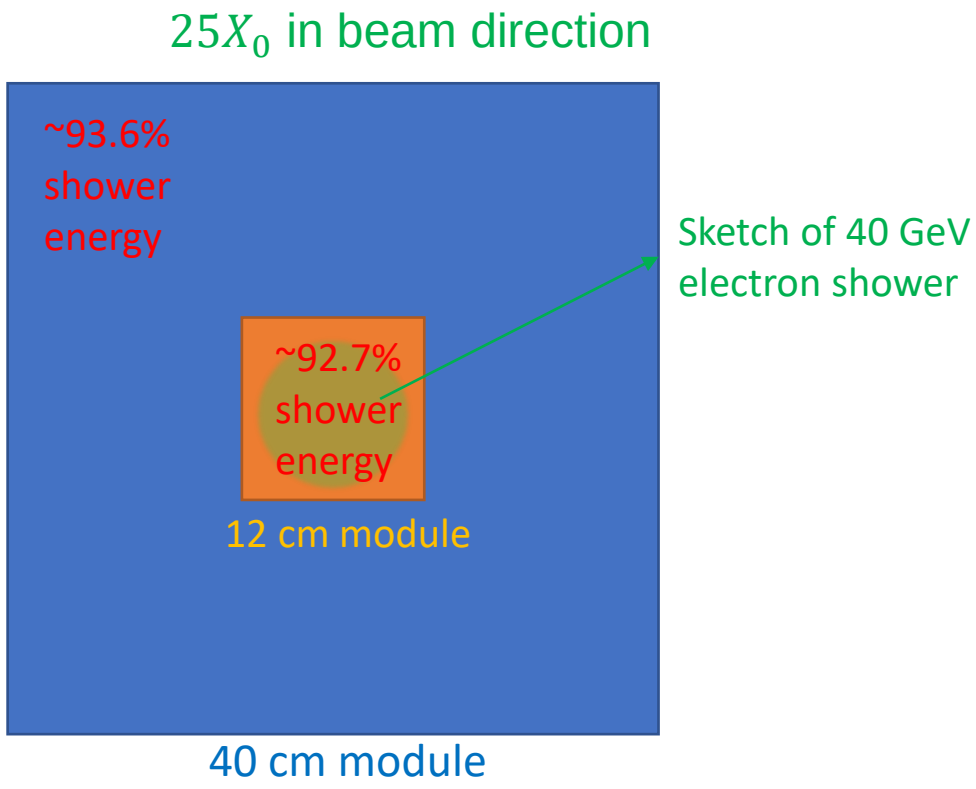


- Second module, 144 channels, $21.4X_0$
- Beamtest at DESY TB22(Oct, 2023)
- Next beamtest at CERN PS-T9(Jun, 2024)
- Main goal: EM performance

Small-Scale Crystal Module Design: Impact of Module Size

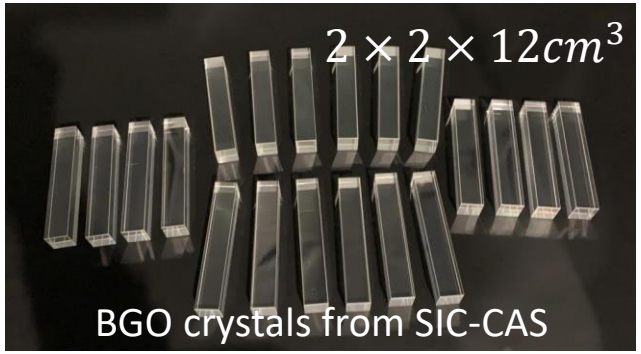
- For EM showers, 12 cm size is enough to contain most of the energy when particles hit on the center of the module
- Degradation of energy resolution: ~0.1% level

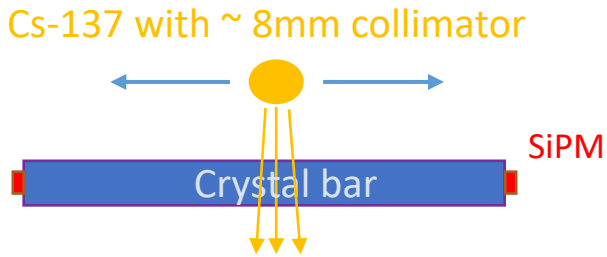




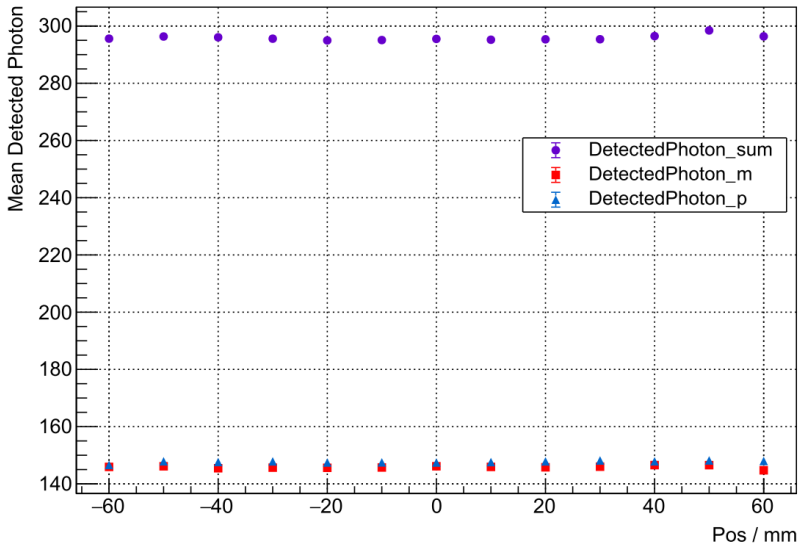
First Crystal Module: Batch Test of BGO Crystal Bars

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

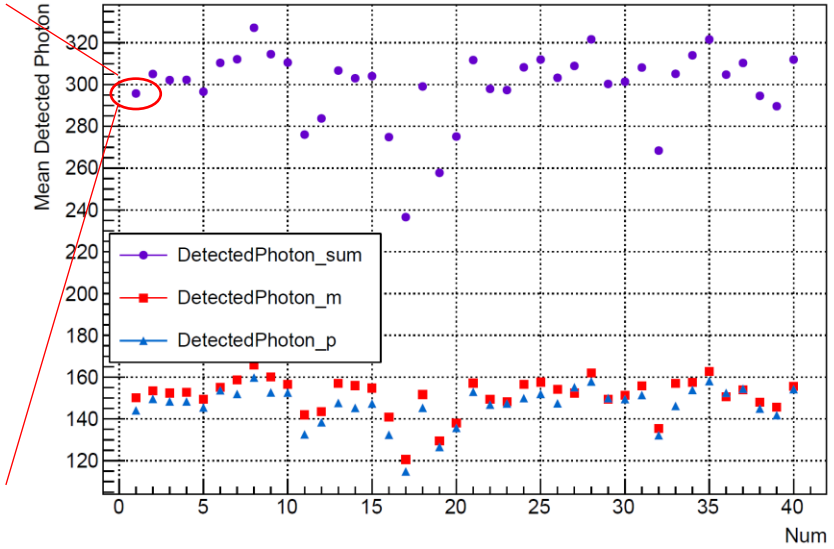


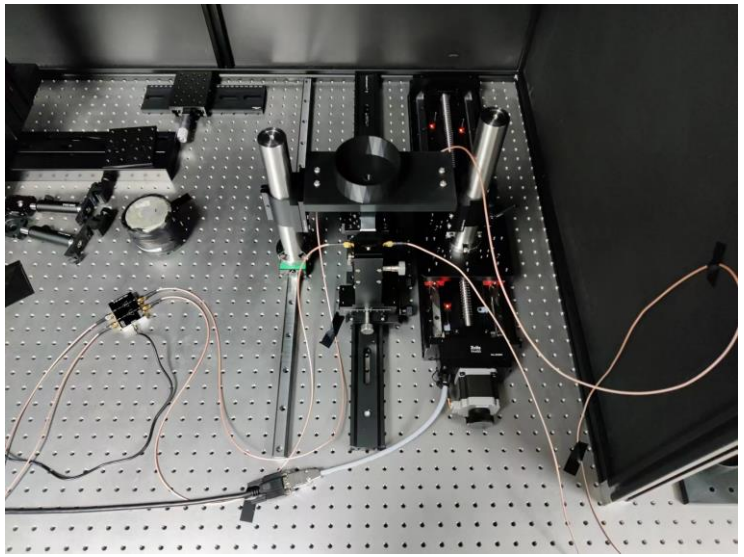


Response uniformity along #1 BGO bar



Comparison of 40 crystal bars





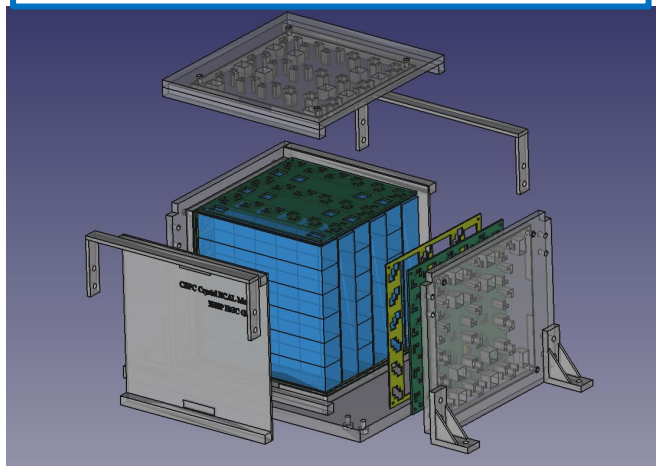
- Generally good uniformity along a single bar
- Response varies among bars, 36 crystals were selected for beamtests

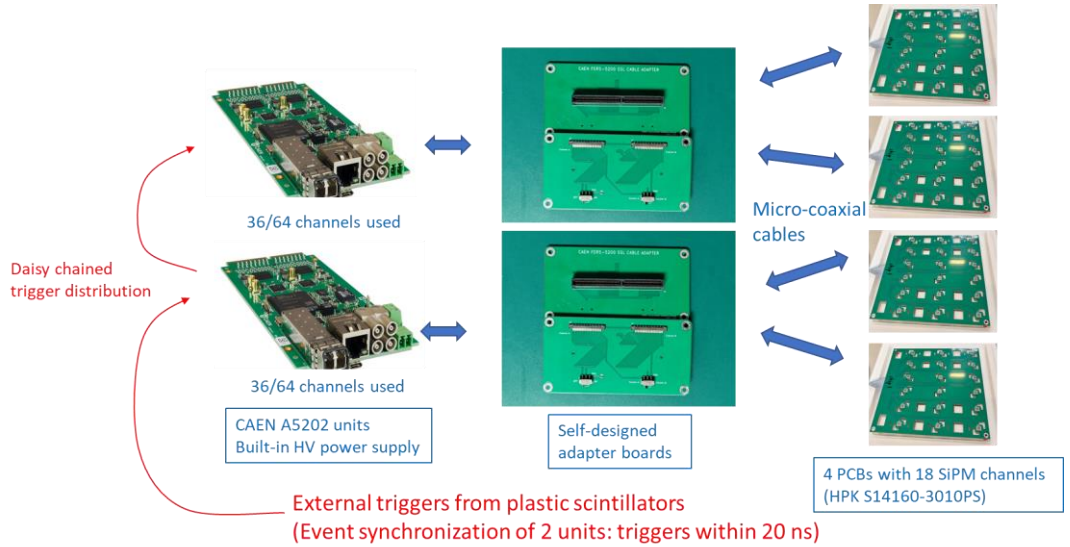
2023 CERN Beamtest: Setup of the First Crystal Module

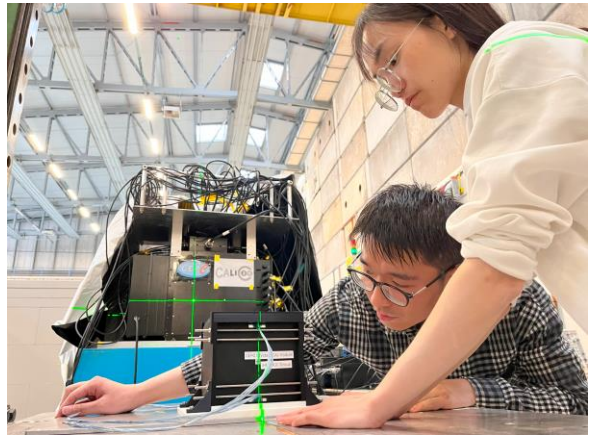
CALICE calorimeter overview – Yong Liu

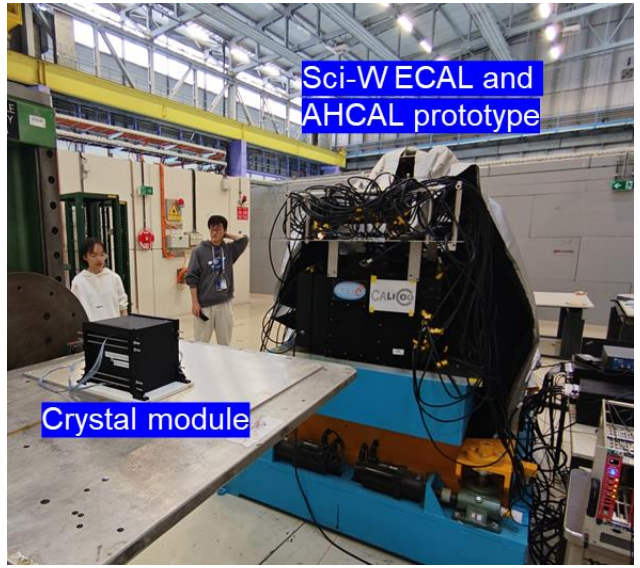
- Beamtest of the first crystal module at CERN PS-T9(May, 2023), together with CALICE Sci-W ECAL and AHCAL prototype
  - EM performance of crystal module
  - Technical issues: design of mechanics and electronics, temperature monitor…

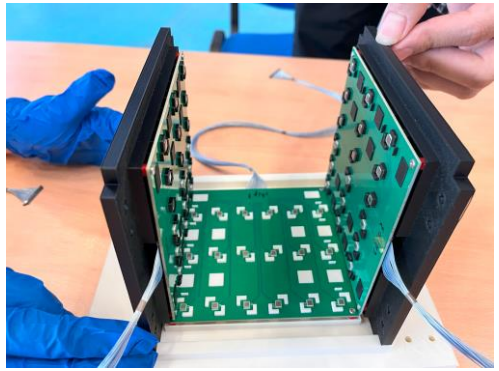
- $2 \times 2 \times 12cm^3$ BGO $\times$ 36, 72ch, 10.7 X_0
- SIPM: HPK S14160-3010PS, 10 µm pixel pitch

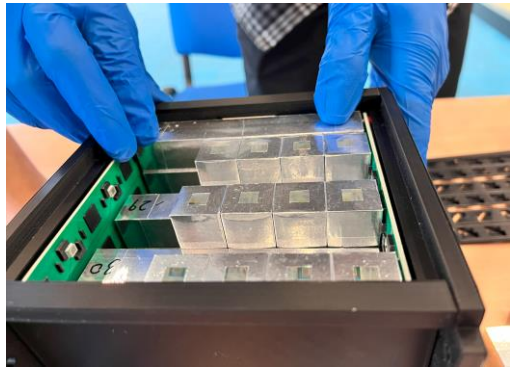


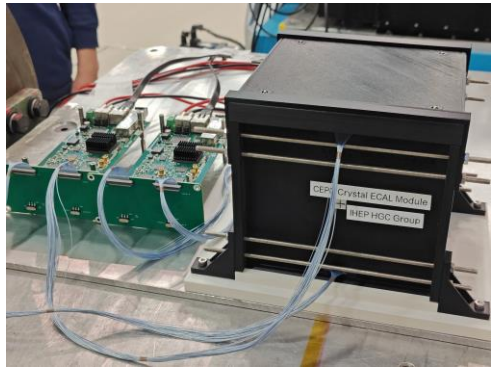






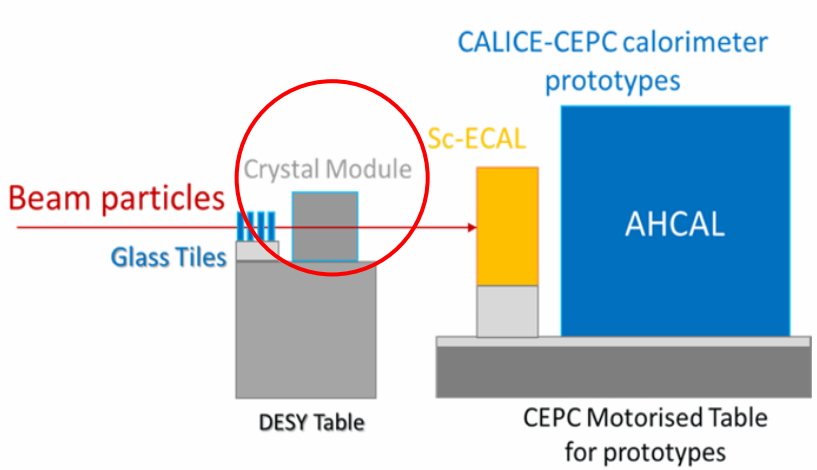


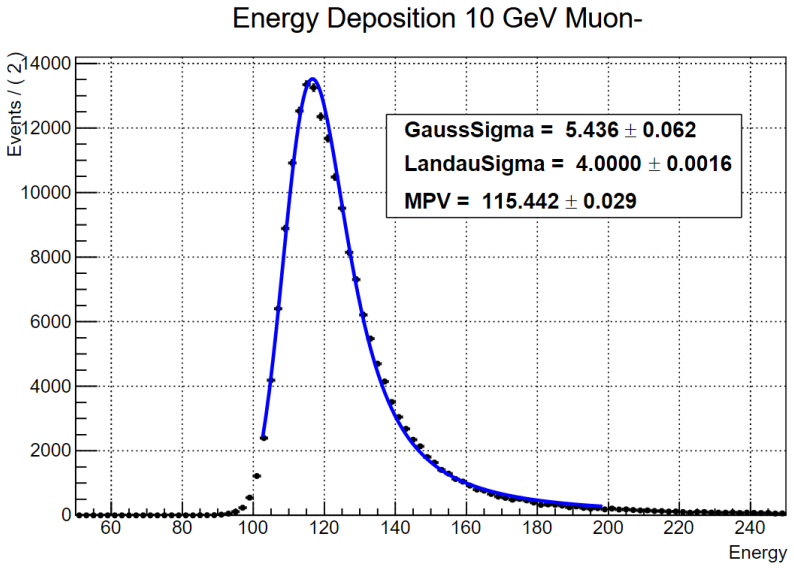


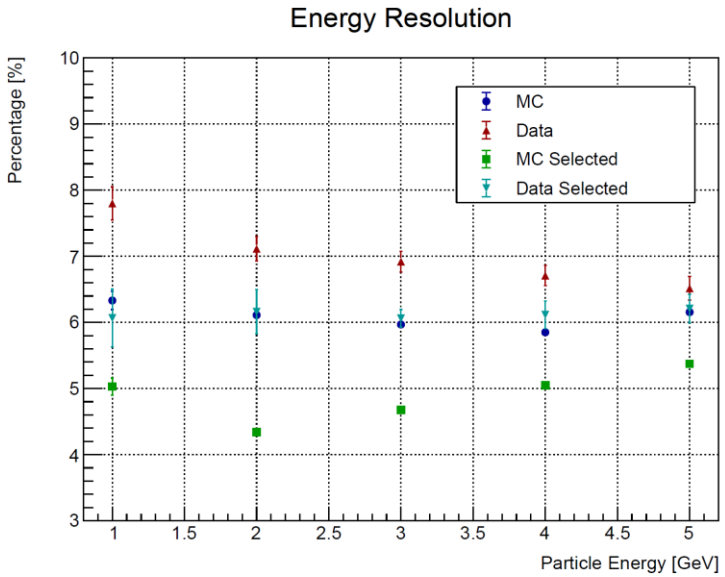


2023 CERN Beamtest: EM Performance

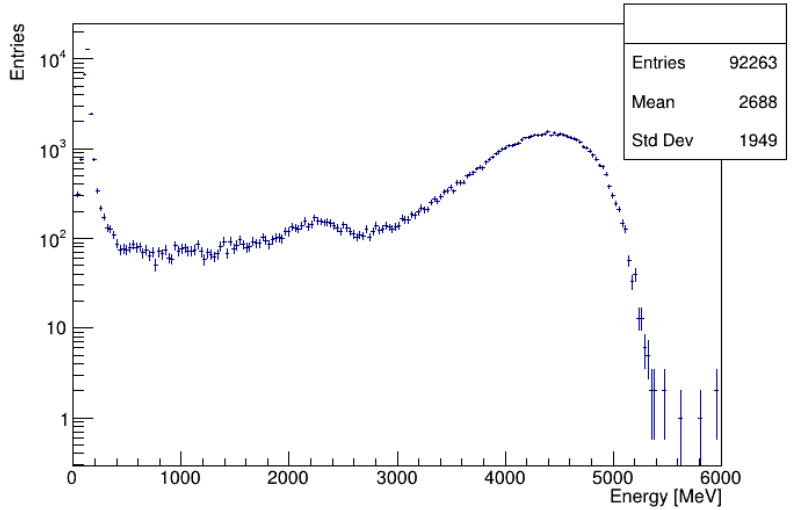
- 10 GeV muon beam: MIP calibration for each channel
- 1-5 GeV electron beam: EM performance
  - Event selection: events hitting at the central 2 bars of the first 2 layers
  - Simulation: realistic module geometry, upstream material, beam profile(energy dependent), momentum spread(0.5% FWHM)…
  - Energy resolution worse than 6%: significant energy leakage due to the limited depth (10.7 X_0)



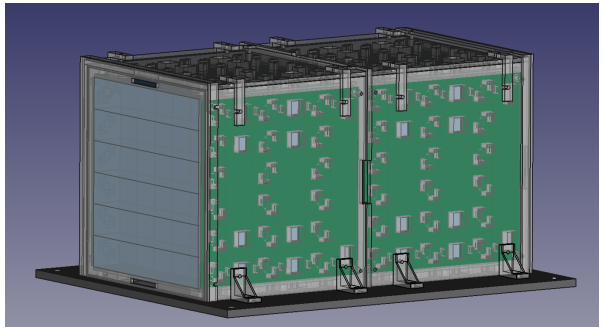


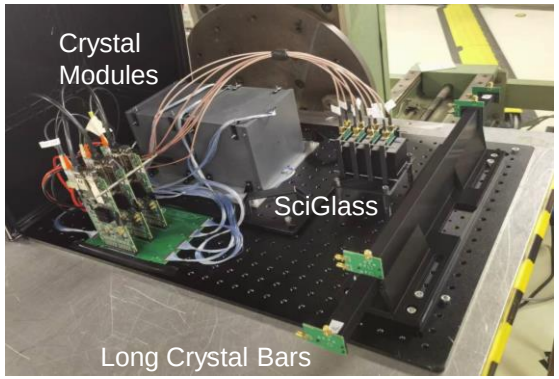


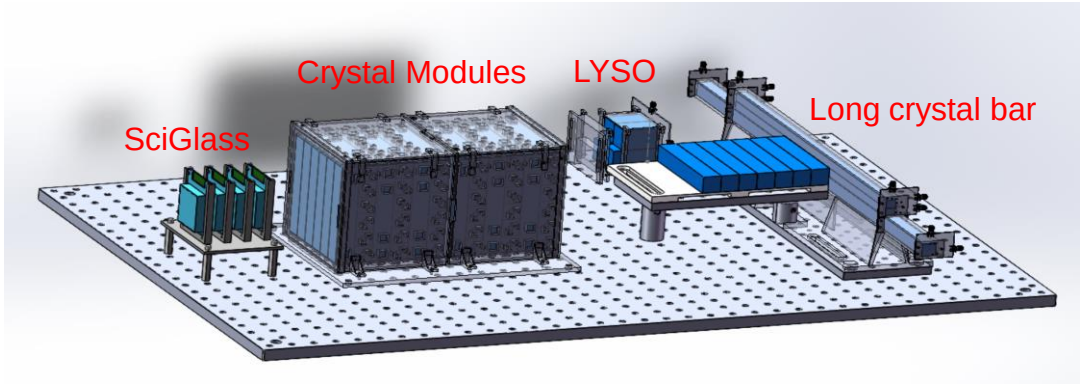
Energy deposition of 5GeV e- in module

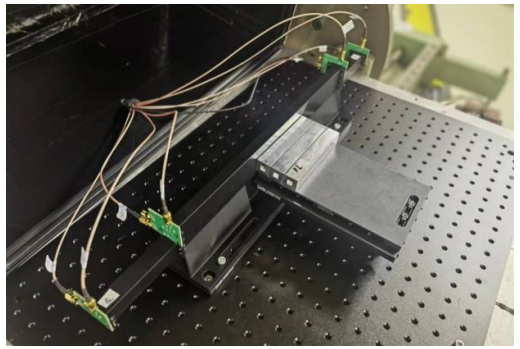


2023 DESY Beamtest: Setup and Tasks







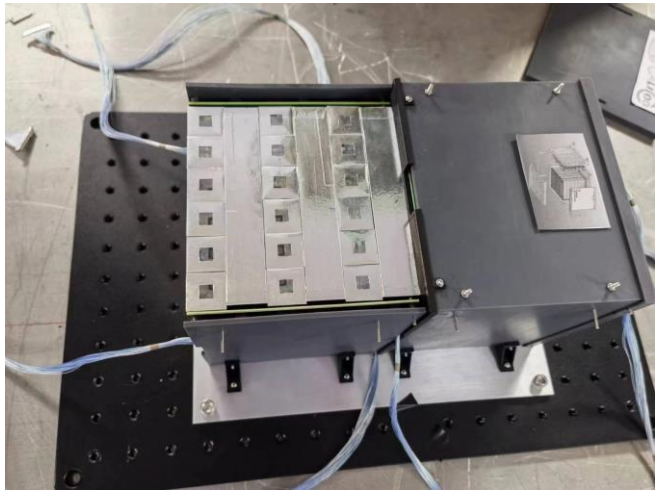


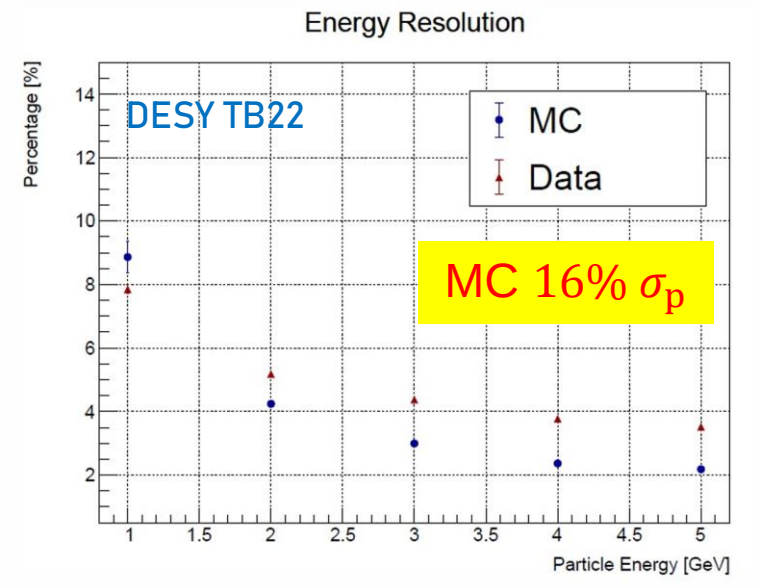
- Items tested with DESY TB22 electron beam(1~6GeV), Oct. 2 ~ Oct. 15, 2023
  - Small-scale prototype of crystal ECAL(21.4 X_0): system integration, EM performance
  - Long BGO crystal bars(40/60cm): time resolution
  - New ASIC(MPT2321) for 32-ch SiPM readout: large dynamic range
  - The 2nd batch of tiles from the “Glass Scintillator Collaboration”($4 \times 4 \times 1\mathrm{cm}^3$): MIP signal

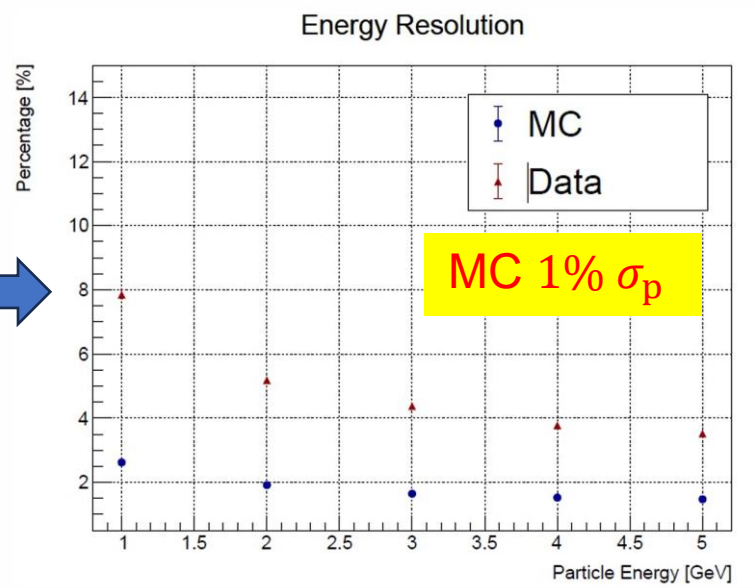
2023 DESY Beamtest: EM Performance of BGO Crystal Module

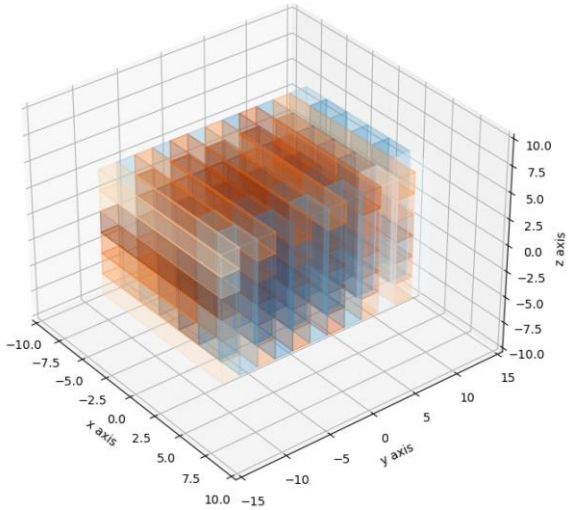
- MIP calibration from CERN is still used here
- Crystal module: 1~5GeV electron beam data
- MC validation
  - Including beam momentum spread and $\pm 3mm$ beam profiles
- EM resolution is significantly impacted from momentum spread

- $2 \times 2 \times 12cm^3$ BGO $\times$ 72, 144ch, 21.4 X_0
- SIPM: HPK S14160-3010/15PS, 10/15 μm pixel pitch



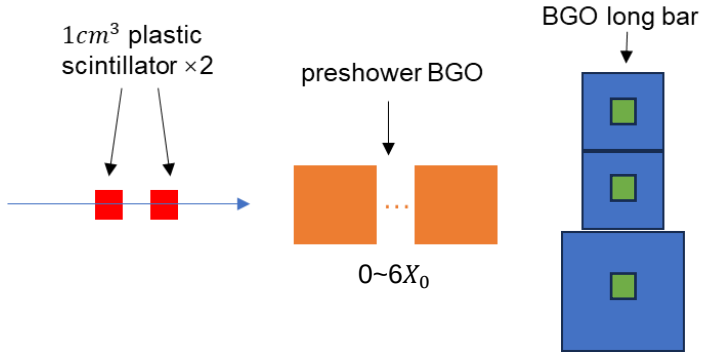




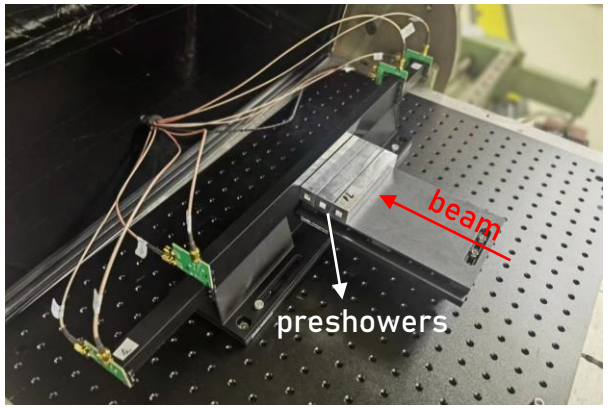


- DESY TB21 momentum spread ~16% at 1 GeV, no measurement for TB22

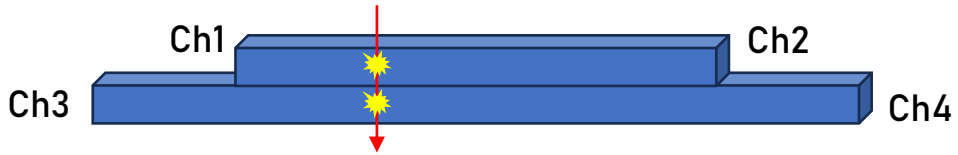
2023 DESY Beamtest: Time Resolution of Long Bars



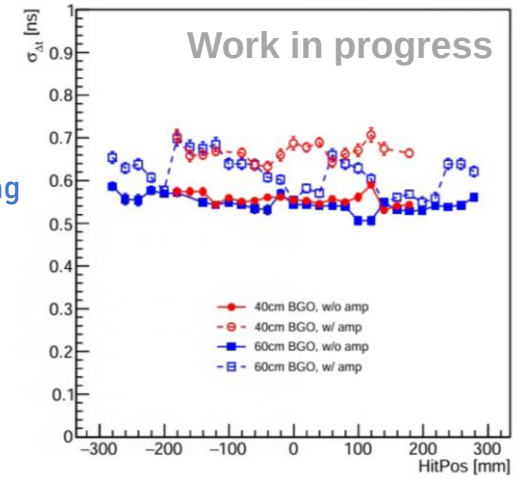
- Time resolution of long crystal bars(40/60cm BGO) with DESY 5GeV e- beam
  - SiPM 25 μm pixel pitch, DAQ with 1.25GS/s sampling rate
  - Good uniformity of time resolution along crystal bars
  - Time resolution varies with signal amplitude:
    - Single bar: 200ps (40cm BGO at >12MIP, 60cm BGO at > 20 MIP)
    - Adjacent bars: 700ps (at > 8MIP)



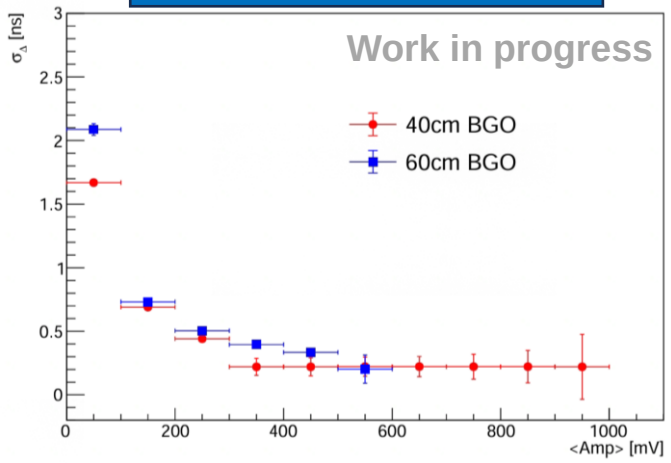
$60 \times 1.5 \times 1.5/40 \times 1 \times 1\ cm^3\ BGO$, 25 μm SiPM



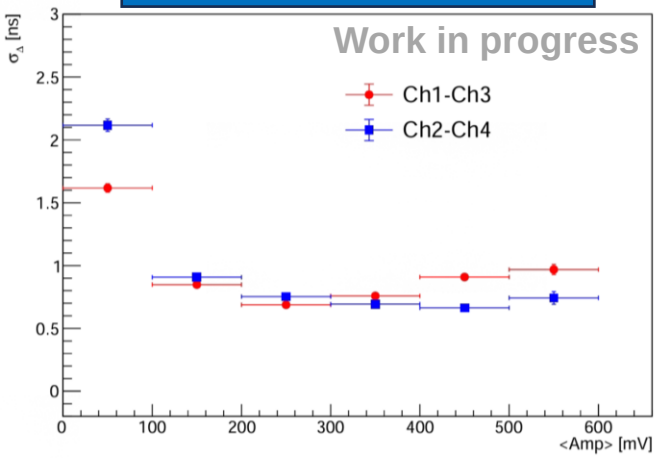
Leading edge fitting with 10% constant fraction timing



Single bar



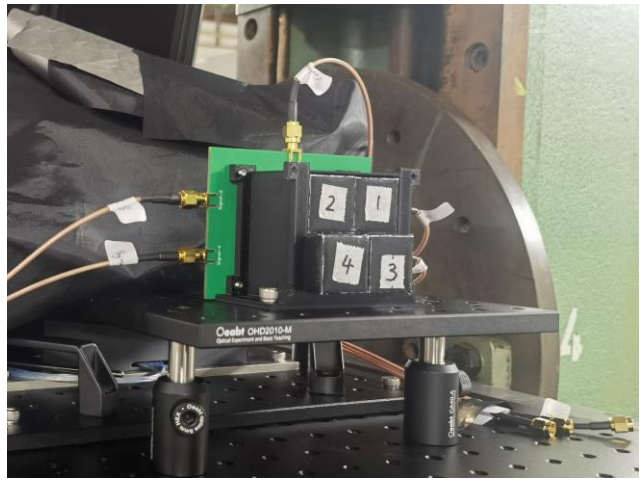
Adjacent bars



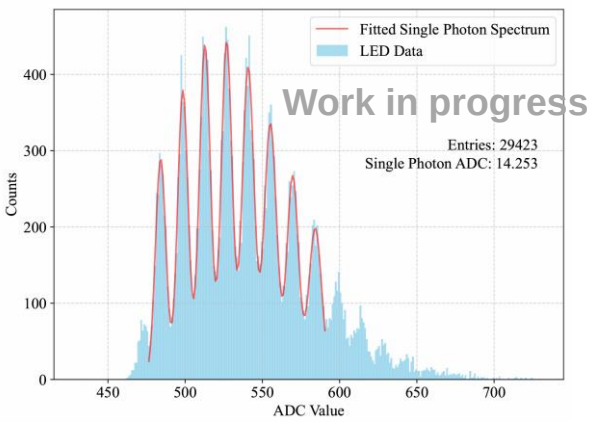
$\langle Amp \rangle = (A_1 + A_2)/2$

2023 DESY Beamtest: ASIC MPT2321

- 32-channel ASIC board for SiPM readout
  - High S/N: single photoelectron calibration in high gain mode
  - Large dynamic range: up to 35k p.e. measured with 5cm LYSO and 25μm SiPM

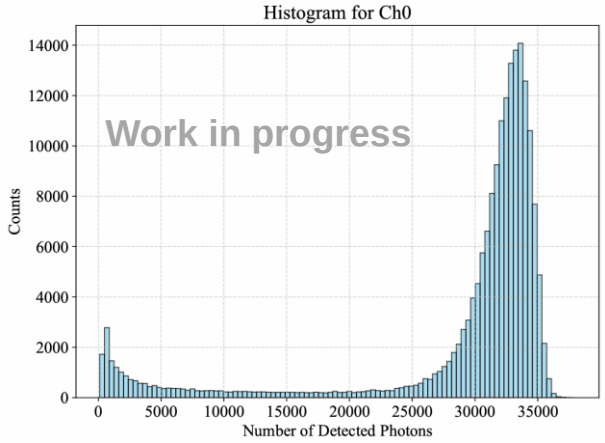


Single photon calibration

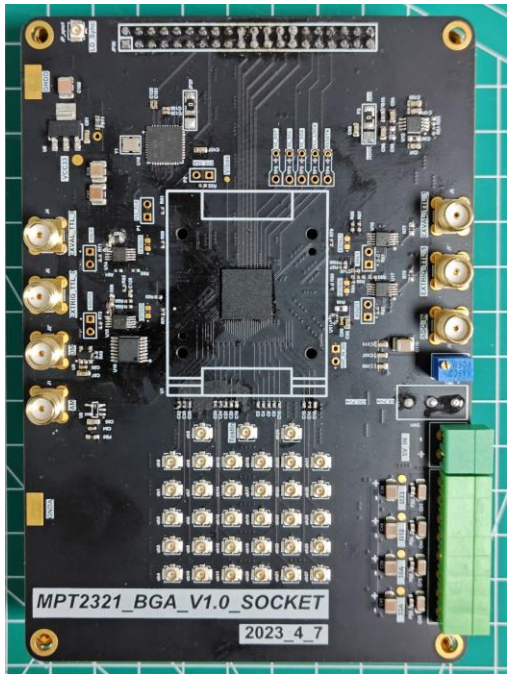


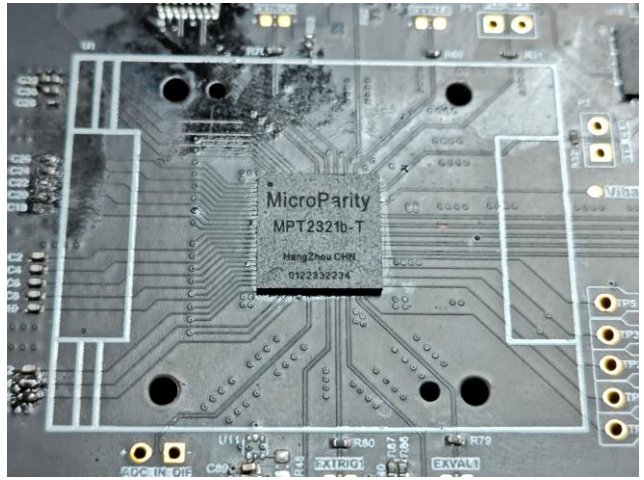
- 25 μm SiPM, LED source

Dynamic range test



- 5cm LYSO + 25 μm SiPM(7×10^5 gain)
- Up to ~ 35k p.e. at 1.6nC



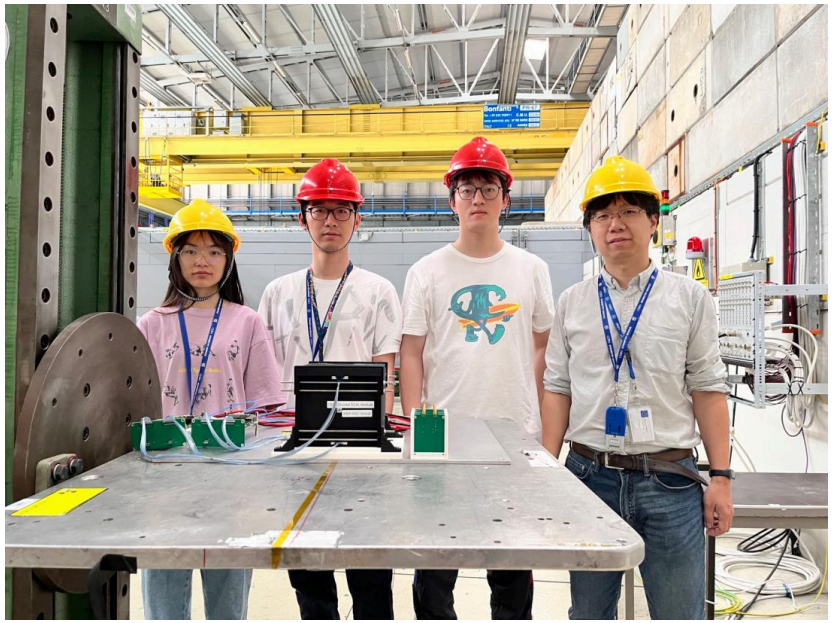


Acknowledgments

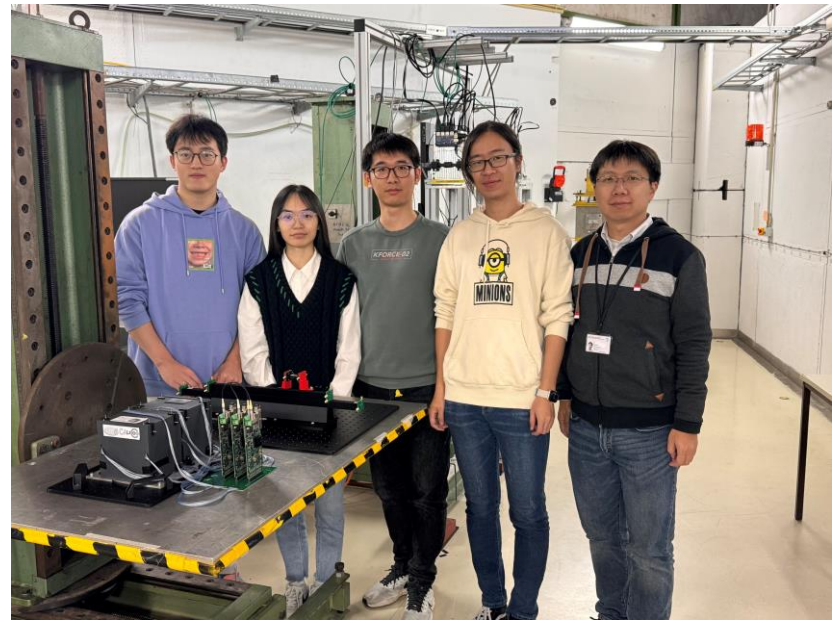
- Thank you to every one who works on the team
- Enormous and substantial support from CERN, DESY, CALICE

CERN PS-T9 May. 2023

CERN PS-T9 May. 2023



DESY TB22 Oct. 2023



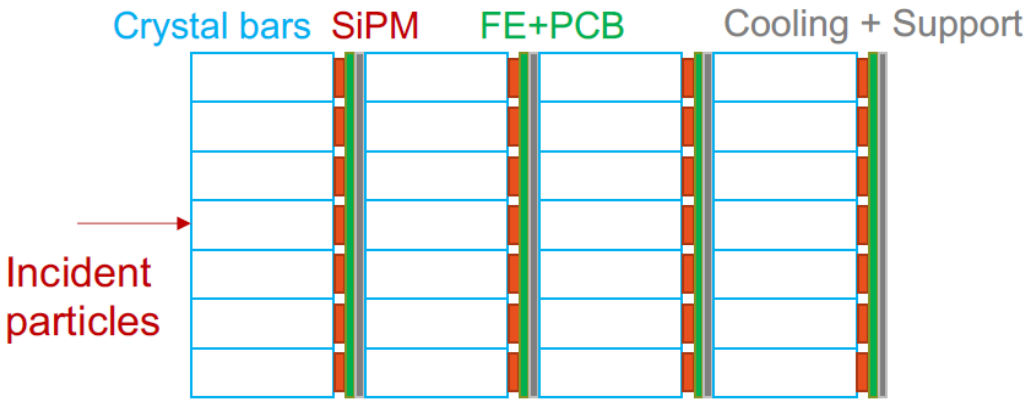
Summary & Prospects

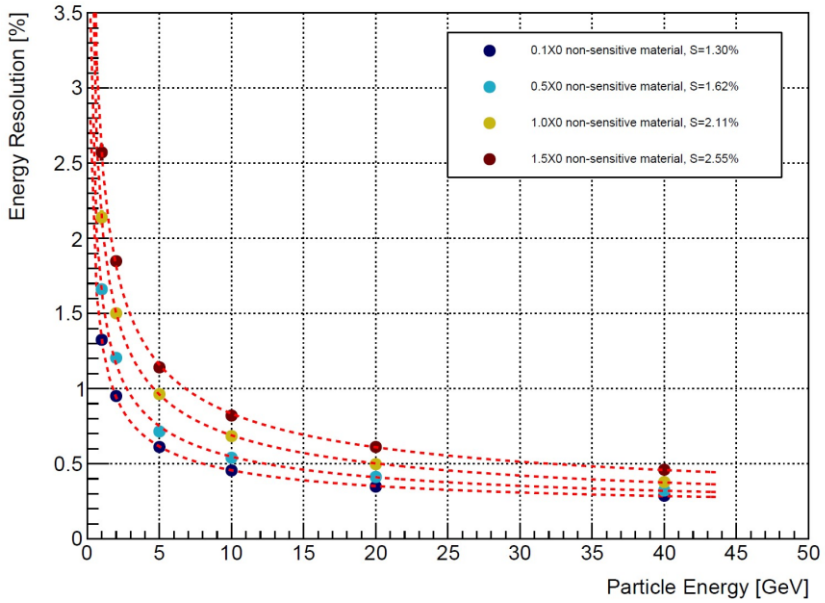
- High-granularity crystal calorimeter: optimal EM energy resolution, promising to improve measurements of higgs and flavor physics.
- R&D on Crystal-SiPM units and modules
  - Series of experiments and simulations were conducted to study the characters of crystal-SiPM units
  - The first crystal module with $10.7X_0$ and the second module with $21.4X_0$ were built to study the EM performance, mechanics, electronics and integration of crystal ECAL design
  - Time resolution of long BGO bars with cosmic ray and electron beam
- Prospects
  - Next beamtest at CERN PS-T9 to study the EM performance of the second module with muon and electron beam
  - Optimize time resolution measurement with high speed DAQ
  - More research on dynamic range and timing performance of new ASIC

Backup

Short Bar Design of Crystal ECAL

- A natural design compatible with PFA: fine segmentation in both longitudinal and transverse directions
- Single-end readout with SiPM
- Large #ch and dead materials

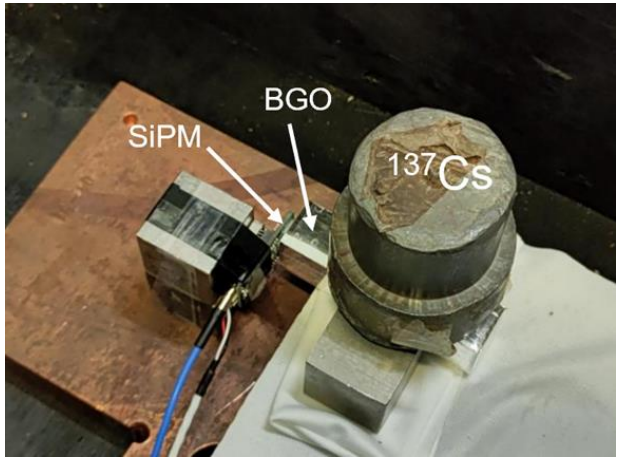




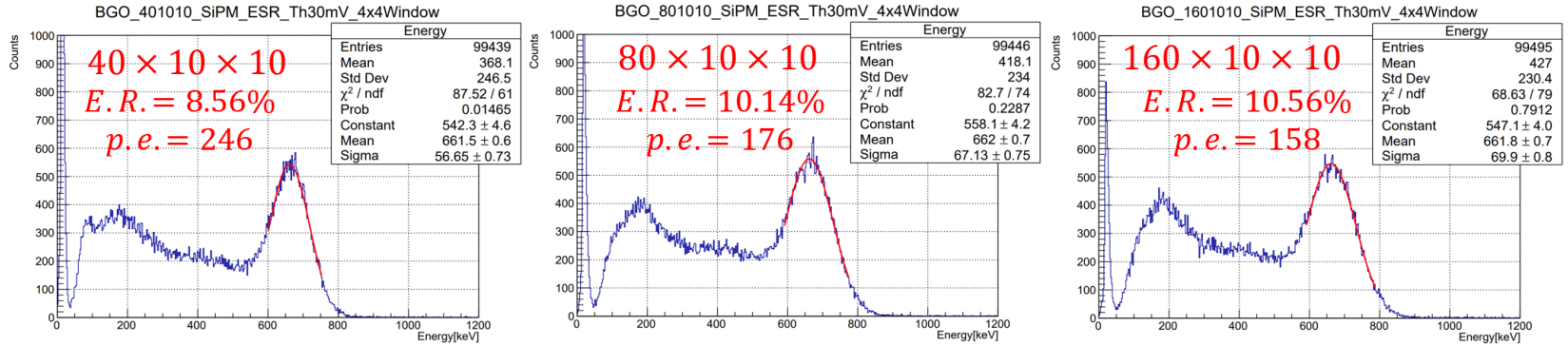
- $40 \times 40 \times 40 cm^3$ module, 1~40GeV e-
- $1 \times 1 \times 4 cm^3$ BGO crystals, with Cu as dead material.
- Energy resolution worsens as the thickness of Cu increases.

Low Energy Photon Detection of BGO

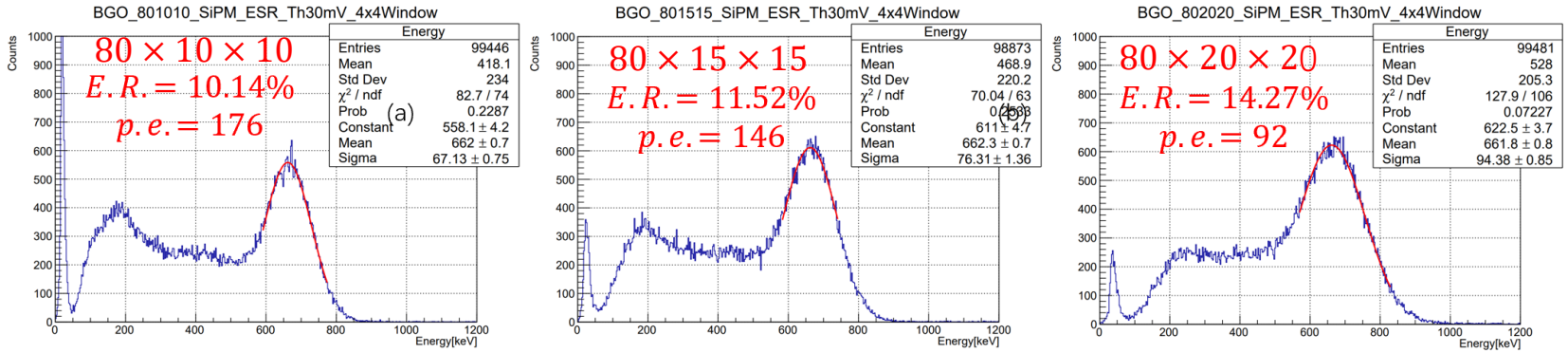
- BGO has the ability to detect low-energy photons
- SiPM: HAMAMATSU C13360-3050SA
- BGO crystals with different sizes
- Source: Cs-137, 662keV γ



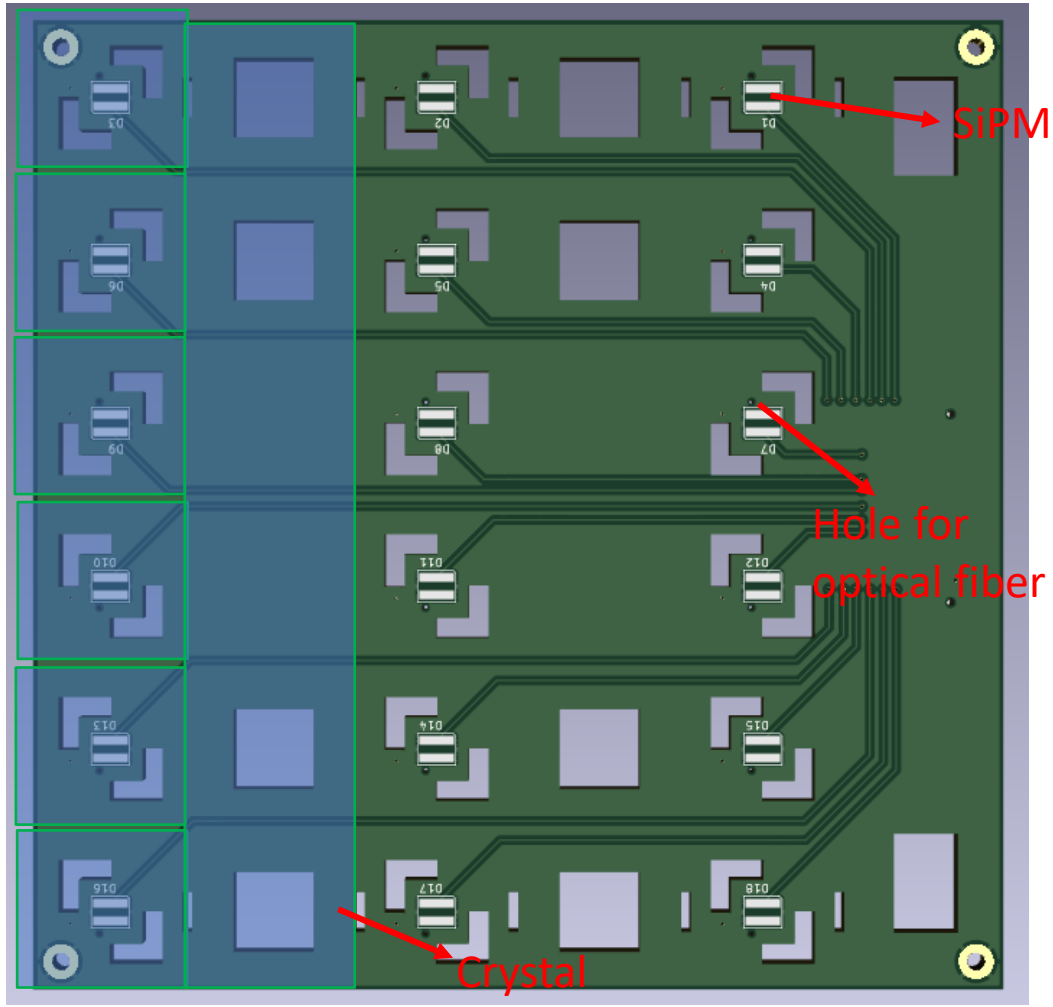
Different lengths



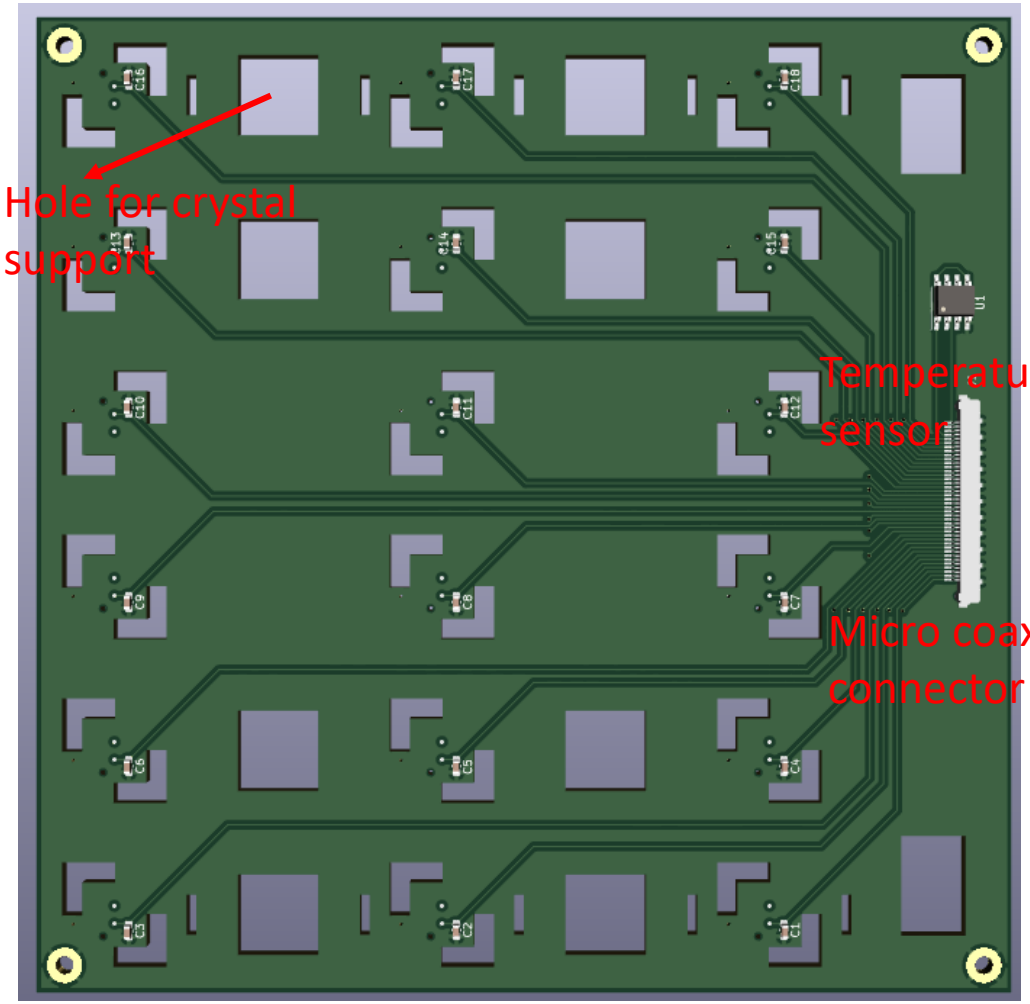
Different cross-sectional areas



PCB Layout of Crystal Module

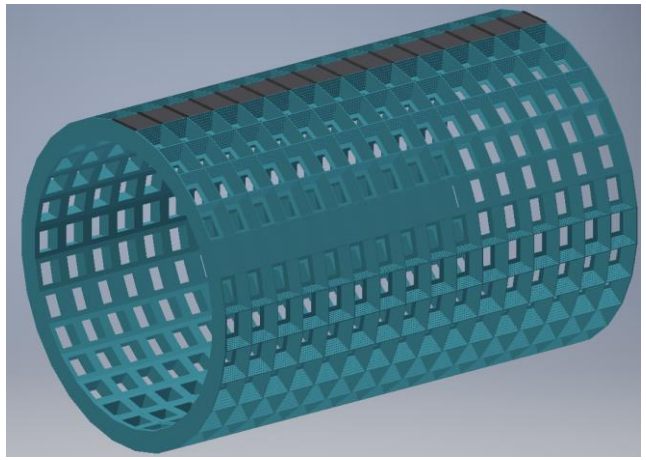


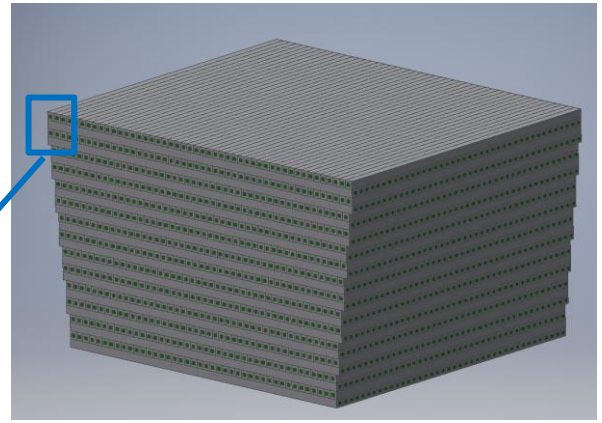
Front side

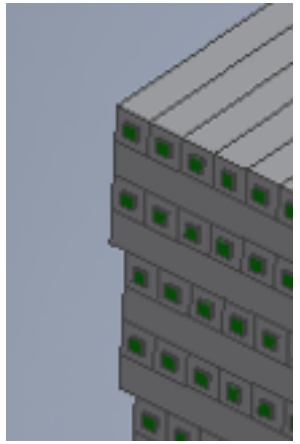


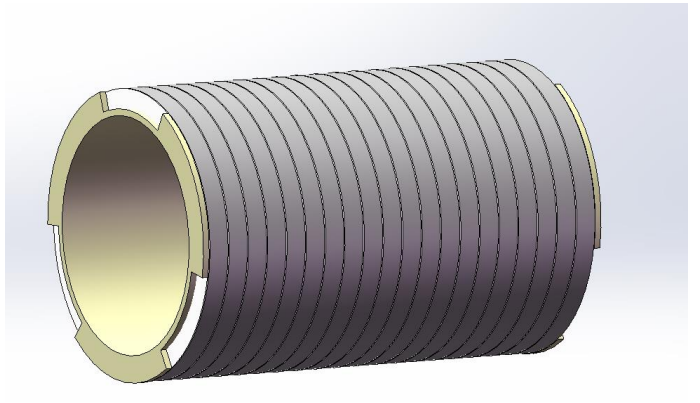
Back side

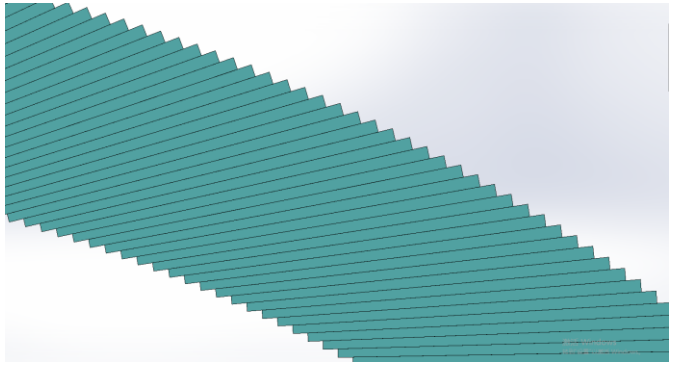
Mechanical Design for Crystal ECAL







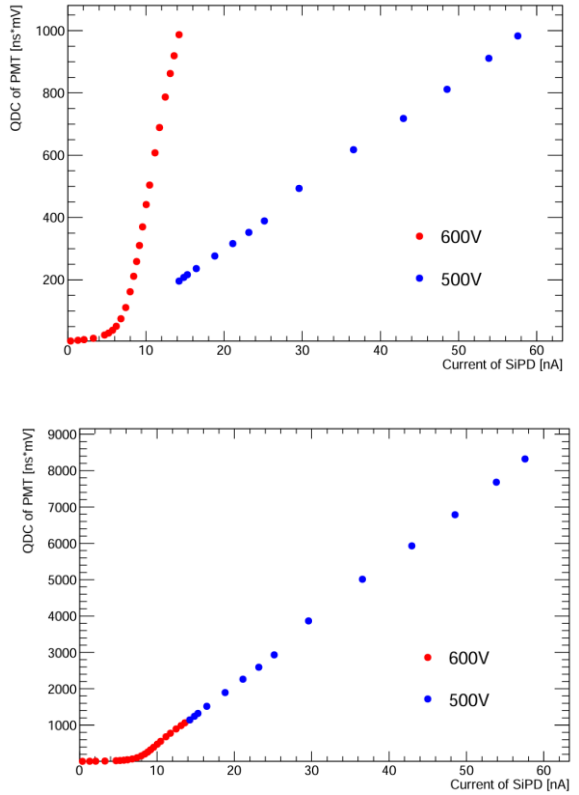




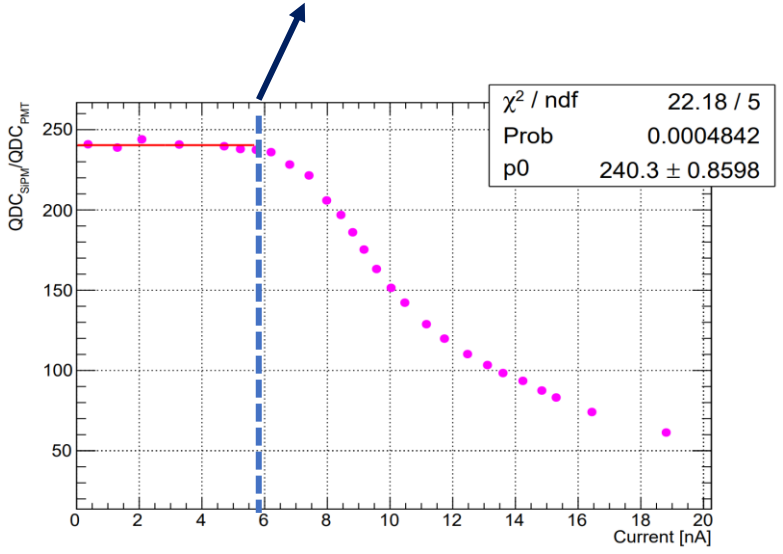
PMT Calibration for the Test of SiPM Dynamic Range

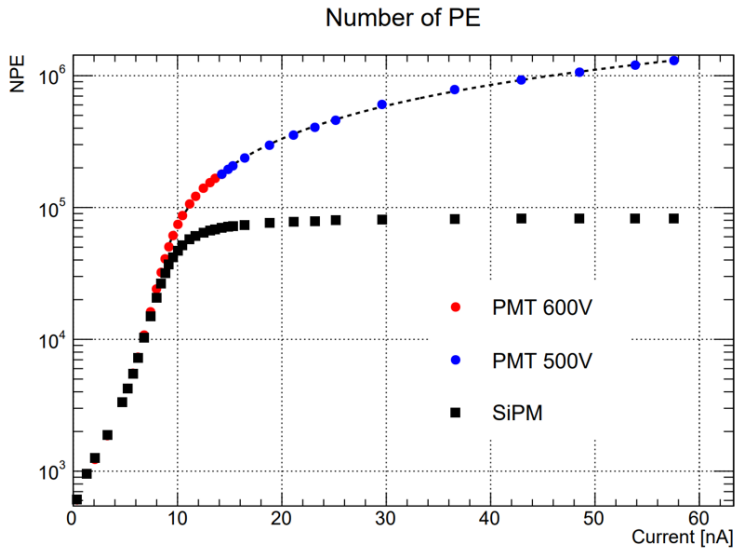
- Select the linear region of PMT with a Si-PIN at different light intensities
  - Weak light intensity → 600V
  - Strong light intensity → 500V
- Gain of PMT is not high enough to discriminate single pe with 600V bias voltage
- SiPM calibrates PMT in weak light intensity region

PMT gain calibration



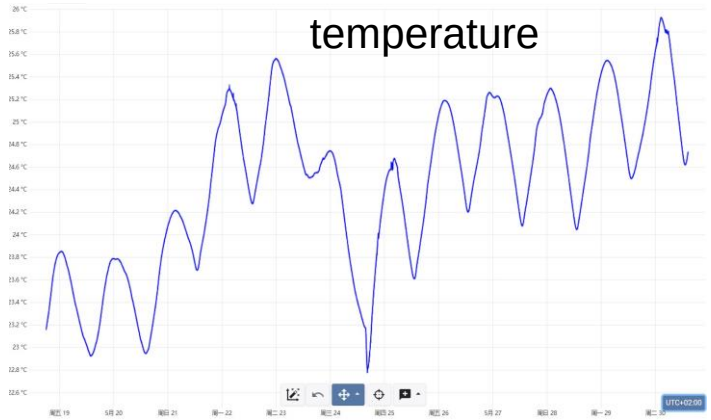
Common Linear region
Let $NPE_{PMT} = NPE_{SiPM}$

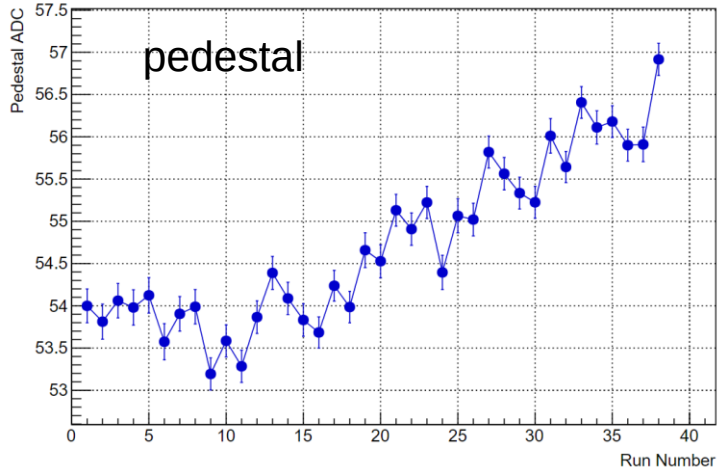




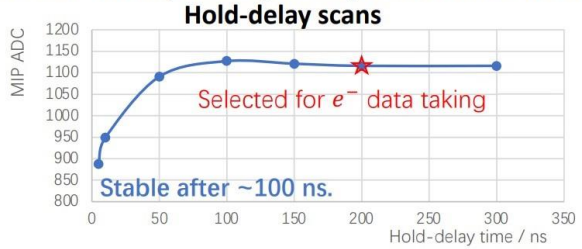
CERN Beamtest: Muon Data for Parameter Scans and Calibration

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

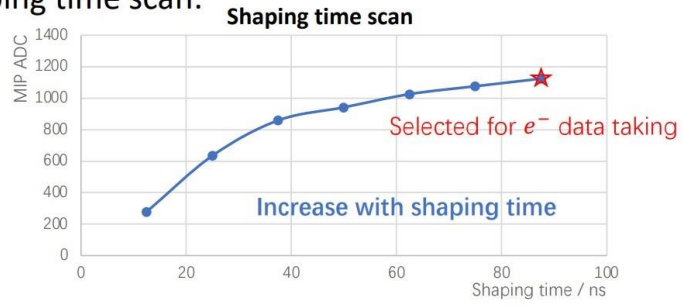


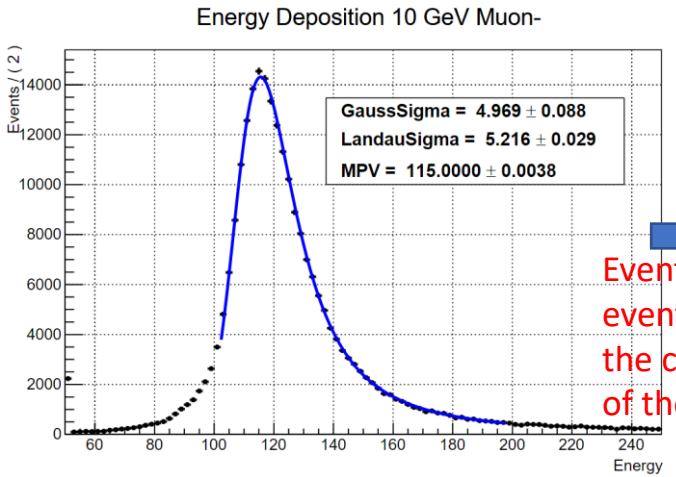


- Hold-delay time scan:
  - 10 GeV muon, HG 59, LG 63, scan from 5 ns to 300 ns.

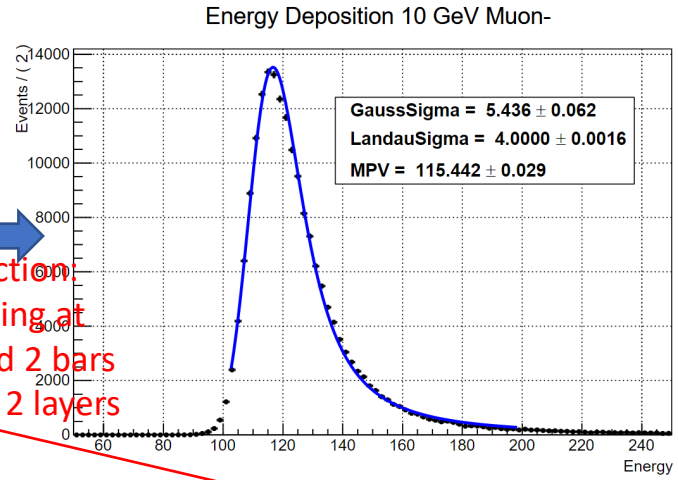


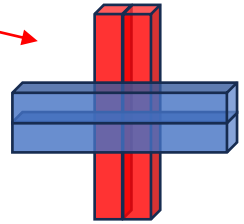
- Shaping time scan:





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

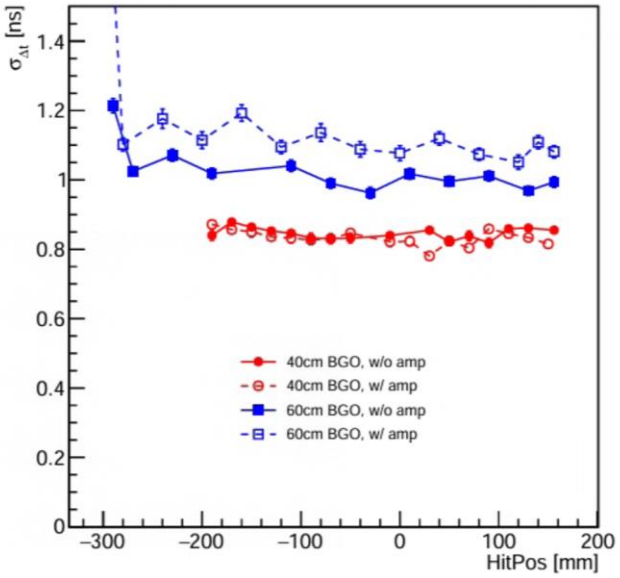
Time Resolution Measured with 15μm SiPM

- SiPM: S14160-3015PS, 15μm pixel pitch, $3 \times 3mm^3$
- Timing method: leading edge fitting with 10% constant fraction timing

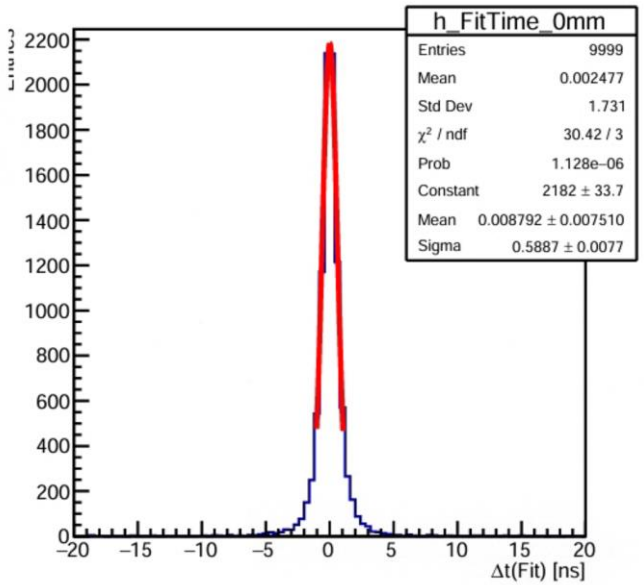
1-10 MIPs

Crystal size	$60 \times 1.5 \times 1.5\ cm^3$	$40 \times 1 \times 1\ cm^3$	$4 \times 1 \times 1\ cm^3$	$2 \times 1 \times 1\ cm^3$
Time resolution (ns) (single bar)	1	0.85	0.66	0.59

40/60cm BGO



2cm BGO



4cm BGO