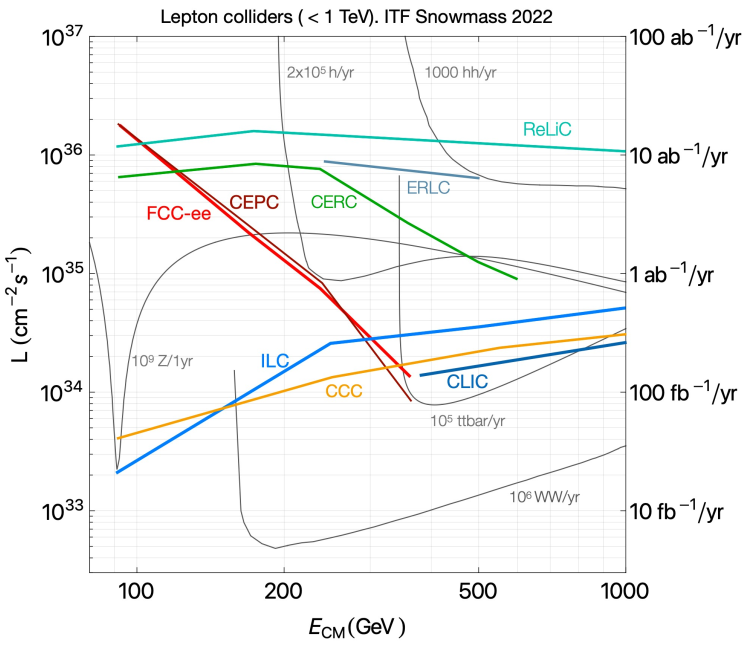
CEPC Crystal Calorimeter: R&D highlights

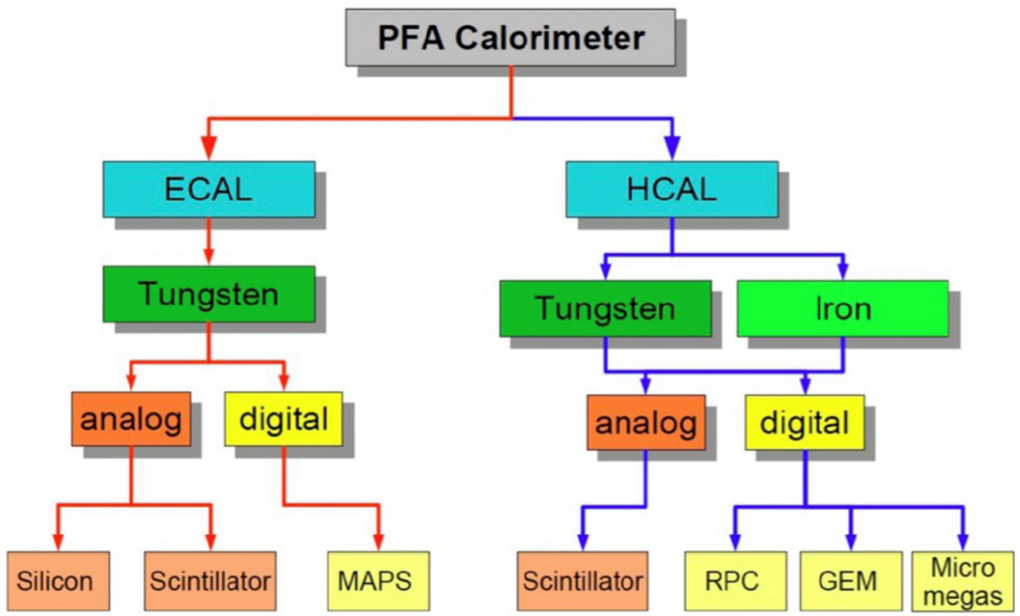
Yong Liu (IHEP) for the CEPC-calorimetry team

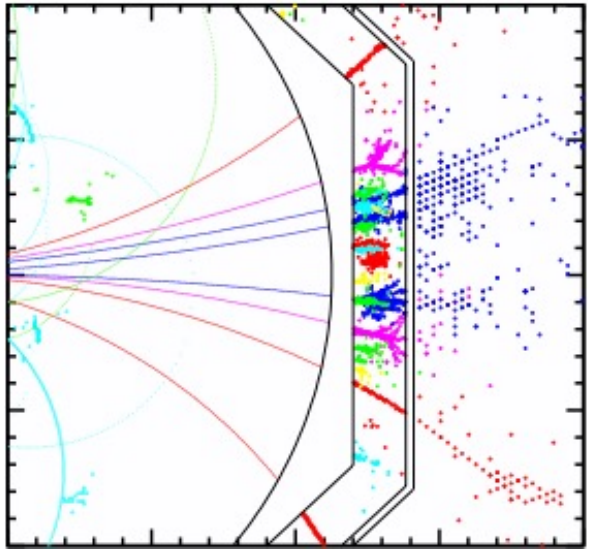
CHiP Cross-Strait Workshop on Advanced Detectors and Technologies

June 17, 2024

High granularity calorimetry





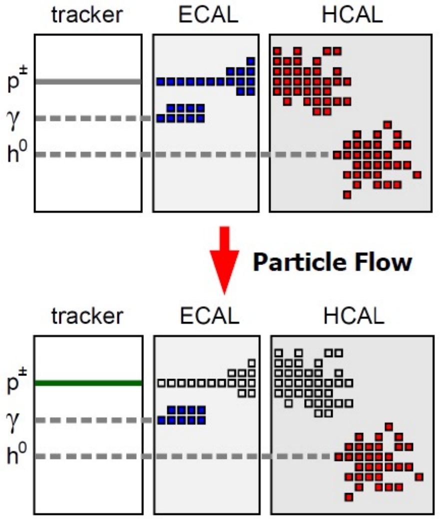


- Future lepton colliders as Higgs/EW/top factories
  - Requires unprecedented energy resolution for jet measurements
  - A major solution: highly granular (imaging) calorimetry + particle flow algorithm (PFA)
- PFA calorimetry: various options explored in the CALICE collaboration
- Focus in this talk: a new option with finely segmented **crystals with SiPM readout**

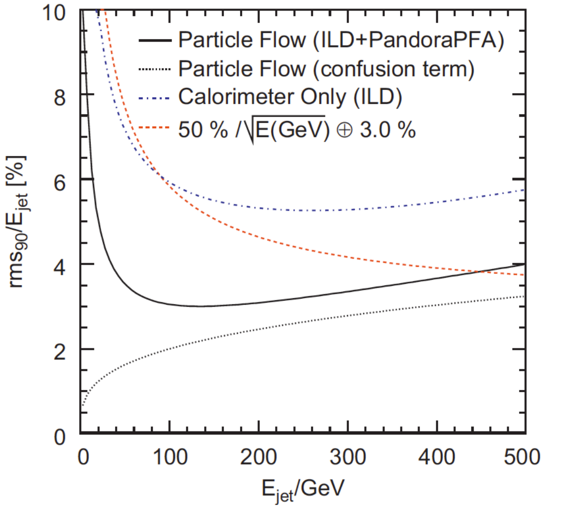
High granularity calorimetry: PFA

Components in jets	Sub-Detectors	Energy fraction (average) within a jet*	(Typical) Sub-detector Resolution
charged particles ($X^{\pm}$)	Tracker	~62% E_j	$10^{-4}E^2{}_X$
photons (γ)	ECAL	$\sim$27% E_j	$0.15\sqrt{E_\gamma}$
neutral hadrons (h)	ECAL+HCAL	$\sim$10% E_j	$0.55\sqrt{E_h}$

*Measurements of jet fragmentation at LEP (and ~1% by neutrinos)



- Particle Flow Algorithm (PFA)
  - To achieve unprecedented jet energy resolution of $\sim 30\%/\sqrt{\mathrm{E_{jet}}}$
    - Reminder: multiple particles within a jet
  - **Choose a sub-detector best suited for each particle type**
    - Charged particles measured in tracker
    - Photons in ECAL and neutral hadrons in HCAL
- Separation of close-by particles in the calorimeters
- PFA-oriented calorimeters: high granularity (1~10 million channels)



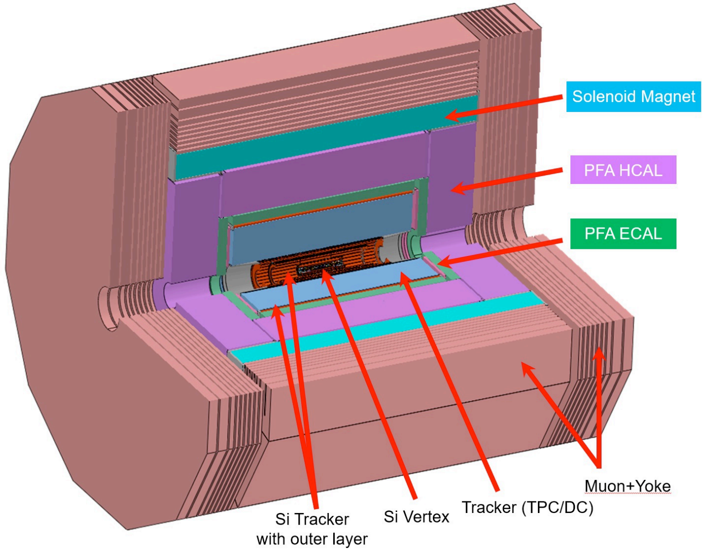
M.A. Thomson, NIM A 611 (2009) 25

High granularity calorimetry: new options

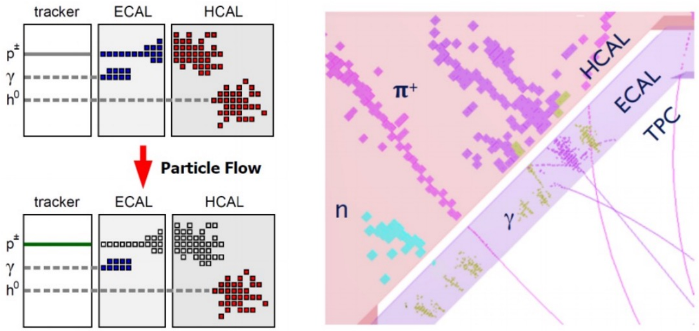
- Future lepton colliders: CEPC as an earliest possible option
  - Precision measurements: Higgs/W/Z bosons, top; BSM searches
  - PFA calorimetry: promising to achieve Boson Mass Resolution (BMR) < 4%

- High-granularity calorimeters with Particle Flow Algorithm
  - (New) Electromagnetic calorimeter with segmented crystals
    - Expect to provide 3D position + energy + time
    - Significantly improve EM energy resolution: $15\%/\sqrt{E}$ to $2\sim3\%/\sqrt{E}$
  - (New) Hadron calorimeter with glass tiles
    - Scintillating glass tiles (dense and bright): highly segmented
    - Hadron energy resolution from $60\%/\sqrt{E}$ (CEPC-CDR) to $30\sim40\%/\sqrt{E}$

CEPC 4th conceptual detector design



PFA-oriented calorimeters

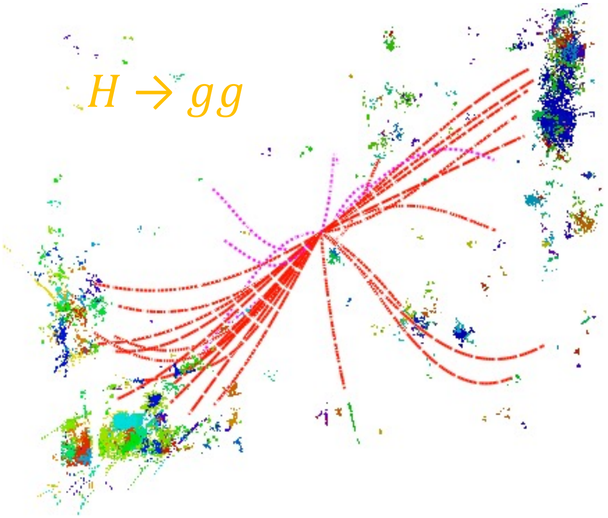


Higgs physics benchmarks

Baohua Qi, Dan Yu (IHEP), Zhiyu Zhao (SJTU)

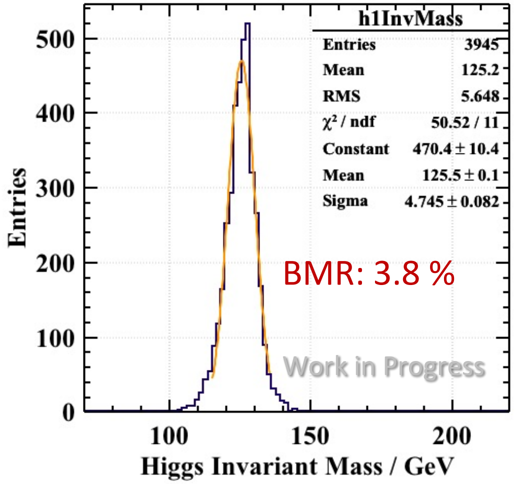
- Physics potentials with crystals
  - Photons and jets
- Boson Mass Resolution (BMR)
  - Jets ($H \rightarrow gg$): 3.8 % → 3.6%
  - Photons ($H \rightarrow \gamma\gamma$): 2.1% → 1.2%

Higgs to 2 gluon jets
(with crystal ECAL)



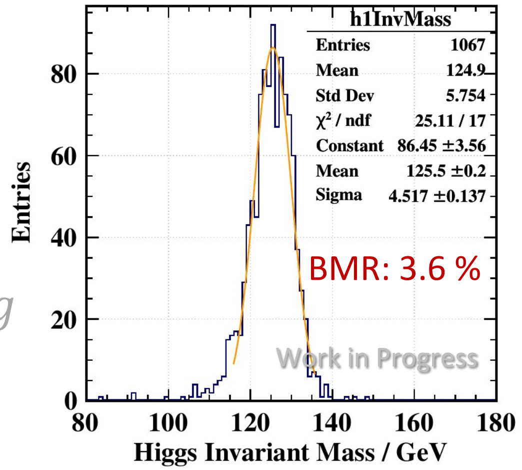
Note: ideal ECAL geometry with 1cm^3 BGO cubes

Detector with SiW-ECAL option

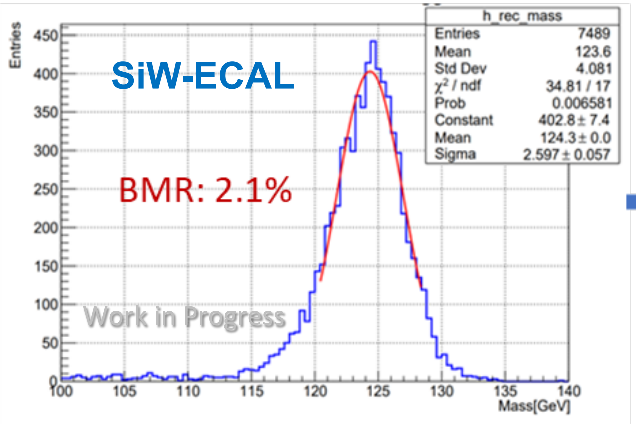


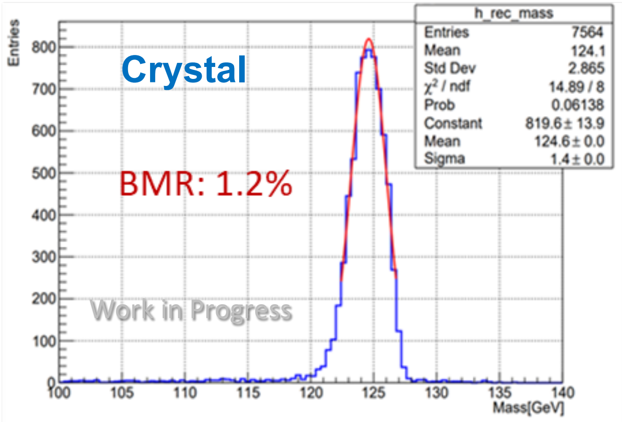
$H \rightarrow gg$

Detector with crystal ECAL option



BMR ($H \rightarrow \gamma\gamma$)





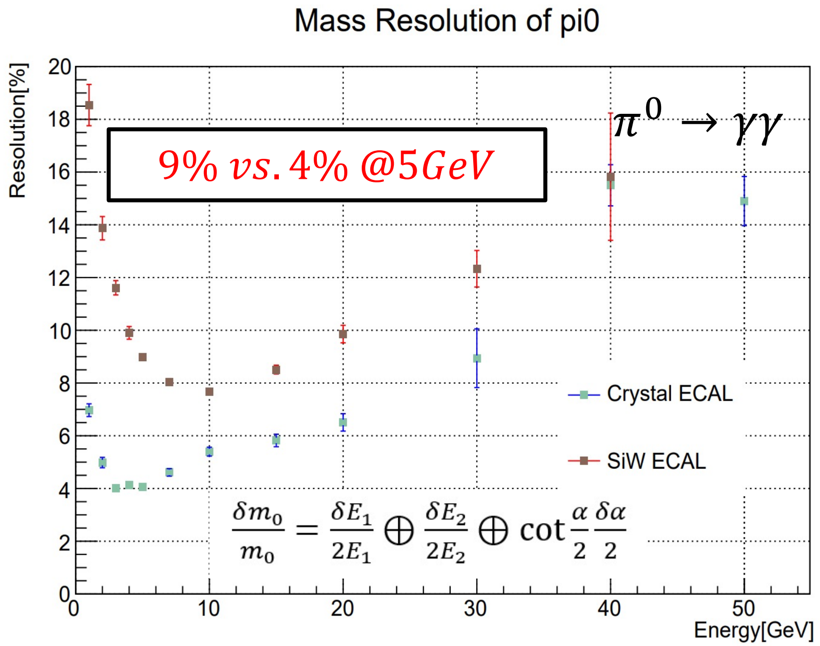
Flavor physics potentials

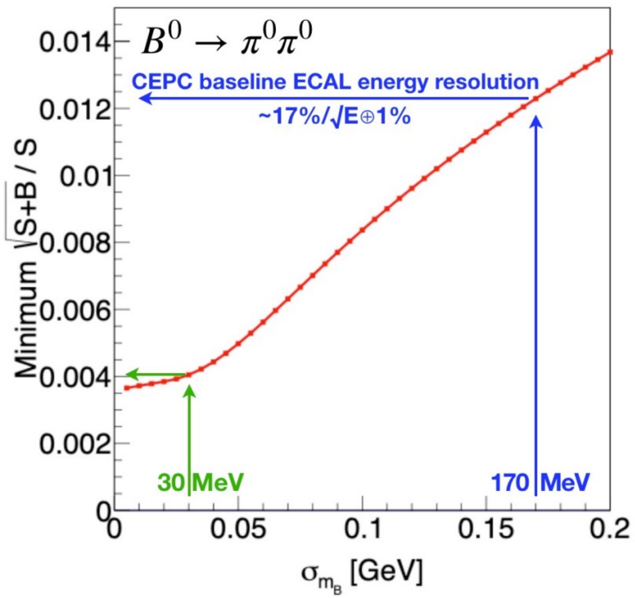
Zhiyu Zhao (SJTU), Yuexin Wang (IHEP)

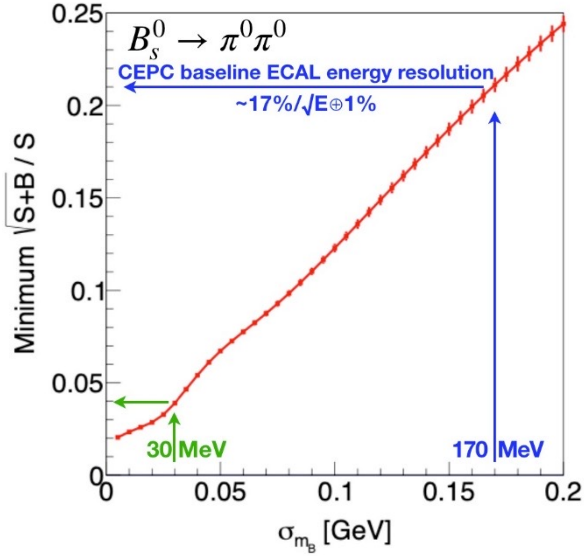
- Crystal ECAL
  - Higher sensitivity to photons and much better EM resolution
- Potentials for π^0/γ in flavor physics

B0 to pipi @CEPC(CEPC Flavor Physics/New Physics/Detector Technology Workshop, Fudan, 2023), Yuexin Wang

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







Note: ideal ECAL geometry with 1cm^3 BGO cubes

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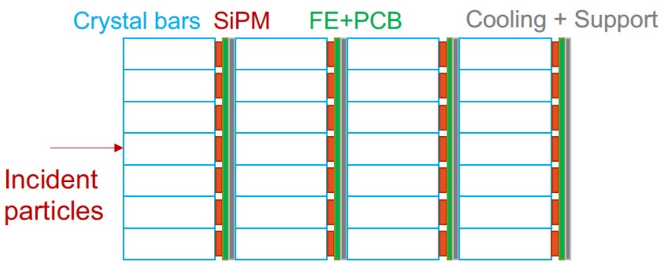
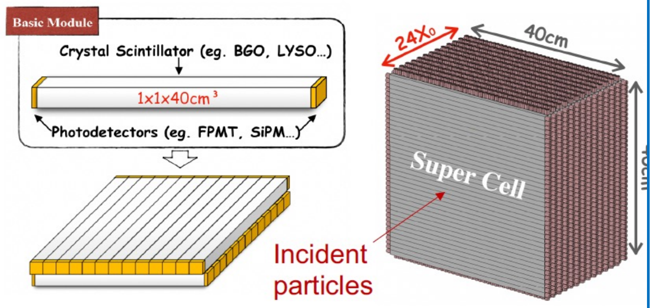
High-granularity crystal calorimeter

Design 1: short bars



- A natural design compatible with PFA
  - Fine segmentation in Both longitudinal and transverse
  - Single-ended readout with SiPM

Design 2: long bars



- Long bars: 1×40cm, double-sided readout
  - Super cell module: 40×40cm
  - Crossed arrangement in adjacent layers
  - Fine longitudinal granularity
- Save #channels and minimize dead materials
- Timing at two sides: positioning along bar

Key Parameters	Value
MIP Response	~200 p.e./MIP
Dynamic Range	$0.1 - 10^3$ MIPs
Energy Threshold	0.1 MIP
Timing Resolution	o(100) ps
Response Non-uniformity	<1%
Temperature Stability	Stable at ~0.05 ℃
Tolerances	~100 µm

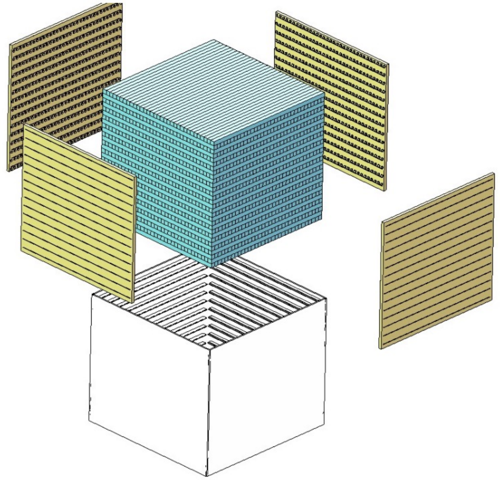
- Designs and specifications
  - Based on G4 simulation and digitisation for crystal-SiPM
  - Low threshold desirable for optimal EM resolution
  - Stringent requirement on dynamic range
  - Timing: as an extra dimension to calorimetry
  - Need validation studies with ***prototyping*** and ***testbeam***

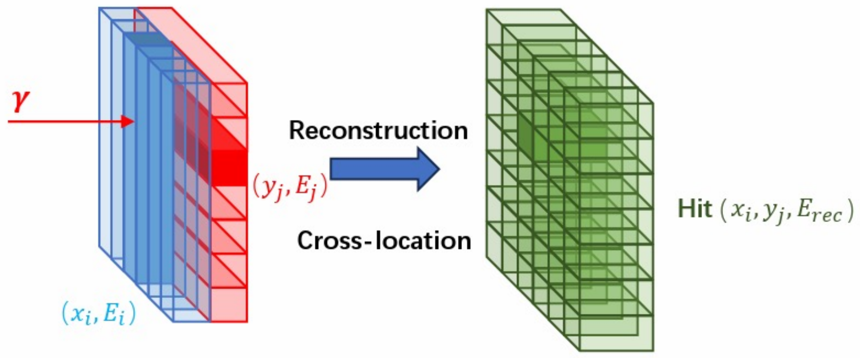
(New) ***Stereo Crystal Calorimeter***
Talk by Huaqiao Zhang (IHEP) in this workshop

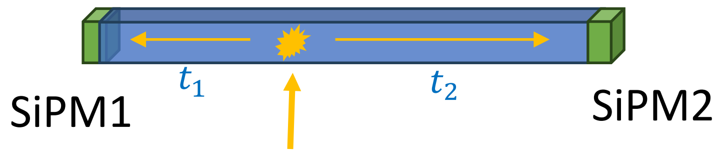
CEPC crystal calorimeter with long bars

- Long crystal bars in orthogonal arrangements
  - $1\times1\times40$ cm^3 crystal bars, double-side readout with SiPMs
  - Save readout channels and minimize dead materials
  - Achieve high granularity with information from adjacent layers
  - Positioning potentials with timing at two sides

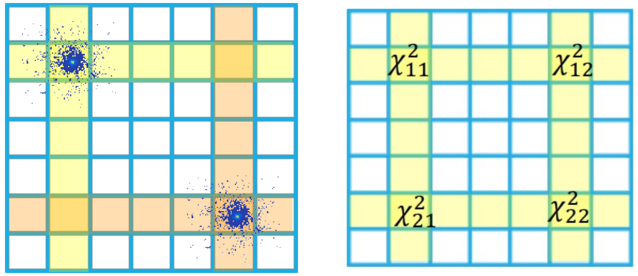
Module with 1×1×40 cm^3 crystals (schematics)







- Key issues and technical challenges
  - Integration of mechanics, cooling and electronics
  - Pattern recognitions with multiple particles (jets)

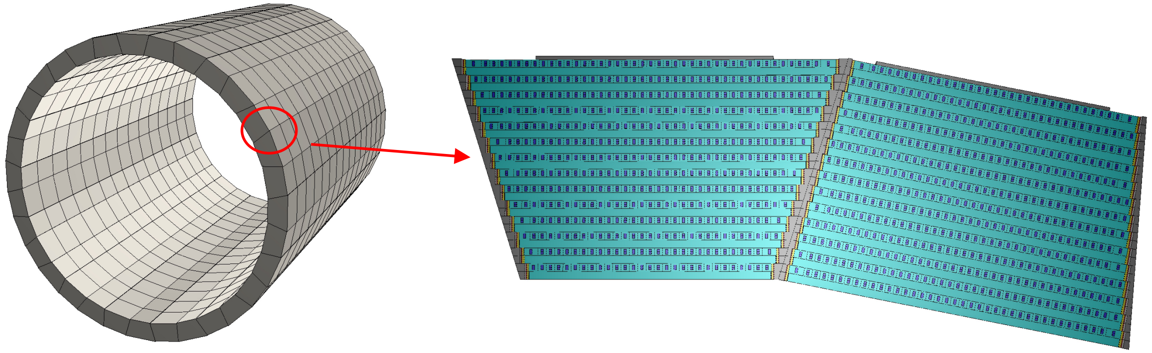


Ghost hits when 2 or more particles hit on one module

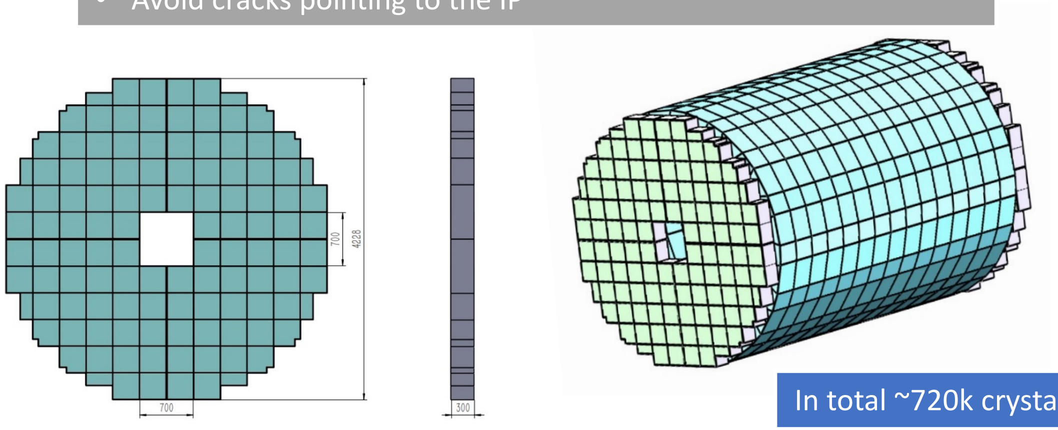
Long-bar crystal calorimeter: latest progress

Mechanics: Shaojin Hou, Quan Ji;
Software: Fangyi Guo, Shengsen Sun, Weizheng Song, Linghui Wu, Yang Zhang (IHEP); Zhiyu Zhao (TDLI)

- Mechanics: preliminary designs for barrel and endcaps
  - ~24 radiation length: BGO crystal 27 layers
  - Barrel: 32 towers per ring, 15 rings; endcap: 2×117 towers



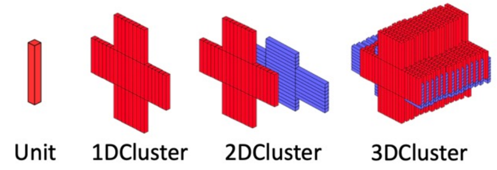
- Cylindrical barrel with alternately arranged trapezoidal supercells
- Avoid cracks pointing to the IP



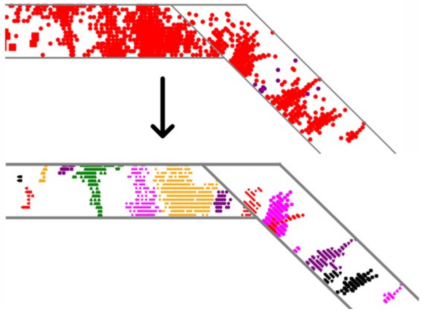
In total ~720k crystals

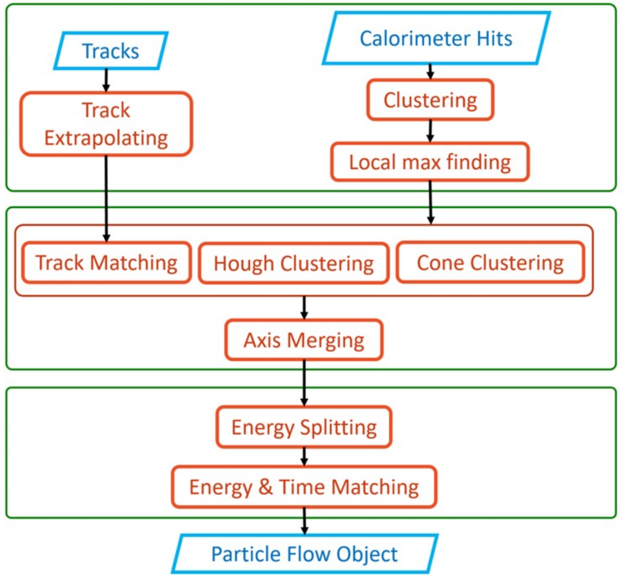
- Disc-shaped endcaps made up of square towers

- Dedicated reconstruction for long bar crystal ECAL
  - PFA reconstruction being developed in CEPCSW
  - Key issues: algorithm for long bar geometry for clustering separation and energy splitting



Clustering from crystal bars to 3D cluster

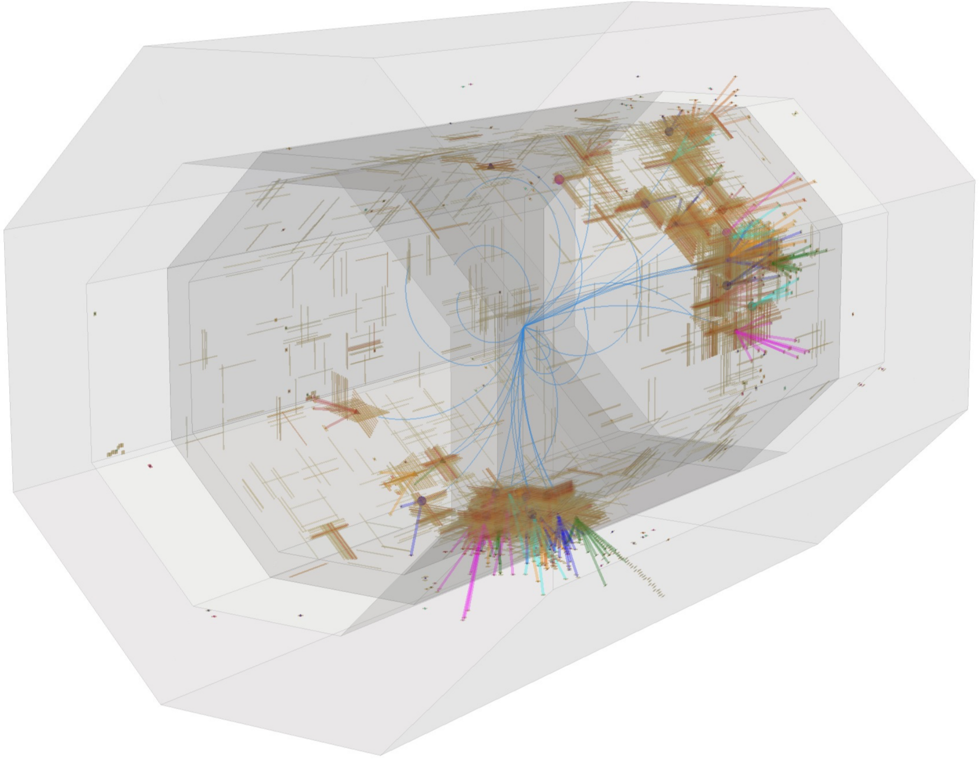




Particle flow algorithm for long crystal bar electromagnetic calorimeter *(CALOR2024 talk)*

Long-bar crystal calorimeter: preliminary results

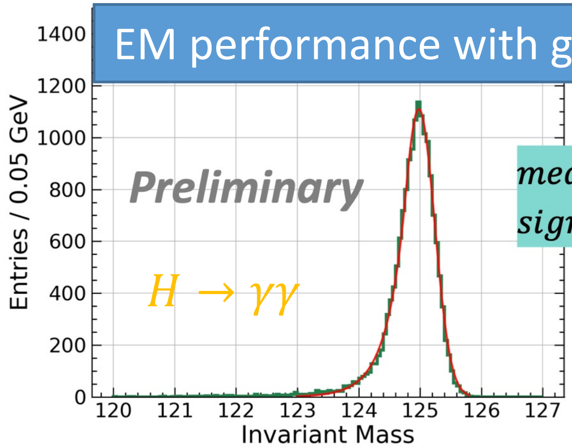
Software: Fangyi Guo, Shengsen Sun, Weizheng Song, Linghui Wu, Yang Zhang (IHEP); Zhiyu Zhao (TDLI)



- Latest progress: promising for BMR<4%
- Plan: full detector integration into CEPCSW

Particle flow algorithm for long crystal bar electromagnetic calorimeter (CALOR2024 talk)

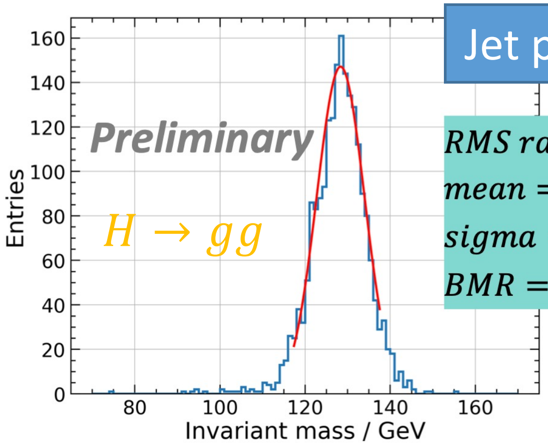
EM performance with gamma's



$mean = 124.9814 \pm 0.0028\ GeV/c^2$

$sigma = 0.2570 \pm 0.0031\ GeV/c^2$

Jet performance with gluon jets



$RMS\ range{:}\ 117.37 \sim 137.53\ GeV/c^2$

$mean = 128.33 \pm 0.16\ GeV/c^2$

$sigma = 5.59 \pm 0.17\ GeV/c^2$

$BMR = 4.36 \pm 0.13\ \%$

Only with idea geometry setup: mechanics, cooling, SiPM/crystal digitisation → to be implemented

Specifications

Key Parameters	Value	Remarks
MIP light yield	~200 p.e./MIP	Ensure EM resolution better than $2\%/\sqrt{E(GeV)}$
Dynamic range	0.1 - 10^3 MIP/channel	Deposited energy up to ~10 GeV per crystal
	(1 - 10^5 p.e./channel)	(With single photon calibration)
Energy threshold	0.1 MIP	Dependent on MIP Signal-to-Noise Ratio
Timing resolution	~400 ps @ 1 MIP	Geant4 simulation; ~100ps desired for position rec.
Crystal non-uniformity	< 1%	Calibration precision
Temperature stability	Stable at ~0.05 °C	CMS ECAL (PWO_4)
Gap tolerance	~100 µm	Crystal calorimeter prototype

- Detector design
- Mechanics + cooling
- Reconstruction software
- Prototyping + beam tests

Performance requirements

- Moderate MIP light yield
- Good response uniformity
- Optimal time resolution
- Large dynamic range
- *Solutions to radiation issues*

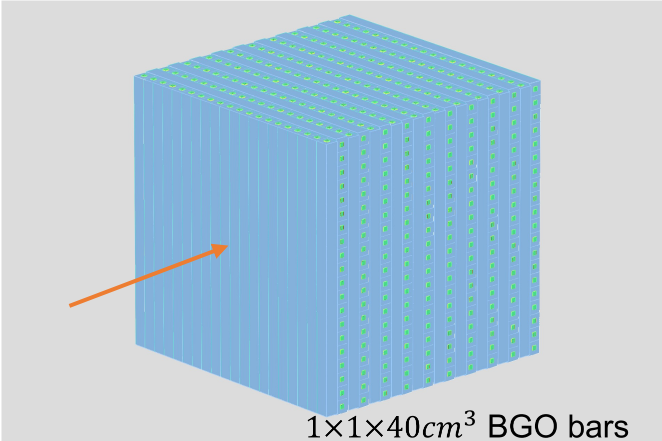
Hardware activities: addressing crucial issues

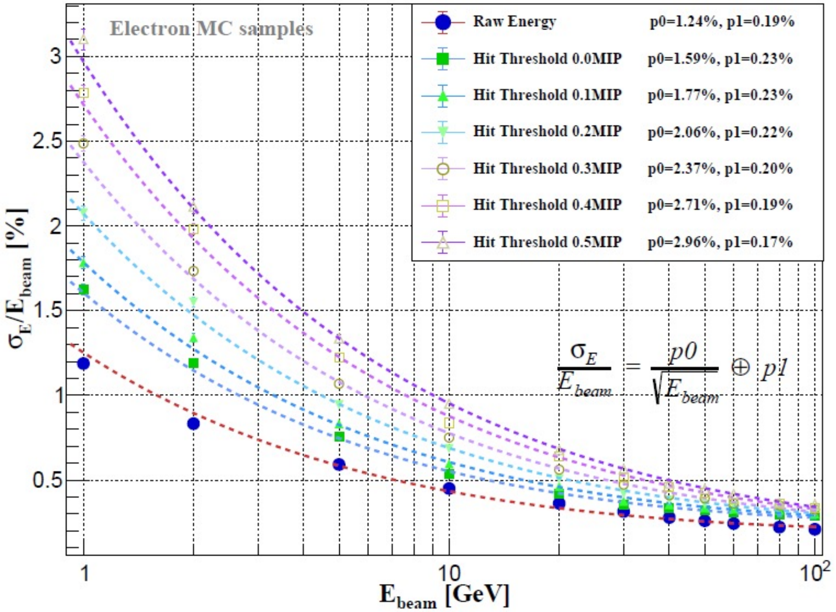
- SiPM response linearity
- Uniformity of long crystal bar
- Time resolution: different crystal dimensions/signals
- Dynamic range of electronics
- Energy response of crystal module
- *Mitigation/calibration schemes for radiation damages*

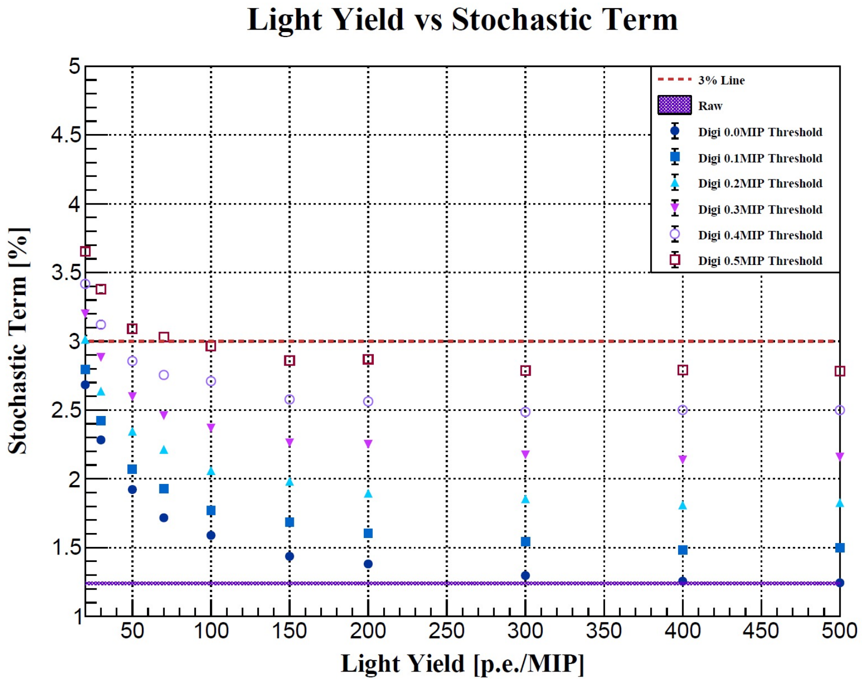
EM Energy Resolution: threshold and MIP response

- EM Energy Resolution: impacts of energy threshold and MIP response
  - Geant4 with digitization: photon statistics (crystal + SiPM), electronics resolution
  - Photon statistics: 200 p.e./MIP sufficient for $3\%/\sqrt{E}$
  - Low energy threshold (0.1MIP) promising to achieve $1.6\%/\sqrt{E}$

Geant4 Simulation (v10.7)







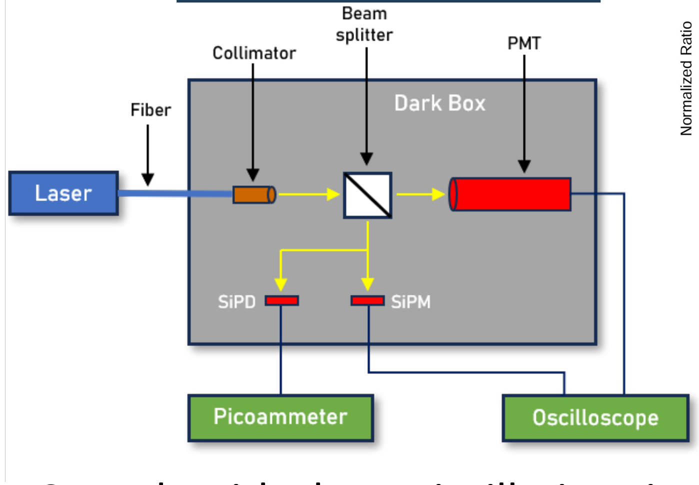
SiPM response linearity: laser tests and simulation

Zhiyu Zhao (TDLI/SJTU)

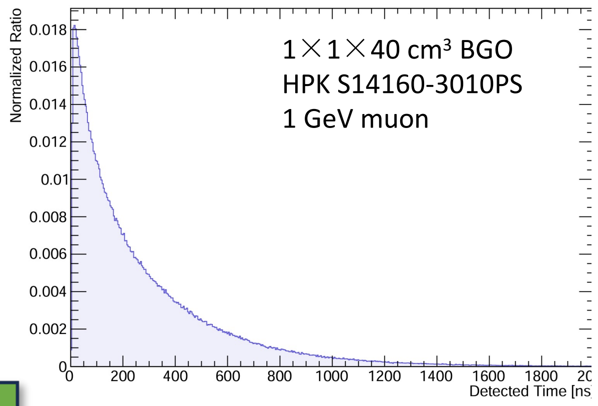
- SiPM candidates: 3×3 mm^2 (6/10 μm pixel pitch)

1. (Intrinsic) Dynamic range tests
   - Pico-second laser: incident photons within ~3ps
   - PMT: reference measurements for laser intensity
2. Toy Monte Carlo simulation
   - Effect from crystal light decay time
   - Recovery of SiPM pixels

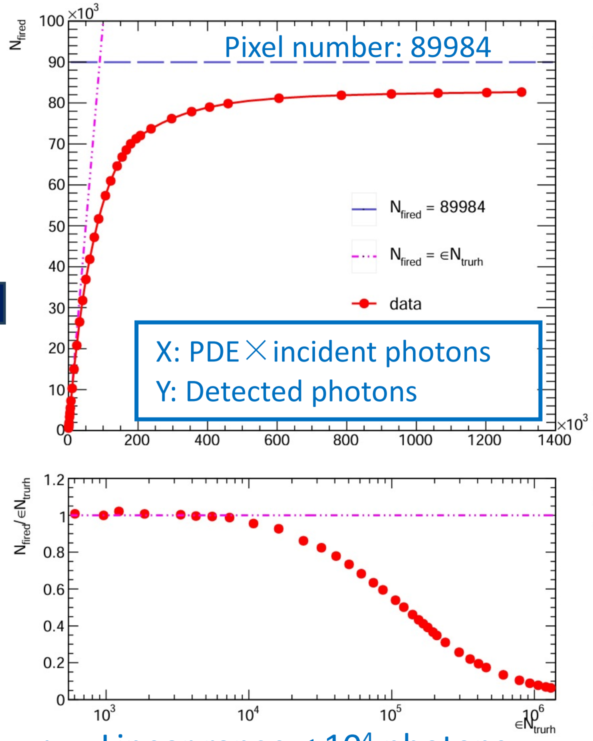
Laser test setup



Geant4 simulated photon detection time

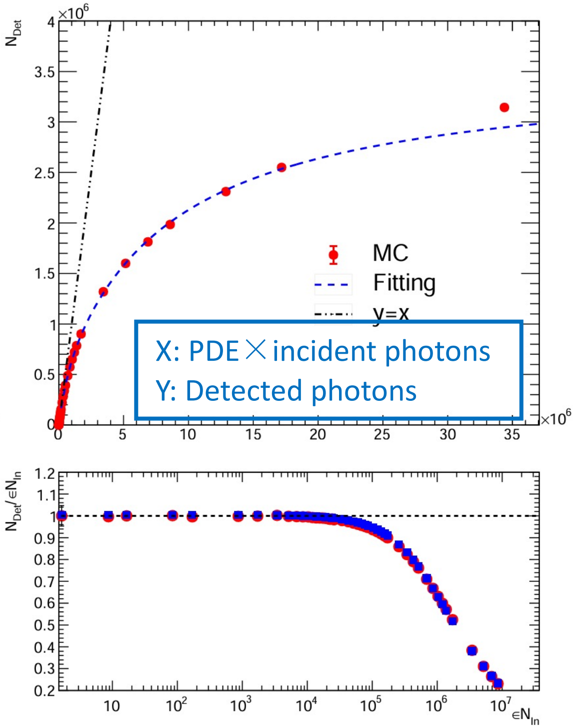


Experiment: Laser + SiPM



- Linear range < 10^4 photons
- Response plateau is close to but smaller than pixel number

Simulation: BGO + SiPM



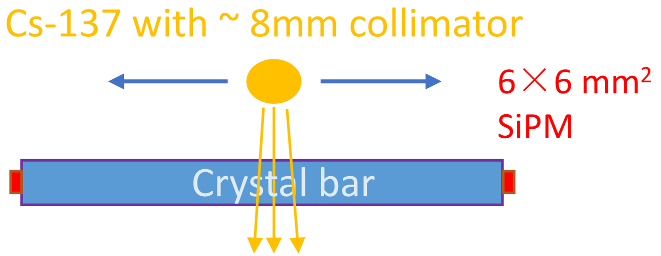
- Recovery effect contributes to a wider linear range

- Crystals with slow scintillation time like BGO
  - SiPM non-linearity: mitigated with fast SiPM pixel recovery
- SiPM with higher pixel density: NDL SiPM (6μm) with ~250k pixels

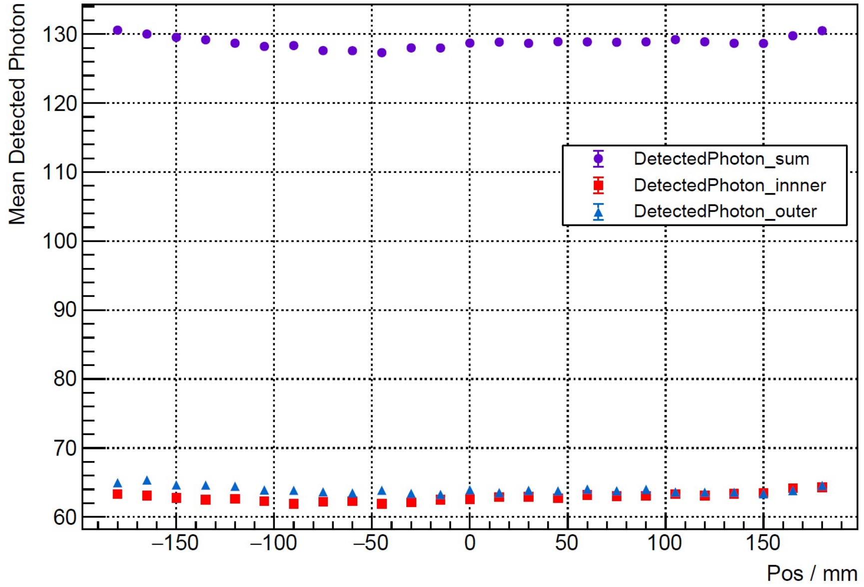
Study on the Dynamic Range of SiPMs with Large Pixel Number (CALOR 2024 talk)

Uniformity studies: BGO crystal bars

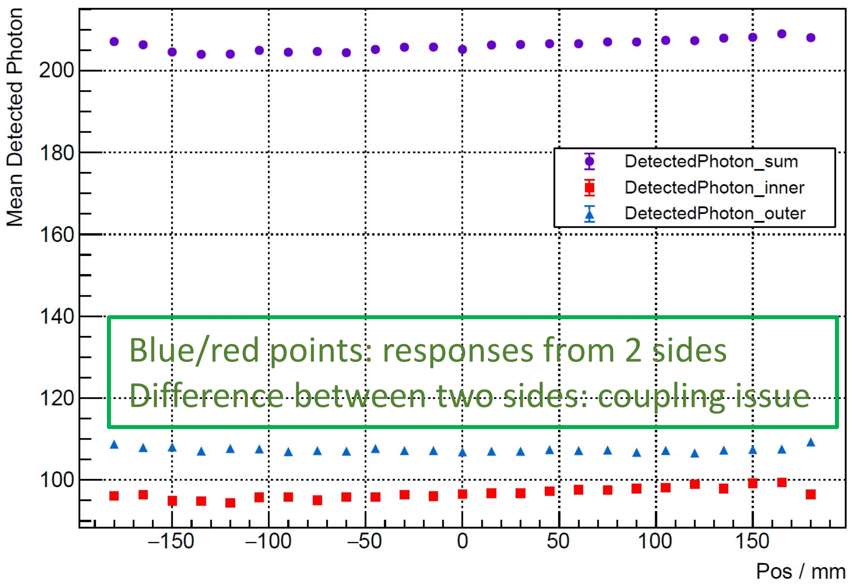
- 1×1×40 cm^3 BGO crystal with ESR wrapping
  - SiPM-crystal couple: air versus optical grease
- Scan with Cs-137 radioactive source (662keV gamma's)

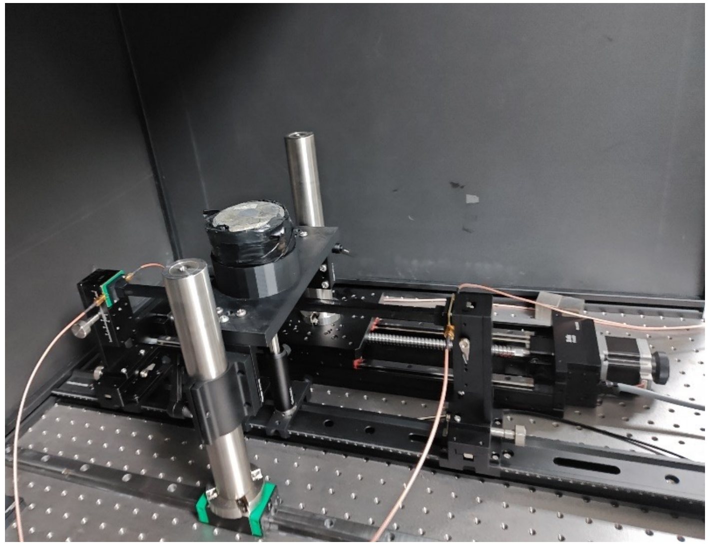


Response uniformity air-coupled



Response uniformity grease-coupled



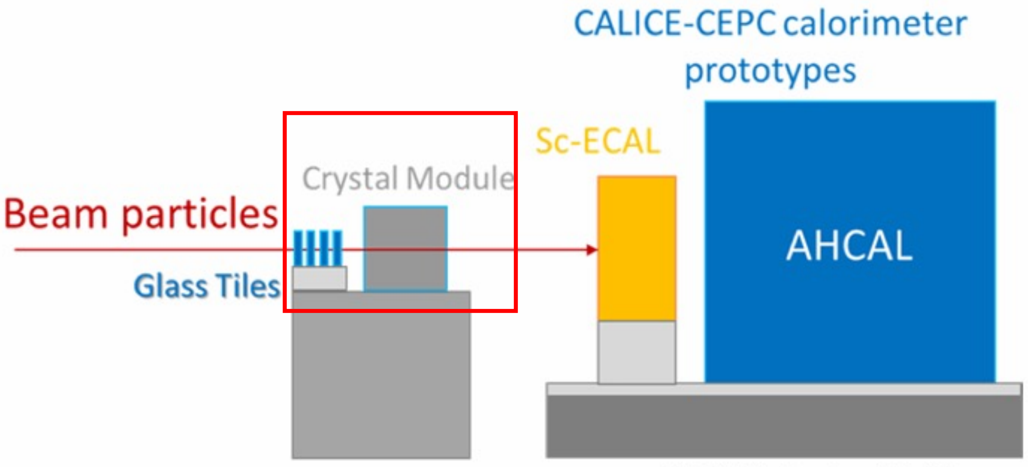


Automated crystal scan platform

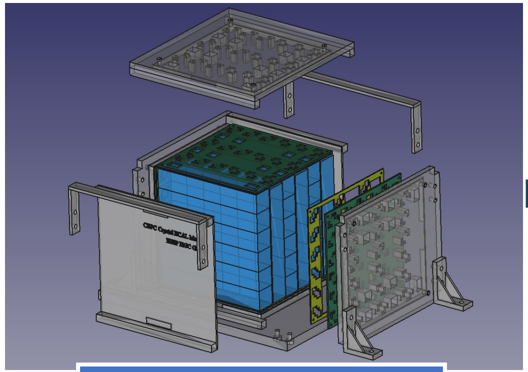
- Generally good uniformity at ~2.5% level along a single bar
- Optical grease coupling leads to 59% more response in p.e.
  - But grease coupling is difficult with good (systematic) control

Crystal modules and beam-test campaigns

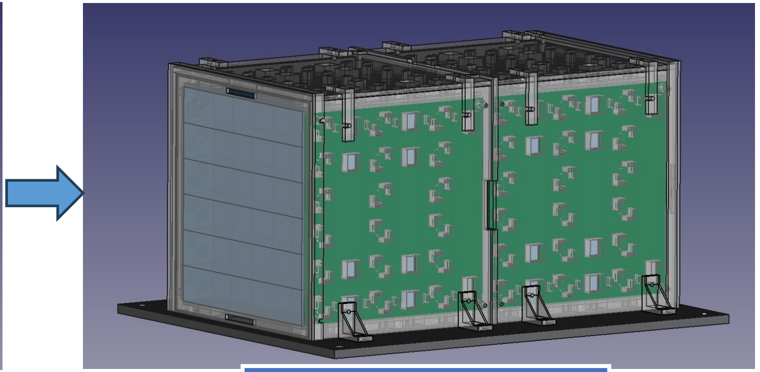
- Motivations
  - Identify and address critical issues at system level
    - Electronics, mechanics and readout PCBs
  - Evaluate EM performance with testbeam data
  - Validation of simulation and SiPM-crystal digitisation
- Beam-test at CERN T9 beamline in 2023
  - One module for commissioning and first parasitic tests
  - Muon (10 GeV) and electron beams (0.5 – 5 GeV)
- Beam-test at DESY TB22 beamline in 2023
  - Two modules for EM performance studies
  - Electron beams: 1 – 6 GeV



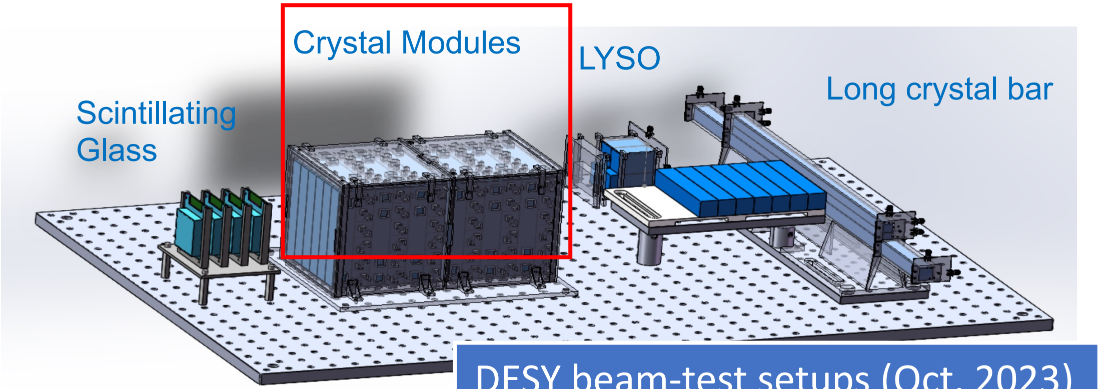
CERN beam-test setups (May 2023)



72 channels , $10.7X_0$



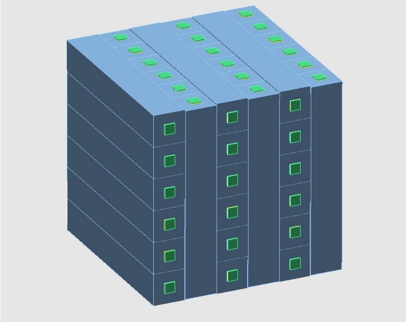
144 channels, $21.4X_0$

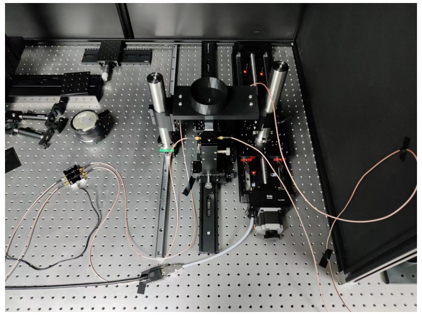


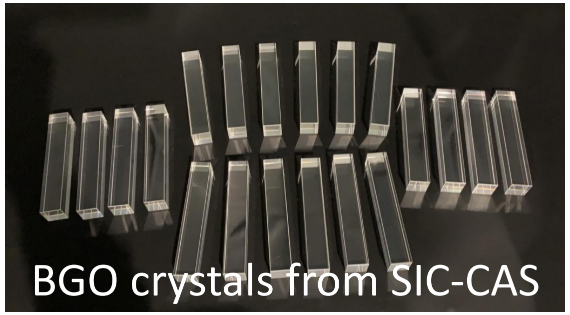
DESY beam-test setups (Oct. 2023)

Crystal calorimeter: module developments

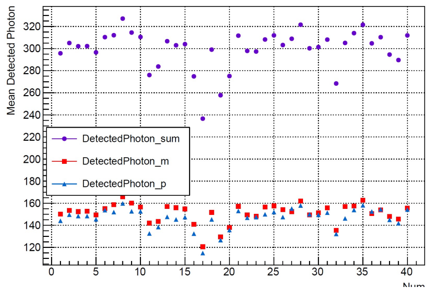
Baohua Qi (IHEP)



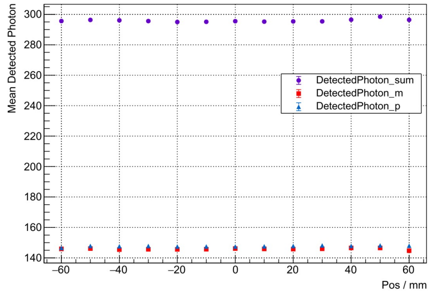


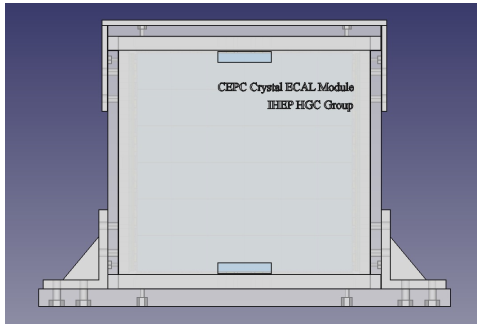


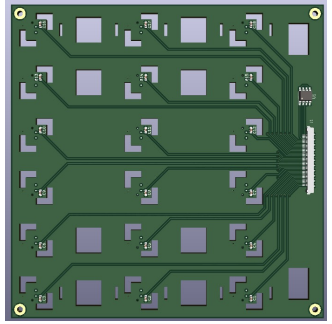
Uniformity of 40 crystal bars

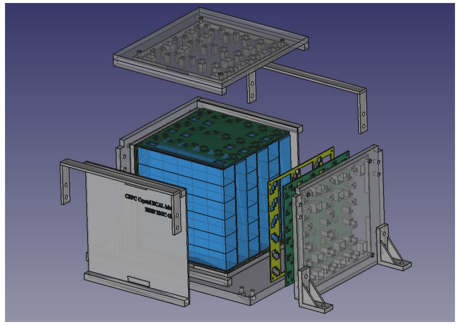


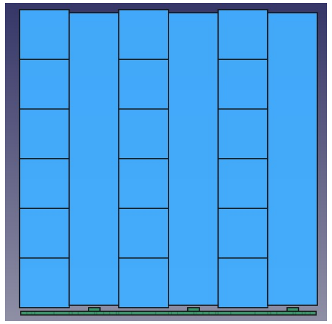
Uniformity along a crystal bar







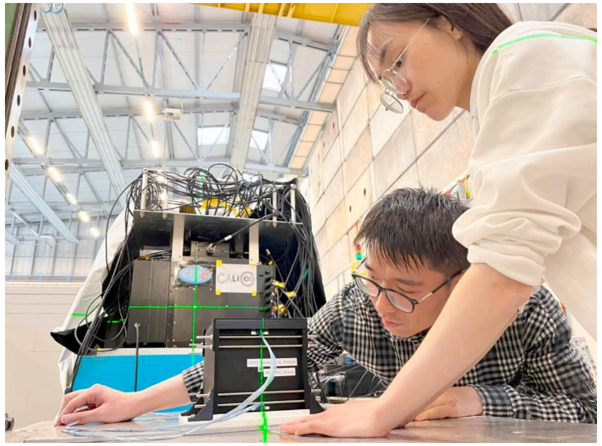


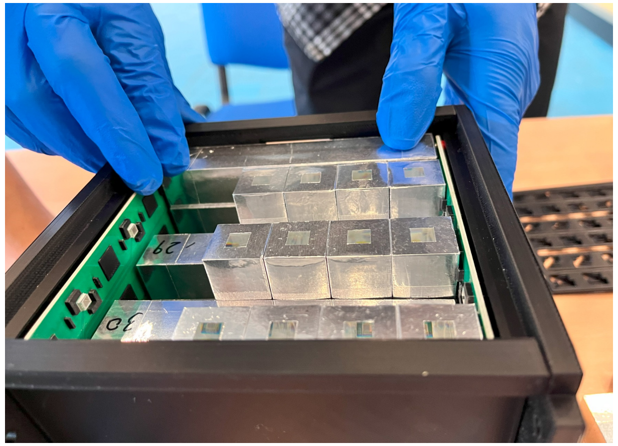


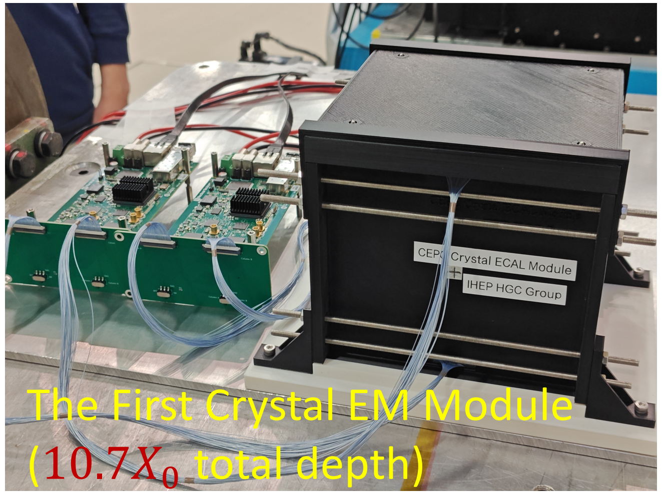
- **First crystal module**: successfully developed in 2022-2023
  - To address key issues on system integration
    - 3D printed supporting structures, readout boards/chips
  - Developed dedicated test stands for crystal uniformity studies
  - To evaluate EM performance with testbeam data

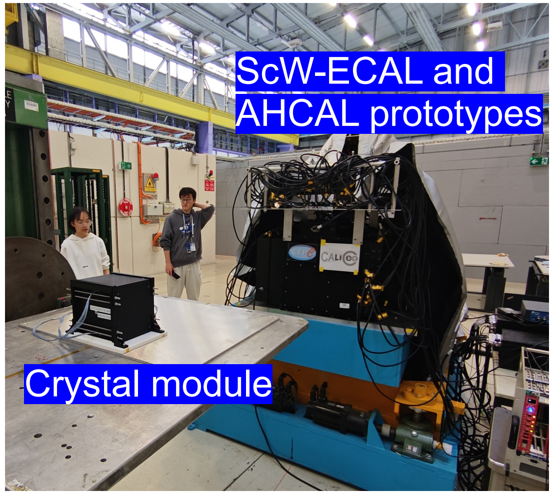
First crystal module in 2023 CERN beamtest

CERN beamtest: parasitic runs at PS-T09 (May 16-23, 2023)

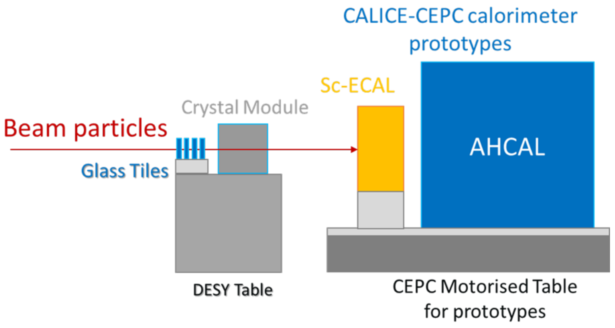




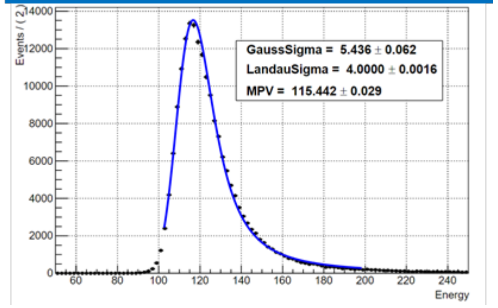




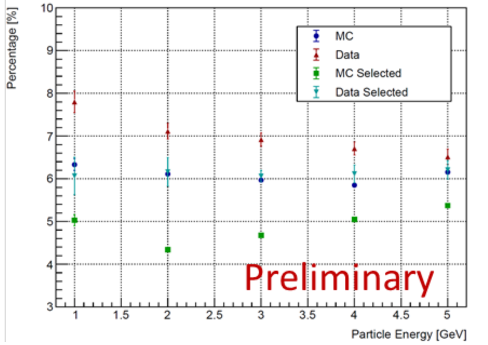
Combined beamtests with CEPC calorimeter prototypes



MIP calibration with muons

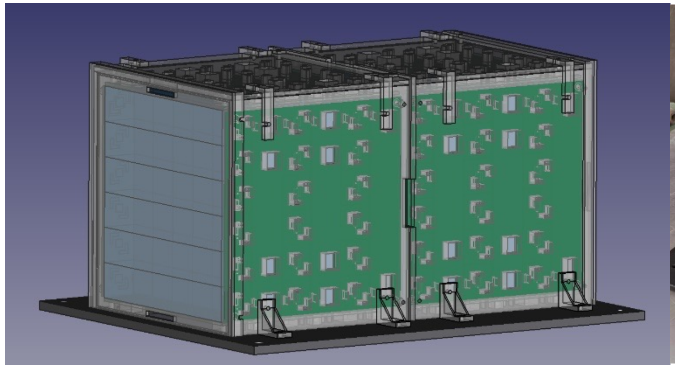


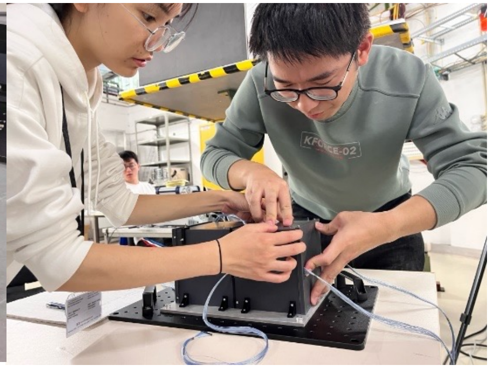
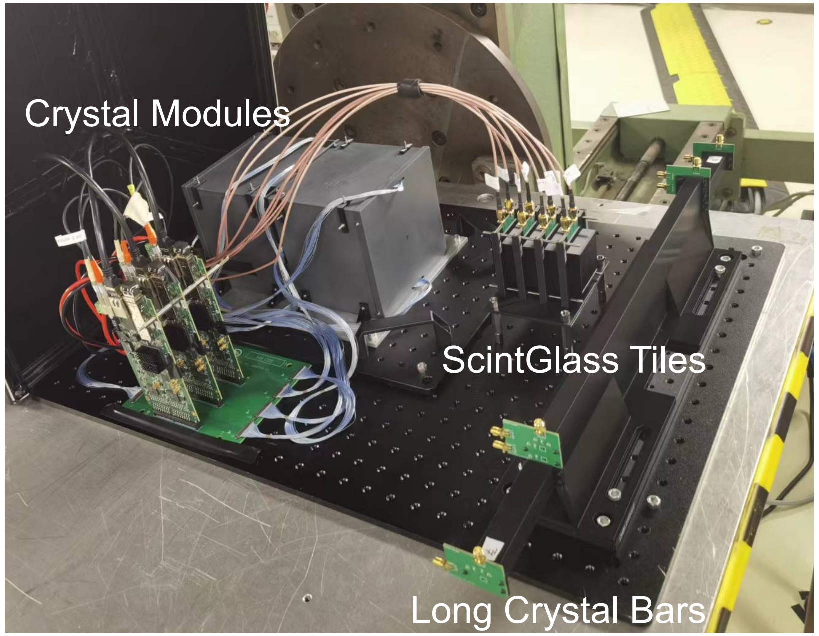
EM resolution: MC vs data

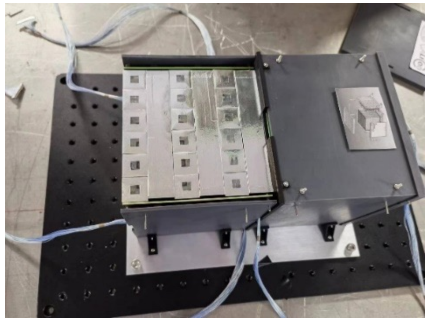
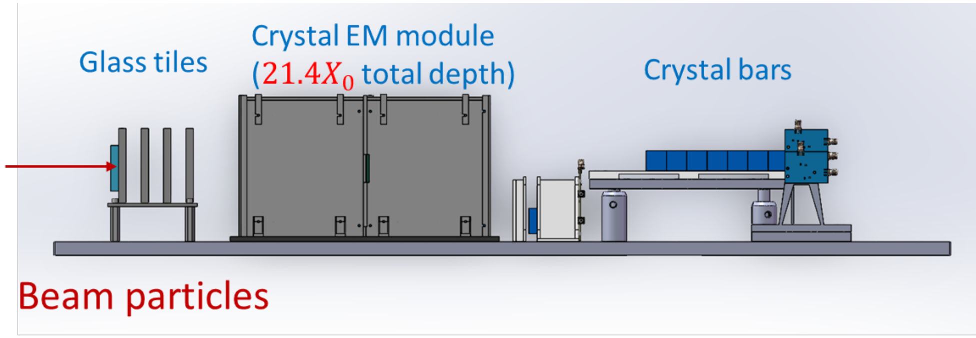


- Successful beamtest with the crystal module
  - 15 GeV muons for MIP calibration: all 72 channels
  - 1-5 GeV electrons for EM shower studies
  - Data sets for validation of simulation + digitisation

DESY beamtest in October 2023

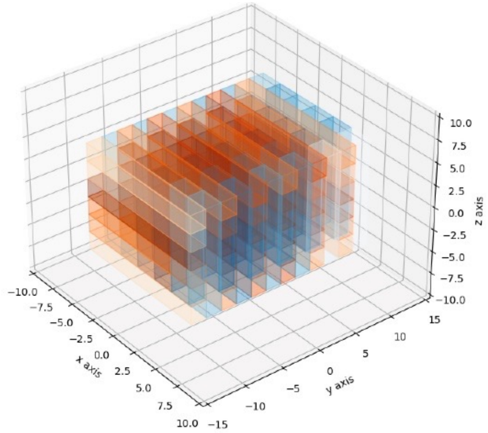


Beamtest at DESY TB22 (Oct. 2-15, 2023)

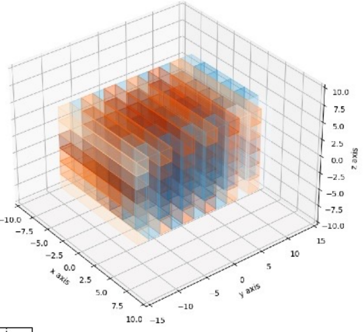
- DESY TB22 electron beam (1-6 GeV) to study new prototype and key components
  - Physics Prototype of Crystal Calorimeter ($21X_0$): system integration, EM performance
  - Long crystal bars (40/60cm): timing resolution
  - A new SiPM-ASIC (32-ch): single photon spectrum, dynamic range
  - The 2nd batch of tiles from the "Glass Scintillator Collaboration" (4x4x1cm): MIP signals

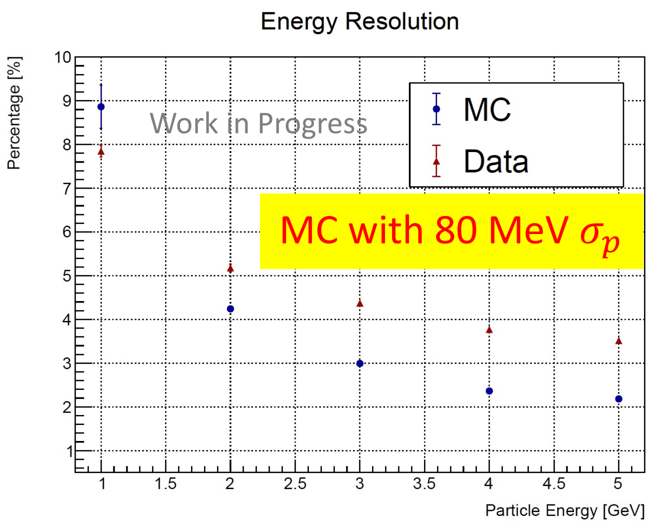


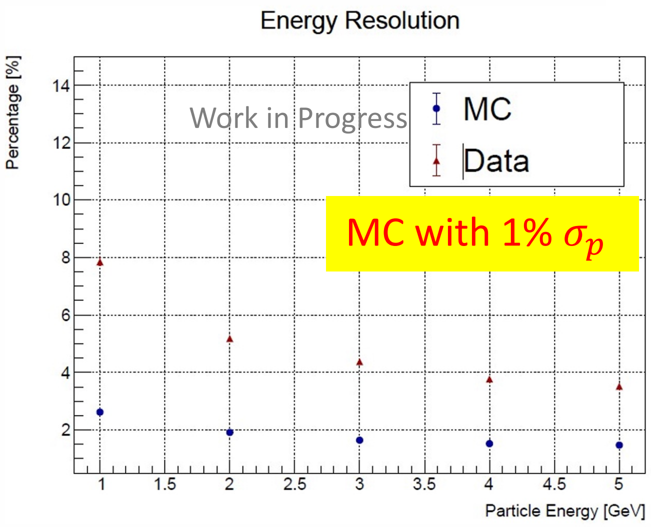
2023 DESY beamtest: EM performance of crystal modules

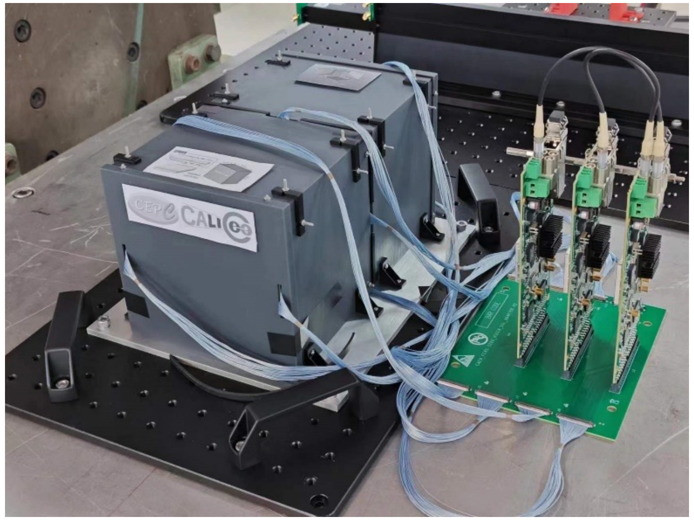
DESY TB22 beamline: $21.4X_0$ crystal module

- 1 cm^3 trigger cubes for beam particle collimation
- 1-6 GeV/c electrons: energy response
- Observed significant beam momentum spread







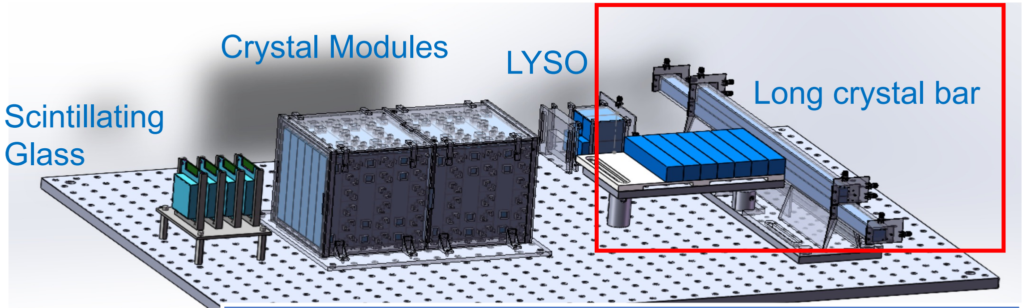


- EM resolution: significantly affected by beam momentum spread
  - No measurements of beam momentum spreads for DESY TB22
  - In-situ MIP calibration for each crystal channel: not possible at DESY
- Further beamtests at CERN PS
  - MIP calibration possible, significantly small momentum spread (~0.5%)

Beam-test scheduled in June 2024 at CERN PS-T09: further performance studies of crystal modules and validation of simulation + digitization

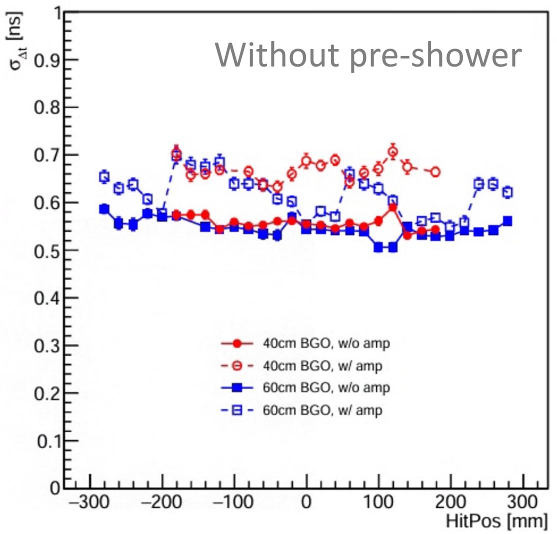
2023 DESY beam-test: time resolution

- (Quasi) 1-MIP response with 5 GeV/c electrons
  - 1×1×40 cm^3 and 1.5×1.5×60 cm^3 BGO crystal bars
  - 25 µm pixel SiPM, DAQ with 4-ch oscilloscope (1.25GS/s)

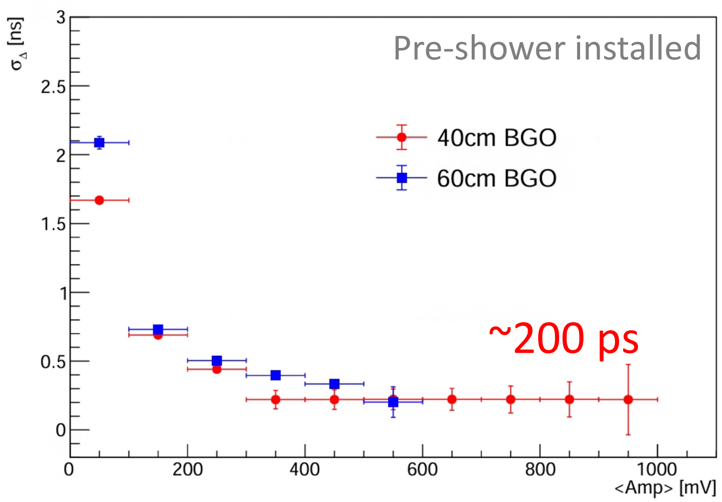


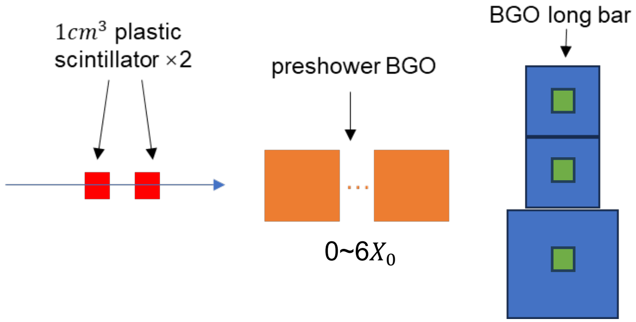
Overview of the 2023 DESY beam-test tasks

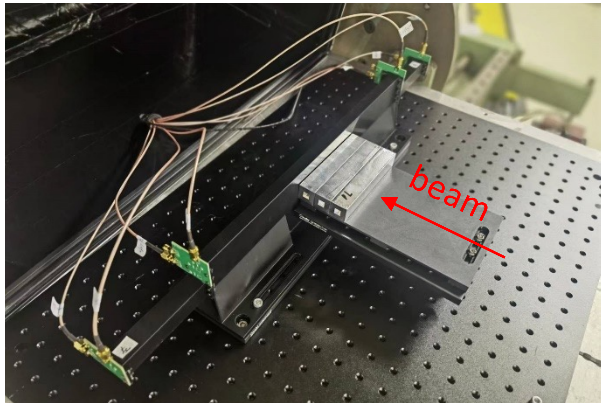
Time resolution: position scan



Time resolution vs signal amplitude



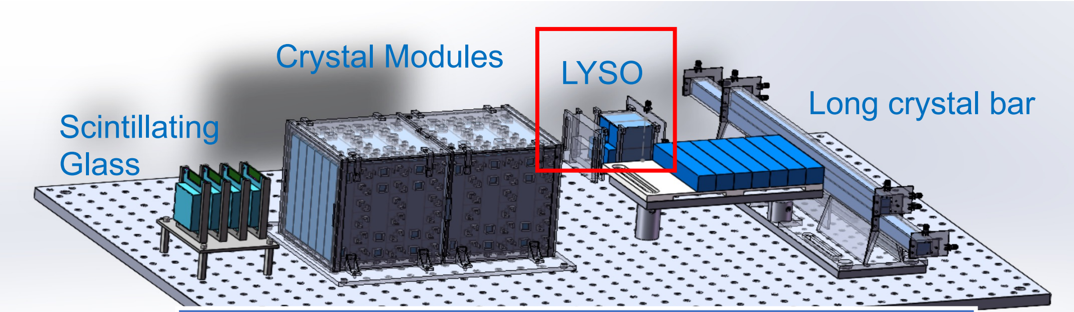




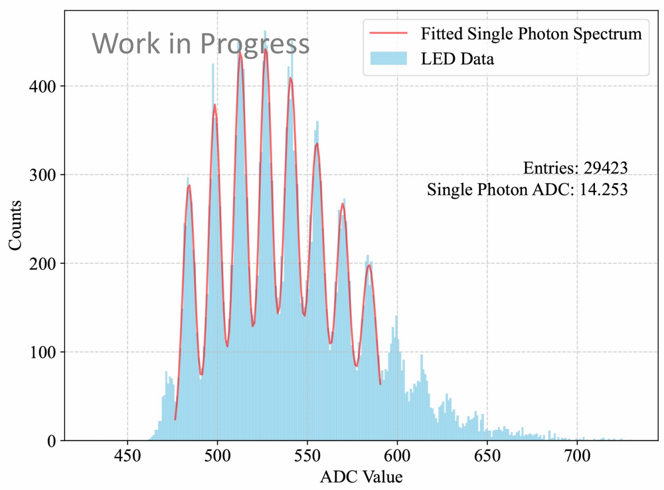
- Quasi 1-MIP time resolution: 500-600 ps (no significant position dependence)
- Time resolution varies with signal amplitude
  - Best timing result: 200 ps at shower maximum (close to DAQ timing limit)
  - 40 cm BGO with > 12 MIP signals
  - 60 cm BGO with > 20 MIP signals

2023 DESY beam-test: SiPM-ASIC studies

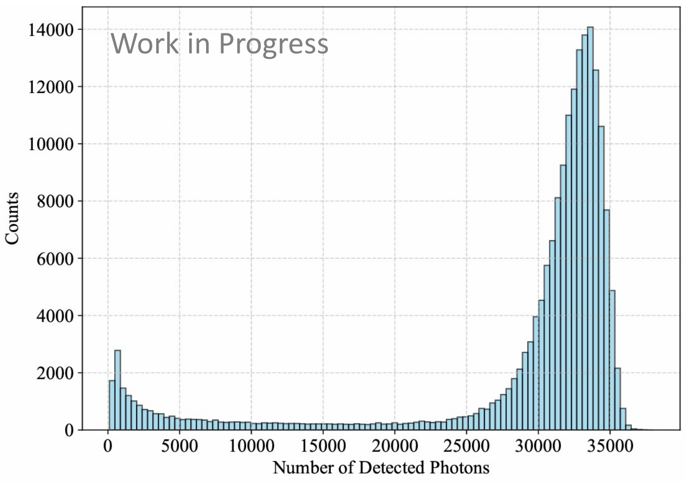
- Specs of state-of-art SiPM-readout chip (MPT-2321)
  - Capability of single photon calibration; up to 1.6 nC; 50 ps TDC
- 5 GeV/c electrons with LYSO crystals in SiPM readout
  - High S/N: single photoelectron calibration in high gain mode
  - Large dynamic range: up to 35k p.e. measured with 5cm LYSO



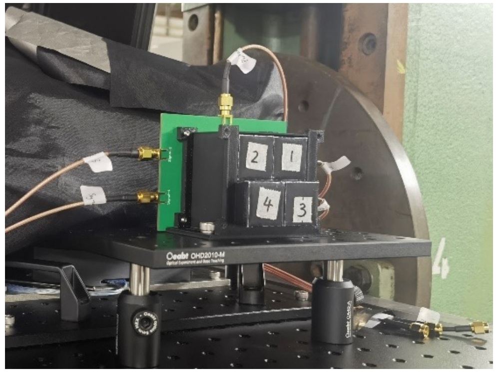
Overview of the 2023 DESY beam-test tasks

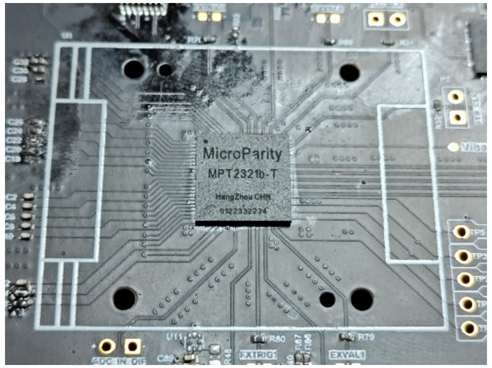


High Gain mode: good S/N for single photon calibration



Low Gain mode: capable to detect ~35k p.e. in LYSO crystals





- Dynamic range can be further extended: lower SiPM gain, shorter SiPM recovery time

Studies of a large dynamic range SiPM readout ASIC MPT2321-B (CALOR2024 poster)

CEPC crystal calorimeter: future R&D activities

- ECFA DRD-on-Calorimetry (DRD6) collaboration
- Subtask 3.1.1:"*High-Granularity Crystal Calorimeter*" (HGCCAL)

Extracted from ECFA DRD6 proposal

Project	Calorimeter type	Scintillator/WLS	Photodetector	DRDTs	Target
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters					
HGCCAL	EM / Homogeneous	BGO, LYSO	SiPMs	6.1, 6.2	e^+e^-
MAXICC	EM / Homogeneous	PWO, BGO, BSO	SiPMs	6.1, 6.2	e^+e^-
Crilin	EM / Quasi-Homog.	PbF_2, PWO-UF	SiPMs	6.2, 6.3	$\mu^+\mu^-$

5.2.1 Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters

- Subtask 3.1.1: The *H*igh-*G*ranularity *C*rystal *Cal*orimeter (**HGCCAL**) [15] is a homogeneous calorimeter with high transverse and longitudinal segmentation based on $1 \times 1 \times 40$ cm^3 crystal bars arranged in a grid structure with double-ended SiPM readout. The calorimeter is optimised for event reconstruction based on particle flow algorithms (PFA) to achieve about a $3\%/\sqrt{E}$ resolution for electromagnetic showers and a $30\%/\sqrt{E}$ energy resolution for jets, crucial for the physics programs of future e^+e^- colliders.
  Key R&D required: Mechanical design and integration, development of an EM shower-scale prototype.

Welcome wider and depper collaborations!

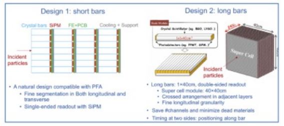
Phillipp Roloff, "WP3: Optical calorimeters" at DRD6 Collaboration Meeting (Apr. 2024)

Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters

HGCCAL:
- Homogeneous ECAL with longitudinal segmentation targeting PFA
- Crystal bars arranged in grid structure with double-ended SiPMs

High-Granularity Crystal Calorimeter (HGCCAL)

- HGCCAL proposed for future Higgs e^+e^- factories
  - Optimal EM resolution: 2~3%/√E
  - Fine segmentations for particle-flow algorithm
- Two designs and features
  - Short crystals: compatible with PFA
  - Long crystals: minimize dead materials, readout channels
- Challenges
  - Short crystals: integration (**light-weighted** materials of *mechanics, cooling* and *readout boards*)
  - Long crystals: **pattern recognition** (ambiguity issues)
  - Common
    - Large **dynamic range** for SiPM + ASIC
    - Front-end ASIC: **low-power** (millions of channels), continuous readout (**high rate** at circular colliders)



DRD 6: Calorimetry (CERN-DRDC-2024-004)

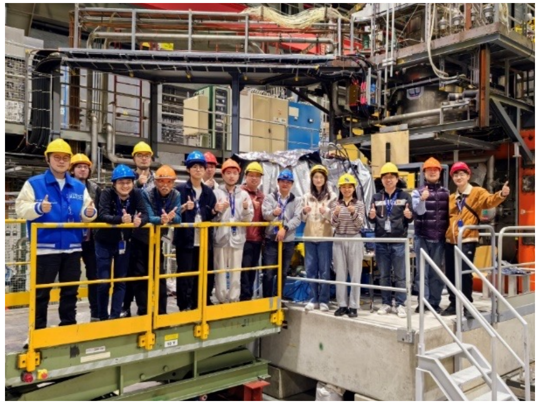
HGCCAL team: IHEP, SIC-CAS, SJTU, TDLI, USTC

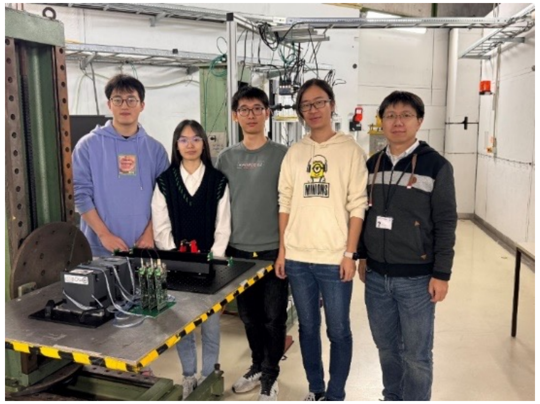
3/5/2024 Yong Liu (liuyong@ihep.ac.cn) ECFA DRD6 WP3 First Meeting: HGCCAL Status and Plans 2

09/04/2024 WP3: Optical calorimeters Philipp Roloff 4

Summary and prospects

- High-granularity crystal calorimeter: a new option for CEPC
  - Steady progress: simulation, reconstruction, mechanics and module prototyping
  - Successful beamtest campaigns at CERN and DESY in 2023
  - Extensive studies and discussions: ongoing for CEPC reference detector TDR
- Further R&D activities
  - International collaborations: e.g. ECFA DRD-on-Calorimetry (DRD6)
  - Future CERN beamtest campaigns: crucial to performance and validation studies



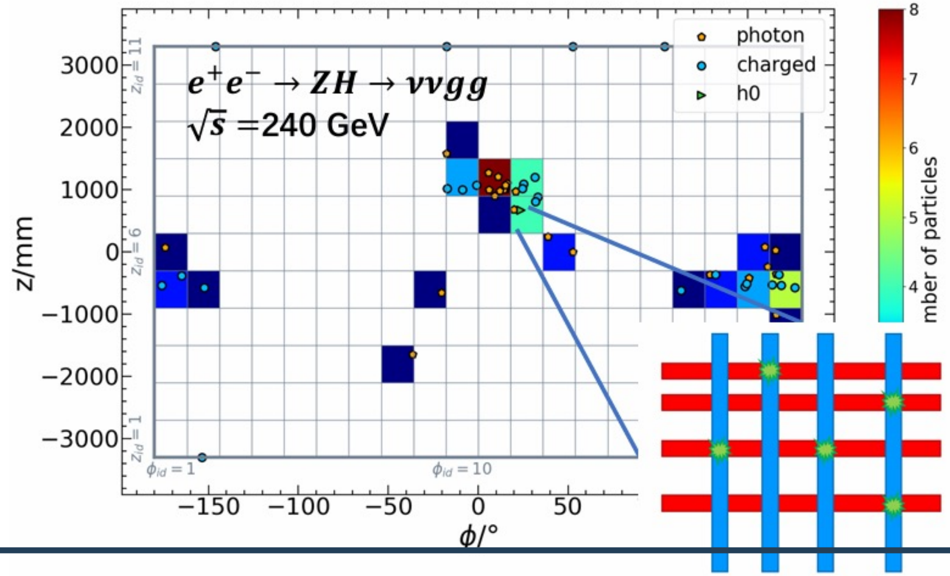



Acknowledgments: enormous and substantial support from CERN, DESY and CALICE

Backup Slides

PFA Reconstruction Algorithm for long-bar layout

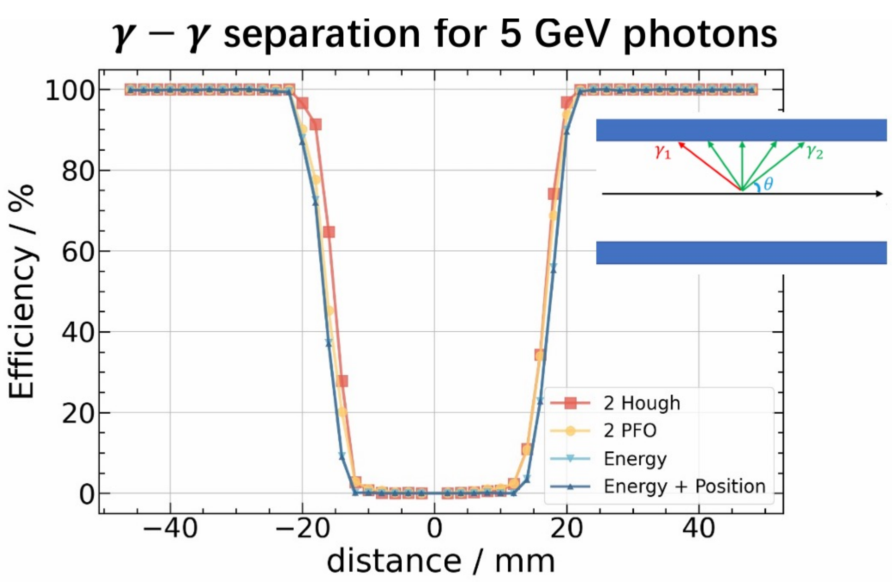
Multi-particle ambiguity in jet event

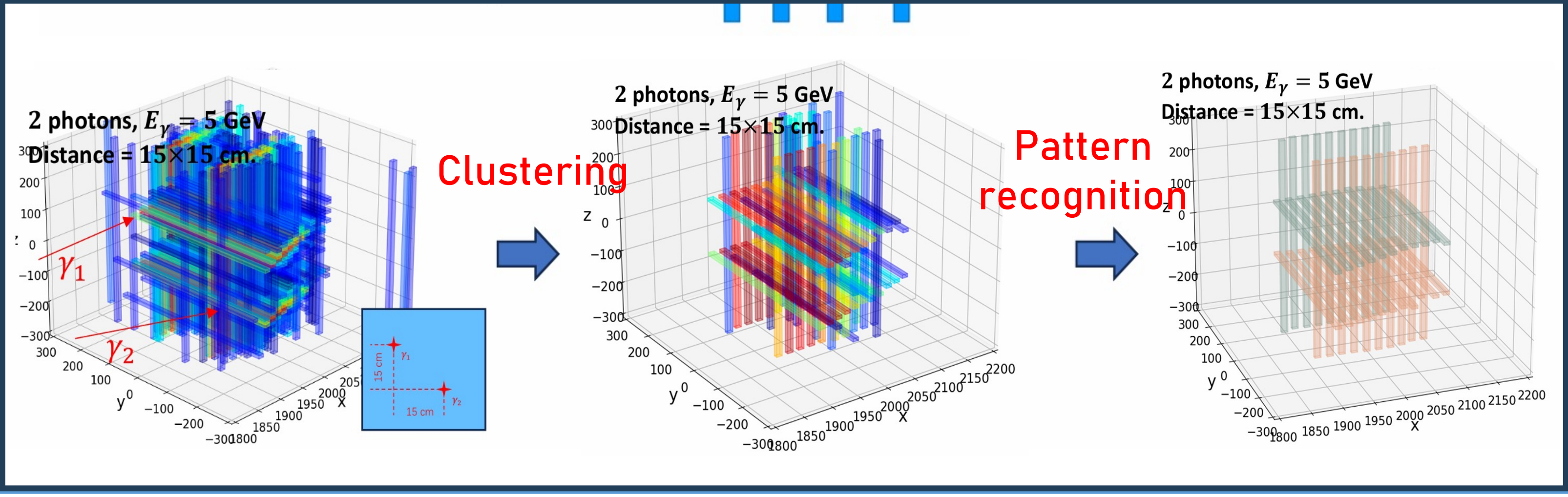


- PFA reconstruction algorithm for long-bar layout
  - Main challenges from overlapping and ambiguity
  - Algorithms are developed and show promising results

Ambiguity removed by information from track, neighbor tower and time

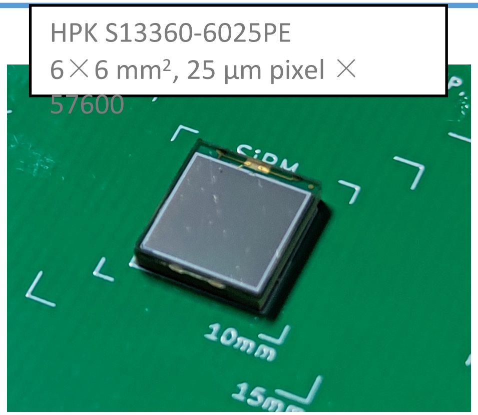
> 90% γ-γ separation efficiency with distance of 2cm

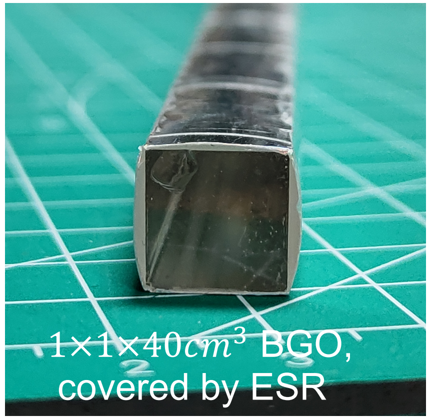


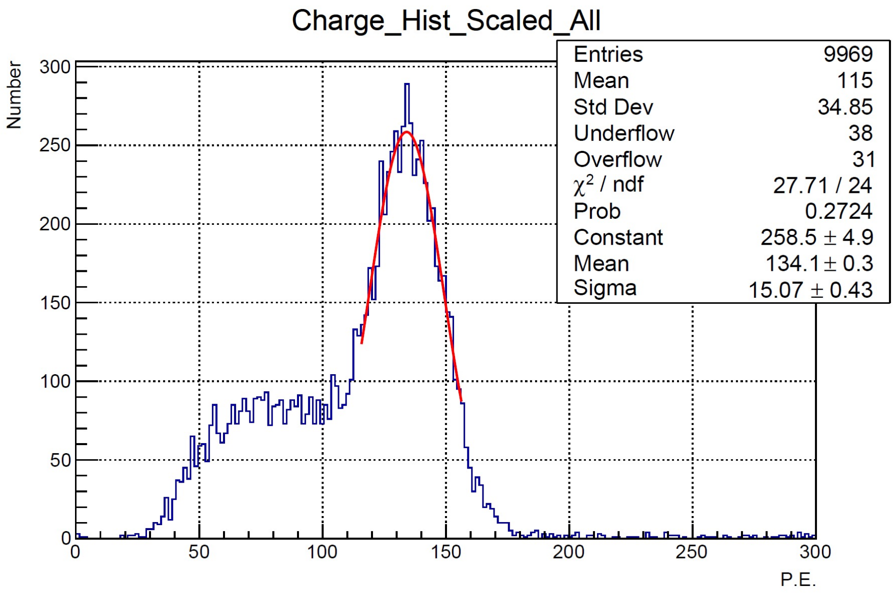


Long Crystal Bar: Tests with Radioactive Source

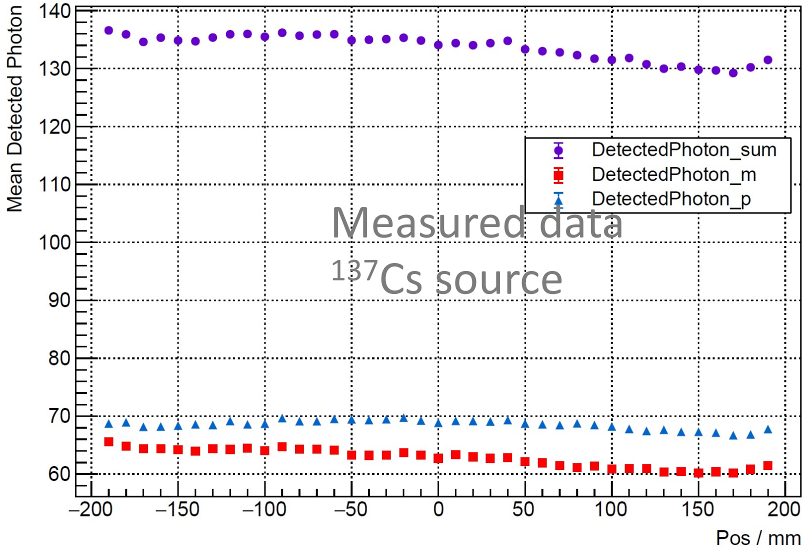
- BGO crystal bar directly air-coupled with SiPM
  - Energy resolution of 11.2% @662keV
  - Light yield: ~200 p.e./MIP enough for the LY requirement
  - Uniformity scan: <5% non-uniformity

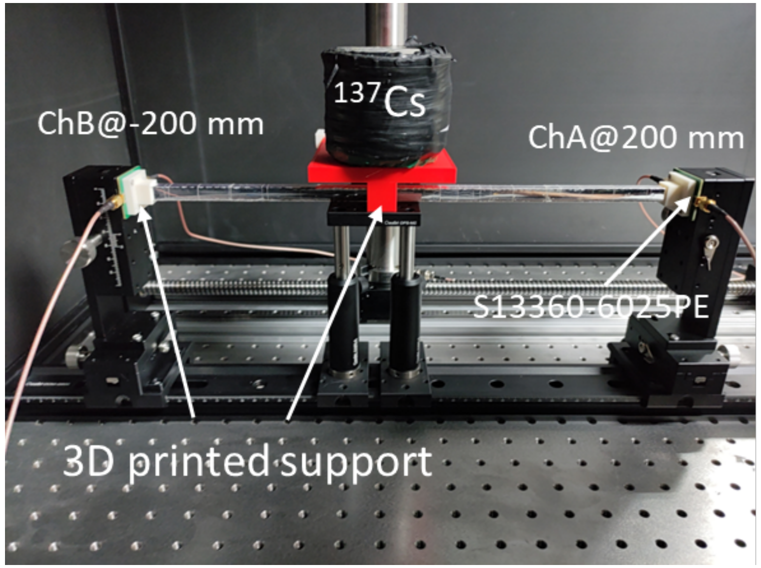






Experiment: detected photon

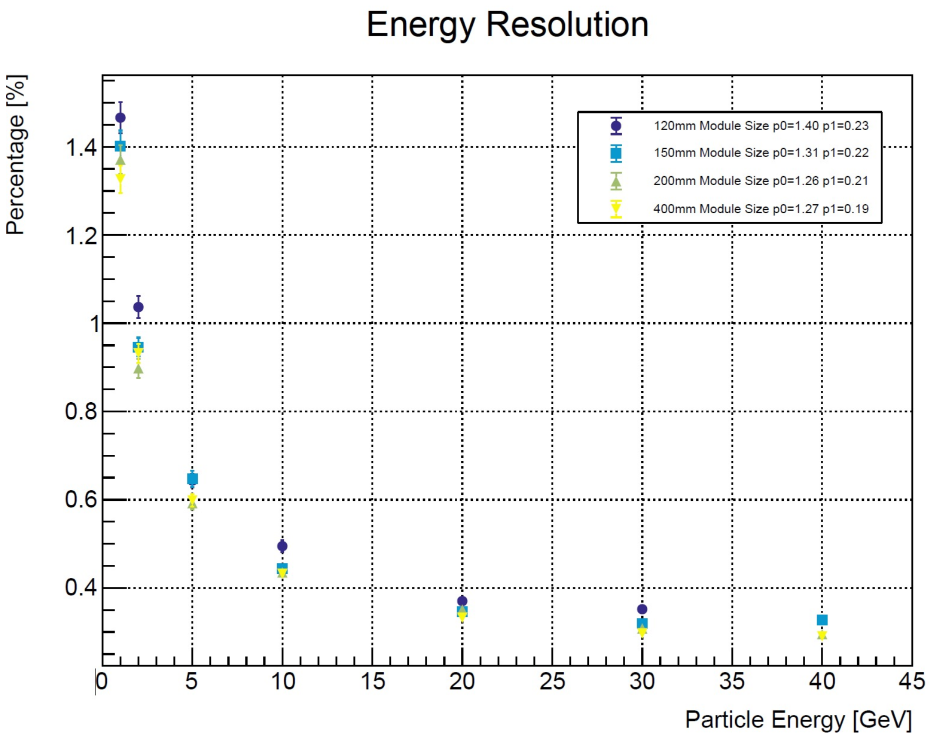




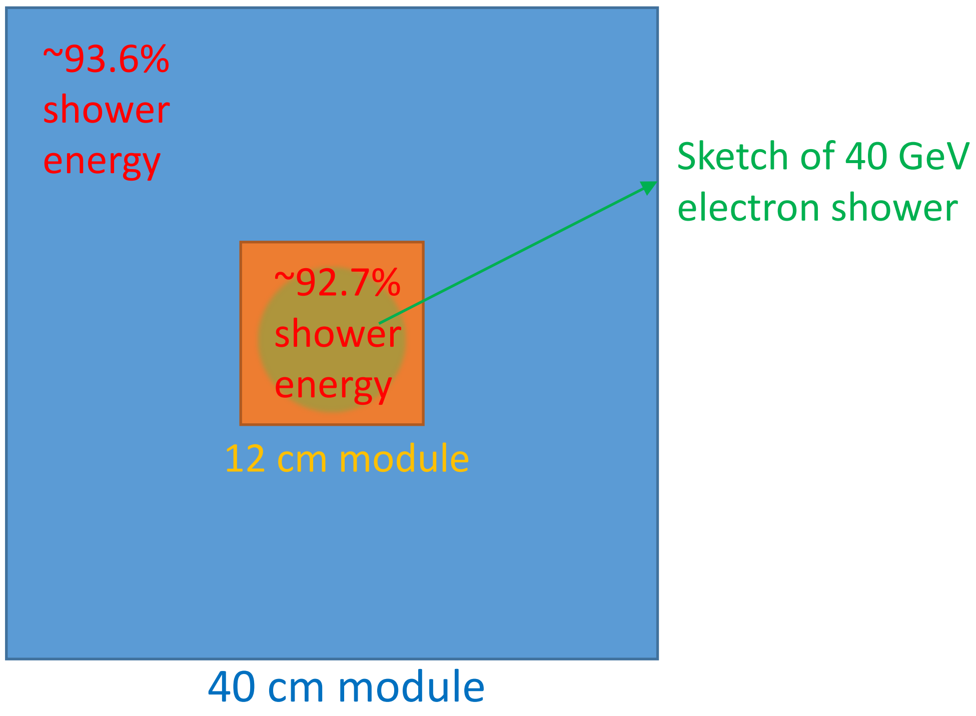
- Relatively low response near one side
- Coupling, crystal manufacture……

Crystal Module Design: Impact of Module Dimensions

- Module with transverse size of $12\times12\ \mathrm{cm}^2$ cm:
  - Sufficient to contain most EM energy with particles hitting module center
  - Degradation of energy resolution: ~0.1% level

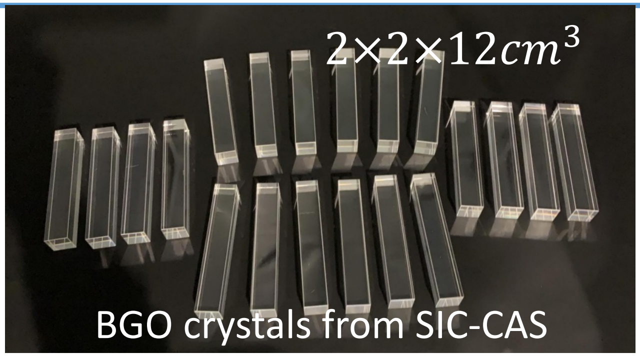


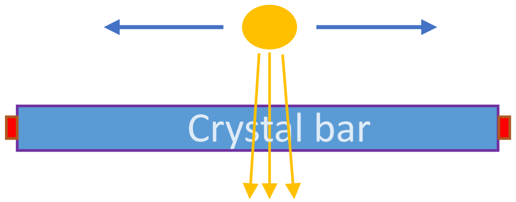
$25X_0$ in longitudinal depth (beam incidence)



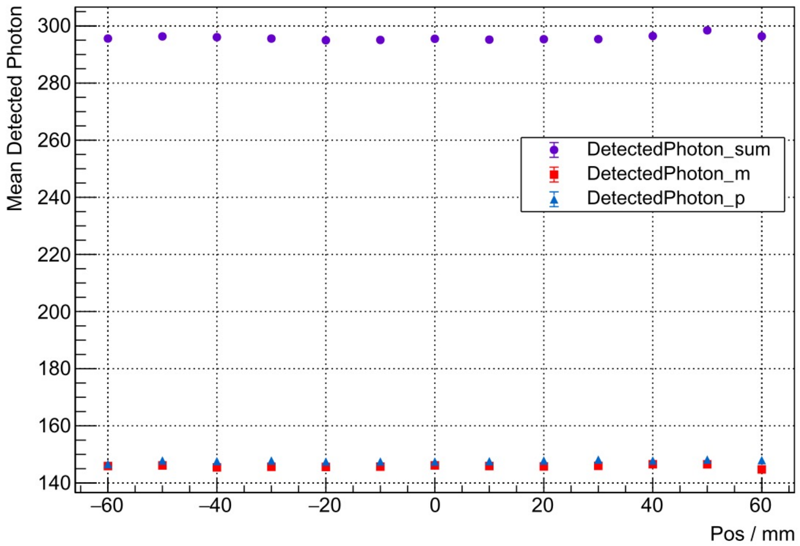
First Crystal Module: Batch Test of BGO Crystal Bars

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

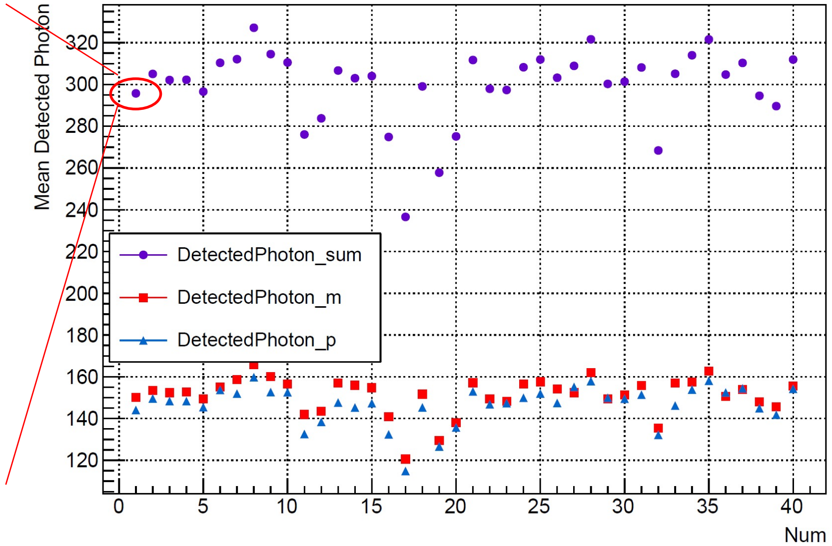


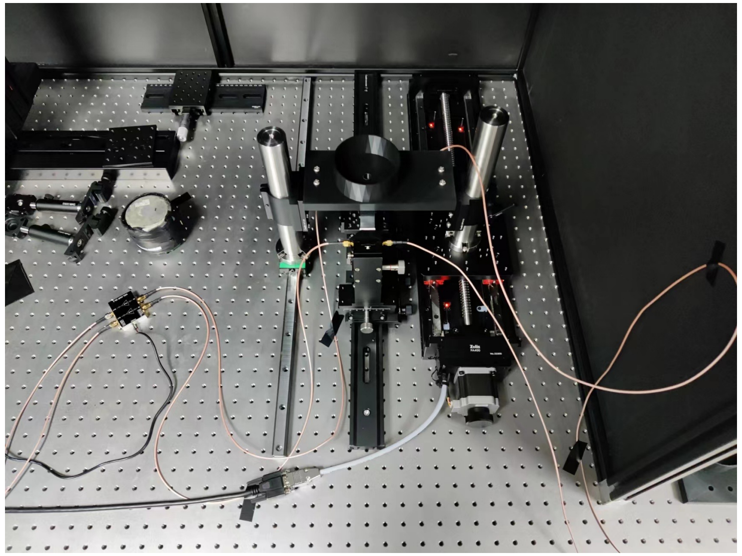


Response uniformity along #1 BGO bar



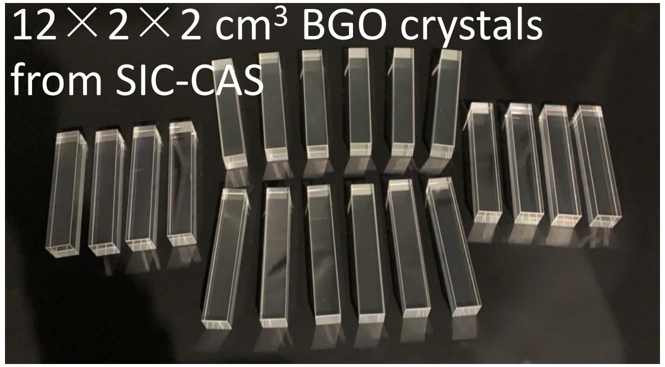
Comparison of 40 crystal bars

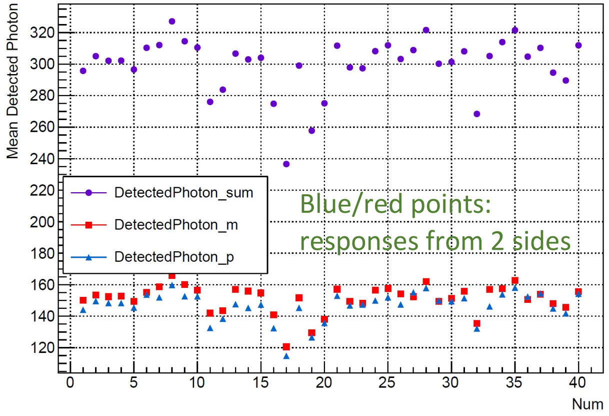




- Generally good uniformity along a single bar
- Response varies among bars, 36 crystals were selected for beamtests

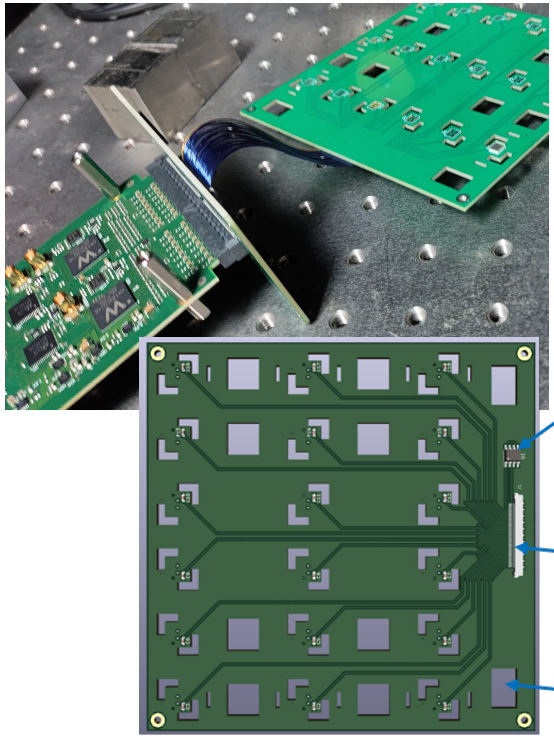
Crystal module prototyping



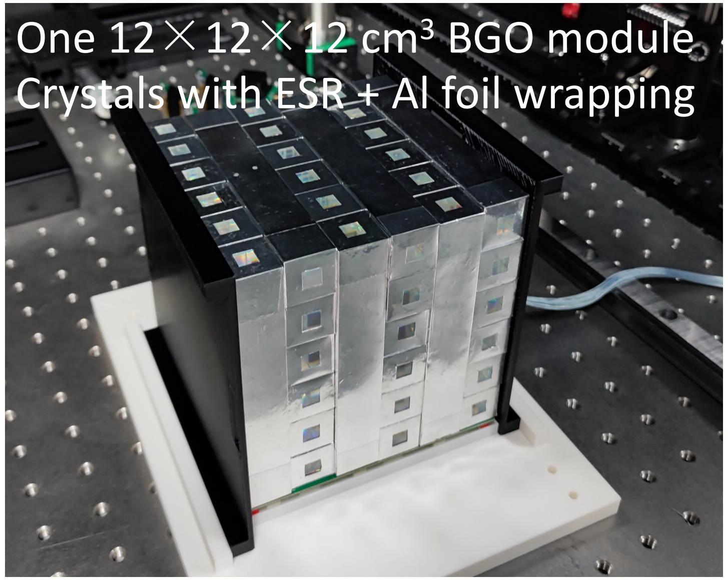


Batch test of BGO crystals

PCB design and electronics test



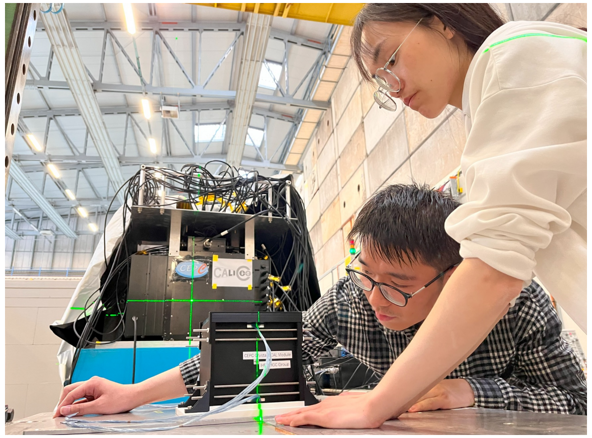
3×3mm² SiPMs with 10/15 µm pixel used



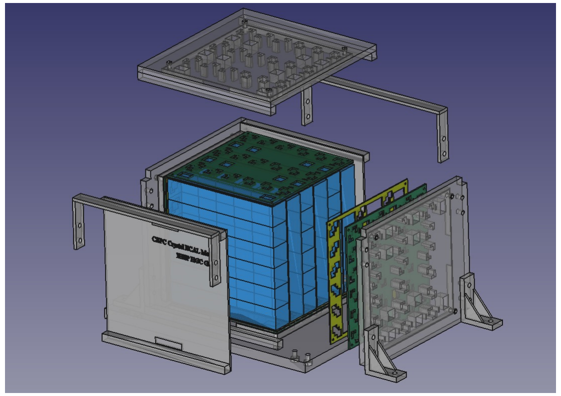
Support structure design and module assembly test

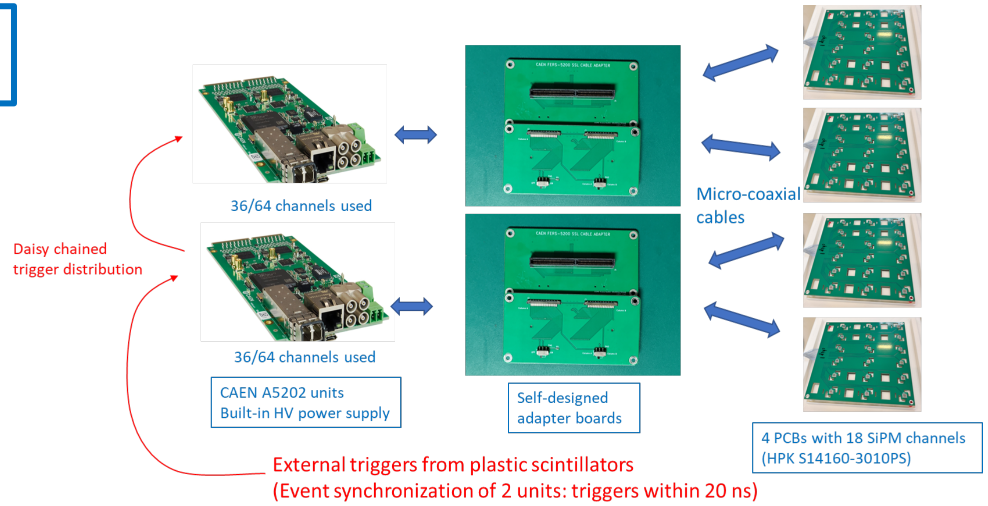
2023 CERN Beamtest: First Crystal Module

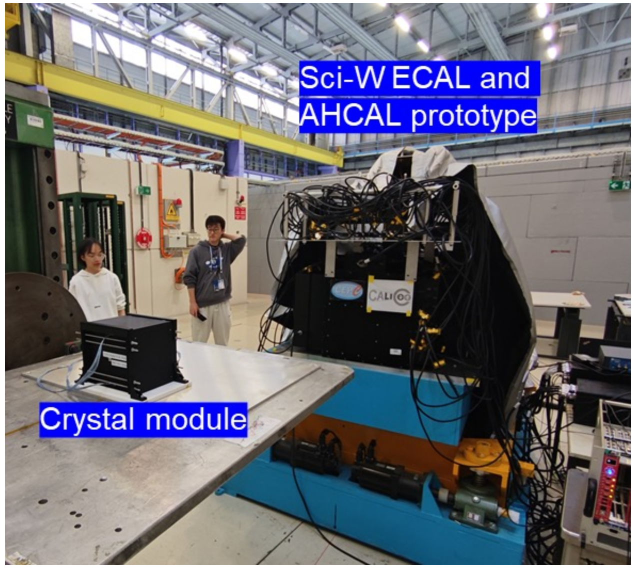
- Beamtest of the first crystal module at CERN PS-T9 (May, 2023)
  - Parasitic runs with CALICE Sci-W ECAL and AHCAL prototype
  - Crystal module: MIP calibration, EM performance
  - Technical issues: design of mechanics and electronics, temperature monitor, etc.

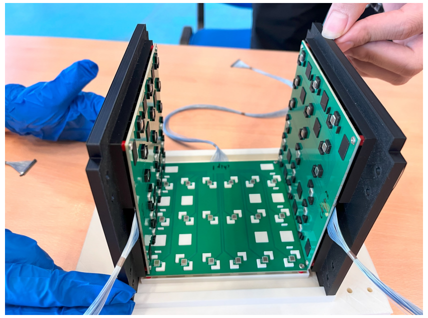


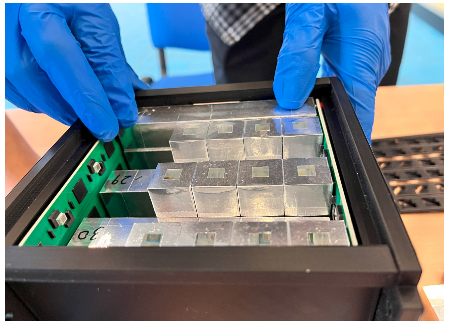
- ➢ $2\times2\times12cm^3$ BGO $\times36$, 72ch, 10.7 X_0
- ➢ SIPM: HPK S14160-3010PS, 10 μm pixel pitch

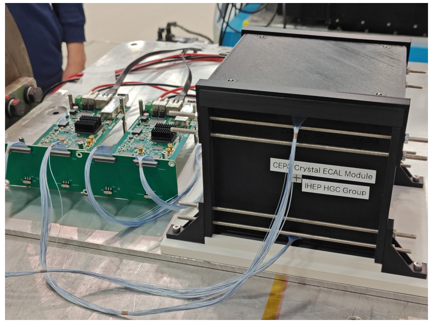






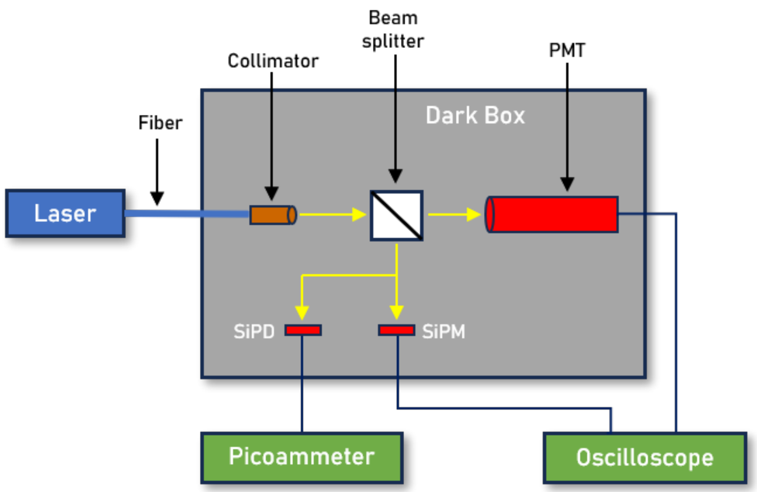


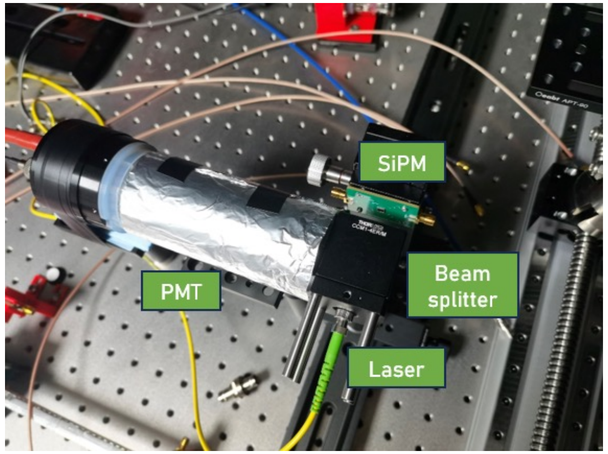




SiPM Dynamic Range studies: Laser Tests

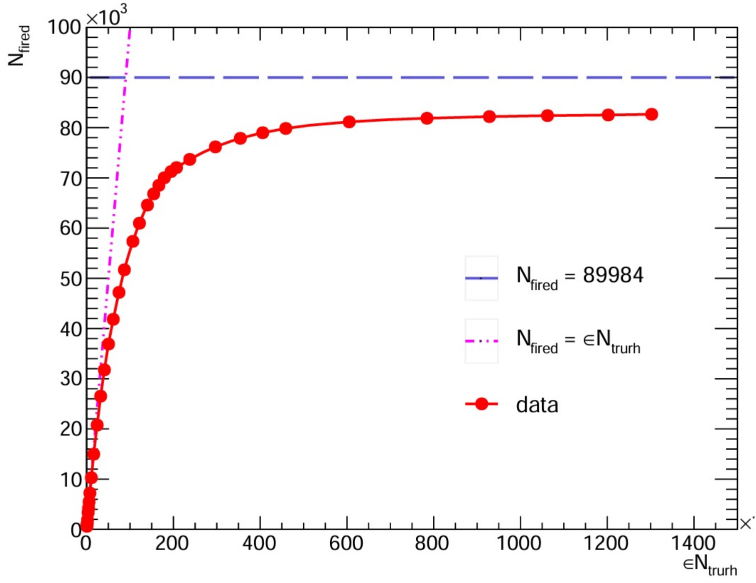
- Experiment to measure the intrinsic dynamic range of SiPM with laser
  - Pico-second laser: <40ps pulse width, 405nm wavelength
  - SiPM: HPK S14160-3010PS, 10μm pixel, 89984 pixels(SiPMs with 50μm and 6μm pixel were also tested)
- Deviation from linearity becomes noticeable starting from 10^4 p.e.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



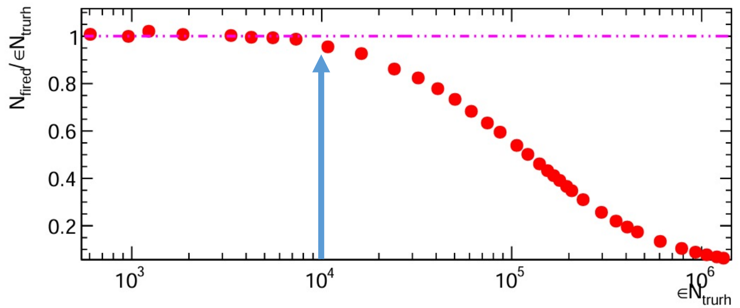


SiPM: $3\times3\ \mathrm{mm}^2$
$10\mu m\ pixel\ \times 89984$

SiPM output vs. input



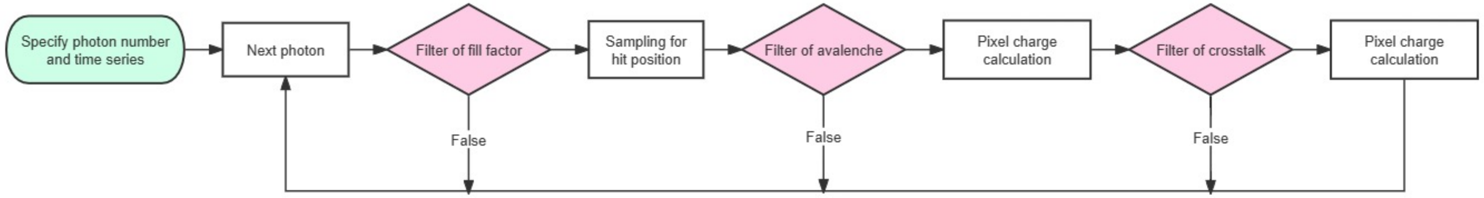
Start to deviate from linearity



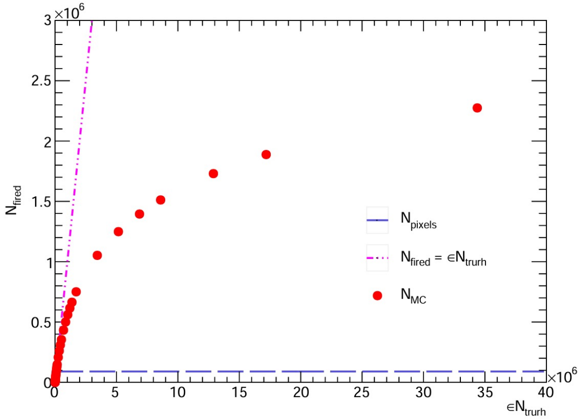
Simulation: crystal-SiPM readout

- 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 $1\times1\times40cm^3$ BGO crystal bar
  - Assuming uniform light profile on SiPM
  - Including SiPM PDE and BGO emission spectra
- $1\times1\times40cm^3$ BGO + $10\mu m$ SiPM with $3\times3cm^2$ size: 10% non-linearity at 1.7×10^5 p.e. -> can be corrected by this model

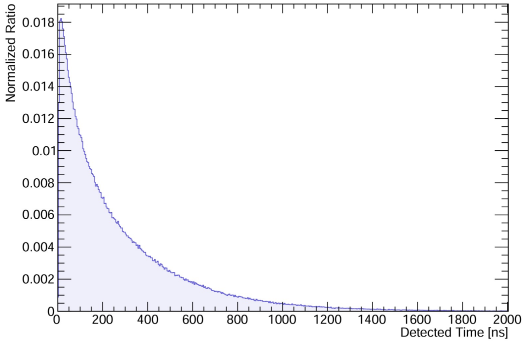
Toy Monte Carlo including
- SiPM pixel density, PDE spectrum, crosstalk, pixel multi-fired effect
- BGO emission spectrum, detected time of scintillation photon

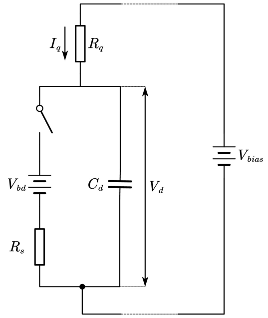


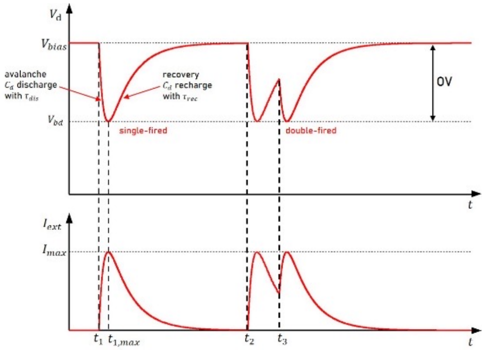
Simulated response curve of SiPM



Detected time of photons (Geant4)







Multiple hits within one SiPM pixel