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

CALOR 2024
Tsukuba

Development of a novel high granularity crystal electromagnetic calorimeter

Baohua Qi
On behalf of CEPC Calorimeter Working Group

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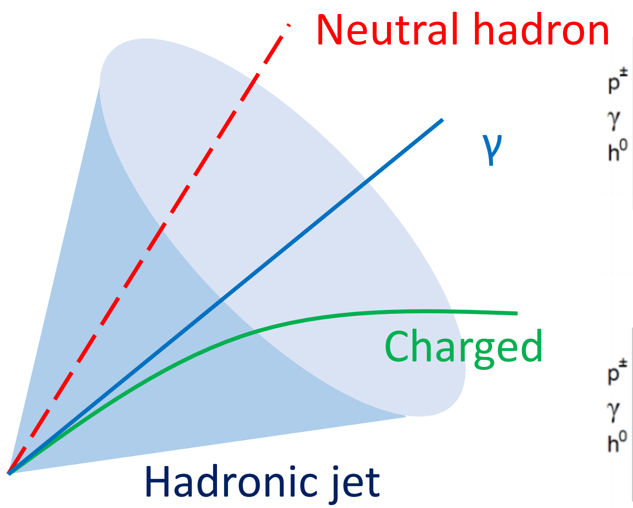
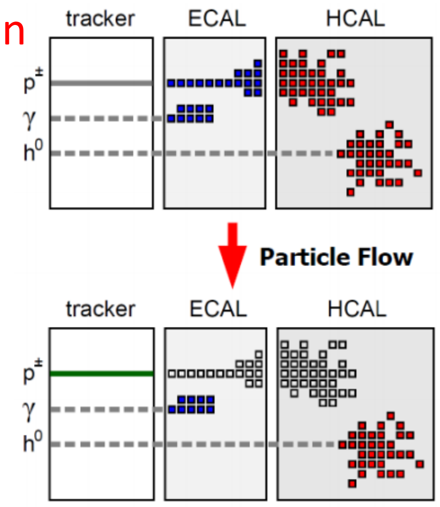
qibh@ihep.ac.cn

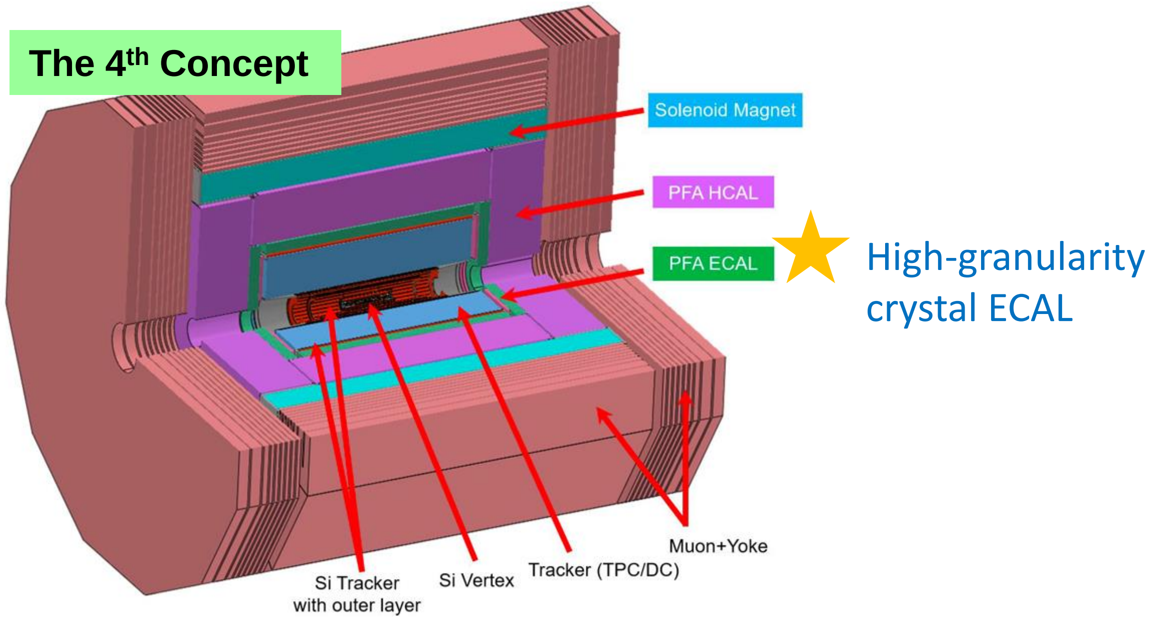
Introduction: new detector for CEPC

- CEPC: future lepton collider (Higgs Factory)
  - Higgs/Z/W bosons, BSM searches, etc.
  - Precision jet measurement
    - Targeting 3% level Boson Mass Resolution (BMR)
  - Particle-Flow Algorithm (PFA) oriented calorimeters
    - High-granularity calorimeter: excellent shower reconstruction





- New "CEPC 4th concept" detector design
  - High-granularity crystal ECAL
    - 5D detector: 3D spatial + energy + time
    - Intrinsic EM energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Scintillating glass HCAL
    - High density for better energy resolution/BMR
    - More compact and cost-effective



CALOR 2024 talk: Performance studies of the GSHCAL based on the simulation

Physics performance: CEPC detector with crystal ECAL

Baohua Qi, Yuexin Wang(IHEP)
Zhiyu Zhao (TDLI/SJTU)

- Studied with 1 cm^3 crystal cubes under CEPC Software with Arbor-PFA
- Crystal ECAL: competitive option for better BMR performance
- SiW ECAL (CEPC baseline) vs Crystal ECAL (4^{th} concept)
  - Jets($H \to gg$) : 3.8% → 3.6%
  - Photons($H \to \gamma\gamma$) : 2.1% → 1.2%
- Superior EM energy resolution for flavor physics
  - Good measurement precision on $B^0/B_S^0 \to \pi^0\pi^0$

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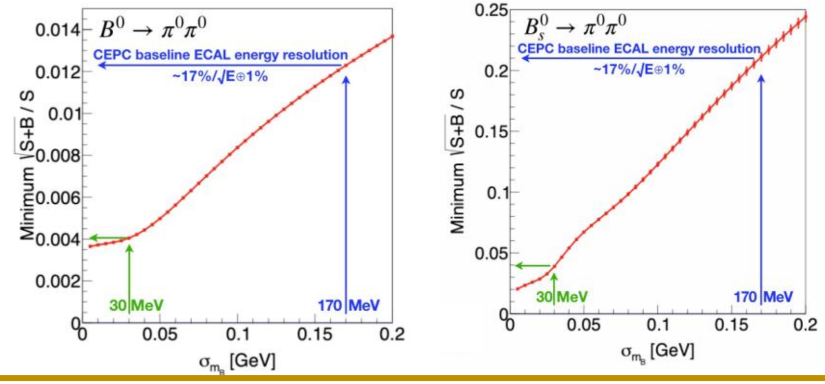
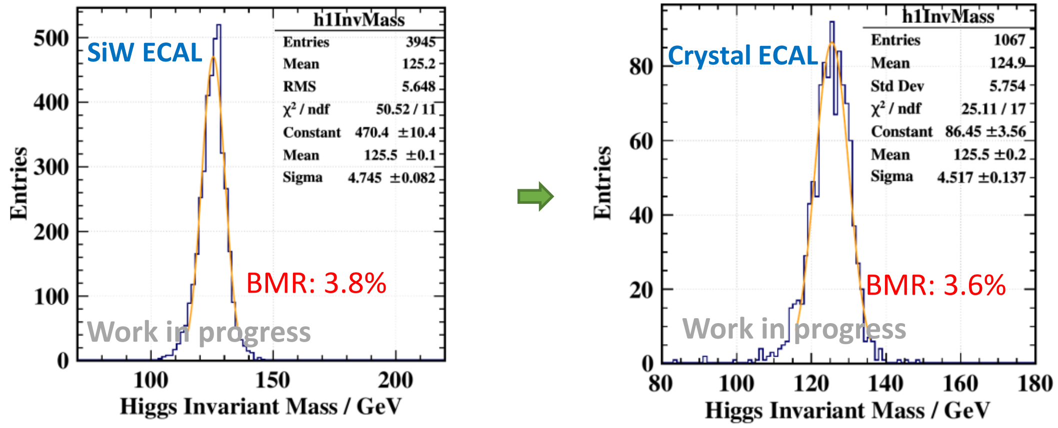
ECAL Resolution	σ_{m_B} (MeV)	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$
$17\%/\sqrt{E}\oplus1\%$	170	~ 1.2%	~ 21%
$3\%/\sqrt{E}\oplus0.3\%$	30	~ 0.4%	~ 4%

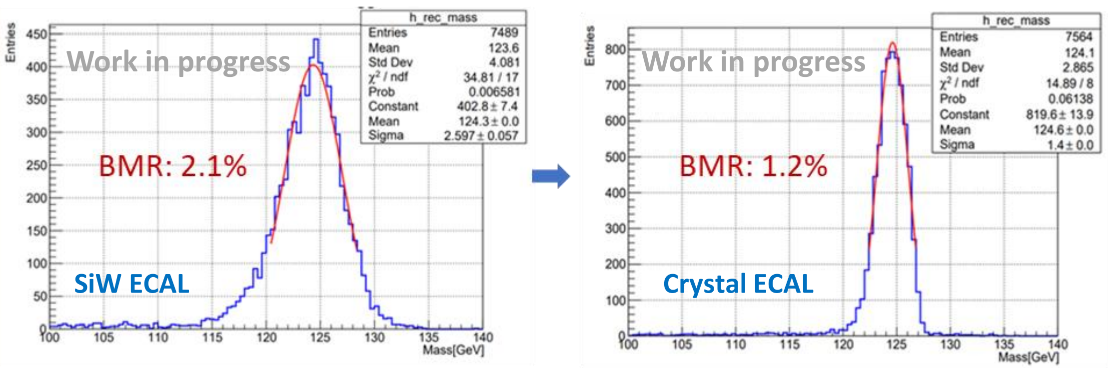
3~5 times improvement in their final precision $\sqrt{S+B}/S$



BMR ($H \to gg$)

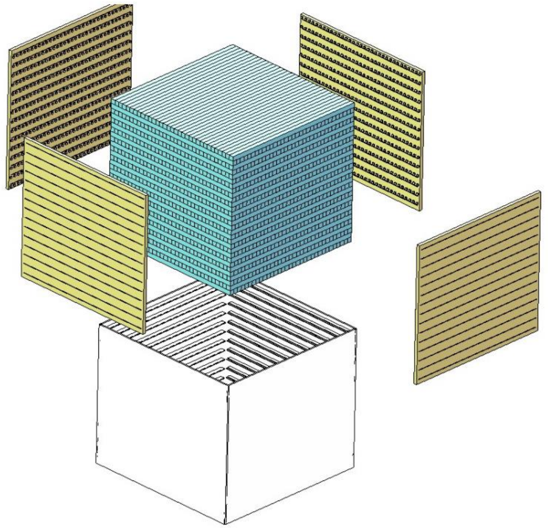


BMR ($H \to \gamma\gamma$)

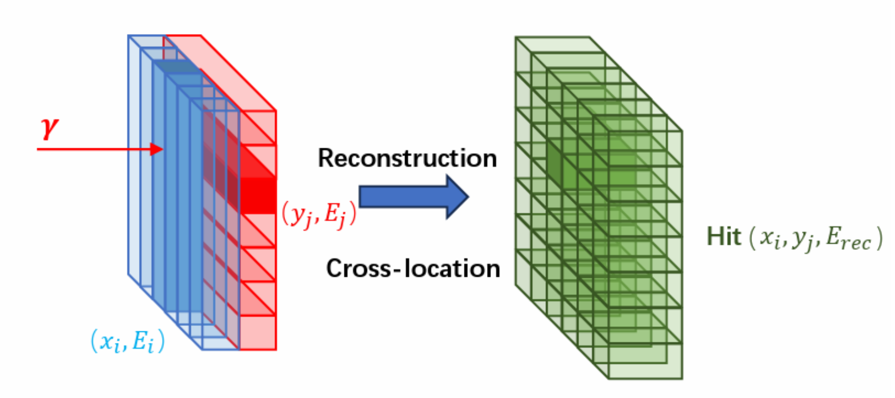


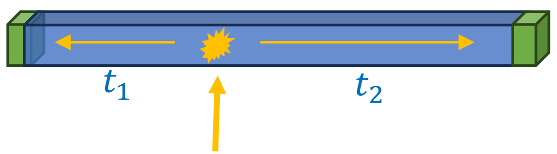
Design concept: crystal ECAL with crisscrossed long bars

- Long crystal bars arranged to be orthogonally
  - $1\times1\times40$ cm^3 crystal units, double-side readout with SiPM
  - Long crystal bars instead of small crystal cubes
    - Save #channels and minimize dead materials
    - Achieve high granularity with information from adjacent layers
  - Double-sided readout
    - Positioning potentials with timing at two sides

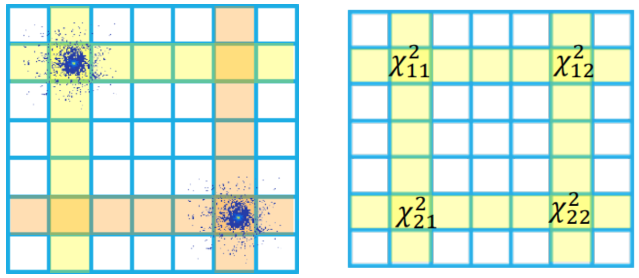


➢ A tower made up of $1\times1\times40$ cm^3 crystals





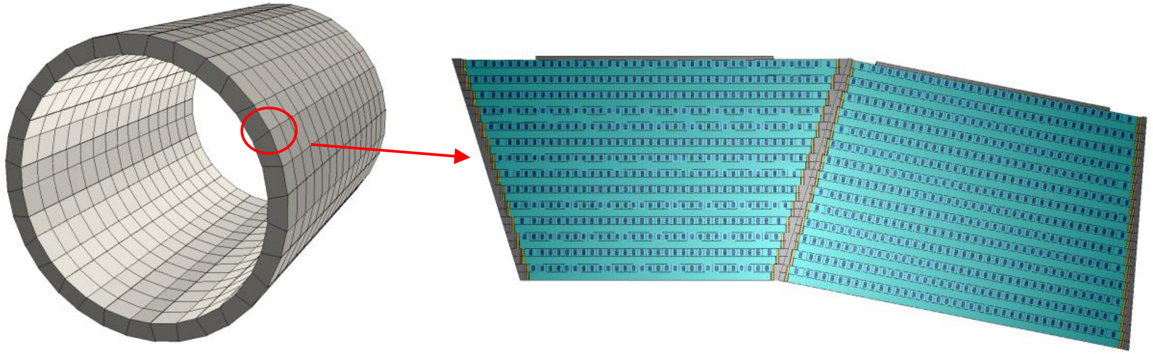
- Challenges
  - Difficulties in the mechanical/geometry design
  - Impact from ghost hits



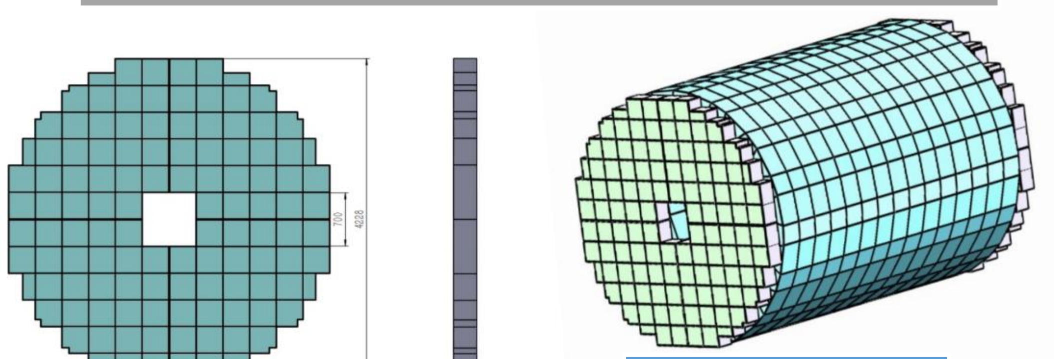
➢ Ghost hits case when 2 or more particles hit on one supercell

Crystal ECAL for CEPC: latest R&D activities

- Preliminary barrel and endcap geometry design
  - ~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

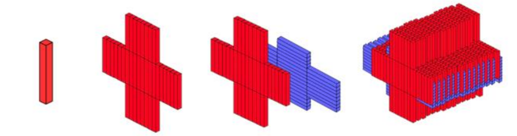


In total ~720k crystals

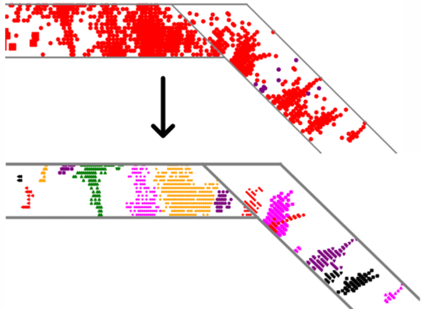
- Disc-shaped endcaps made up of square towers

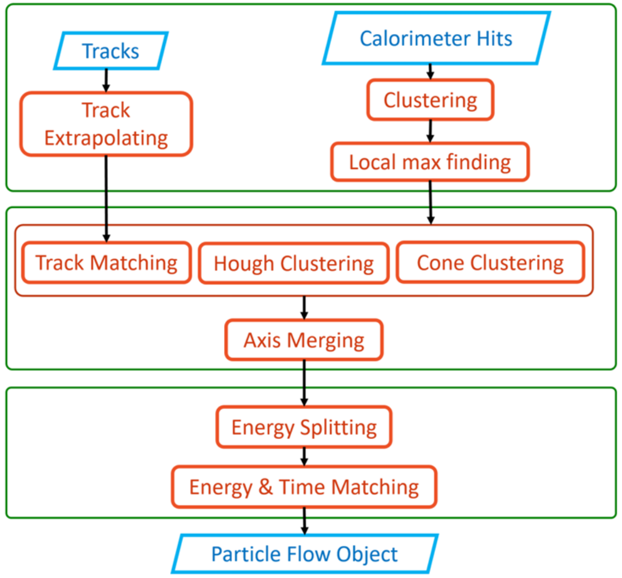
Quan Ji, Shaojing Hou, Weizheng Song, Yang Zhang, Fangyi Guo (IHEP)

- Dedicated reconstruction software for long bar crystal ECAL
  - Reconstruction flow has been built under CEPCSW
  - Key issues: sophisticated algorithm for long bar geometry



Clustering from crystal bars to 3D cluster





CALOR 2024 talk: Particle flow algorithm for long crystal bar electromagnetic calorimeter

Extensive efforts for CEPC calorimeter R&D

Another concept: stereo crystal ECAL
CALOR 2024 talk: Stereo crystal ECAL design and simulation studies

Crystal ECAL: specifications

Key Parameters	Value	Remarks
MIP light yield	~200 p.e./MIP	~8.9 MeV/MIP in 1 cm BGO
Dynamic range	1~4.5×10^5 photons per channel	Deposited energy up to 40 GeV per crystal bar
Energy threshold	0.1 MIP	Depends on S/N and light yield
Timing resolution	~400 ps @ 1 MIP	Ideal value from Geant4 simulation
Crystal non-uniformity	< 1%	Calibration precision
Temperature stability	Stable at ~0.05 Celsius	Reference from CMS ECAL
Gap tolerance	~100 μm	TBD

Detector requirements

- Moderate MIP light yield
- Good uniformity
- Optimal time resolution
- Large dynamic range
- High S/N

→

Hardware activities: addressing crucial issues

- SiPM response linearity
- Uniformity of long crystal bar
- Time resolution: different crystal sizes/Edep
- Dynamic range of electronics
- Energy response of crystal module
- …

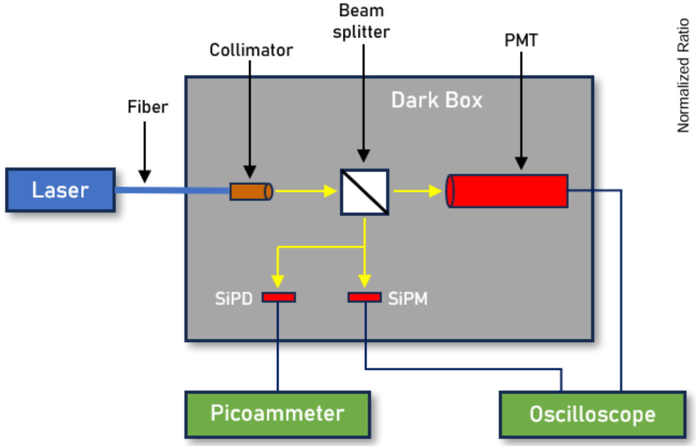
SiPM response linearity: laser test and simulation

Zhiyu Zhao (TDLI/SJTU)

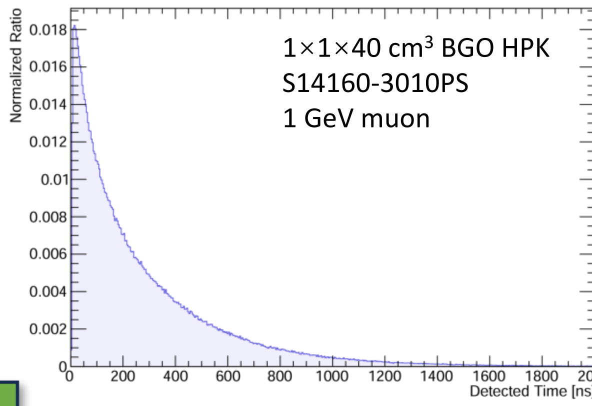
- SiPM candidates: 3×3 mm^2, 10 μm pixel pitch **Requirement: 4.5×10^5 photons**

1. Intrinsic dynamic range test
   - Pico-second laser: photons arrive at the same time
   - PMT: scale for light intensity
2. Toy Monte Carlo simulation
   - Effect from crystal light decay time
   - Recovery of SiPM pixels

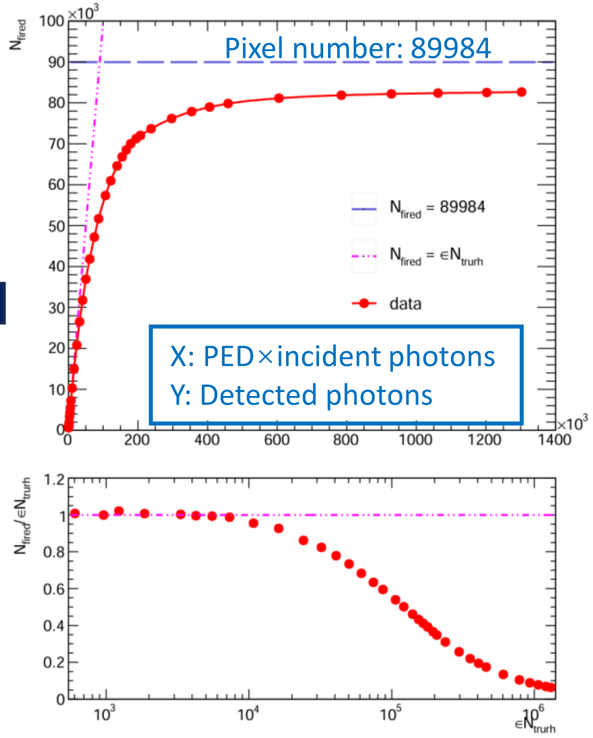
Laser test setup



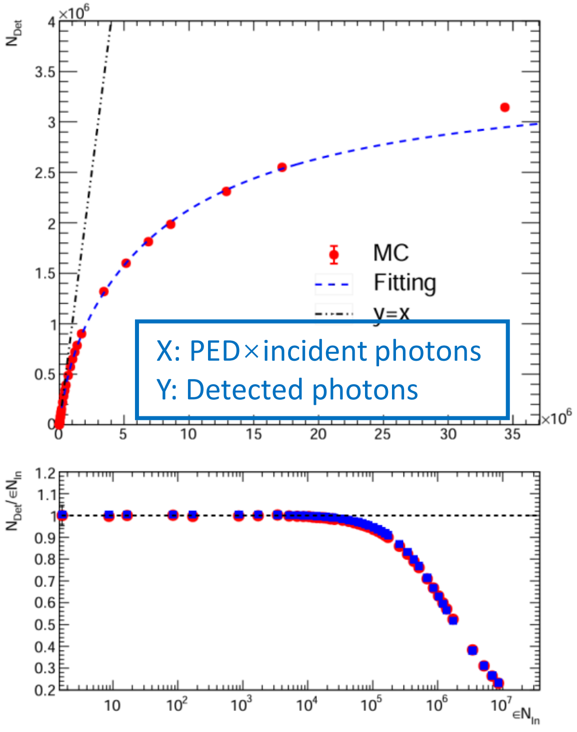
Geant4 simulated photon detection time



Experiment: Laser + SiPM



Simulation: BGO + SiPM



- For crystals with relatively slow decay time, the pressure on the SiPM dynamic range is lower than expected
- SiPM with higher pixel density is feasible (e.g. 6 μm products)

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

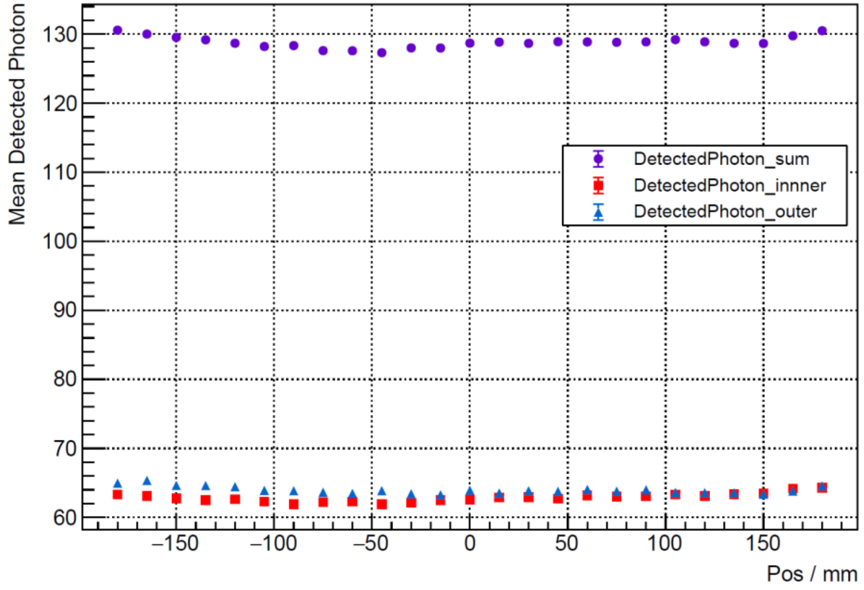
- Recovery effect contributes to a wider linear range

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

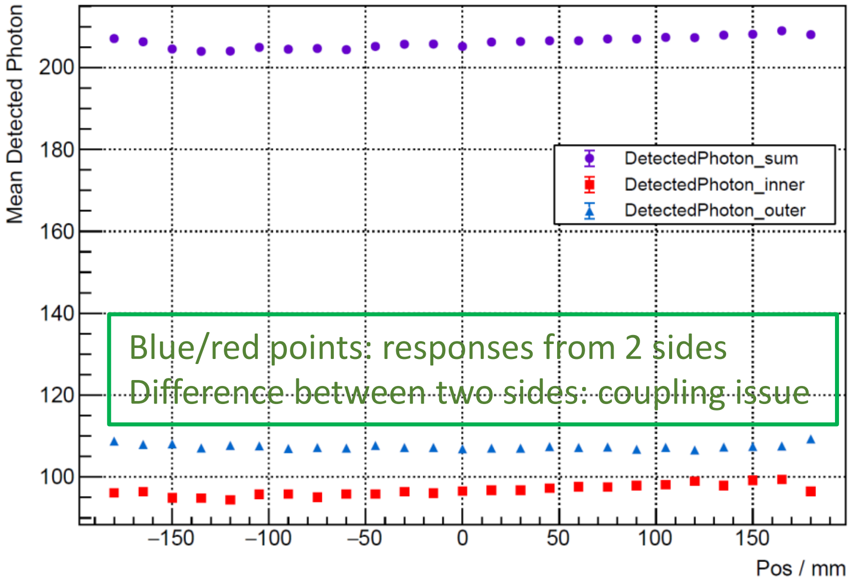
Uniformity scan of BGO crystal bars

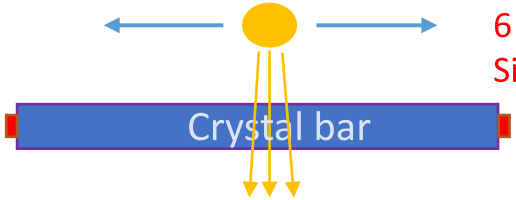
- 1×1×40 cm^3 BGO crystal with ESR wrapping
- Air/optical grease coupling
- Scan with Cs-137 radioactive source

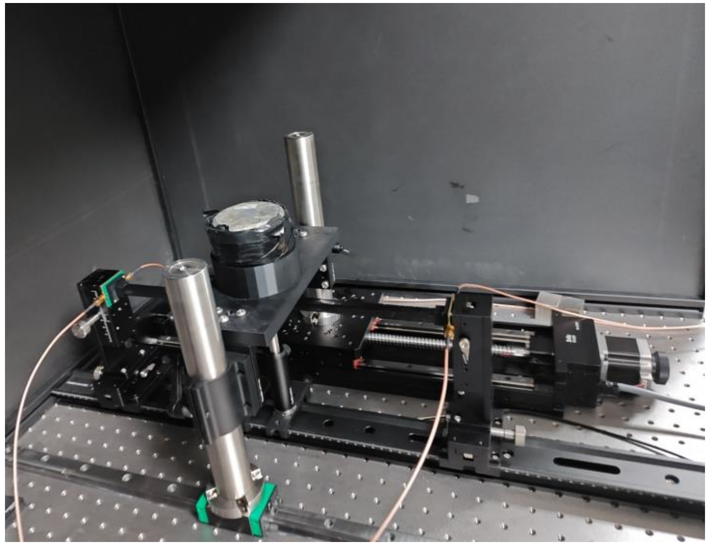
Response uniformity air-coupled



Response uniformity grease-coupled







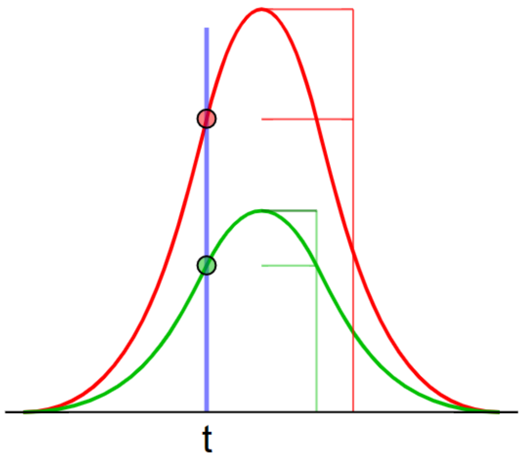
Automated crystal scan platform

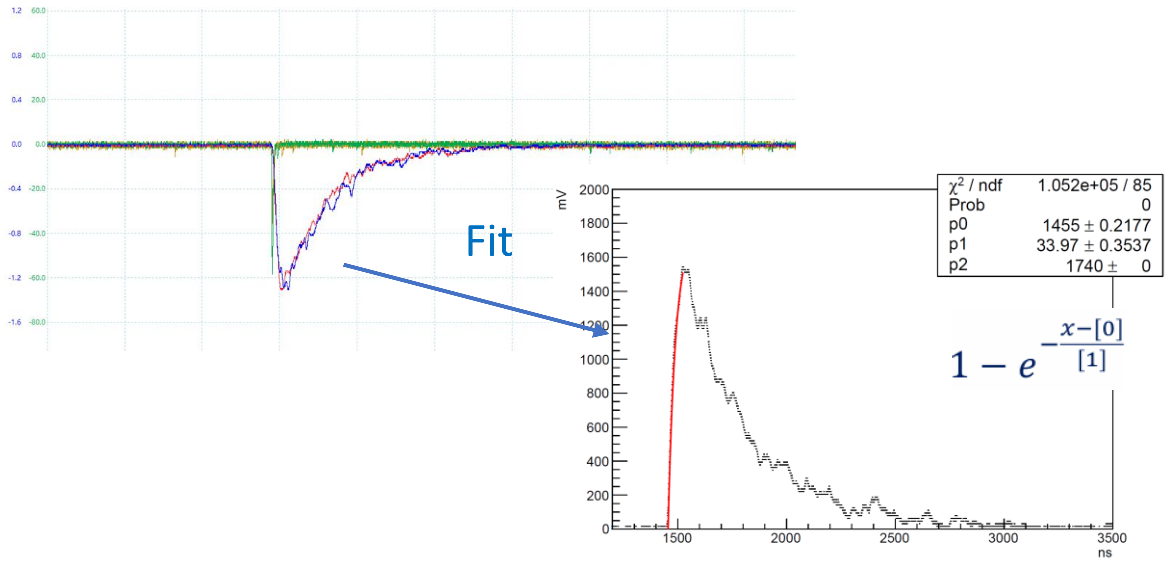
- Generally good uniformity at ~2.5% level along a single bar
- Optical grease gives 59% improvement on detected photons
- Grease coupling is difficult to control

Study of time resolution: two timing methods

Zhiyu Zhao (TDLI/SJTU)

- Time resolution for crystal ECAL
  - Time information for PID
  - Potential position reconstruction for long crystal bar
- Timing method for experiments with waveform sampling
  - Constant fraction discrimination timing / leading edge fitting timing

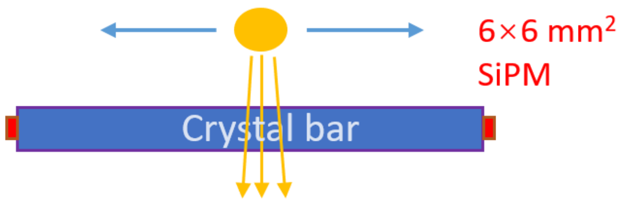




- "CFD": Constant Fraction Discrimination timing
  - Trigger times independent from peak heights
  - Resolved the effects of time-walk
- "Fitting": leading edge fitting timing
  - Obtain a smoother rising edge of the signal
  - Selection of time stamps is consistent with CDF

Long crystal bar time resolution: radioactive source and cosmic-ray tests

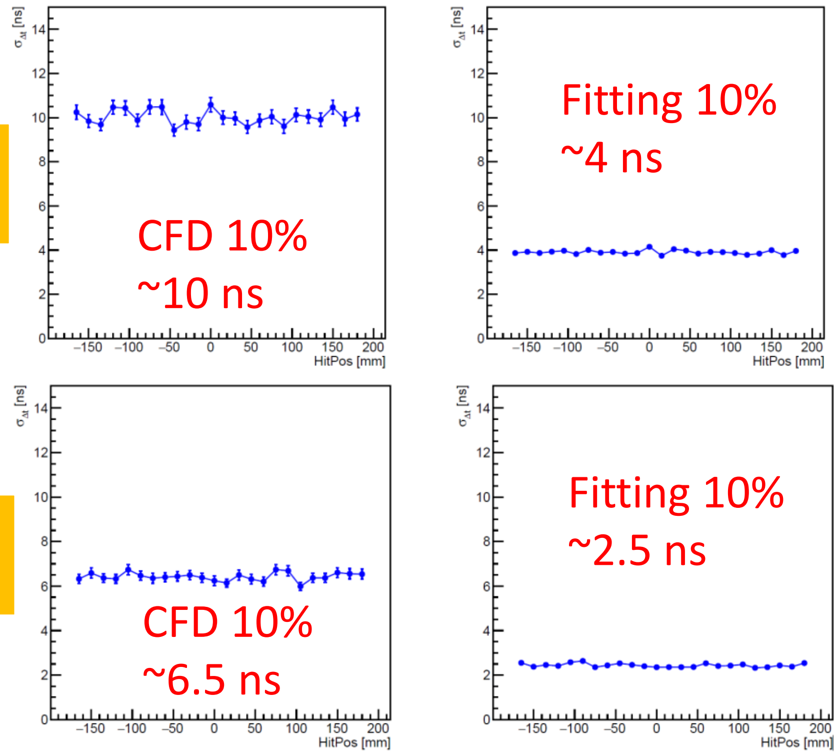
Cs-137 with ~ 8mm collimator



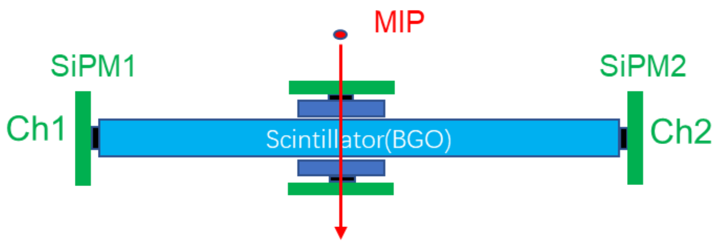
E_{dep}: 662 keV

Time resolution Air-coupled

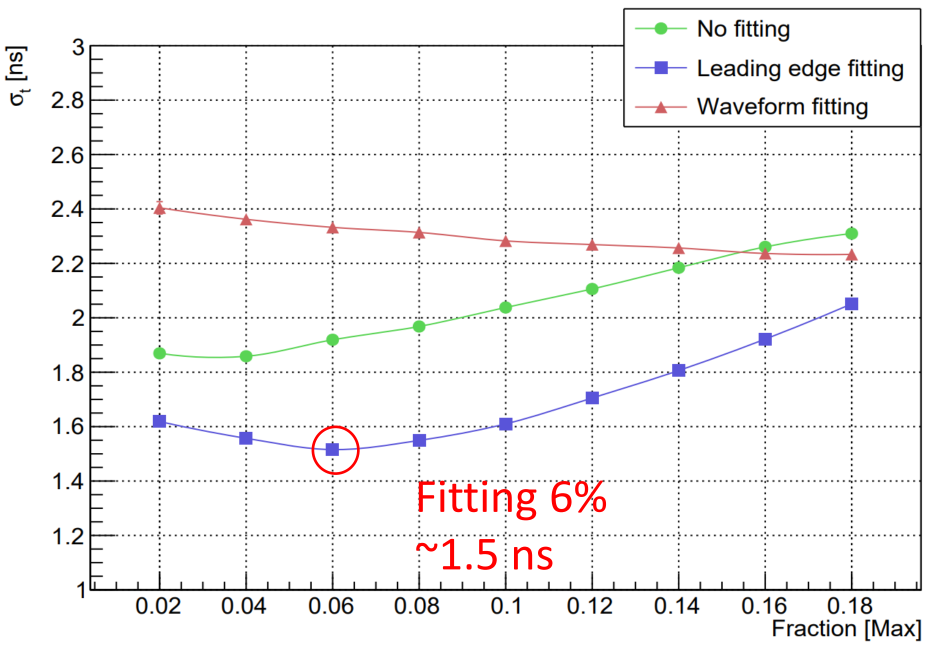
Time resolution Grease-coupled



Zhiyu Zhao (TDLI/SJTU)



E_{dep}: ~8.9 MeV

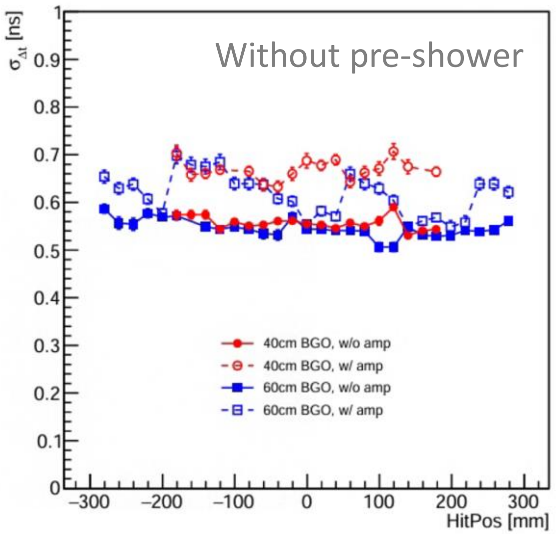


- Time resolution: ~4 ns at 662 keV (2.5 ns with grease), ~1.5 ns for MIP signals

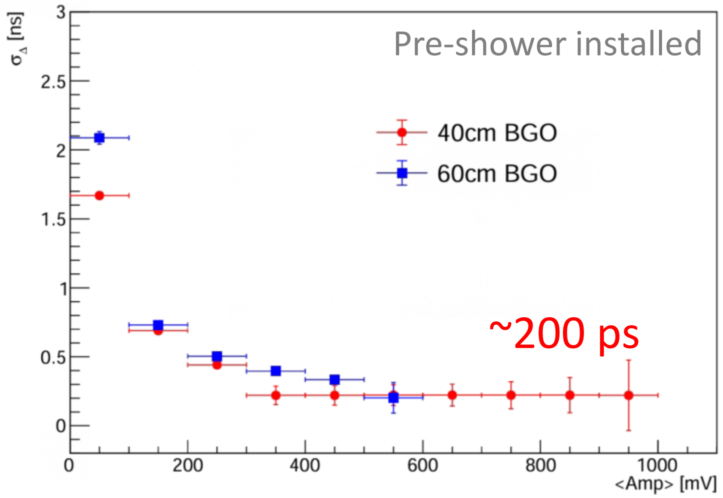
Long crystal bar time resolution: 2023 DESY beam-test

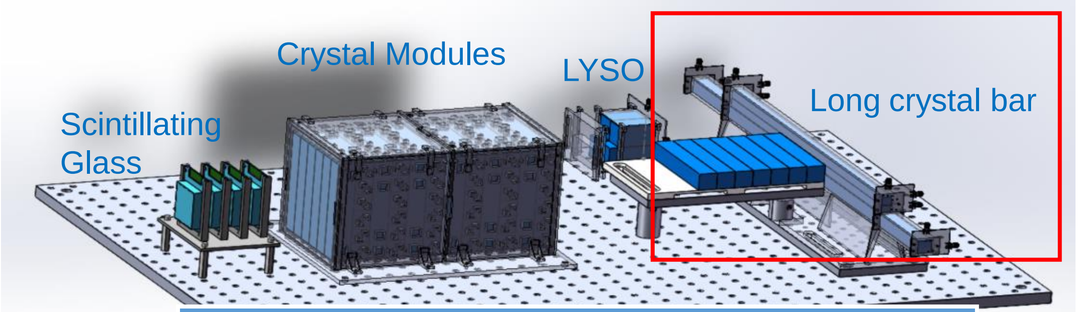
- Time resolution with 5 GeV/c electron beam
  - 1×1×40 cm^3 and 1.5×1.5×60 cm^3 BGO crystal
  - 25 µm pixel SiPM, DAQ 1.25GS/s DAQ

Time resolution: position scan

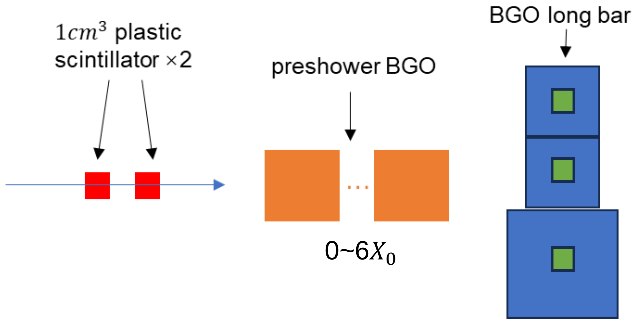


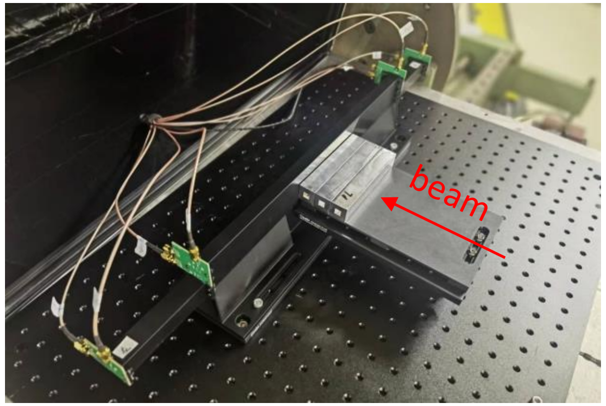
Time resolution vs signal amplitude





Overview of the 2023 DESY beam-test tasks

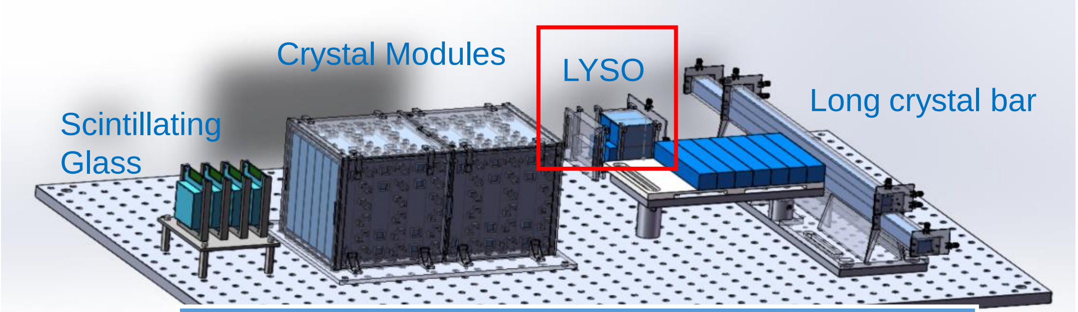




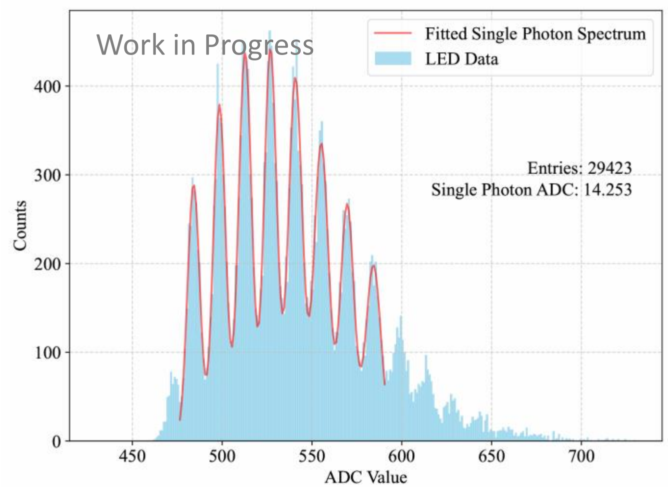
- Time resolution generally does not change significantly with position
- Time resolution varies with signal amplitude
  - Best result: 200 ps (40 cm BGO with >12 MIP signal, 60 cm BGO with > 20 MIP signal), potential limitation from electronics
- Potential for shower reconstruction still needs to be evaluated

Dynamic range of electronics: 2023 DESY beam-test

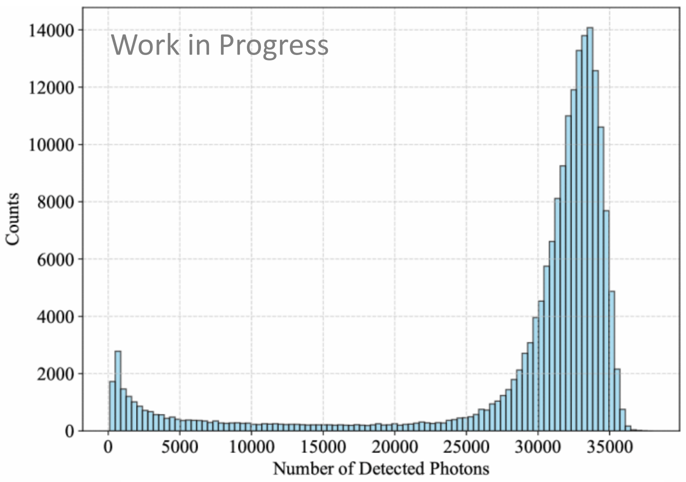
- Requirement: detecting 1~4.5×10^5 photons
  - Significant challenge: dynamic range of electronics
- Beam-test of large dynamic range electronics candidate MPT2321
  - 5 GeV/c electron beam hits on LYSO crystal matrix
  - Readout with MPT chip + 25 μm pixel SiPM



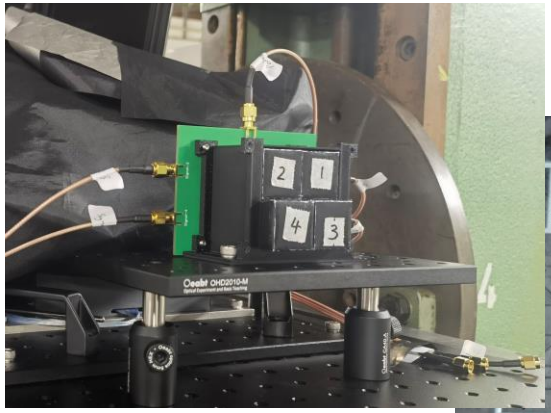
Overview of the 2023 DESY beam-test tasks

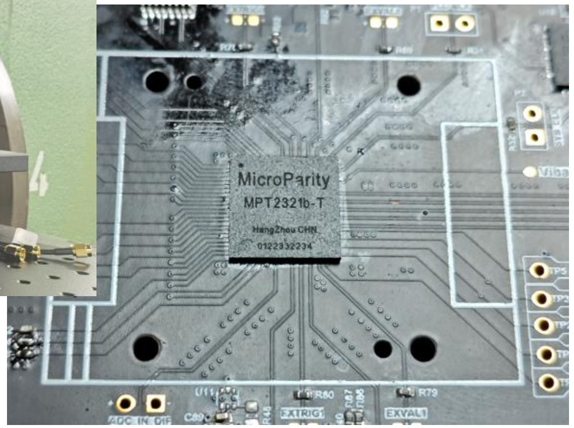


Highest gain: good S/N for single photon calibration



Lowest gain: capable for detecting ~33,000 photons





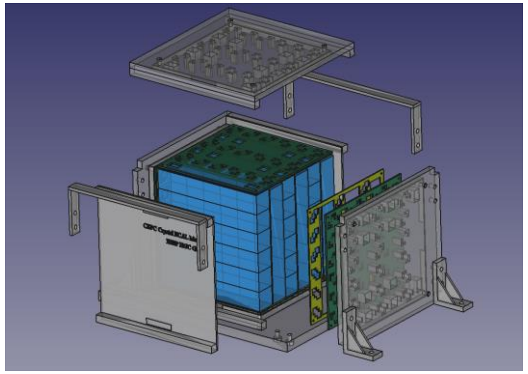
Future chip iterations with better performance expected

- MPT chip: moderately large dynamic range product with high S/N for single photon calibration
- Dynamic range could be further improved with lower gain SiPM, shorter shaping time, etc.

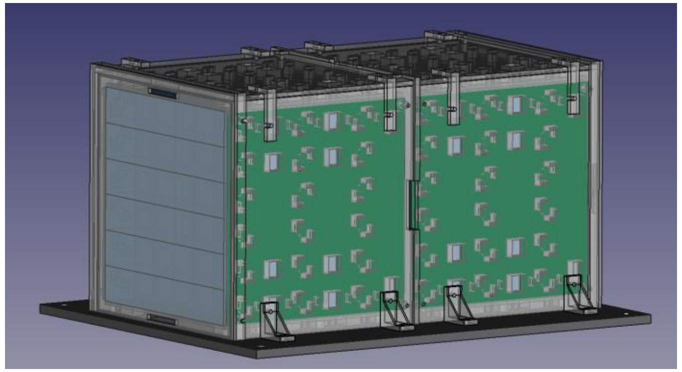
CALOR 2024 poster: Studies of a large dynamic range SiPM readout ASIC MPT2321-B

Energy response of crystal modules: 2023 CERN and DESY beam-tests

- Motivations
  - Identify critical questions/issues on the system level
    - Mechanical design, PCB and electronics…
  - Evaluate EM performance with TB data
  - Validation of simulation and digitization
- Beam-test at CERN T9 beamline
  - One module for commissioning and first parasitic tests
  - Muon, electron and pion beam
- Beam-test at DESY TB 22beamline
  - Two modules for EM energy response study
  - Electron beam

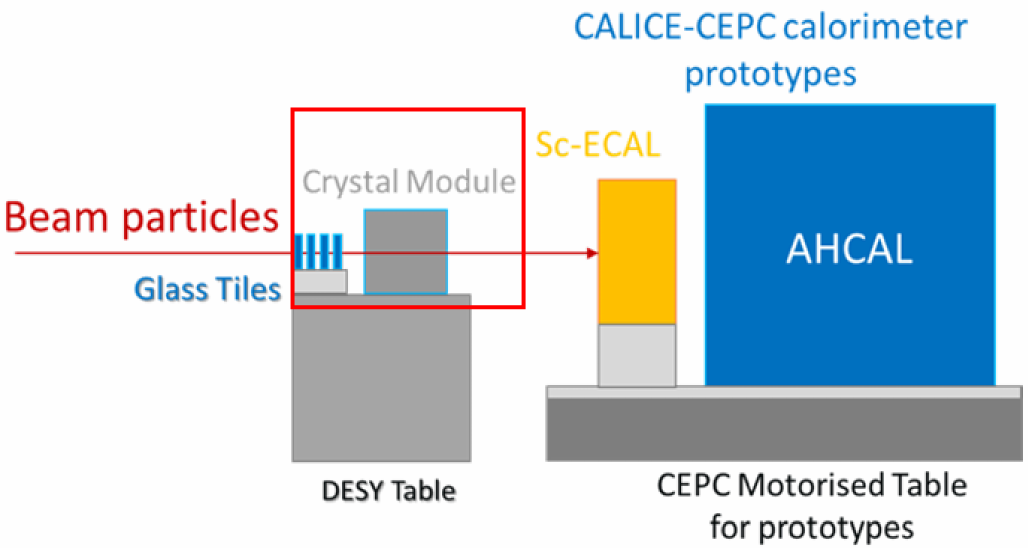


72 channels , $10.7X_0$



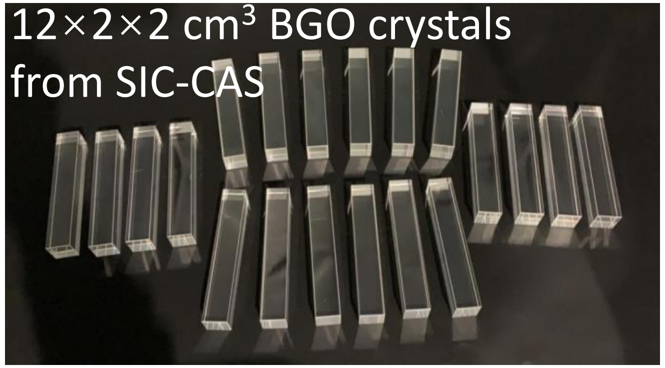
144 channels, $21.4X_0$

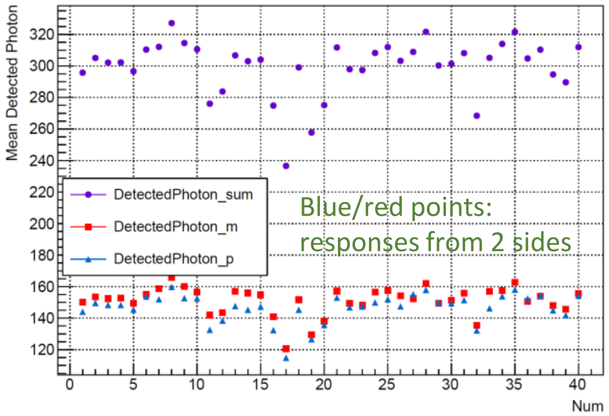
Overview of the 2023 DESY beam-test tasks



Overview of the 2023 CERN beam-test tasks

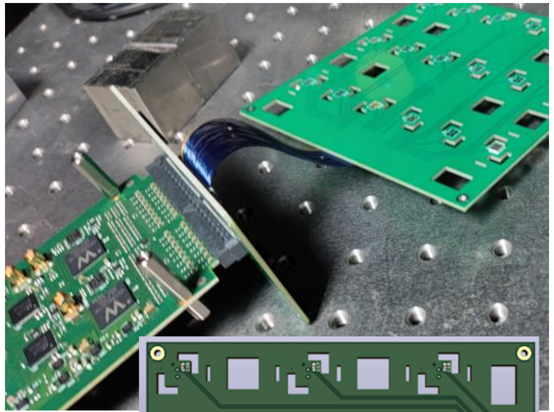
Beam-test early-stage preparations

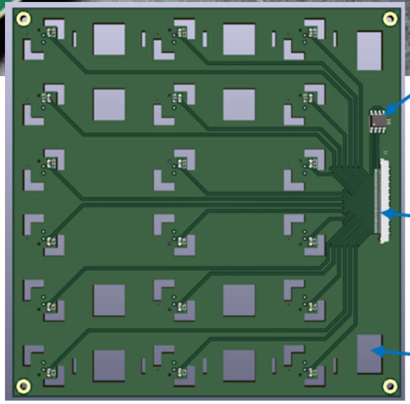




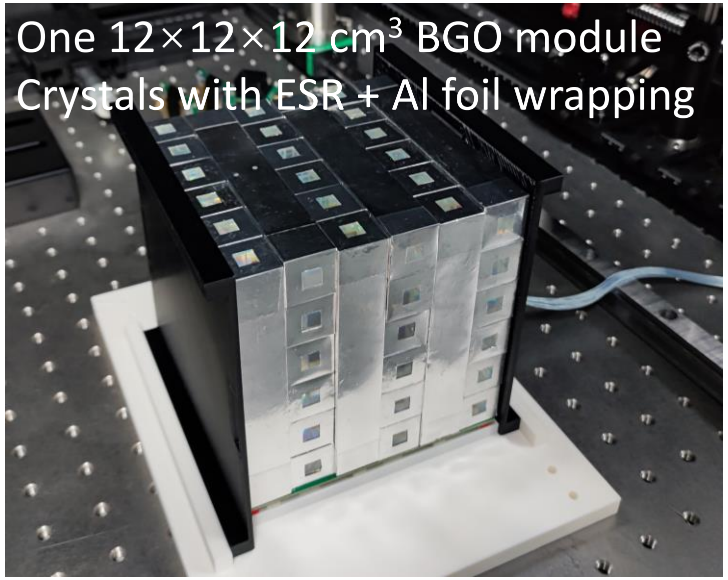
Batch test of BGO crystals

PCB design and electronics test





3×3mm² SiPMs with 10/15 µm pixel used

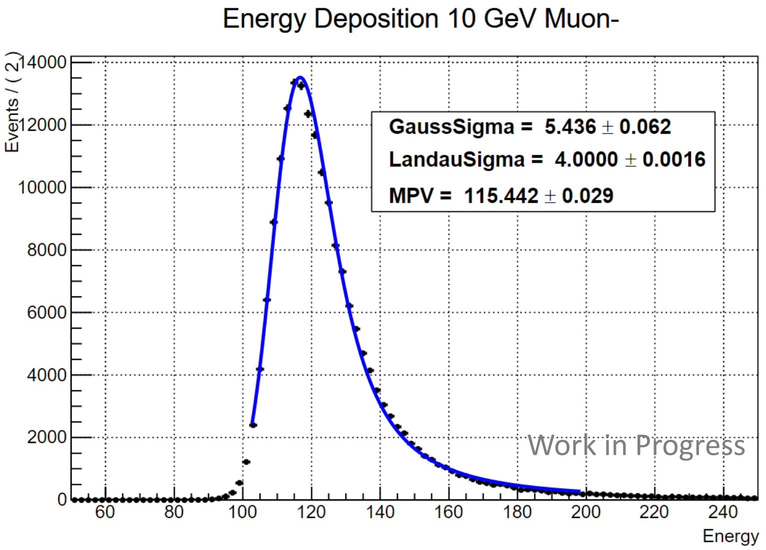


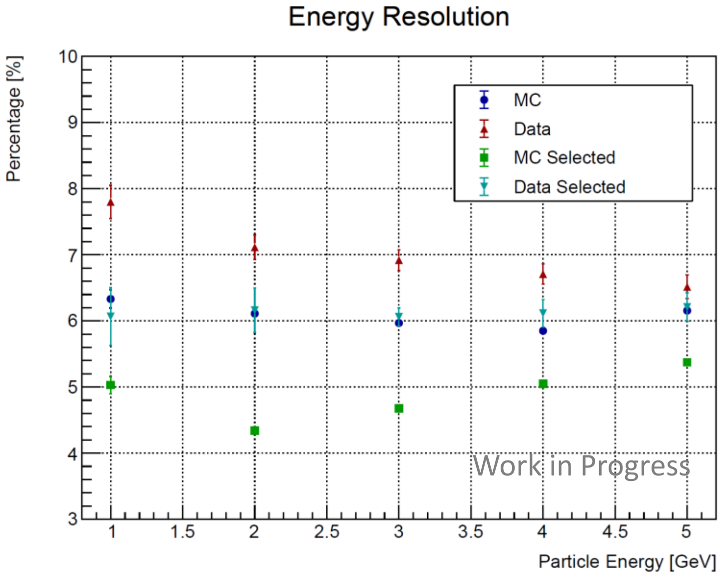
Support structure design and module assembly test

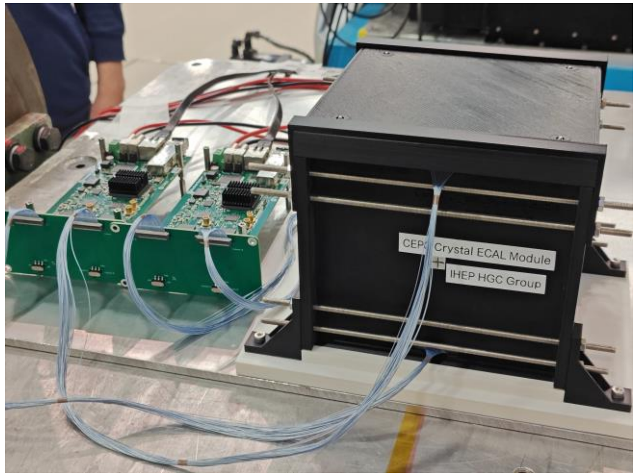
2023 CERN beam-test of the crystal module

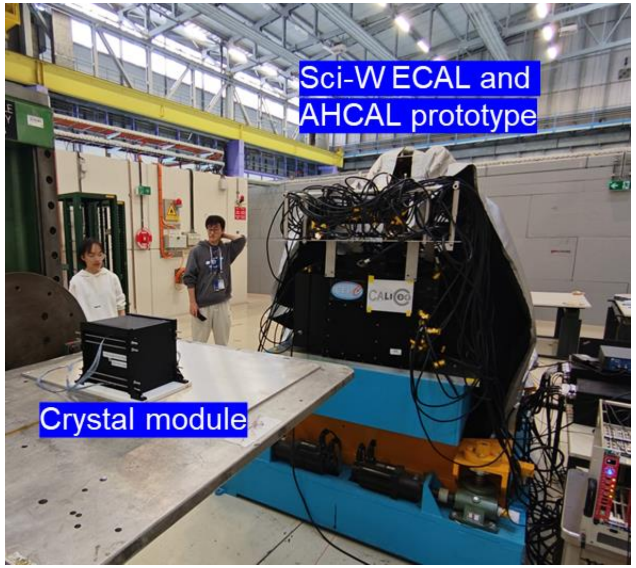
CERN PS T9 beamline: parasitic runs with CEPC calorimeter prototypes

- Muon data: MIP calibration
- Electron data: energy response
  - 1-5 GeV/c electrons, select events hitting at the central 2 bars
  - Geant4 simulation: crystal module geometry, upstream material, beam profile, momentum spread (0.5% FWHM)…









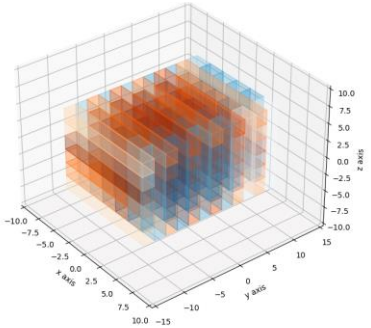
- Successful commissioning of the first module
- Clear MIP peak obtained with muon beam
- Electron beam for data/MC validation: further studies on MC digitization needed

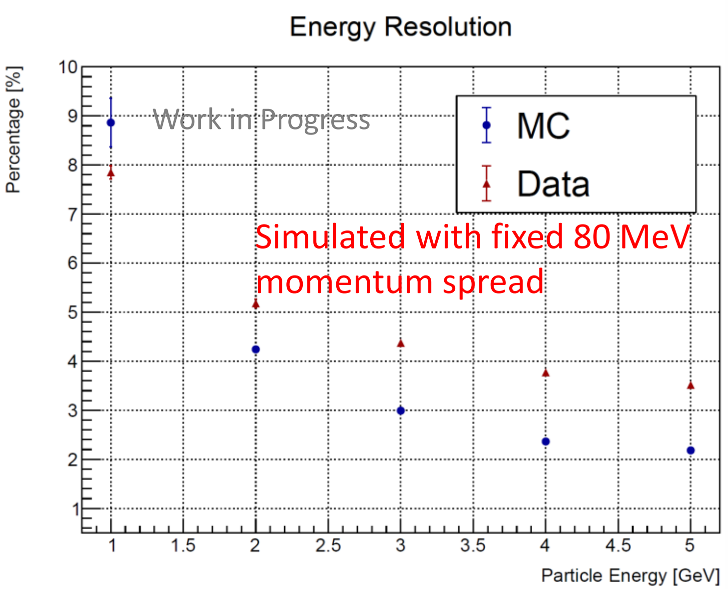
Significant energy leakage ($10.7X_0$)

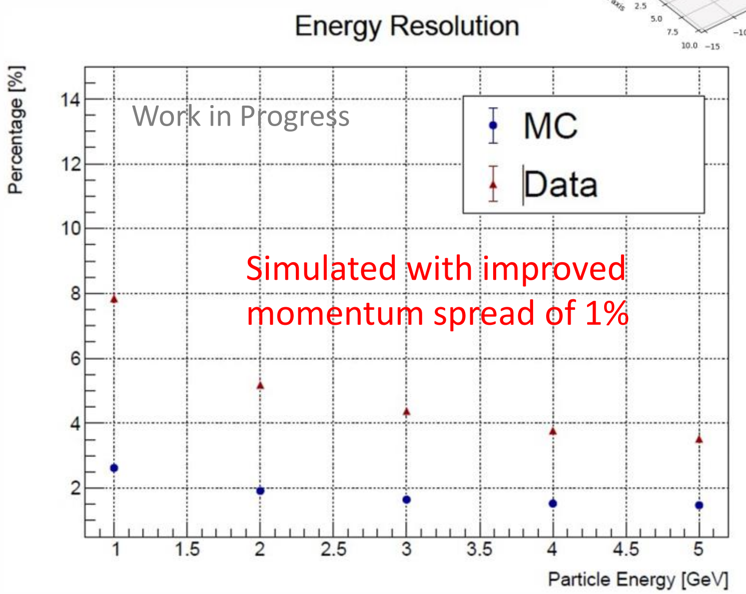
2023 DESY beam-test of the crystal modules

DESY TB22 beamline: $21.4X_0$ crystal module, twice thickness

- 1 cm^3 triggers for better collimation
- 1-5 GeV/c electrons: energy response
- Challenge with beam site: uncertain momentum spread







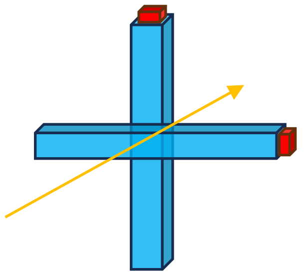
- EM resolution: significantly affected by beam momentum spread
  - Description of beam momentum spread has to be refined
- Lack of in situ MIP calibration without muon beam
  - Further calibration and data analysis needed

★ Planned beam-test in June 2024 at CERN PS: further study and understanding of the performance of crystal modules

New material worth R&D: BSO crystal

Baohua Qi, Zhiyu Zhao (TDLI/SJTU)

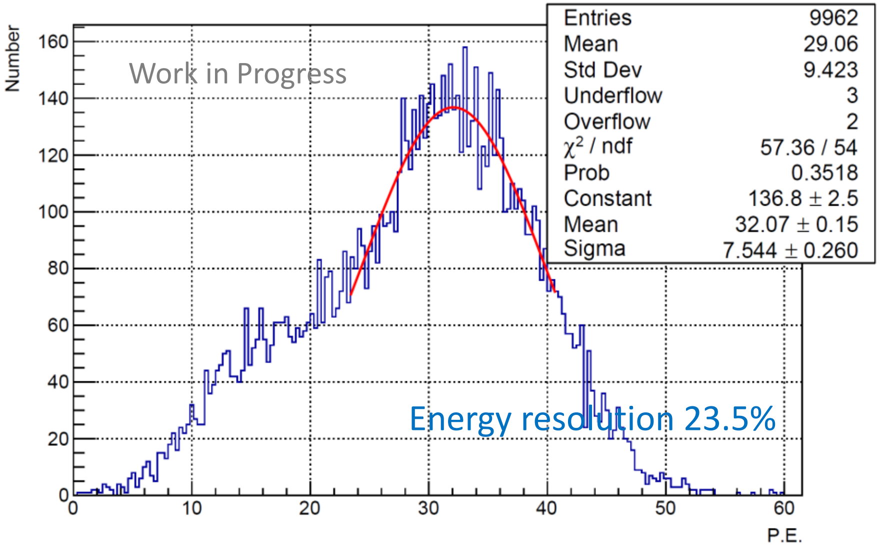
- BSO crystal: similar density, faster decay time than BGO
  - Potential for better time resolution
- Radioactive source test / cosmic-ray test
  - 1×1×7 cm^3 BSO with Teflon wrapping

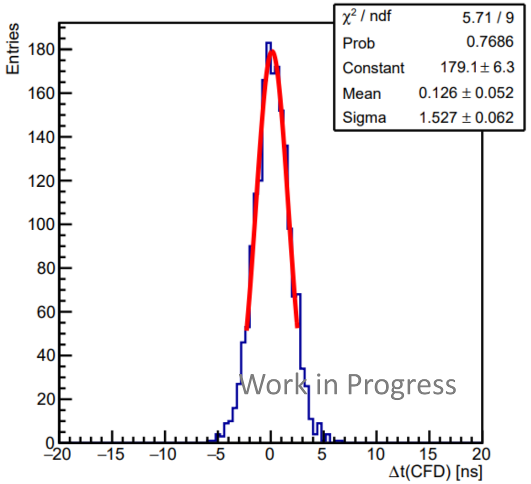


Cosmic-ray test: coincidence of 2 crystals, readout from one side

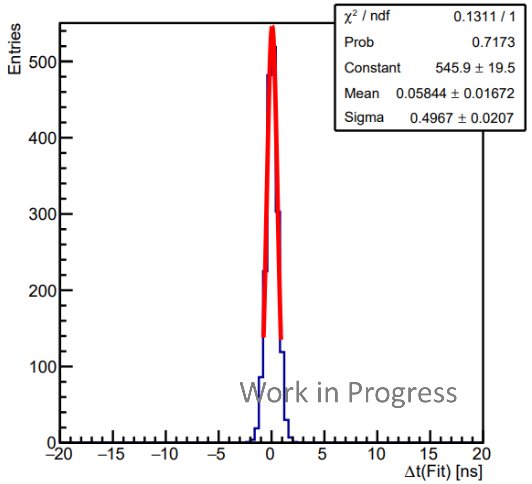
$Bi_4Si_3O_{12}$ crystal
- Density: 7.12 g/cm^3
- Light yield: ~3000 p.e./MeV
- Decay time: ~100 ns

Cs-137 test with S13360-6025PE





CDF 10%: ~1.5ns



Fitting 10%: ~0.5ns

- Generally good energy resolution for energy calibration
- MIP time resolution ~0.5 ns, good crystal candidate for time measurements, 2-side readout experiments ongoing
- The other properties need further studies (e.g. mechanical processing capability for long bar)

Summary and prospects

Campaign on high-granularity crystal ECAL R&D

- Geometry design: optimizing
- Software development: dedicated for long bar
- Hardware activities: lab/beam experiments
  - Validating crystal ECAL design specs

- Next beam-test at CERN PS
  - Crystal module performance
  - Study with long crystal bars
- Further issues
  - Calibration scheme: ageing, radiation damage
  - Temperature control, etc.

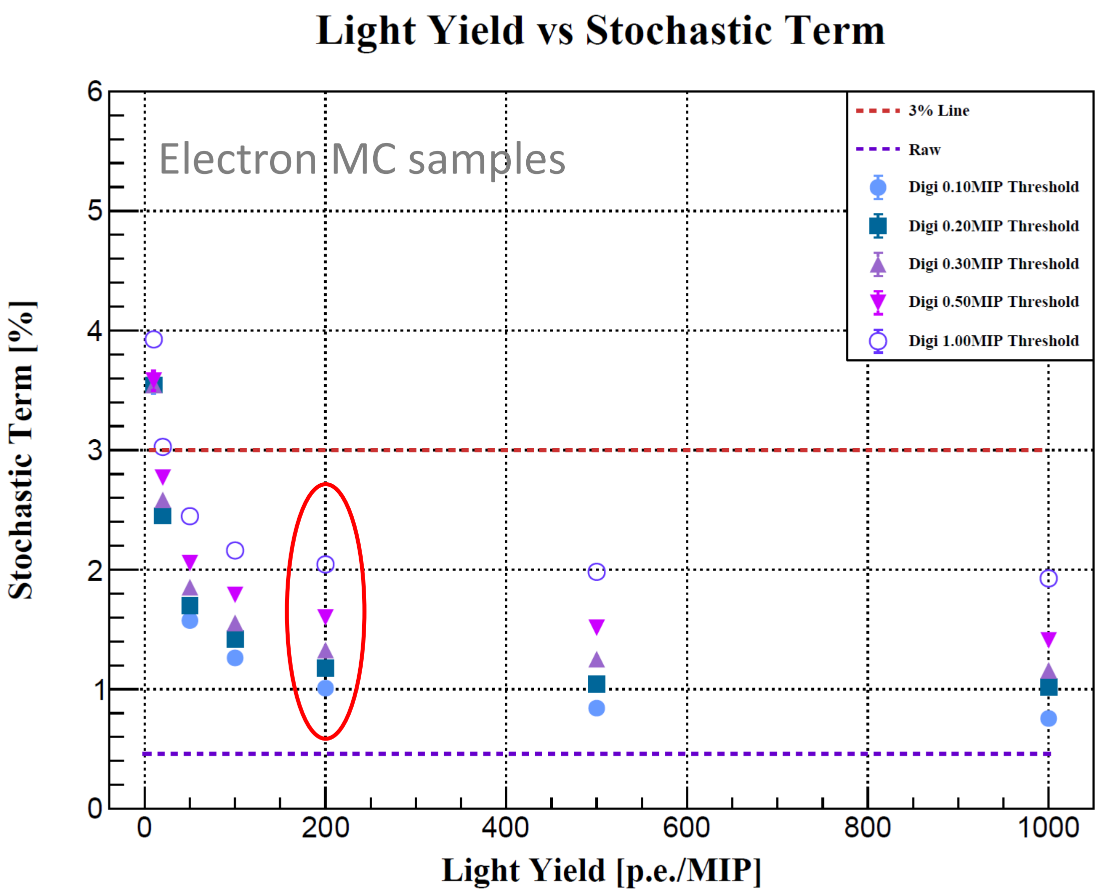
Thanks to every teammate for their contributions!

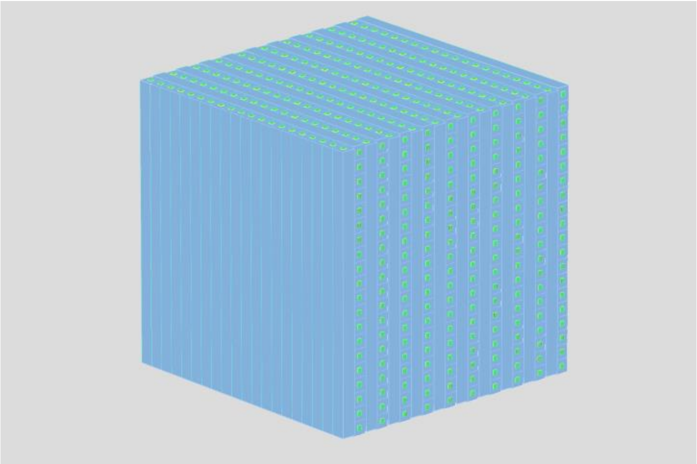
Backup

EM energy resolution: light yield requirements

Geant4 Simulation (v11.0)

- Light yields: number of detected photons per MIP
- Energy resolution: need stochastic term < 3%





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

- Good resolution requires
  - Moderately high light yield → dynamic range
  - Low energy threshold → noise level

Key requirements

- Light yield required for one crystal: ~200 p.e./MIP (1 cm BGO)