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

High-granularity Crystal ECAL R&D for Future Higgs Factories

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On behalf of CEPC Calorimeter Working Group

中国物理学会高能物理分会第十四届全国粒子物理学术会议
August 12-18, 2022

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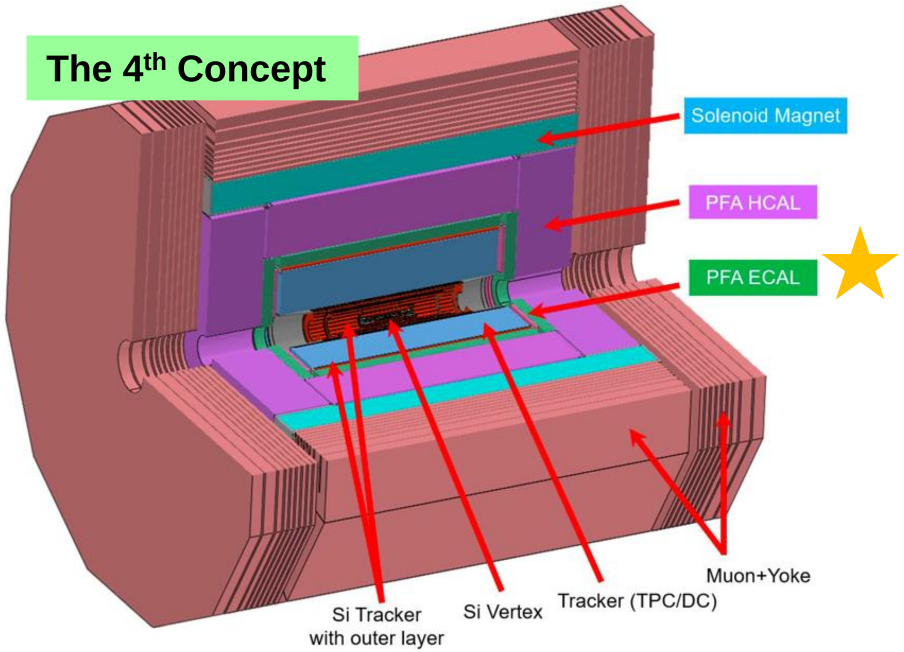
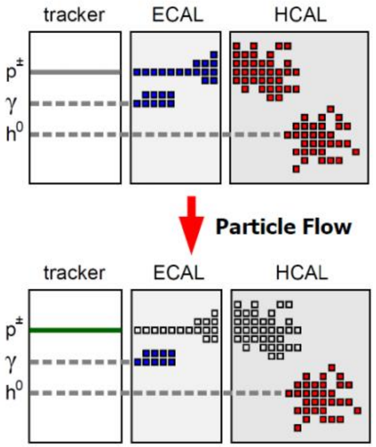
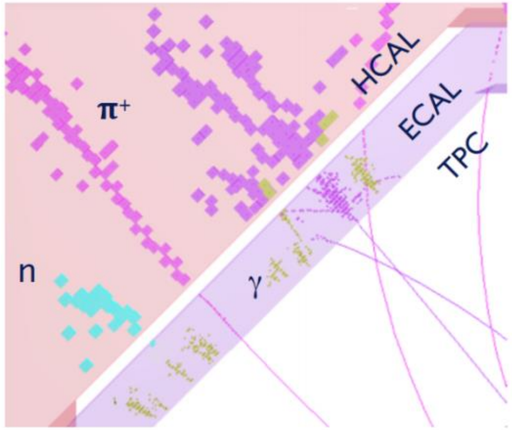
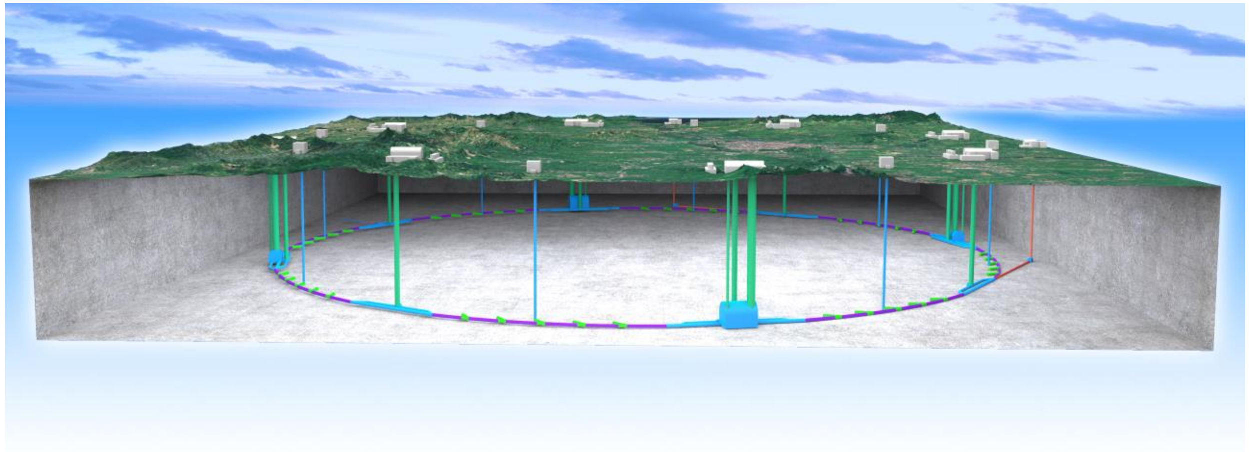
Motivations for crystal ECAL

- Calorimeter for future lepton colliders (e.g. CEPC, FCC-ee, ILC, CLIC…)
  - Precise measurement of Higgs/Z/W bosons, BSM physics, etc.
  - Detector requirement: targeting 3% level Boson Mass Resolution (BMR)
- Particle-flow oriented detector: “CEPC 4th concept”
  - High-granularity homogeneous crystal ECAL
    - 5D detector: 3D spatial + energy + time
    - Intrinsic EM energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Scintillating glass HCAL (Poster)
    - High density for better energy resolution/BMR
    - More compact and cost-effective









Physics performance: CEPC detector with crystal ECAL

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

- First study with 1 cm^3 crystal cubes under CEPC Software with Arbor-PFA
- Crystal ECAL: competitive option for better performance
- SiW ECAL (CEPC baseline) vs Crystal ECAL (4th 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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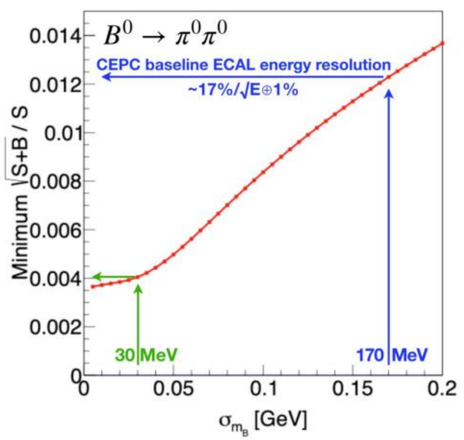
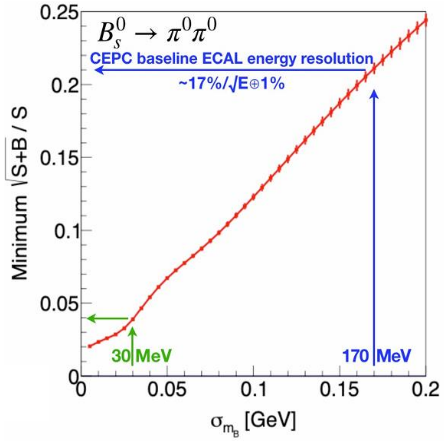
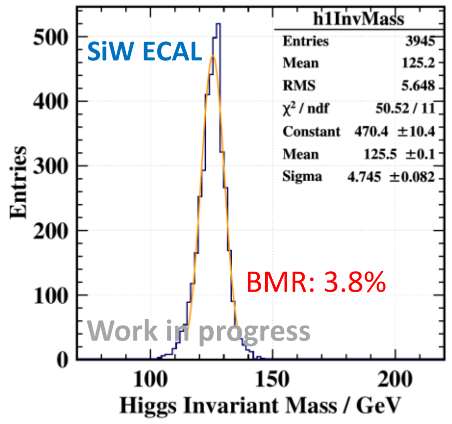
ECAL Resolution	σ_{m_B} (MeV)	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$
$17\%/\sqrt{E} \oplus 1\%$	170	~ 1.2%	~ 21%
$3\%/\sqrt{E} \oplus 0.3\%$	30	~ 0.4%	~ 4%

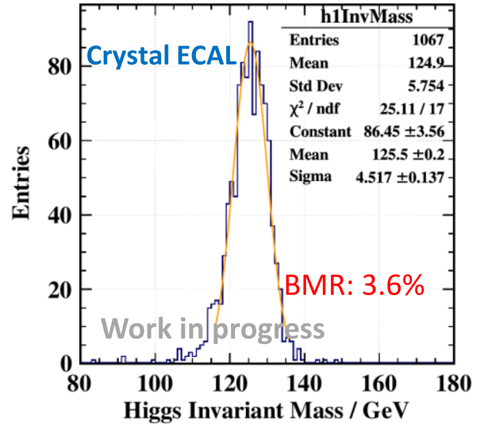
3~5 times improvement in their final precision $\sqrt{S+B}/S$



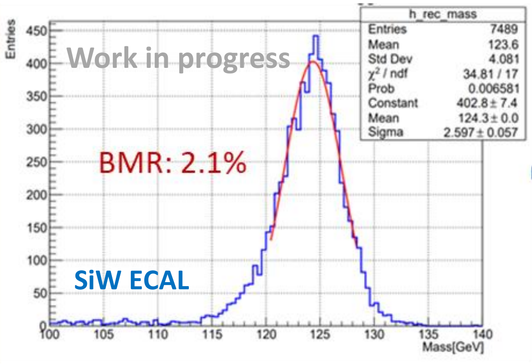


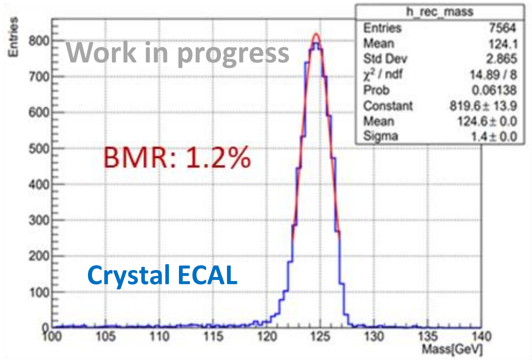
BMR ($H \to gg$)





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

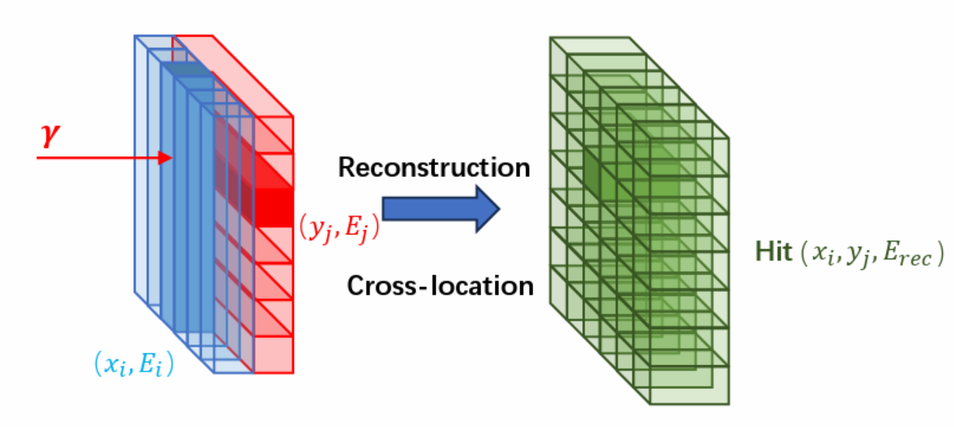


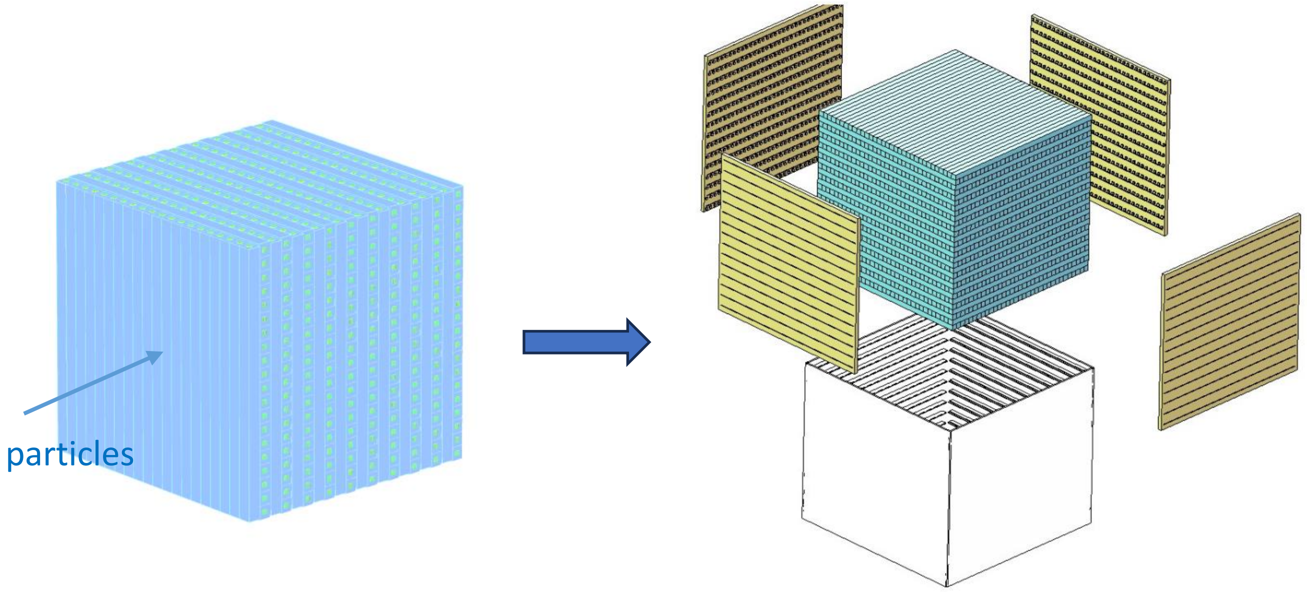


Design of the long crystal bar ECAL

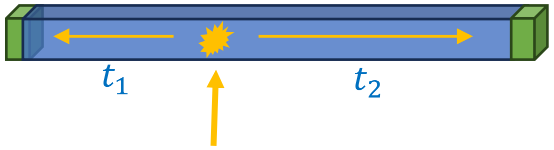
- $1 \times 1 \times 40$ cm^3 crystal units, double-side readout with SiPMs
- Crisscrossed arrangement between layers

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





- 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

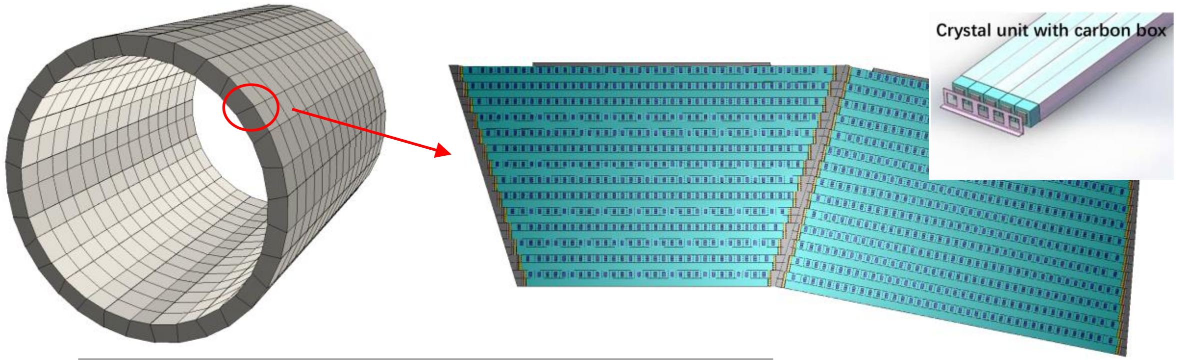


- Key issues need to be validated
  - Dedicated reconstruction software
  - Mechanical design
  - System-level performance

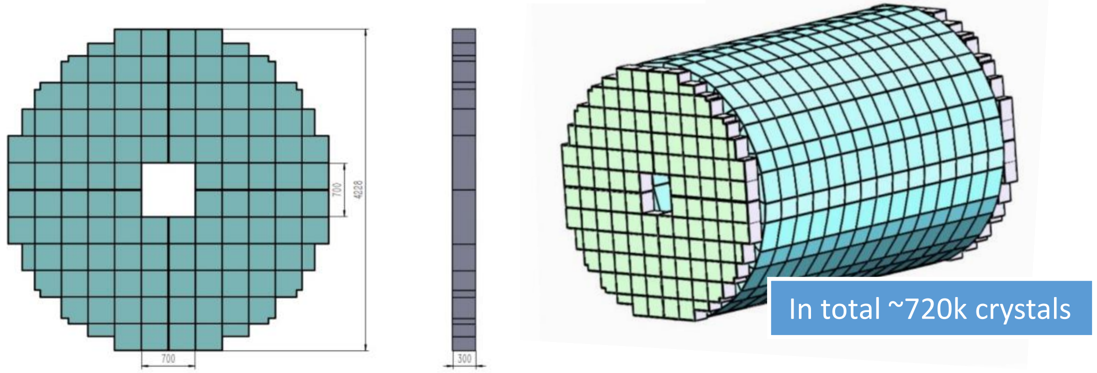
Latest R&D activities on geometry and software

- 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

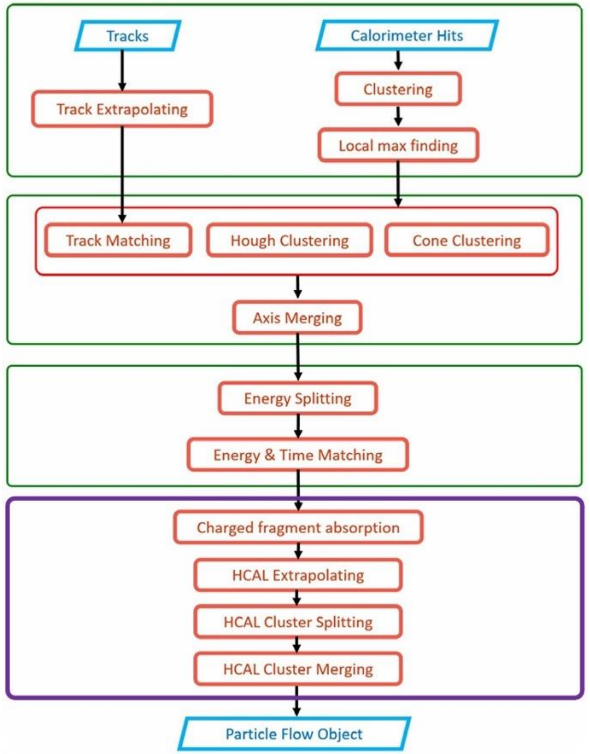


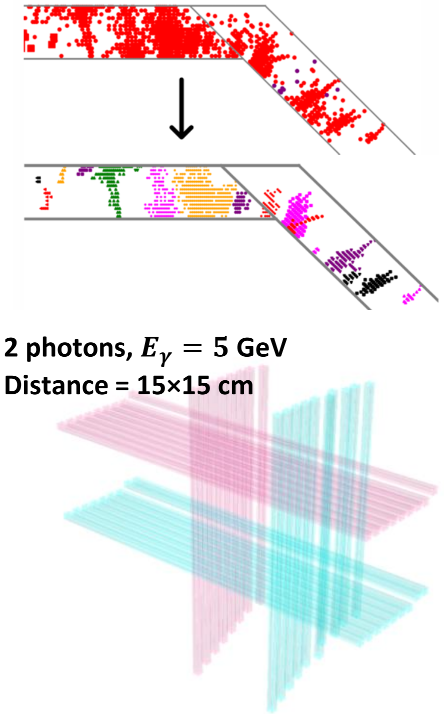
- Disc-shaped endcaps made up of square towers



Quan Ji, Shaojing Hou, Weizheng Song(IHEP)

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





Talk: *Particle Flow Algorithm for Long Crystal Bar ECAL*

Weizheng Song, Yang Zhang, Fangyi Guo (IHEP)

Crystal ECAL: specifications

Key Parameters	Value	Remarks
MIP light yield	~200 p.e./MIP	Ensure EM resolution $\sim 3\%/\sqrt{E}$
Energy threshold	0.1 MIP	Depends on S/N and light yield
Crystal non-uniformity	< 1%	Along the crystal length and between crystals
Dynamic range	0.1~3000 MIPs / channel	Maximum deposited energy in 360 GeV Bhabha events
Timing resolution	~500 ps @ 1 MIP	For position reconstruction
Temperature stability	Stable at ~0.05 ℃	Reference from CMS ECAL

**Preliminary requirements, updating with growing understandings*

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
- Dynamic range of electronics
- Time resolution: different crystal sizes/Edep
- Energy response of crystal module

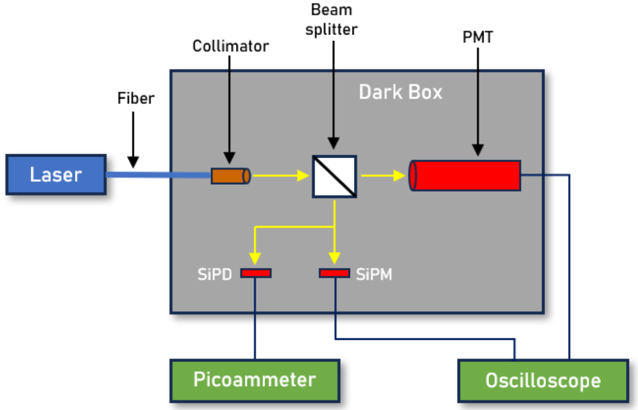
Lab tests and beam tests

Poster: Studies on timing performance of BGO crystal scintillator

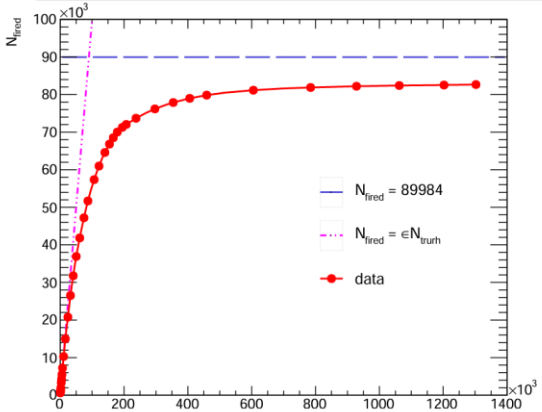
Lab test: SiPM response, crystal uniformity, electronics, etc.

- SiPM candidates: 3×3 mm^2, 10 μm pixel pitch
- Intrinsic dynamic range test
  - Pico-second laser: photons arrive at the same time
  - PMT: scale for light intensity

Laser test setup

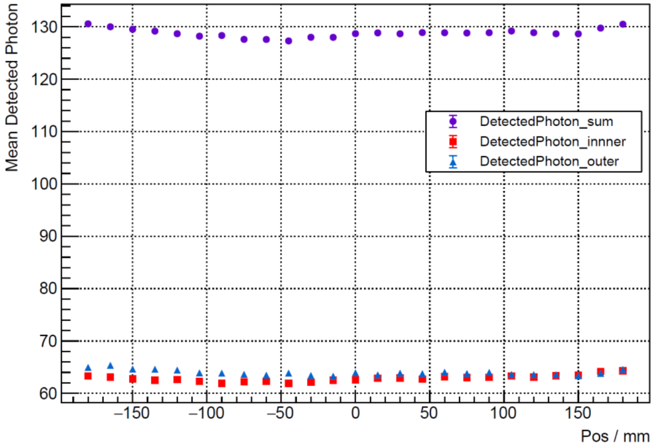


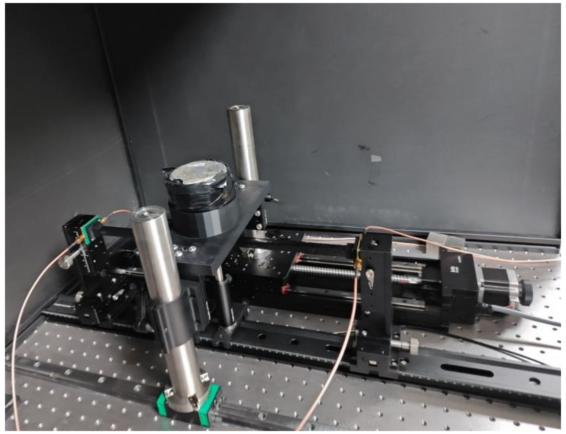
Experiment: Laser + SiPM



- Crystal candidate: 1×1×40 cm^3 BGO crystals
- Radioactive source scan

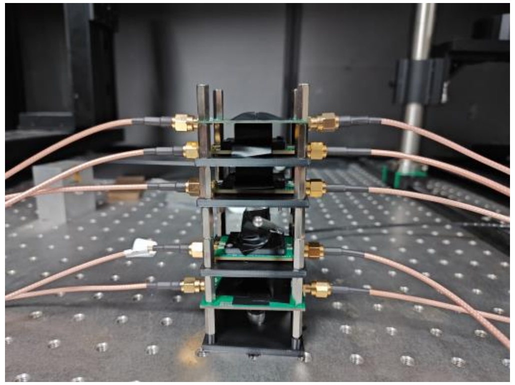
Response uniformity air-coupled

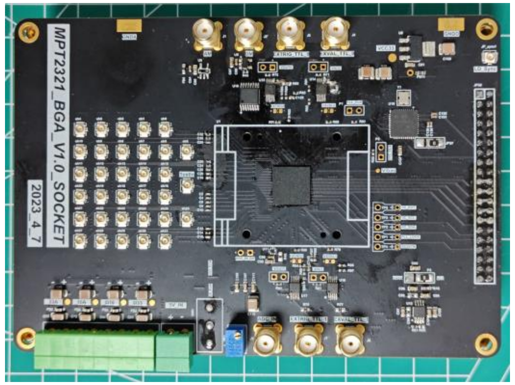


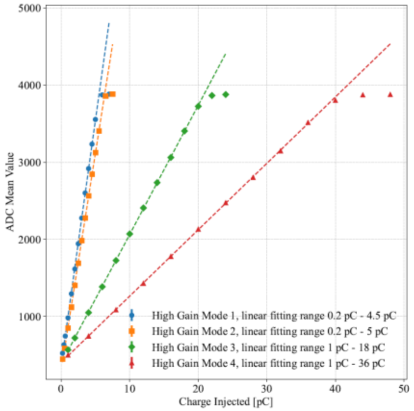


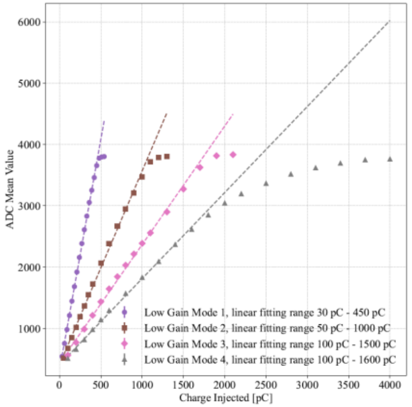
Automated crystal scan platform

- Electronics
- MPT-2321 chip
- High dynamic rage ASIC for SiPM readout
- Charge injection and cosmic-ray tests



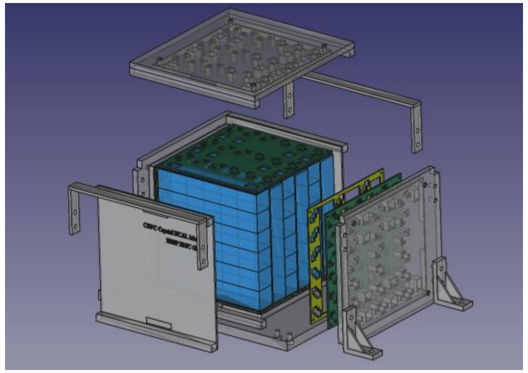




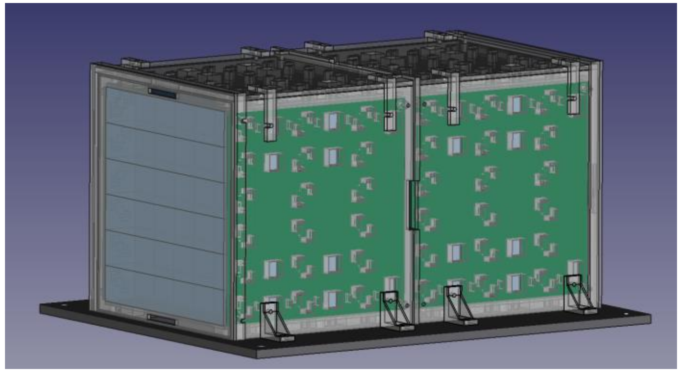


Energy response of crystal module: introduction

- 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
- Module design
  - 72 BGO crystals (2×2×12 cm^3 bars)
  - Self-designed PCBs with 10/15 μm pixel SiPMs
  - 3D printed support structure
  - Citiroc-1A readout chips

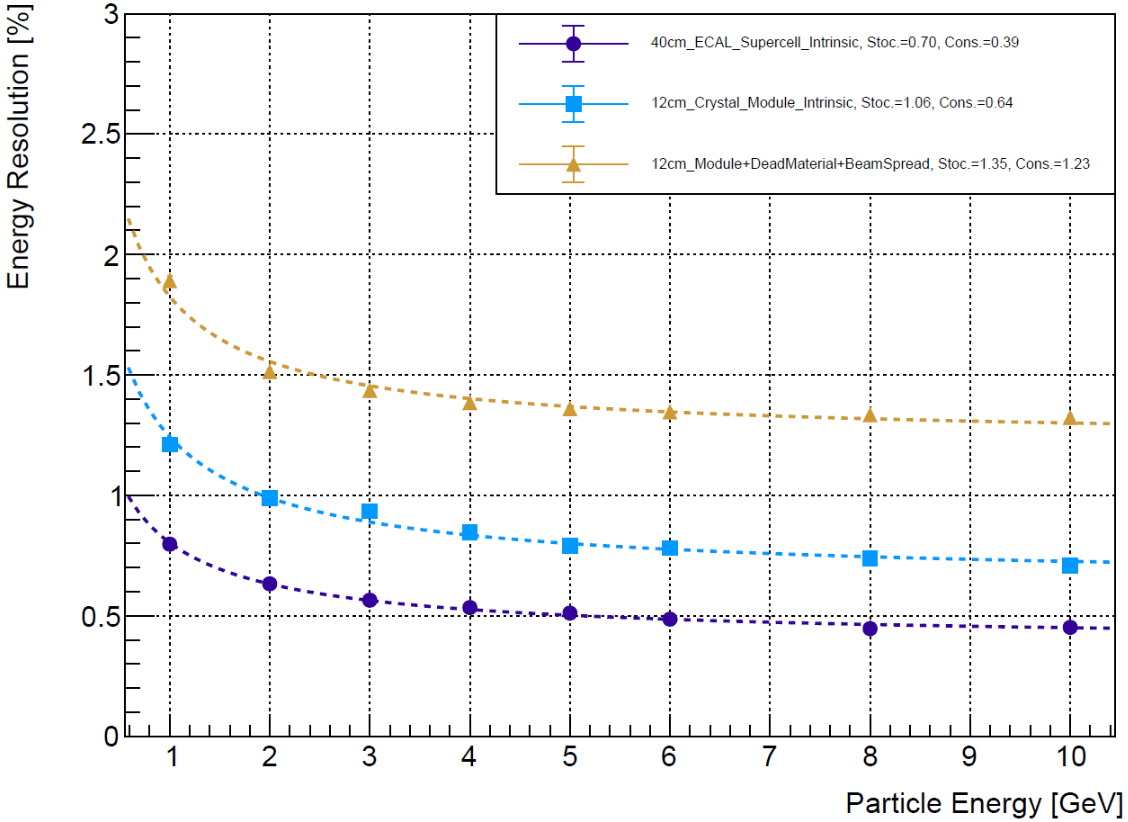


72 channels , $10.7X_0$



144 channels, $21.4X_0$

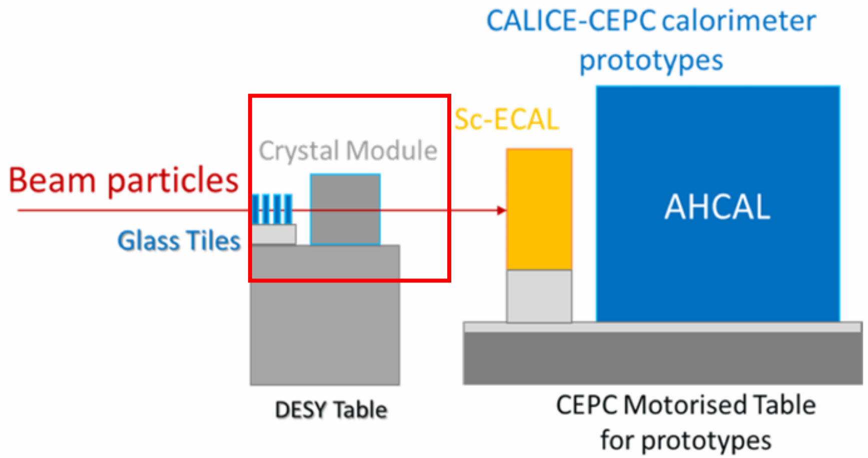
Energy response: 12cm module vs 40cm supercell

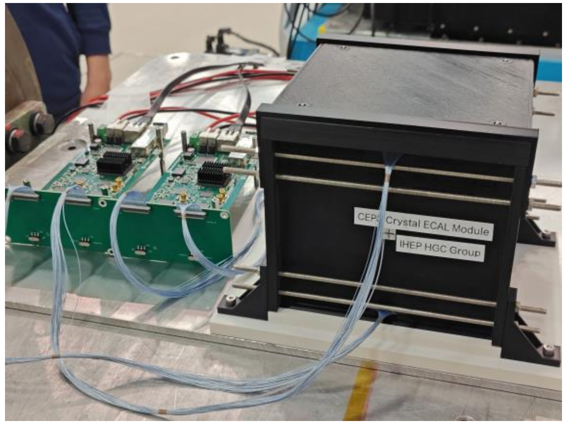


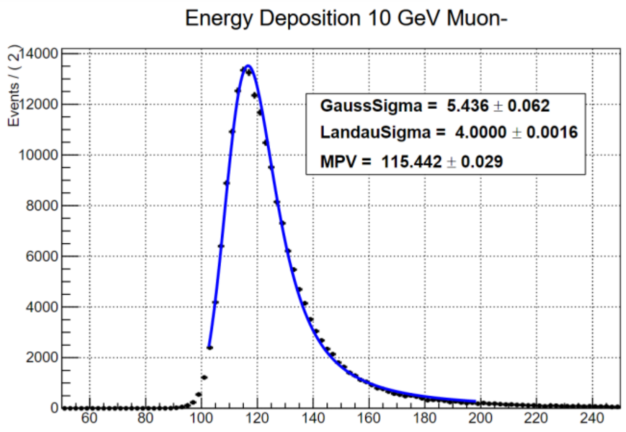
- Intrinsic energy resolution better than 3%
- A small module is feasible for 1- 10 GeV energy response study

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

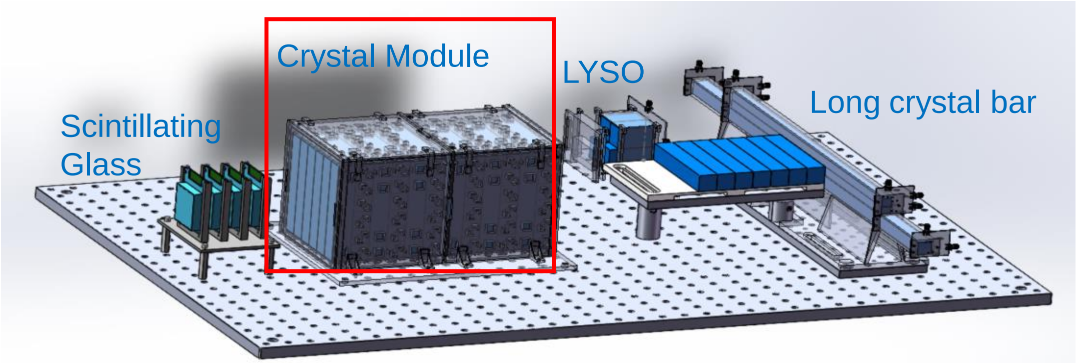
- Beamtest at CERN T9 beamline (2023)
  - $10.7X_0$ module for commissioning and parasitic tests
  - Muon, electron and pion beam

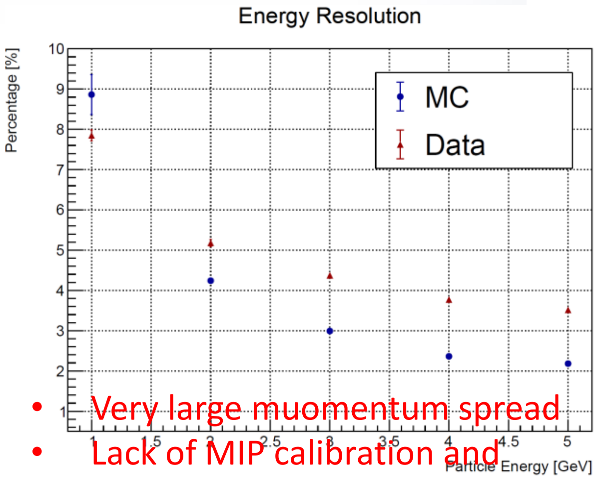






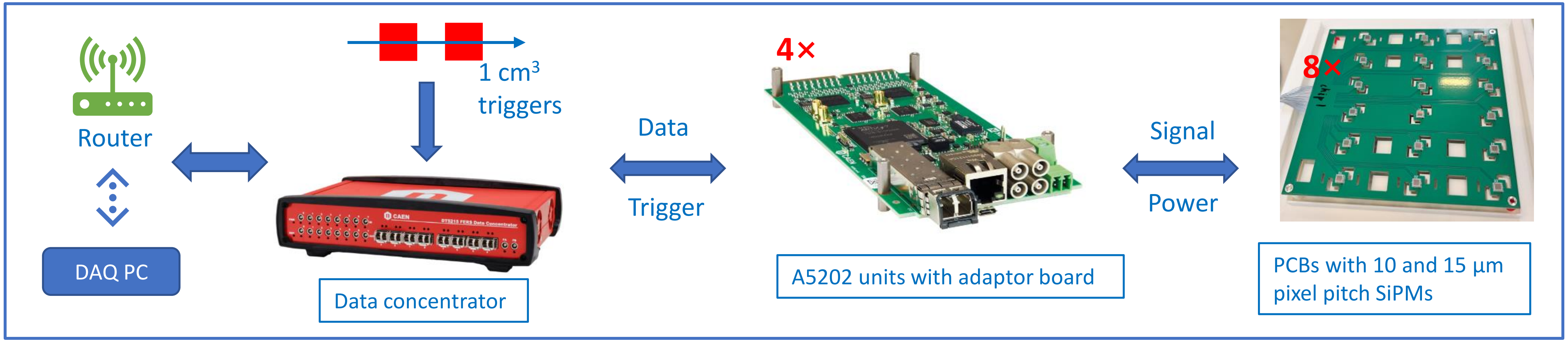
- Beamtest at DESY TB22 beamline
  - $21.4X_0$ module for EM energy response study
  - Electron beam

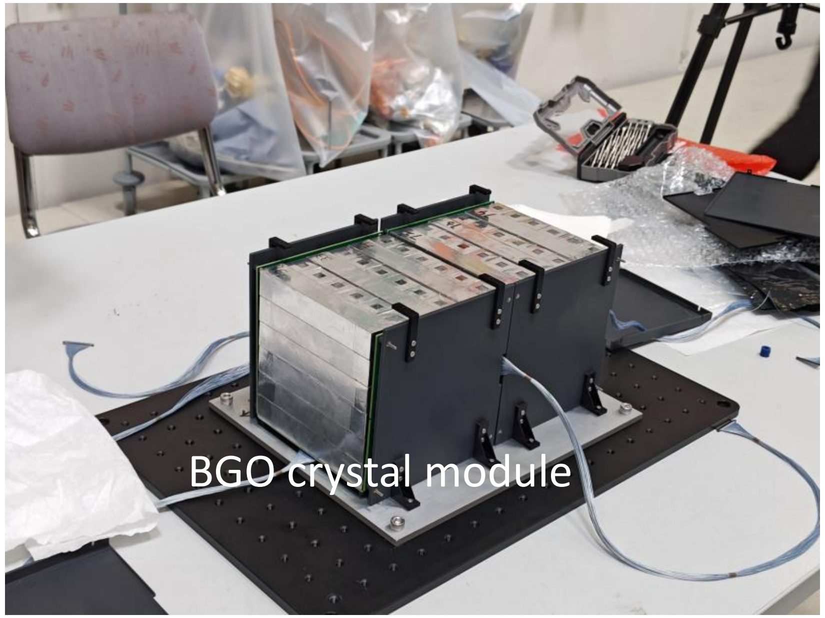


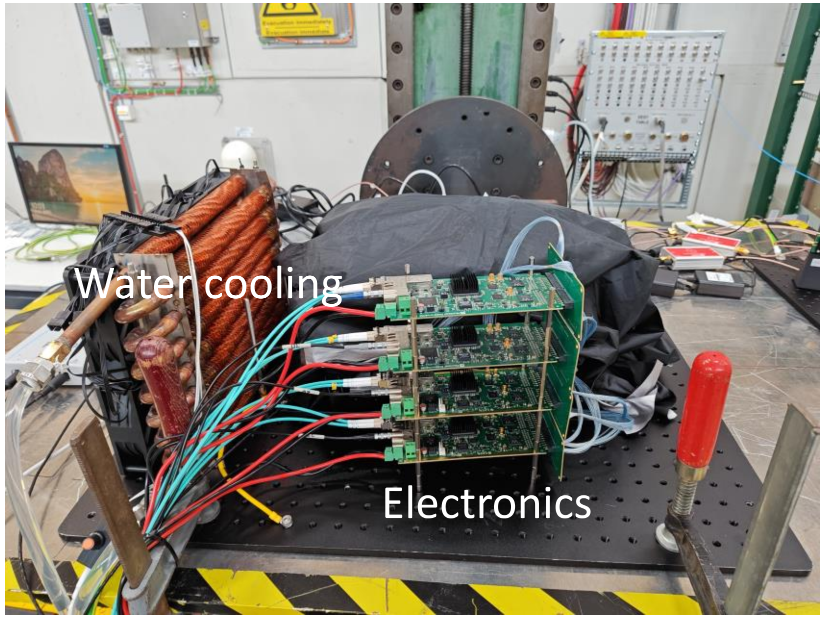


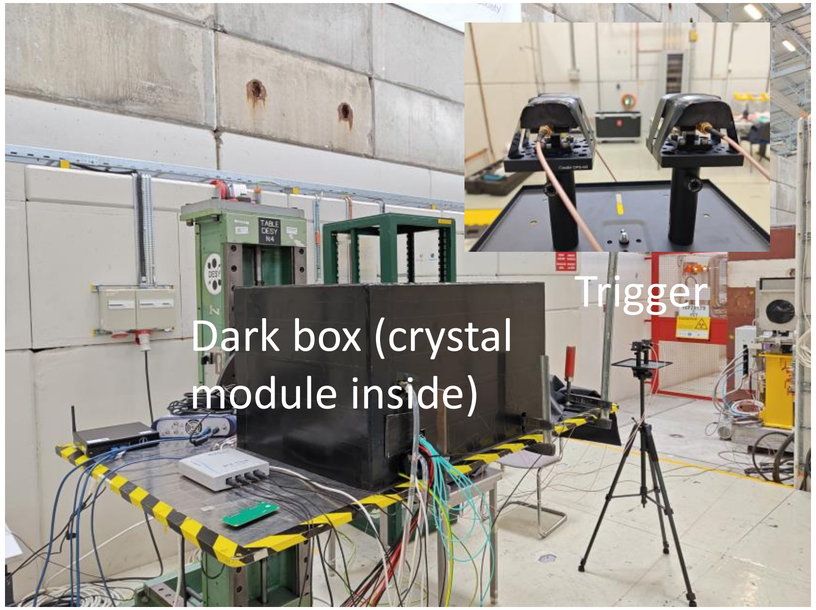
- Very large muomentum spread
- Lack of MIP calibration and temprature control

Overview of 2024 CERN beamtest: improved setup







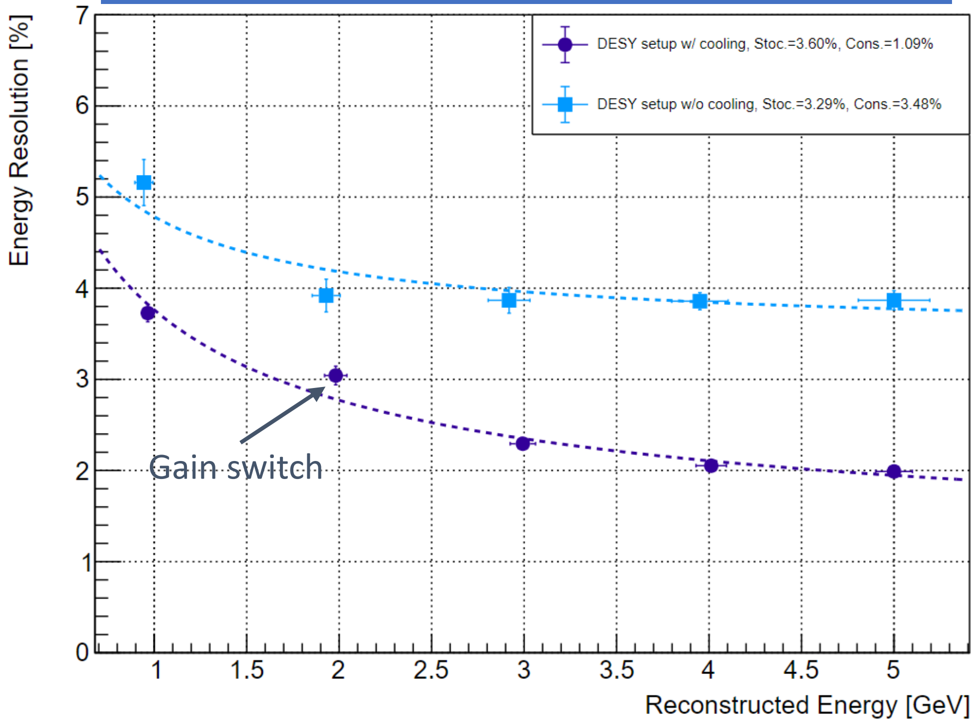


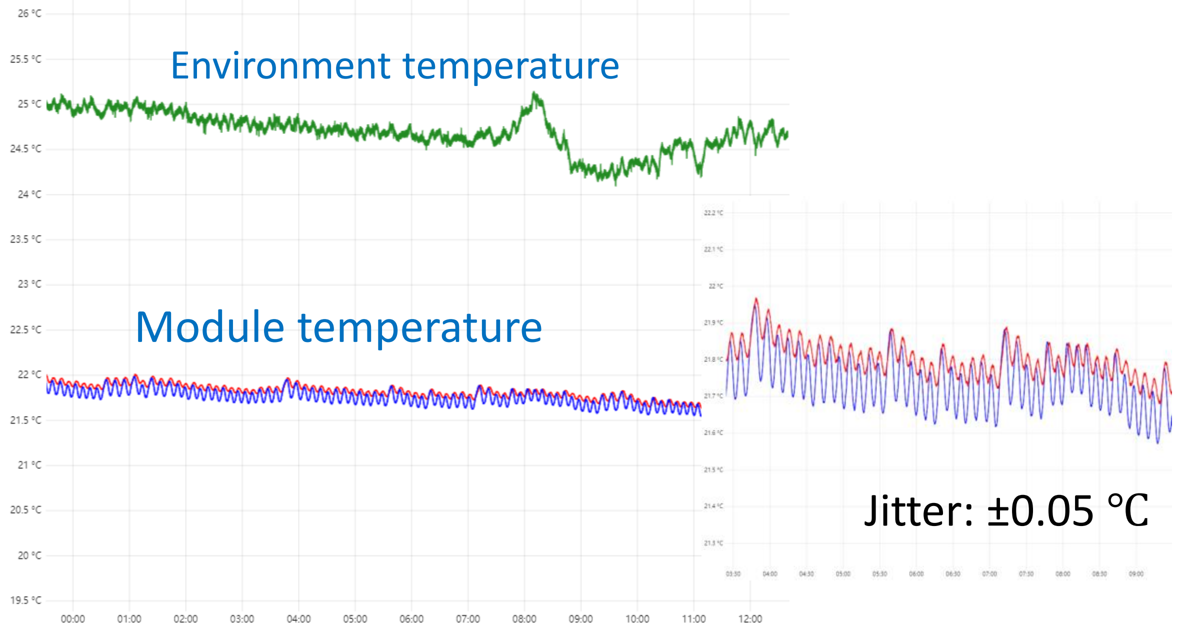
2024 CERN beamtest: test with DESY parameters

- CERN T9 beamline: $21.4X_0$ BGO crystal module
  - Repeat electron beamtest with the same parameters as DESY

- 1 cm^3 triggers: better collimation
- Cooling system: provide a stable temperature
- Beam momentum spread: ~1%
- 1-10 GeV/c electrons: energy response study
- 5/10 GeV/c Muon beam: MIP calibration

Energy resolution: DESY parameters





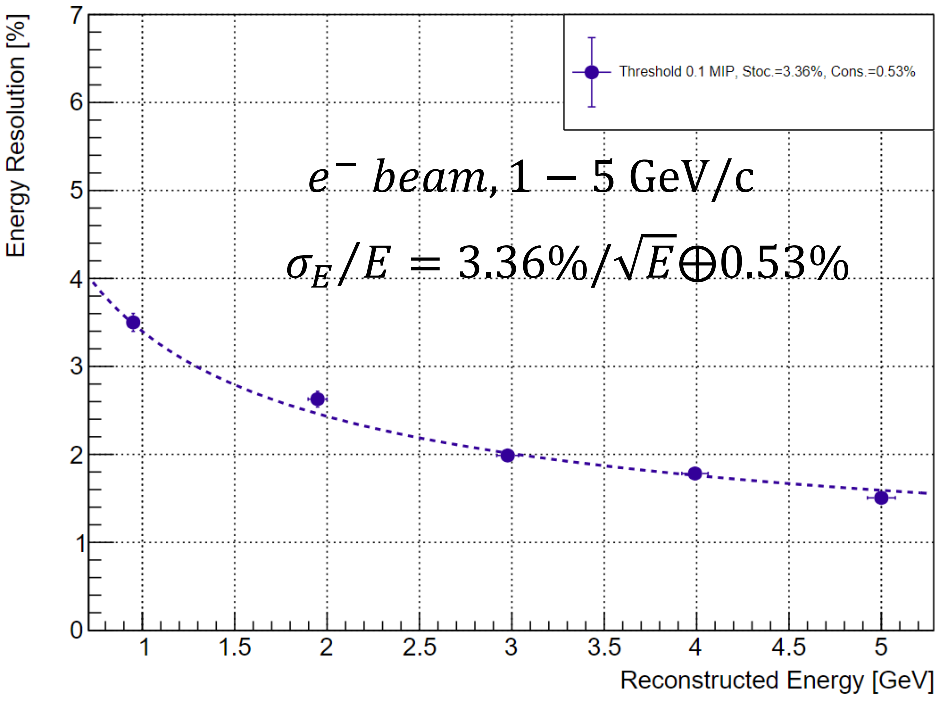
- Improved performence (~8% (DESY) → ~4% @ 1 GeV)
- Confirmed the necessity of the cooling system

- With a water cooling system, the temperature jitter can be controlled at ±0.05 ℃ level
- Environment temperature still has an impact

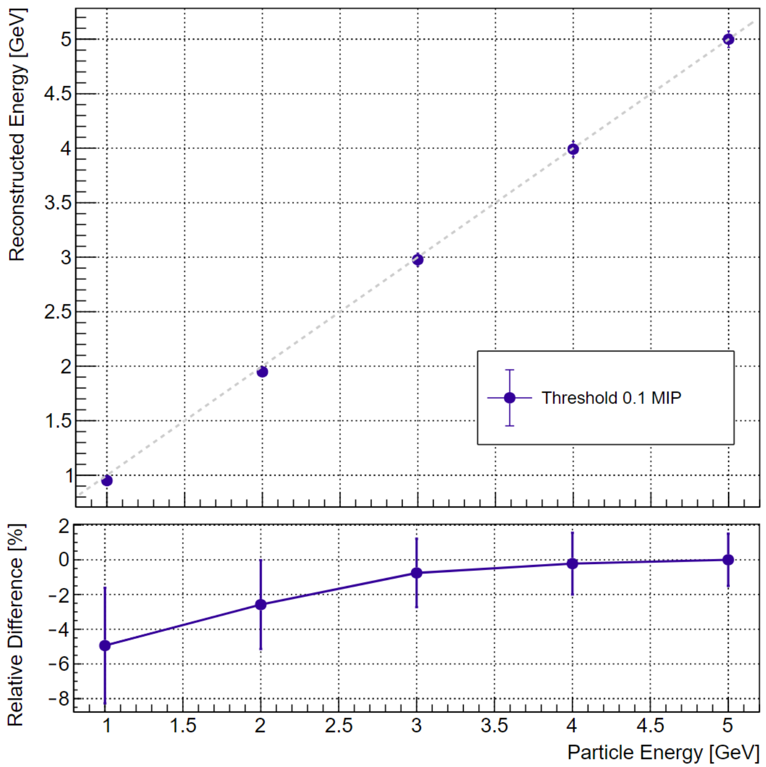
2024 CERN beamtest: test with new parameters

- CERN T9 beamline: $21.4X_0$ BGO crystal module
  - New setup of electronics: 18 channels per Citiroc-1A chip
  - Scan HighGain and LowGain values for best performance
  - Pion rejection with Cherenkov detector for 6-10 GeV electrons (still under analysis)

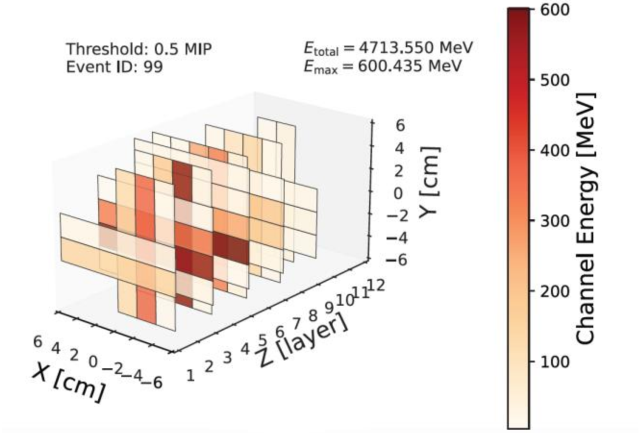
Energy resolution of crystal module



Energy linearity



- 5 GeV/c electron event display



- Successful electron data taking with good performance
- Energy linearity and resolution
  - Beam momentum spread
  - Gain switch of electronics
  - Pedestal stability
  - Saturation effects
  - Upstream material

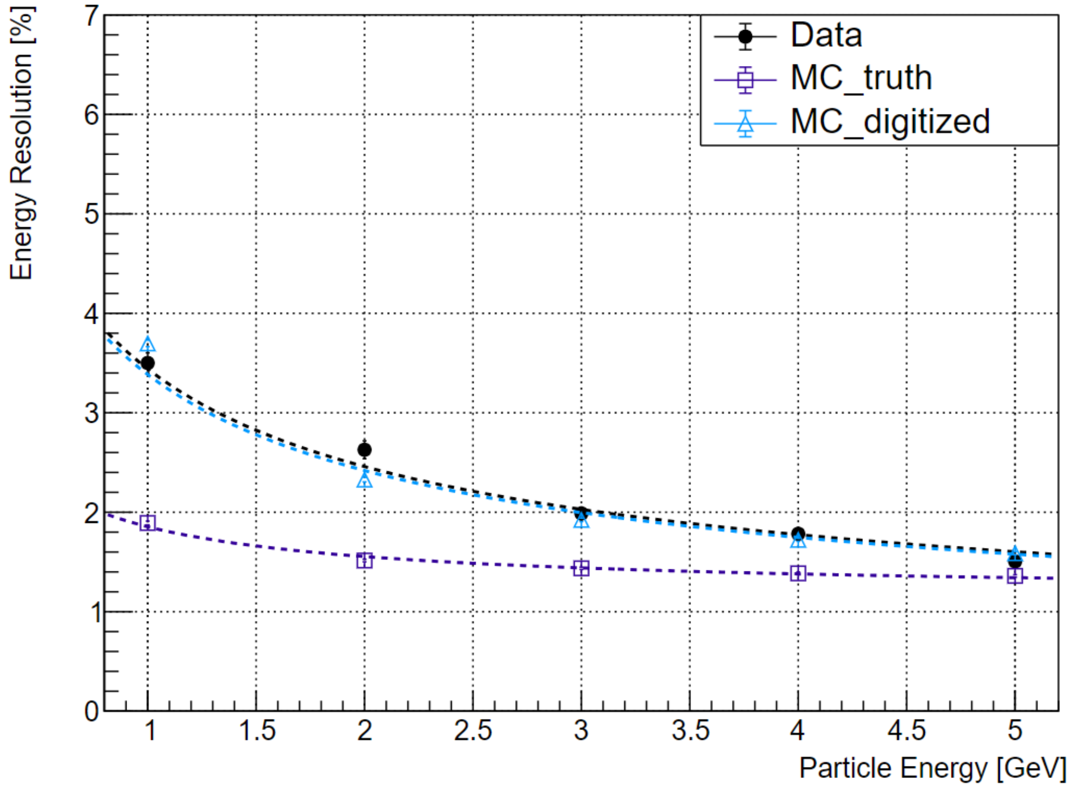
2024 CERN beamtest: MC validations

Geant4 Simulation (v11.1)

- CERN T9 beamline: $21.4X_0$ BGO crystal module, electron data
- Geant4 simulation: electron samples with the same geometry
  - Consider 1% beam momentum spread, upstream material

Digitization process
- Calibration and charge conversion precision: assuming 2%
- Noise level: gain-wise adjusted according to beam data
- MIP response: channel-wise adjusted according to beam data
- Consider HighGain and LowGain switch, electronic saturation
- Consider photon statistics, SiPM response non-linearity

Energy resolution: Data vs MC



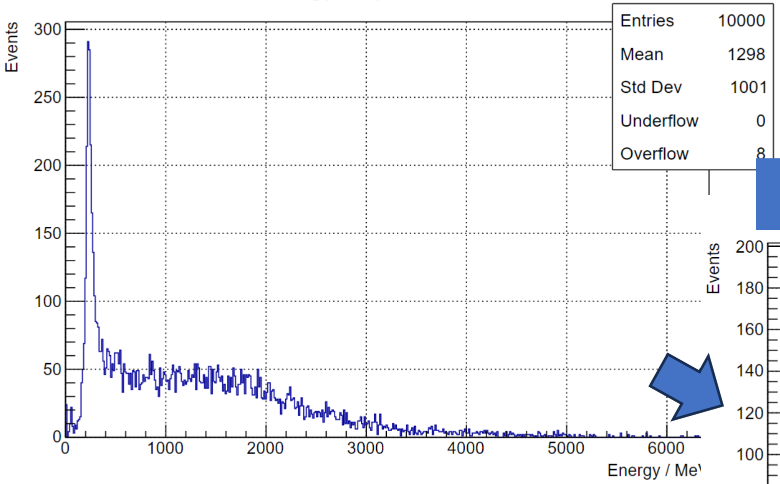
- Digitized MC shows a similar energy response to Data
  - Further investigation: saturation effect
  - Description of upstream material, noise could be improved

- Digitization tool has been preliminary validated with beam data
  - Estimated energy resolution of the ECAL is reasonable
  - Beamtest result shows, with further optimized SiPM, readout electronics, the crystal ECAL could give better than 3% level energy resolution

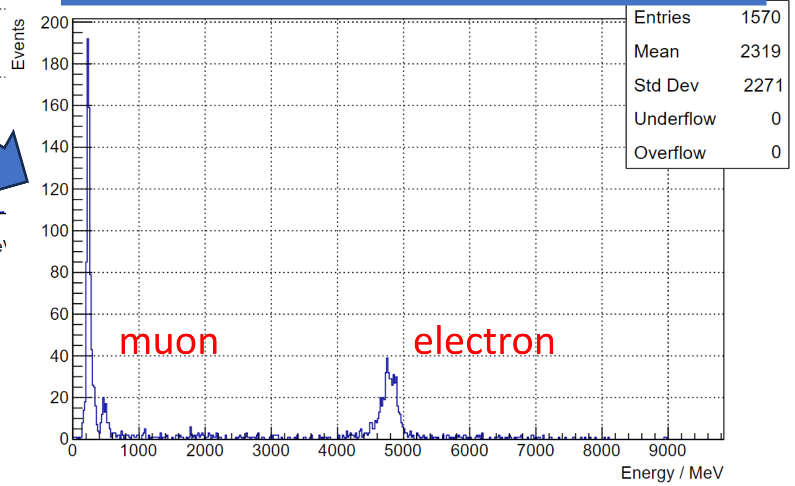
2024 CERN beamtest: preliminary studies with pion beam

- CERN T9 beamline: $21.4X_0$ BGO crystal module
  - Pion beam: study of pion response and beam purity

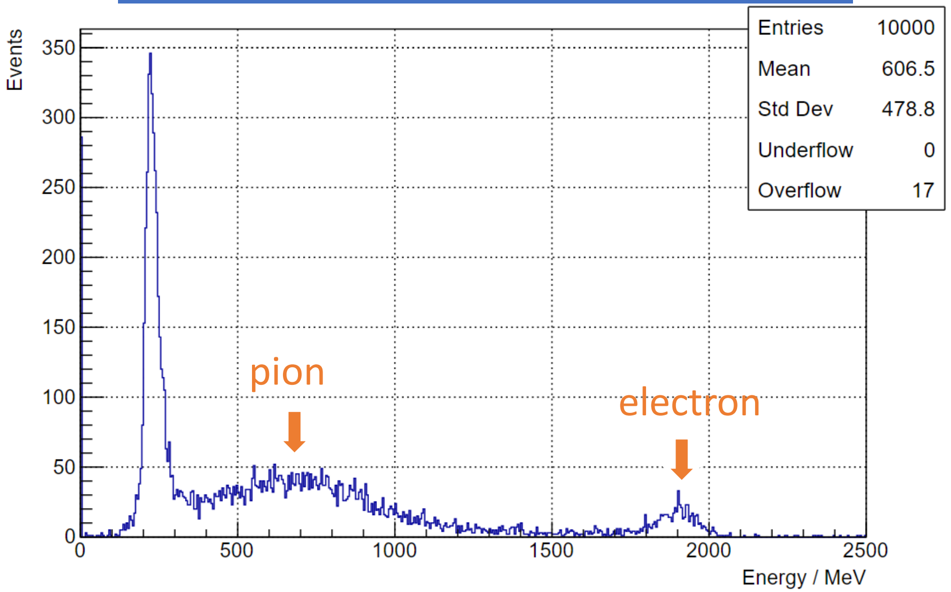
5 GeV/c pion-



5 GeV/c pion-: pion rejected



2 GeV/c pion-



- Pion response with BGO module ($\sim 1\lambda_I$)
- Impact on the resolution of the hadron calorimeter still need further studies

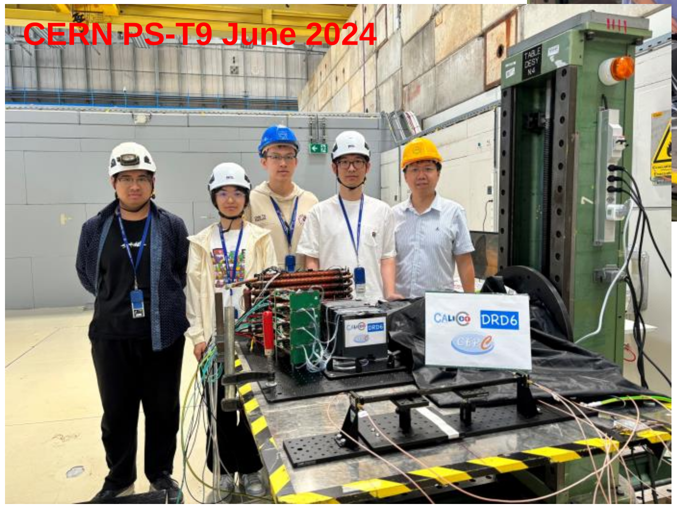
- Electron and muon exists in pion beam
- Proportion changes with energy, need further studies

Summary and prospects

Campaign on high-granularity crystal ECAL R&D

- Mechanical design: optimizing
- Software development: dedicated for long bar
- Hardware activities: lab/beam experiments
  - Crystal module validated 3% level EM resolution
  - Further validation of crystal ECAL design specs
- Further issues
  - Investigation on timing performance
  - Calibration scheme: ageing, radiation damage
  - New material studies
  - …

Thanks to every teammate for their contributions!

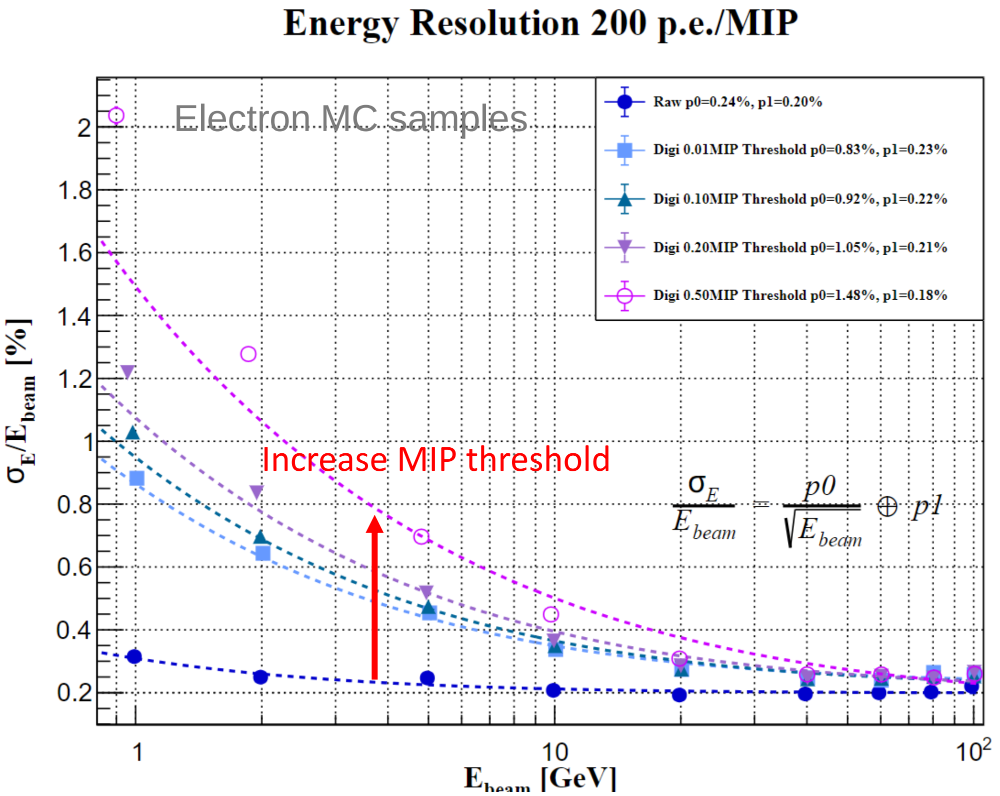


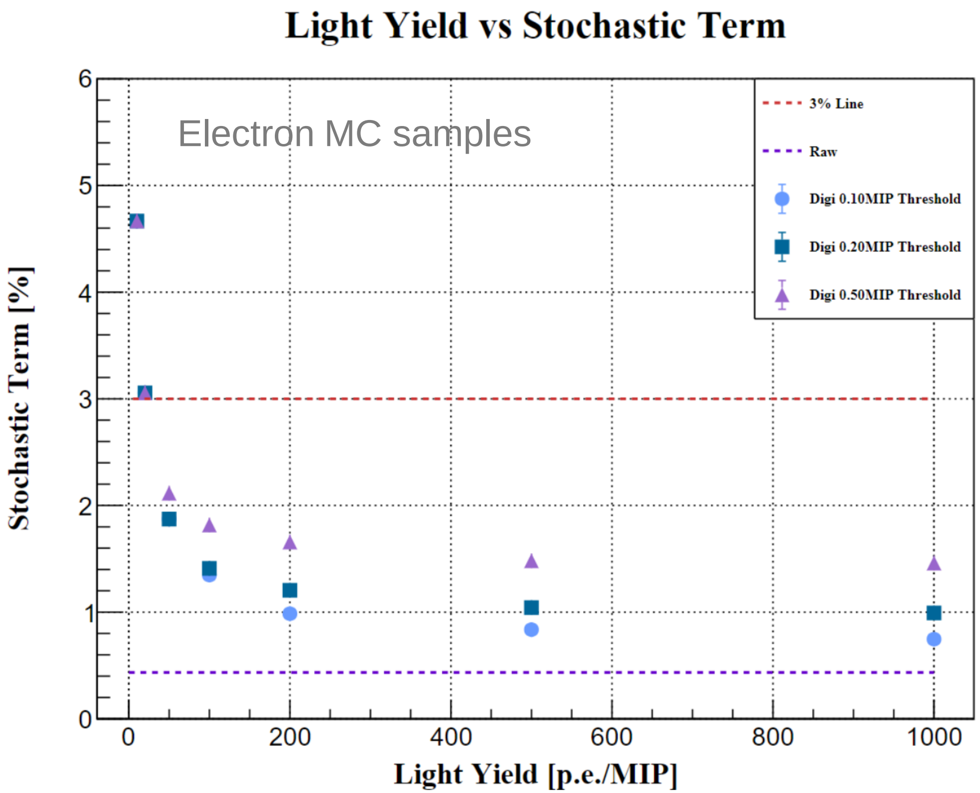
Backup

EM energy resolution: light yield requirements

Geant4 Simulation (v10.7)

- Impact of energy threshold (in MIP) and #detected photons (in p.e./MIP) with 40 cm BGO bar
  - Digitization: photon statistics (crystal + SiPM), electronics resolution





- Moderately high light yield (#detected photons) and low threshold required
- Low energy threshold can be feasible with low crosstalk SiPMs
- 200 p.e./MIP light yield is enough for $\sim 3\%/\sqrt{E}$ energy resolution, taking into account some margin

SiPM response linearity: laser test and simulation

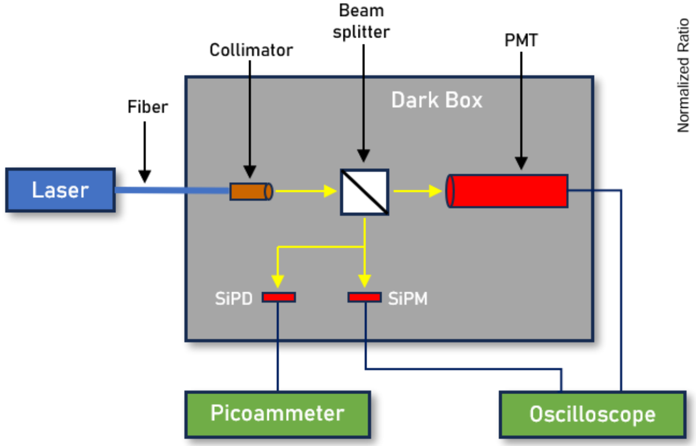
Zhiyu Zhao (TDLI/SJTU)

- SiPM candidates: 3×3 mm^2, 10 μm pixel pitch

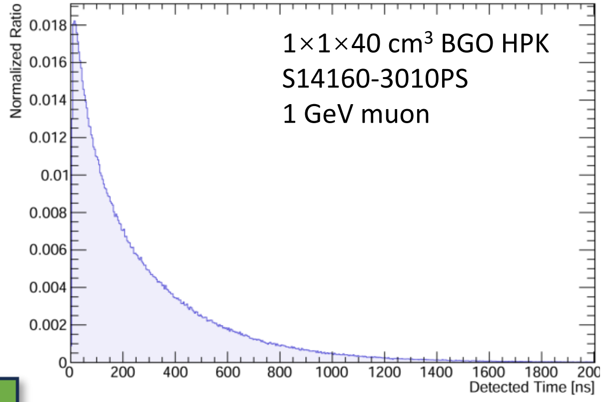
Requirement: 4.5×10^5 photons

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

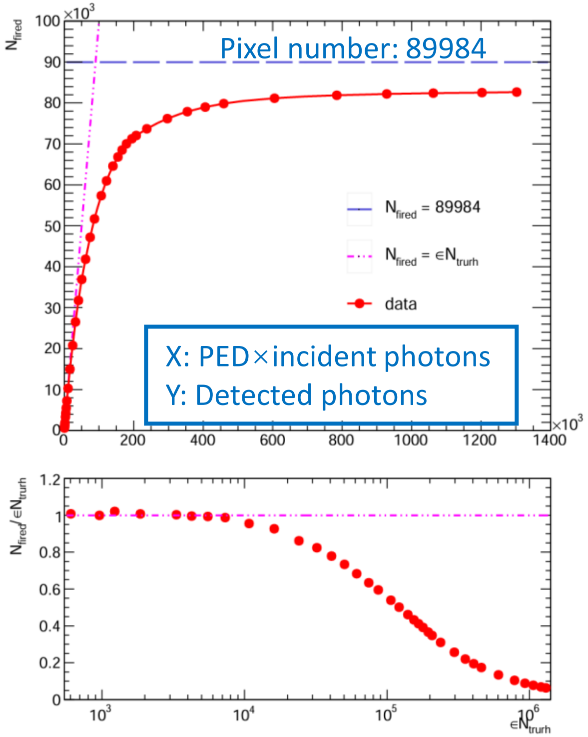
Laser test setup



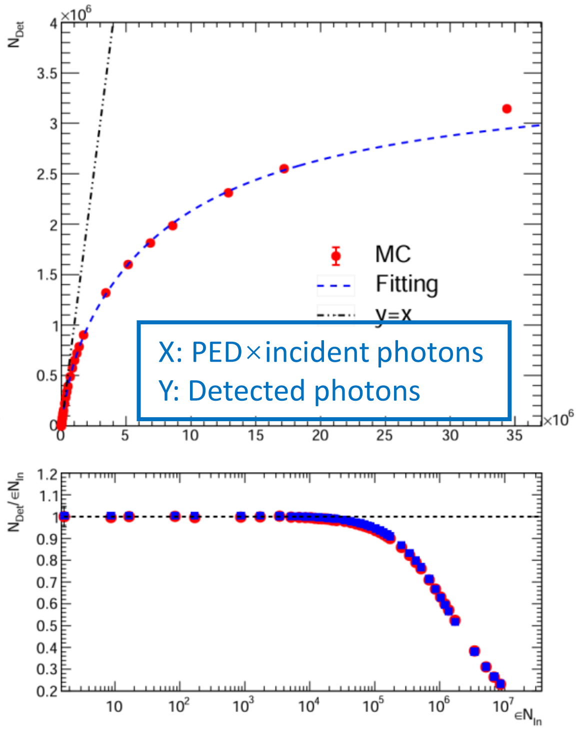
Geant4 simulated photon detection time



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)

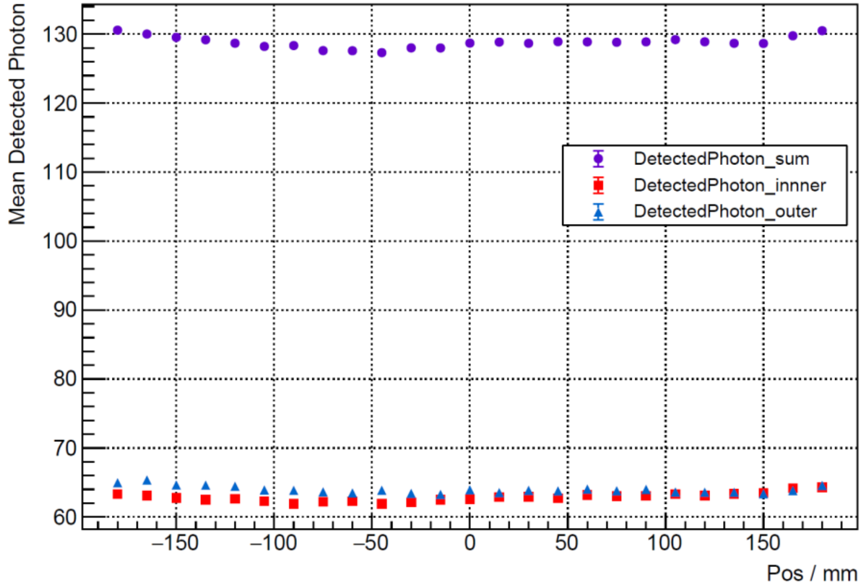
- Linear range < 10^4 photons
- Response plateau is close to but smaller than pixel number

- Recovery effect contributes to a wider linear range

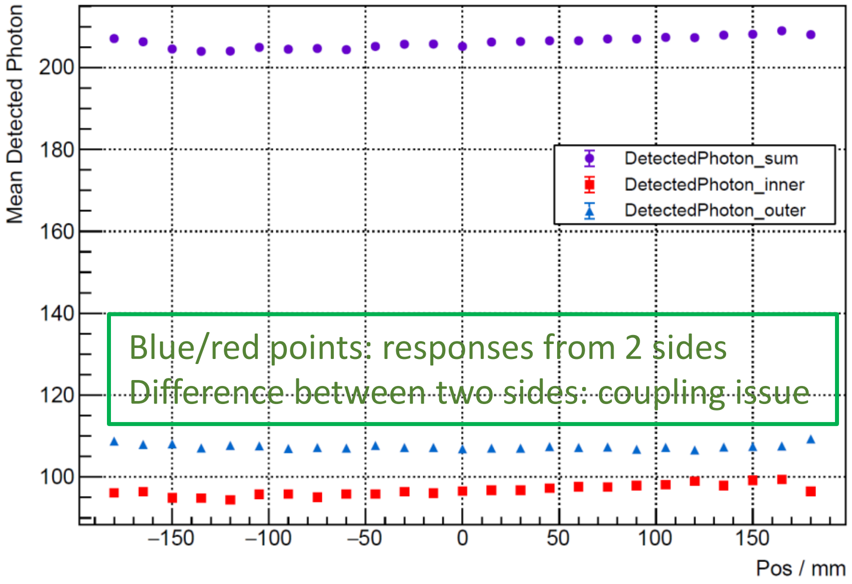
Uniformity scan of BGO crystal bars

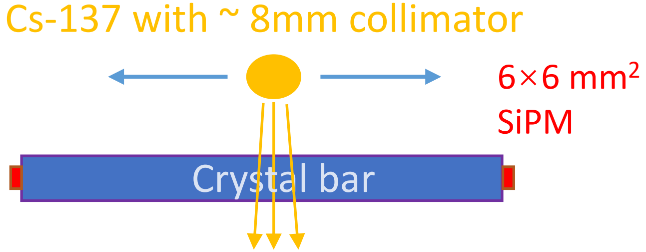
- $1\times1\times40$ cm^3 BGO crystal with ESR wrapping
- Air/optical grease coupling
- Scan with Cs-137 radioactive source

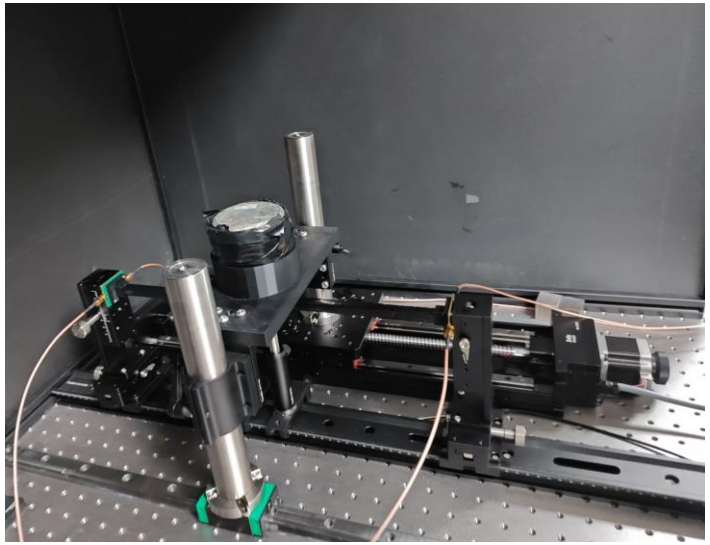
Response uniformity air-coupled



Response uniformity grease-coupled





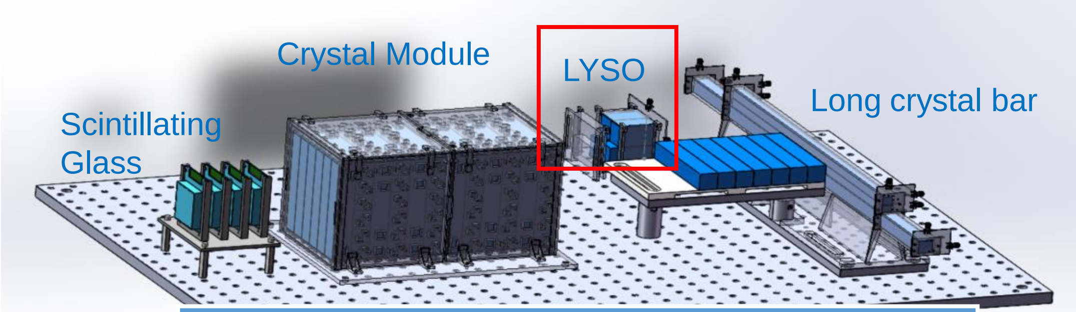


Automated crystal scan platform

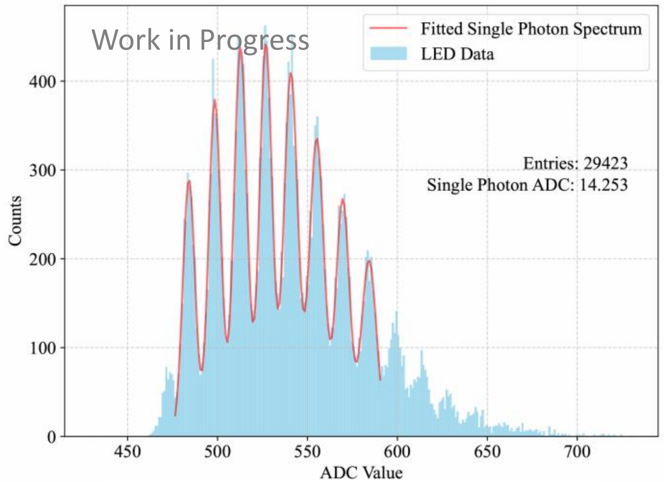
- Generally good uniformity at ~2.5% level along a single bar
- Optical grease gives 59% improvement on detected photons
- Grease coupling is difficult to control

Dynamic range of electronics: 2023 DESY beam-test

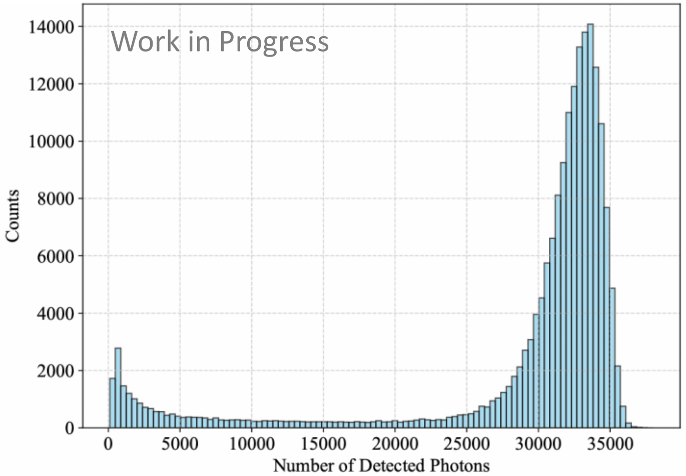
- Requirement: detecting 1~4.5×10^5 photons
  - Significant challenge: dynamic range of electronics
- Beam-test of large dynamic range electronics candidate MPT2321
  - 5 GeV/c electron beam hits on LYSO crystal matrix
  - Readout with MPT chip + 25 µm pixel SiPM



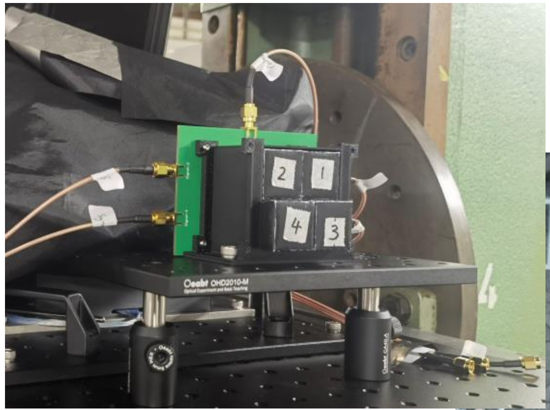
Overview of the 2023 DESY beam-test tasks

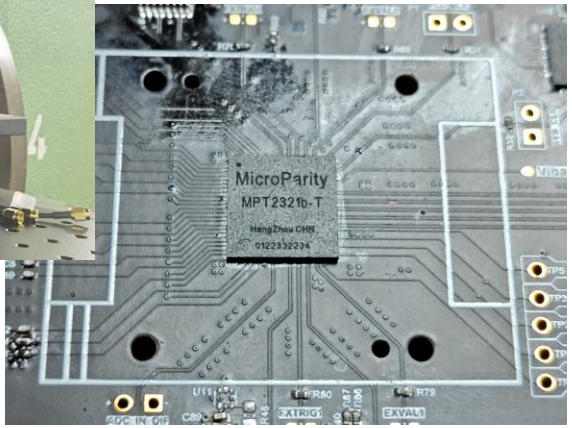


Highest gain: good S/N for single photon calibration



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.