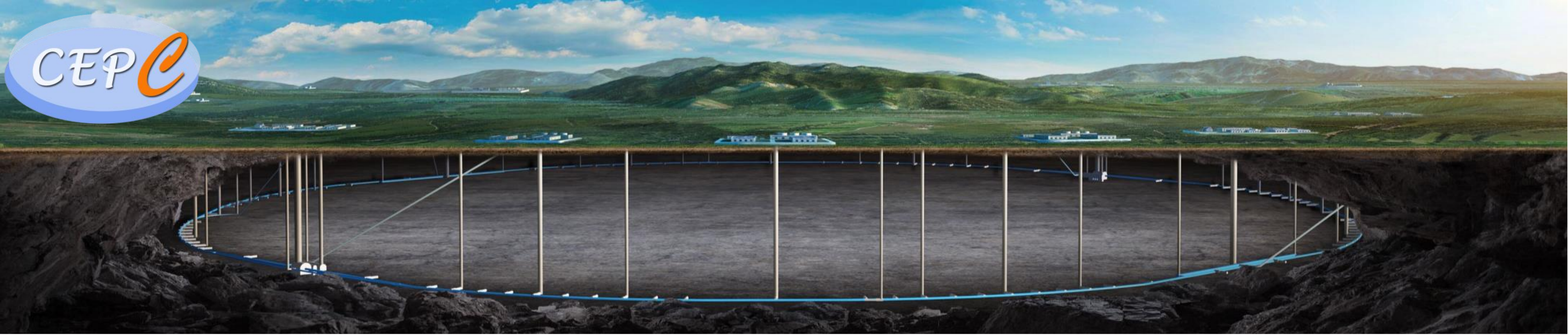

Beamtests of the small-scale crystal module for future high-granularity crystal ECAL

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The 2024 CEPC Workshop at Hangzhou

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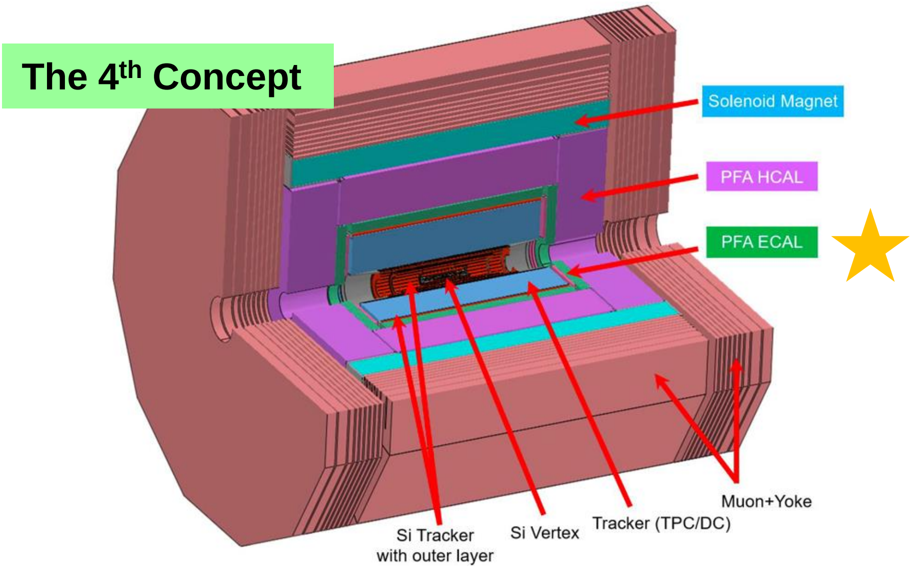
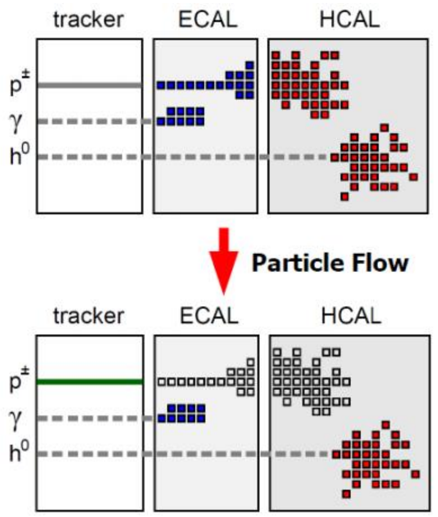
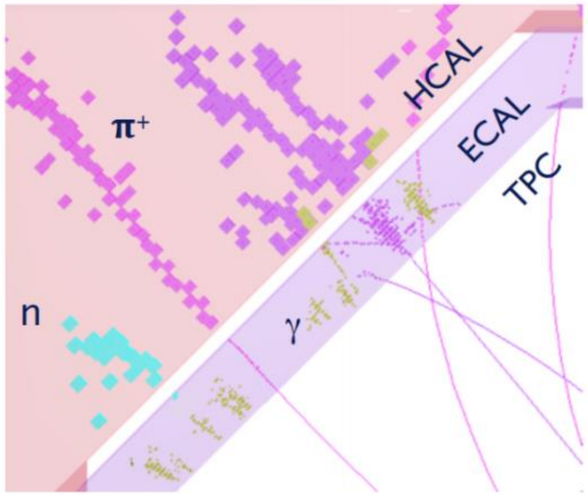
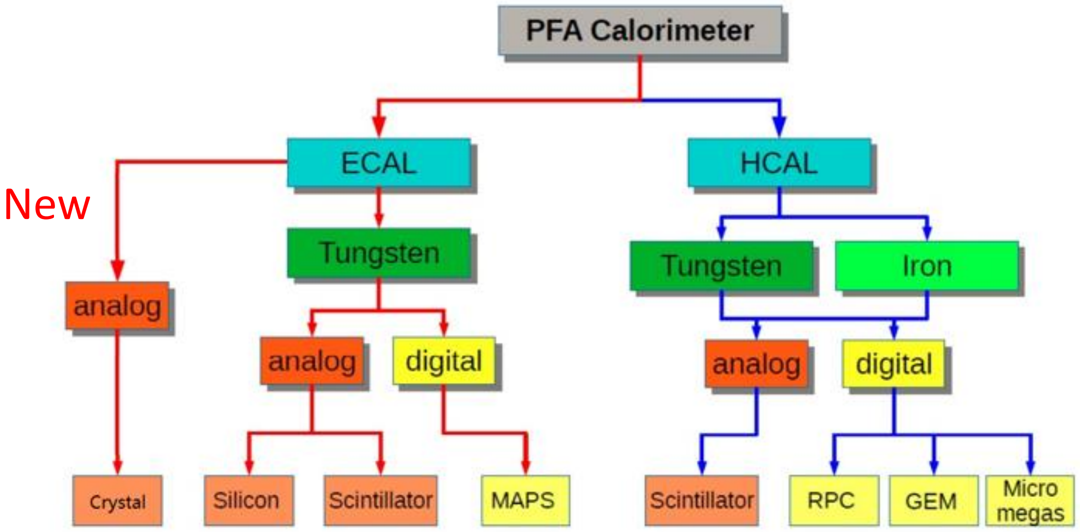
Crystal ECAL option for future Higgs factories

- Calorimeter for future lepton colliders (e.g. CEPC)
  - Precise measurement of Higgs/Z/W bosons, BSM physics, etc.
  - Aim to achieve an unprecedented Boson Mass Resolution (BMR) of 3 - 4%
- Particle-flow oriented detector: “CEPC 4th concept”
  - High-granularity crystal ECAL: homogeneous option
    - 5D detector: 3D spatial + energy + time
    - Intrinsic EM energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$



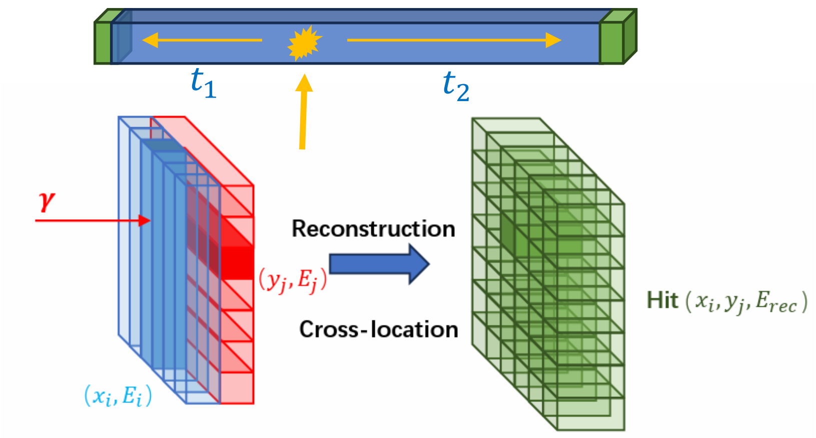


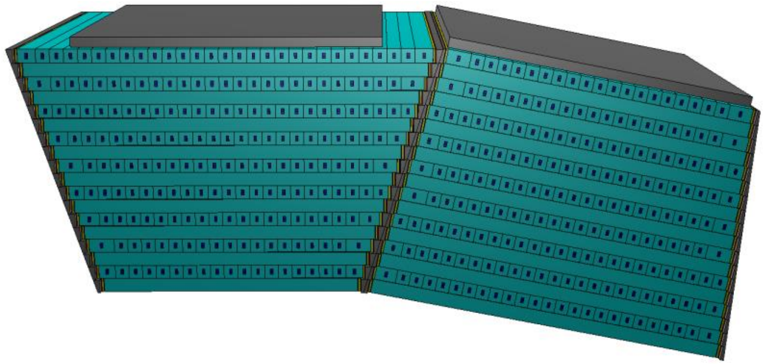


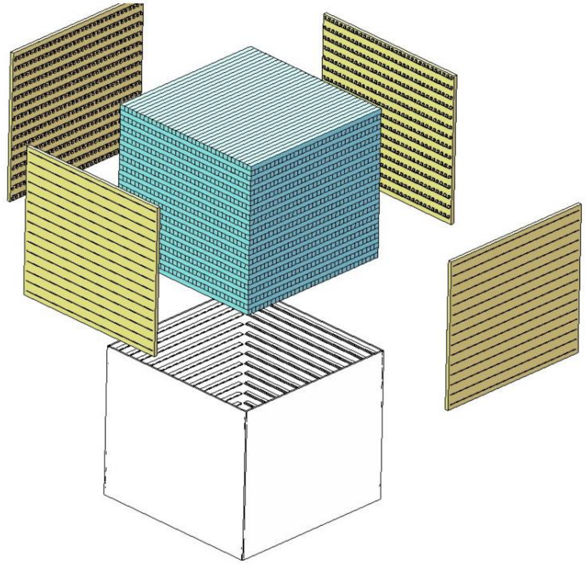


Design of the long crystal bar ECAL

- $1\times1\times40$ cm^3 crystal units, double-side readout with SiPMs
- Crisscrossed arrangement between layers







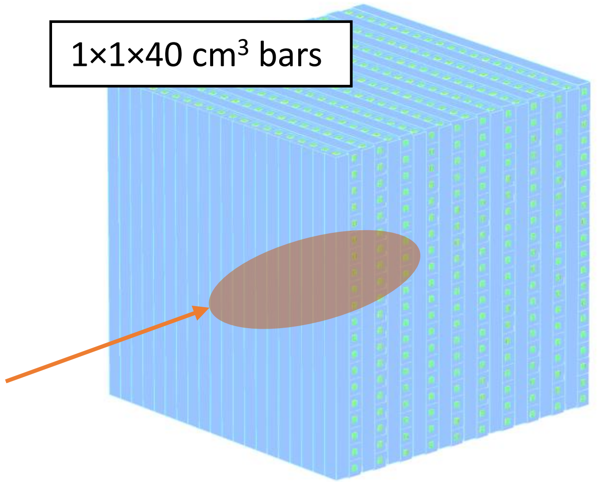
- Long crystal bars instead of small crystal cubes
  - Save number of channels
  - Minimize longitudinal dead materials
  - High-granularity with orthogonally arranged bars
- Double-sided readout
  - Positioning potentials with timing
  - Better uniformity

➢ Geometry design of the crystal ECAL towers made up of $1\times1\times40$ cm^3 crystals

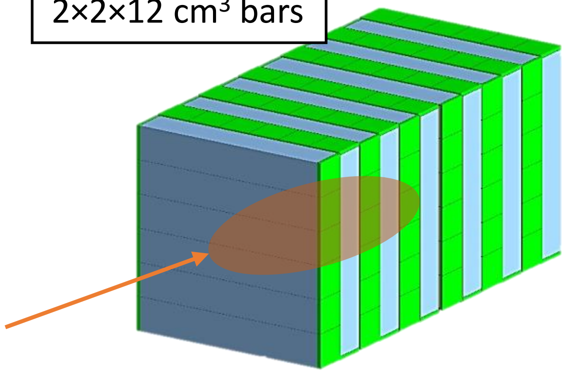
- Key issues need to be validated
  - Estimation for system-level performance

Motivations of the small-scale crystal module

- For 1-10 GeV EM shower: compact profile is sufficient with a 12 cm module

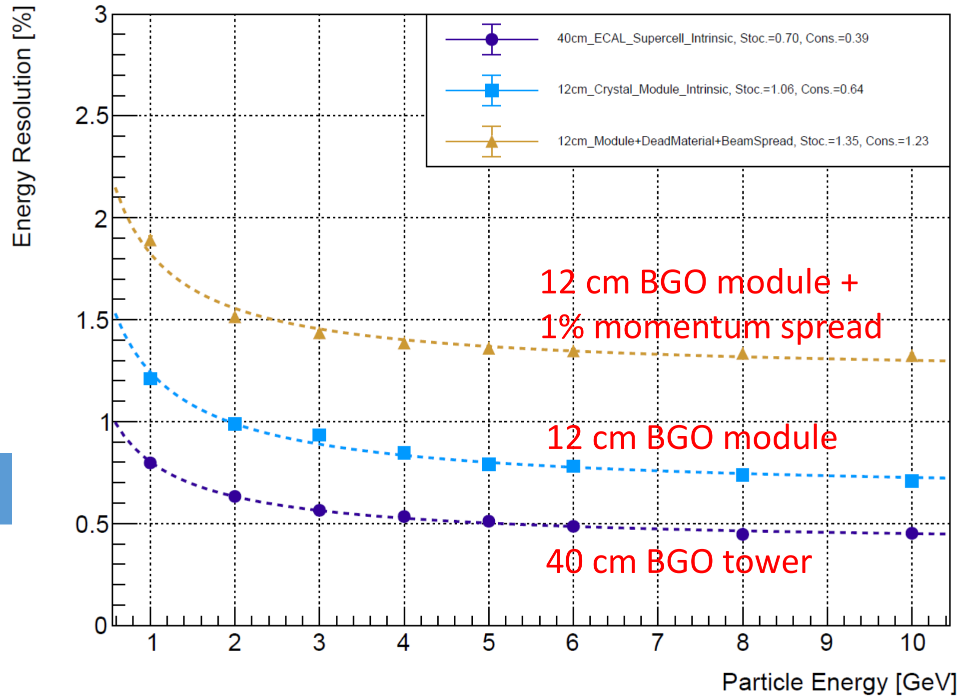


40 cm: 95.1% shower energy deposited



12 cm: 93.8% shower energy deposited

Energy resolution: 12cm module vs 40cm tower



- Small-scale crystal module
  - Evaluate crystal ECAL EM performance with TB data
  - Validation of simulation and digitization
    - Solid input for detector performance studies
  - Identify critical questions/issues on the system level
    - Mechanical design, PCB and electronics, cooling…

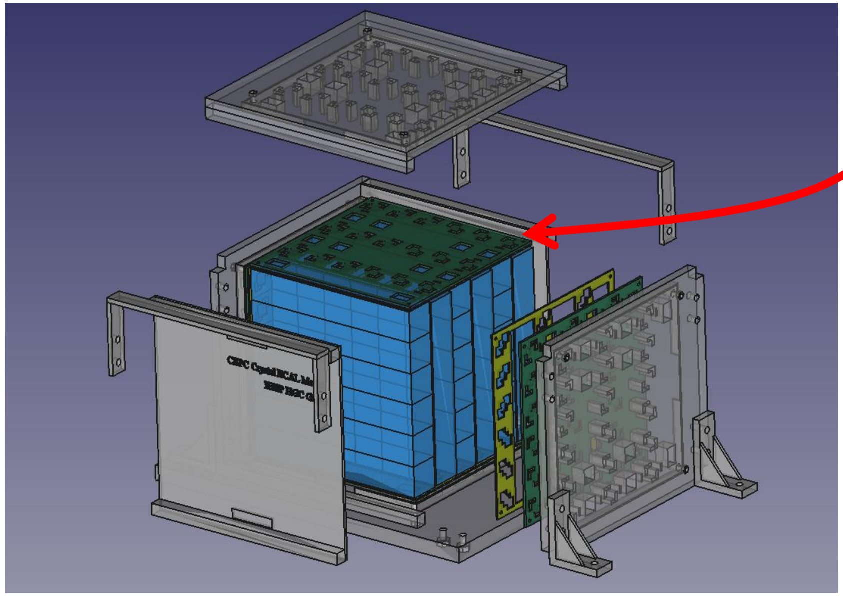
- 12 cm module: energy resolution better than 3%
- A small module is feasible for 1- 10 GeV energy response study

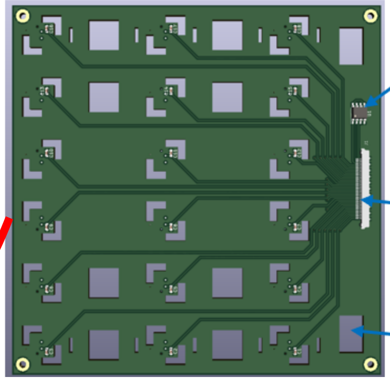
Construction and commissioning of the crystal module: Phase-I

- Module design
  - 36 BGO crystals (2×2×12 cm^3 bars, 6 layers)
  - Self-designed PCBs
    - 10 µm pixel SiPMs (HPK S14160), readout from 2 sides
  - 3D printed support structure
  - Citiroc-1A readout chips (CAEN FERS-5200)

Phase-I:
- A $10.7X_0$ BGO module for first commissioning
- First parasitic test at CERN T9 beamline
  - Muon tests and parameter scans

72 channels , $10.7X_0$
ESR and Al foil wrapping



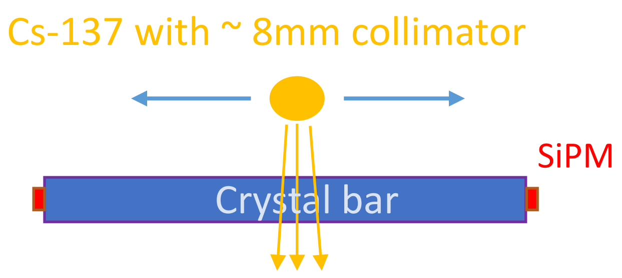


Key issues:
- Mechanical design: PCB is non-load-bearing and should be decoupled with support
- Crystal quality control: batch test of crystals
- Electronics and trigger scheme

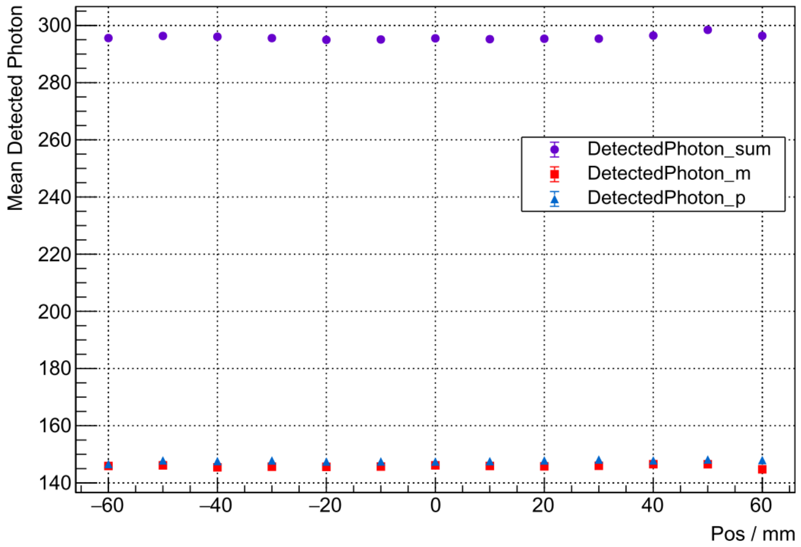
Batch test BGO crystal bars

Zhikai Chen (USC)

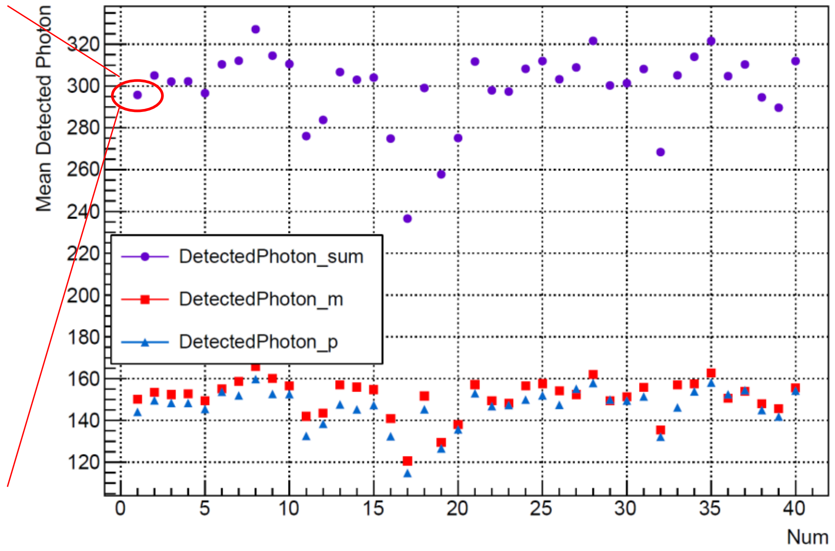
- Batch test of SIC-CAS BGO crystal bars
  - Crystals with ESR and Al foil wrapping
  - 7.5 mm windows at two sides for SiPM readout
  - Scan with Cs-137 radioactive source

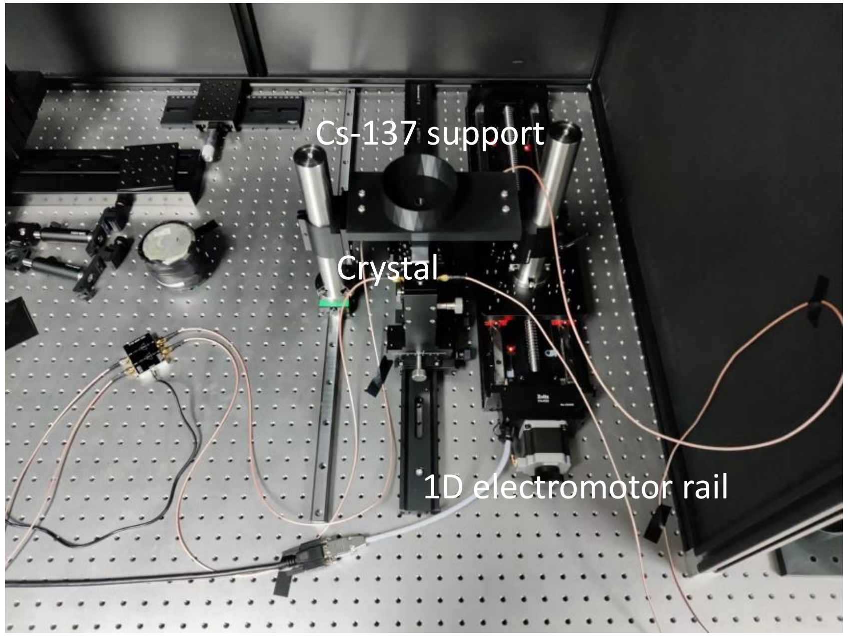


Response uniformity along #1 BGO bar



Mean response of the crystal bars

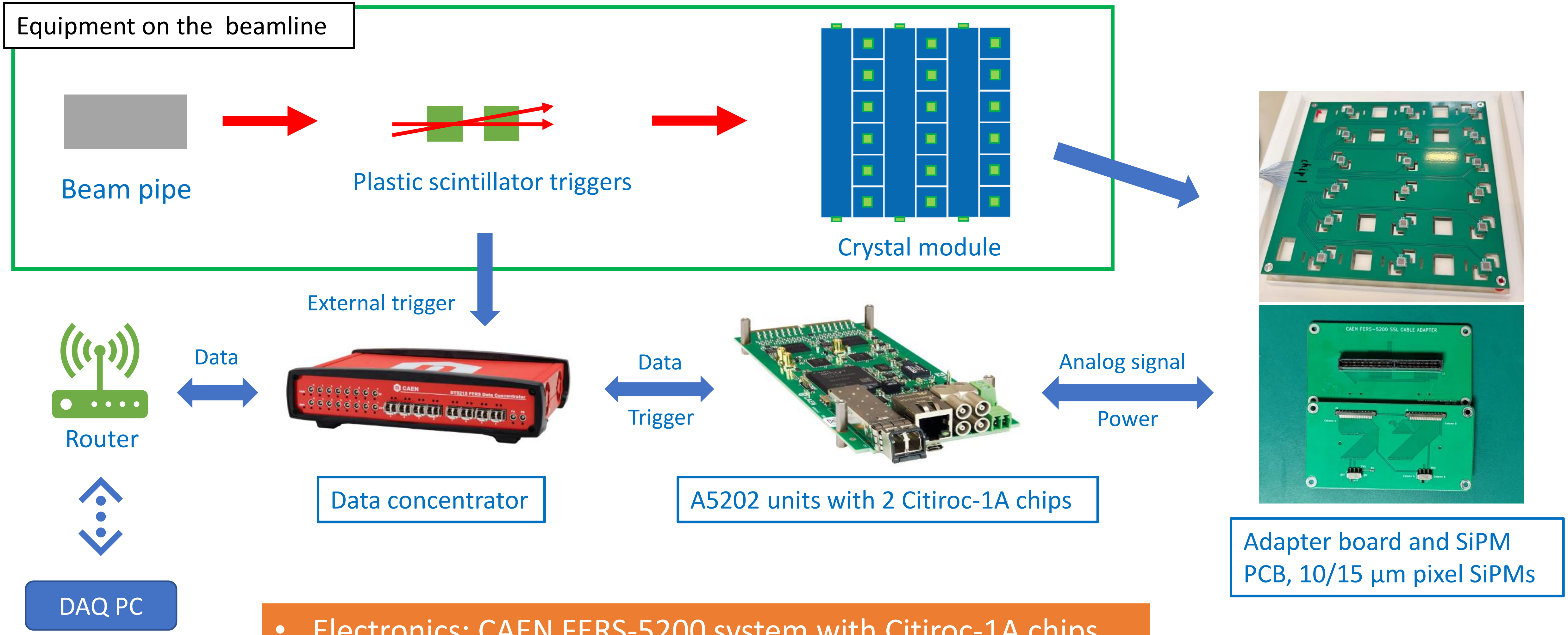




Automated crystal scan planform

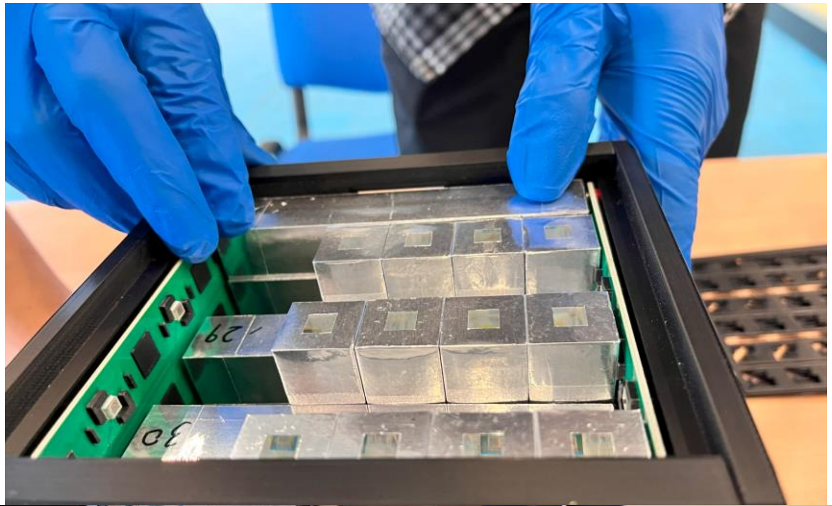
- Generally good uniformity along a single bar at ±0.7% level
- Response varies among different crystal, contribute to MIP response difference

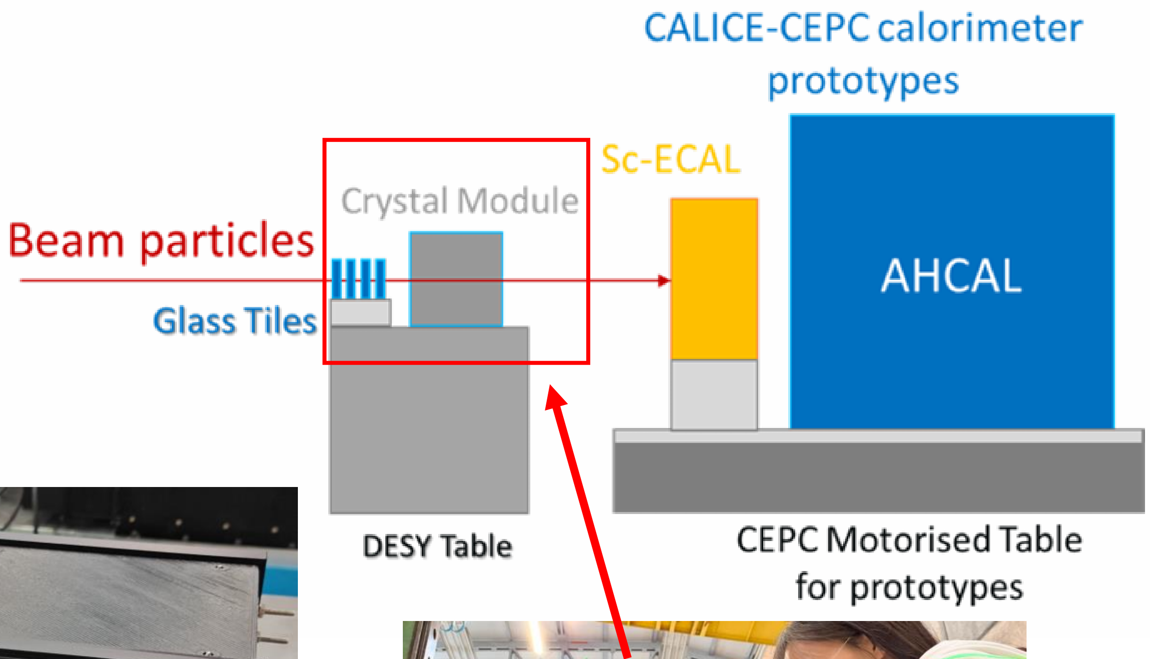
Electronics and trigger scheme

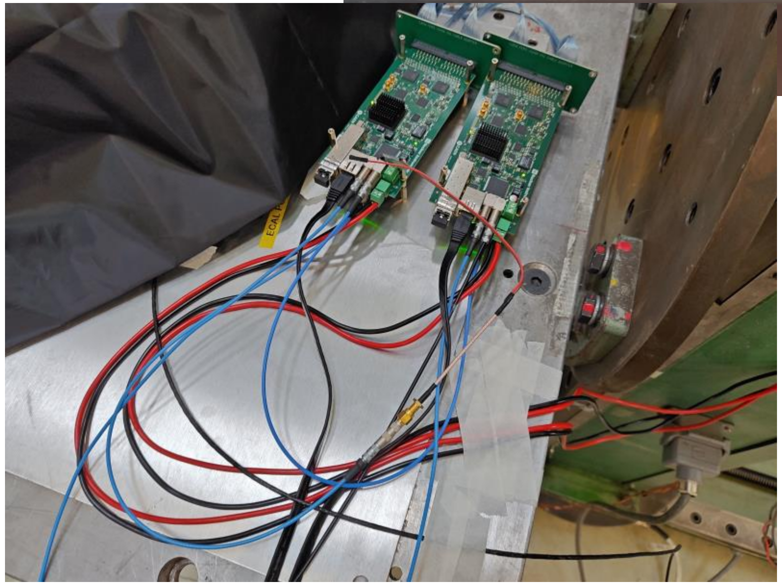


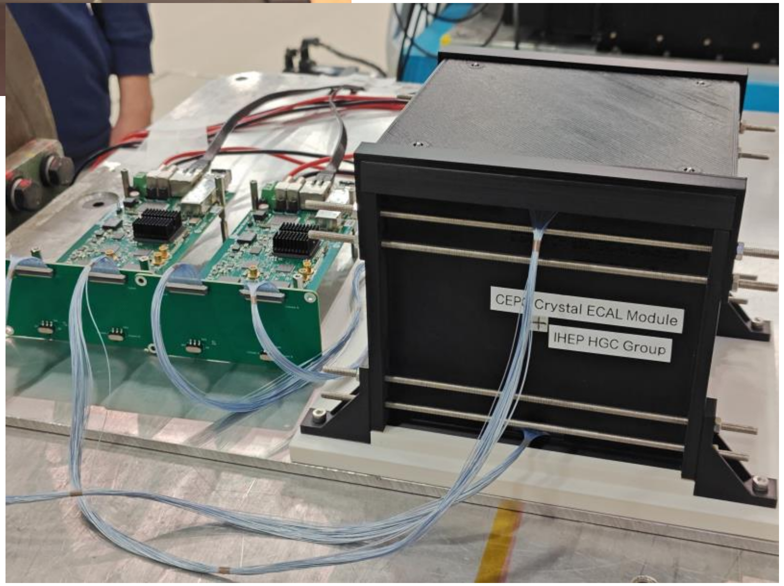
- Electronics: CAEN FERS-5200 system with Citiroc-1A chips
- External trigger available for better beam collimation

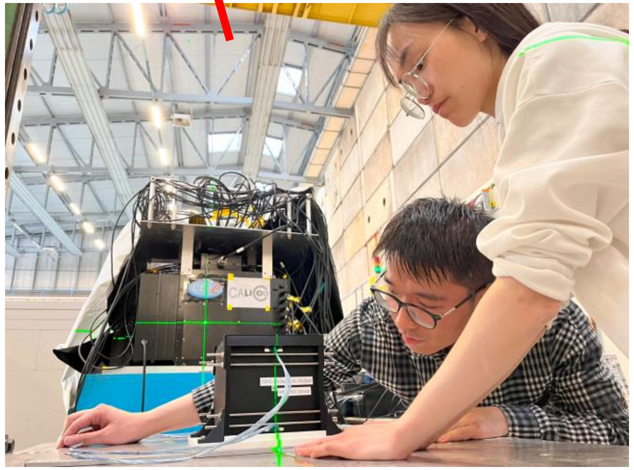
2023 CERN T9 beamtest: module installation



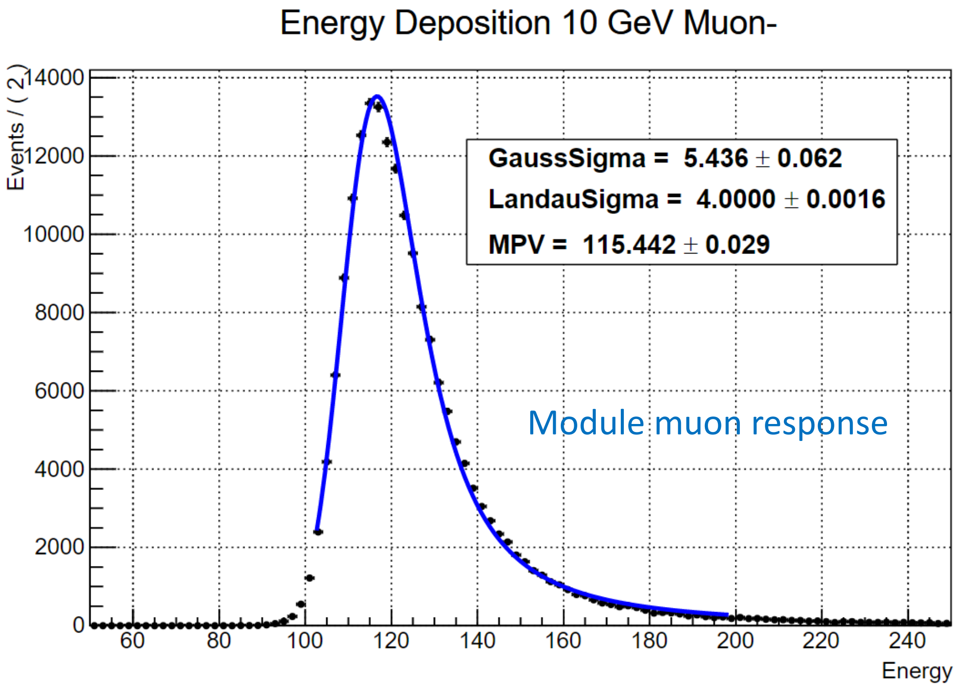




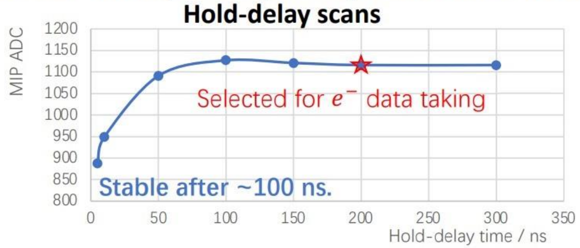




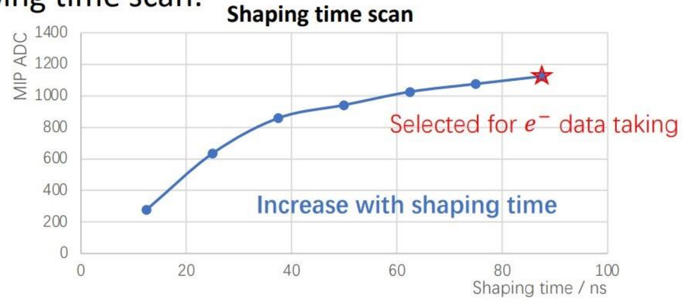
2023 CERN T9 beamtest: muon data analysis



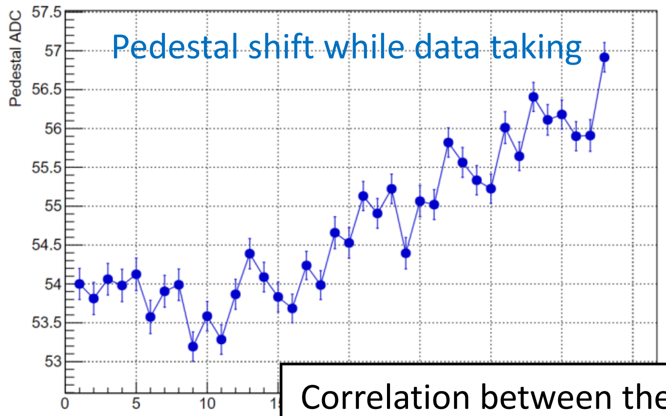
- Hold-delay time scan:
  - 10 GeV muon, HG 59, LG 63, scan from 5 ns to 300 ns.

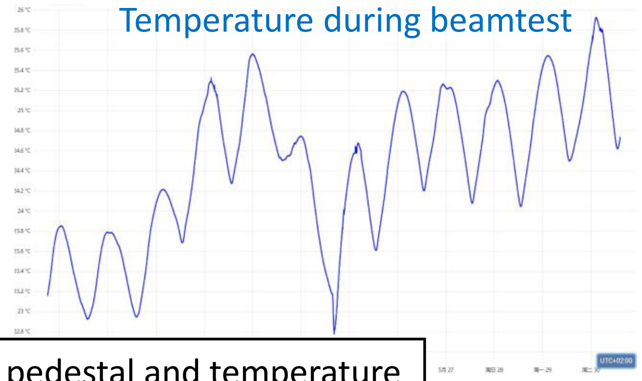


- Shaping time scan:



Selected parameters for electron data taking:
- Hold-delay: 200 ns
- Shaping time: 87.5 ns (max)



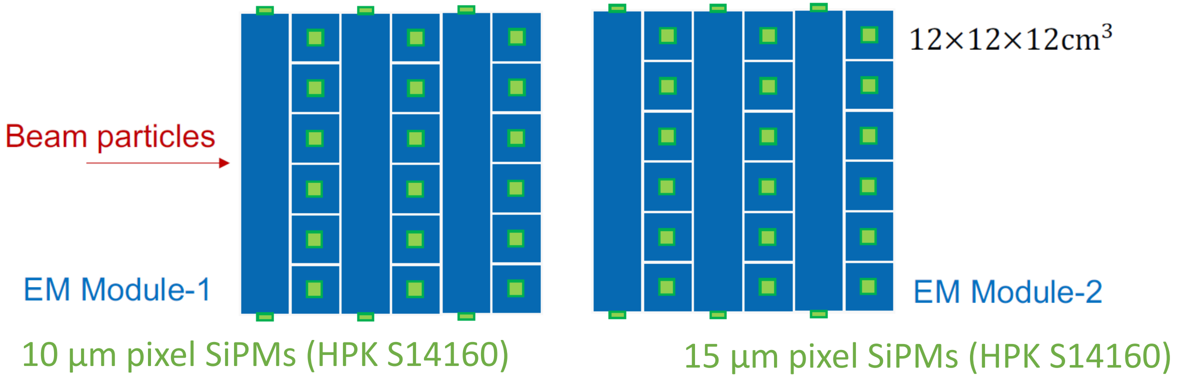


Correlation between the pedestal and temperature

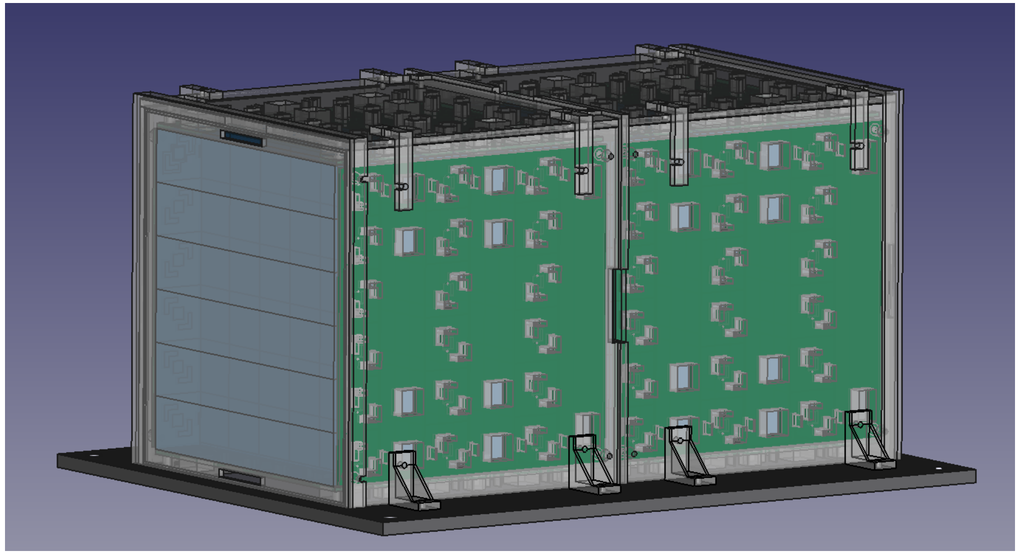
2023 CERN T9 beamtest:
- Successful system commissioning
- Clear MIP signals for all channel
- Parameter scans for future electron beamtests
- Gain substantial experience for future tests

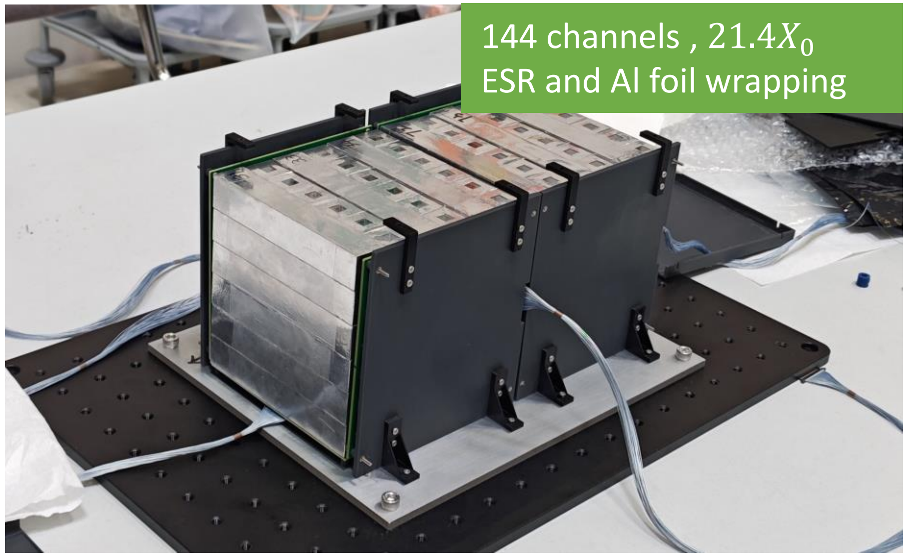
Construction and commissioning of the crystal module: Phase-II

- Improved design: 72 BGO crystals ($2\times2\times12\ cm^3$ bars, 12 layers)
- New support structure and SiPM



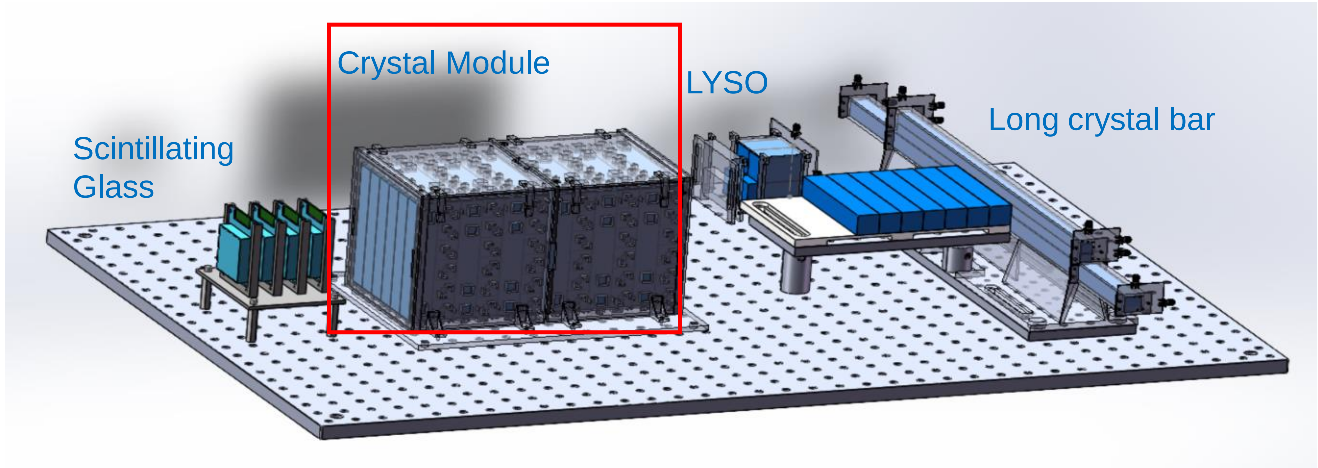
Phase-II:
- A $21.4X_0$ BGO module for performance tests
- Electron beam test at DESY TB22
  - First glance of EM performance
- Electron beam test at CERN T9 beamline
  - Evaluate EM performance with better beam momentum spread control
  - Effect of cooling system





144 channels , $21.4X_0$
ESR and Al foil wrapping

2023 DESY beamtest of the crystal module: setup

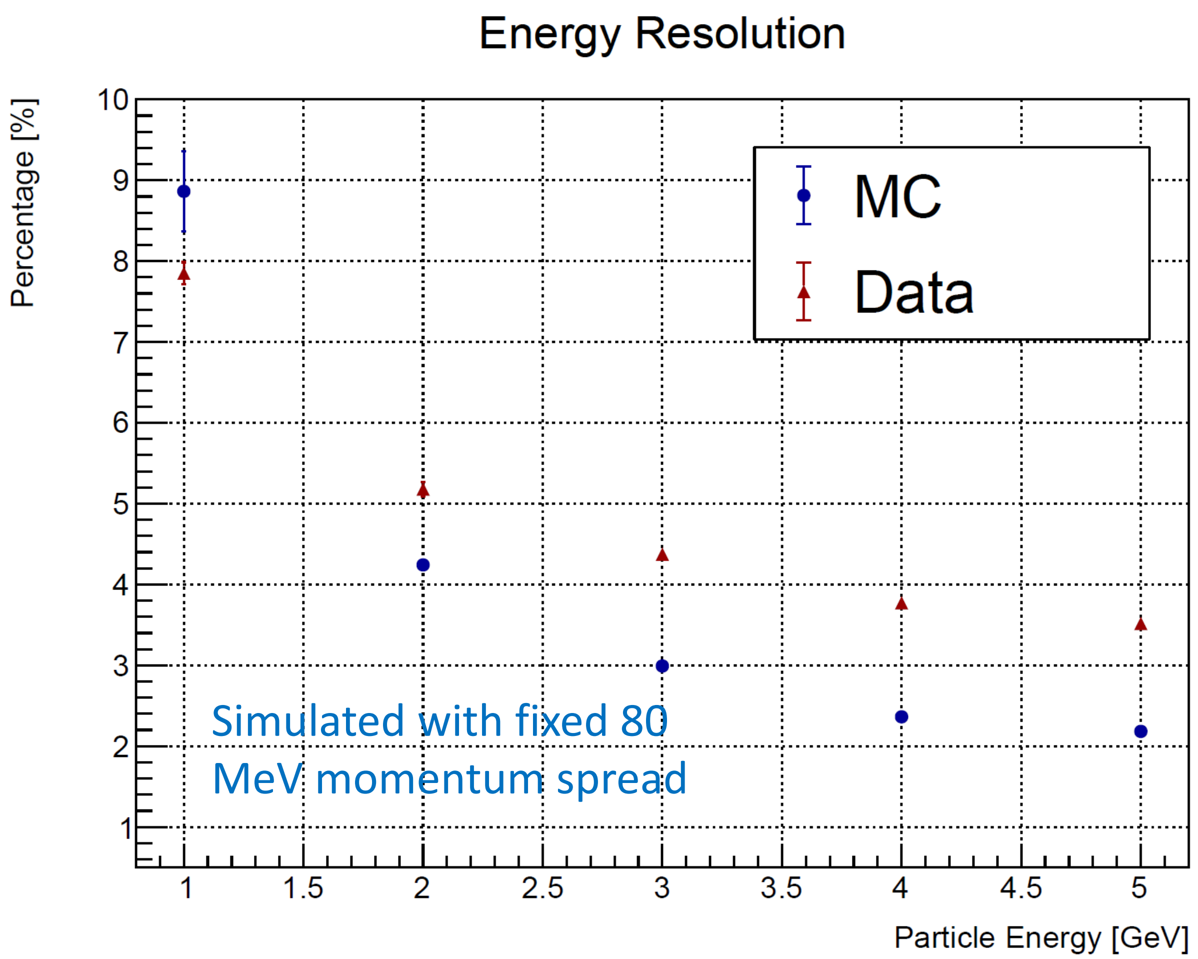


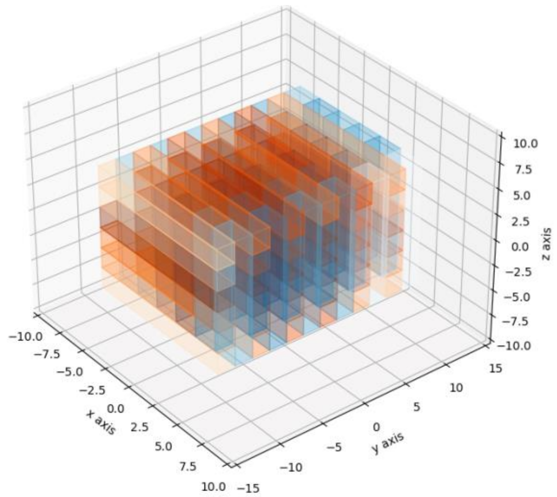
Beamtest at DESY TB22

- $21.4X_0$ crystal module
- Readout with 6 Citiroc chips
- Two 1 cm^3 triggers for electron collimation
- 1-5 GeV/c electrons: energy response studies

2023 DESY beamtest of the crystal module: electron data

- EM performance with electron beam



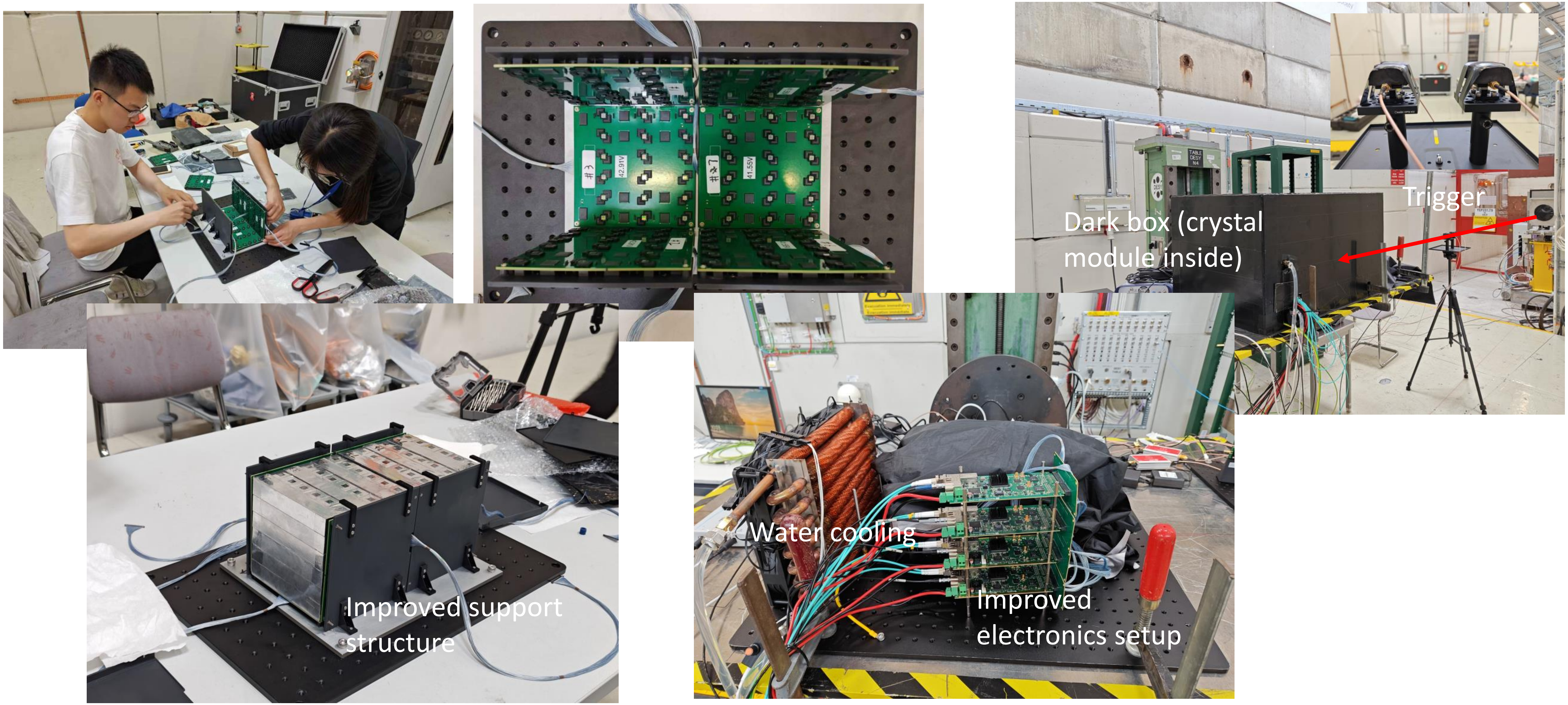


A typical 5 GeV/c electron event

- EM resolution: large discrepancy between data and MC
  - Challenge with TB22: uncertain momentum spread
  - Significant calibration uncertainty without muon beam
  - Lack of temperature control

2023 DESY beamtest: insights gained for future tests
- Control of beam momentum spread is crucial
- Muon beam is mandatory for in-situ MIP calibration
- Effects of cooling need further investigation

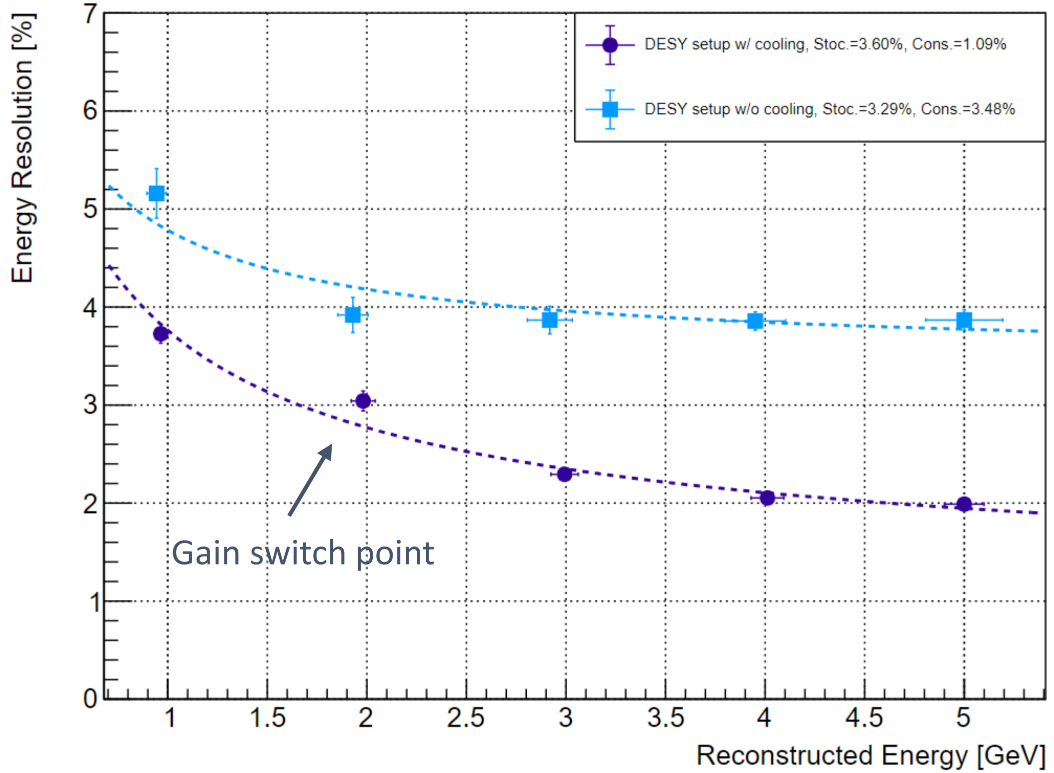
2024 CERN beamtest: improved setup

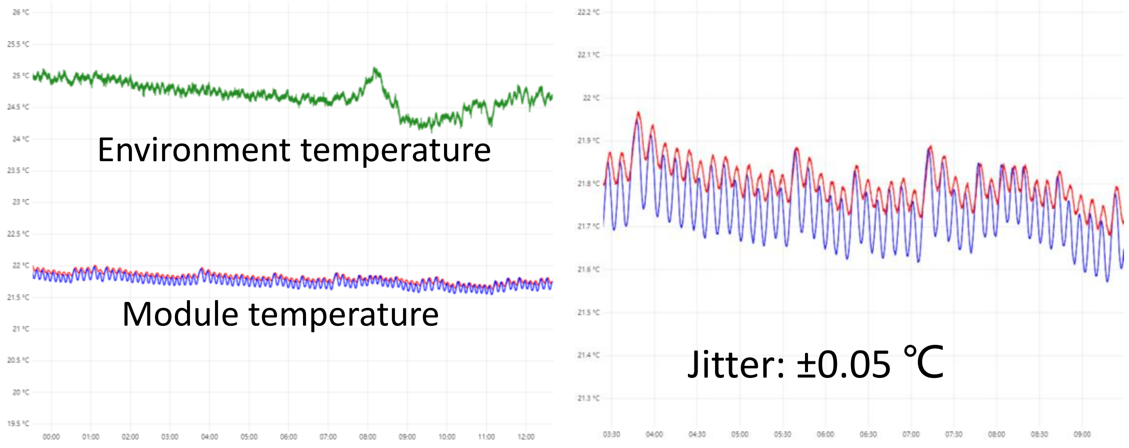


Repeat 2023 DESY beamtest

- 2024 CERN T9 beamtest: completely the same as DESY setup
  - Electron beam from 1 to 5 GeV/c
  - Better momentum spread (intrinsically 1% from accelerator)
  - Water cooling system added

Energy resolution with or without cooling





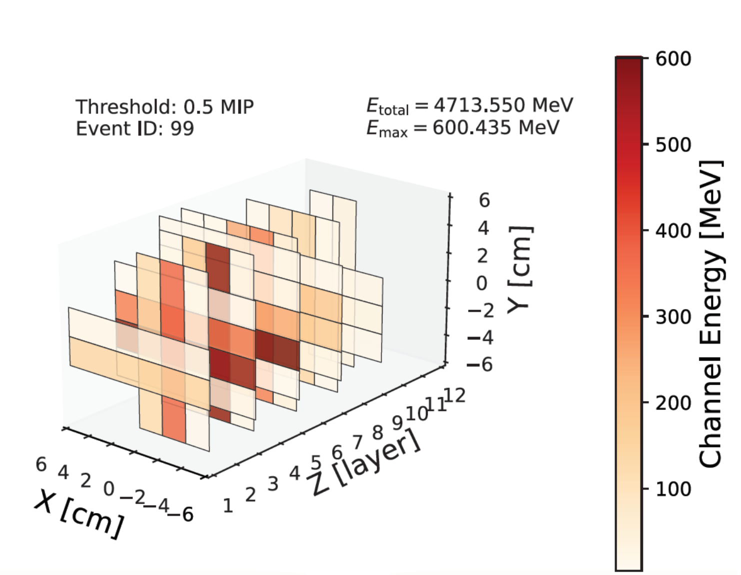
- Improved performance (<8% (DESY) → <4% @ 1 GeV)
- Studies of the temperature control
  - Without cooling: a large constant term contributed to energy resolution
  - Temperature jitter can be controlled at ±0.05 ℃ level, consistent with the CEPC ECAL requirements

2024 CERN beamtest: test with optimized setup

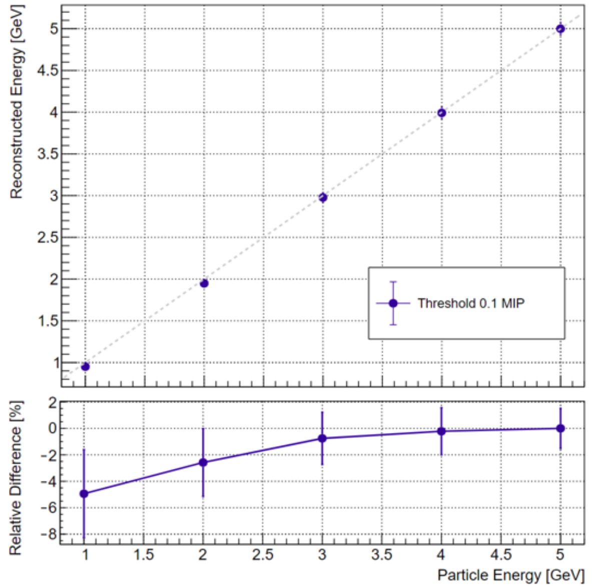
2024 CERN T9 beamtest: updated electronics setup and optimized parameters
- Successful electron data taking with good quality
- Scan HighGain and LowGain values for best performance
- Sufficient muon calibration data for all channels

Key issues affect performance
- Beam momentum spread
- Gain switch of electronics
- Pedestal and MIP stability
- Saturation and crosstalk effects

First glance: performance with 1-5 GeV electron beam



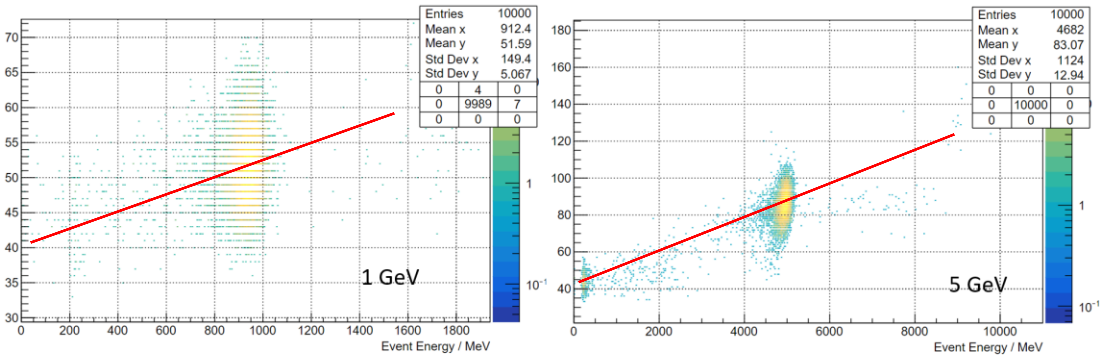
5 GeV/c electron event display



Energy linearity (1-5 GeV): worse than expected, crosstalk effect exists

- Electronic crosstalk calibration

A channel with NO connection: extra crosstalk energy

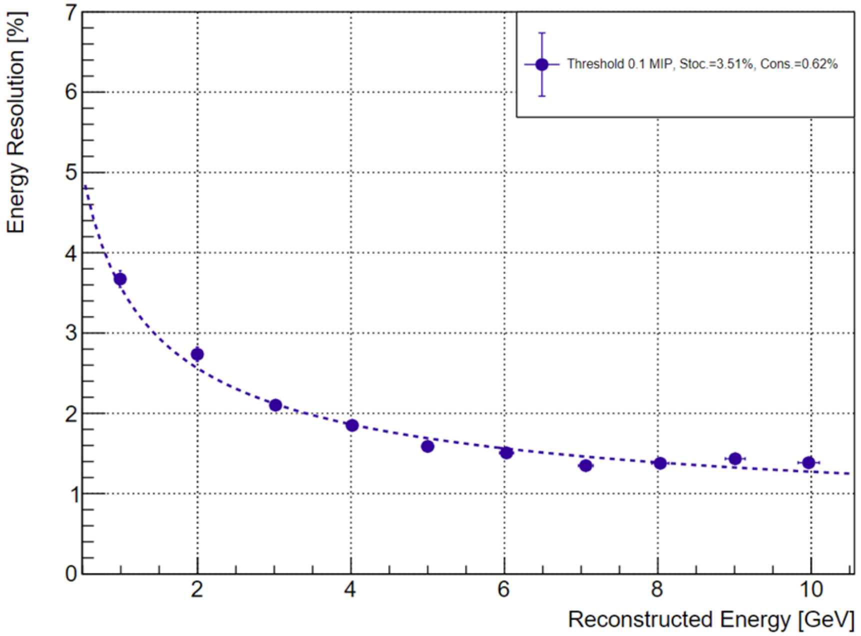


- Pedestal shift with incident particle energy
- Assume linear crosstalk effect for HighGain channels
- Assume insignificant LowGain crosstalk effect
- Extra energy can be subtracted
  - An essential correction for energy linearity

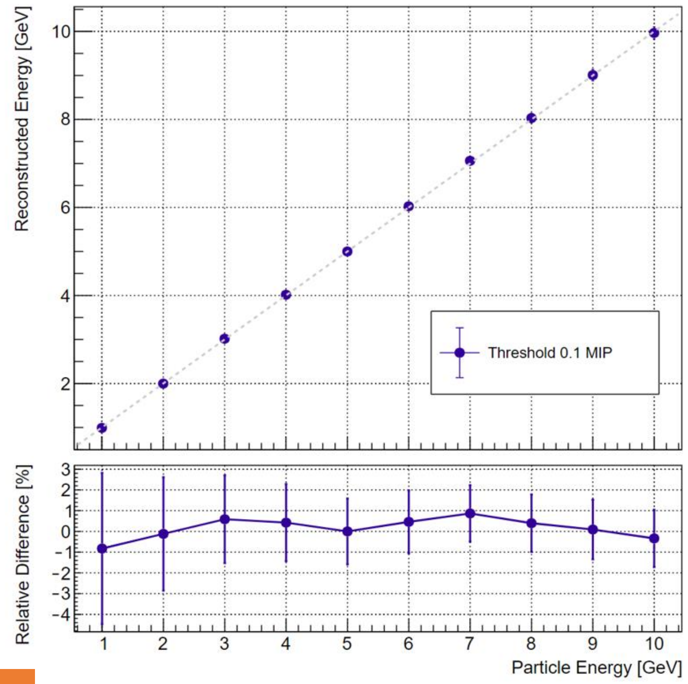
Electronic crosstalk corrected result for 1-10 GeV electron

- Energy correction: subtraction of extra energy
- Further analysis plans
  - LowGain saturation and pedestal shift, SiPM response non-linearity

Energy resolution: crosstalk corrected



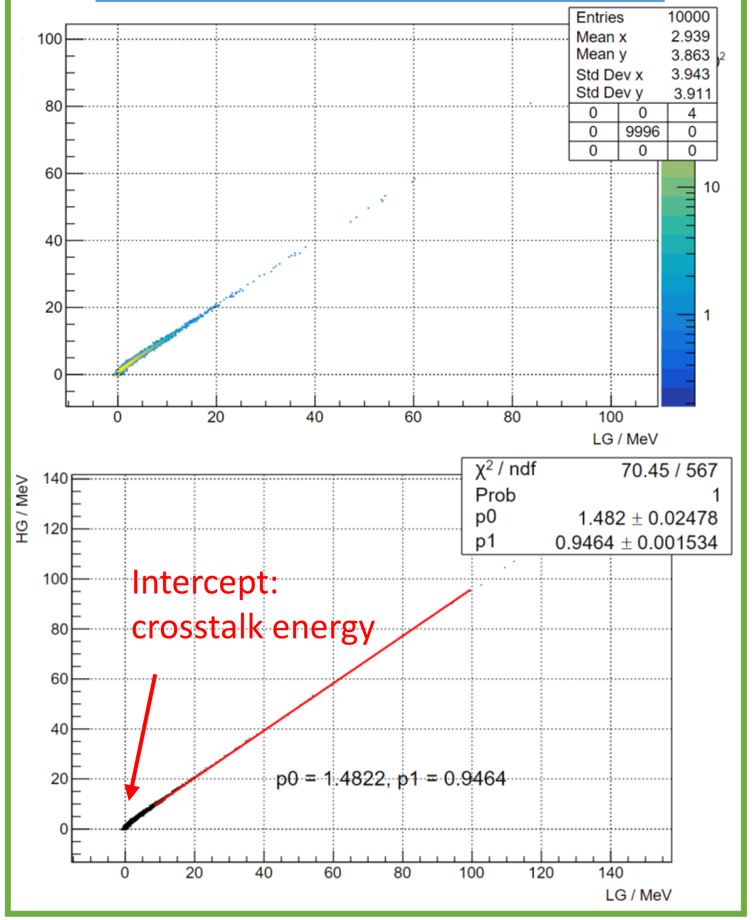
Energy linearity: crosstalk corrected



Performance of the crystal module:
- Energy linearity: ±1% level
- Energy resolution: $3.5\%/\sqrt{E} \oplus 0.6\%$

Dominated by beam momentum spread

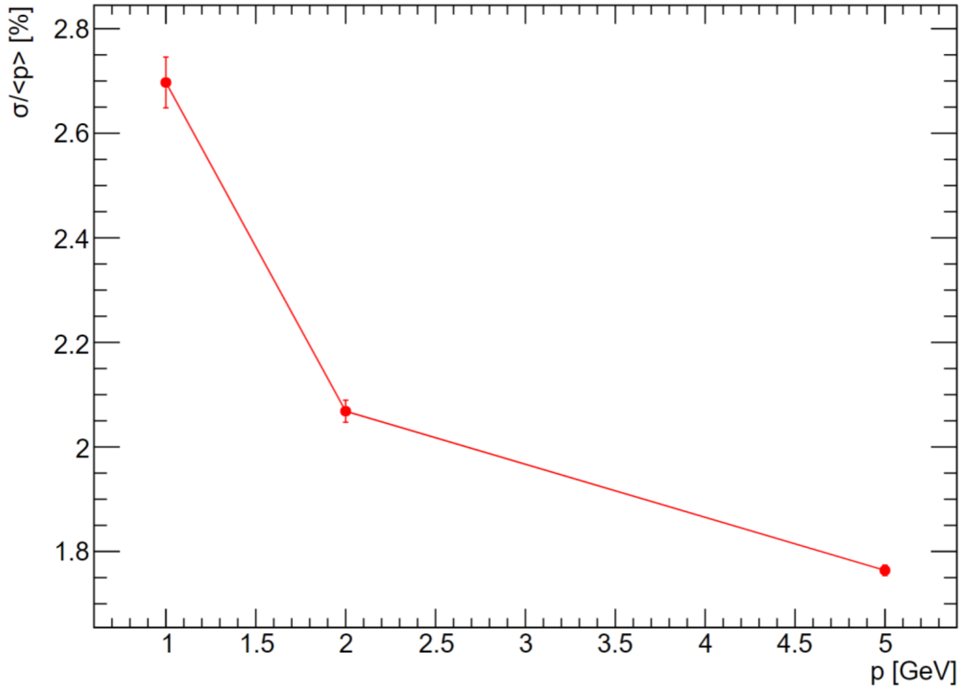
HighGain vs LowGain

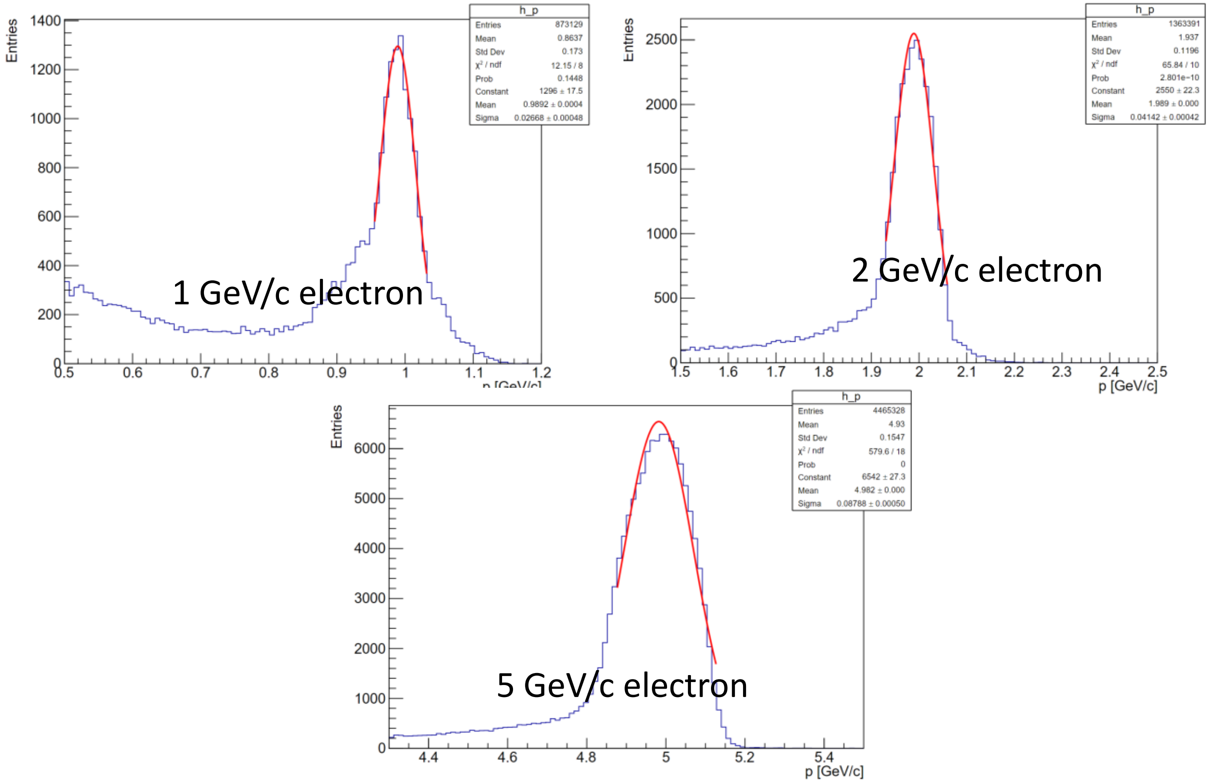


MC validations: beam momentum spread

- Beam momentum spread is assumed as 1% despite materials on the beamline
- CERN expert confirmed our observation: significant contribution of the beamline instrumentations
  - Beamline simulation provided by CERN: 1, 2, 5 GeV/c electron samples available

CERN T9: momentum spread of electron beam





- Significant momentum spread at low energy part
- MC electrons for validation: 5D sampling (x, y, px, py, p) of electron beam, considering 1 cm trigger

Moreover: digitization process

Zhiyu Zhao (TDLI/SJTU)

Process	Parameters	Value	Note
Scintillation	Intrinsic light yield	8200 ph/MeV	BGO properties (8000~10000 ph/MeV)
	Effective light yield	760/1340 p.e./MIP	Module-1/2, measured, $12 \times 2 \times 2cm^3$ BGO
	MIP energy	17.8MeV	5 GeV muon pass through 2cm BGO
	Photon detection efficiency	17%/30%	(HAMAMATSU S14160-3010/15PS)
	Light collection efficiency	3.1%/5.4%	$LCE = LY_{Eff}/(LY_{Int} * E_{MIP} * PDE)$
SiPM	Active area	$3 \times 3\ mm^2$	(HAMAMATSU S14160-3010/15PS)
	Pixel pitch	$10\ \mu m/15\ \mu m$	(HAMAMATSU S14160-3010/15PS)
	Pixel number	89984/39984	(HAMAMATSU S14160-3010/15PS)
	DCR	700 kHz	(HAMAMATSU S14160-3010/15PS)
	Gain fluctuation	5%	(HAMAMATSU S14160-3010/15PS)
	Crosstalk	0.5%	(HAMAMATSU S14160-3010/15PS)
ADC	Time window	87.5 ns	CAEN A5202, Citiroc-1A
	Number of gains	2	CAEN A5202, Citiroc-1A
	Dynamic range	0.1~80 MIP	CAEN A5202, Citiroc-1A
	Vertical accuracy	13-bit, 8192 ADC	CAEN A5202, Citiroc-1A
	Switching point	7900 ADC	CAEN A5202, Citiroc-1A
	Pedestal position	40~80 ADC	CAEN A5202, Citiroc-1A
	Pedestal width	3-6/4-10 ADC	CAEN A5202, Citiroc-1A

Energy deposition in Geant4

- Crystal scintillation
- Light transmission

Number of photons

- SiPM gain, DCR, crosstalk
- Non-linearity effect

ADC values of charge

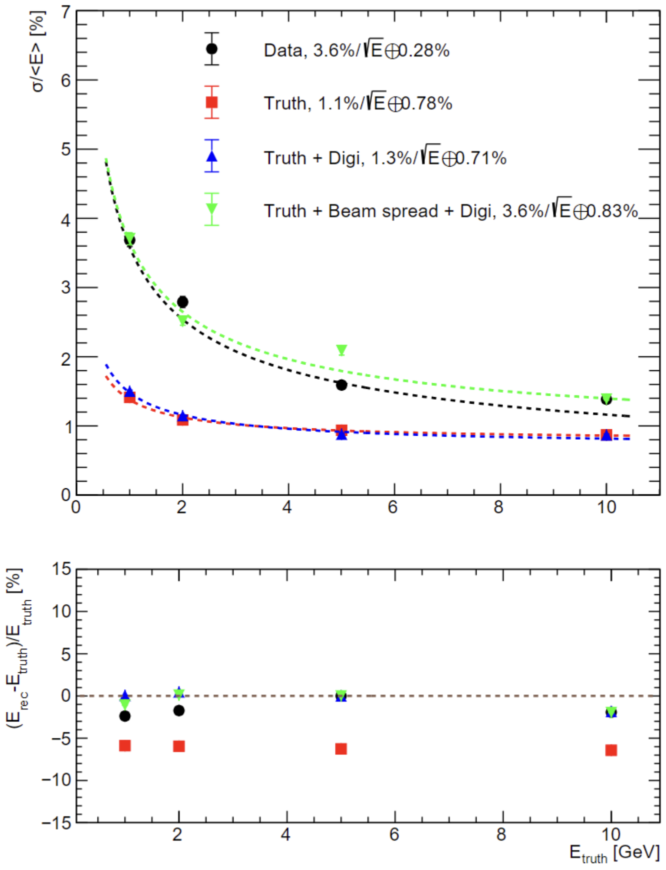
- Pedestal, MIP response
- ADC accuracy, uncertainty
- Gain switch

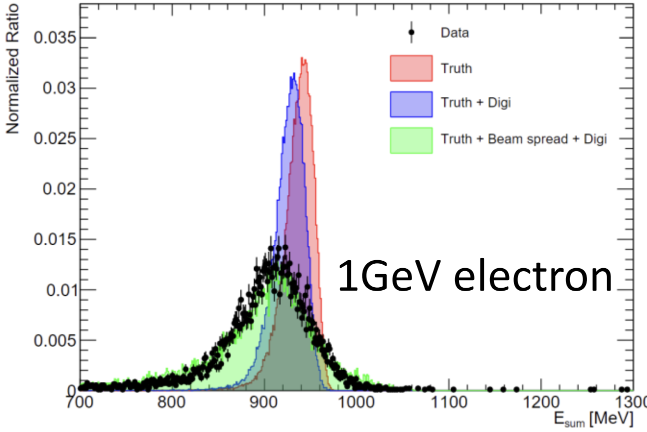
Digitized energy response

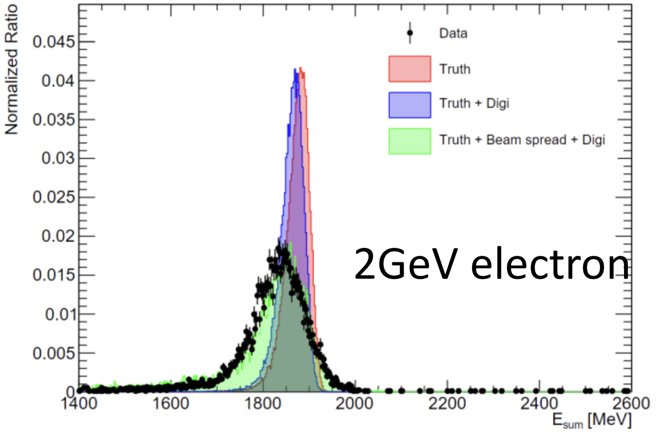
Note: dedicated digitization parameters for crystal module (1-10 GeV performance studies), different from final detector requirements

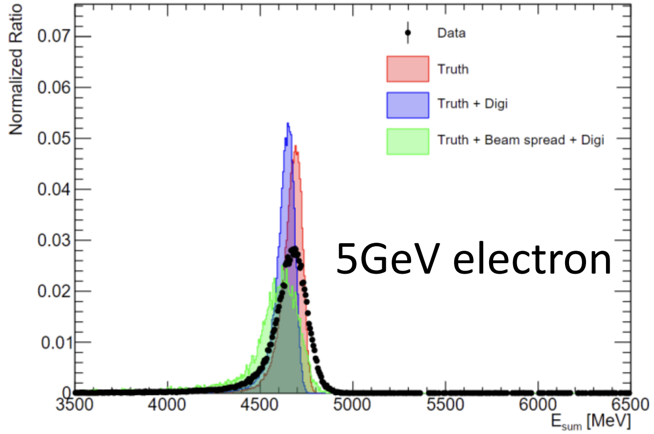
Simulation and digitization: validation of data

- MC: 5D sampling (x, y, px, py, p) of beamline simulation + digitization
- Momentum spread of 10 GeV/c electron: assume 1%









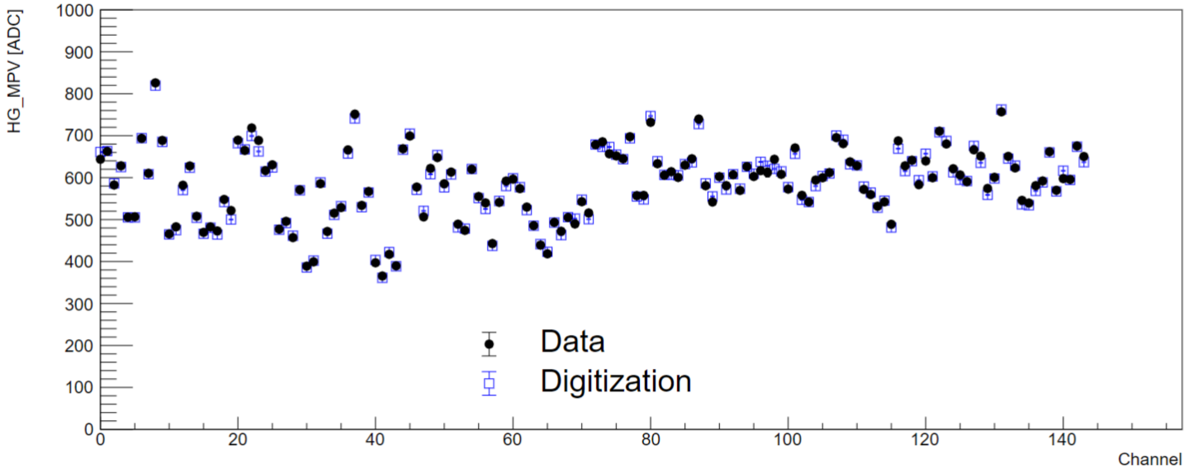
Energy distribution:

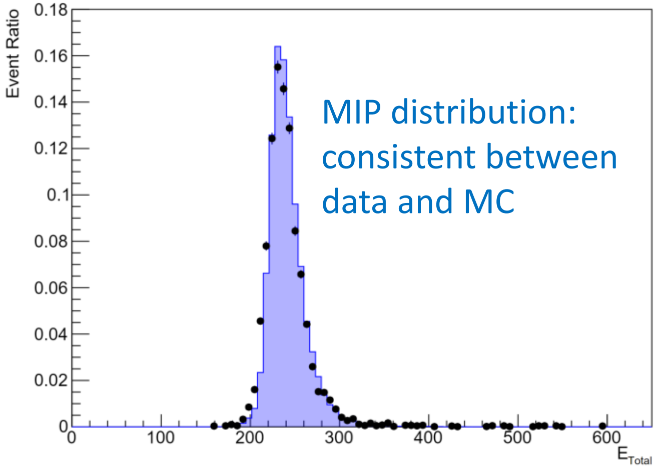
- Low energy part (1-2 GeV), MC is generally consistent with data
- For 5 GeV, data shows better resolution and larger peak value
  - Digitization model should be improved to describe crosstalk and non-linearity effect more accurately

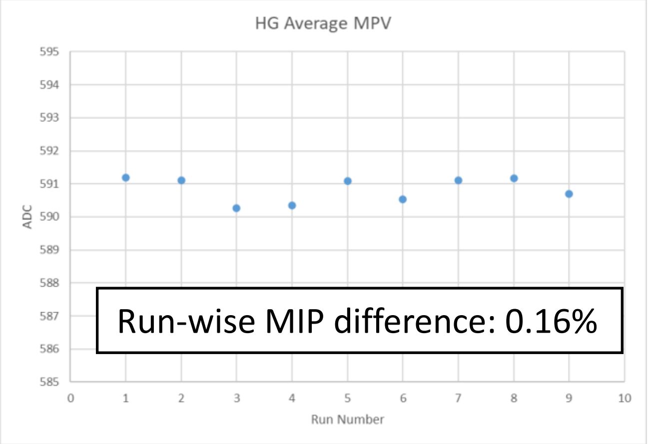
- MC can reproduce the distribution of data, especially at low energy part
- Energy resolution excluding beam momentum spread: $1.3\%/\sqrt{E} \oplus 0.7\%$, <1% stochastic term expected for crystal ECAL tower

Studies of pedestal and MIP stabilities

- MIP response: channel/run-wise difference

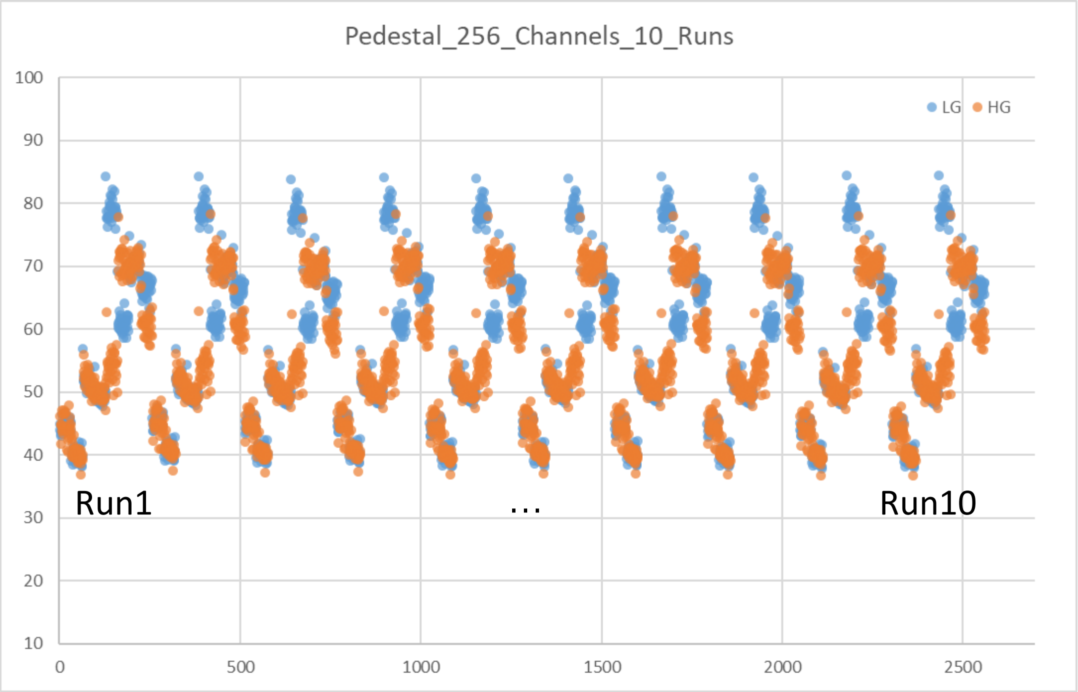






- MIP calibration precision with data from multiple runs
  - Assumed 0.5% sigma, contributed to final energy resolution

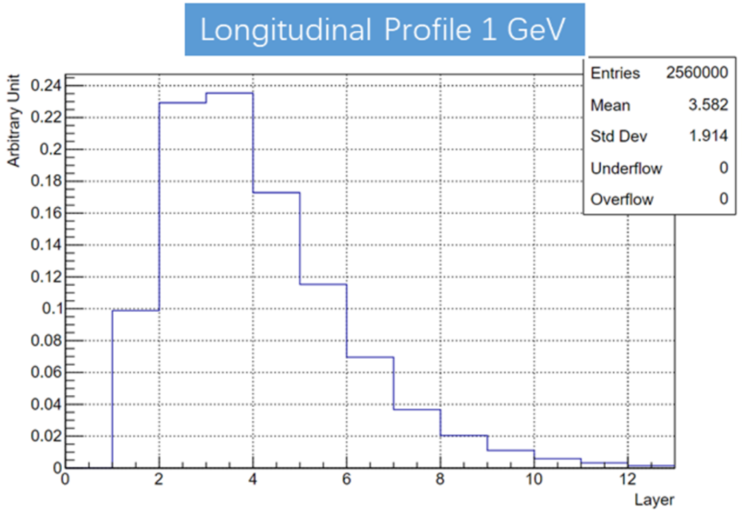
- Pedestal stability

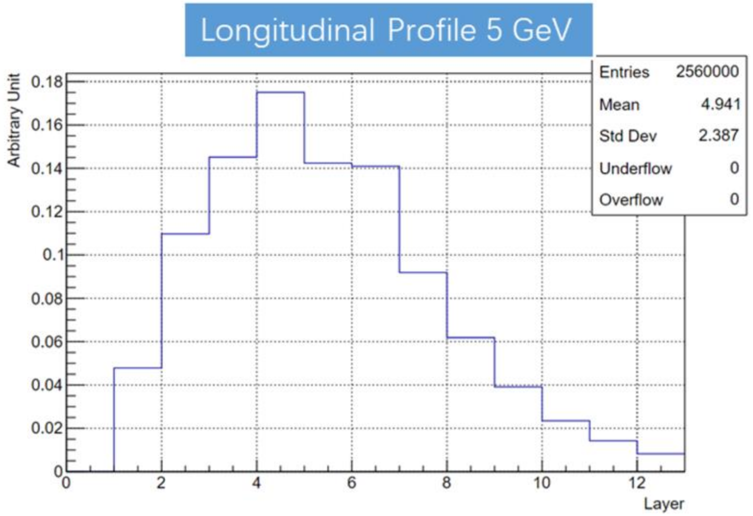


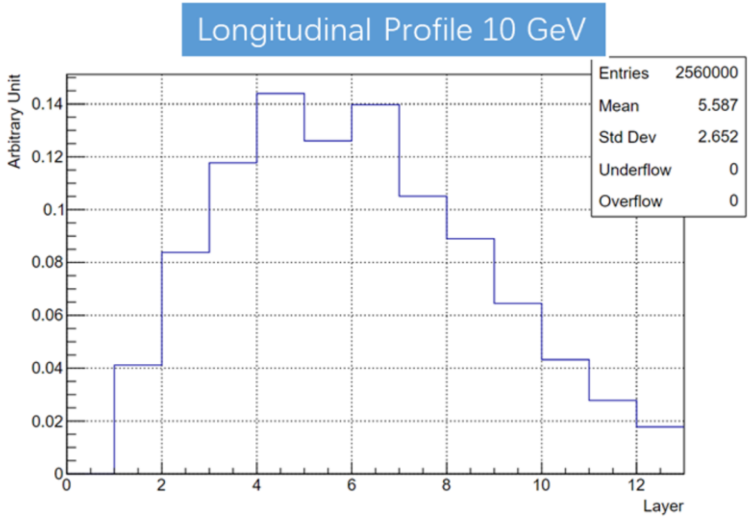
- Max run-wise difference: 1.44%
- Pedestals are generally stable during muon data taking
- Temperature dependence needs further investigation

Shower/beam profile

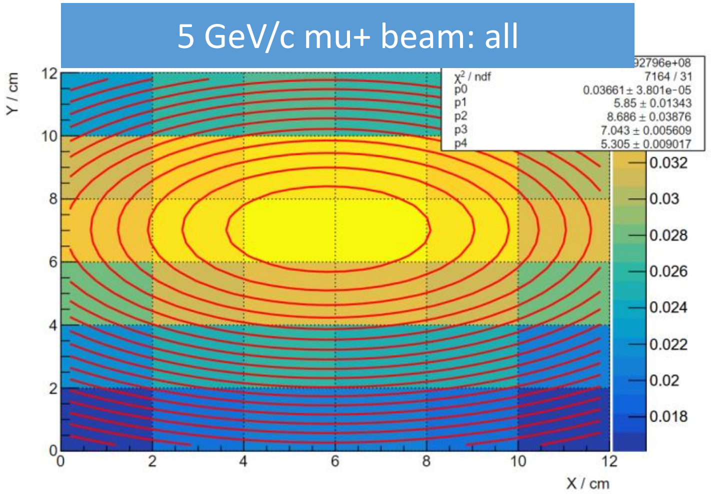
- First study on the longitudinal shower distribution in high-granularity crystal calorimeters, need further understanding

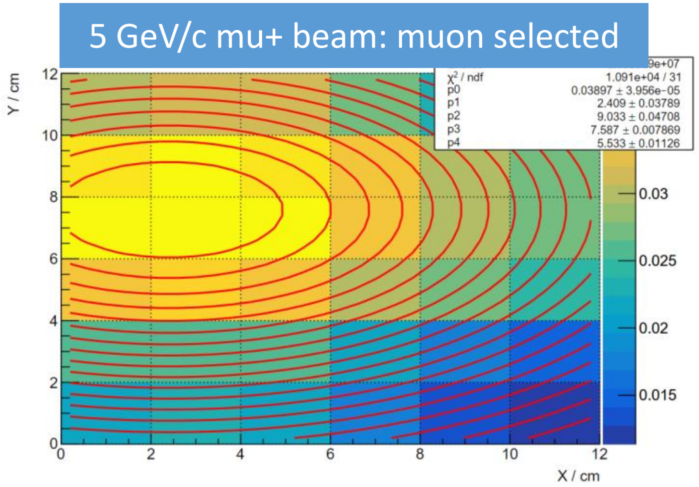


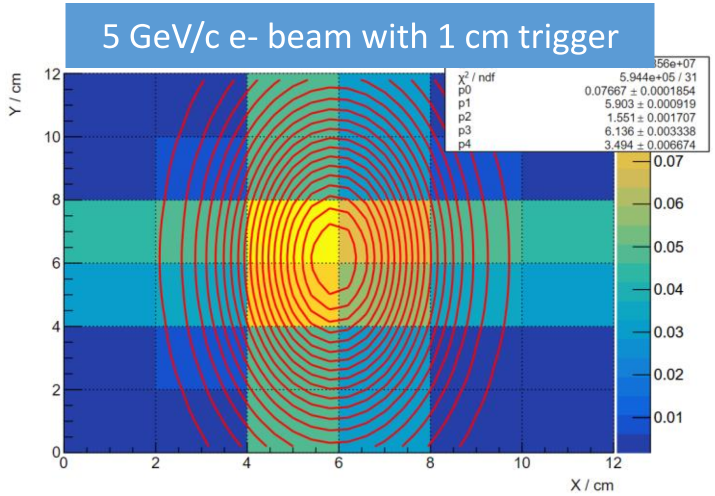




- Transverse profile: particle distribution with beam, need further understanding



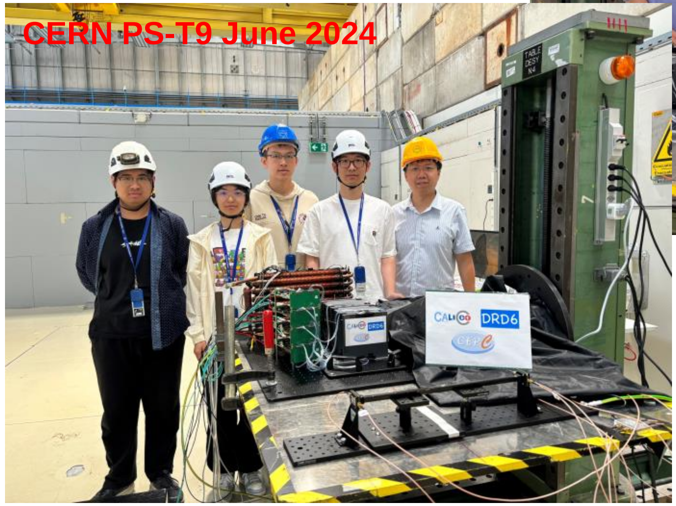




Summary and prospects

Crystal ECAL R&D: beamtest of crystal module

- Successful design, construction and commissioning
  - Three beamtests conducted at DESY and CERN
- Crystal module performance
  - Linearity: ±1% level
  - Energy resolution: $3.5\%/\sqrt{E} \oplus 0.6\%$, dominated by beam momentum spread
- MC simulation: validated digitization model
  - Energy resolution: $1.3\%/\sqrt{E} \oplus 0.7\%$, excluding beam momentum spread



Prospects on crystal module

- Further analysis of beamtest data: electron, pion
- Validation of crystal ECAL design specs
- Investigation on timing performance
- Calibration scheme, radiation damage, …

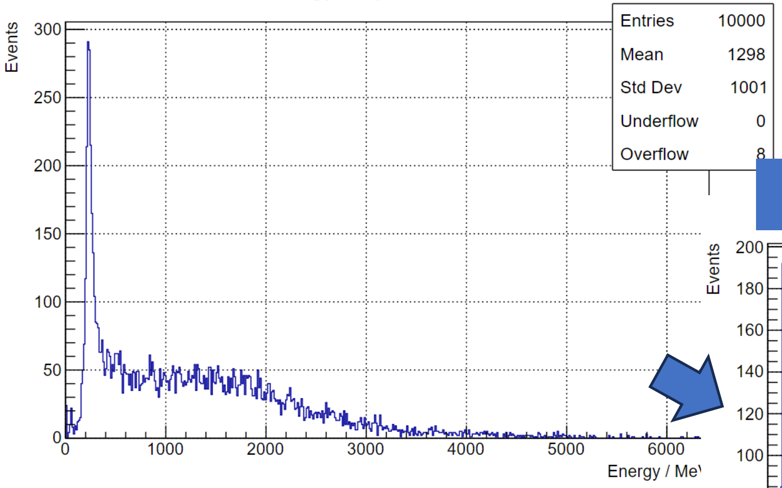
Thanks to every teammate for their contributions!

Backup

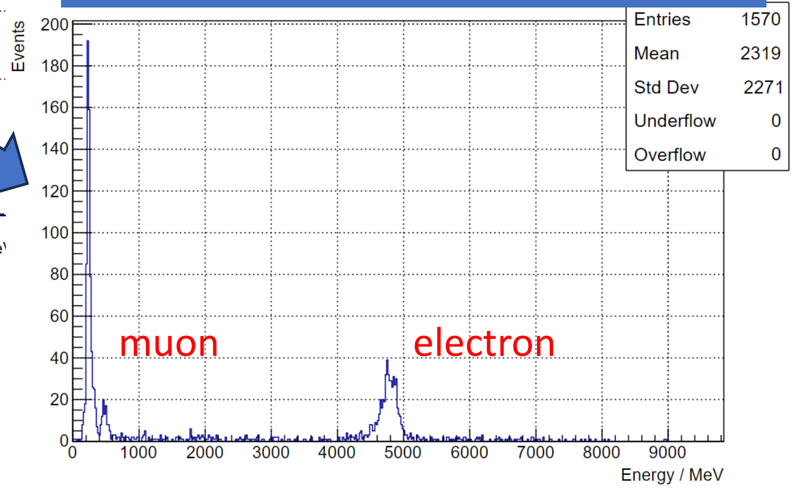
2024 CERN beamtest: preliminary studies with pion beam

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

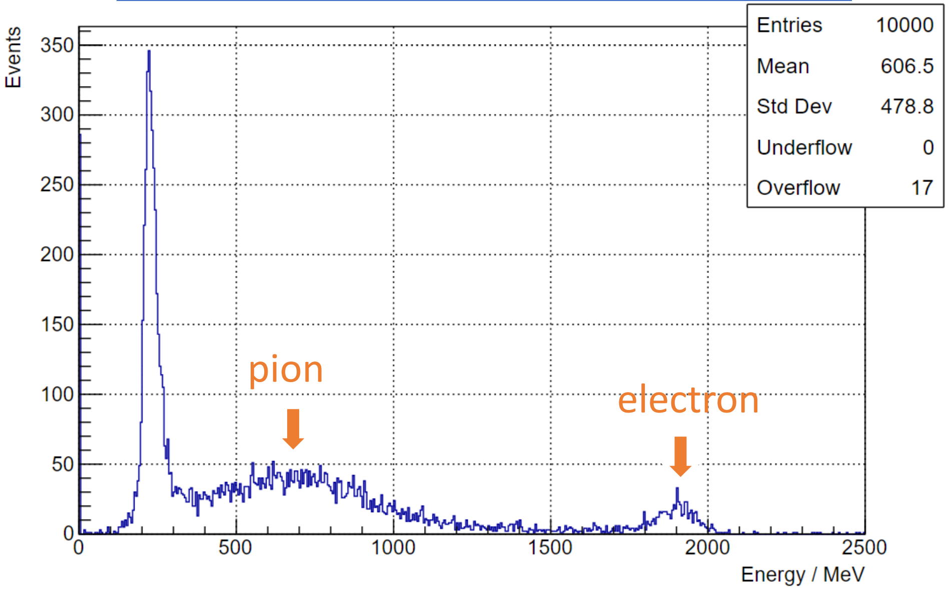
5 GeV/c pion-



5 GeV/c pion-: pion rejected



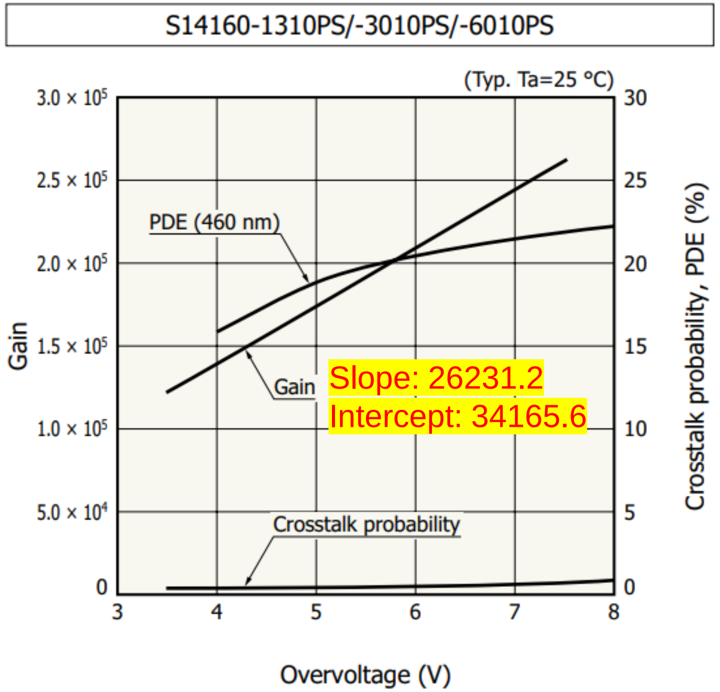
2 GeV/c pion-

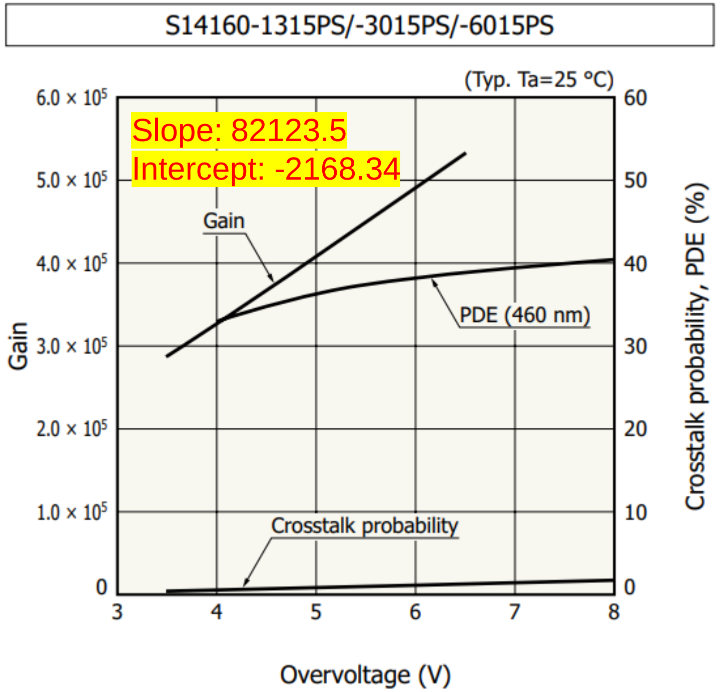


- Electron and muon exists in pion beam
- Proportion changes with energy, need further studies

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

Effect of temperature changes on SiPM





<1℃ temp. change

Temperature coefficient of Vop ΔTVop (mV/°C)
34

The gain increases by 0.54%, with temperature increases by 1℃

The gain increases by 0.86%, with temperature increases by 1℃

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