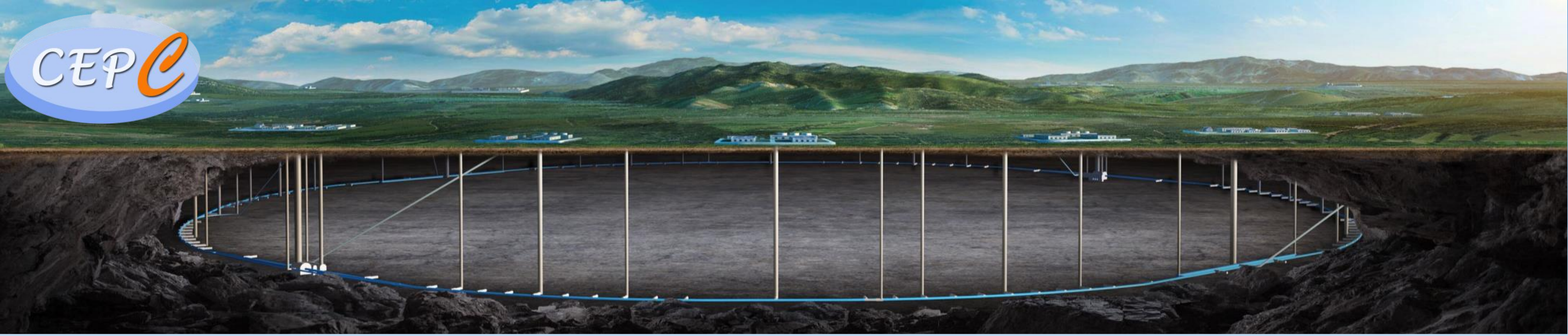

CEPC Crystal Calorimeter: R&D Progress and Highlights

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Institute of High Energy Physics, Chinese Academy of Sciences

drdcalo

Baohua Qi
On behalf of the CEPC Calorimeter Working Group

November 7, 2025

The 2025 CEPC Workshop at Guangzhou

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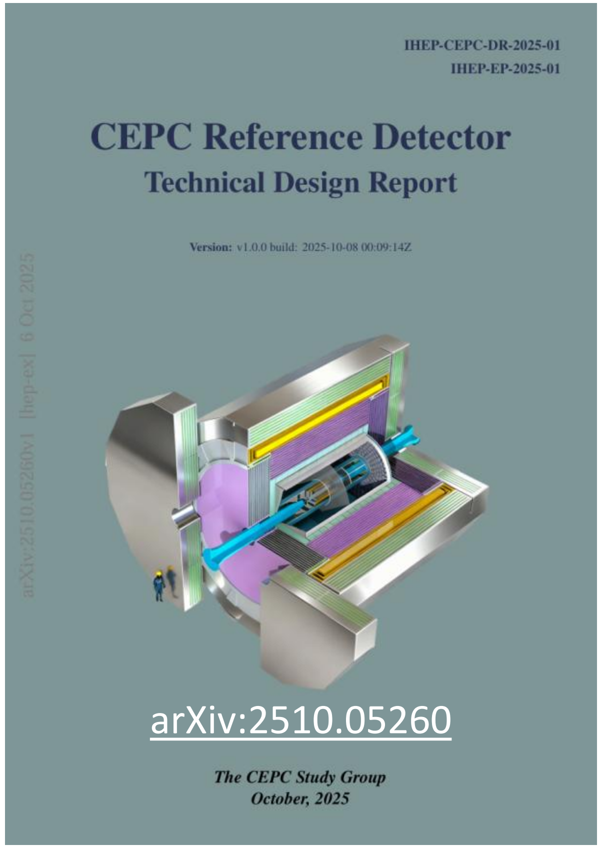
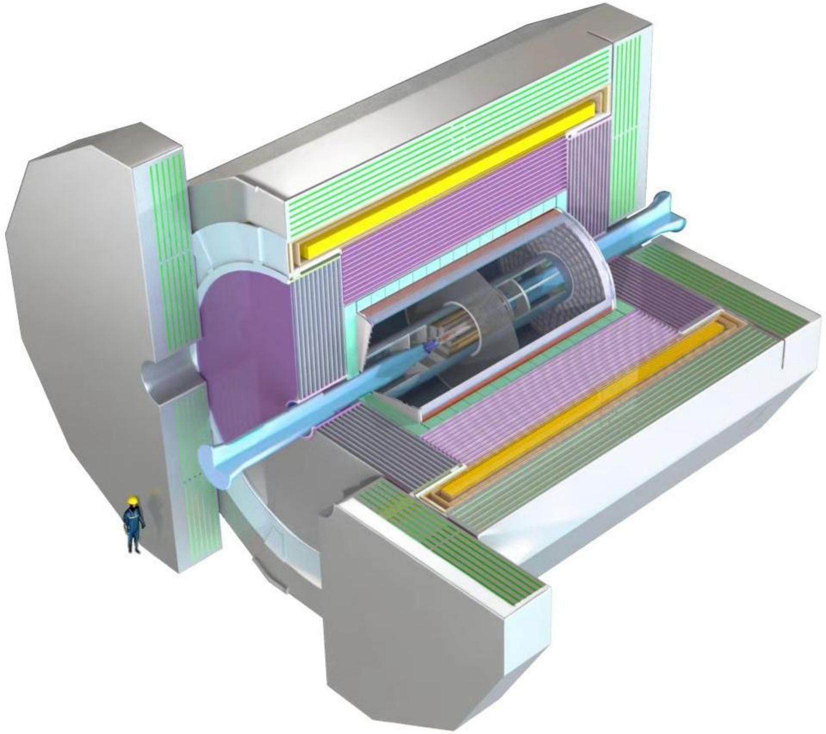
The Reference Detector for the CEPC

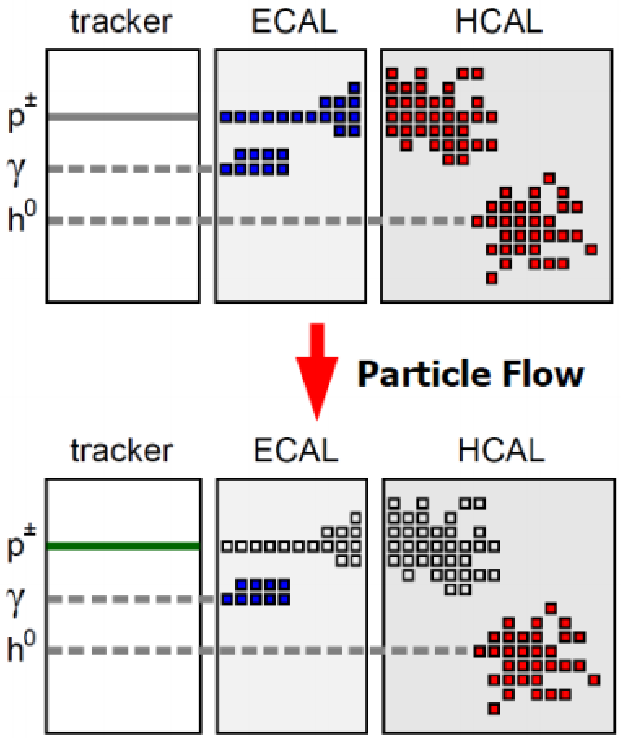
- Future lepton colliders (e.g. CEPC)
  - Higgs/Z/W bosons, top quark, BSM physics, etc.
  - Requirement: Boson Mass Resolution (BMR) < 4%
  - A particle-flow-oriented detector system

CEPC Reference Detector TDR
A reference detector concept for the CEPC



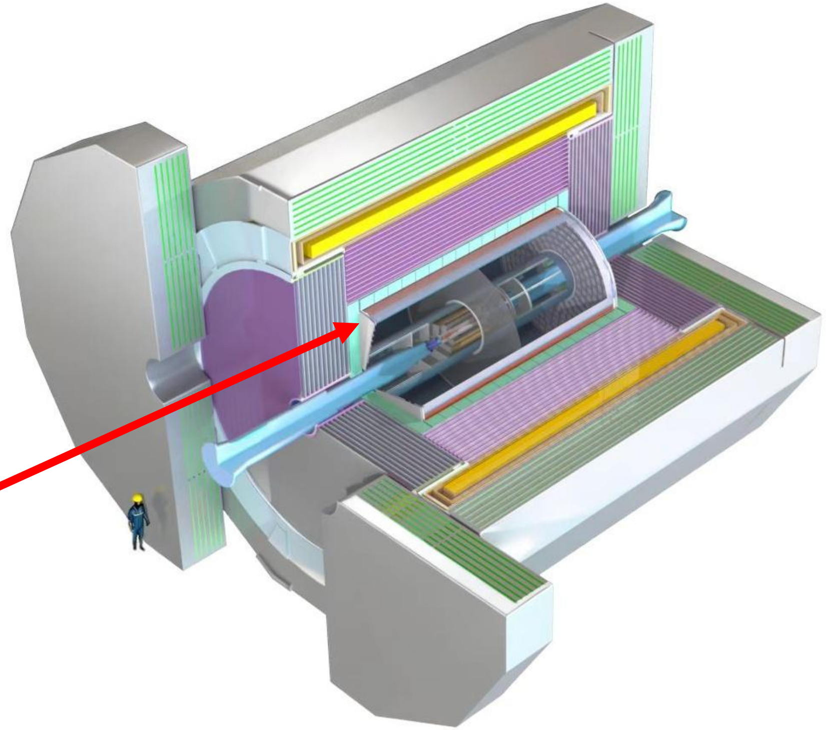


Layout of the CEPC Reference Detector



High-granularity crystal calorimeter option

- Future lepton colliders (e.g. CEPC)
  - Higgs/Z/W bosons, top quark, BSM physics, etc.
  - Requirement: Boson Mass Resolution (BMR) < 4%
  - A particle-flow-oriented detector system
- High-granularity crystal ECAL (HGCCAL): a homogeneous ECAL option
  - 3D spatial + energy + time information
  - EM energy resolution: $< 3\%/\sqrt{E} \oplus 1\%$
  - Precise γ/π^0 reconstruction



★High-granularity Crystal ECAL

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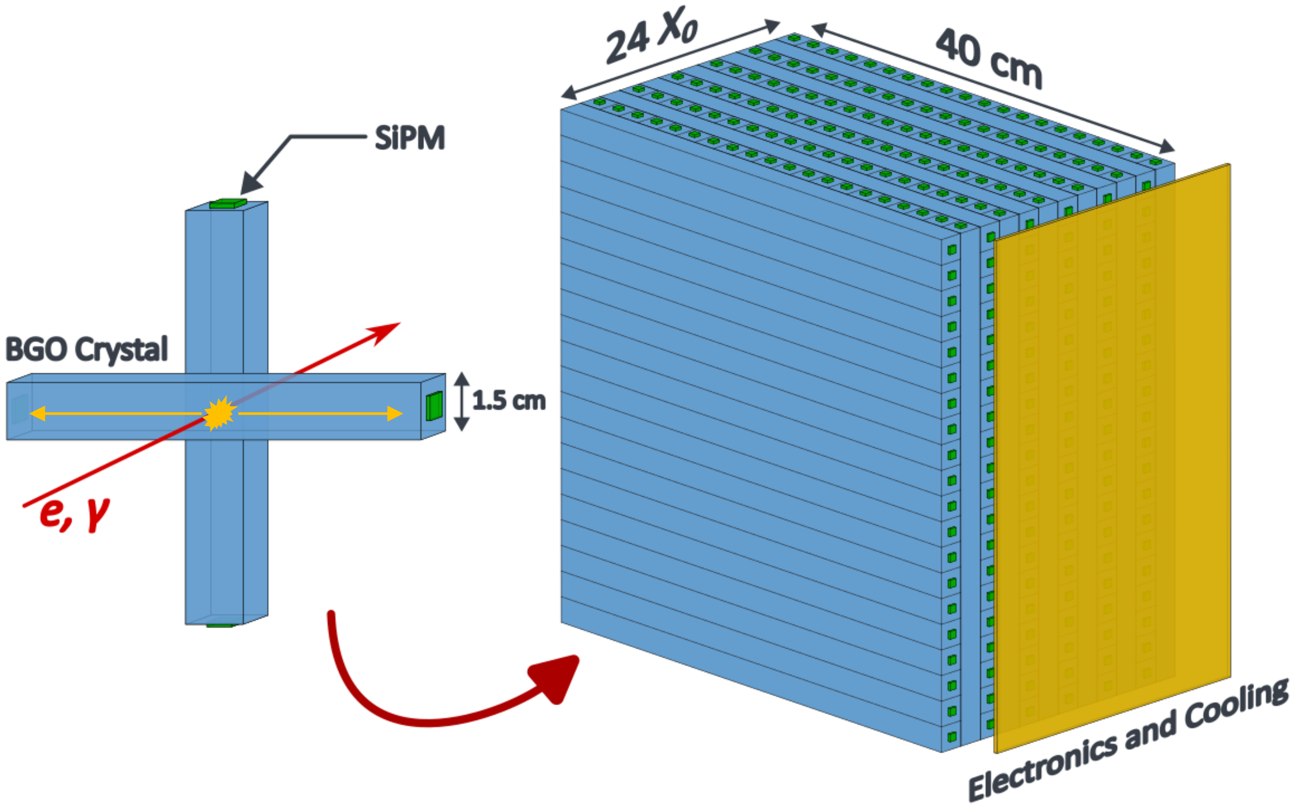
Work Package 3 – Optical Calorimeters

International collaboration: DRD Calo Work Package 3
- New calorimeter concepts R&D based on scintillating materials
- Improve the spatial granularity, the time and energy resolution
- Explore, optimise and demonstrate with full shower-containment prototypes

Design of the long crystal bar ECAL

- Basic units: 1.5×1.5×40 cm^3 BGO crystals, double-sided readout with SiPMs
- Module design: 18 orthogonally arranged layers (24 X_0)



Extensive R&D efforts throughout the Ref-TDR phase

Key features:

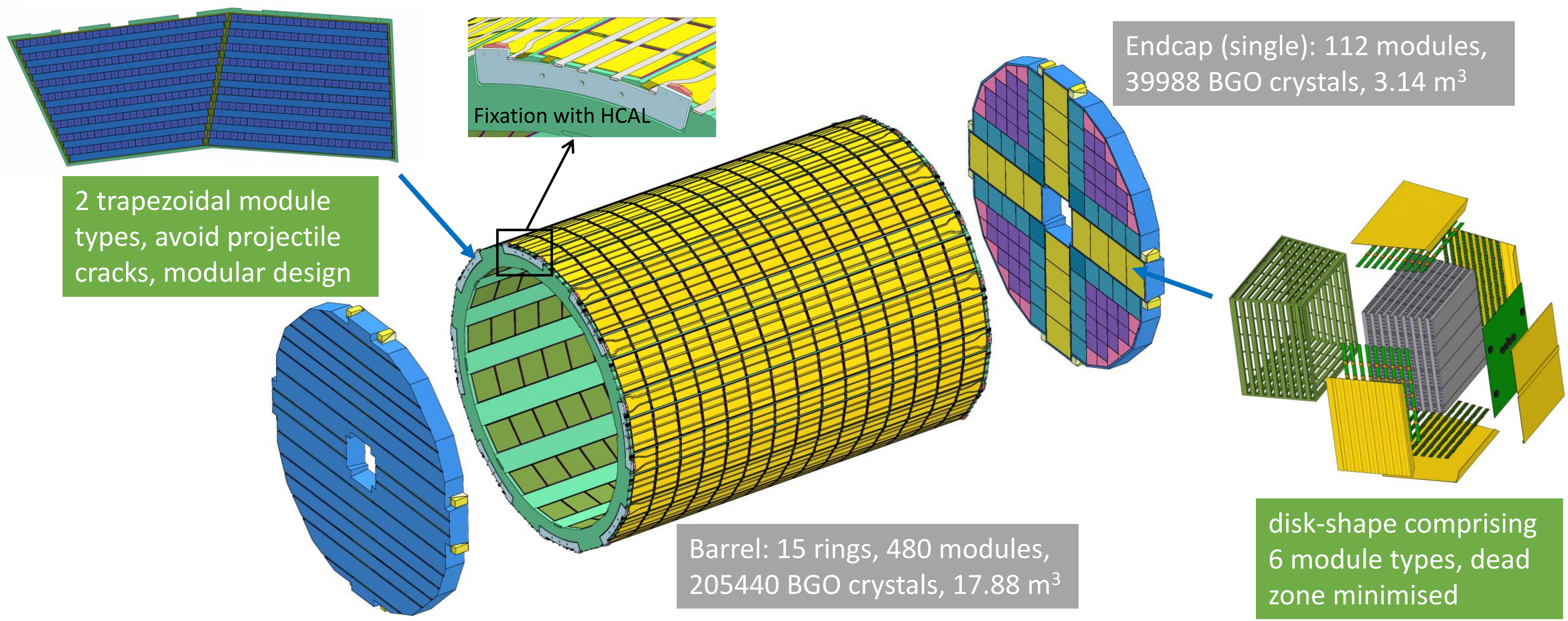
- Long crystal bars to achieve high-granularity
  - Save number of readout channels
  - Minimise longitudinal dead materials
- Double-sided SiPM readout
  - Better response uniformity
  - Timing potentials

Key technical challenges:

- System design and integration
  - Mechanics, cooling, readout, etc.
- Dedicated PFA for long bar ECAL
  - To meet the reconstruction requirements
- Optimal EM performance
  - To be validated with prototype development

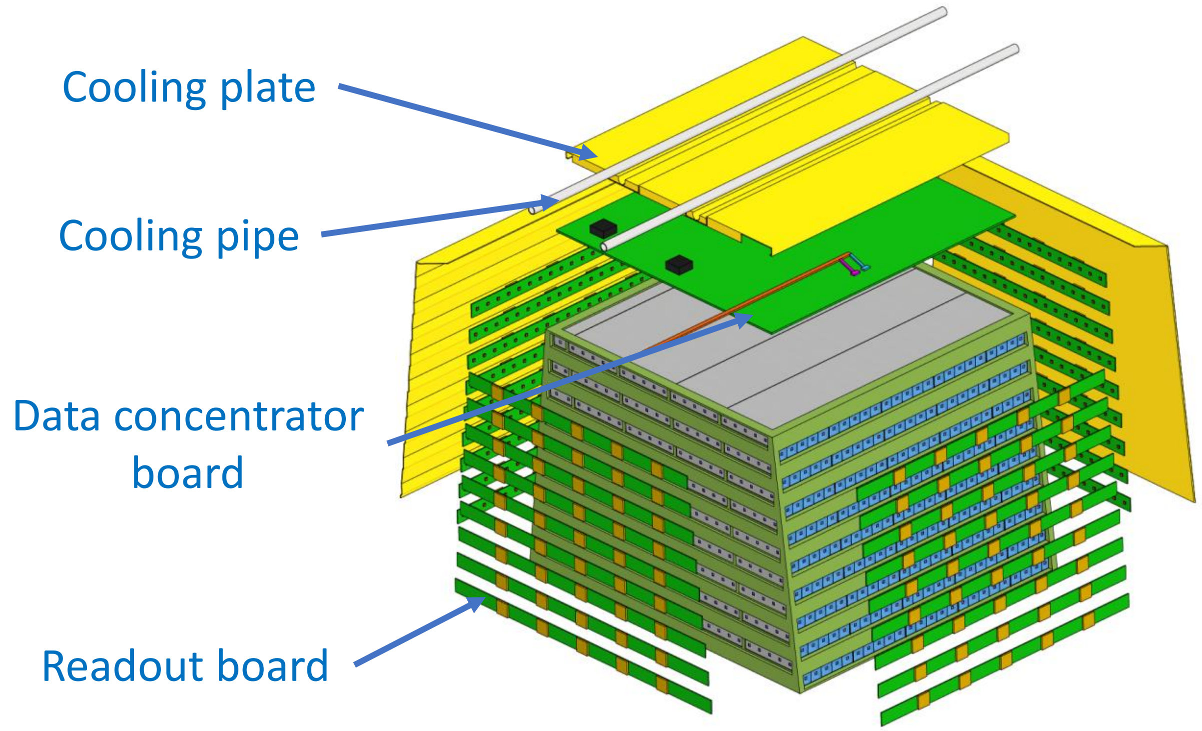
Integration of the crystal ECAL

- Overview of the crystal ECAL engineering design: barrel + 2 endcaps, 24 m^3 crystal, 0.57M readout channels
  - Key design points: carbon fibre frame support, cooling system, readout integration, etc.

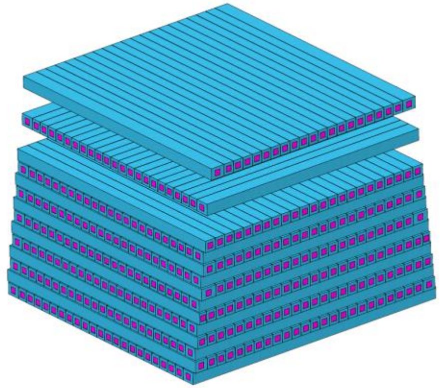


Integration of the crystal ECAL module

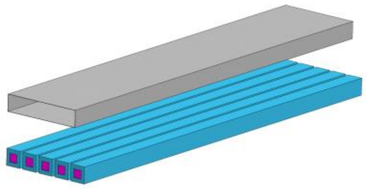
- Overview of the crystal ECAL engineering design: barrel + 2 endcaps, 24 m^3 crystal, 0.57M readout channels
  - Key design points: carbon fibre frame support, cooling system, readout integration, etc.
- General module engineering design:



Barrel crystal ECAL module



Crystal bars



Crystals grouped in carbon fibre box

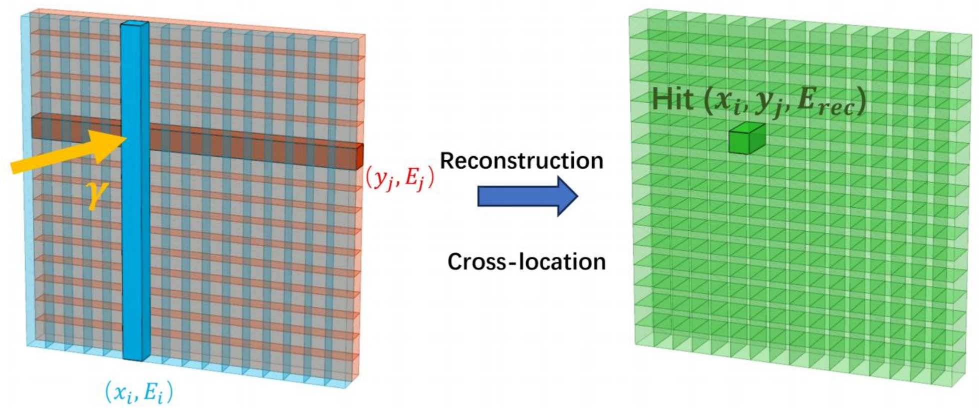
Carbon fibre frame

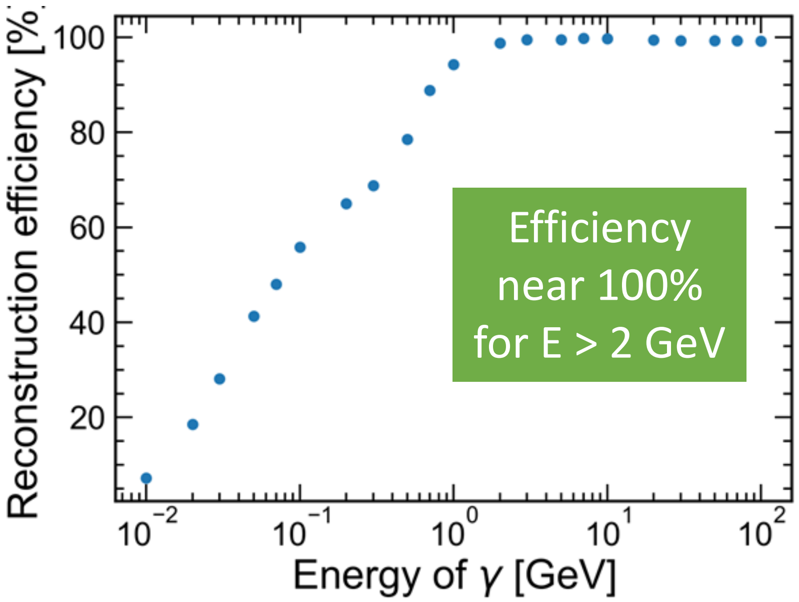
System integration of the crystal ECAL has been well-defined

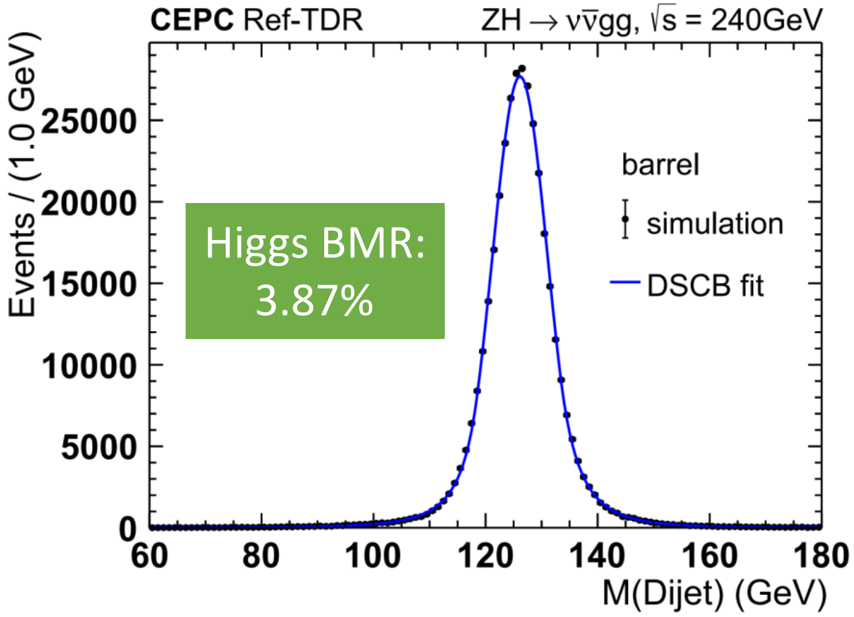
PFA performance of the long crystal bar ECAL

Talk by Yang Zhang: CyberPFA: Particle Flow Algorithm for Crystal Bar ECAL

- CyberPFA: a dedicated PFA software for the crystal bar ECAL
  - Energy-core-based pattern recognition
  - Ghost hit removal with multiple variables
- Key benchmarks to validate PFA performance
  - Photon reconstruction efficiency
  - BMR in $e^+e^- \to ZH \to \nu\nu gg$



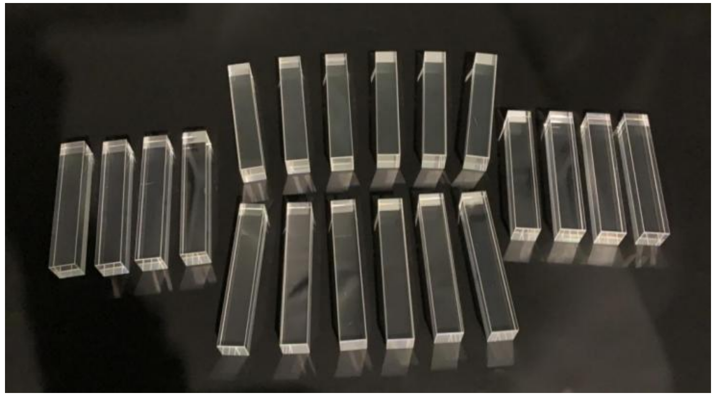




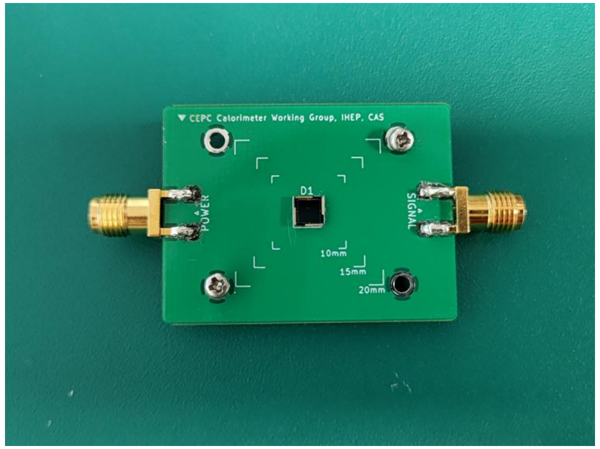
PFA performance meet the requirements for jet reconstruction

Crystal prototype R&D: performance validation

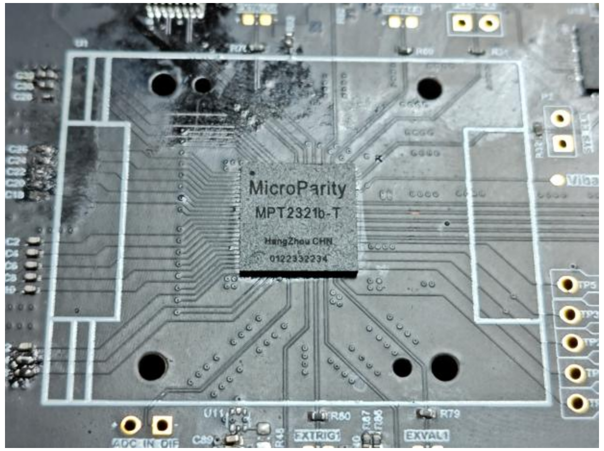
- Key technical challenges: optimal EM performance
  - Validation phase: understand the system-level performance of the crystal ECAL
- The critical R&D efforts centre on:



Crystal



SiPM



Electronics

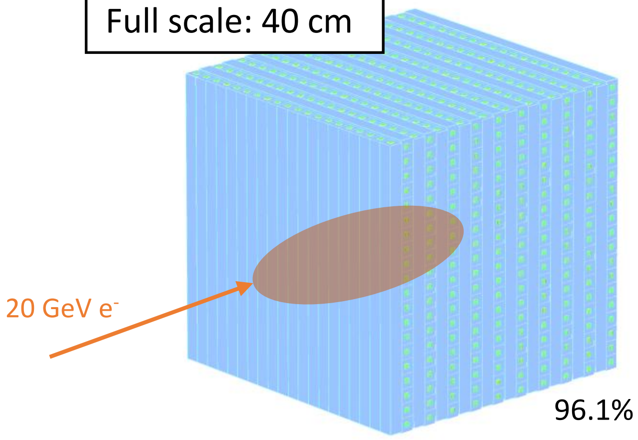
Develop a crystal ECAL prototype for EM resolution studies

Prototype design: studies on dimensions

What we want:

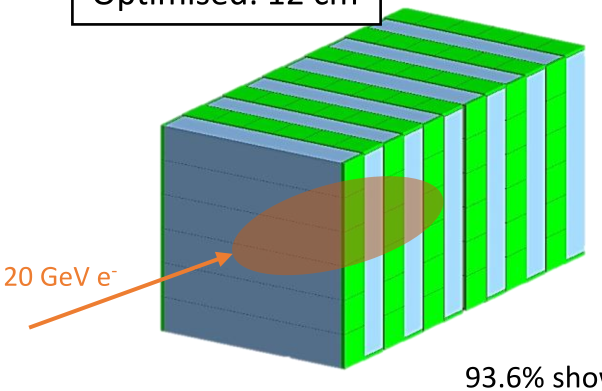
- Prototype for 1-10 GeV EM performance studies
- Granularity validation is NOT the main focus at this stage

Full scale: 40 cm



96.1% shower energy contained

Optimised: 12 cm

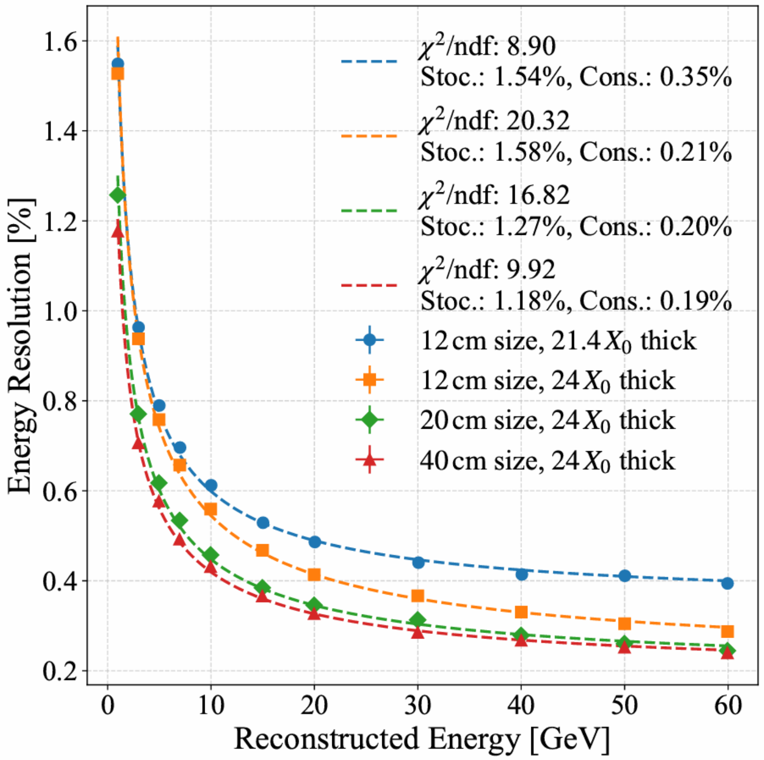


93.6% shower energy contained

Performance: $1.18\%/\sqrt{E} \oplus 0.19\%$ ➡ Performance: $1.54\%/\sqrt{E} \oplus 0.35\%$

- 12 cm module: EM performance much better than $3\%/\sqrt{E} \oplus 1\%$
- Prototype design
  - $12\times12\times24$ cm^3 ($21.4\ X_0$) BGO prototype with external ASIC readout
  - 72 $2\times2\times12$ cm^3 crystal bars, 144 SiPM channels

Energy resolution vs prototype size



Dimension studies with Geant4 simulations:

- Balance between EM performance and cost/complexity

Prototype development: key issues

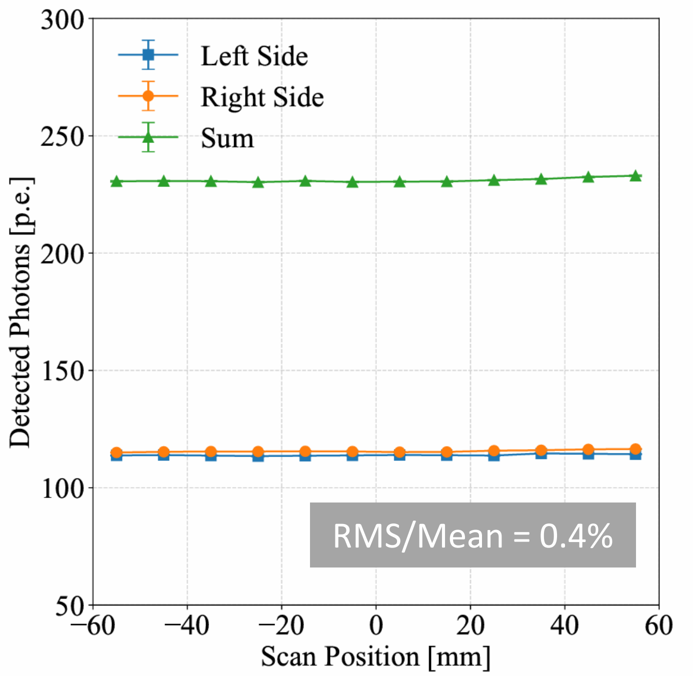
Understand key aspects leading to the optimal EM performance

- SiPM: non-linear response → SiPM lab and beam tests *Talk by Zhiyu Zhao*
- Crystal: response uniformity → Batch test for quality control
- Mechanics: support structure → Design and integration
- Electronics: readout stability → Setup and commissioning
- Temperature: performance shift → Active cooling system

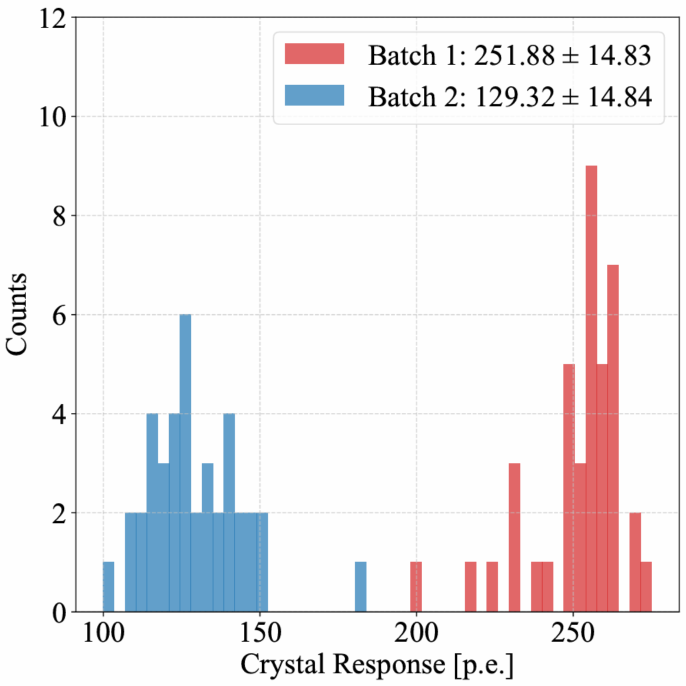
Prototype development: batch test of BGO crystal bars

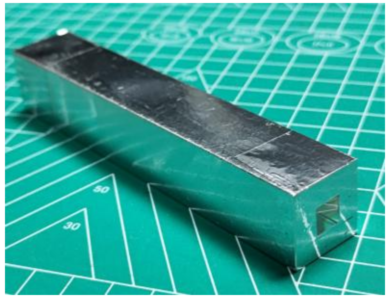
- Uniformity scan of 80 (2 batches) SIC-CAS BGO crystal

Response inside a typical crystal

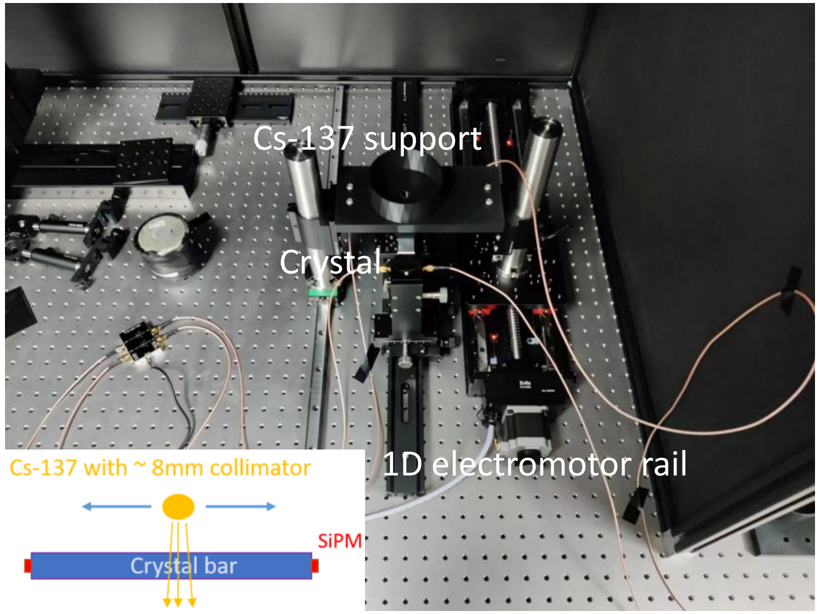


Responses of all crystals





- $2\times2\times12$ cm^3 BGO
- ESR and Al foil wrapping
- 7.5 mm windows for SiPMs

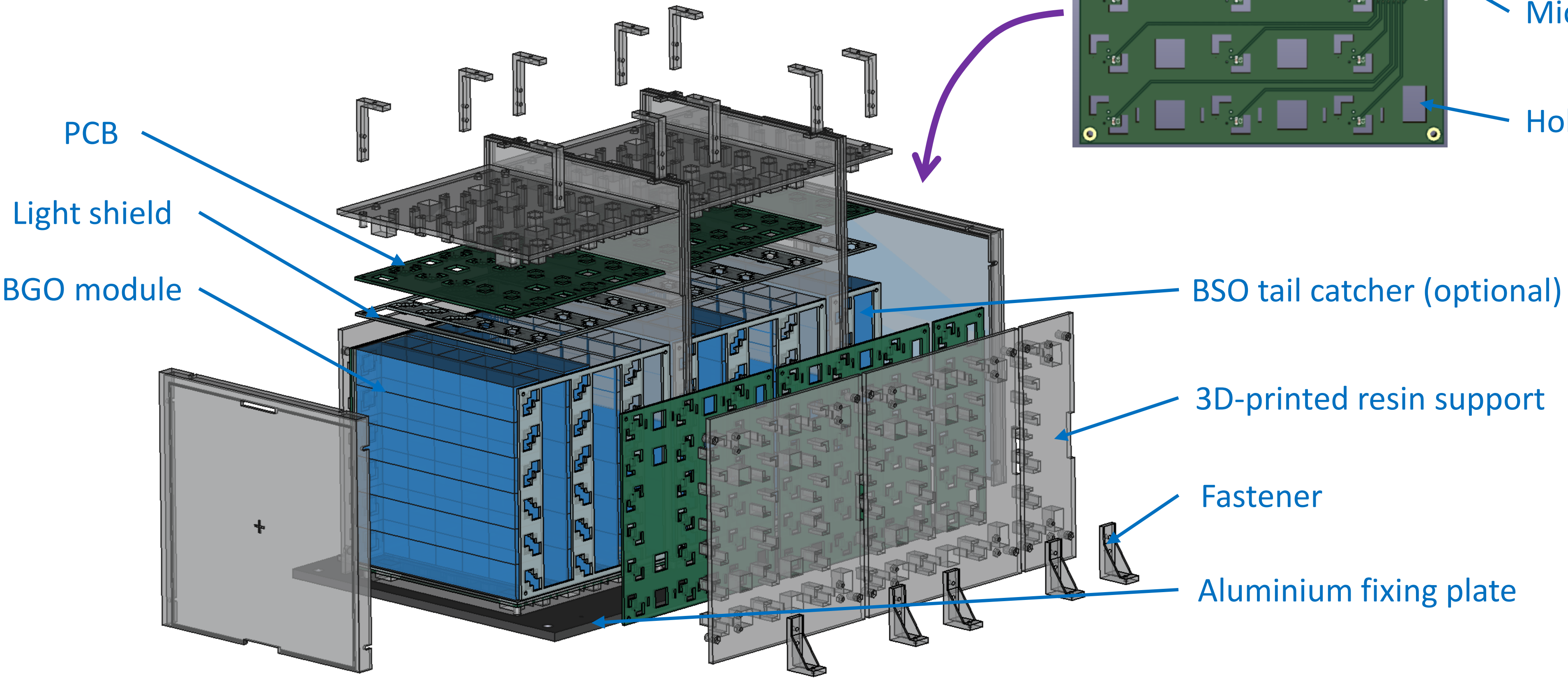


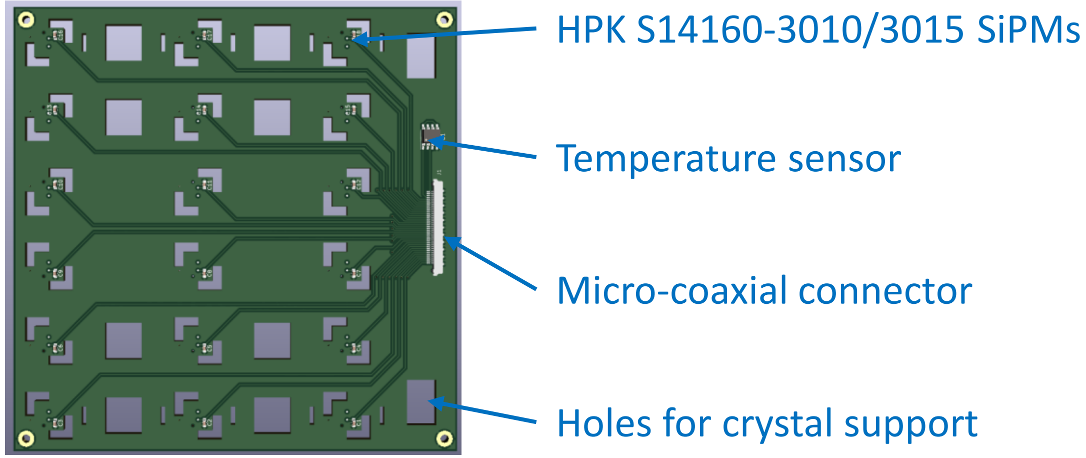
Automated crystal scan planform

- BGO crystal with good quality -> typical uniformity at 0.4% level
- Response variations among crystals/batches -> in-situ calibration with MIP

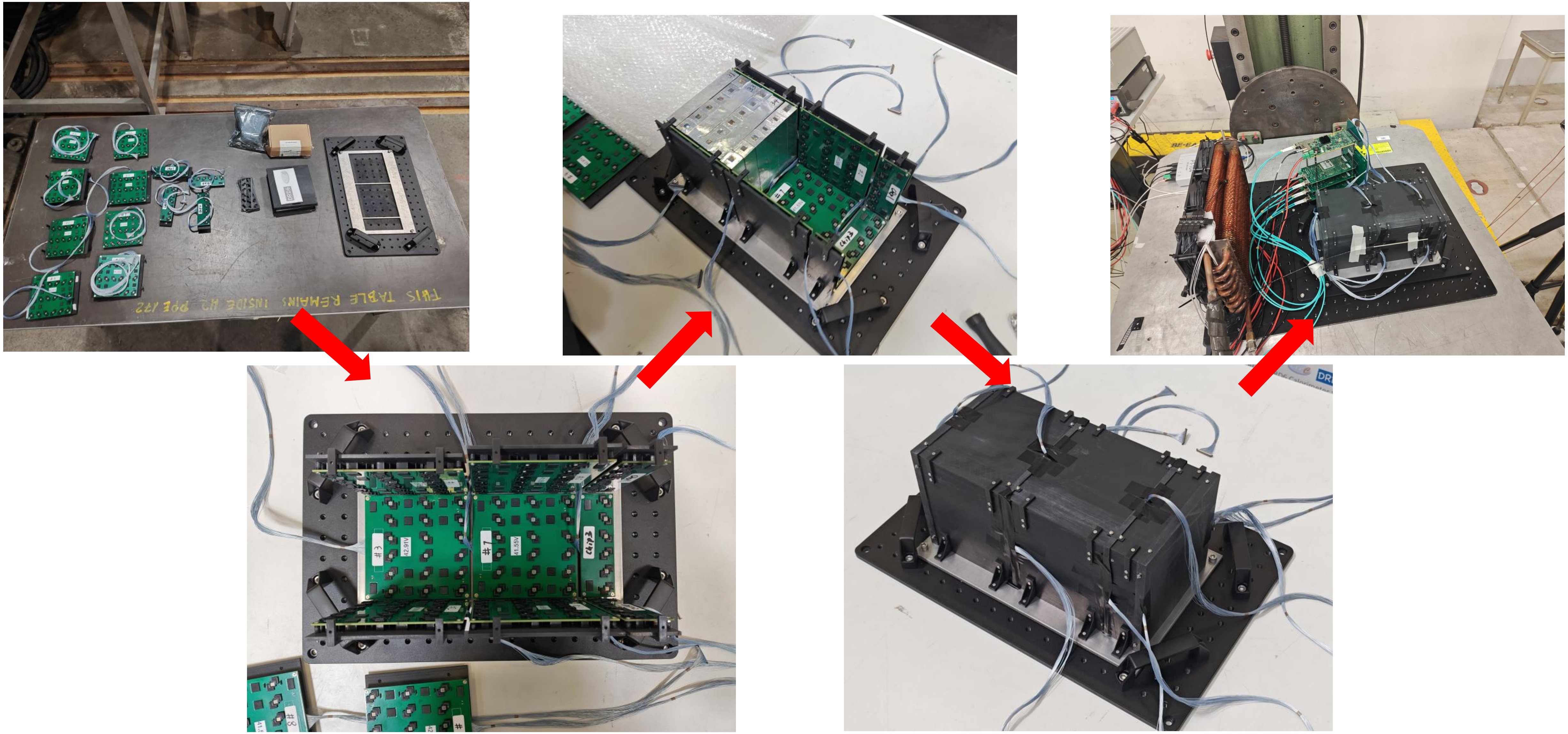
Prototype development: mechanical support and PCB design

- Key challenges:
  - Minimise material budget
  - Decouple crystal gravity from PCB
  - Shield the signal from EM interference





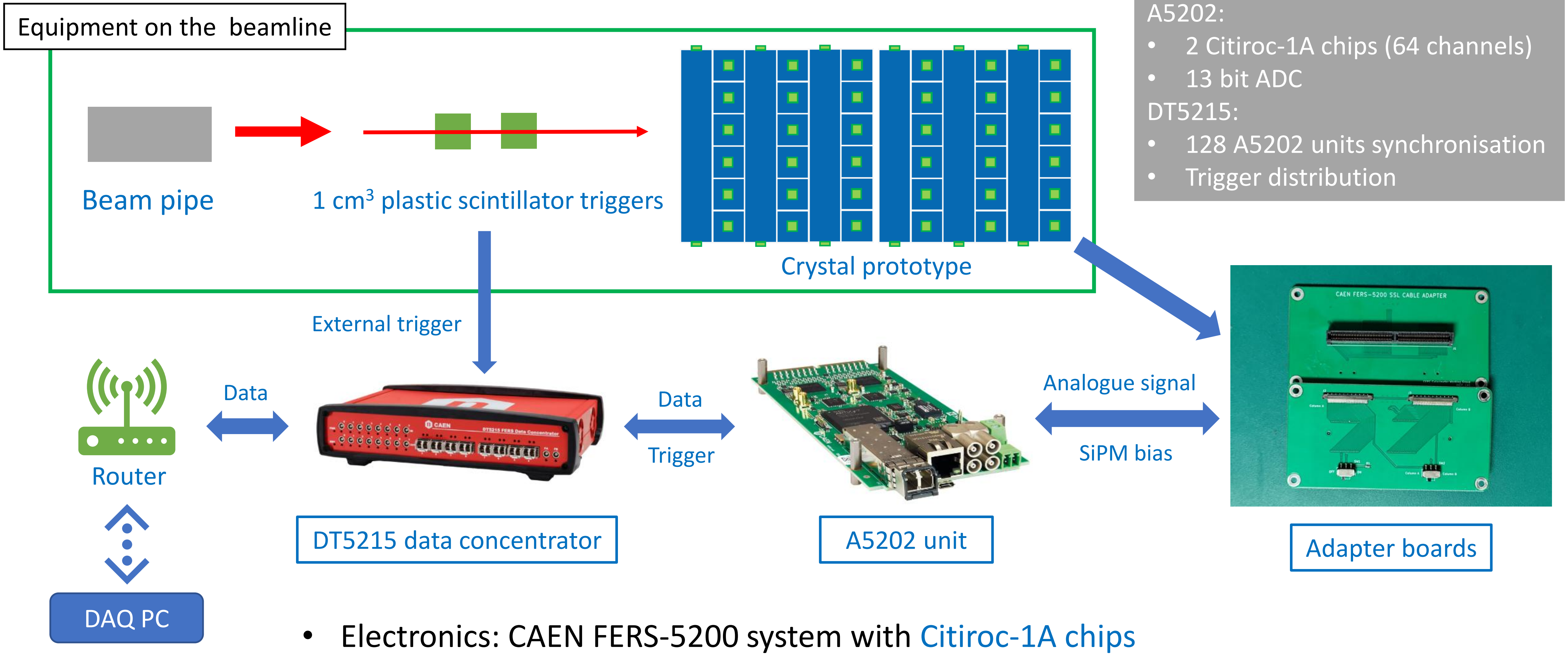
Prototype development: integration



Prototype development: electronics setup and trigger scheme

A5202:
- 2 Citiroc-1A chips (64 channels)
- 13 bit ADC

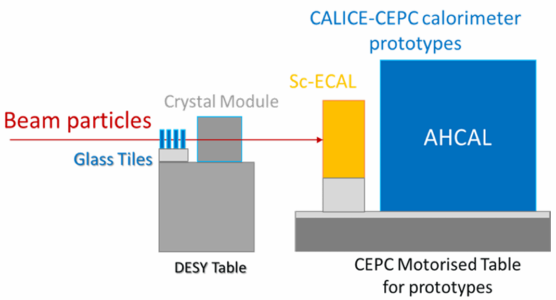
DT5215:
- 128 A5202 units synchronisation
- Trigger distribution

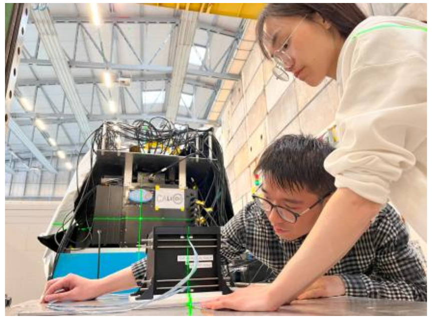


- Electronics: CAEN FERS-5200 system with Citiroc-1A chips
- External trigger cubes for better beam collimation

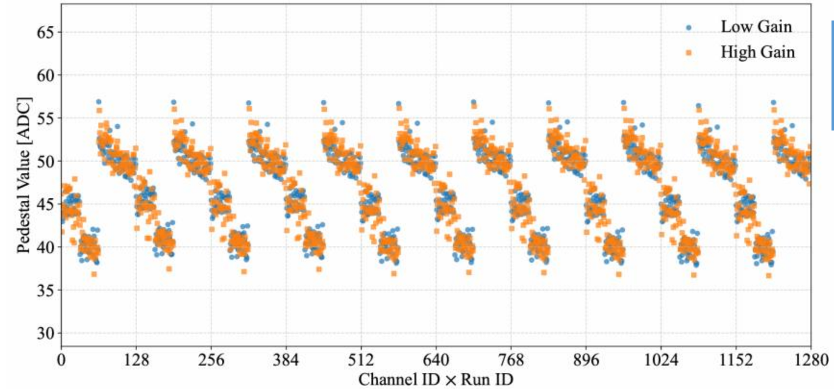
Prototype development: first electronics commissioning test

- Successfully developed the first $10.7\ X_0$ HGCCAL module (6 layers)
- Successful commissioning for 72 SiPM channels
  - Parasitic tests with CALICE calorimeter prototypes at CERN PS-T9

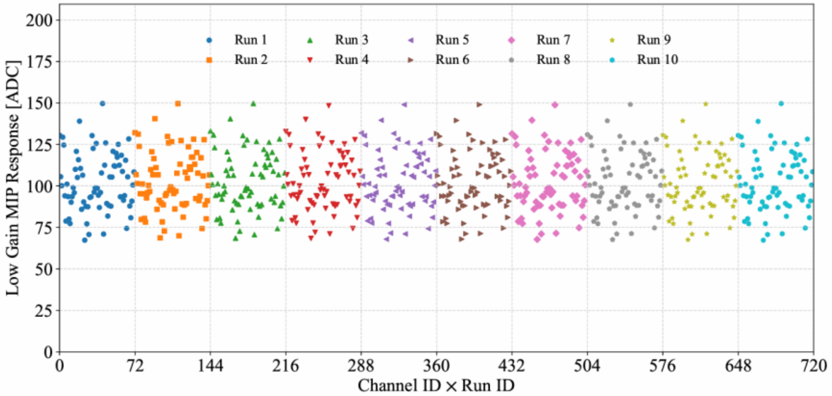




Pedestal and MIP response stability: 10 Runs



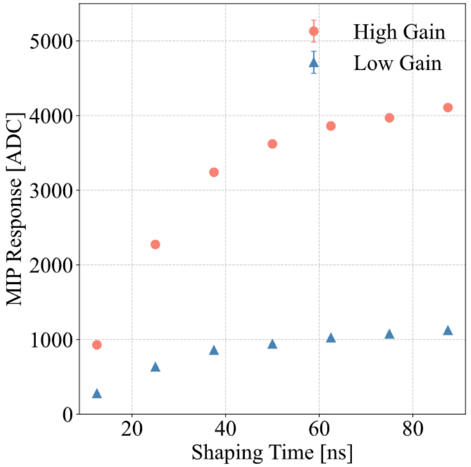
Max. pedestal shift: 3.62%
Avg. pedestal shift: 1.77%

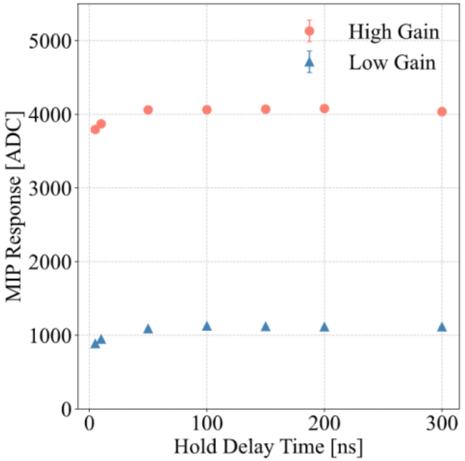


Max. MIP shift: 2.97%
Avg. MIP shift: 1.41%

Good electronics stability

Electronics parameter scans

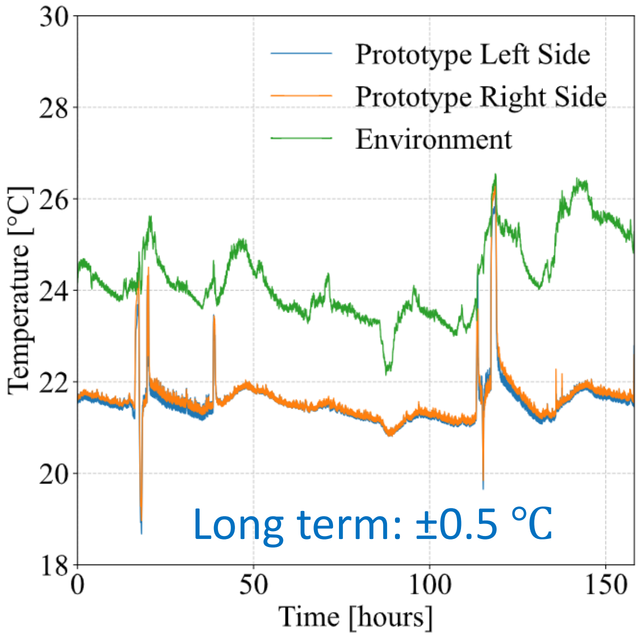


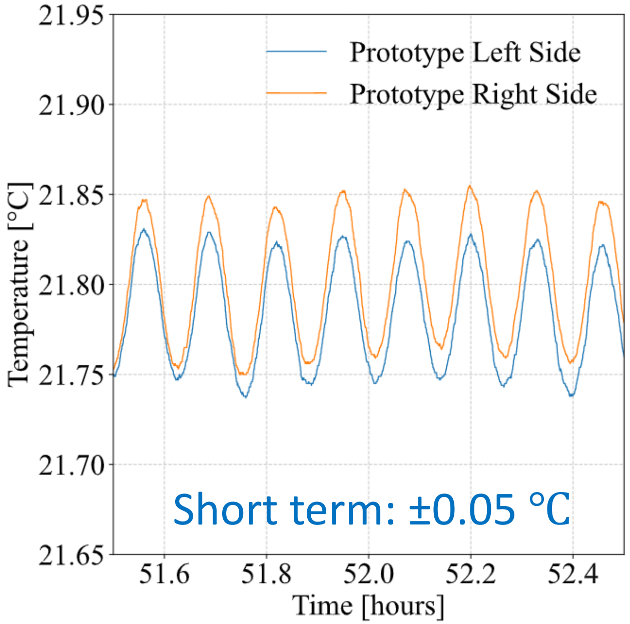


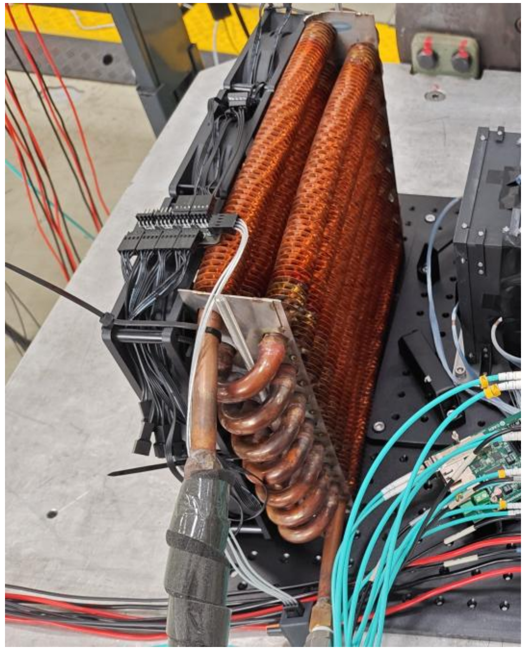
Optimised ASIC parameters
- Hold Delay: >200 ns, Shaping time: 87.5 ns

Prototype development: active cooling system

- Temperature monitoring and control
  - Active watering cooling system integrated
  - Sensors in environment and inside prototype dark box







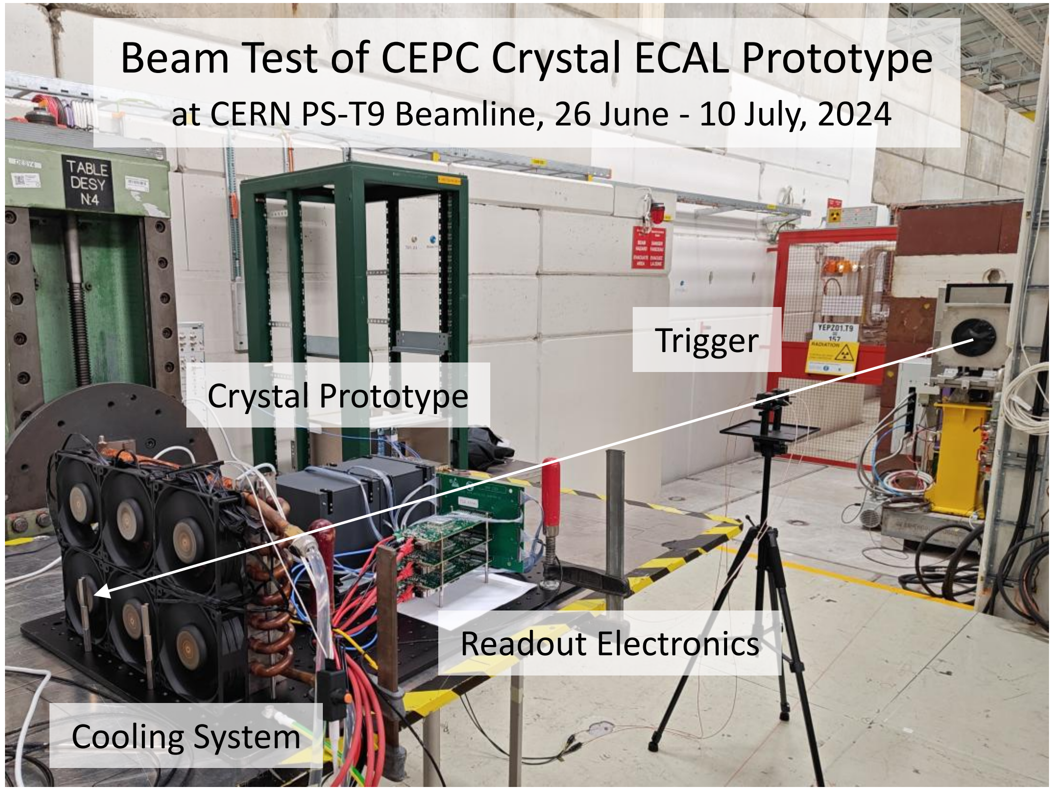
Fan and heat sink

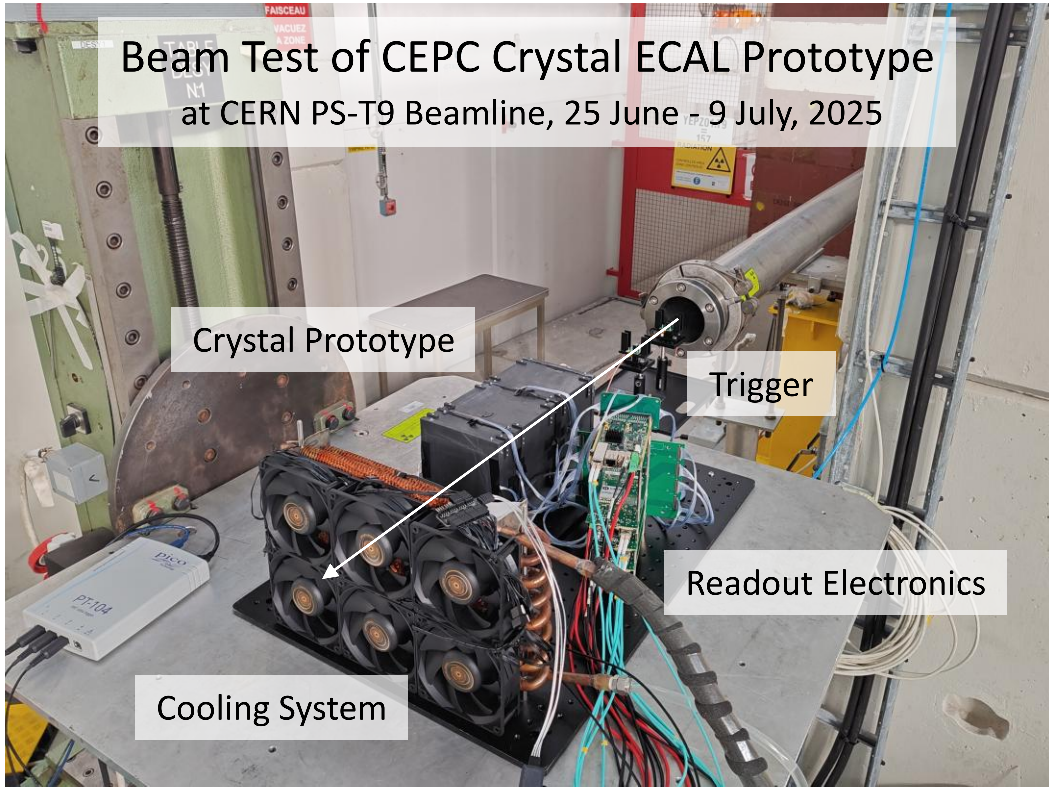
Chiller

Temperature fluctuations can be controlled within ±0.05 °C with active water cooling

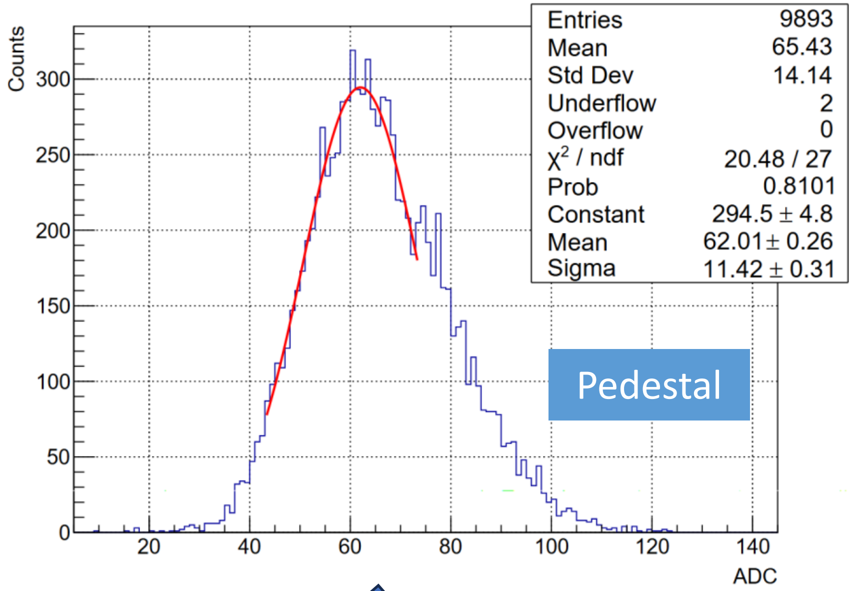
Testbeam campaigns: prototype EM performance evaluation

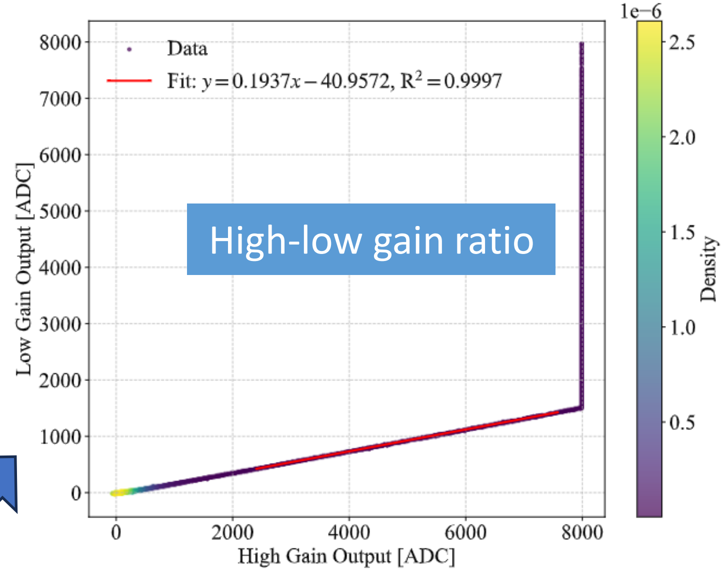
- Two major beam tests for EM performance evaluation
  - 2024 CERN PS-T9: 21.4 X_0 BGO module, standard beamline setup
    - 5 GeV muon, 0.5-10 GeV electron, 2.1M electron events taken
  - 2025 CERN PS-T9: 21.4 X_0 BGO module (with 2 layers of BSO tail catcher), low-energy beamline setup
    - 5 GeV muon, 0.1-10 GeV electron, 20.8M electron events taken

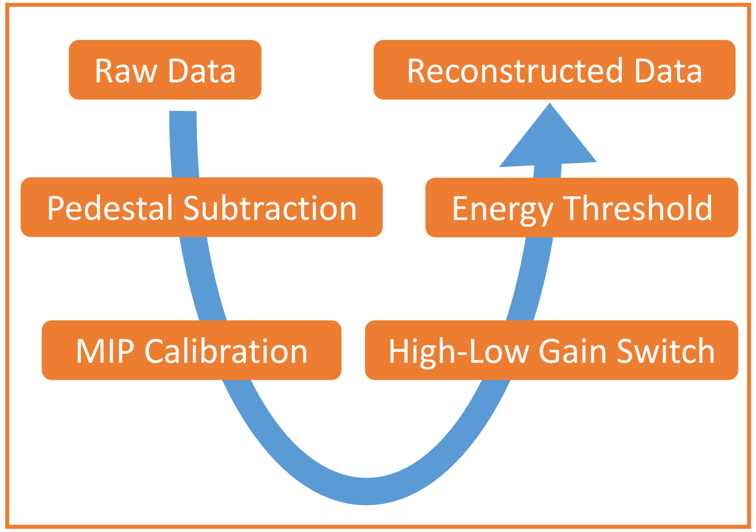


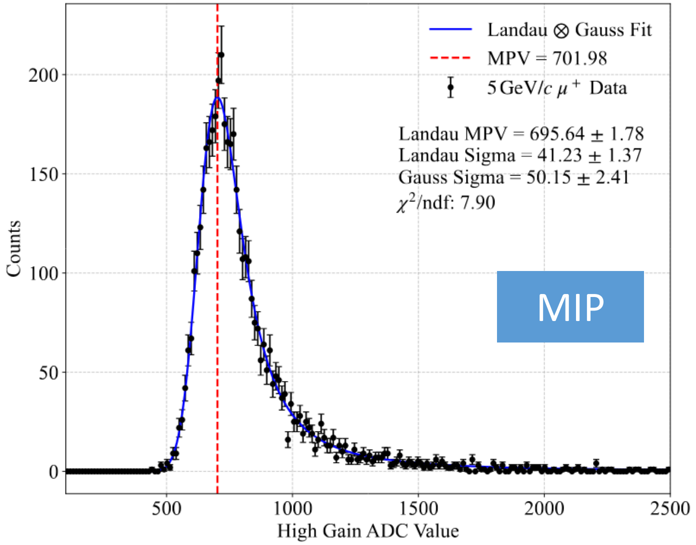


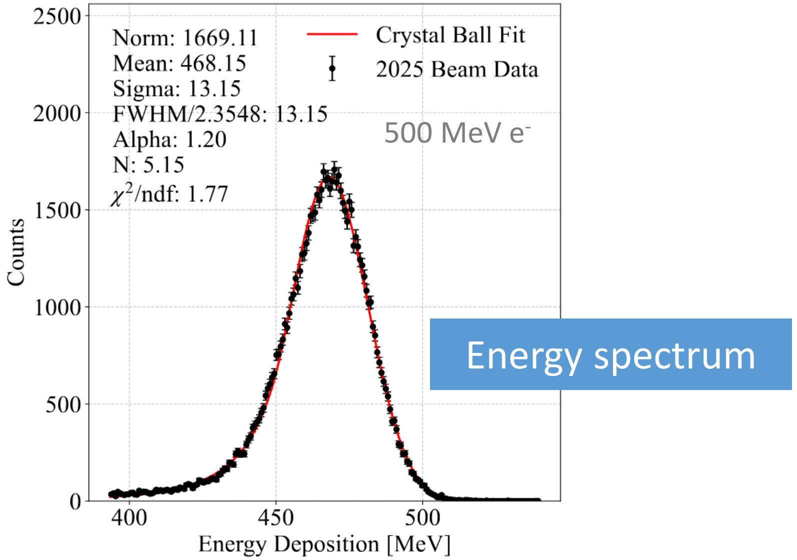
Beam data calibration and reconstruction











2024 CERN PS-T9: beamtest setup

- 2024 CERN PS-T9: 0.5-10 GeV electron, 5 GeV muon
  - 21.4 X_0 full size BGO module
  - Standard beamline setup: with Cherenkov detectors, SciFi trackers, etc.
    - Momentum spread: multiple scattering effect of beam instrumentations

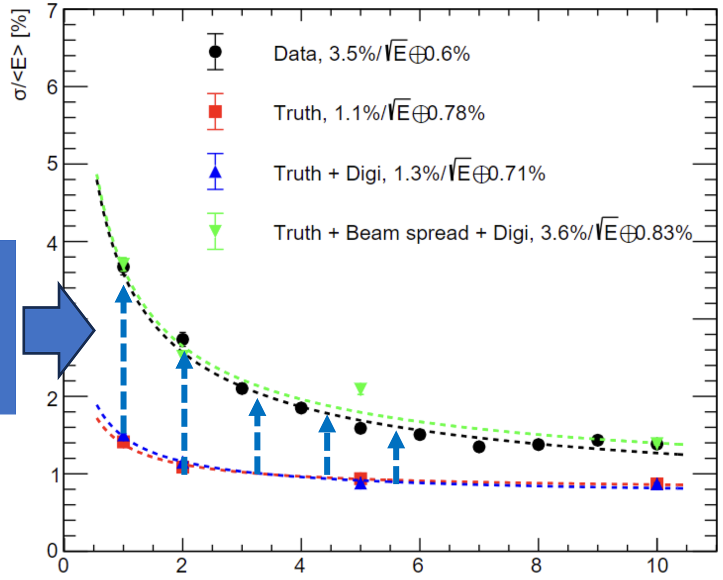
June 2024 CERN PS-T9

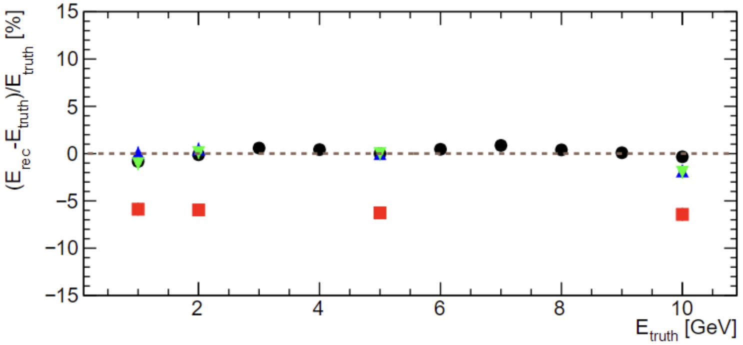
Standard beamline configuration at CERN PS-T9: beam instrumentations in upstream

2024 CERN PS-T9: EM performance

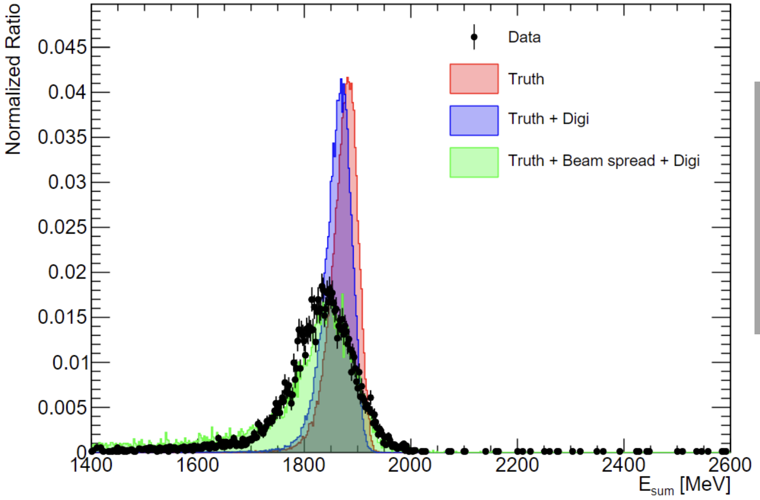
- EM performance studies based on 1-10 GeV electron data
- Beamline simulation: momentum spread estimated with beamline simulations (1, 2, 5, 10 GeV)

Add beam momentum spread





Energy spectrum: 2 GeV electron



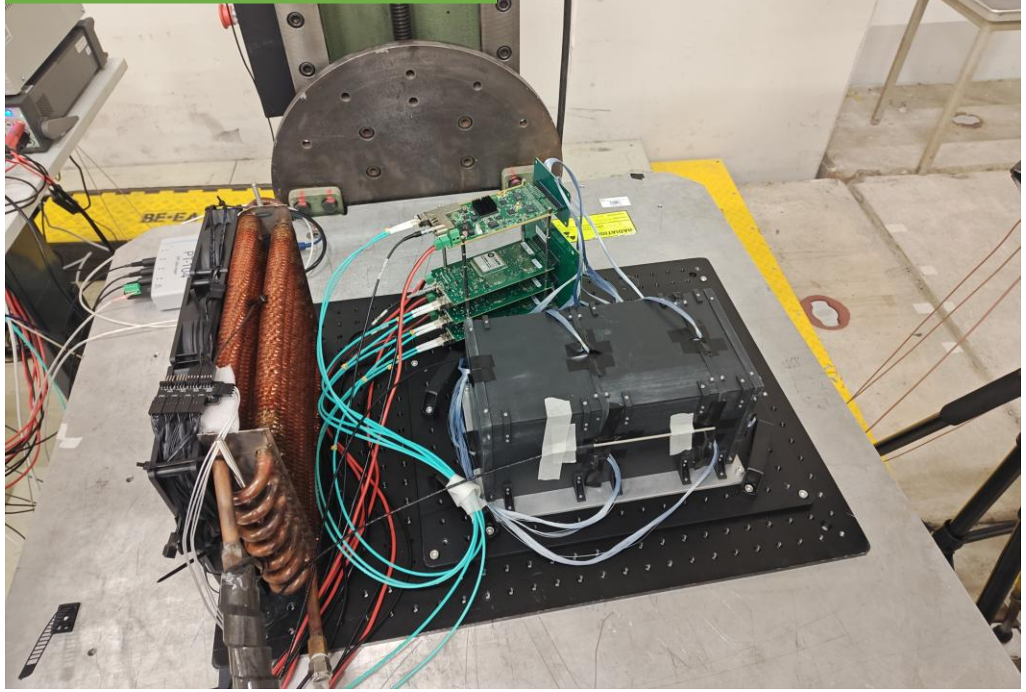
Generally good consistency:
- Geant4 simulation + digitisation + momentum spread vs Data

2024 TB prototype EM performance:
- EM energy linearity: within 1%
- EM energy resolution: $3.5\%/\sqrt{E} \oplus 0.6\%$
  - Beam momentum spread dominates
  - Stochastic term < 2% "excluding" momentum spread

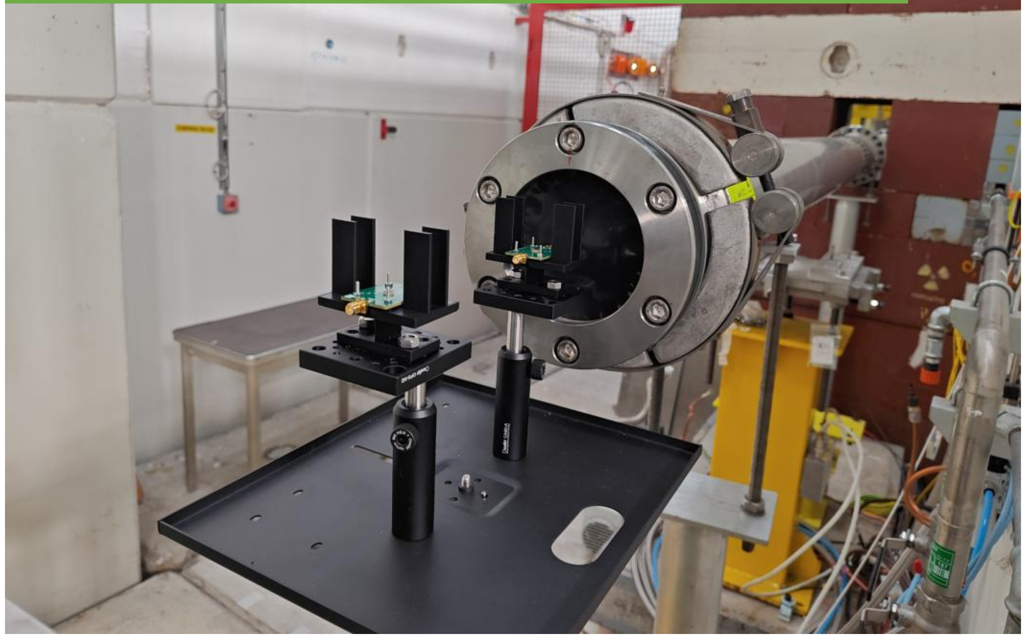
2025 CERN PS-T9: beamtest setup

- 2025 CERN PS-T9: 0.1-10 GeV electron, 5 GeV muon
  - 21.4 X_0 full size BGO module + 2 layers of BSO crystal tail catcher
  - Low-energy beamline setup: all beam instrumentations removed
    - Significantly reduce momentum spread -> better performance expected

June 2025 CERN PS-T9

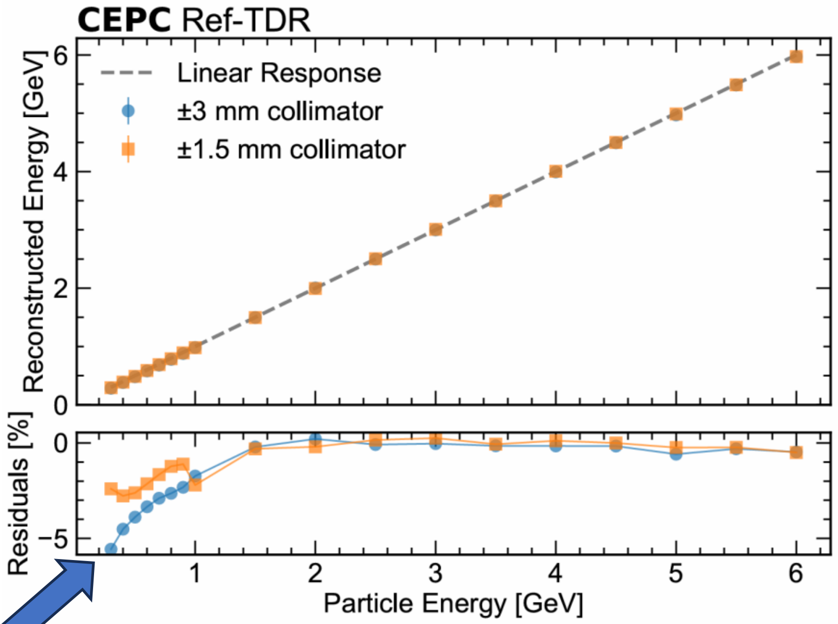


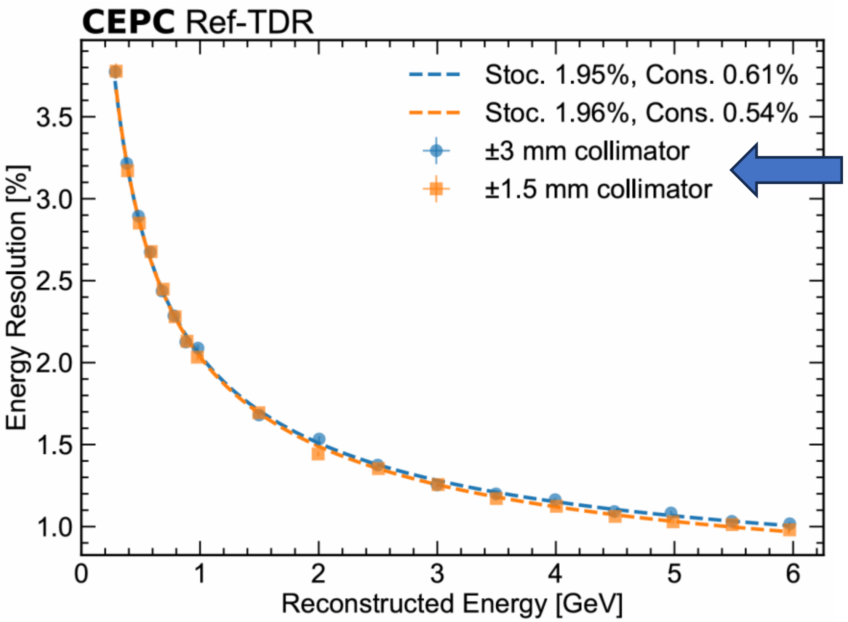
Low-energy beamline configuration at CERN PS-T9: all beam instrumentations removed



2025 CERN PS-T9: EM performance

- EM performance studies based on 0.3-6 GeV electron data
- Optimal momentum spread: around 1% at 1 GeV from beamline simulations (ongoing)





Collimator size: related to momentum spread, negligible here

Non-linear at low-energy part: material effect, energy threshold, albedo leakage

2025 TB prototype EM performance:
- EM energy linearity: < 1% for electron energy > 1 GeV
- EM energy resolution: $1.96\%/\sqrt{E} \oplus 0.54\%$
  - Better than $2\%/\sqrt{E} \oplus 1\%$ even in the presence of beam momentum spread

Note:
- Overall 1% level momentum spread expected
- Negligible effect of the BSO tail catcher

Summary

CEPC Crystal ECAL R&D:

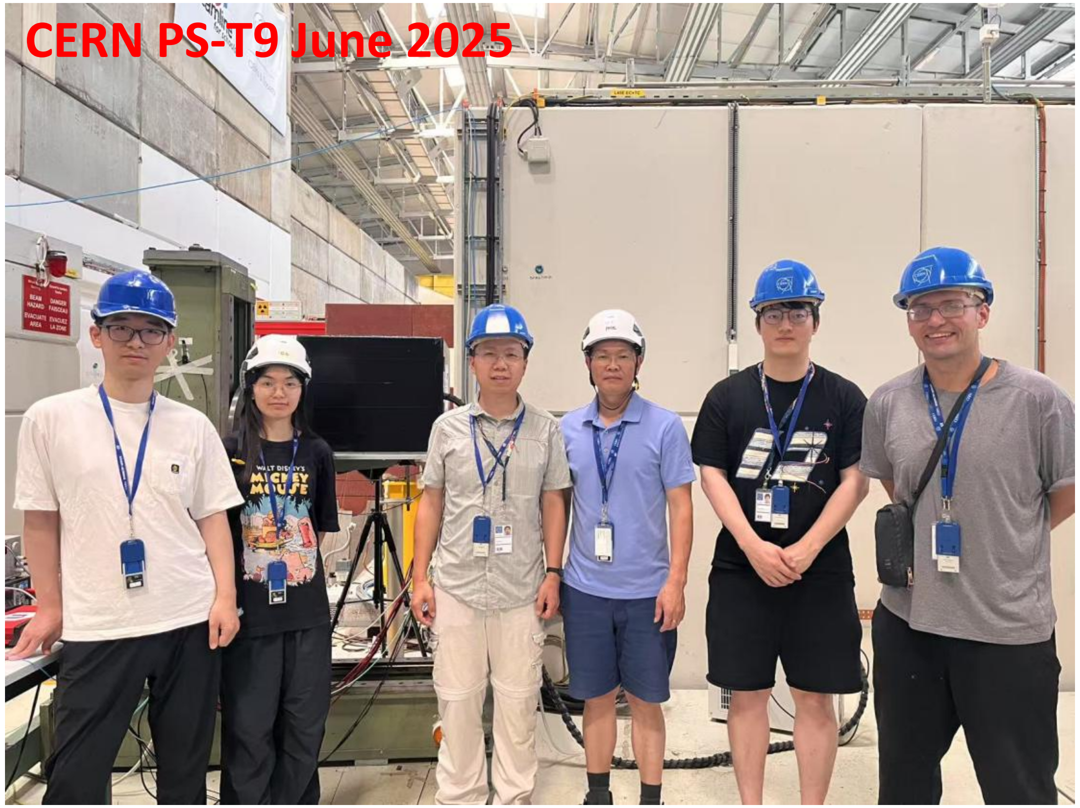
- Ref-TDR phase: extensive work on PFA software, system integration studies, etc.
- Successful development and beam tests of the crystal ECAL prototype
- EM performance validation
  - Linearity: better than 1% for > 1 GeV electrons
  - Resolution: $1.96\%/\sqrt{E} \oplus 0.54\%$ (about 1% momentum spread included)
  - Meet the design requirements of the CEPC ECAL

Prospects

CEPC Crystal ECAL R&D at post-TDR phase:

- Further investigation of beam data and beamline simulation
- Low-energy photon reconstruction studies
- Full scale crystal ECAL prototype R&D (planned)
- Combined measurements: tracker, calorimeter, magnet
    - Direct measurements of beam momentum
        - Excellent resolution of crystal ECAL -> limited by testbeam facilities
    - Test of PFA performance with a complete set of PFA sub-detectors

Acknowledgement

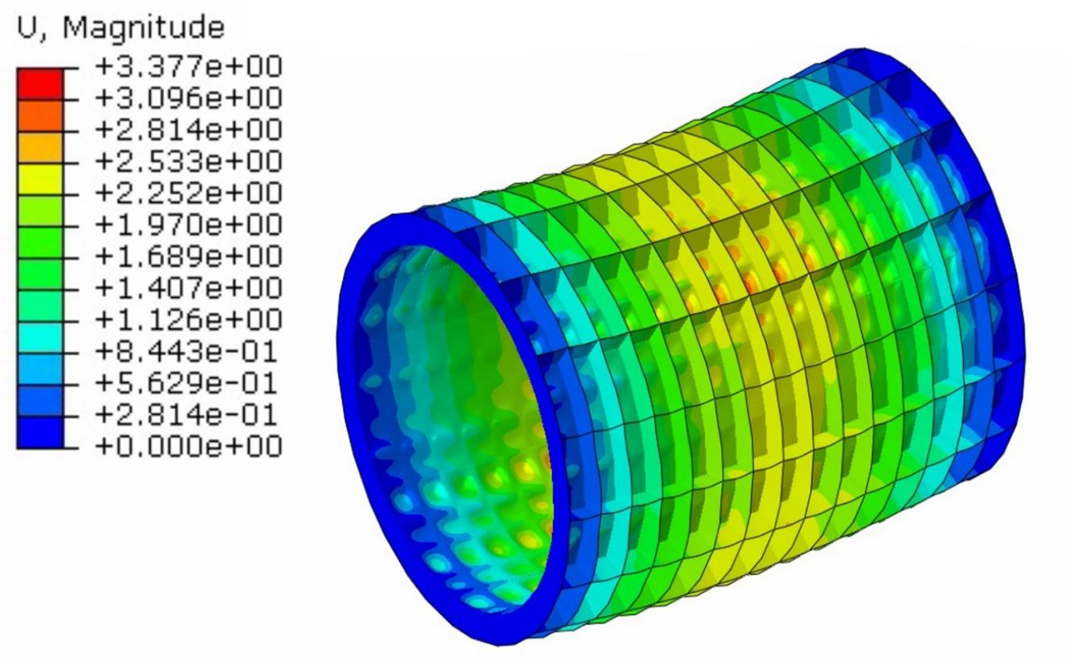


Thanks to the entire team for their dedicated efforts!
Thanks to the CERN testbeam facilities for the excellent platform and technical support!

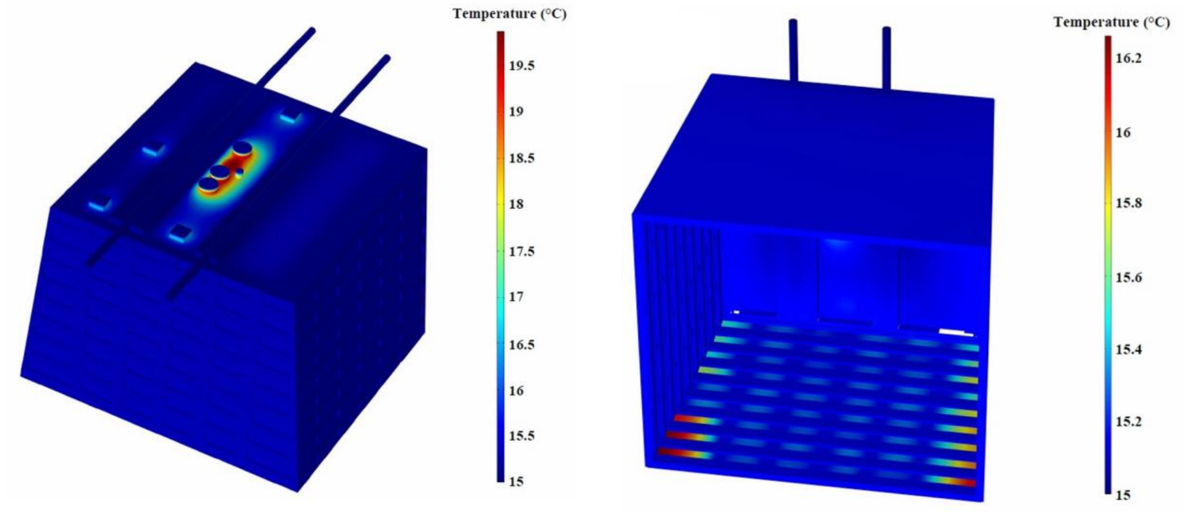
Backup

FEA studies: structure deformation and temperature distribution

- Finite-Element Analysis (FEA) studies: fully integrated ECAL barrel / single modules



Barrel maximum deformation: 3.4 mm



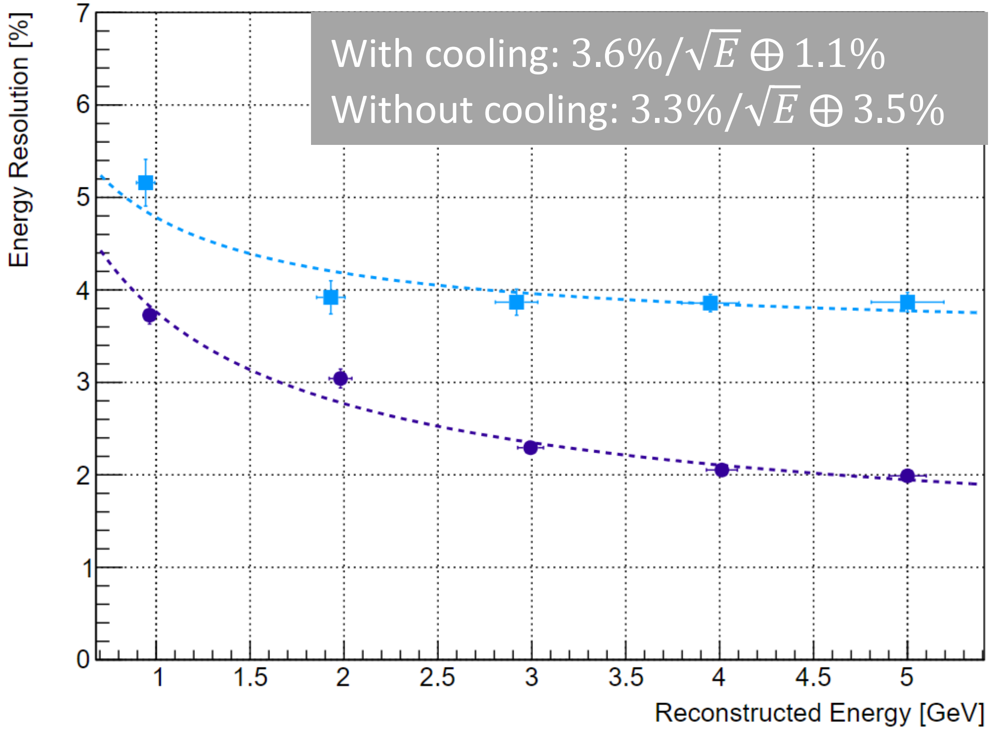
Module maximum temperature variation < 1.2 ℃

The structural stability and cooling performance can satisfy the requirements

Prototype development: active cooling system

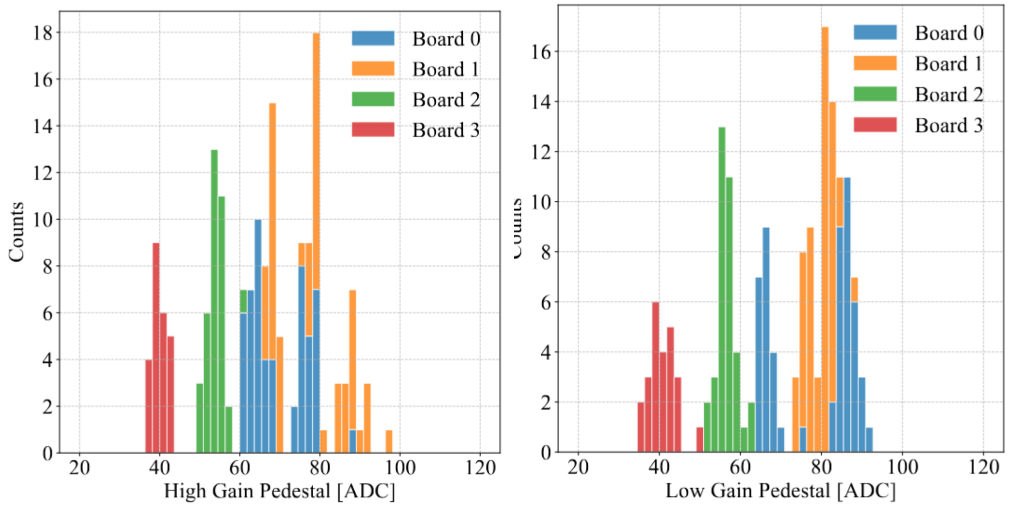
- 2024 CERN T9 beam test: $21.4\ X_0$ HGCCAL prototype

Energy resolution w/wo active cooling

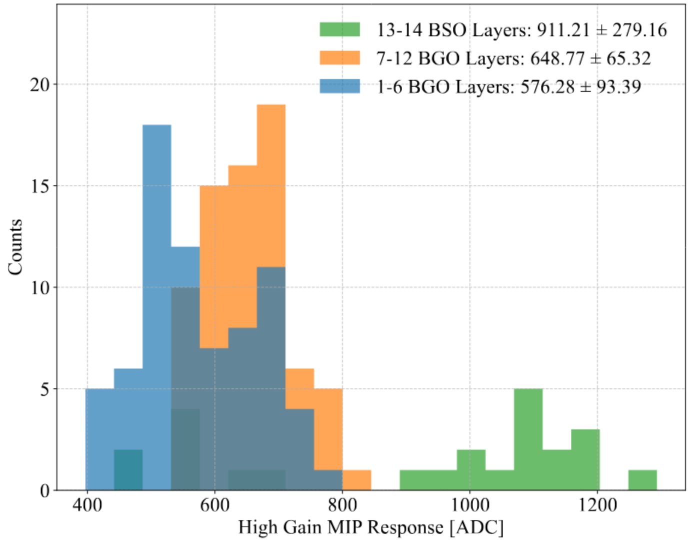


- Temperature stability significantly impact EM resolution, especially the constant term

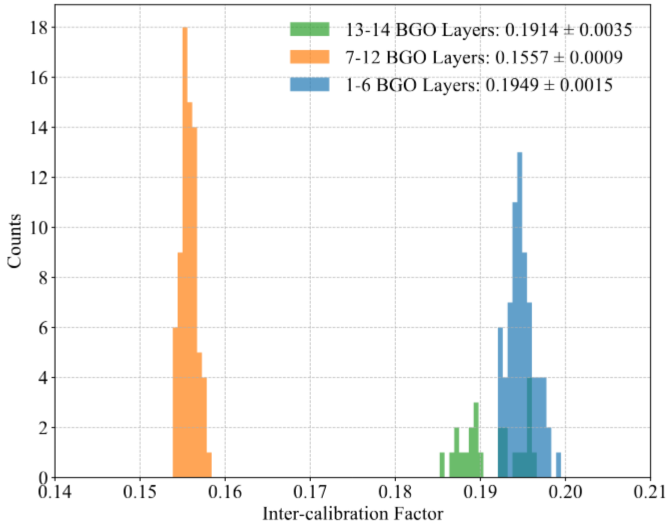
2025 CERN PS-T9: calibration status



Pedestal distribution



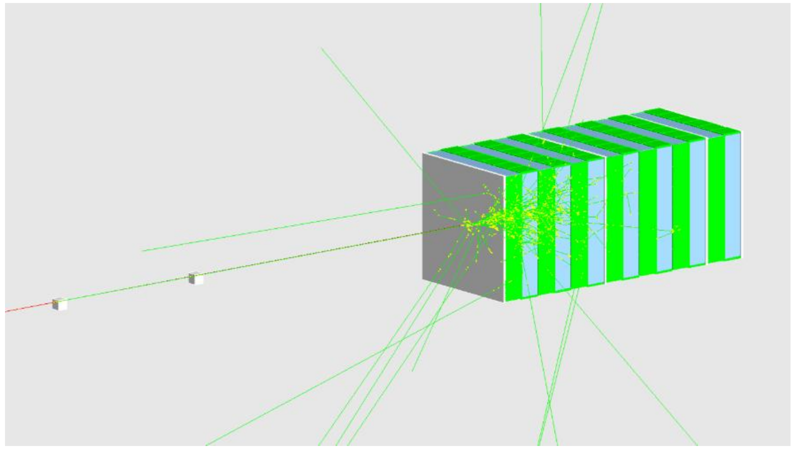
MIP response distribution

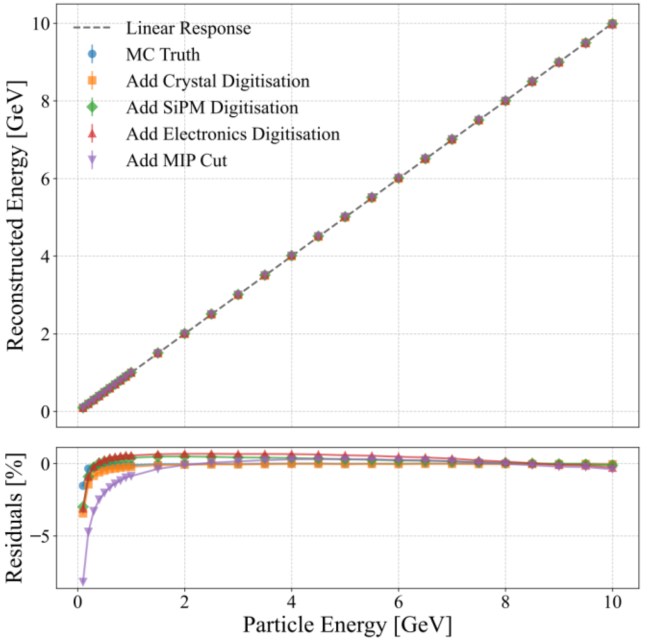


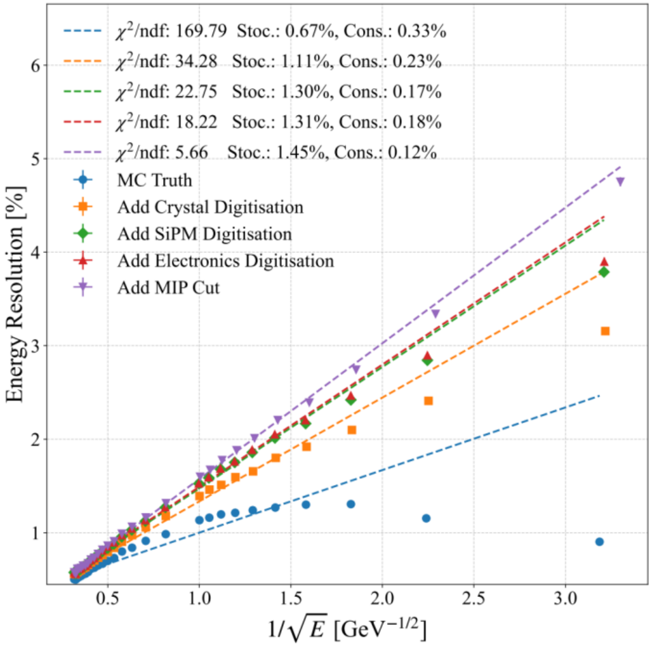
Gain ratio distribution

Geant4 simulation and digitisation

- Geant4 standalone simulation: full geometry of the prototype
  - 0.1 to 10 GeV electrons, events selected by two $1 cm^3$ triggers
- Digitisation tool: response of detector hardware
  - Photon statistics (crystal digitisation)
  - SiPM non-linear response
  - ADC output and gain switch (electronics digitisation)
  - Energy calibration and MIP threshold cut







Digitisation impact breakdown

- Generally impact from photon statistics > SiPM response > MIP threshold > electronics response