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

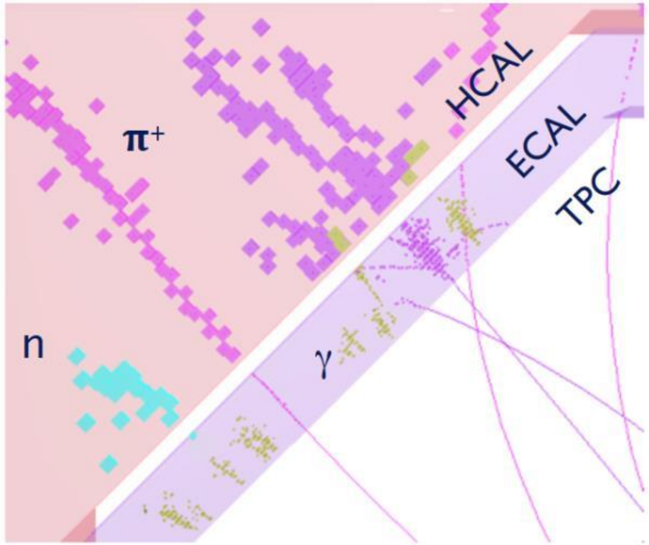
CERN beam test of first CEPC crystal ECAL module and scintillator glass tiles

Yong Liu (Institute of High Energy Physics, CAS),
on behalf of the CALICE-CEPC Calorimetry Team

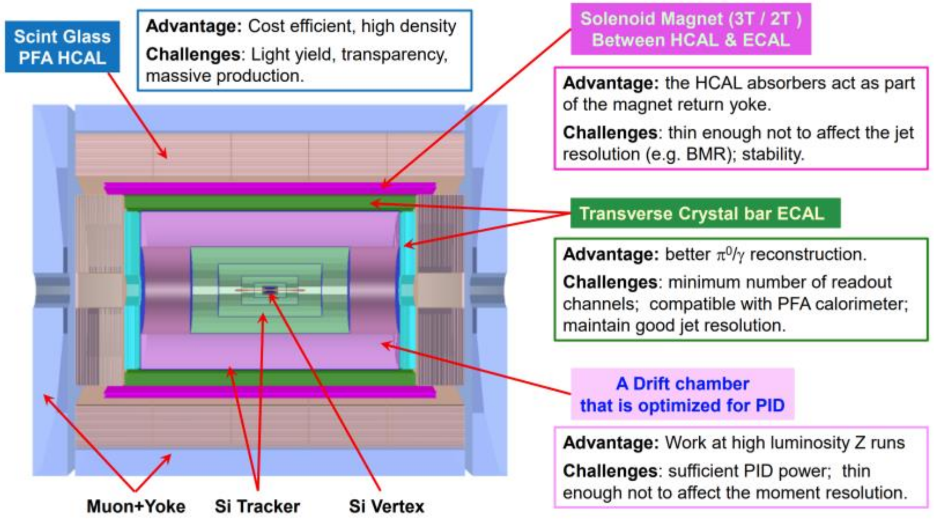
CEPC Day
Jun. 21, 2023

Motivations

- Calorimetry for future lepton colliders (e.g. CEPC, etc.)
  - Precision measurements: Higgs and Z/W bosons
  - Jet energy resolution requires better than $30\%/\sqrt{E_{\text{jet}}(\text{GeV})}$
  - Particle flow paradigm: high-granularity calorimetry



- PFA-oriented detector: the CEPC 4th concept detector
  - Crystal electromagnetic calorimeter
    - Optimal EM energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
    - High sensitivity to low energy particles
    - Fine segmentation: PFA capability for jets
  - Hadronic calorimeter with glass scintillator tiles
    - Glass scintillator with high density and light yield
    - Better hadronic energy resolution



Outline

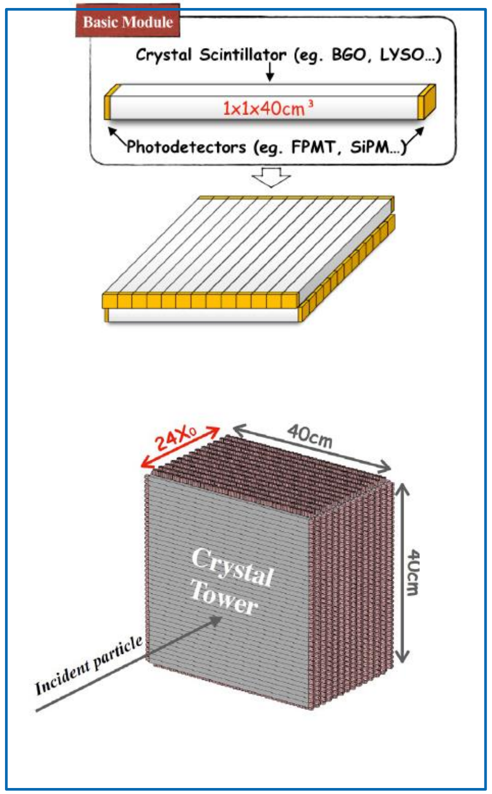
- High granularity crystal calorimeter
  - Development of the first crystal module
  - Crystal module: beam test with muons and electrons

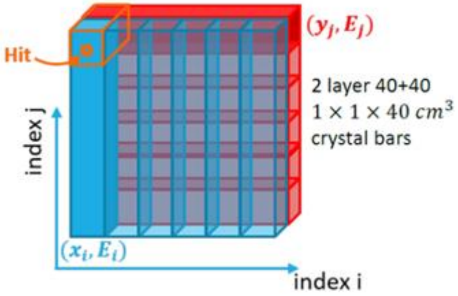
- PFA-oriented hadronic calorimeter with glass scintillator tiles
  - Glass scintillator tiles: beam test with muons

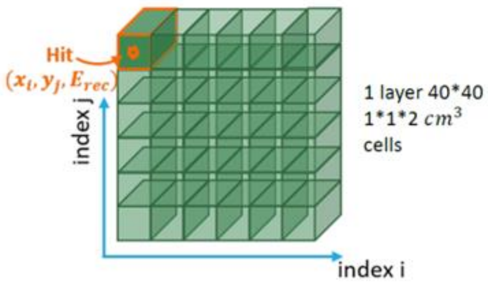
- "Parasitic" beam time with CALICE-CEPC calorimeter prototypes
  - 15 days (May 17-31, 2023) at CERN PS-T9

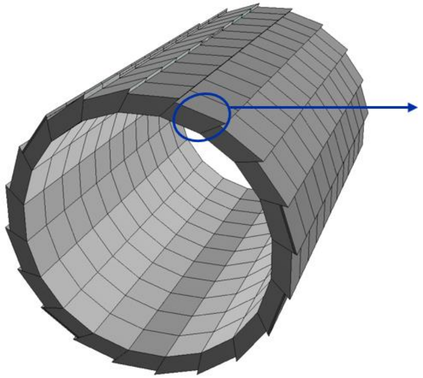
Crystal calorimeter: R&D overview

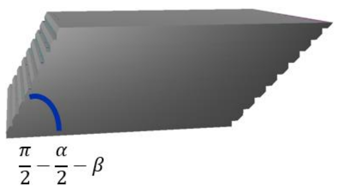
Close collaboration with hardware, software and PFA/physics teams

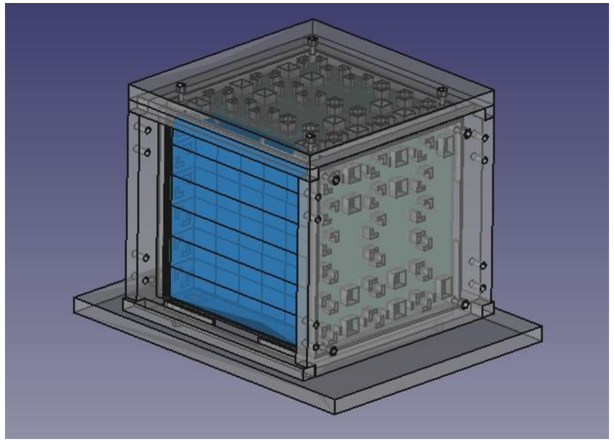












Hardware development: key questions and specs

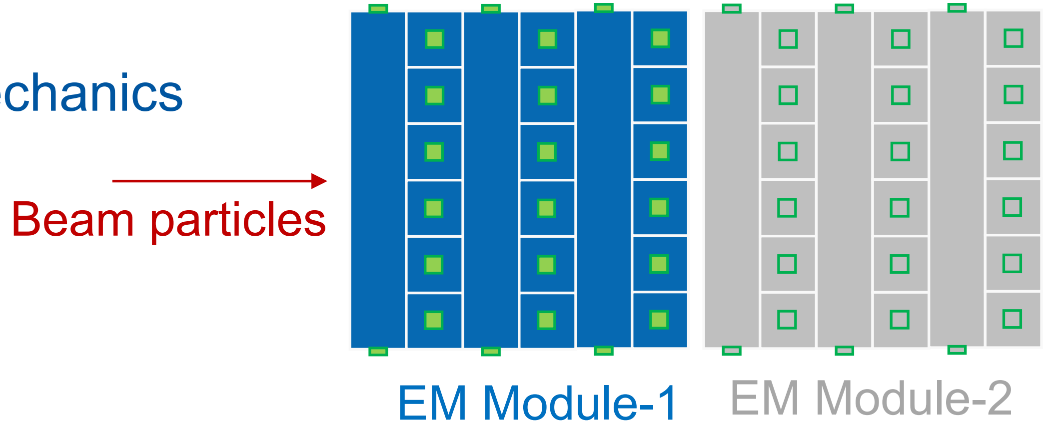
- New reconstruction software for long bars
- Geometry design and optimization

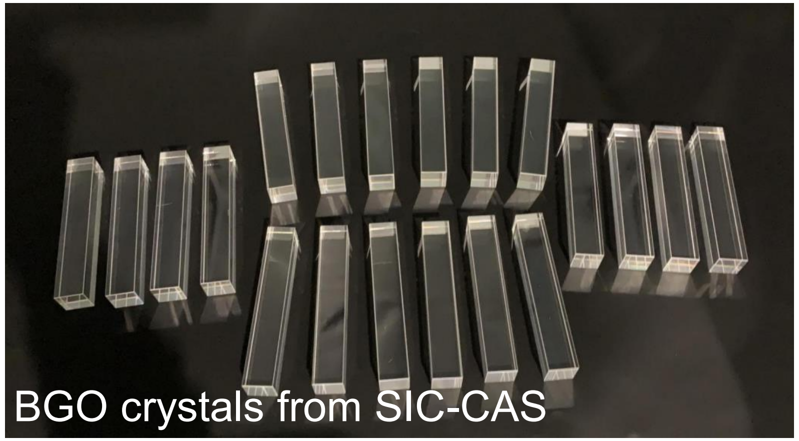
Development of crystal module(s) for beam tests

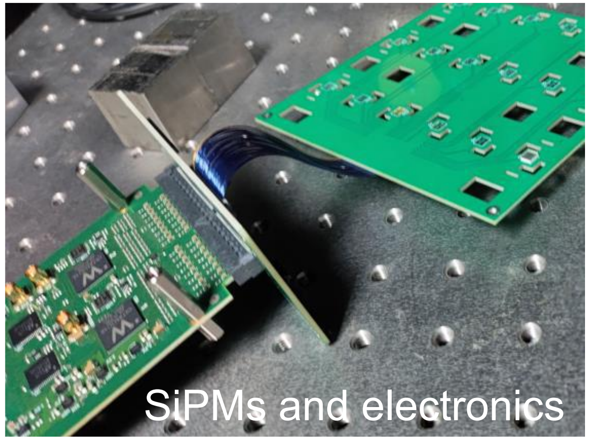
Crystal module R&D

- Motivations: to address critical issues at system level
  - Validation: design of crystal-SiPM, light-weight mechanics
  - EM shower performance
- Plans: beamtests with 2 crystal modules
- The first crystal module development
  - Crystals: 40 BGO bars from SIC-CAS
  - SiPM: 3×3 mm^2 sensitve area, 10μm pixel pitch
  - Front-end electronics with ASICs (Citiroc-1A)

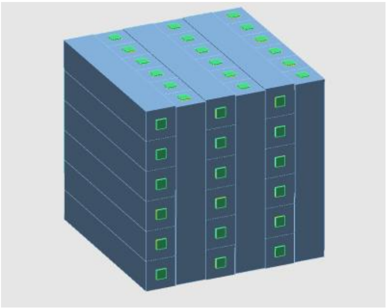
Single module: $12 \times 12 \times 12 \mathrm{cm}^3$

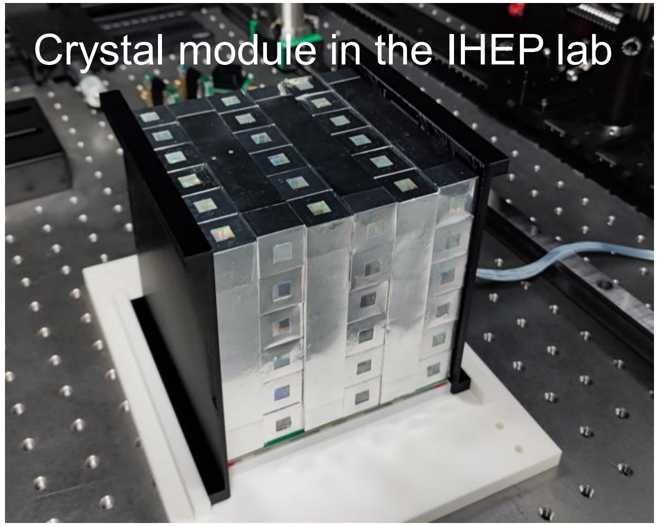






Crystal module (on paper)



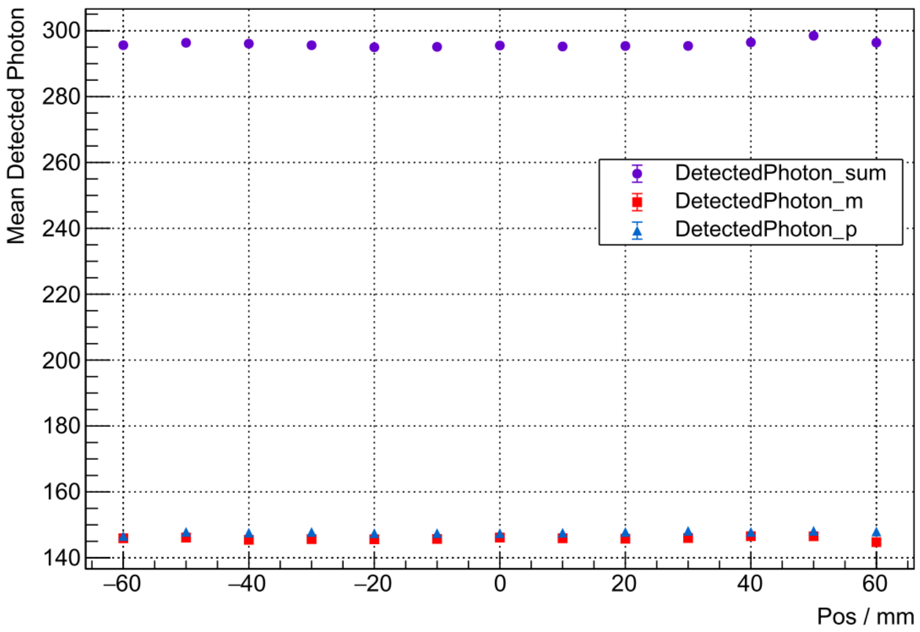


BGO crystal: uniformity studies

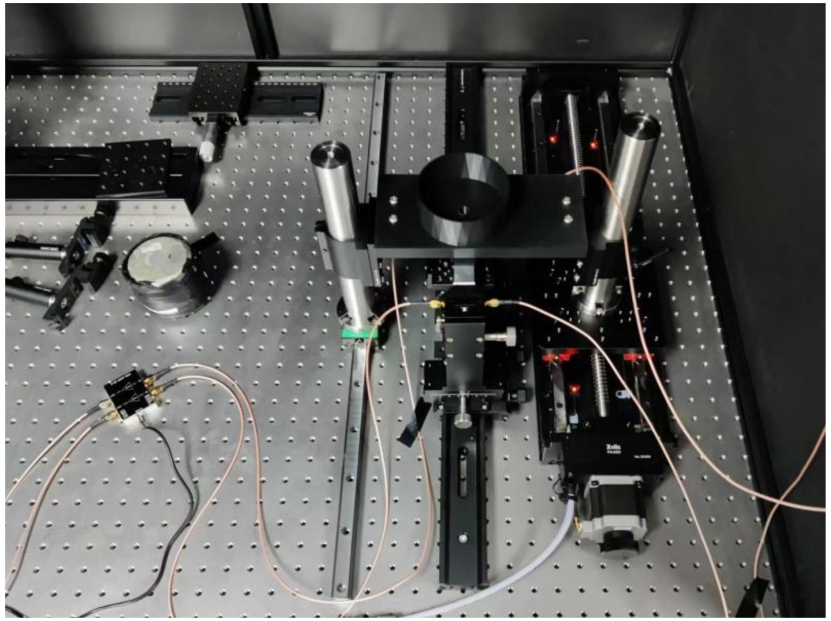
Zhikai Chen (USC)

- Developed an automated test stand for uniformity scans
- Batch test of BGO crystal bars: done
  - Cs-137 source: scanned 40 crystals (wrapped with ESR and Al foil)
- Excellent good uniformity along the crystal length direction: ~1% level

Response uniformity along crystal bar length



Automated Teststand for uniformity scans

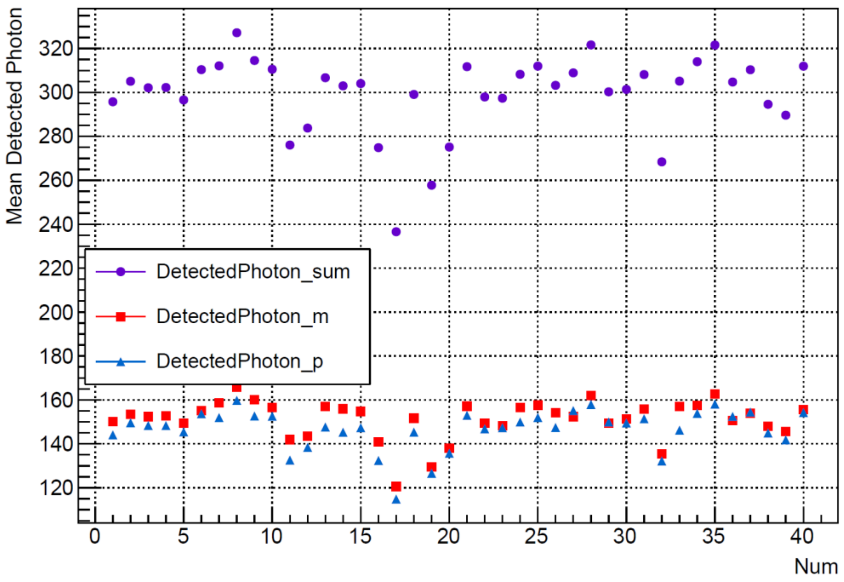


BGO crystal: uniformity studies

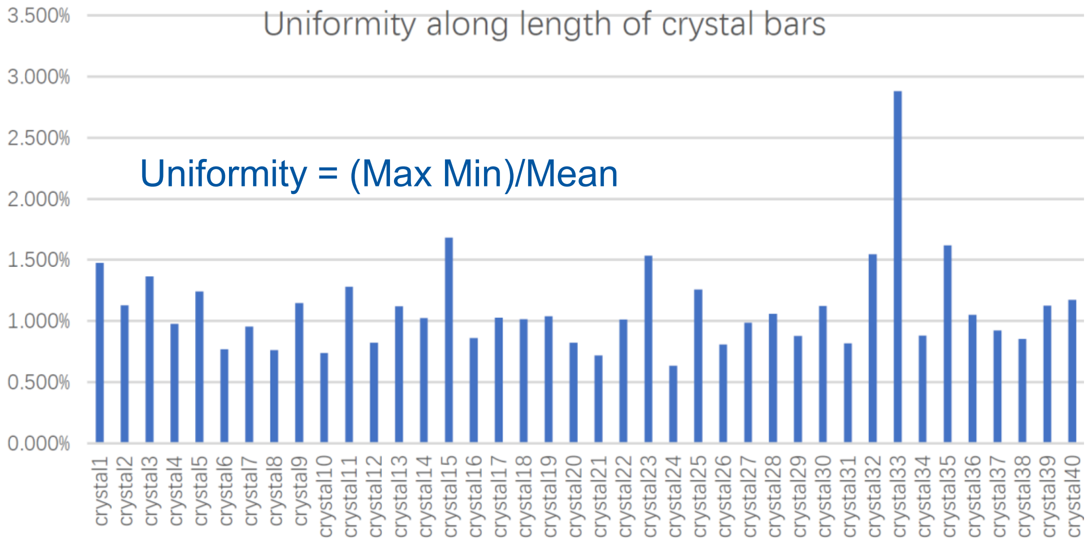
Zhikai Chen (USC)

- Developed an automated test stand for uniformity scans
- Batch test of BGO crystal bars: done
- Excellent good uniformity along the crystal length direction: ~1% level
- Selected 36 out of 40 crystal bars for the first crystal module

Average response to Cs-137 of each BGO bar



Uniformity along crystal bar length direction

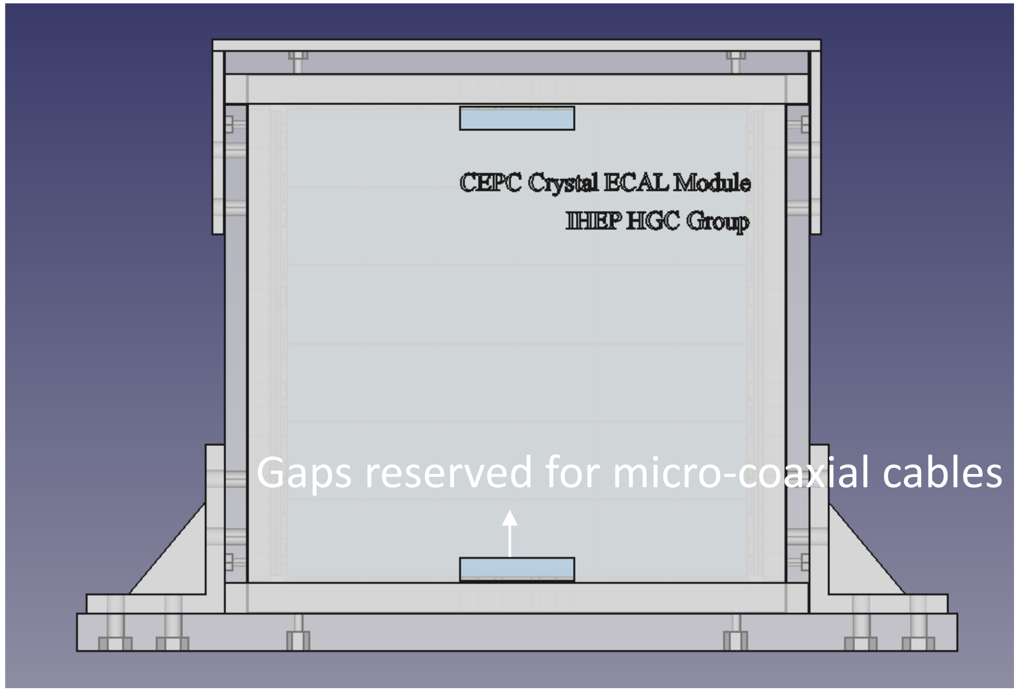


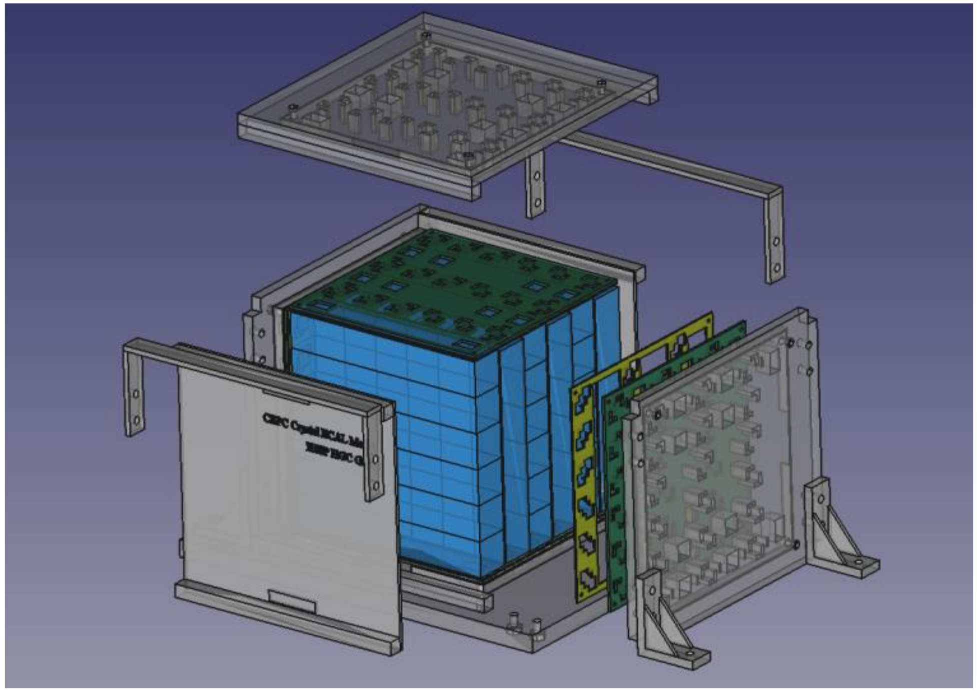
Crystal module: mechanics and readout PCB

Baohua Qi (IHEP)

- Strong correlation among key aspects of
  - Mechanical support structure: light weighted, mechanical strength
  - Readout PCBs: high pin-count (HPC) connectors for SiPM signals, temperature
  - Module integration: assembly procedure

All mechanical parts are custom-made by 3D printer

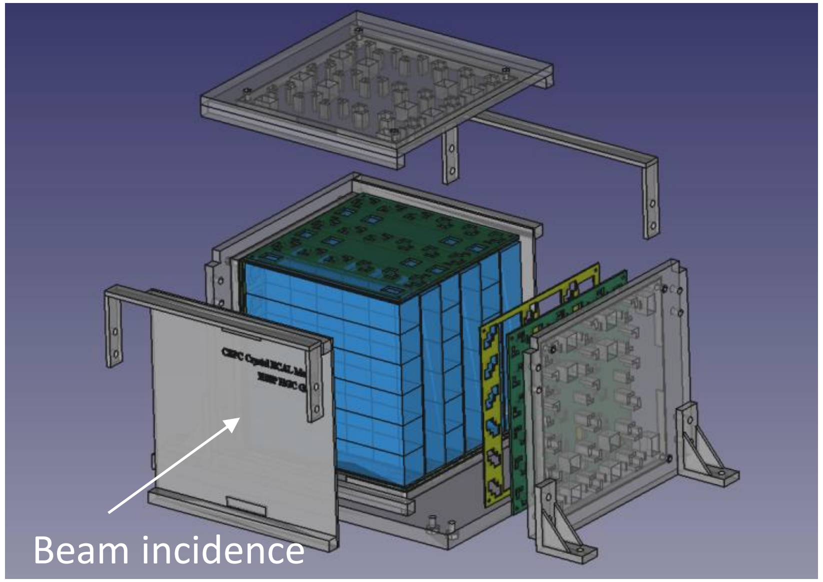




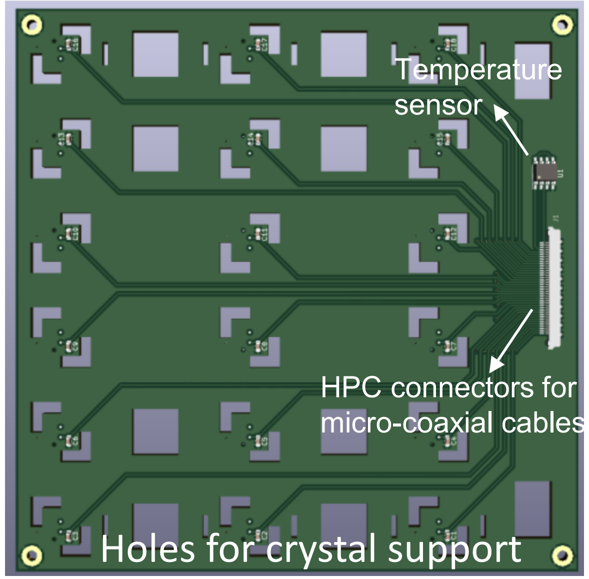
Crystal module: mechanics and readout PCB

Baohua Qi (IHEP)

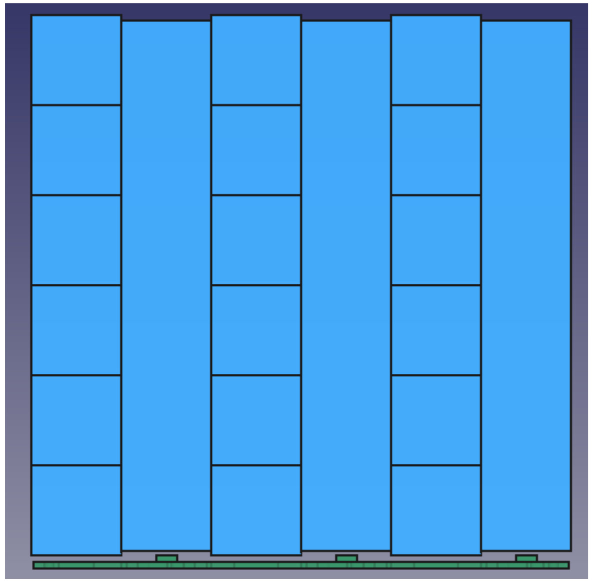
- Major challenges
  - Readout boards from 4 lateral sides → sufficient room for various tolerances
  - Decouple gravity/stress from readout PCB (+SiPMs) → extra support for crystals
  - Orthogonal arrangement of crystals → specific assembly procedure



Custom SiPM readout PCB

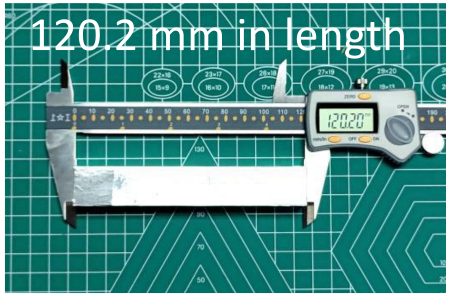


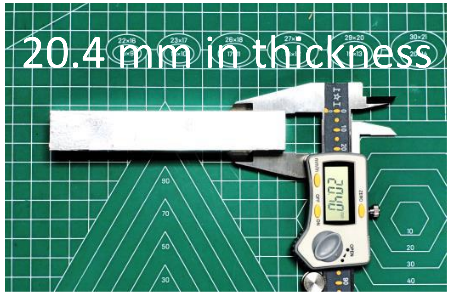
Module dimensions



Tolerance accumulation:
many layers of wrapping foils

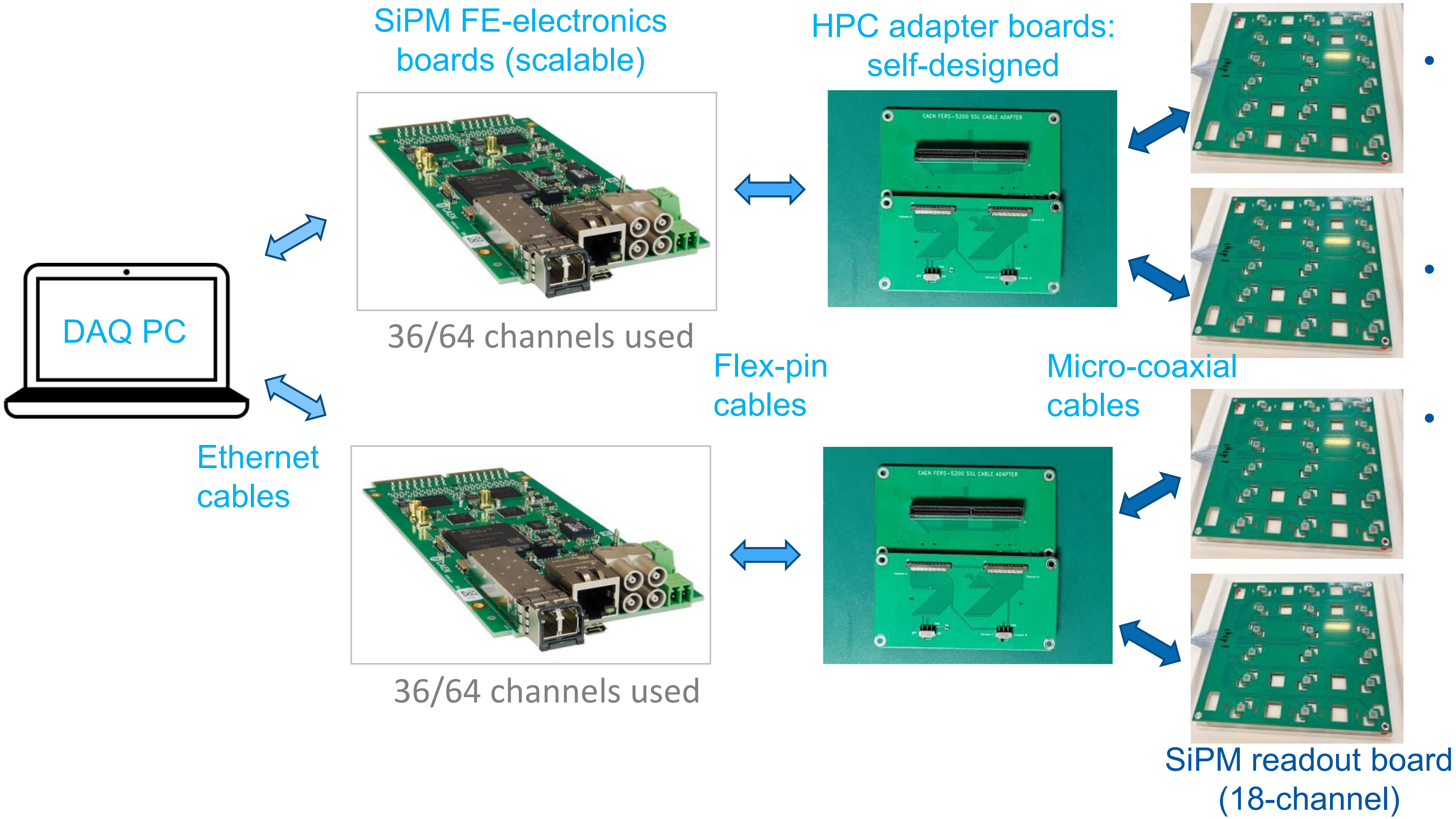
Crystal dimensions:
with wrapping





Crystal module: front-end electronics and DAQ

Baohua Qi (IHEP)

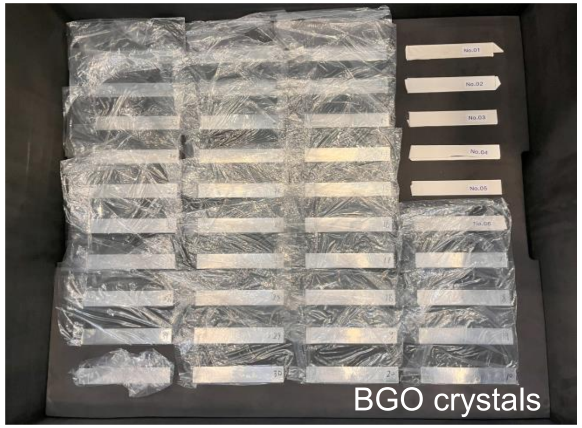


- Data acquisition
  - ADC in high gain
  - ADC in low gain
  - Timing: ToA
- Event synchronization
  - Trigger within 20 ns of two boards
- Trigger modes
  - External trigger: support **daisy chain**
  - Auto trigger: support **coincidence** of 2 channels

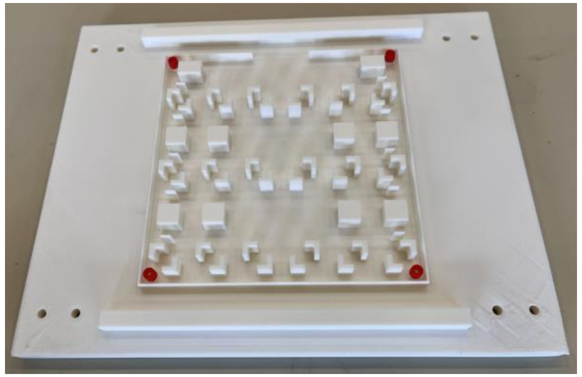
Logistics and preparations for CERN beamtest

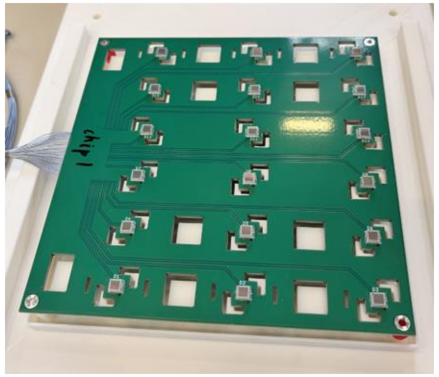
- Successful transportation from IHEP to CERN
  - Started from Beijing in May 6; delivered to CERN in May 16

Box with crystals, glass tiles and accessories (75kg)



BGO crystals

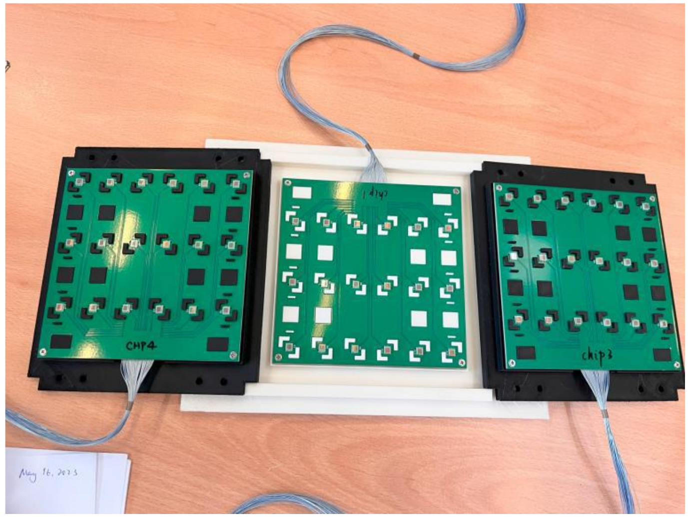


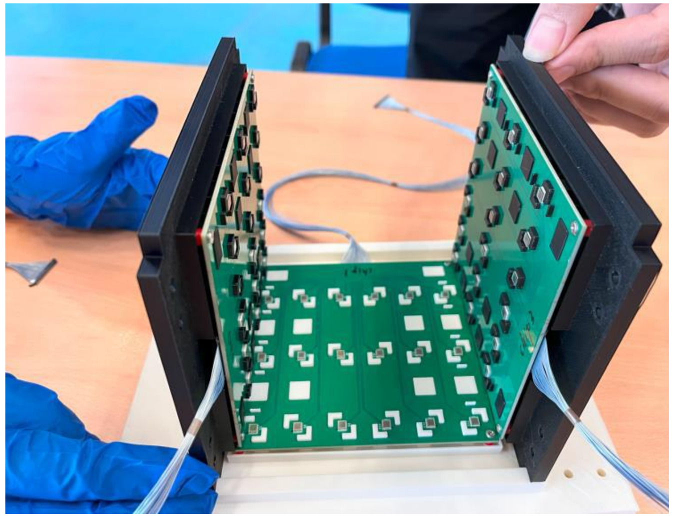


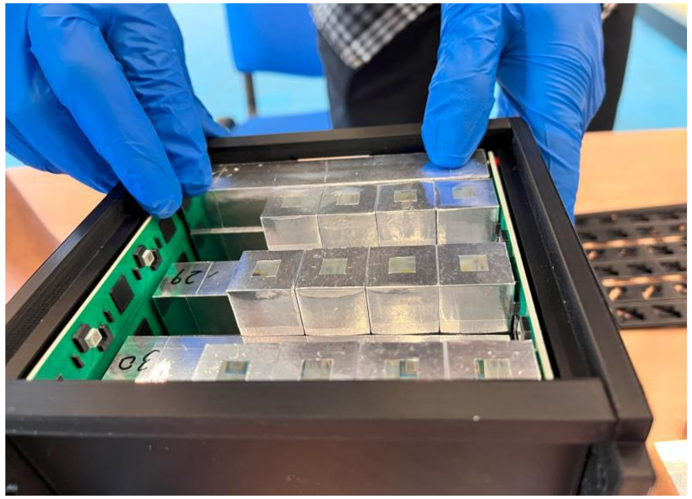
BGO module on DESY table

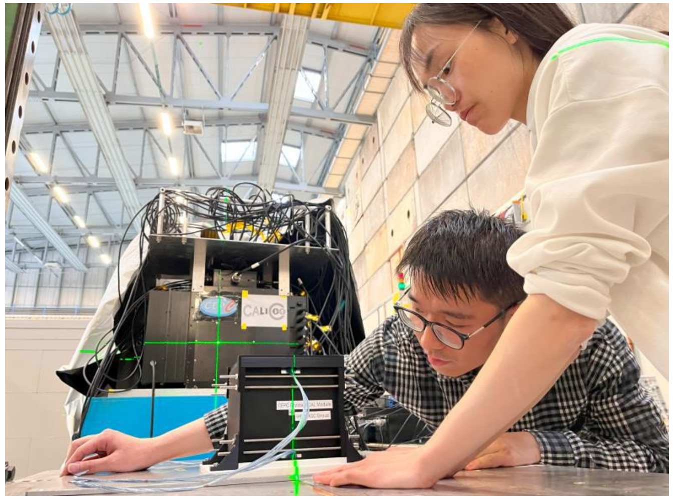
Crystal module placed on a motorized table, in upstream of ScECAL and AHCAL prototypes

Crystal module assembly

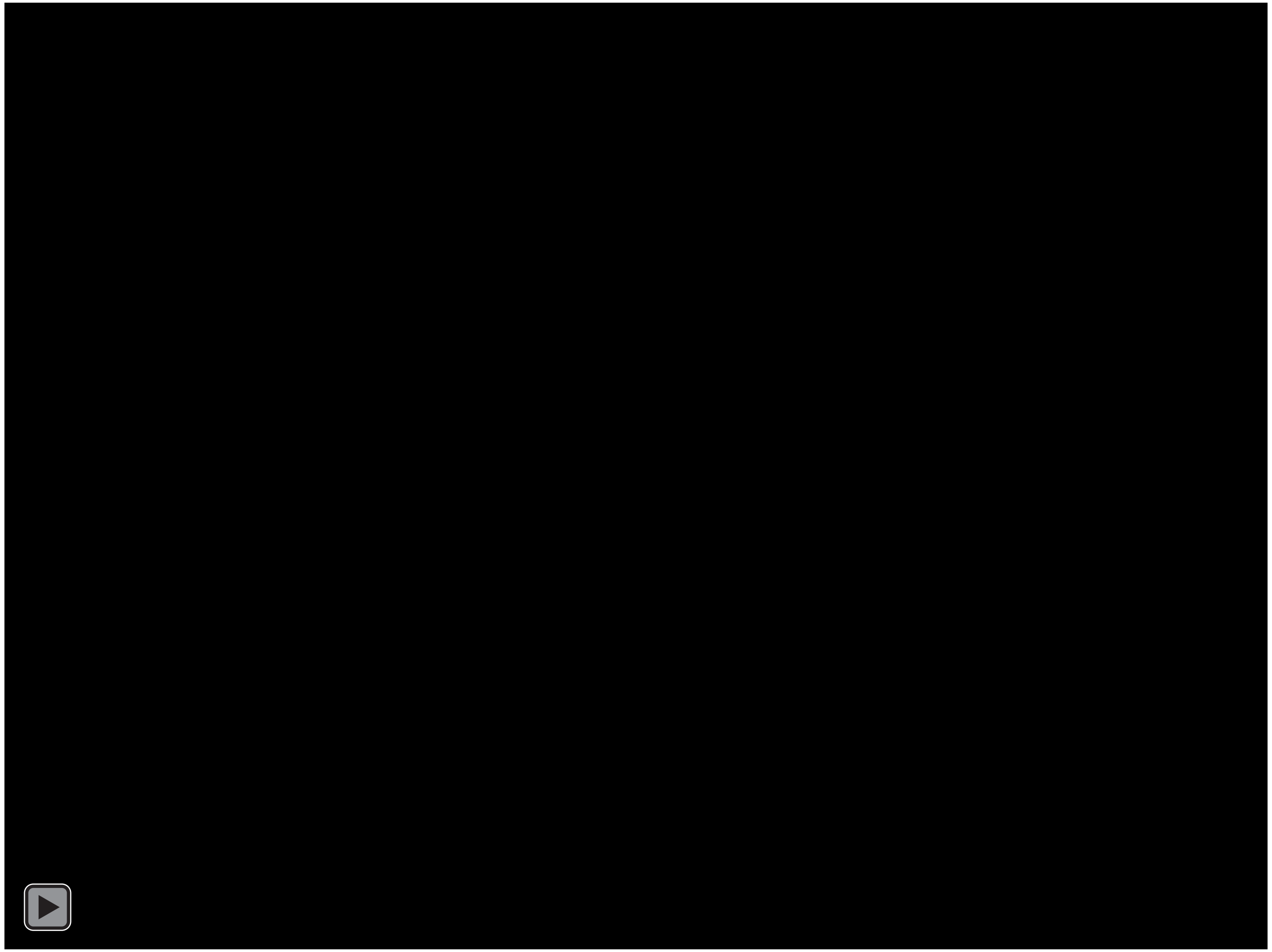




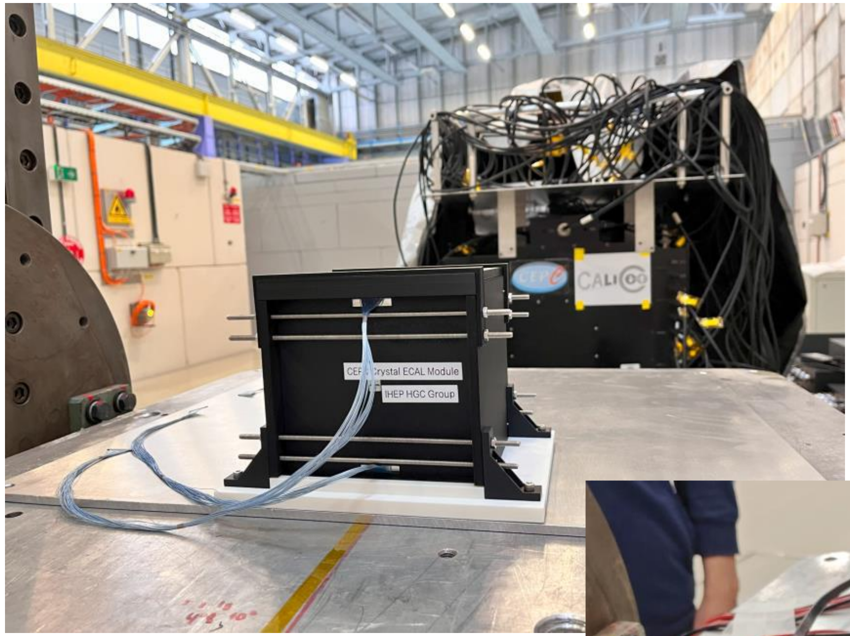


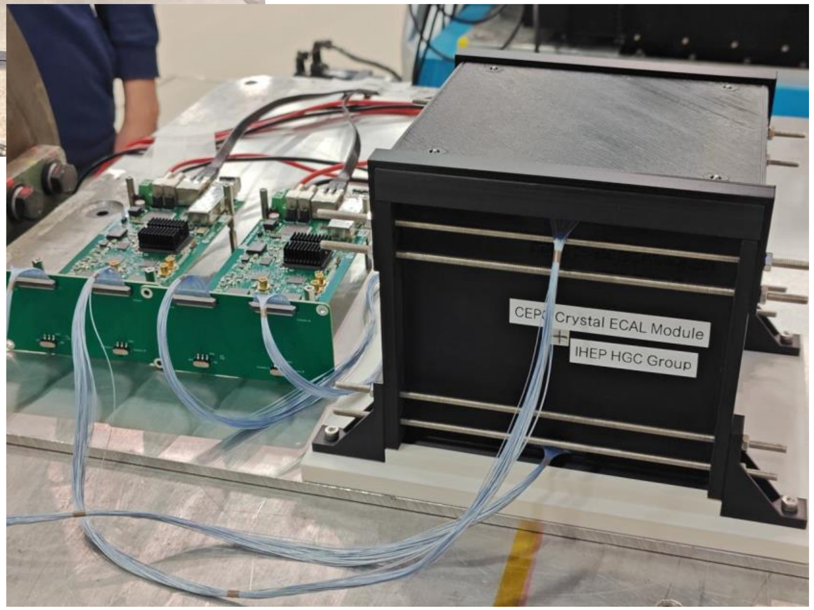


Crystal module assembly

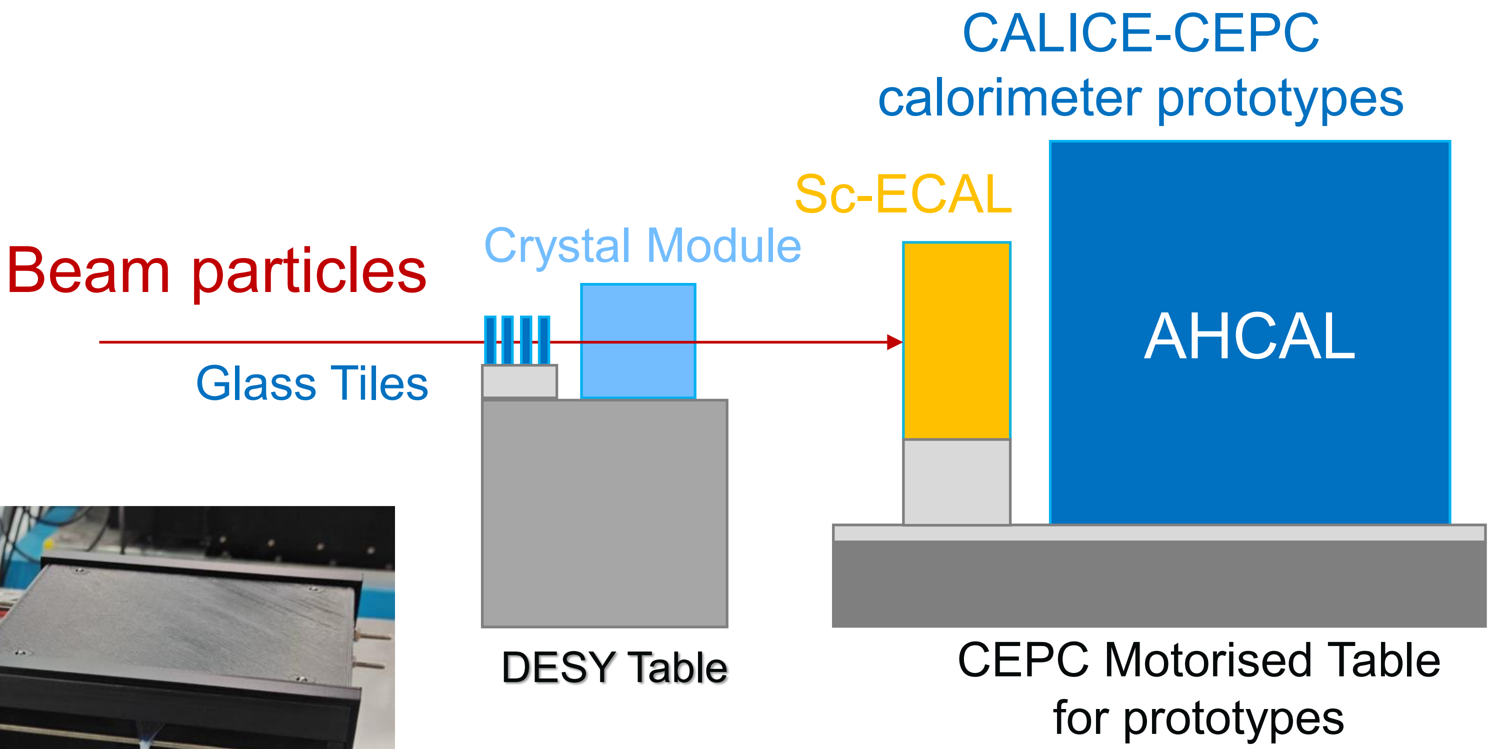


Crystal module in PS-T9 beamline





Parasitic runs with CEPC calorimeter prototypes

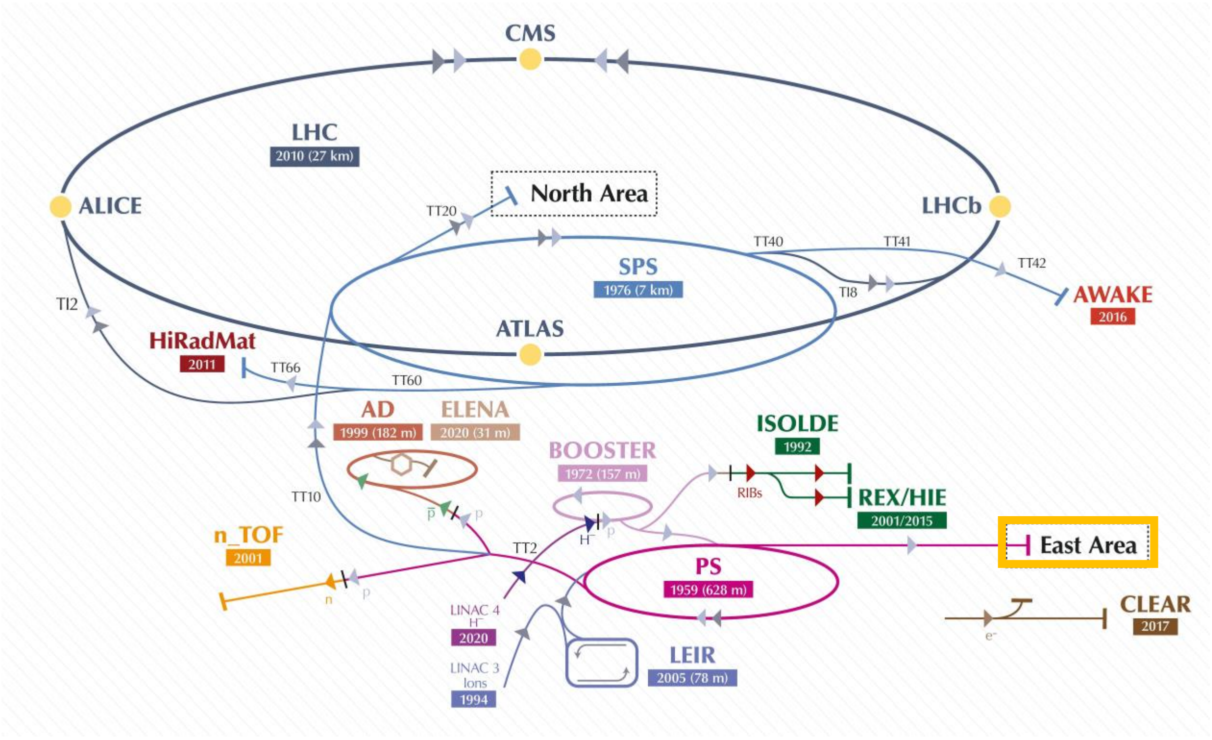


DESY Table: remote control for vertical/horizontal movements of crystal module and glass tiles

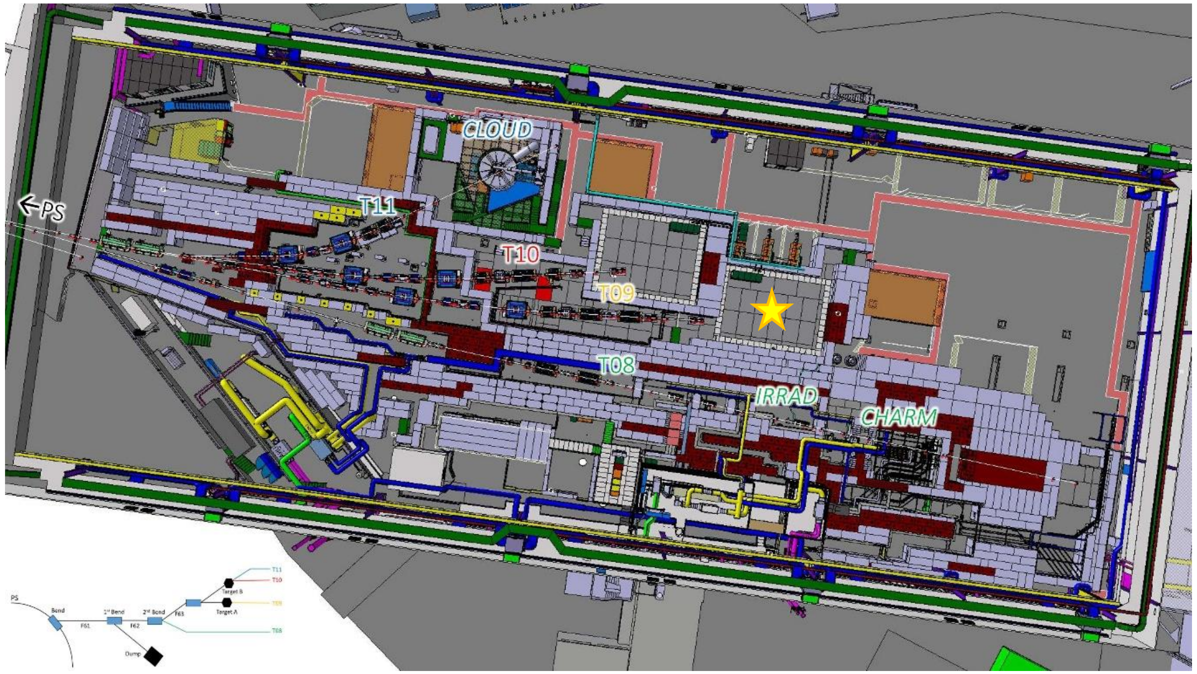
Move IN/OUT of beamline: coordination with testing of CEPC calorimeter prototypes

CERN PS and T9 beamline: a quick reminder

- CERN Proton Synchrotron: primary 24GeV protons
- Secondary particles at PS-T09
  - Muons, electrons (up to 5 GeV/c), charged hadrons (up to 15 GeV/c)
  - Typical beam structure: 0.4s/spill, 1-2 spills/SC, 10-30s for a super cycle



★ East Area (B.157) PS-T9



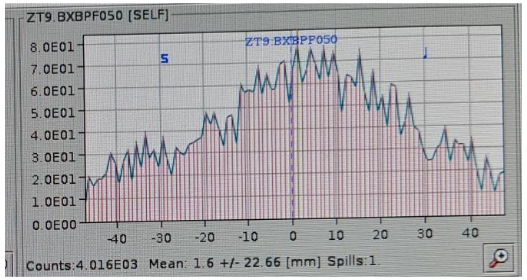
Crystal module: beam test with muons

Collected ~5.5M muon events

- External trigger from beam telescopes: ~2k per spill
- 10 GeV/c muons: ASIC parameter scans
  - High gain and low gain
  - Hold delay time
  - Shaping time
  - Muon beam position
  - HG discriminator

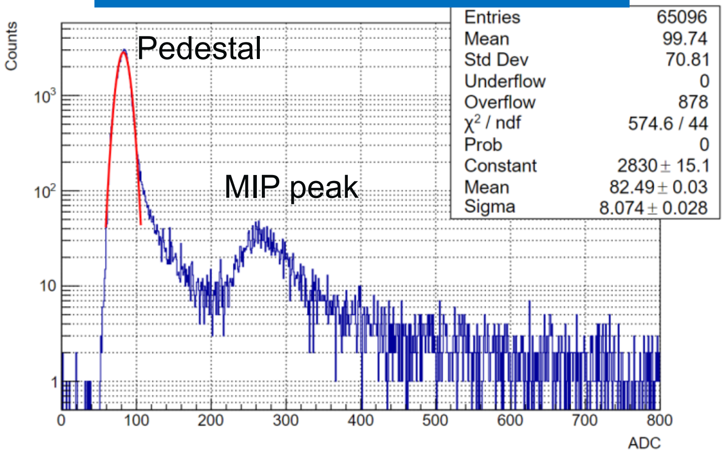
Delay of external trigger: ~130 ns

Muon beam profile

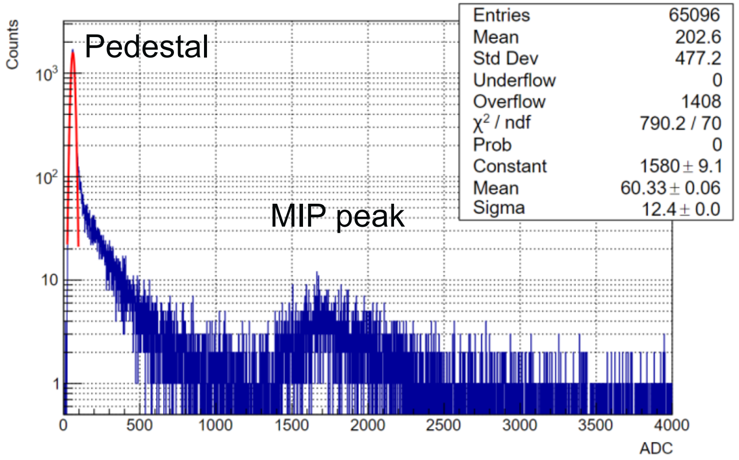


HG	LG	Hold-Delay Time	Shaping Time
34	4	5 ns	12.5 ns
44	24	10 ns	25 ns
49	34	50 ns	37.5 ns
54	44	100 ns	50 ns
59	52	150 ns	62.5 ns
	56	200 ns	75 ns
	58	300 ns	87.5 ns
	61		
	62		
	63	Parameters for electron tests in red	

Energy (ADC) in Low Gain



Energy (ADC) in High Gain

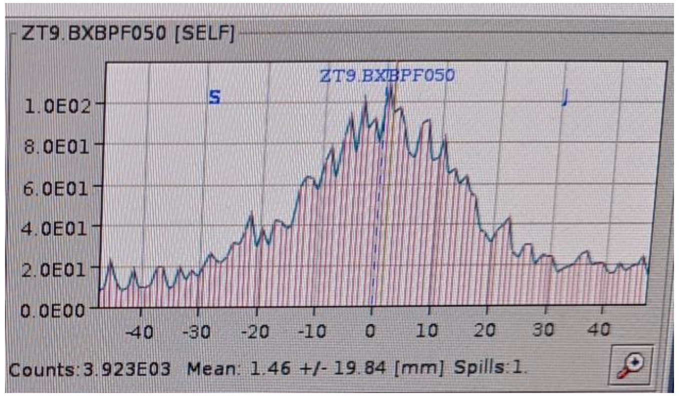


Crystal module: beam test with electrons

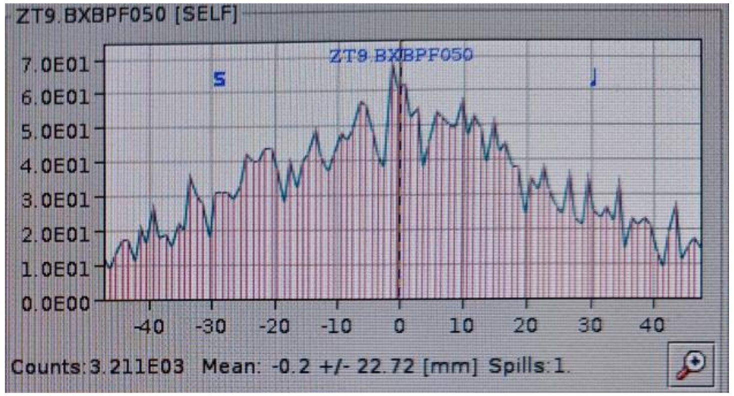
Collected ~1M electron events
(with ~4h beam time)

- Electron beam
  - Energy scans: 0.5, 1, 2, 3, 4, 5 GeV
  - Optimising ASIC settings
  - Considerable impacts from upstream materials
    - Beam instrumentation: Cherenkov detector, SciFi hodoscope, …
    - Would lead to significant momentum spread → G4 simulation to be done
  - Larger beam spread with lower beam energy

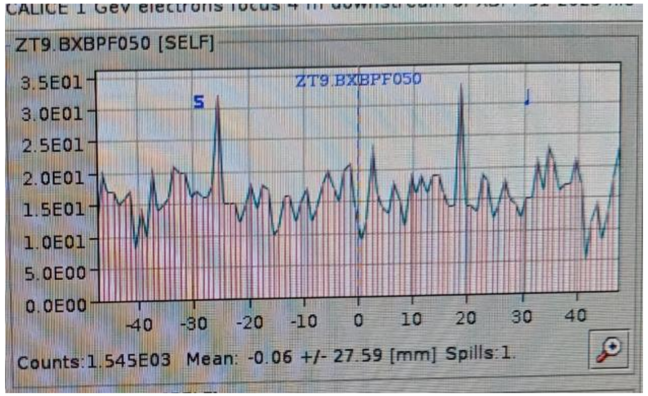
Electron beam profiles from SciFi hodoscope



4 GeV/c electrons



2 GeV/c electrons



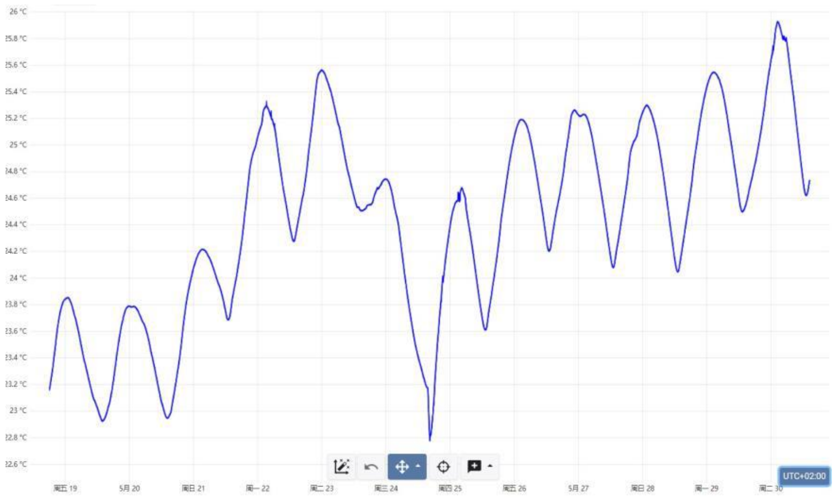
1 GeV/c electrons

Crystal module: other data sets

- Parasitic runs: at a lower position outside beamline
  - Almost MIP-like particles
  - Validation of long term data taking capability
- Pion beam: testing DAQ with ~20k events per spill (0.4s)
  - > 80% trigger loss at such a high beam intensity
- Temperature monitoring
  - PS-T9 experimental area: ~2℃ temperature change during the full period

Collected ~3.3M muon events

Collected ~140k pion events

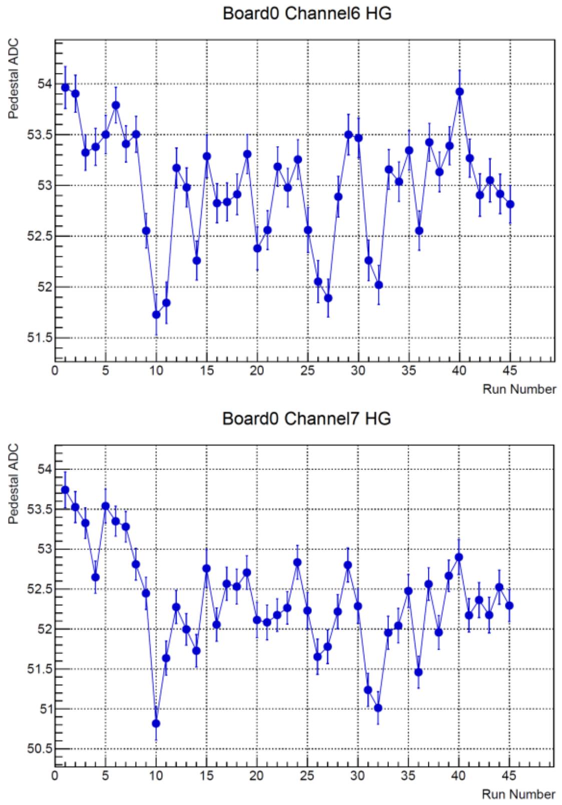


Crystal module beam data: a first glance

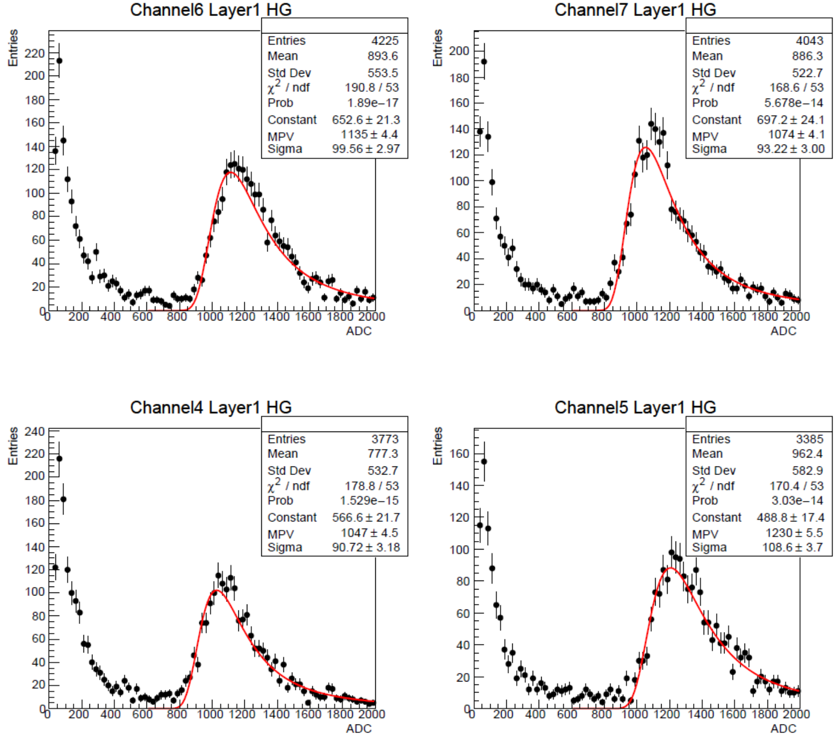
Baohua Qi (IHEP),
Zhiyu Zhao (SJTU)

- Focusing on muon data sets: pedestal and MIP calibration
- Generally shows good stability: to combine muon runs for higher statistics

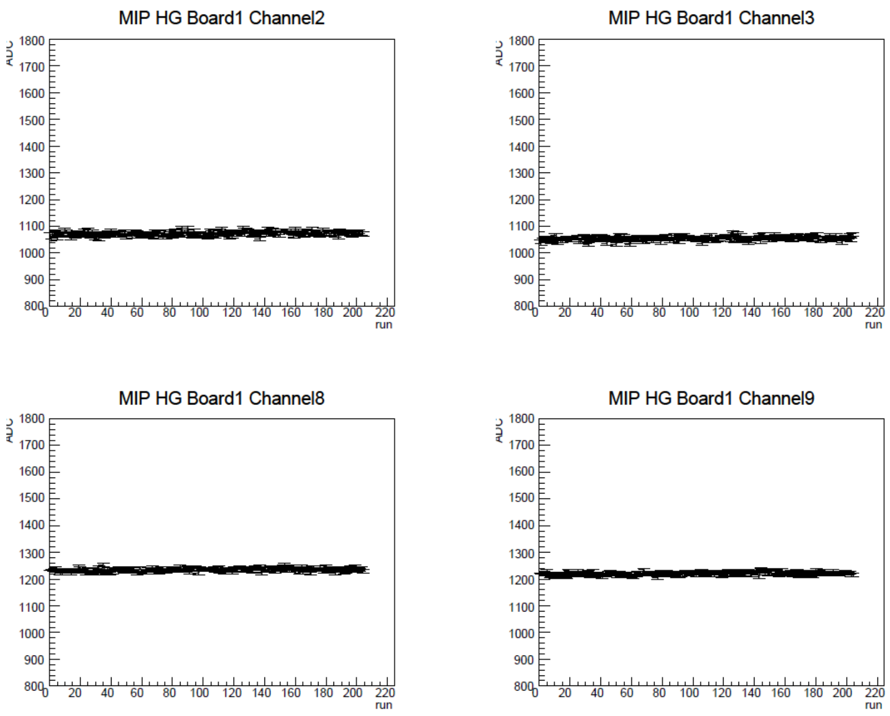
Pedestal stability over 40 runs



MIP response in selected channels

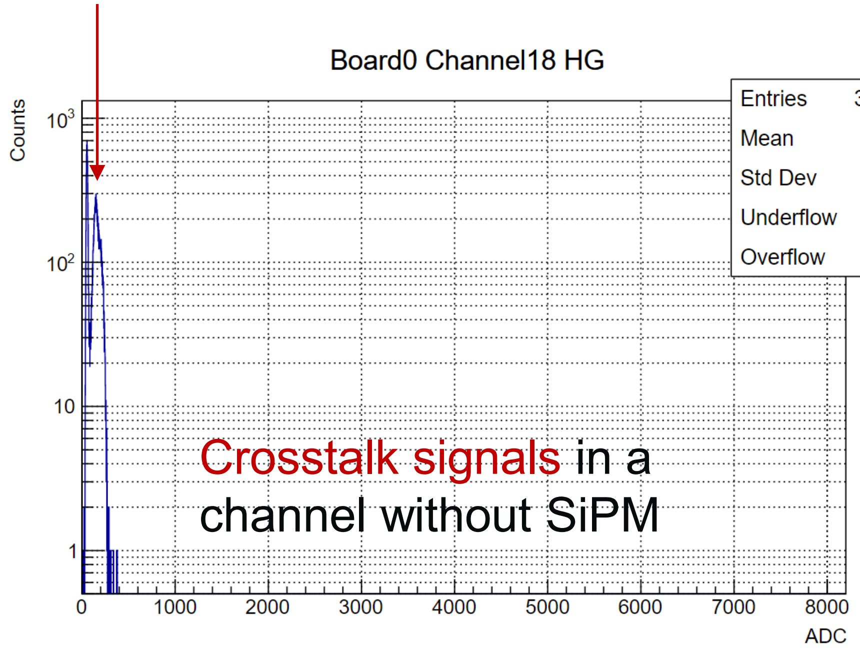


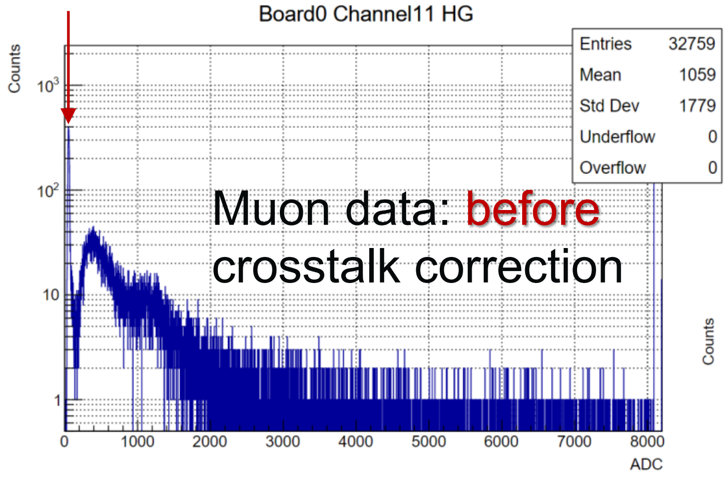
MIP MPV stability in >200 muon runs



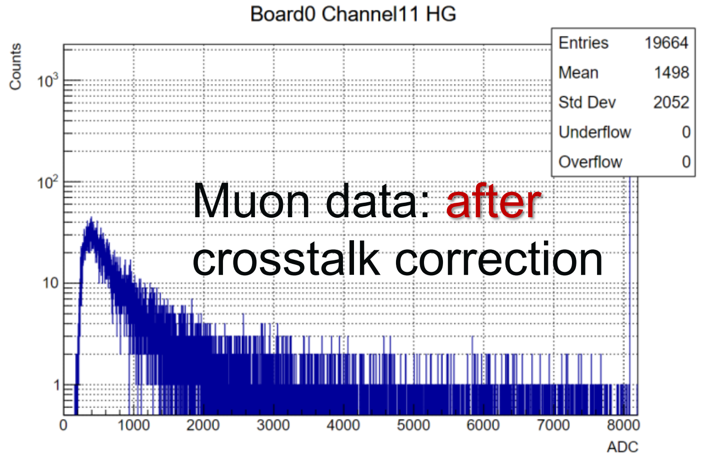
"Surprise": crosstalk issue

- Observed crosstalk signals in beam data
  - Channels without connecting to SiPMs
  - MIP/pedestal data: no significant contributions to crosstalk
  - Need to investigate possible reasons: adapter board and/or readout PCB?





→Low-energy hits in EM showers



Crystal module: status and plan

- Ongoing activities
  - Data conversion and selection: event synchronization and crosscheck
  - Geant4 simulation and realistic digitisation: EM energy resolution
  - MIP calibration channel by channel
  - Event display tool

- Plan
  - Modelling of upstream beam instrumentation in G4: beam momentum spread
  - Energy reconstruction of electron data
  - Timing data analysis: ToA timestamps
  - Temperature corrections for crystals and SiPMs
  - Influences of crosstalk and background of DESY table
  - Development of the 2nd crystal module

PFA hadronic calorimeter with glass scintillator tiles

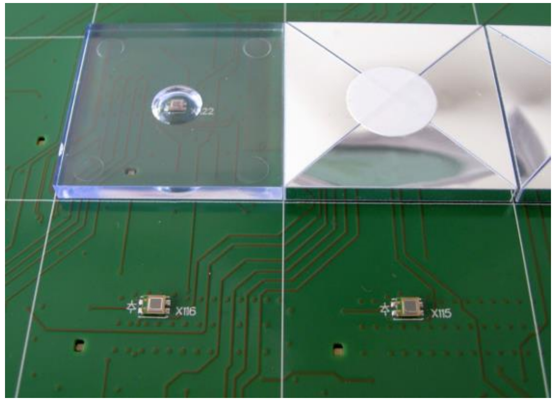
- Calorimetry for future lepton colliders (e.g. CEPC, etc.)
  - Precision measurements: Higgs and Z/W bosons
  - Jet energy resolution requires better than $30\%/\sqrt{E_{\mathrm{jet}}(\mathrm{GeV})}$
  - Particle flow paradigm: high-granularity calorimetry
- PFA-oriented detector: the CEPC 4th concept detector
  - Crystal electromagnetic calorimeter
  - Hadronic calorimeter (HCAL) with glass scintillator tiles
    - Glass scintillator with high density and light yield
    - Better hadronic energy resolution
- R&D activities for glass scintillator HCAL
  - HCAL design, simulation studies and hardware developments
  - Glass Scintillator Collaboration: material synthesizing and testing
  - PFA optimisation and physics performance studies

Glass Scintillator Collaboration

闪烁玻璃合作组

Glass Scintillator Collaboration

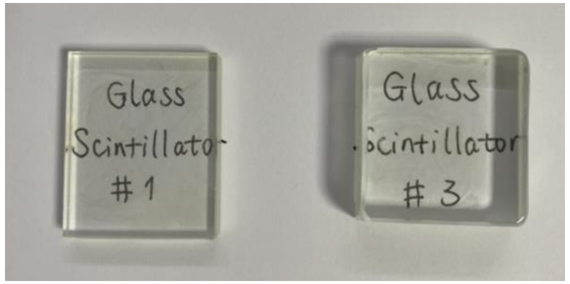
"SiPM-on-Tile" design for HCAL

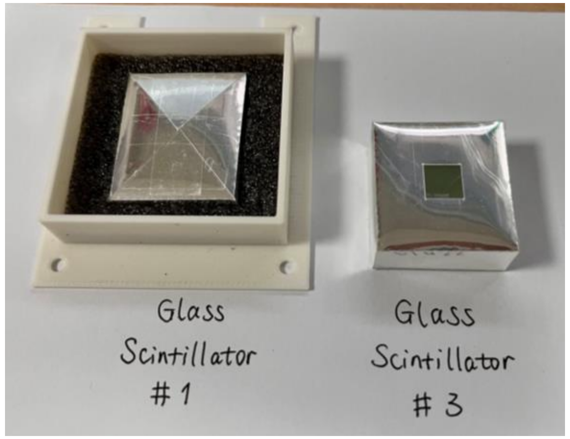


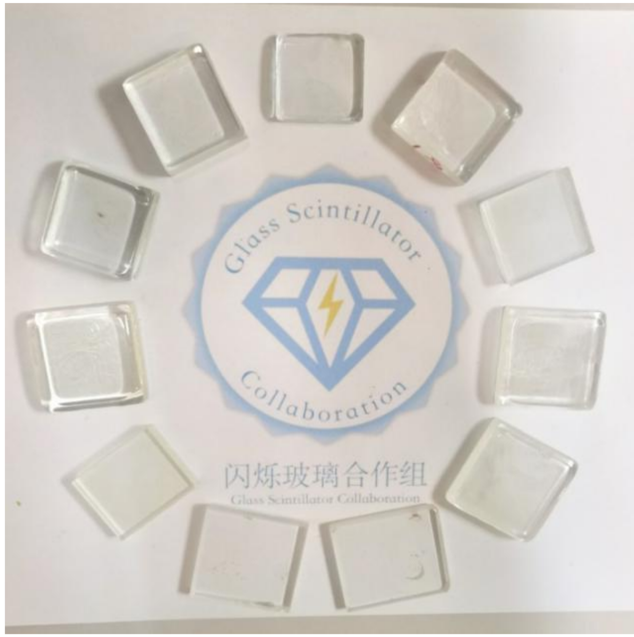
CERN beam test of glass scintillator tiles

- 11 scintillator glass tiles successfully delivered from IHEP to CERN
- First batch of large-scale glass samples from the Glass Scintillator Collab.
- Major motivation: use muon beam to measure MIP response of each glass tile

Glass tiles wrapped with Teflon and black tapes



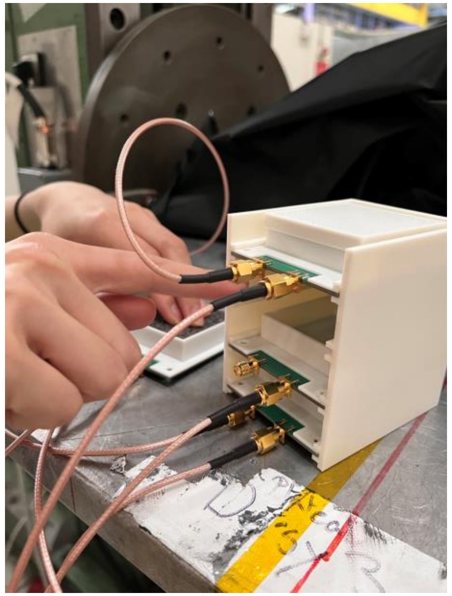


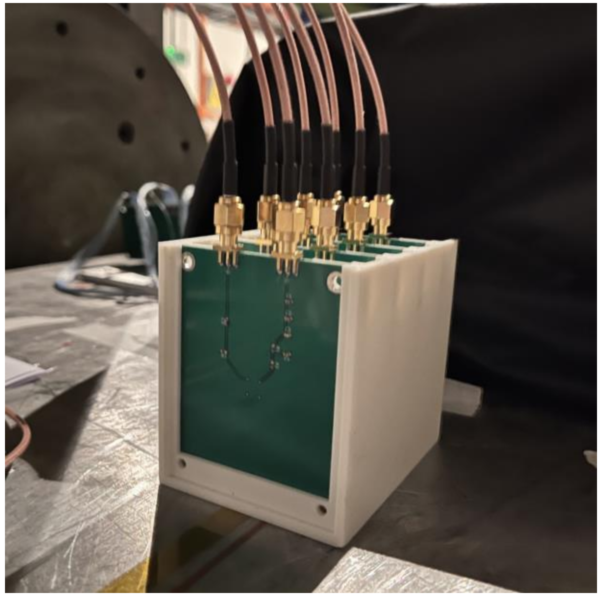


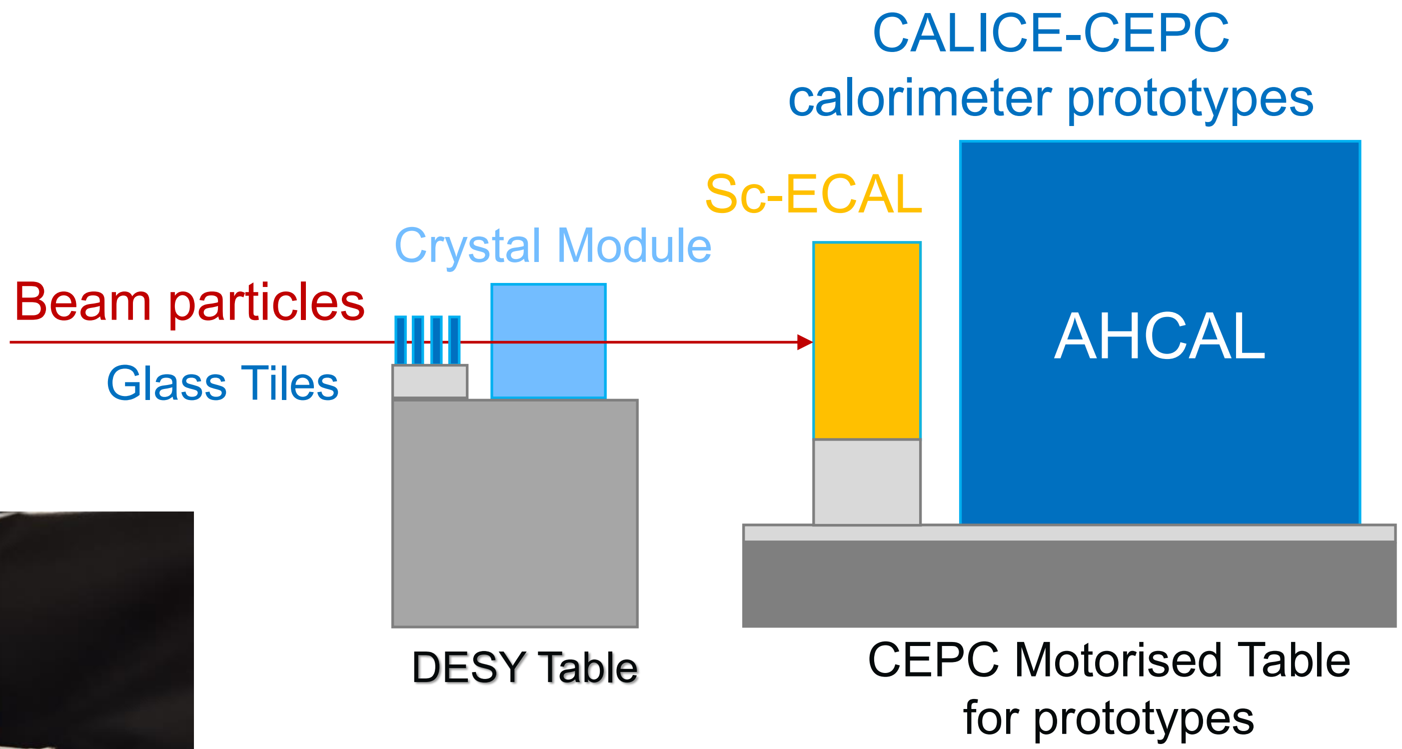
Glass tiles re-wrapped with ESR

Glass tiles in PS-T9 beamline

- Beam test setup
  - 4 tiles with individual SiPM readout
  - 3 scintillator glass tiles and 1 plastic scintillator tile (as reference)
  - Data acquisition using a 4-ch fast oscilloscope (5GS/s)





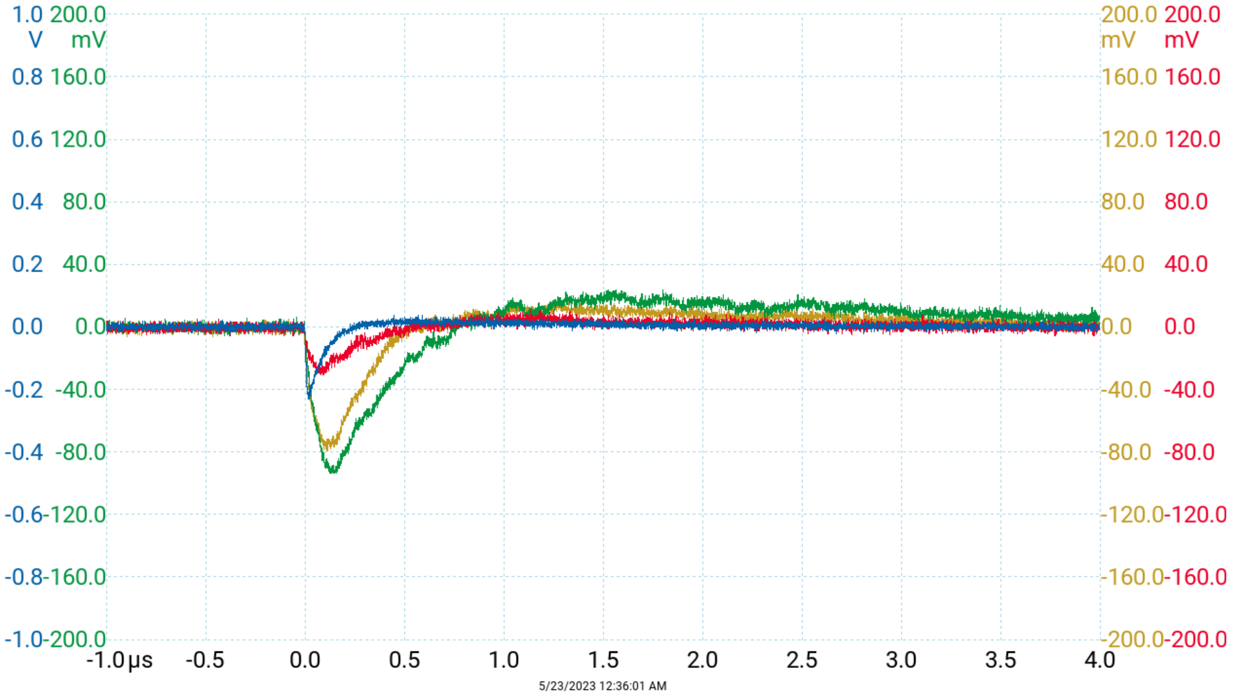


DESY Table: remote control for vertical/horizontal movements of crystal module and glass tiles

Move IN/OUT of beamline: coordination with testing of CEPC calorimeter prototypes

Glass tiles with muon beam

- Use 10 GeV muons to test 11 glass tiles and a plastic scintillator tile (reference)
- Glass scintillator: MIP response target (reminder)
  - ~150 p.e./MIP for large-scale glass tiles (3-4cm in length, 1cm in thickness)

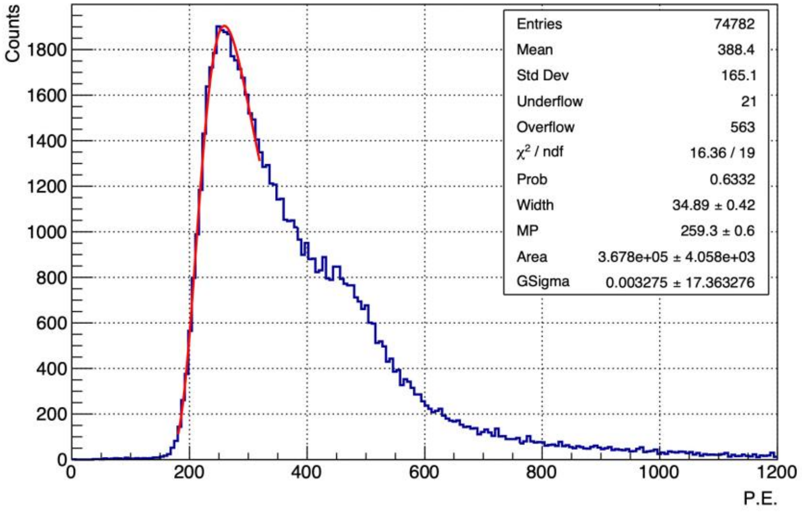


Typical waveforms with muon beam
- 1 plastic tile (blue)
- 3 glass tiles (green, yellow, red)

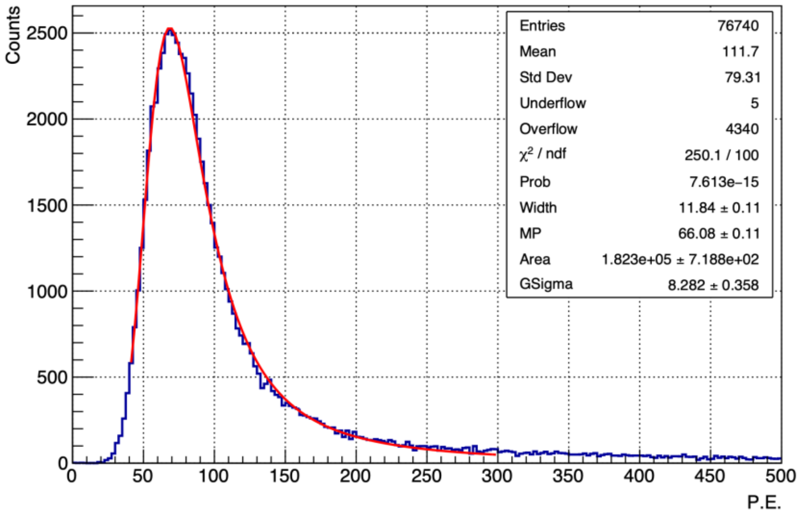
Preliminary results with muon beam

Dejing Du (IHEP)

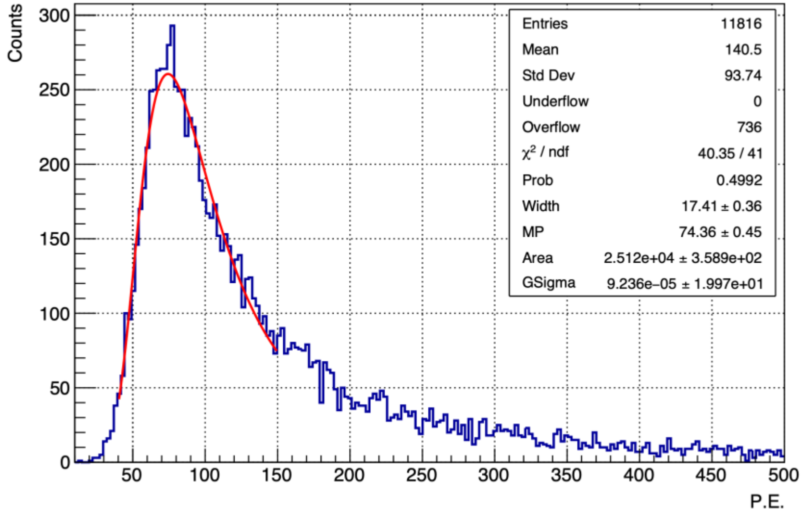
- Observed clear MIP signals in all 11 glass samples
  - Various glass tile dimensions: 25-40 mm in length, 5-10mm in thickness
- Preliminary results look promising
  - Typical glass MIP response: 15 – 74 p.e./MIP
- Also observed other structures in energy spectrum: due to 2-muon incidence?



Plastic scintillator: 259 p.e./MIP
$(40 \times 40 \times 10\ \mathrm{mm}^3)$



Glass scintillator (#3): 66 p.e./MIP
$(29.8 \times 28.1 \times 10.2\ \mathrm{mm}^3)$



Glass scintillator (#10): 74 p.e./MIP
$(34.7 \times 35.2 \times 7.4\ \mathrm{mm}^3)$

Summary: preliminary beamtest results of all glass tiles

Dejing Du (IHEP)

Index	Dimensions (mm)	Transmittance	Decay Time (ns)	Muon response (p.e./MIP)	Scale to 10mm thickness (p.e/MIP)
#1	33.5×27.6×5.1	69 %	300 (19%), 881	15	29
#1 ESR				42	82
#2	30.2×29.5×6.6	61 %	114 (11%), 770	35	53
#3	29.9×28.1×10.2	70 %	90 (6%), 754	66	65
#3 ESR				69	68
#4	37.2×35.1×5.3	80 %	96 (6%), 1024	31	59
#5	40.0×35.1×4.2	78 %	335 (26%), 1068	38	91
#6	30.3×29.8×9.4	55 %	134 (5%), 1132	67	71
#7	34.8×34.8×7.5	65 %	113 (27%), 394	60	80
#8	27.8×25.6×5.0	81 %	136 (23%), 933	41	82
#9	34.6×34.7×7.5	49 %	141 (12%), 771	69	92
#10	34.7×35.2×7.4	64 %	129 (10%), 819	74	100
#11	30.5×30.0×8.7	81 %	153 (12%), 1085	73	84

Beam test of scintillator glass tiles: status and plan

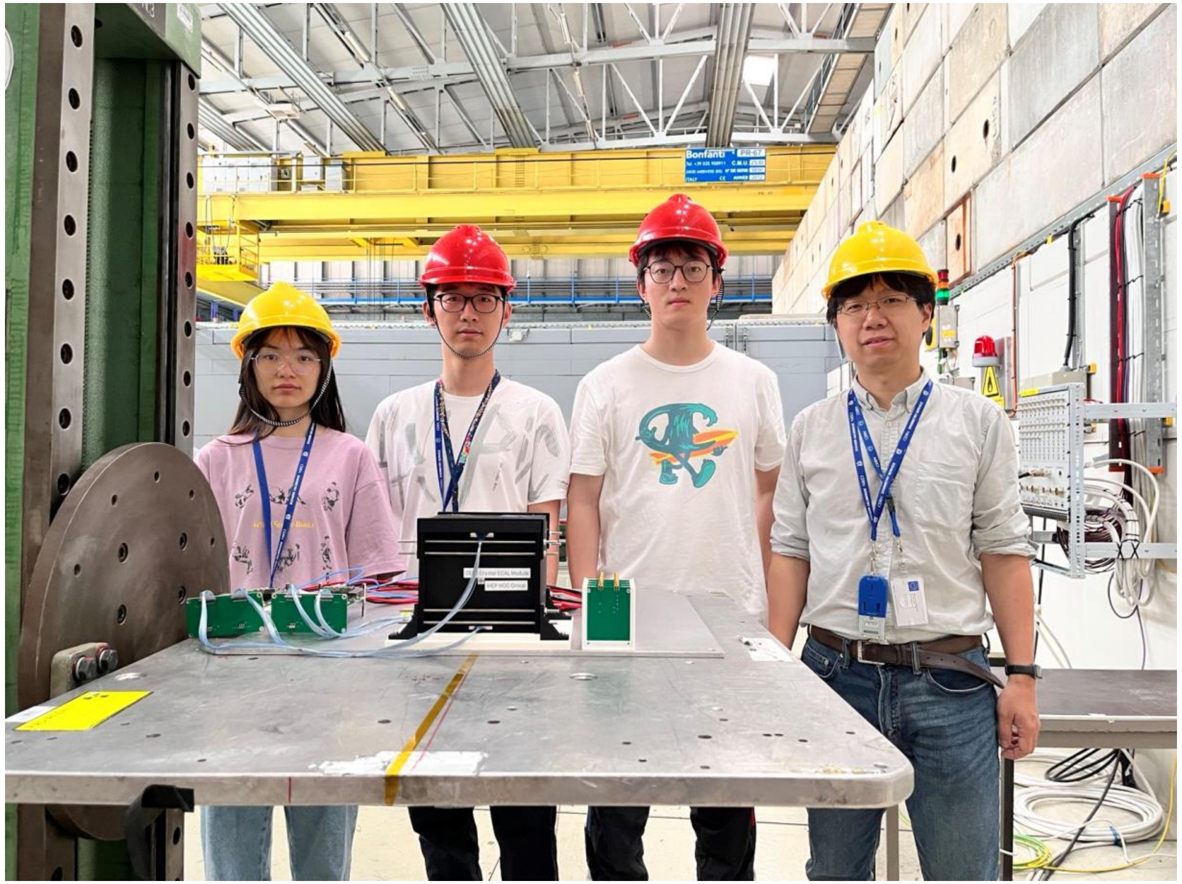
- Obtained full muon data sets for all 11 scintillator glass tiles

- Ongoing activities with muon data
  - Comparison of muon beam data with radioactive tests
  - Scintillation time studies: fast and slow components

- Plan
  - Investigation of possible multiple incident muons: pile-up effects in glass?
  - Continue to take more data with cosmic muons in lab: further crosschecks
  - Revisit glass tile design with new beam results
    - MIP response requirement
    - Possible impacts to HCAL performance

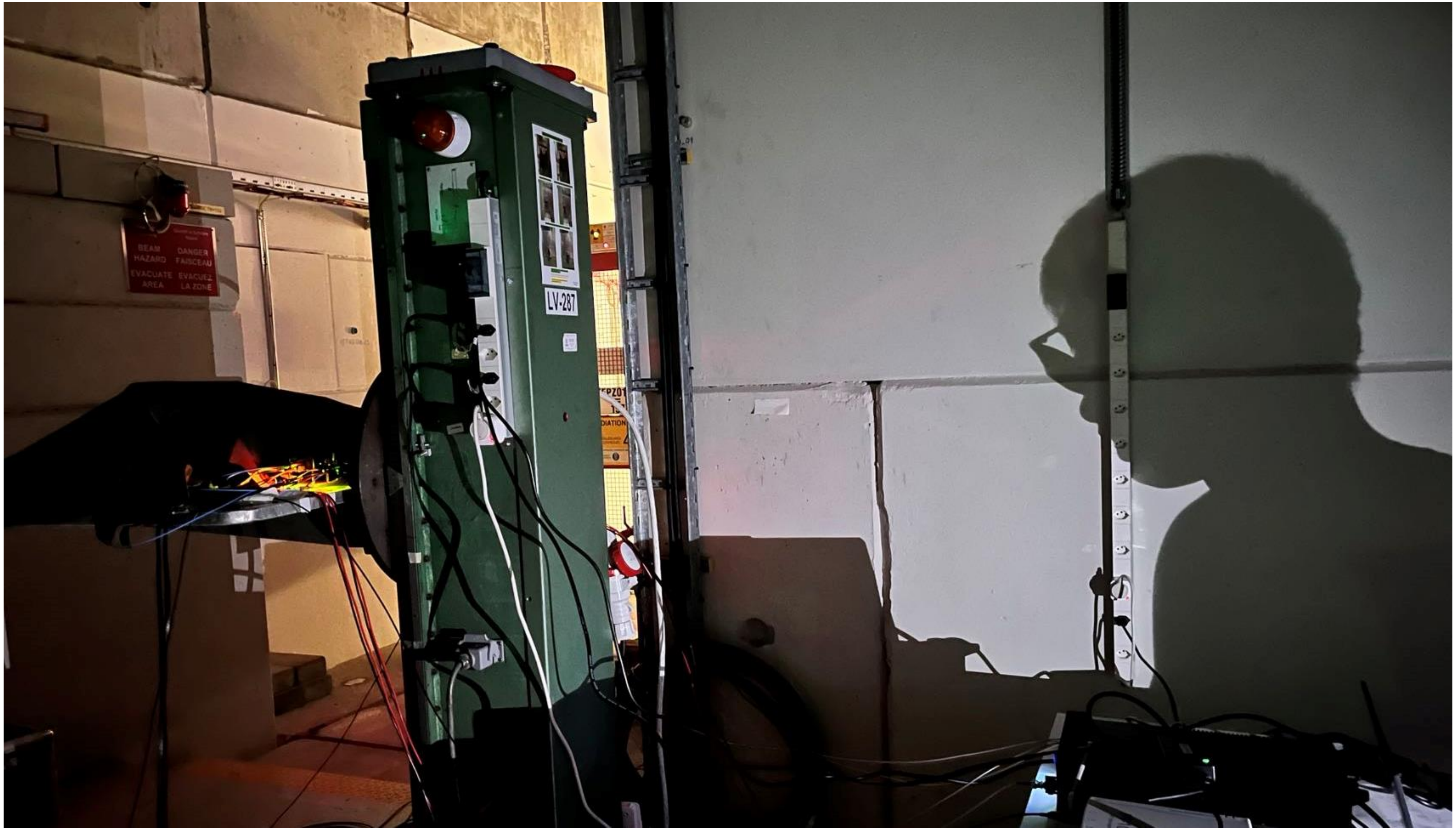
Acknowledgements

- Strong teamwork and team’s hardworking spirit in day and night
- Enormous and substantial support from CERN and CALICE



Very successful beam test campaigns:

A big Thank You to the whole CALICE and CEPC calorimeter teams


BEAM HAZARD
EVACUATE AREA
DANGER FAISCEAU
EVACUEZ LA ZONE
LV-287

Thank you !