SECOND • ECFA • WORKSHOP
on e^+e^- Higgs / Electroweak / Top Factories
11-13 October 2023
Paestum / Salerno / Italy

R&D of the high granularity calorimeter in CEPC

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2nd ECFA workshop on e^+e^- Higgs/EW/top factories

Paestum, Oct 11-13 2023

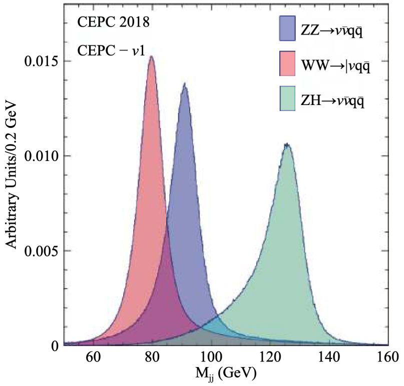
闪烁玻璃合作组
Glass Scintillator Collaboration

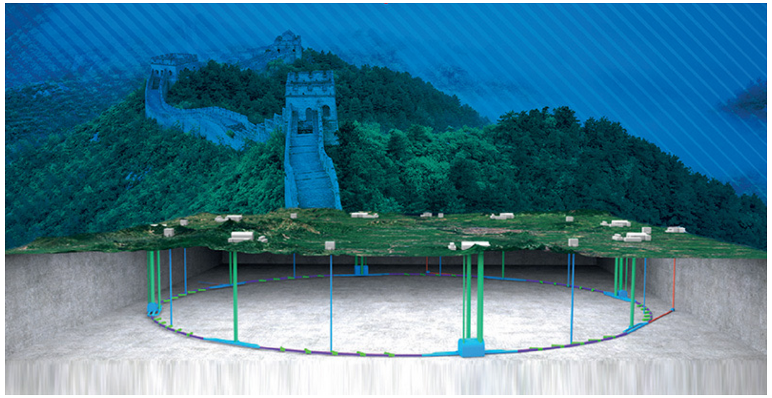
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Introduction

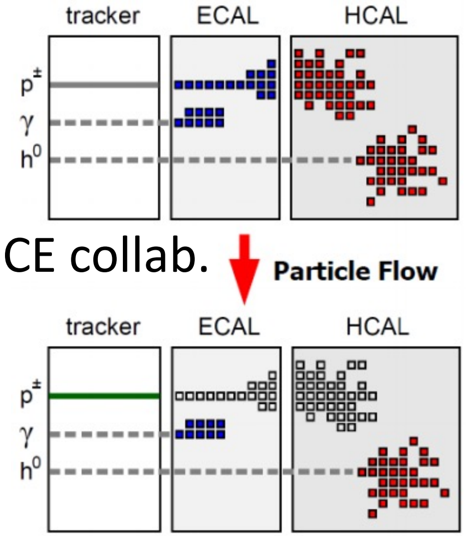
- **CEPC: Future circular e^+e^- collider experiment**
  - Aiming the precise measurement of Higgs/EW/top/flavor physics & BSM search.
  - Detector requirement:
    - Jet energy resolution $< 30\%/\sqrt{E}$.
    - $W/Z \rightarrow qq$ separation: BMR~4%.

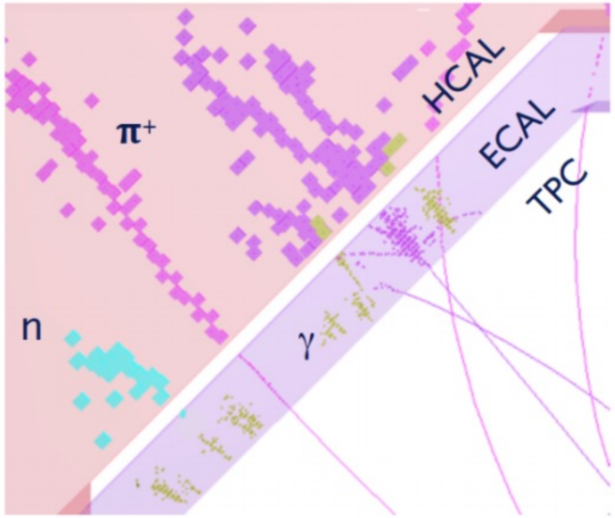
  ➡ Particle flow approach.





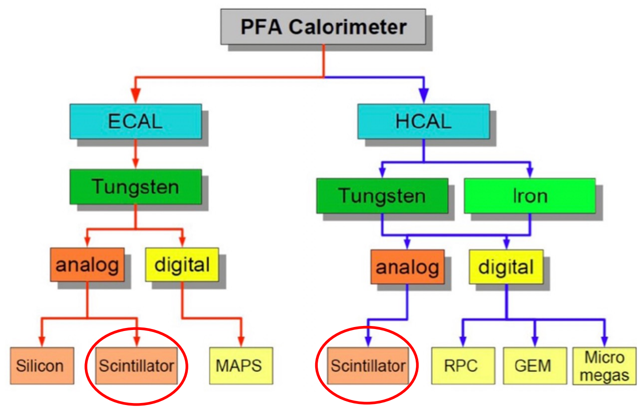
- **Particle flow in the calorimetry:**
  - Hardware + Software
  - Hardware: various options explored in the CALICE collab.
  - Software: PandoraPFA, ArborPFA, etc.



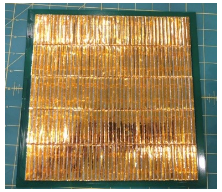


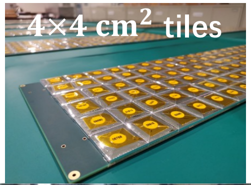
Introduction

- **CEPC efforts for the PFA calorimetry**
  - Follows the CALICE strategy: high granularity sampling calorimeter.
    - ECAL prototype: scintillator strip + SiPM + CuW (ScW)
    - HCAL prototype: scintillator tile + SiPM + steel (AHCAL)
  - From 2016 to now:
    - Technical R&D, prototype development, beam test @ CERN…



ScW ECAL prototype

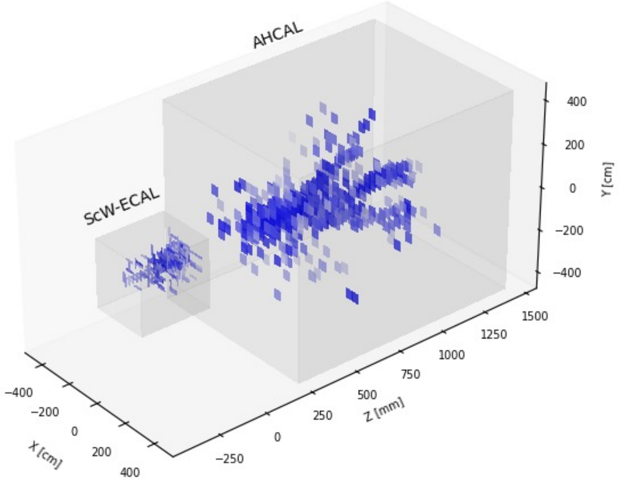

$5\times45\ \mathrm{mm}^2$ strips

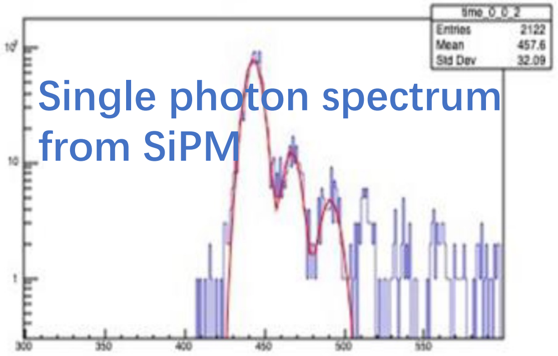

$4\times4\ \mathrm{cm}^2$ tiles

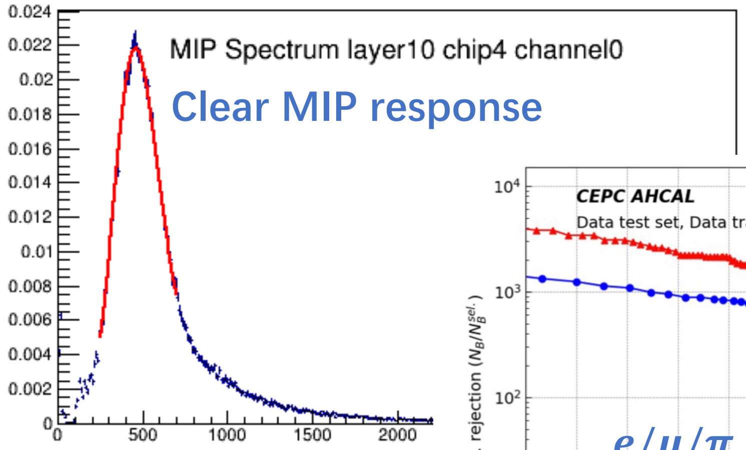
Introduction

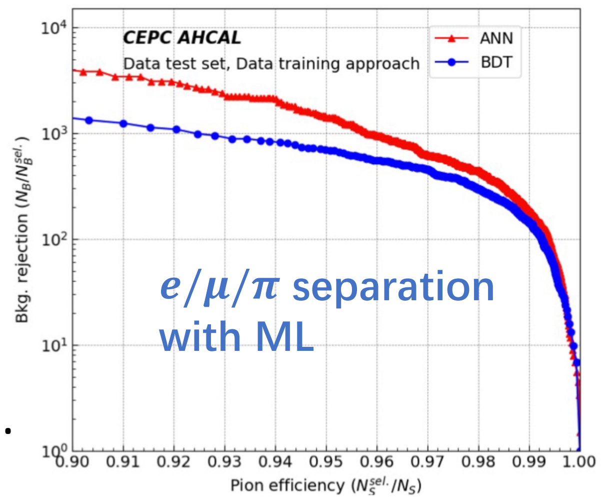
Reports in CALICE Collaboration meeting, TIPP2023 by team members

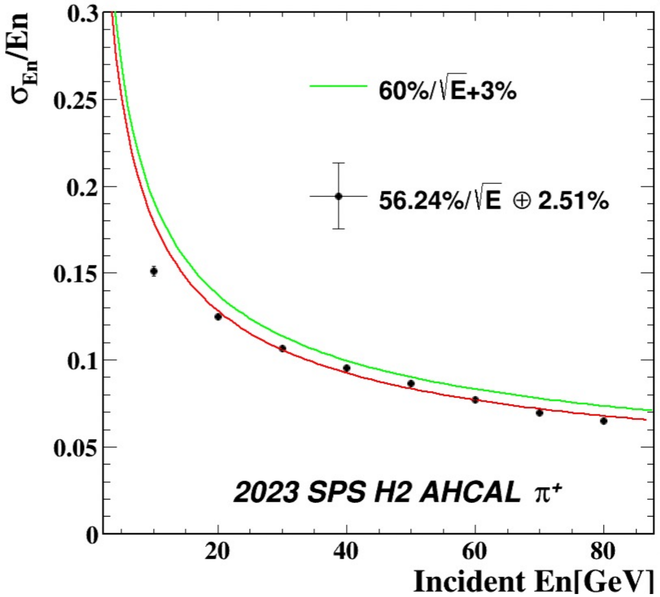
- **CEPC efforts for the PFA calorimetry**
  - 3 beam tests @ CERN SPS H2, H8 & PS T9 in 2022-2023.
  - Very successful tests and promising results:
    - Scintillator + SiPM response, electronics, system robustness…
    - Calorimeter-only PID with hit information.
    - Energy linearity and resolution.









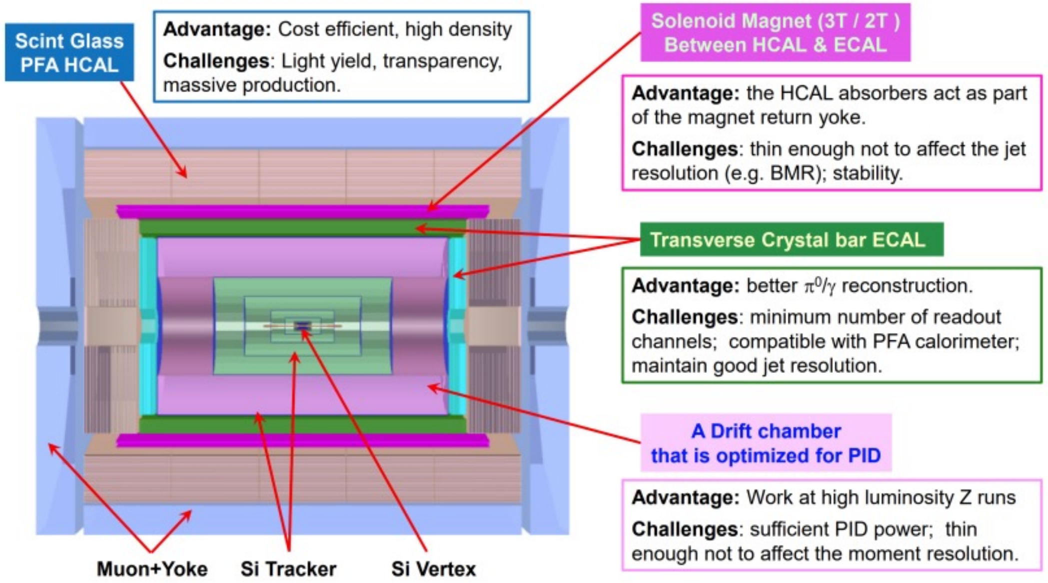


- **But we want more!**
  - New ideas, new designs, new technics …

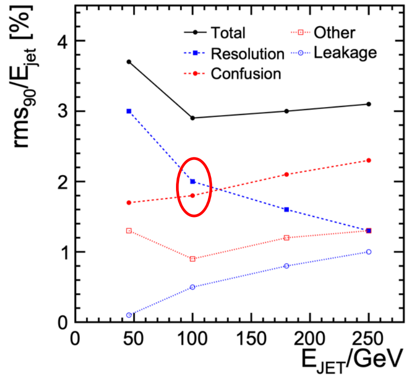
Introduction

- **New concept: CEPC 4th conceptual design**
  - Better low energy response for flavor @ Z mode: **Crystal ECAL.**
    - Large light yield crystal + SiPM for small signals.
    - Time response for 5D measurement (x, y, z, E, t).
    - Expected EM resolution $1\% \oplus 3\%/\sqrt{E}$.
  - Reduce confusion in PFA: **Dedicated reconstruction algorithms.**
    - New crystal dedicated reconstruction algorithm.
  - Better HCAL resolution: **Scintillate glass tile HCAL**
    - Higher density for higher sampling fraction.

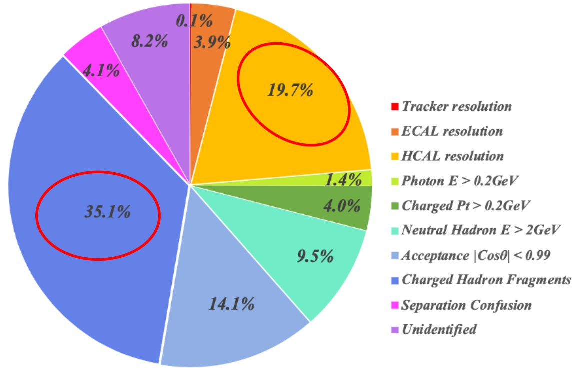
Key limitations in PFA



PandoraPFA



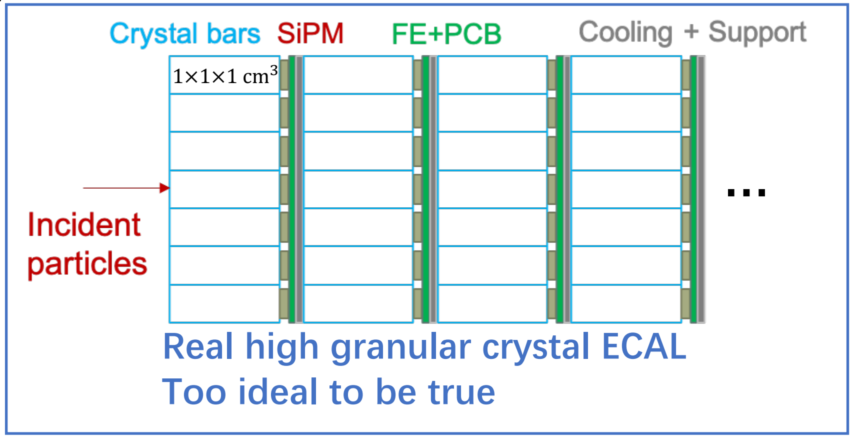
ArborPFA

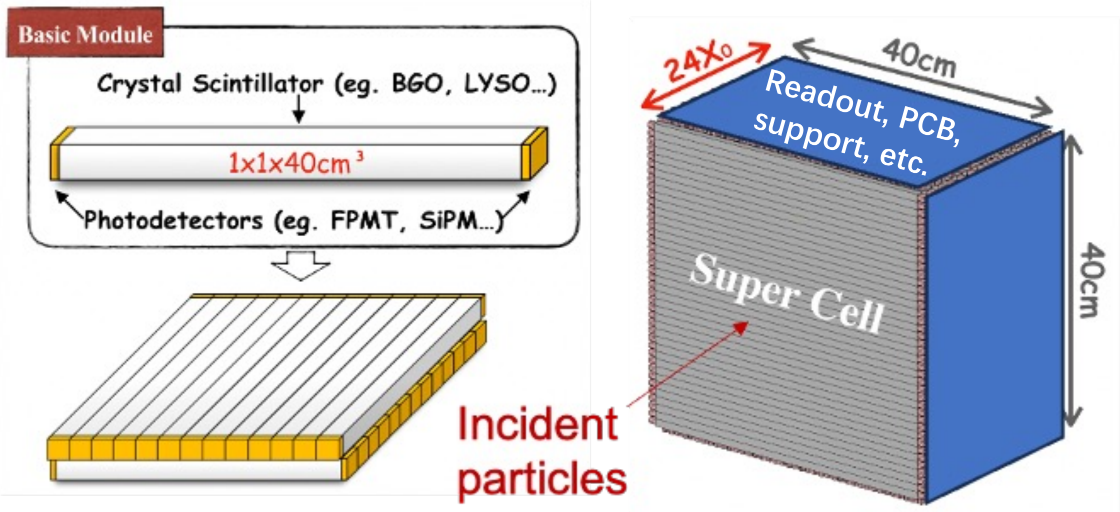


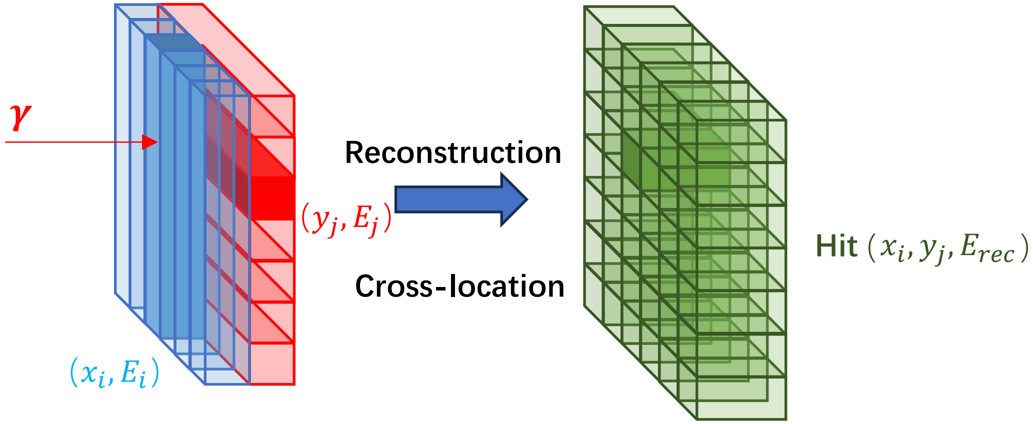
Homogeneous crystal ECAL

- **General design concept: orthogonal arranged crystal bars.**
  - A pseudo-granular calorimeter:
    - 3D info from adjacent layers by reconstruction.
  - Double-end readout with SiPM (Q, T).
    - Less #channels, lower cost in electronics.
    - Minimized dead materials.

Fangyi & Shengsen, TIPP2023



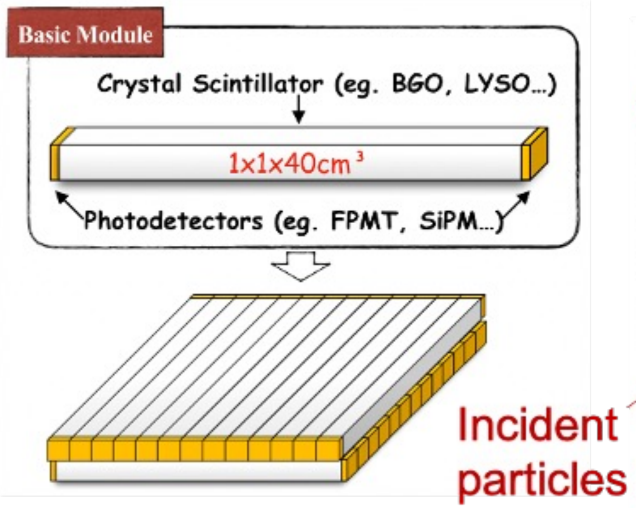


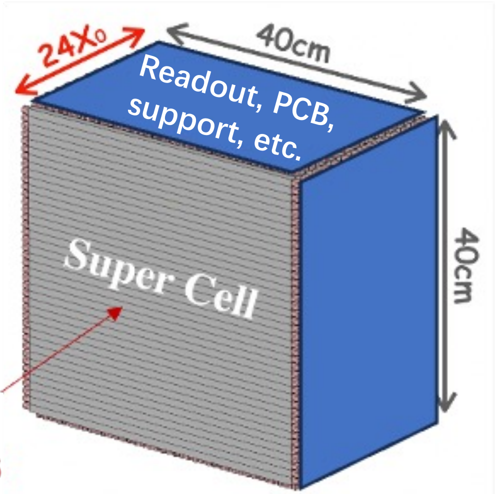


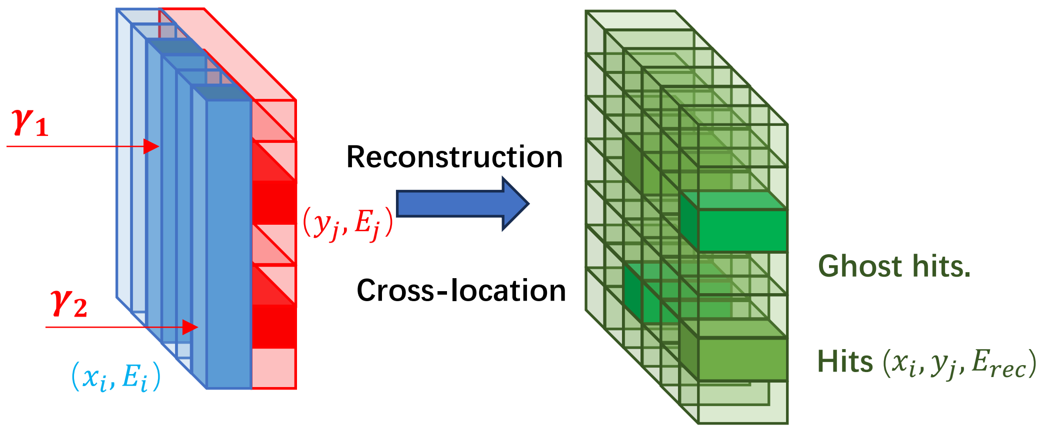
Homogeneous crystal ECAL

- **General design concept: orthogonal arranged crystal bars.**
  - Main challenge in software:
    - Difficulties in the mechanical/geometry design.
    - More shower overlap with larger crystal R_M and X_0/λ_I.
    - Multi-particle ambiguity.

PFA software task:
* Clustering
* Pattern recognition.
+ Overlap: energy splitting.
+ Ambiguity removal





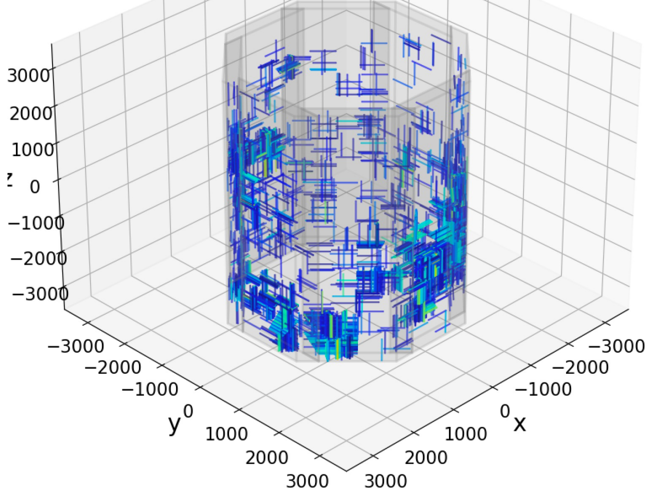


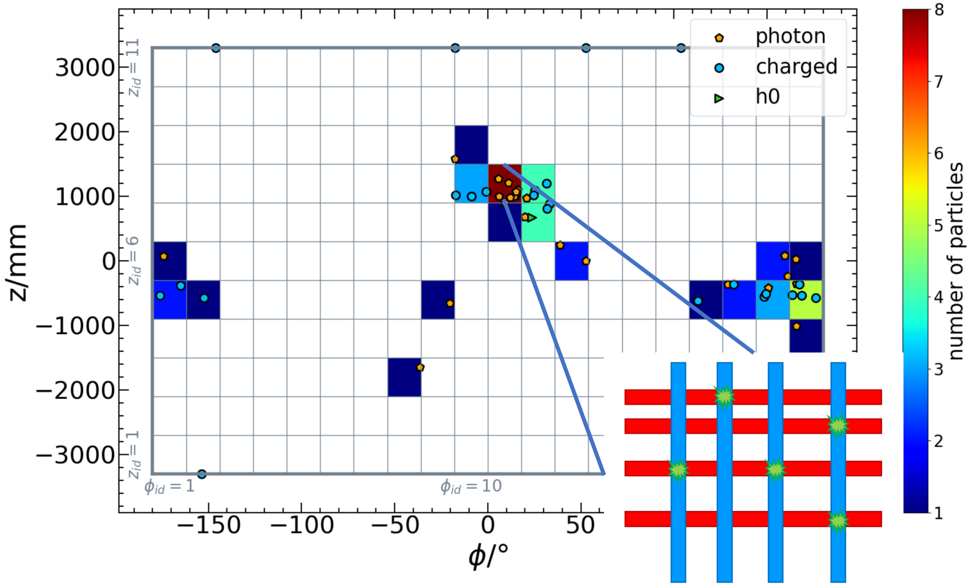
Homogeneous crystal ECAL

- **General design concept: orthogonal arranged crystal bars.**
  - Main challenge in software:
    - Difficulties in the mechanical/geometry design.
    - More shower overlap with larger crystal R_M and X_0/λ_I.
    - Multi-particle ambiguity.
    - Severer in real physics case.

PFA software task:
* Clustering
* Pattern recognition.
+ Overlap: energy splitting.
+ Ambiguity removal

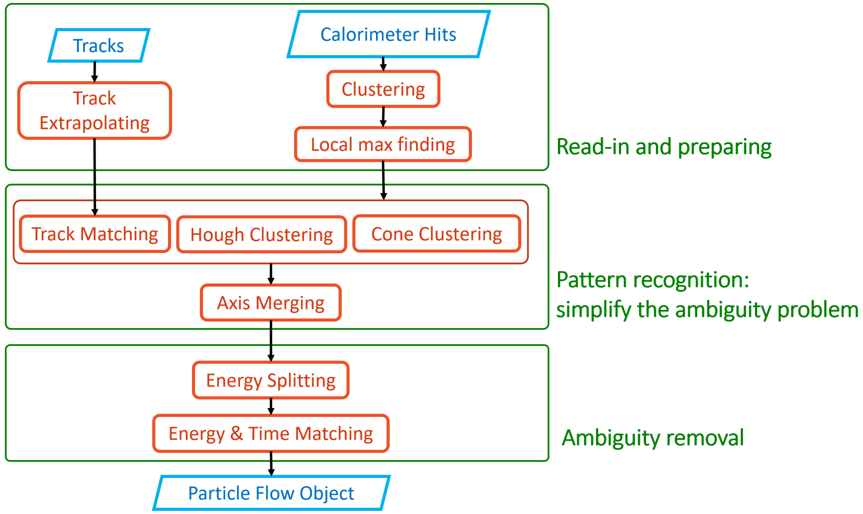
$e^+e^- \to ZH \to \nu\nu + 2jets,$
$\sqrt{s} = 240$ GeV

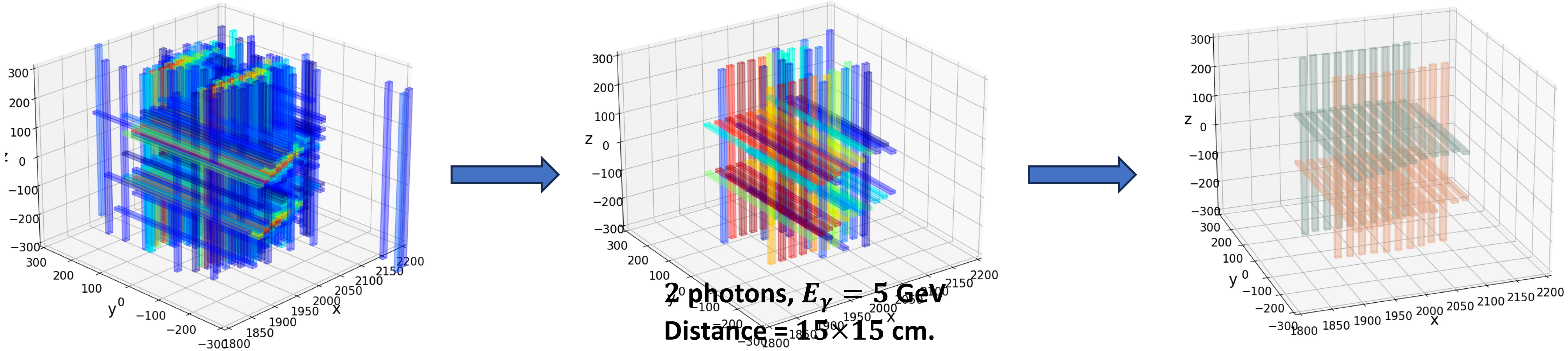




Homogeneous crystal ECAL

- **Dedicated PF reconstruction algorithm**
  - Global neighbor clustering.
  - Shower recognition.
    - Extract the *local maximum* to simplify the pattern.
    - 3 dedicated algorithms & topological cluster merging.
  - Energy splitting for overlapped showers.
  - Ambiguity removal with *track + neighbor tower + time.*

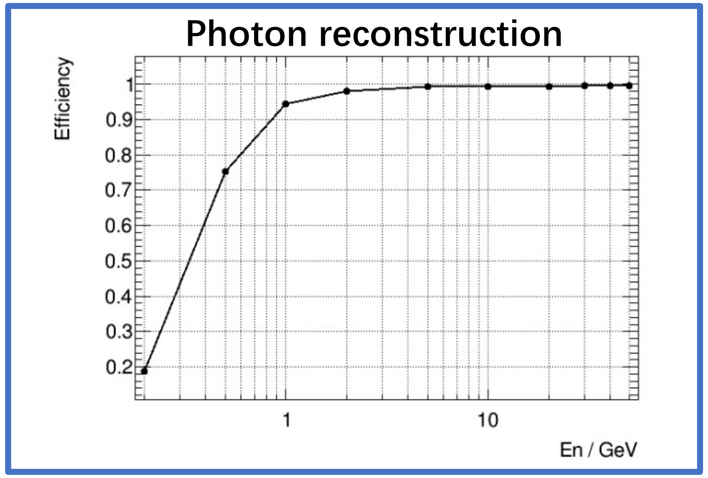


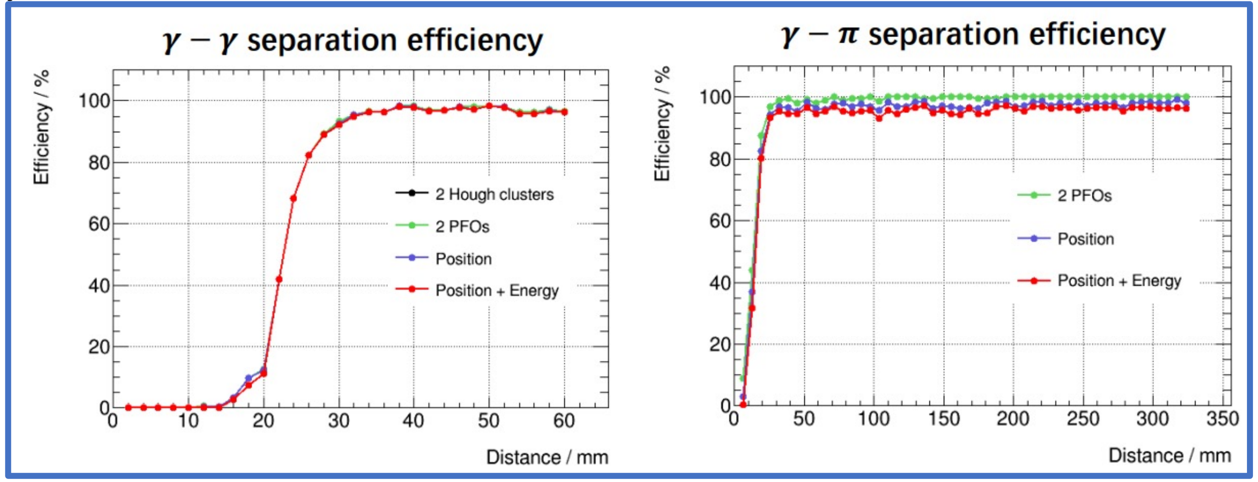


2 photons, $E_\gamma = 5$ GeV
Distance = 15×15 cm.

Homogeneous crystal ECAL

- **Preliminary performance**
  - Single photon: ~100% efficiency for $E_\gamma > 1$ GeV.
  - 2-particle separation: >95% efficiency with distance > 30 mm.



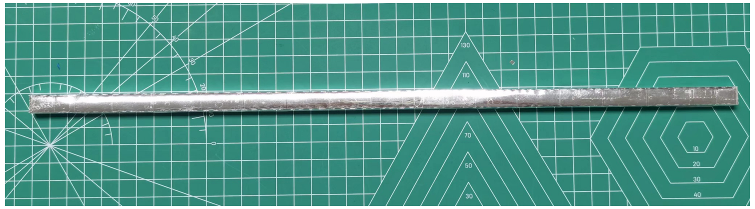


- **This is still ongoing…**
  - Clustering together with HCAL
  - Final reconstruction of jets & BMR
  - Timing information
  - **A large field waiting for exploration!**

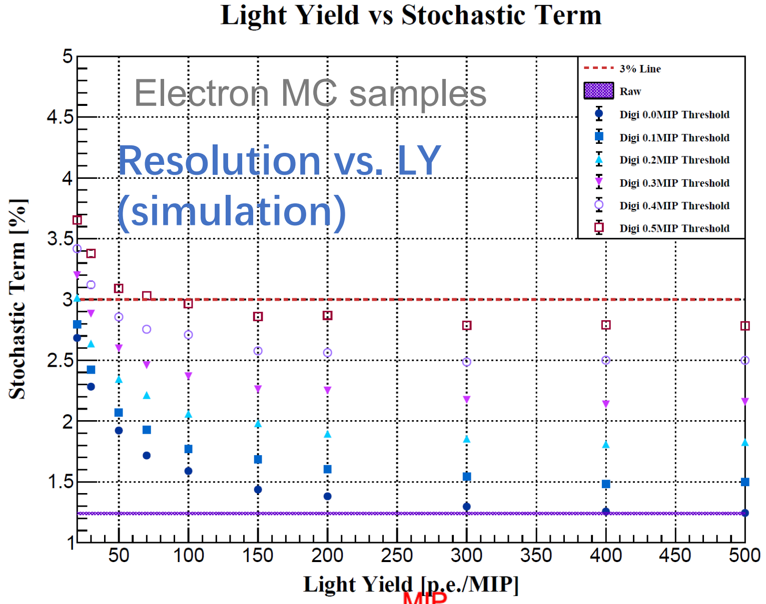
Homogeneous crystal ECAL

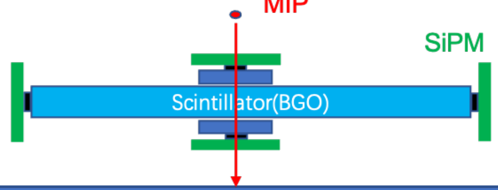
- **In the real world: hardware study for crystal bars.**
  - Better EM resolution needs large light yield
  - Lab test: BGO crystal satisfy the requirement.
  - Very promising energy resolution with ^{137}Cs: 11.2% @ 662 keV

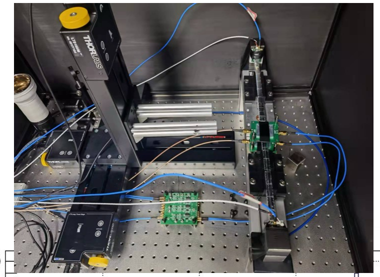
Baohua, ICHEP2022

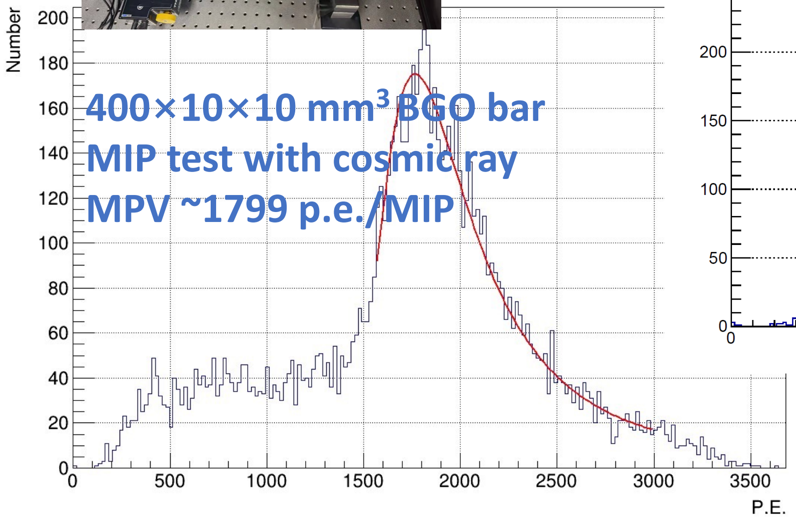


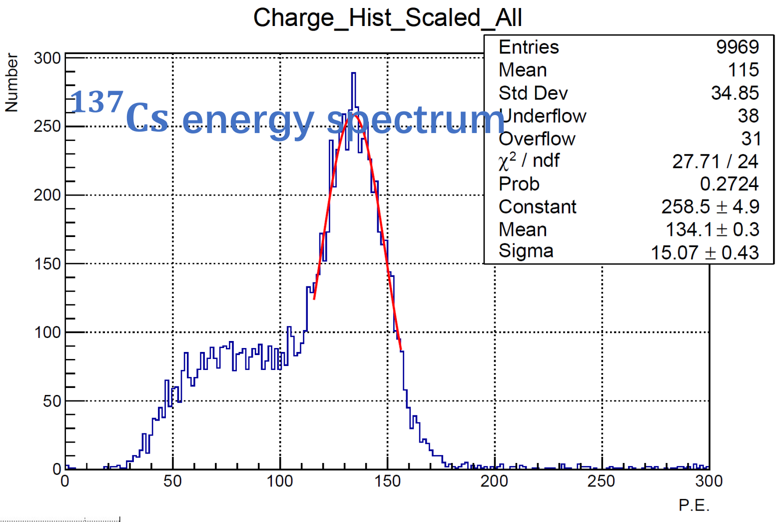
BGO bars





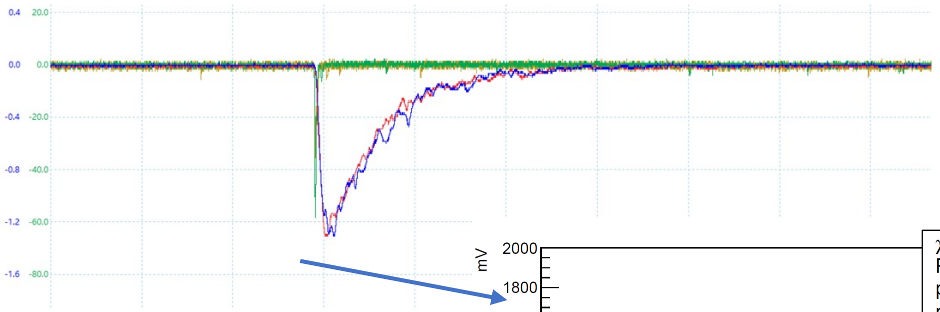


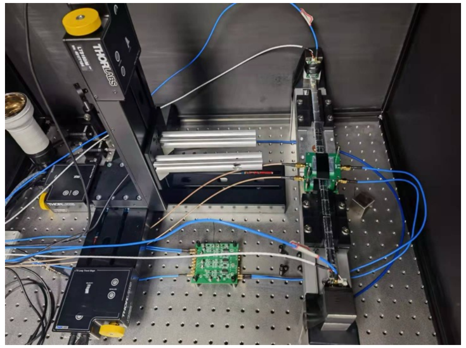


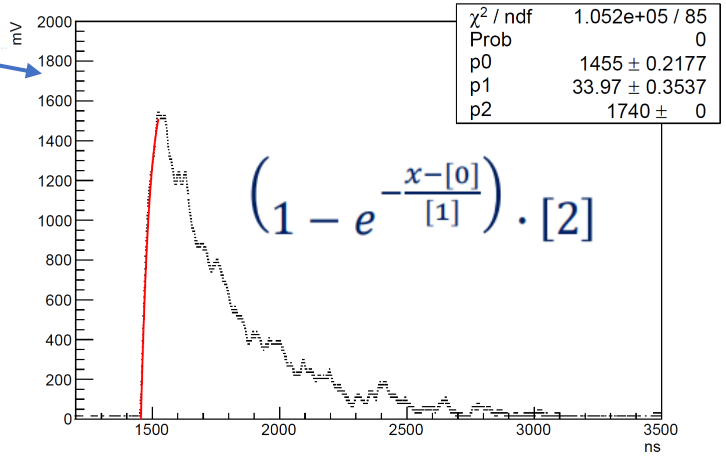


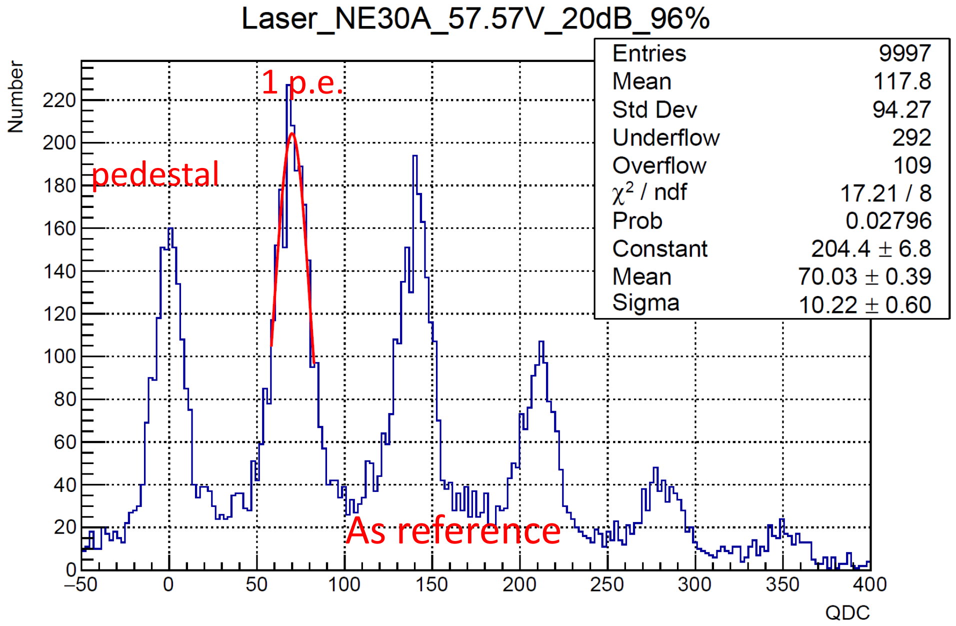
Homogeneous crystal ECAL

- **In the real world: hardware study for crystal bars.**
  - Time resolution: O(1) ns level with leading edge waveform fit.
    - Can be improved with the Cherenkov light detection ~O(100) ps.
  - Electronics: SiPM dynamic range tests.





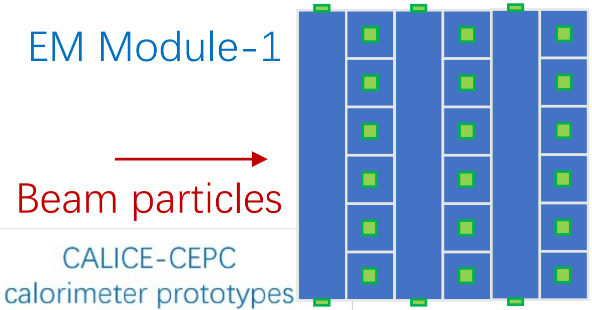


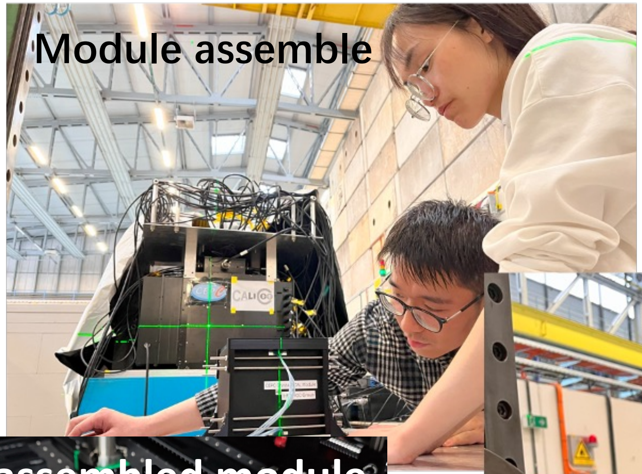


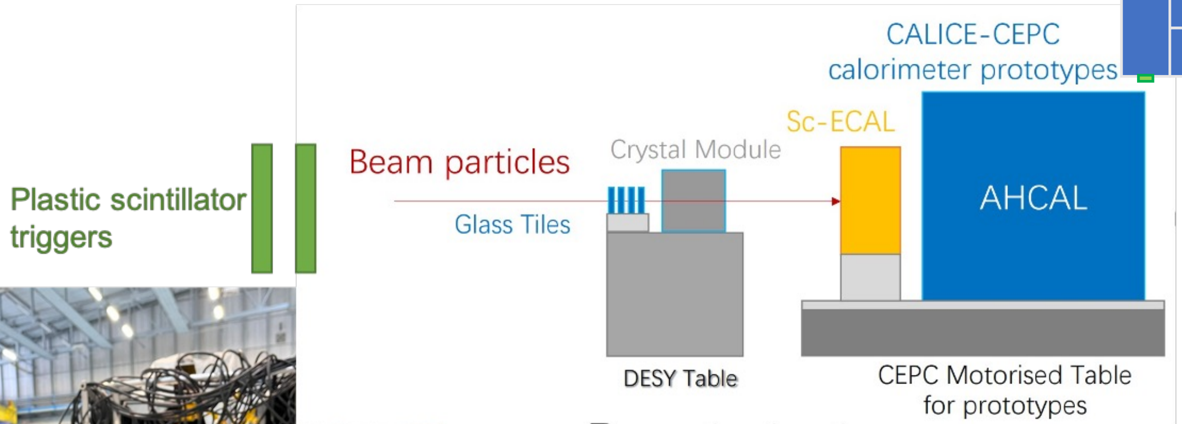
Homogeneous crystal ECAL

Baohua, TIPP2023

- **In system level: crystal module construction**
  - $12\times12\times12$ cm^3 BGO module, with 36 $2\times2\times12$ cm^3 BGP bars.
  - Beam test @ CERN, together with CEPC/CALICE ScW+AHCLA.





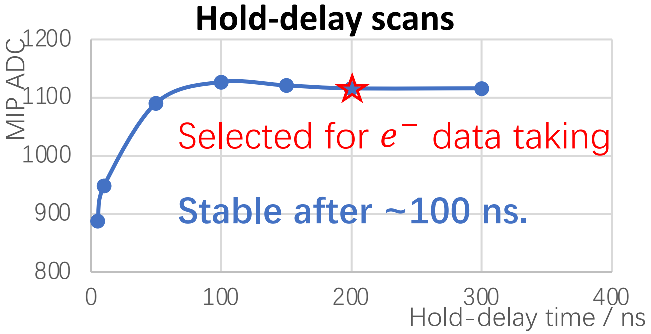


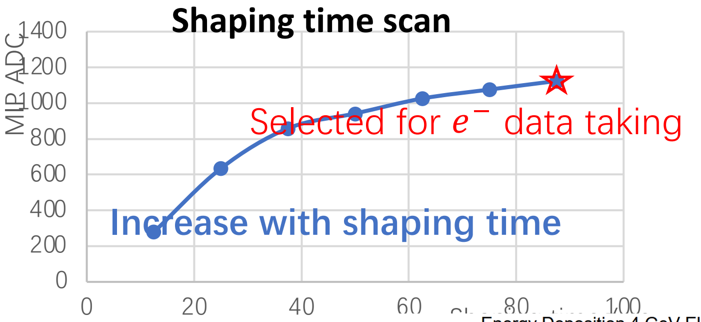
Beam test setup

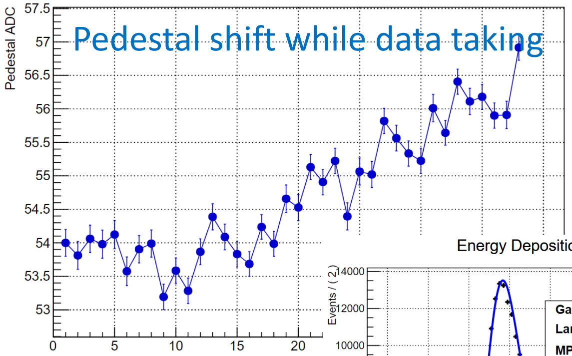
Crystal module and CEPC/CALICE prototype

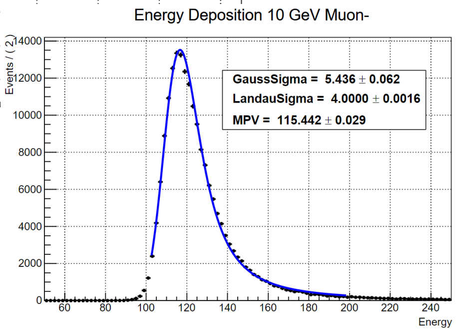
Homogeneous crystal ECAL

- **Beam test @ CERN T9: Muon beam for MIP response**
  - High/low gain, hold-delay and shaping time scan.
  - Provide channel-by-channel calibration.

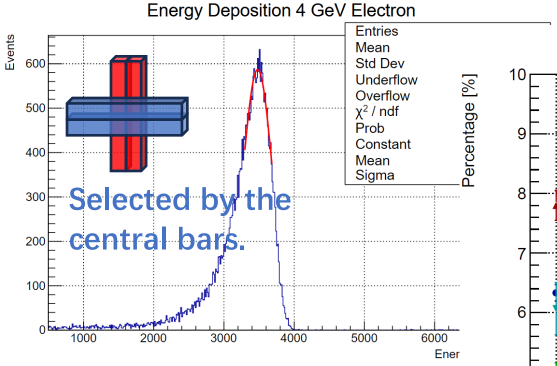


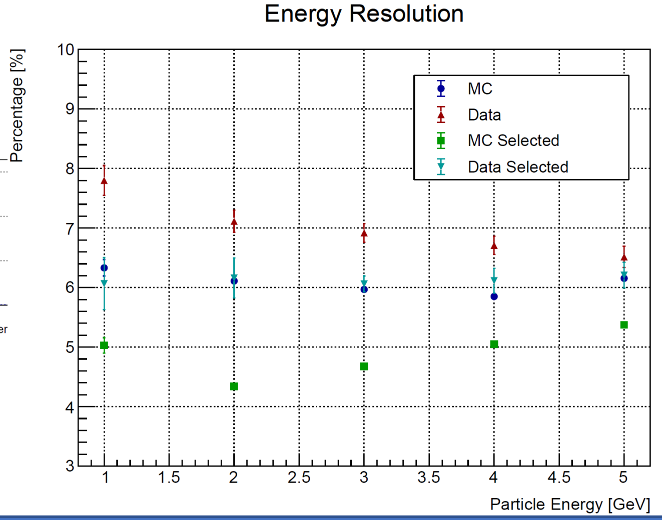






- **Electron energy performance**
  - Significant energy leakage.
  - Not perfect data-MC match.
    - Data has worse energy resolution.
    - Data shows better linearity and larger E_{mean}.

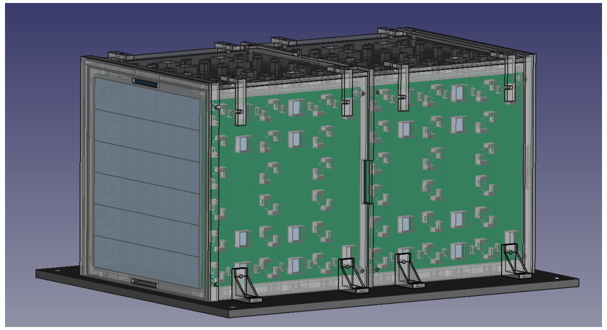




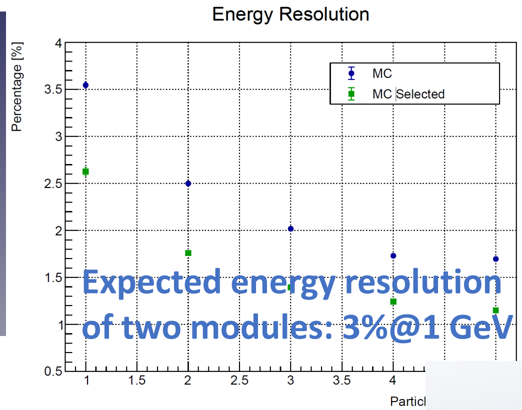
- **Preliminary results. Further studies is ongoing!**

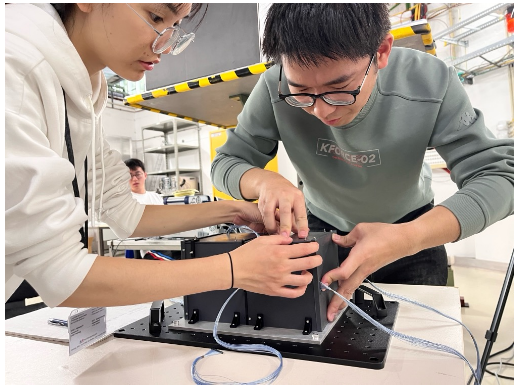
Homogeneous crystal ECAL

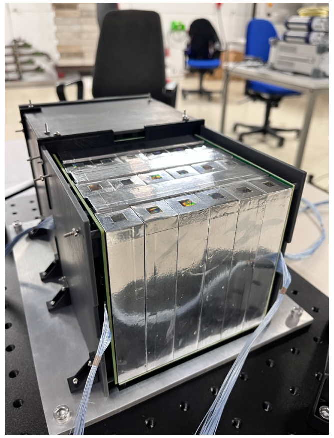
- **On-going beam test @ DESY TB22**
  - DESY TB22 CALICE-Crystal beamtest NOW!



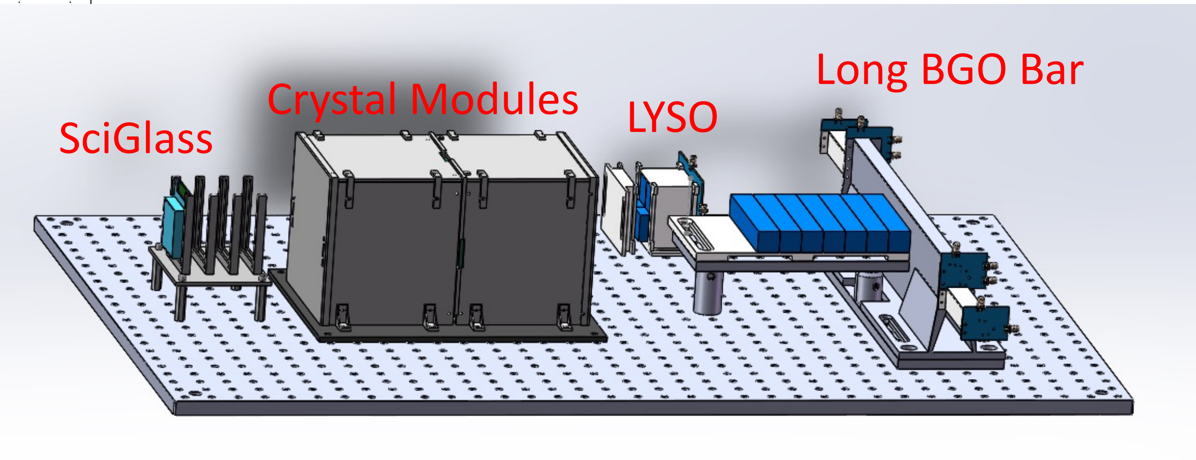
2 modules in serial







  - Targets
    - Timing studies with 40/60 cm long crystal bars
      - Timing performance for MIP/shower
      - Time resolution of 2 cm BGO as reference
    - Scintillating glass
    - LYSO with MPT2321 electronics.

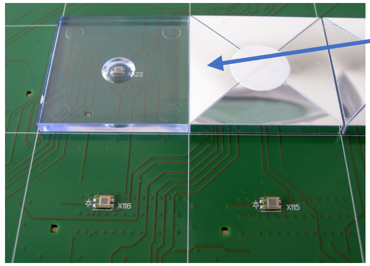


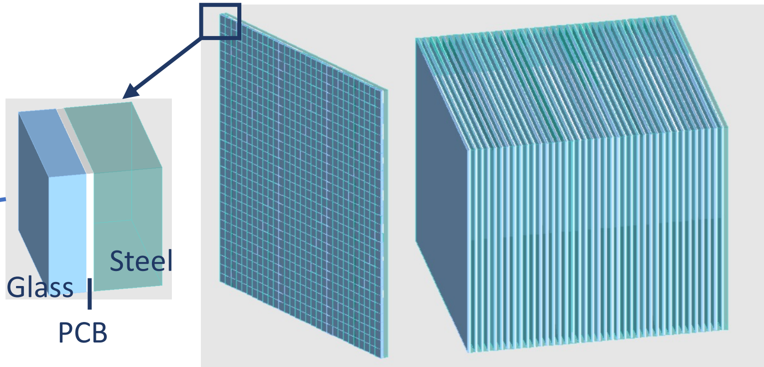
➢ Overview of the planned beamtest setup at DESY

Glass scintillator HCAL

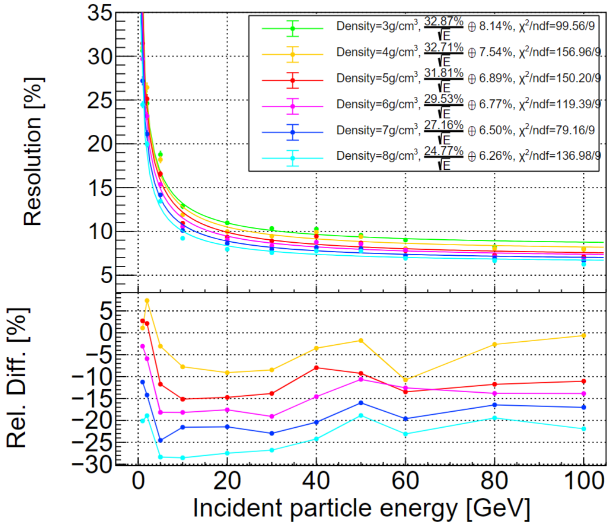
[Sen](#) & [Dejing](#), TIPP 2023

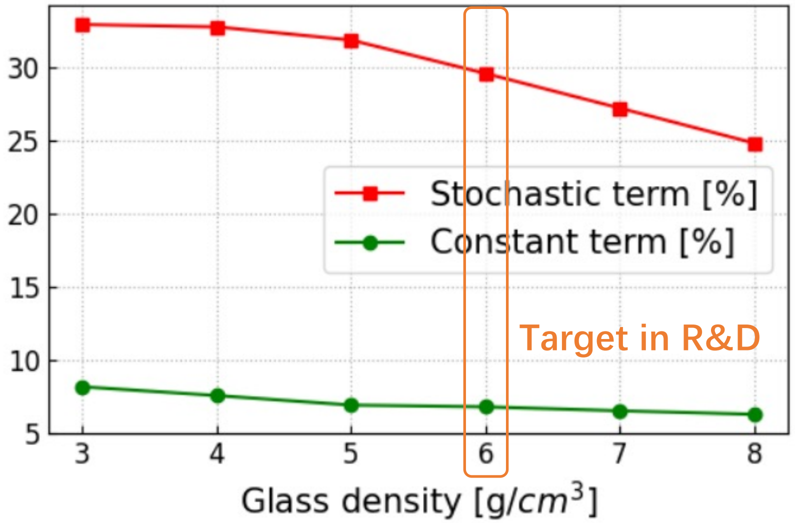
- **Motivation: better energy resolution**
  - Higher density ➡ higher sampling fraction.
- **Validate with standalone simulation:**
  - $\lambda_I = 23.83$ cm, MIP response ~7 MeV/cm.
  - Standalone simulation of glass-steel:
    - 40 layers, total depth 5λ.





“SiPM-on-tile” design
AHCAL-like glass HCAL

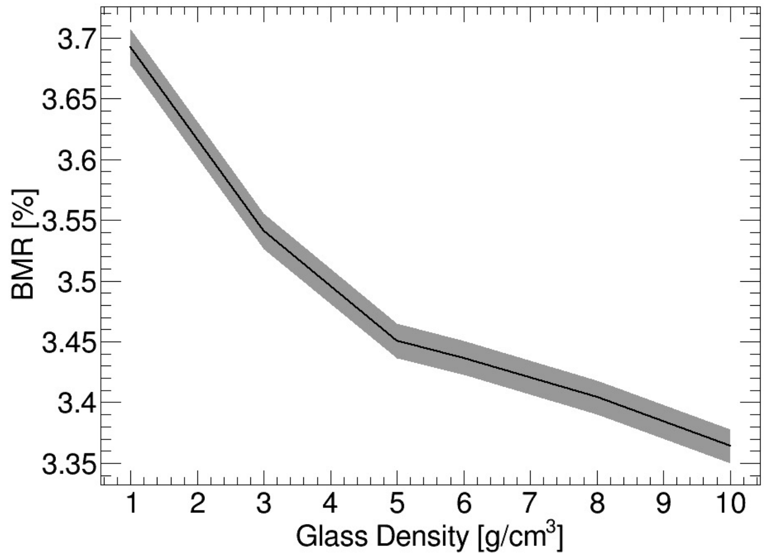


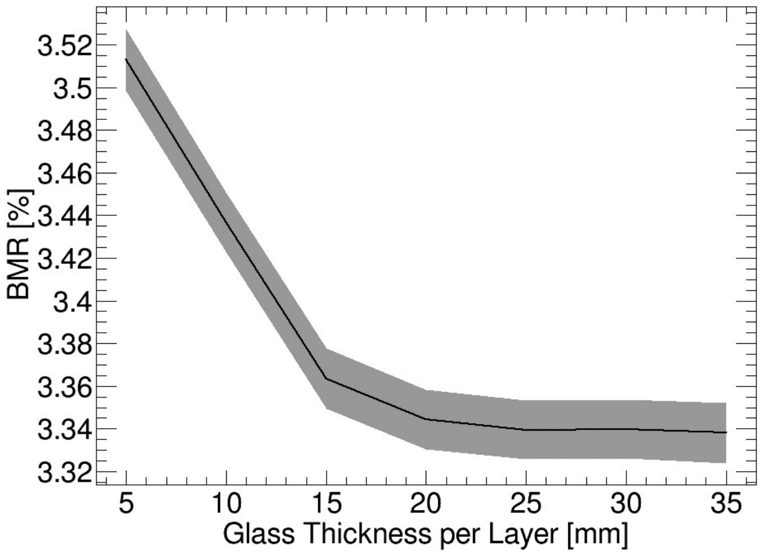


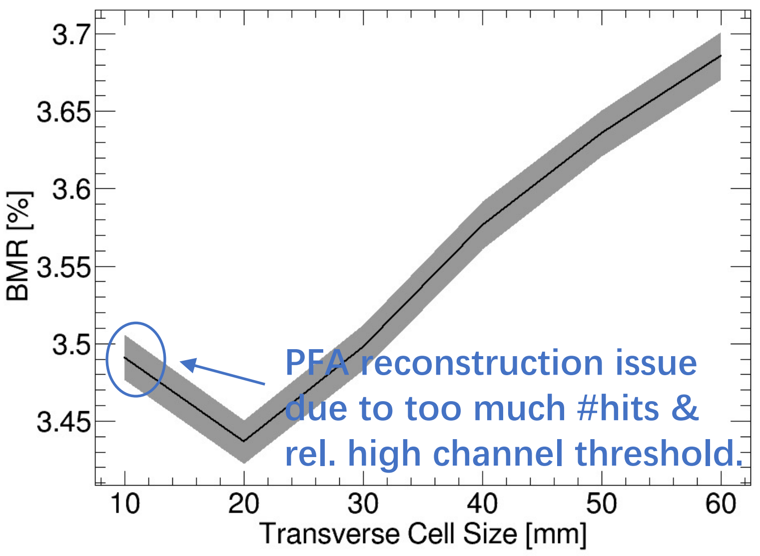
- HCAL resolution can be improved with higher density.
- Consider $6\ \mathrm{g/cm^3}$ as glass scintillator R&D target (a balance with the light yield).

Glass scintillator HCAL

- **Global performance with Arbor PFA**
  - Design optimization with the main CEPC benchmark: Higgs mass resolution @ 240 GeV
  - Study with CEPC baseline detector: TPC + SiW ECAL + glass-scintilator HCAL.
  - BMR is improved with higher density, larger thickness and smaller cell size.
  - 3.4% BMR achieved with glass-scintillator HCAL. New goal: BMR ~ 3%.

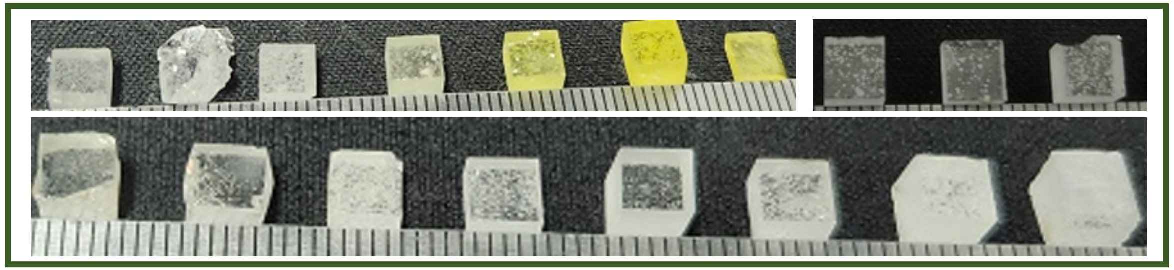
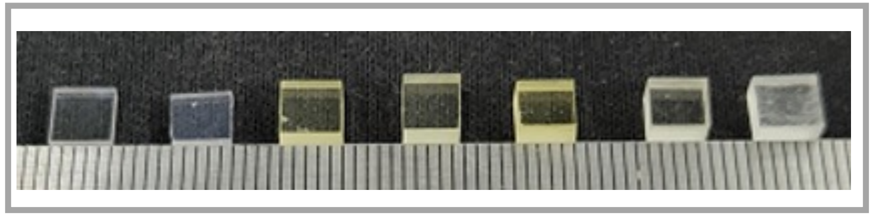
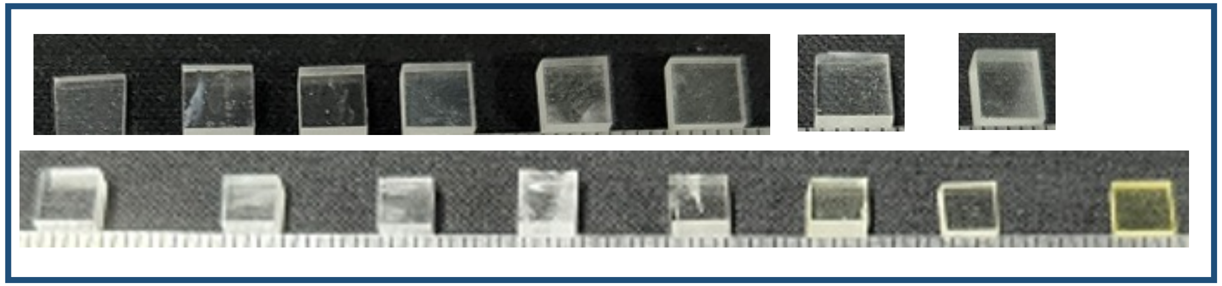
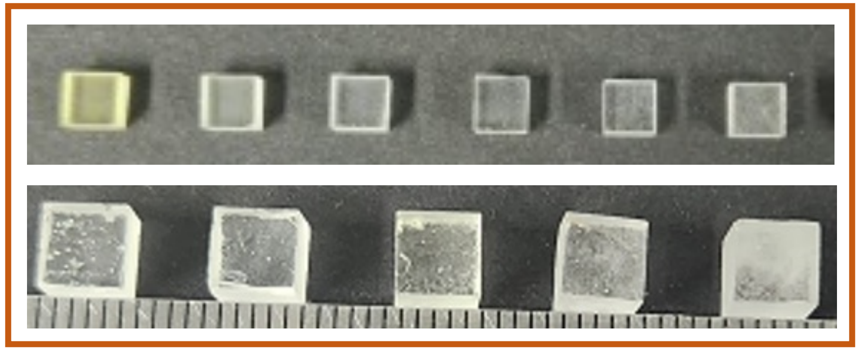




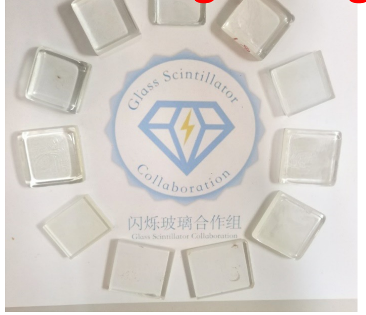


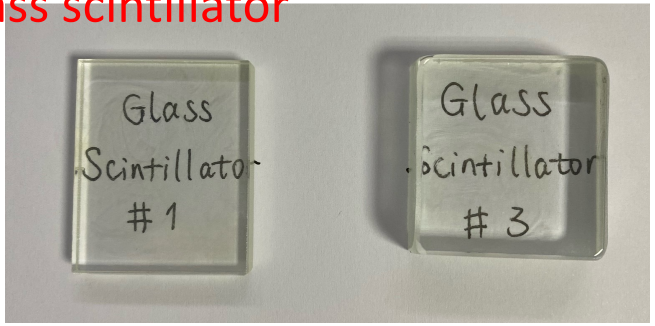
Glass scintillator HCAL

- **Glass samples in the lab: >400 samples from 11 institutes/universities/factories**

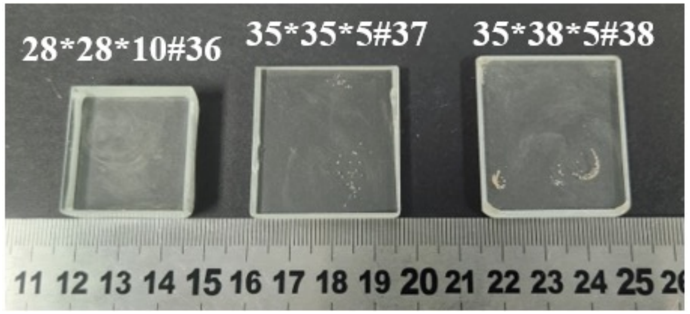





R&D of large size glass scintillator





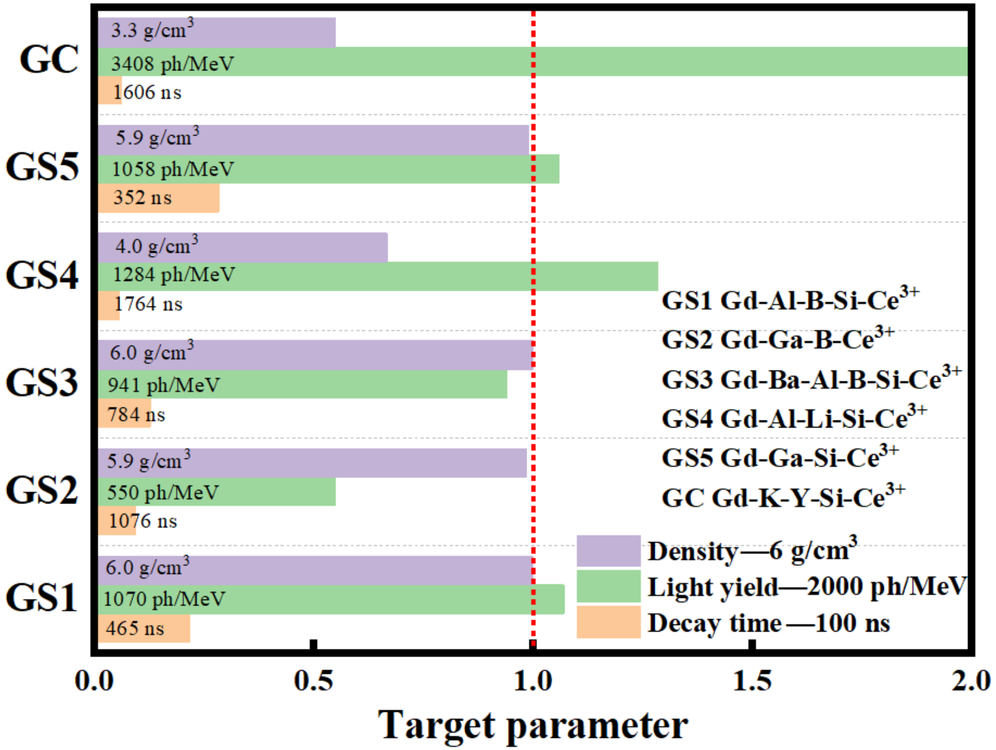
Gd-Al-B-Si-Ce^{3+} glass
42mm*51mm*10mm



Glass scintillator HCAL

- **Glass component study**
  - Key parameters: density, light yield, decay time.

Energy resolution   Time response



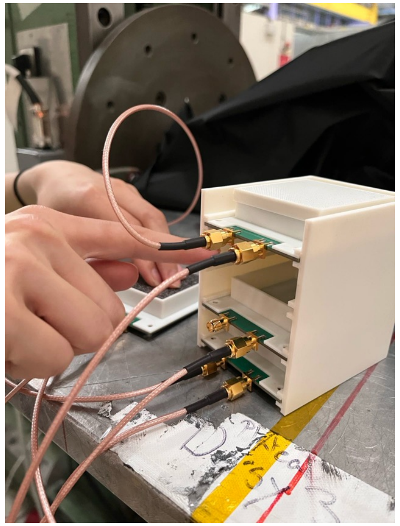
- Targets
  - 6 g/cm^3, 2000 ph/MeV, 100 ns
- Best glass sample in mm scale
  - 5.9 g/cm^3, 1058 ph/MeV, 352 ns

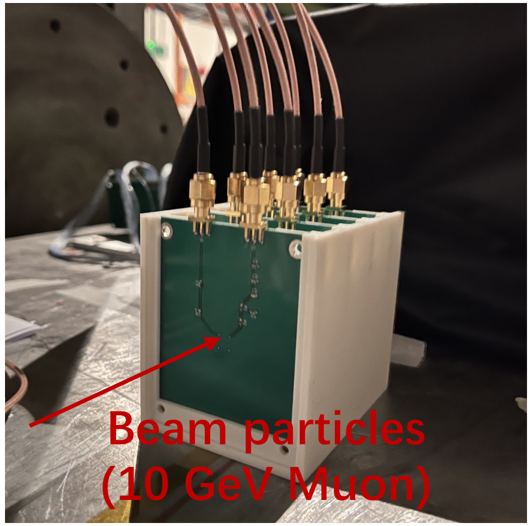
    (not at the same time unfortunately)
- Challenges
  - Increase density while keeping high light yield and transparency
  - Synthesizing large cm-scale glass tiles with good scintillation and optical properties

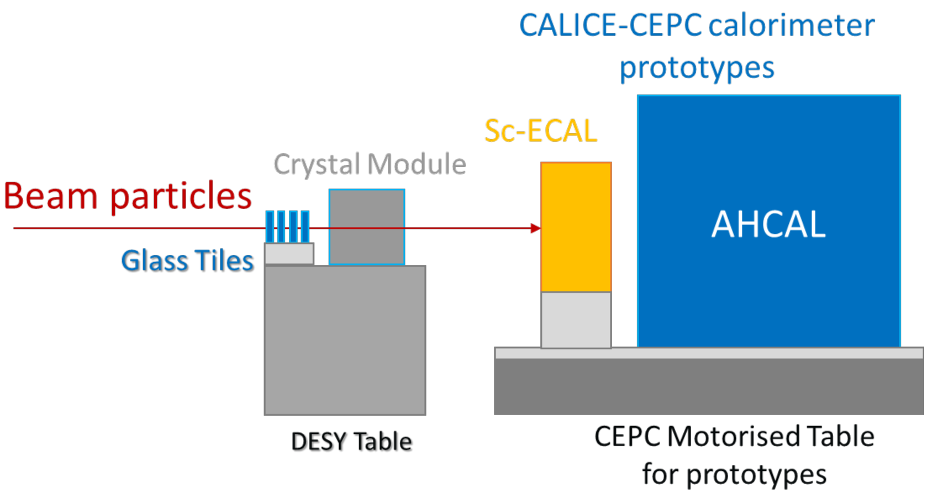
Glass scintillator HCAL

- **11 large glass tiles for the beam test**
  - Sample size $\sim 3\times 3\times 1\ \mathrm{cm}^3$.
  - Key target: glass MIP response.
- **Beam setup @ CERN T9**
  - 4 tiles with individual SiPM readout
  - 3 glass tiles and 1 plastic tile (reference)
  - Data acquisition using a 4-ch fast oscilloscope (5GS/s)

Glass tiles wrapped with Teflon and black tapes

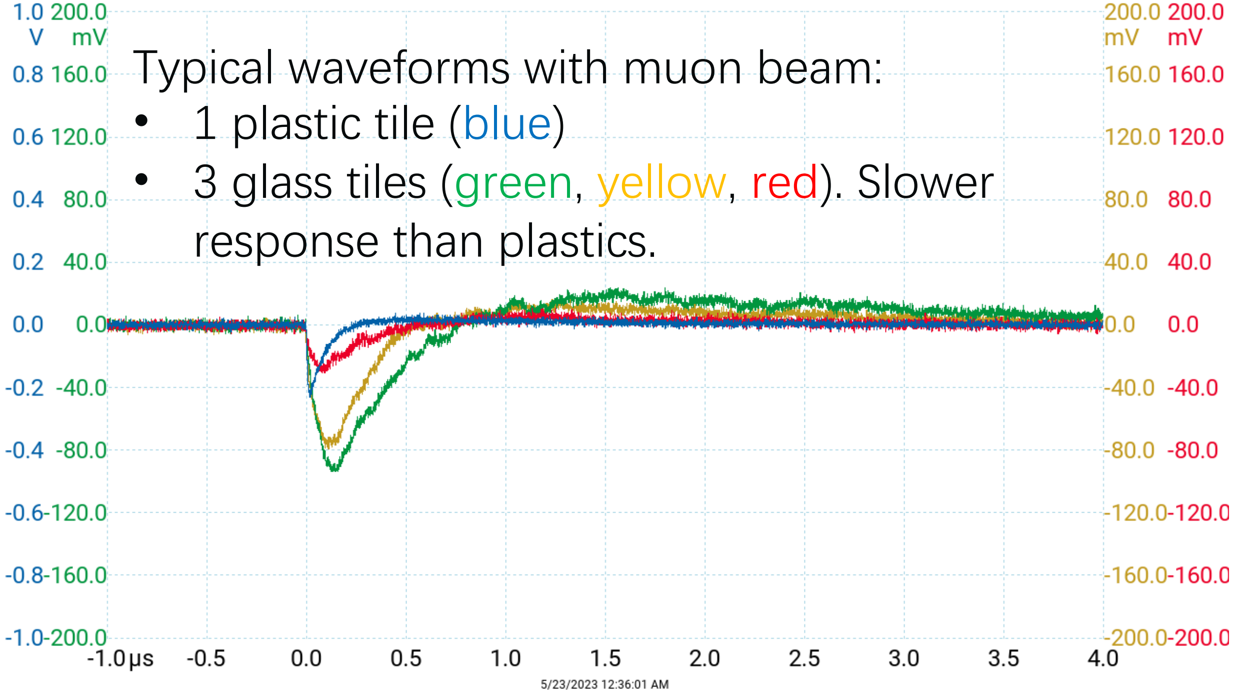


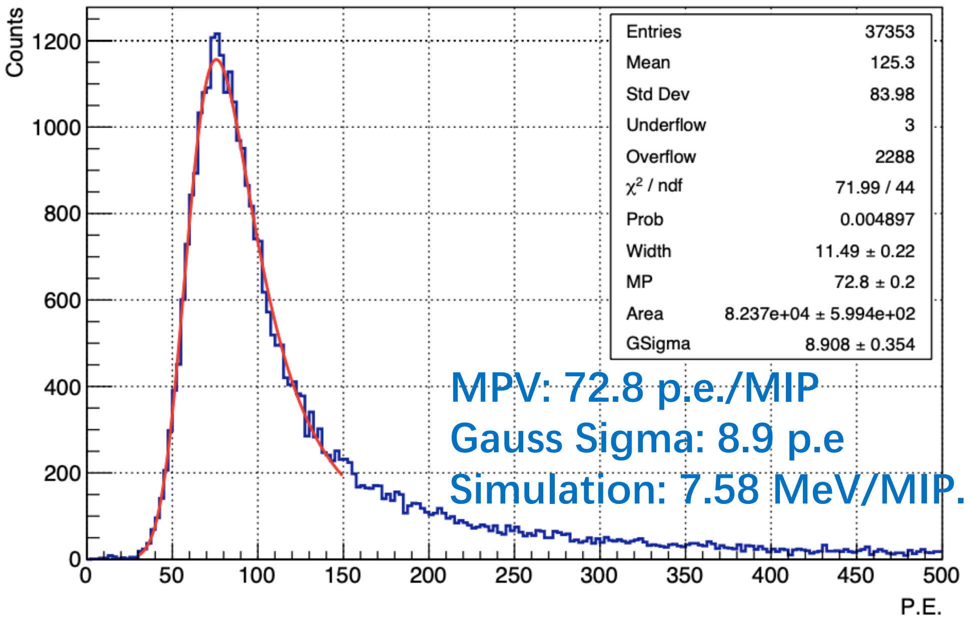




Glass scintillator HCAL

- **Beam test @ CERN: MIP response**
  - Target for samples: ~150 p.e. / MIP.
  - Observed: clear MIP signal in all 11 samples. Typical response: 15~74 p.e. / MIP.
  - **Looks promising! Will go further for the detector performance & construction.**





Glass scintillator tile #11: $30.5 \times 30.0 \times 8.7\ \mathrm{mm}^3$

Summary

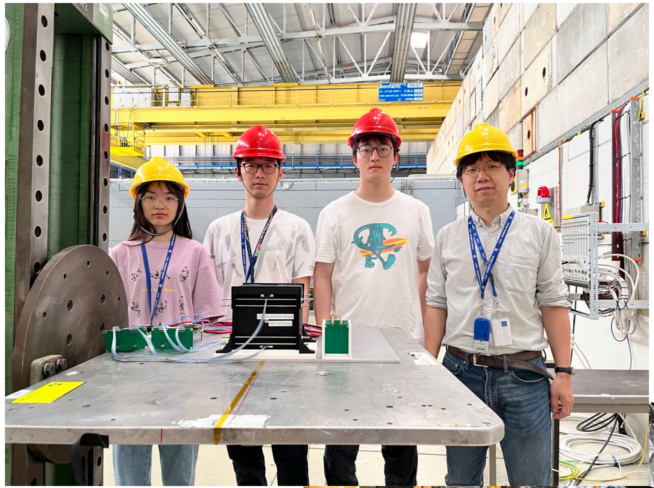
- **Enormous efforts in CEPC HG calorimeter**
  - 2 prototypes developed and tested.
  - Preliminary results look promising, detailed studies under way.

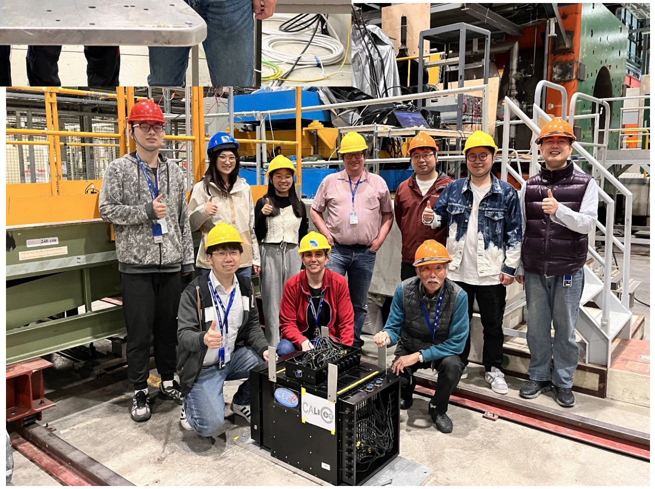
- **New ideas are always on the way:**
  - Homogeneous crystal ECAL for EM resolution and flavor.
    - Dedicated PFA reconstruction algorithms.
  - Glass scintillator HCAL for hadronic resolution.

- **Still large fields for studies:**
  - PID with HG calorimeter: GNN with hits?
  - New DL-based PFA?
  - Better sensitive materials?
  - More advanced electronic technics?

Acknowledgement

- **A big THANK YOU to CEPC calorimeter teams, CALICE and GS Collaboration!**
- **And GREAT test environment @ CERN & DESY !**





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University of Science and Technology of China 1958

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信州大学
SHINSHU UNIVERSITY

Jinggangshan University
井冈山大学

Beijing Glass Research Institute
北京玻璃研究院

China Building Materials Academy
中国建筑材料研究院

China Jiliang University
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Harbin Engineering University
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Harbin Institute of Technology
哈尔滨工业大学

Sichuan University
四川大学

Shanghai Institute of Ceramics，CAS
中国科学院上海硅酸盐研究所

Shanghai Institute of Optics and Fine Mechanics，
中国科学院上海光学精密机械研究所

CNNC Beijing Unclear Instrument Factory
中核（北京）核仪器有限责任公司

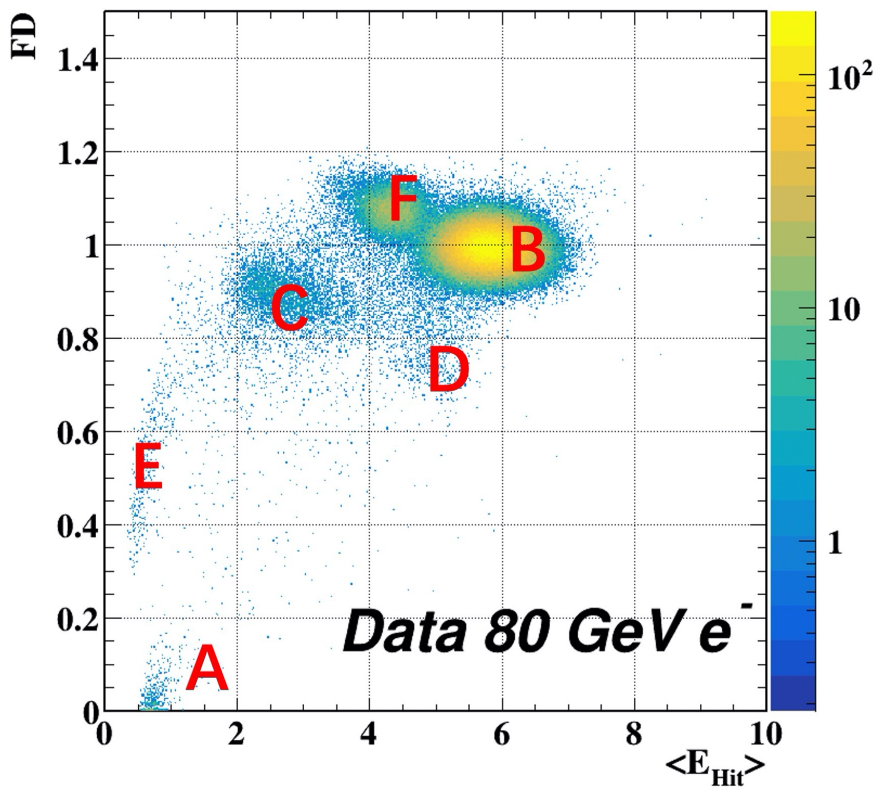
Glass Scintillator Collaboration
闪烁玻璃合作组

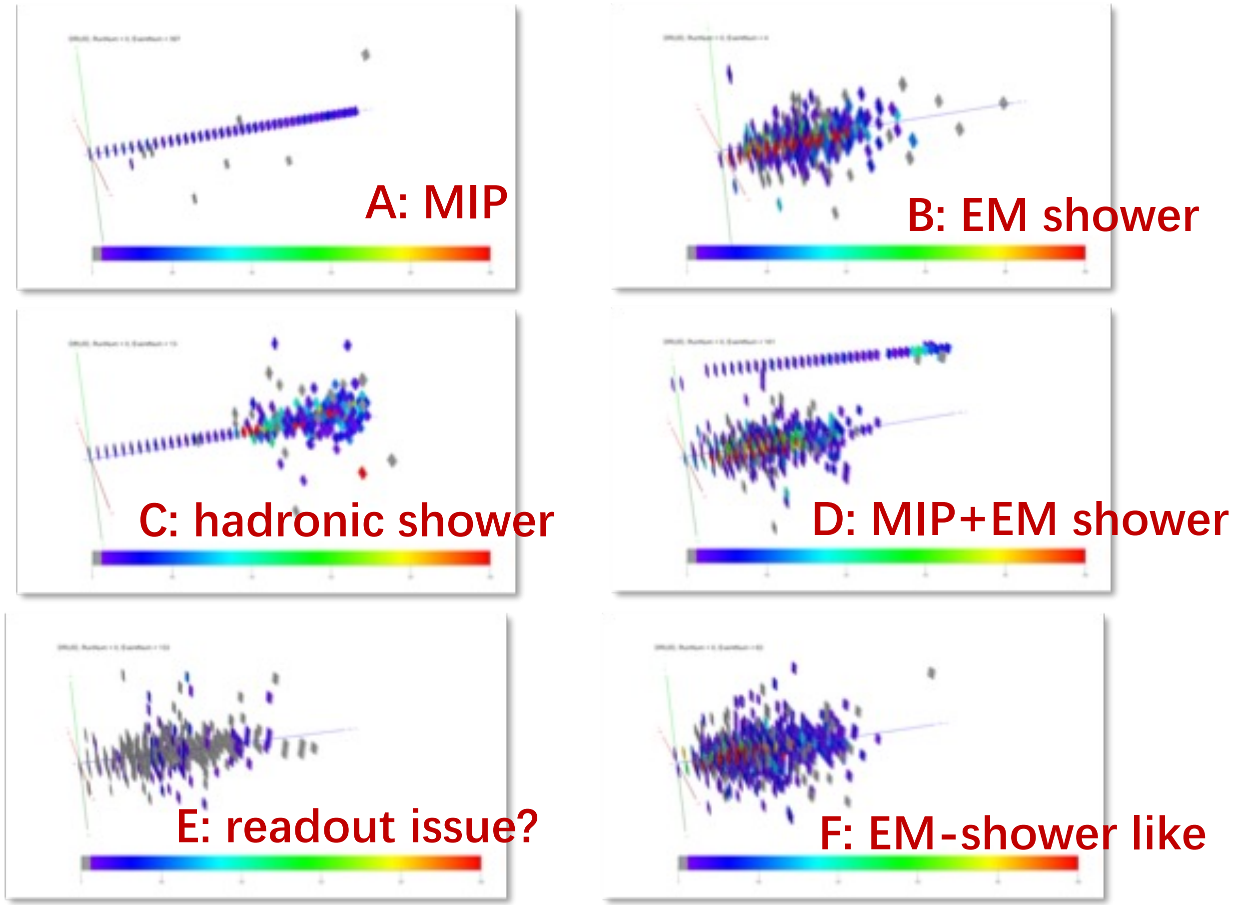
Backup

PID studies in HG AHCAL

- **Characteristics of fractal dimension (FD) with different beam particles**
  - Only possible with imaging calorimeter (high granularity)

Xin Xia (IHEP)



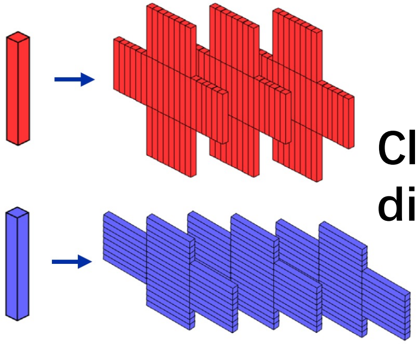


FD methodology based on
M. Ruan et al., Phys. Rev. Lett. **112**, 012001

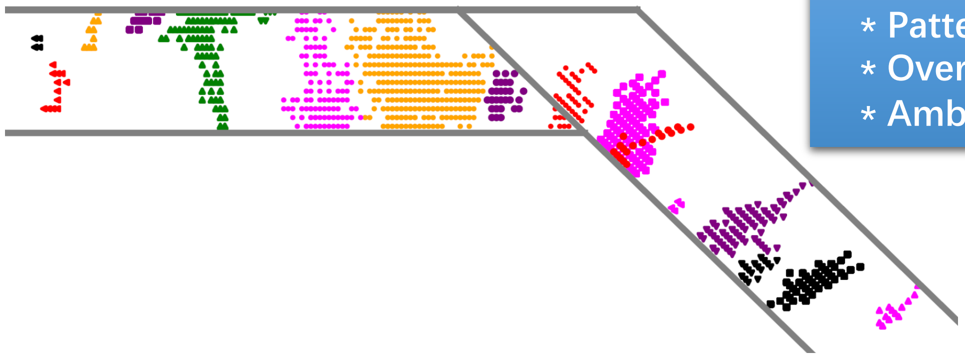
Crystal ECAL reconstruction

- **Global neighbor clustering for pre-processing.**

Crystal bars

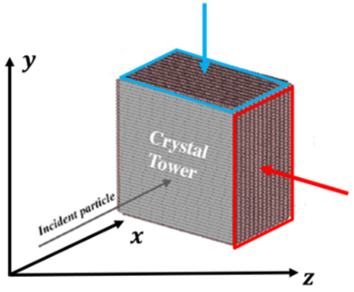


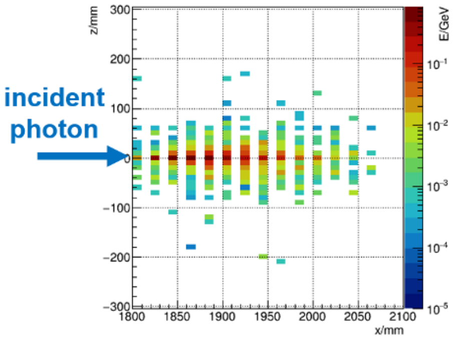
Cluster in 2 directions.



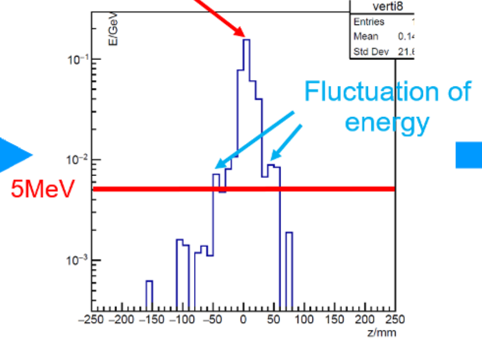
Software task:
✓ * Clustering
* Pattern recognition.
* Overlap: energy splitting.
* Ambiguity problem.

- **Shower recognition:**
  - Use the local maximum to simplify the pattern in homogeneous ECAL

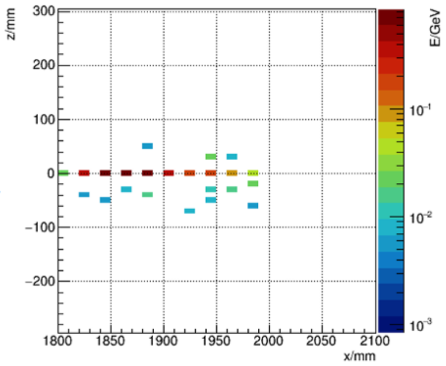




Energy deposits in crystals



Picking out local-max in each layer

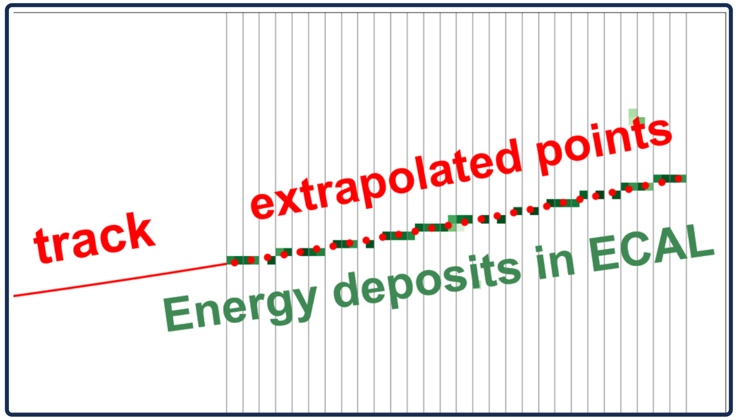


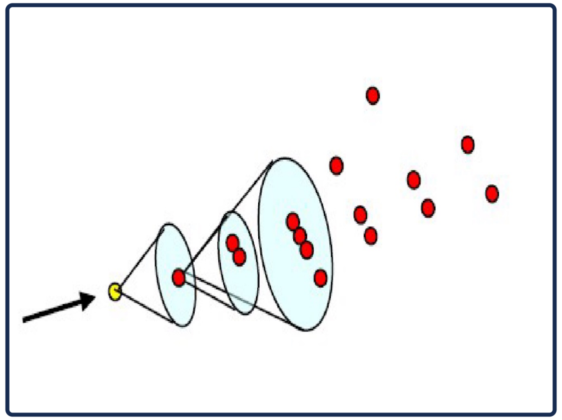
Local Maximum Distribution

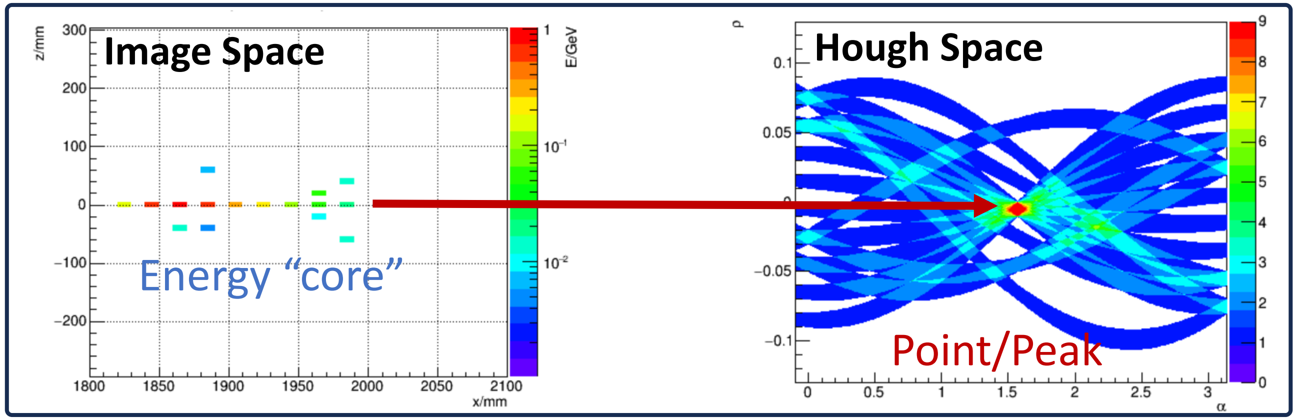
Crystal ECAL reconstruction

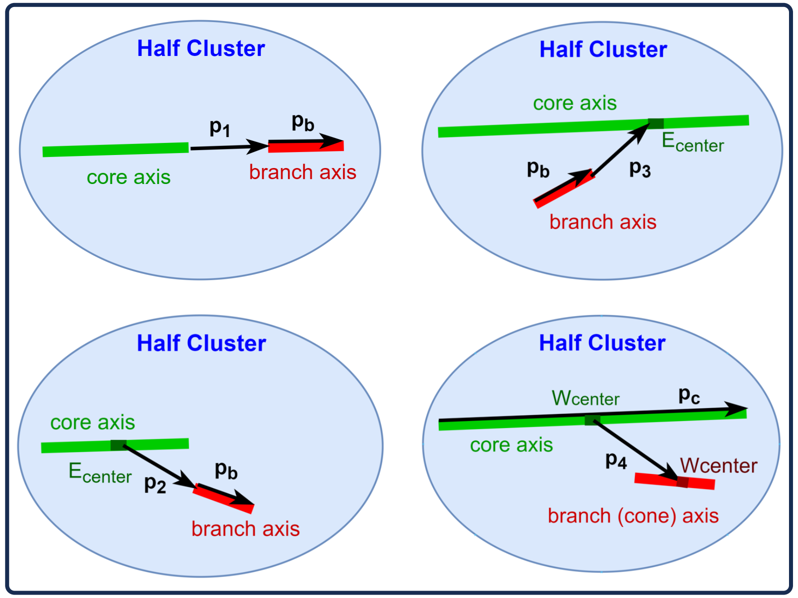
- **Shower recognition:**
  - 3 individual algorithms for different type: track-match, Hough, Cone-clustering.
  - A set of topological cluster merging.

Software task:
✓ * Clustering
✓ * Pattern recognition.
* Overlap: energy splitting.
* Ambiguity problem.





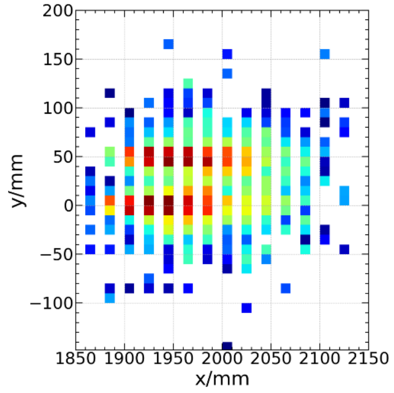


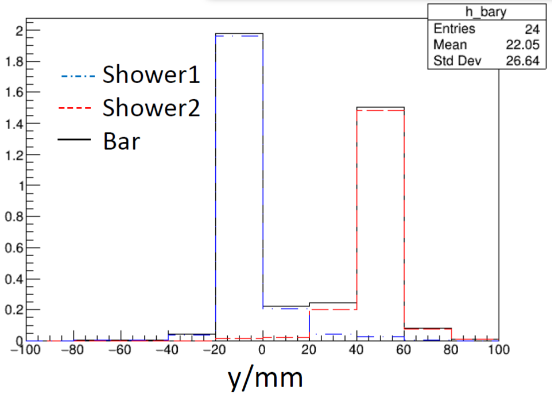


Crystal ECAL reconstruction

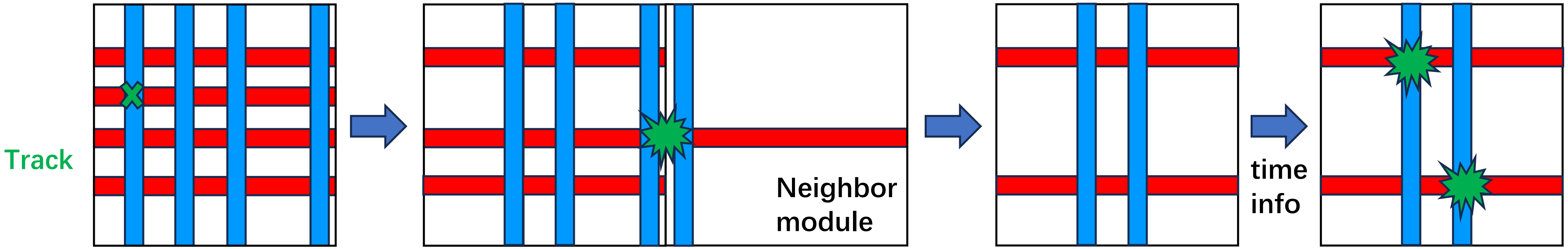
- **Splitting for the overlapped shower:**
  - Calculate the expected energy deposition from EM profile.
    - Expected energy : $E_{i\mu}^{exp} = E_{\mu}^{seed} \times f(|x_i - x_c|)$
    - Assigned weight: $w_{i\mu} = \frac{E_{i\mu}^{exp}}{\sum_{\mu} E_{i\mu}^{exp}}$

Software task:
- ✓ * Clustering
- ✓ * Pattern recognition.
- ✓ * Overlap: energy splitting.
- ✓ * Ambiguity problem.



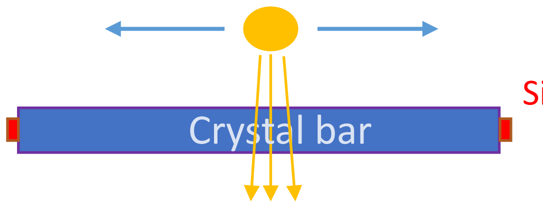


- **Ambiguity removal:**
  - Information from: track, neighbor tower, time.



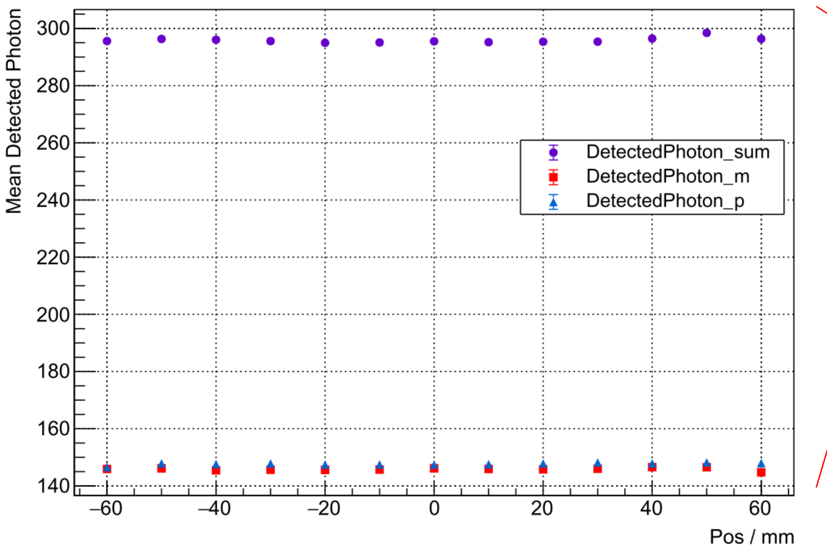
Crystal ECAL beam test

- **Uniformity scan of BGO crystal bars**
  - Batch test of SIC-CAS BGO crystal bars
    - 40 crystals with ESR and Al foil wrapping
    - Scan with Cs-137 radioactive source

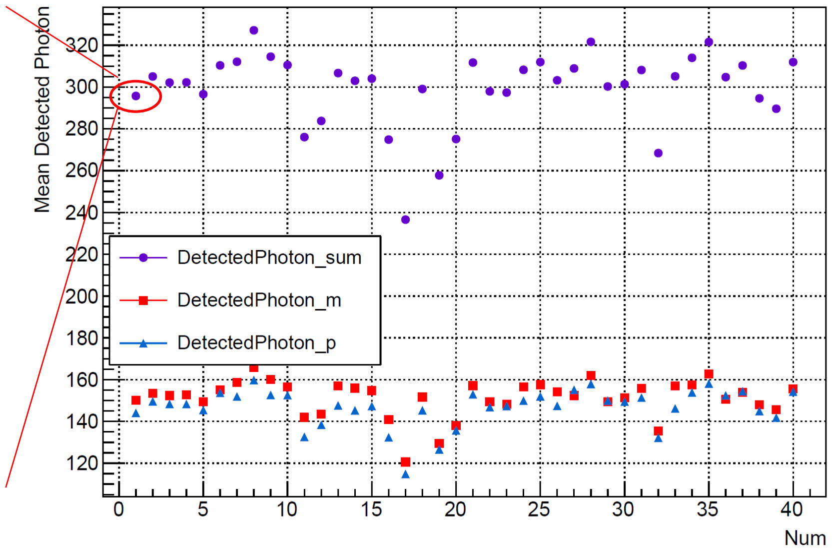


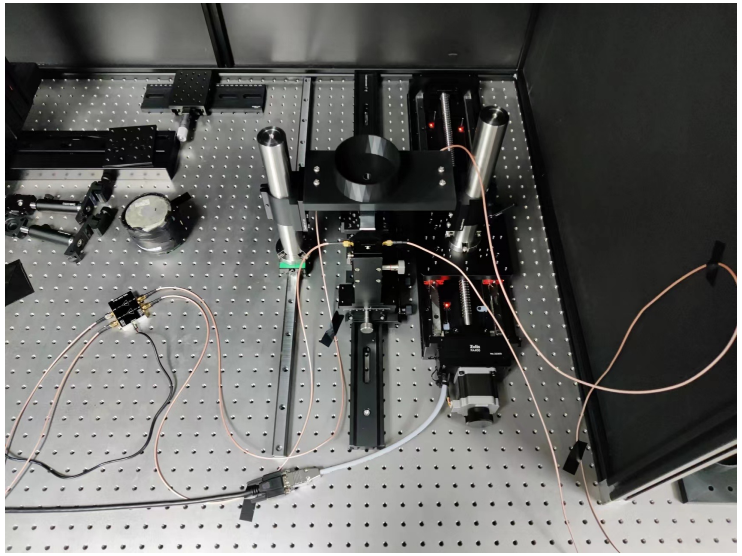
Zhikai Chen (USC)

Response uniformity along #1 BGO bar



Comparison of 40 crystal bars

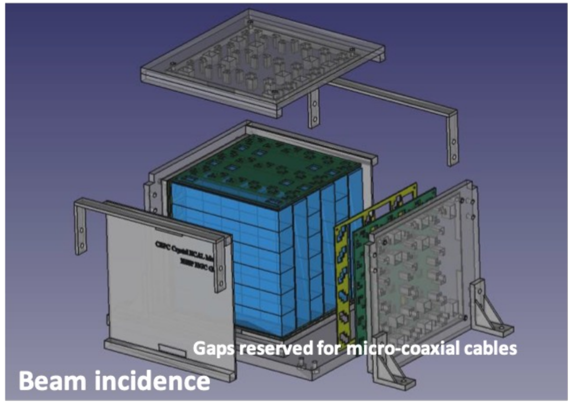


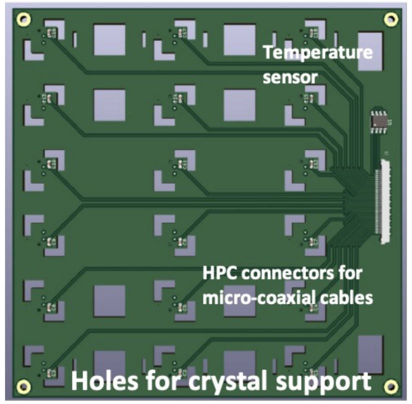


- Generally good uniformity along a single bar
- Response varies among bars, 36 crystals were selected for beamtests

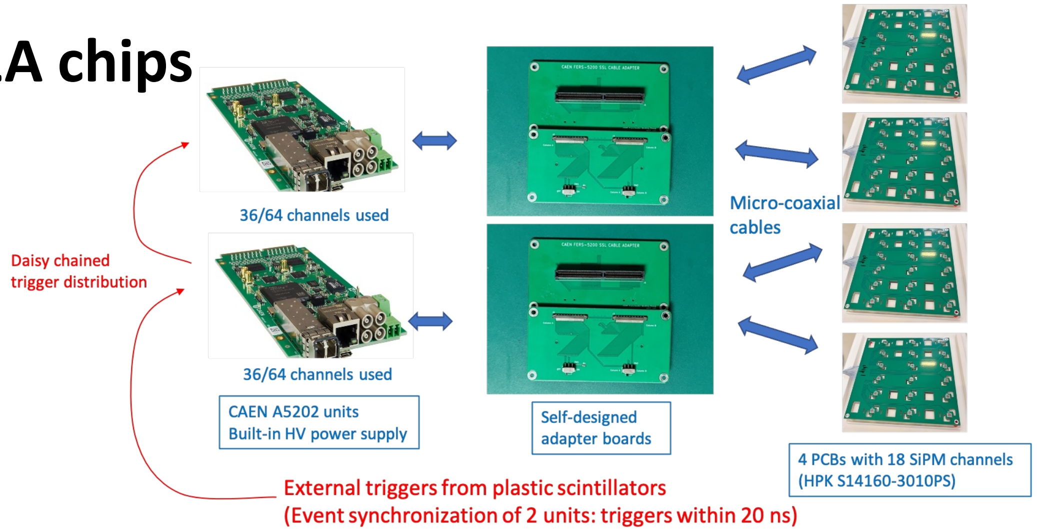
Homogeneous crystal ECAL: hardware

- **Mechanical and PCB design:**
  - Special mechanical support:
    - Light weight and enough strength
    - Support for crystal to decouple with PCB.
    - Assemble procedure.
  - Readout PCB:
    - HPC connectors for SiPM signals.
    - temperature monitor.





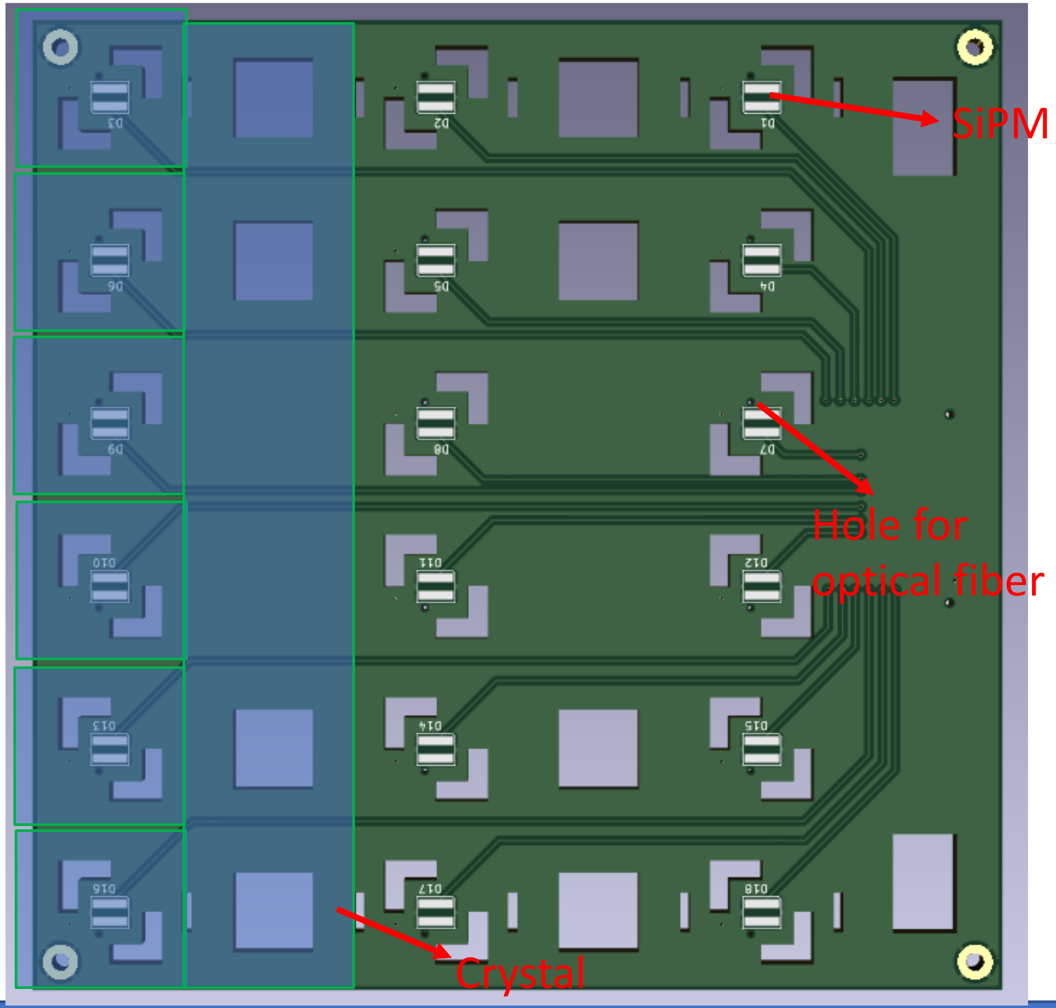
- **Electronics: CAEN A5202 units with Citiroc-1A chips**
  - High & low gain ADC
  - Timing: ToA, ToT
  - External trigger & self trigger supported.



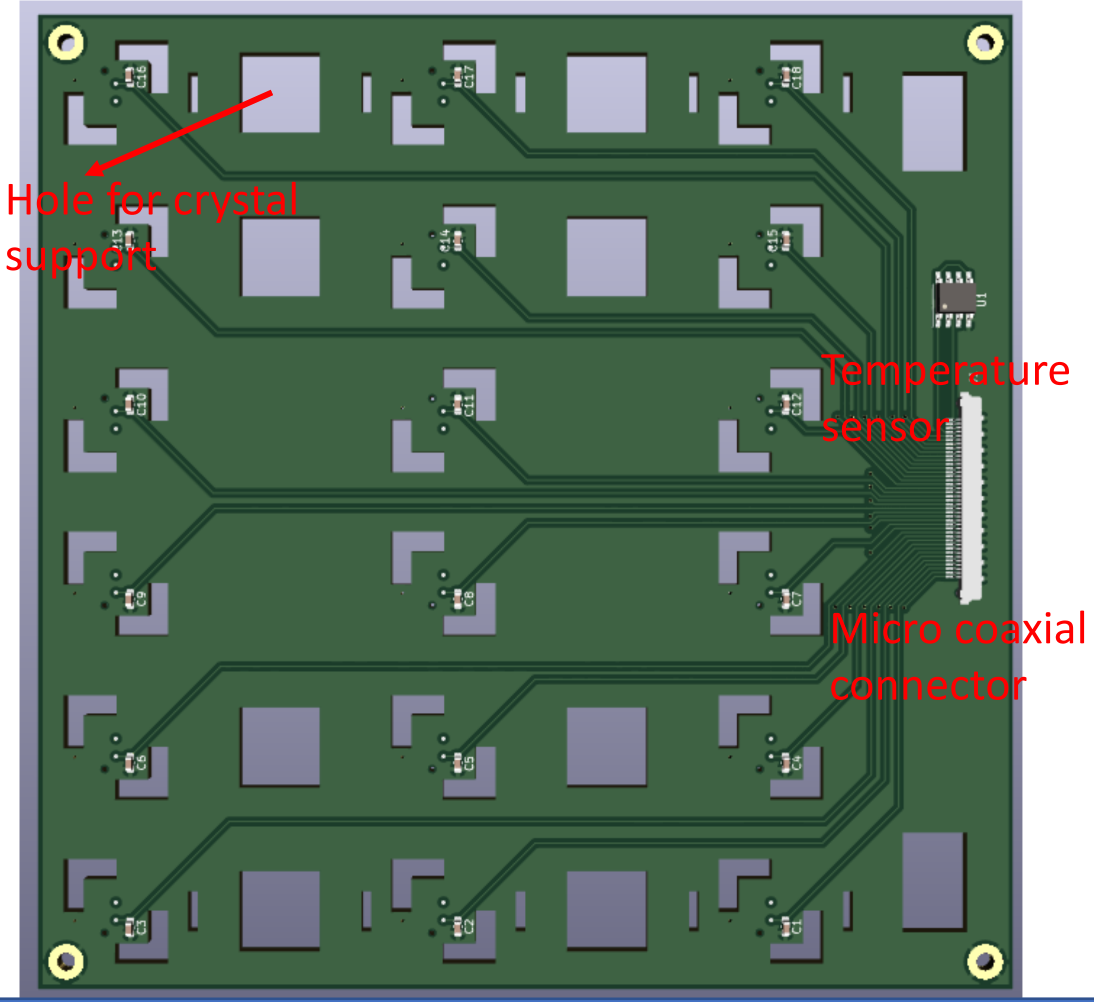
Crystal ECAL beam test

- **PCB layout**

Front side



Back side

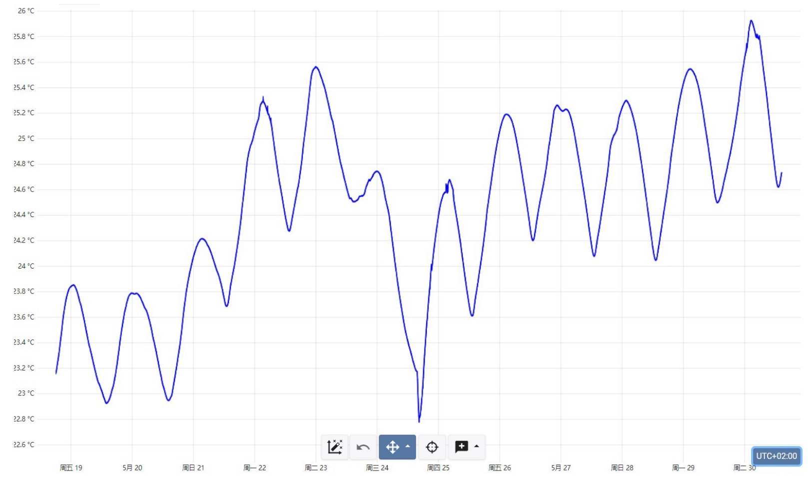


Crystal ECAL beam test

- **Data taking summary**
  - 10 GeV/c muon beam: MIP response
    - High/low gain, Hold-Delay time, shaping time scans
    - ~5.5M events acquired
  - 0.5~5 GeV/c electron beam: energy response
    - ~980k events acquired.
  - Other data
    - Pion- data for high fluence test
      - > 80% trigger loss at ~20 k events per beam spill
      - Performance of A5202 units: ~4-5 kHz under current beam status: dead time + event synchronization….
    - Self-trigger of "leaked particles" from upstream
      - Muon events can be clearly observed
    - Temperature monitoring data

- Verification of the system
- Parameter scans

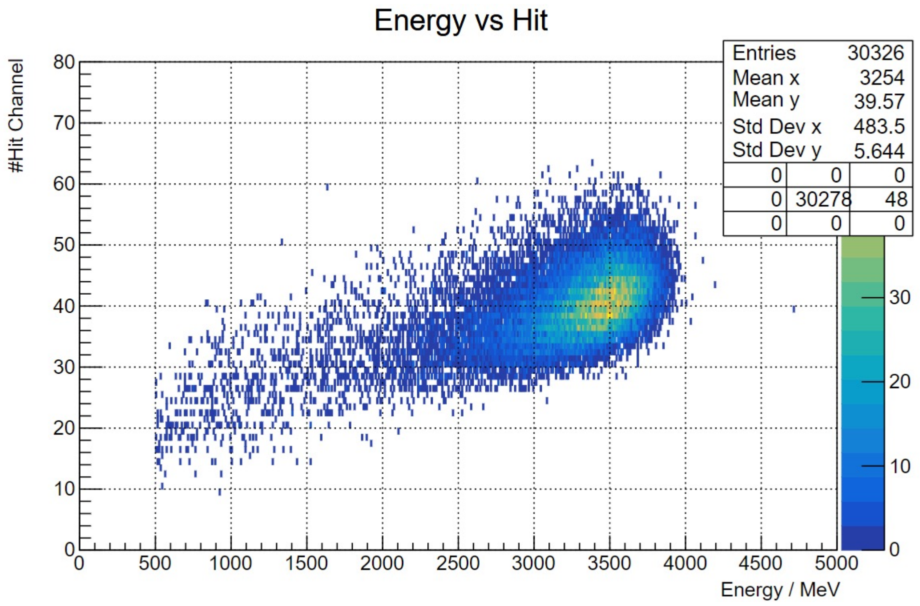
- Severe energy leakage is expected
- Preliminary reference for energy resolution

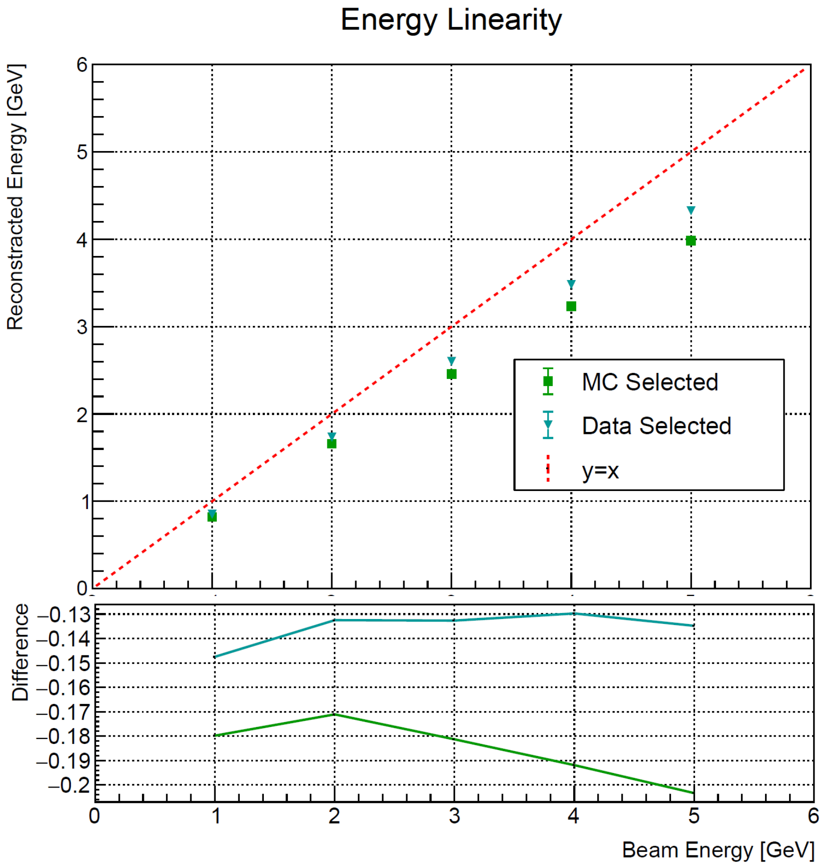


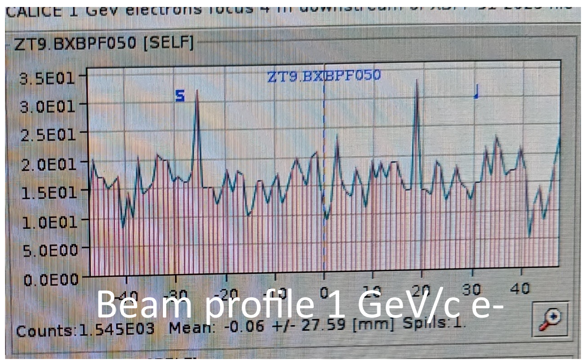
➢ ~2°C temperature change during the beamtest

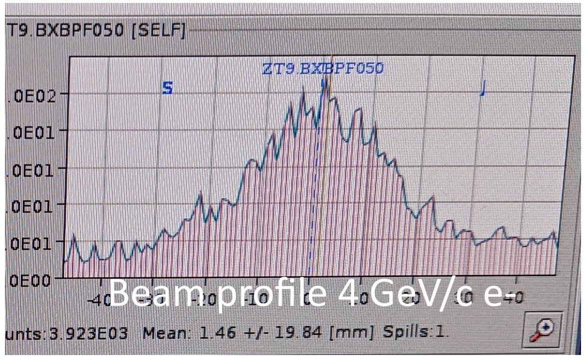
Crystal ECAL beam test

- **Electron data performance**
  - Energy leakage observed.

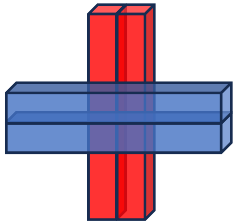








➢ Events hitting at the centred 2 bars of the first 2 layers



➢ Beam profile: severe changes in the spatial distribution of the beam spot

Crystal beam test

Digitization in simulation:

- Energy deposition
- Incident photons
- SiPM response
- Charge output
- Digitized energy

Edep

↓ Photon statistics (**Poisson distribution**)

Scintillation photons

↓ $Nfired = Npixel \times e^{-\frac{Nphoton}{Npixel}}$

Detected photons

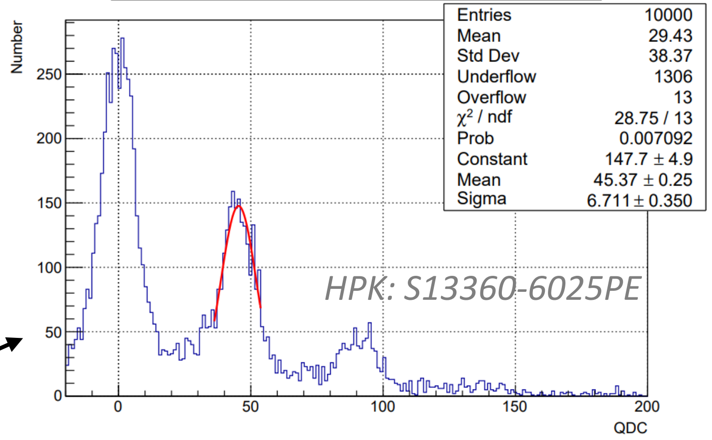
↓ SiPM gain and its error

Charge

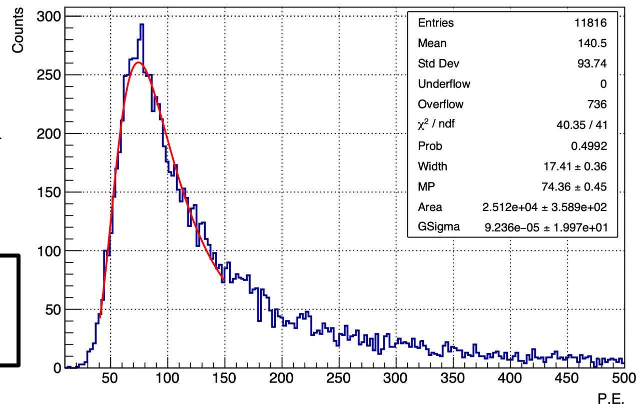
↓ MIP cut

Edigi

Single photon calibration



MIP response of glass tile

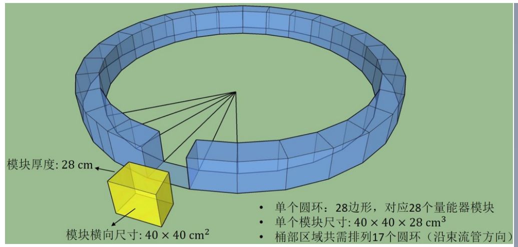


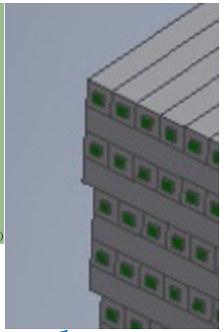
74p.e./MIP @ 7.4mm thick
100p.e./MIP @ 10mm thick

Cylindrical geometry design for CEPC ECAL

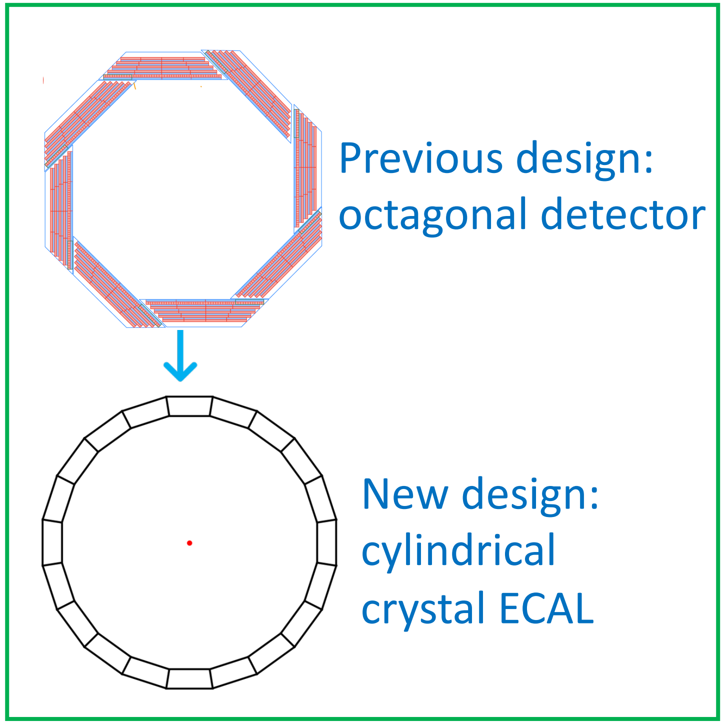
Quan Ji, Chang Shu (IHEP)

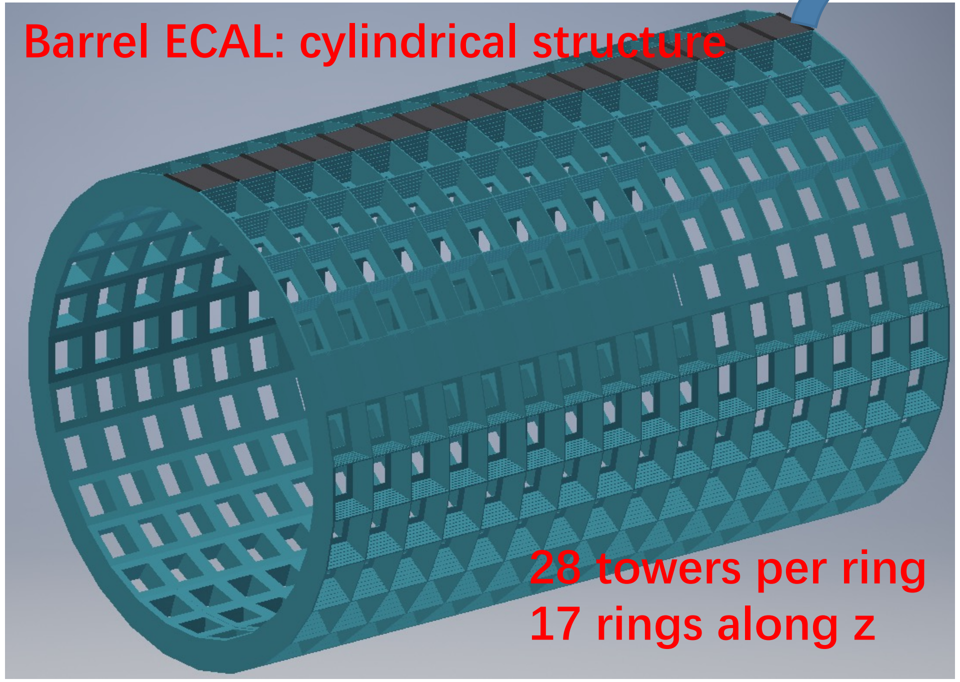
- **CEPC crystal ECAL barrel geometry design**
  - Finer segmentation of towers for better homogeneity
  - Decrease outer radius for lower cost of the outer detectors
  - 28 towers per ring, 17 rings along beam direction
  - ~25 radiation length: 28 layers

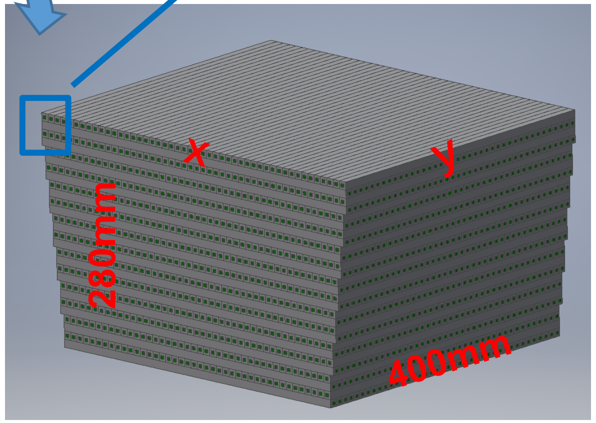




4 layers per "step" with the same transverse size





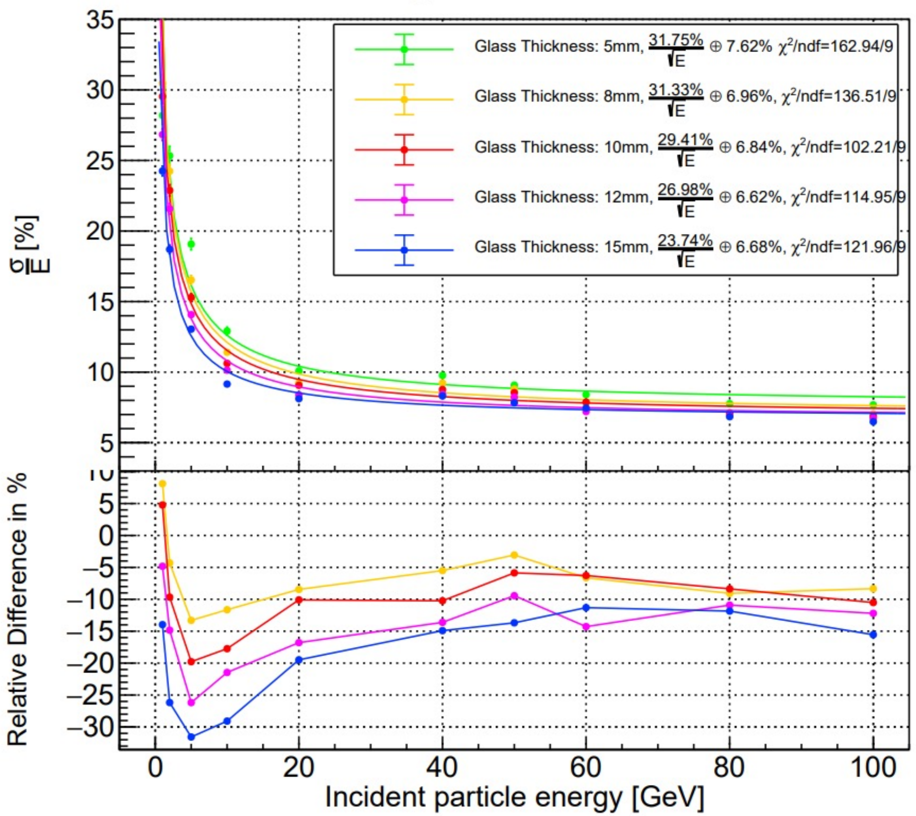


Key questions
- Space for electronics and cooling
- Assembly

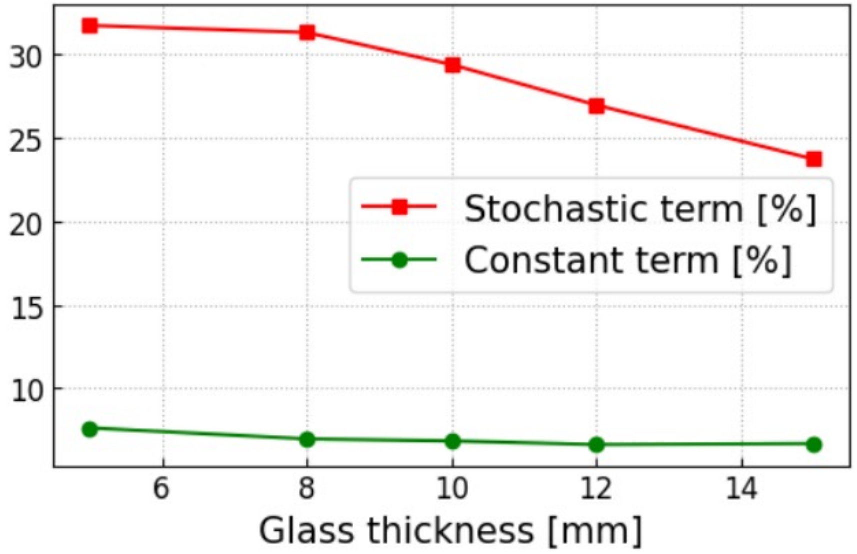
Glass scintillator HCAL

- **Simulation: Impact of glass thickness to energy resolution**

Energy resolution vs. glass thickness



- Varying glass scintillator thickness
  - Shower starting layer < 5 to mitigate leakage effects
- Stochastic and constant terms in energy resolution



➢ The hadronic energy resolution can be improved with thicker glass tiles, especially the stochastic term

➢ Glass thickness of 10 mm will be chosen for current design

Glass scintillator HCAL

- **Lab test for small glass samples**

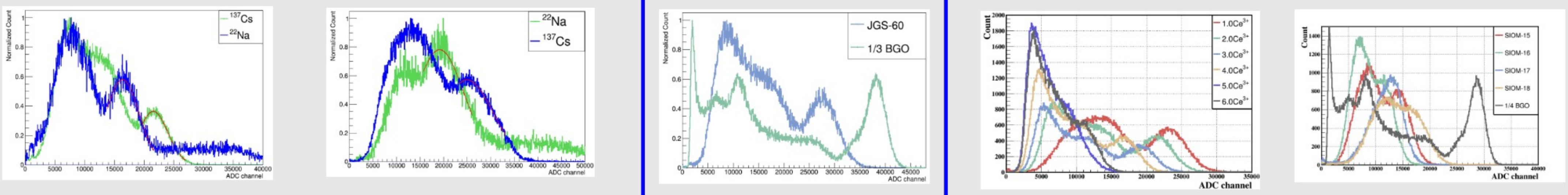
2021.11
- Density~4.5 g/cm³
- LY=802 ph/MeV
- ER=26.8%
- Decay=262 (18%) 1235 ns

2022.11
- Density~6.0 g/cm³
- LY>1000 ph/MeV
- ER=49.6%
- Decay=847 ns

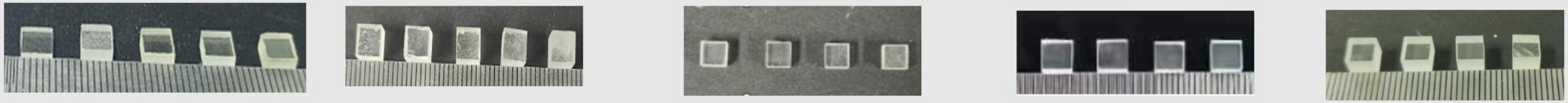
2023.02
- Density~6.0 g/cm³
- LY~1100 ph/MeV
- ER=24.4%
- Decay=460 ns

2023.04
- Density~5.8 g/cm³
- LY~1000 ph/MeV
- ER=26.8%
- Decay=1091 ns

2023.07
- Density~6.0 g/cm³
- LY~700 ph/MeV
- ER=32.3%
- Decay=382 ns



2021.11 | 2022.11 | 2023.02 | 2023.04 | 2023.07

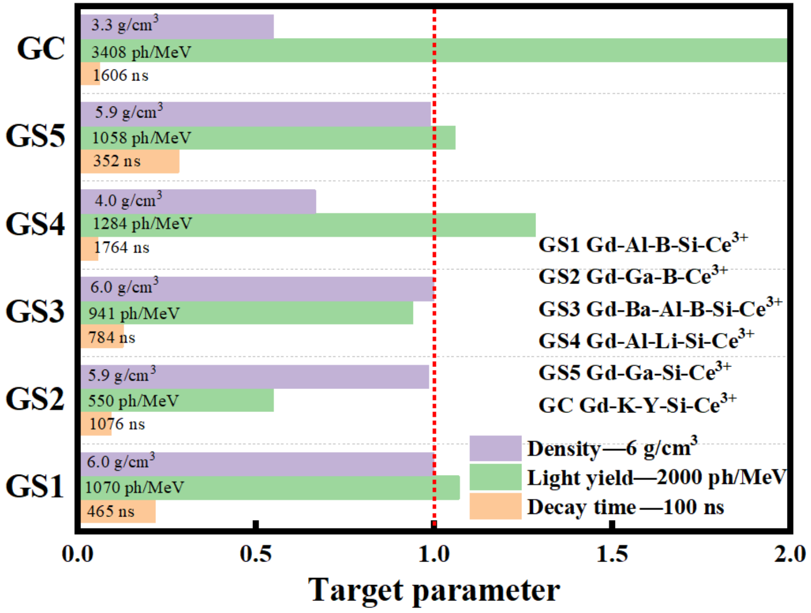


- ➢ There are 5 types of SG for the study, and focous on the GS1, the Borosilicate Glass for better performance;
- ➢ Finally, the Density~6.0 g/cm³, LY>1100 ph/MeV, ER=24.4%, could be accept to be the candidate for GS-HCAL
- ➢ But the Decay time =460 ns, still need to improve.

Glass scintillator HCAL

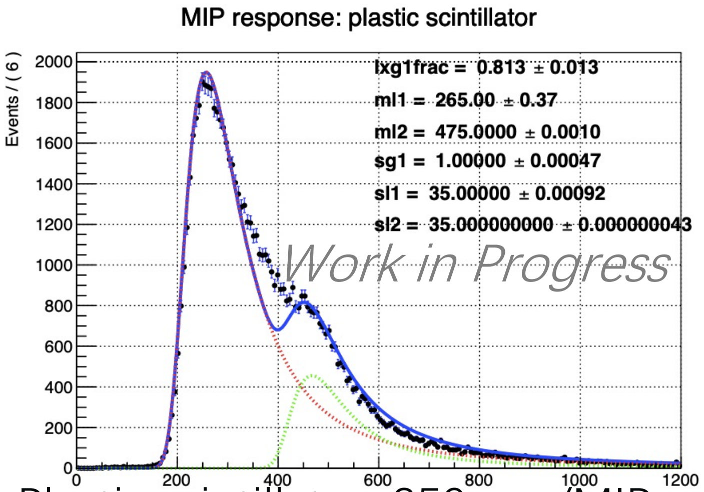
- **Beam test results of 11 glass tiles**

Index	Dimensions (mm)	Muon response (p.e./MIP)	Scale to 10mm thickness (p.e/MIP)
#1	33.5×27.6×5.1	15	29
#1 ESR		42	82
#2	30.2×29.5×6.6	35	53
#3	29.9×28.1×10.2	66	65
#3 ESR		69	68
#4	37.2×35.1×5.3	31	59
#5	40.0×35.1×4.2	38	91
#6	30.3×29.8×9.4	67	71
#7	34.8×34.8×7.5	60	80
#8	27.8×25.6×5.0	41	82
#9	34.6×34.7×7.5	69	92
#10	34.7×35.2×7.4	74	100
#11	30.5×30.0×8.7	73	84



Glass scintillator HCAL

- **Beam test analysis @ CERN T9**
  - Observed (unexpected) structures in energy spectrum. (Partially) due to incidence of two muons



Plastic scintillator: 259 p.e./MIP ($40\times40\times10$ mm^3)

SiPM-Tile waveforms: two muons in a short time window