



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

Beam test campaigns of a Crystal Calorimeter Prototype for future Higgs factories

CEPC Day

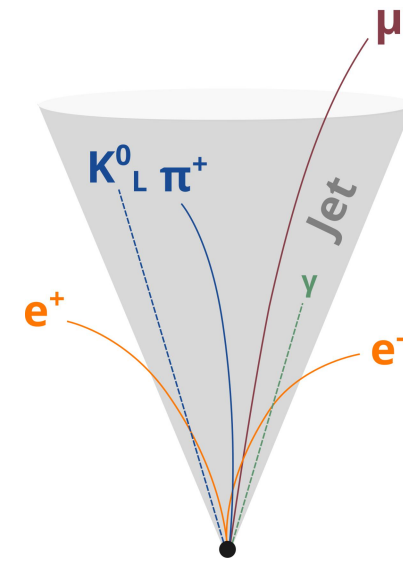
Jack Rolph, on behalf of the AGORA/CEPC Calorimetry Team

September 21, 2026

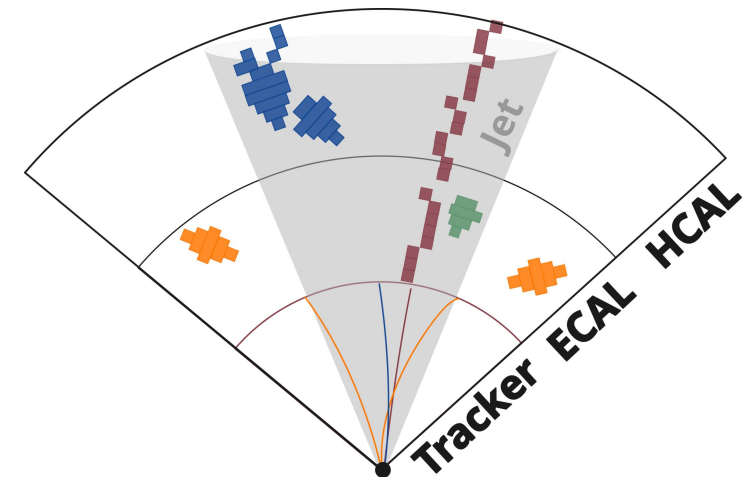




- Future electron positron colliders require **exceptional jet energy resolution (3-4%)**
- **Reason: hadronic final states are common in processes of interest;**
 - e.g. $HZ \rightarrow gg\bar{\nu}\nu$, dijet final state;
 - BMR required to be $<4\%$ for CEPC;
- **Problem:** Cannot be achieved with traditional calorimetry;
- **Solution: Particle Flow**
 - **Tracker:**
measures momentum of charged particles;
 - **Highly Granular Calorimeters:**
measures energy deposits by particles;
 - **Sophisticated Clustering Algorithms:**
associate energy deposits to tracks;
only neutral energy measured in calorimeters.



Particle Flow



Highly granular crystal ECAL developed for future Higgs factories:

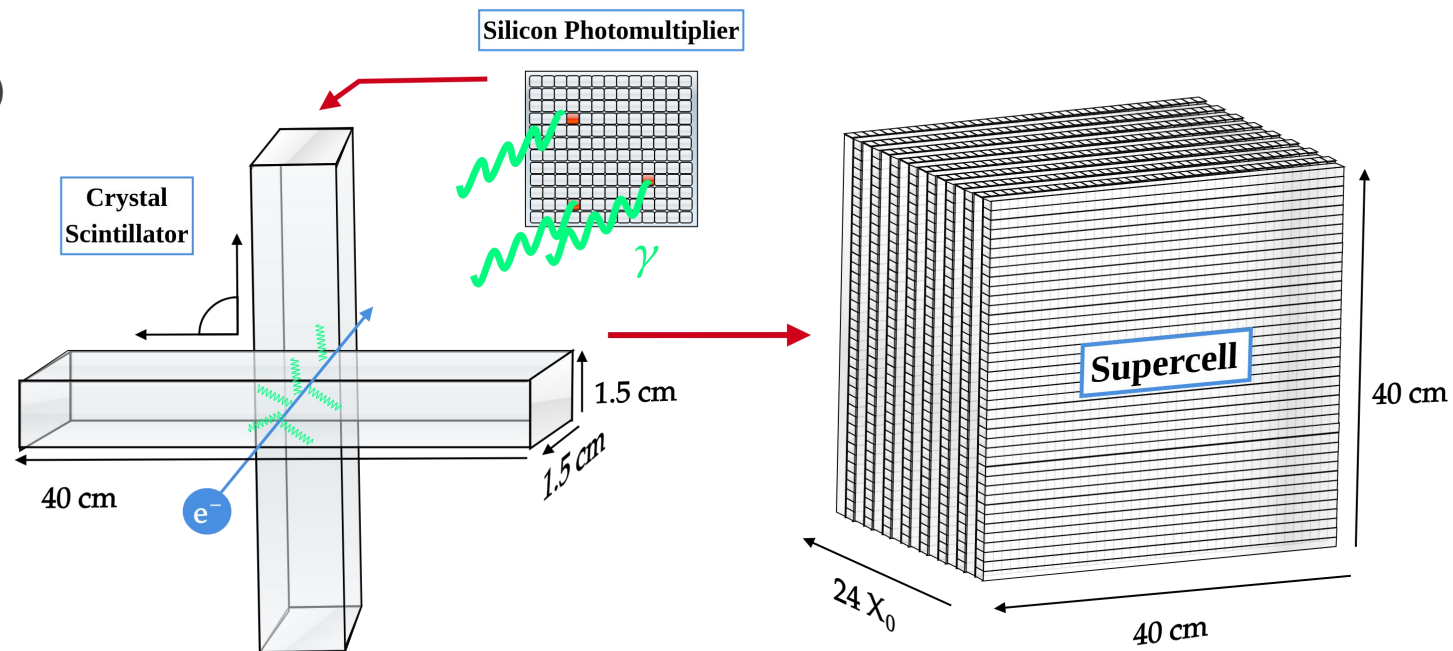
- scintillating crystal active material (BGO/BSO)
- 'cross-hatched' crystal bar design;
- 4D readout: spatial position and energy;

Best of both worlds:

- high granularity:
→ full module, $15 \times 15 \text{ mm}^2$;
- homogenous crystal design:
→ ensures good energy resolution;

Required to have:

- Sufficient granularity to separate closeby particles
→ evaluated in simulation using CyberPFA in CEPC TDR
- **energy resolution $< 2\%$**
→ **requires testbeam experiment**



Take Home Message:

2025 Testbeam experiments performed at CERN to evaluate calorimeter performance;

Goals:

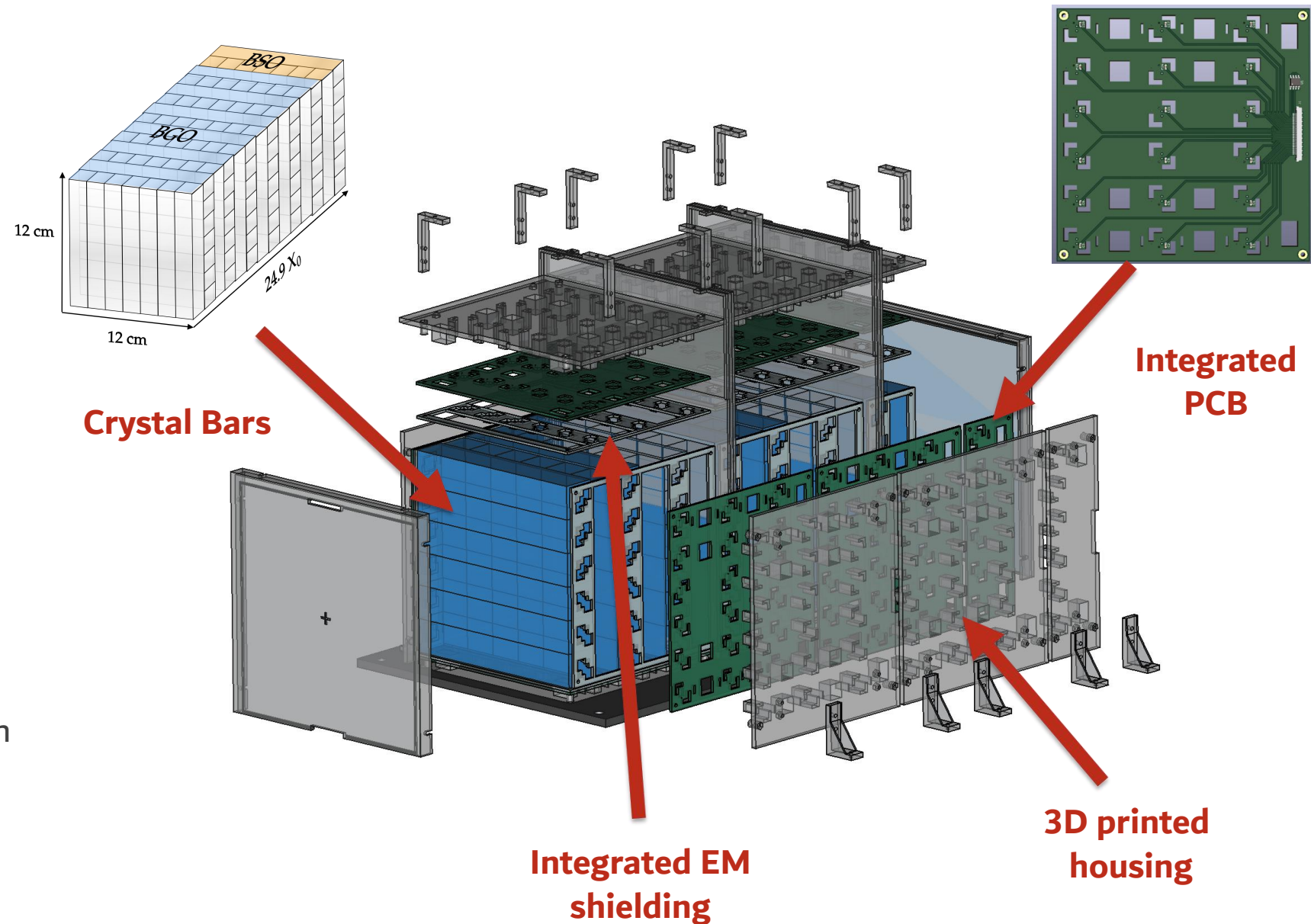
- minimize material budget;
- minimize stress on PCB;
- shield signal from EM interference;
- maximize scintillation light;

Calorimeter:

- $12 \times 2 \times 2 \text{ cm}^3$ BGO/BSO bars
- 20 GeV $e^- \rightarrow 93.6\%$ containment;
- granularity selected via simulation:
 - resolution
 - compact/cheaper;

Structure:

- lightweight 3D-printed resin housing;
- PCB and shield fully integrated with support structure
- crystal bars wrapped in ESR foil;



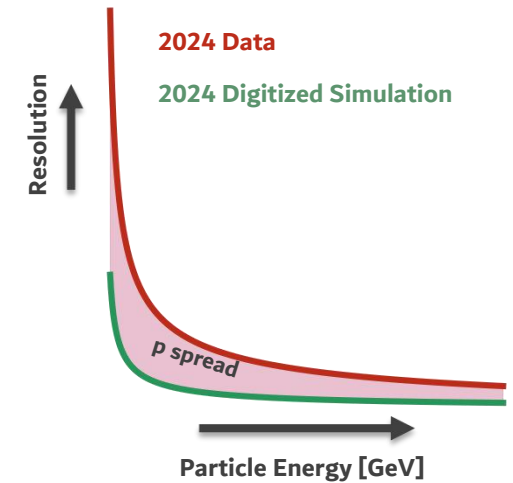
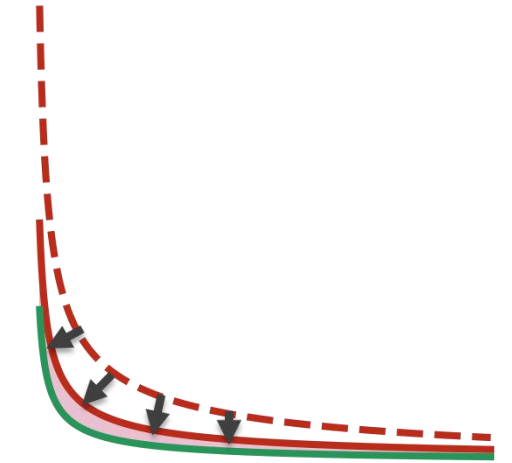
Goal: measure linearity/energy resolution of calorimeter

- **Problem:**
beam momentum spread of the same order as the resolution;
- **Reason:**
Testbeam in 2024 included upstream instrumentation:
 - SciFi trackers;
 - Cherenkov Detectors;
- **Solution:**
remove upstream instrumentation
 - reduce momentum spread;
 - measure resolution more accurately;

PS-T9 2024 (Before)



PS-T9 2025 (After)



MIP calibration

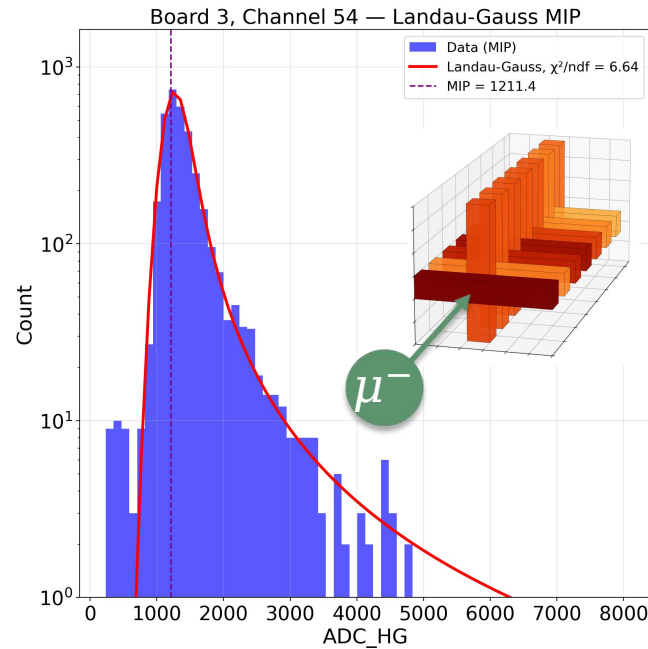
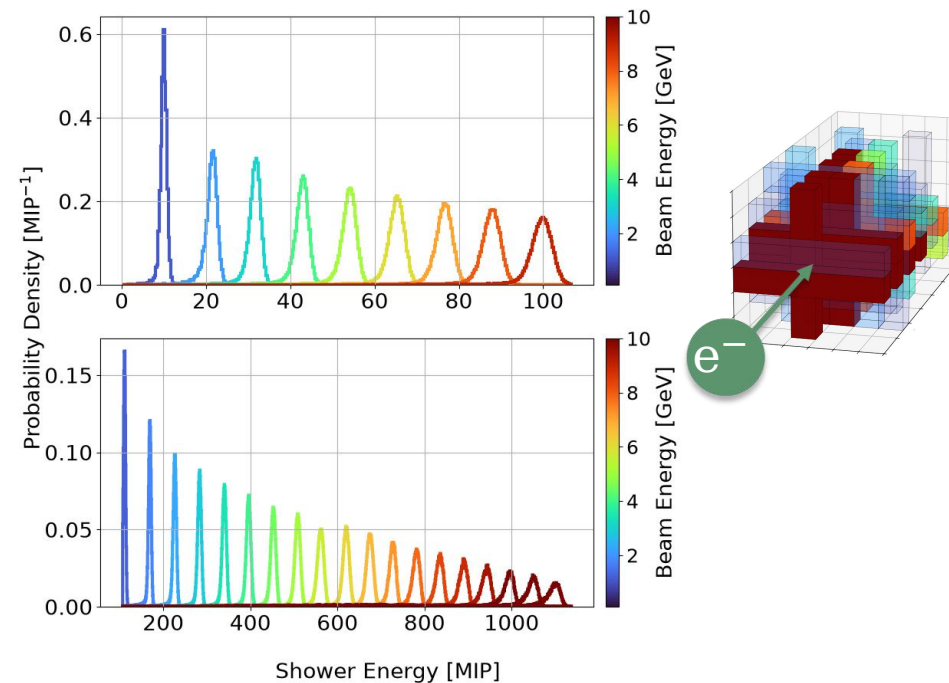
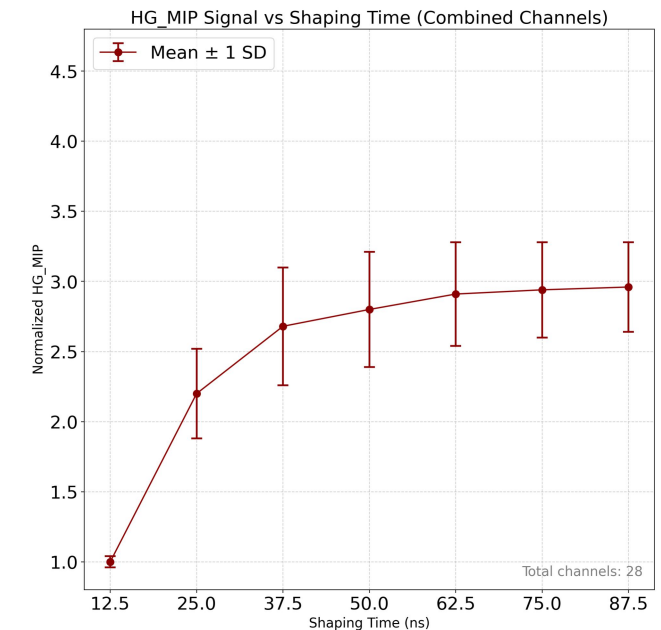
- Studied 5 positions on front face;
- μ^+/π^+ used for MIP calibration;
- Repeated through campaign;

Electron scans

- electrons from 0.1-10 GeV;
- 0.1 GeV steps below 1 GeV;
- 0.5 GeV steps above 1 GeV;
- collimation settings (± 3 / ± 1.5 mm);
- calorimeter inverted (i.e. BSO preshower/tailcatcher)

Systematics:

- ASIC shaping time (12.5-87.5 ns)
- SiPM overvoltage scan (+2V)
- Spill structure/pile-up studies from waveforms;



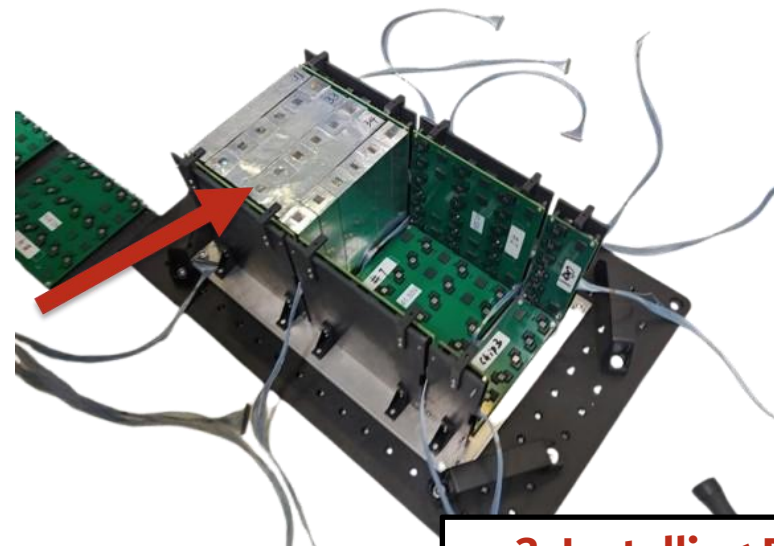
PCB with SiPMs

Baseplate

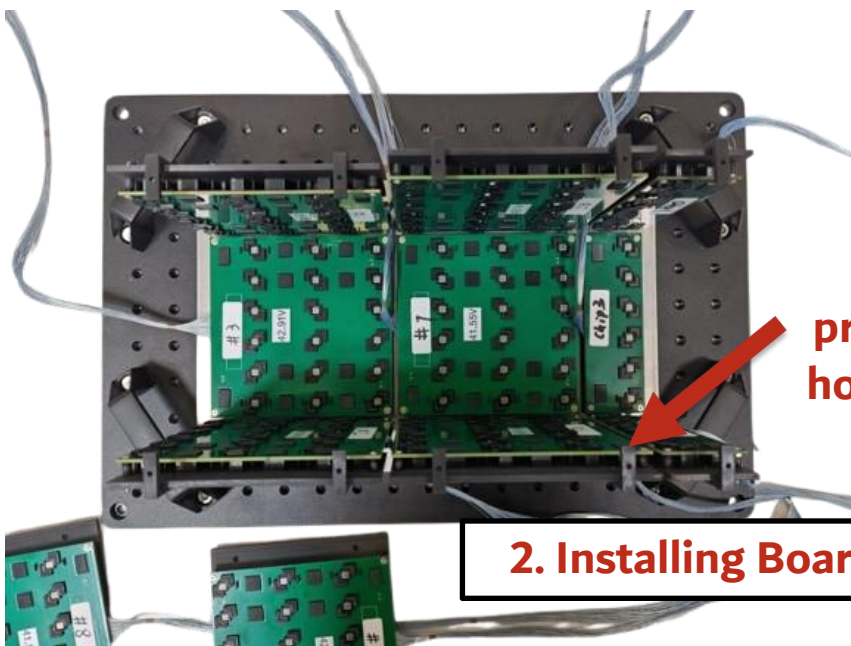


1. Pre-Assembly

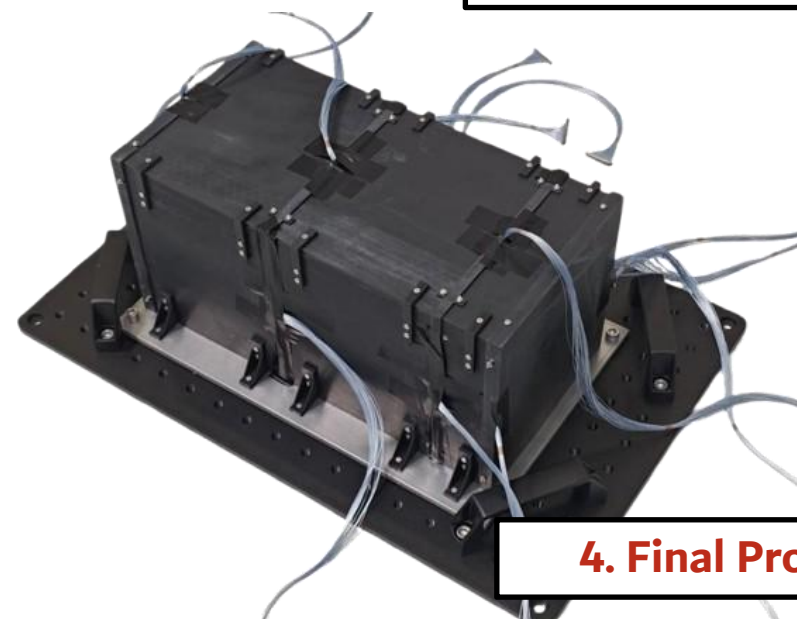
ESR-
Wrapped
Crystal
Bars



3. Installing Bars



2. Installing Boards



4. Final Product

Main Setup (Top View)

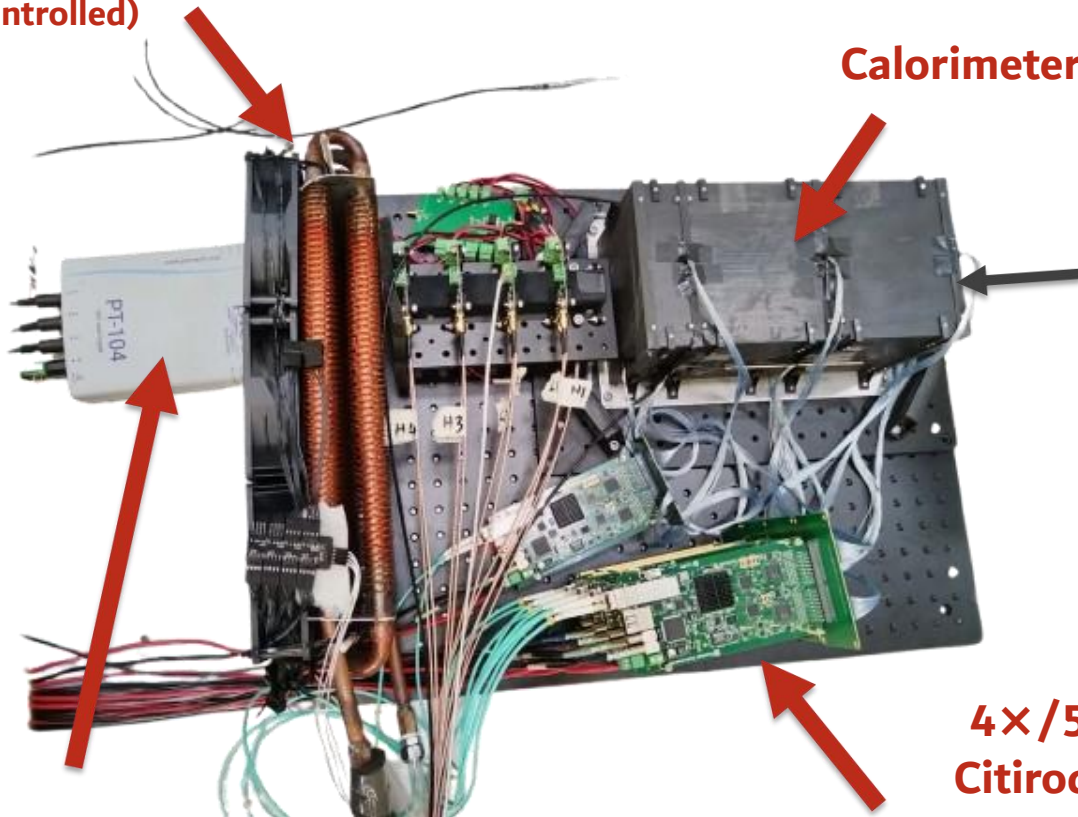
**Cooling
Radiator**
($15 \pm 0.5^\circ\text{C}$,
controlled)

Calorimeter

Beam
(aligned to
calorimeter
with Bosch
laser)

**4x/5x CAEN A5202 +
Citiroc 64-channel front-
end readout board**

**PT-104
Temperature
Logger**



Trigger Setup (Side View)

Beam Pipe



**Two $1 \times 1 \times 1 \text{ cm}^3$
($6 \times 6 \times 1 \text{ cm}^3$)
Gls. Sc. Trigger Cubes**



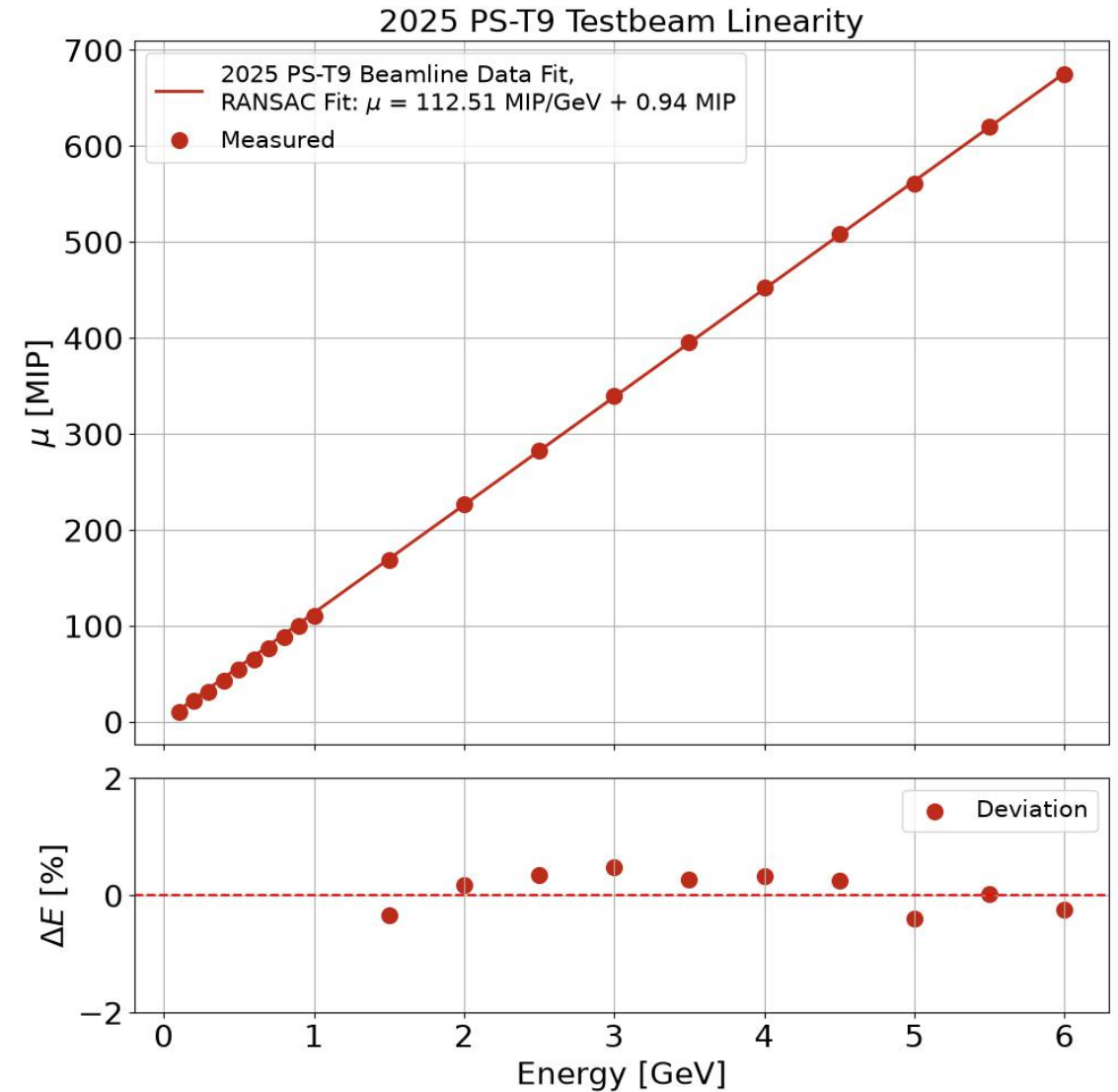


Goal: measure energy linearity of calorimeter

- linearity measured from 0.1-6 GeV
- **Calorimeter linear within ~1% above 1 GeV;**
- **Below 1 GeV, noise threshold effect/albedo leakage causes deviation from linearity.**
- Linearity recoverable via shower-shape based leakage correction;

Take Home Message:

HG Crystal Calorimeter linear within 1%

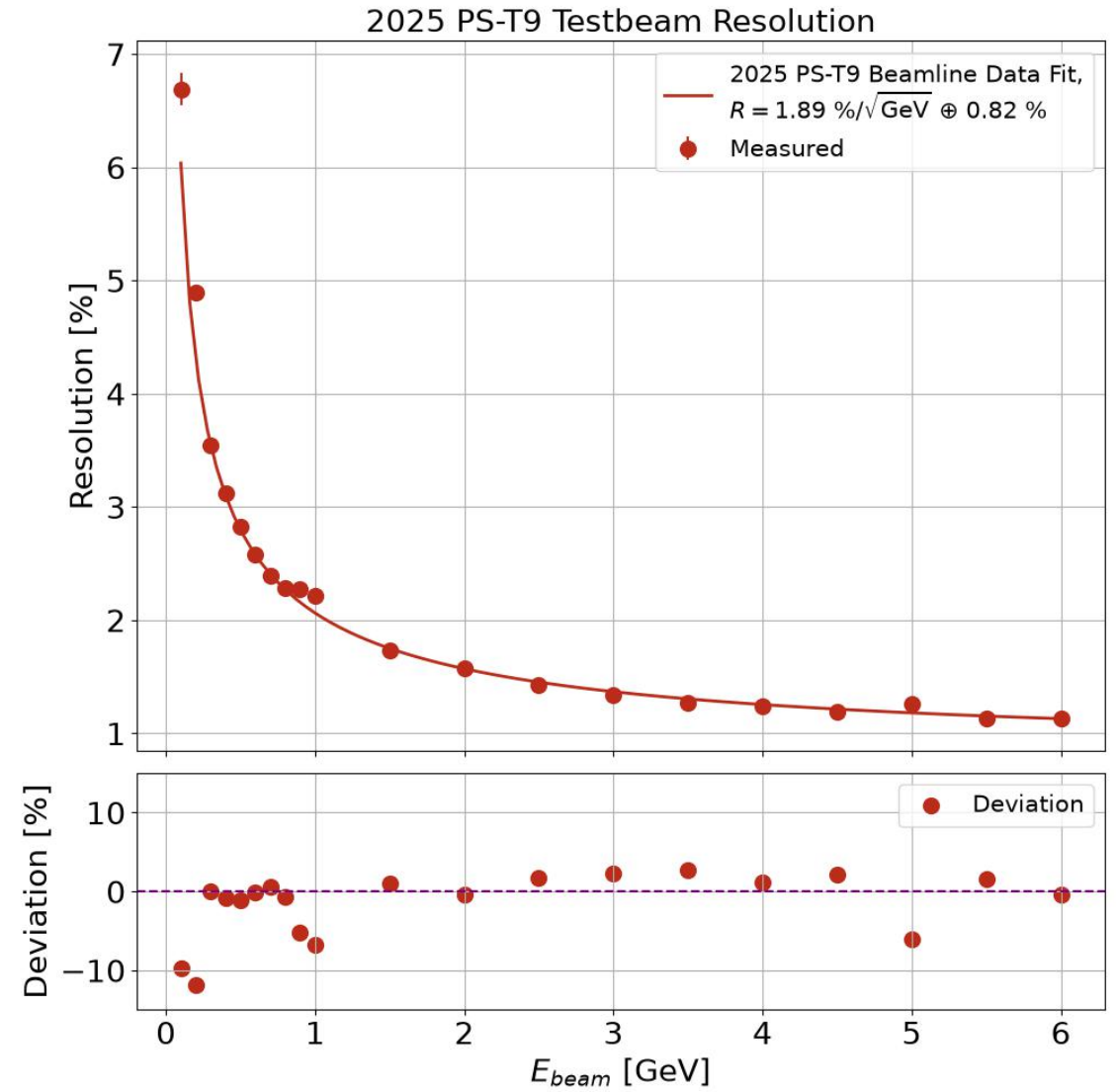


Goal: measure energy resolution of calorimeter

- resolution measured from 0.1-6 GeV
- **resolution better than target 2% including beam momentum spread**;
- **stochastic resolution term reduced by ~30% from 2024 due to reduced beam momentum spread**;
- momentum spread must be modelled to measure resolution;

Take Home Message:

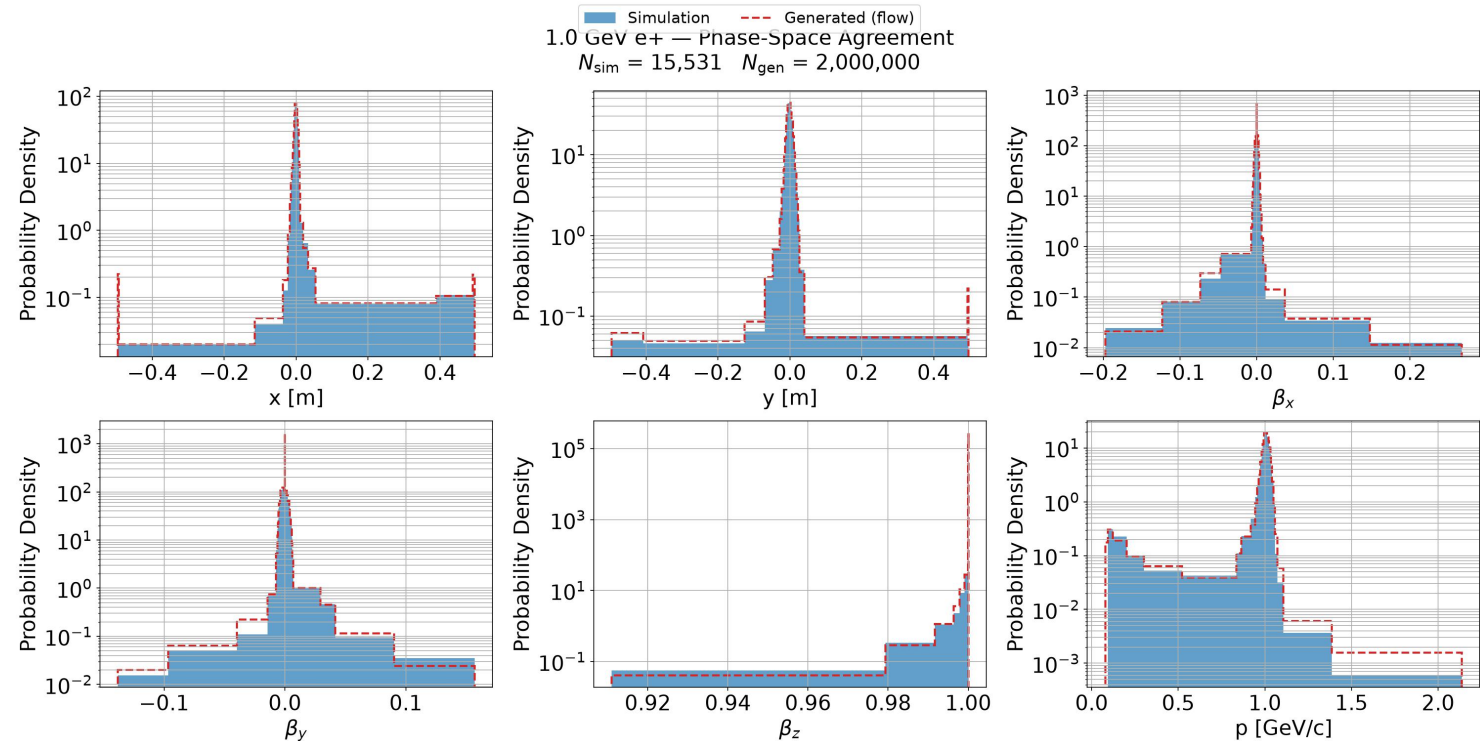
HG Crystal Calorimeter achieves the CEPC TDR resolution target





Goal: resample available beamline simulation;

- CERN experts provide simulations of beam particles':
 - spatial distribution;
 - momentum distribution;
- **Problem:**
 - small number of statistics;
 - long simulation time;
- **Solution:**
 - conditional normalizing flow;
 - median reduced χ^2 of 4.0 over all particles;
 - 33 μs per sample
 - ONNX allows deployment in Geant4



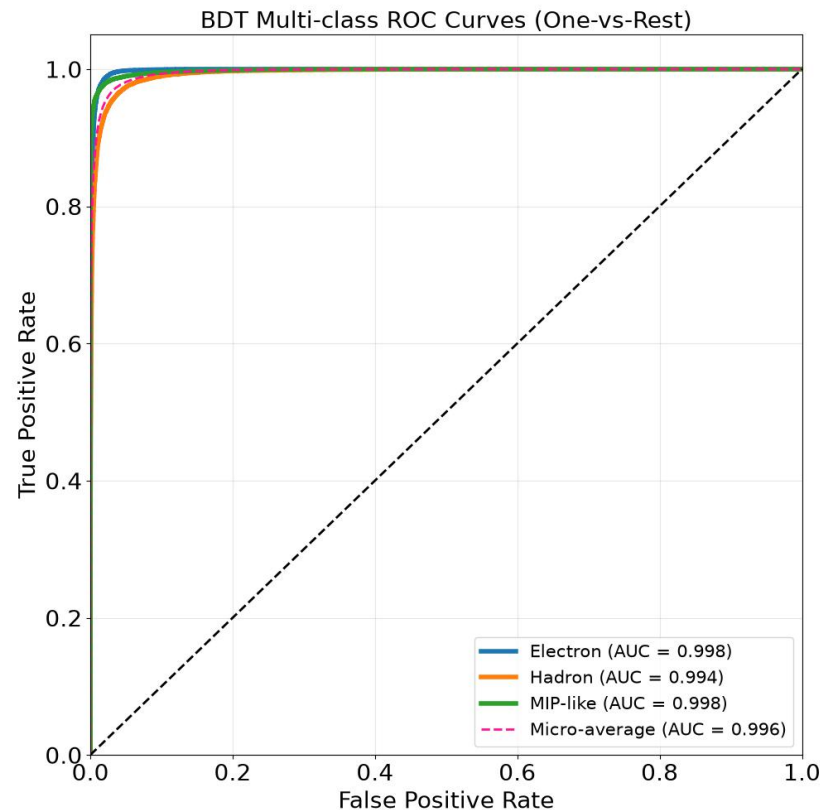
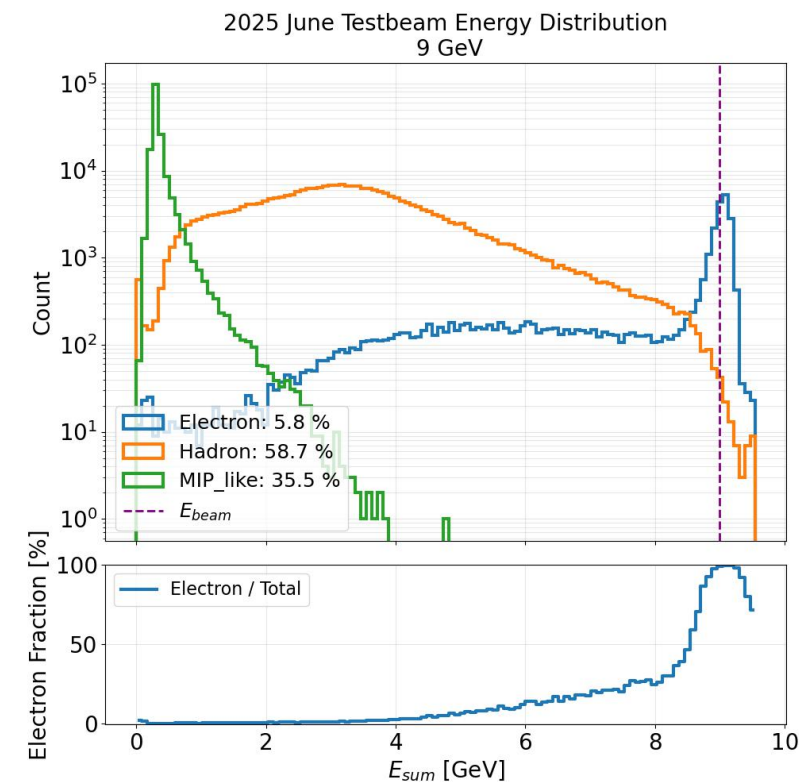
Take Home Message:

Fast, accurate beamline simulation integrated with Geant4



Goal: use calorimeter to determine event type from energy distribution in calorimeter

- No Cherenkov detector/tracker → calorimeter must select particles;
- Boosted decision tree trained on simulation to classify:
 - electron;
 - showering hadron-like;
 - MIP-like;
- Event level information used:
 - centre-of-gravity (CoG);
 - mean distance to CoG;
 - fraction of energy deposited per layer;



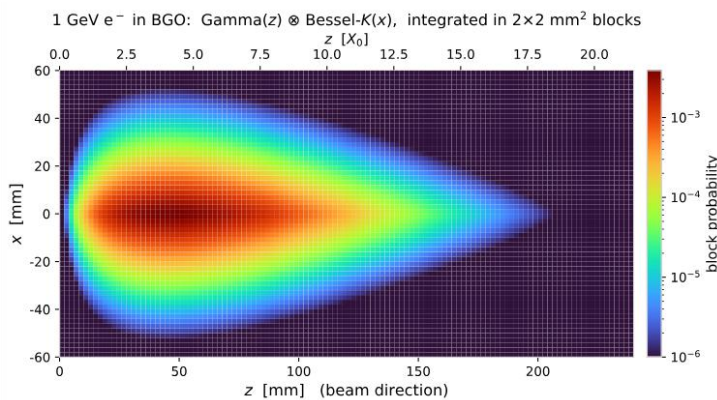
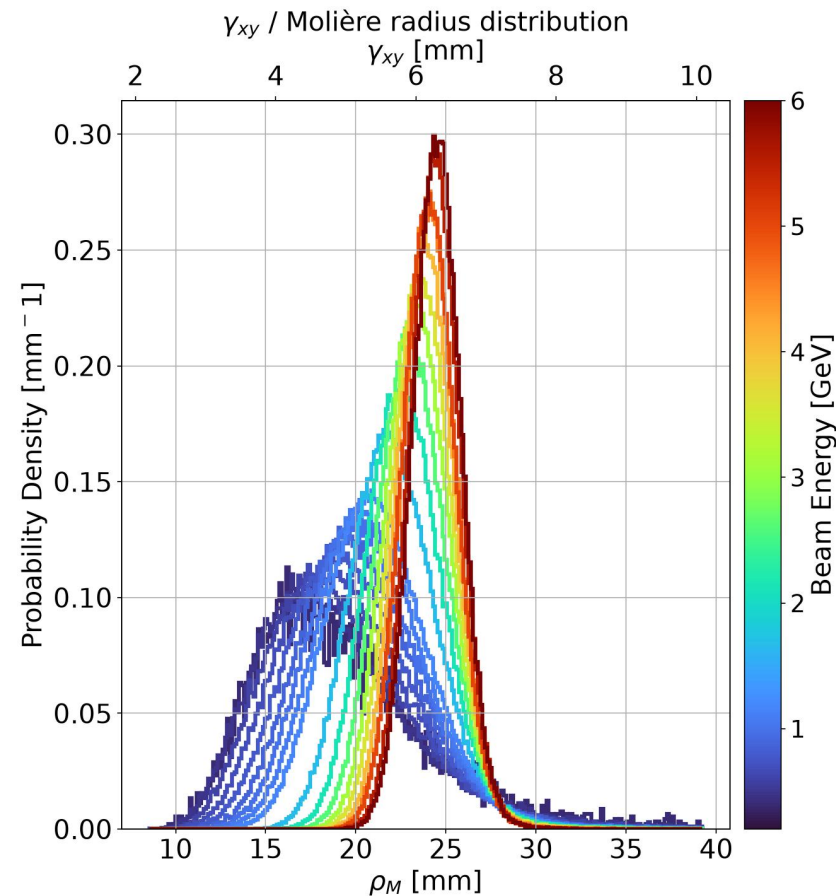
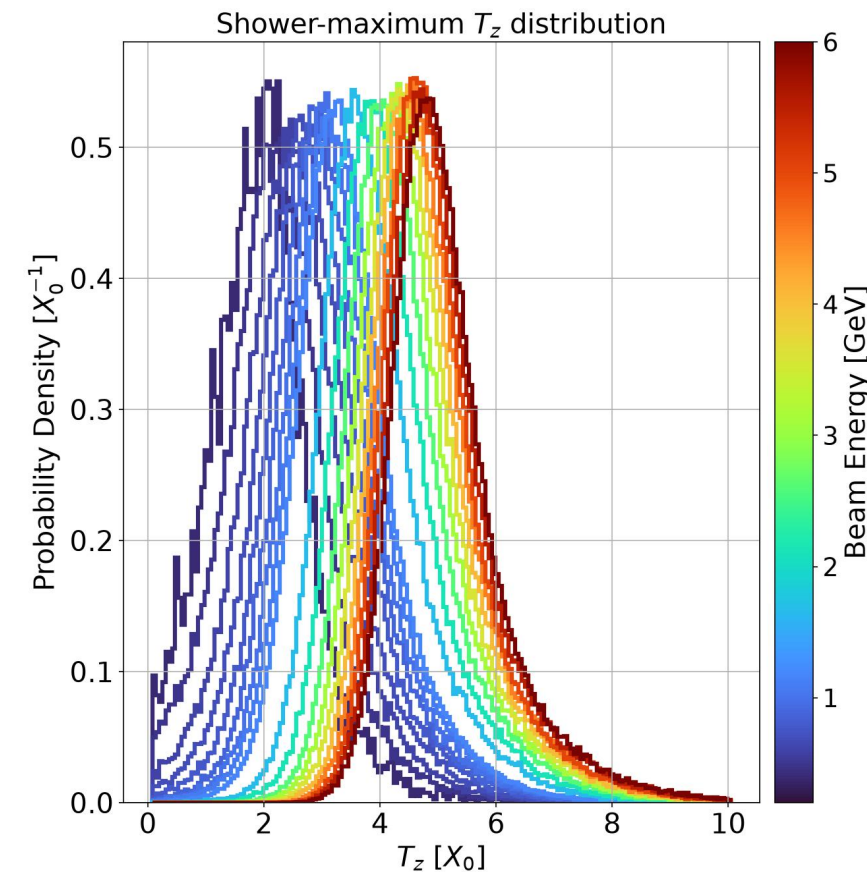
Take Home Message:

- Receiver Operating Characteristic AUC : **0.996**
- **Highly granular crystal ECAL could be used for Particle Flow PID → promising future prospects!**



Goal: study shower shape fluctuations

- Shower maximum/Moliere radius measured from 0.1-6 GeV
- **Fitted event by event;**
- Lateral development: exponential model
- Longitudinal development: gamma model



Take Home Message:

- Shower shapes are $\sim$ log-normally distributed
- **New measurement as far as we know below 1 GeV**
- **Highly granular structure exploited with homogenous design**



Goal: extract BGO/calorimeter absorber properties from shower shapes

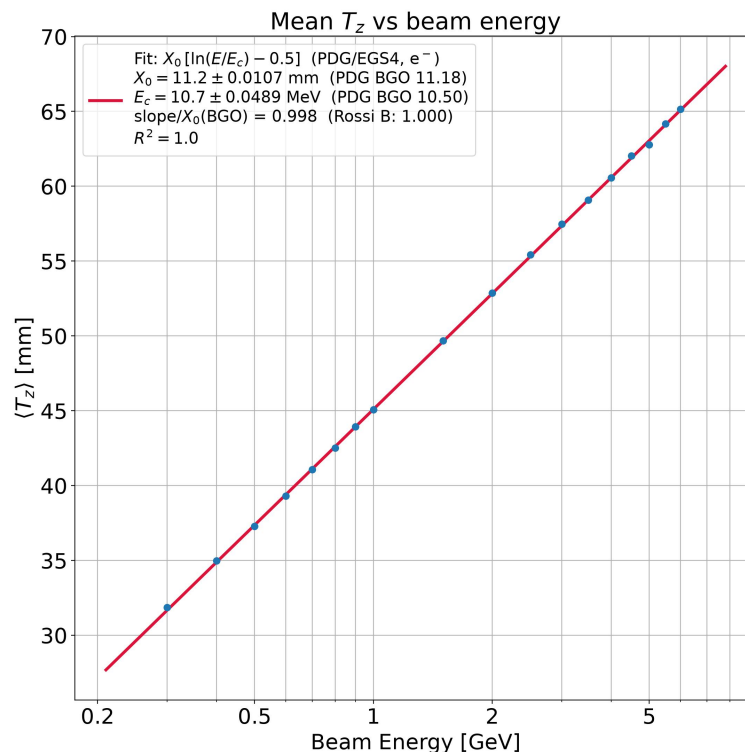
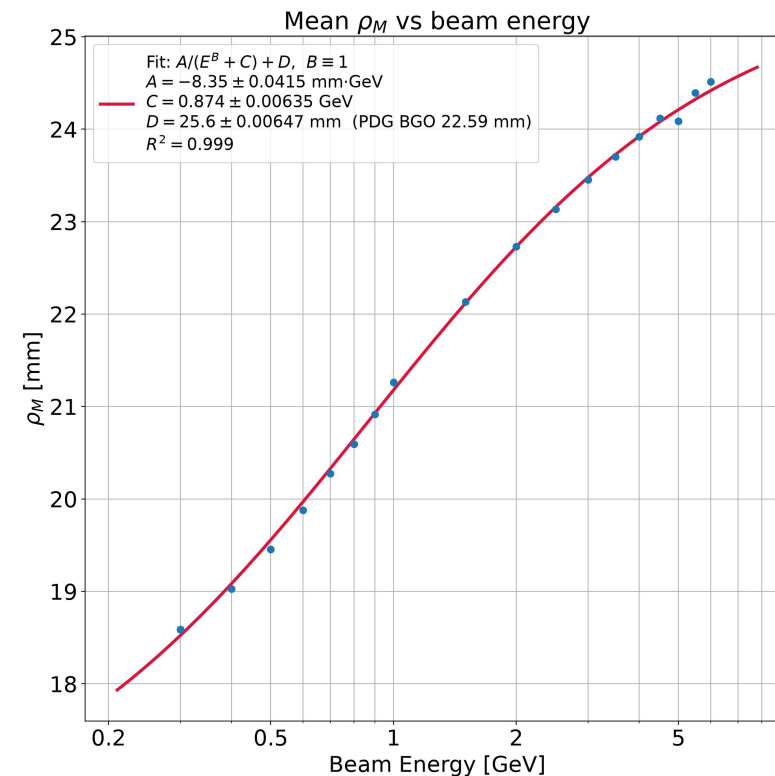
$$\langle T_z \rangle = X_0 \left(\log \left(\frac{E}{E_c} \right) - 0.5 \right)$$

Radiation Length (X_0):
distance over which electron loses 63.2% of its energy;

Critical Energy (E_c):
energy below which shower extinction more probable than multiplication;

$$\langle \rho_M \rangle = \frac{A}{(E^B + C)} + D$$

Effective Moliere Radius (D , $B=1$):
Lateral radius containing 90% of shower energy in highly granular calorimeter;

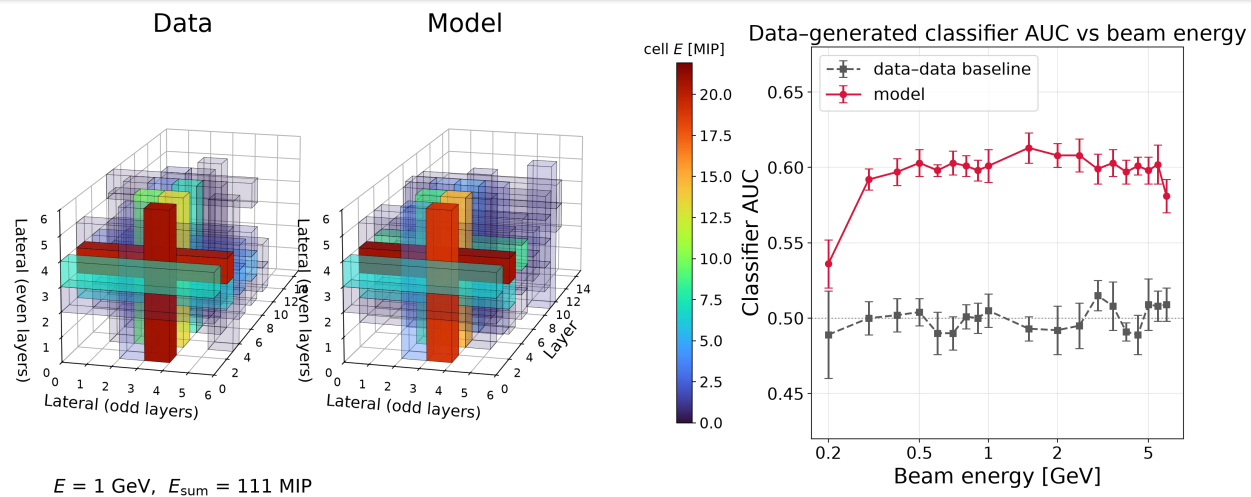


Take Home Message:

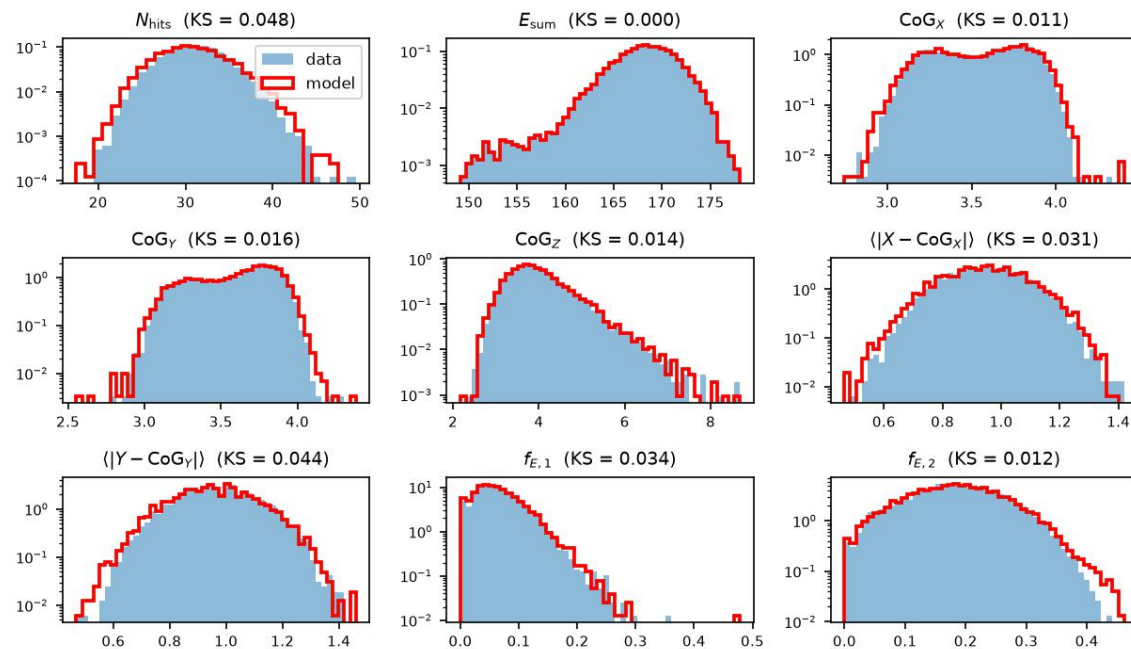
- Radiation Length: **11.2 ± 0.01 mm** → PDG: 11.18 mm
- Critical Energy: **10.7 ± 0.05 MeV** → PDG: 10.5 MeV
- Effective Moliere Radius: **25.6 ± 0.01 mm** → PDG, nominal: 22.59 mm

Goal: build fast shower simulation;

- Excellent energy resolution/granularity means bar-by-bar energy fluctuations can be studied;
- Key Result:**
Bar-to-bar energy fluctuations follow a single simple distribution once the shower shape is known;
- Sampling this distribution given a shower shape reproduces a full shower;



Aggregate features — Data vs model — $E = 1.5 \text{ GeV}$ ($N = 8000$)



Take Home Message:

- Benchmark generated/real classifier (CaloChallenge 2022) of similar quality to state of the art;
- Aggregate features well reconstructed;
- 33 μs per shower
- Research possible only due to the homogenous/highly granular design**

- Rich physics program conducted at CERN in 2025;
- CEPC crystal ECAL achieves resolution requirements of CEPC;
- Granularity of calorimeter is sufficient to measure absorber properties;
- Experiences can be useful for future scintillating glass calorimeter prototyping and beam tests
- Analysis will continue during the long shutdown at CERN

PS-T9 Beamline

