



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

A high-granularity crystal calorimeter for future Higgs factories

2025 International Conference on Instrumentation
for Colliding Beam Physics

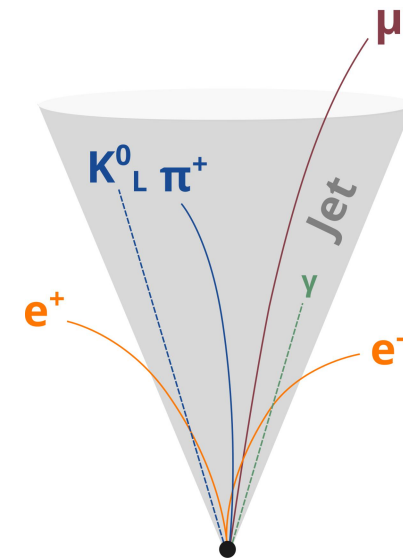
Jack Rolph, on behalf of the AGORA/CEPC Calorimetry Team

October 14, 2026

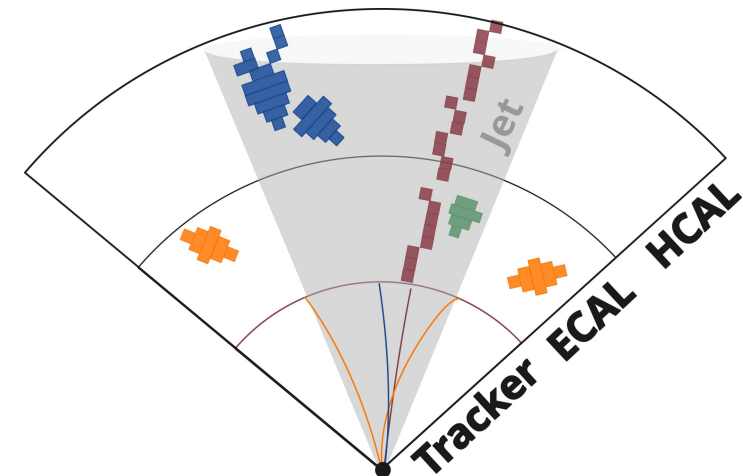




- Future electron positron colliders require **exceptional jet energy resolution (3-4%)**;
- **Reason: hadronic final states are common in processes of interest;**
 - e.g. $HZ \rightarrow gg\bar{\nu}\nu$, dijet final state;
 - BMR required to be $<4\%$ for CEPC;
- **Problem:** Cannot be achieved with 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

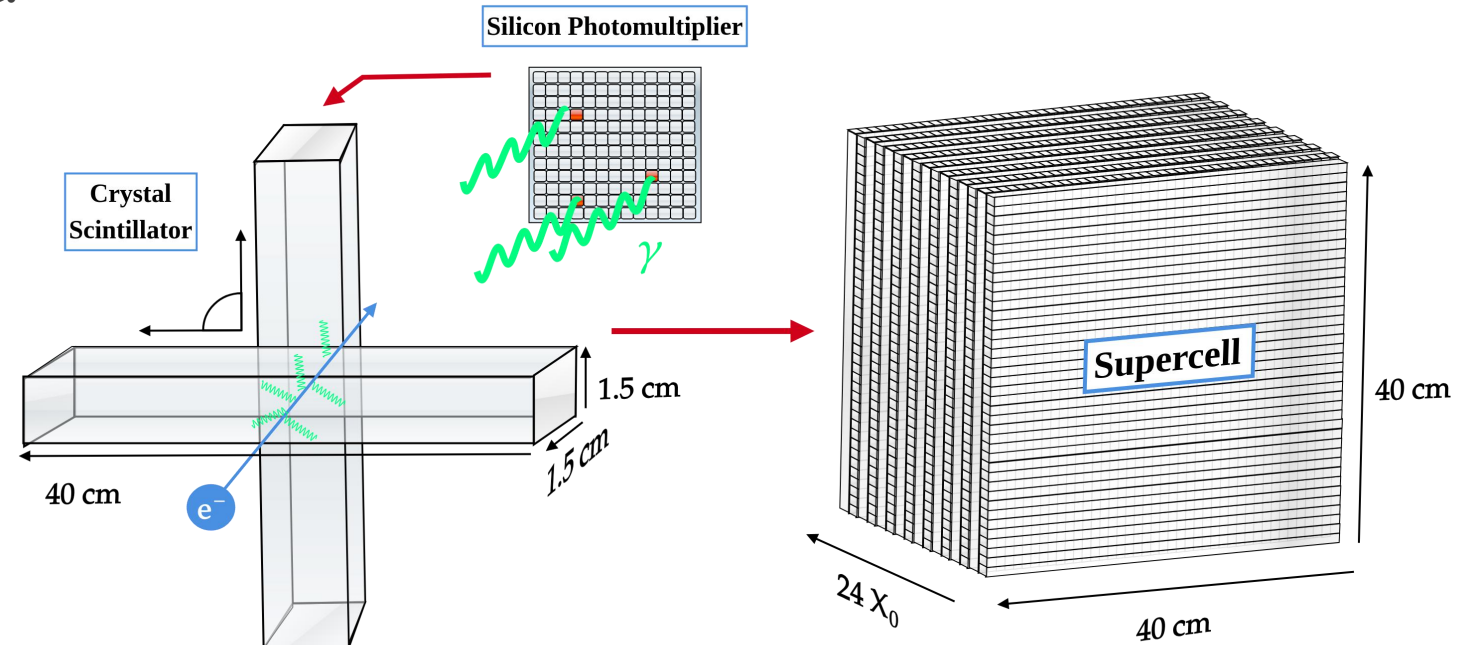


Highly granular crystal ECAL developed for CEPC:

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

Best of both worlds:

- high granularity:
→ final module, $15 \times 15 \text{ mm}^2$;
- homogeneous crystal design:
→ ensures excellent energy resolution;



A Highly Granular Crystal Calorimeter



- Scalable, modular design for ECAL for AGORA/CEPC Reference Detector;

- **Design features:**

Depth: 18 layers ($24 X_0$);

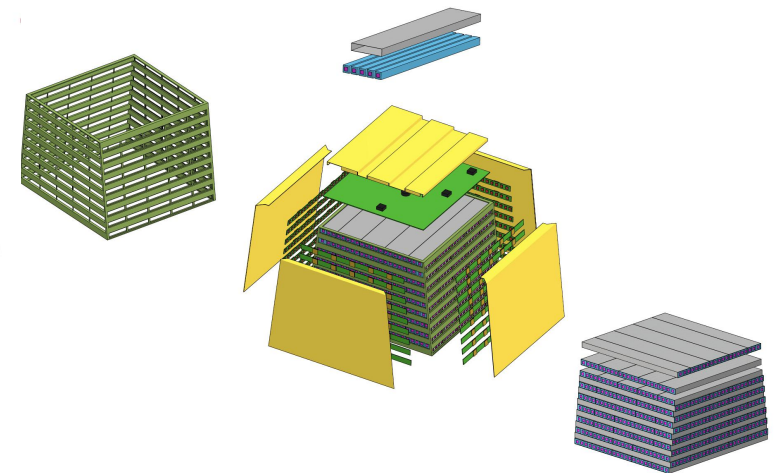
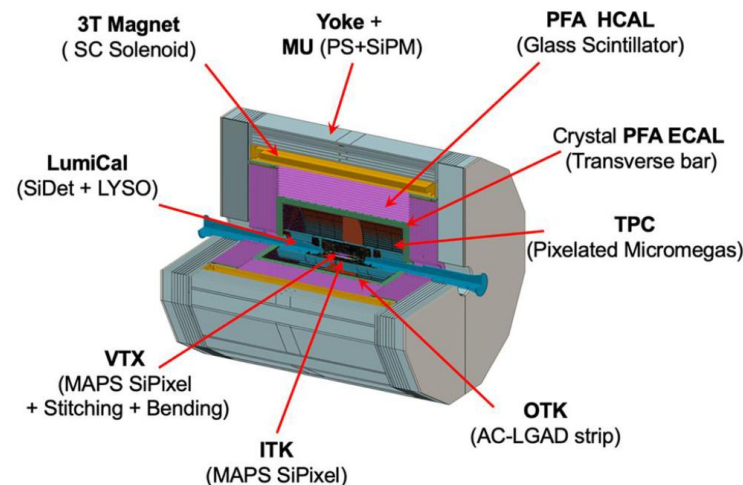
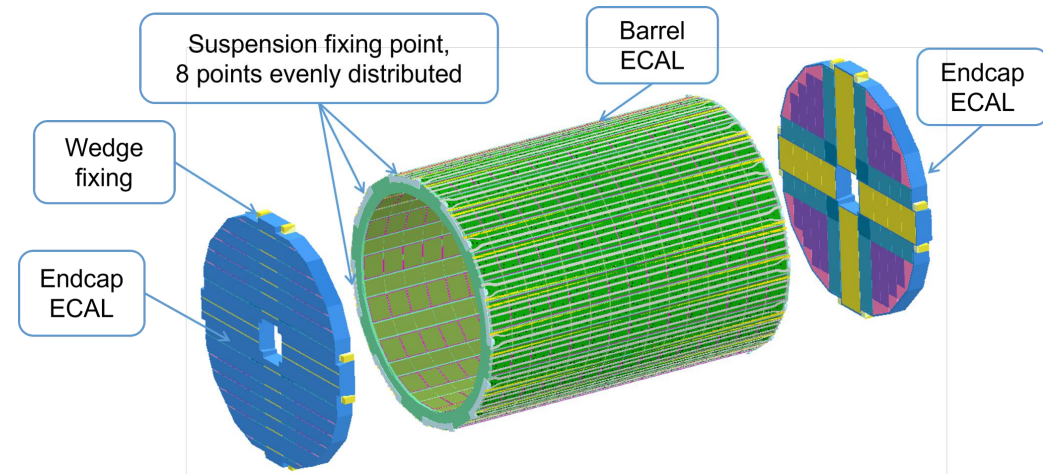
Volume: 24 m³ BGO crystal;

Bars: 285,500 bars;

Sensors: 571,000 SiPMs;

Mechanical structure: Carbon Fiber;

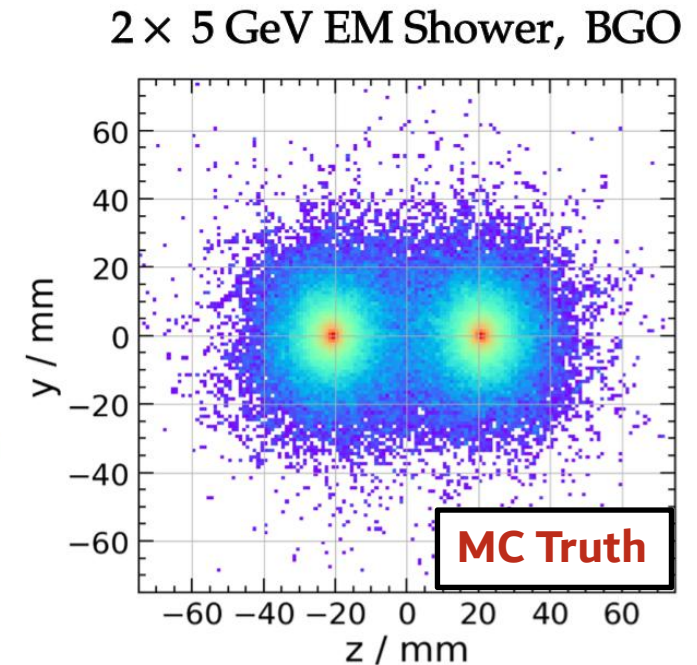
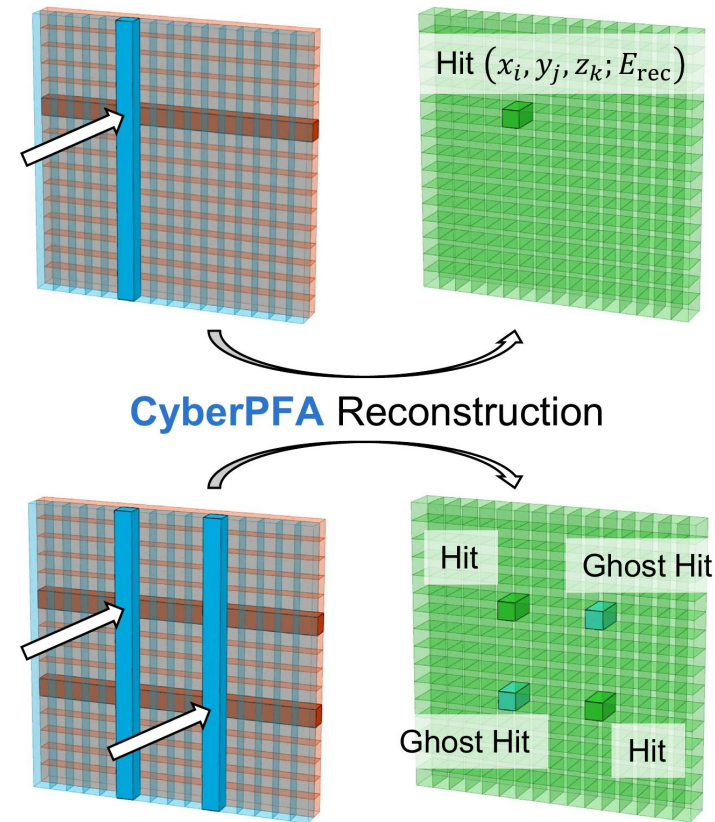
- FEA studies on:
 - stress;
 - deformation;
 - temperature gradient;
- **No showstopper seen.**



- **Unique crystal bar design:**
 - criss-crossing crystal bars;
 - intrinsic hit ambiguity;
 - **multiple locations overlap between layers;**
- Energy deposits overlapping between particles;
- Requires custom Particle Flow Algorithm.

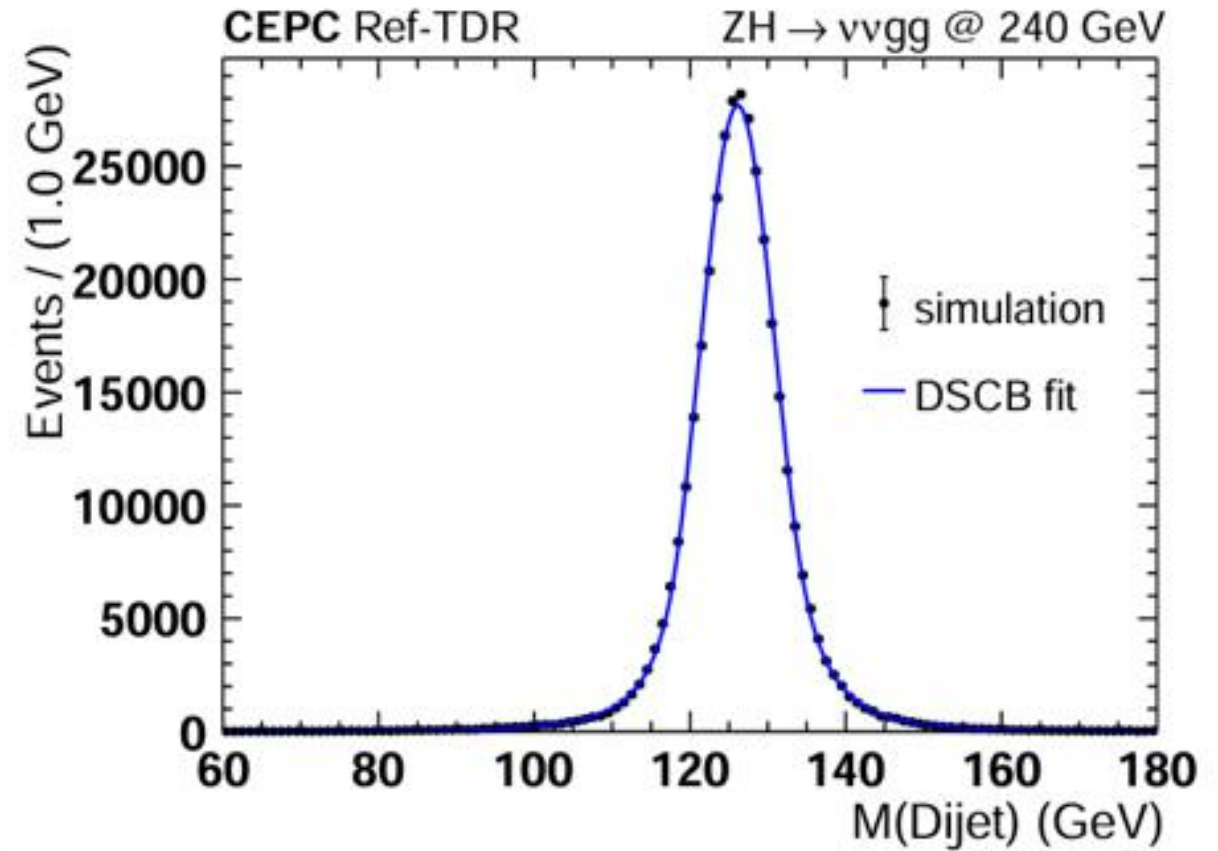
CyberPFA

CrYstal Bar ECAL Reconstruction
Particle Flow Algorithm



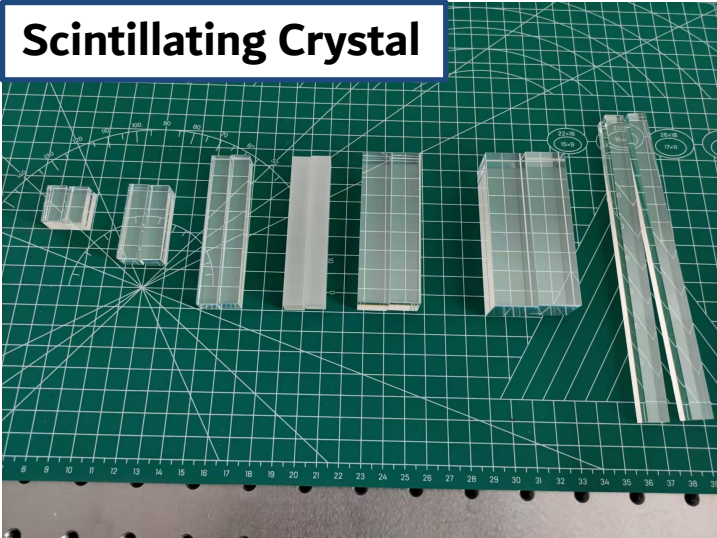


- Higgs mass reconstruction demonstrated for AGORA/CEPC Reference Detector;
- Process:
 $e^+e^- \rightarrow HZ \rightarrow gg\bar{\nu}\nu$
- Center-of-mass Energy:
 $\sqrt{s} = 240 \text{ GeV}$
- Fit:
double-sided Crystal Ball distribution (DSCB)

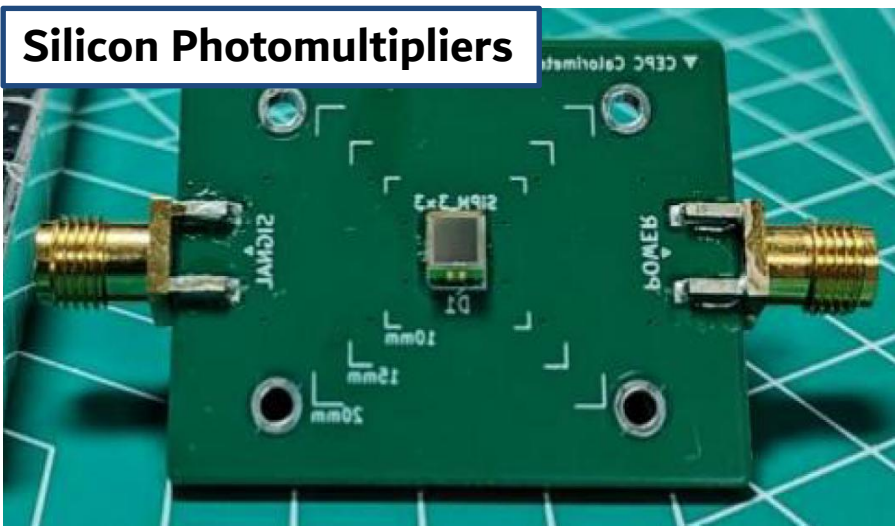


Take Home Message:

- m_H resolution: $3.87 \pm 0.1 \%$
- achieves $<4\%$ BMR



Property	BGO	BSO
<i>Light Yield</i>	8-10 kγ/MIP	2.25 kγ/MIP
Decay Time	300 ns	100 ns
Density	7.13 g cm ⁻³	6.80 g cm ⁻³
Radiation Length (X ₀)	1.12 cm	1.10 cm
Moliere Radius (ρ _M)	2.26 cm	2.18 cm



Property	NDL EQR06	NDL EQR10	HPK S14160
Pixel Pitch	6 μm	10 μm	10 μm
<i># Pixels @ 3x3mm²</i>	244 719	90 000	89 984
PDE	30% @ 420 nm	36% @ 420nm	18% @ 460 nm
DCR @ 20°C	2.5 MHz	3.6 MHz	700 kHz
Crosstalk Probability	12%	N/A	< 1%

Goals:

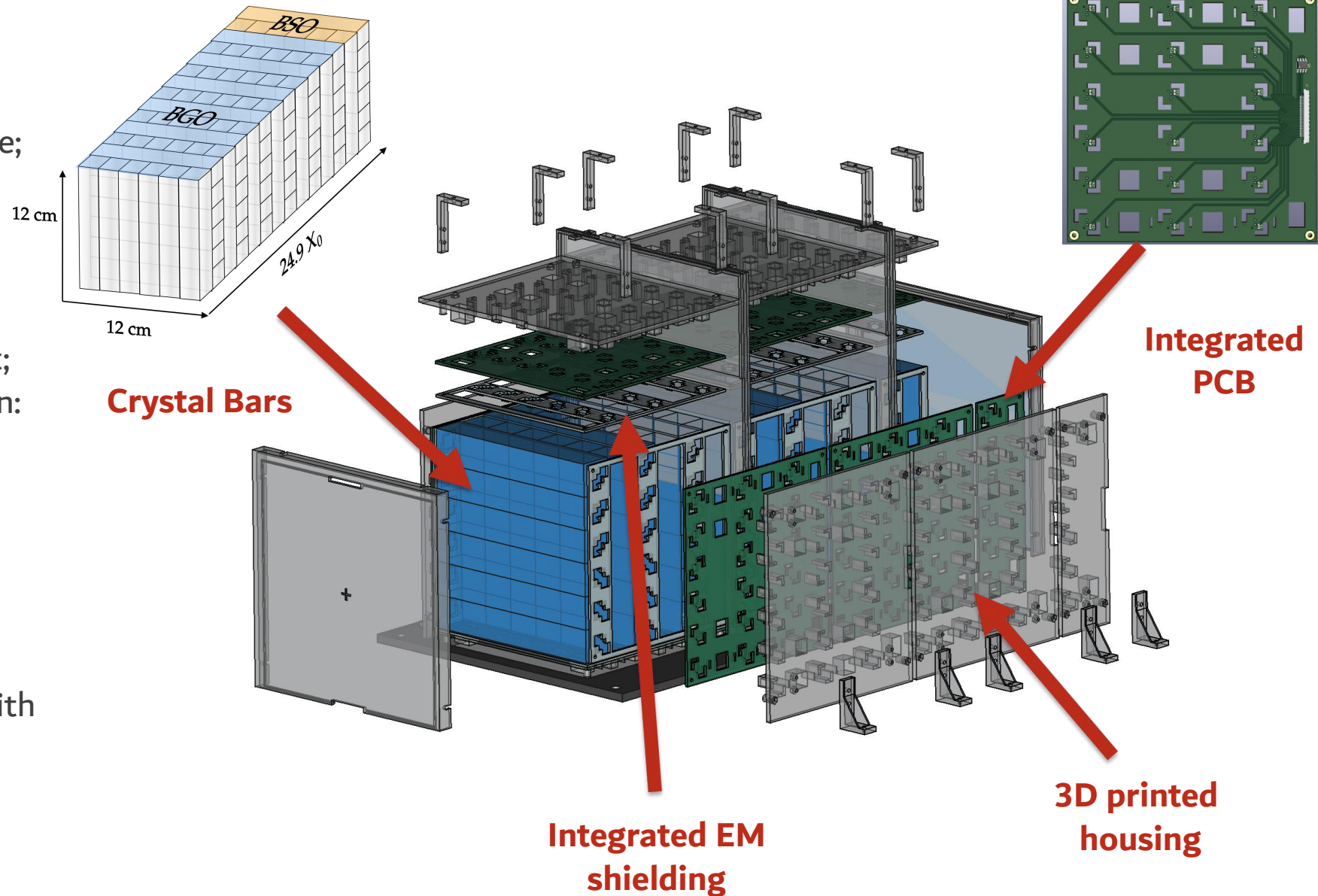
- minimize material budget;
- minimize stress on PCB;
- shield signal from EM interference;
- maximize scintillation light;

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;



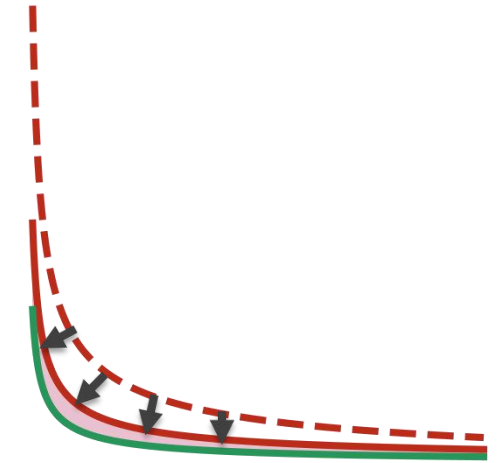
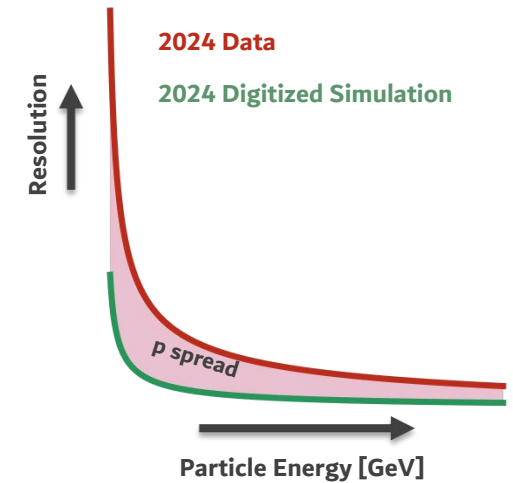
Goal: measure linearity/energy resolution of calorimeter

- **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

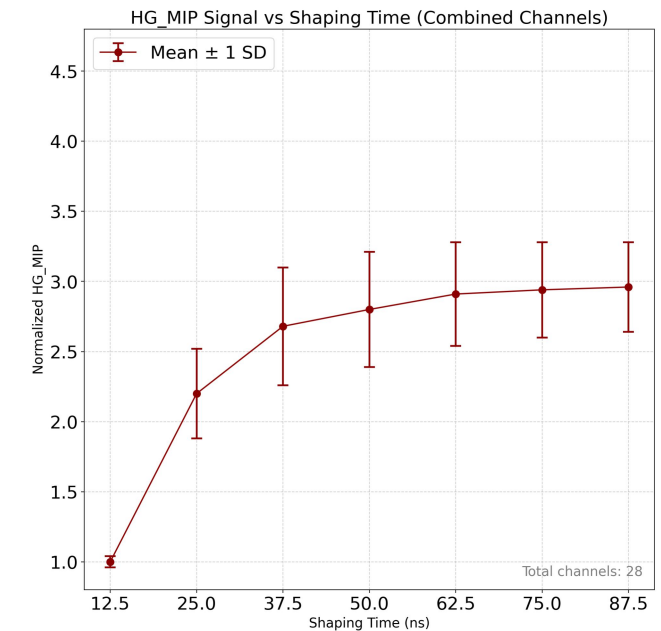
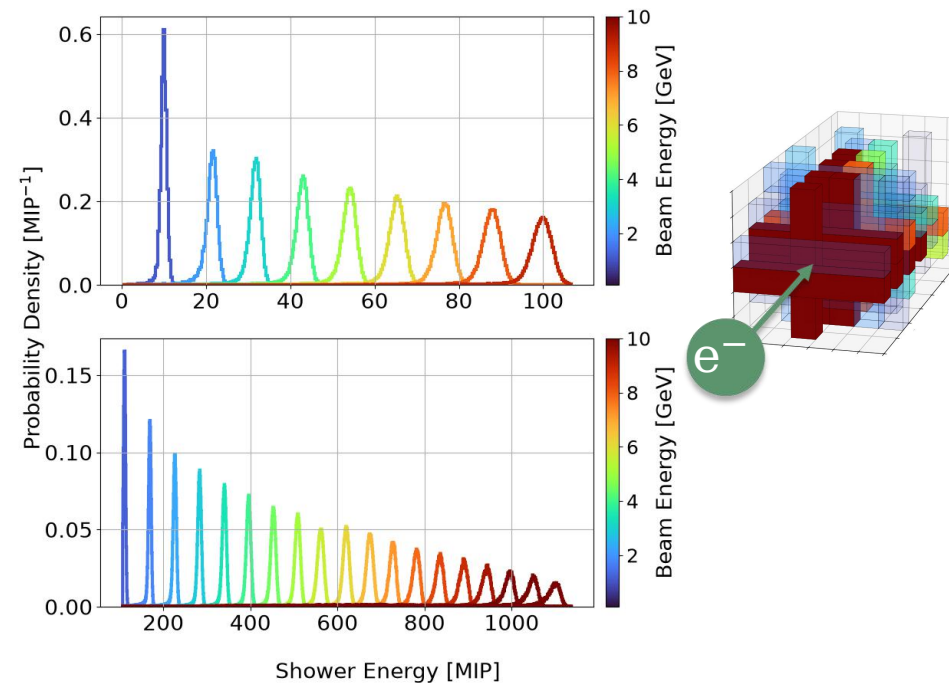
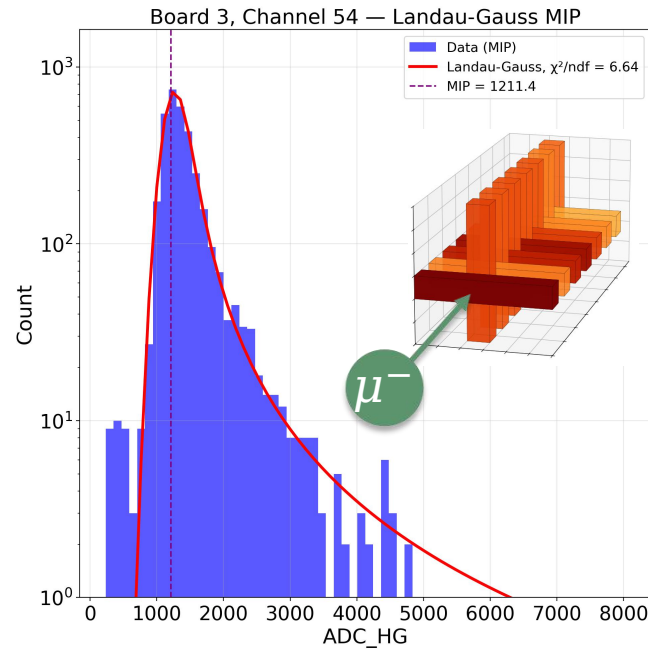
- Studied 5 positions on front face;
- μ^+/π^+ used for MIP calibration;
- Repeated through campaign;

Electron scans

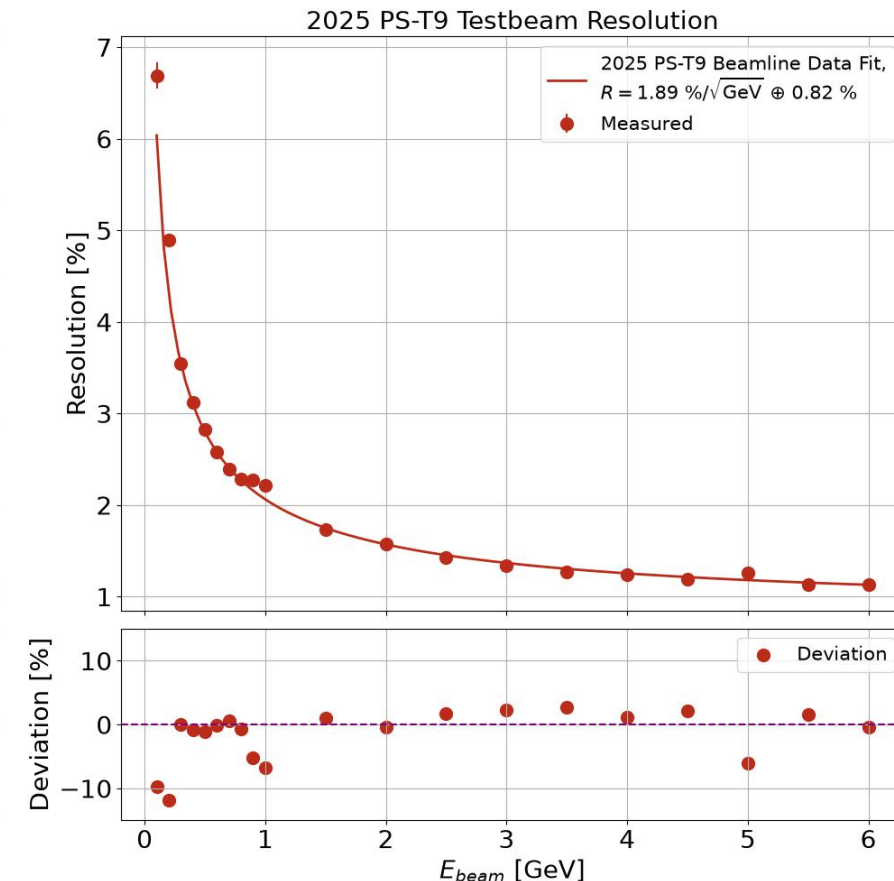
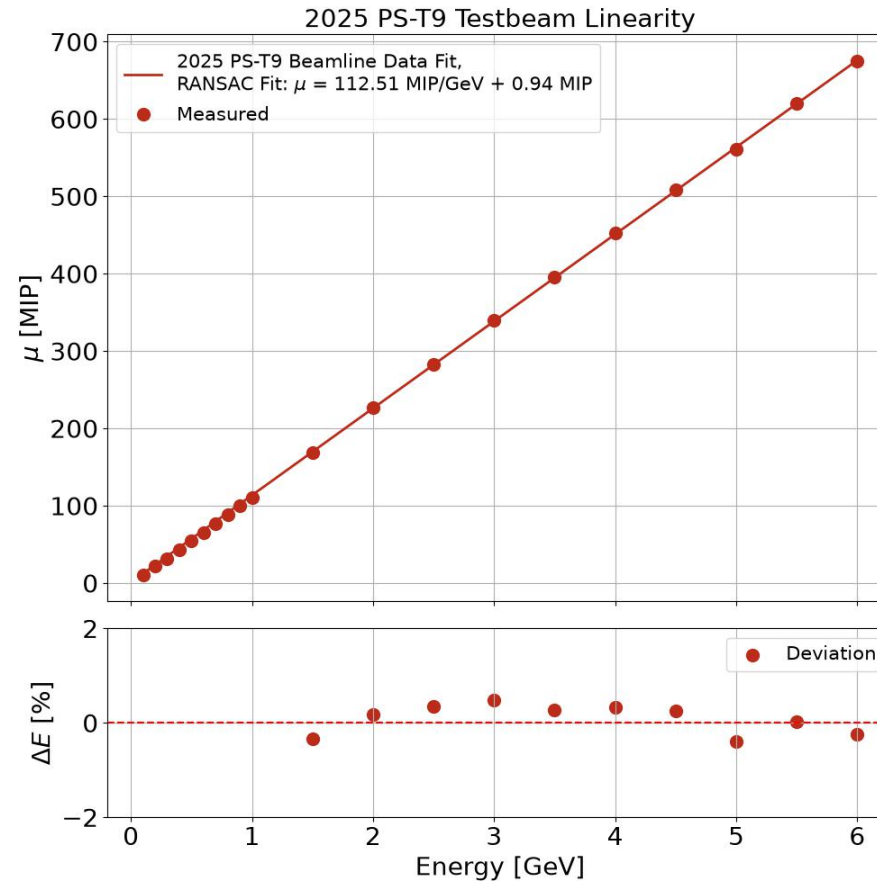
- electrons from 0.1-10 GeV;
- 0.1 GeV steps below 1 GeV;
- 0.5 GeV steps above 1 GeV;
- collimation settings (± 3 / ± 1.5 mm);
- calorimeter inverted (i.e. BSO preshower/tailcatcher)

Systematics:

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



- Goal: measure linearity/resolution of calorimeter
- linearity/resolution measured from 0.1-6 GeV
- **calorimeter linear within ~1% above 1 GeV;**
- **resolution better than target 2% including beam momentum spread;**
- <1 GeV, noise threshold/albedo leakage cause deviation from linearity
→ recoverable via algorithm



Take Home Message:

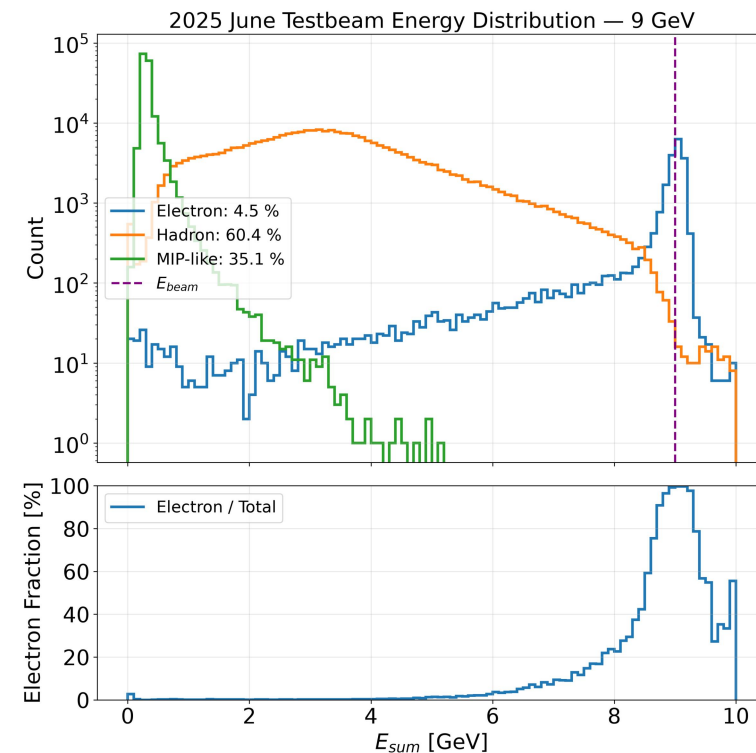
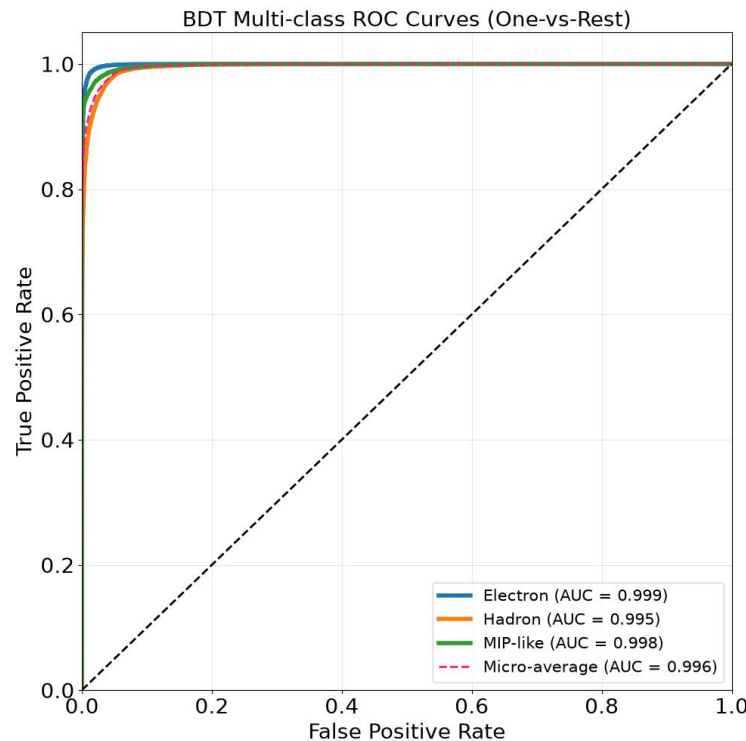
HG Crystal Calorimeter:

- linear within 1%
- achieves 2% resolution target



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;



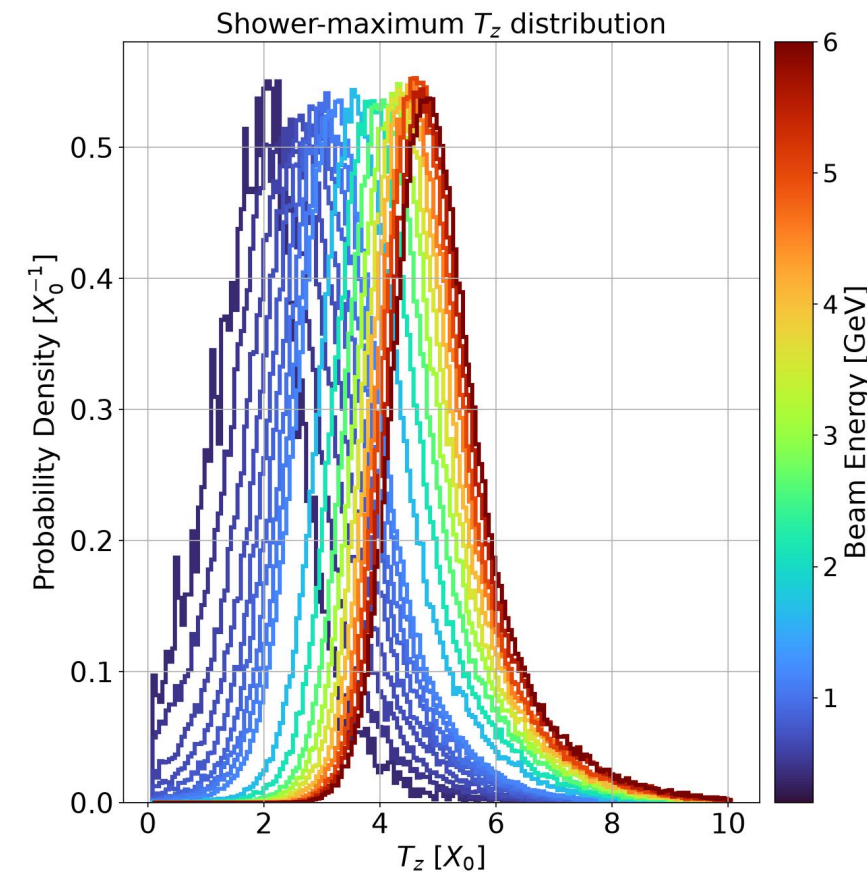
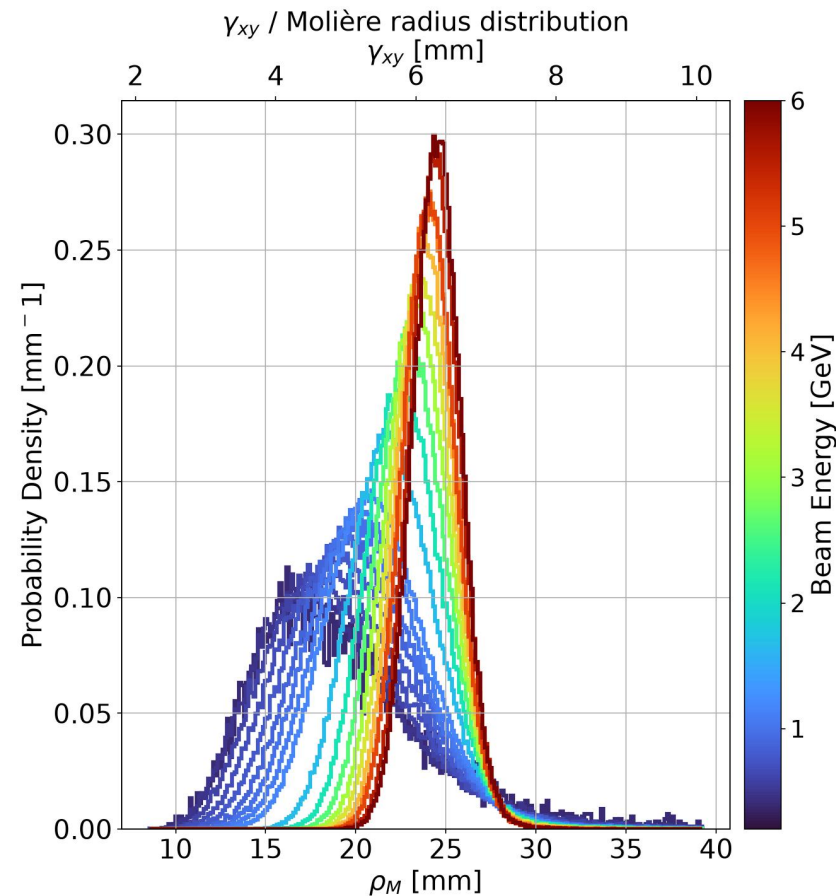
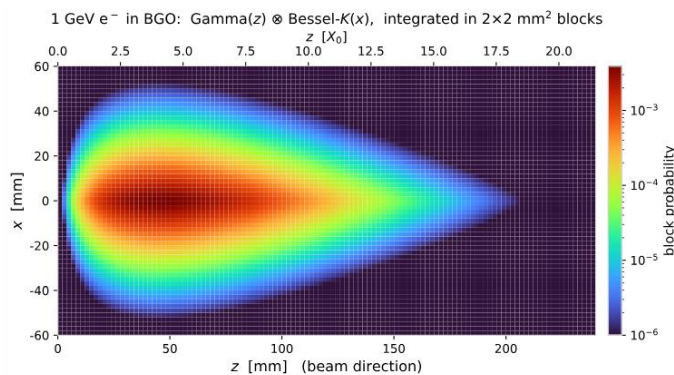
Take Home Message:

- 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**



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;

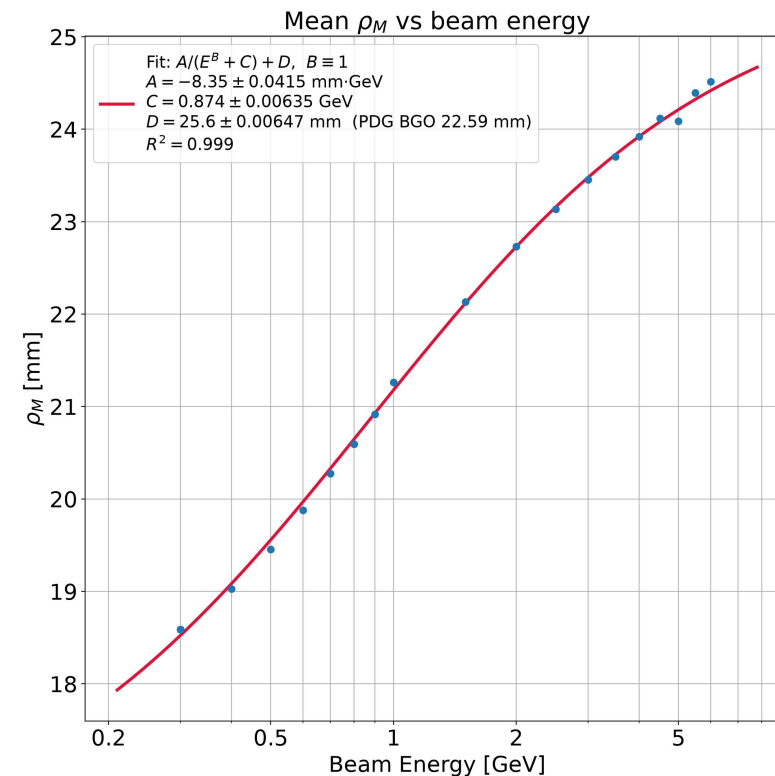
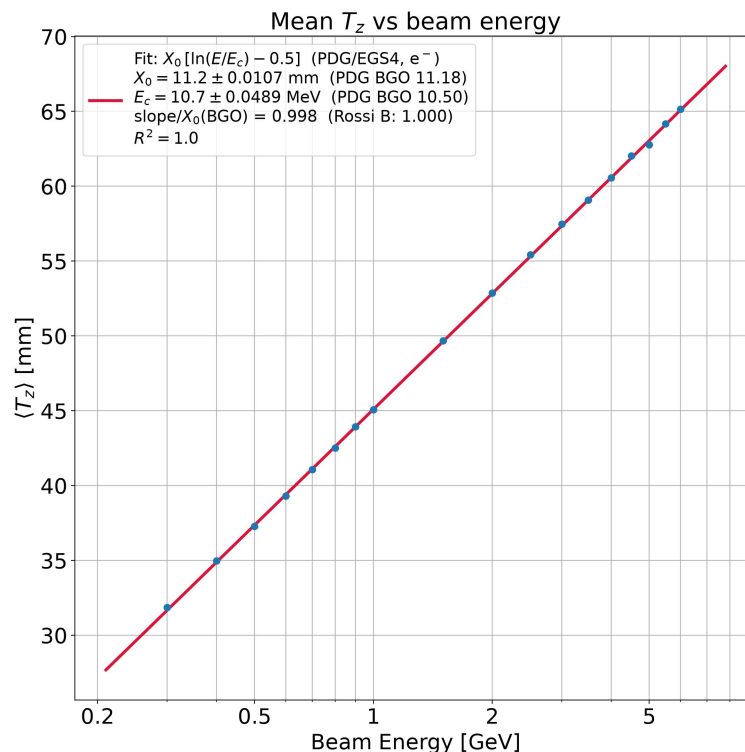
Critical Energy (E_c):

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;

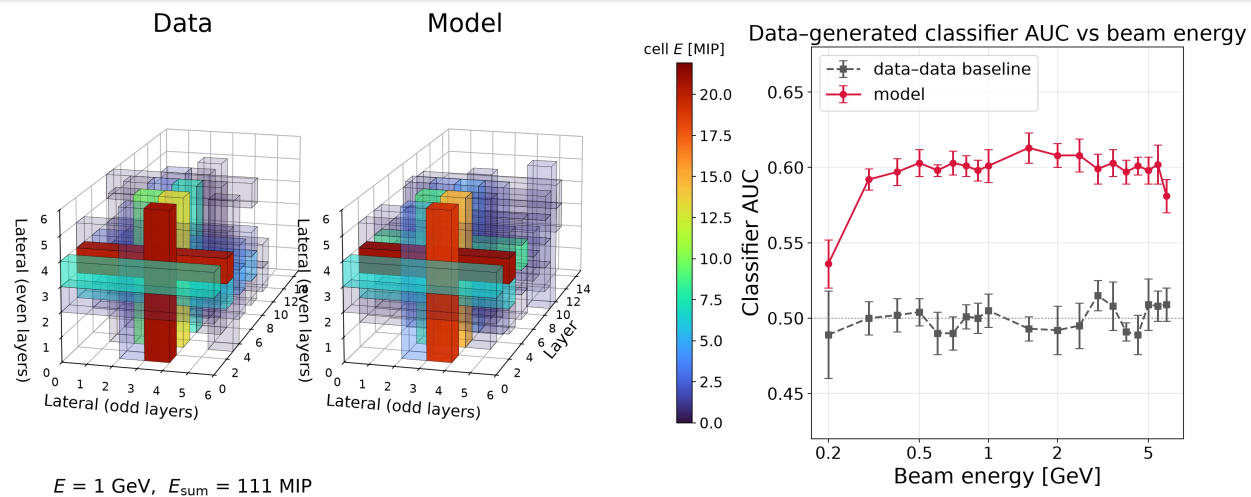


Take Home Message:

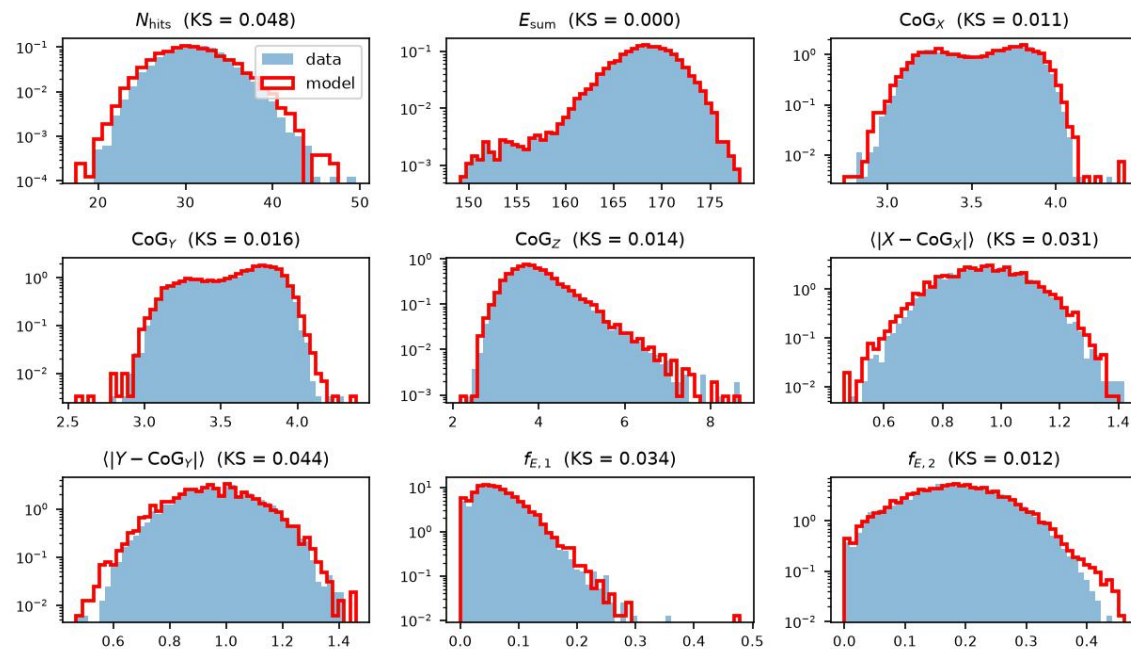
- Radiation Length: **11.2 ± 0.01 mm** → PDG: 11.18 mm
- Critical Energy: **10.7 ± 0.05 MeV** → PDG: 10.5 MeV
- Effective Moliere Radius: **25.6 ± 0.01 mm** → PDG, nominal: 22.59 mm

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 — $E = 1.5 \text{ GeV}$ ($N = 8000$)



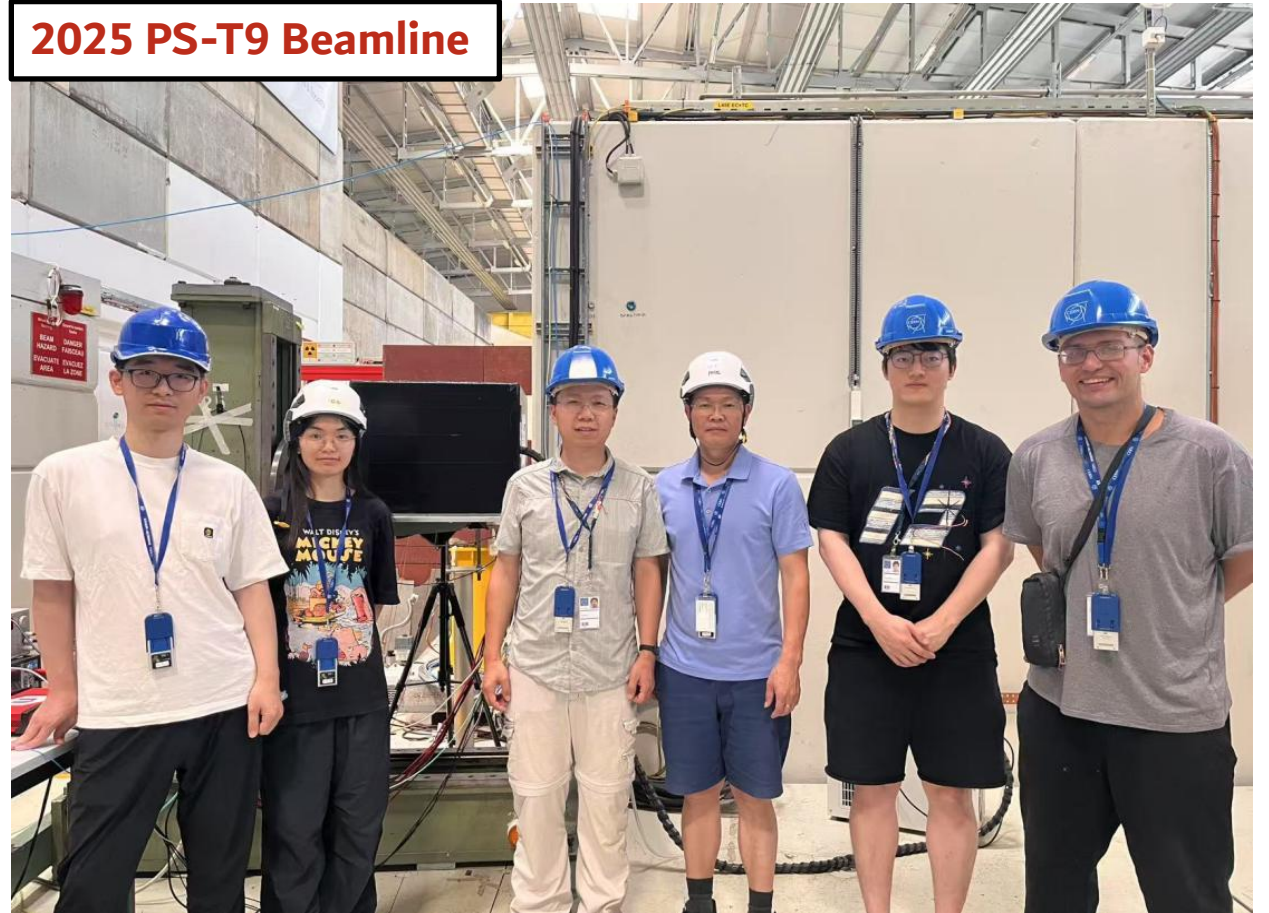
Take Home Message:

- 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**

Take Home Messages:

- Rich physics program conducted at CERN in 2025;
- CEPC crystal ECAL achieves CEPC resolution requirements;
- Research ongoing into crystal bars and SiPMs;
- Granularity of calorimeter is sufficient to measure absorber properties;
- Analysis and R&D will continue during the long shutdown at CERN

2025 PS-T9 Beamline

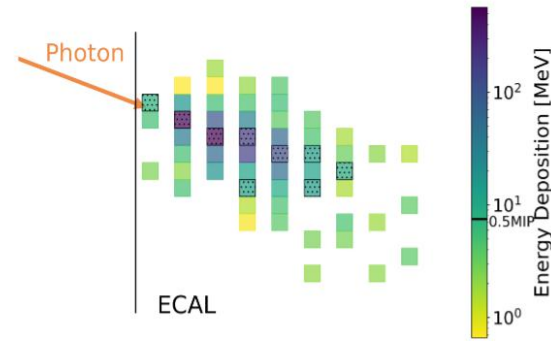




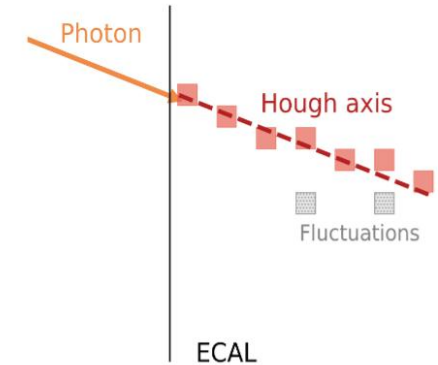
Key innovations

1. Shower recognition using the 'energy core'
→ i.e. shower-axis finding for photons;
2. Fit of longitudinal profile to split nearby energy deposits;
3. 'Optimized' selection of hits based on 'best matching hit combinations';
(i.e. longitudinal shower profiles)

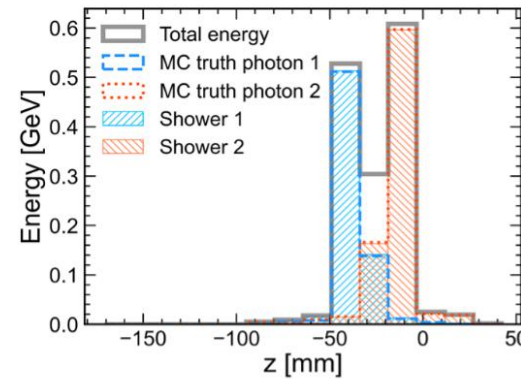
1. Select local energy maxima



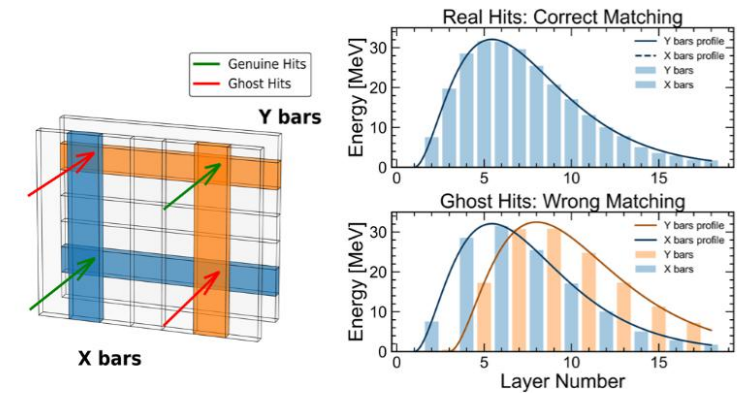
2. Find shower axis



3. Split closely showers using weighted longitudinal profile

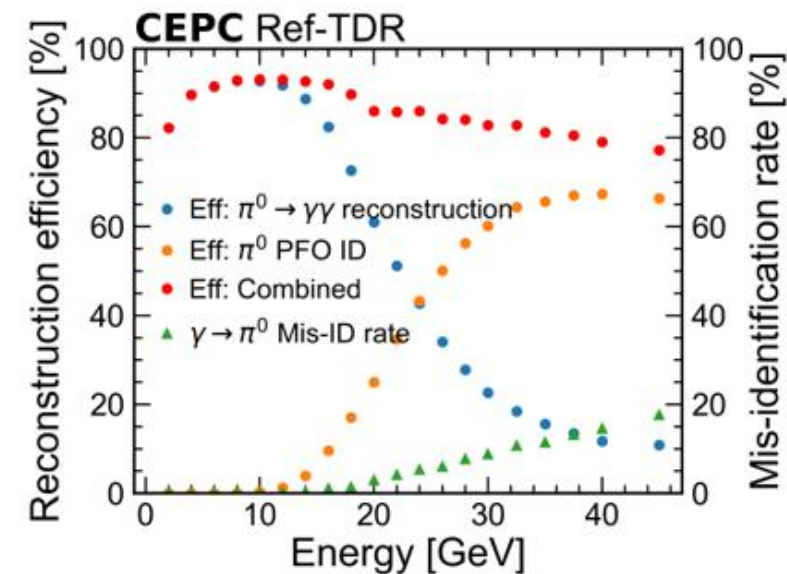
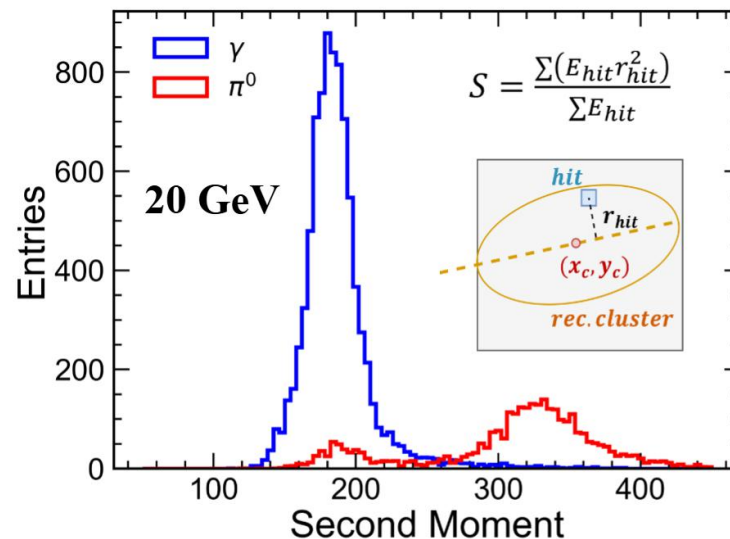


4. Find optimal hit combination (profile, timing, nbr. module)





- π^0 reconstruction possible
(relevant for e.g. $Z \rightarrow \tau\bar{\tau}$, $H \rightarrow \tau\bar{\tau}$)
- Low energy: 2γ PFO
- High energy: PID via mean energy-weighted distance (2nd moment) from axis;
- π^0 reconstruction efficiency:
 - 2 neutral PFOs, energies equal within 50–200 MeV;
 - correctly identified π^0 by PID;
 - caveat: No PID for other particles:
→ 'ideal scenario'



Take Home Message:

- γ and π^0 distinguishable;
- Further possible PID improvements:
 - shower profile
 - ML/multivariate analysis

Take Home Message:

- > 80% reconstruction efficiency from 1-45 GeV
- Typical range of energies for $Z/H \rightarrow \tau\bar{\tau}$, others

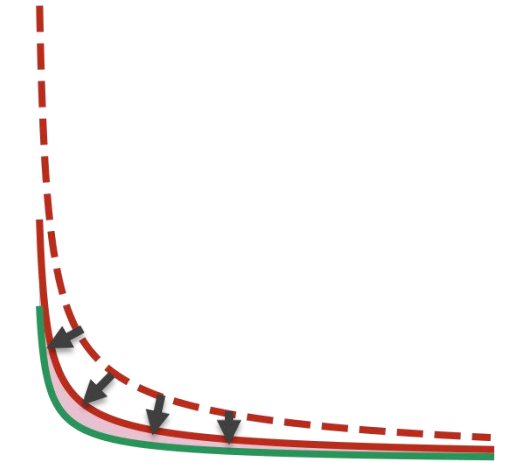
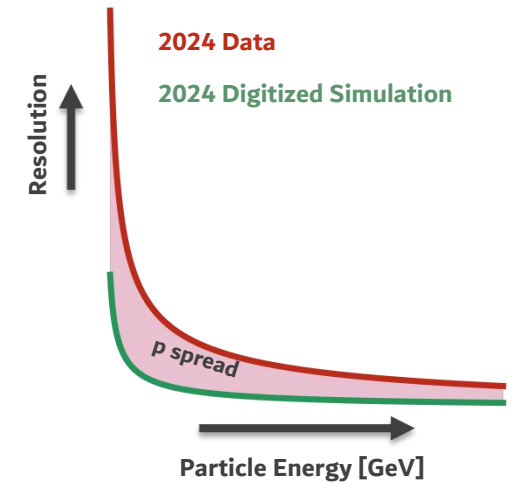
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remove upstream instrumentation
 - reduce momentum spread;
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PS-T9 2024 (Before)



PS-T9 2025 (After)



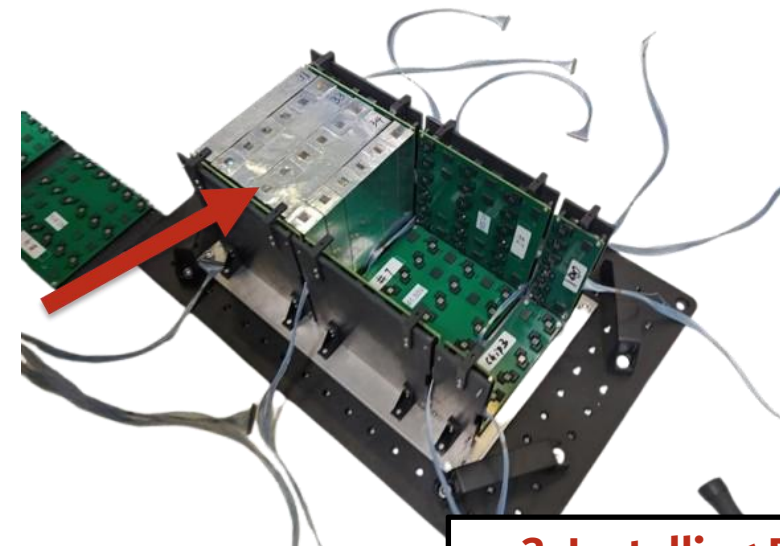
PCB with SiPMs

Baseplate

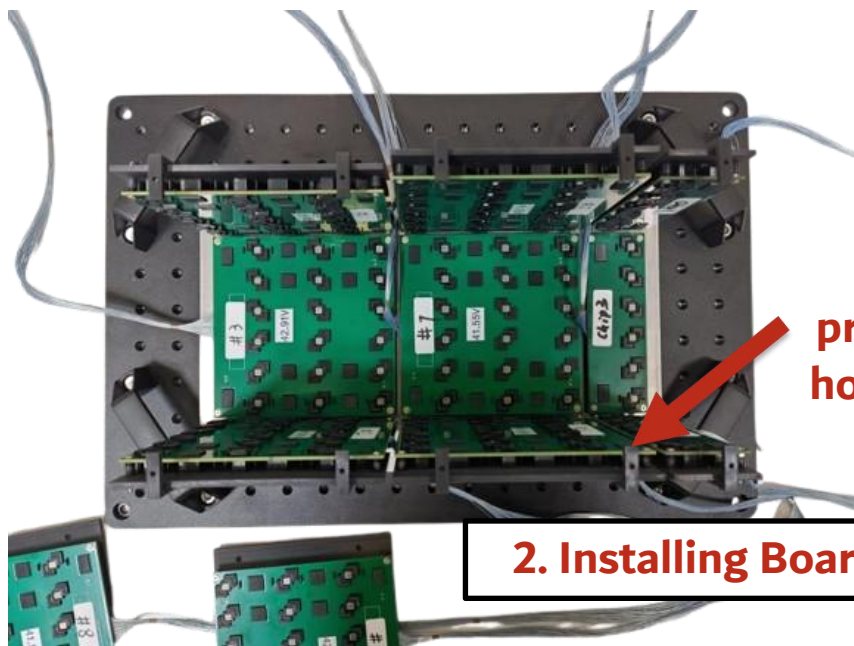


1. Pre-Assembly

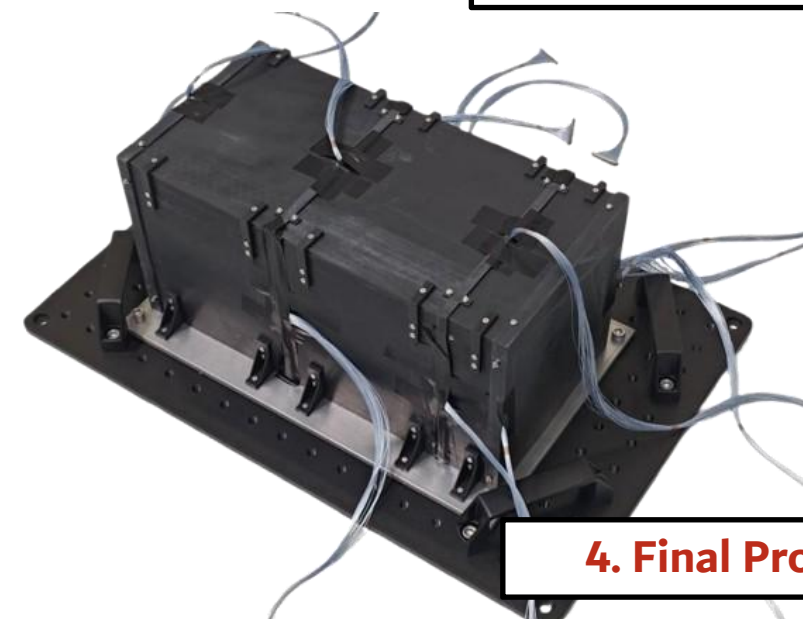
ESR-
Wrapped
Crystal
Bars



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)

**4×/5× 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**



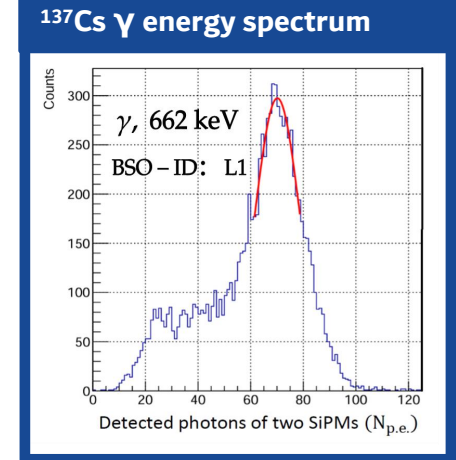
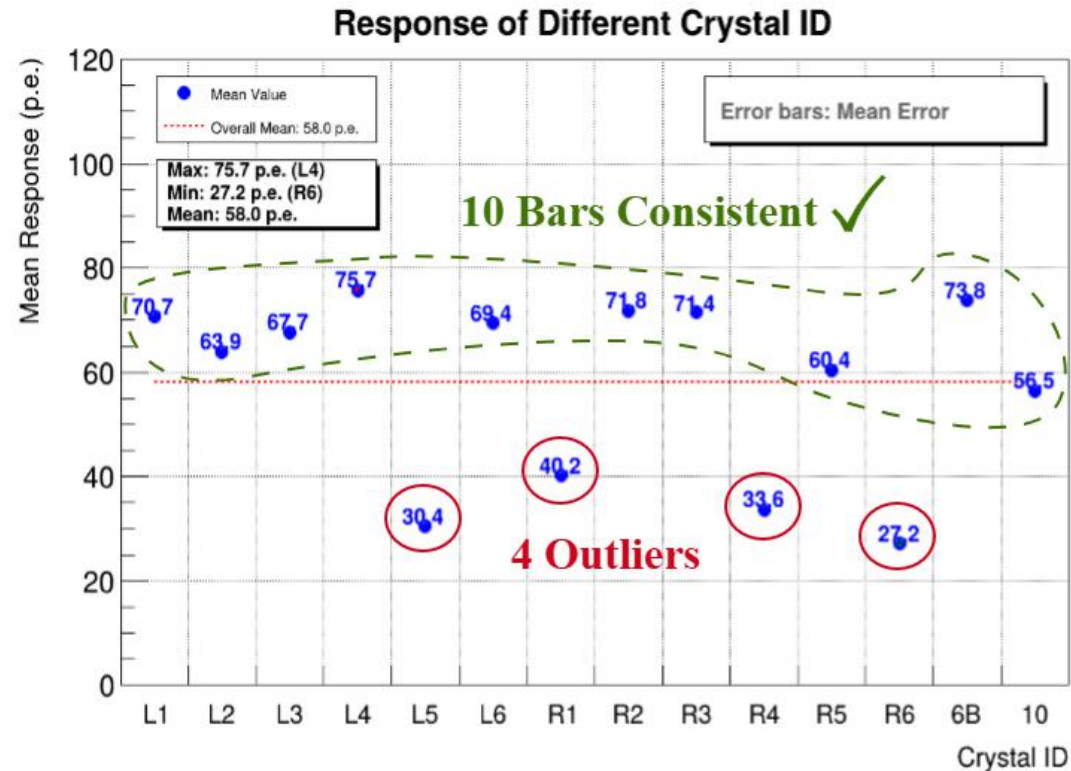


- **BSO advantages:**

- $\tau_{\text{BSO}} \approx 100 \text{ ns}$
→ 3× faster than BGO;
- **High UV transmittance**
→ dual readout/fast timing (?)
- **Germanium-free**
→ **lower cost**

- Response uniformity of batch of fourteen $2 \times 2 \times 12 \text{ cm}^3$ bars measured;

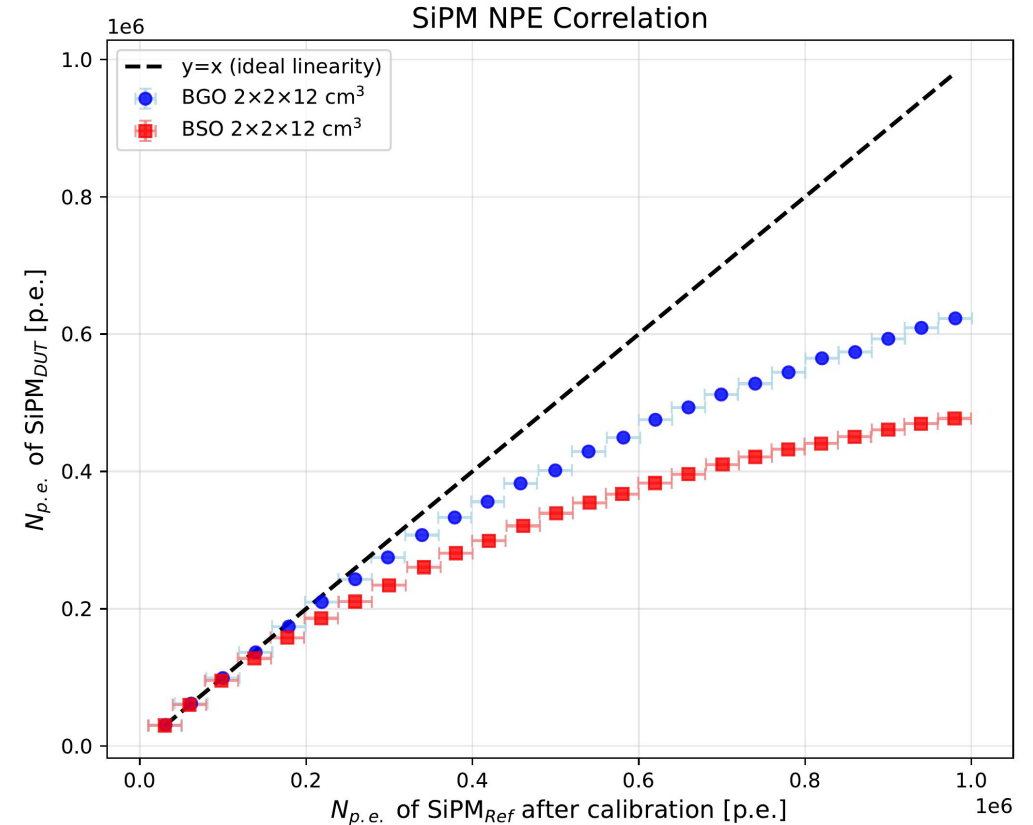
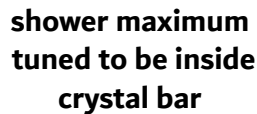
- Source: ^{137}Cs (662 keV γ)
→ intra-crystal uniformity via mean response;



Take Home Message:

- Good uniformity for 10 BSO bars;
- 4 outliers (L5, R1, R4, R6);
- One of the first sets of long BSO bars → **promising start.**

- **Test setup:**



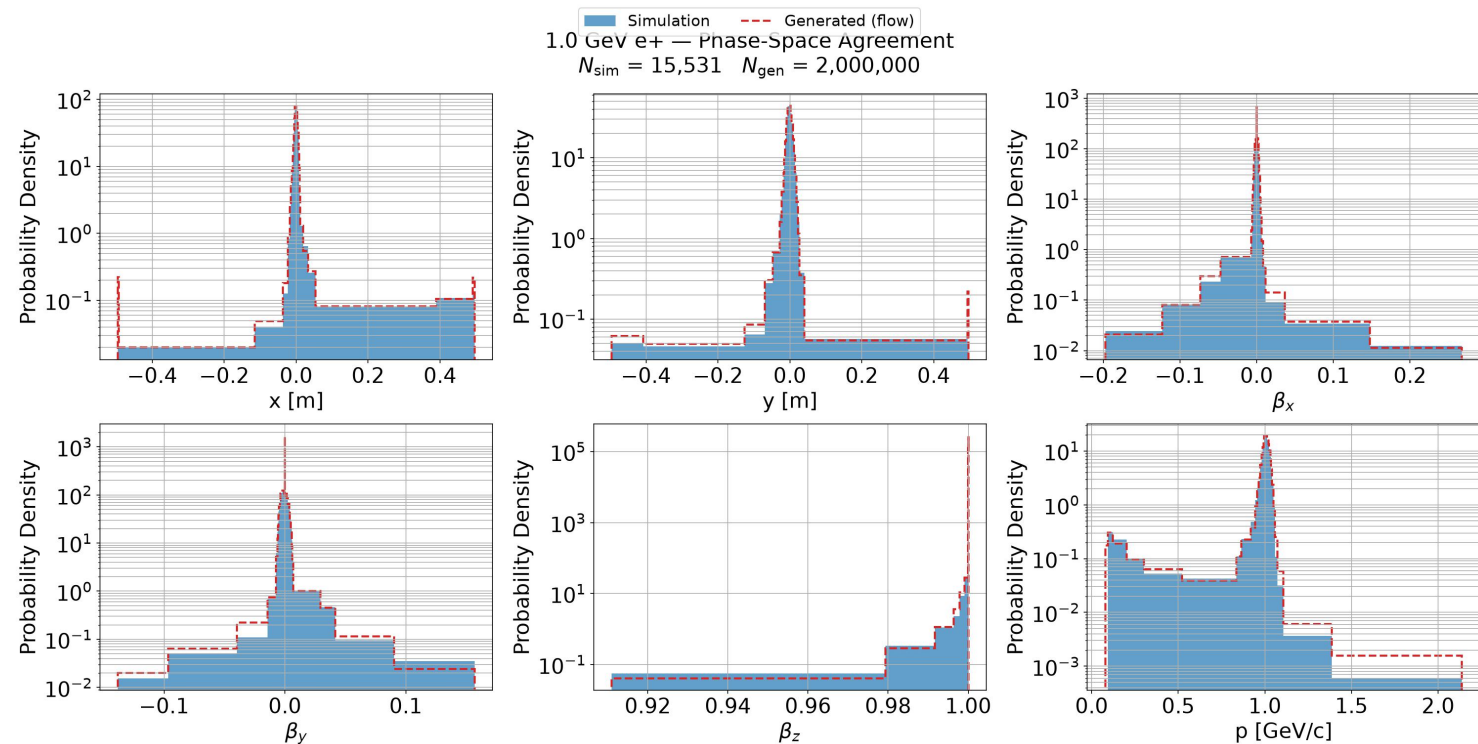
Take Home Message:

- BGO deviates 12% less than BSO from linearity;
- BGO slower → more pixels can fire, non-linearity less severe



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 μ s per sample
 - ONNX allows deployment in Geant4



Take Home Message:

Fast, accurate beamline simulation integrated with Geant4