

中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

A high-granularity crystal calorimeter for future Higgs factories



2026 International Workshop on the High Energy Circular Electron Positron Collider

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

October 23, 2026

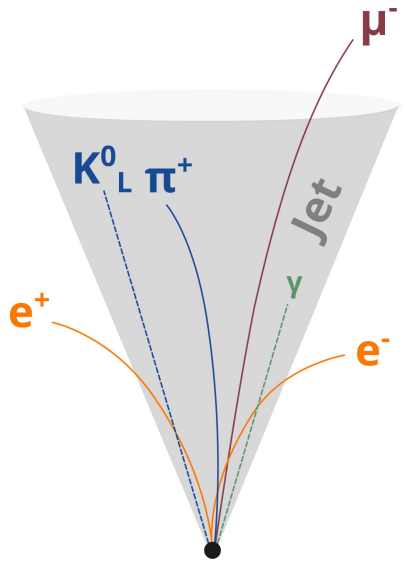
Motivation

- Future electron positron colliders require **exceptional jet energy resolution (3-4%);**

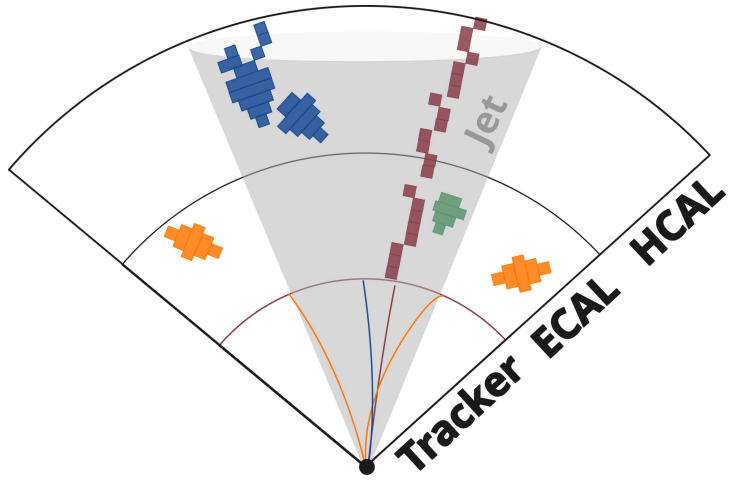
- **Reason: hadronic final states are common in processes of interest;**
  - e.g. HZ → gg$\bar{\nu}\nu$, dijet final state;
  - BMR required to be <4% for CEPC;

- **Problem:** Cannot be achieved with traditional calorimetery;

- **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



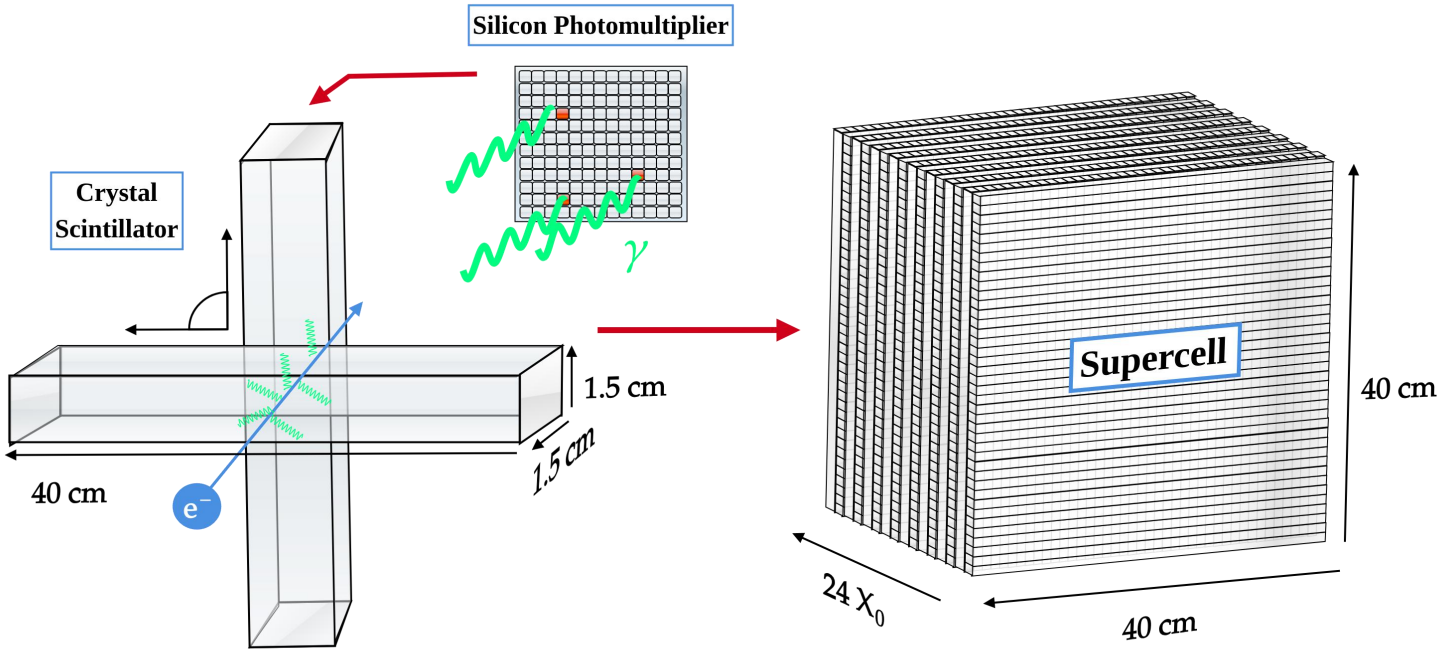
A Highly Granular Crystal Calorimeter

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 x 15 mm^2;
- homogeneous crystal design:
  → ensures excellent energy resolution;



ECAL design applicable to other future Higgs factories i.e. FCC-ee

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 m^3 BGO crystal;

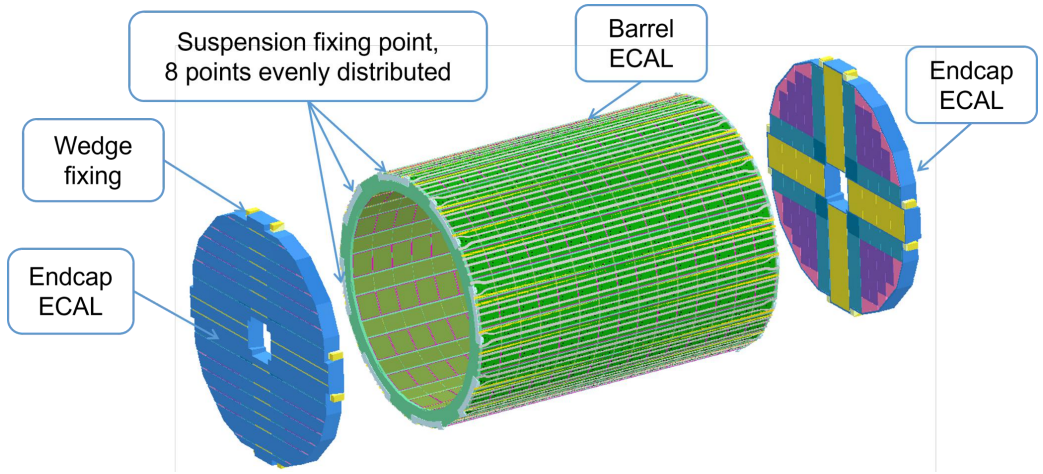
  # Bars: 285,500 bars;

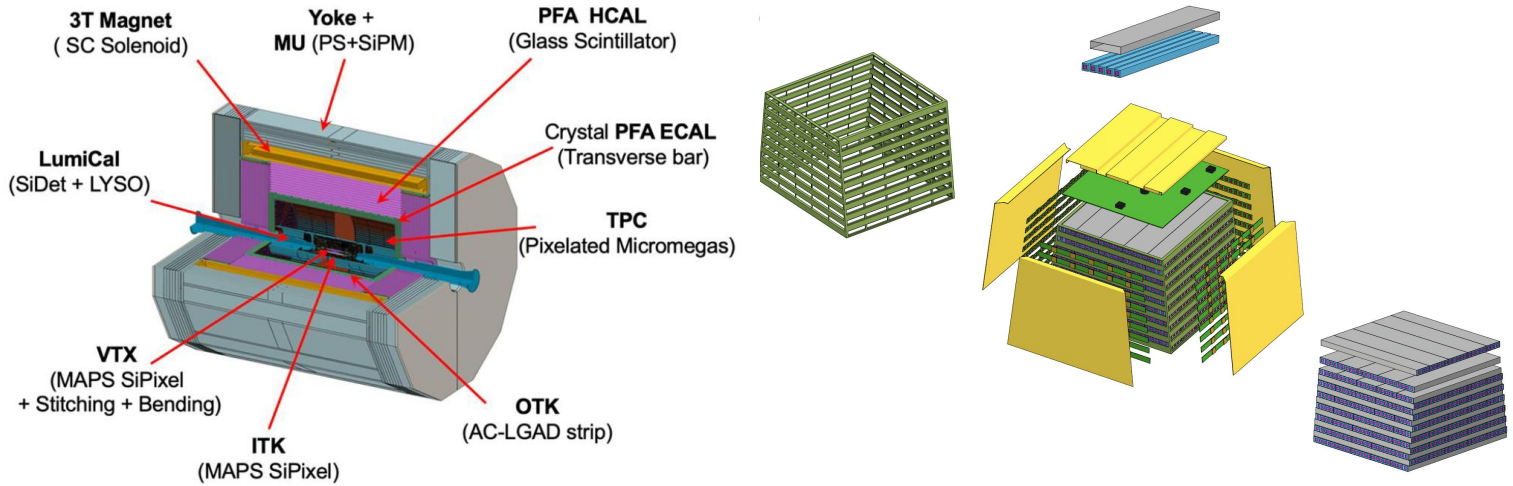
  # Sensors: 571,000 SiPMs;

  Mechanical structure: Carbon Fiber;

- FEA studies on:
  - stress;
  - deformation;
  - temperature gradient;

- **No showstopper seen.**



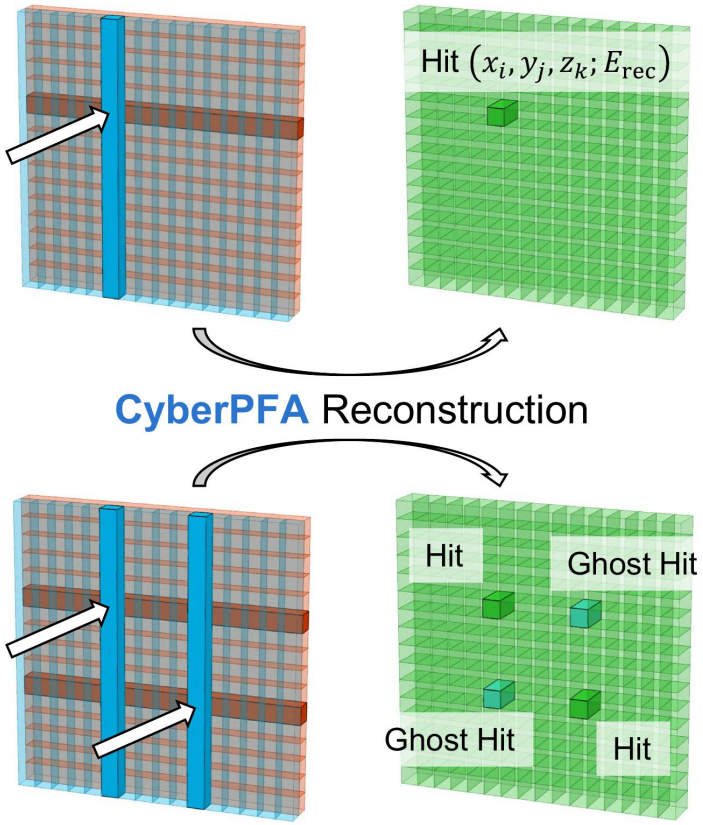


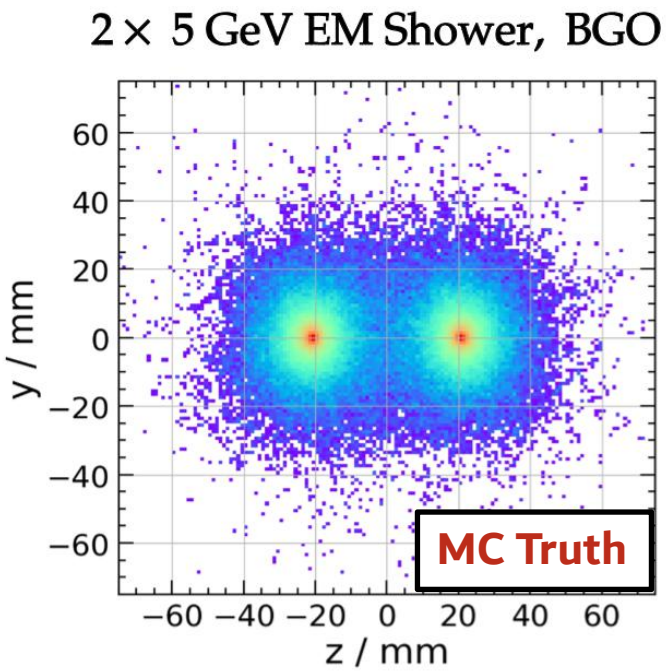
CyberPFA

- **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

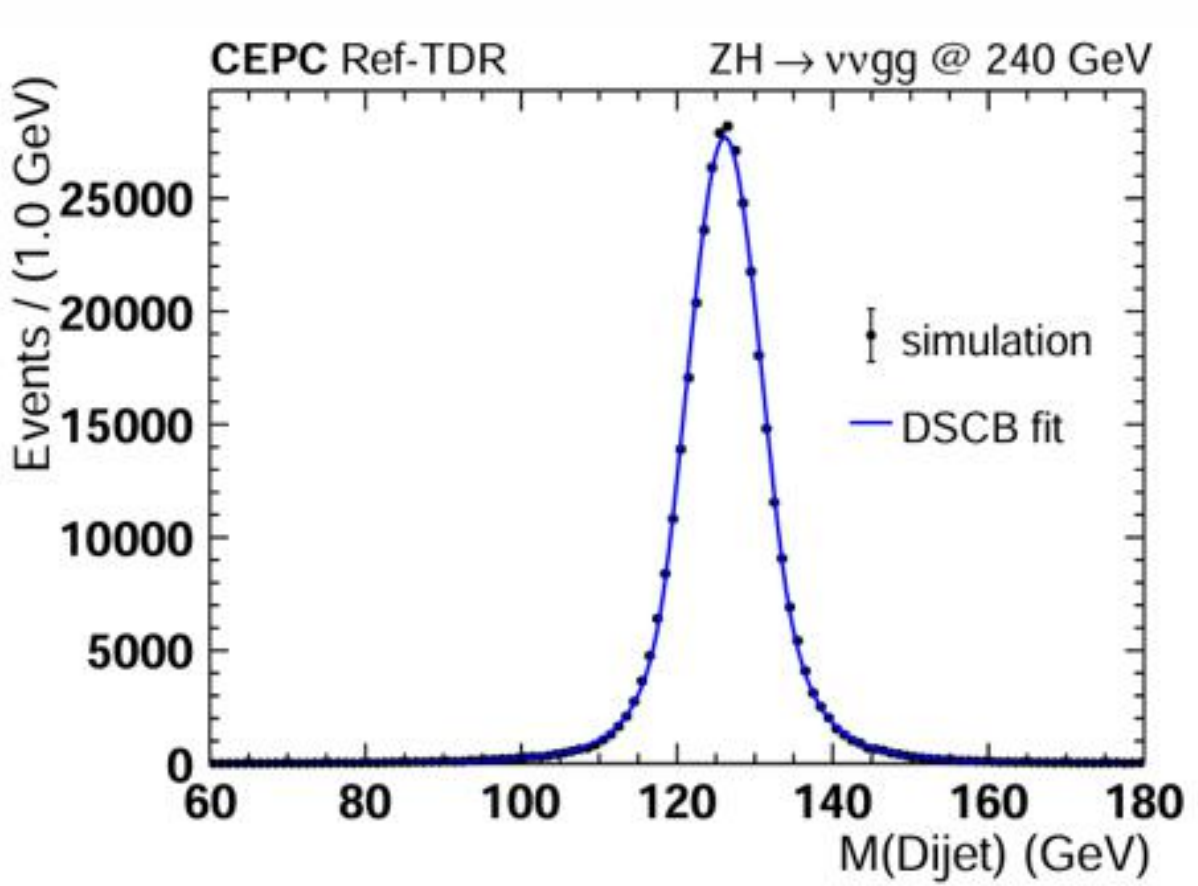
Crystal **B**ar **E**CA**L** **R**econstruction
Particle **F**low **A**lgorithm





CyberPFA: Higgs Mass Reconstruction

- **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 GeV
- **Fit:**
  double-sided Crystal Ball distribution (DSCB)



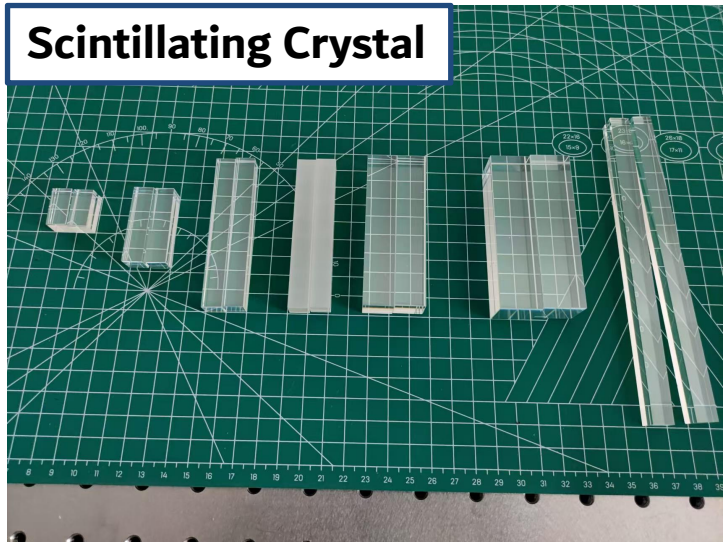
Take Home Message:

- m_H resolution: 3.87 ± 0.1 %
- achieves <4% BMR

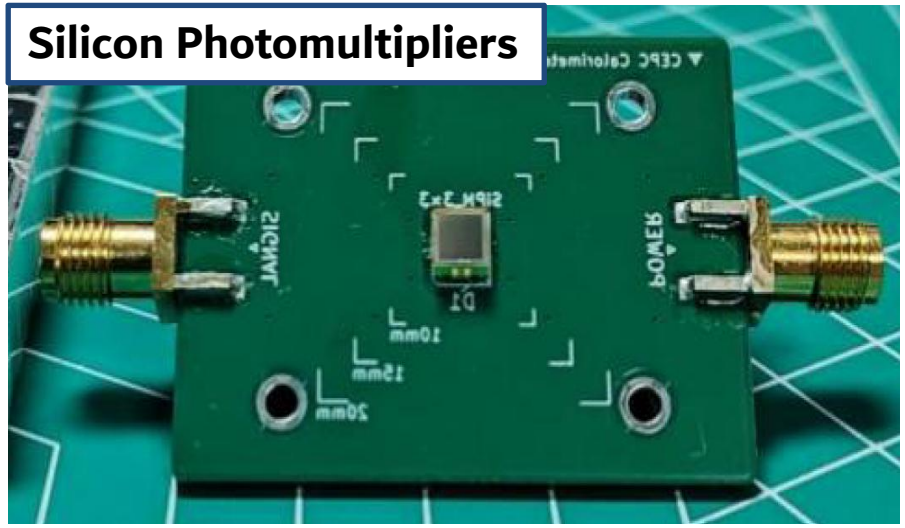
Preprint:arXiv:2602.21489

Crystal ECAL: Key Ingredients

Scintillating Crystal



Silicon Photomultipliers



Property	BGO	BSO
Light Yield	**8-10 kPh/MIP**	2.25 kPh/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**

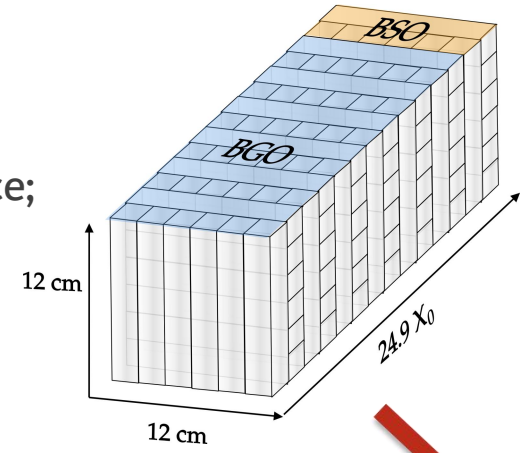
Property	NDL EQR06	NDL EQR10	HPK S14160
Pixel Pitch	6 µm	10 µm	10 µm
# Pixels @ 3x3mm^2	**244 719**	90 000	89 984
PDE	30% @ 420 nm	**36% @ 420nm**	18% @ 460 nm
DCR @ 20^{0}C	2.5 MHz	3.6 MHz	**700 kHz**
Crosstalk Probability	12%	N/A	**< 1%**

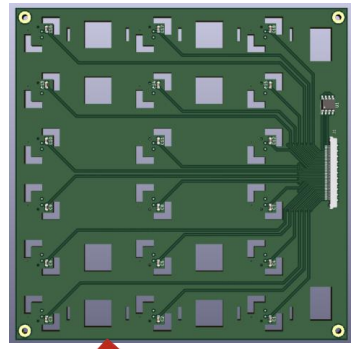
Physics Prototype Design

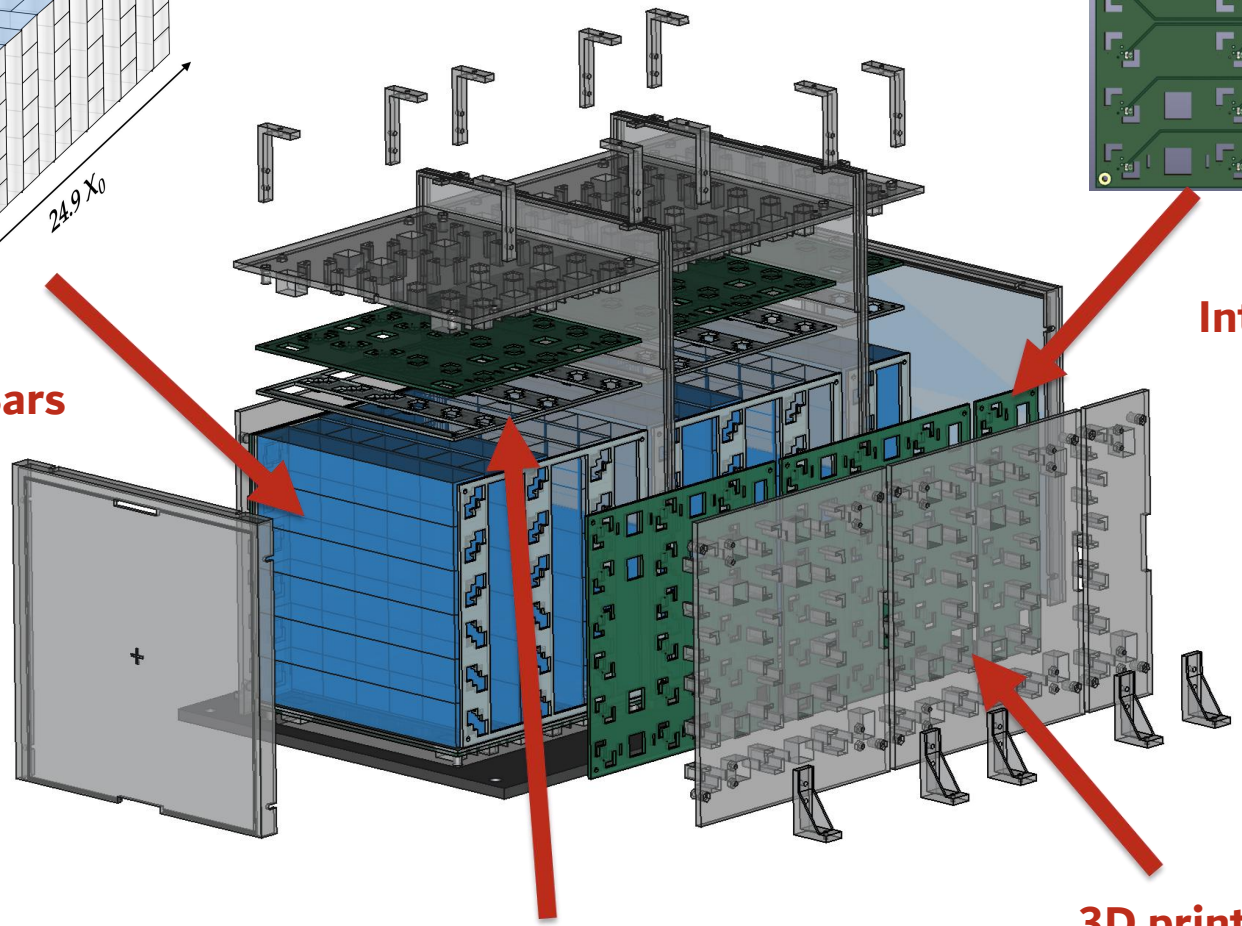
Goals:
- minimize material budget;
- minimize stress on PCB;
- shield signal from EM interference;
- maximize scintillation light;

Calorimeter:
- 12×2×2 cm^3 BGO/BSO bars
- 20 GeV e^- → 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;







PS-T9: Experimental Goals

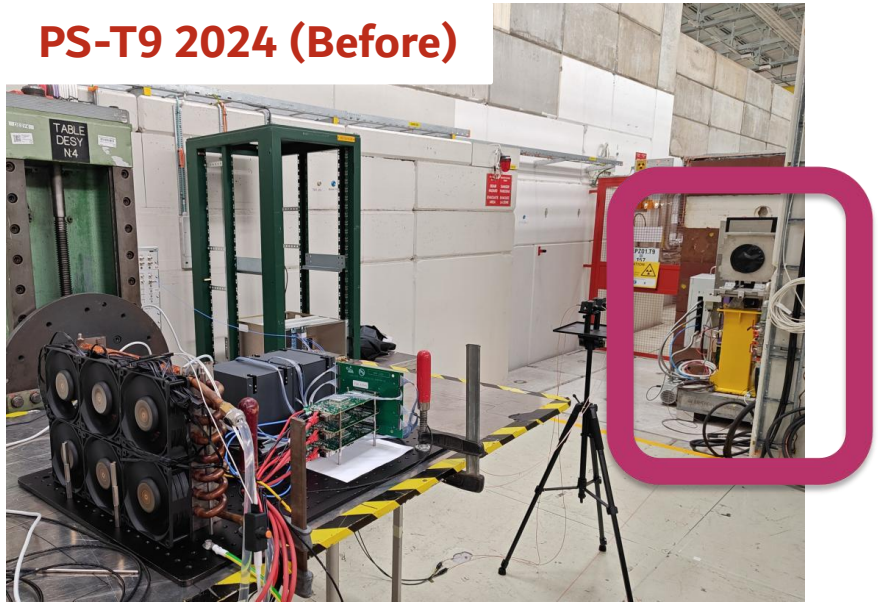
Goal: measure linearity/energy resolution of calorimeter

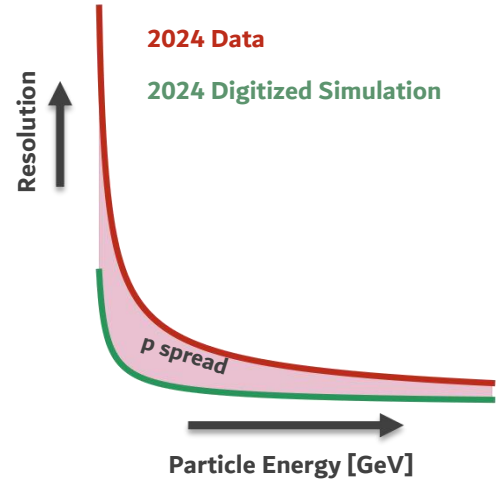
- **Problem:**
  beam momentum spread of the same order as the resolution;

- **Reason:**
  Testbeam in 2024 included upstream instrumentation:
  → SciFi trackers;
  → Cherenkov Detectors;

- **Solution**:
  remove upstream instrumentation
  → reduce momentum spread;
  → measure resolution more accurately;

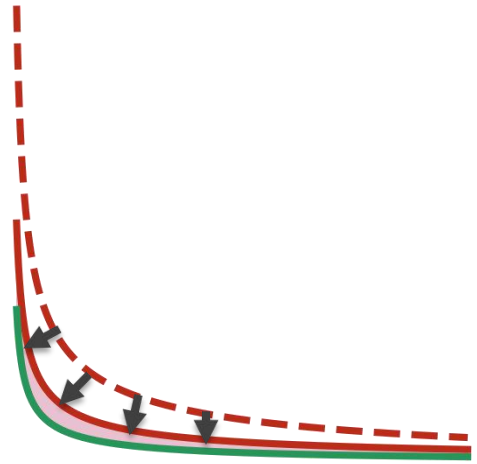
PS-T9 2024 (Before)





PS-T9 2025 (After)



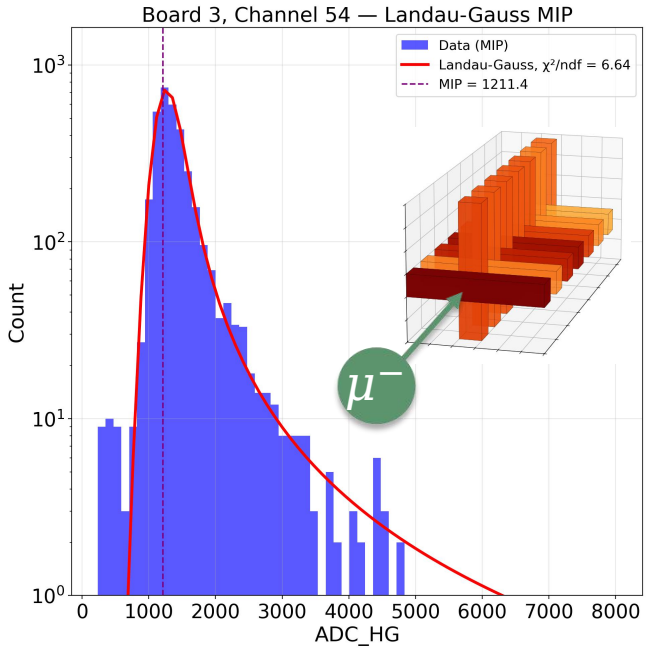


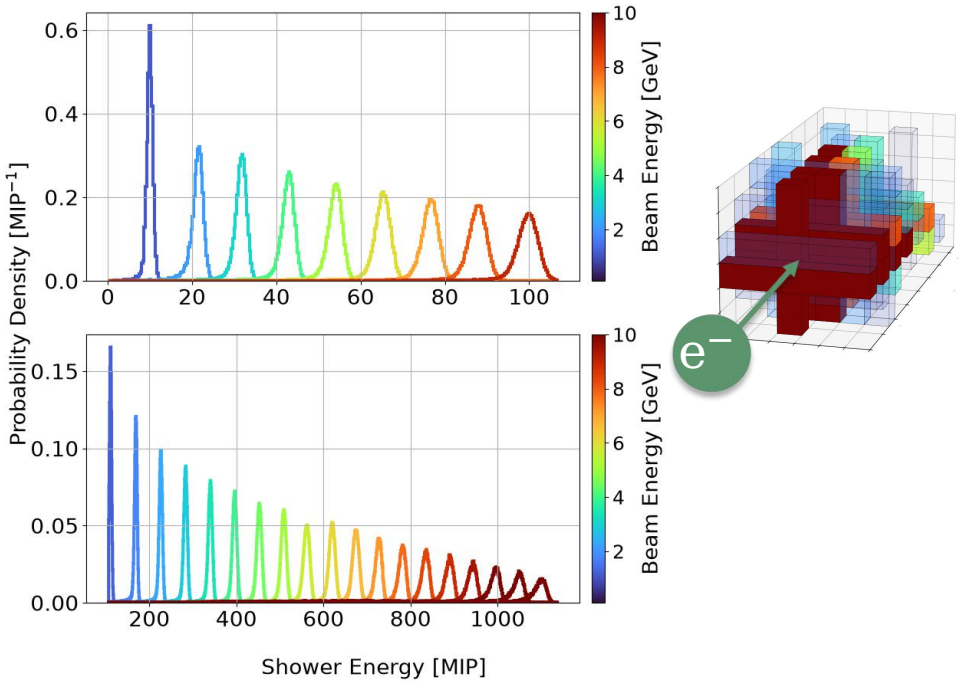
PS-T9: Study Programme

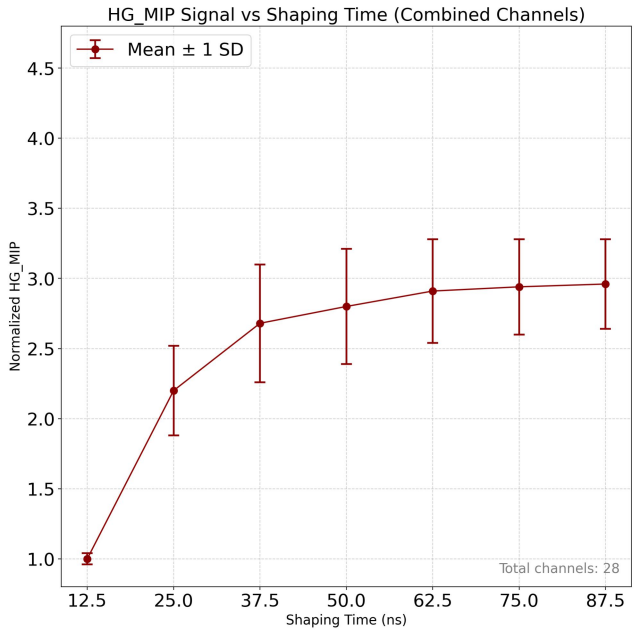
MIP calibration
- Studied 5 positions on front face;
- μ^+/π^+ used for MIP calibration;
- Repeated through campaign;

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;

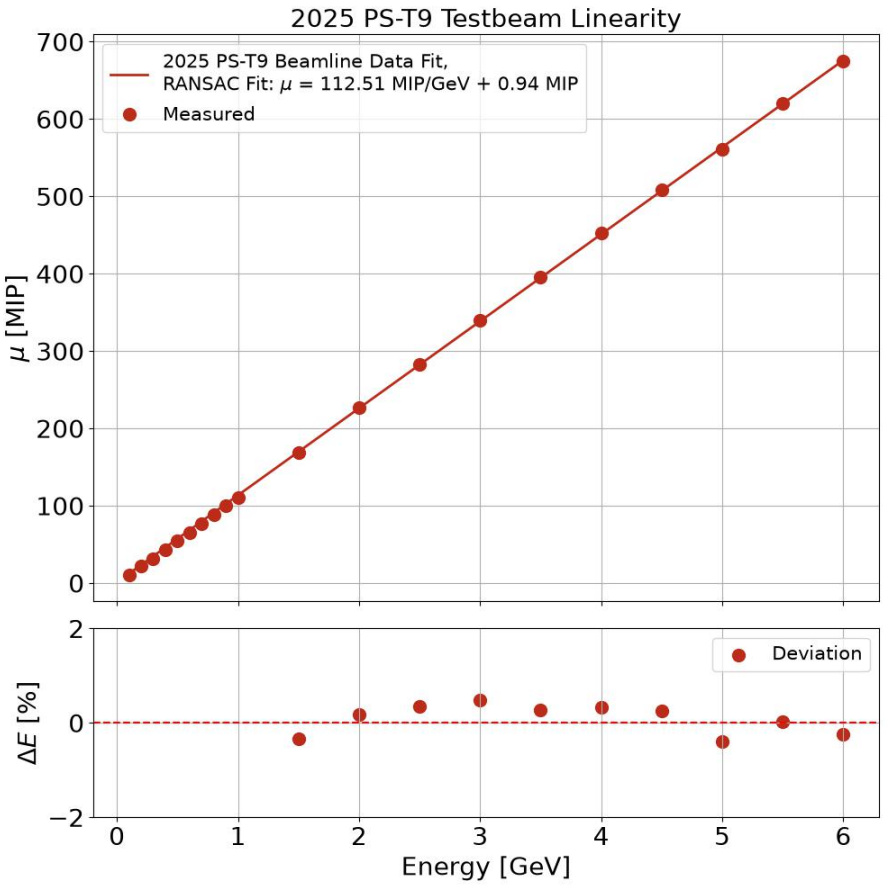


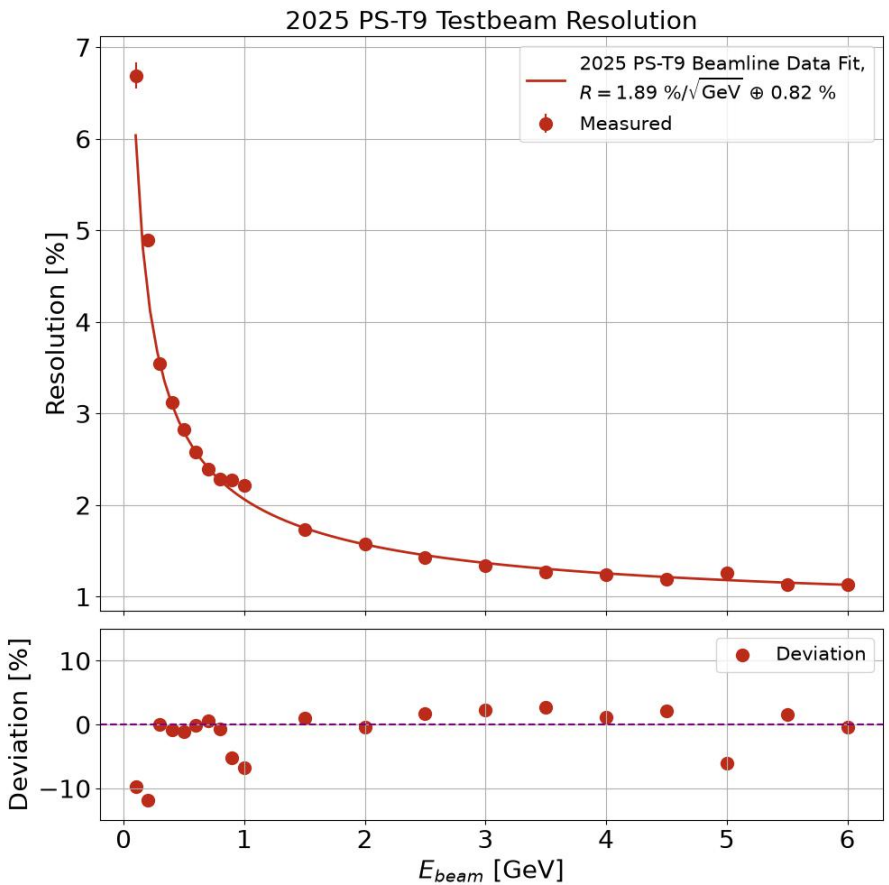




PS-T9: Linearity and Resolution

- **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:

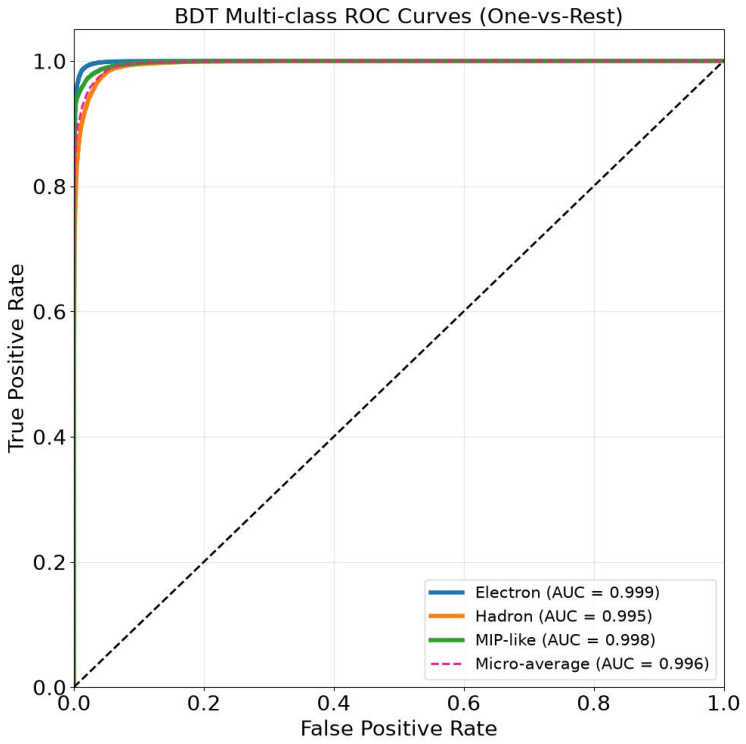
HG Crystal Calorimeter:

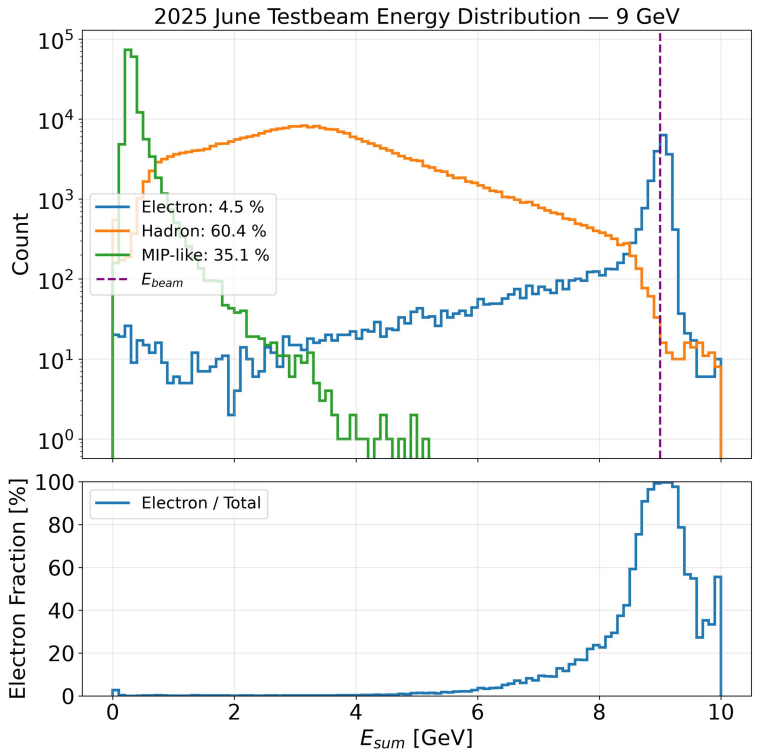
- linear within 1%
- achieves 2% resolution target

PS-T9: Particle Identification

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!**

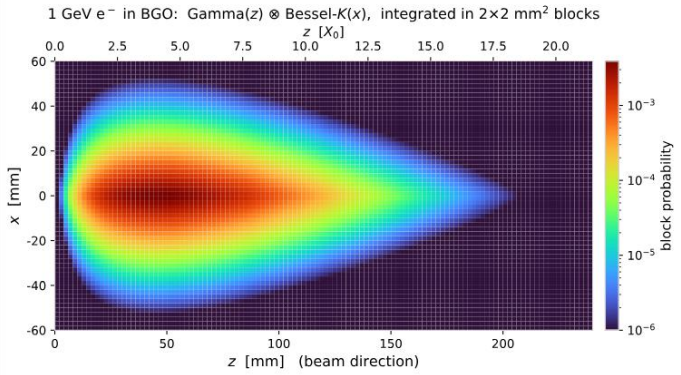
Paper: Preprint pending

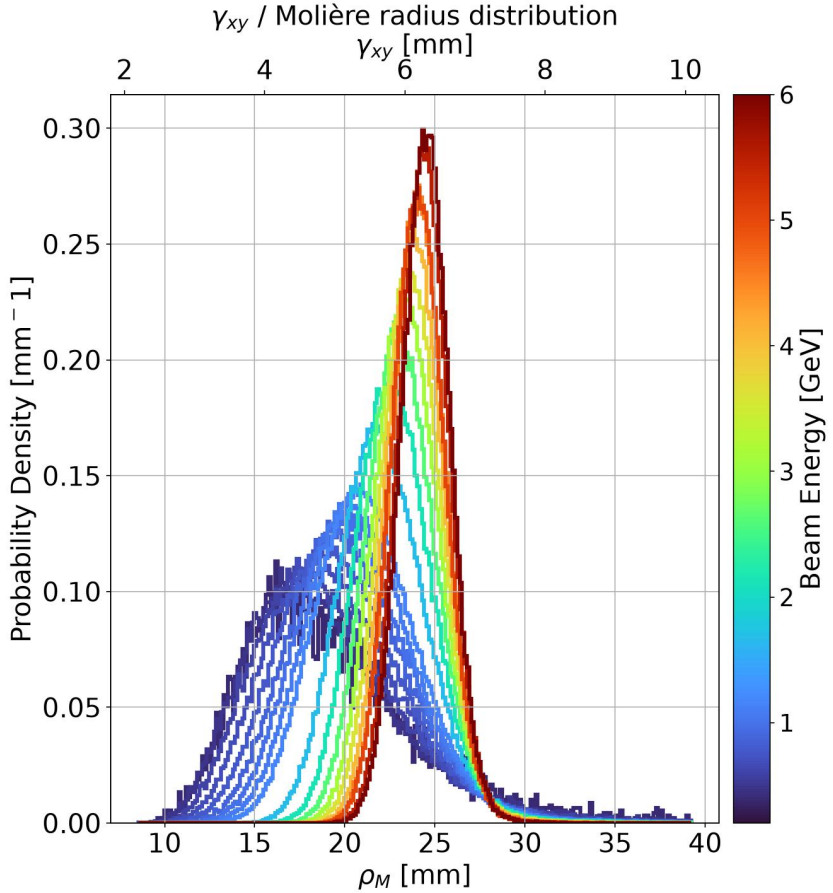
See more on Poster C04

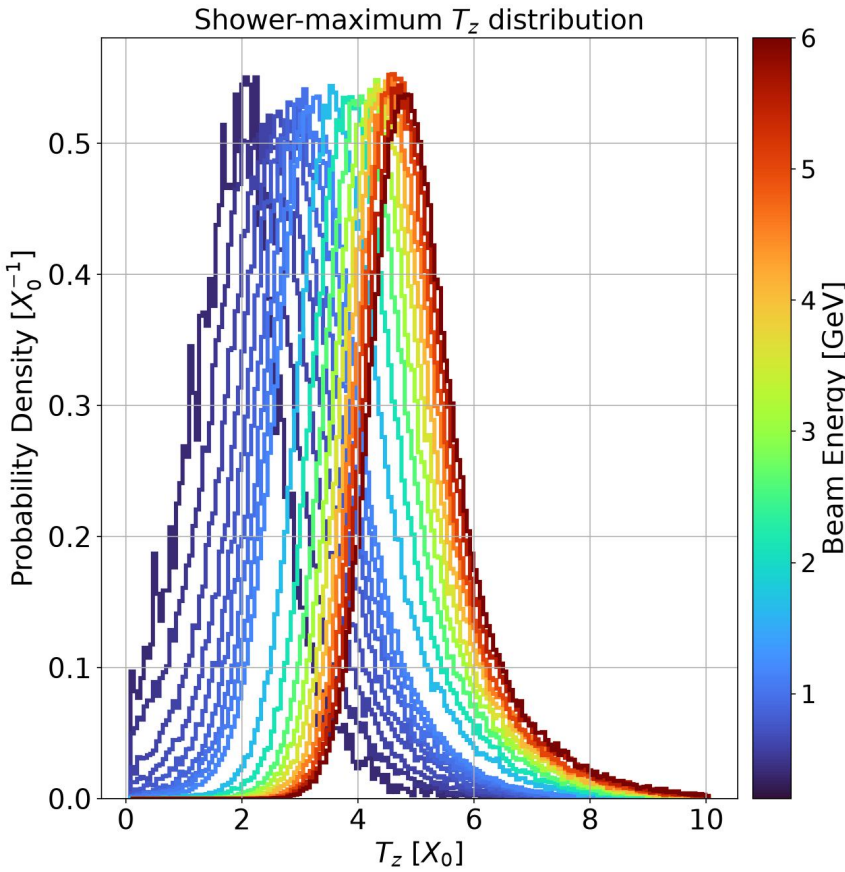
PS-T9: Shower Shape Distributions

Goal: study shower shape flucuations

- 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 ~log-normally distributed
- **New measurement as far as we know below 1 GeV**

Paper: Preprint pending

See more on Poster C01

PS-T9: Absorber Properties

Goal: extract BGO/calorimeter absorber properties from shower shapes

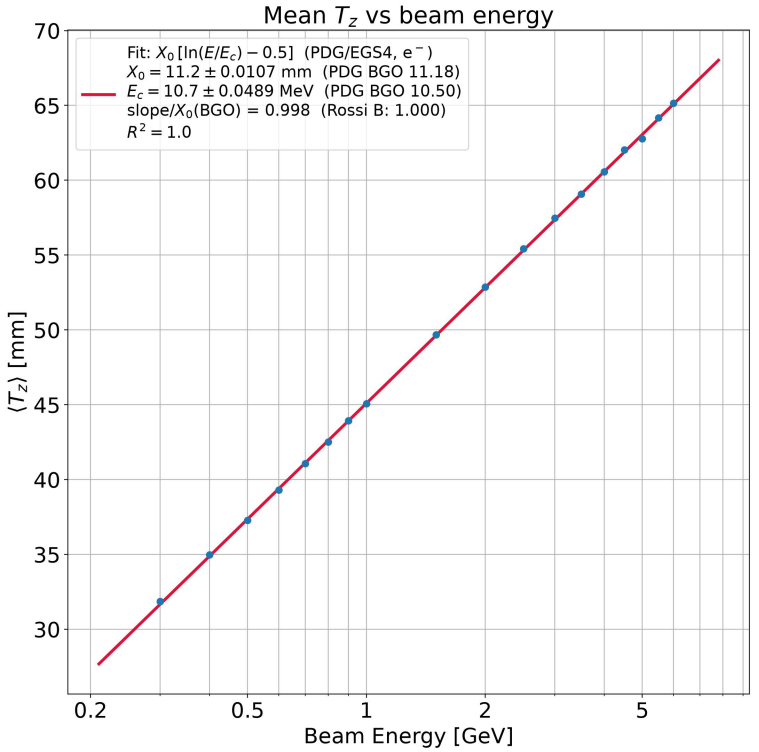
$$\langle T_z \rangle = X_0 \left(\log \left(\frac{E}{E_c} \right) - 0.5 \right)$$

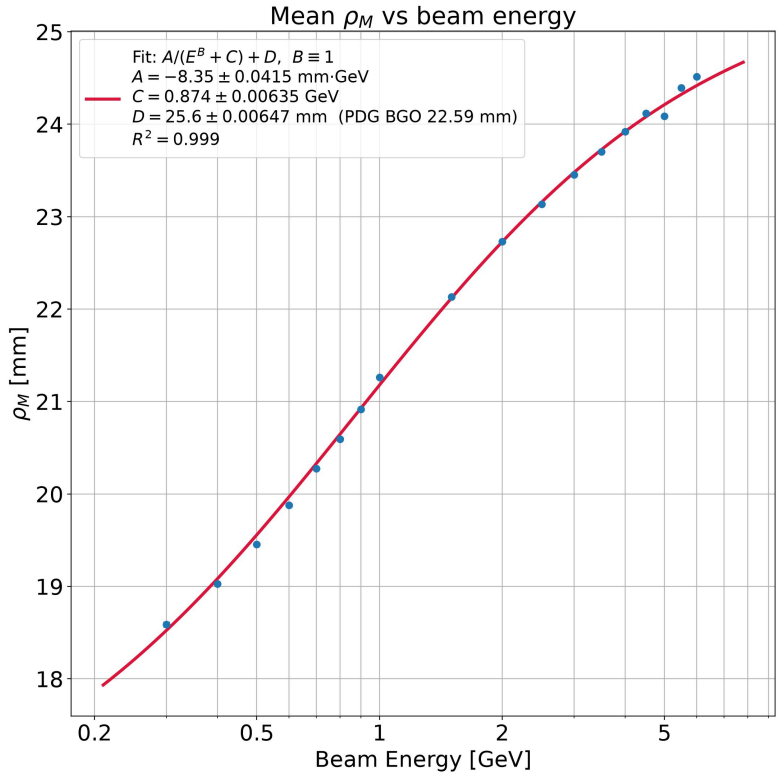
Radiation Length (X_0):
distance over which electron loses 63.2% of its energy;

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

Paper: Preprint pending

See more on Poster C01

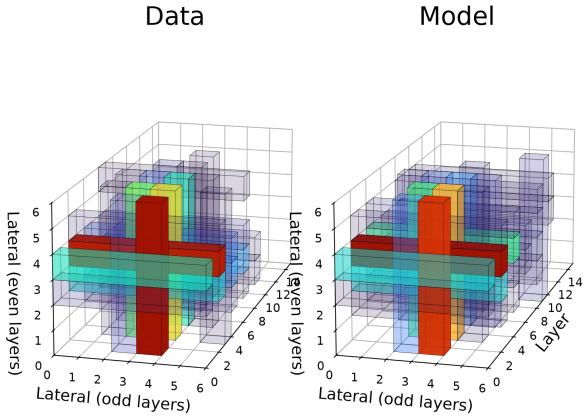
PS-T9: Fast Shower Simulation

Goal: build fast shower simulation;

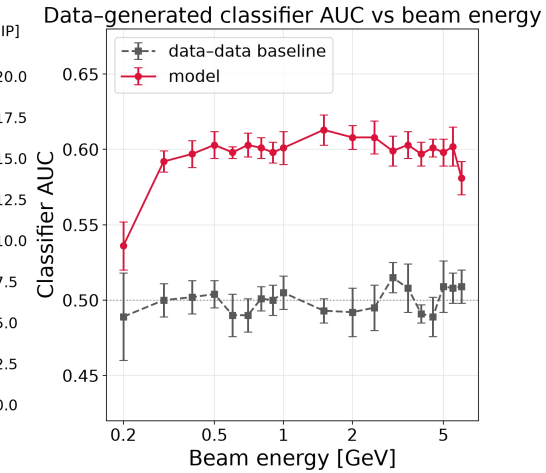
- Excellent energy resolution/granularity means bar-by-bar energy fluctuations can be studied;
- **Key Result:**
  Bar-to-bar energy fluctuations follow a single simple distribution once the shower shape is known;
- Sampling this distribution given a shower shape reproduces a full shower;

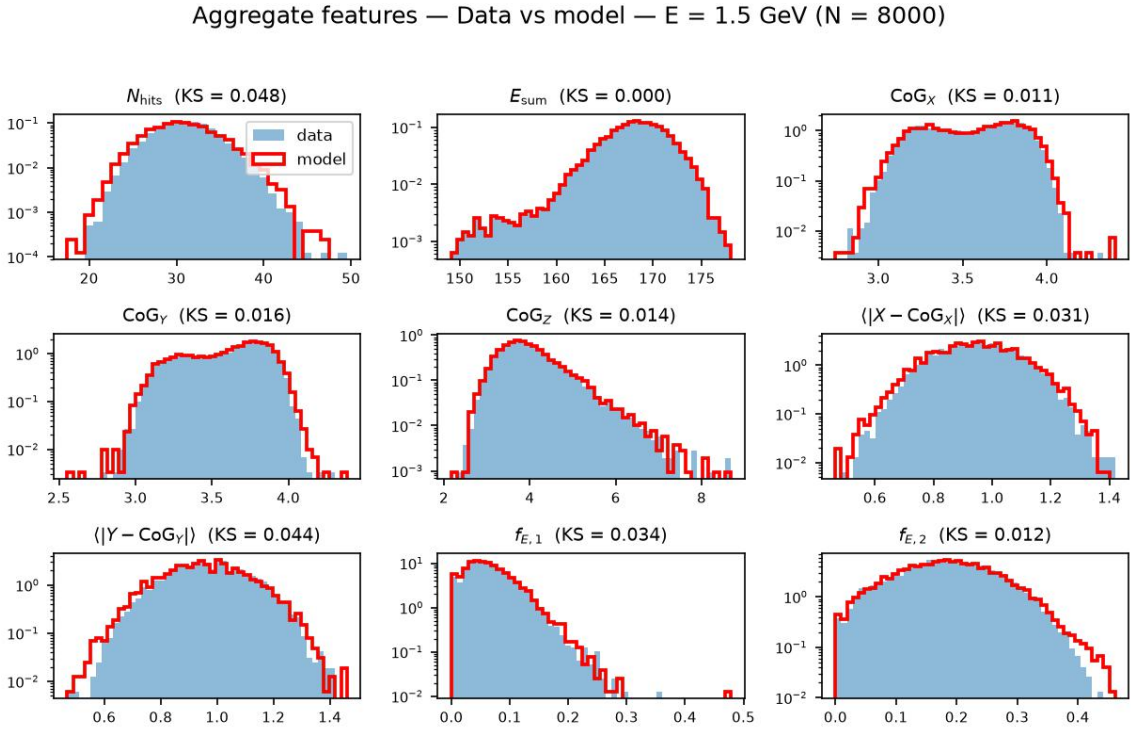
Take Home Message:

- 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**



E = 1 GeV, E_{sum} = 111 MIP





Paper: Preprint pending

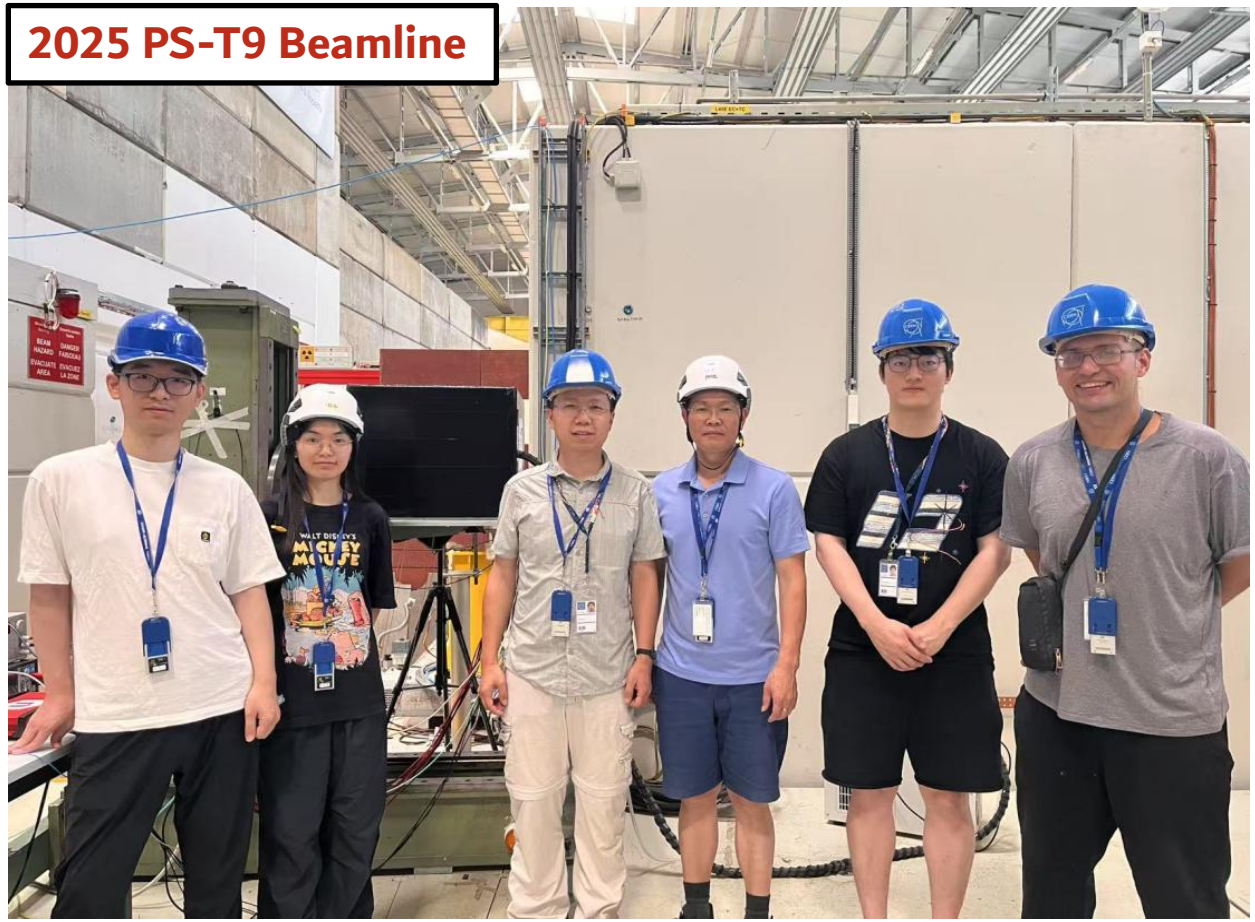
See more on Poster C01

Conclusion

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



Backup: CyberPFA: Innovations

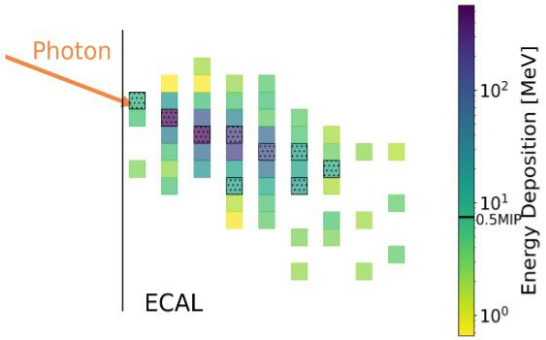
Key innovations

1. Shower recognition using the 'energy core'
   → i.e. shower-axis finding for photons;

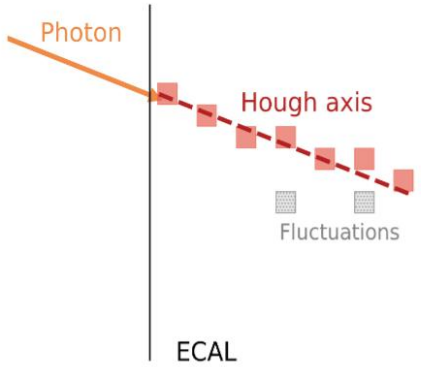
2. Fit of longitudinal profile to split nearby energy deposits;

3. 'Optimized' selection of hits based on 'best matching hit combinations';
   (i.e. longitudinal shower profiles)

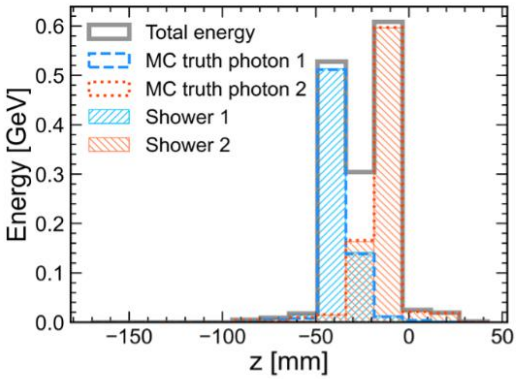
1. Select local energy maxima



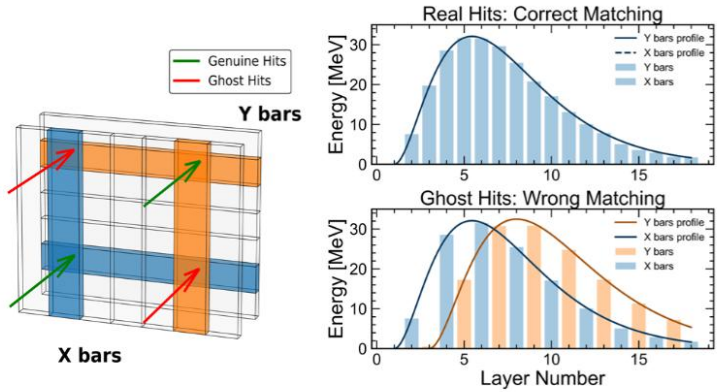
2. Find shower axis



3. Split closeby showers using weighted longitudinal profile



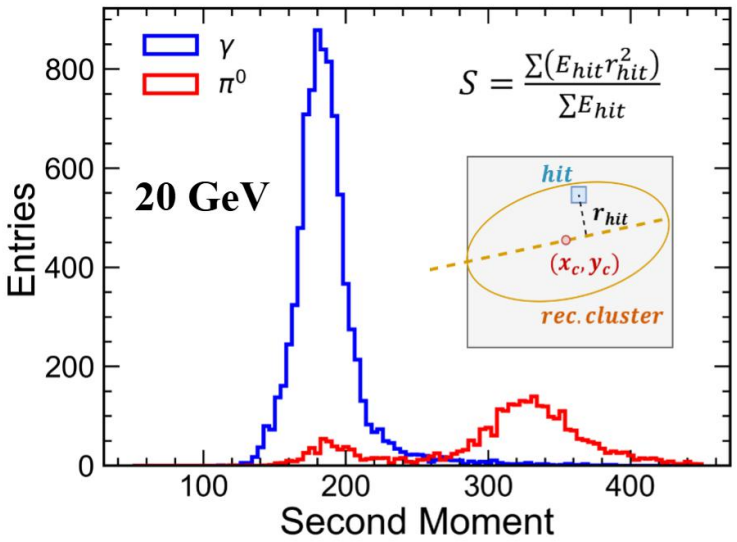
4. Find optimal hit combination (profile, timing, nbr. module)

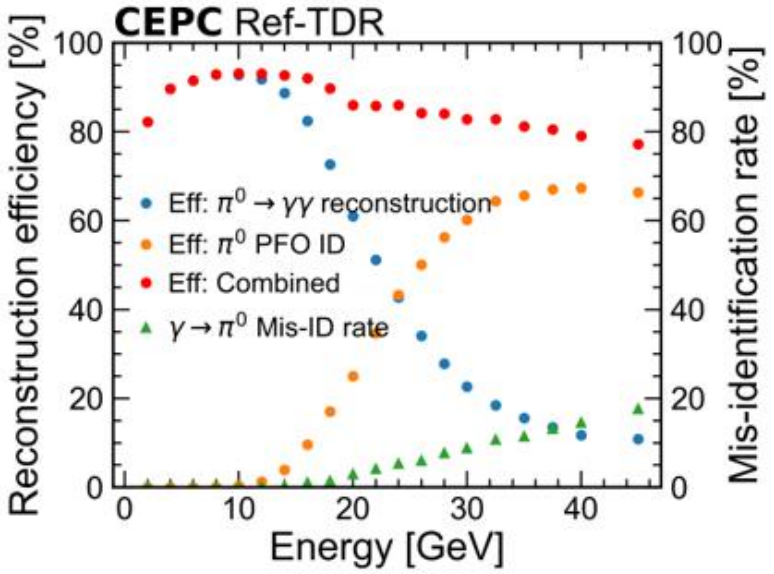


Paper: 10.1088/1748-0221/21/03/P03003

Backup: CyberPFA: $\pi^0 \rightarrow \gamma\gamma$

- **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

Backup: PS-T9 Experimental Goals

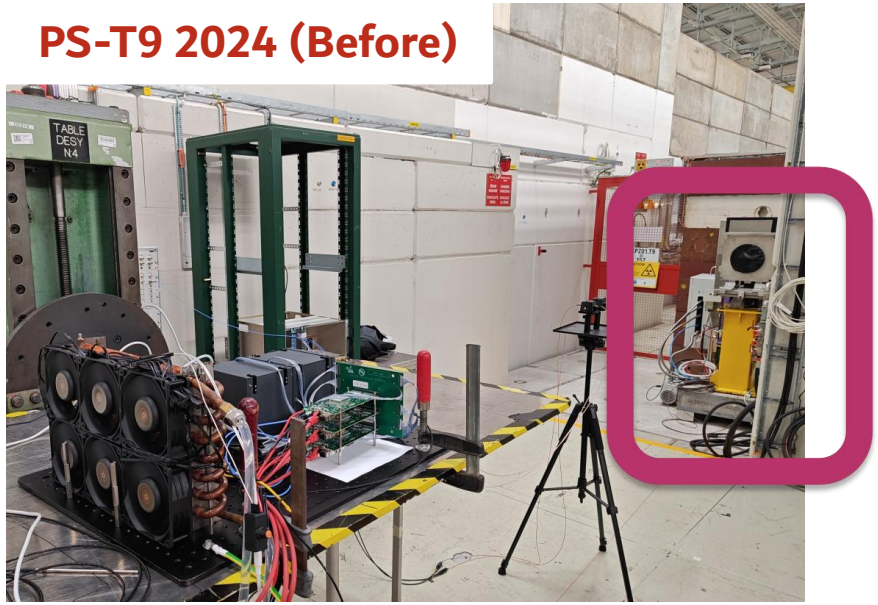
Goal: measure linearity/energy resolution of calorimeter

- **Problem:**
  beam momentum spread of the same order as the resolution;

- **Reason:**
  Testbeam in 2024 included upstream instrumentation:
  → SciFi trackers;
  → Cherenkov Detectors;

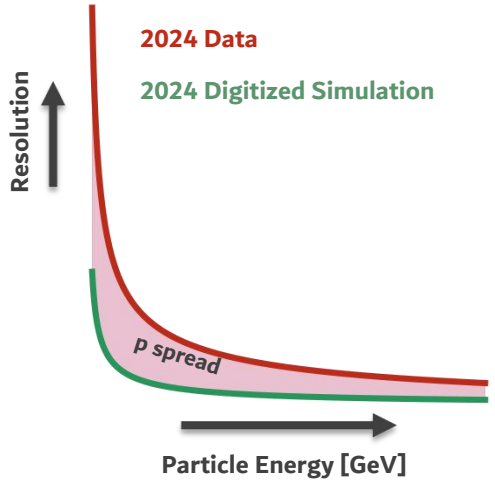
- **Solution**:
  remove upstream instrumentation
  → reduce momentum spread;
  → measure resolution more accurately;

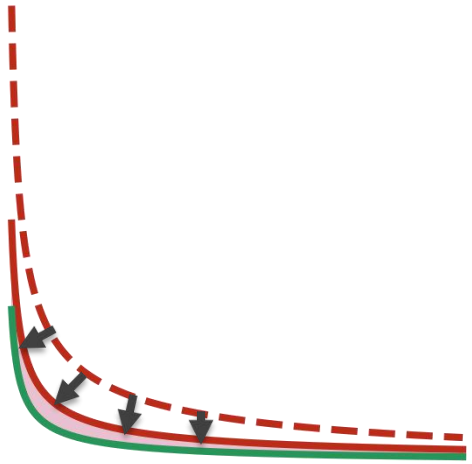
PS-T9 2024 (Before)



PS-T9 2025 (After)







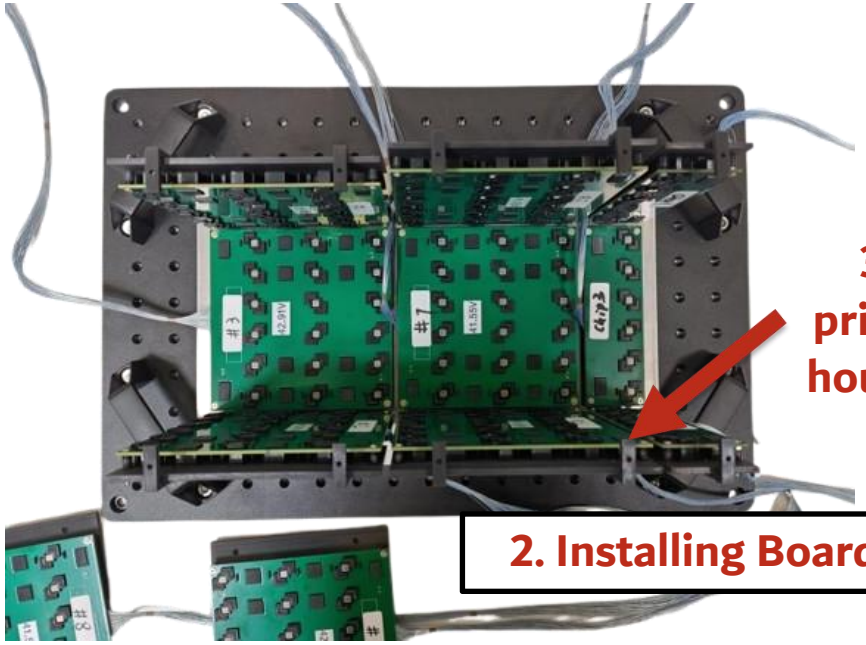
Backup: Calorimeter Commissioning

PCB with SiPMs

Baseplate



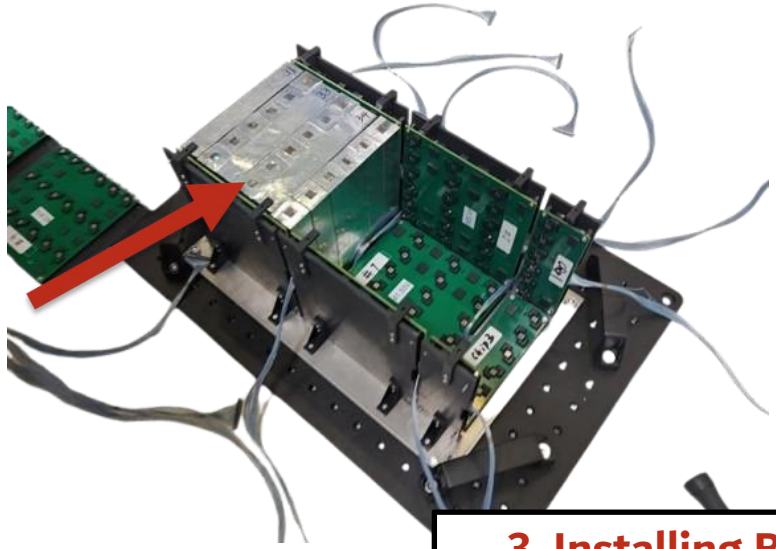
1. Pre-Assembly



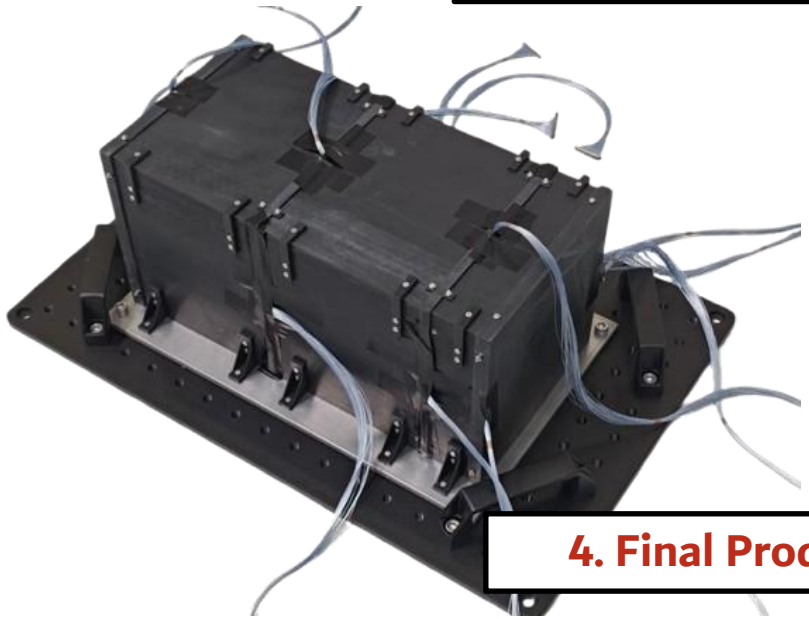
3D printed housing

2. Installing Boards

ESR-Wrapped Crystal Bars



3. Installing Bars



4. Final Product

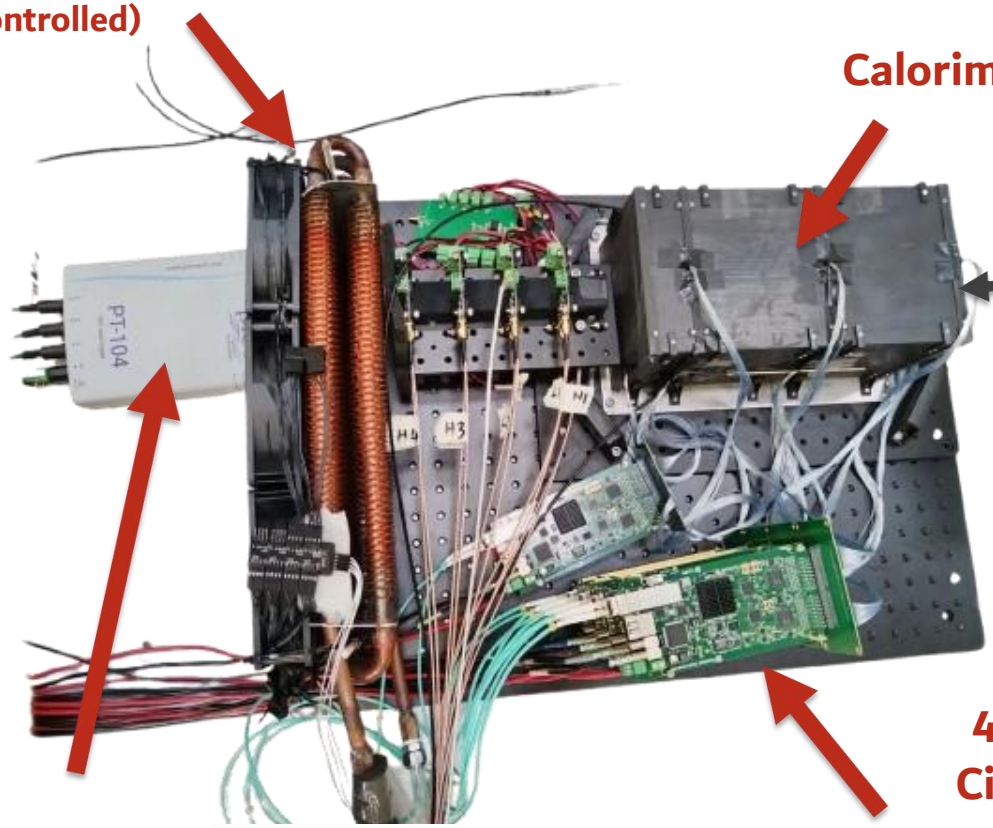
Backup: PS-T9 setup

Main Setup (Top View)

Cooling Radiator (15 ± 0.5C, controlled)

Calorimeter

Beam (aligned to calorimeter with Bosch laser)



PT-104 Temperature Logger



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

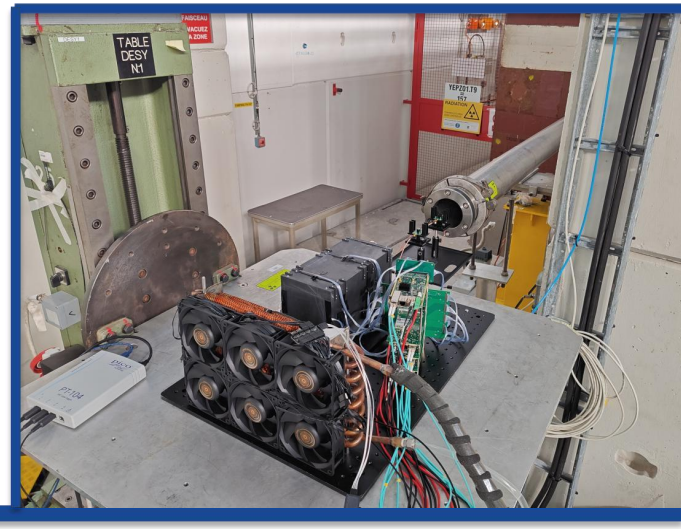


Trigger Setup (Side View)

Beam Pipe



Two 1×1×1 cm³ (6×6×1 cm³) Gls. Sc. Trigger Cubes

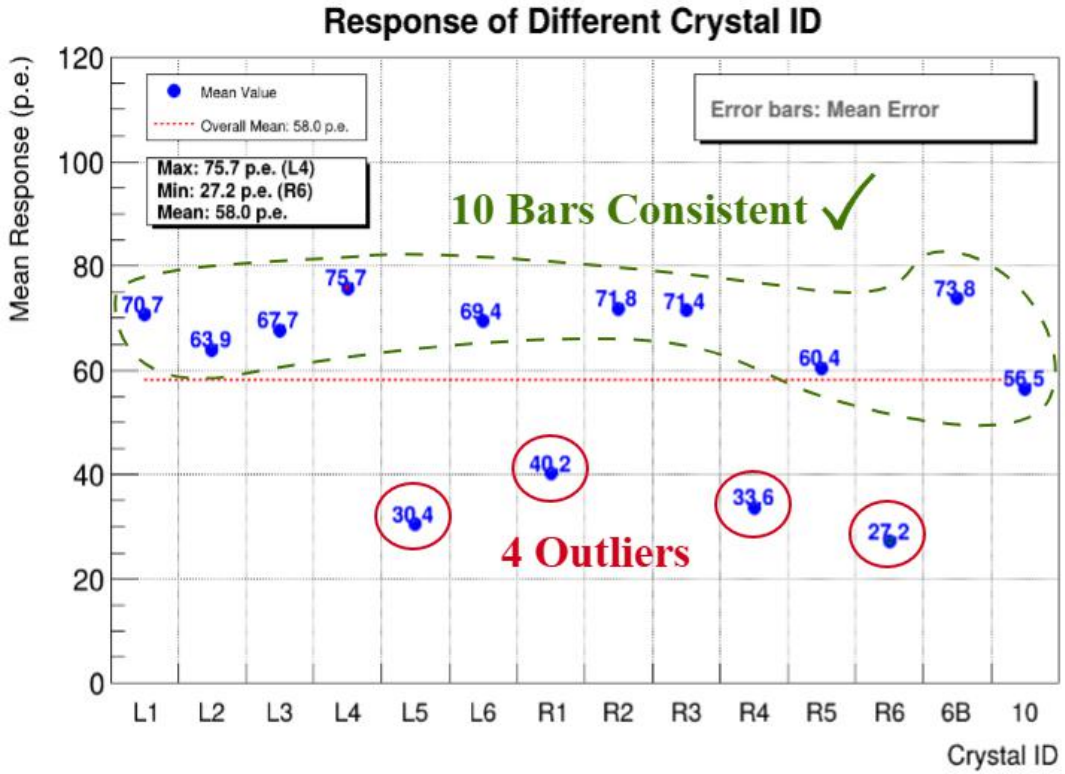


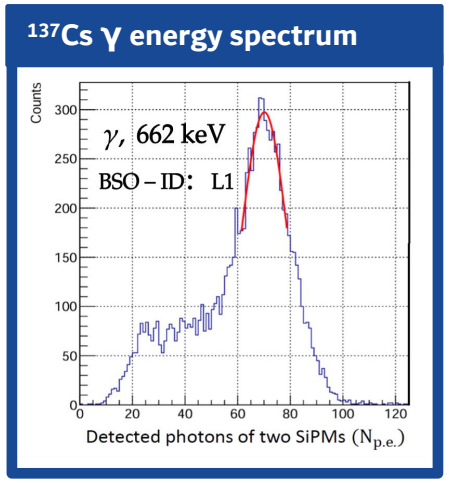
Backup: Crystal: Uniformity Studies

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

- Response uniformity of batch of fourteen 2×2×12 cm^3 bars measured;

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



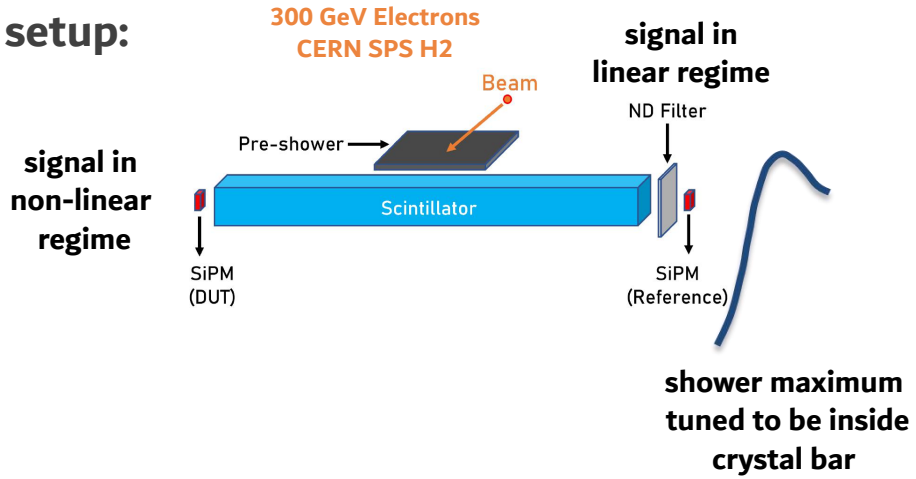


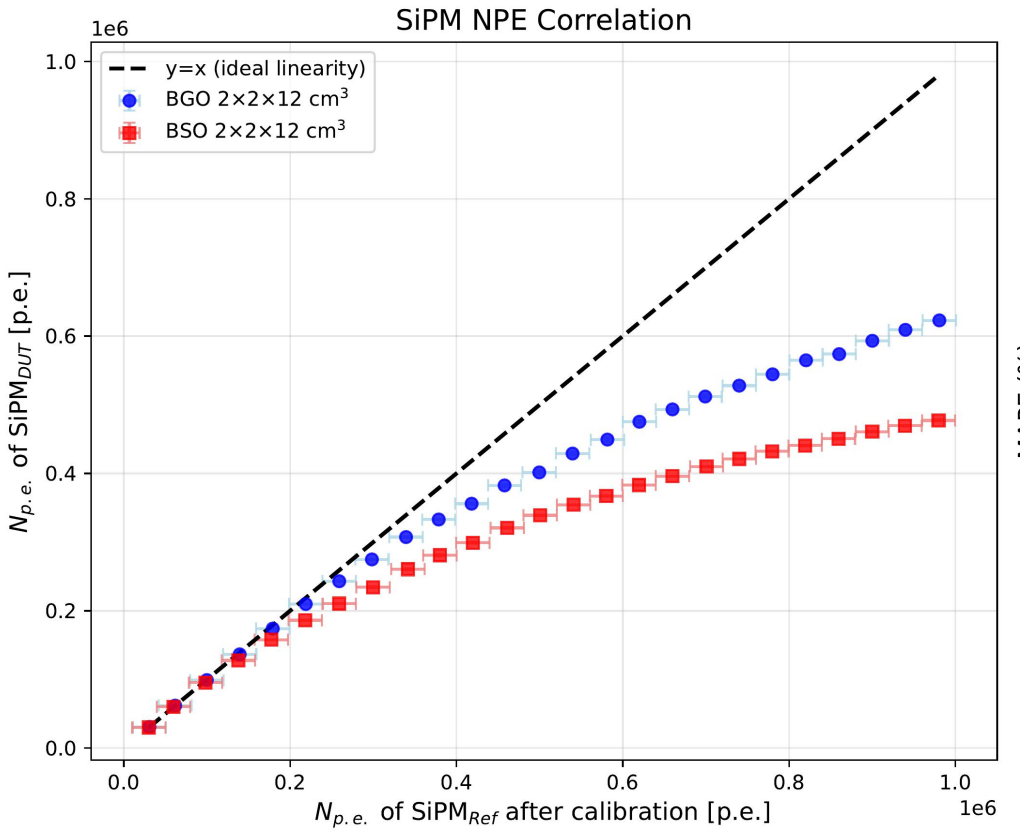
Take Home Message:

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

Backup: SiPM: Nonlinearity Studies

- **SiPMs required to operate up to 5×10^5 p.e;**
- **SiPMs have limited pixels**
  → **non-linearity** is a correctable problem;
- **Slow scintillation time** of BGO can be advantageous:
  - SiPM pixels recover in $\tau_{rec} \approx 20$ ns
  - Scintillation time of BGO $\tau_{scint} \approx 300$ ns
  - **Higher effective # pixels can fire;**
- **Test setup:**





Take Home Message:

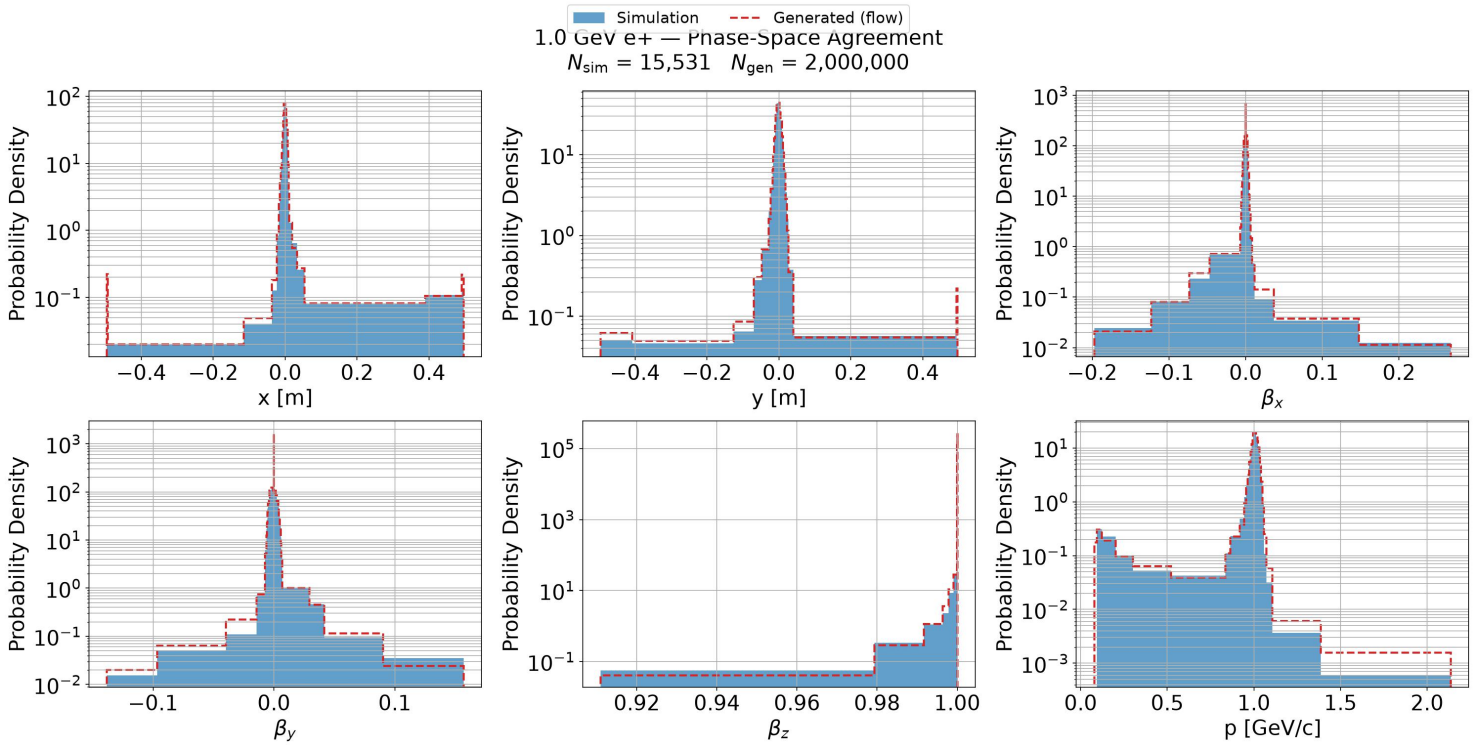
- BGO deviates 12% less than BSO from linearity;
- BGO slower → more pixels can fire, non-linearity less severe

Preprint: arXiv:2603.08167v1

Backup: PS-T9 Results: Beamline Fast Simulation

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