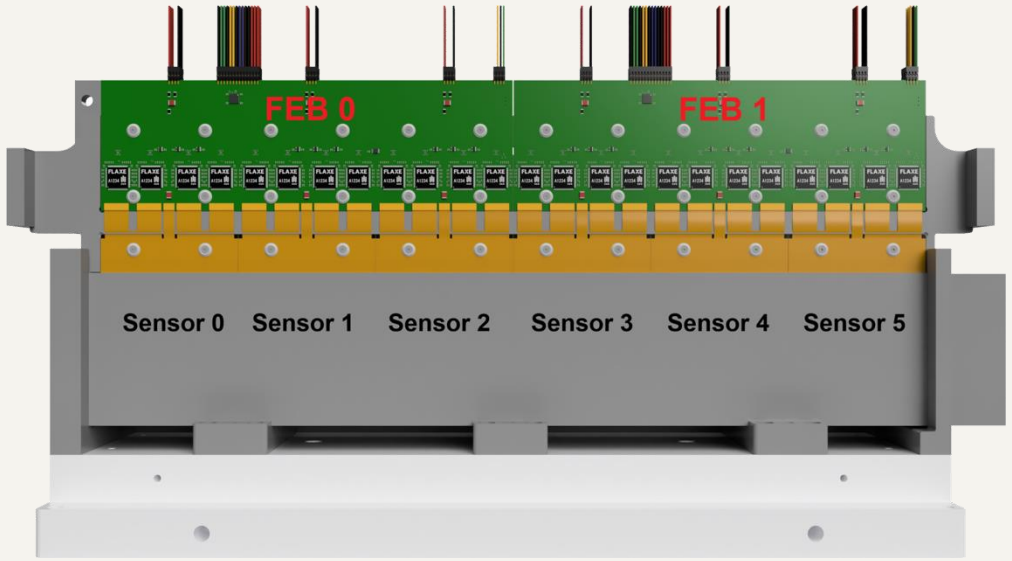
LCWS2026, KEK, Tsukuba · 12 November 2026

Performance of a compact and finely granulated ECAL in an electron beam of 1–6 GeV energy

Yan Benhammou · Tel Aviv University

on behalf of the FCAL (LUXE ECAL-P) collaboration · results shown are preliminary



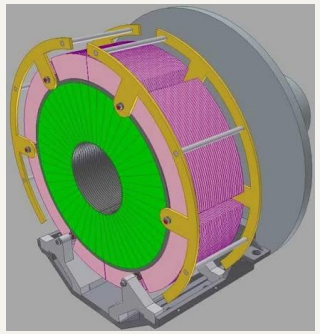


The ECAL-P : two front-end boards (FEB 0, FEB 1) and six silicon sensors

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

ECAL-P: a calorimeter built to be compact for LUXE

- Measures the number and energy spectrum of positrons after each LUXE bunch crossing (1Hz)
- Multiplicity spans about 10^{-4} to 10^{7} positrons per laser pulse
- Low Multiplicity : single showers on a wide background. High Multiplicity : overlapping showers, only the total multiplicity is accessible
- Both regimes need the smallest possible transverse shower size, hence a W-Si sandwich with very thin gaps
- Concept inherited from FCAL compact luminosity calorimeters for future Higgs factories



21 × 3.5 mm
tungsten plates, 1 X0 each

1 mm
gap for each silicon sensor sandwich

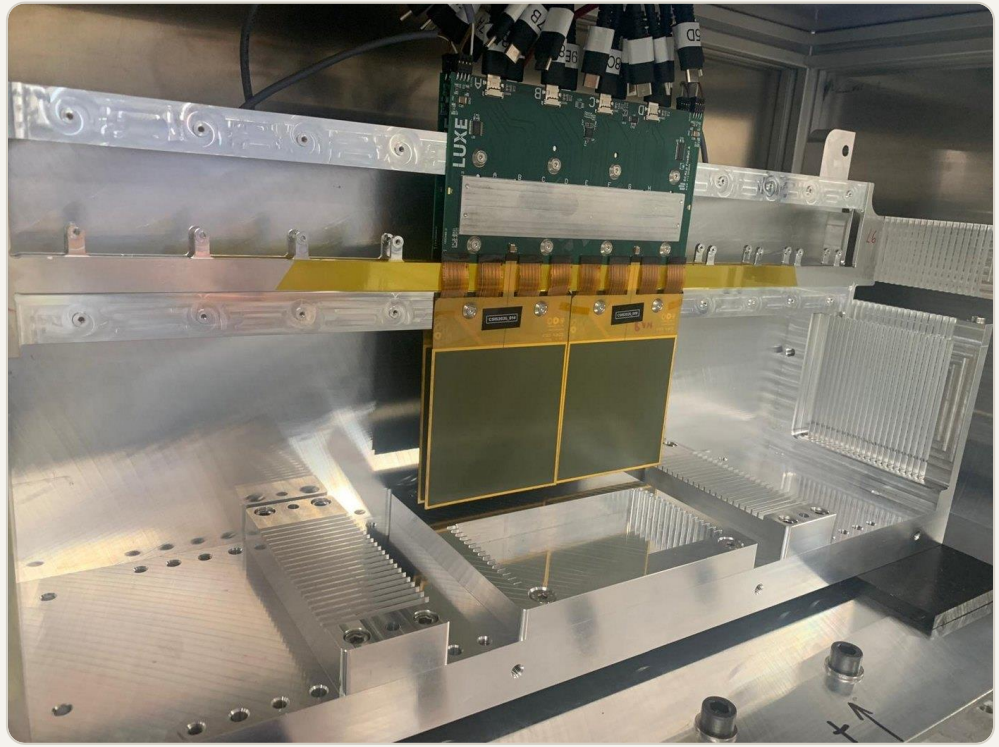
20
active planes

6 sensors
per plane, 550 × 90 mm²

5.5 mm
pads, 16 × 16 on a 320 µm sensor

30,720
readout channels

TB2025 at DESY: setup and data



250 M
events, about 1 kHz

1–6 GeV
electron beam at DESY

11 layers
Si-W, extra W in front, 6 ALPIDE telescope planes

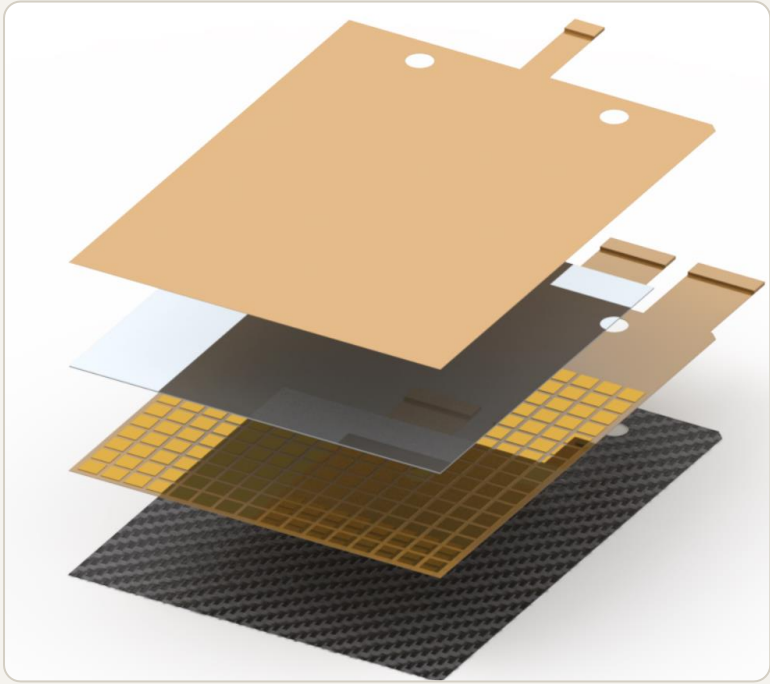
1.2 Gbps
after FPGA data reduction at 1 kHz; stable to 2 kHz

Uptime: 11 layers for 5 d 17 h, about 71 FPGA-days in total

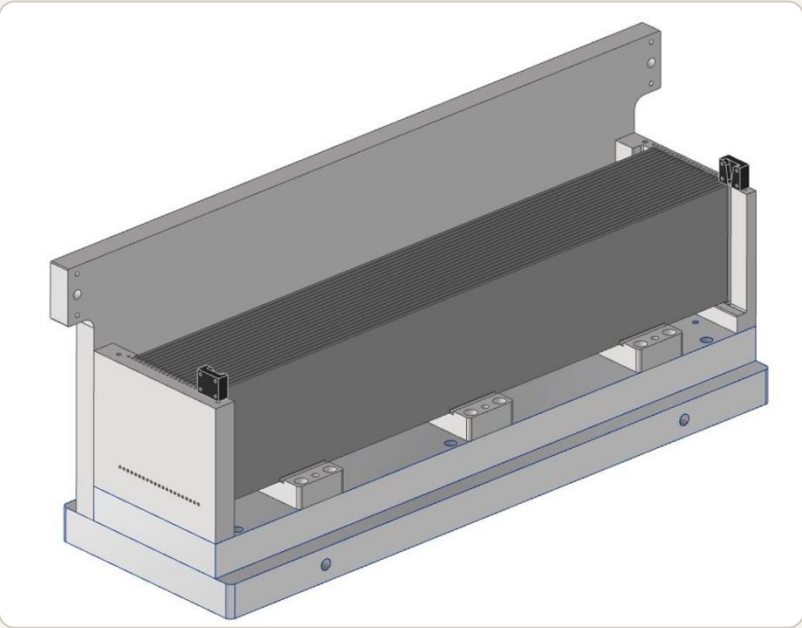
Issues: ASIC-to-FPGA link drops, one ASIC lost from the start, noise from non-optimal grounding and shielding

ECAL-P sensor: Compact Sensor Interface System (CSIS)





Mechanics



Aluminium frame, machined to 10 µm



Nine plates from three different vendors

Nominal sensor gap of 1.2 mm

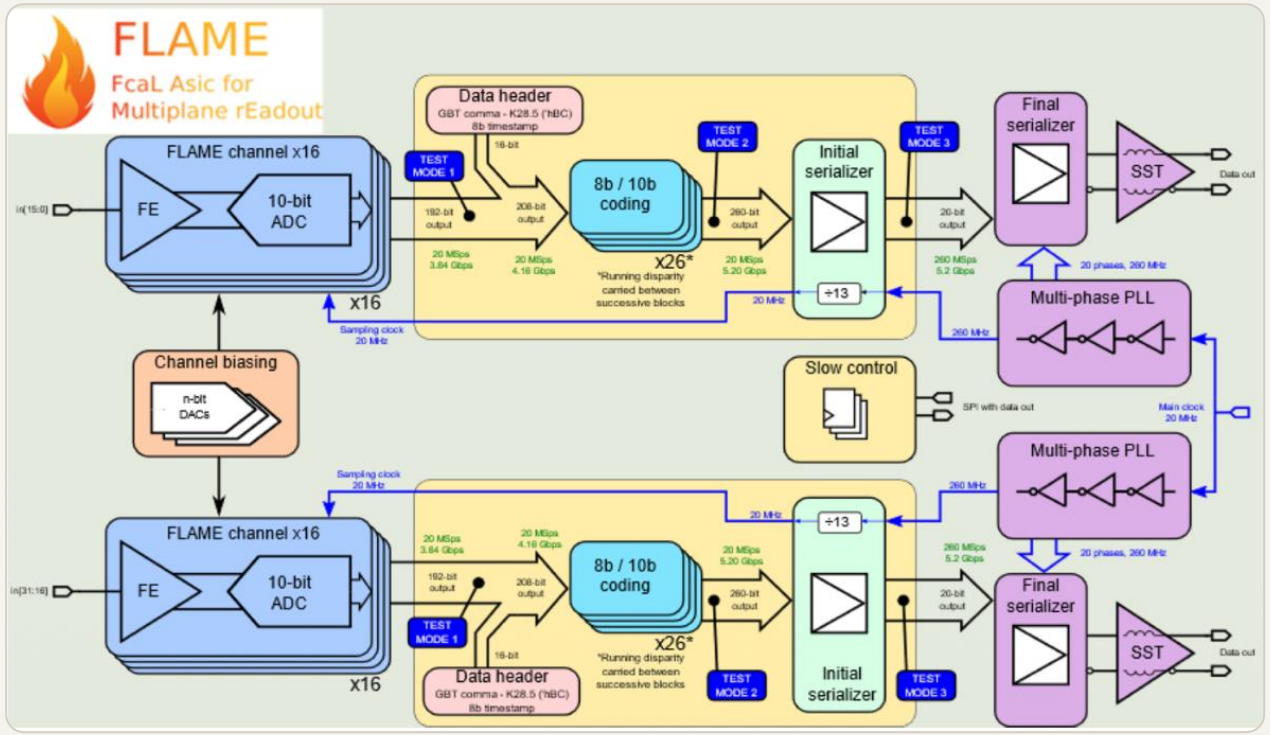
Read out

Flame (**F**cal **A**sic for **M**ultiple r**E**adout) is a 32-channel ASIC in CMOS 130 nm with analog front-end and 10-bit ADC in each channel, followed by two fast (5.2 Gbps) serializers and data transmitters. FLAME has been already used in several test-beams of FCAL and LUXE-ECAL-P collaborations.

FLAME ASIC specification:

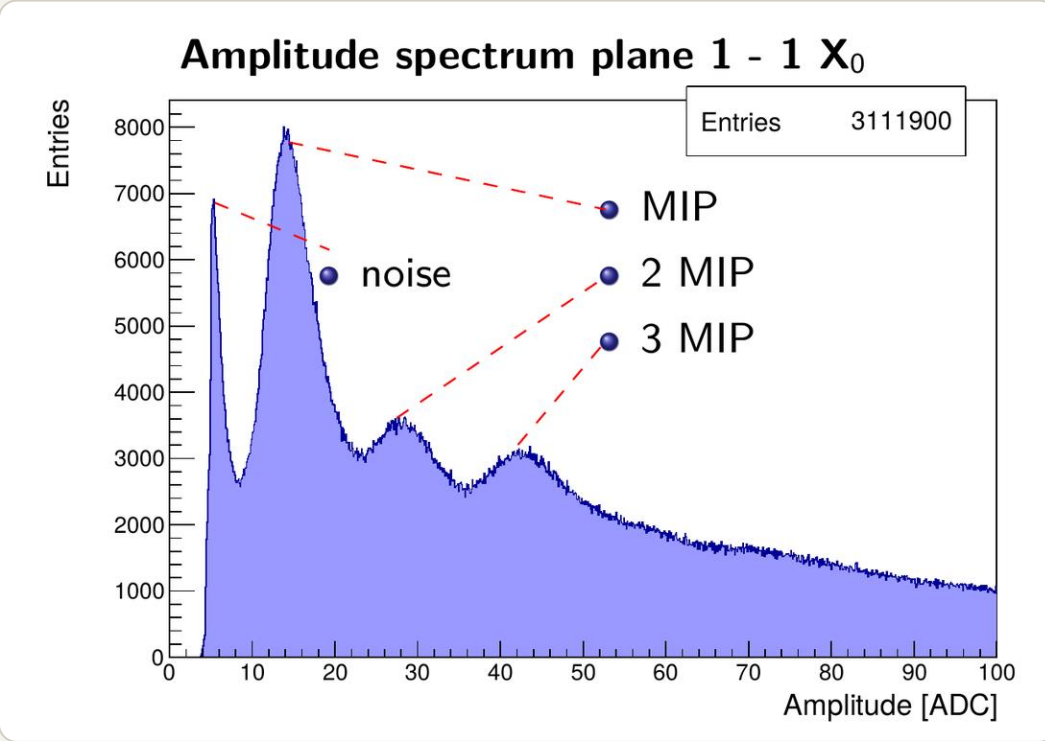
- Analog front-end in each channel
  - CR-RC shaping (T_{peak} ~ 50 ns)
  - Switched gain (high gain for MIPs, low gain for showers): high gain was use during the test beam
  - C_{in} 20 – 40 pF
- 10-bit ADC in each channel
  - f_{sample} = 20 MHz
  - ENOB > 9.5
  - Power < 350 μW 20 MHz

The final version of the experiment will use a new front-end ASIC FLAXE, which is based on FLAME.



Signal processing and calibration

1. Pedestal subtraction; dead and corrupted channels removed
2. Signal candidates masked, common-mode subtraction
3. Amplitude from CR-RC fit or Finite Impulse Response filter; pulse integral in the saturation region
4. Per-channel MIP calibration (Landau-Gauss): S/N ≈ 10
5. Telescope-to-calorimeter alignment: Hough transform or maximum likelihood



Plane 1 amplitude spectrum, 5 GeV electrons: noise, MIP, 2 MIP, 3 MIP

Dead pad compensation

Some channels (~6%) were dead or unreliable in TB2025; three ways to recover their signal were examined

1 Z-axis average

Take the same pad in the previous and the next plane and average their amplitudes

$$E_{dead} = (E_{i-1} + E_{i+1}) / 2 / 2$$

Simple; assumes the shower profile is smooth along z

2 Sub-pad division

Split each 5.5 × 5.5 mm² pad into N × N sub-pads. In each radial ring dr, count the expected sub-pads N_total and the active ones N_good

$$E_{corr} = E_{meas} \times N_{total} / N_{good}$$

Builds on the sub-pad radial-profile method

3 Working-pad training

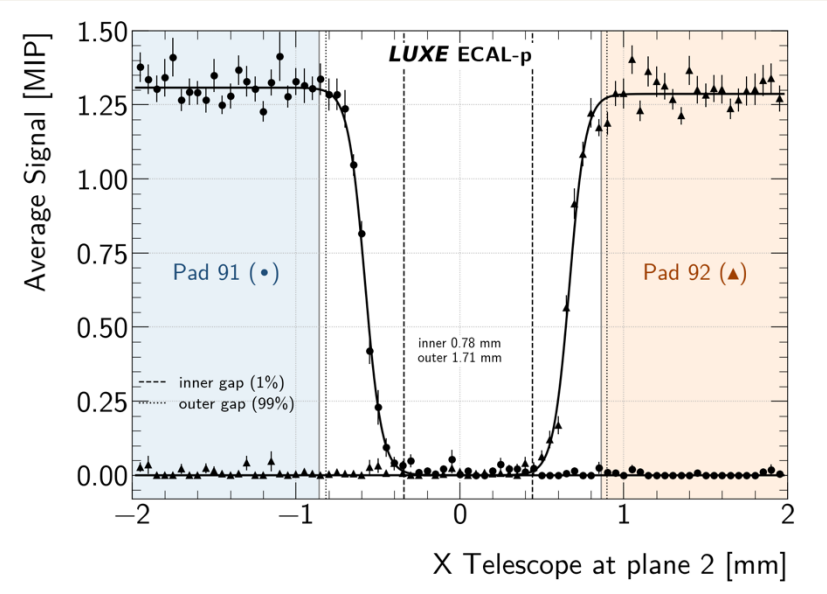
Training: on a working pad, measure the hit probability P(R) and the amplitude distribution versus the square-ring distance R from the telescope entry point to the pad centre

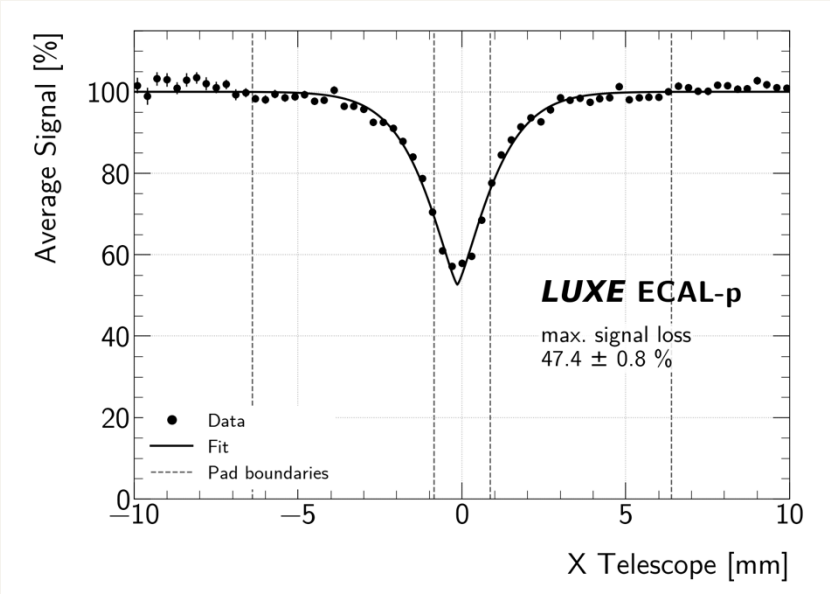
Reconstruction: take R for the dead pad, draw hit yes/no from P(R), then sample an amplitude if there is a hit

New algorithm; first tests on simulated files

The three dead-pad recovery methods are still under study and will be compared on simulated showers, where the true amplitude of every pad is known, before one is applied to the test-beam data.

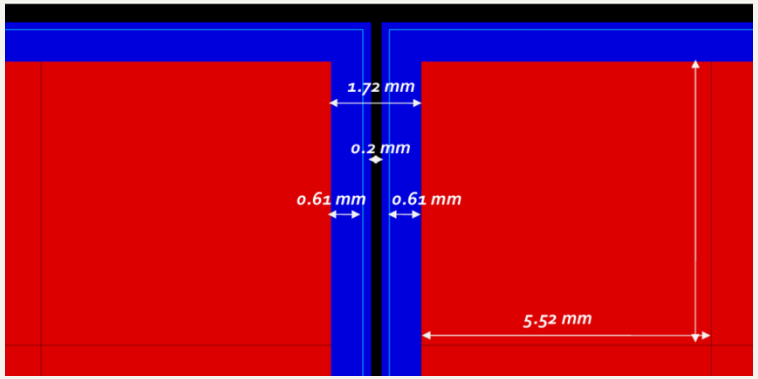
Dead gap between sensors



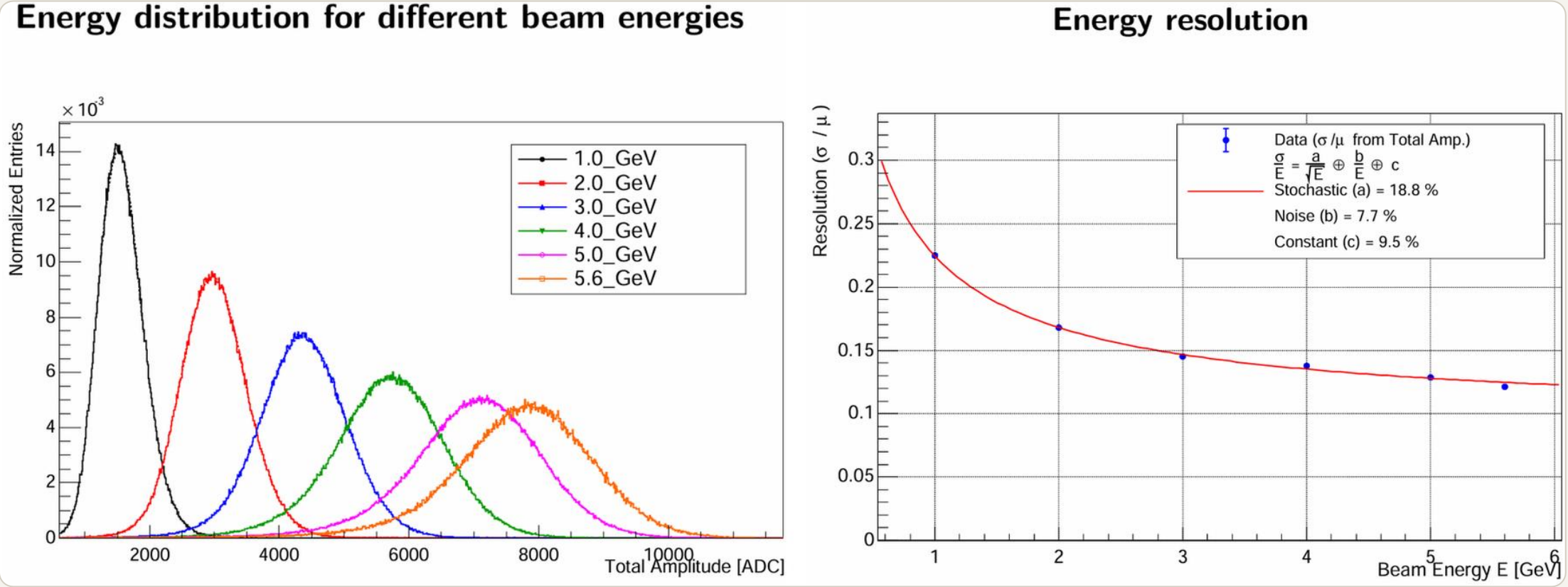


The electron tracks are perpendicular to the detector. It will not be the case in LUXE

Loss decreases in deeper planes as the shower widens; comparison with MC in progress

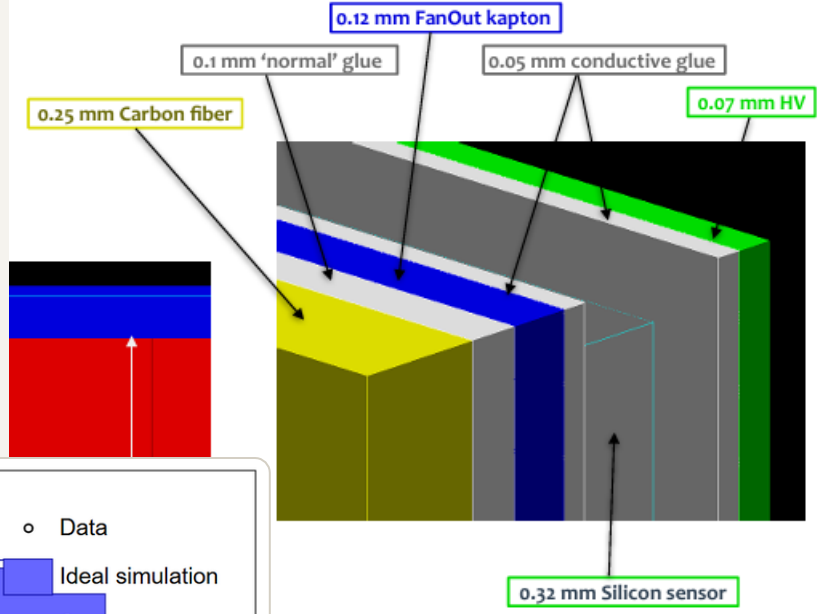


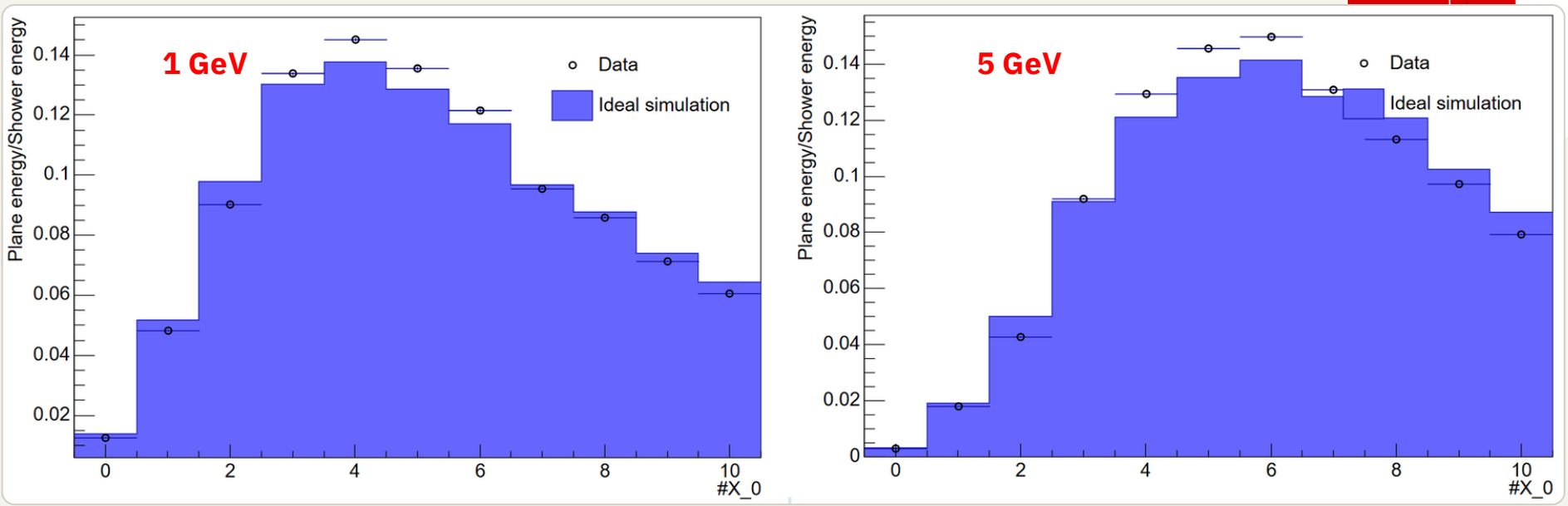
Energy response and resolution



comparison with MC in progress

Longitudinal profile: data and Geant4 (preliminary results)





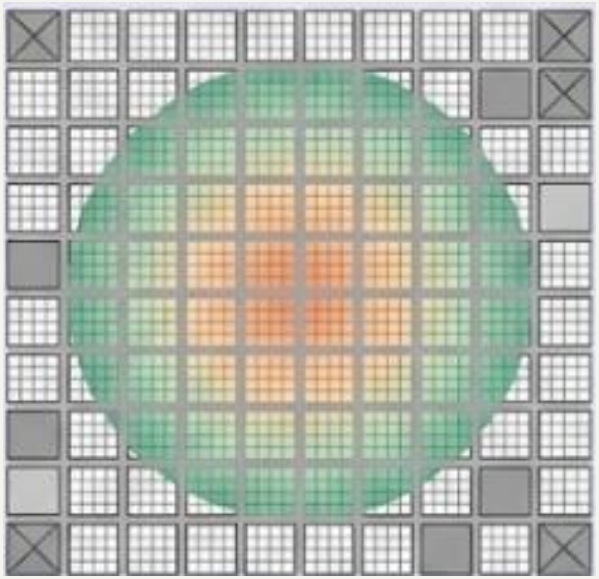
Shower maximum moves from layer 4 (1 GeV) to layer 6 (5.6 GeV)

Geant4 reproduces the position of the shower maximum

Simulation is low at the maximum and high in later planes; total-energy peak about 6 % off

Transverse shower profile and (effective) Molière radius

Cumulative radial profile

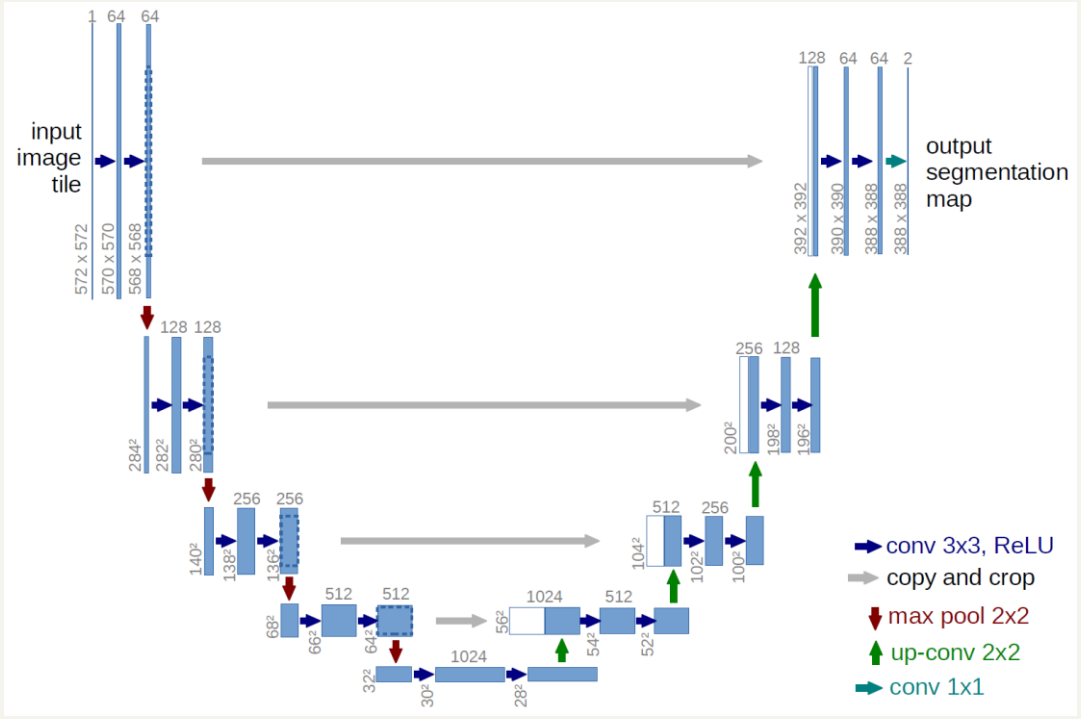


Virtual sub-pad division method

Fit to Gaussian Core + Grindhammer-Peters Tail:

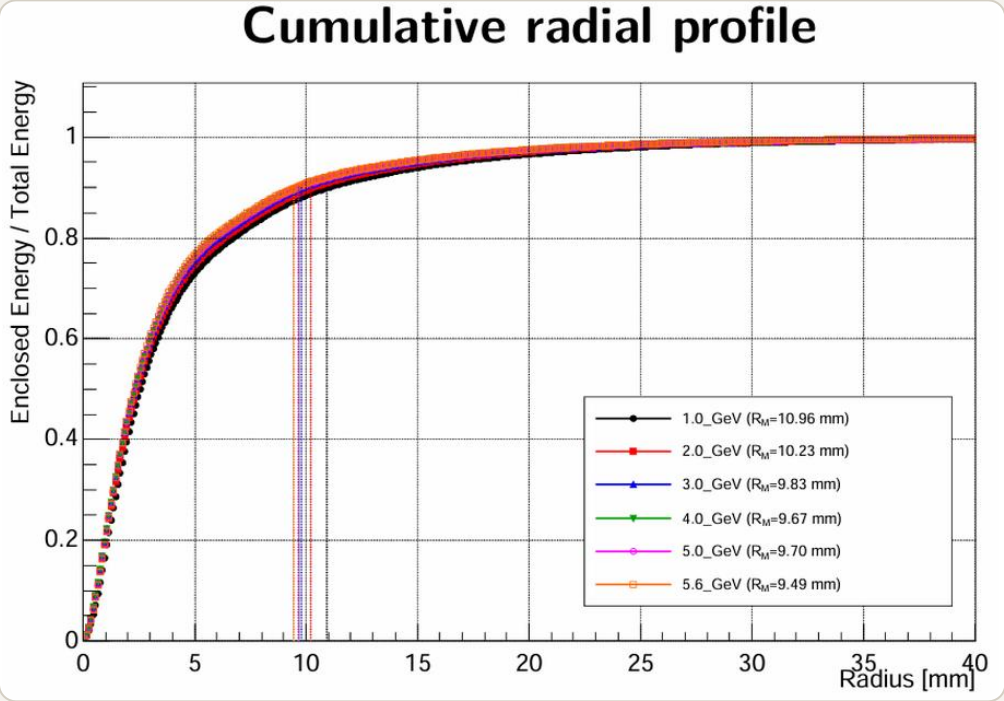
$$A_C \exp\left(\frac{-r^2}{R_C^2}\right) + A_T \frac{2r^{\alpha} R_T^2}{\left(r^2 + R_T^2\right)^2}$$

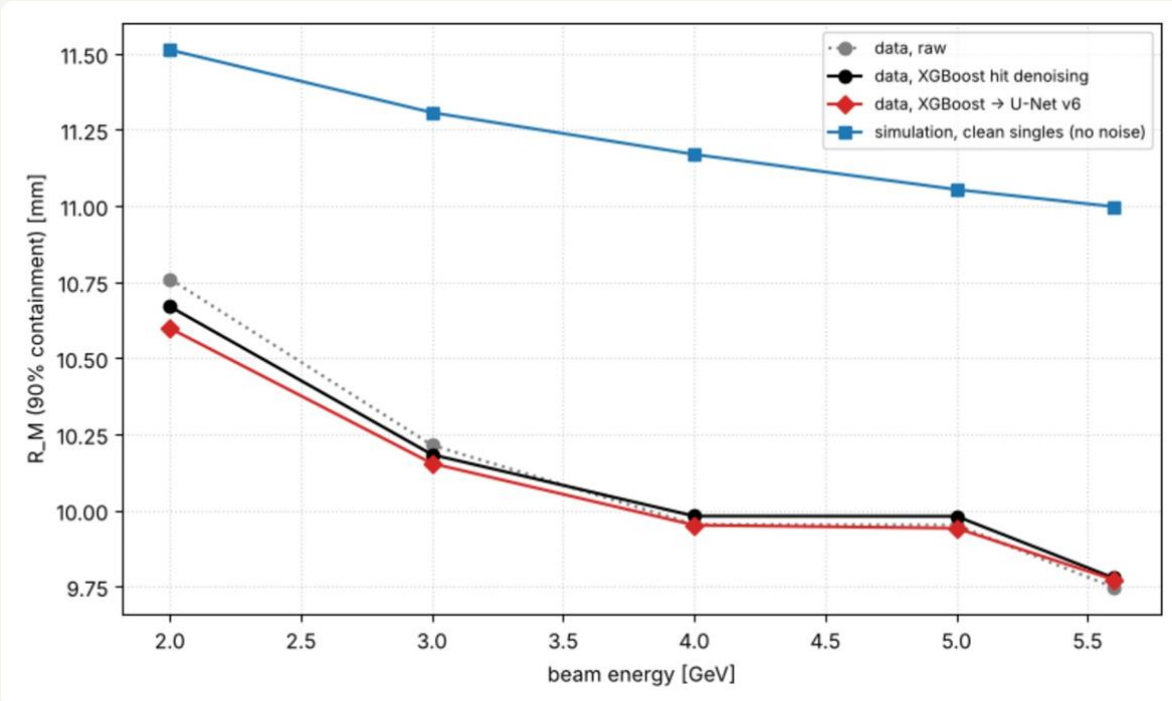
ML method



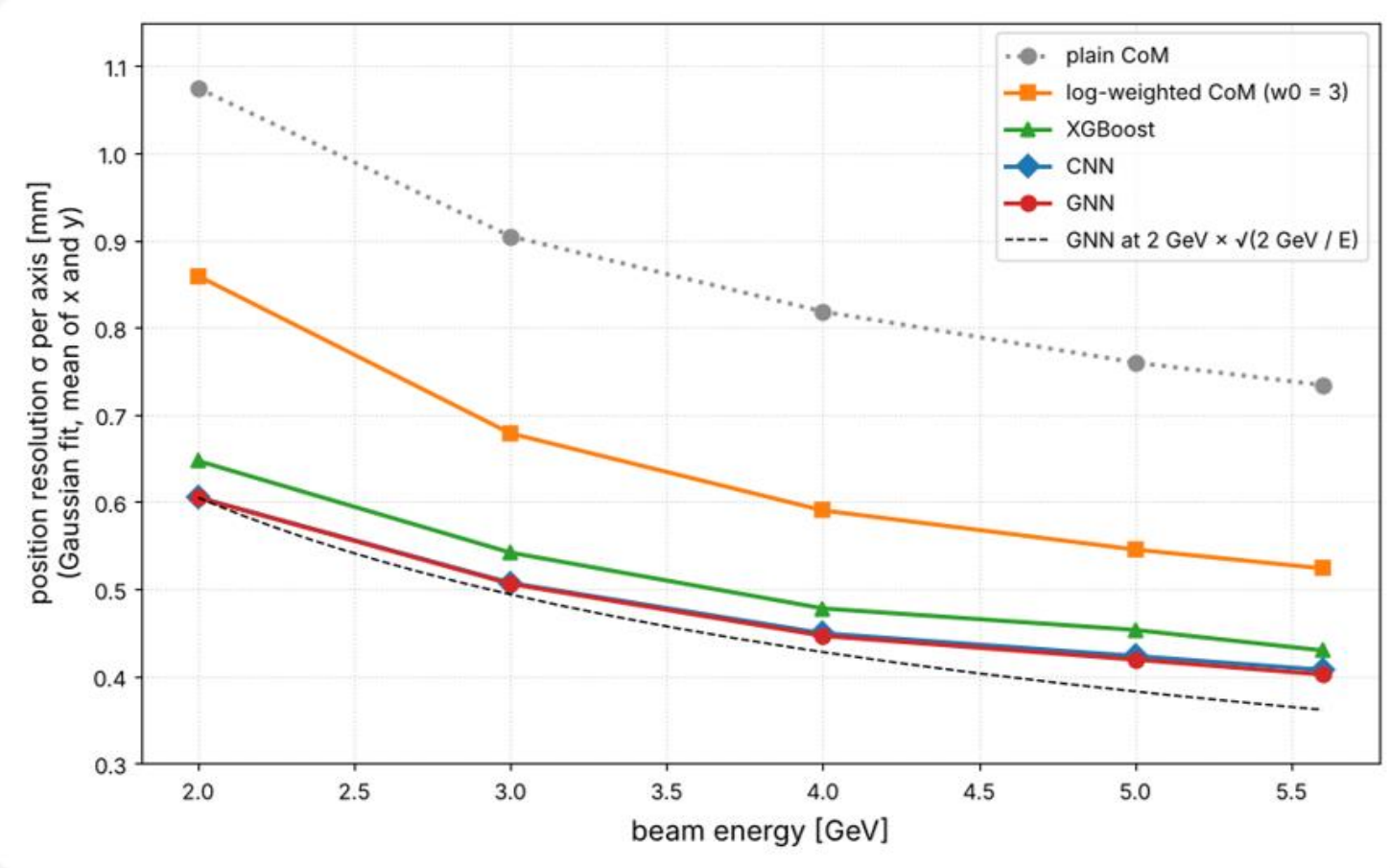
XGBoost enhanced U-Net model

Transverse shower profile and (effective) Molière radius





Position resolution

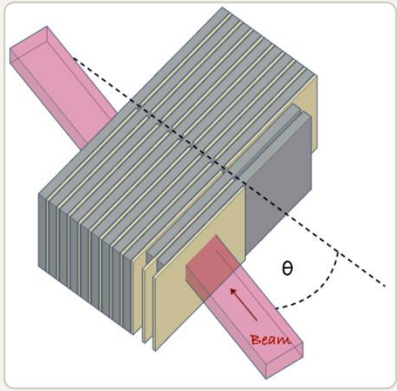


Shower angle

Nominal	Peak	Std
+15°	14.19°	2.49°
+10°	9.21°	3.33°
+5°	3.98°	2.97°
0°	−0.90°	2.74°
−5°	−5.94°	2.84°
−10°	−10.93°	3.69°
−15°	−15.63°	2.61°

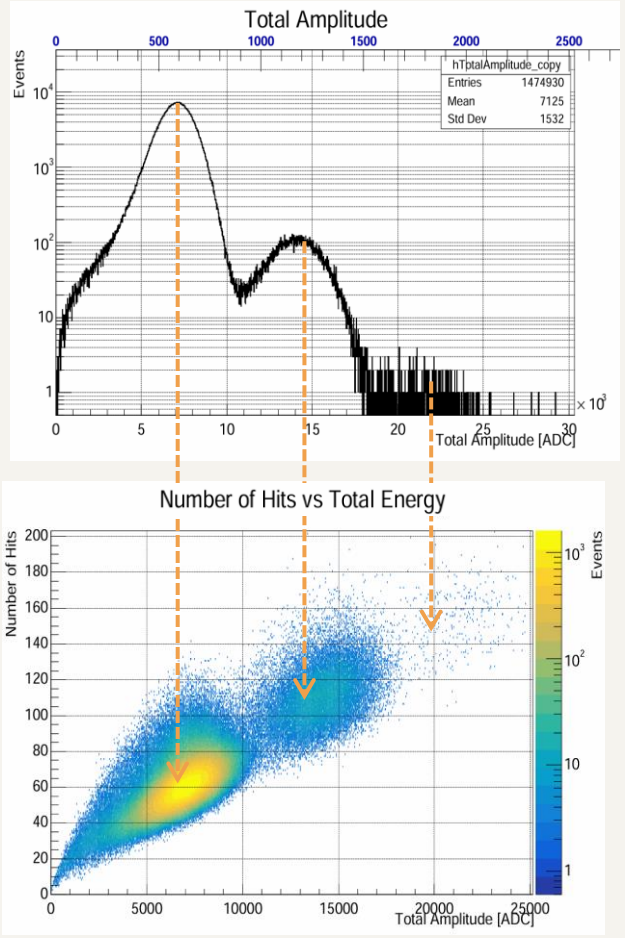


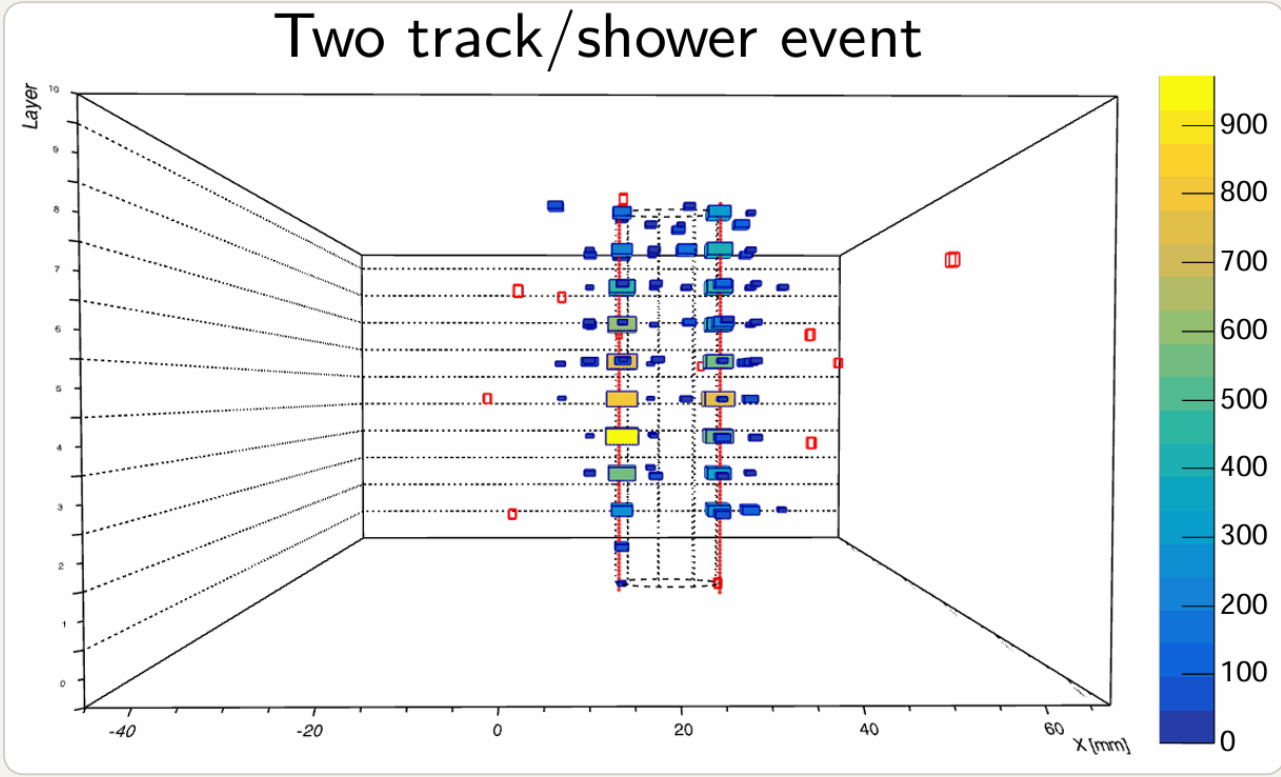




Angle resolution ~3°

Multi-shower events

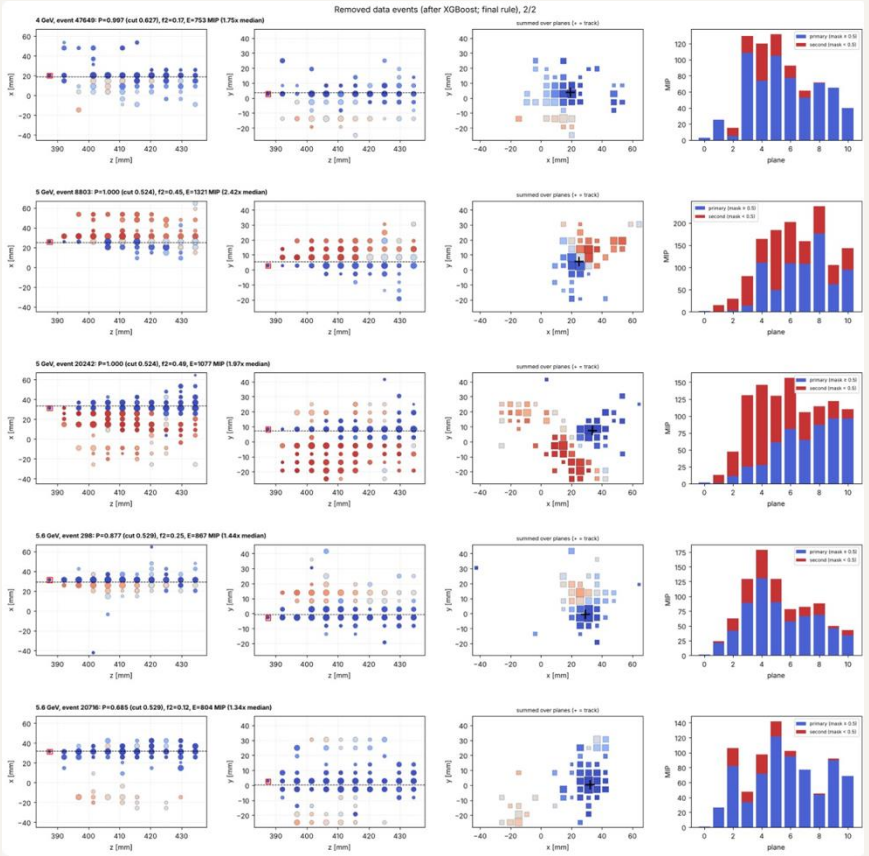


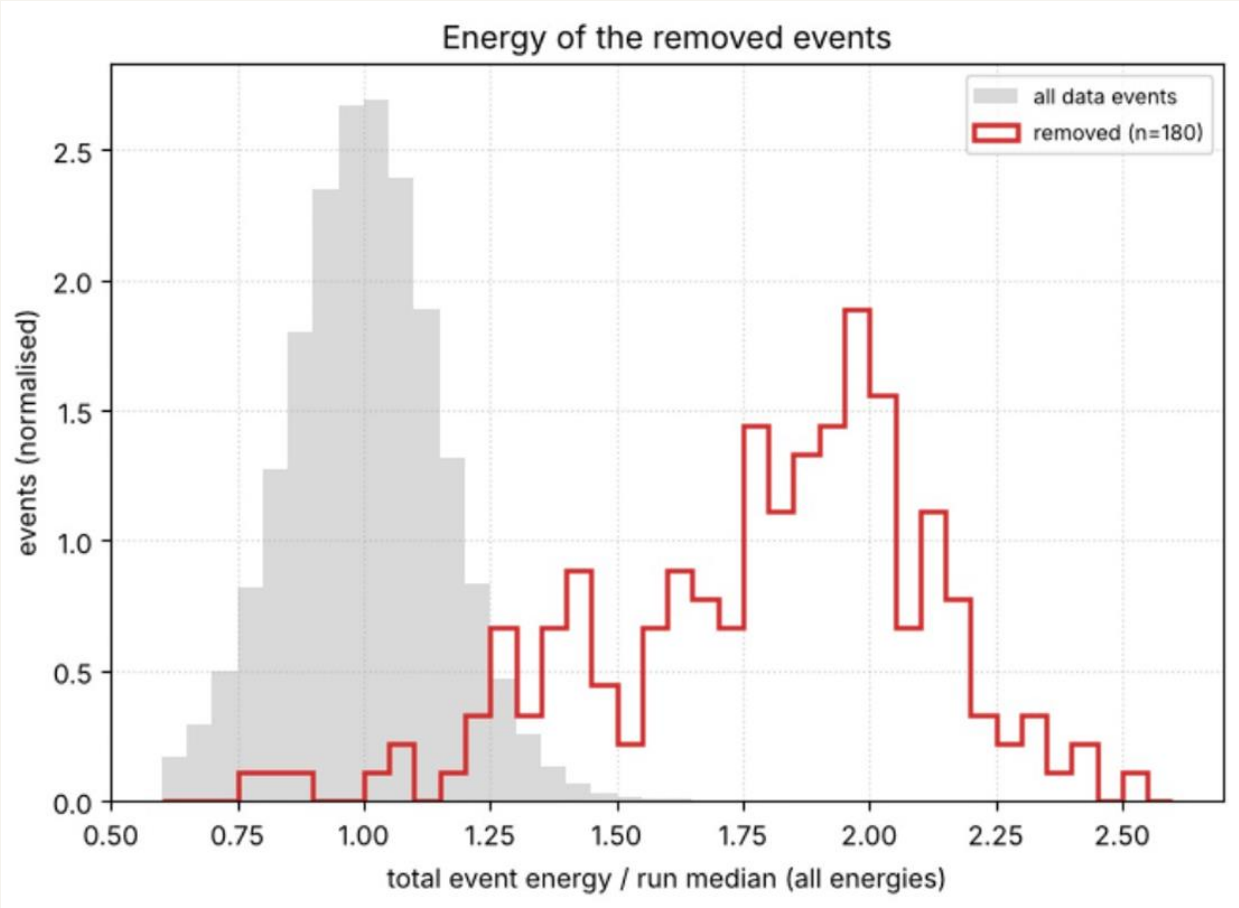


- Telescope cannot separate one, two or three particles; multi-shower events flagged by hit count and total energy
- Neural-network shower separation in development

Multi-shower rejection

Rejection using XGBoost+U-net





Summary

Data set
250 M events with 1–5.6 GeV electrons at DESY; 11 Si-W layers plus ALPIDE telescope

Calibration
Pedestal and common-mode subtraction; per-channel MIP calibration, S/N ≈ 10

Energy resolution
22.5 % at 1 GeV to 12.2 % at 5.6 GeV, with only 10 X0

Longitudinal profile
Shower maximum moves from layer 4 (1 GeV) to layer 6 (5.6 GeV)

Molière radius
Sub-pad and ML methods agree at 5 GeV, R_M = 9.7 mm (sub-pad) vs ≈ 10.0 mm (ML)

Position and angle
Position resolution ≈ 0.6 mm at 2 GeV to ≈ 0.4 mm at 5.6 GeV (GNN); angle ~3°

Detector effects
Up to 47 % of the signal lost at the sensor gap for perpendicular tracks; dead-pad recovery methods under study

Multi-shower events
XGBoost + U-Net flags overlapping showers

Thanks for your attention

R&D: readout electronics

FLAME (TB2025)

32 channels, CMOS 130 nm, 10-bit ADC at 20 MS/s in each channel

CR-RC shaping, 50 ns peaking; two 5.2 Gbps serializers

8 ASICs per 256-channel FEB; one ASIC lost from the start

FLAXE (LUXE)

32 channels with CSA, shaper and 10-bit SAR ADC

On-chip memory for 64 ADC samples, SPI readout between bunch crossings

One FEB with 24 ASICs reads three sensors

First run, 2024

1000 ASICs fabricated, production failed

Only a few work: 35 % dead short, 60 % overcurrent

Analogue part of working channels in spec; dominant issue: DAQ RAM errors

Second run, 2026

1000 FLAXEs was produced

More than 100 FLAXEs was packaged.
chips work very well, by now the yield is ~90%
next step: package >800 FLAXEs

Plans

Analysis

- Molière radius, energy, angular and position resolution
- Reconcile the two Molière-radius methods
- Adjust simulation to data
- ML shower separation for multi-shower events

Hardware

- Frame with 1.0 mm gap, tested with real silicon
- CSIS without carbon fibre, alignment fiducials
- Repeat two density and the N7 thickness measurements
- FLAXE rev. B tests, then packaging

Next beam test

- **More likely date 2028**
- **readout: FLAXE**

Backup: DAQ and readout performance

83.2 Gbps
per FEB: 16 links at 5.2 Gbps

915.2 Gbps
continuous stream from 11 FEBs

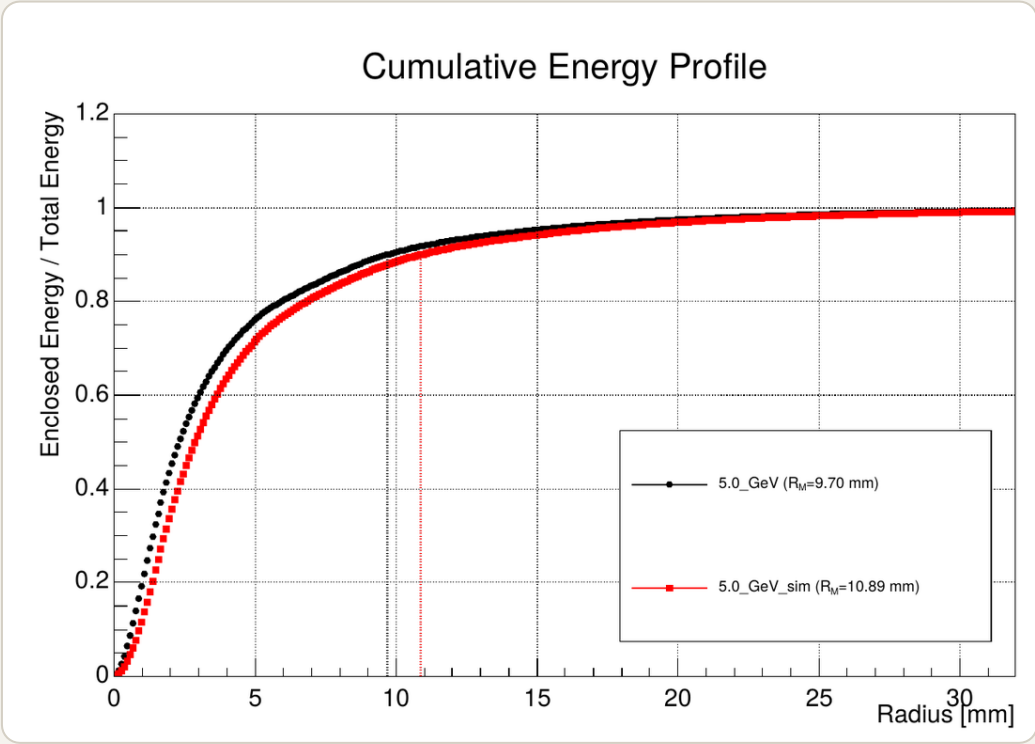
1.2 Gbps
after FPGA reduction at 1 kHz (143 MB/s)

2 kHz
event rate with stable DAQ

- Uptime: 8 layers for 21 h 46 min, 11 layers for 5 d 17 h 56 min (about 71 FPGA-days)
- Minor issues: one SEU in FPGA configuration memory, no trigger in second rack after 8 to 11 layer step, one lost synchronisation
- Dominant: ASIC-to-FPGA link drops, one ASIC (two uplinks) lost from the start; biggest: noise from grounding and shielding

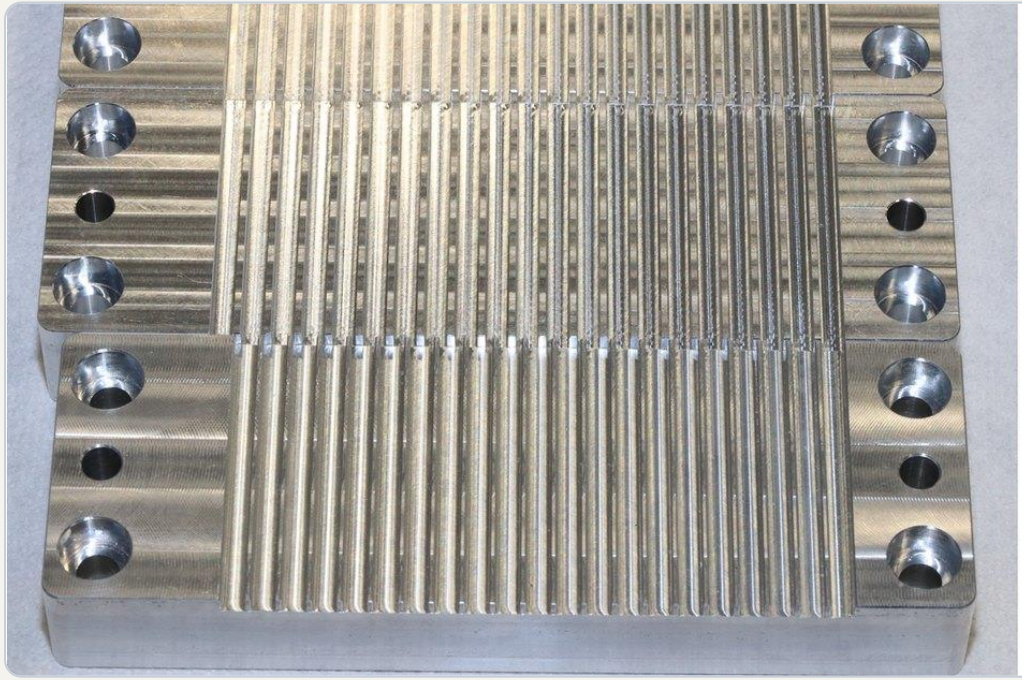
Backup · Sources: D. Pietruch (ICHEP 2026); R. Shahar Reshef (TAU)

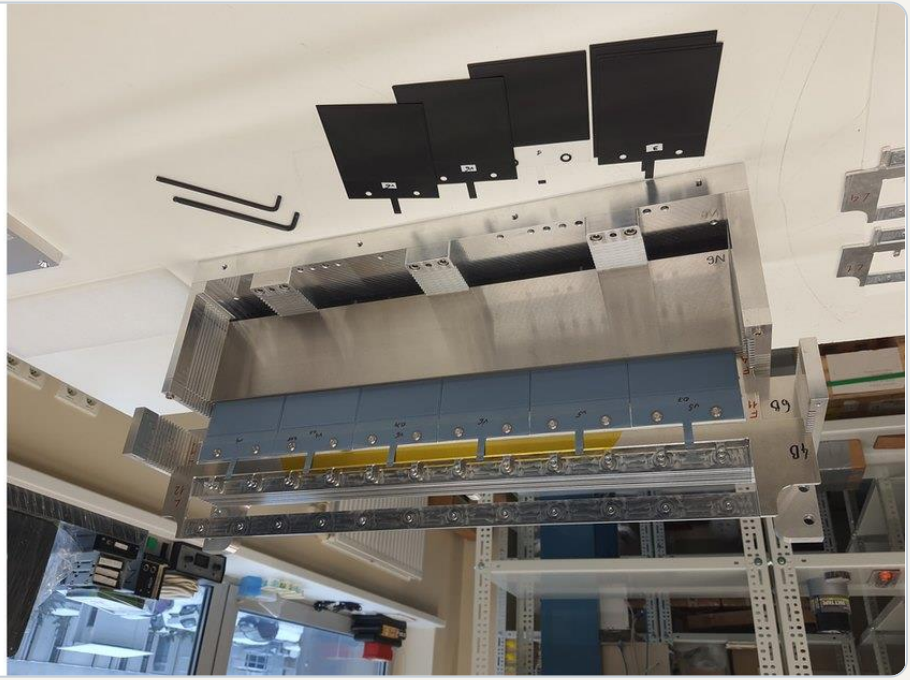
Backup: Molière radius, data vs Geant4



- 5 GeV: R_M = 9.70 mm in data, 10.89 mm in Geant4
- Same iterative correction applied to simulated showers: similar results, but less sharp core after the same number of iterations
- Origin to be understood: geometry and materials, bremsstrahlung, definition

Backup: frame and dummy sandwich insertion





- Aluminium frame machined to 10 μm at University of Warsaw; modular, so only the combs and T-frames change for the 1.0 mm gap
- New prototype: 3.55 + 1.0 mm pitch (4.55 mm) accommodates all plates

Acknowledgements

- National Science Centre, Poland, grant 2021/43/B/ST2/01107
- EU Horizon 2020 programme, GA 101004761
- Weissfeld Family Charitable Foundation; Israeli PAZY Foundation (ID 318)
- Spanish MICIU/AEI and EU/FEDER, grant PID2024-158190NBC21; Generalitat Valenciana PlanGenT CIDEGENT/2020/021
- University of Warsaw Excellence Initiative IDUB, SP-501-D113-20-0001380
- Romanian Ministry of Research (LAPLAS VII, 30N/2023; CERN-RO 005/2024)
- Measurements performed at the DESY Test Beam Facility, Hamburg (Helmholtz Association)