Performance of a highly granular silicon-tungsten electromagnetic calorimeter prototype

Shan Huang (on behalf of the FCAL-LUXE Collaboration)

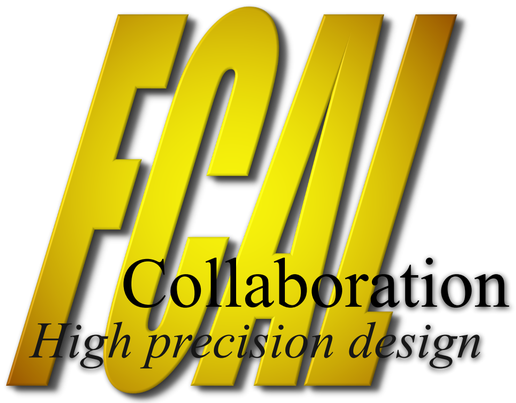
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The speaker thanks the LOC of this CEPC Workshop. This presentation is partially funded by:

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- Motivation of highly granular and compact calorimetry
- The prototype: design and construction
- The recent test and analysis









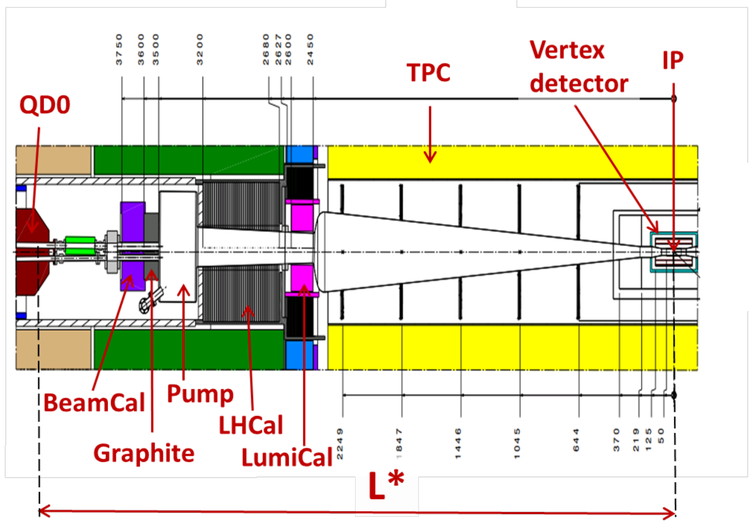


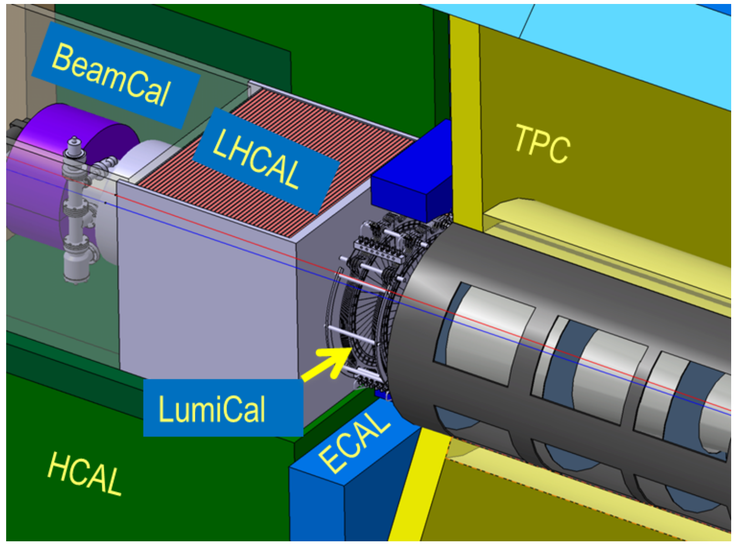


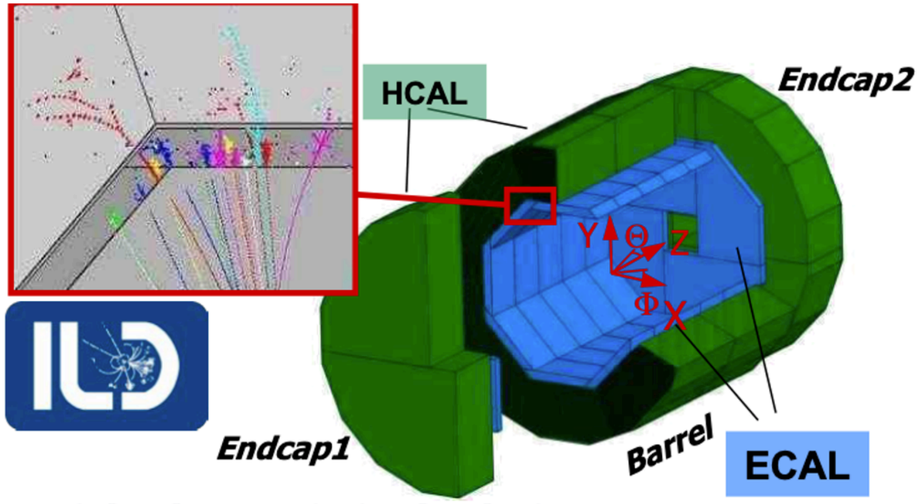
Higgs factories

- Luminometers on a e^+e^- collider
- Highly granular forward calorimeters use
  - beamsstrahlung (BeamCal) and
  - Bhabha scattering (LumiCal)

  to provide fast and precise measurements in the ILD
- Main detector enables the particle-flow approach (PFA)
- Able to distinguish particles within jets with high precision
- CALICE SiW-ECAL is one of these PFA calorimeters

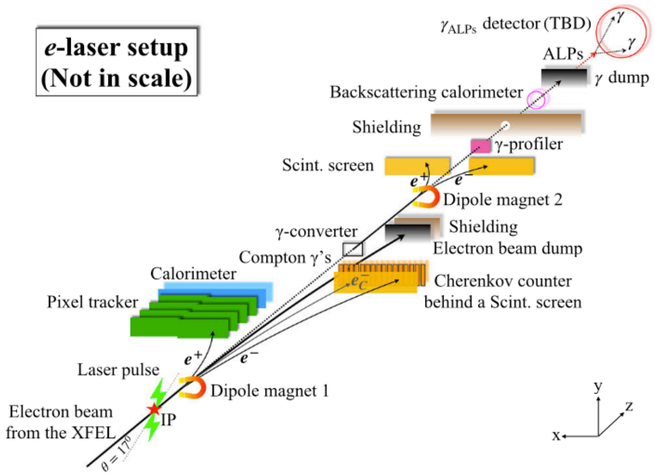


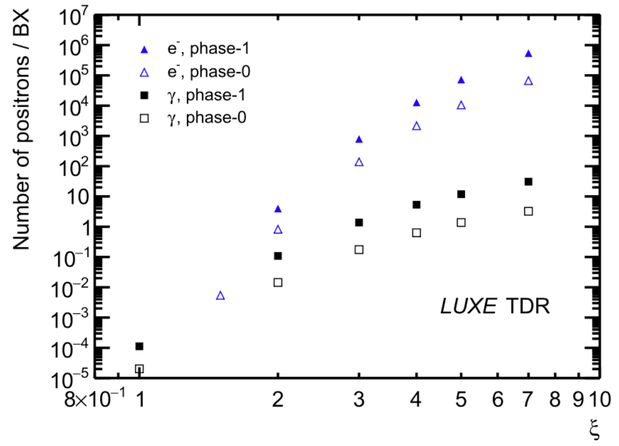


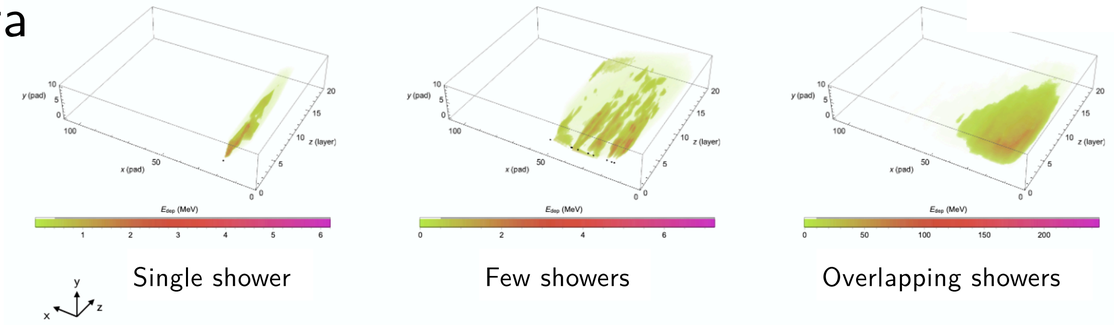


Strong-field QED

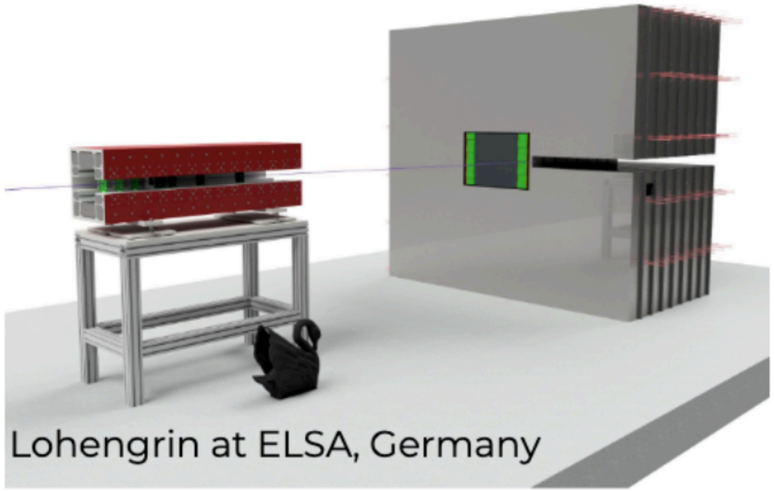
- Strong electromagnetic fields turn QED into non-perturbativity
  - Example of the strong fields: PW laser beams at Zhangjiang
- LUXE studies the collision of electron/photon and laser beams
  - nonlinear Compton scattering
  - nonlinear (BW) pair production
- Expectation of signal positions per event spans from 10^{-4} to 10^{7}
- High granularity and compactness are required to
  - contain the shower in small radius
  - measure the number of particles and
  - measure the energy spectra in high-multiplicity cases

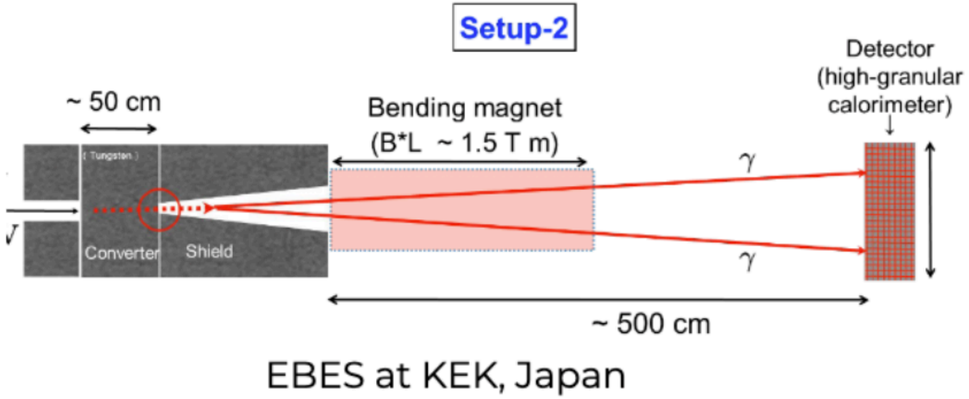






BSM particle search





EBES at KEK, Japan

- Beamdump experiments of dark matter candidates/ BSM particles look for signals of photon pair
- Position resolution and shower containment play a key role in the measurement
- Examples include LUXE-NPOD, Lohengrin, EBES, SHiP, ...

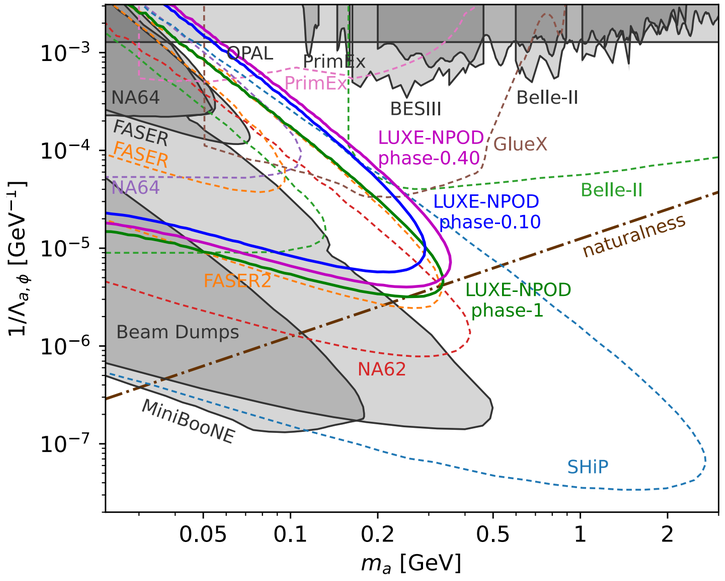
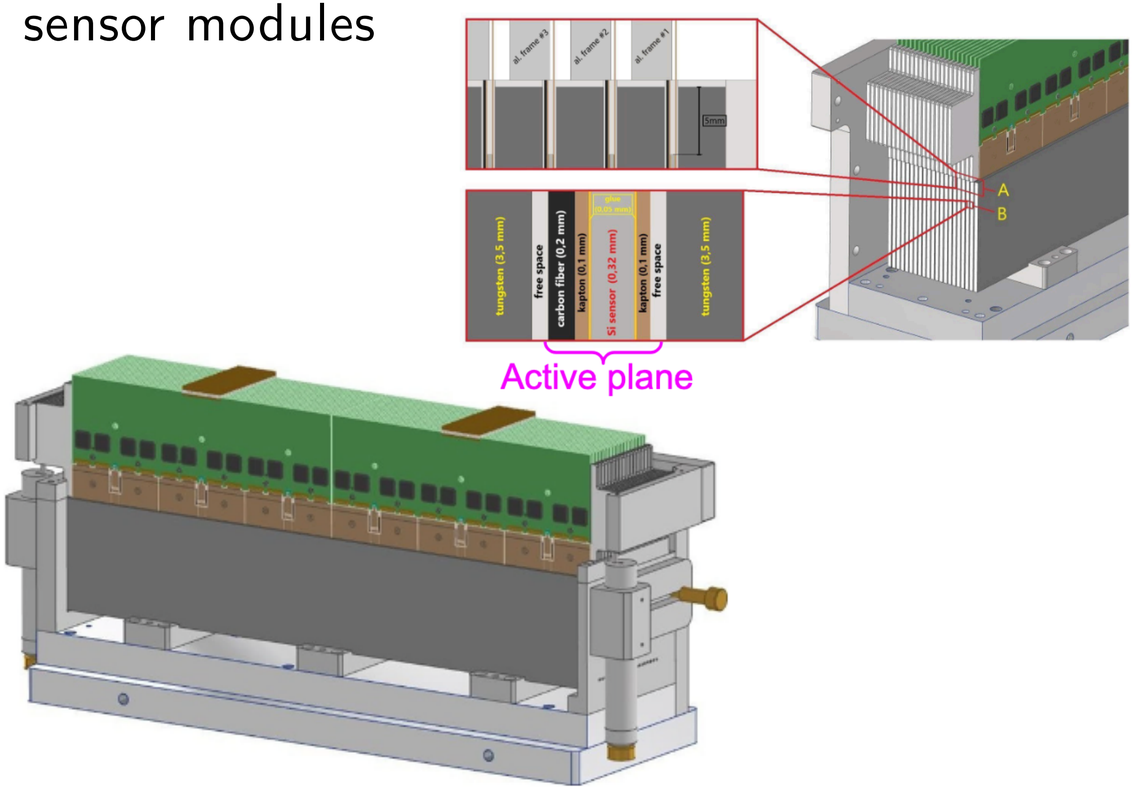


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- Motivation of highly granular and compact calorimetry
- The prototype: design and construction
  - Structure
  - Sensor module integration
  - Readout electronics
  - Testbeam prototype
- The recent test and analysis

LUXE ECAL-P

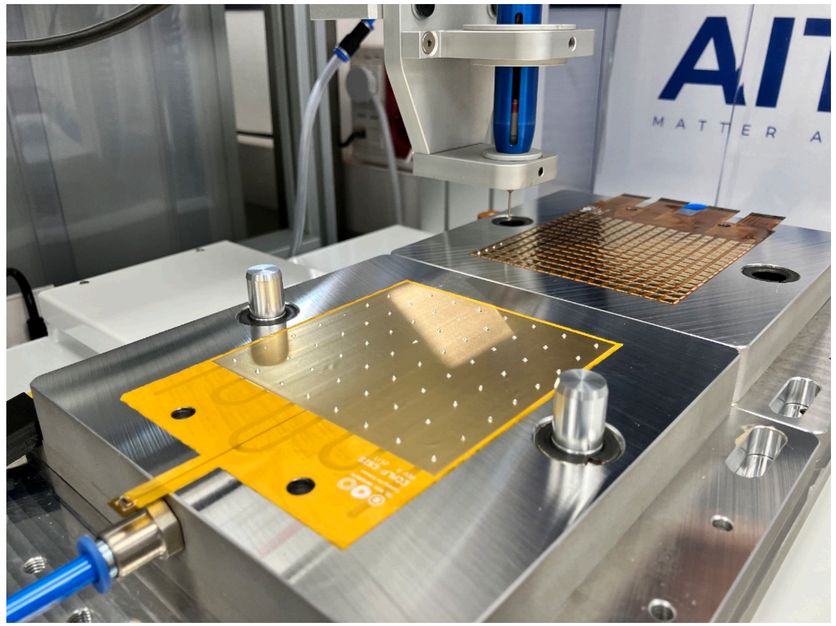
- Based on the R&D initiative of BeamCal and LumiCal for ILC and CLIC
- It adapts and optimizes their design of sensor modules

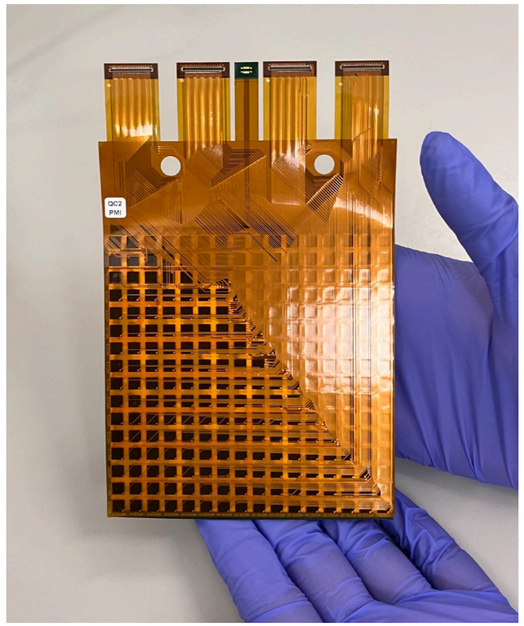


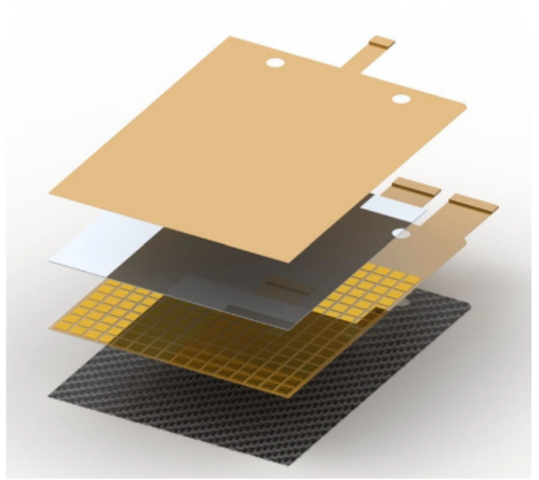
- Long, thin, and super flat tungsten plates with thickness of 3.5 mm (1 X_0)
  - Produced in China (intermediated by IHEP) and Germany
- 20 active layers, each has 6 silicon sensors (9 x 9 cm^2 pixelated into 16 x 16 pads)
- High-precision mechanical structure ensures 4.5 mm layer pitch
  - Each active layer must fit into 1 mm gap
- Signals are read out through dedicated PCB with embedded traces
- Readout electronics on the top, 1536 channels per layer

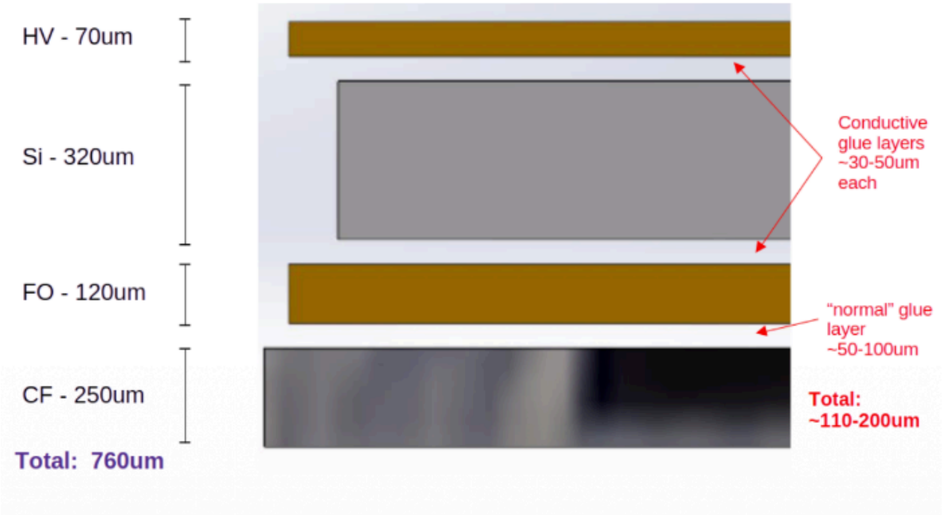
Compact silicon sensor (CSIS) module

- Sandwich structure with two PCBs and supported by carbon fibre
- Glued to the sensor with conductive adhesive
- Glue dispensed by a robot to ensure uniformity
- Final thickness is below 800 μm





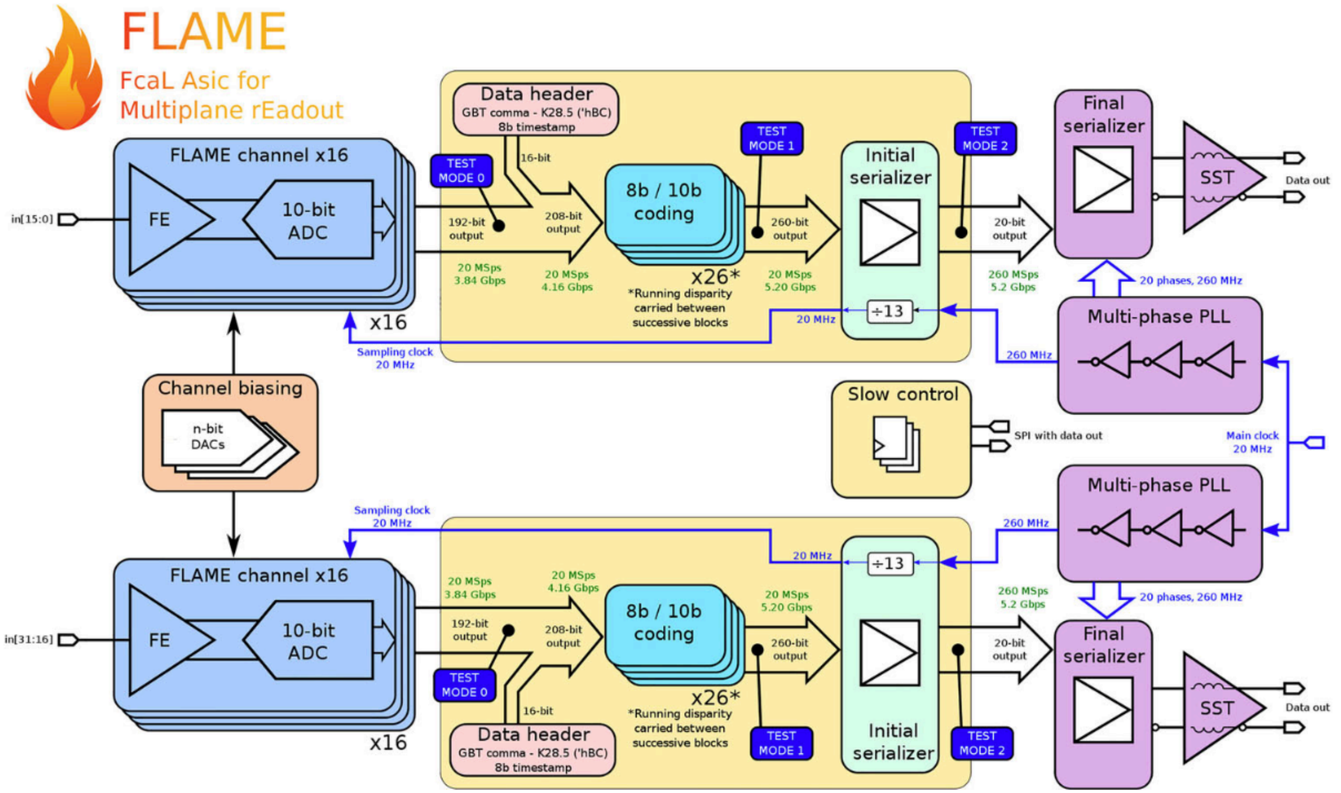




FLAME electronics

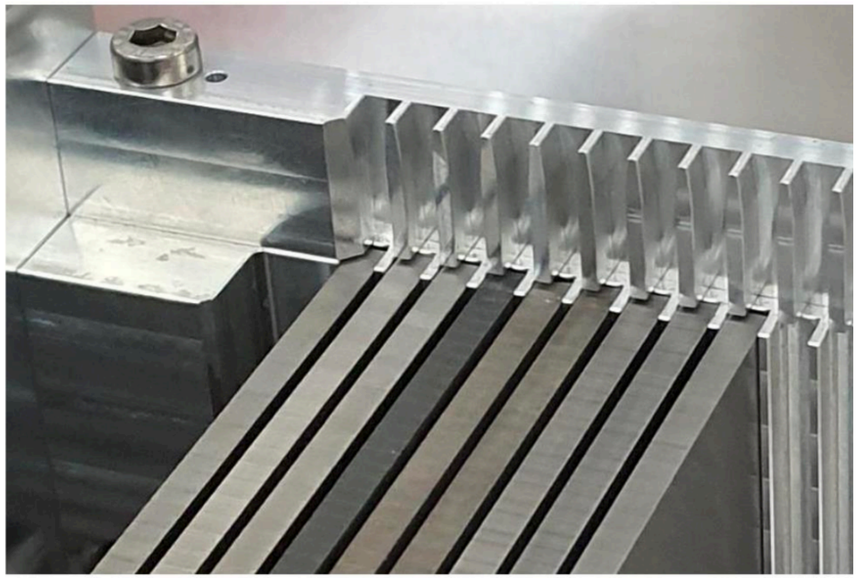
- 32-channel ASIC using 130 nm CMOS technology
- Analogue front end followed by 10-bit ADC
- CR-RC shaping and $T_{peak} = 50$ ns
- Two switchable gaining modes for low- and high-multiplicity scenarios
- 20 MHz sampling rate

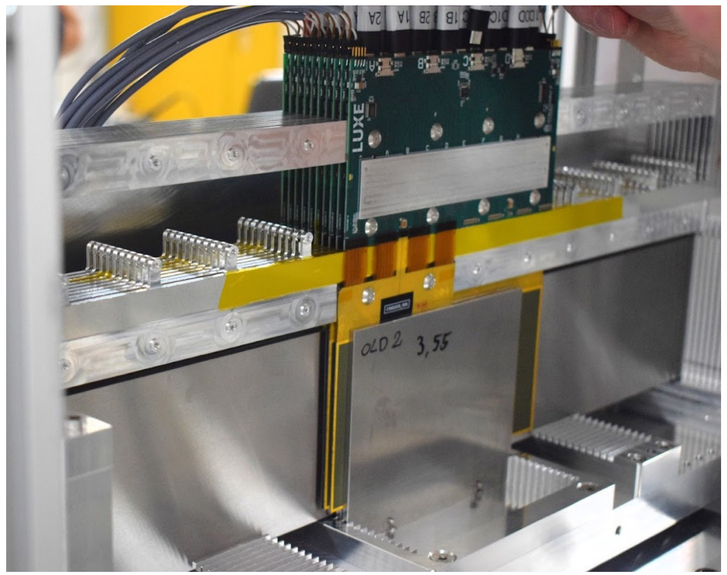
- A derived version FLAXE is dedicated to LUXE ECAL-P but yet to be tested with beams



Construction

- A test configuration was built in 2025
- 11 active layers and 2 towers (out of 6) were populated
- CSIS modules successfully slid into the gap between W plates
- Mixed old and new FEBs were used during the test
- The whole structure was mounted on a rotatable stage





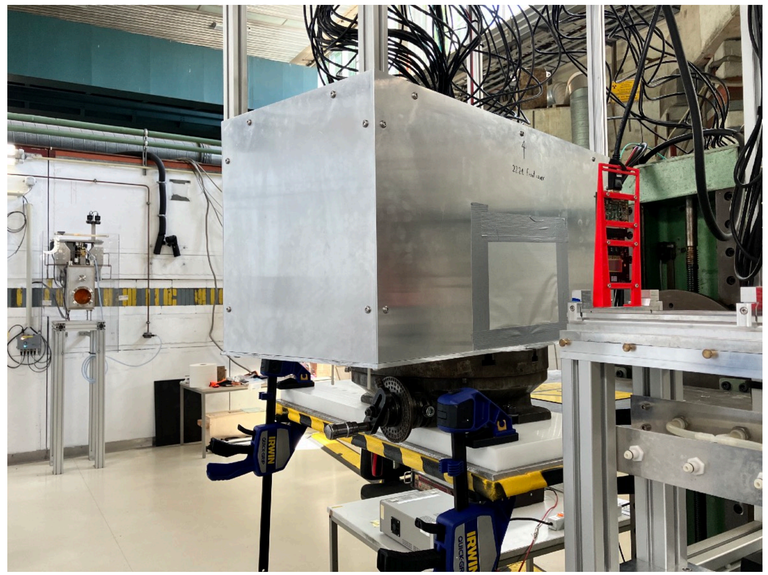
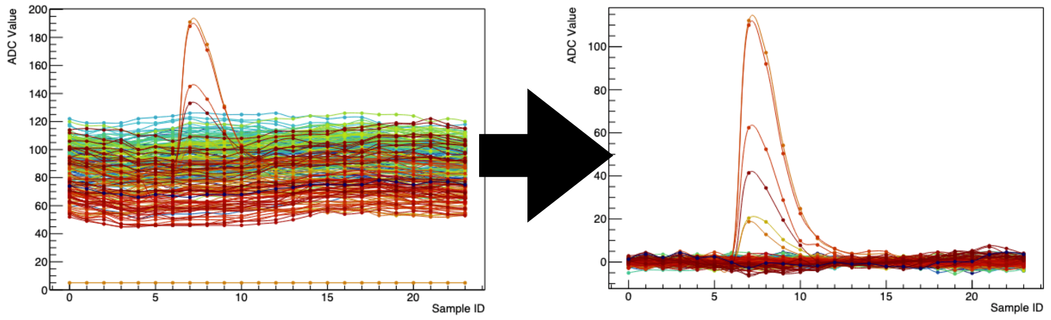


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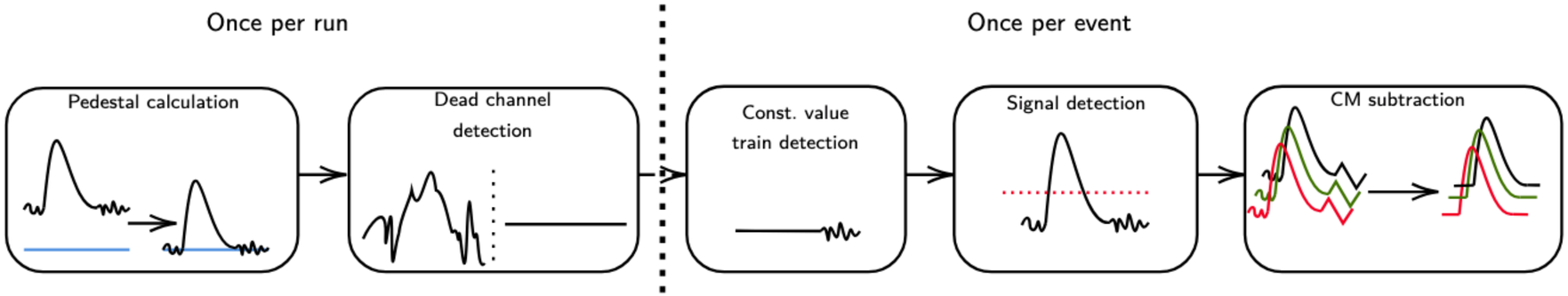
- Motivation of highly granular and compact calorimetry
- The prototype: design and construction
- The recent test and analysis
  - Signal processing
  - Detector alignment
  - Dead channel compensation
  - Energy resolution
  - Shower profiling
  - Simulation benchmark

Signal processing

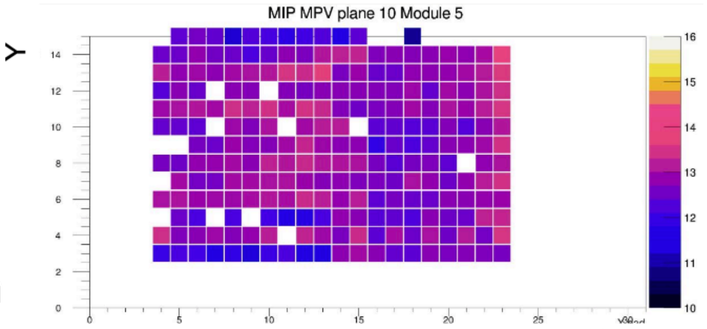
- 30 TB data were taken during the TB campaign
- 24 samples per channel per trigger
  enable detailed offline analysis:
  - Pedestal and common-mode are subtracted



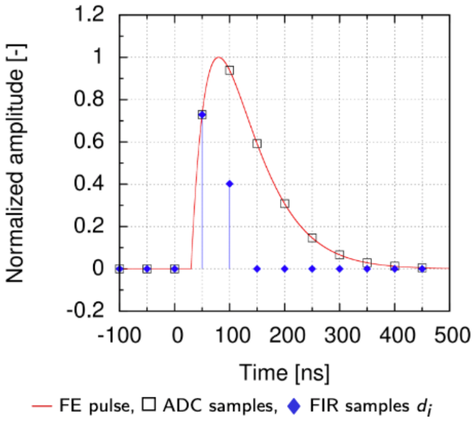
Curves fitted to CR-RC shape



- Two independent estimations of signal amplitude agree with each other
- The faster method (deconvolution) is used
- Channels are calibrated by experimental data



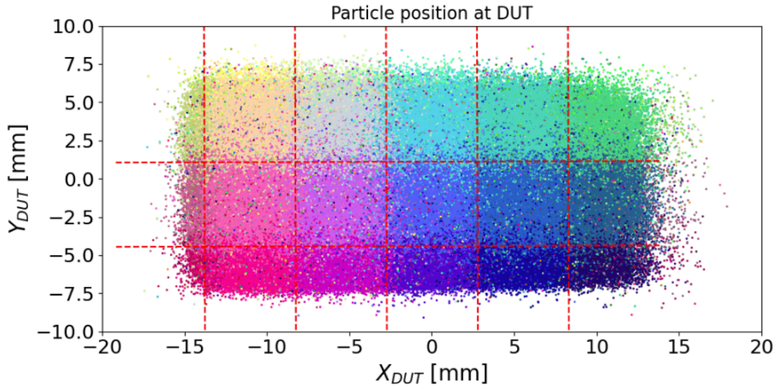
Calibration factor

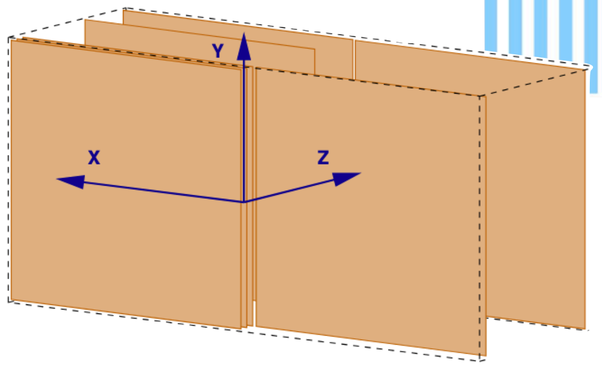


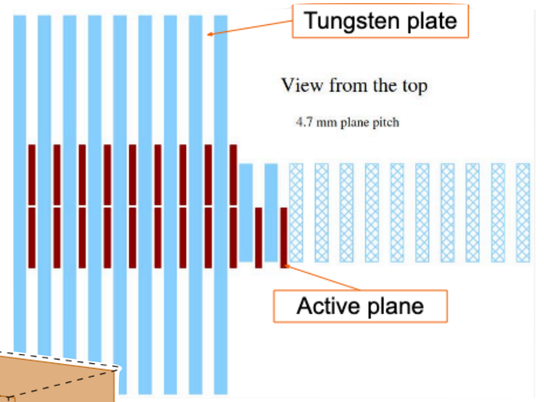
Deconvolution method with finite-impulse response filter

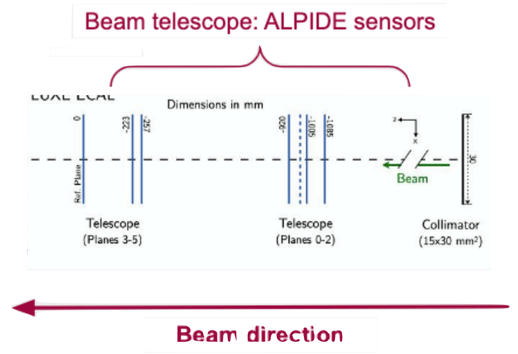
Detector alignment

- The sensor modules are internally aligned by max. likelihood method
- Displace and rotation of sensor modules are fitted

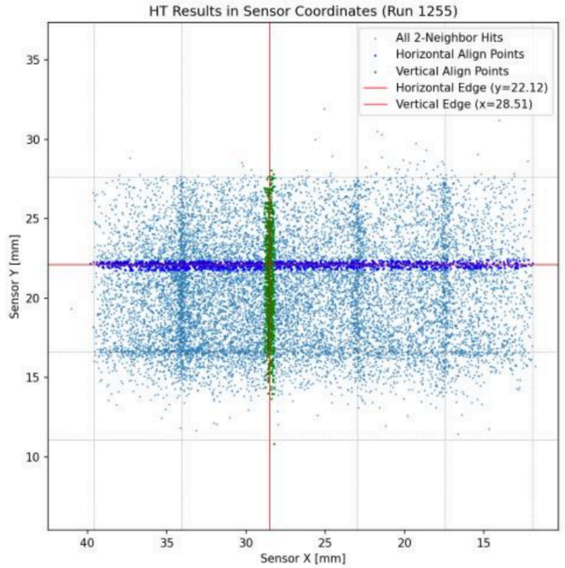






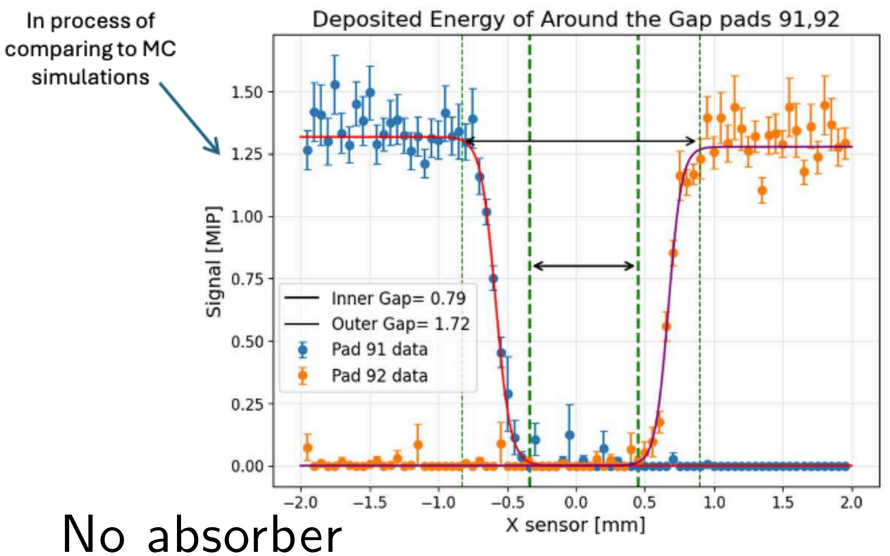


- The prototype (first active layer) is also aligned to the beam telescope using Hough transform
- The internal alignment is done per configuration, and the beam telescope alignment is done per run

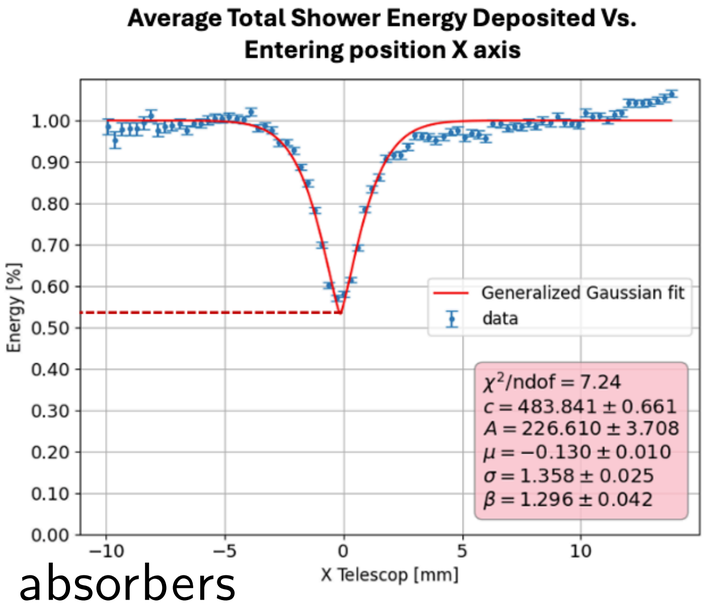


Dead area between modules

- Two neighbouring sensors are distanced by a 1.7 mm gap
- This is to avoid sensor collision
- Signal could be lost when electron passing through the gap
- Averagely, we can recover 54% of the energy deposit in the calorimeter mode with $8X_0$ absorbers

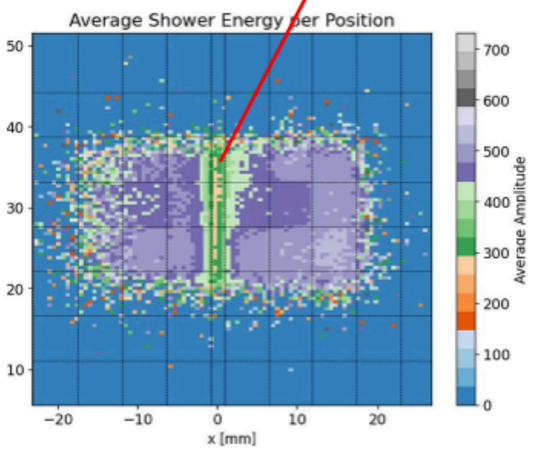


No absorber



$8X_0$ absorbers

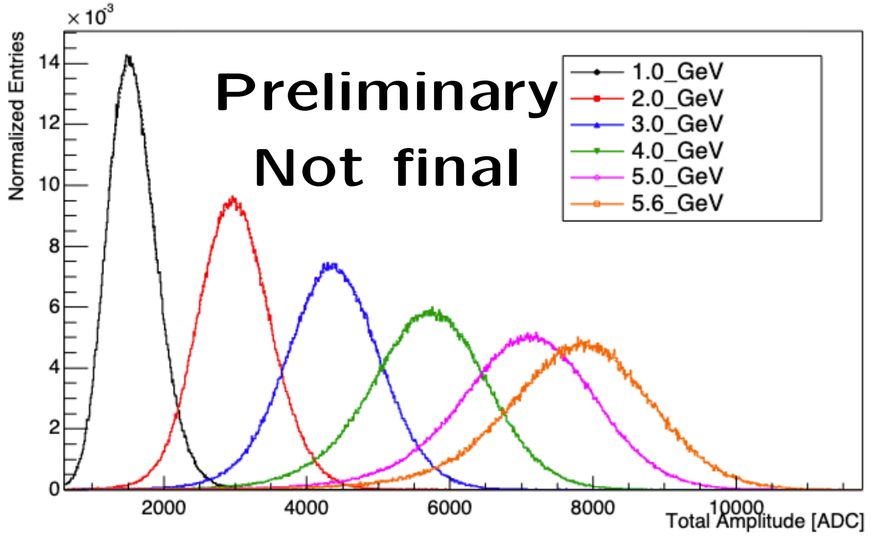




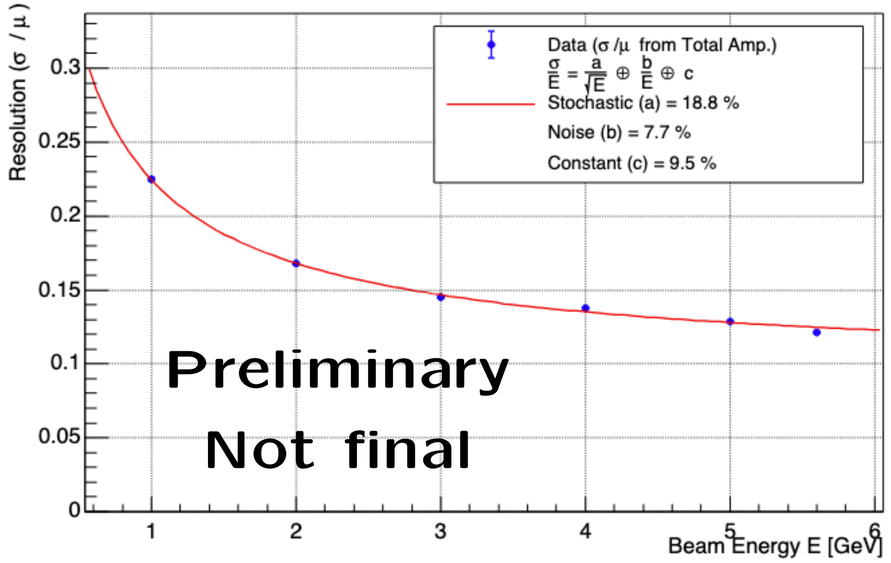
Middle green area is the gap between the 2 sensors

Energy resolution

- With only $11X_0$ absorbers, we are still able to obtain a not-so-bad energy resolution curve despite
  - Longitudinal leakage
  - Dead channels (2%) and noisy channels (4%)
- The results are now comparing with MC simulation



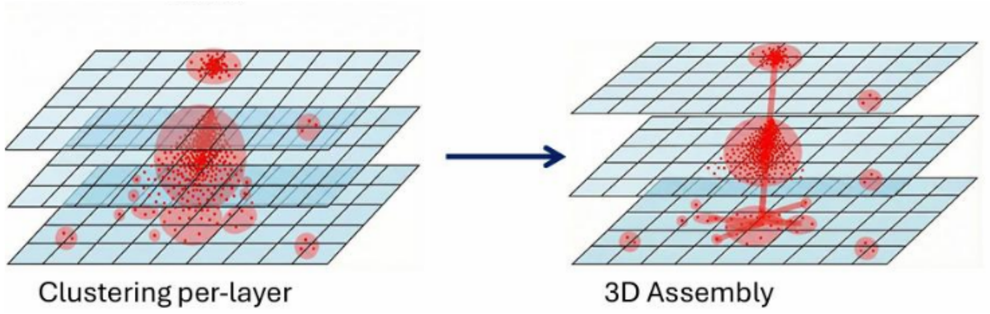
For higher energy longitudinal energy leakage occurs.

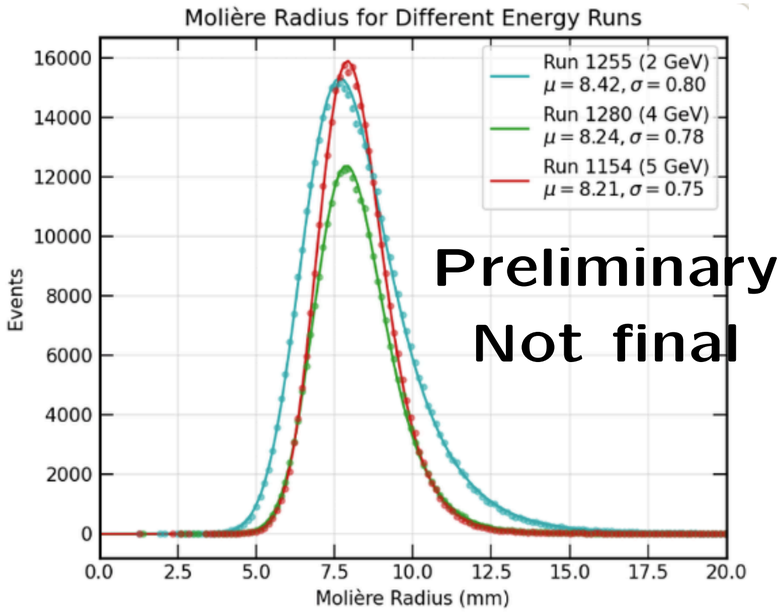


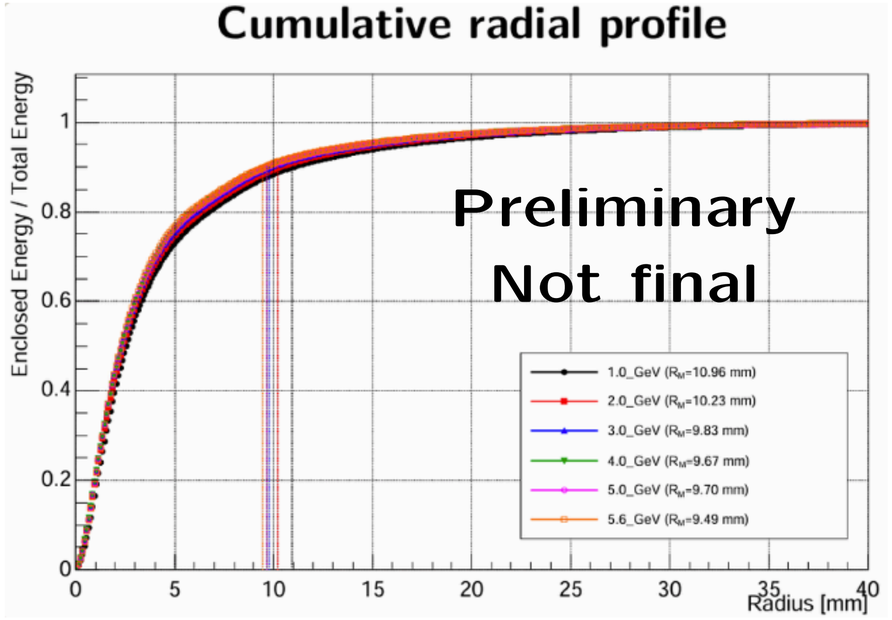
These results are obtained for only 10 X_0

Shower radial profile

- Preliminary results shows 9.5 to 11 mm effective Molière radius (90%) for the detector
- The results are obtained with dead channel compensation and clustering method

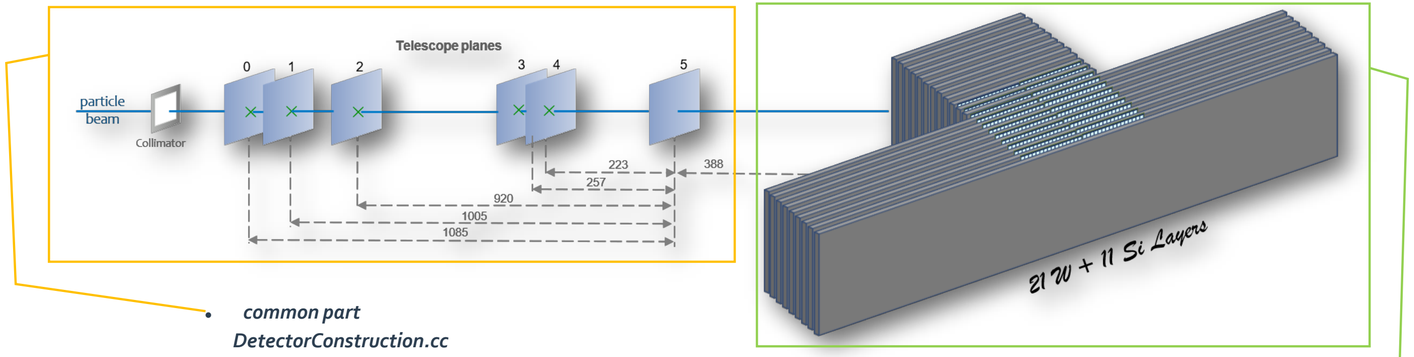




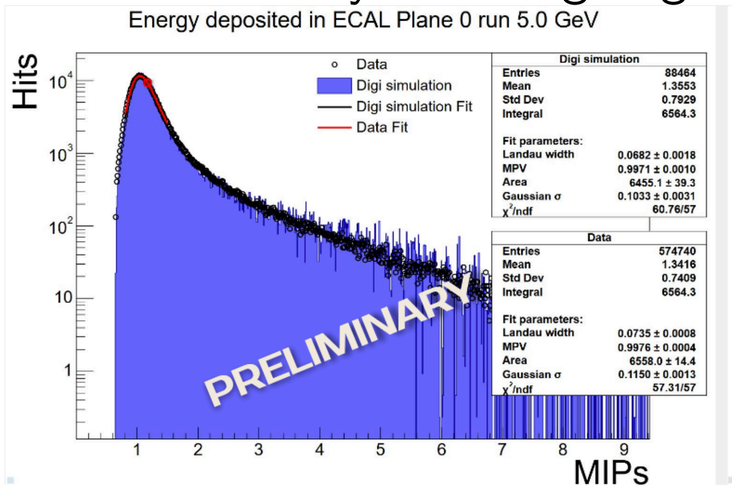


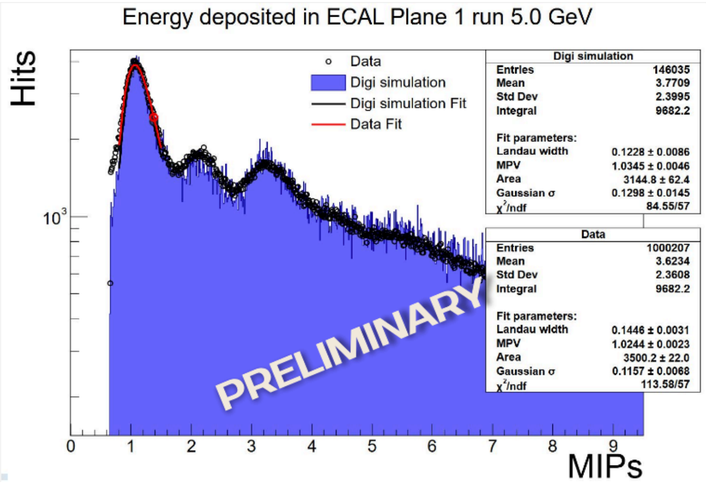
MC simulation

- Dedicated Geant4 application for the campaign has been implemented
- Simulations of various configurations were launched
- Normalized energy deposit distribution is compared plane by plane
- Preliminary results show agreement on first two planes
- More analysis is ongoing



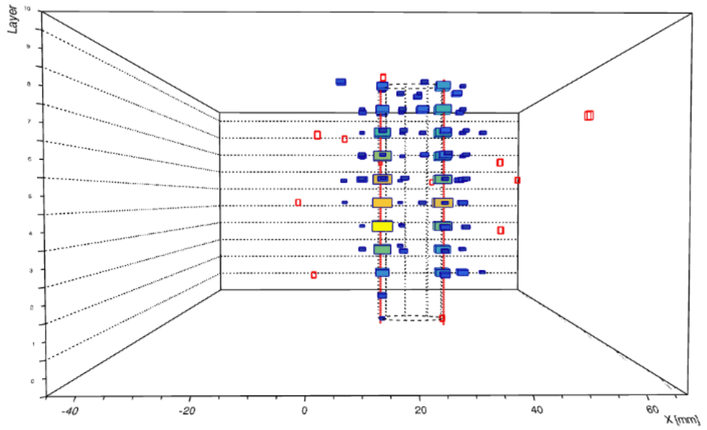
- *common part DetectorConstruction.cc*
- *changing part /TB2025/geomX.list*





Summary

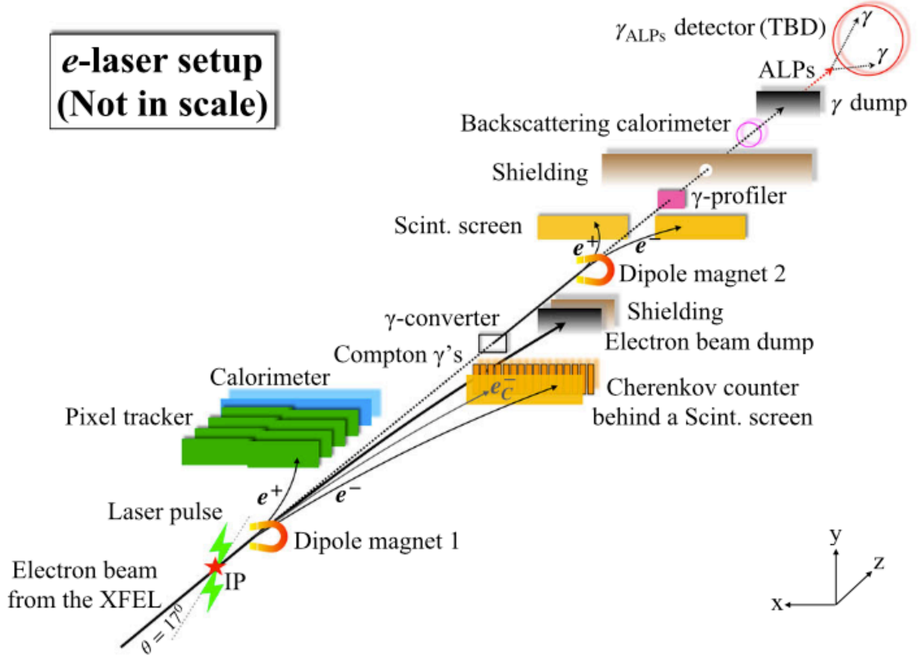
- The highly granular and compact calorimetry are important to future experiments on Higgs factories and also many other subjects such as strong-field QED and dark matter search
- The FCAL-LUXE Collaboration has designed a prototype
- A partially populated configuration was tested on electron beamline
- The preliminary results of TB data analysis are promising and a manuscript is under preparation
- LUXE is now exploring the alternative locations for the laser-electron/photon collision experiments

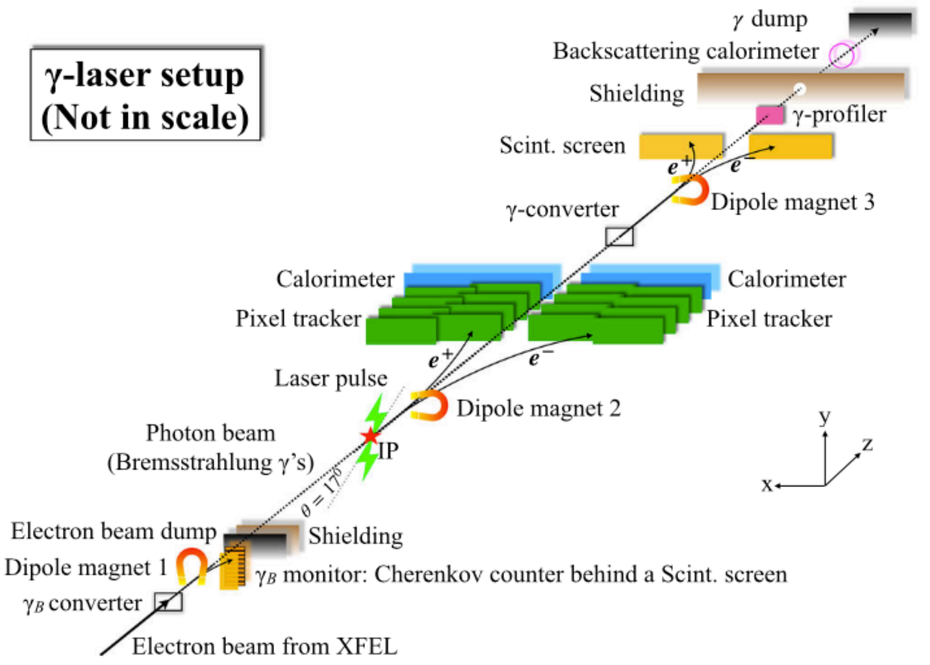




Backup

LUXE setups


e-laser setup
(Not in scale)
γ_{ALPs} detector (TBD)
ALPs
γ dump
Backscattering calorimeter
Shielding
γ-profiler
Scint. screen
Dipole magnet 2
γ-converter
Shielding
Compton γ's
Electron beam dump
Calorimeter
Cherenkov counter
behind a Scint. screen
Pixel tracker
Laser pulse
Dipole magnet 1
Electron beam
from the XFEL
IP
θ = 17°
y
z
x


γ-laser setup
(Not in scale)
γ dump
Backscattering calorimeter
Shielding
γ-profiler
Scint. screen
γ-converter
Dipole magnet 3
Calorimeter
Calorimeter
Pixel tracker
Pixel tracker
Laser pulse
Dipole magnet 2
Photon beam
(Bremsstrahlung γ's)
IP
θ = 17°
y
z
x
Electron beam dump
Shielding
Dipole magnet 1
γ_B monitor: Cherenkov counter behind a Scint. screen
γ_B converter
Electron beam from XFEL

Dead channel compensation

Some channels 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

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

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

Assuming shower is radially symmetric

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

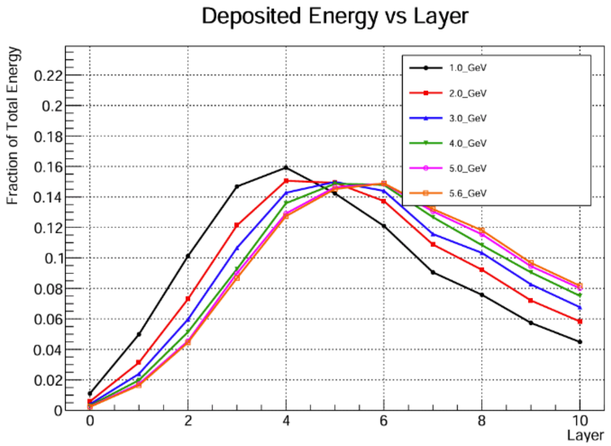
Reconstruction: take R for the dead pad, draw hit yes/no from P(R), then sample an amplitude if there is a hit

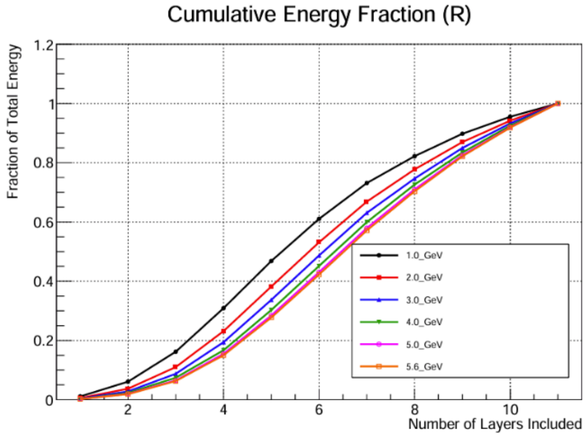
New algorithm; first tests on simulated files

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.

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Shower profiling





Longitudinal profile

Radial profile

