Test-beam Measurements of Instrumented Sensor Planes for a Highly Compact and Granular Electromagnetic Calorimeter

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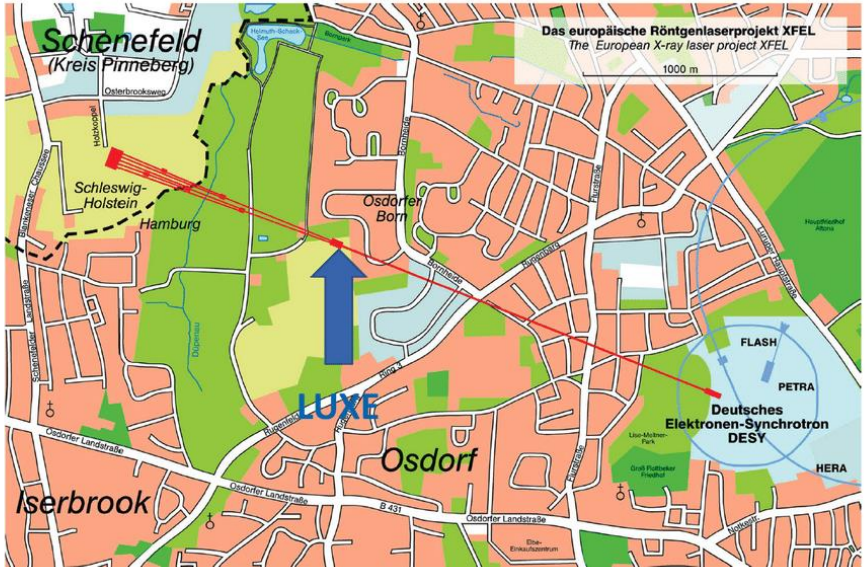
on behalf of LUXE ECAL group

31/10/2024

LUXE: Laser Und XFEL Experiment

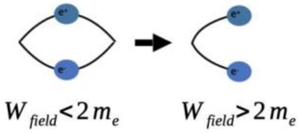
Based at DESY and XFEL, Hamburg



- LOI (2019) 1909.00860
- CDR (2021) Eur. Phys. J. ST 230, 2445-2560
- TDR (2024) Eur. Phys. J. ST 233, 1709-1974

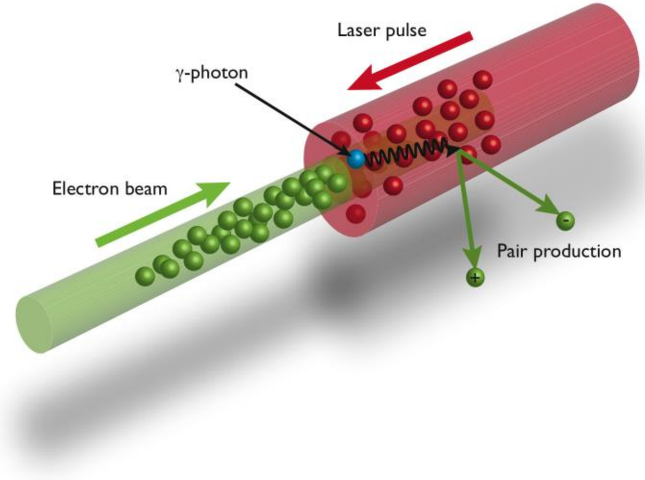
<u>Main goals</u>

- Study **QED** in the **strong-field** regime where it is **non-perturbative** (at and above the Schwinger limit) and the vacuum becomes unstable to pair-production
- Study of the **transition region** from perturbative to non-perturbative QED
- Search for **new particles** beyond the Standard Model, that couple to **photons**



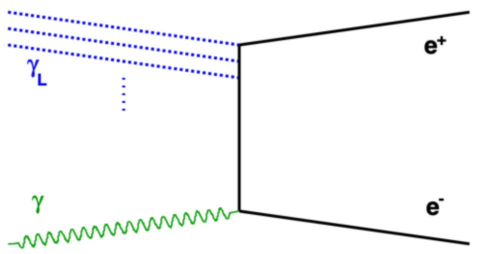
$$W_{field} = \frac{\varepsilon e}{m_e}$$

Achieved by colliding high energy electrons (16.5 GeV) with photons from a high-power laser (40 TW, 350 TW).



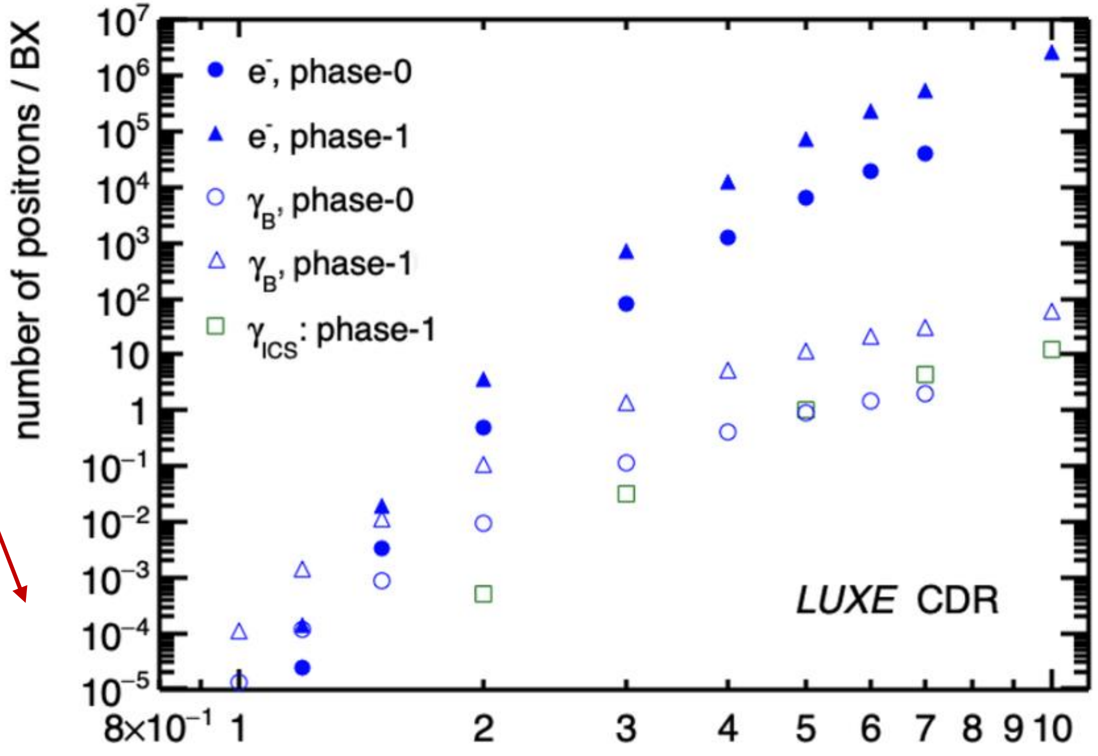
Physics and Challenges

- Strong field → e^+e^- **pair production**
- Expected **multiplicities span over orders of magnitude** per BX
- EM showers overlap at high multiplicities



nonlinear Breit-Wheeler

Many orders of magnitude



(laser field intensity parameter) ξ

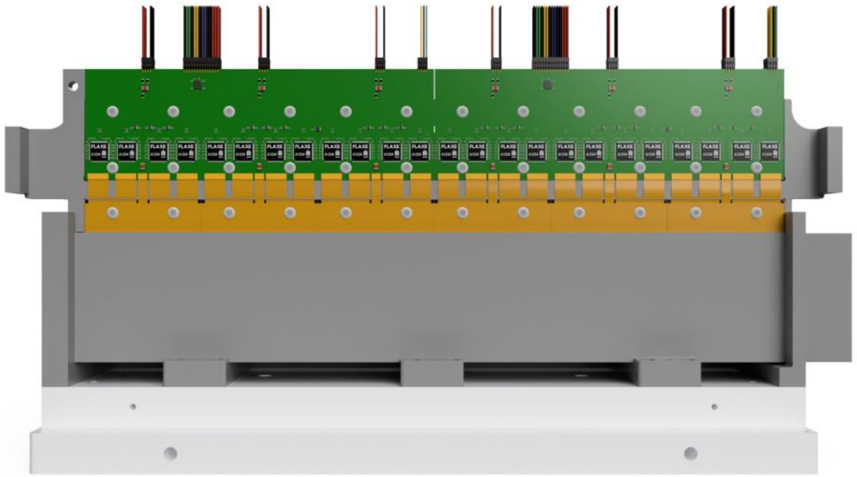
Energy spectra to be measured by a **compact EM calorimeter**

The ECAL-p group

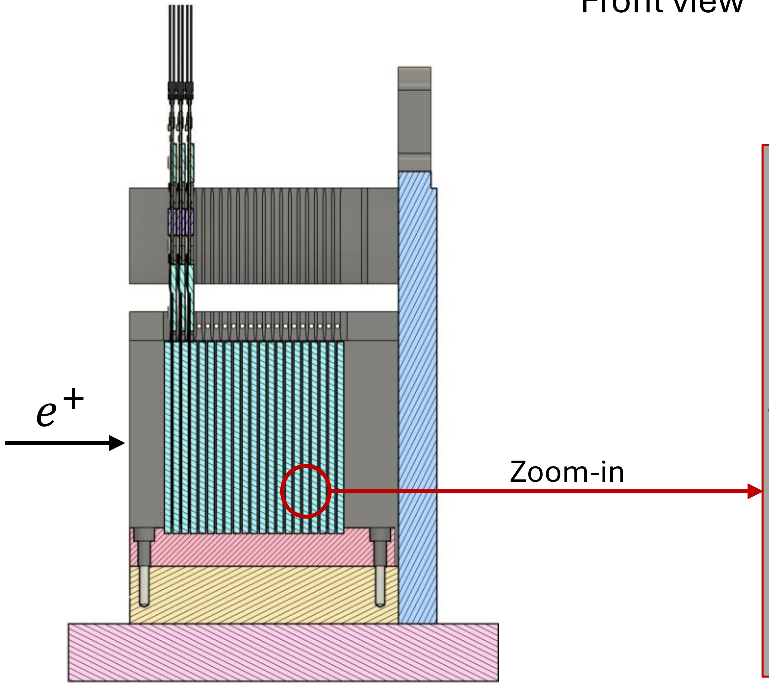
ECAL-p

e^+ sampling calorimeter characteristics:

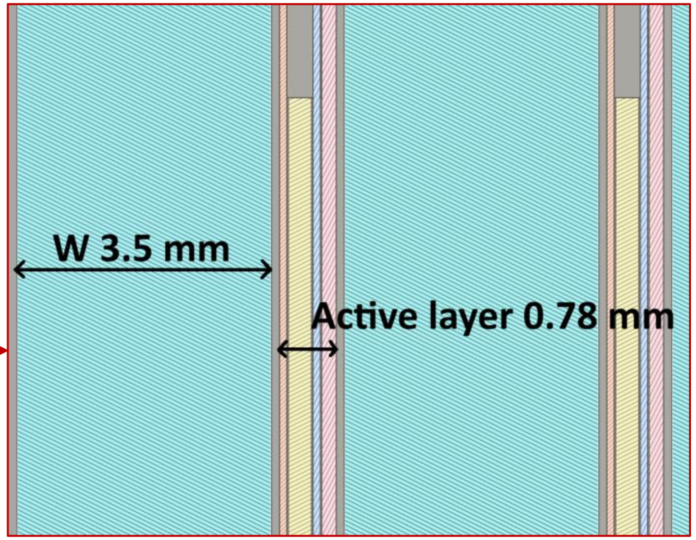
- Compact → small Molière Radius (~ 9 mm)
- 21 tungsten plates of $1X_0$ (3.5 mm) thickness
- **1 mm** gaps between absorbers
- 20 active sensor planes instrumented in the gaps
- High granularity



Front view



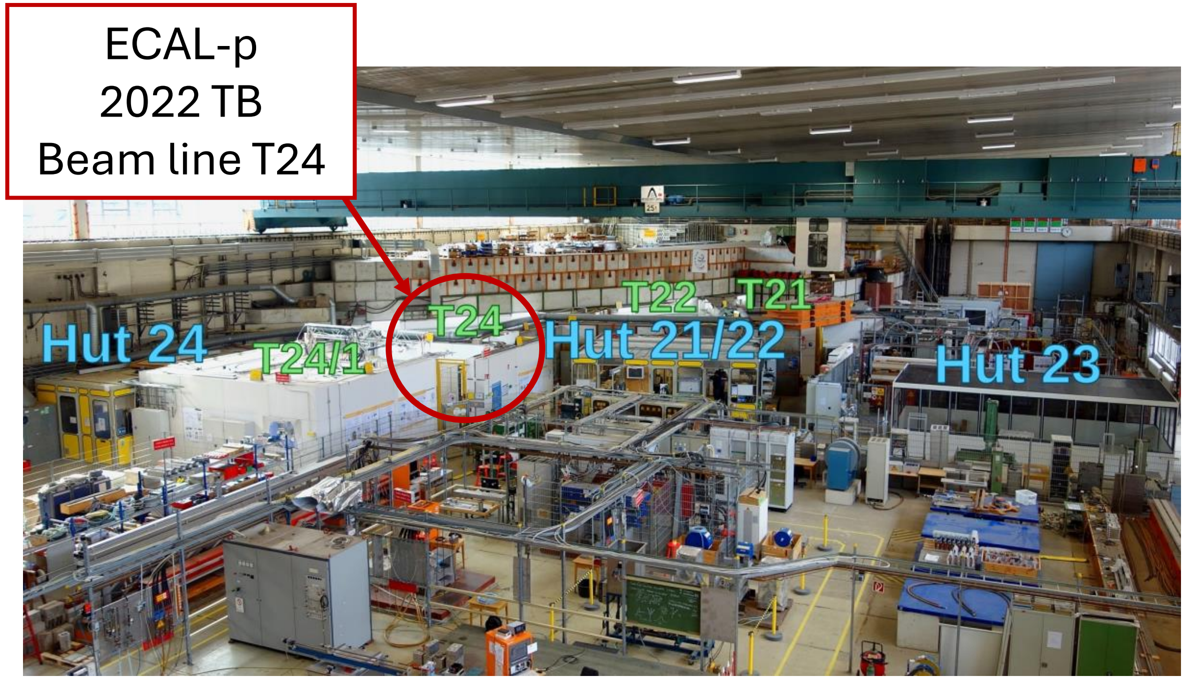
Side view (3 connected layers)

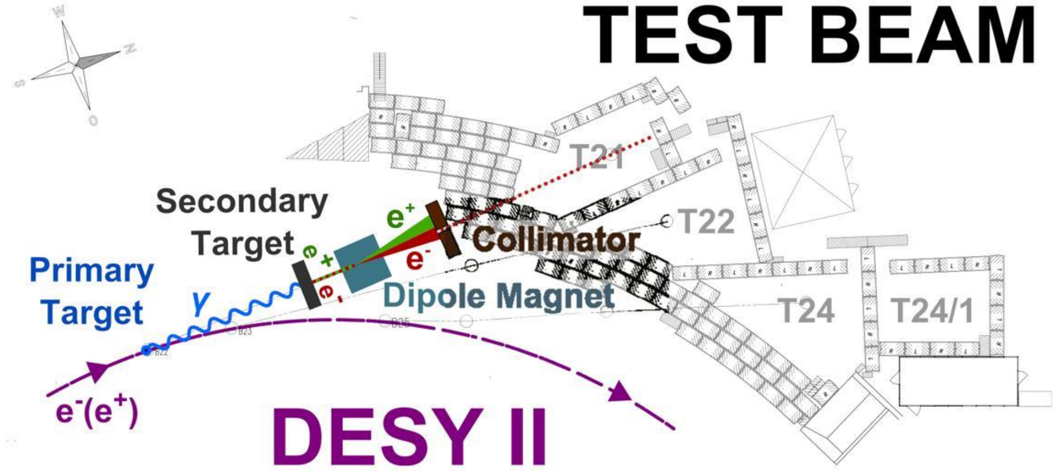


Zoom-in on side view

Test-Beam @ DESY

- 5 GeV electron beam
- ~1.5 kHz particle rate
- TLU
- Telescope based on 6 Alpide sensor planes





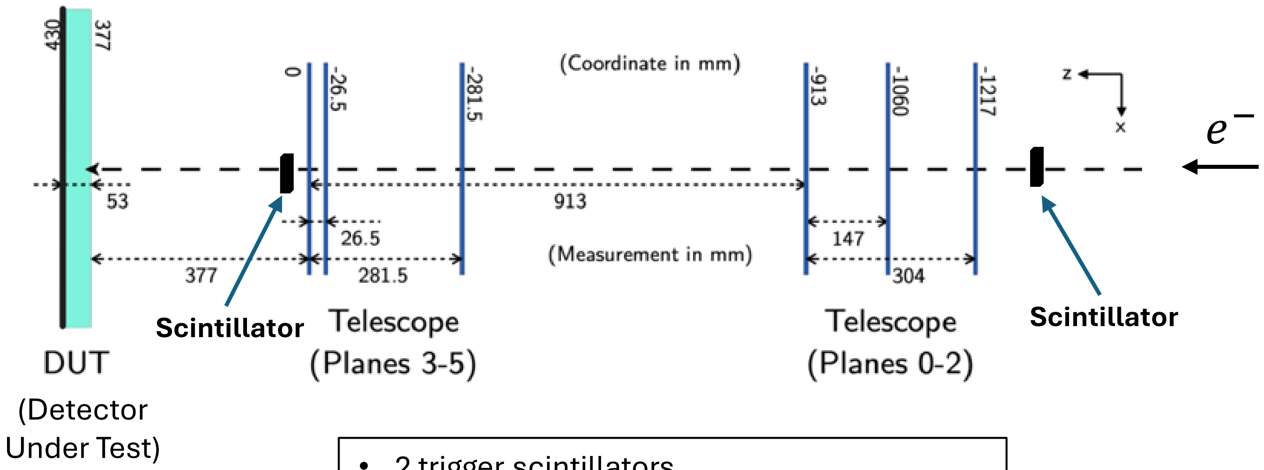
Test beam generation, here for beam line TB21
"The DESY II test beam facility"
(https://doi.org/10.1016/j.nima.2018.11.133)
NIMA, Volume 922, 1 April 2019, Pages 265-28

2022 Test-Beam @ DESY

Two types of semiconductor sensors tested:
Silicon and **Gallium Arsenide (GaAs)**

Test-beam done in 2 steps.

1) **Single sensor setup**. Studied:
    - Homogeneity of sensor response
    - Edge effects
    - Signal sharing between pads
2) **Pseudo Calorimetry.** A single sensor mounted with $1 - 15$ tungsten plates in front



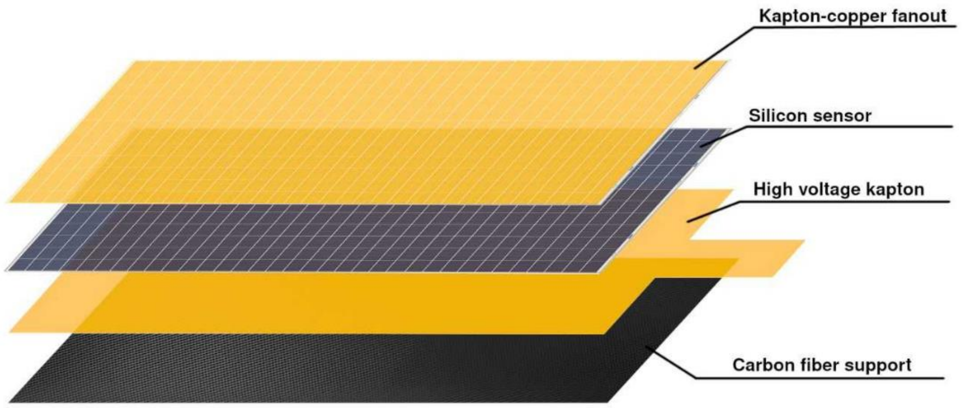
- 2 trigger scintillators
- 6 ALPIDE pixel sensors – resolution of the reconstructed tracks on the DUT $\sim 35\mu m$.
- EUDAQ framework

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

Sensors under investigation @ TB

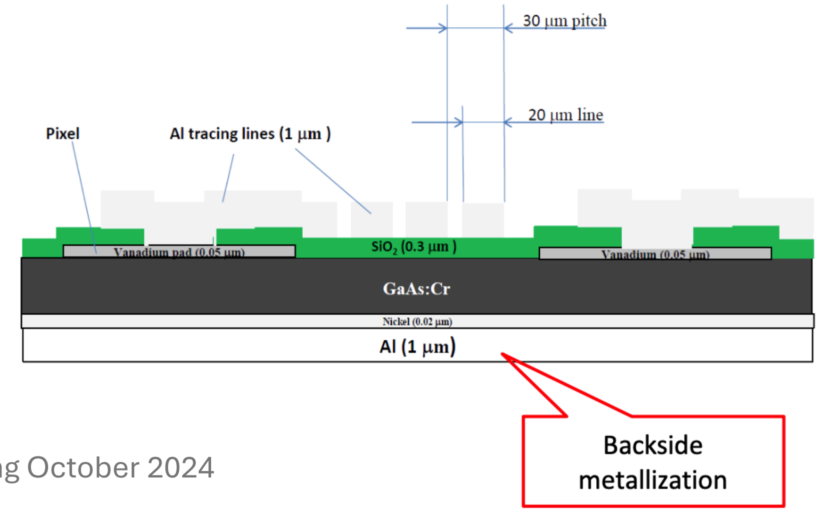
Silicon

- Produced by Hamamatsu (**CALICE** design)
- 500 μm thickness
- 5.5×5.5 mm^2 pads, 10 μm gap
- External **Kapton fan-outs** with copper traces connected to the sensor pads with **conductive glue** (EPO-TEK E4110)



Gallium Arsenide

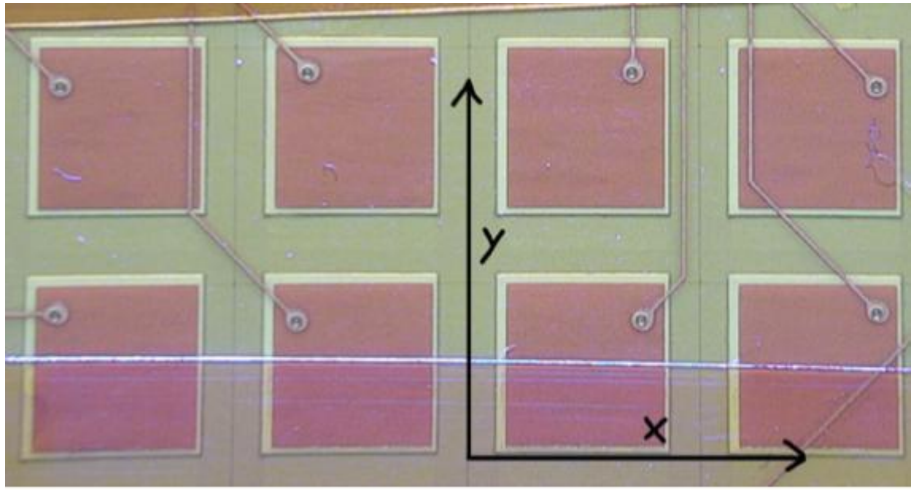
- Produced by National Research **Tomsk** State University
- 500 μm thickness
- 4.7×4.7 mm^2 pads, 300 μm gap
- 10 μm Aluminum traces in the gaps, 20 μm apart from each other



Sensors under investigation @ TB

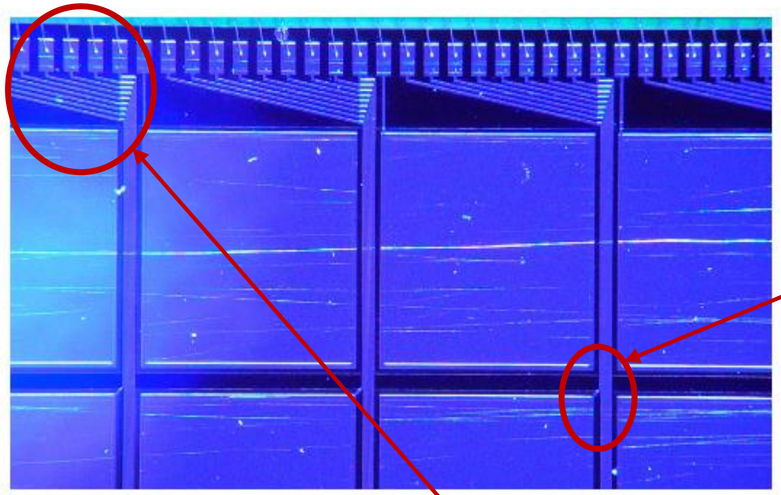
Silicon

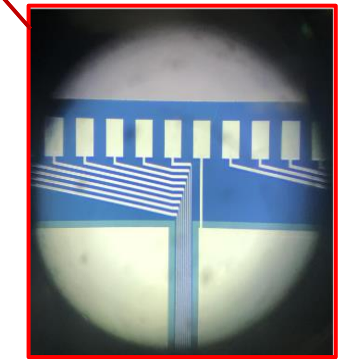
- 16×8 pads

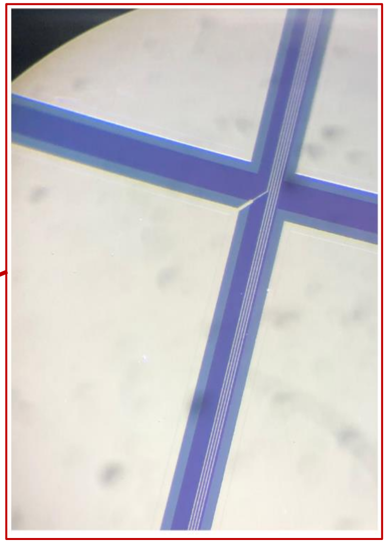


Gallium Arsenide

- 15×10 pads

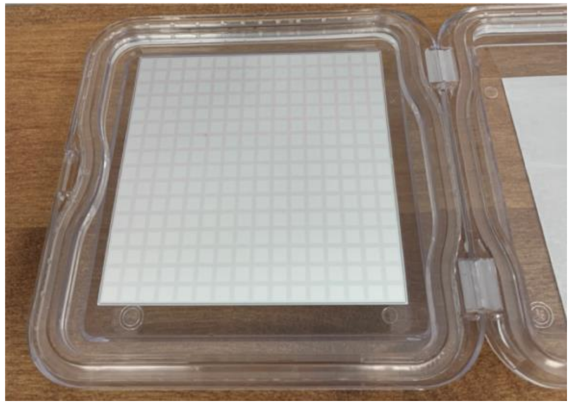






Aluminum Traces

2022 Test-Beam @ DESY



Silicone sensor

GaAs sensor

Telescope-Sensor Alignment

Modified Hough Transform – aim to find the position of the gaps between pads ("edge detection").

- Select events with signal in exactly 2 adjacent pads – aiming to find hits in the gaps
- Find the densest area in x and the densest area in y – discard other points
- Calculate the line equation between each pair of points in an area
- Fit a gaussian in parameter space and take the Most Probable Value (MPV)

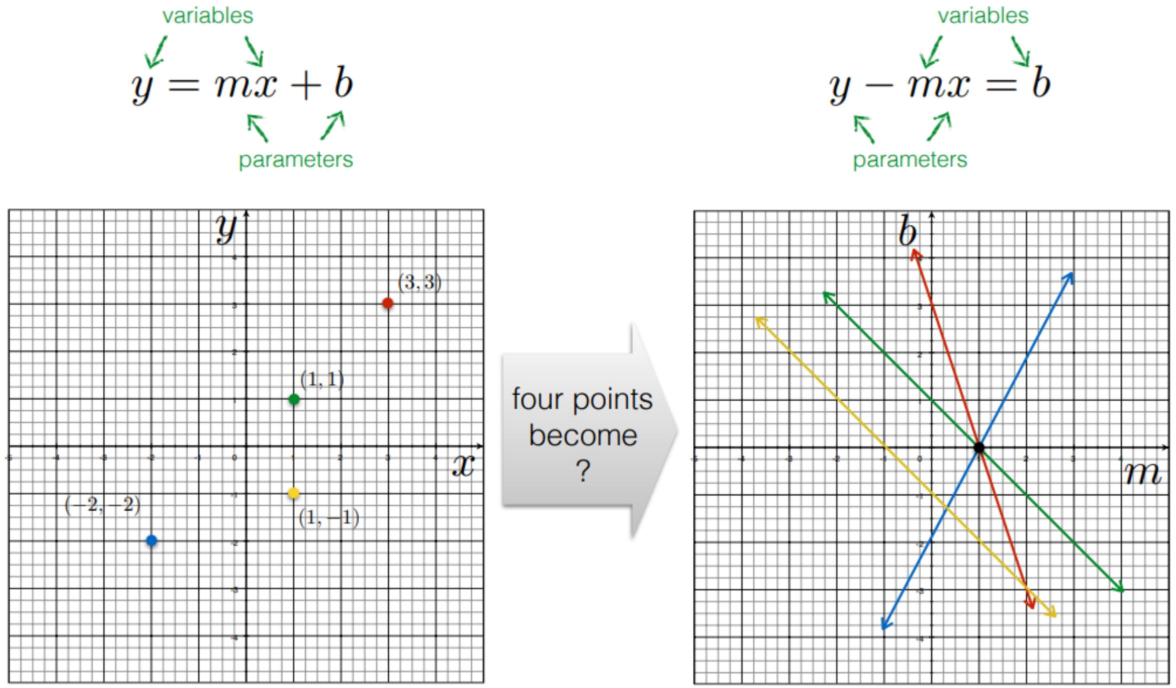
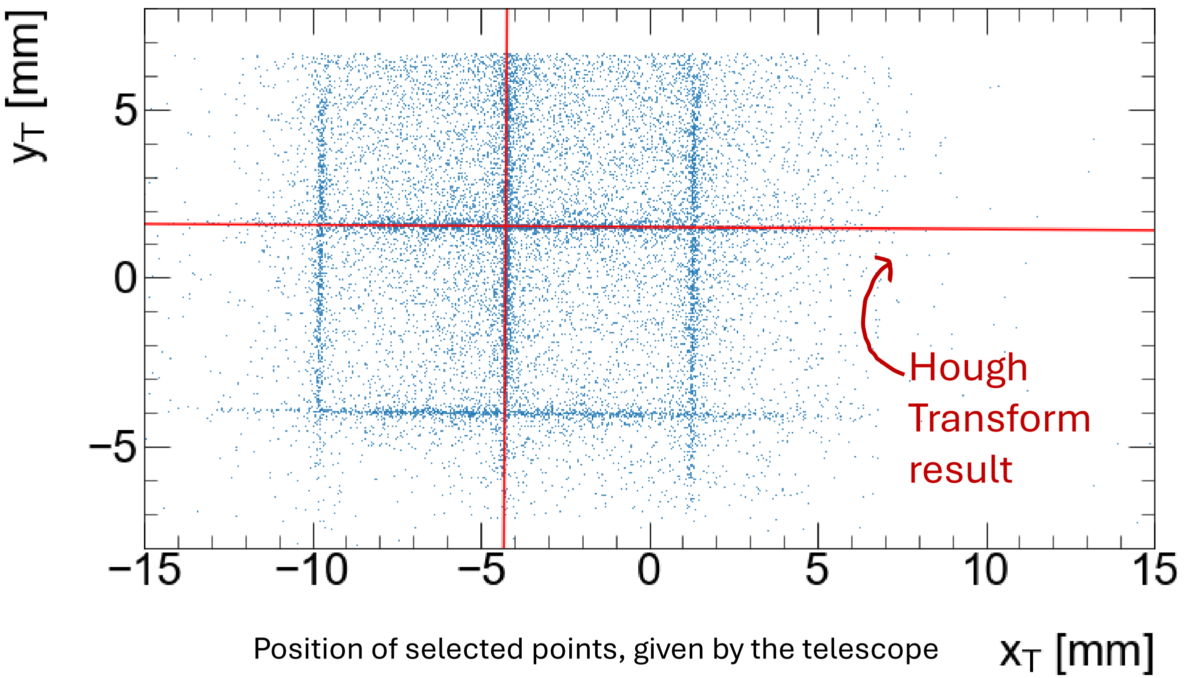


Image Space

Parameter Space

Image from: https://www.cs.cmu.edu/~16385/s17/Slides/5.3_Hough_Transform.pdf

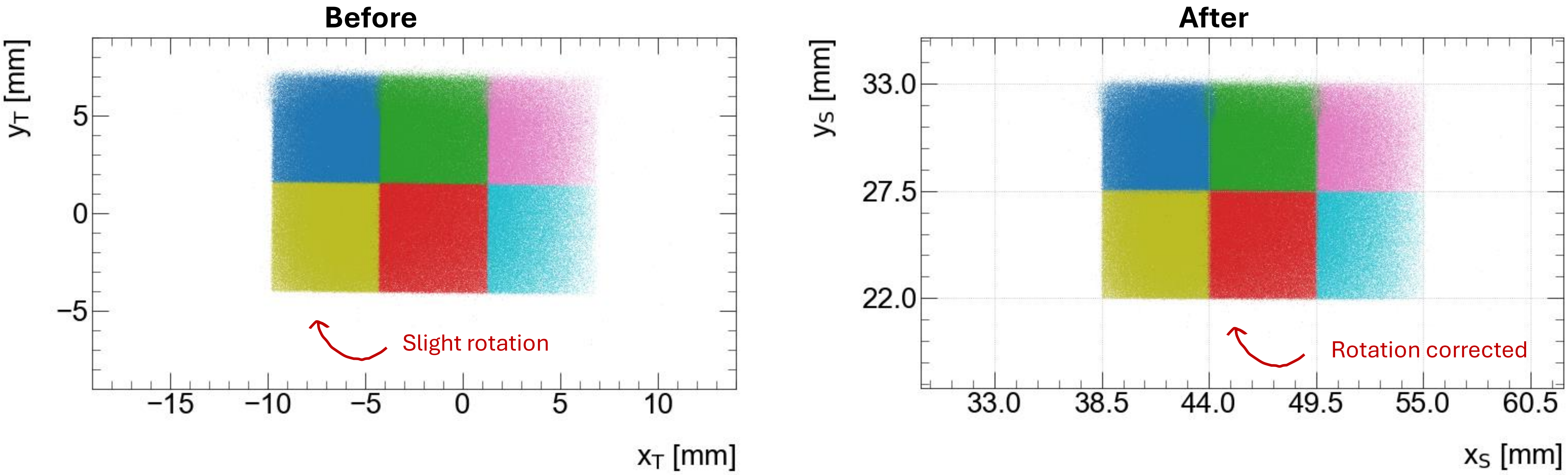


Position of selected points, given by the telescope

Telescope-Sensor Alignment

Finding the gaps between pads allows to map the coordinates and correct for relative angles between the telescope and the sensor.
Sensor coordinates represent the position **relative** to the bottom left **corner**.

Silicon sensor



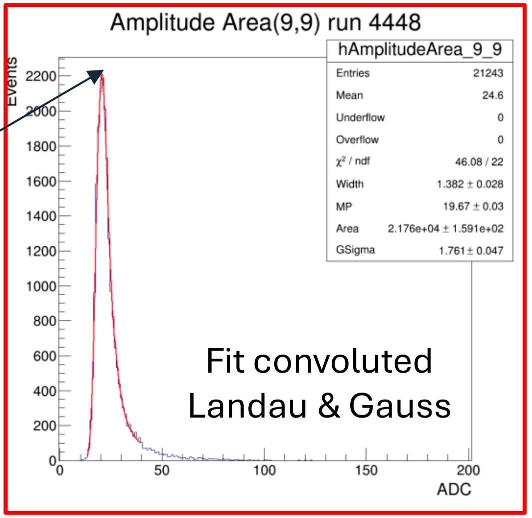
Expected track position on the face of the sensor in the telescope coordinate system, x_T and y_T before alignment (left) and in the sensor coordinate system, x_S and y_S, after alignment (right). Each pad is assigned the same colour in both maps.

Pad homogeneity study

A single pad, subdivided into 10×10 equally sized sections.
Plotted is the MPV in ADC count in each section.

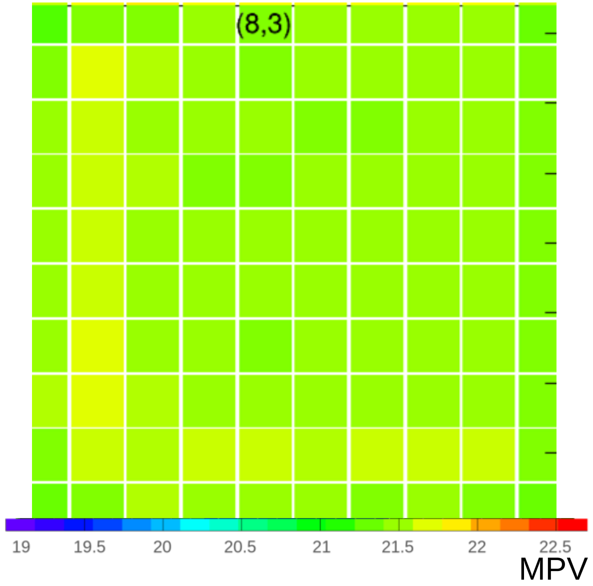
MPV=Most Probable Value

$$\mathrm{MPV} \; = \; \mathrm{MIP}$$
$$\mathrm{Si_{MIP}} \cong \mathrm{GaAs_{MIP}}$$



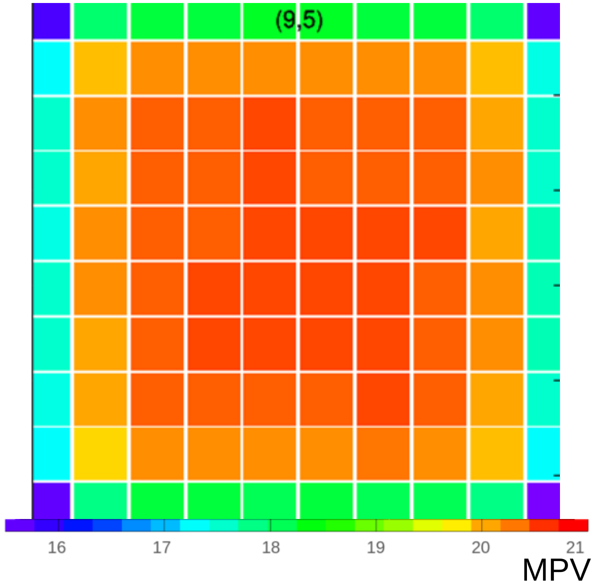
Silicon pad

- Roughly uniform response



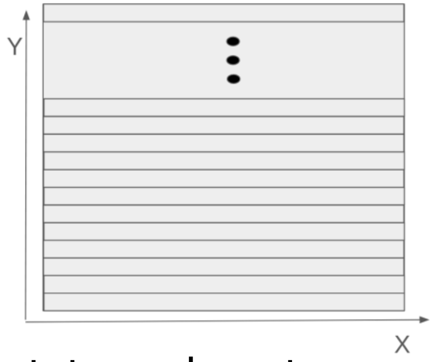
GaAs pad

- Drop in amplitude around the edges



Pad homogeneity study (cont.)

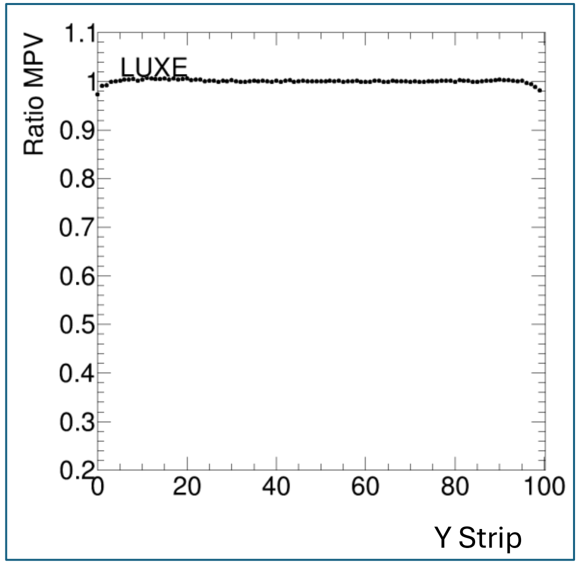
Strip subdivision



A single pad, subdivided into 100 equally sized strips along Y.
Plotted is the MPV in the strip normalized to MPV of central strip.
Similar response along X direction.

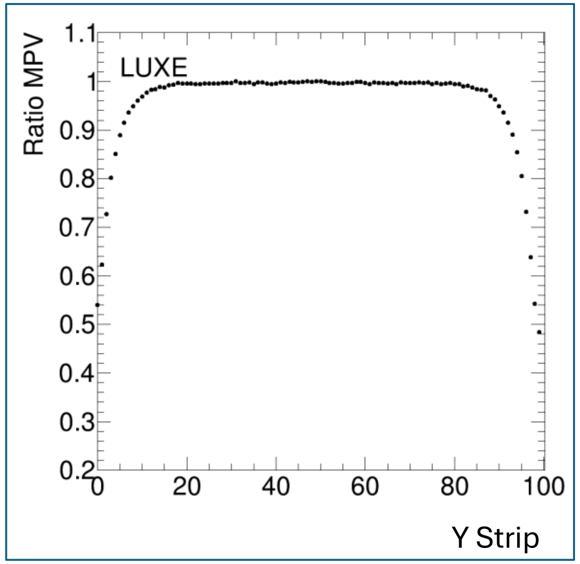
Silicon

- $2-3\%$ drop at the edges w.r.t. to pad center



GaAs

- 50% drop at the edges w.r.t. to pad center

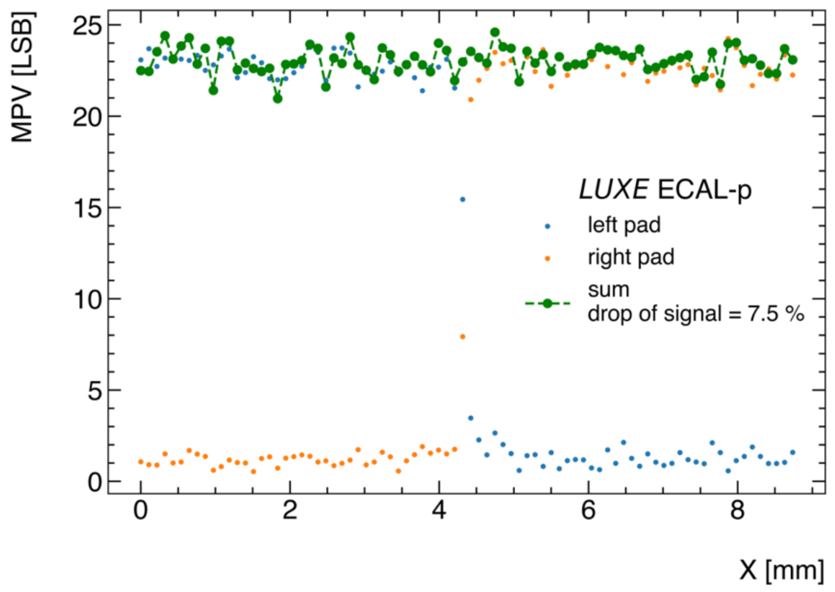


Signal sharing – X scan

MPV measured as a function of X, crossing the area between two pads.

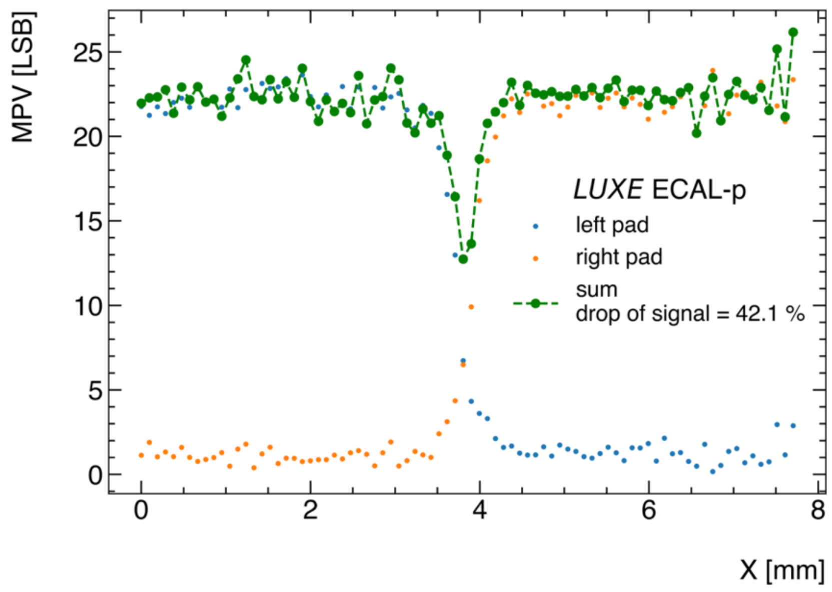
Silicon

- $10\ \mu m$ gap size
- No visible drop in the gap area between pads



GaAs

- $300\ \mu m$ gap size – with traces
- Up to 40% drop at the traces area



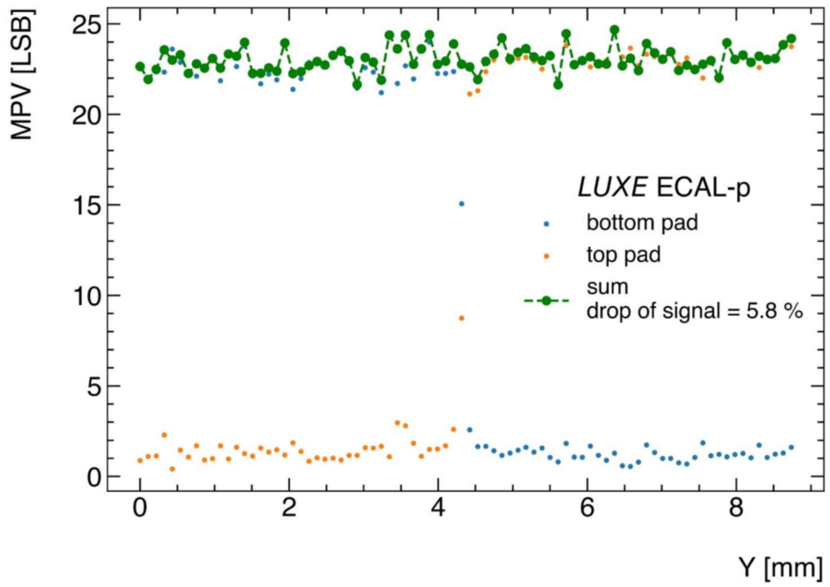
In green:
Sum of signals in both pads

Signal sharing – Y scan

MPV measured as a function of Y, crossing the area between two pads.

Silicon

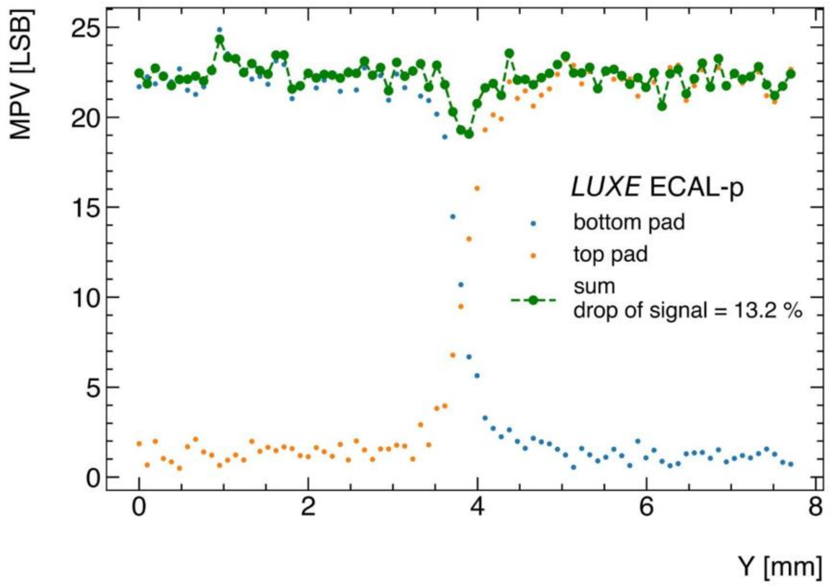
- 10 μm gap size
- No visible drop in the gap area between pads



GaAs

- 300 μm gap size – no traces
- Only 10% drop at the gap area

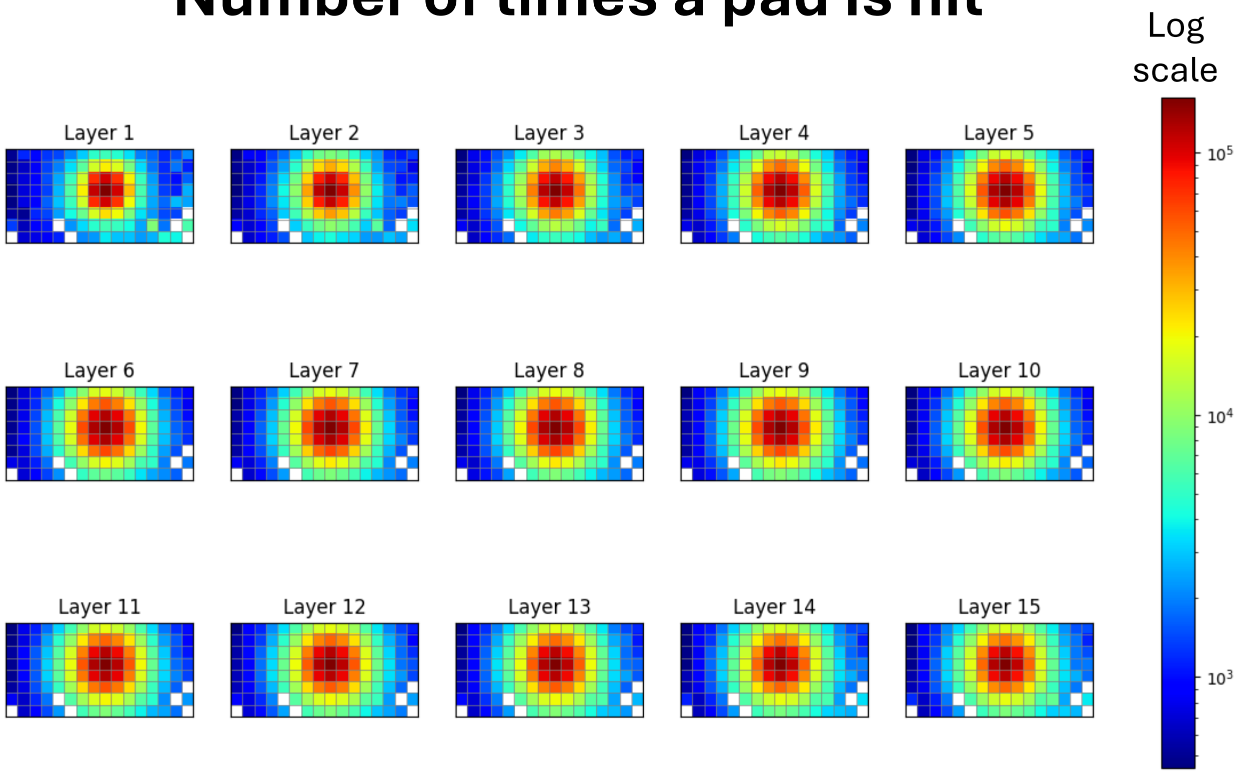
In green:
Sum of signals in both pads



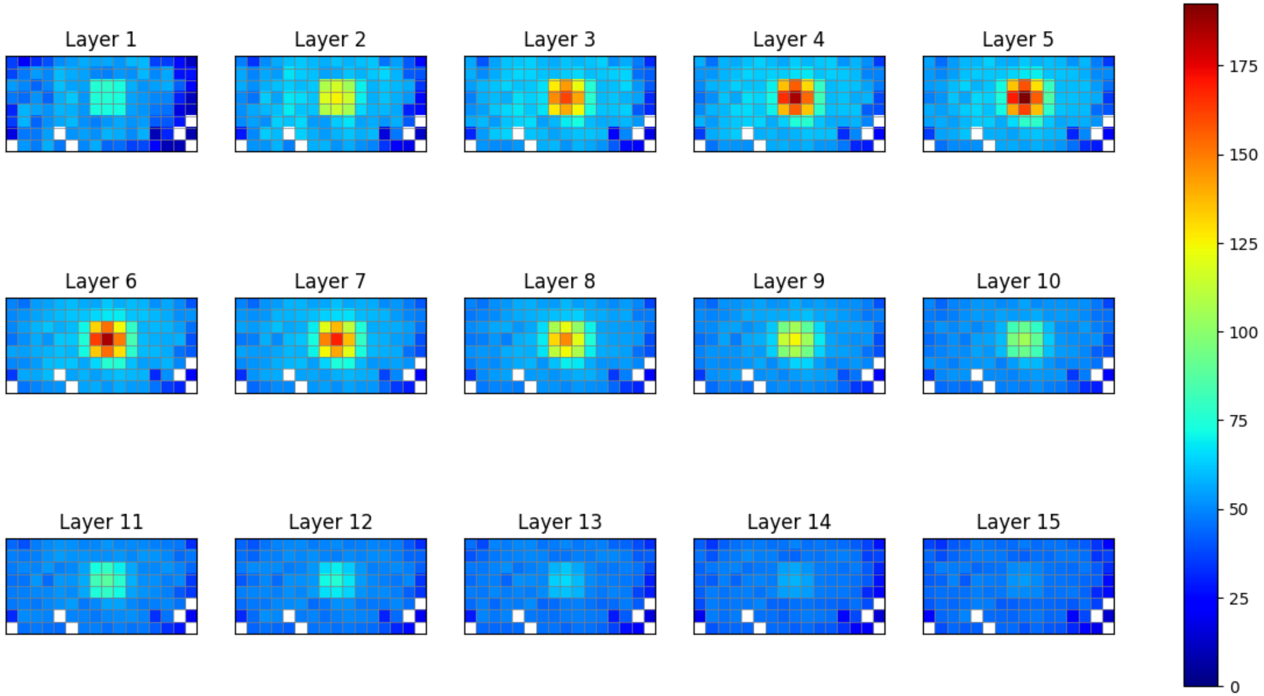
Calorimetry runs (prelim) - Silicon

“Layer i” means i Tungsten plates in front of the sensor.
Isotropic in the radial direction as desired.

Number of times a pad is hit



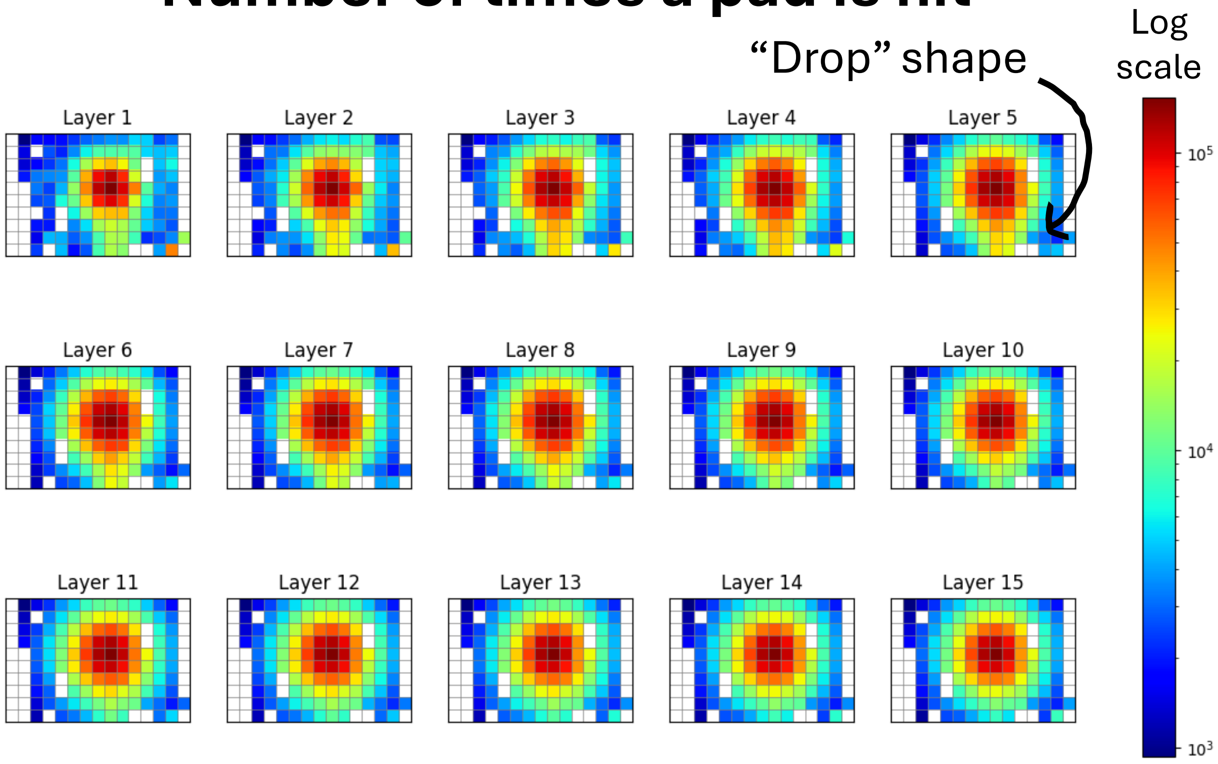
Average ADC count per pad



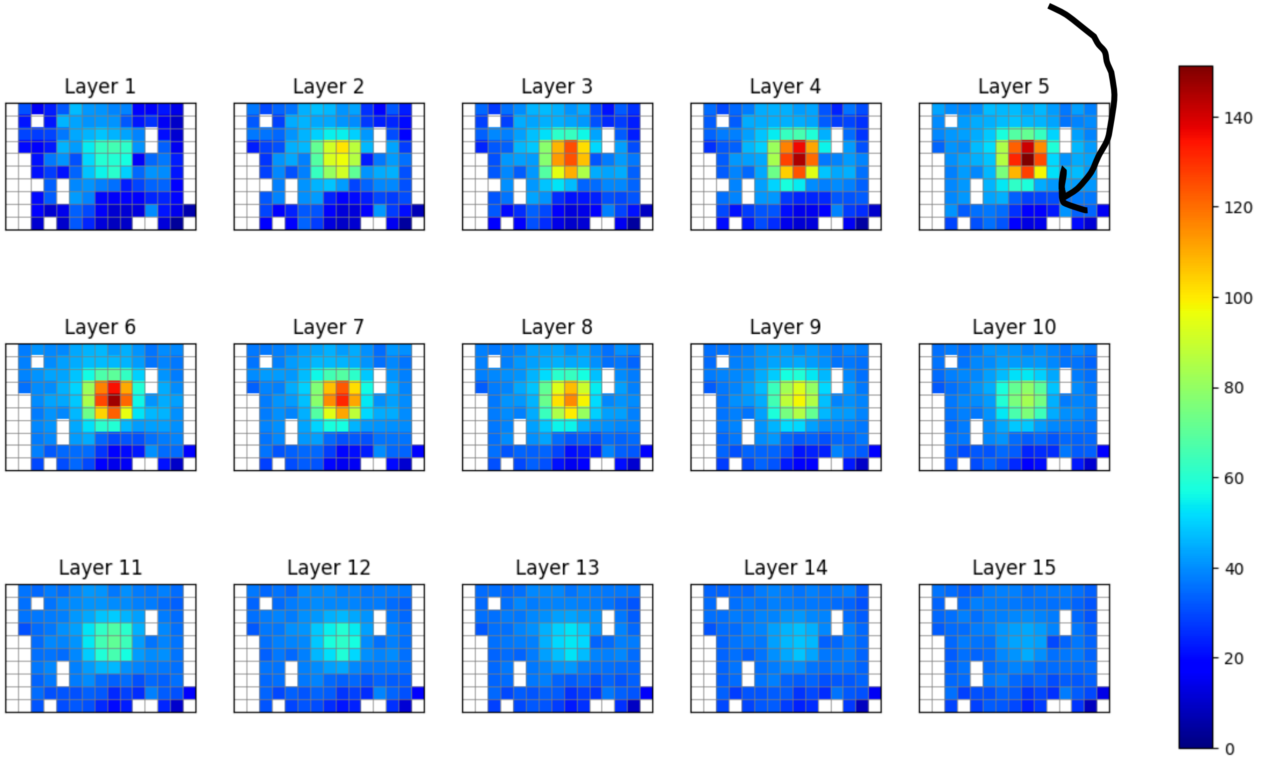
Calorimetry runs (prelim) - GaAs

“Layer i” means i Tungsten plates in front of the sensor.
Non symmetric vertically – different values below vs above the beam center.
Most likely due to the traces.

Number of times a pad is hit



Average ADC count per pad



Summary & Conclusion

- Individual pad-response studies were possible thanks to the telescope and a successful alignment
- Hough Transform-based alignment shows to be a helpful tool
- Silicon sensors presented expected satisfactory behaviour
- GaAs sensors with embedded aluminum traces present a drop of signal amplitude on the pad edges
- First evidence of signal picked up by the traces in GaAs sensors
- Investigation of calorimetry is in process

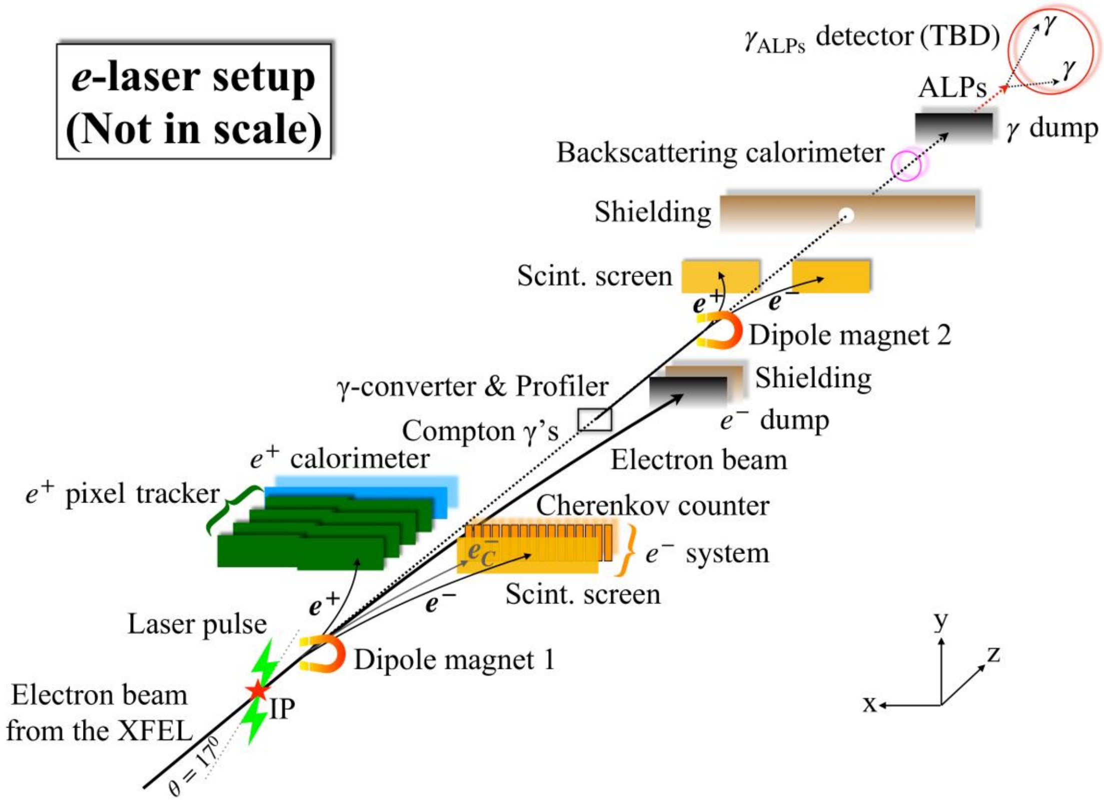
TB experience overview

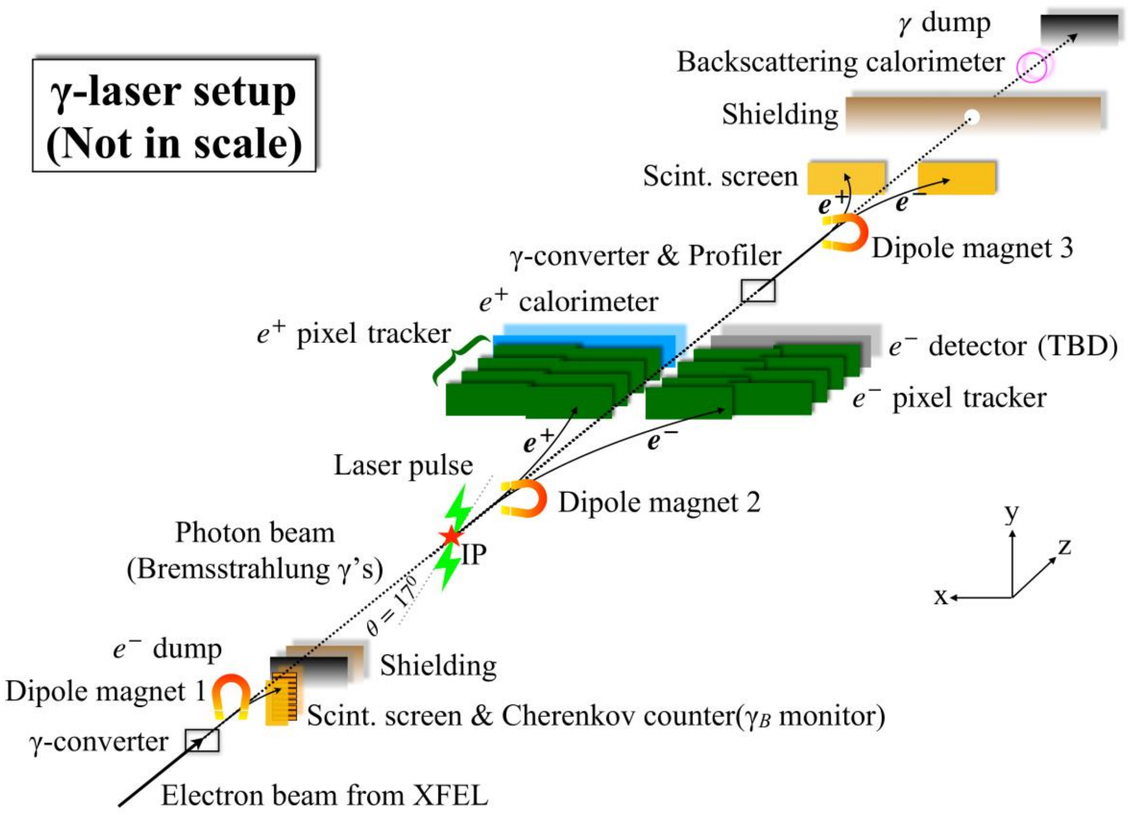
- 2021 TB – readout issues. Detected during TB but on the last day.
- 2022 TB – successful and fruitful thanks to simple **ready-to-run** analysis tools used **during TB** to verify a smooth run.
- 2025 (planned) – at least 6 planes of Tungsten with 12 silicon sensors (CALICE)

Thank you for your attention!

Backup

Two LUXE Setups

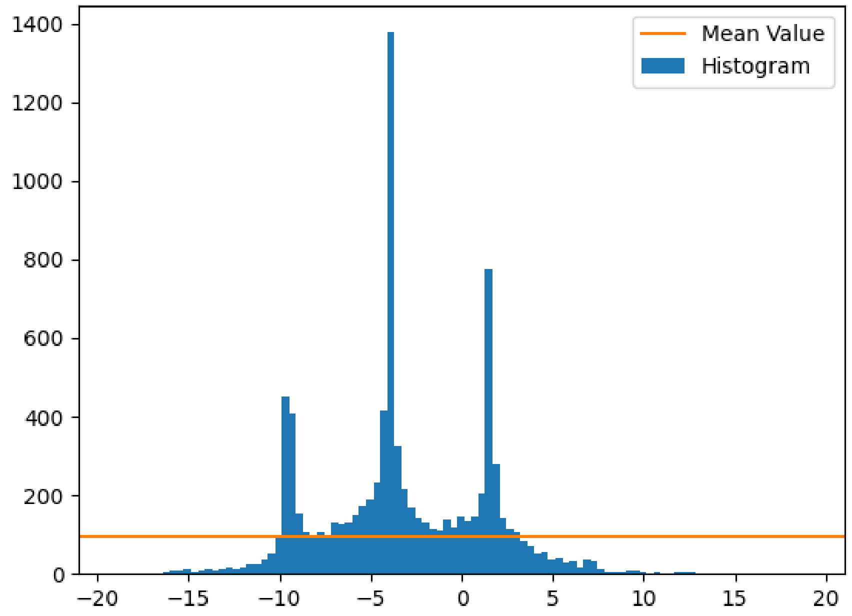


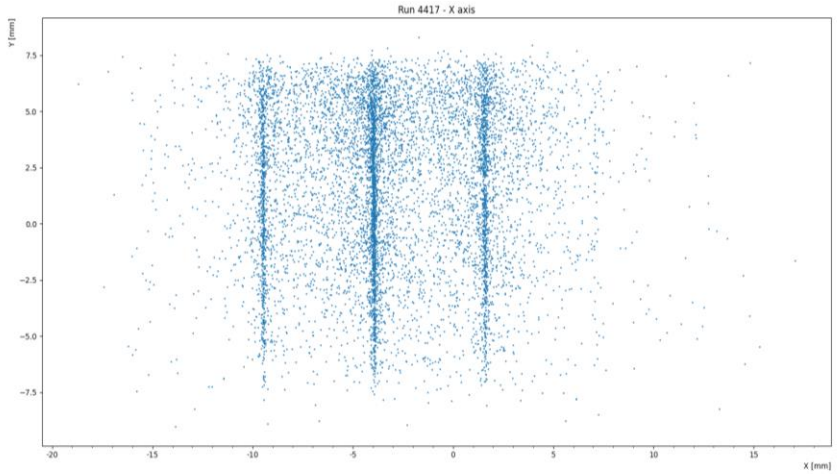


Hough Transform

Finding an initial “edge” estimation:

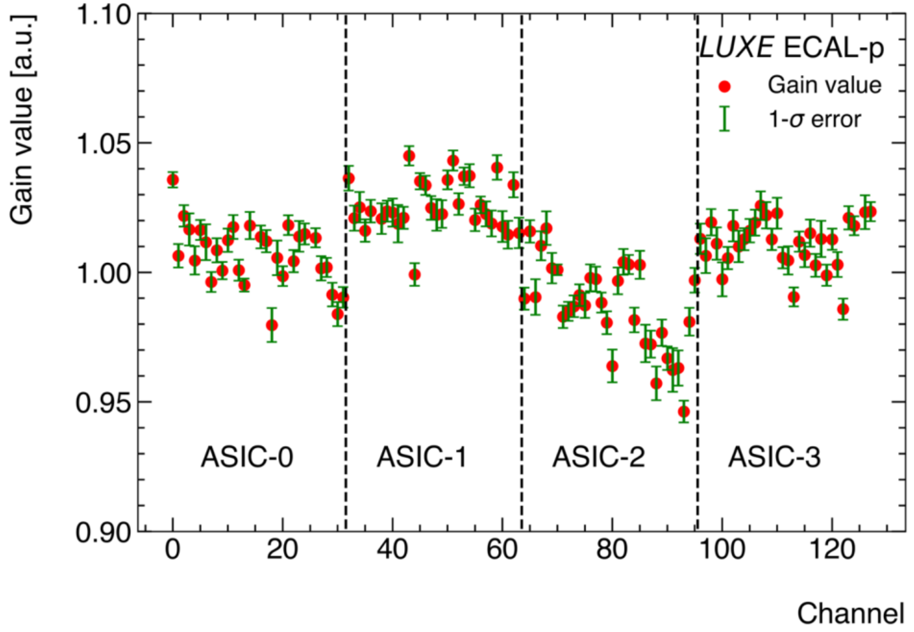
- Separately for horizontal and vertical gaps:
  - vertical – select events with 2 adjacent pads in the same row
  - Horizontal – select events with 2 adjacent pads in the same column
- Project the hits position onto x for vertical gaps and onto y for horizontal ones
- From the histogram – find the highest peak and take points in its vicinity as the area relevant for the Hough Transform algorithm



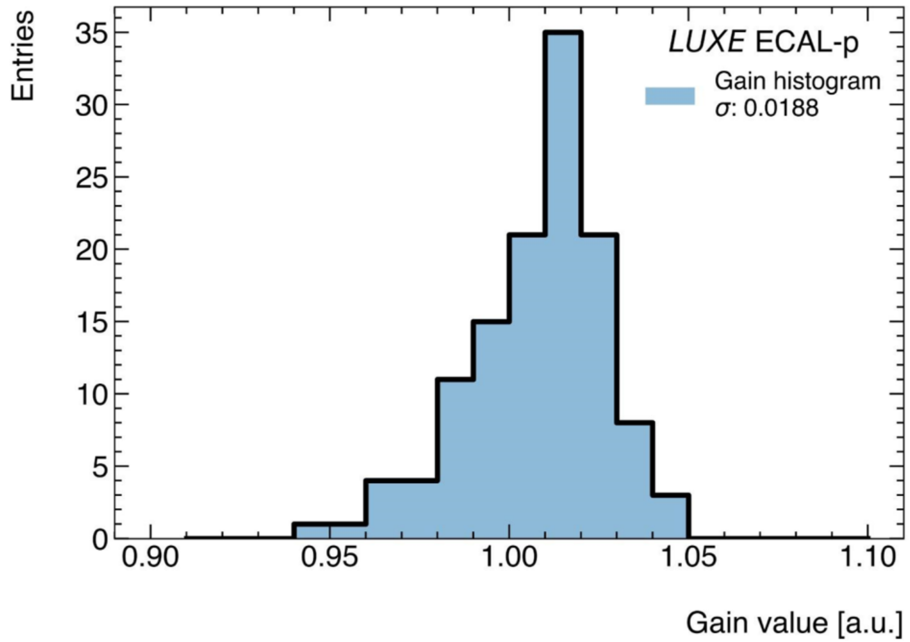


2022 TB: Gain Calibration

Readout channels were calibrated for differences in pre-amplification and applied to the data.



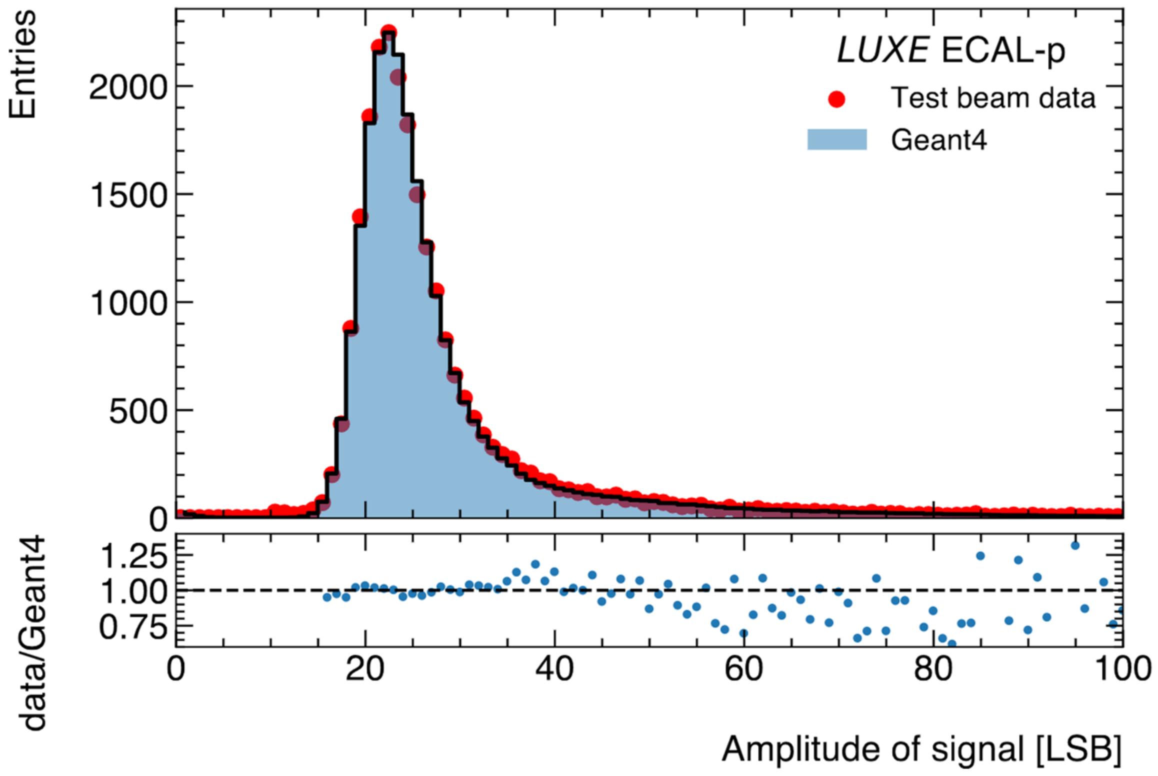
Relative gain values of readout channel obtained by using calibrated injector



Histogram of the relative gain values

2022 TB: Comparison with simulation

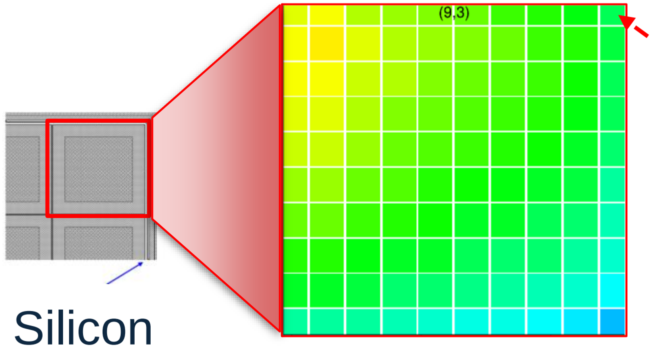
Comparison between data and Geant4 MC simulation of signal of a 5 GeV electron beam in a silicon sensor.



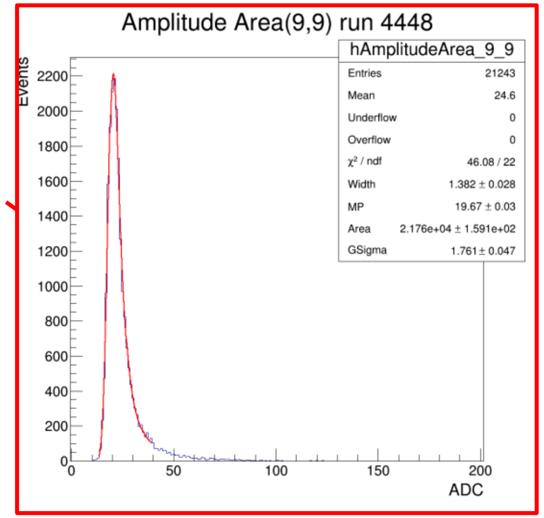
2022 TB: Pad homogeneity of response

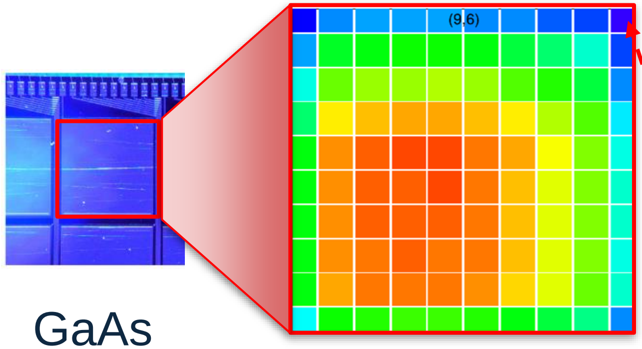
MPV=Most Probable Value

Subdivided pad into sections and plotted amplitude distribution of electrons in each section

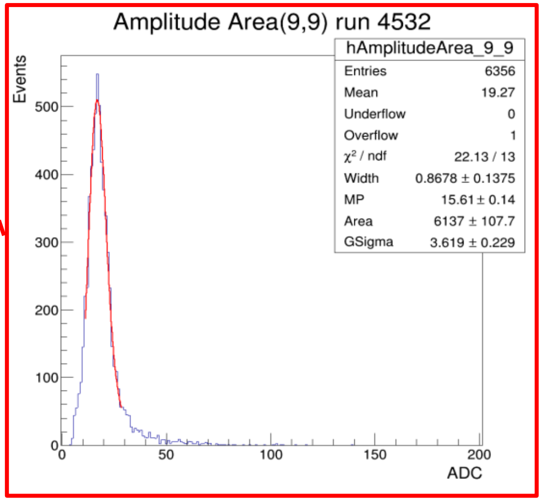


Silicon



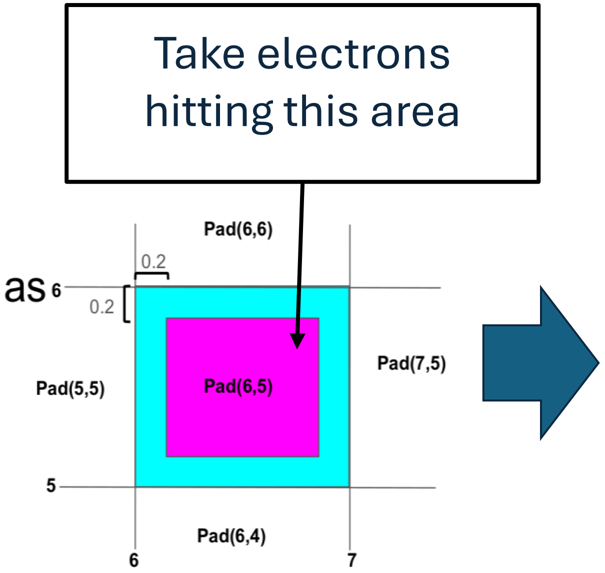


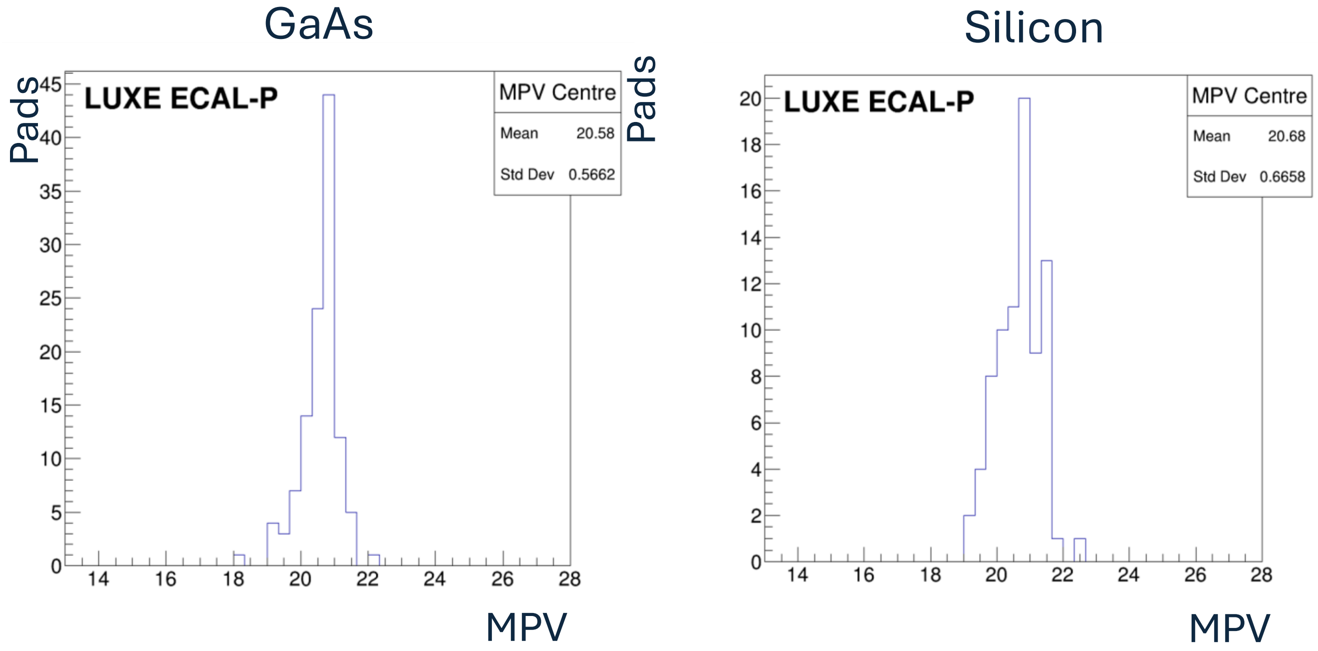
GaAs



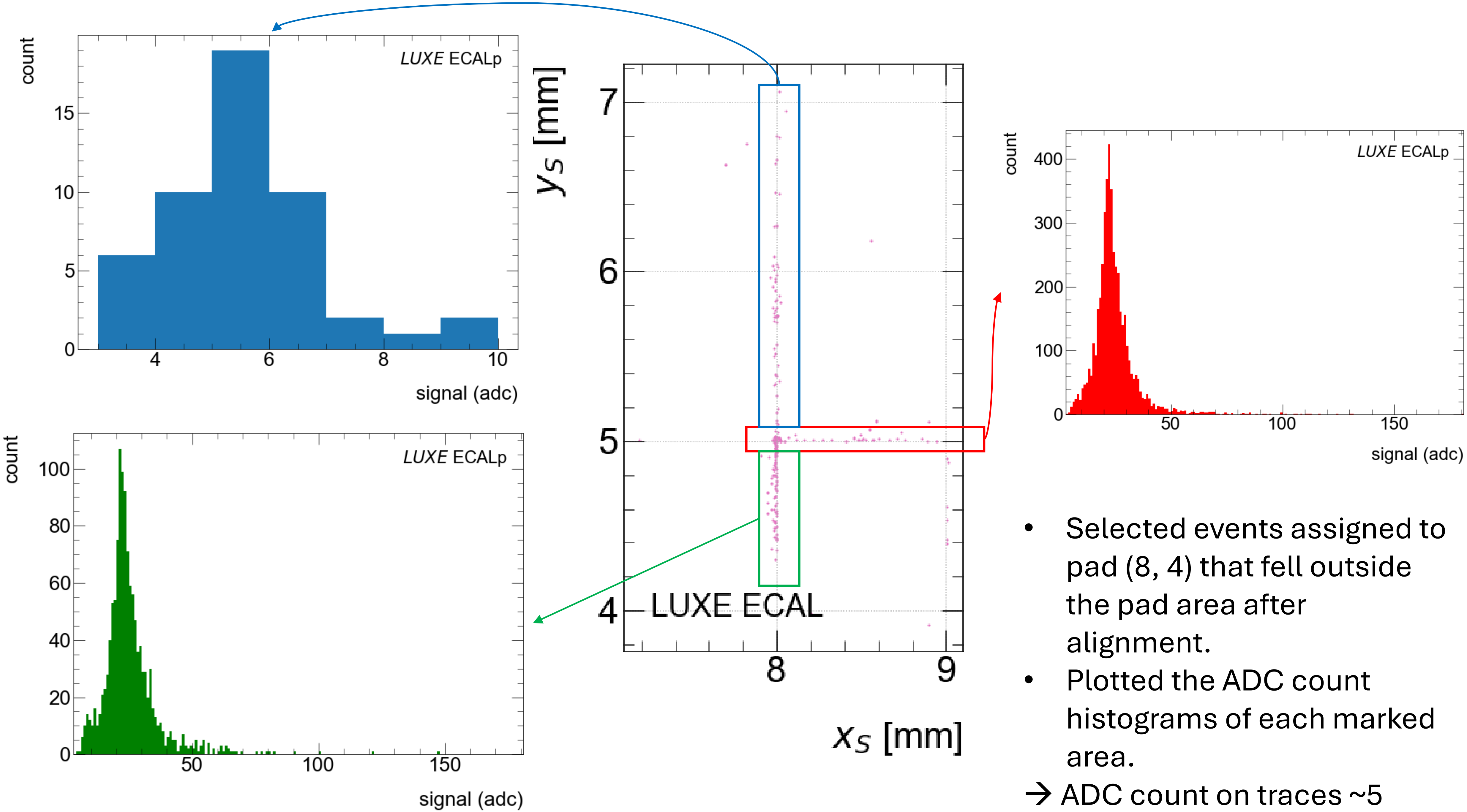
Z scale represents number of entries for the section

2022 TB: Homogeneity of sensor response





MPV distribution after gain correction, excluding edge effect (20% margin)
For both sensors, the RMS is about 3%



- Selected events assigned to pad (8, 4) that fell outside the pad area after alignment.
- Plotted the ADC count histograms of each marked area.

→ ADC count on traces ~5