Beam test of sensors for a compact ECAL

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work in progress for the LUXE Collaboration

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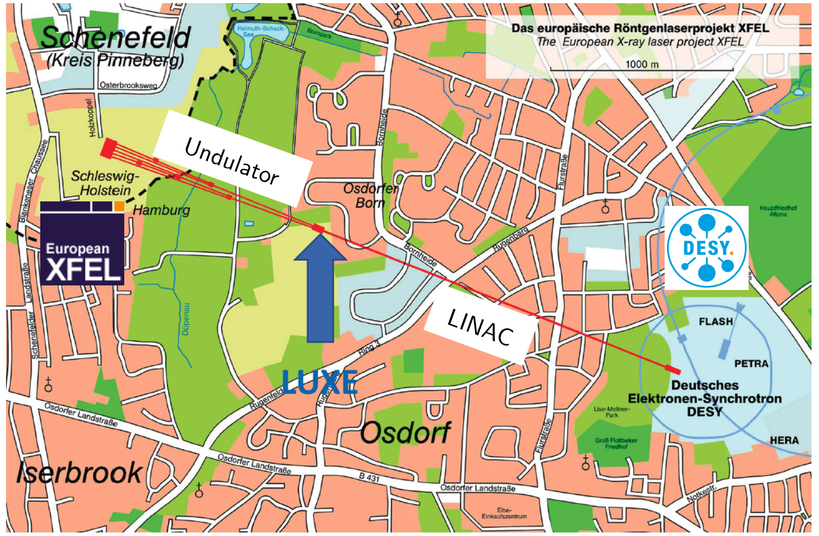
LUXE ECAL Overview

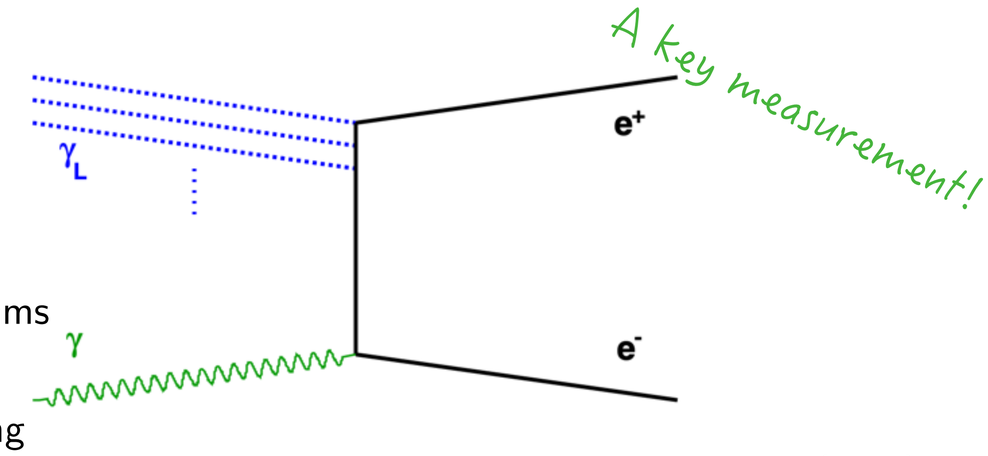
LUXE: ***Laser und XFEL Experiment***

- A "photon collider" (electron-laser or photon-laser)
- Energy: 16.5 GeV
- High energy density photon beam by laser

Physical goal: non-perturbative QED

- Observables departure from perturbative prediction
  - Breit–Wheeler pair spectrum
  - Compton photon spectrum (edge position)
- Challenges on positron detecting system:
  - high precision to verify the departure
  - large dynamic range
    (positron number/BX: 10^{-4} to 10^{6})





One of the Feynman diagrams
Photons from Compton
scattering or Bremsstrahlung

LUXE CDR, EPJ ST 230 2445 (2021)

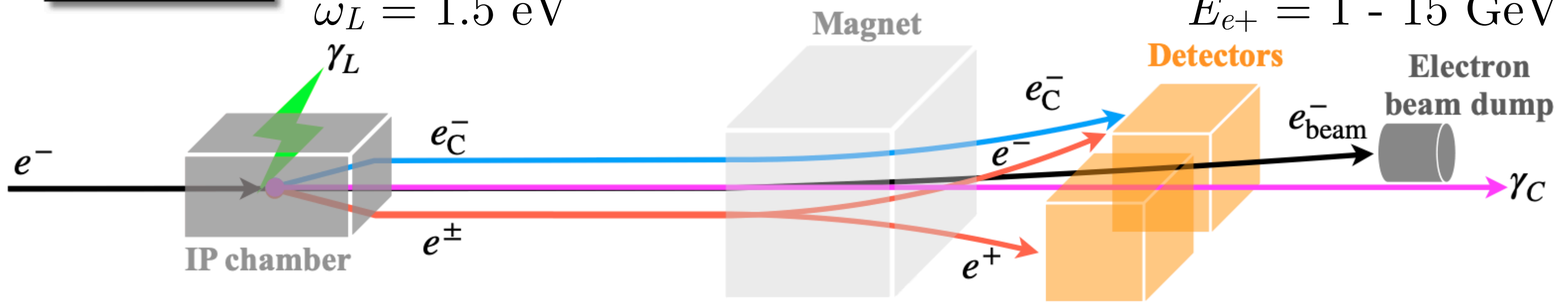
LUXE ECAL Overview

$\mathrm{BX} = 1.5{\times}10^9$
$E_e = 16.5$ GeV

LUXE SFQED (not to scale)

$I_L \approx 10^{18}$ - 10^{21} W cm^{-2}
$\omega_L = 1.5$ eV

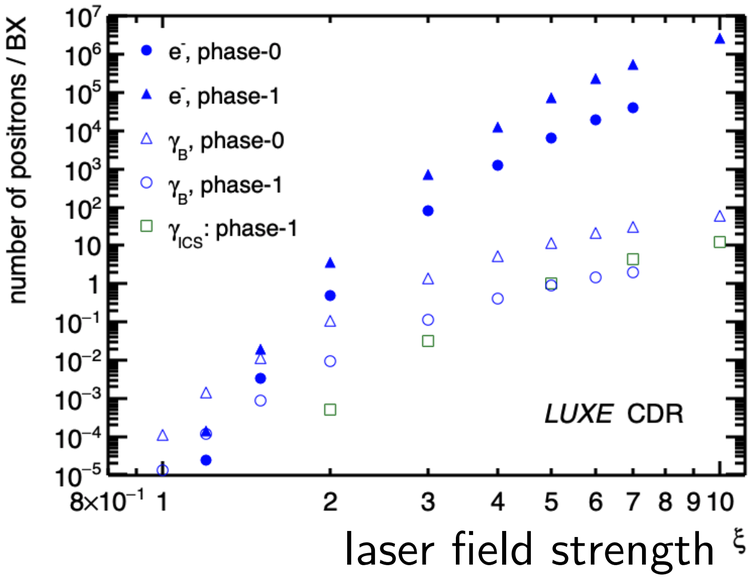
$n_{e+} \approx 10^{-4}$ - 10^{6} BX^{-1}
$E_{e+} = 1$ - 15 GeV

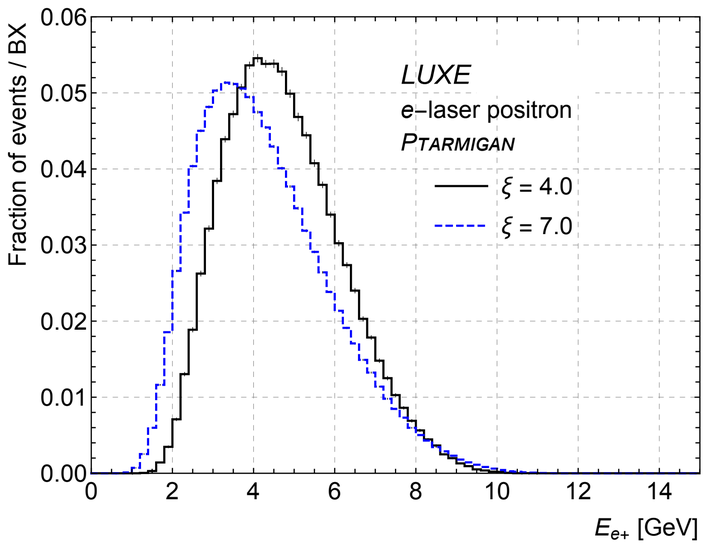


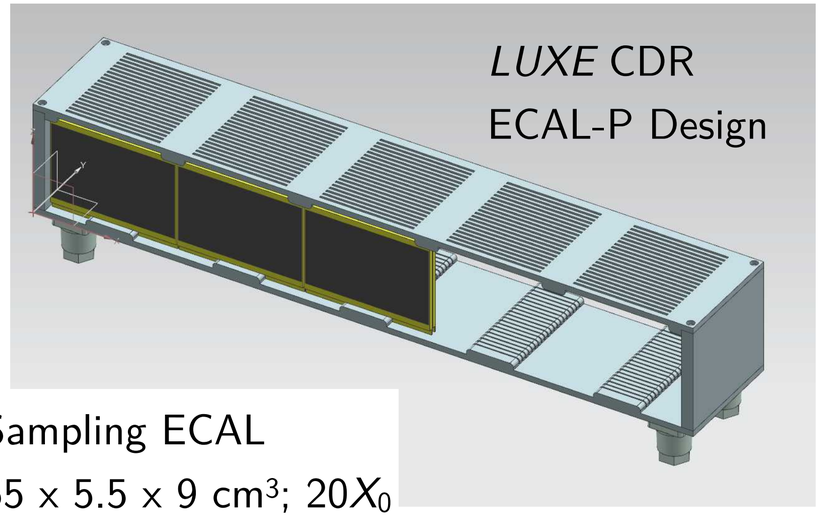
Detectors for e⁺:
8 Tracker staves
1 Compact ECAL

electron-laser mode

z



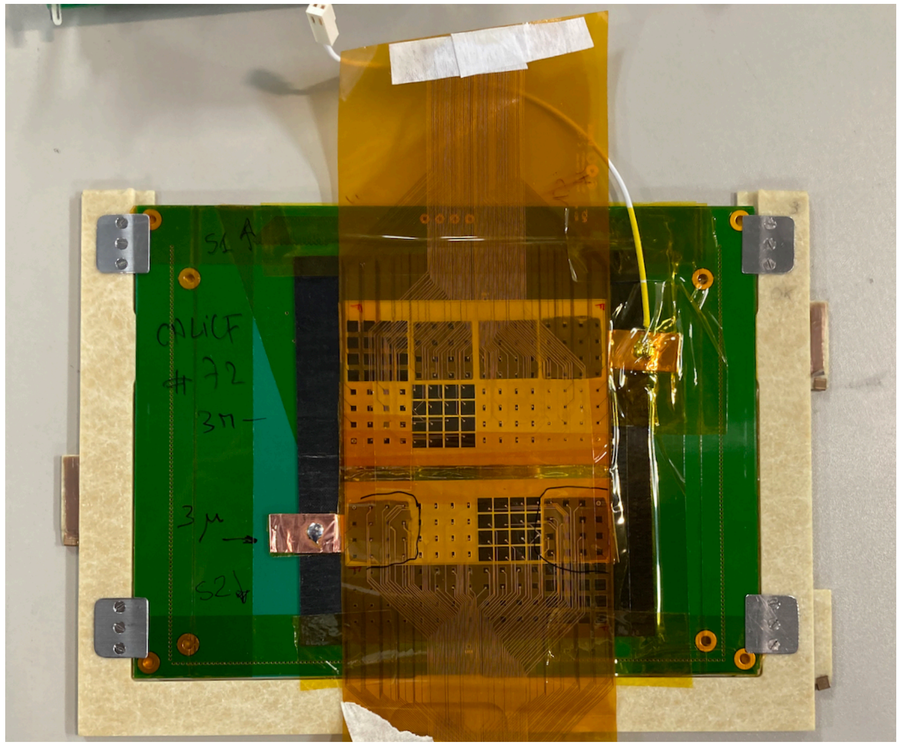




Sampling ECAL
55 x 5.5 x 9 cm³; 20X_0

LUXE CDR, EPJ ST 230 2445 (2021)

Sensors under test



Silicon sensor for test manufactured by Hamamatsu, connected with conductive glue

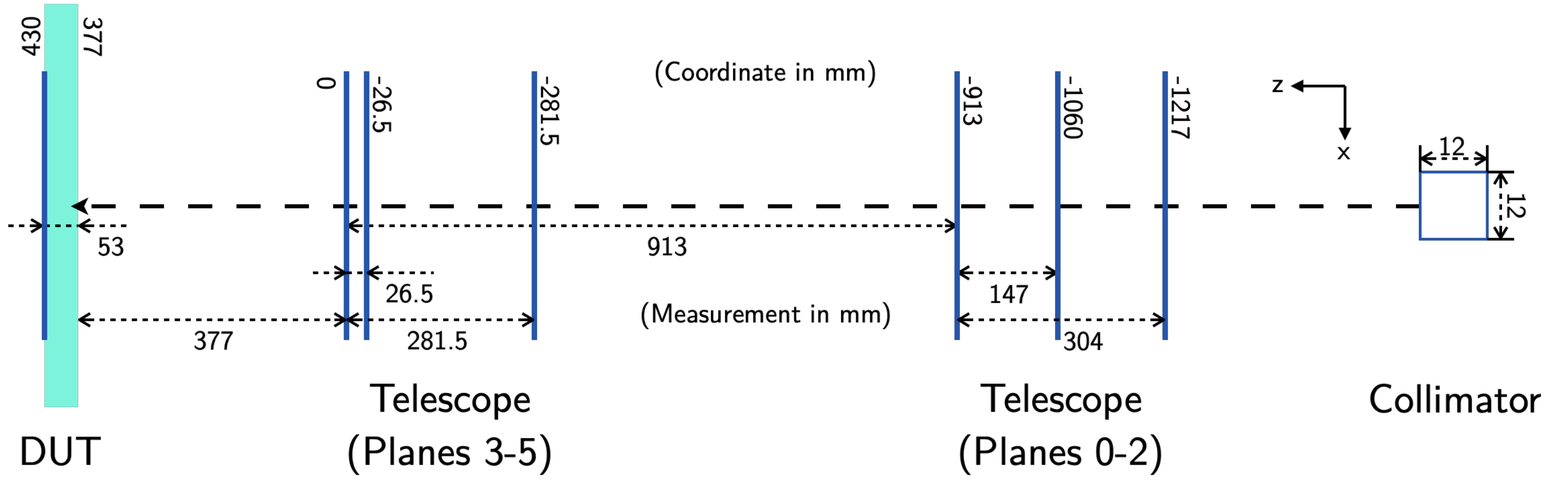
Questions to be answered by beam test:

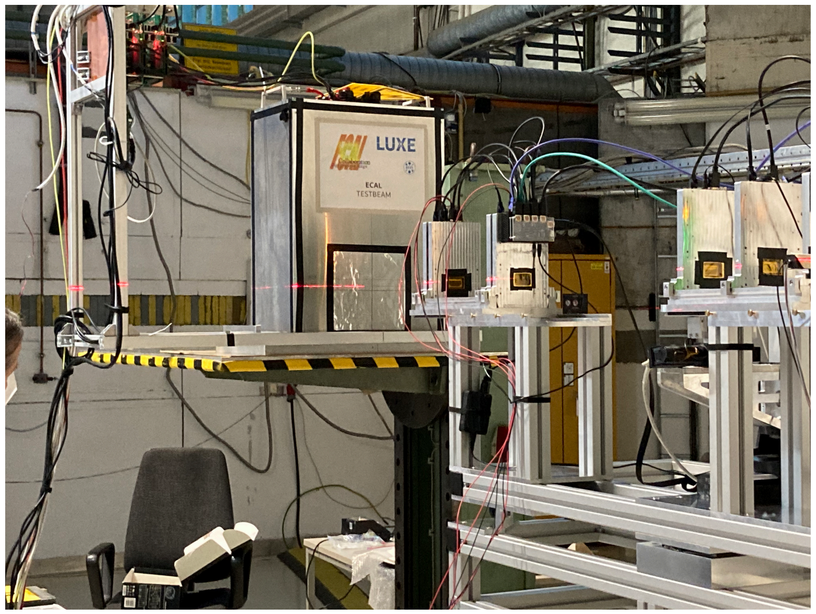
- How do different sensors response to the electron beam/shower?
- Do different pixels on a sensor perform homogeneously?
- What happens when the electron comes in between two pixels?
- Is there cross talk between read out channels?
- How to calibrate the Monte Carlo simulation?

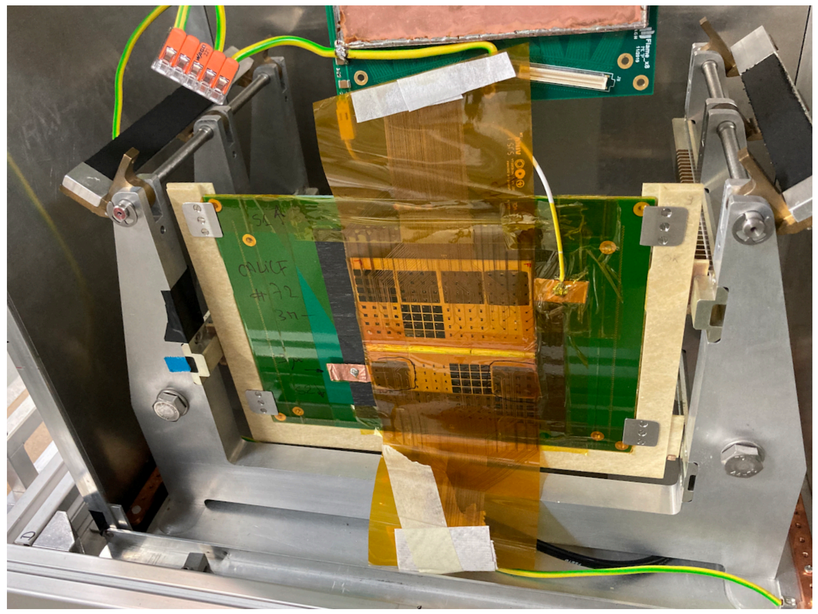
... and other questions need input from the telescope!

	Silicon	GaAs	Tungsten
Pixel size [mm]	5.5×5.5	5.0×5.0	
Pixel number	16×16	15×11	
Thickness [um]	320	500	3,500
Samples under test	4	2	

Test layout





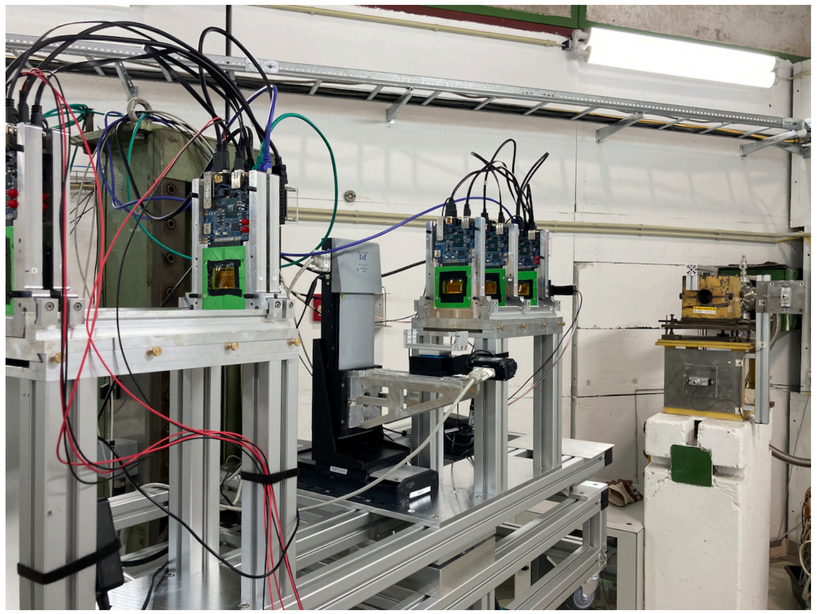


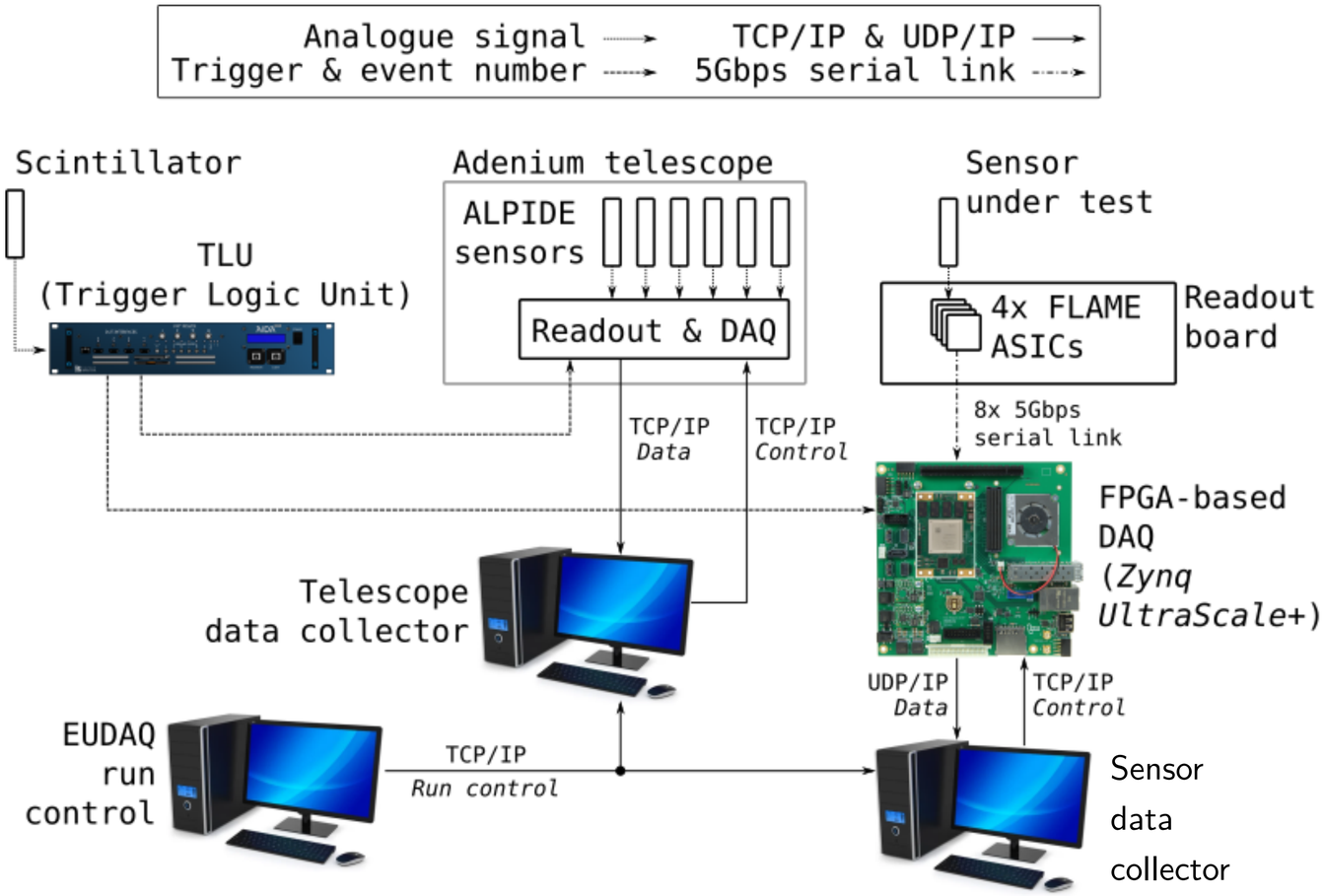
- Two planes close to DUT
- Not the ideal layout for resolution

- Hardware:
  - 6 Adenium planes
  - Sensors with or w/o W plates
- DAQ control:
  - EUDAQ/FireDAQ
- Alignment:
  - Corryvreckan
  - Extrapolation of broken lines
  - Telescope-sensor synchron./ alignment is done separately

Data acquisition

- DAQ is orchestrated by the TLU
  - Possible trigger ID drifting
- ASIC keeps reading out data and stores ± 150 ns when gets trigger
- FPGA deconvolutes signal's temporal distribution into amplitude

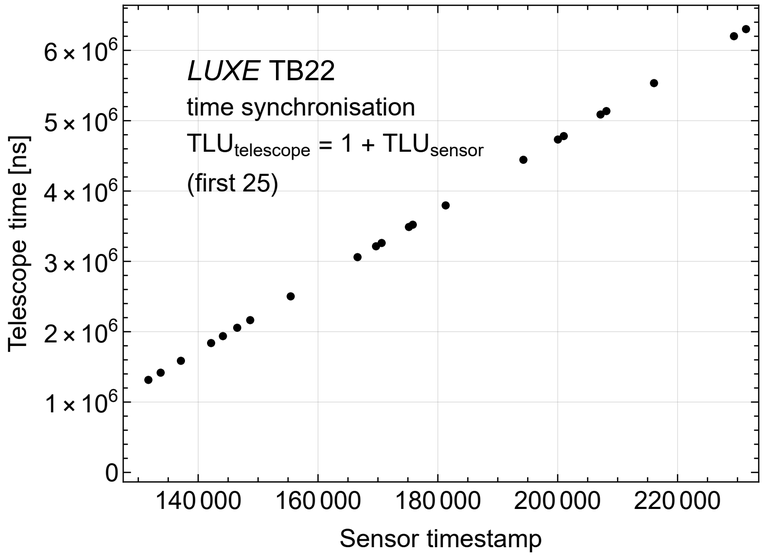


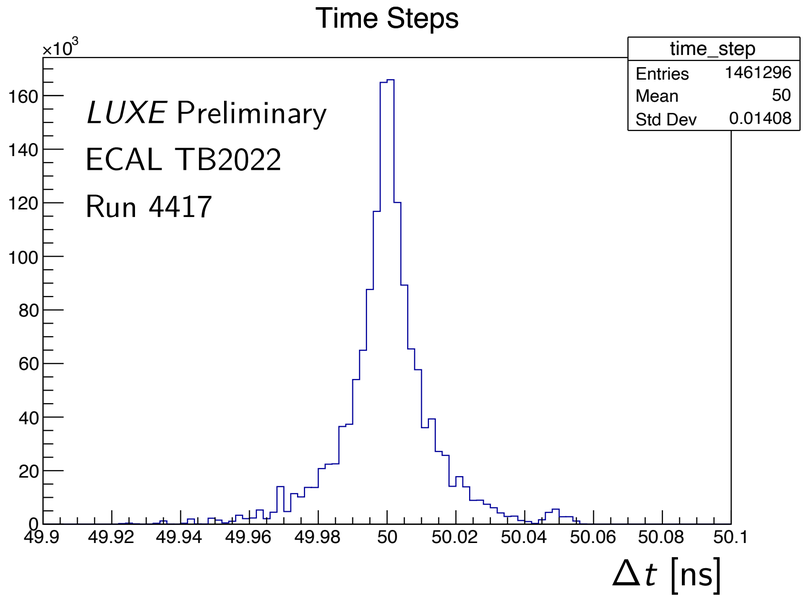


Credit: Jakub Moroń (AGH)

Synchronisation

- Telescope's DAQ and the sensor's DAQ use different time "recorder"
  - telescope: time in ns
  - sensor: timestamp, one stands for 50 ns
- Events are labelled with TLU IDs, but they can be shifted in different DAQs
- The shift may be drifting over time

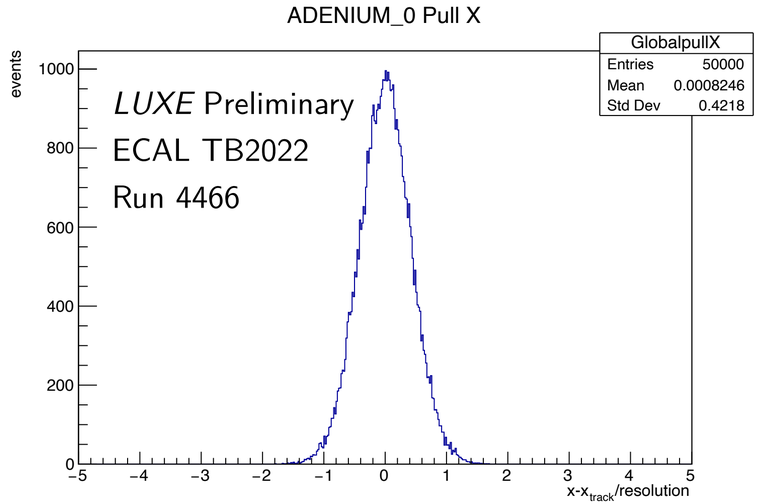


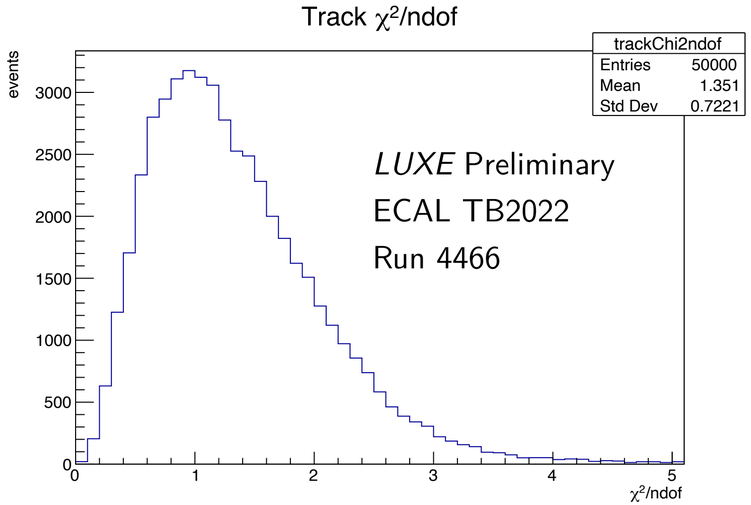


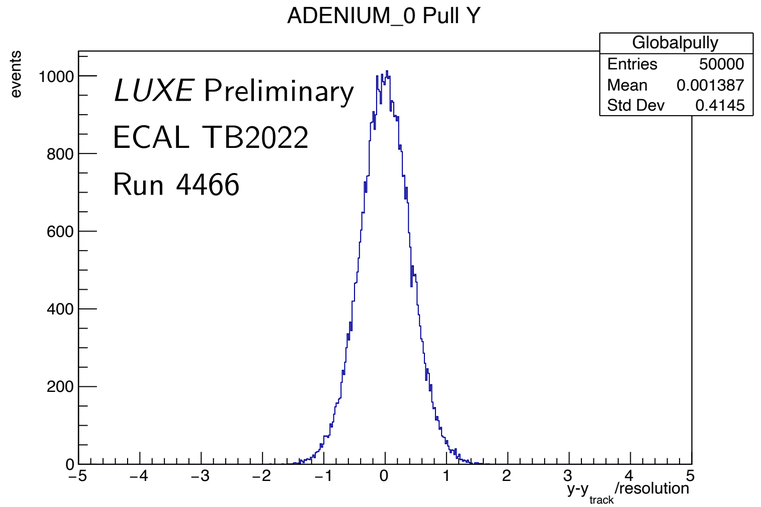
- Electrons are coming with different intervals
- The time interval between neighbouring events in the two DAQs should be proportional if they are synchronised
- One case of drift in the first 100 runs

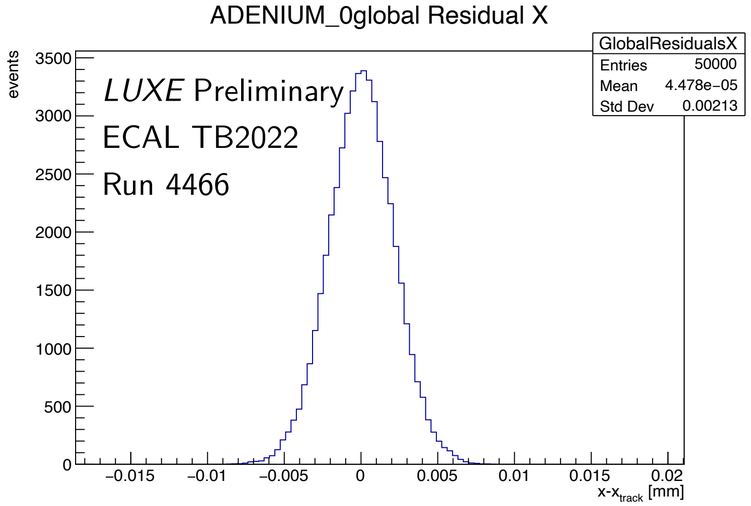
Telescope alignment

- Procedure of alignment
  - Conducted by Corryvreckan
  - Pre-alignment
  - Alignment with the best tracks
- Tracking models:
  - General broken line (GBL)
- Tracking efficiency near 90%
- Indicators of a good alignment
  - Pull function
  - Residues smaller than 1 um
  - χ^2/n_{DoF} peaks at 1
- Extrapolation to the DUT using the last three planes





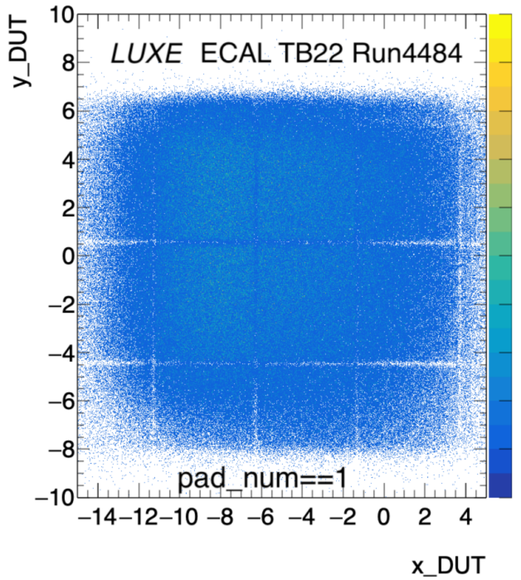


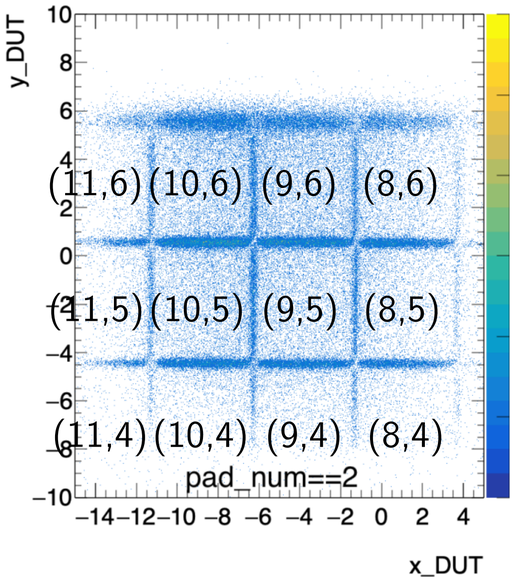


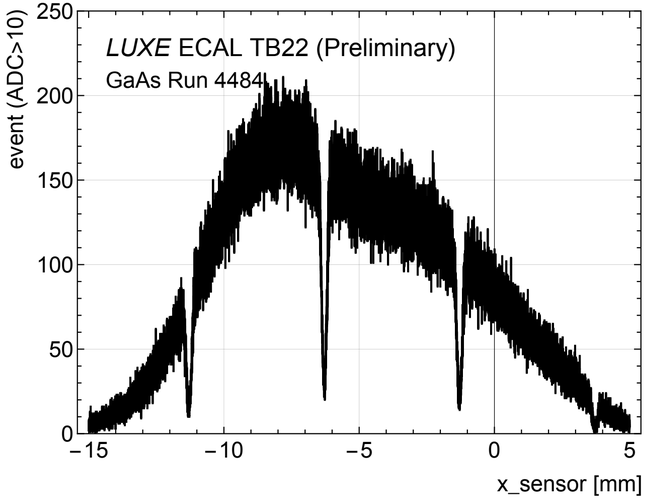
Residue on the furthest plane

Sensor alignment

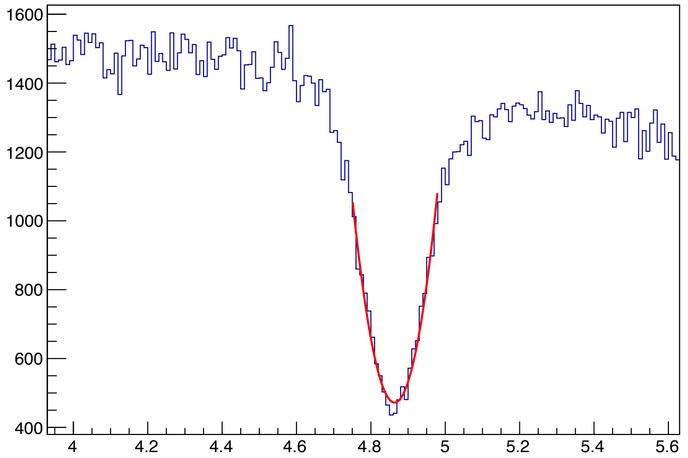
- When one electron hits on the sensor, there should be only one sensor pixel having signal readout
- When the electron comes in between two pixels, the sensor either has no readout (“dead” area) or has multiple readouts (signal sharing area), resulting in a dip
- The dips become clearer when applying amplitude cut
- The pixel boundaries are fitted with the dips to a precision better than 100 um





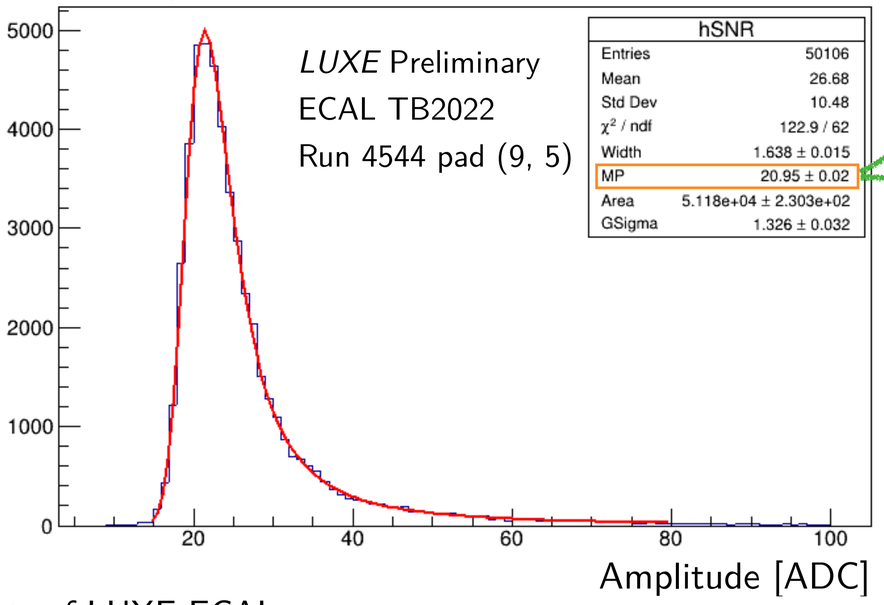


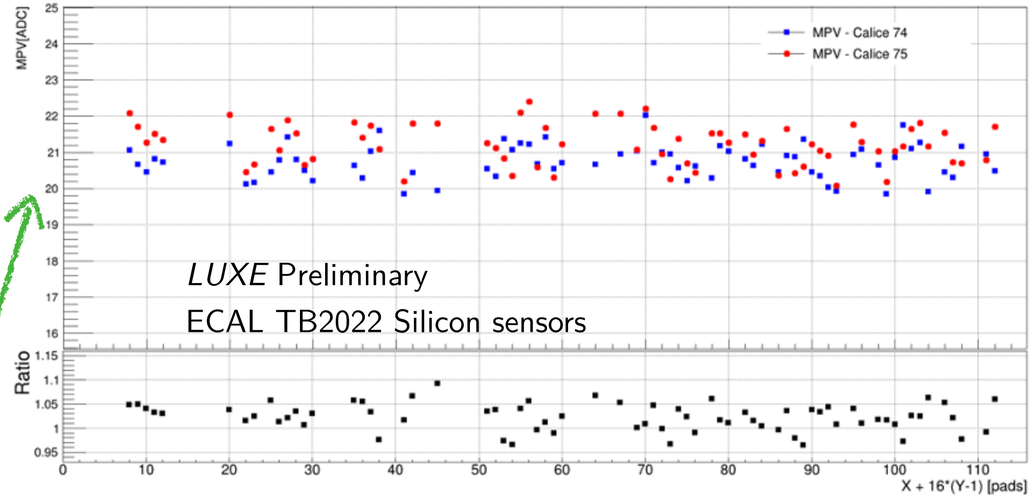
y projection

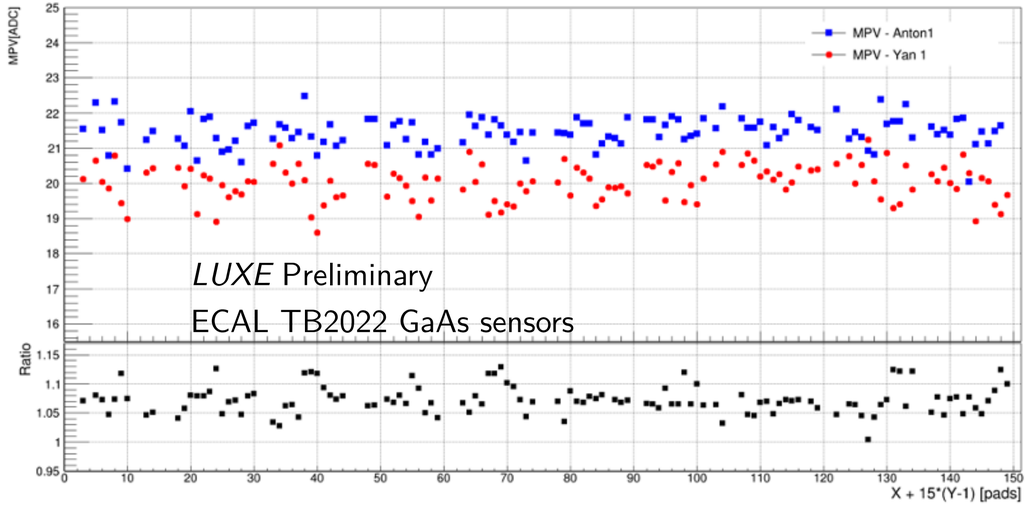


Homogeneity

- Select the events with one electron and one pixel response at the corresponding area
- Amplitude distribution fitted into a Landau-Gaussian convoluted function
- Amplitude (MPV) fluctuates over 1 ADC count, possibly due to differences on pixel wiring techniques, channel amplification, ...



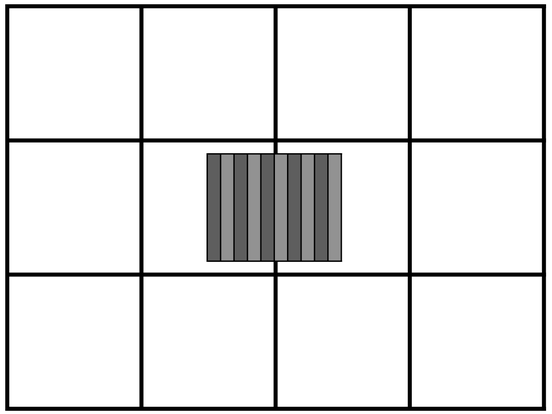




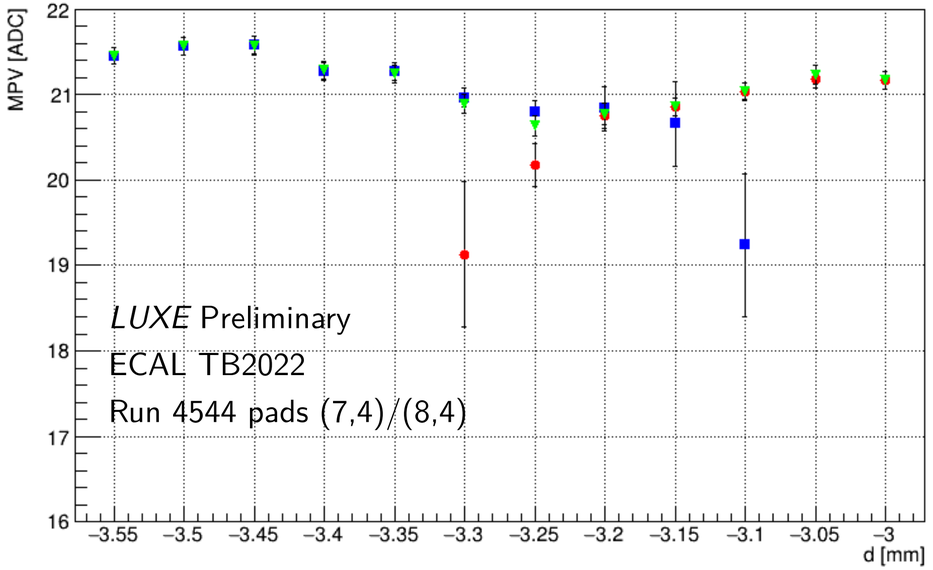
Credit: Veta Ghenescu (Romanian ISS)

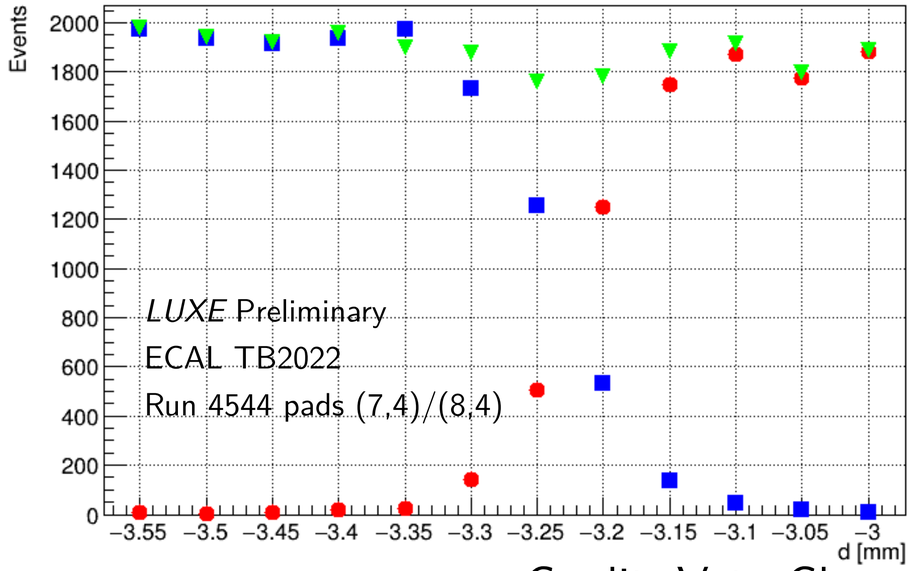
Signal sharing

- When an electron comes in between two pixels, it is possible that the sensor has multiple readouts from both pixels
- Select the events with one electron that hits on a specific stripe area
- Scan through two neighbouring pixels
- Check the two pixel's signal amplitude (if any) changing over stripes



Step: 50 nm; Pixel size: 5.5 mm





Blue: left pixel

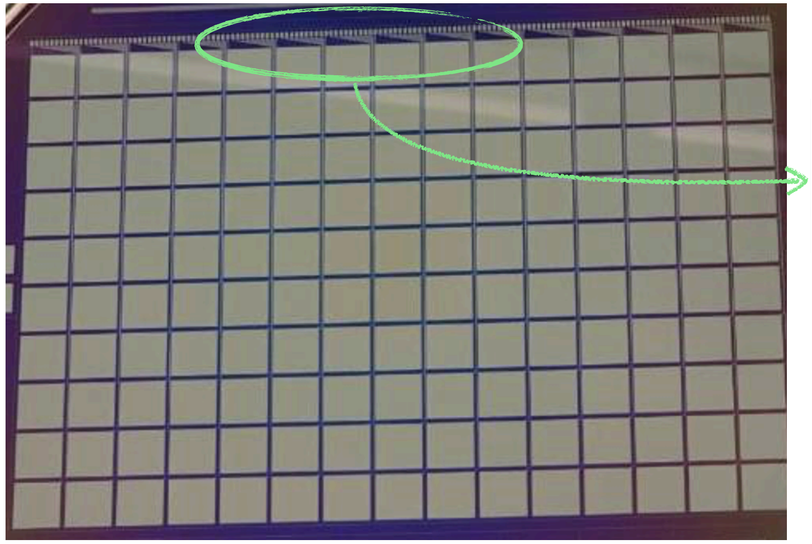
Red: right pixel

Green: sum of two pixels

Credit: Veta Ghenescu (Romanian ISS)

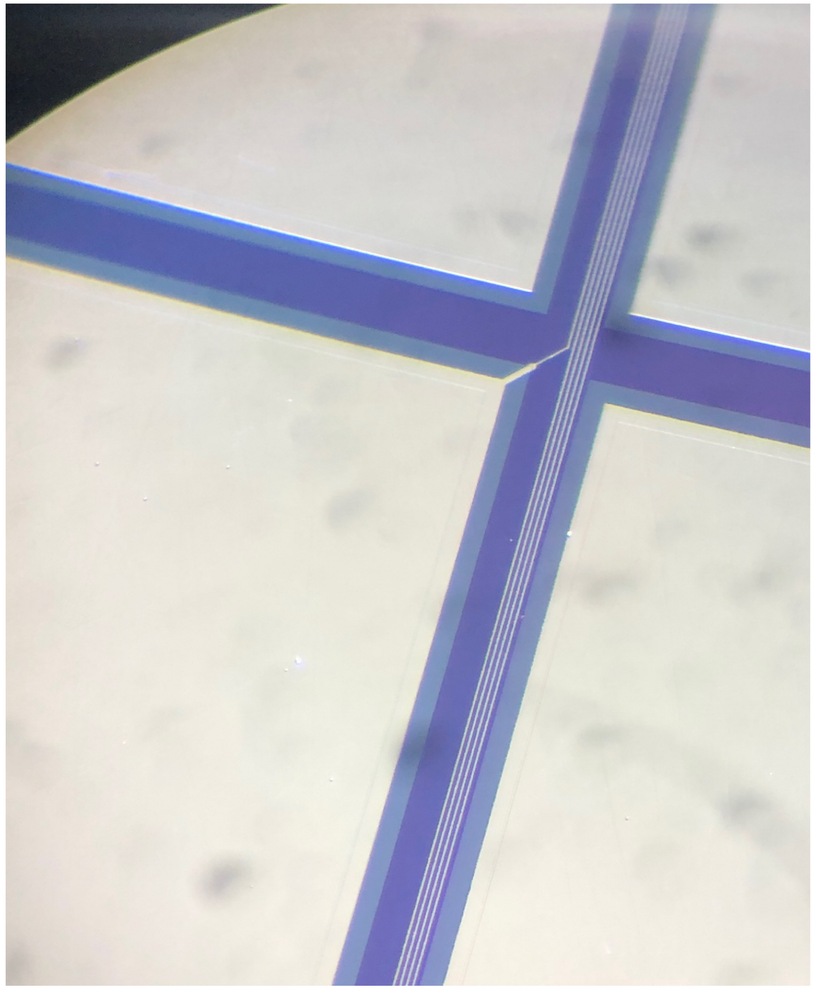
Traces in GaAs sensor

- Aluminium traces, a new method to connect pixels with the readout frontend, are used on GaAs sensor to make the sensor more compact
- The traces are bunched along *y*-direction and it is theoretically possible that fake signals could be induced in between traces
- Select the events with one electron that hits on a specific pixel centre
- Check the response of this particular pixel
- Check the response of all other pixels



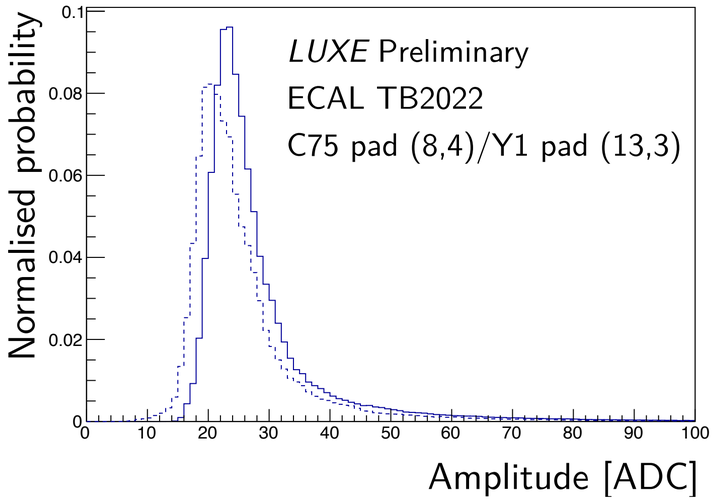
Bonded towards readout system

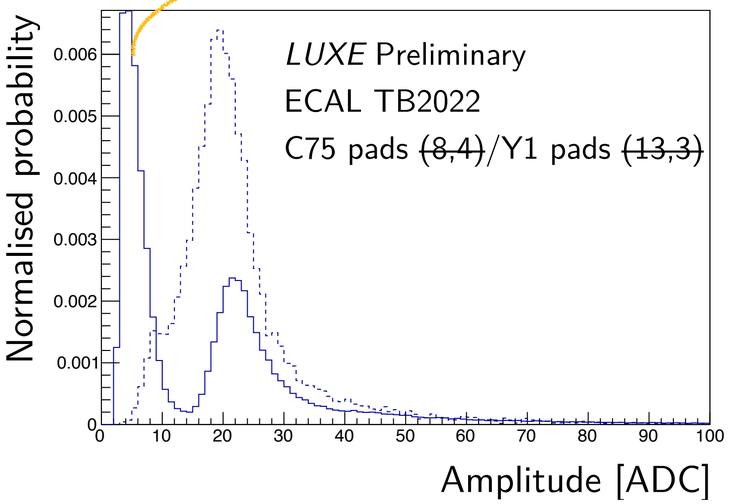
Trace bunches along *y* direction

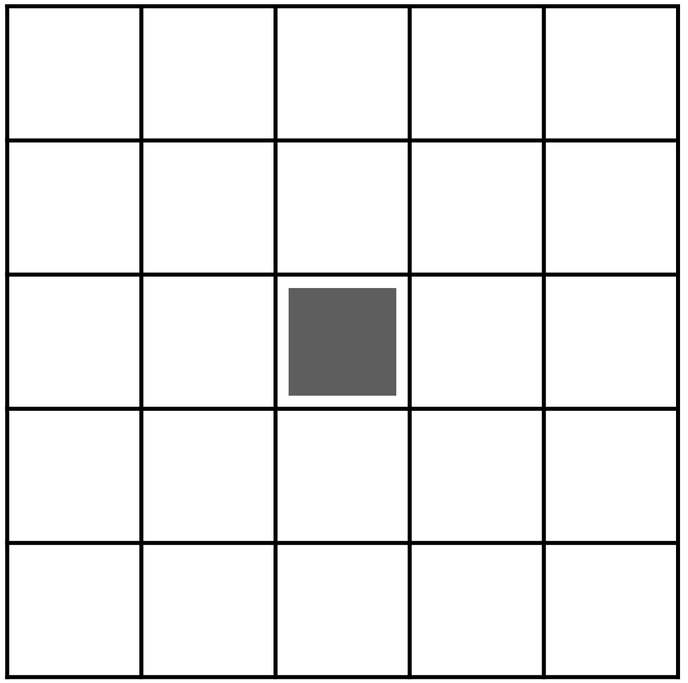


Cross-talk

- Aluminium traces, a new method to connect pixels with the readout frontend, are used on GaAs sensor to make the sensor more compact
- The traces are bunched along *y*-direction and it is theoretically possible that fake signals could be induced in between traces
- Select the events with one electron that hits on a specific pixel centre
- Check the response of this particular pixel (left)
- Check the response of all other pixels (right)







Silicon sensor (>1 means multi. pixels):

- On-pixel response: 99.7%
- Off-pixel response: <6.20% (noise)

GaAs sensor:

- On-pixel response: 94.4%
- Off-pixel response: 8.65%

Summary & Outlook

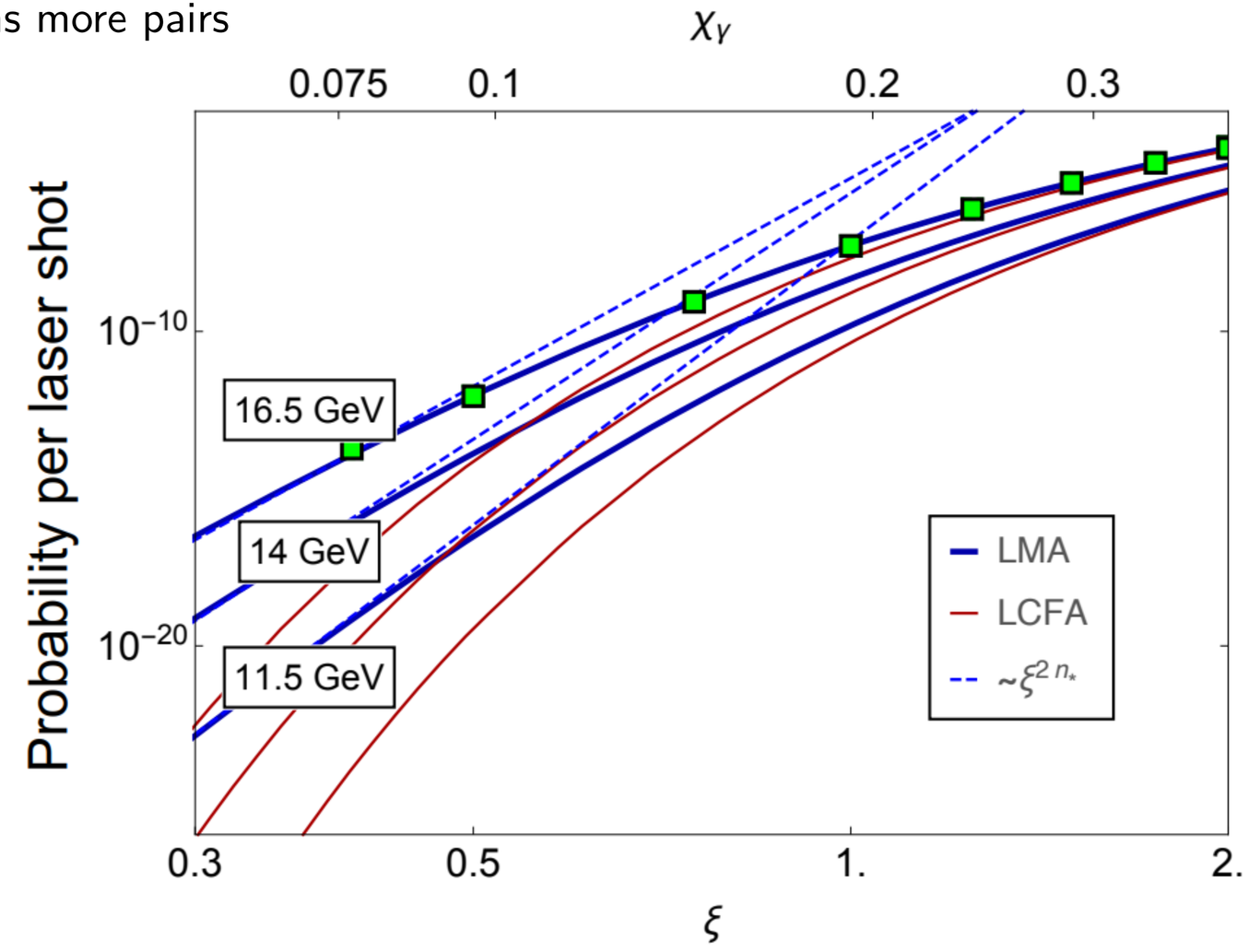
- On beam tests are conducted on DESY-II TB24 for LUXE ECAL sensors
- We have successfully synchronised and aligned the telescope with the sensors under test
  - Multiple scattering considered (general-broken-line model) except the last two planes
  - Small residues, nice pull functions and χ^2/n_{DoF} distribution
- We are able to study the sensor's properties with the help of the telescope
  - Pixels in one sensor are generally homogeneous
  - Signal sharing is observed near the boundary of two pixels (around 250 um)
  - Proofs are found indicating different behaviours for sensors with and without traces
- Some useful software tools in GitHub
  - Corryvreckan LUXE-ECAL configures: https://github.com/shan-yamabuki/TBTelescope-Configure/tree/TB22
  - Corryvreckan module for data dumping: https://github.com/LUXEsoftware/TBTelescope-TrackingInfo
  - Telescope resolution: https://github.com/eutelescope/eutelescope/tree/master/processors/include/legacy
- **Many thanks to the most kind and helpful DESY testbeam crew!**

Thank you for your attention!

Back Up

Perturbative prediction:

More photons more pairs

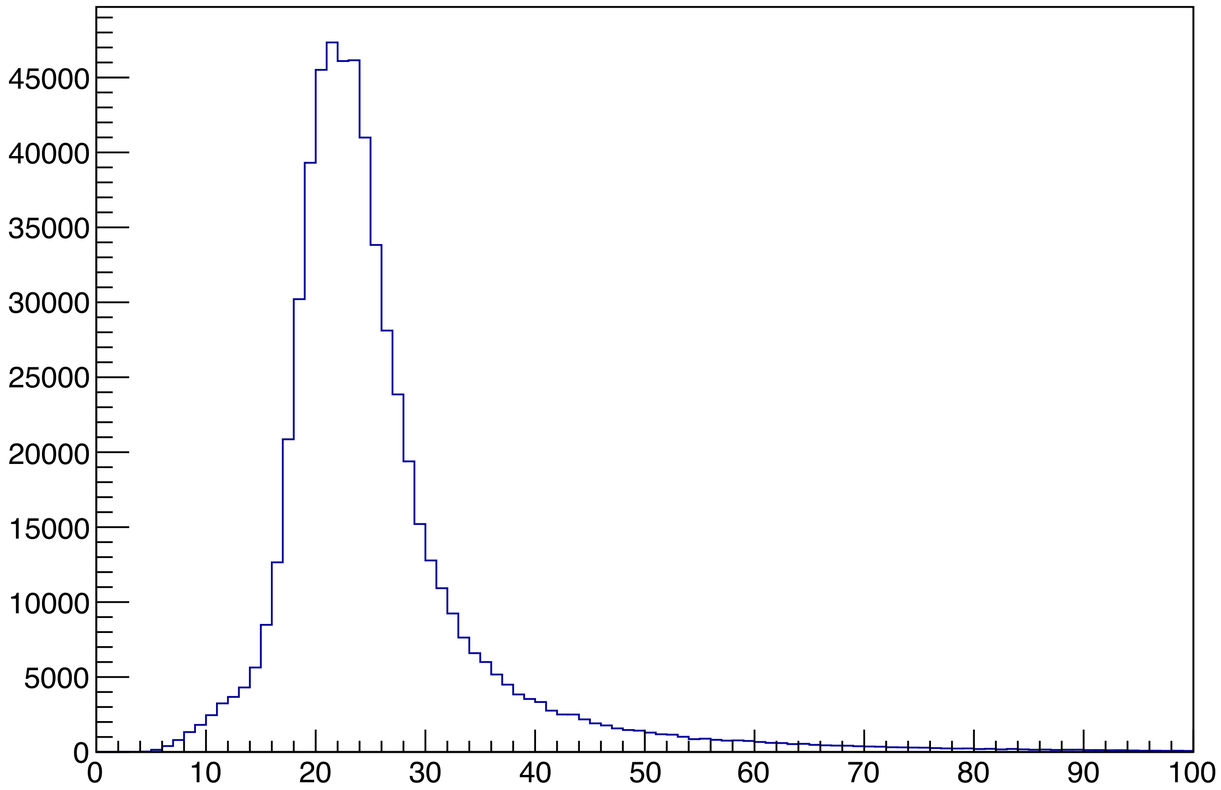


Nonperturbative prediction:

Fewer pairs (more photons) due to strong field

LUXE CDR, EPJ ST 230 2445 (2021)

Signal with “no” electron

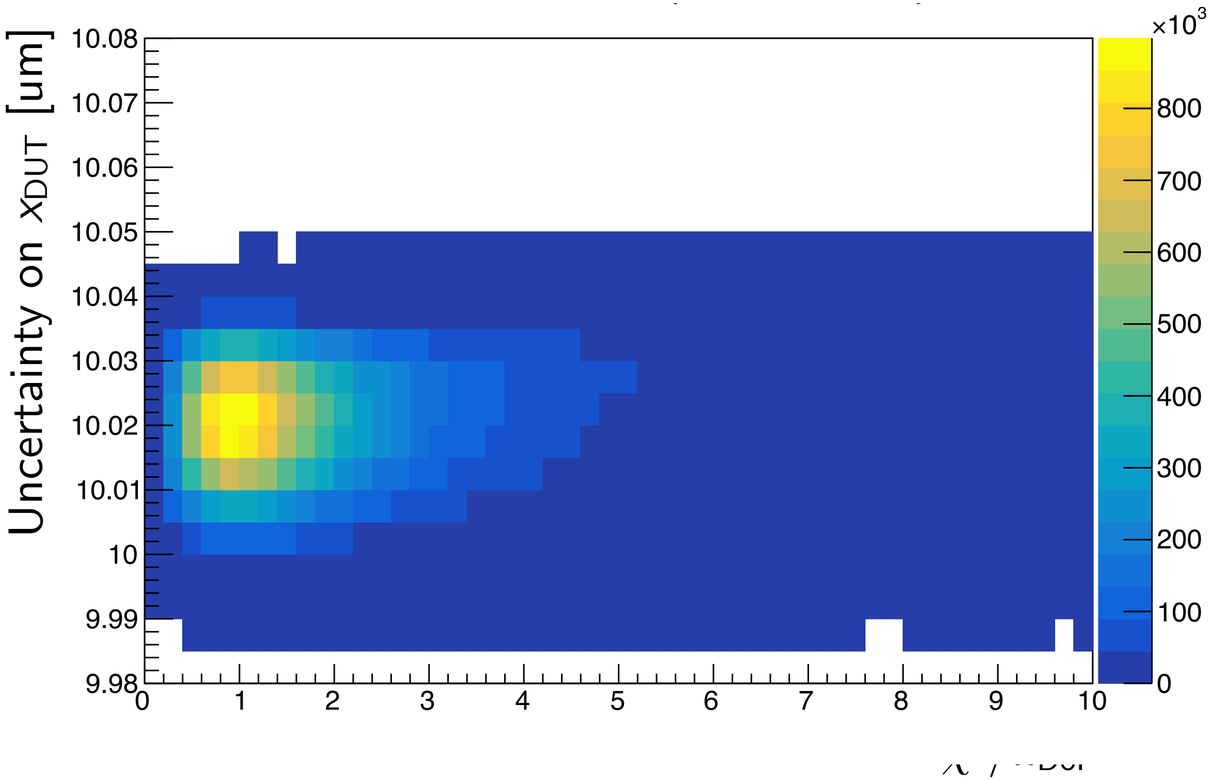


- Signal observed when there is no track reconstructed in the telescope
- About 15% of all events
- Caused by strong requirement for tracking: needs all six planes to reconstruct a track

Uncertainty

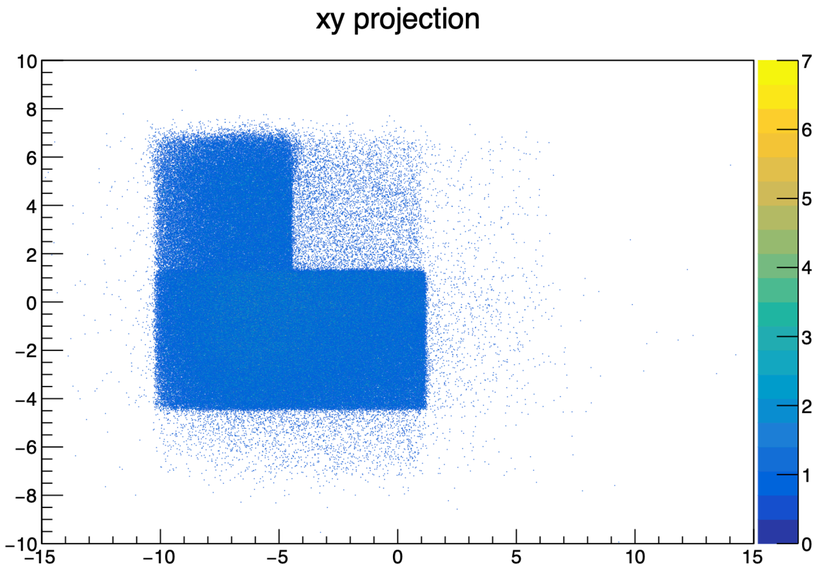
- Quality cut
  - No obvious connection between track reconstructing χ^2/n_{DoF} and intercept uncertainties provided by GBL track module
  - Propagated uncertainties do not consider the scattering at the last two telescope planes
- Uncertainty estimated by another code

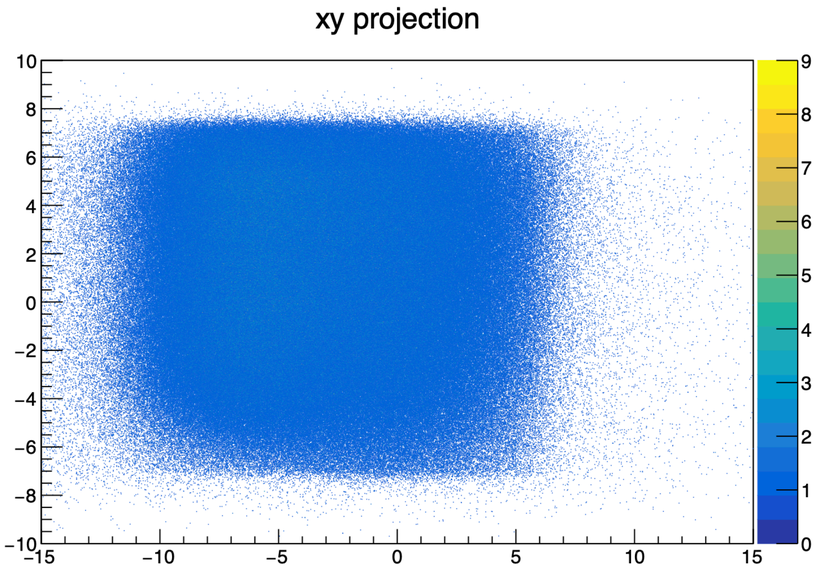
Configuration		TB21	TB22
Vacuum	1 GeV	96.3 μm	129.3 μm
	3 GeV	39.5 μm	48.1 μm
	5 GeV	27.7 μm	31.0 μm
Air	1 GeV	119.9 μm	151.9 μm
	3 GeV	47.4 μm	56.5 μm
	5 GeV	32.9 μm	36.8 μm



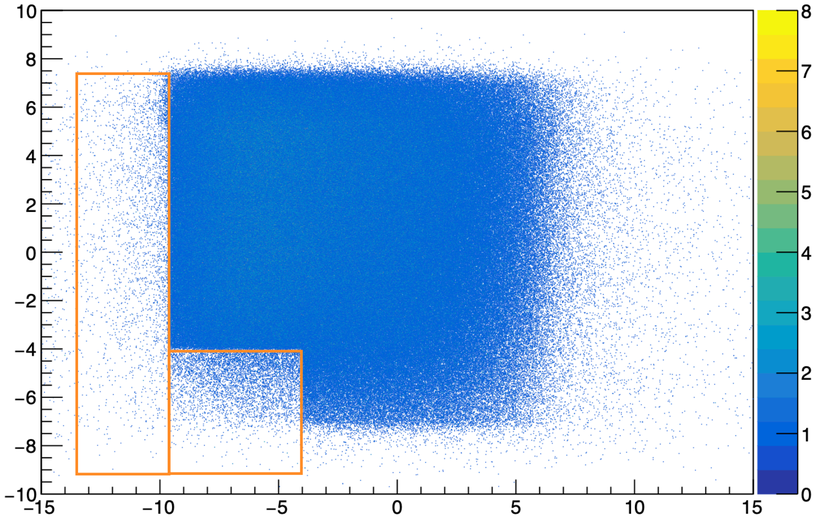
EUTelescope code for calculating uncertainty for a layout
https://github.com/eutelescope/eutelescope/tree/master/processors/include/legacy

Findings by the telescope





Left-Top: Electron profile with pixel (2, 1) having response, showing the three pixels are connected for readout



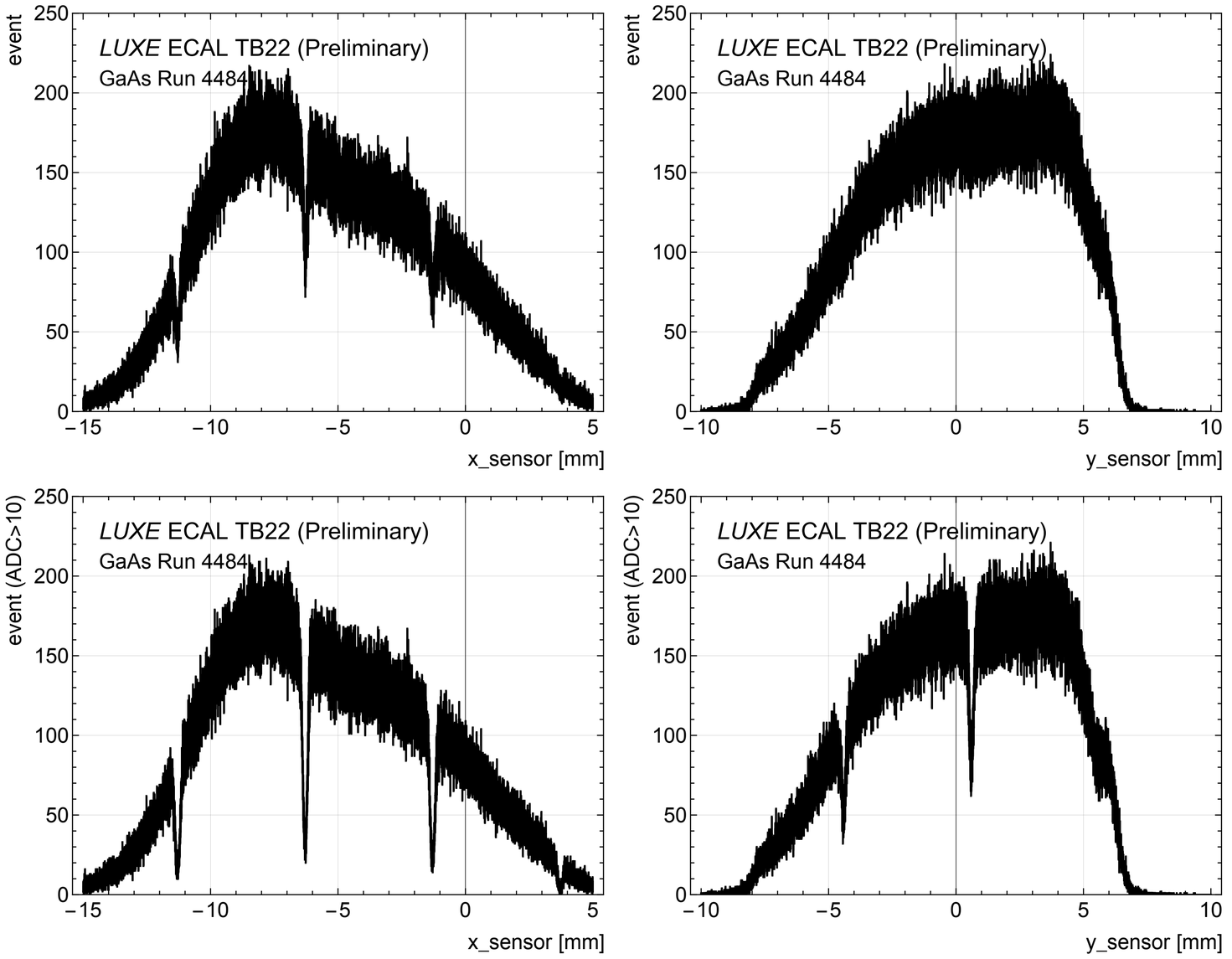
Right-Top: Telescope electron profile

Bottom: Electron profile with sensor response, showing a dead area on the sensor

Possible effect from traces

Run 4484: GaAs sensor “A1”

- Tops: electron x/y-distributions with response from only one pixel
- Bottoms: same distributions with strong response from only one pixel
- Asymmetry can be easily observed on x and y directions: no dip on y-distribution without amplitude cut
- Possible cause: traces are bunched along y direction



Preliminary trace analysis

- Gap of event between sensor channels
- Different ADC distribution when shooting electron to the centre and to the edge
- We need to process more runs for higher statistics on trace analysis