Test-beam measurements of instrumented sensor planes for a highly compact and granular electromagnetic calorimeter

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For the LUXE ECAL-P group

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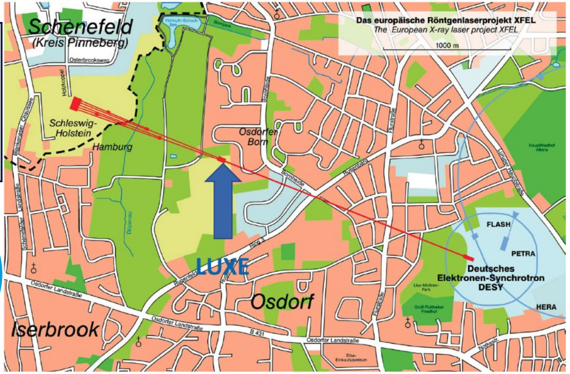
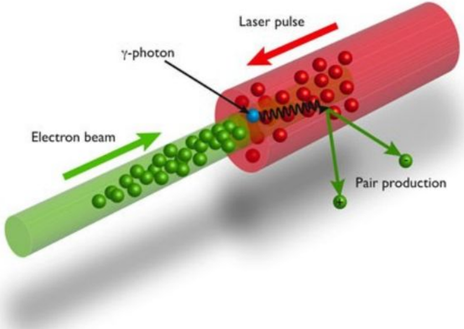
LUXE (Laser Und XFEL Experiment)

Mission: Observe the behavior of QED in the strong field non-perturbative regime (Schwinger limit)

High-energy electron beam from European XFEL + **High-power laser** = **Production of physical e^-e^+ pairs from the QED vacuum**





LOI (2019) [1909.00860]

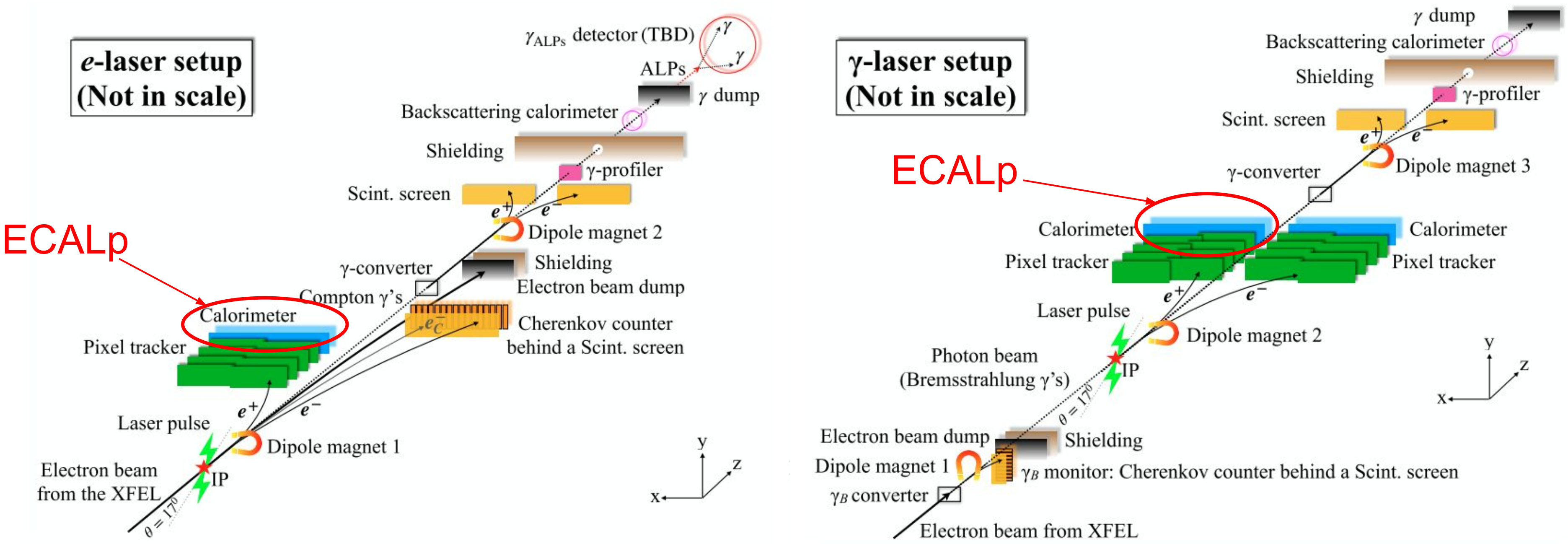
CDR (2021) Eur. Phys. J. Spec. Top. 230, 2445–2560

TDR (2023) [2308.00515] EPJST Accepted

LUXE opens the possibility to study:

- The interaction of real photons with electrons and photons at field strengths where the coupling to charges becomes non-perturbative
- e^--ɣ and ɣ-ɣ interactions in the transition from perturbative to non-perturbative regime of QED
- Strong-field QED processes to design a sensitive search of new particles BSM that couple to photons

Two modes for the experiment



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The ECAL-P group

Participating institutes

DESY.

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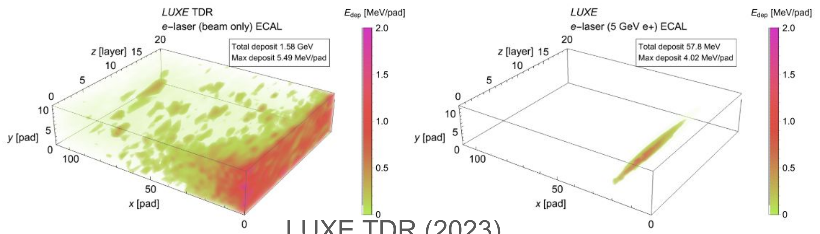
AGH UNIVERSITY OF KRAKOW

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Challenges

- Two modes with expected number of positrons varying from 10^{-4} to 10^{7}
- EM shower overlap at high multiplicity
- Low multiplicity showers immersed in low energy widely spread background



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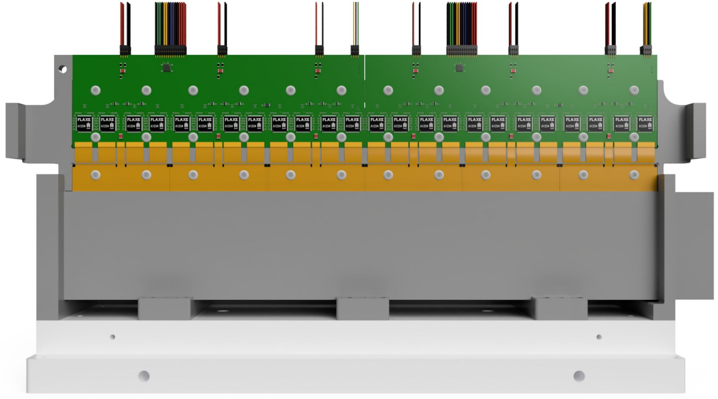
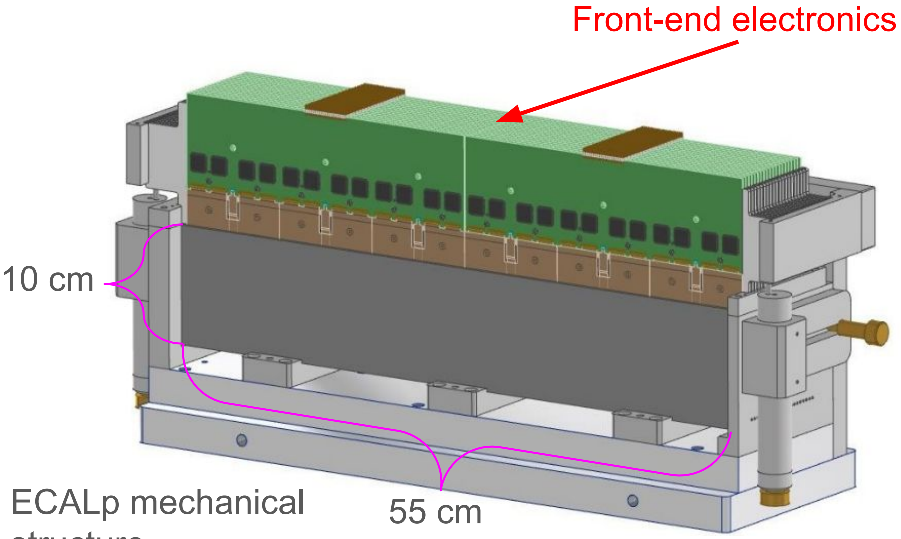
Solutions

- Compact sampling calorimeter
- Small Molière radius
- High granularity



ECALp design

- 21 layers of 3.5 mm tungsten (Molière radius=9.3mm) for absorber
- Active layers including sensors and readout will be kept to less than 1 mm in thickness.



ECALp mechanical structure

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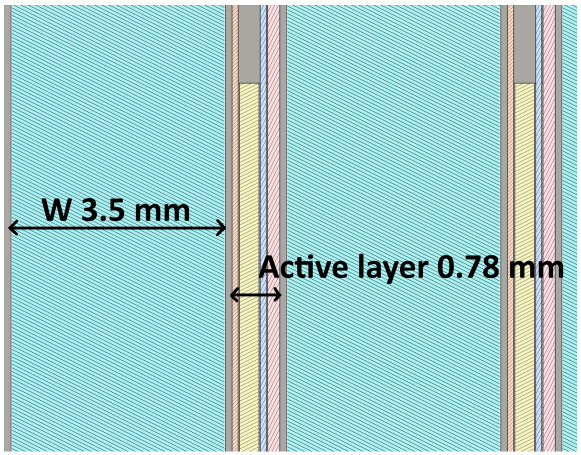
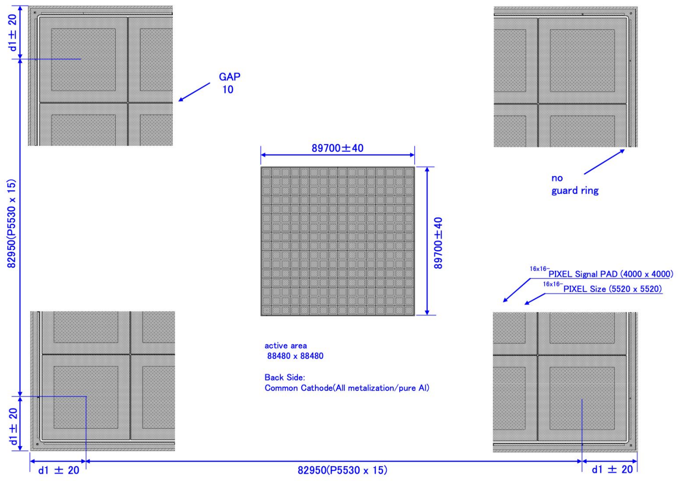
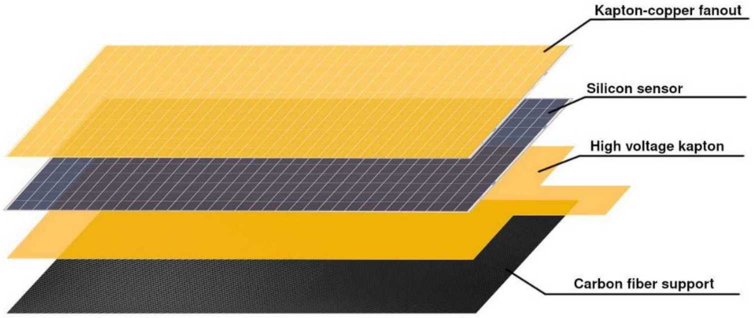


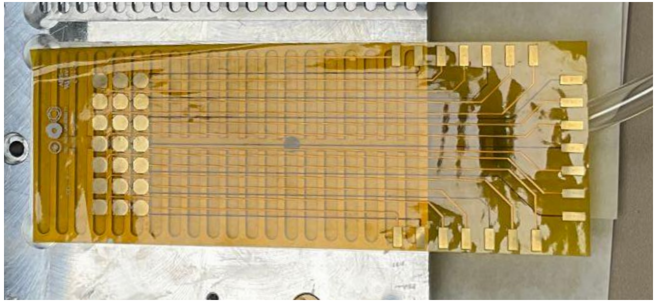
Sensors: Silicon

- Manufactured by Hamamatsu
- The readout: Kapton fan-outs with copper traces connected to the sensor pads with conductive glue.
- 320/500 µm thick, 5.5 × 5.5 mm^2 pad
- Small gap of 0.01 mm between pads



LUXE TDR (2023)





Flex Kapton PCB Example

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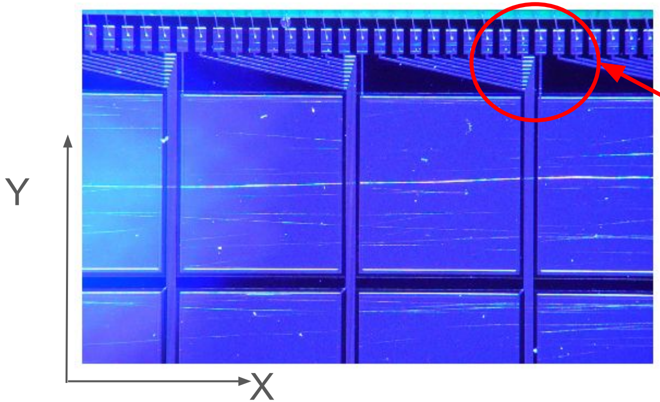
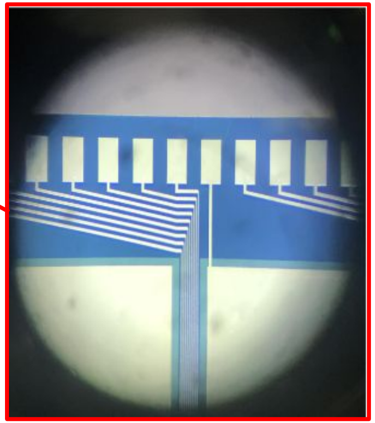
Sensors: Gallium Arsenide

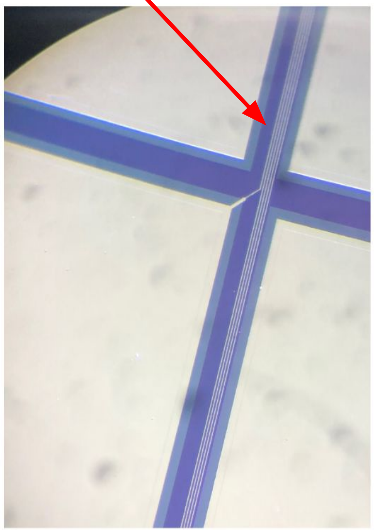
- Produced by National Research Tomsk State University
- Single GaAs crystals compensated with chromium.
- Pads are made of 0.05 µm vanadium layer
- Pad area of 4.7 × 4.7 mm^2
- 0.3 mm gap between pads
- Al traces in the gaps between pads.
- Sensor thickness of 500 µm.
- Tolerate higher radiation dose than silicon.



Credit: Dawid Pietruch (AGH University of Krakow)



Aluminium traces

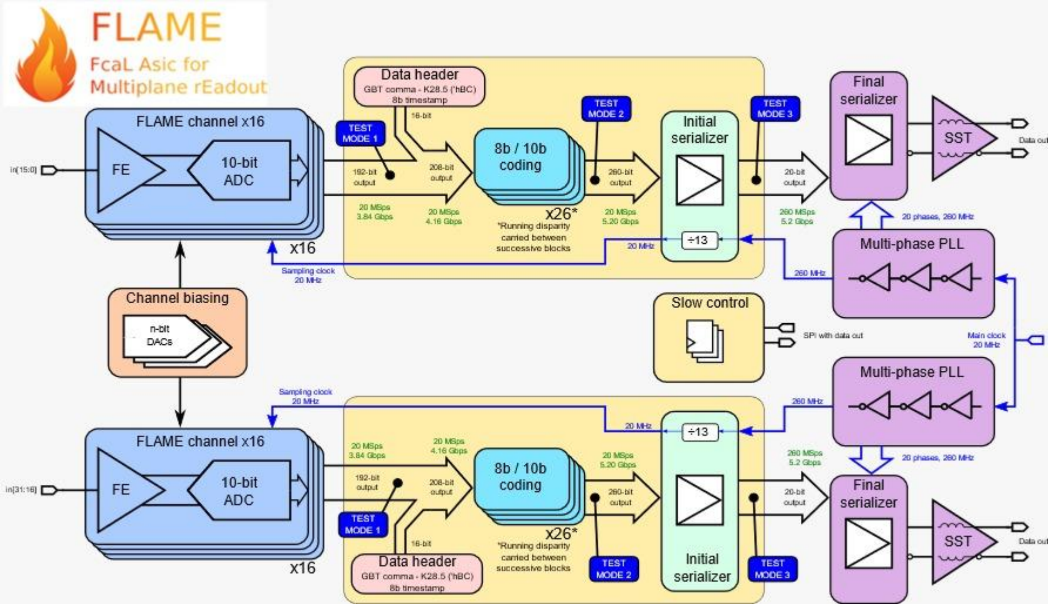


FLAME front-end ASIC

FLAME (**F**ca**L** **A**sic for **M**ultiplane 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.

Specifications:

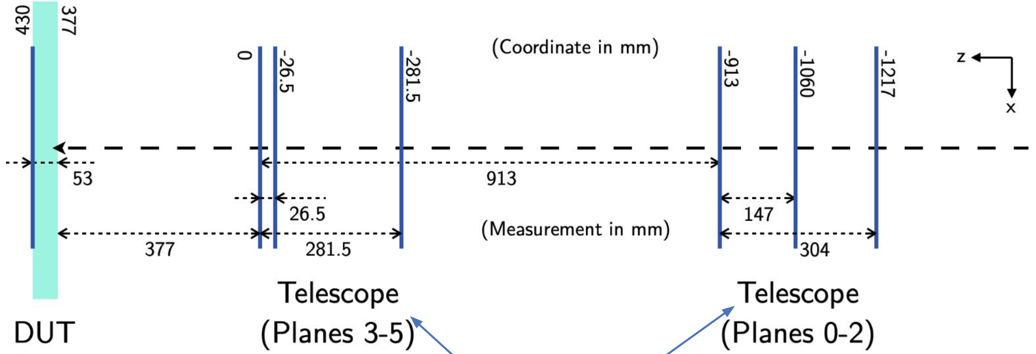
- Analog front-end in each channel
  - CR-RC shaping (T_{peak} ~50 ns)
  - Switched gain (high gain for MIPs and low gain for showers)
  - C_{in} 20-40 pF
- 10-bit ADC in each channel
  - f_{sample} = 20MHz
  - ENOB > 9.5



ECAL-P will use a new front-end ASIC based on FLAME called FLAXE.

Test beam 2022

Two 16 × 8 pad arrays of silicon sensors and two 15 × 10 pad arrays of GaAs sensors were tested in a 5 GeV electron beam at the DESY-II facility.



Measures the energy deposited by the particle

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Gives a precise measurement of the path of electrons from beam.

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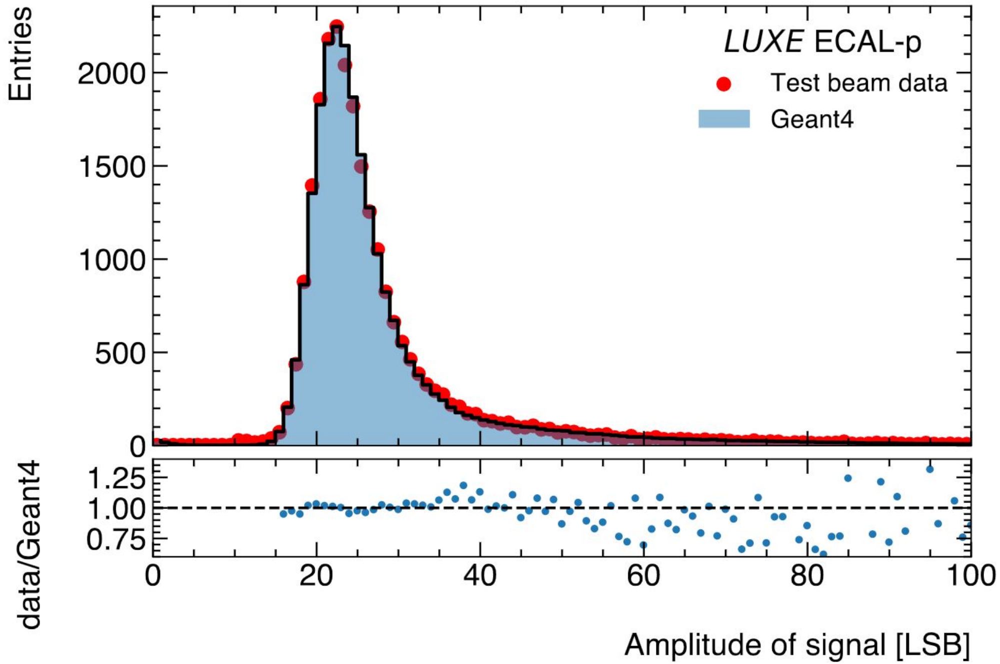
Data for sensor homogeneity studies!

Monte Carlo simulation

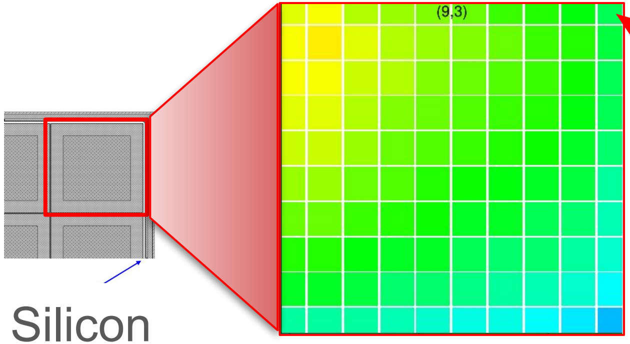


- The response of a silicon sensor plane to 5 GeV electrons was simulated using Geant4
- The simulation included the four sublayers of an sensor plane

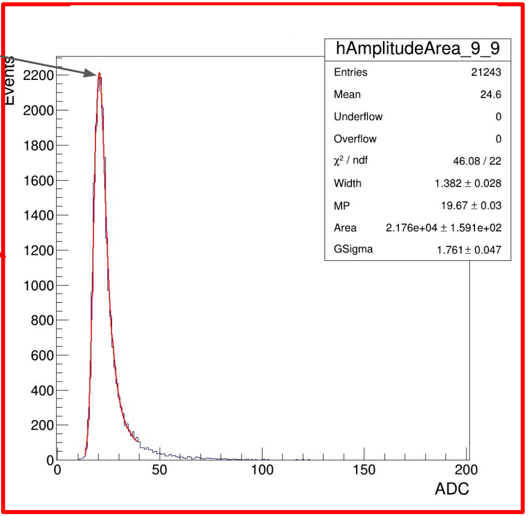
Homogeneity of individual pad response

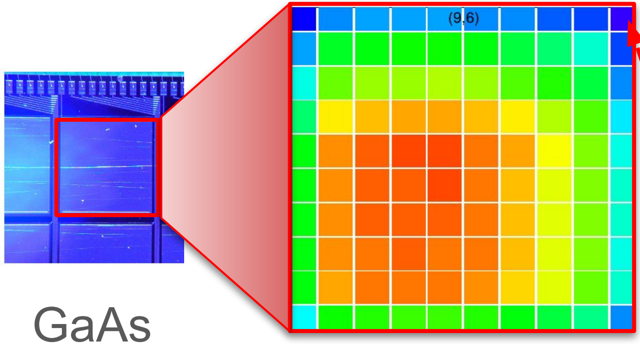
Subdivided pad into sections and plotted amplitude distribution of electrons in each section

MPV=Most Probable Value

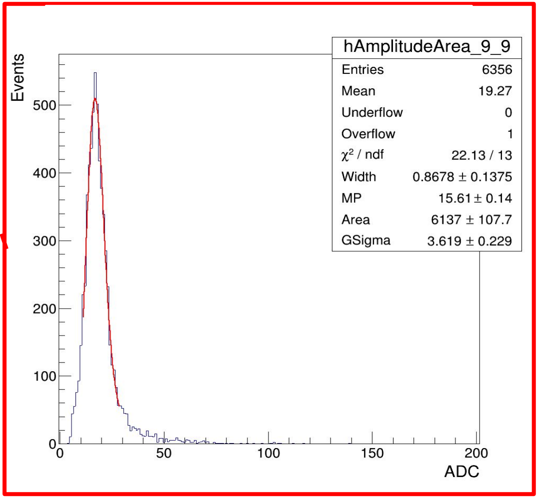


Silicon





GaAs



Z scale represents number of entries for the section

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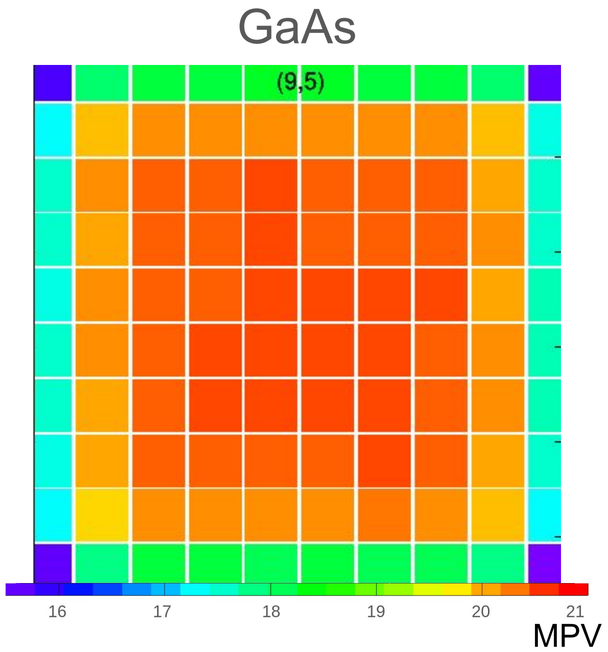
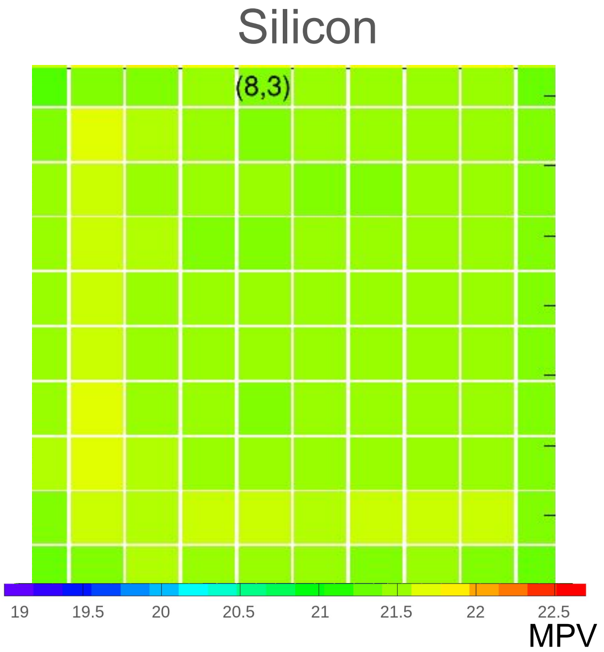
Examples of average response in pad sections

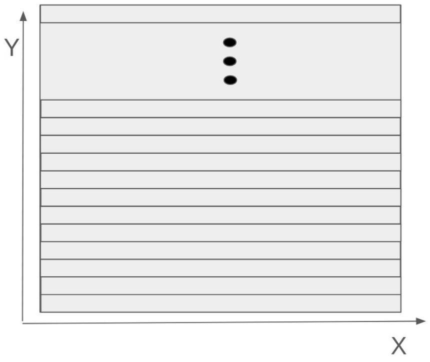




- Drop in amplitude around edges for GaAs
- L-shaped higher amplitude area for silicon sensor.

Examples of average pad response near edges

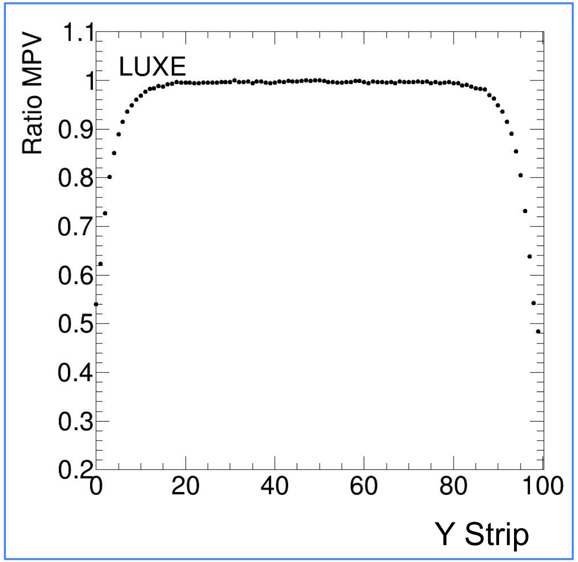
Subdivided pad into strip sections



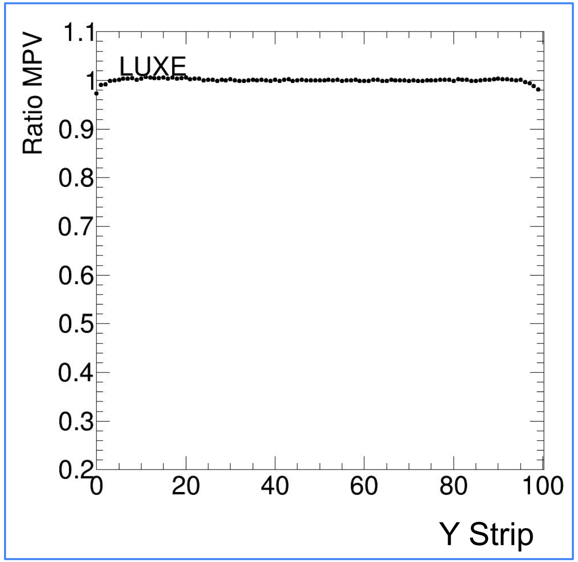
Calculated the MP amplitude of electrons in each strip

Normalized to MPV of center strip

GaAs

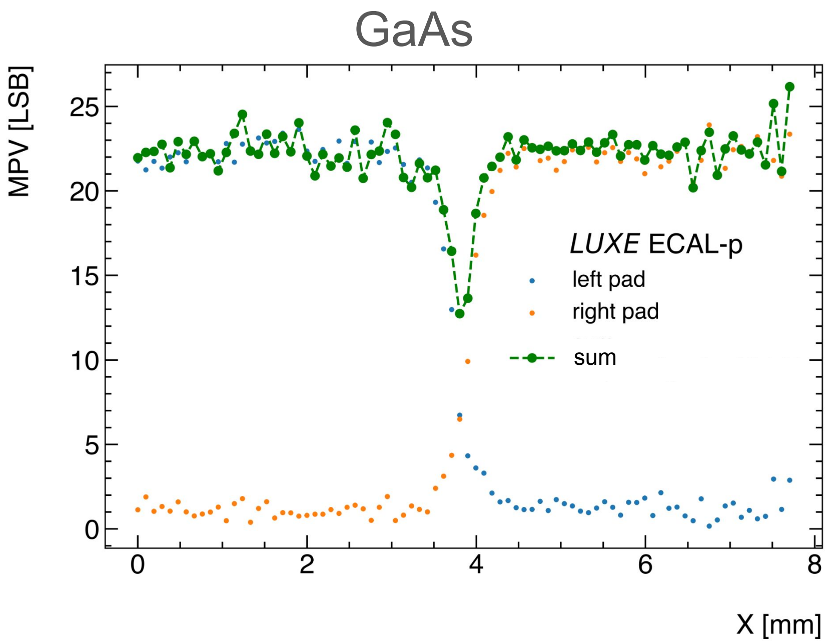


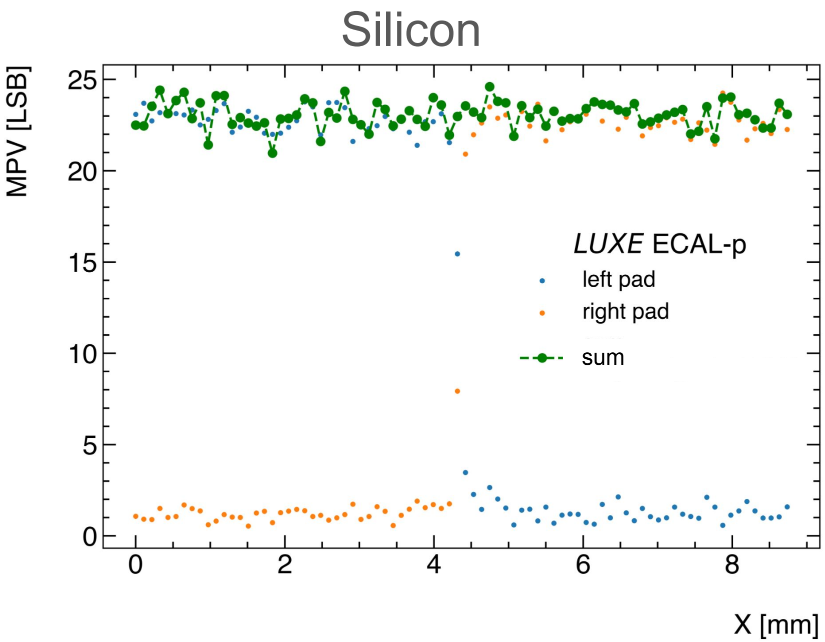
Silicon



- 50% drop in amplitude wrt center for edges of GaAs pads
- 2-3% drop in amplitude for silicon wrt center
- The response along X was found to be similar

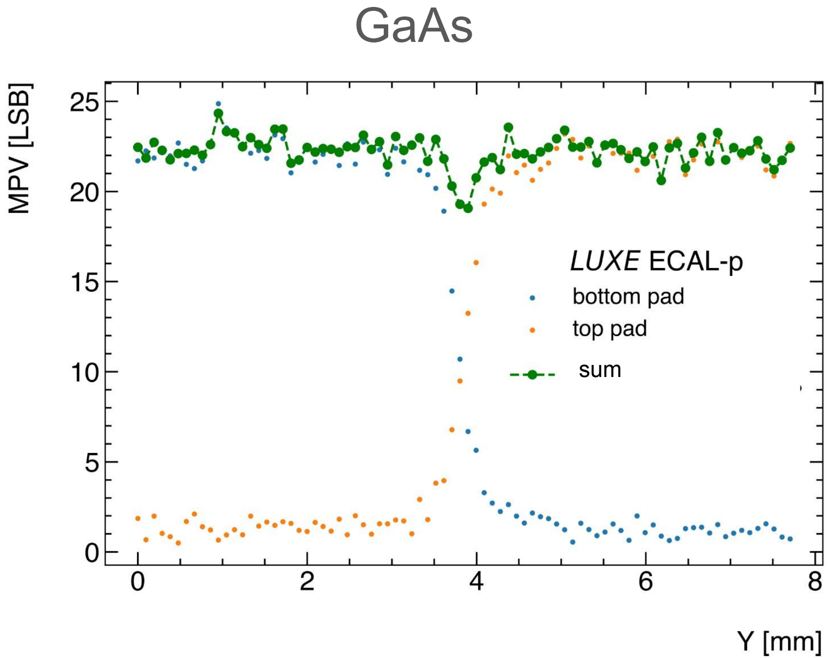
Edge effects: sum of neighbouring pads X

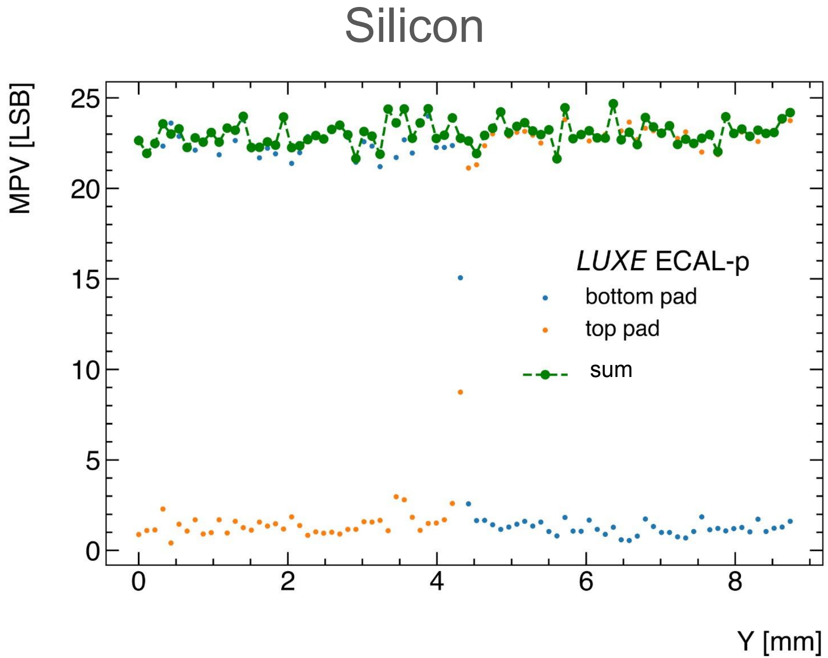




- For GaAs: when an electron hits the Al traces the sum of the signals for two adjacent pads has a drop of 40%
- For silicon there is no drop in the gap area between pads.

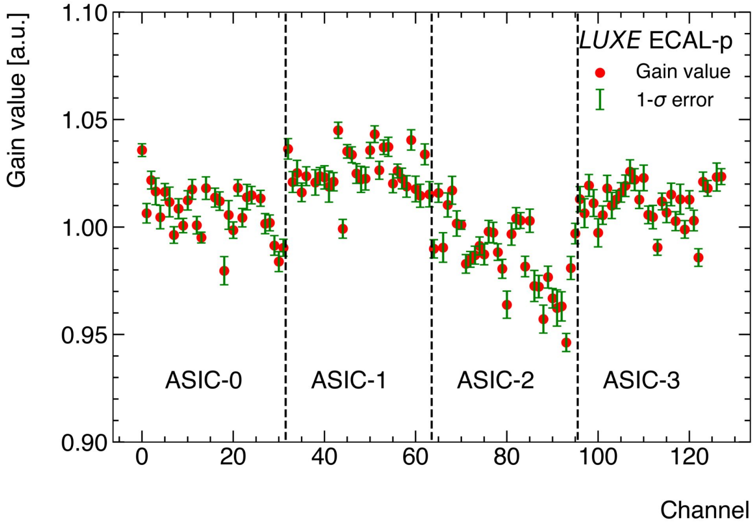
Edge effects: sum of neighbouring pads Y

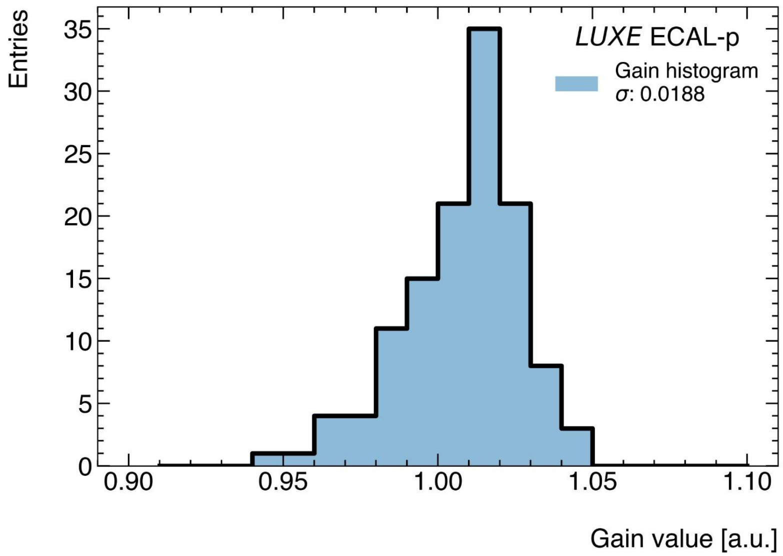




- For GaAs: in the Y-coordinate (gaps without traces) the net drop amounts to 10%
- For silicon no loss of signal is observed

Gain calibration

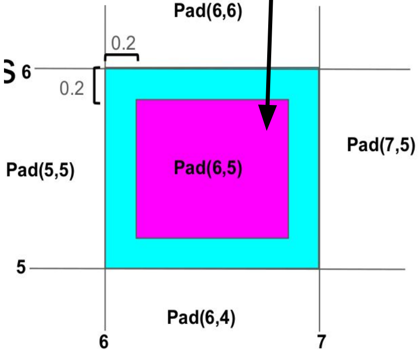


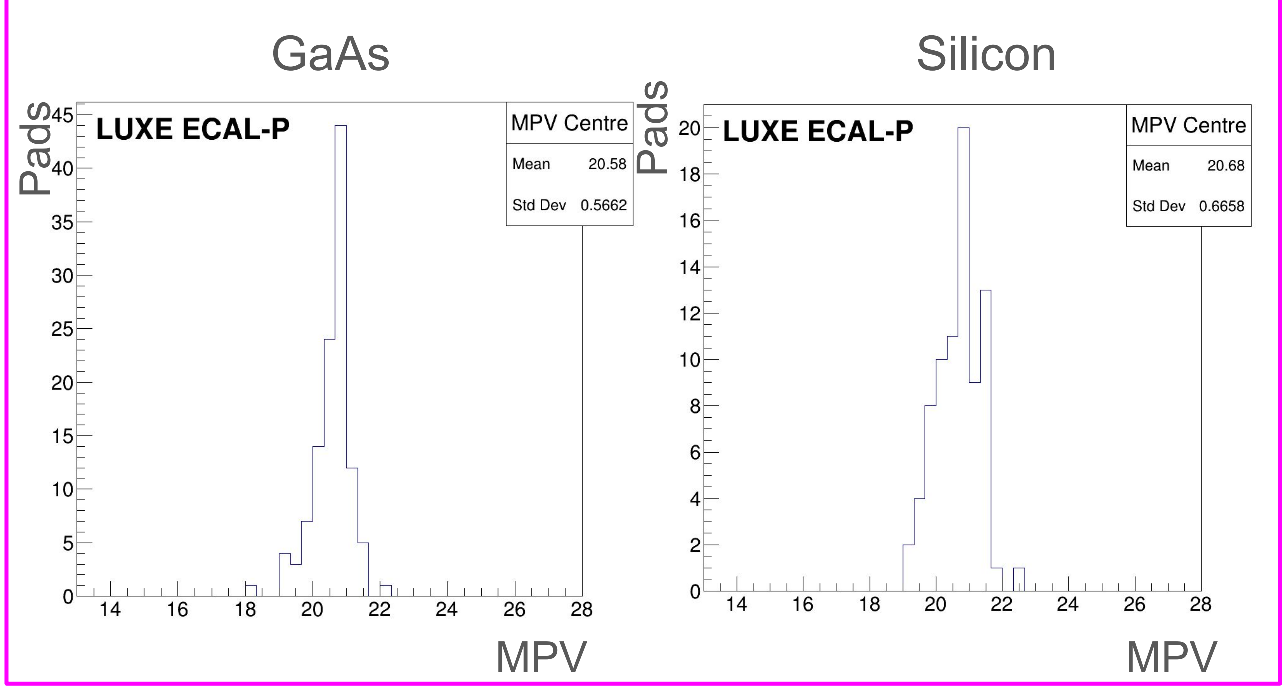


- The readout channels, common to the two sensors in the test-beam, were calibrated for differences in the pre-amplification
- These factor were applied to the data

Homogeneity of sensor response

Take electrons hitting this area





- For both sensors, the response between pads varies within 3%

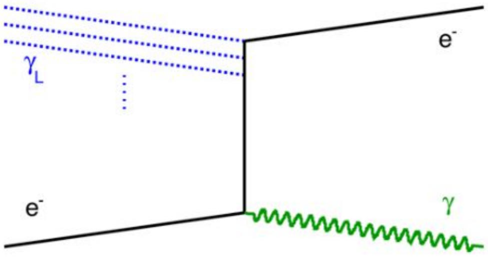
Conclusion and Summary

- A Monte Carlo simulation of the instrumented silicon plane was performed and found to be a good modeling of the test-beam data
- Individual pad-response studies were possible with the help of the telescope
- The GaAs sensors with aluminium traces present edge-effects involving a drop in the amplitude of signals
- This effect is small for the tested silicon sensors
- Gain calibration factor were applied to the test-beam data
- After removing the pad's edges from the GaAs sensor, the homogeneity of response was found to be comparable to that of the silicon sensor

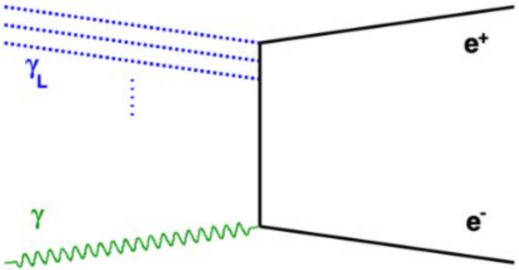
Thank you for your attention!

Backup

Physics processes at LUXE

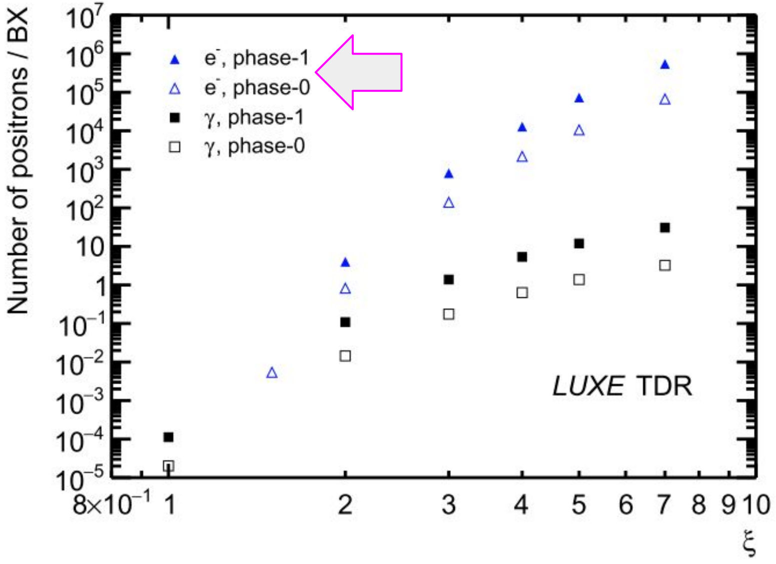


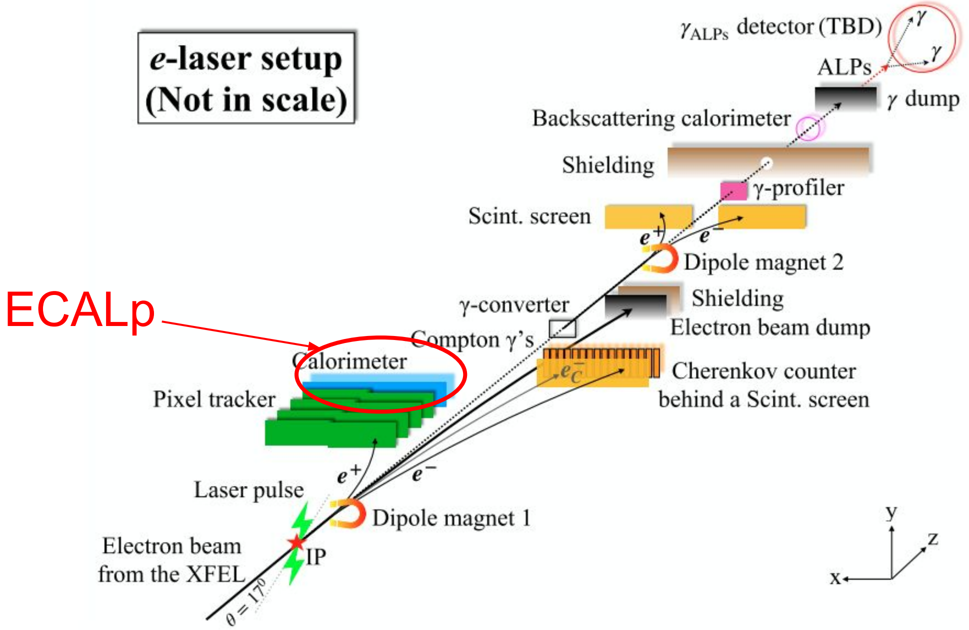
Nonlinear Compton



Nonlinear Breit-Wheeler

Initial mode for LUXE: e-laser





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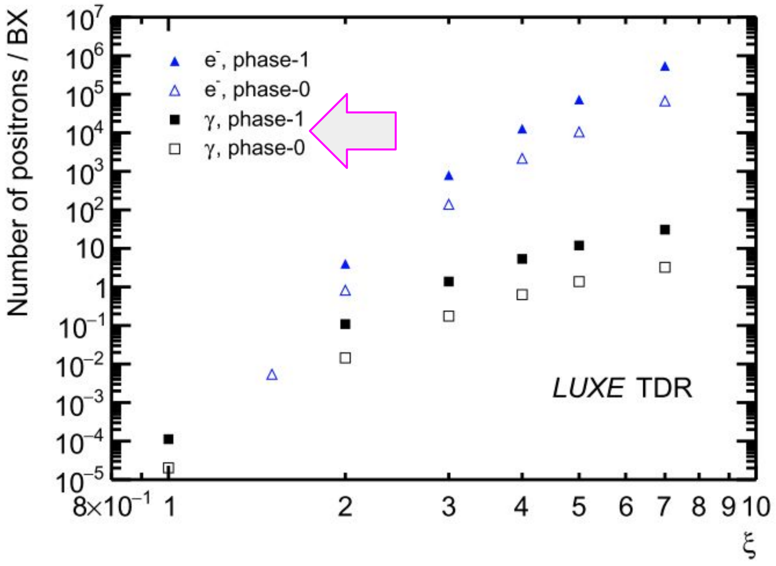
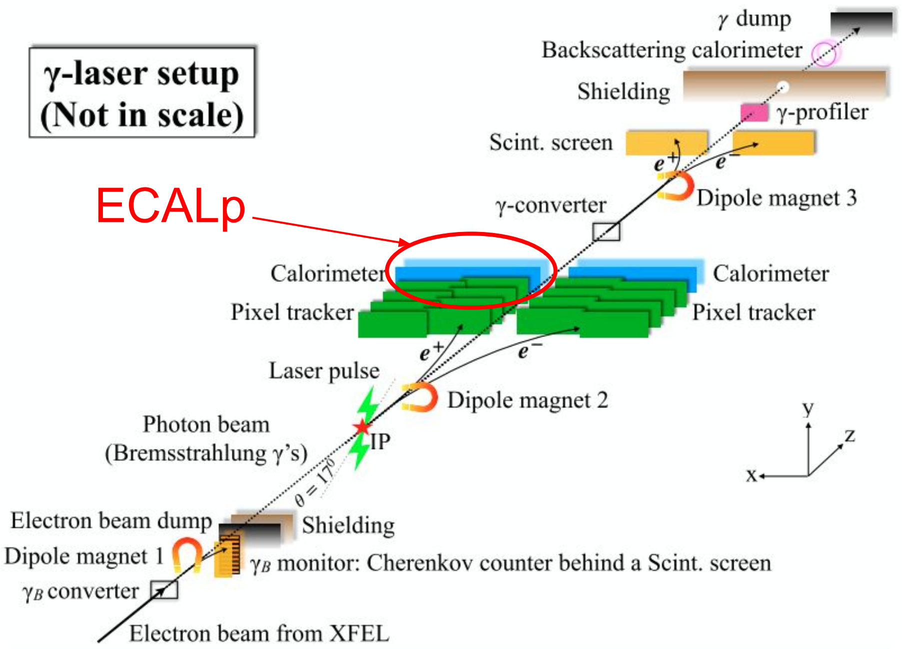
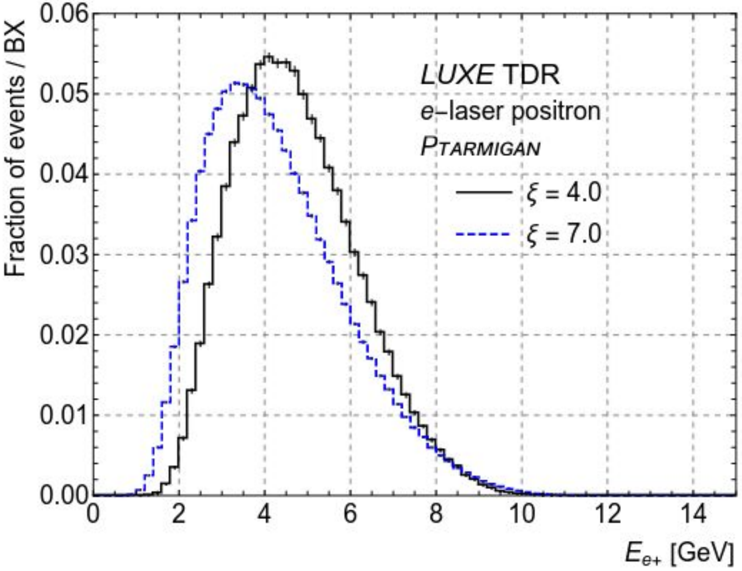
Second mode: γ-laser

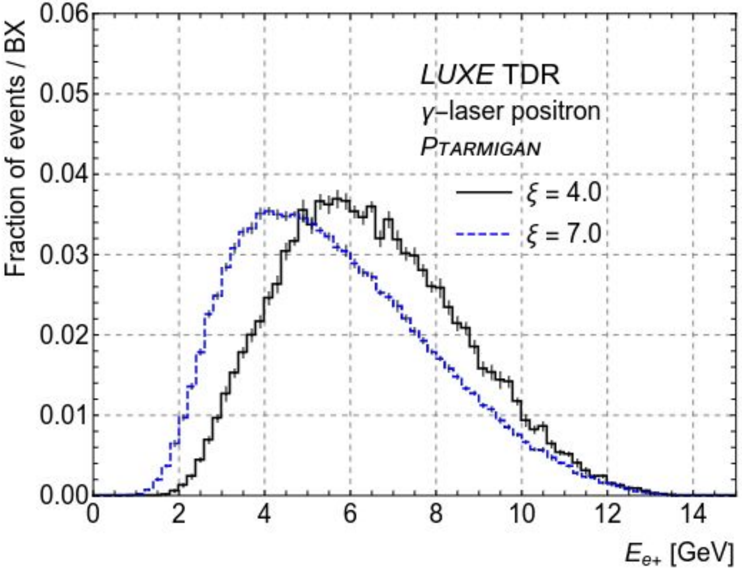




LUXE TDR (2023)

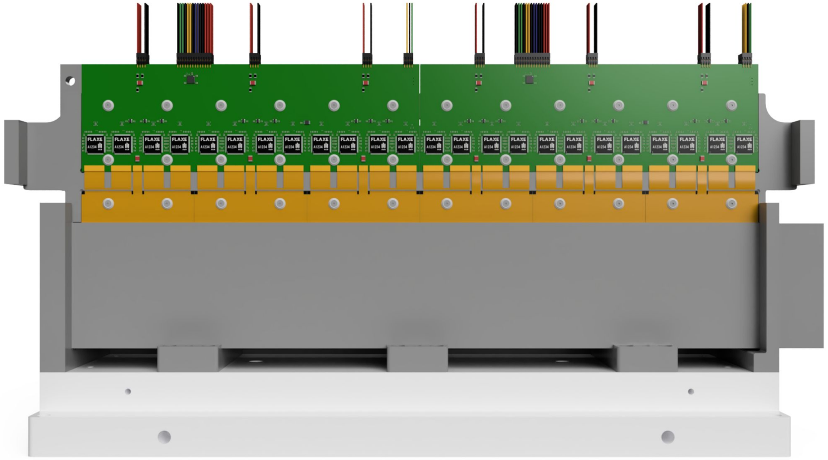
Expected positron energy spectra

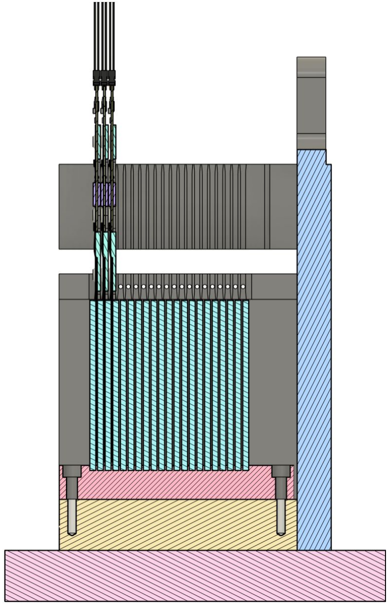




LUXE TDR (2023)

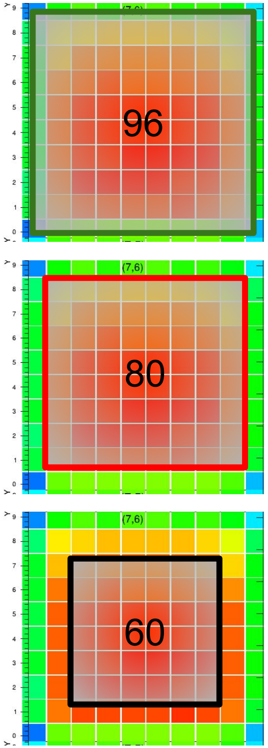
Detailed ECAL-P structure

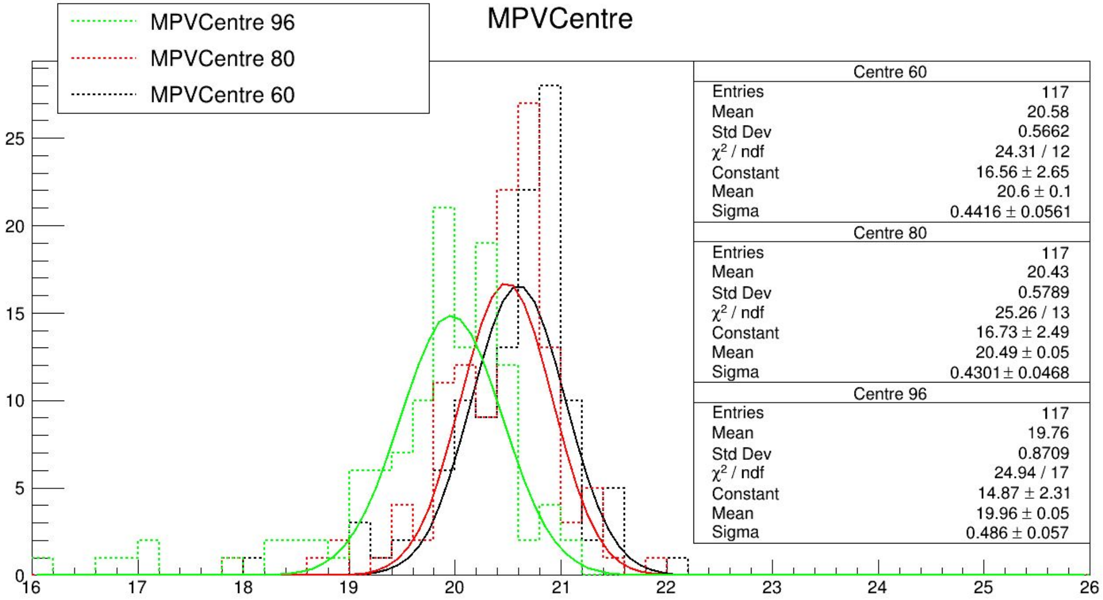




Edge-effects in homogeneity

Results on amplitude varying the centre area

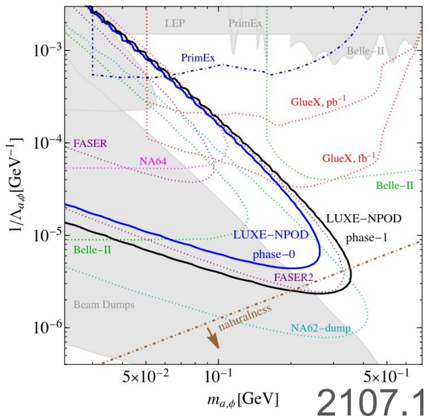




- Mean sensor amplitude drops by less than 1% from area 60 to 80, and by around 3% when taking area 96.

Probing physics Beyond the Standard Model at LUXE

The high photon rate from LUXE gives the opportunity to search for physics BSM



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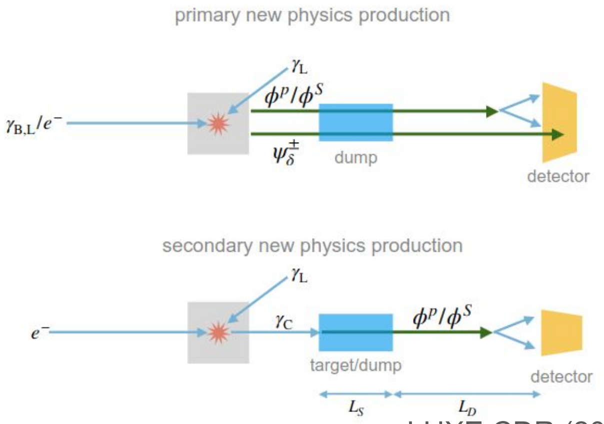
Two NP production modes for ALPs and scalars that couple to photons and electrons



LUXE CDR (2021)

Proposals to set a calorimeter at a fixed distance from photon dump to probe ALPs decays to two photons