R&D for compact calorimeters for e^+e^- collider, and application to the LUXE experiment

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[on behalf of the FCAL and LUXE Collaborations]

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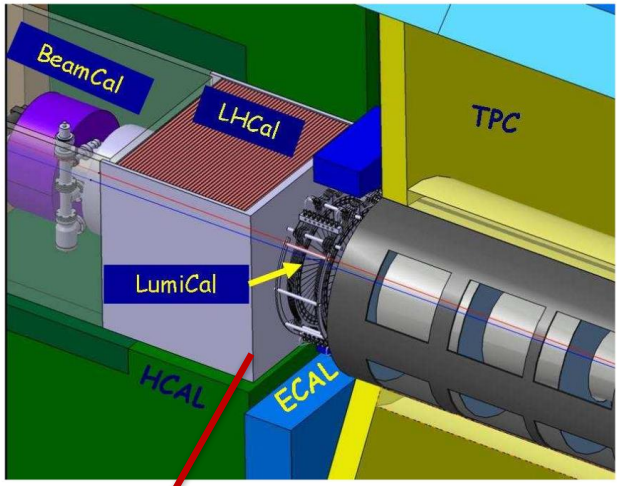
ONLINE EDITION

Overview

- Forward region calorimeters in e^+e^- collider
- Compact and highly granular design
- FLAME - dedicated readout ASIC for LumiCal
- Performance of LumiCal prototype
- Application of the FCAL technology
  - LUXE experiment – overview
  - ECAL concept
  - ECAL - 1st beamtest at DESY
- Conclusions and Future Steps

Forward region in e^+e^- collider

The luminosity can be measured by counting number (N_B) of Bhabha events in a certain polar angle (θ) range of the scattered electron.

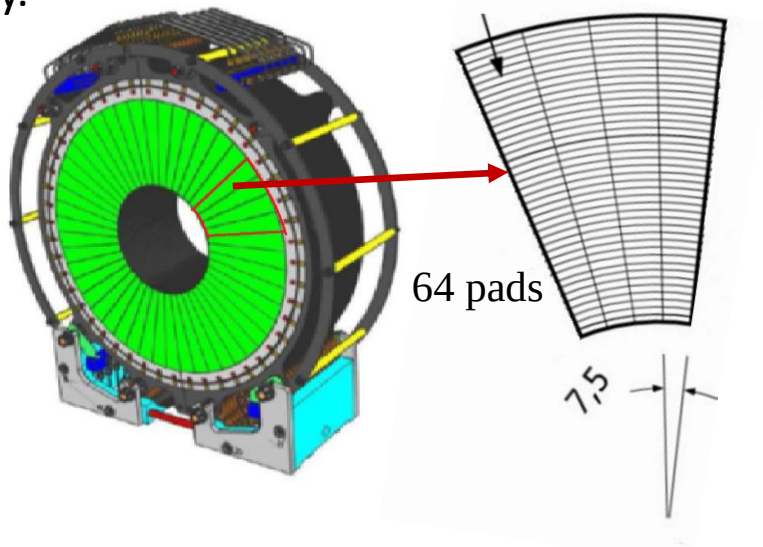


LumiCal:

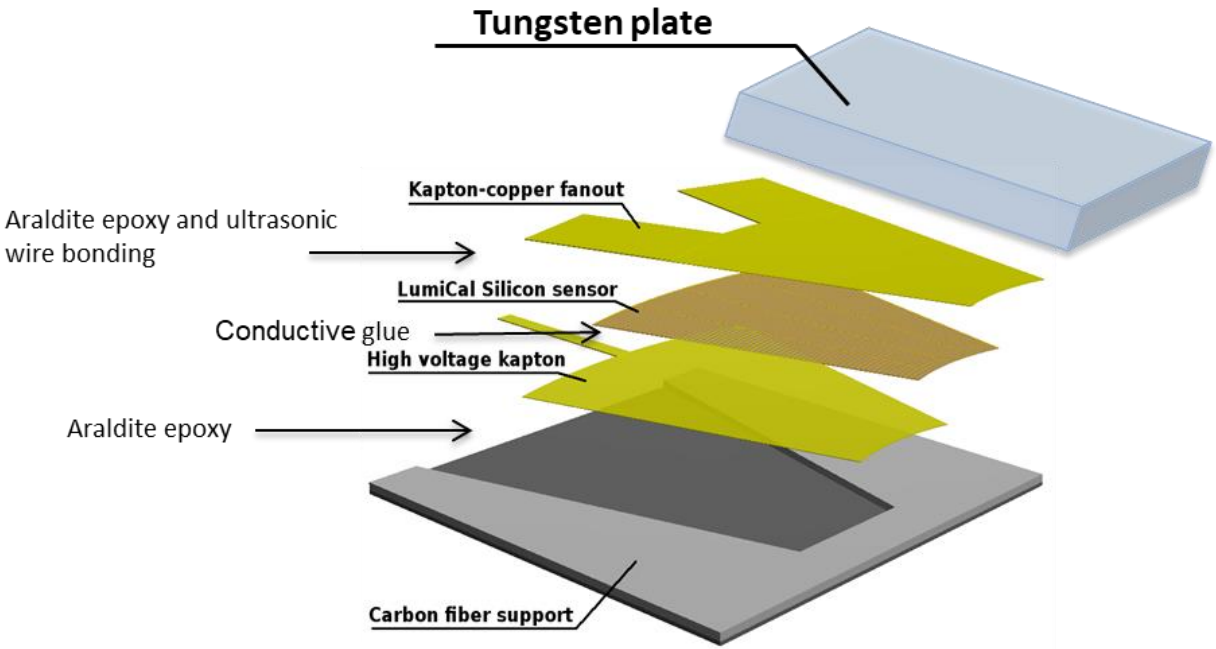
- Si-W electromagnetic sandwich calorimeter;
- Highly compact;
- Small Moliére radius;
- Fast readout;
- Designed to measure the integrated luminosity.

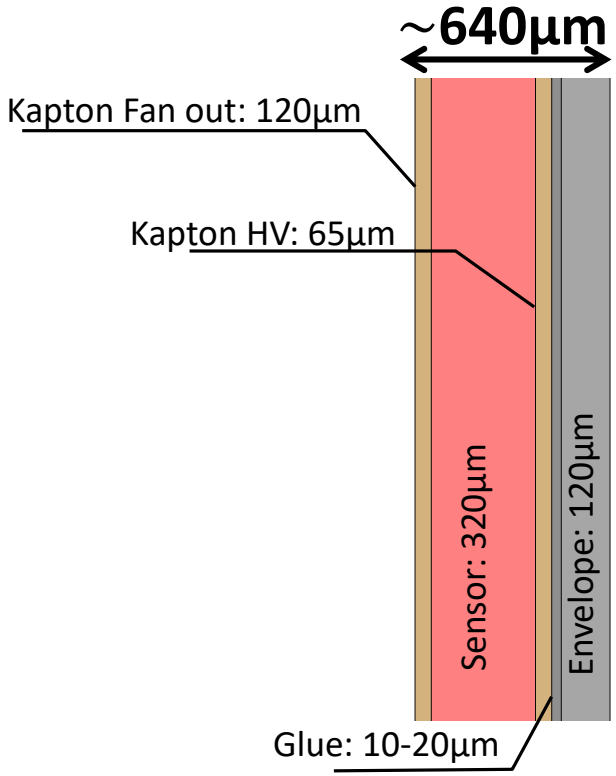
Si sensor prototype:

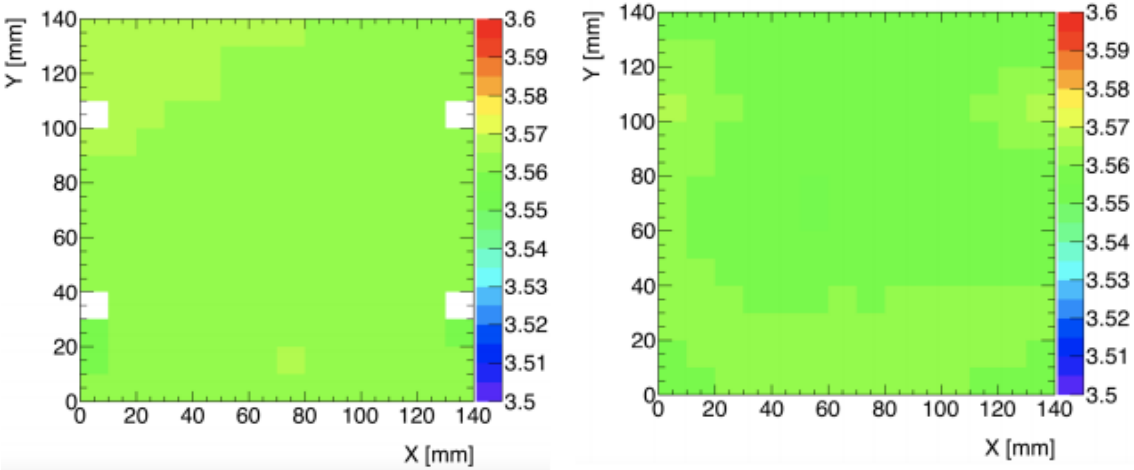
- 6-inch wafer;
- Radially segmented – 64 pads with 1.8 mm pitch;
- 4 azimuthal sectors in one tile, each 7.5 degrees;
- 320 μm thickness;
- 12 tiles makes full azimuthal coverage.

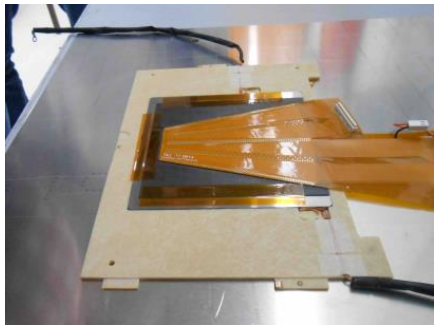


Thin LumiCal detector plane





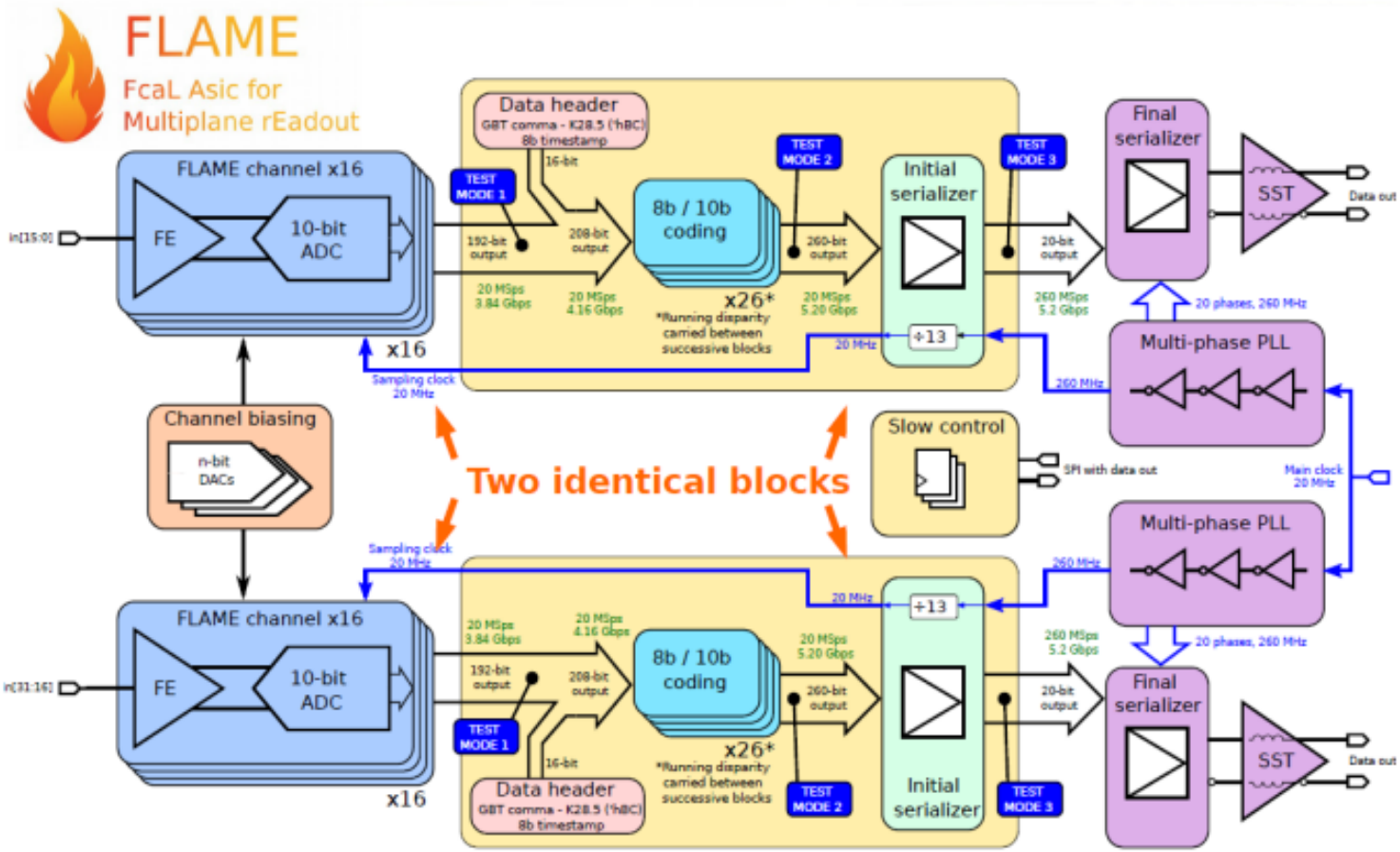




Good flatness ~30 µm observed

https://arxiv.org/pdf/1703.10496.pdf

FLAME - LumiCal new readout



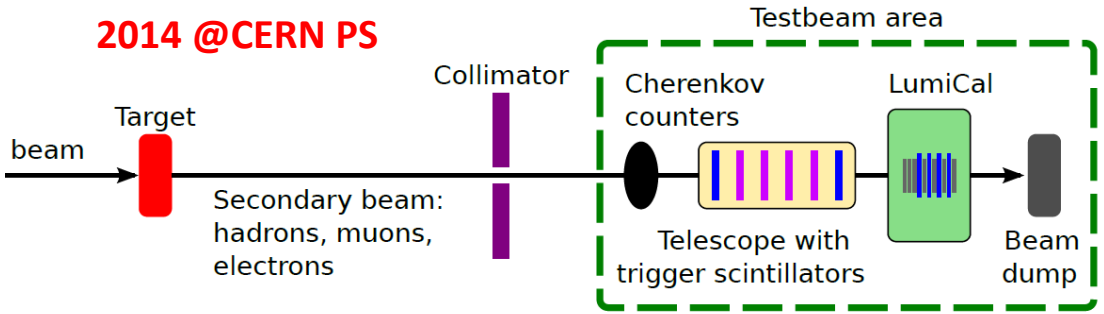
Architecture of **FcaL Asic for Multiplane rEadout**:

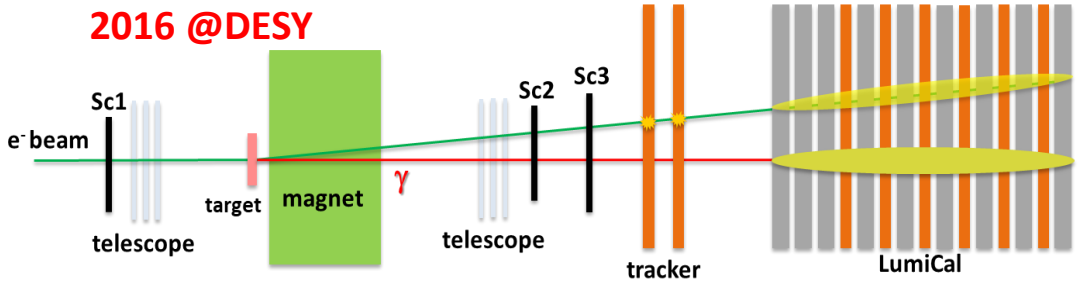
- ✓ Designed in CMOS 130nm;
- ✓ 32 mix-mode channels per ASIC;
- ✓ Each channel contains FE+10 bit ADC;
- ✓ Followed by high speed data link.

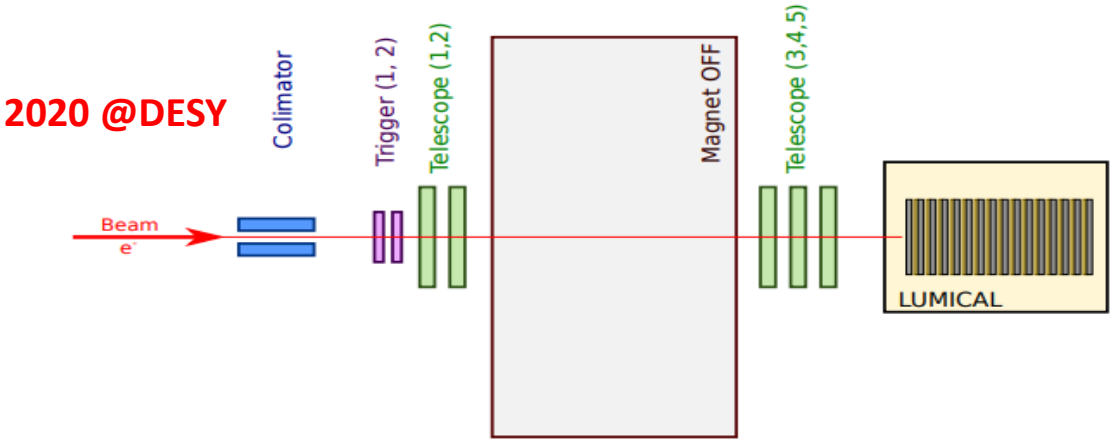
Data send directly to **Zynq UltraScale FPGA** for online processing:

- ✓ pedestal, CM subtraction;
- ✓ Pulse detection;
- ✓ Deconvolution;
- ✓ ToA and amplitude reconstruction.

Beam-test campaigns



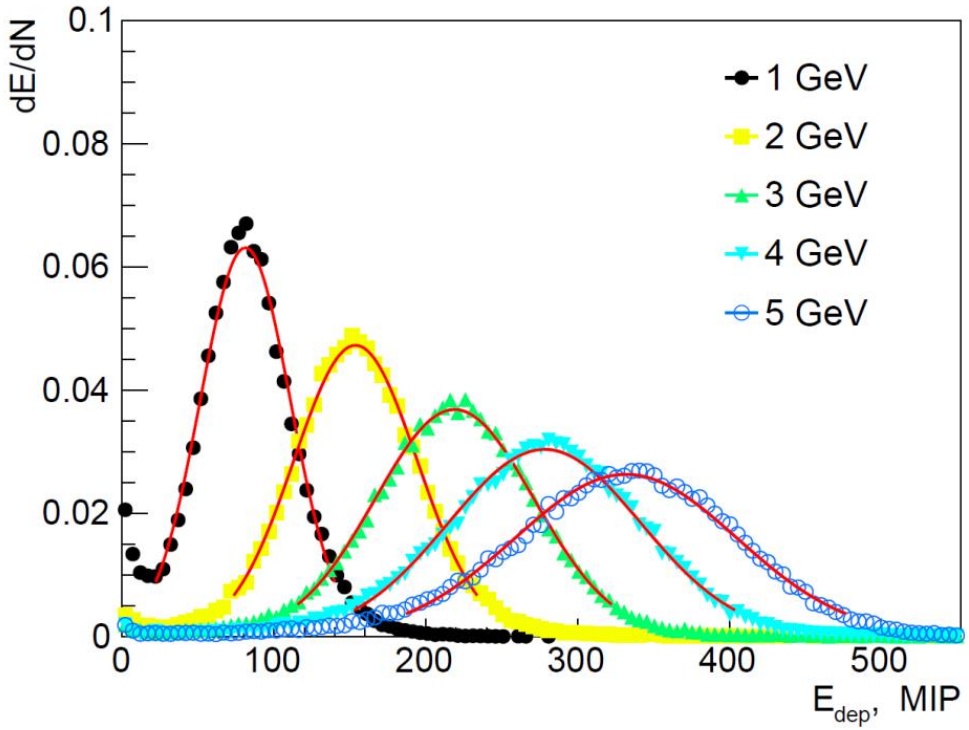




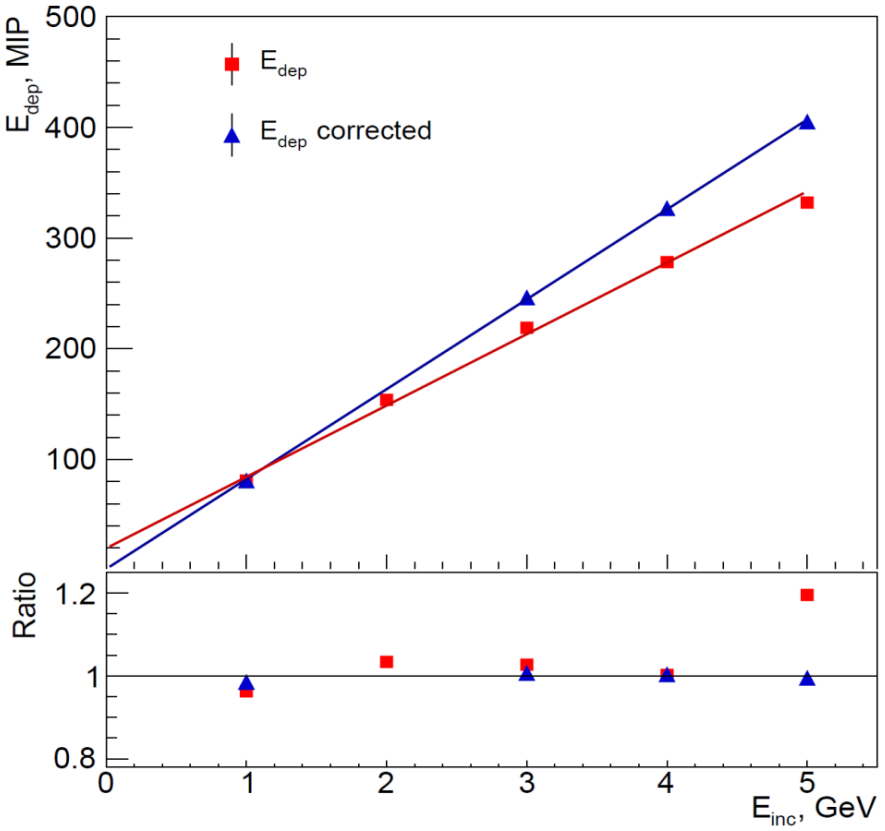
Goals:

- Demonstration of multi-plane operation of the forward detector prototype;
- Study of the electromagnetic shower in a precise and well known structure and comparison with MC simulations;
- Measurement of Molière radius;
- Study of e-/γ identification using bremsstrahlung;
- Energy and spatial resolution studies;
- Polar angle bias study;

Results

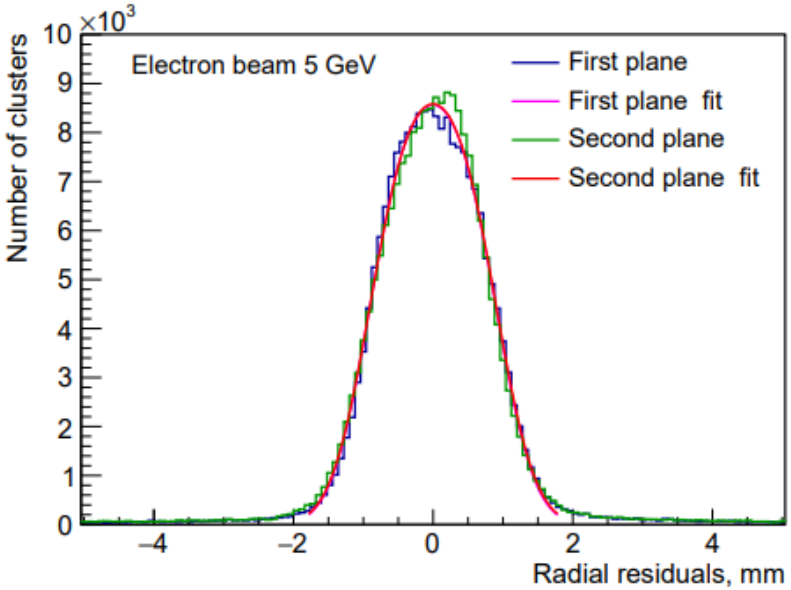


Energy deposited distribution in LumiCal prototype for different beam energy - fitted with Gaussian distribution function.

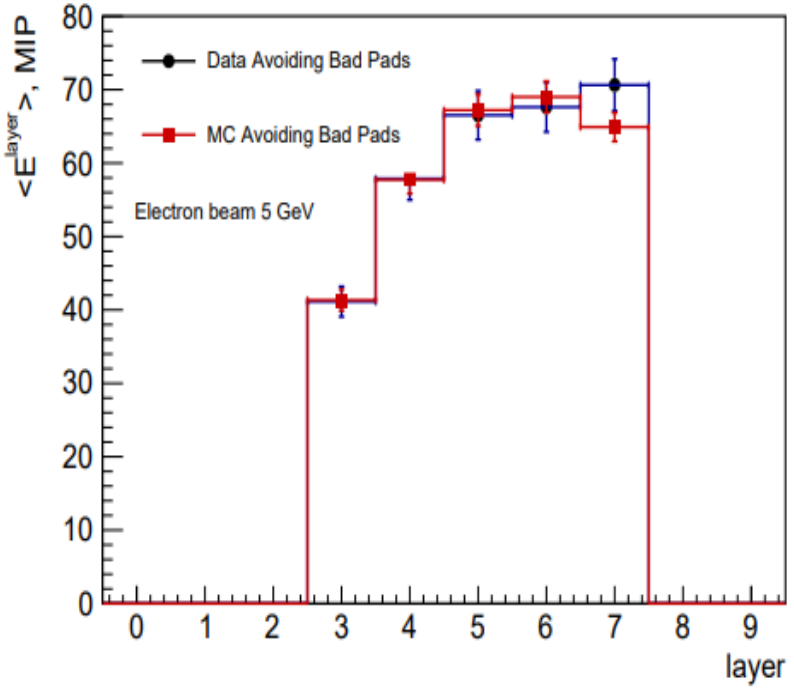


Average total energy deposited in LumiCal prototype as a function of beam energy before (red) and after (blue) APV25 front-end chip calibration. The lower part shows the ratio of the E_{dep} to the straight line.

Results



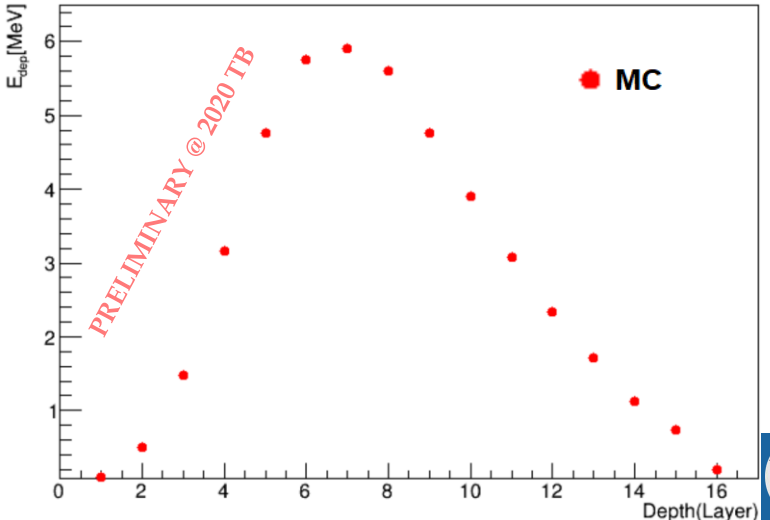
Residuals distribution of the radial position measurements in the two the tracker planes and the calorimeter.



Longitudinal shower profile.

The resolution $\boldsymbol{\sigma}$ of the shower position reconstruction is:

$$\boldsymbol{\sigma = (440 \pm 20)\mu m}$$



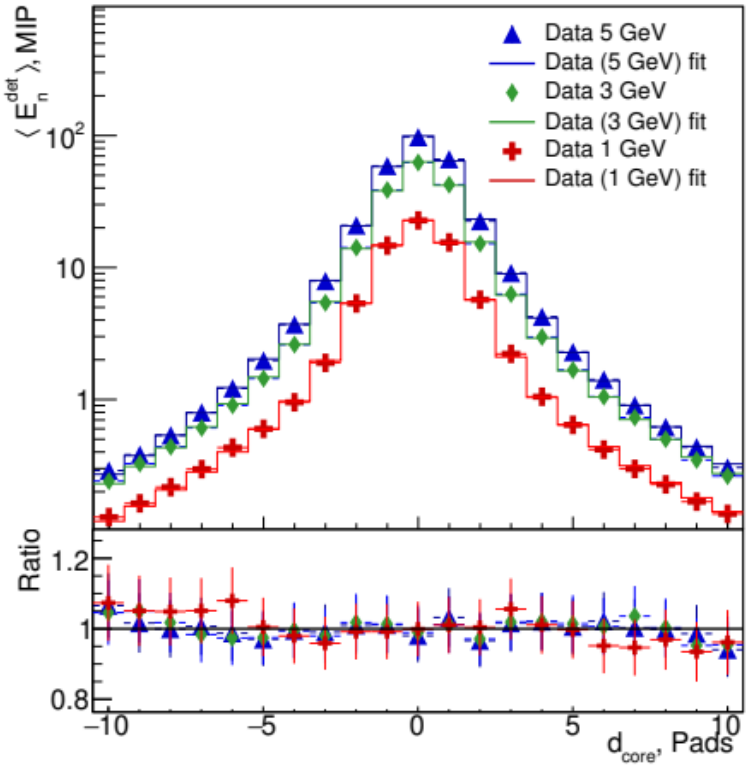
Results

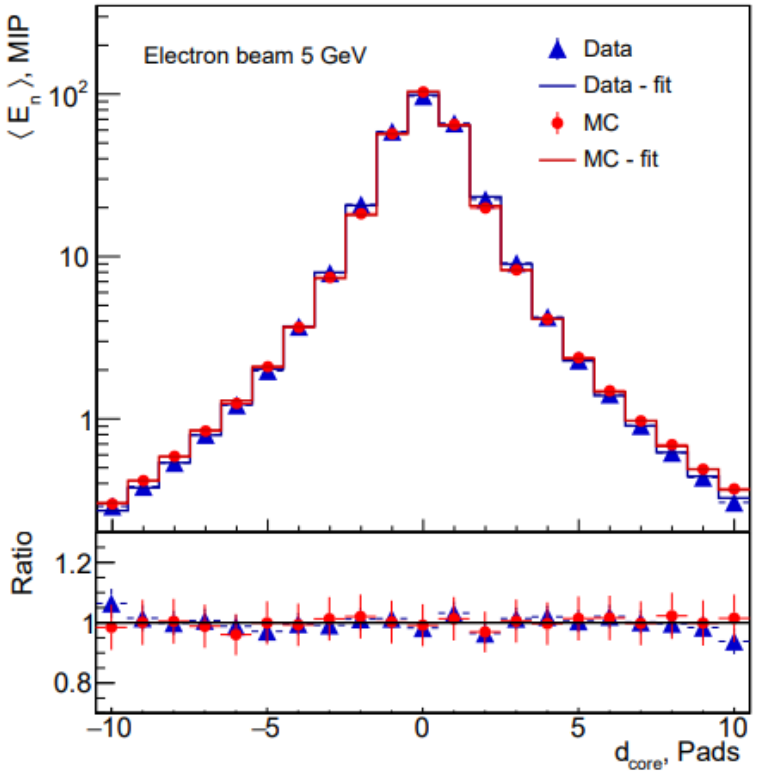
Shower parametrization in radial direction:

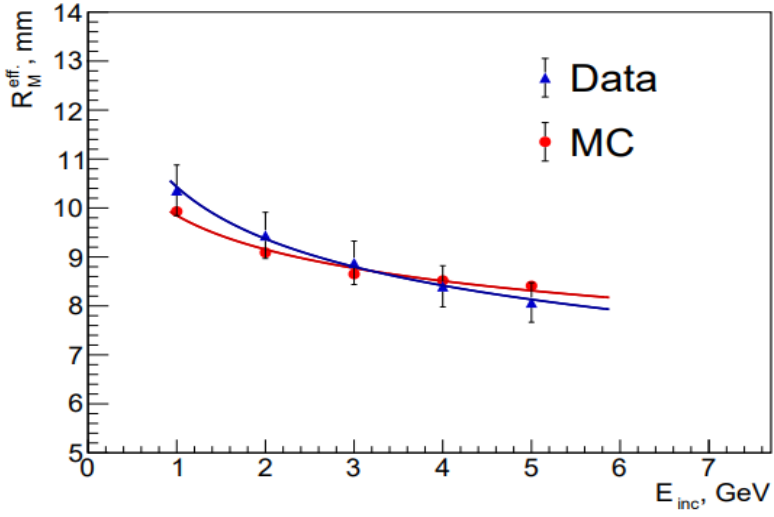
$$F_E(r) = A_C e^{-\left(\frac{r}{R_C}\right)^2} + A_T \frac{2r^{\propto} R_T^2}{\left(r^2 + R_T^2\right)^2}$$

Equation for Moli`ere radius R_M calculation:

$$0.9 = \int_0^{2\pi} d\varphi \int_0^{R_M} F_E(r)\, r dr$$







R_M = 8.1 ± 0.1 (stat) ± 0.3 (syst)) mm (data)

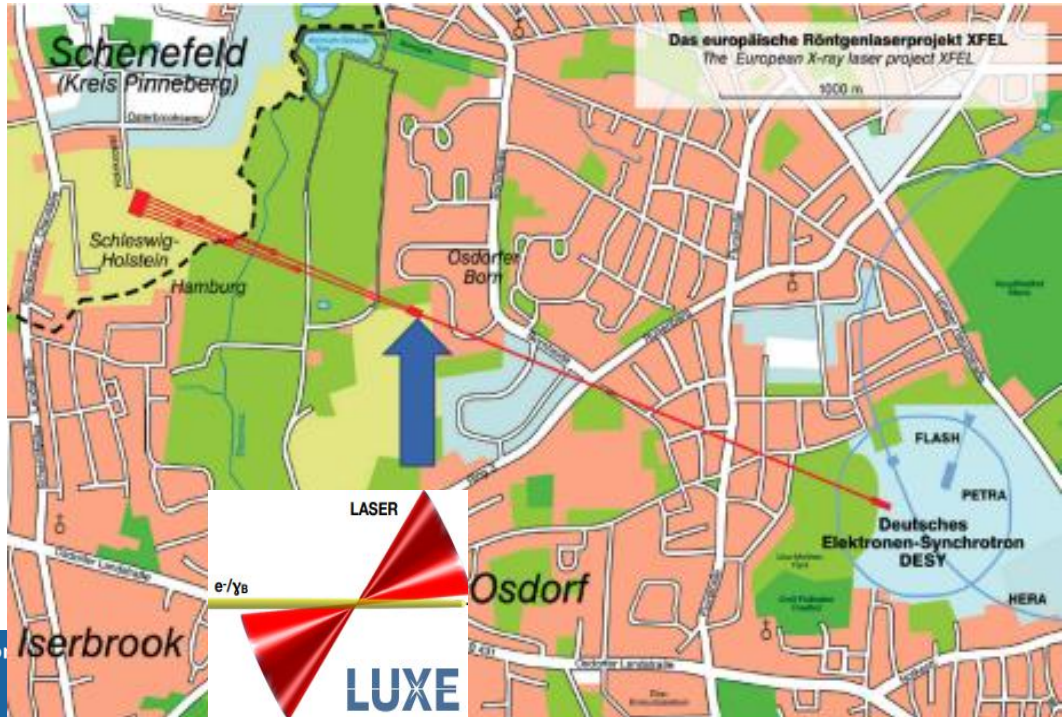
R_M = 8.4 ± 0.1 mm (MC)

Eur. Phys. J. C 79, 579 (2019)

LUXE experiment – overview

What is LUXE experiment?

- new experiment proposed at DESY in Hamburg using:
  - XFEL electron beam;
  - High power LASER;
- Probe QED at very high fields, approaching and beyond the Schwinger limit;
- International collaboration:
  - 88 members from 26 institutes.



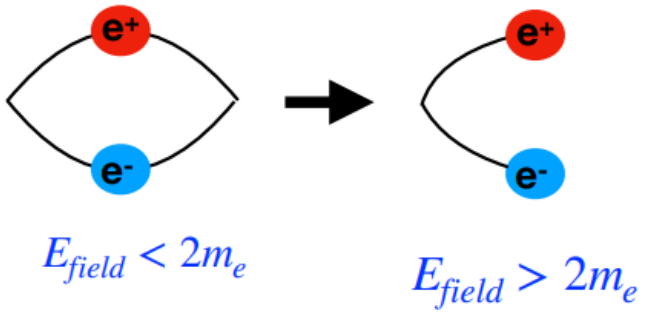
More details on LUXE physics:

- LUXE CDR: Eur.Phys.J.ST 230 (2021) 11, 2445-2560
- LUXE website: https://luxe.desy.de

LUXE experiment – overview

Strong-Field QED

- QED: most well-tested theory in physics → based on perturbative calculations;
- LUXE will study QED in the strong field regime;
- Strong external field: work by field $\lambda_{Compton} > 2m_e$ → **Schwinger-Limit**



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

QED becomes non-perturbative above Schwinger-Limit!

Schwinger-Limit:

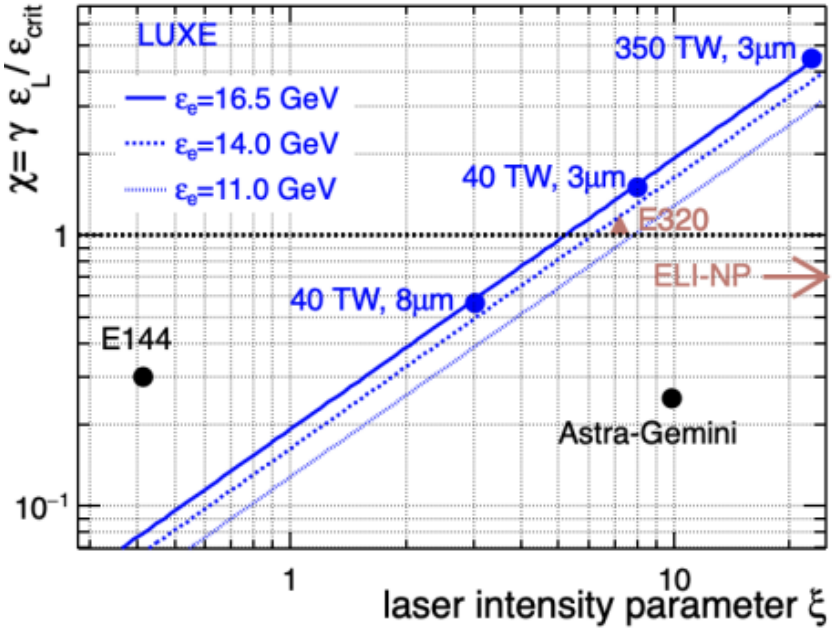
$$\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e}$$

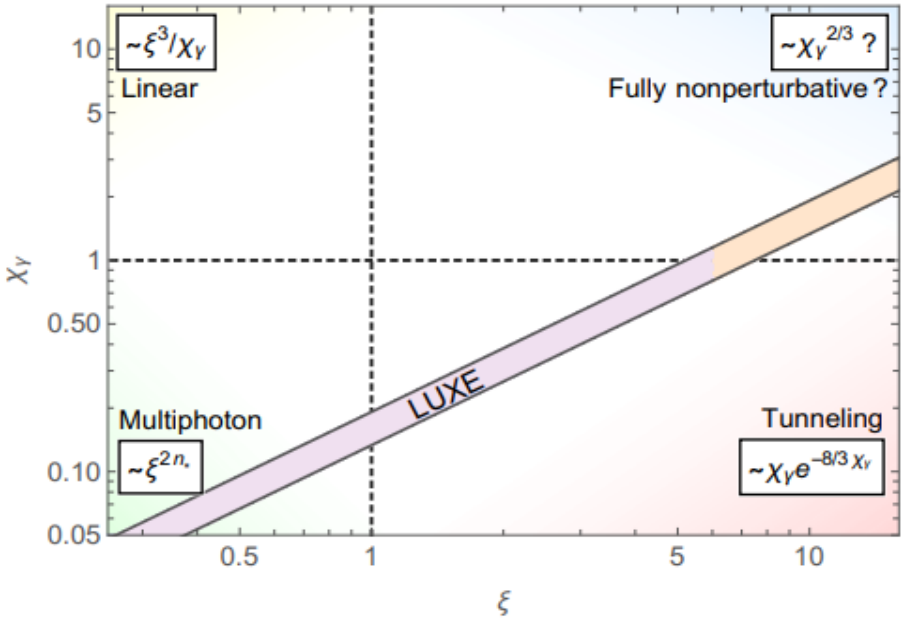
e.g. for electrical field:

$$\varepsilon_{crit} \cong 1.3 \cdot 10^{18}\, V/m$$

Exciting analogy: Hawking radiation!
no em field -> Gravitational field

LUXE experiment – overview



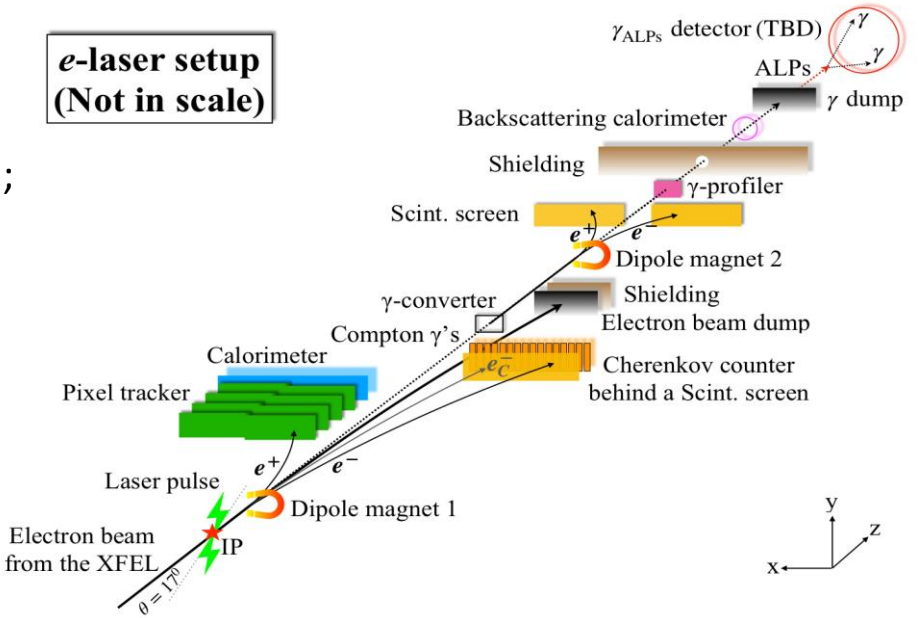


- **E144**: SLAC experiment in 1990's, using 46,6 GeV electron beam and 1TW power laser;
  → reached $\xi < 0.4$, $\chi \leq 0.25$, observed $e^- + n\gamma_L \rightarrow e^- e^+ e^-$ process;
  → observed start of the ξ^{2n} power law.
- **LUXE**: might be the 1st experiment to report observation of non perturbative regime;
  → directly explore photon-laser interactions;
  → measure positron rate as function of laser intensity;
  → measure Compton edge;
  → study BSM physics (search for ALPs or MCPs in photon beam-dump).

LUXE setup

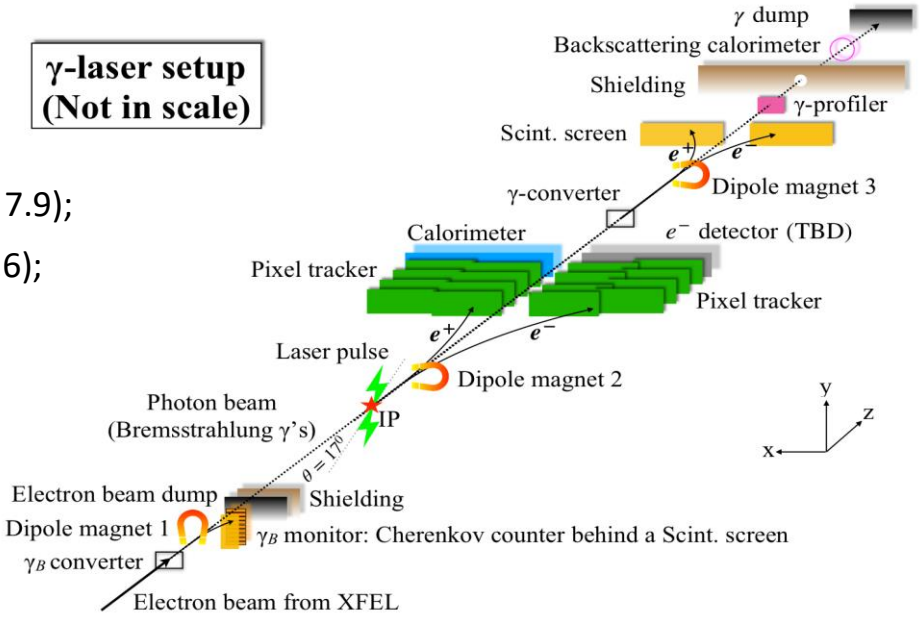
European XFEL electron beam:

- Energy 16.5 GeV (possible 10 GeV and 14 GeV);
- LUXE uses one out of 2700 bunches per train;
- Repetition rate 10 Hz;
- Normalized emittance 1.4 mm mrad;

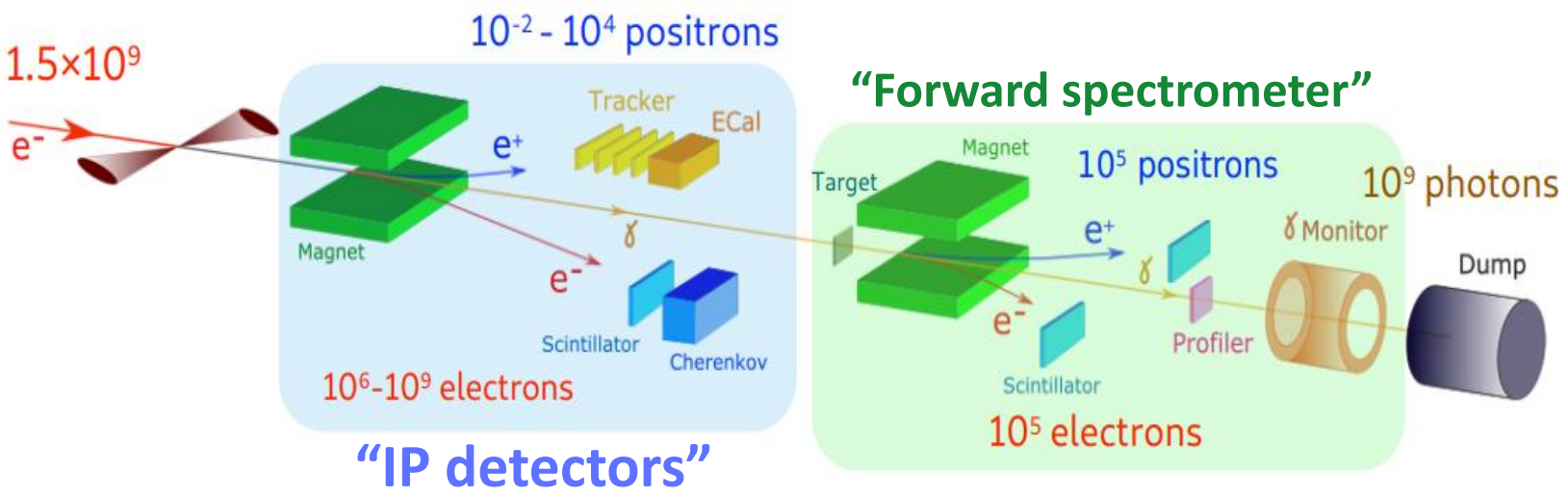


Laser:

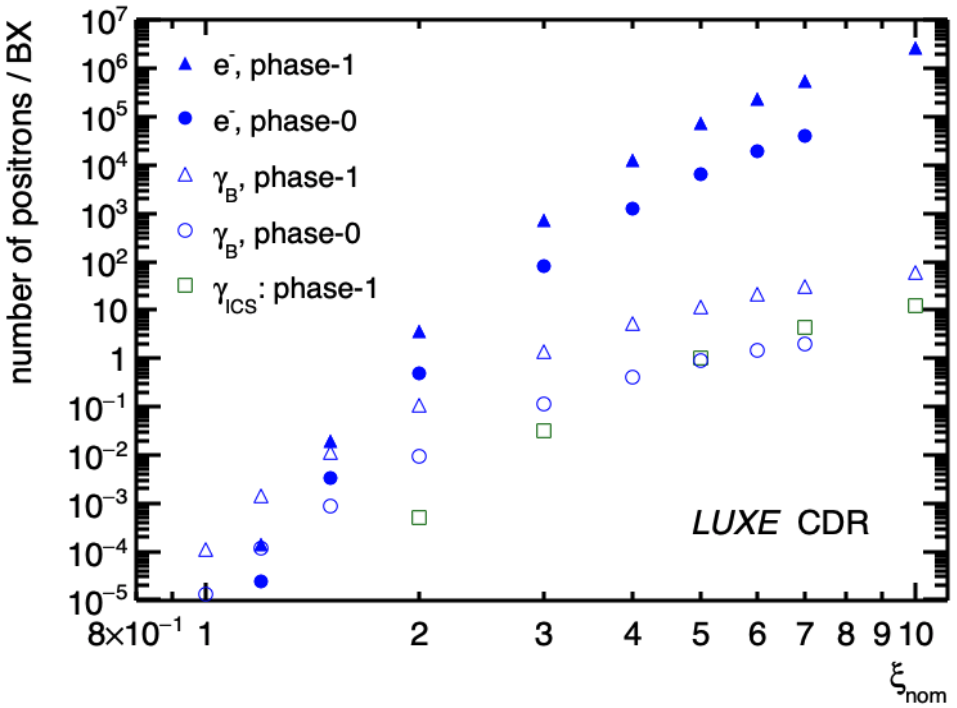
- Laser wavelength = 800.00 nm (1.5498 eV);
- Repetition rate ~1 Hz;
- Power:
  - ✓ Phase 0: 40 TW, focal spot size: 3 or 8 μm (ξ = 7.9);
  - ✓ Phase 1: 350 TW, focal spot size: 3 μm (ξ = 23.6);



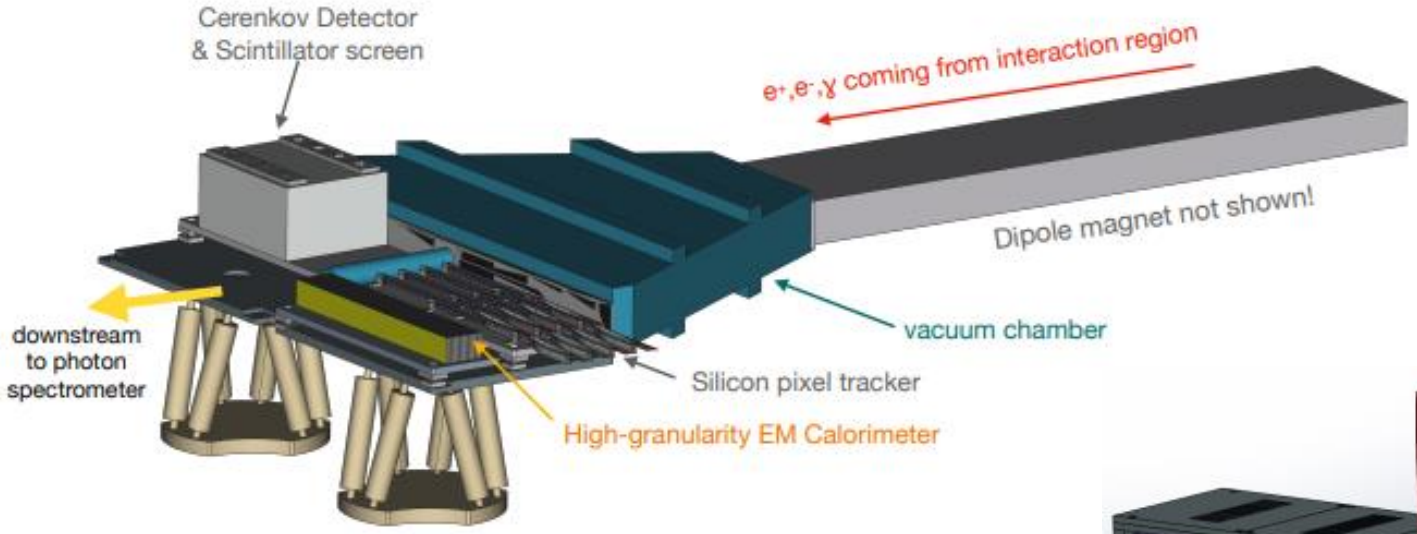
LUXE – particle detectors

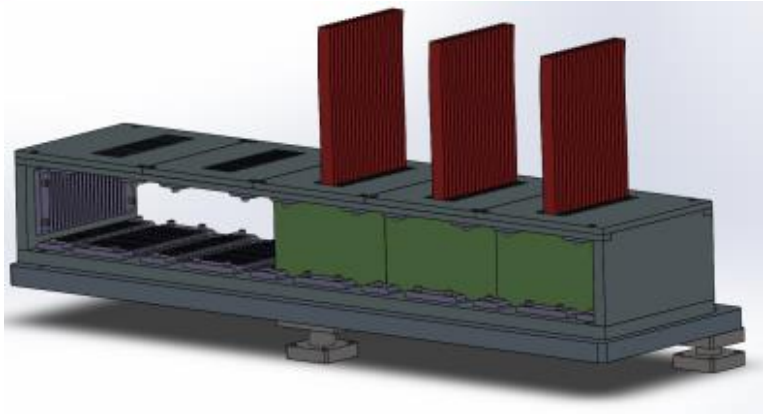


- Goal: Detection of electrons, positrons and photon fluxes and measure their energy spectra;
- Particle fluxes vary between 10^{-2} and 10^{9} (in different locations) per laser shot!
- Use technologies adapted to respective fluxes of signal and background.

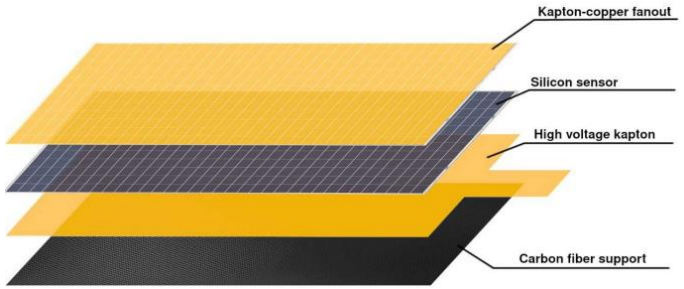


ECAL Calorimeter

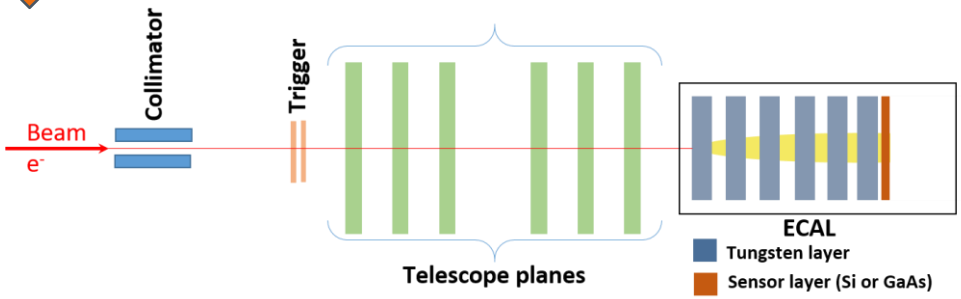


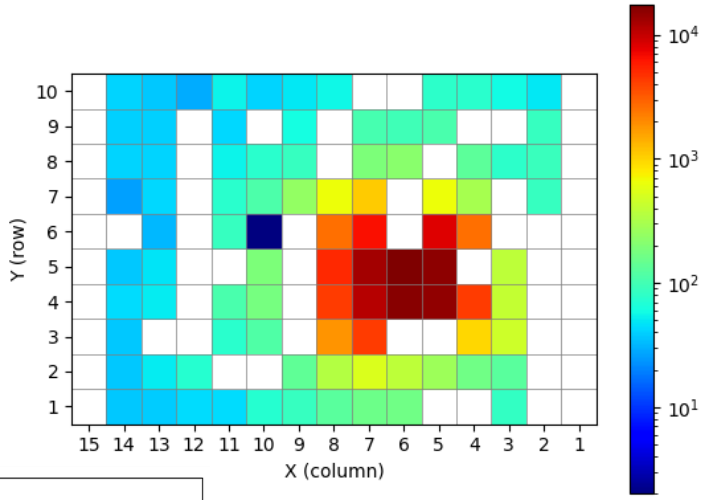


- High granularity calorimeter;
- Sampling calorimeter with 20 tungsten plates (3.5 mm thickness);
- Silicon or GaAs sensors (5x5 cm^2 pads) installed in 1 mm gap between absorbers;
- Small Moliére radius;
- Dedicated readout based on FLAME ASIC (developed for FCAL).



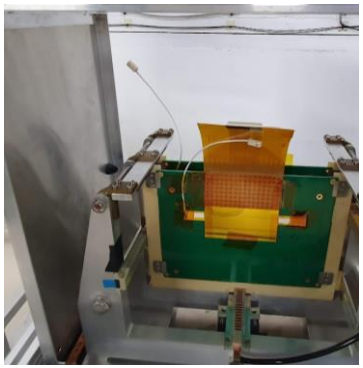
ECAL – 1st beamtest @ DESYII

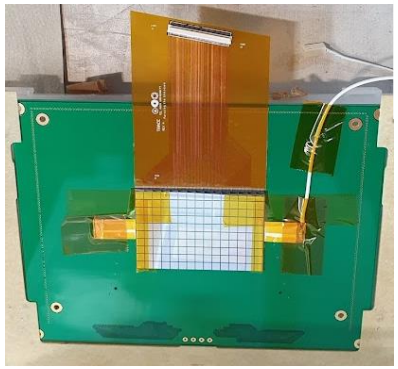


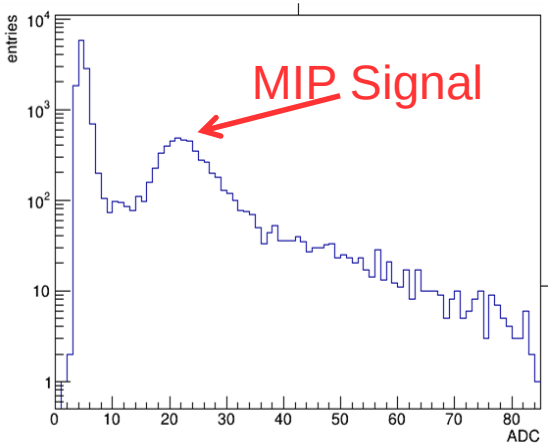


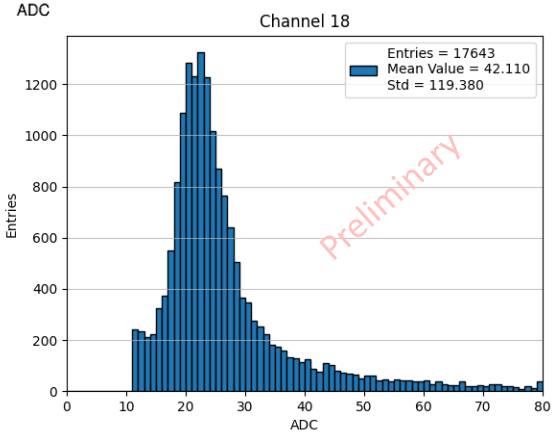
Test beam infrastructure @ DESY-II:

- **Electron** beam **1 - 5 GeV energy**;
- **ALPIDE telescope planes**;
- **DUT (ECAL calorimeter)**:
  - Sub-millimeter ECAL detector module;
  - Si sensors (320μm thick);
  - GaAs sensors (500μm thick) with traces;
  - FLAME ASIC;









Conclusions and Future Steps

- Very forward calorimeter prototype developed by **FCAL Collaboration** can be operated as a system in future e^+e^- collider.
- Thin LumiCal detector plane with submillimeter thickness was developed and produced. Its geometry leading to a highly compact design.
- Technologies developed in FCAL are applied in other experiments, e.g. CMS, XFEL and considered for LUXE at DESY.
- The LUXE experiment will explore strong-field QED using European XFEL and high power laser.
- The calorimeter is designed to measure the number of positrons per bunch crossing in a wide range;
- Parasitically: search for BSM physics (axion-like particles (ALPs) or milli-charged particles (mCPs) produced in dump).
- Installation is foreseen in 2024 during the extended shutdown of the European XFEL.
- Data taking phase 0 from 2024 and 2025, phase 1 will start in 2026.

FCAL Collaboration
High precision design

LUXE
LASER Und XFEL Experiment

THANK YOU FOR YOUR ATTENTION

Backup

Architecture of **Fca**L **A**sic for **M**ultiplane r**E**adout:

- ✓ Designed in CMOS 130nm;
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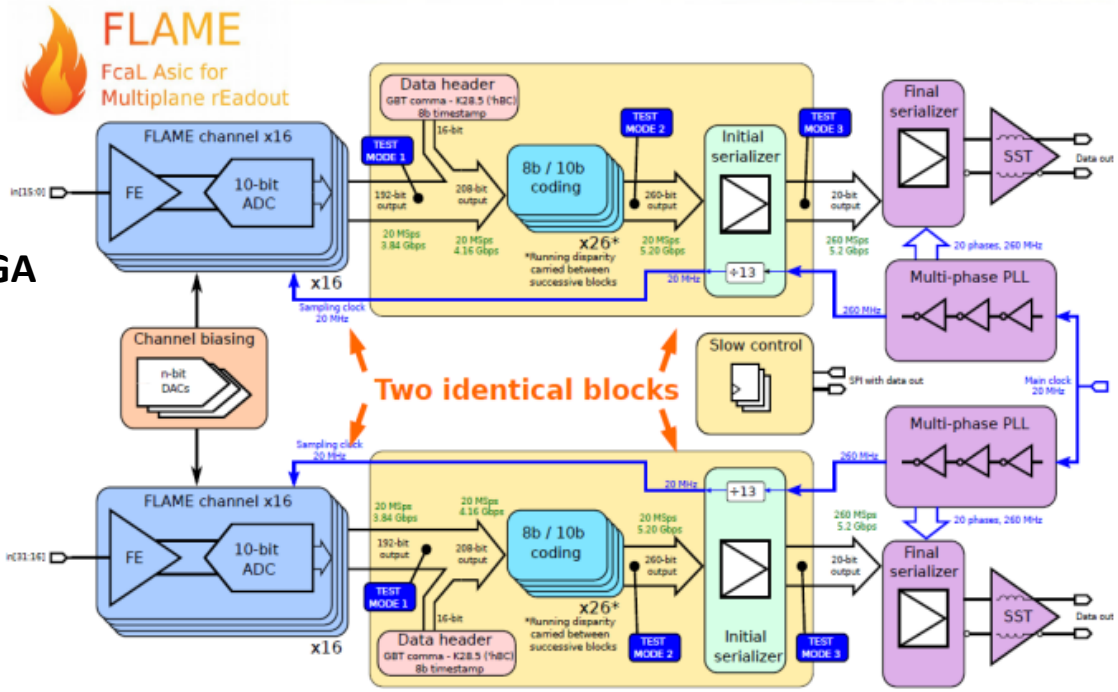

Analog front-end:

- ✓ Charge sensitive preamplifier with variable gain from 4fC (1 MIP) up to 6pC;
- ✓ Different CR-RC shaper – for simple amplitude and time deconvolution;
- ✓ Power consumption ~1mW.

10-bit SAR ADC:

- ✓ Sampling rate 20MS/s (Max 50MS/s);
- ✓ ENOB > 9.5;
- ✓ DNL, INL < 0.5 LSB;
- ✓ Ultra low power consumption (0.5mW/ch @ 20MS/s).

Serializer & driver:

- ✓ PLL generates 260MHz clocks from 20 MHz reference (x13);
- ✓ 5.2 Gb/s output data rate.