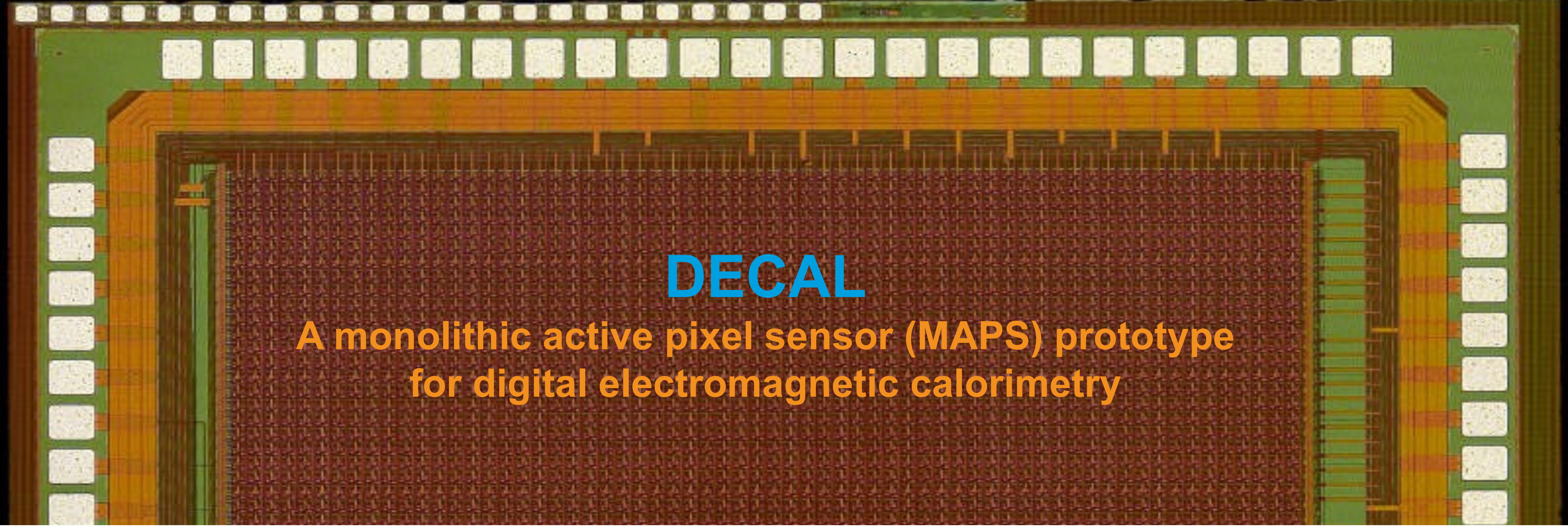


DECAL

A monolithic active pixel sensor (MAPS) prototype for digital electromagnetic calorimetry

Lucian Fasselt
Berlin, 12 June 2023
DESY Zeuthen Particle Physics Mini-Retreat

Deutsches Elektronen-Synchrotron DESY, Zeuthen, Germany
Humboldt University, Berlin, Germany

In collaboration with Rutherford Appleton Laboratory, University of Birmingham and University College London, UK

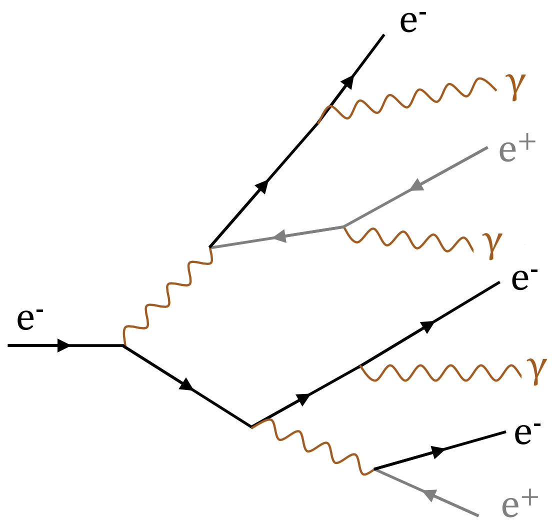
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

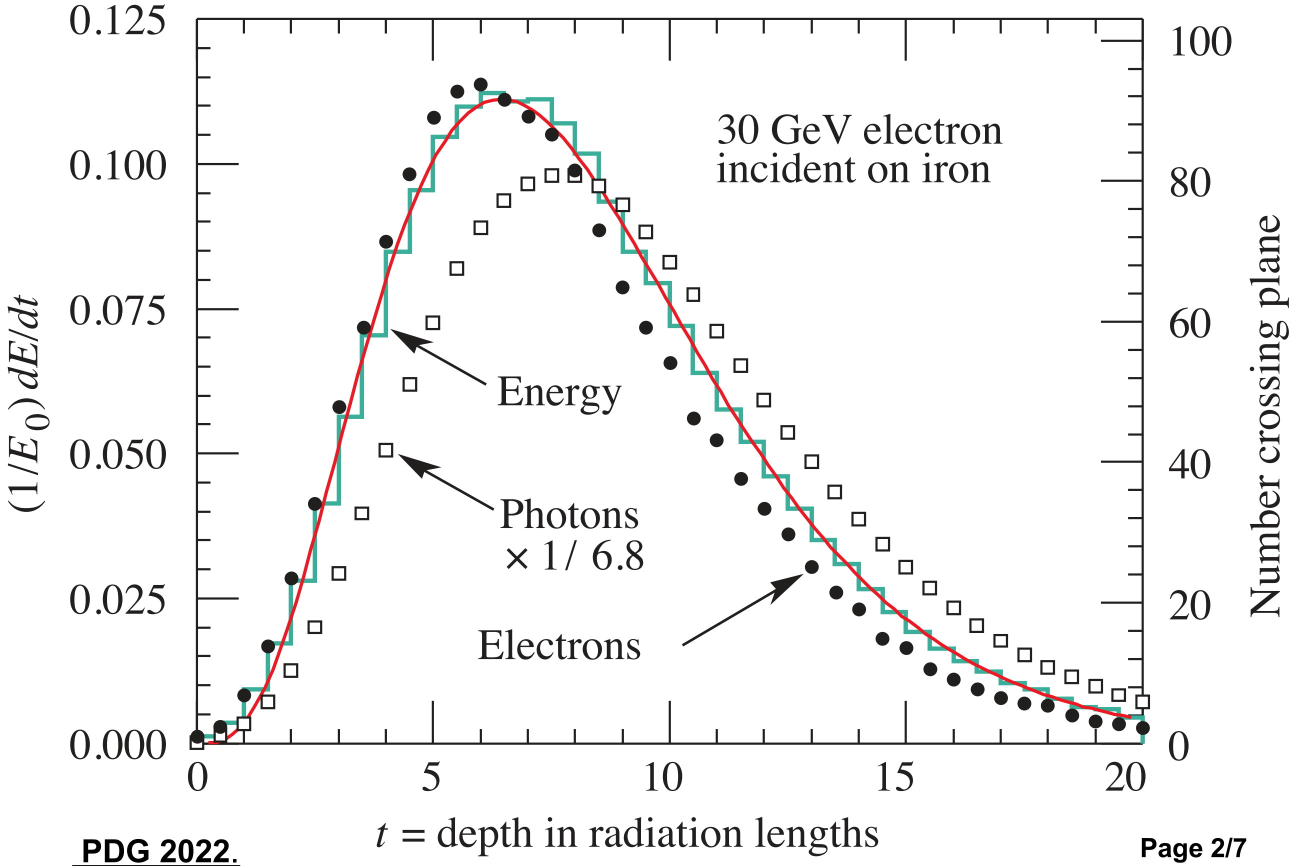
Digital calorimetry (Concept)

- **Analogue**: Summing energy deposits, which fluctuate, following a Landau-distribution
- **Digital**: Counting hits of shower particles

- **Figure:** Simulation of electron-induced cascade in iron.
  Left scale: Energy deposition per radiation length (analogue concept)
  Right scale: Number of electrons and photons with E≥1.5 MeV (digital concept)

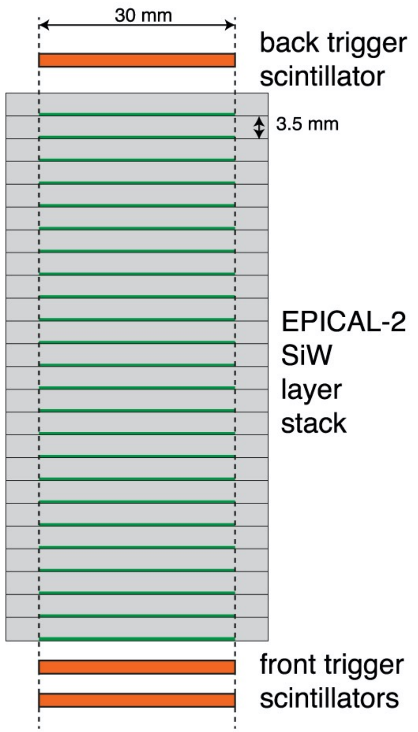
- Technological requirements:
  - High granularity to avoid saturation
  - Fast readout (40 MHz)
  - Radiation hard

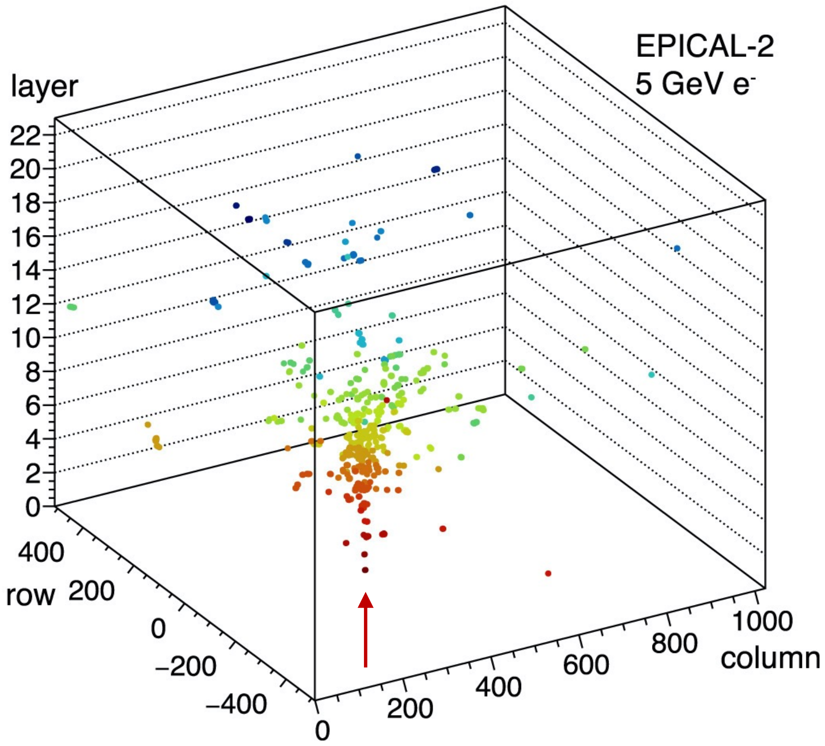


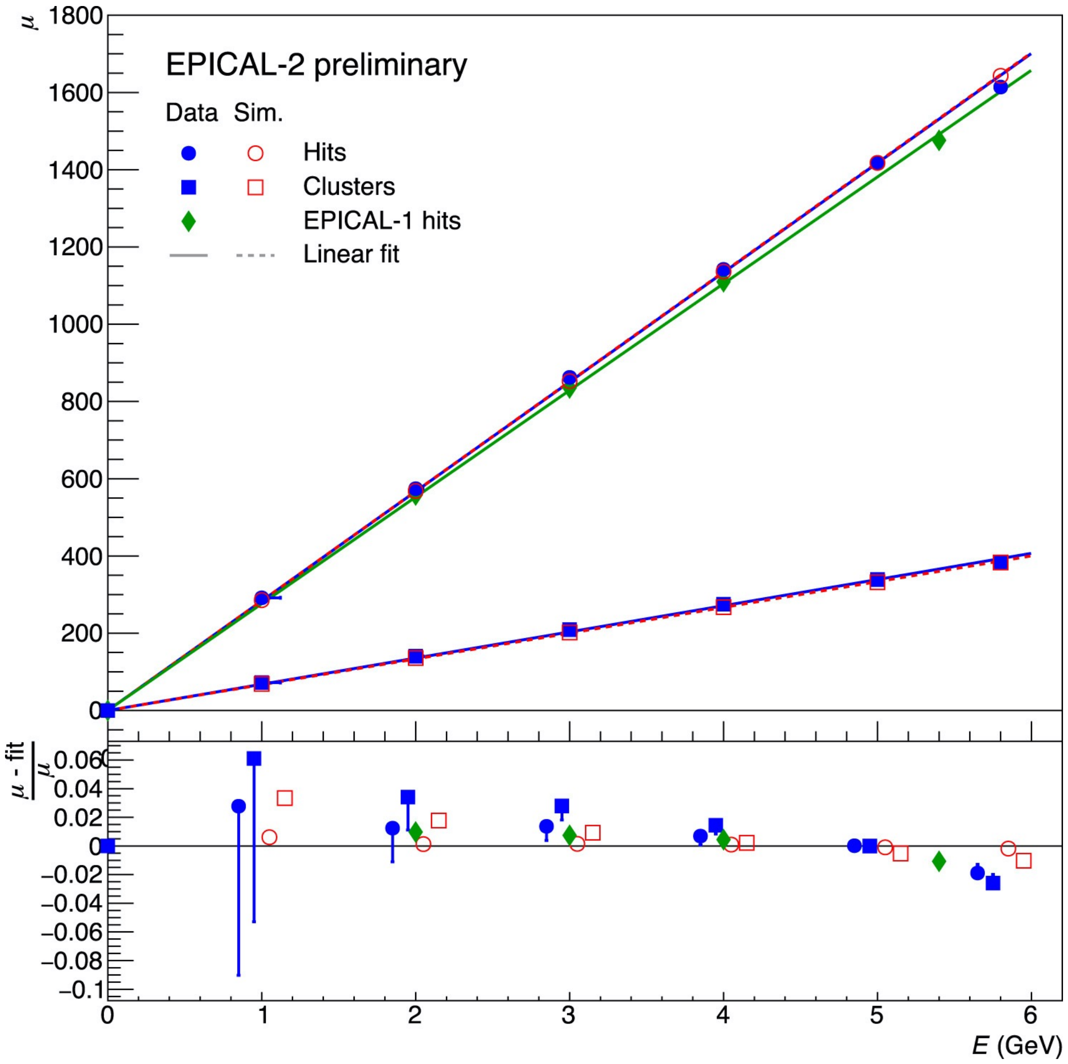


PDG 2022.

Digital calorimeter (example from EPICAL-2)





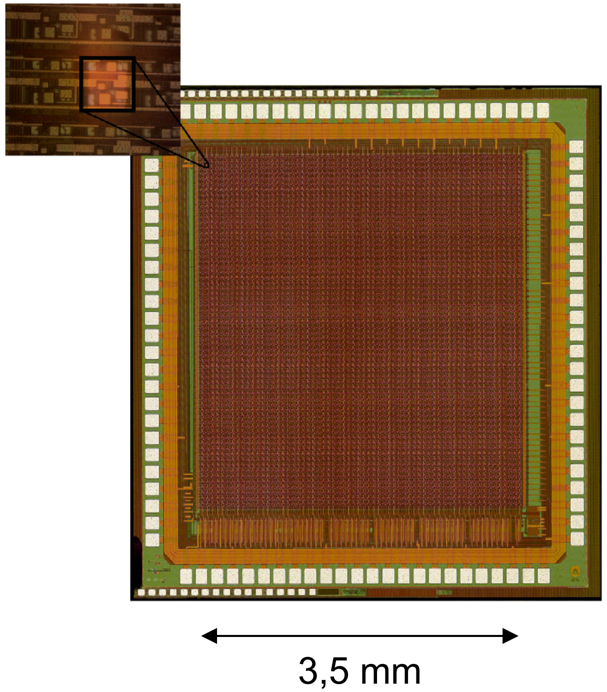


- Active Si pixel layers / W absorber
- Count hits or clusters
- High-granularity
  - Good shower separation of incident particles
  - Shower/ jet substructure
  - Benefitial for particle flow algorithms
- Saturation → Unlinearity at large energies
- Integration time ~ 600 μs → too slow for p-p @ LHC

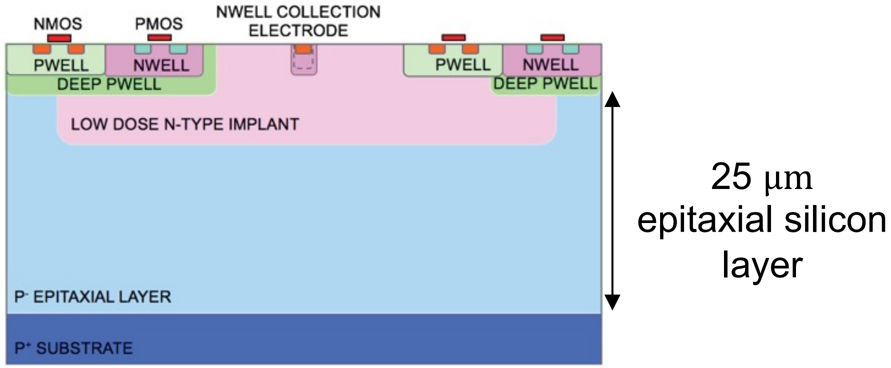
T. Peitzmann, et al. Results from the EPICAL-2 ultra-high granularity electromagnetic calorimeter prototype, Nucl. Instrum. Methods A 1045 (2023)

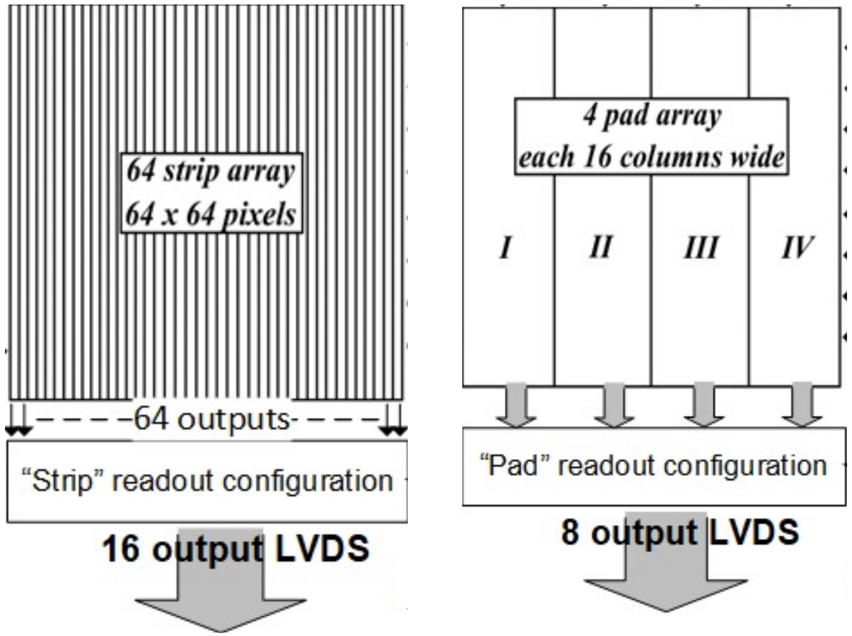
The DECAL sensor

A monolithic active pixel sensor prototype



- 40 MHz readout
- 55×55 μm^2 pixel in a 64×64 pixel matrix
- Fabricated in the Tower 180 nm CMOS optical process
- Low bias voltage of 3 V
- Reconfigurable digital readout logic as:
  - 1x64 pixel strips for tracking
  - 16x64 pixel pads for calorimetry
- One pixel with analogue readout in top left corner





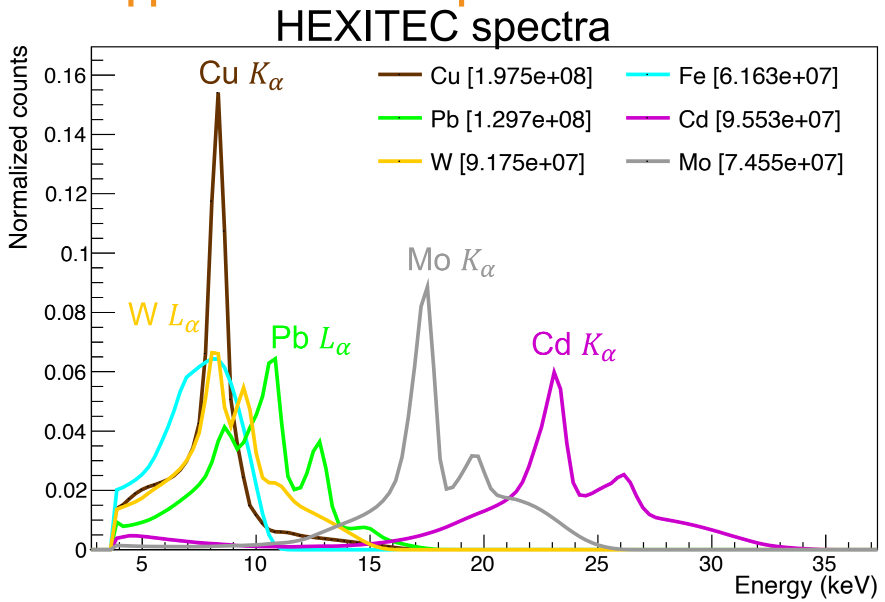
- Max 3 hits/strip
- Higher granularity for tracking

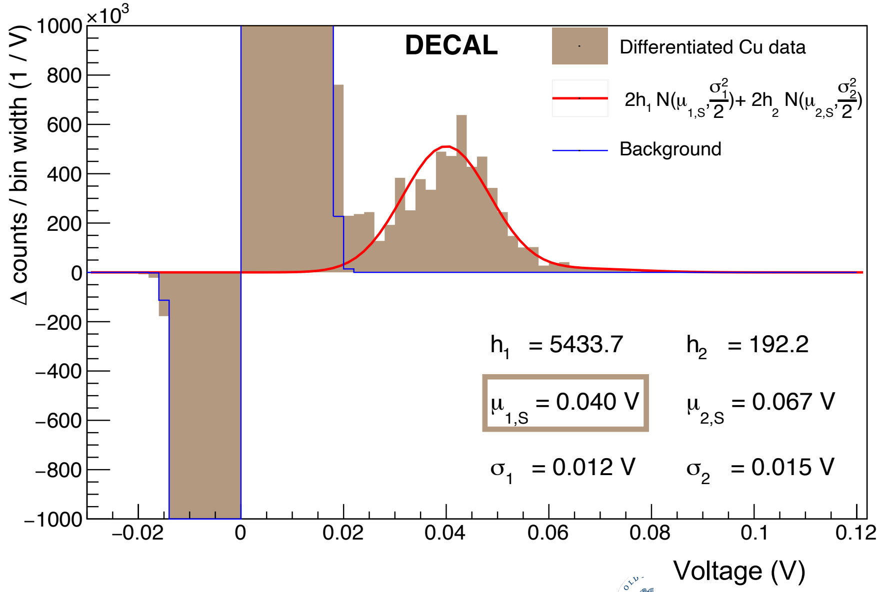
- Max 15 hits/strip
- 240 hits/pad
- More counts per strip while maintaining lower data rate for calorimetry

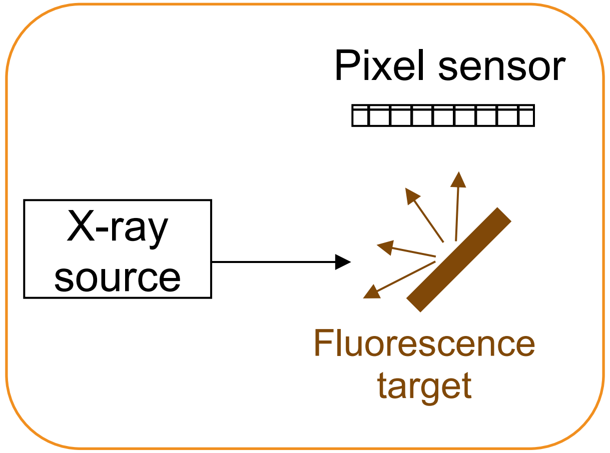
DECAL: A Reconfigurable Monolithic Active Pixel Sensor for use in Calorimetry and Tracking
Seddik Benhammadi et al., *TWEPP 2019*

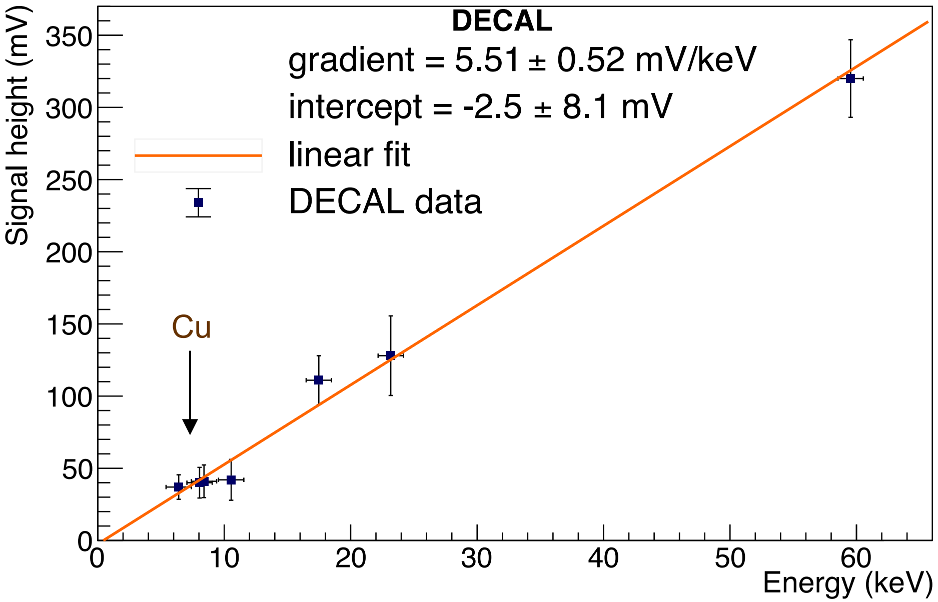
DECAL X-ray measurement

Copper fluorescence peak at 8.05 keV









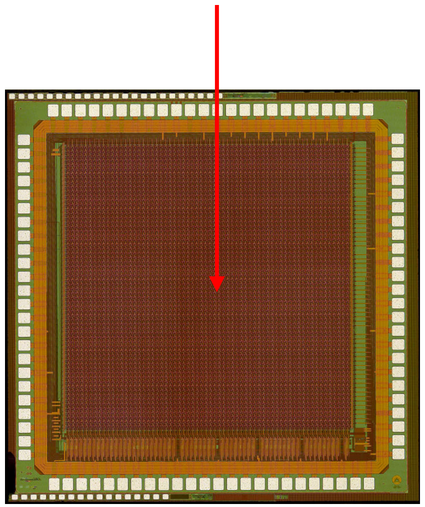
Identification of signal height μ_S and Cu K_α energy of 8.05 keV

- Signal height per photon energy is compatible with linear model: $m = 5.51 \pm 0.52\ \mathrm{mV/keV}$
- Minimum-ionizing-particle (MIP) deposits $237\,\frac{\mathrm{eV}}{\mu\mathrm{m}}$. In 25 μm silicon that corresponds to 5.9 keV → Signal height of 32.8 mV

Characterization of the DECAL sensor, Master thesis, Fasselt L. (2023)

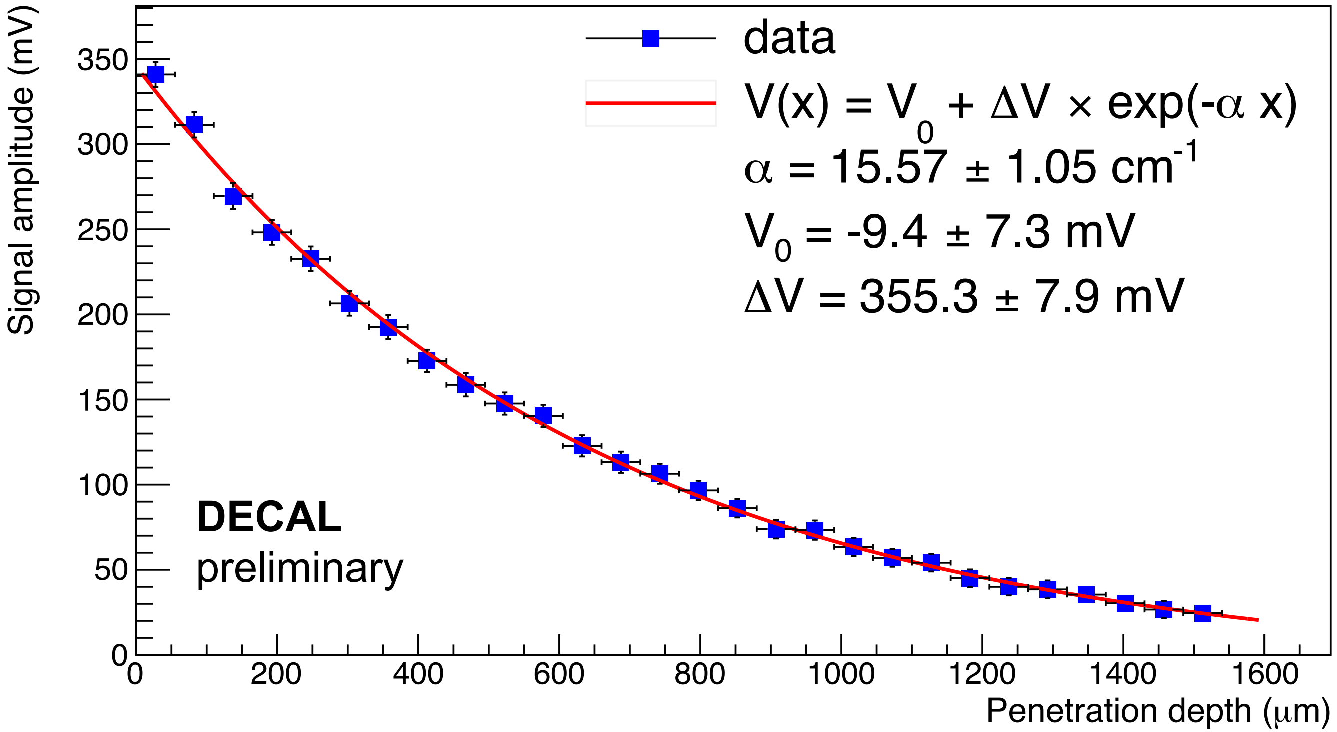
Edge illumination

1064 nm laser penetrates ~1000 μm of silicon



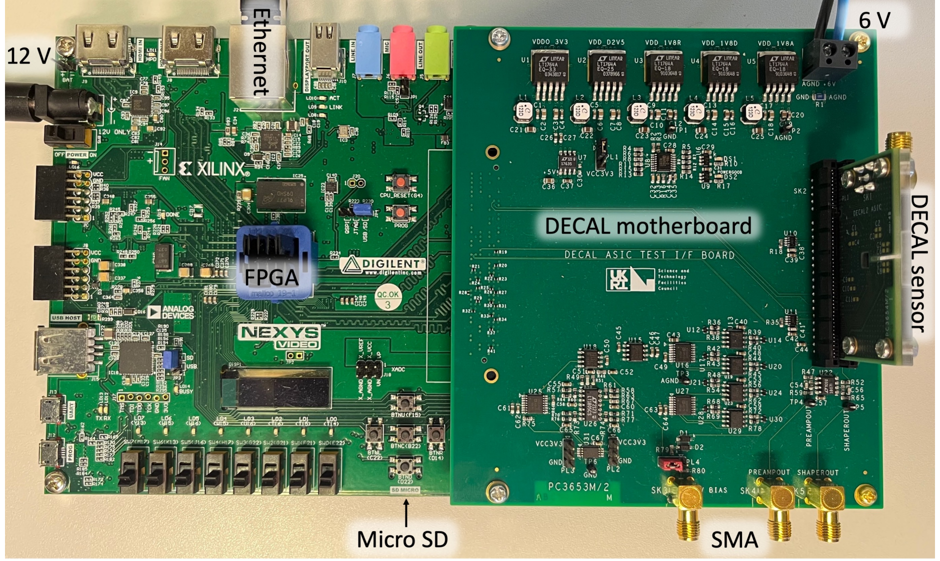
Exponential decay of light intensity

Signal amplitude at different depths in silicon

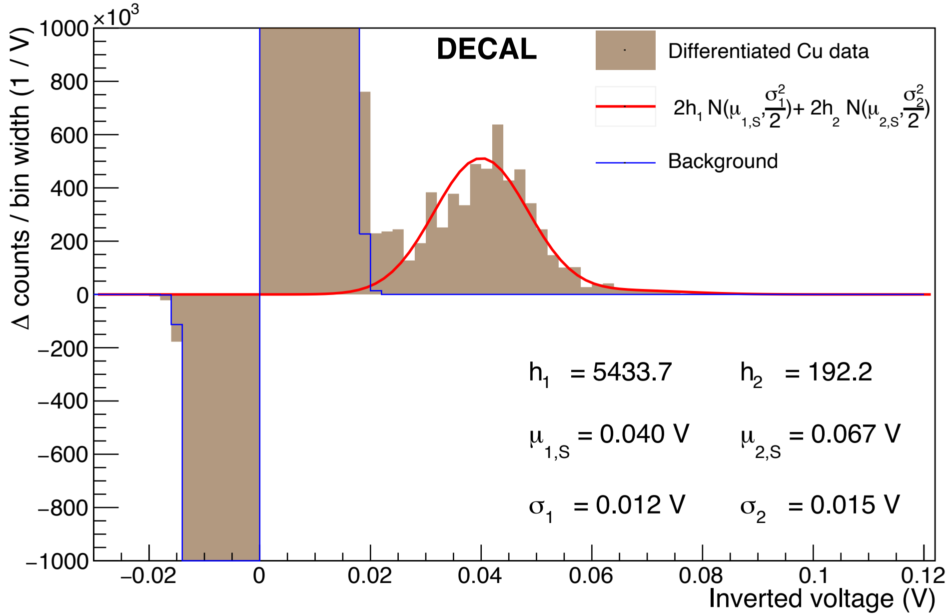


Summary and outlook

- 3 DECAL setups for sensor testing
- Fruitful knowledge transfer with UK institutes



Sensor testing
- Understanding X-ray absorption
  →Linear dependence of signal height in photon energy range of 4 to 60 keV
- Infrared laser for edge TCT



New sensor design aims towards multi-layered calorimeter prototype
- Simulation studies on single pixel performance (TCAD, Allpix^2)
- Simulation of digital calorimeter prototype (Geant4)

Commonalities with other Zeuthen groups

In collaboration with:

P. Allport[1], S. Benhammadi[2], R. Bosley[1], J. Dopke[2], S. Flynn[1], N. Guerini[2], L. Gonella[1], I. Kopsalis[1], K. Nikolopoulos[1], P. Philips[2], T. Price[1], A. Scott[2], I. Sedgwick[2], E. G. Villani[2], M. Warren[3], N. Watson[1], F. F. Wilson[2], A. Winter[1], Z. Zhang[2]

[1] School of Physics and Astronomy, University of Birmingham, UK
[2] STFC Rutherford Appleton laboratory, Didcot, UK
[3] Department of Physics and Astronomy, University College London, UK

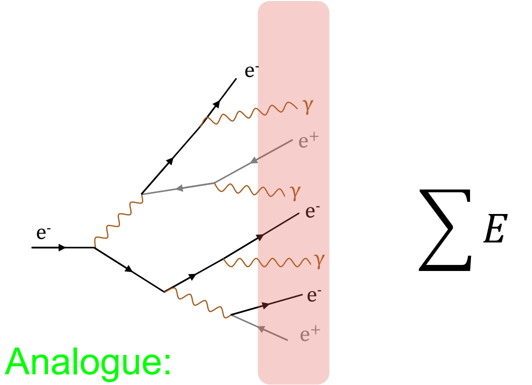
Publications and talks

- *First tests of a reconfigurable depleted MAPS sensor for digital electromagnetic calorimetry*, Nucl. Inst. and Meth. A (2020), doi: 10.1016/j.nima.2019.162654
- *A reconfigurable CMOS sensor for tracking, pre-shower and digital electromagnetic calorimetry,* Nucl. Inst. and Meth. A (2020), doi: 10.1016/j.nima.2020.164459
- *Evaluation of the DECAL Fully Depleted monolithic sensor for outer tracking and digital calorimetry,* Nucl. Inst. and Meth. A (2022), doi: 10.1016/j.nima.2022.166955
- *DECAL: A Reconfigurable Monolithic Active Pixel Sensor for Tracking and Calorimetry in a 180 nm Image Sensor Process*, Sensors 2022 MDPI, doi: 10.3390/s22186848
- *Characterization of the DECAL sensor - a CMOS MAPS prototype for digital electromagnetic calorimetry and tracking,* Master thesis (2023), CDS 2852973
- *Energy calibration through X-ray absorption of the DECAL sensor, a monolithic active pixel sensor prototype for digital electromagnetic calorimetry and tracking,* Publication in progress (2023)

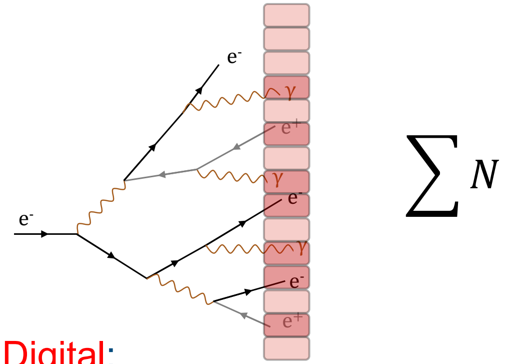
- *SiW ECAL Studies for FCC-hh and Their Implications for FCC-ee*, 3rd FCC Physics and Experiments Workshop, CERN (2020), P. Allport
- *A reconfigurable HR-CMOS sensor for Tracking, Pre-Shower and Digital Electromagnetic Calorimetry,* 36th RD50 Workshop, CERN (2020), I. Kopsalis
- *Towards a Reconfigurable CMOS Sensor suitable for Outer Tracking, Pre-shower and Digital EM Calorimetry at Future Facilities*, CERN Detector Seminar (2021), P. Allport
- *CMOS MAPS-based digital ECAL*, ILC Workshop LCWS2021, CERN (2021), F. Wilson
- *CMOS Monolithic Sensor for Calorimetry and Outer Tracking at Future Colliders*, CPAD Workshop 2021, Stony Brook NY, P. Freeman
- *Evaluation of the new version of the DECAL CMOS MAPS*, CALICE meeting (2021), I. Kopsalis
- *A reconfigurable CMOS sensor for digital EM calorimetry,* High-D Consortium Meeting (2022), https://indico.desy.de/event/33151/, L.Fasselt

Digital electromagnetic calorimeter (DECAL)

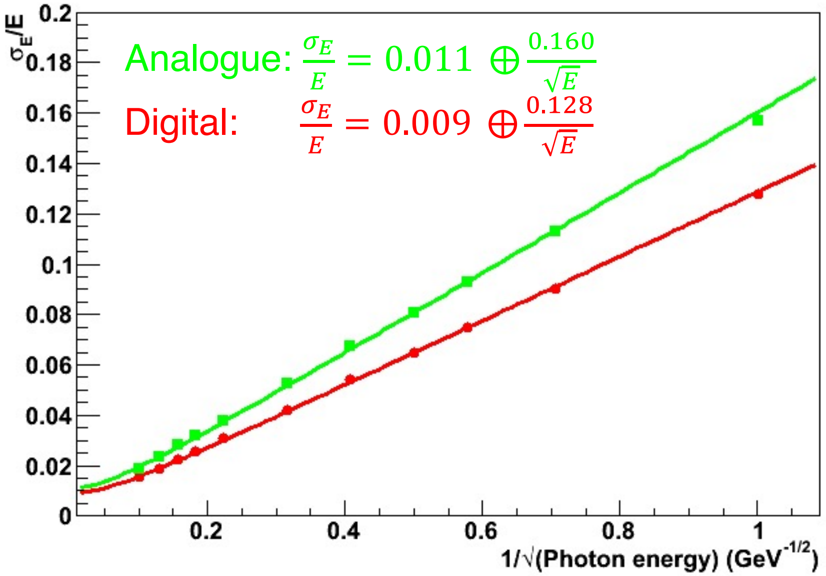
Comparison with conventional analogue ECAL



Analogue:
Sum deposited energy in each layer



Digital:
Sum number of particles in each layer



Simulated digital ECAL shows better σ_E/E than analogue one

- Deposited energy in detector fluctuates, following Landau-distribution
- Stochastic term reduced by 20% as landau fluctuation from energy deposition vanishes
- Technological requirements:
  - High granularity to avoid saturation
  - Fast readout (40 MHz)
  - Radiation hard
- On top: High granularity benefitial for particle flow algorithms and identification of pileup

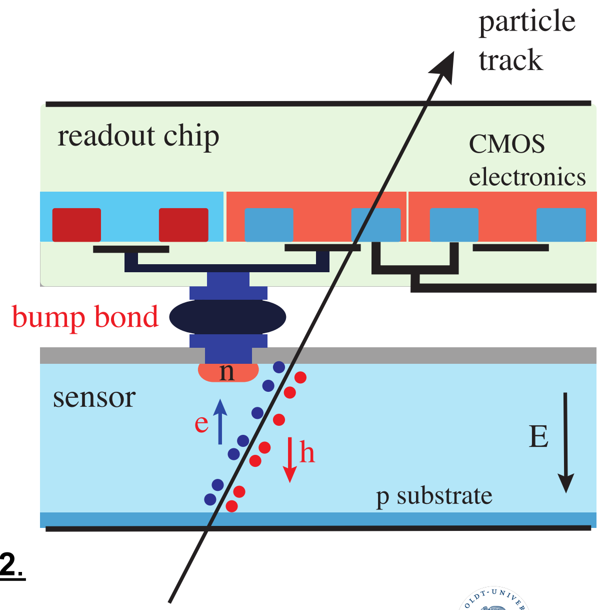
P. Dauncey et al. *Performance of CMOS sensors for a digital electromagnetic calorimeter,* ICHEP 2010.

Proposed technology for a DECAL

Silicon pixel sensors

Hybrid sensors

- Sensor and readout chip separated, connected by bump bonds
- State of the art in collider experiments for tracking
- Complex readout circuits possible
- Choice of sensing material not restricted to silicon
- Expensive bump bonding process

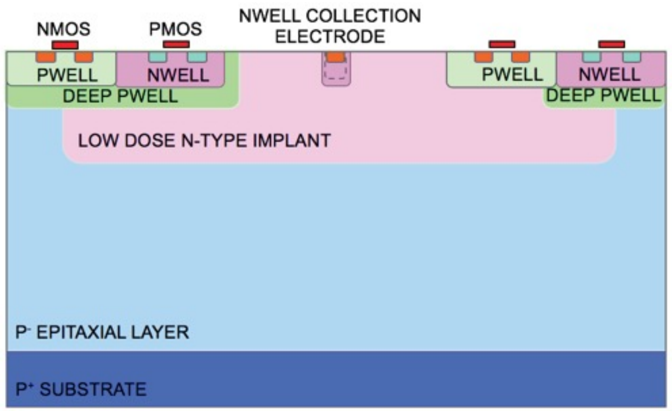


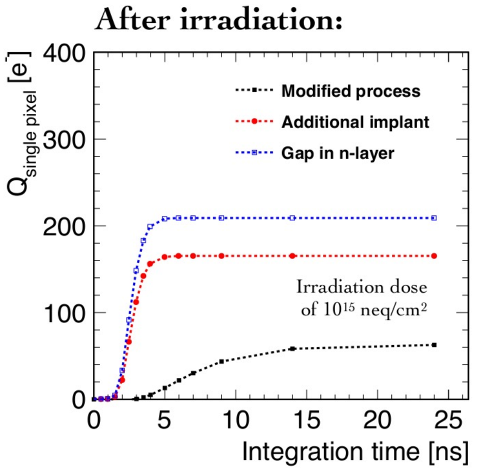
PDG 2022.

Monolithic active pixel sensors (MAPS)

- Sensor and readout circuit on same silicon substrate
- Lower costs expected as industry uses this CMOS technology
- Thin sensors → Lower material budget
- Lower power consumption
- Improvement in radiation tolerance > 10^{15} n_{eq}/cm^2

ALICE installed first MAPS Inner Tracker at LHC

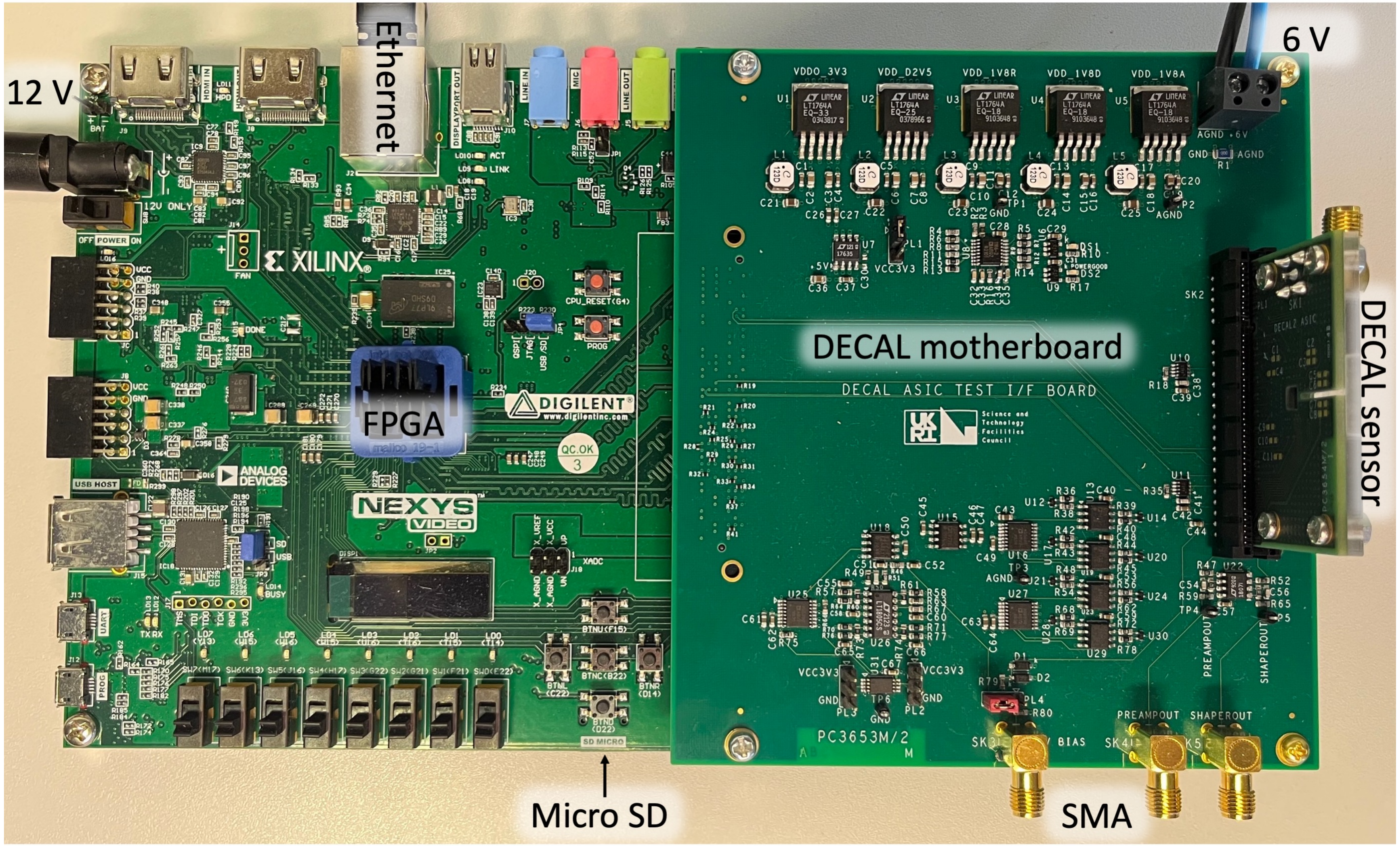


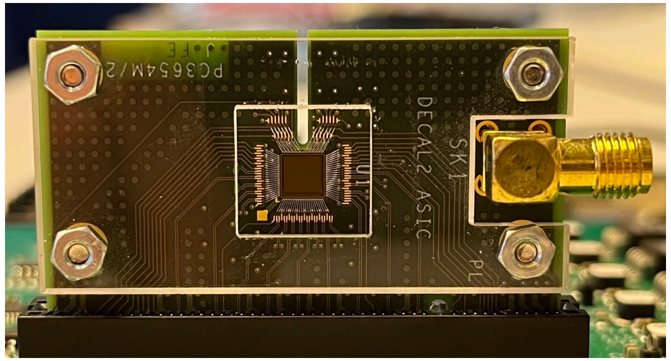


H. Pernegger, Depleted CMOS sensors for HL-LHC, VERTEX 2018

DECAL setup

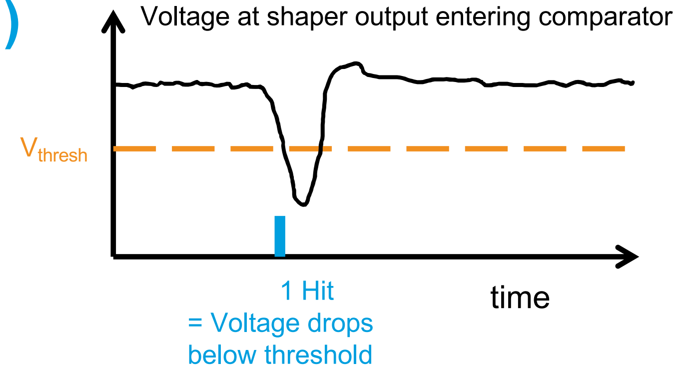
- 3 setups at the laboratory
- Motherboard produced at DESY Zeuthen
- Data acquisition via ATLAS ITSDAQ software
- 40 MHz readout
- Stable temperature
- Optimal current and voltage settings



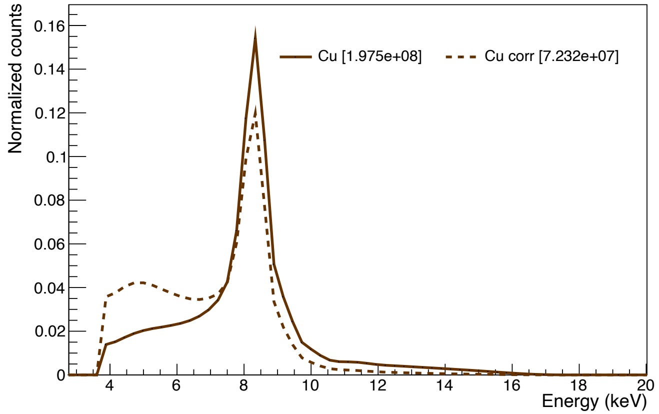


DECAL X-ray measurement (detail)

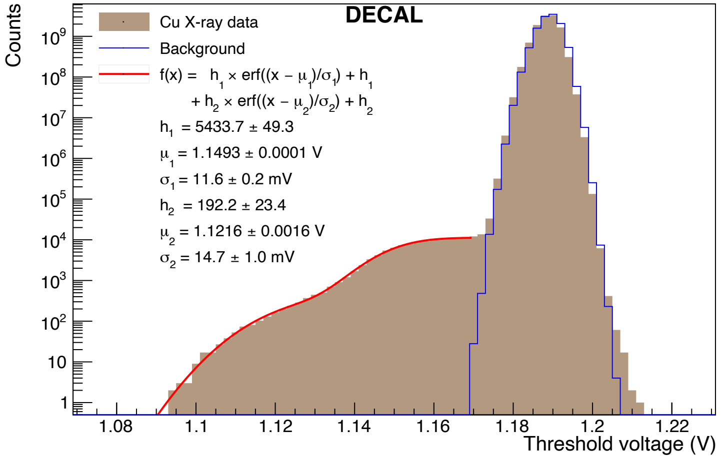
Copper fluorescence peak at 8.05 keV

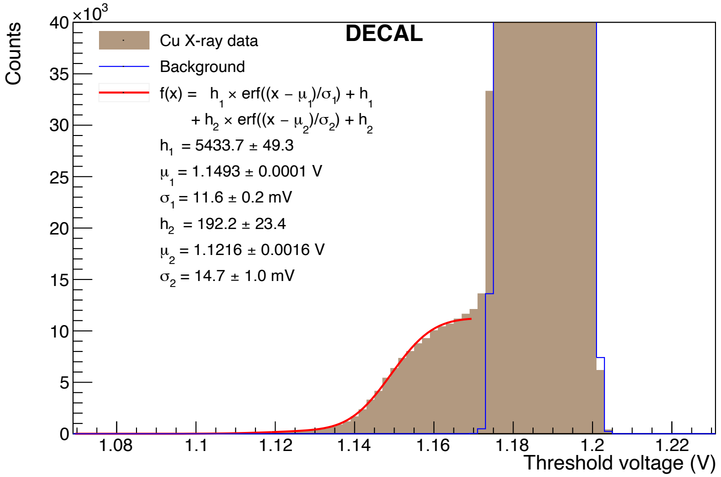


HEXITEC detector at RAL, UK



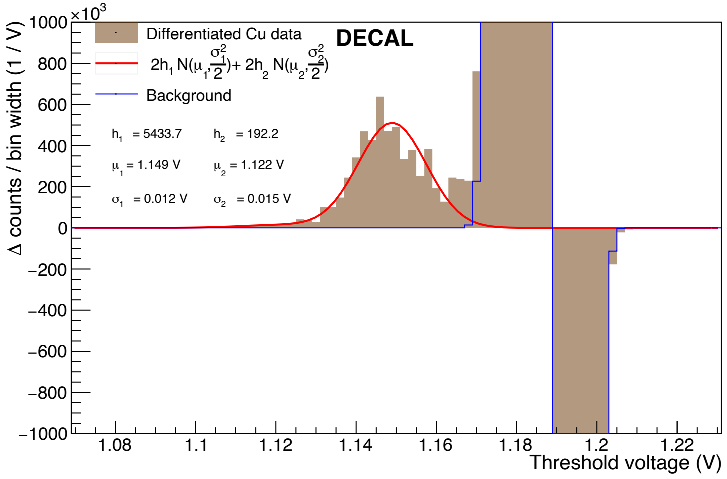
1) Error function fit to threshold scan on Log and Lin scale:



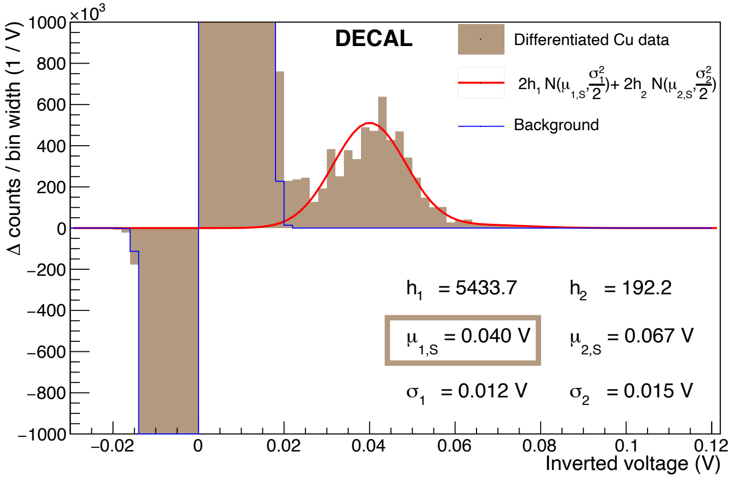


2) Translation from threshold scan to energy-like spectrum

- Numerical differentiation of data
- Analytical differentiation of fitted error function gives Gaussian



4) Identification of signal peak mean μ_S and Cu K_α energy of 8.05 keV



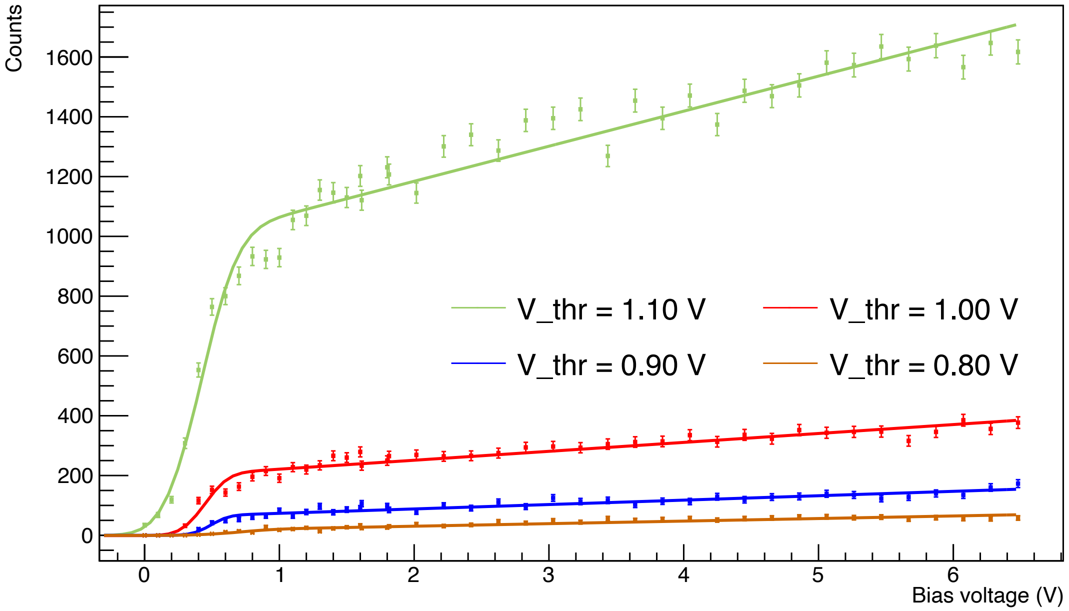
P. Allport et al., *DECAL: A Reconfigurable Monolithic Active Pixel Sensor for Tracking and Calorimetry in a 180 nm Image Sensor Process*, Sensors, 2022.
https://doi.org/10.3390/s22186848

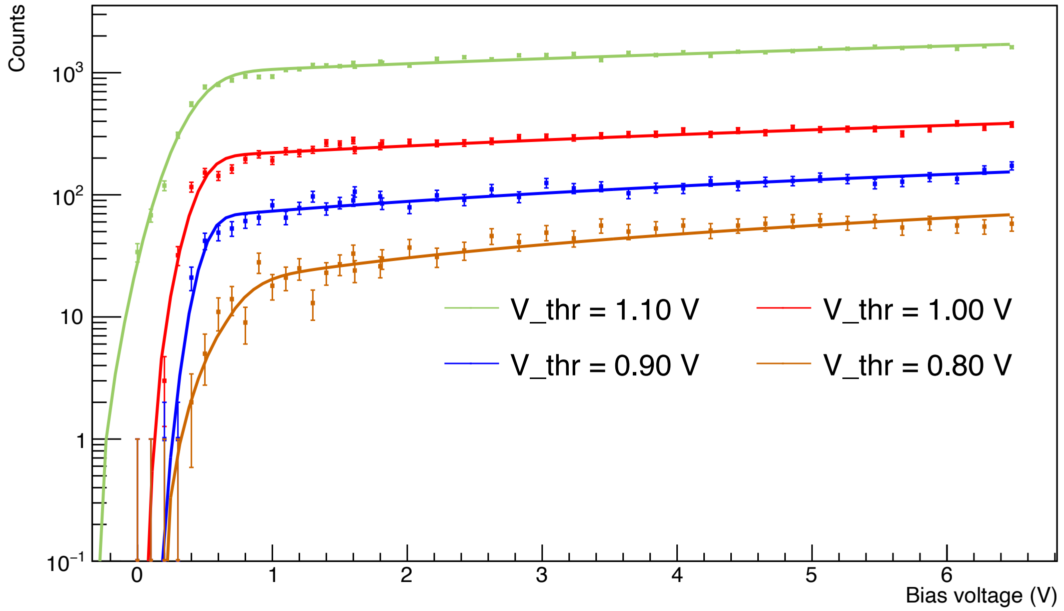
3) X-axis inversion and shifting mean of noise peak to origin

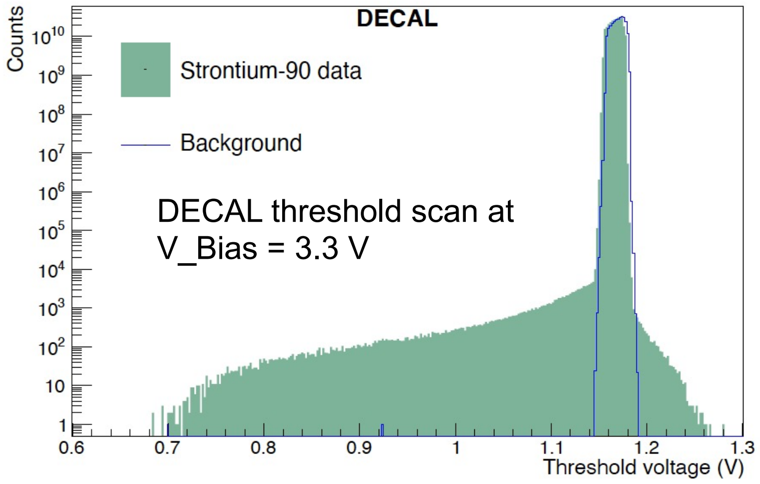
5) Do so for more targets (next slide)

Bias voltage variation with Sr-90 source

Linear and Log y-scale





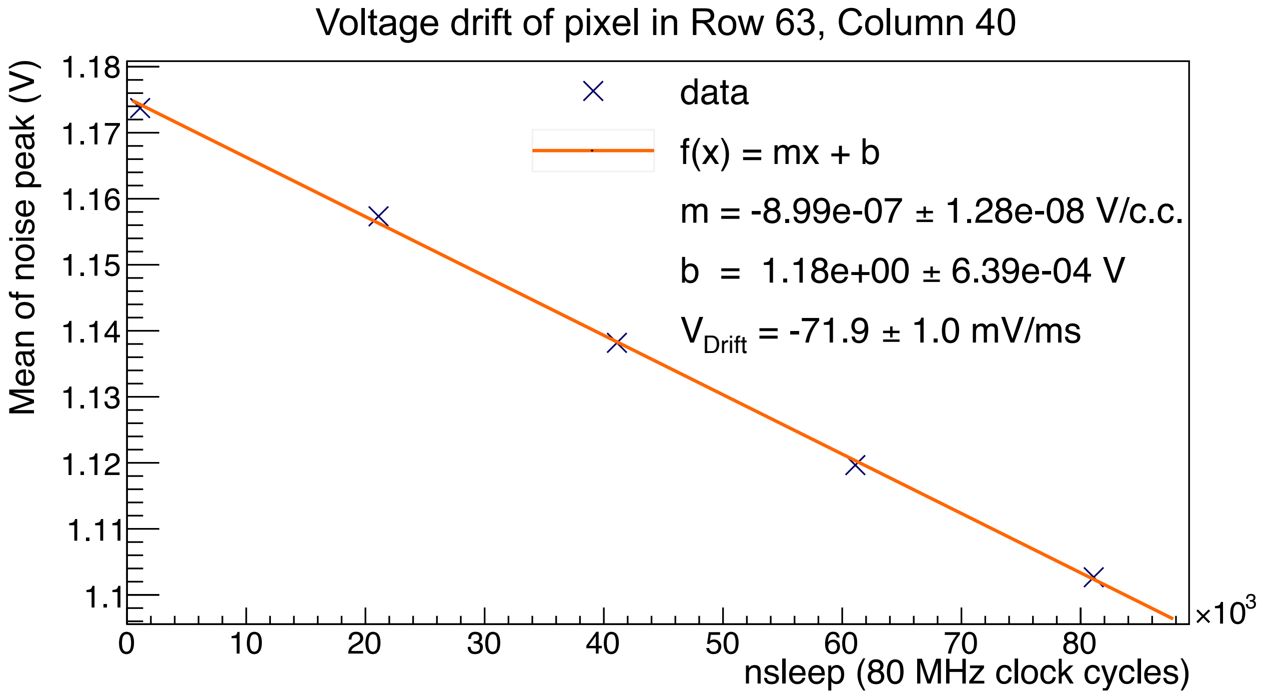


- Turn on around 0.5V
  - Model: Error-function + linear fit after turn on
- Approximately linear rise after turn on
- Noise peak is located at V_thr = 1.17 V (see spectrum at bottom left)
  - → V_thr = 1.10 V is close to the noise peak (corresponds to small signals)
  - → V_thr = 0.80 V is far away from noise peak (corresponds to large signals)

Problem 1: Voltage drift of each pixel

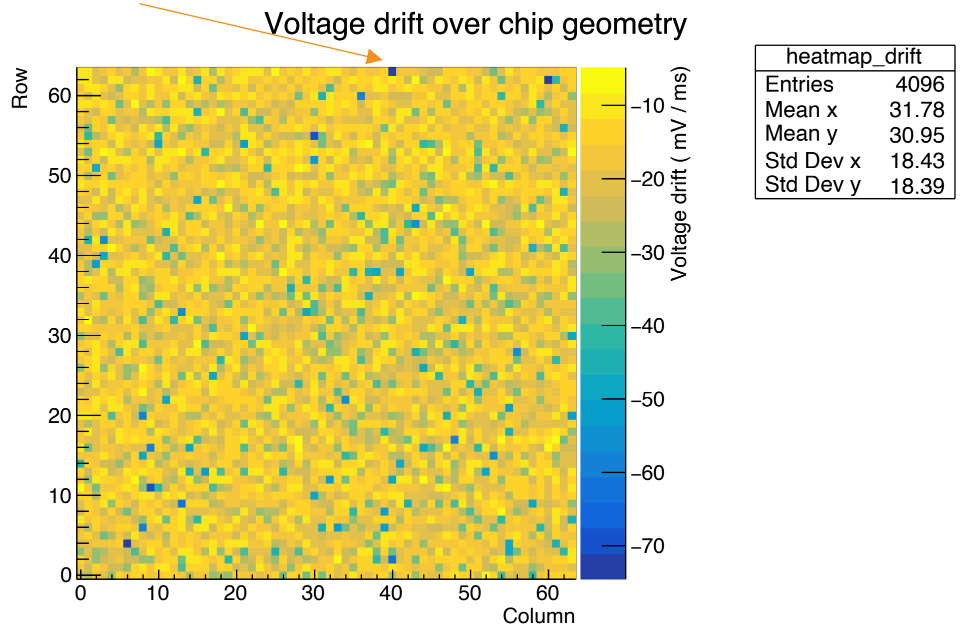
Voltage drift is determined for each pixel individually.

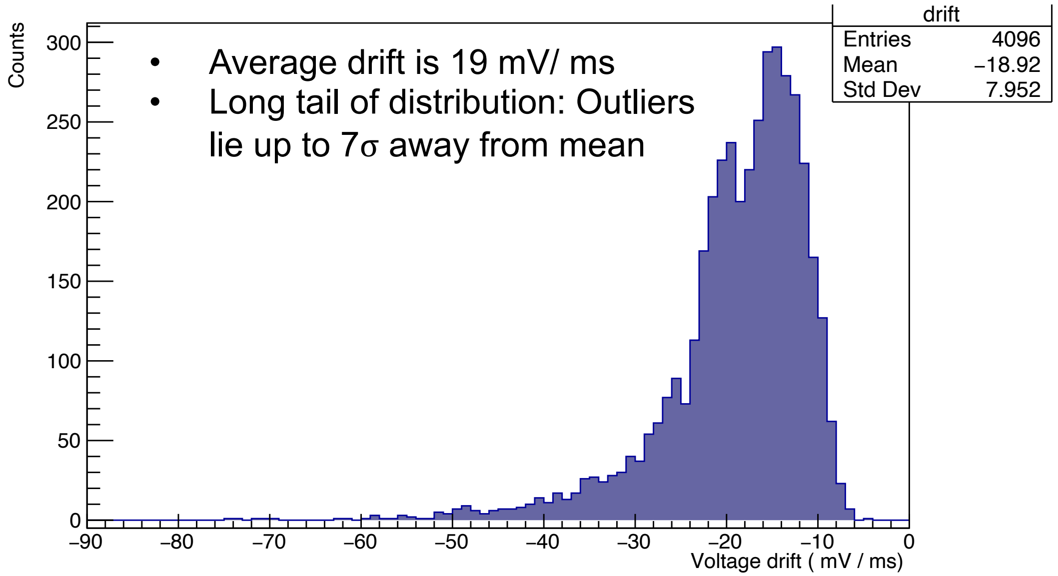
- Pixels are tuned to the same voltage baseline
- Wait "nsleep" clock cycles before capturing hits
- Pixelwise linear fit to data (example below)
- The gradient of the fit gives the voltage drift



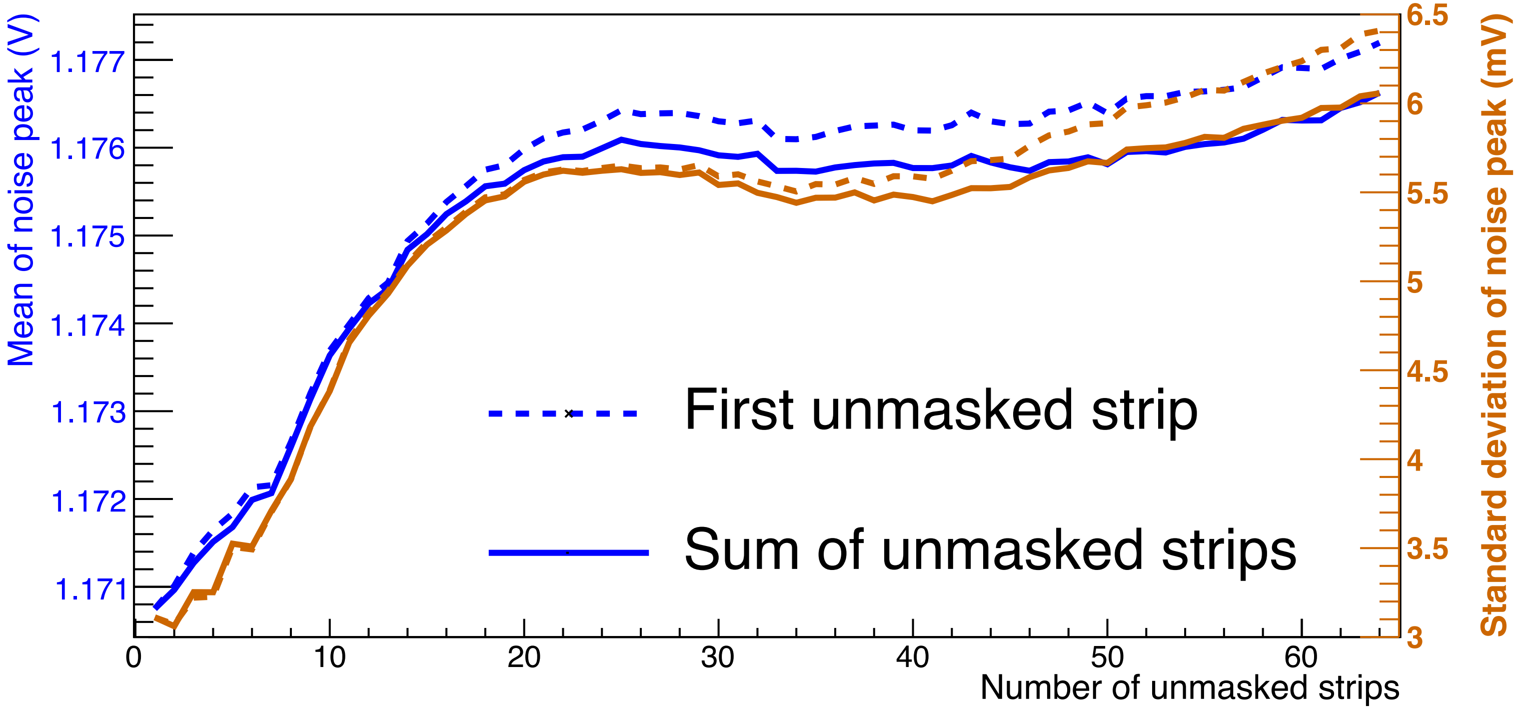
→ Voltage baseline drifts constantly with time

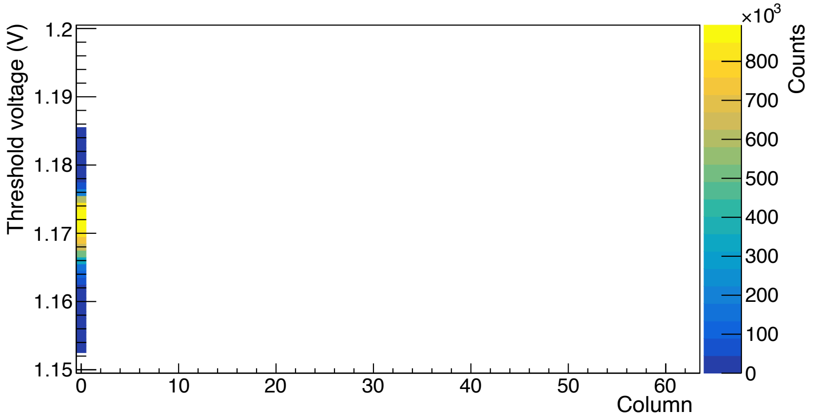
Example fit plotted of pixel with a large V_{drift}

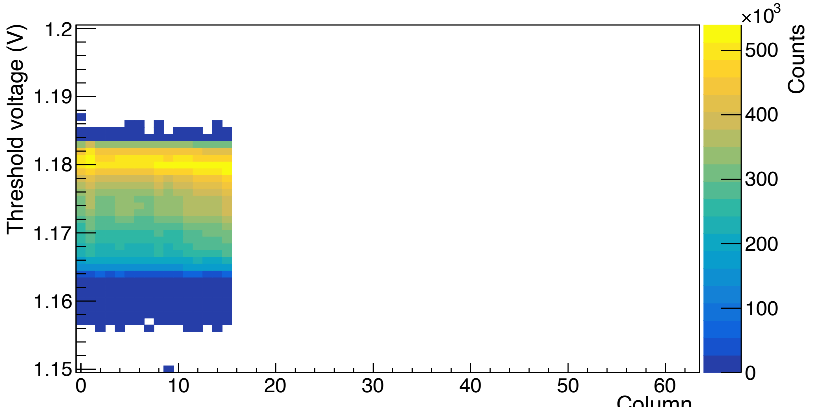


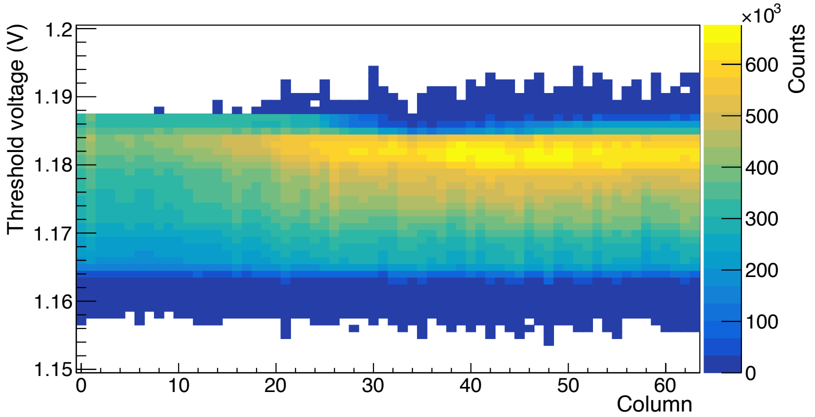


Problem 2: Noise peak broadening









More strips enabled → more baseline fluctuations in each pixel

Pixel schematics

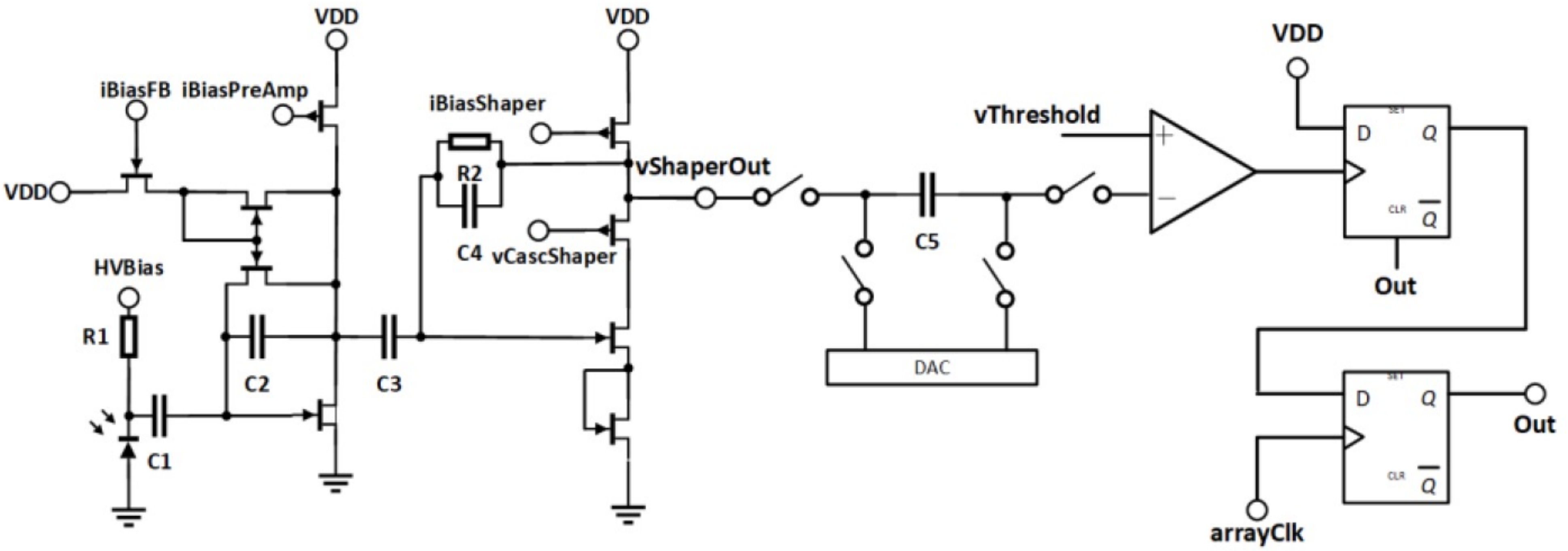
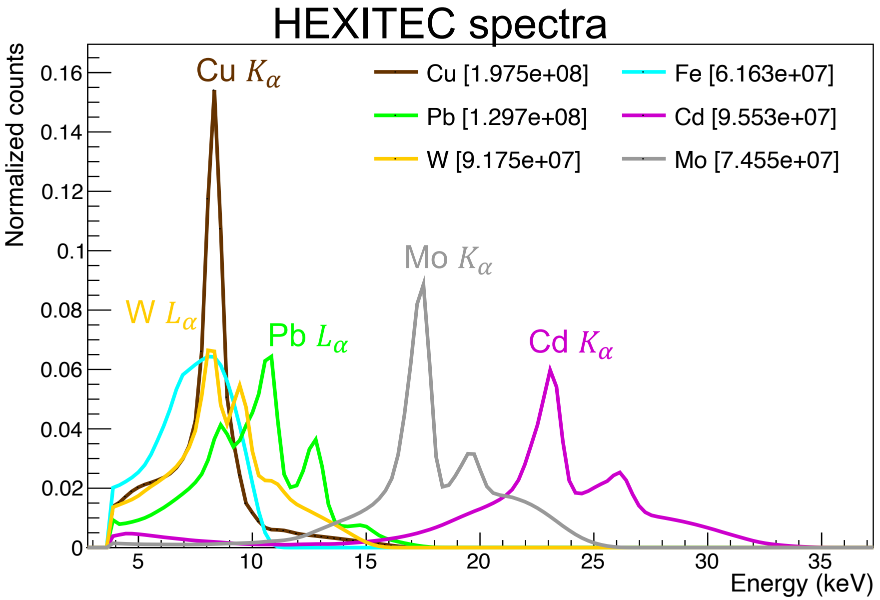


Figure 2 Overview of the architecture of the pixel.

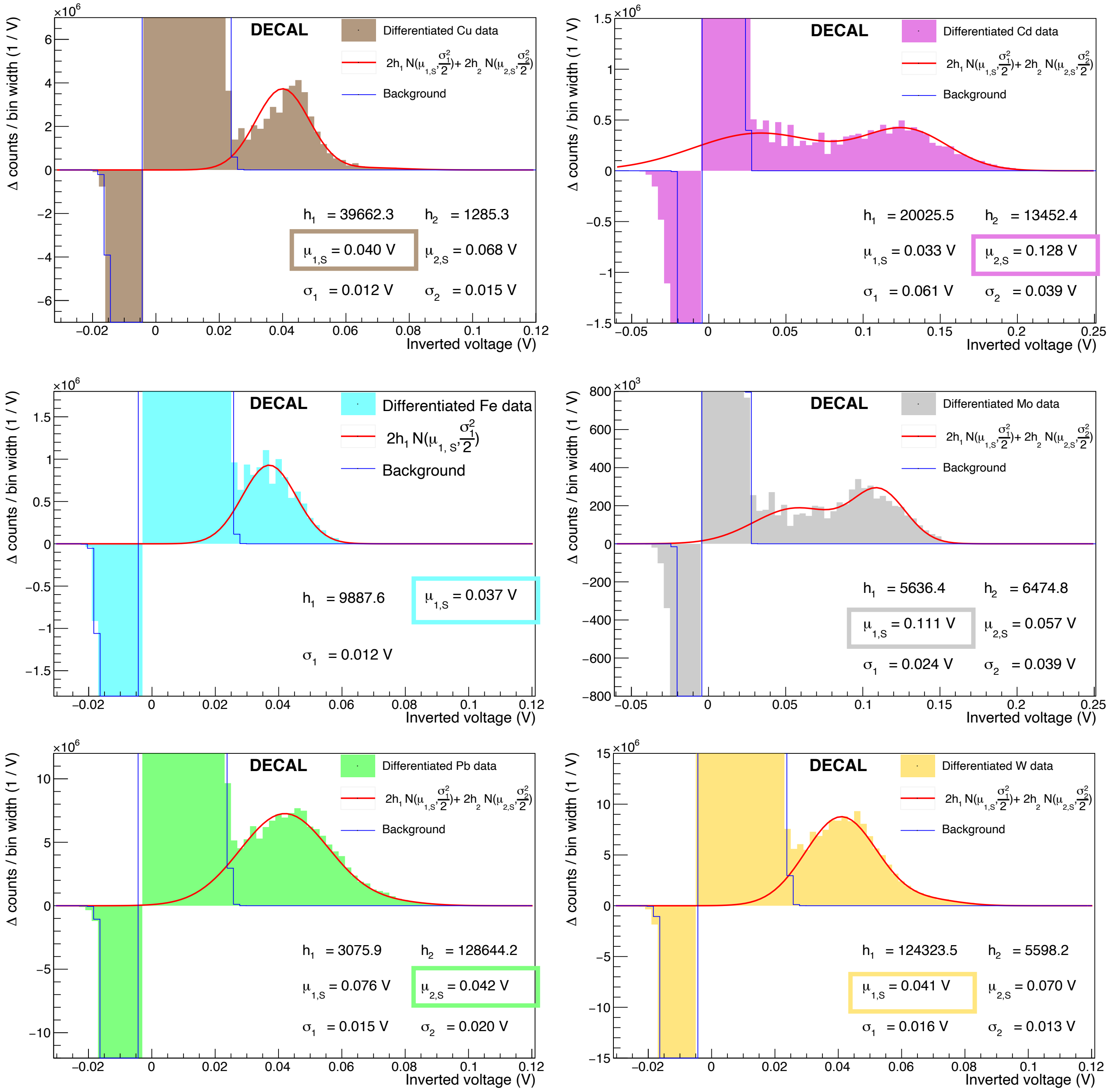
DECAL energy calibration

Method 1: Peak position comparison

- HEXITEC and DECAL scans for six X-ray fluorescence targets (Cu, Cd, Fe, Mo, Pb, W)
- Compare mean of main Gaussian peak in differentiated spectrum with K_α or L_α energy of target material.



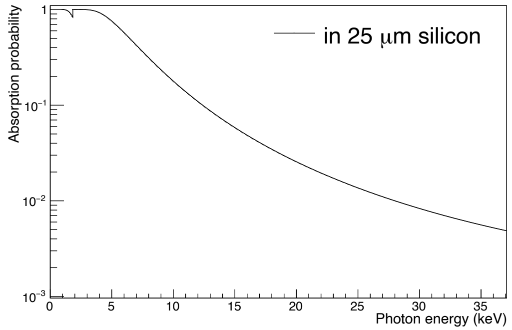
	Fe	Cu	W	Pb	Mo	Cd	Am
Peak energy (keV)	K_α: 6.40	K_α: 8.05	L_α: 8.40	L_α: 10.55	K_α: 17.48	K_α: 23.17	Decay: 59.54
μ_S of DECAL peak (mV)	37	40	41	42	111	128	320



Advanced DECAL energy calibration

Method 2: Fitting corrected and smeared HEXITEC spectra

$$p_{\text{absorption}}(x) = 1 - e^{-x\,\mu/\rho}$$

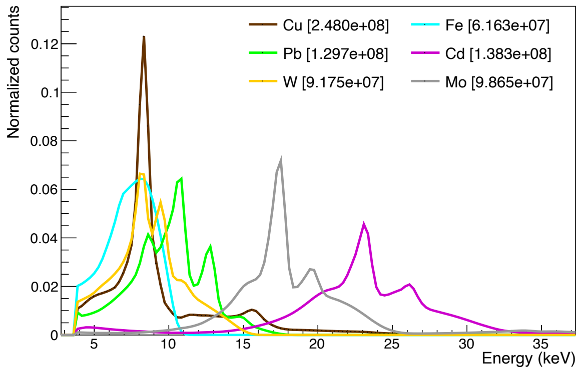


Attenuation coefficients from:
NIST Standard Reference Database
https://dx.doi.org/10.18434/T4D01F

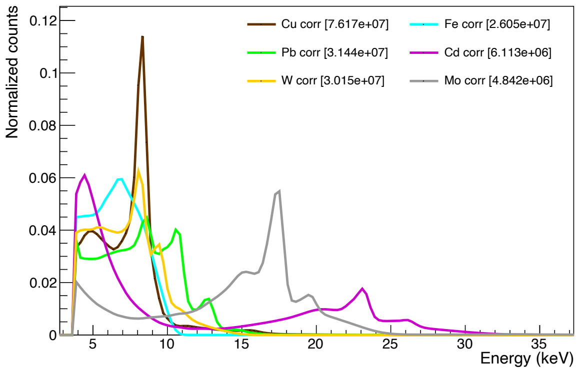
Idea to use whole spectral data rather than peaks only

1. HEXITEC pixels absorb all photons (1 mm CdTe) so spectra have to be corrected for absorption probabilities for DECAL (25 μm Si).

uncorrected HEXITEC



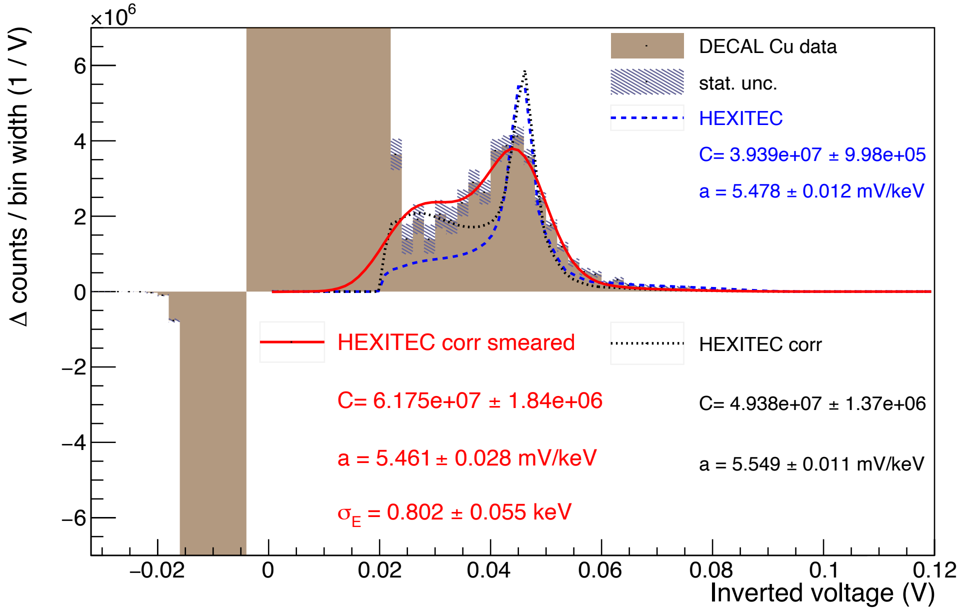
corrected HEXITEC



2. Fitting corrected and uncorrected HEXITEC spectra with parameters for x-axis calibration: Translation from energy E (keV) to voltage V (mV): $V = a \cdot E$

3. Include Gaussian smearing parameter in corrected HEXITEC spectrum with energy resolution σ_E (keV)

4. Obtain signal height from parameter a



Advanced DECAL energy calibration

Method 2: Fitting corrected and smeared HEXITEC spectra

--- Raw HEXITEC spectrum
--- 25 μm Si corrected spectrum
___ additional Gaussian smearing

- Translation from energy E (keV) to voltage V (mV): $V = a \cdot E$
- Signal height is on average $a = 5.54 \pm 0.37$ mV/keV
- From e^-- hole pair creation energy $\varepsilon = 3.6$ eV
  → conversion gain $c_g = 19.95 \pm 1.32\ \mu V/e^-$
- Relative energy resolution via linear fit:

$$\frac{\sigma_E}{E} = 12.2 \pm 3.5\ \%$$