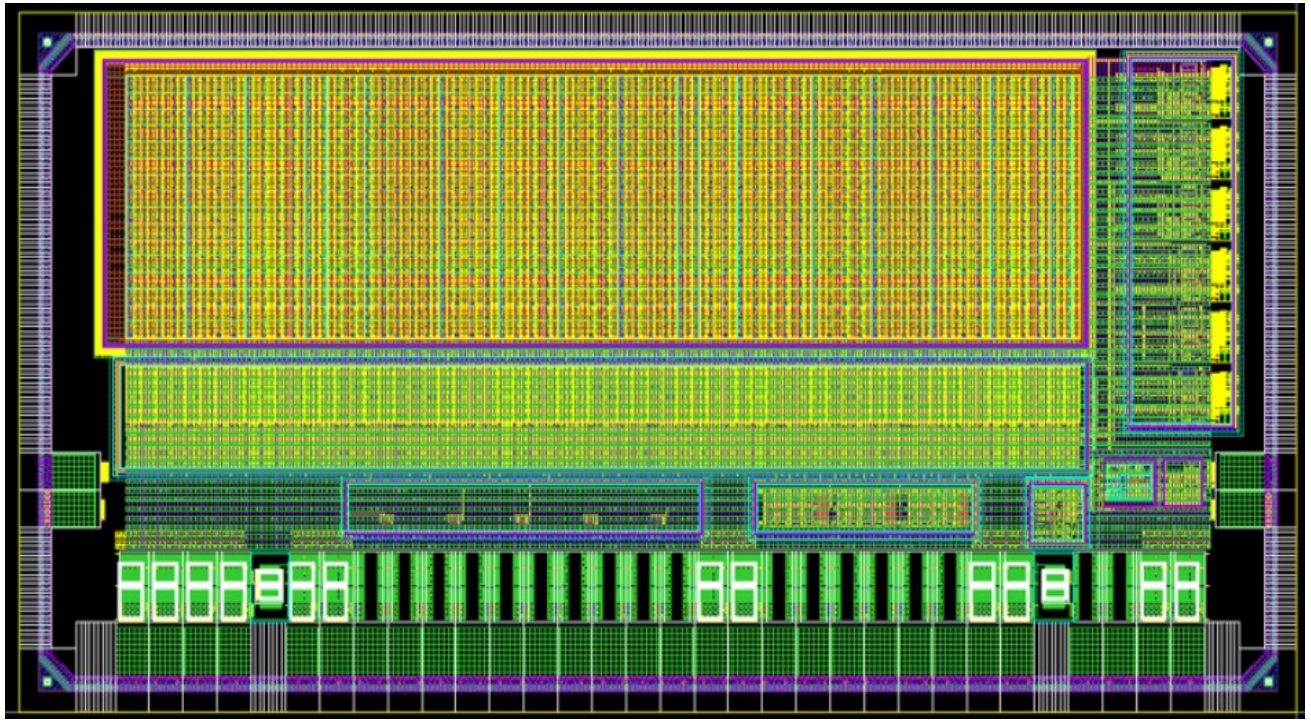


The H2M project: Porting the functionality of a hybrid readout chip into a monolithic 65 nm CMOS imaging process

3rd ECFA workshop on e+e- Higgs, Electroweak and Top Factories, Paris

October 9th, 2024

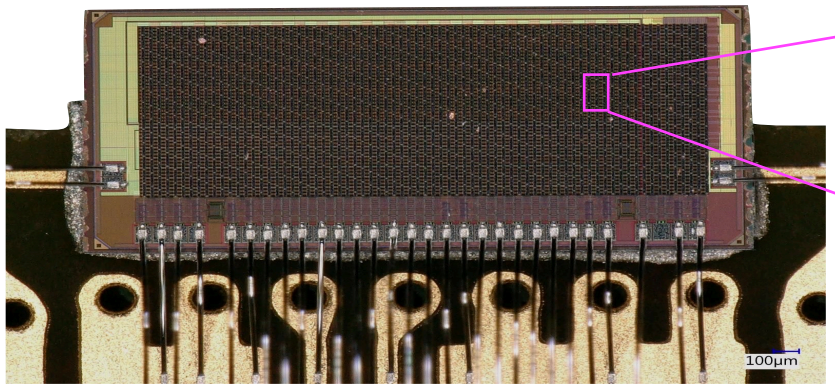
Rafael Ballabriga, Eric Buschmann, Michael Campbell, Raimon Casanova Mohr, Dominik Dannheim, Ana Dorda, Finn Feindt, Philipp Gadow, Ingrid-Maria Gregor, Karsten Hansen, Yajun He, Lennart Huth, Iraklis Kremastiotis, Corentin Lemoine, Stefano Maffessanti, Larissa Mendes, Younes Otarid, Christian Reckleben, Sebastien Rettie, Manuel Alejandro del Rio Viera, Sara Ruiz Daza, Judith Schlaadt, Adriana Simancas, Walter Snoeys, Simon Spannagel, Peter Svihra, Tomas Vanat, Anastasiia Velyka, Gianpiero Vignola, Håkan Wennlöf

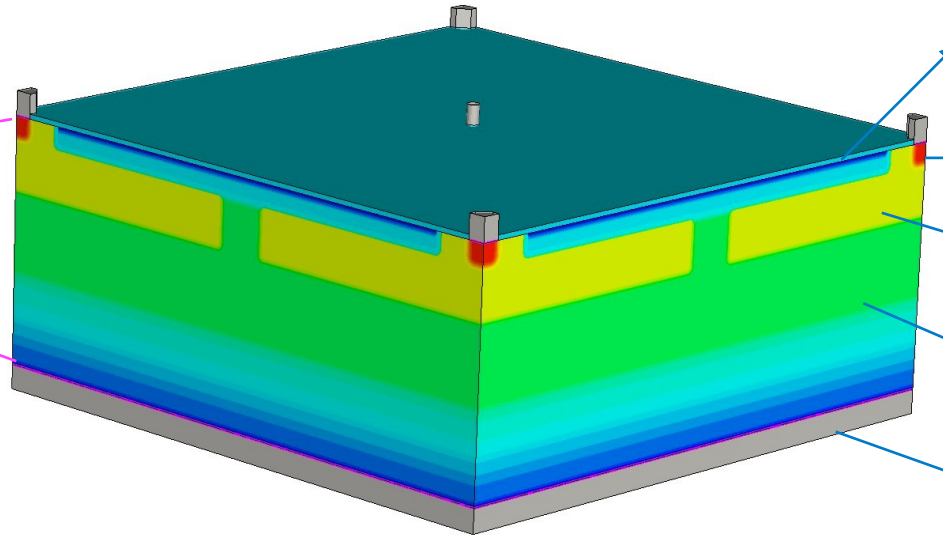
H2M (Hybrid-to-Monolithic)

- Ports a **hybrid pixel detector architecture into a monolithic chip**.
- **Digital-on-top** design workflow.
- Manufactured in a TPSCo **65 nm CMOS imaging process**.

- **35 µm pixel pitch in 64x16 pixel matrix** (total sensitive area: 2.24 × 0.56 mm^2). Total thickness ~ 50 µm.
  (p-epitaxial layer ~ 10 µm)

- Analog and digital front-end per pixel.





P-well hosting full CMOS circuitry

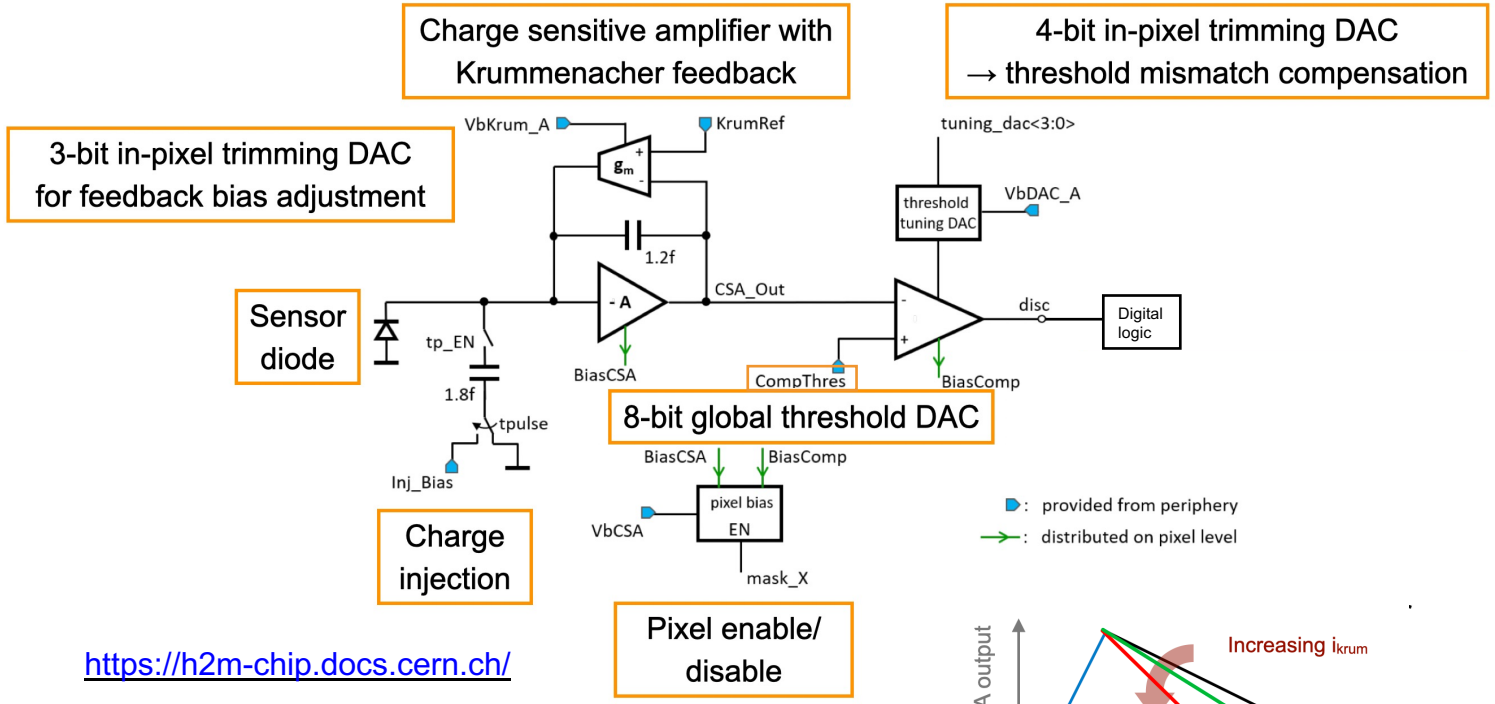
Small n-collection electrode

Low dose n-implant layer with a gap

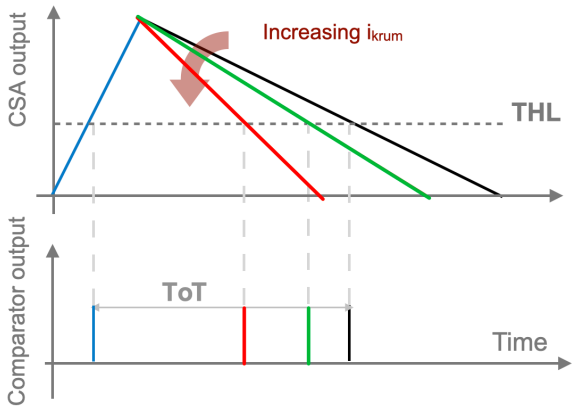
Charge collection in thin (~ 10 µm) depleted p-epi layer

Low-ohmic p-substrate

Analog front-end design

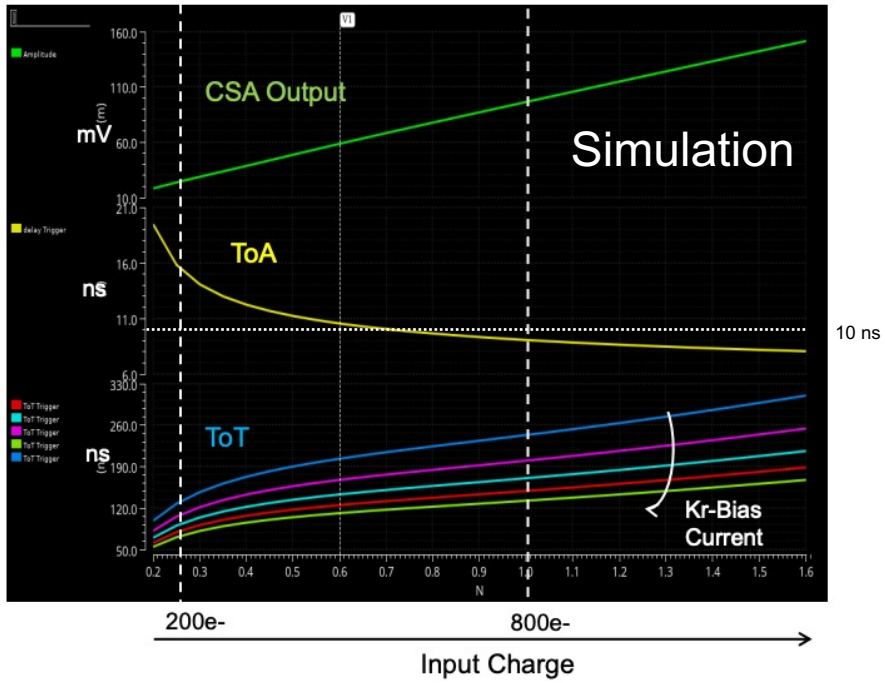


https://h2m-chip.docs.cern.ch/



Slope of falling edge tuned with Krummenacher feedback current (ikrum).

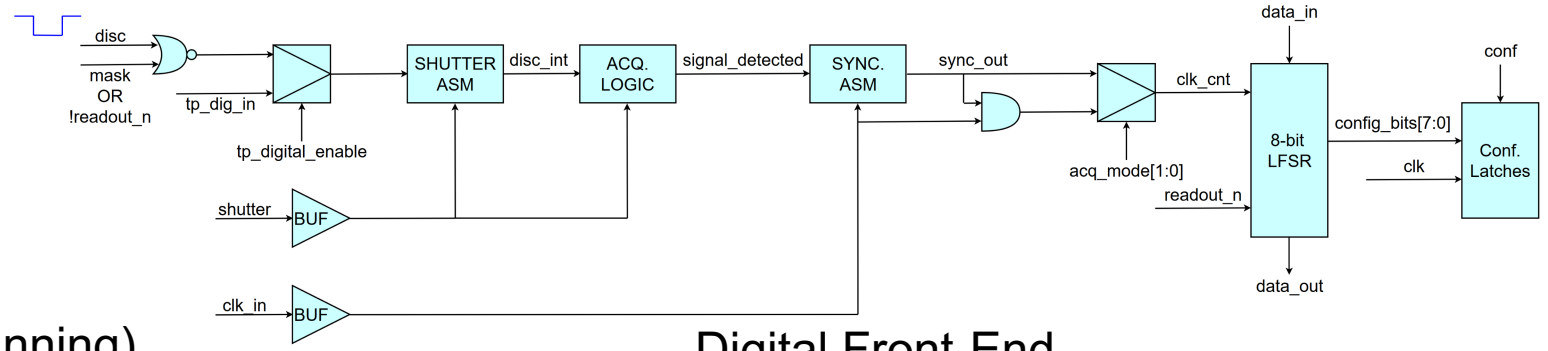
ToA/ToT as function of input charge



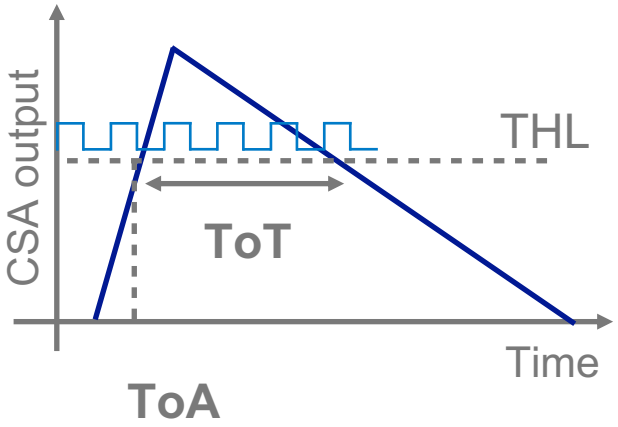
Simulated time walk below 10 ns for input charges larger than 400 electrons.

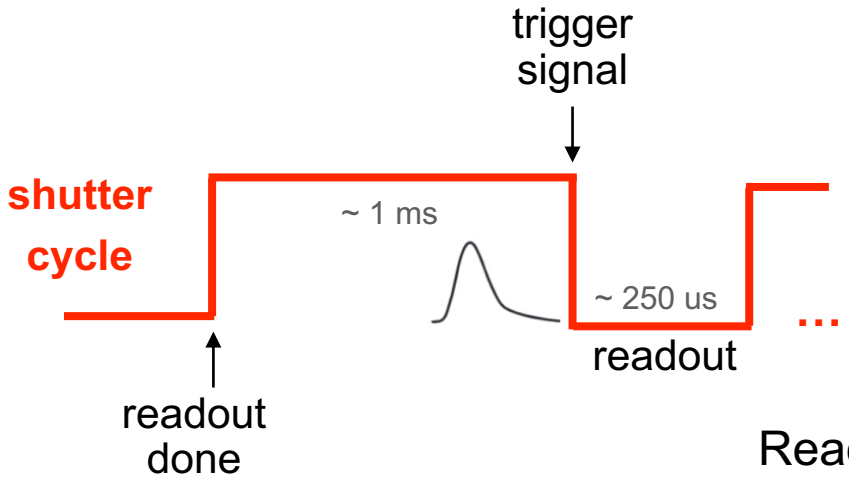
Data Acquisition

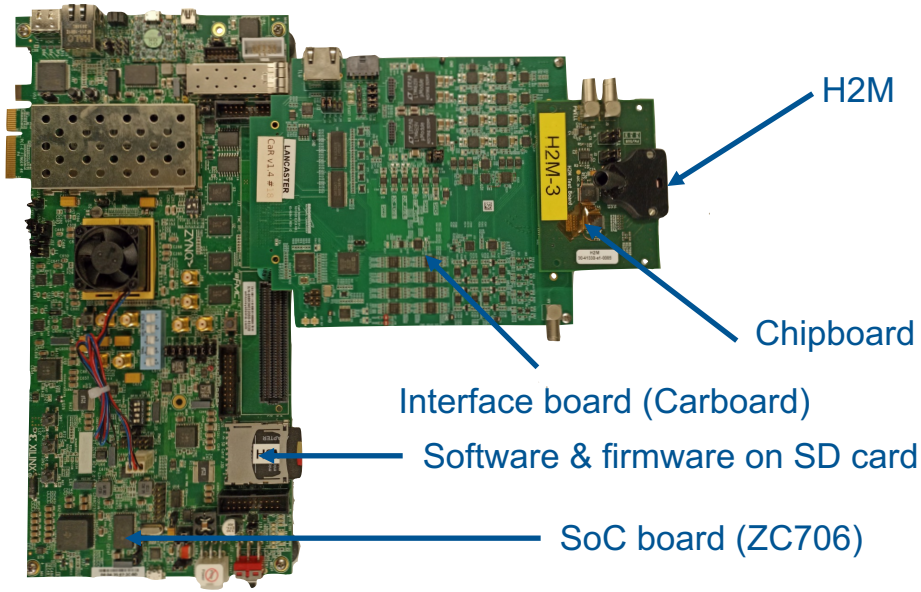
- **4 acquisition modes** per pixel:
  - 8 bit ToT,
  - 8 bit ToA (100 MHz clock - 10 ns binning),
  - counting (#number of hits above threshold),
  - triggered.
- **Readout**: 40 MHz clock, frame-based without zero-suppression.



Digital Front-End



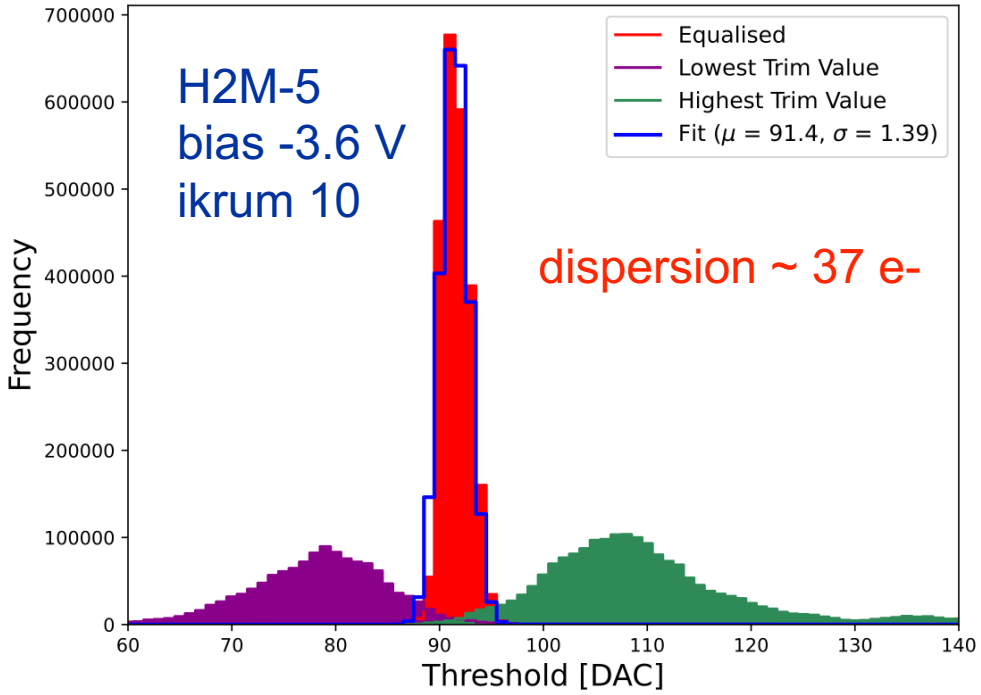


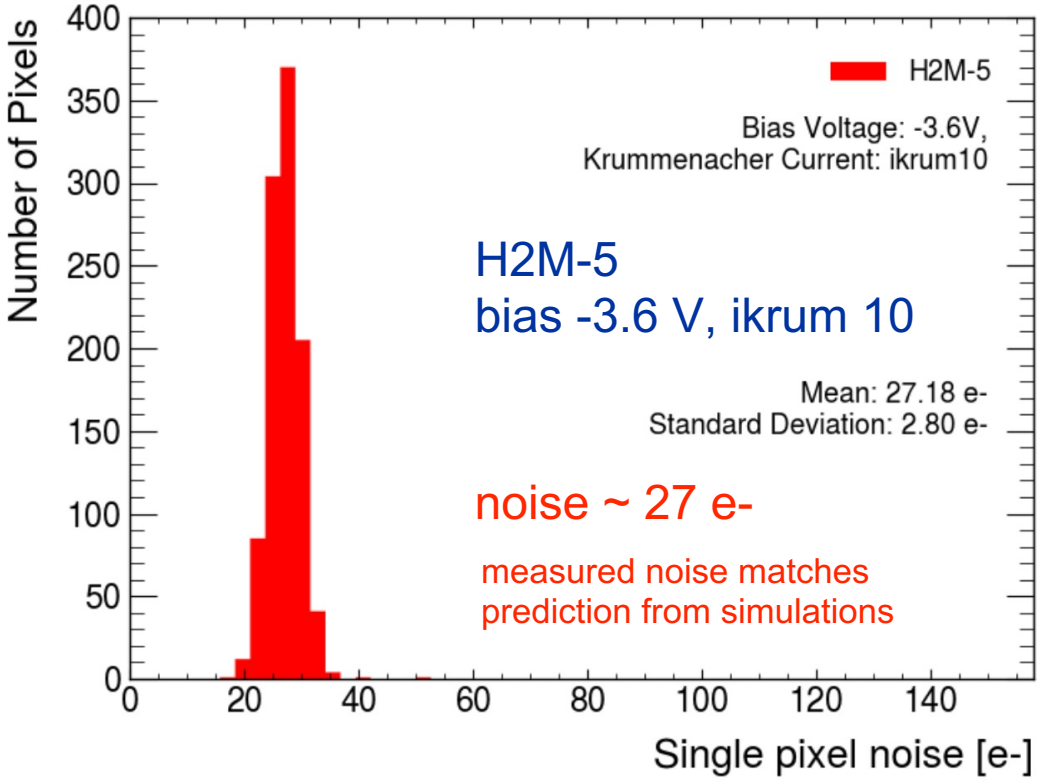


T. Vanat, TWEPP2019:100, 2020.

Readout system based on the **Caribou DAQ**.

Threshold equalisation and single-pixel noise



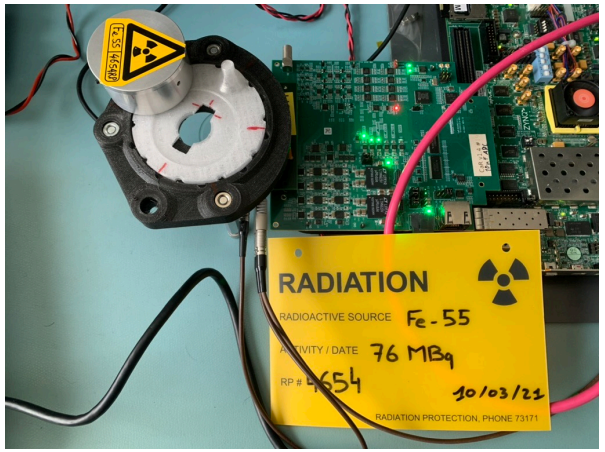


Equalisation of the hit detection threshold:

1) Threshold scan in counting mode for the 16 trimming values.
2) Determine the baseline for each pixel for each trimming value.
3) For each pixel, the trimming DAC is adjusted to the one with baseline closest to a fixed trimming target.
4) Single-pixel noise obtained from width of threshold turn-on curves.

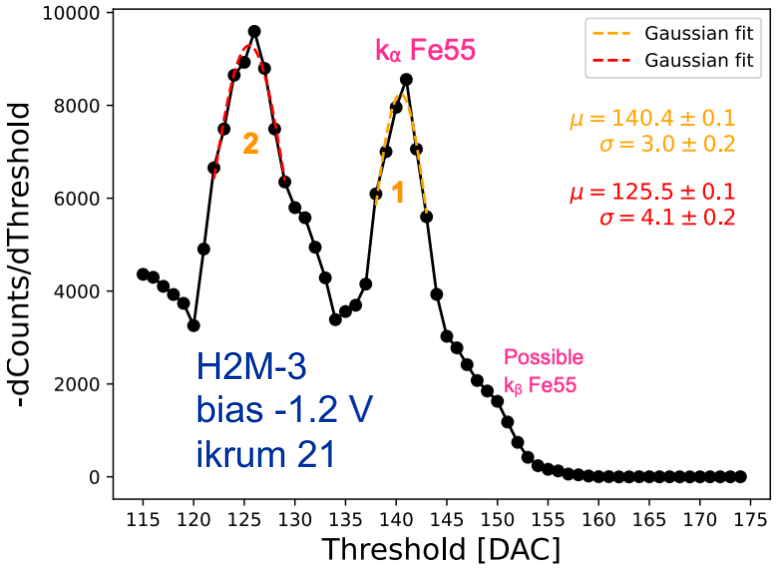
Threshold and ToT calibration

H2M-2, pixel [2,14]
Vbias -1.2V,
ikrum 21,
thr 120 DAC

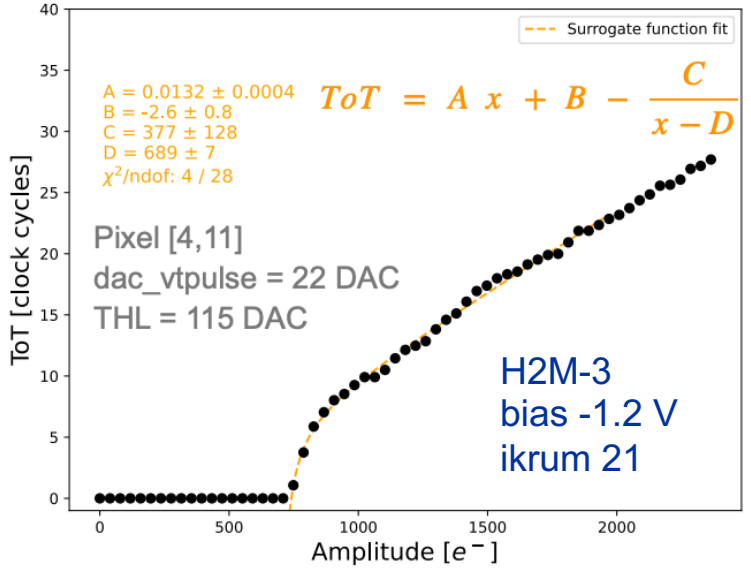


- Source measurement (Fe-55 and Ti) for global energy calibration of threshold and for calibration of test-pulse injection energy scale
  → two peaks originating from fast/slow charge-collection regions inside pixel (ballistic deficit + CSA response, depends on Krummenacher feedback current)
- Calibration of per-pixel ToT scale with test-pulse injection
- Calibrated ToT accuracy ~5%

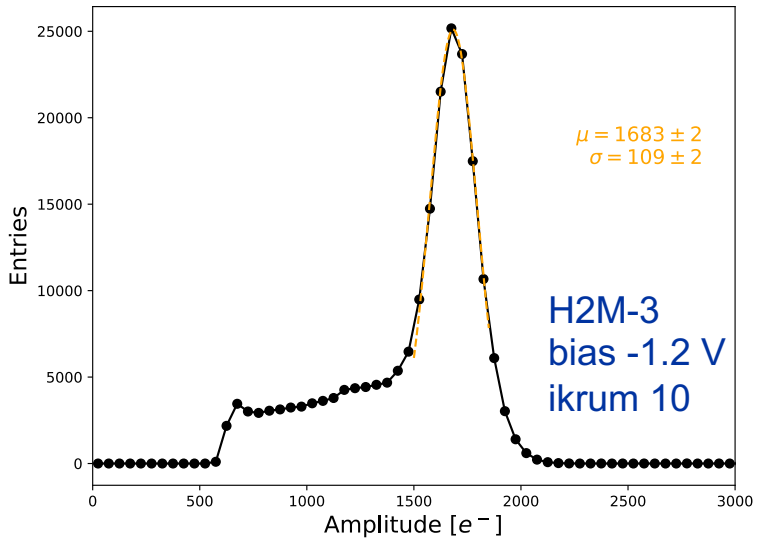
threshold calibration



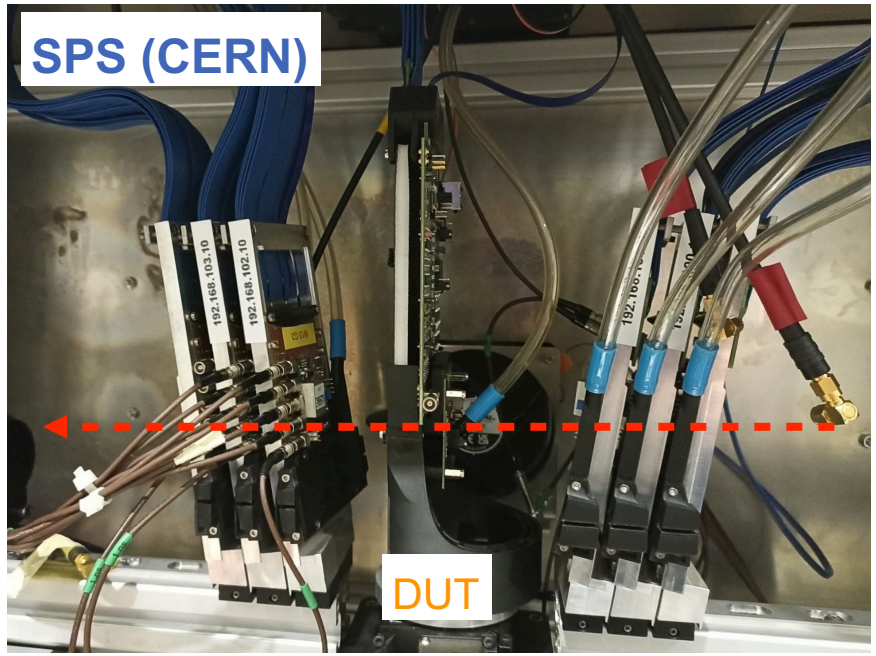
ToT calibration



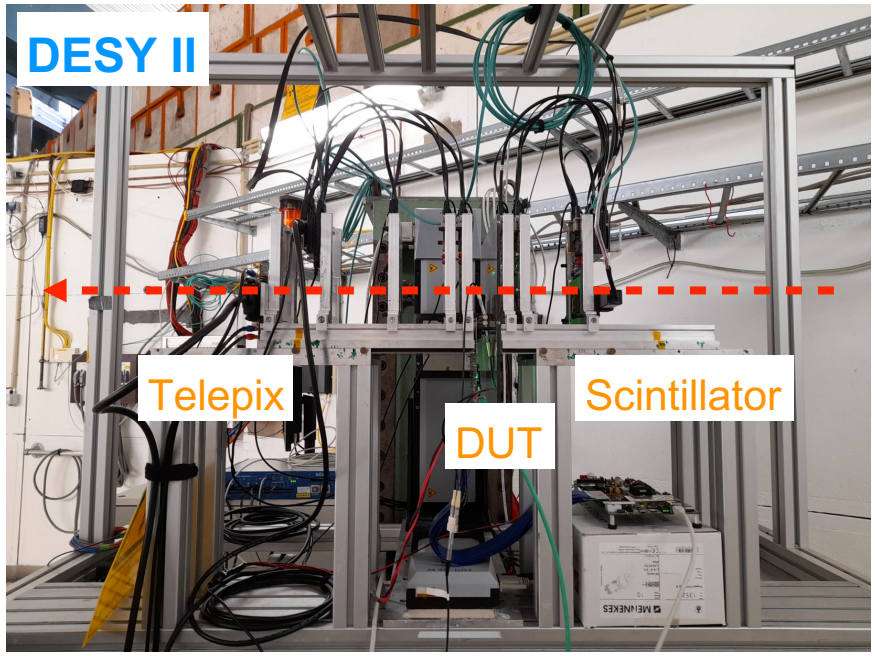
Calibrated Fe55 spectrum



Test beam campaigns

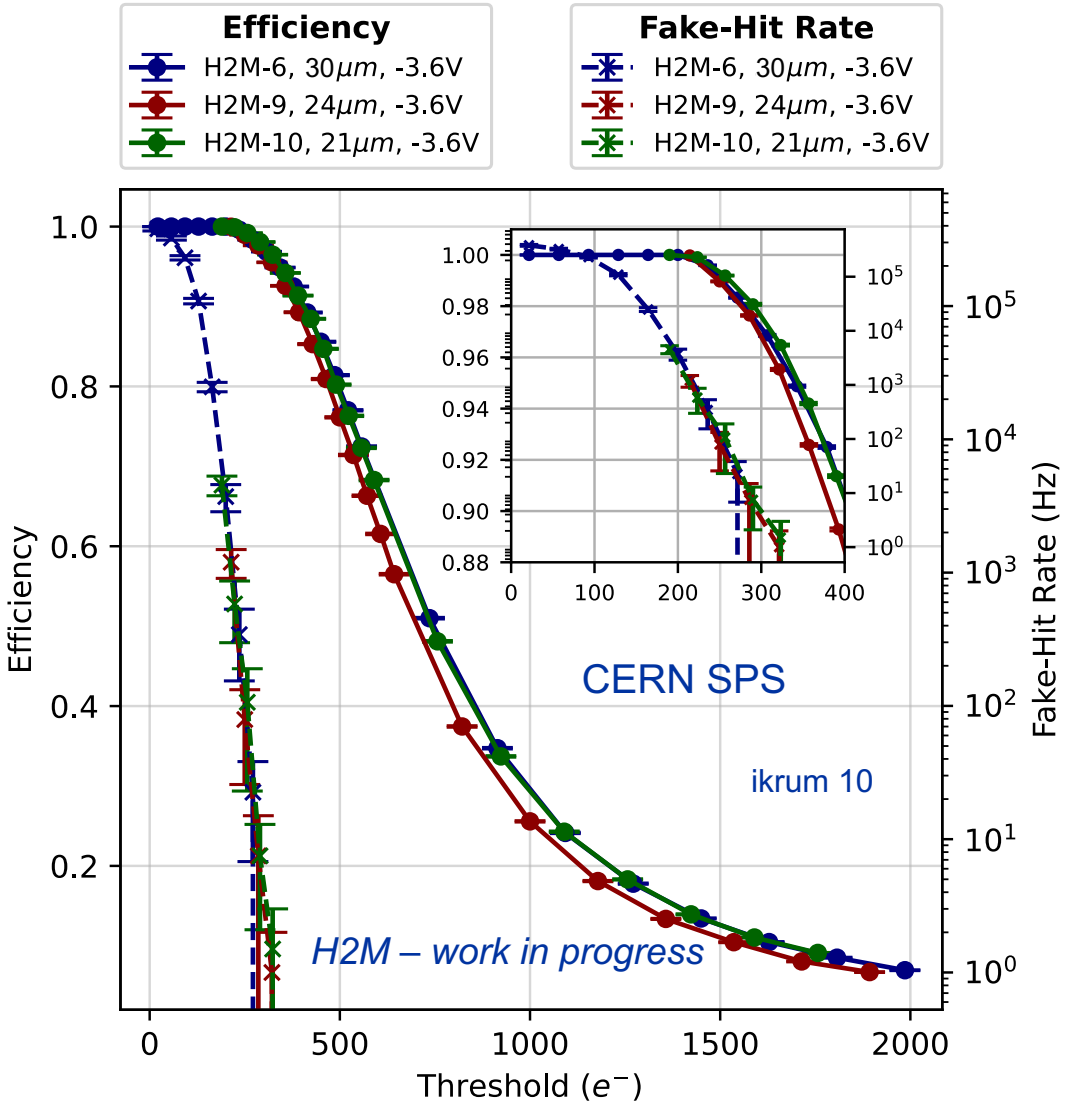


- H6 beam line, 120 GeV charged pions.
- **Timepix3 reference telescope.**
  - Pointing resolution ~ 1.5 µm,
  - Track time resolution ~ 1 ns,
  - Continuous readout with 150 us (2.56 us) shutter duration for ToT (ToA) mode.

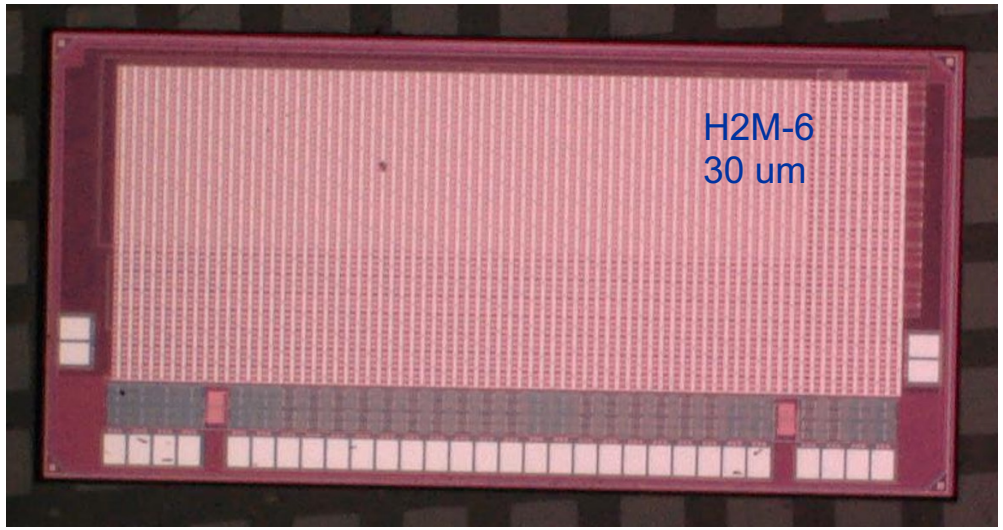


- Beamline 22, electron beam ~4.8 GeV.
- **ALPIDE reference telescope.**
  - Pointing resolution ~ 3 µm
- Scintillator & Telepix used as region-of-interest triggers (~5ns resolution).

Efficiency and fake hit rate of thinned samples



- **Single-die backside thinning of H2M samples, performed by OPTIM WS**
  → 30-21 µm physical thickness
- **Includes ~5 µm circuitry + ~10 µm epitaxial layer**

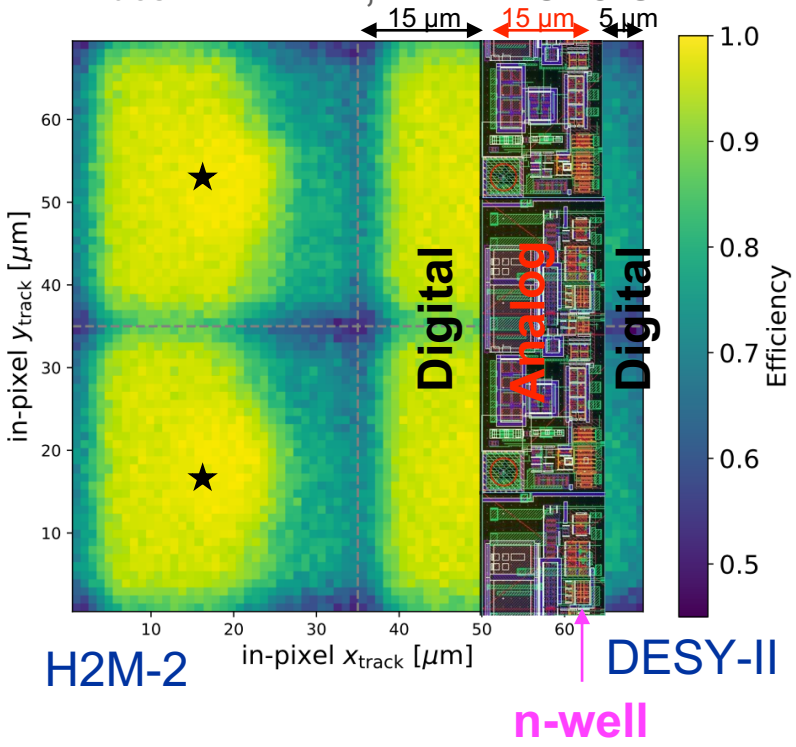


- **Efficiency >99% for ~250 e- threshold @ ~100 Hz fake-hit rate (with up to 11 pixels masked)**
- **No performance degradation from thinning**

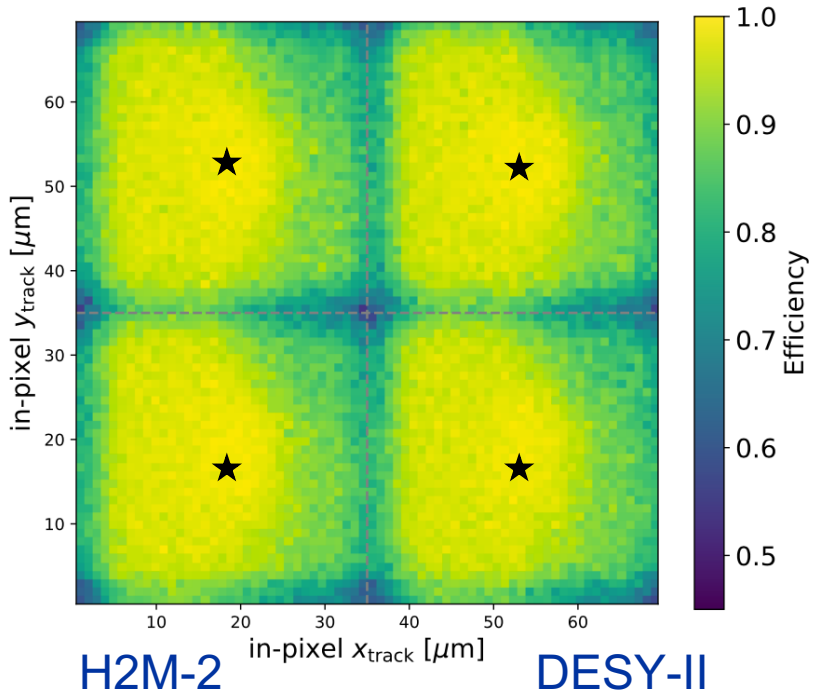
In-pixel efficiency map

★ Collection electrode

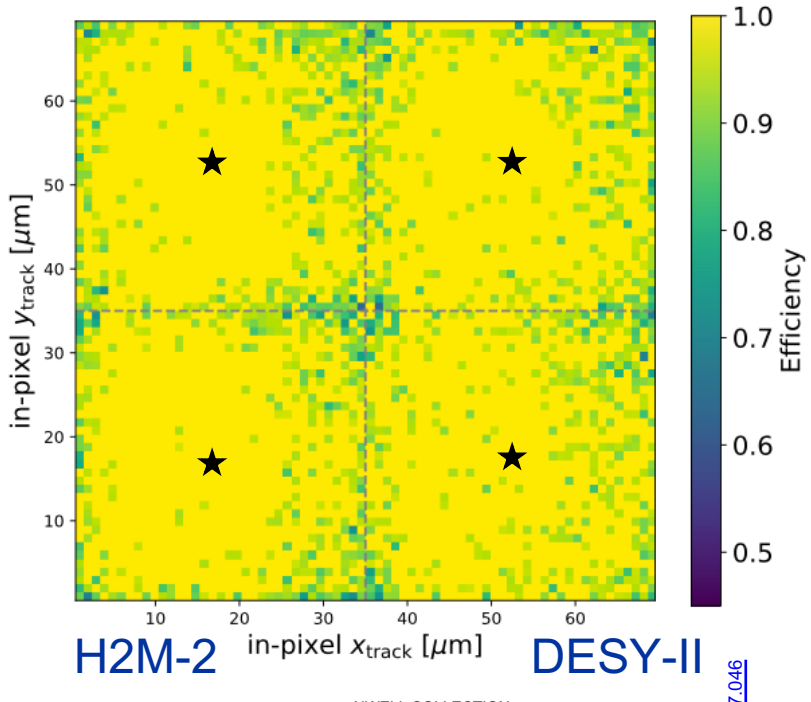
V_{bias} = - 1.2 V, THL ≈ 520 e⁻

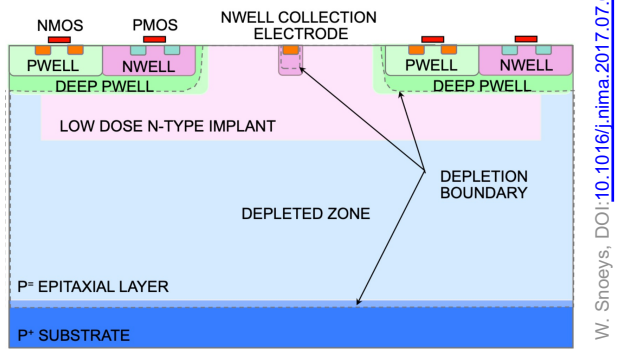


V_{bias} = - 3.6 V, THL ≈ 520 e⁻



V_{bias} = - 3.6 V, THL ≈ 400 e⁻





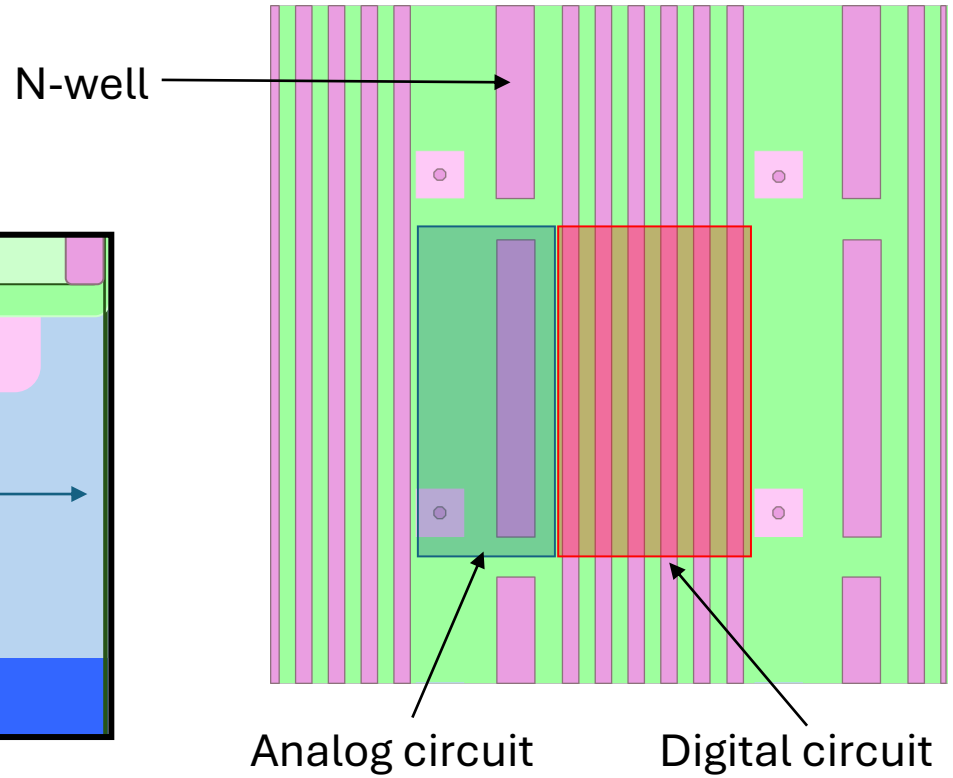
W. Snoeys, DOI:10.1016/j.nima.2017.07.046

Non-uniform in-pixel efficiency:

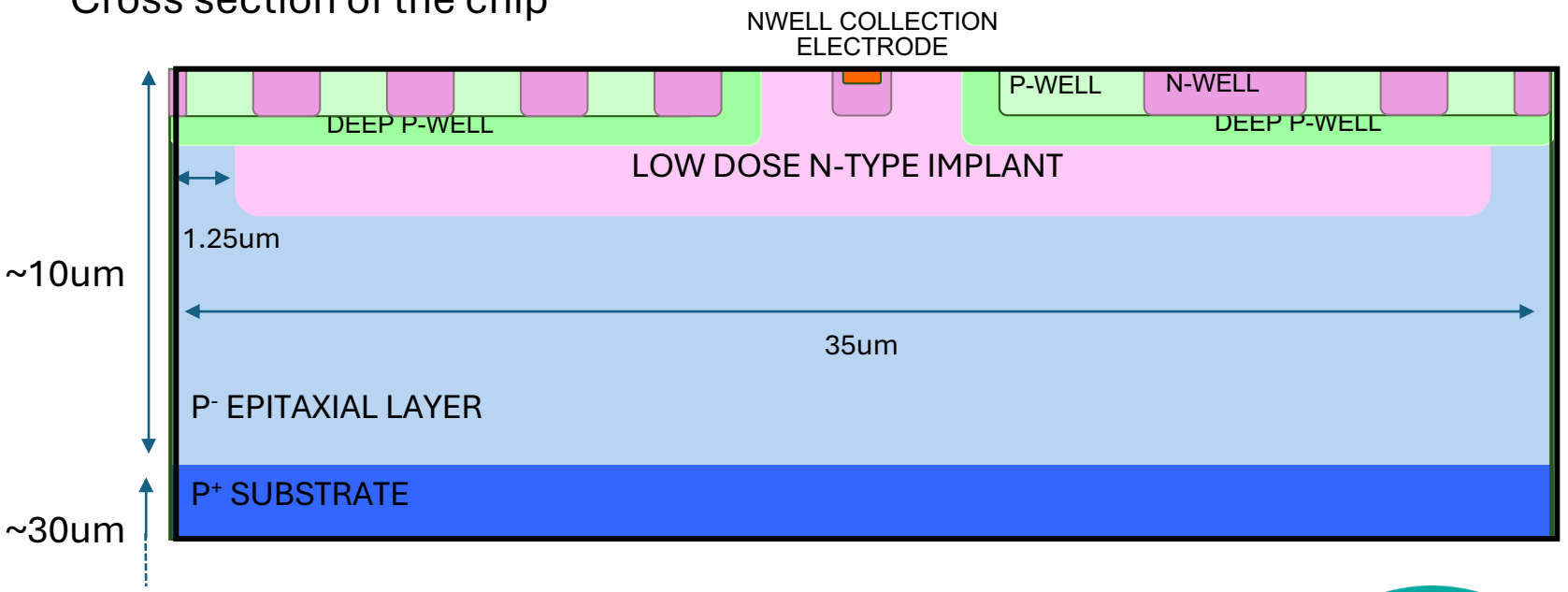
- Related to the size and location of the n-wells of the analog circuitry.
- Mitigated at larger V_{bias} and lower thresholds.
- Additionally, effects of fast front-end and large pixel size.

TCAD+MC simulation workflow

Layout of the H2M (top view)



Cross section of the chip



Sensor structure

Sentaurus TCAD

SYNOPSYS

Electric field

ap² allpix squared

Pixel hits

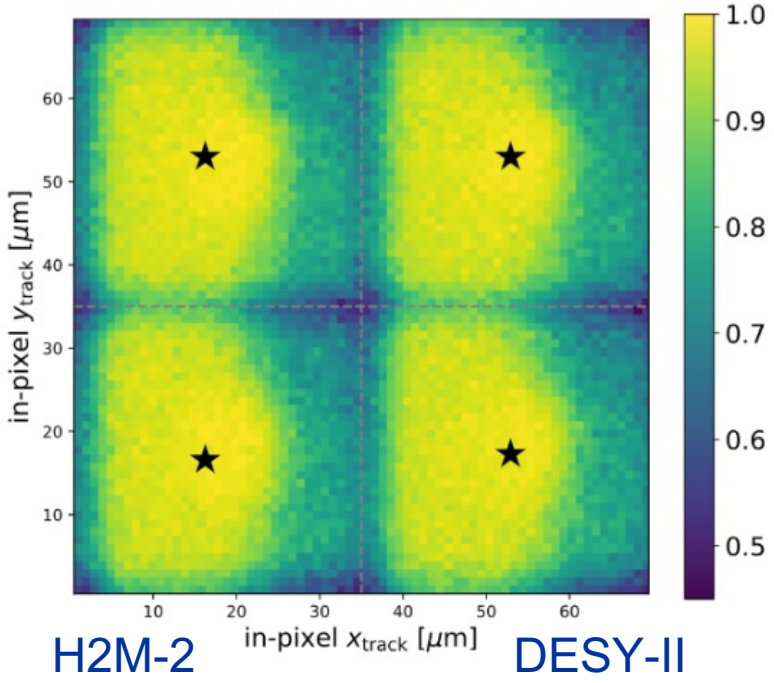
Analysis

(added custom CSA model in Allpix-Squared)

In-pixel efficiency in measurements and simulations

Test beam

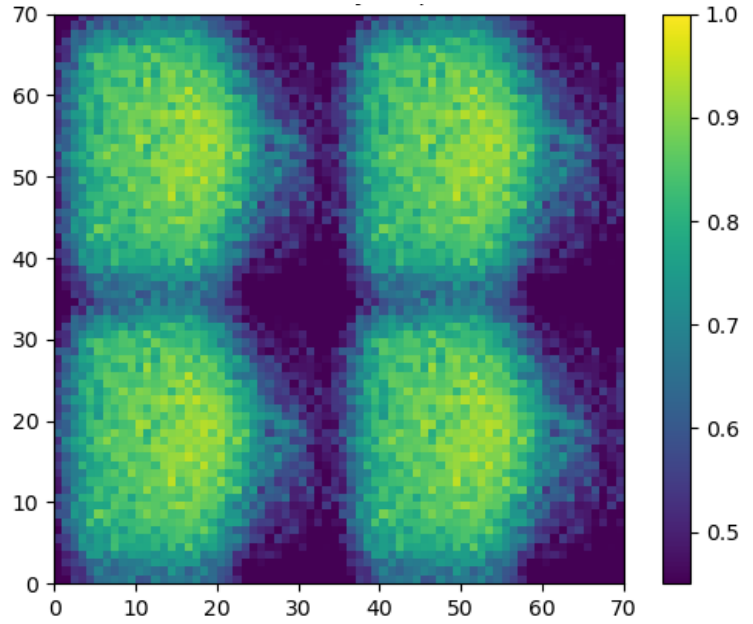
Vsub = -1.2V, THLD=520e-



H2M-2 DESY-II

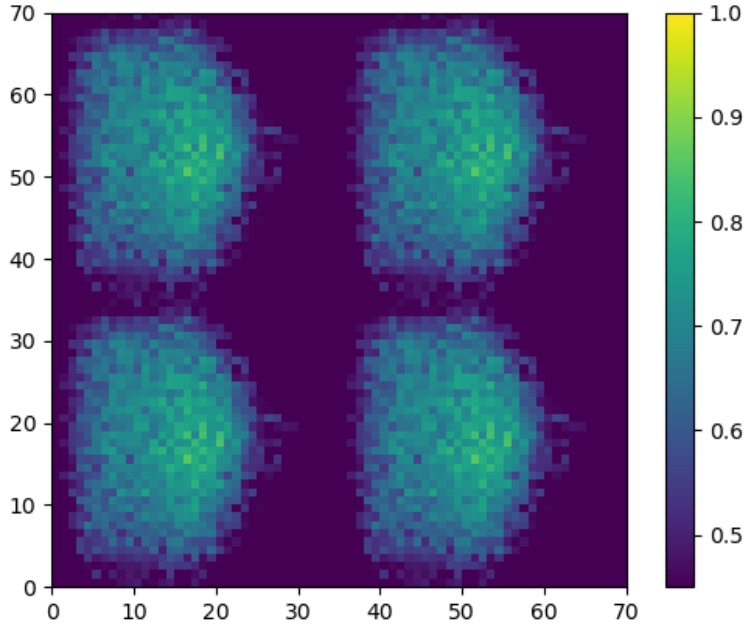
Simulations

Vsub = -1.2V, THLD=400e-



Simulation

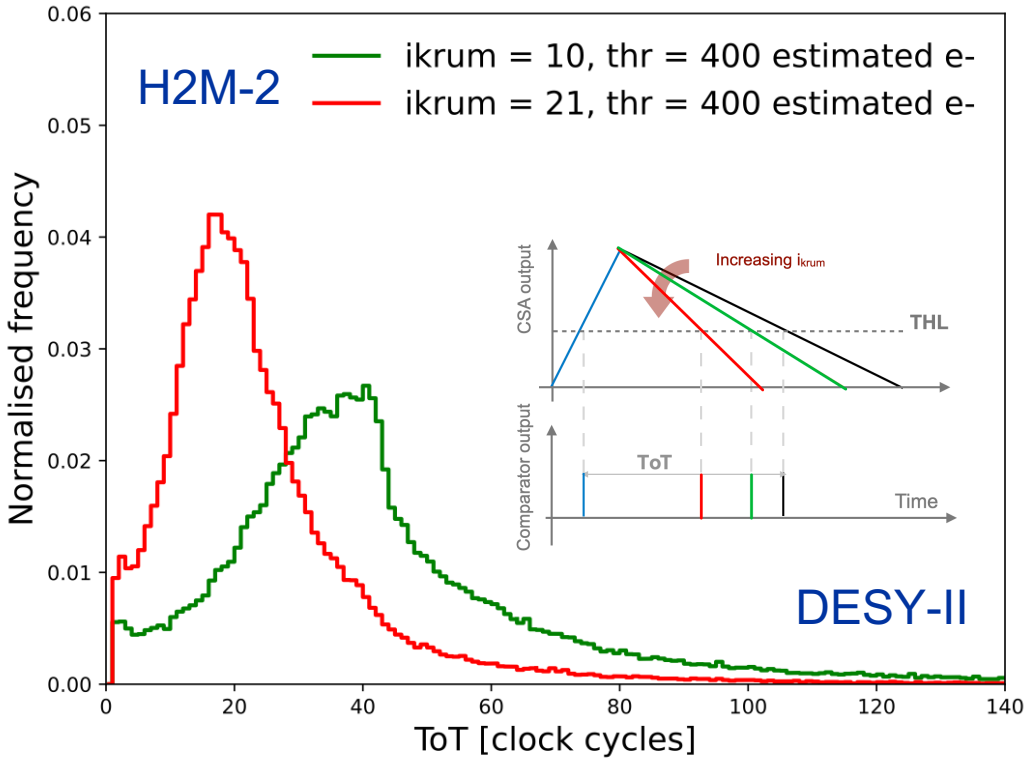
Vsub = -1.2V, THLD=520e-



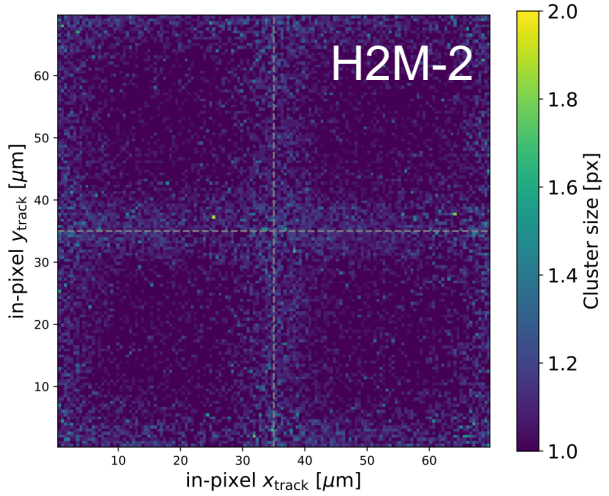
Simulation

Good qualitative matching of the pattern. Current simulation predicts too low efficiency: quantitative matching is ongoing work.

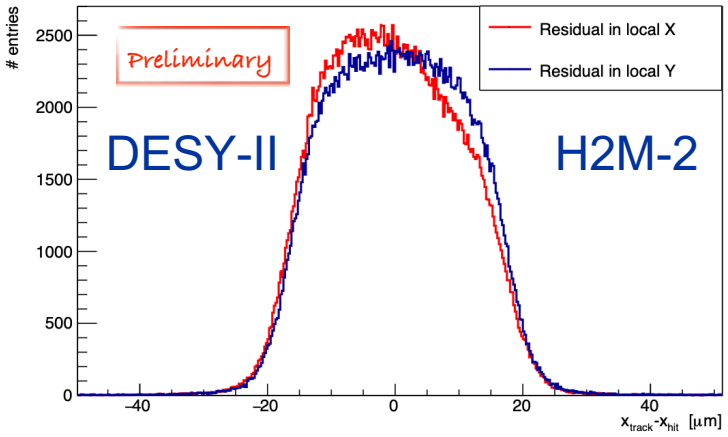
ToT, cluster size and spatial resolution



Cluster size



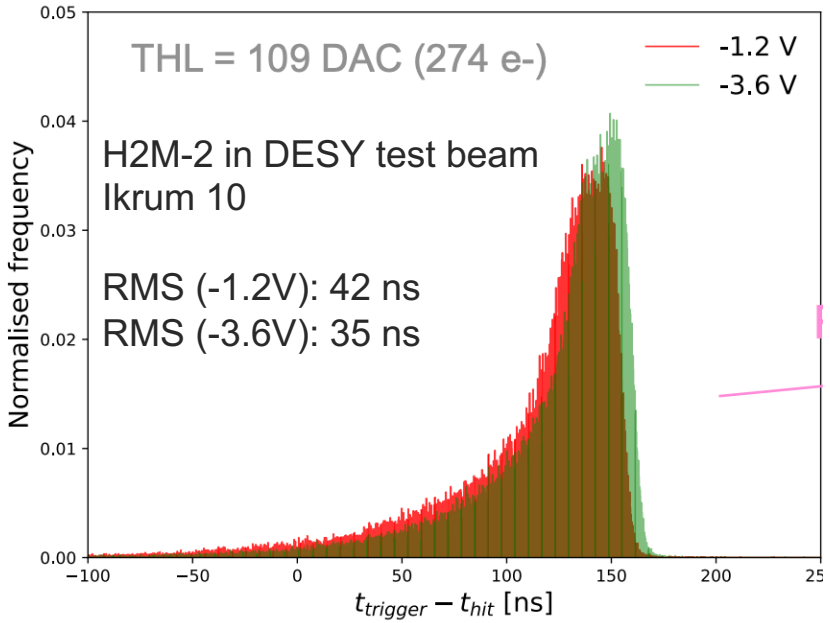
Spatial resolution

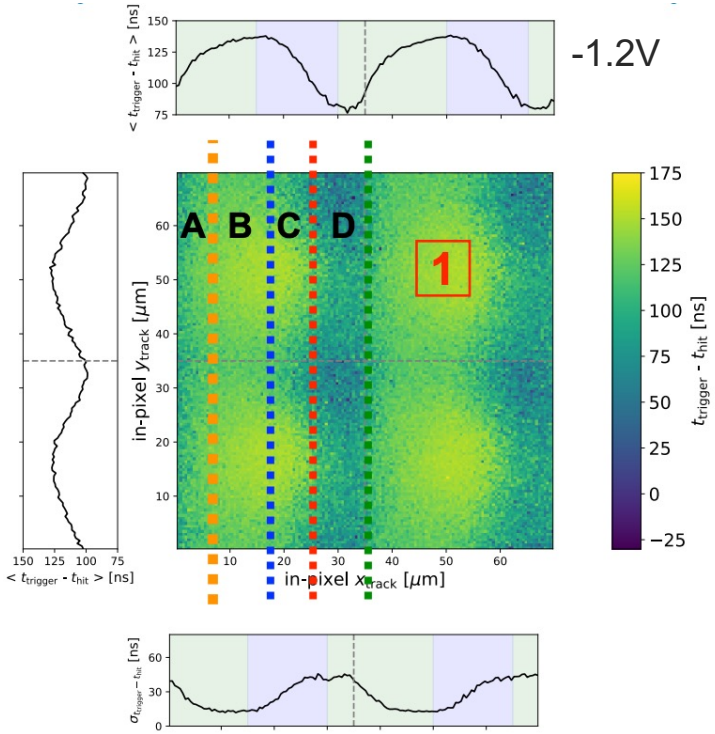


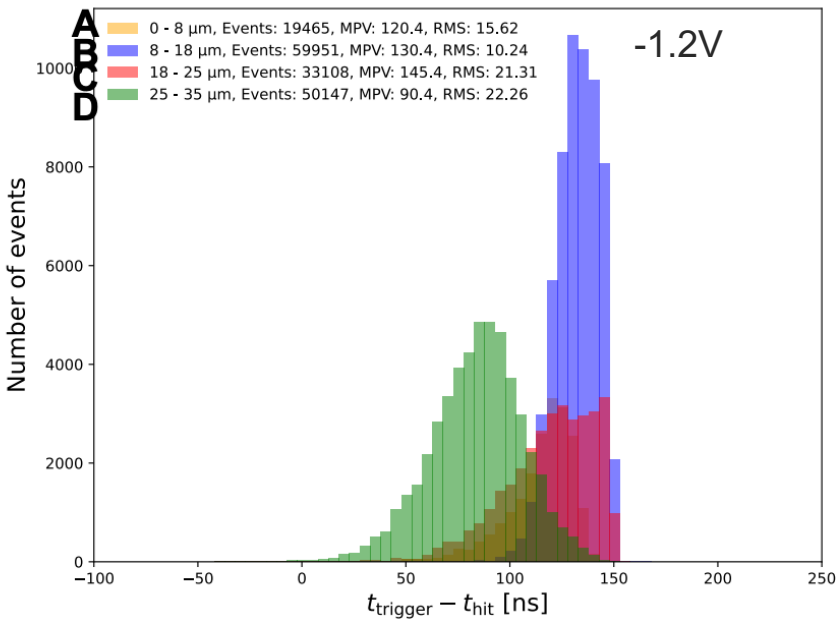
ToT measurement, threshold ~ 400 electrons

- Spatial resolution and cluster size dominated by the ~35 μm pitch and the high threshold.
- Asymmetric residuals in X due to the low-efficiency part.

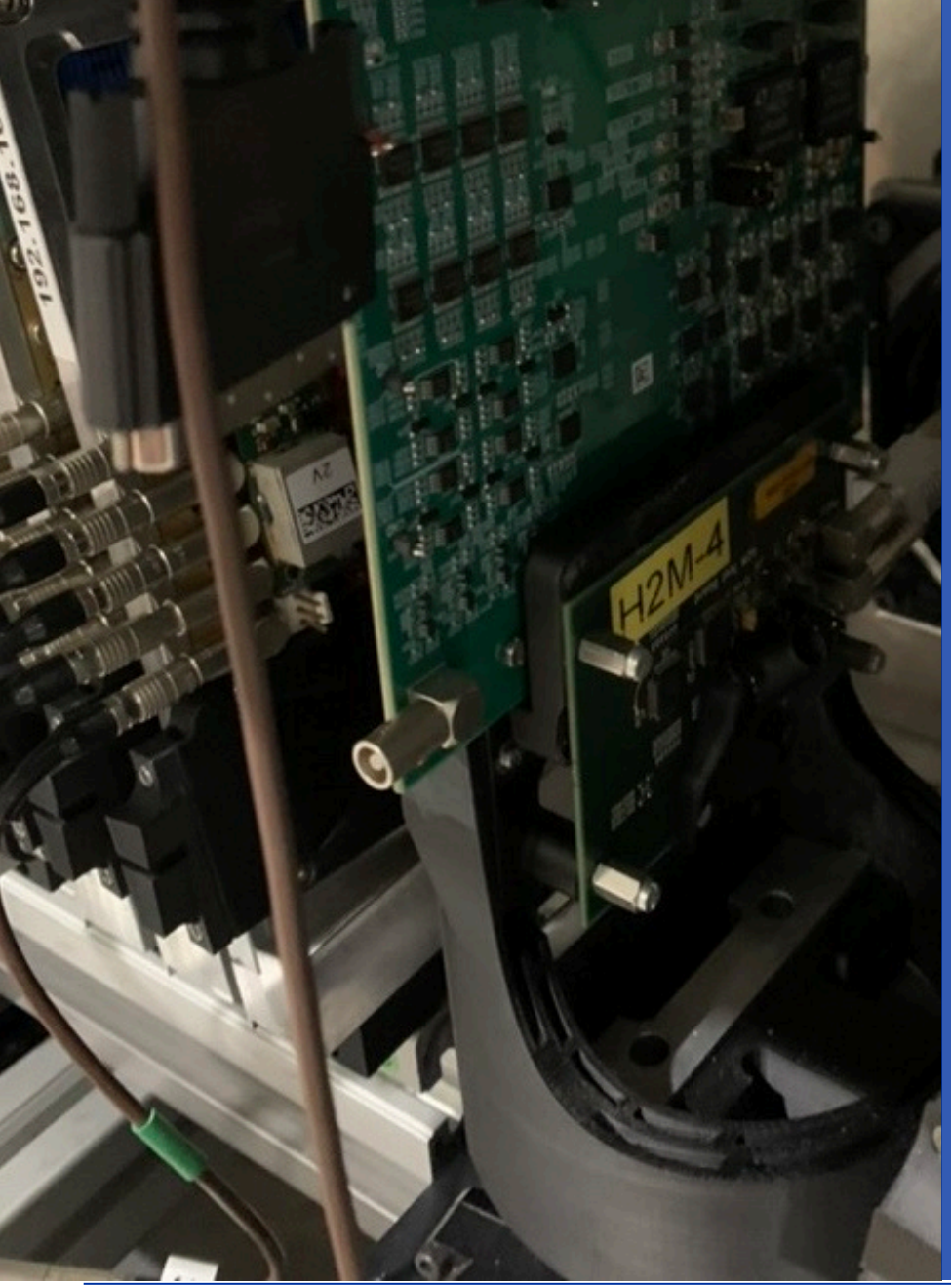
Time resolution (ToA)







- **Better timing resolution for -3.6 V than -1.2 V.**
  Due to more uniform charge-collection time across the pixel cell.
- **Strong dependency of arrival time on track impact position**
  → timing limited by non-uniformity of charge collection



Conclusions

Fully functional digital-on-top monolithic sensor in 65 nm CMOS

Calibration and characterization of performance with laboratory and test beam measurements.

- Excellent performance in test beam
  - <30 e- noise, ~200 e- minimum threshold, >99.1% efficiency
  - Thinning down to ~20 microns w/o performance loss
- Impact of n-wells on charge-collection observed and qualitatively confirmed by simulations
- Timing limited by non-uniform charge collection to ~30 ns

Outlook

- Analysis of rotation data (grazing-angle study)
  → extract active thickness
- Further improvements/tuning of simulation
- Long-term: Follow-up project in DRD3 for 65 nm CMOS sensor targeting Higgs-Factory vertex detector
  → smaller pixels, optimized sensor and frontend
  (https://indi.to/vMzqK)