Simulations and Test Beam Characterization of a MAPS in 65 nm CMOS Imaging Technology

Adriana Simancas, Justus Braach, Eric Buschmann, Ankur Chauhan, Dominik Dannheim, Manuel Del Rio Viera, Katharina Dort, Doris Eckstein, Finn Feindt, Ingrid-Maria Gregor, Karsten Hansen, Lennart Huth, Larissa Mendes, Budi Mulyanto, Daniil Rastorguev, Christian Reckleben, Sara Ruiz Daza, Paul Schütze, Walter Snoeys, Simon Spannagel, Marcel Stanitzki, Anastasiia Velyka, Gianpiero Vignola, Håkan Wennlöf.

11th Beam Telescopes and Test Beams Workshop
Hamburg, April 19th 2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

EP R&D

UNIVERSITÄT BONN

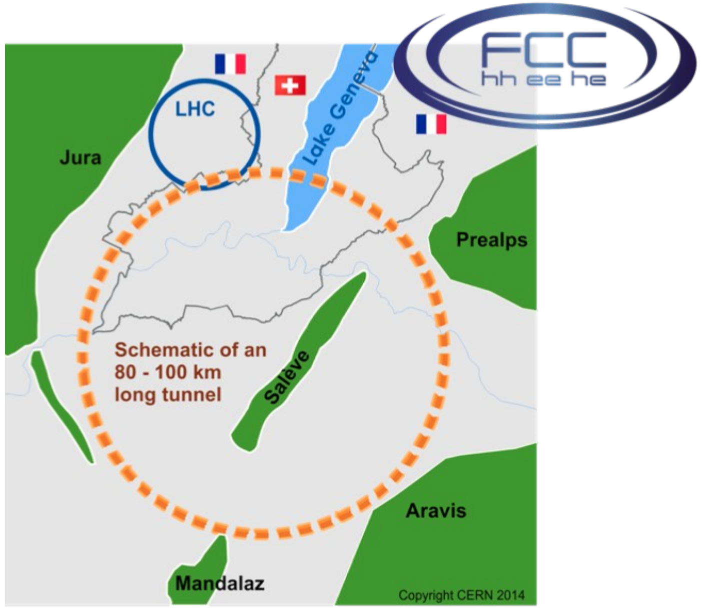
DESY.

The Tangerine Project

Towards Next Generation Silicon Detectors

- ✔ Develop the next generation of silicon pixel sensors:
  - ✔ Vertex detector for future lepton colliders
  - ✔ **Reference detector at DESY-II test beam**

DESY TEST BEAM.



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- ✔ Develop the next generation of silicon pixel sensors:
  - Vertex detector for future lepton colliders
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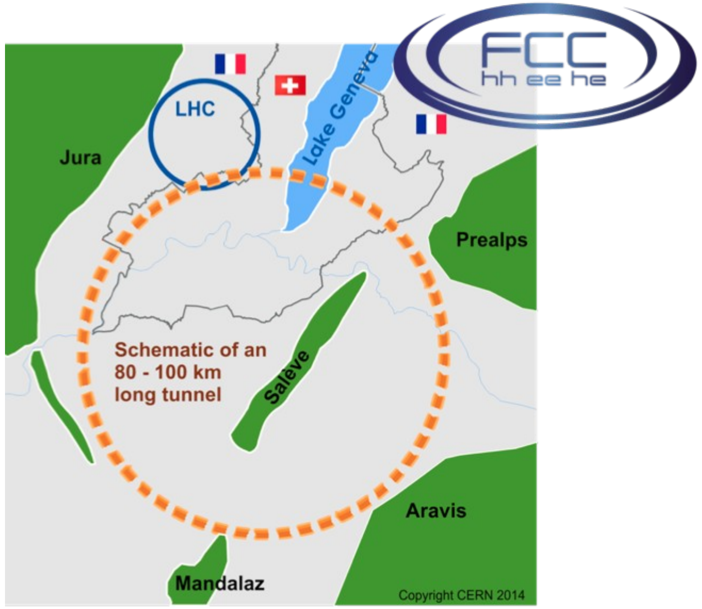
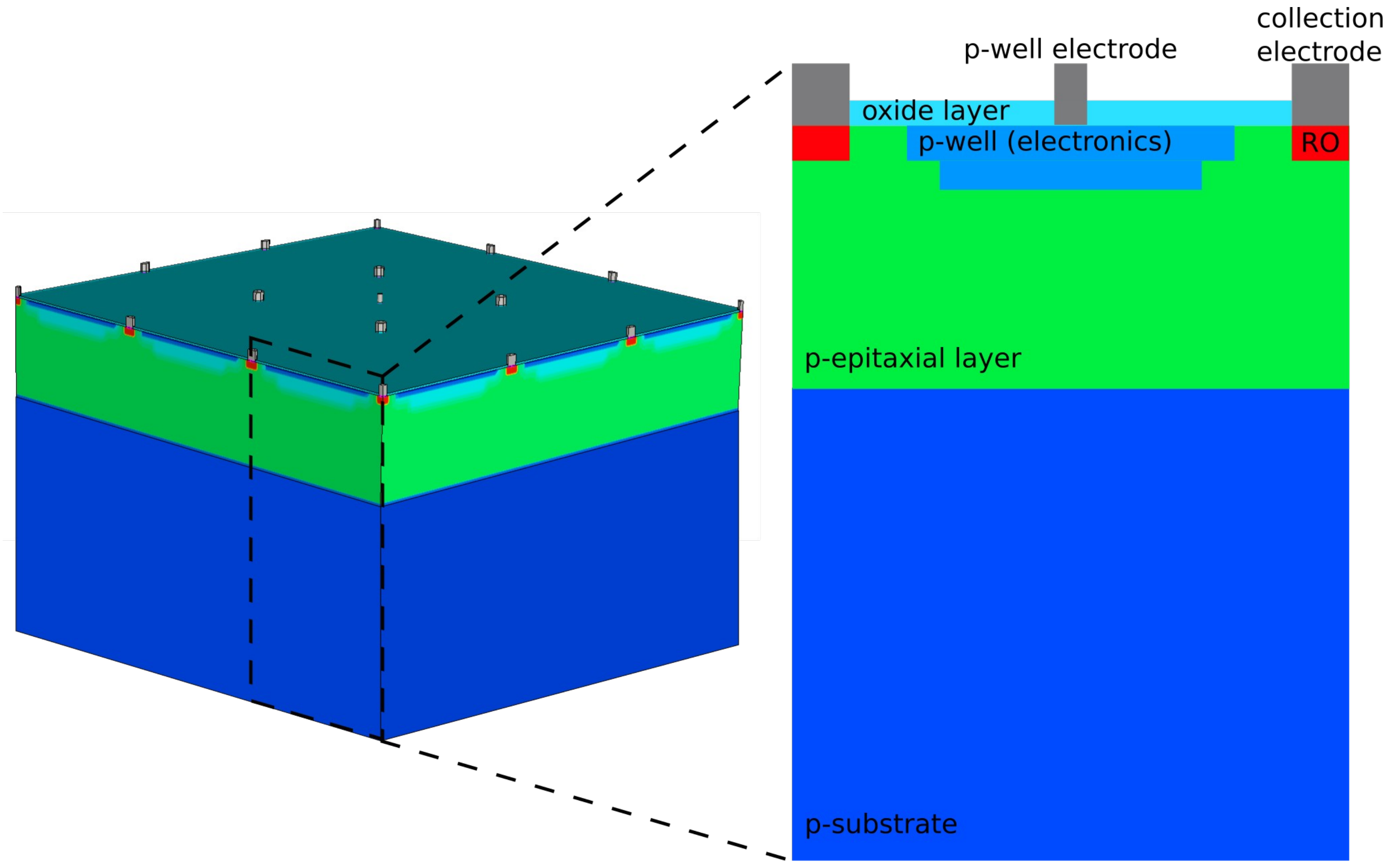
- ✔ Performance parameters:
  - Material budget: ~ 50 µm silicon
  - Spatial resolution: ≤ 3 µm
  - Time resolution: ~ ns



Monolithic Active Pixel Sensor (MAPS)



Monolithic Active Pixel Sensor (MAPS)

Characteristics and Advantages

✔ Readout electronics integrated inside in sensor volume

→ reduction of costs and material

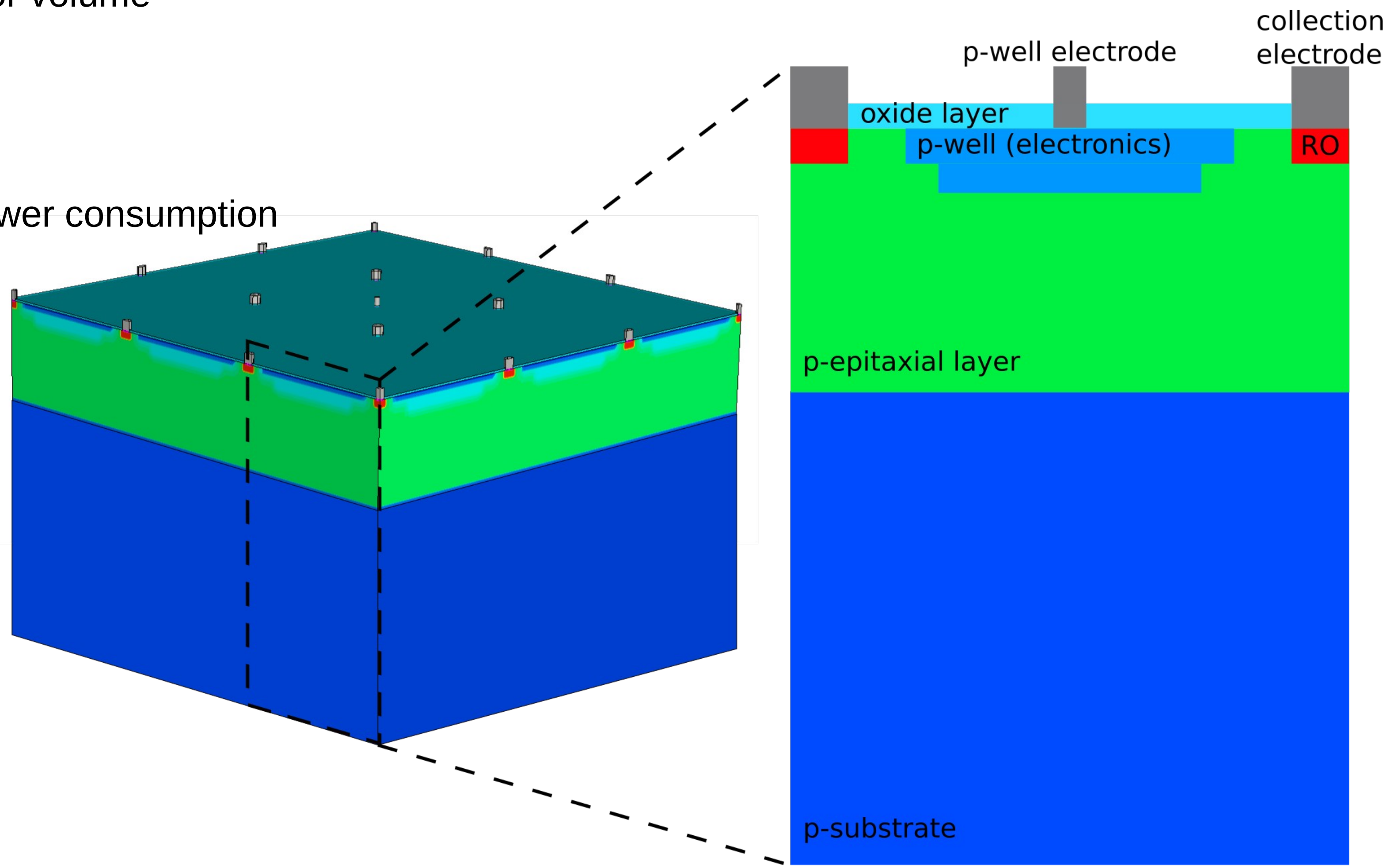
✔ 65 nm CMOS imaging process

→ improvement in logic density of pixels and power consumption

✔ Small collection electrode

→ small capacitance

→ improvement in S/N and power consumption



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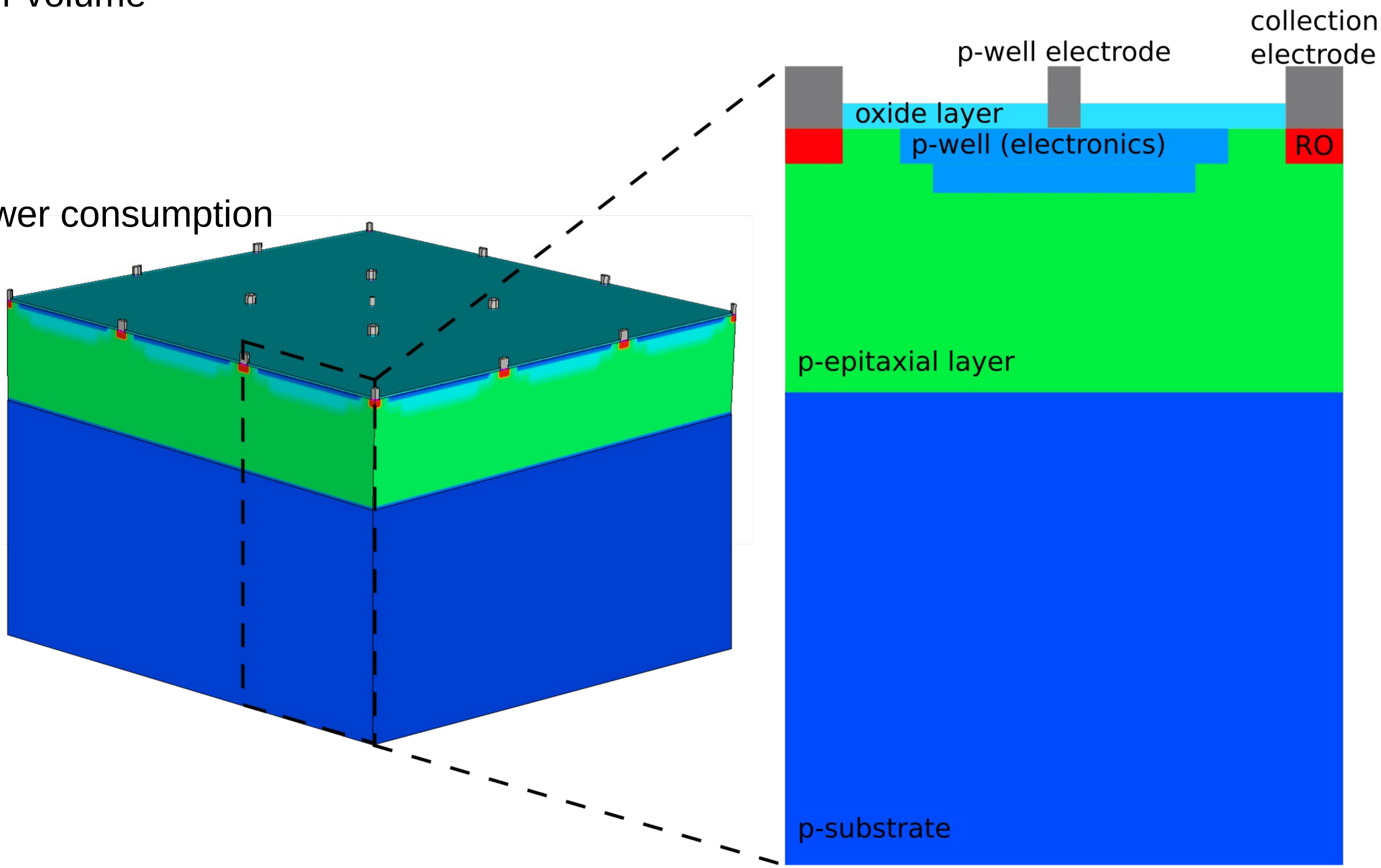


It's not all fun and games...

Small pn-junction → small depleted volume

→ low efficiency and slow charge collection

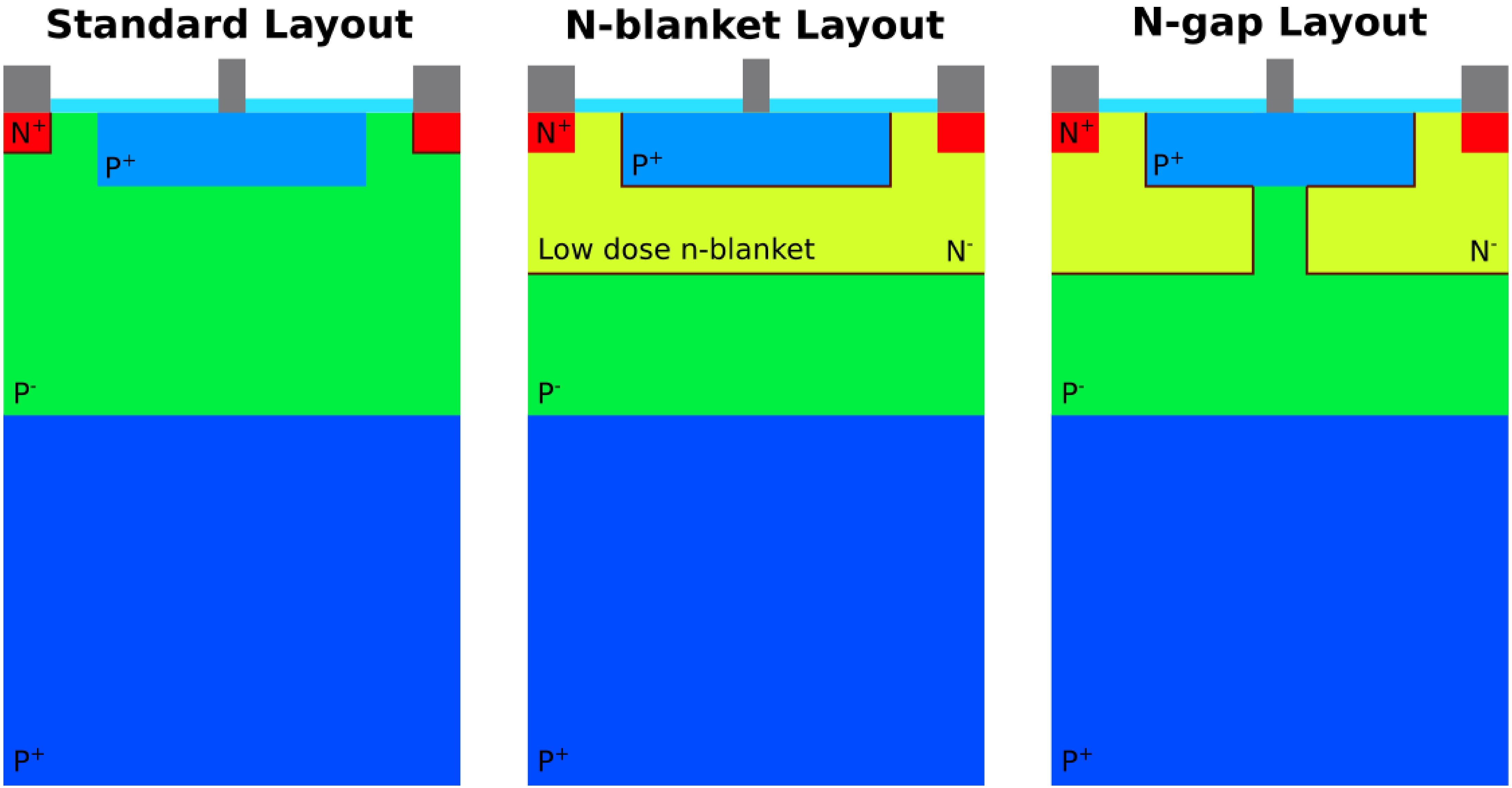
⇩

Electric Field Optimization

⇩

Sensor Design

Sensor Modifications



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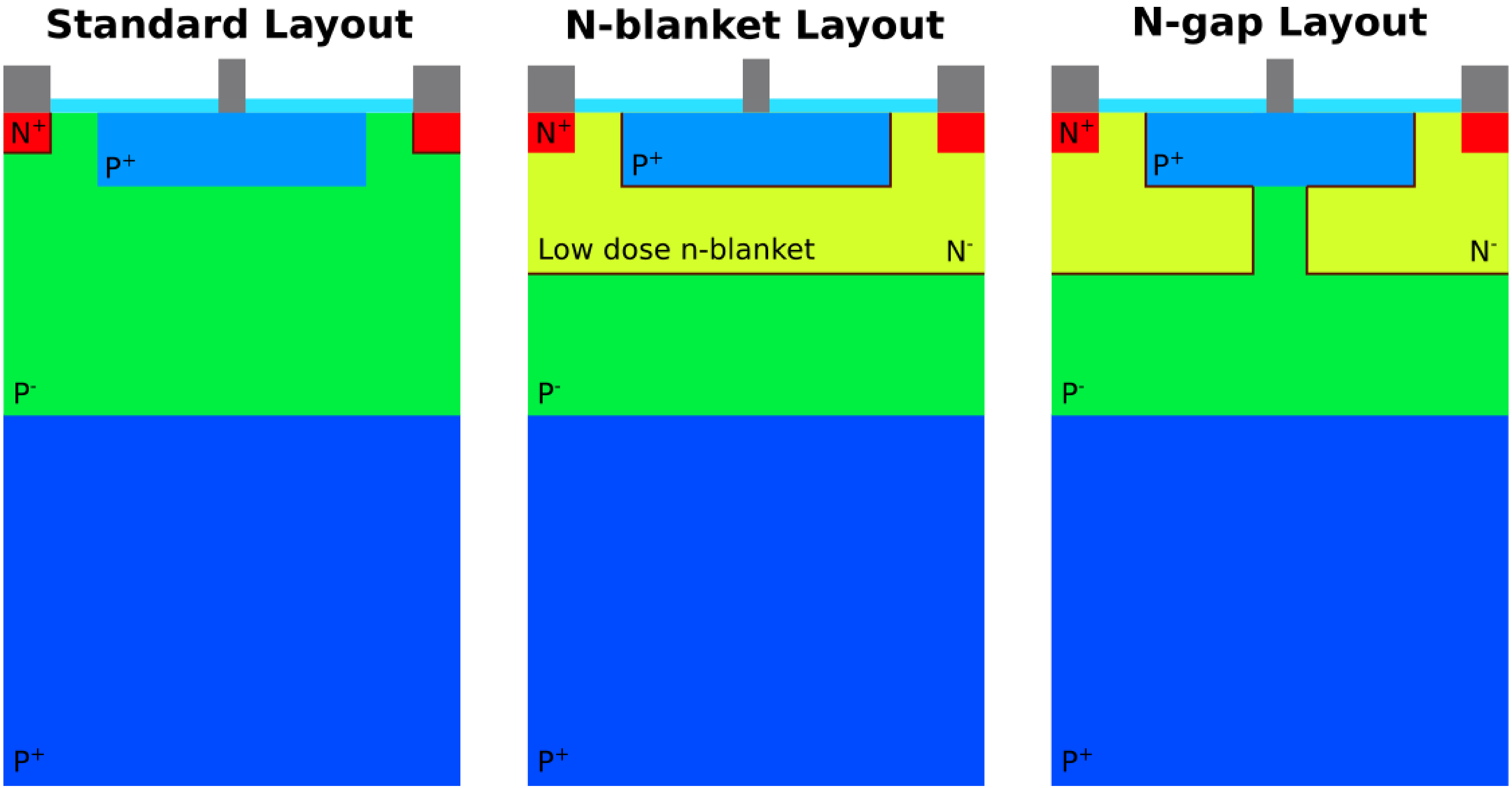

Sensor layouts are studied with **simulations** and **prototype testing**

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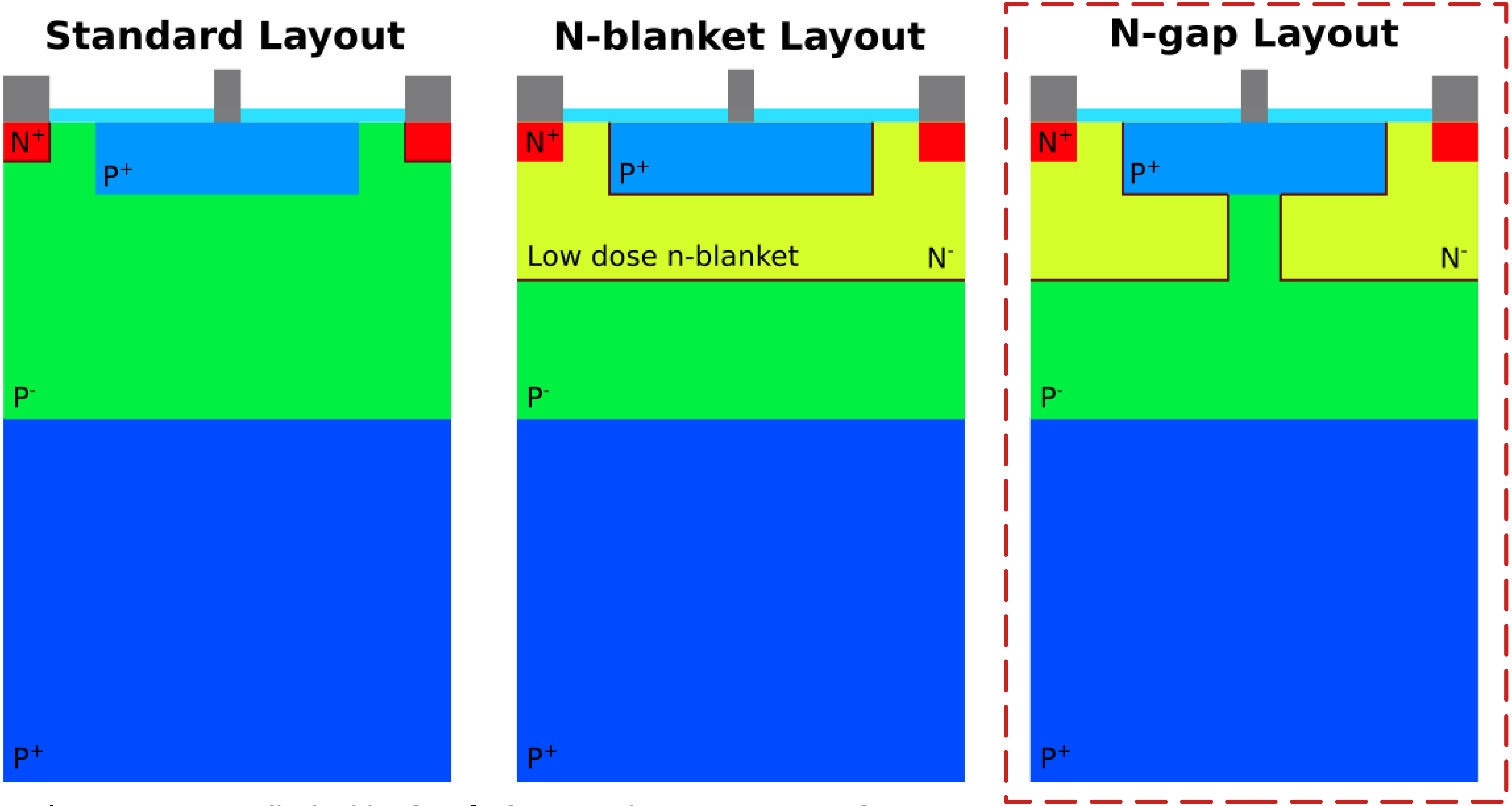

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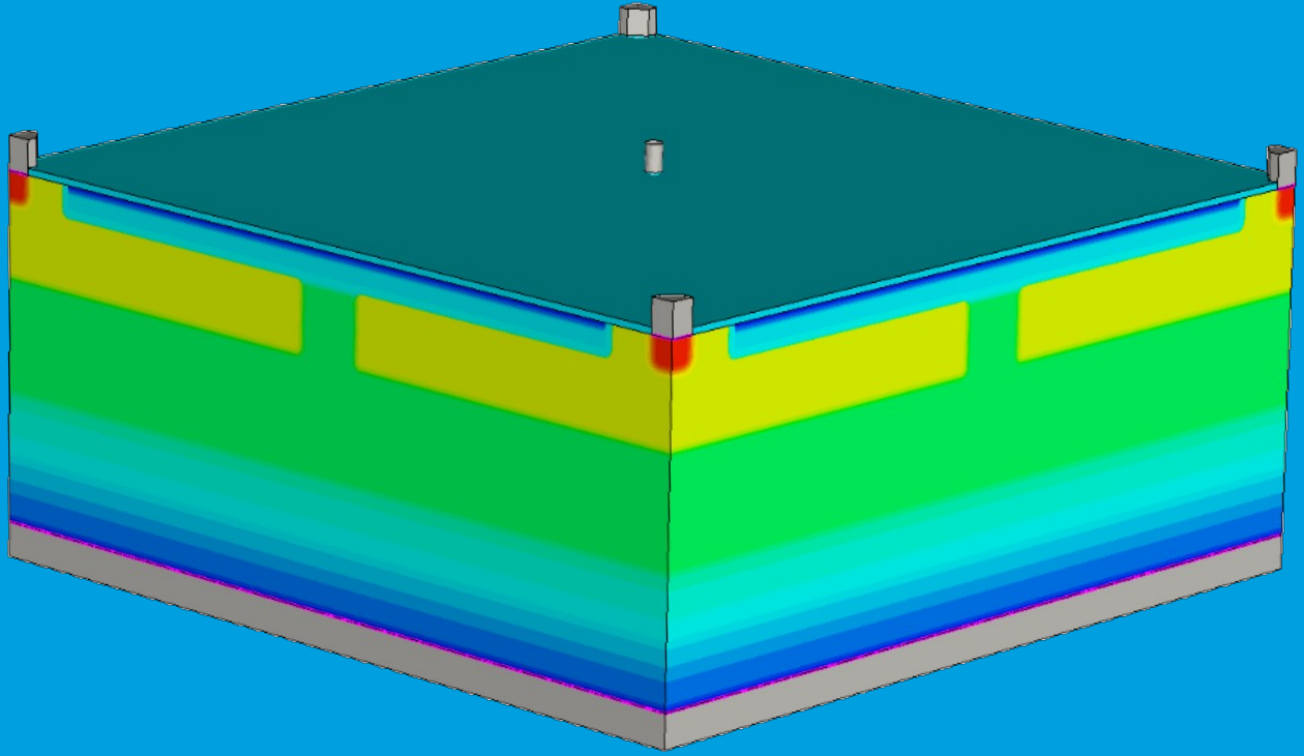
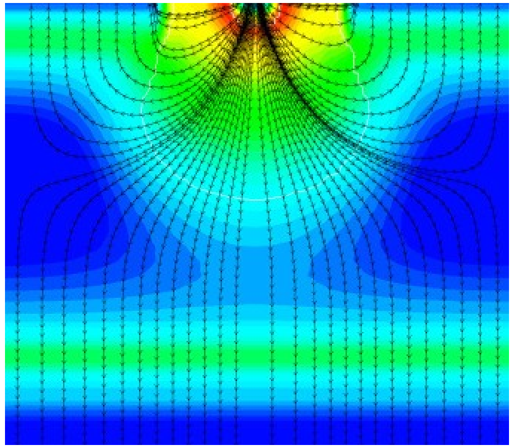
Simulations



Simulation Tools

Technology **C**omputer-**A**ided **D**esign

- ✔ Model semiconductor fabrication and device operation
- ✔ Electric Fields: accurate and realistic



Electric field of MAPS near collection implant

S. Spannagel et al.

Simulation Tools

Sentaurus TCAD — SYNOPSYS® Silicon to Software™

Technology **C**omputer-**A**ided **D**esign

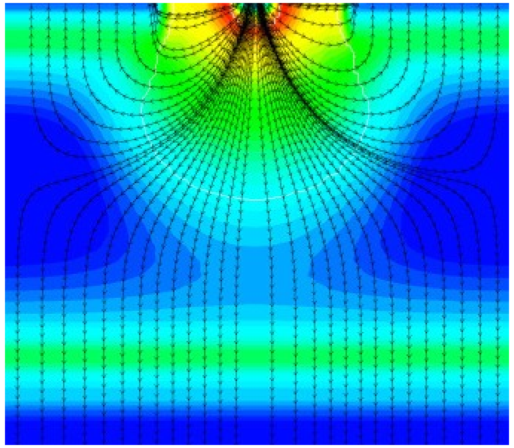
+

ap² allpix squared — Allpix^2: Monte Carlo Simulations for Semiconductor Detectors

S. Spannagel et al.

- ✔ Model semiconductor fabrication and device operation
- ✔ Electric Fields: accurate and realistic

- ✔ Simulate full response of semiconductor detector
- ✔ Particle Events: fast and high statistics



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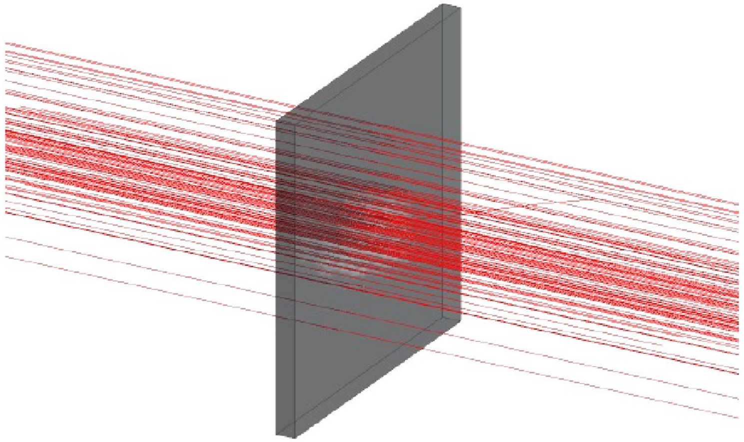
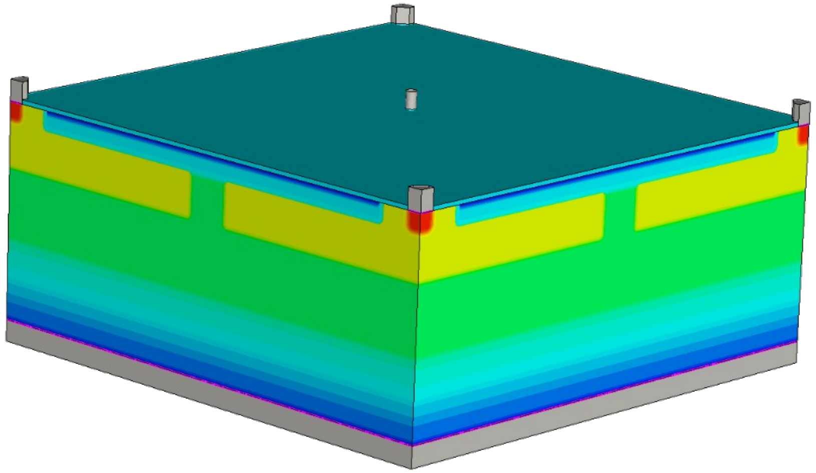


Simulations

TCAD Workflow | N-gap Layout

- ✔ Results in BTTB10
- ✔ Create realistic design with generic doping profiles
- ✔ Scans over different geometrical and functional parameters
- ✔ Observe the behavior of the electric field, lateral electric field and depleted volume
- ✔ Select sensible parameters

Doping Concentration



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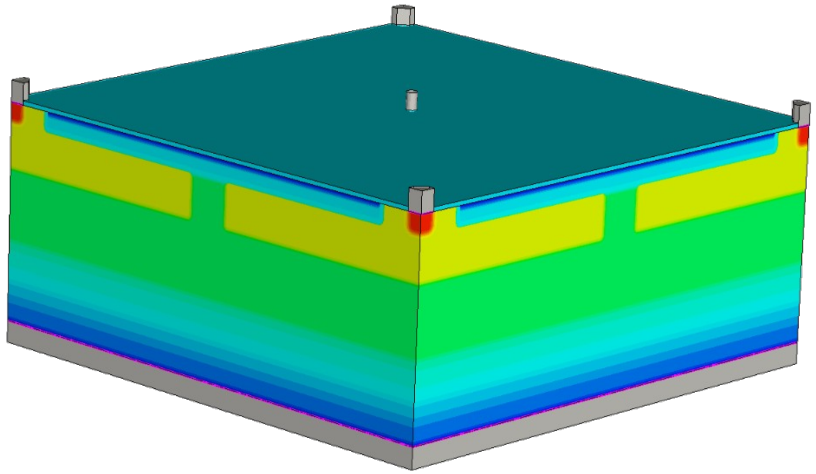
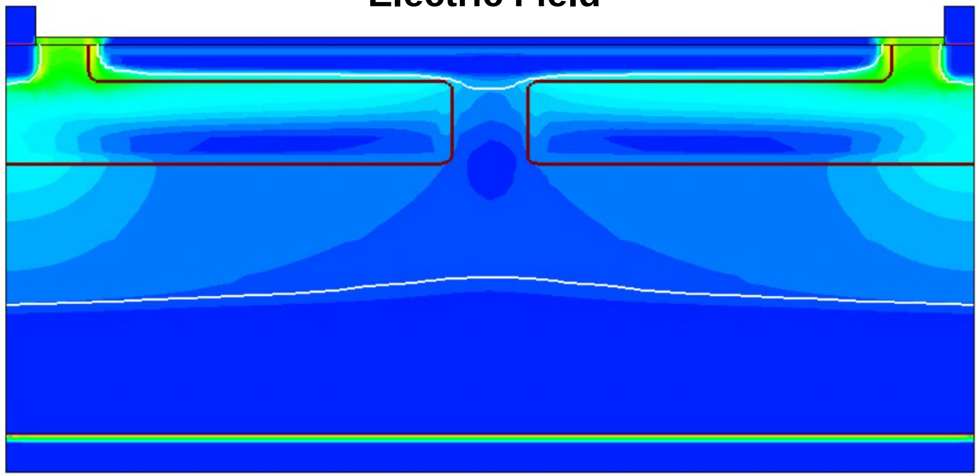
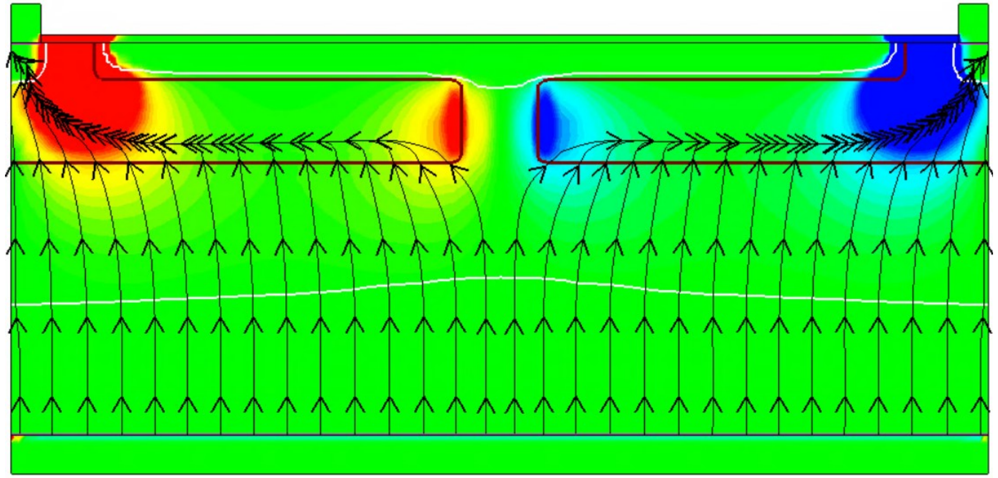


Electric Field



Lateral Electric Field



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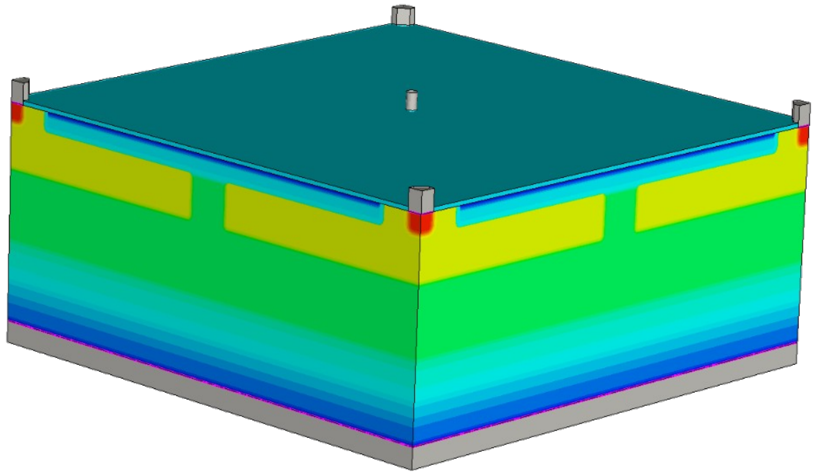
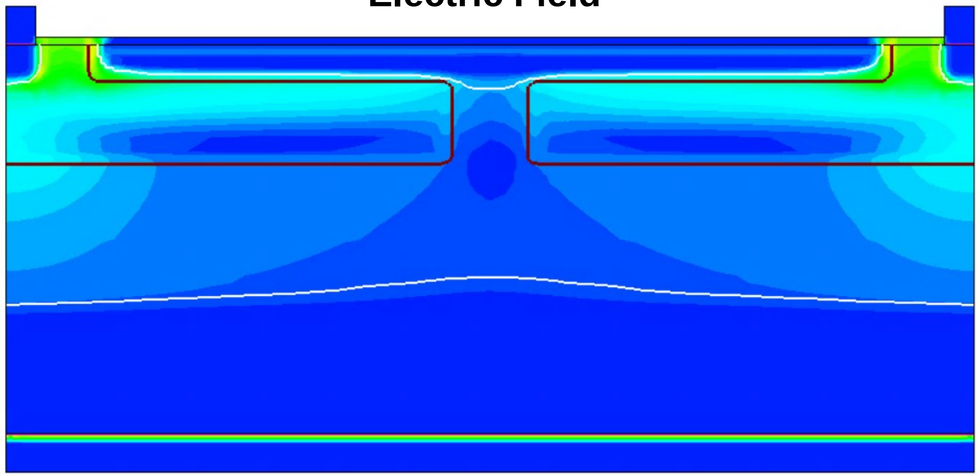


Electric Field



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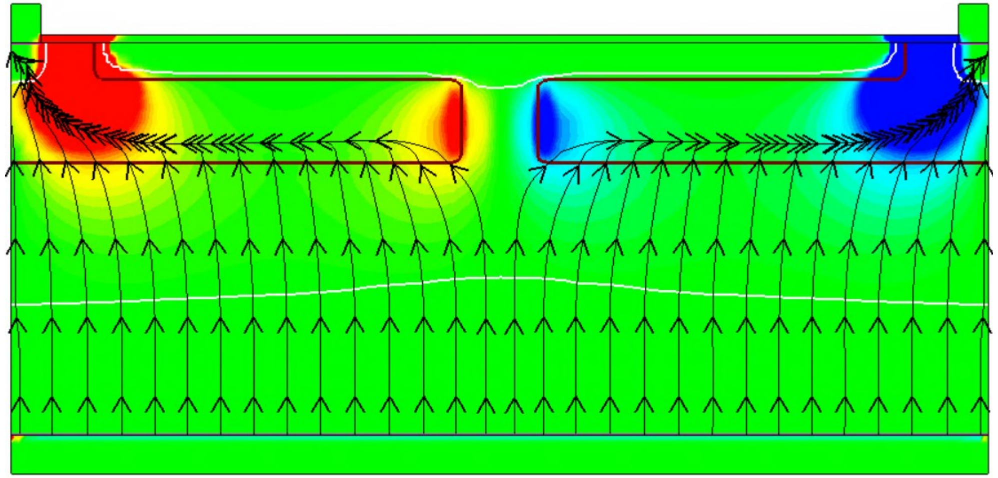
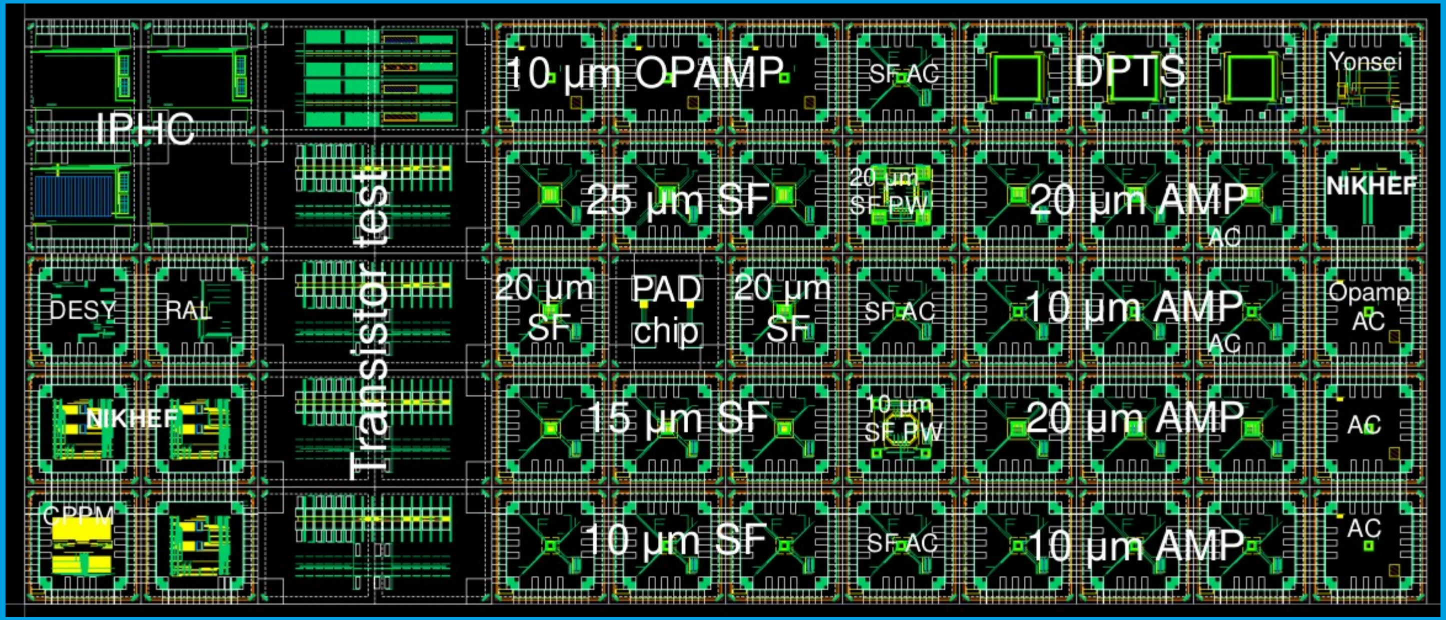


higher lateral electric field in pixel corners → - improvement in efficiency and charge collection time
- impairment of resolution

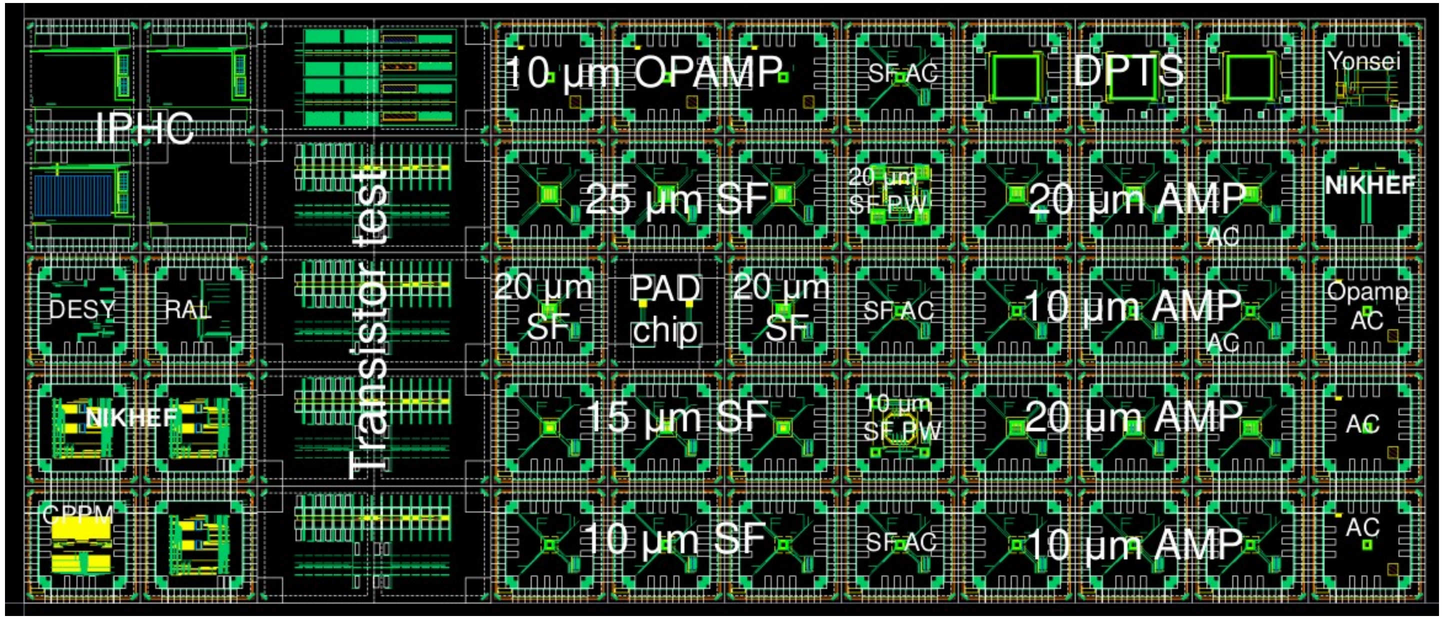
TCAD electric field input for **Monte-Carlo simulations** with Allpix^2 to produce performance plots.

Prototype Testing



The Prototype

- ✔ International collaboration for common submissions to foundry with 65 nm CMOS process
- ✔ A first submission was done as a Multi Layer Reticle (MLR1)



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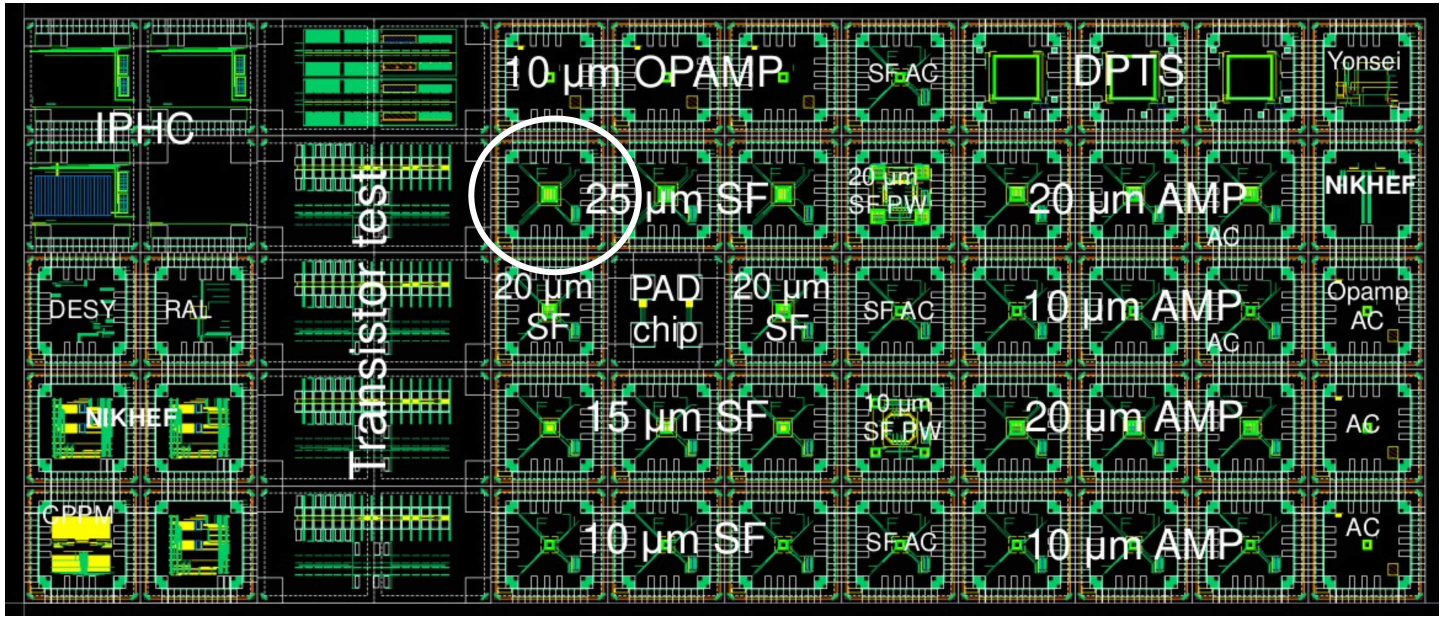
Analog Pixel Test Structure (APTS) W. Deng et al.

- ✔ Designed by ALICE
- ✔ Available in all layouts
- ✔ 4x4 pixels
- ✔ More about this in G. Alocco's talk



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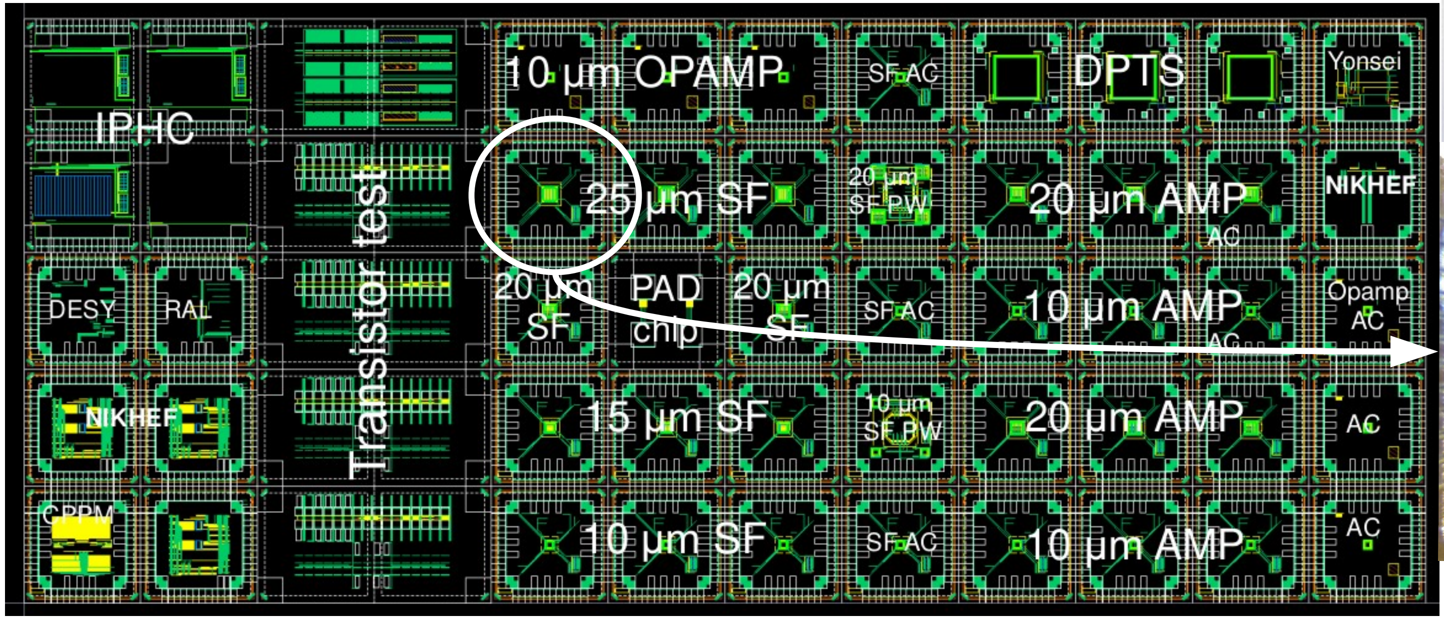
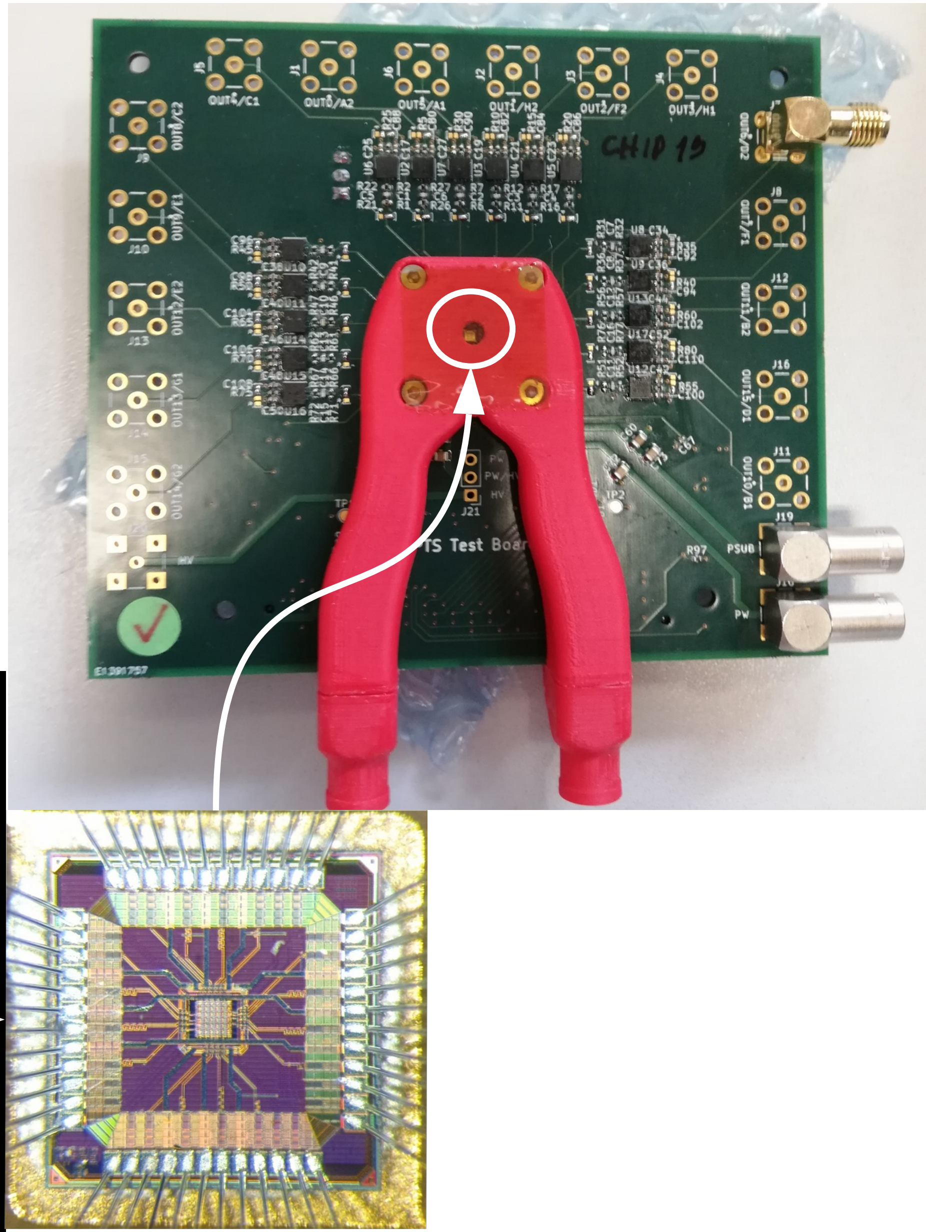
ALICE EP R&D





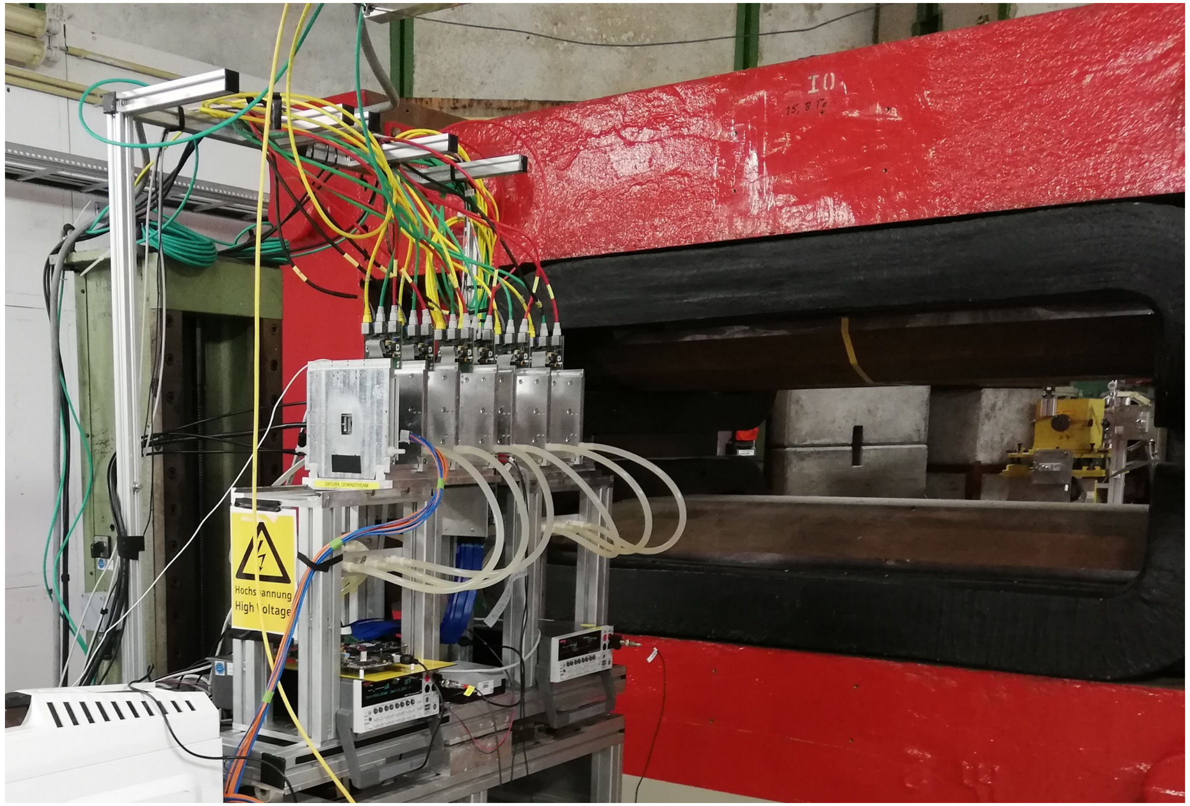
The Test Beam

Facility

- ✔ Used for testing and characterizing new devices under realistic conditions
- ✔ Tests performed at DESY-II with 4 GeV e^- beam and MIMOSA26 telescope

J. Dreyling-Eschweiler et al.

H. Jansen et al.



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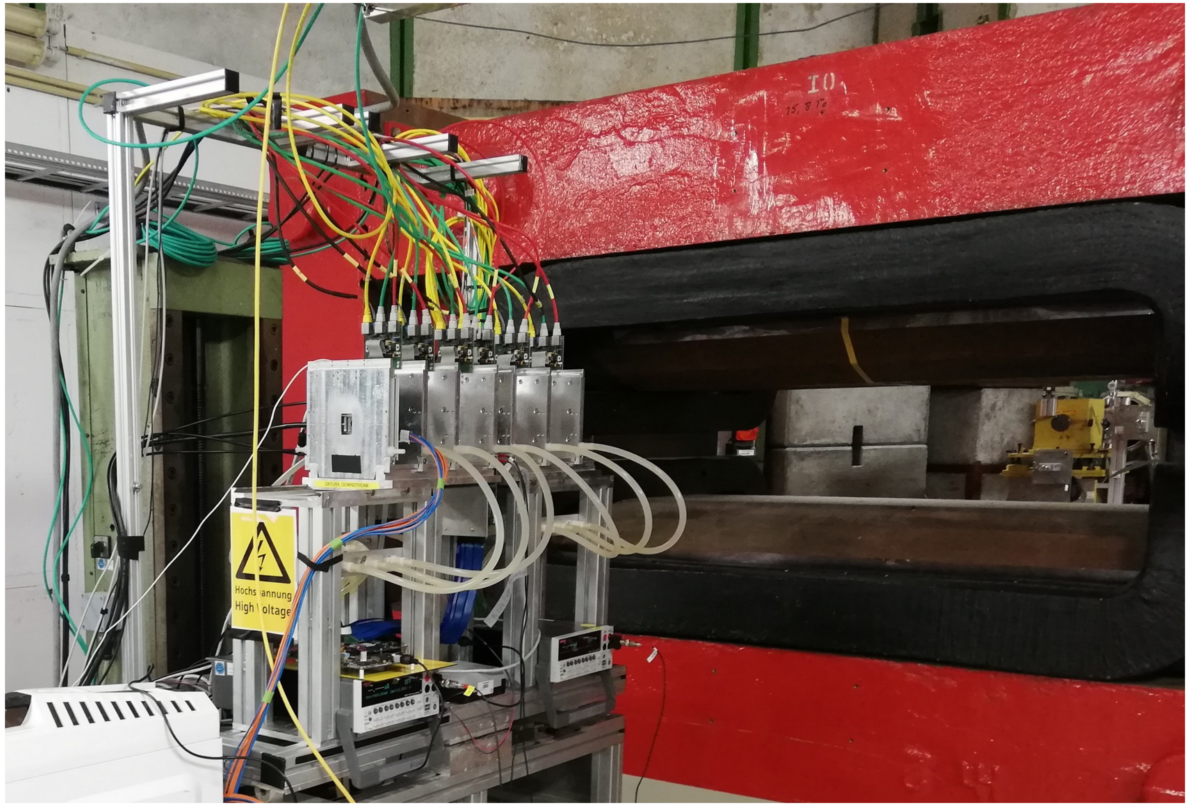

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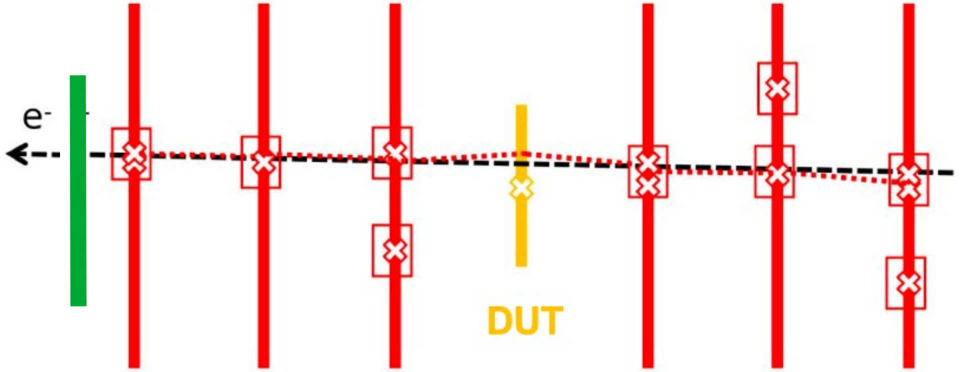
  J. Dreyling-Eschweiler et al. DESY TEST BEAM.
  H. Jansen et al. EUDET

Setup

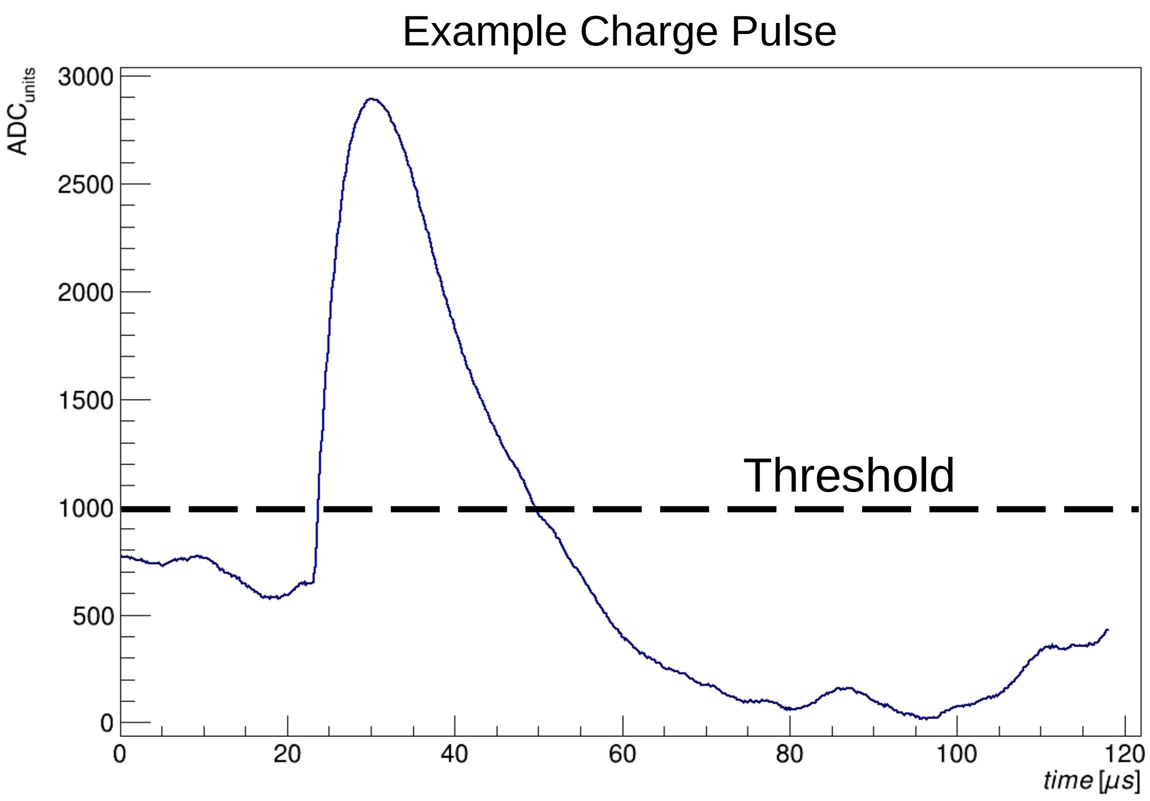
- ✔ Telescope: 6 detector planes perpendicular to beam → tracking
- ✔ Trigger plane: Telepix (See A. Wintle's talk) L.Huth et al.
- ✔ DUT: Device Under Test → placed in the center
- ✔ DAQ system based on Caribou T. Vanat EUDAQ P. Ahlburg et al.
- ✔ Corryvreckan framework for track reconstruction
  D. Dannheim et al.



Data Analysis

Corryvreckan

- ✔ Particle tracks reconstructed with Telescope data
- ✔ DUT pulse shape per pixel acquired
- ✔ Threshold applied to pixel with highest charge (seed pixel) and surrounding pixels to form clusters
- ✔ Clusters associated to tracks
- ✔ Perform studies: **detection efficiency**, spatial resolution, **charge distribution**, etc.



- ✔ ADC units calibrated to charge
- ✔ 1000 ADC units ~ 200 e

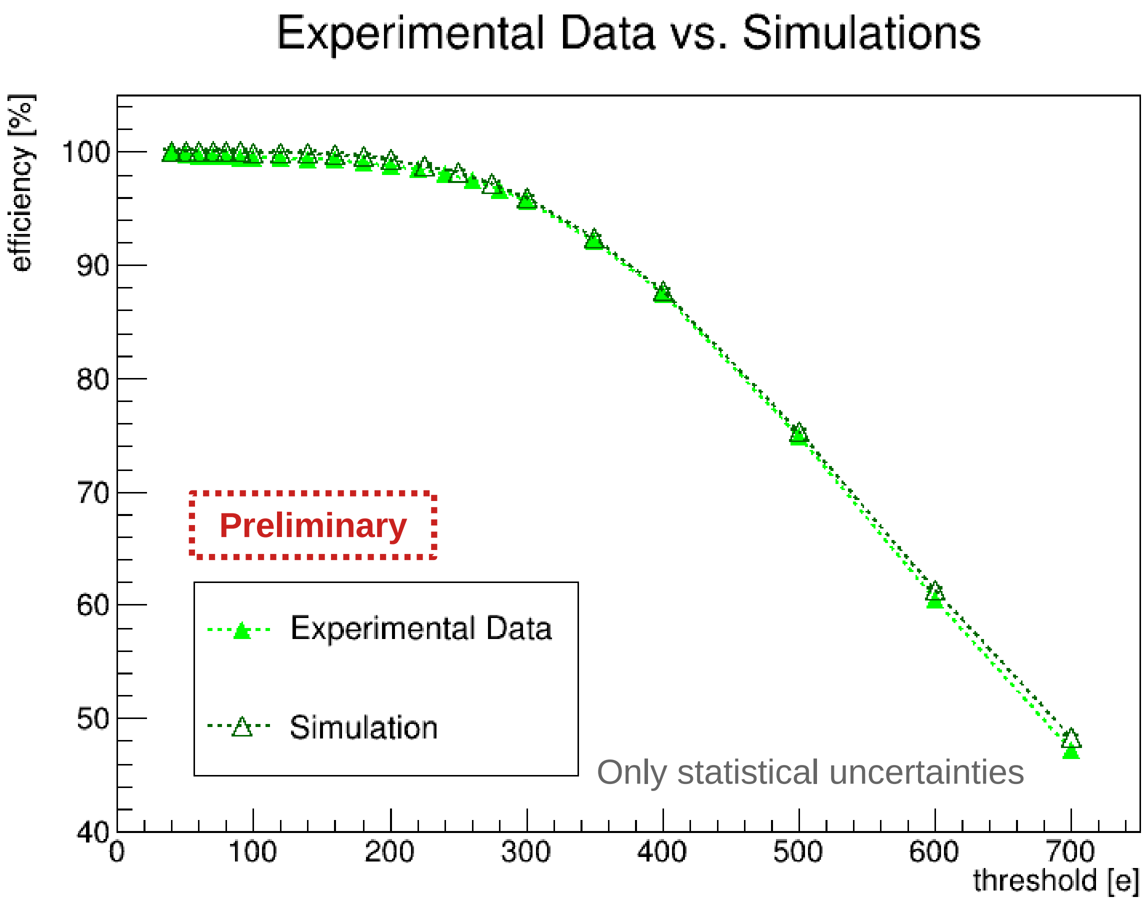
Efficiency vs. Threshold

N-gap Layout

APTS
25 µm pitch
Bias = -4.8 V

Simulation vs. Experiment

✔ Similar trend in experimental data and simulation



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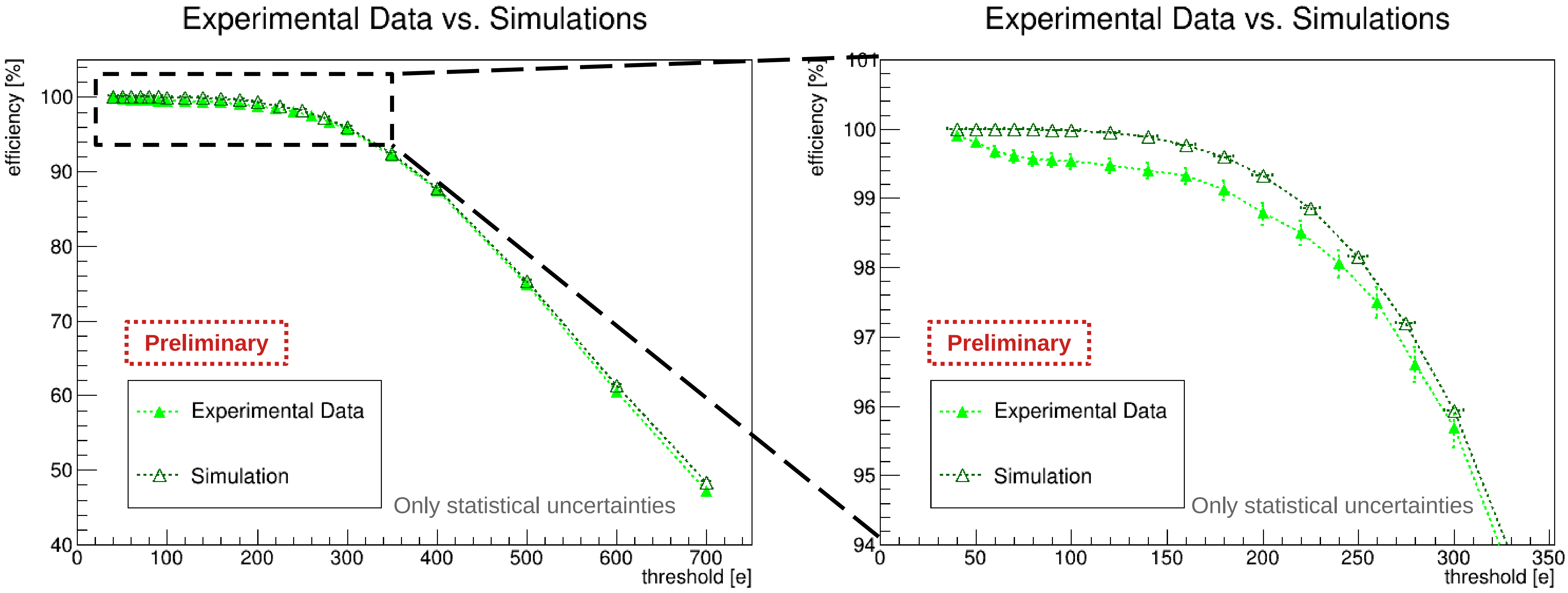
- ✔ Experimental efficiency < simulated efficiency → might recover experimental efficiency with finer analysis



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Simulation vs. Experiment - Bias Voltage Comparison

- ✔ No significant impact
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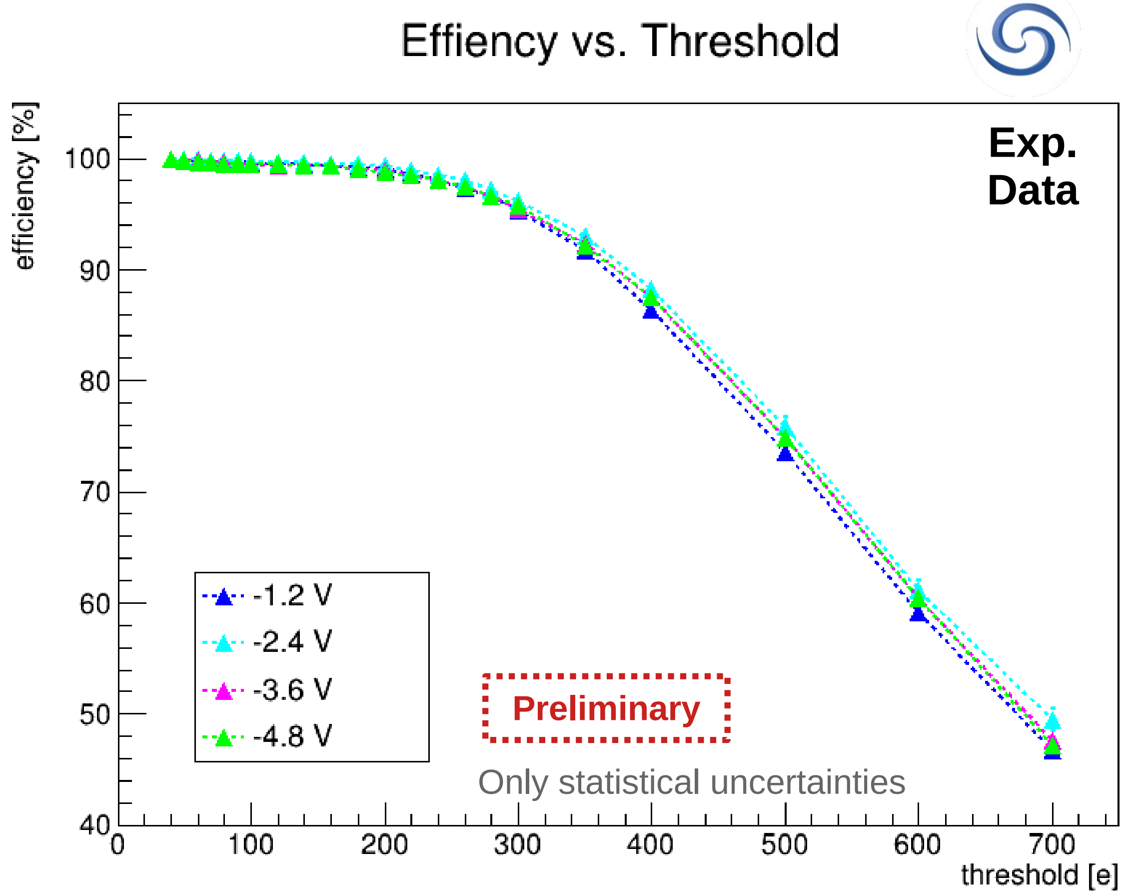

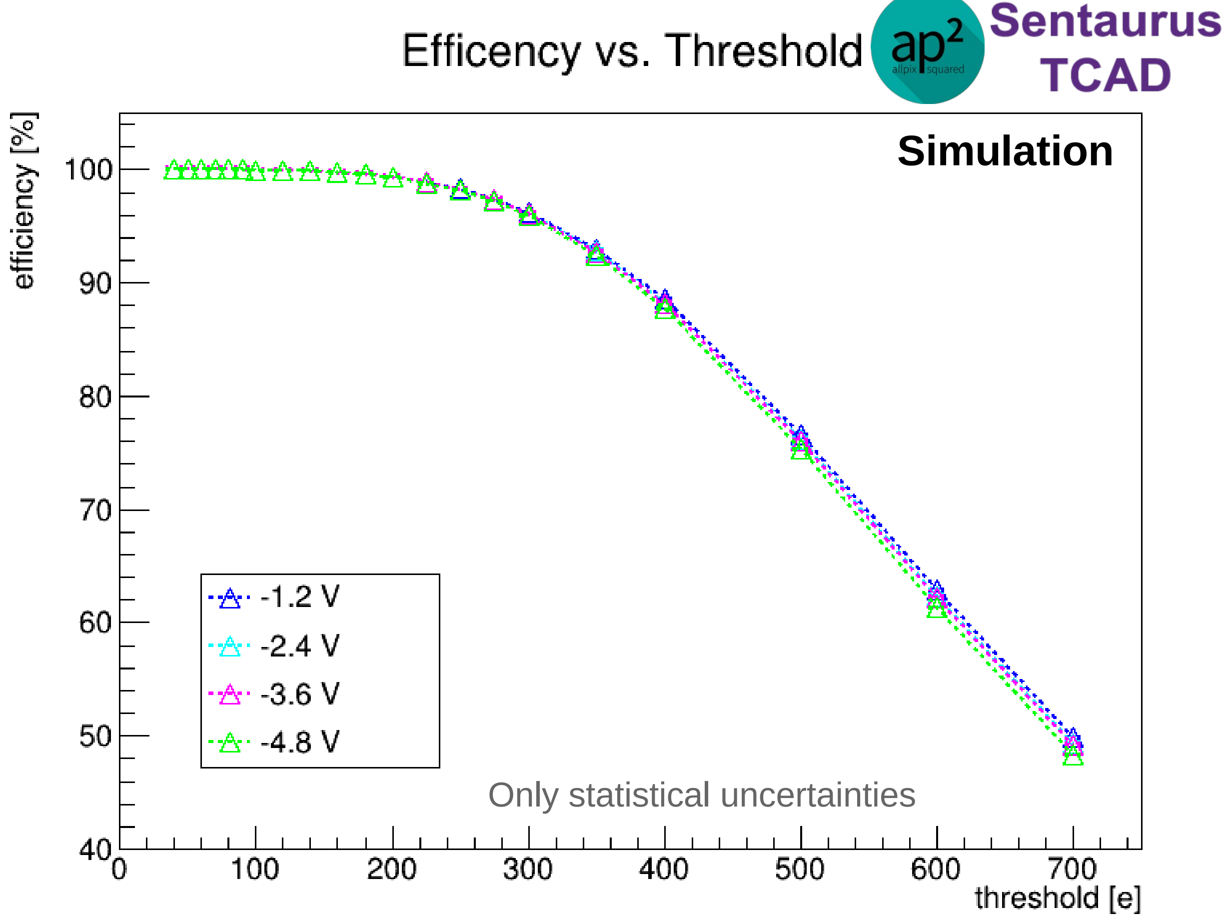

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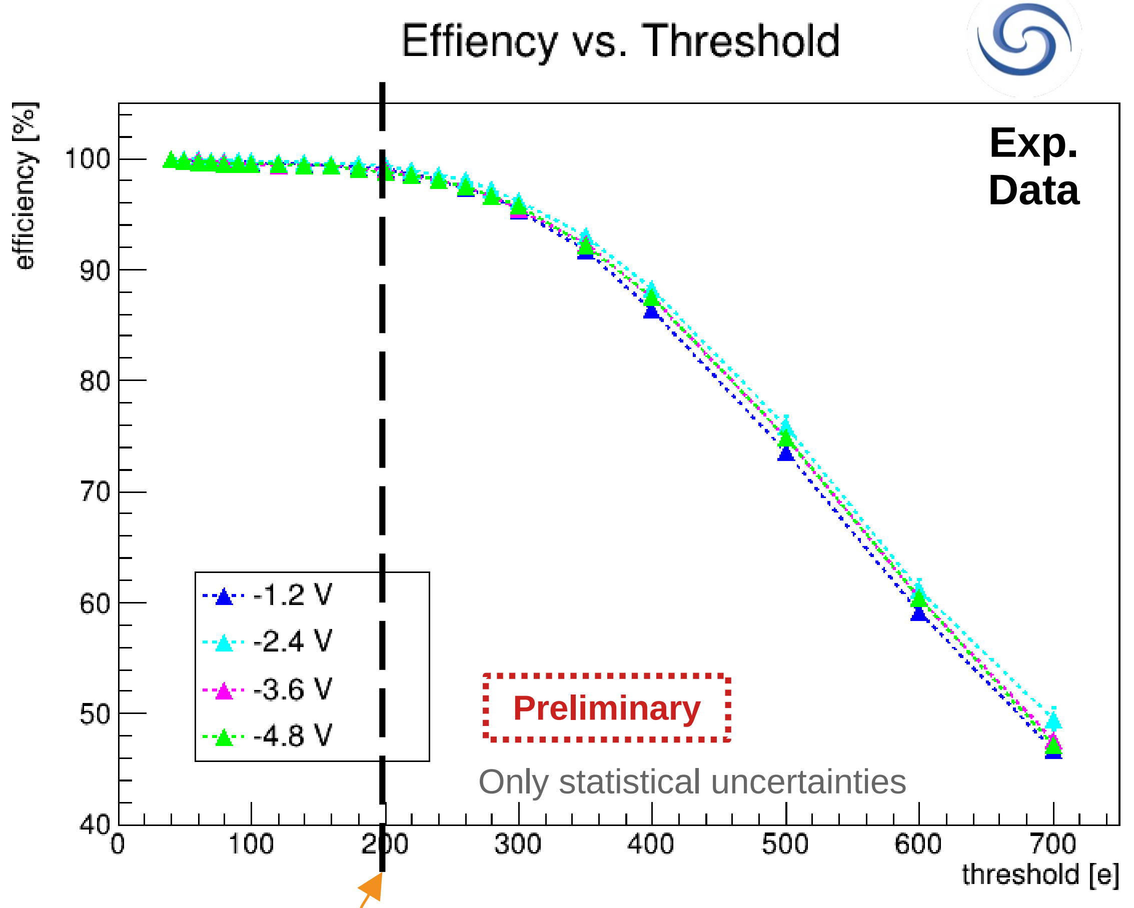
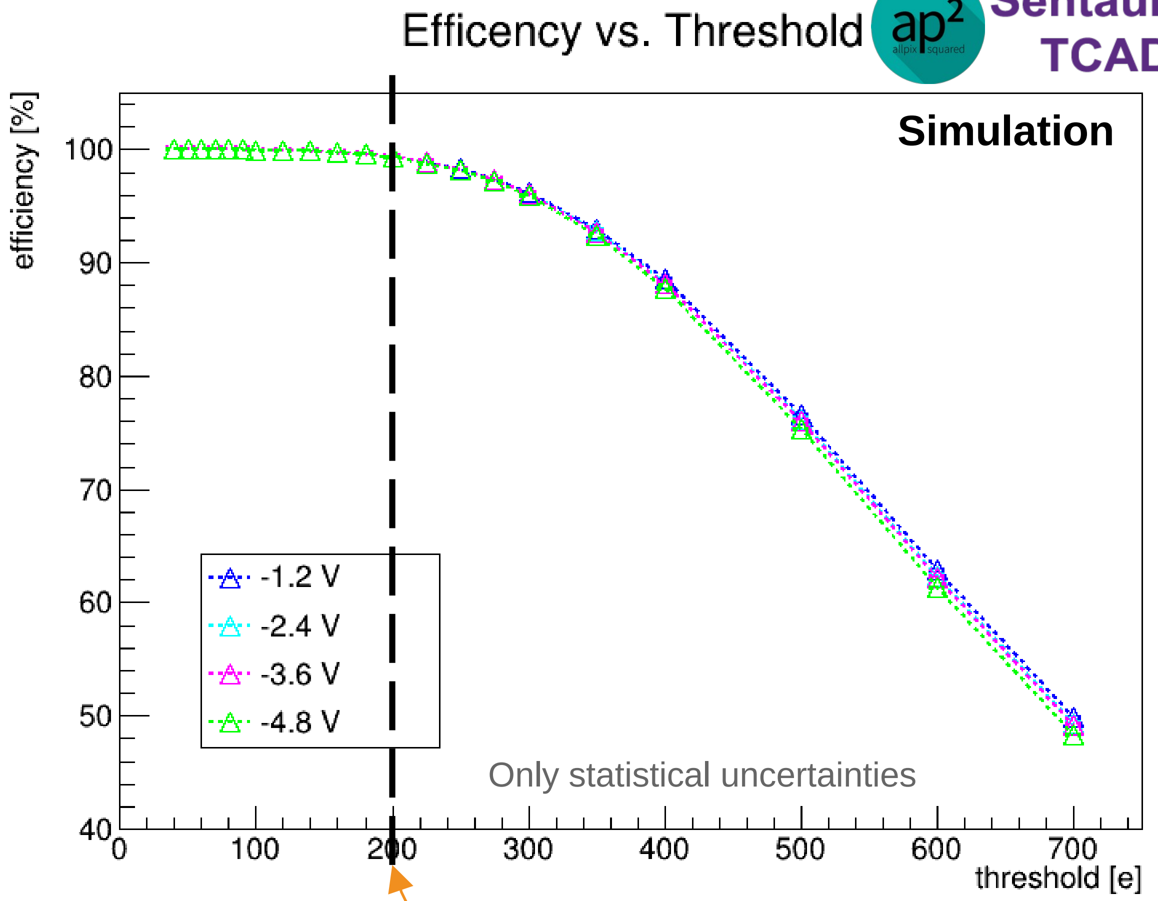




We can take a look at a specific threshold...

In-pixel Efficiency

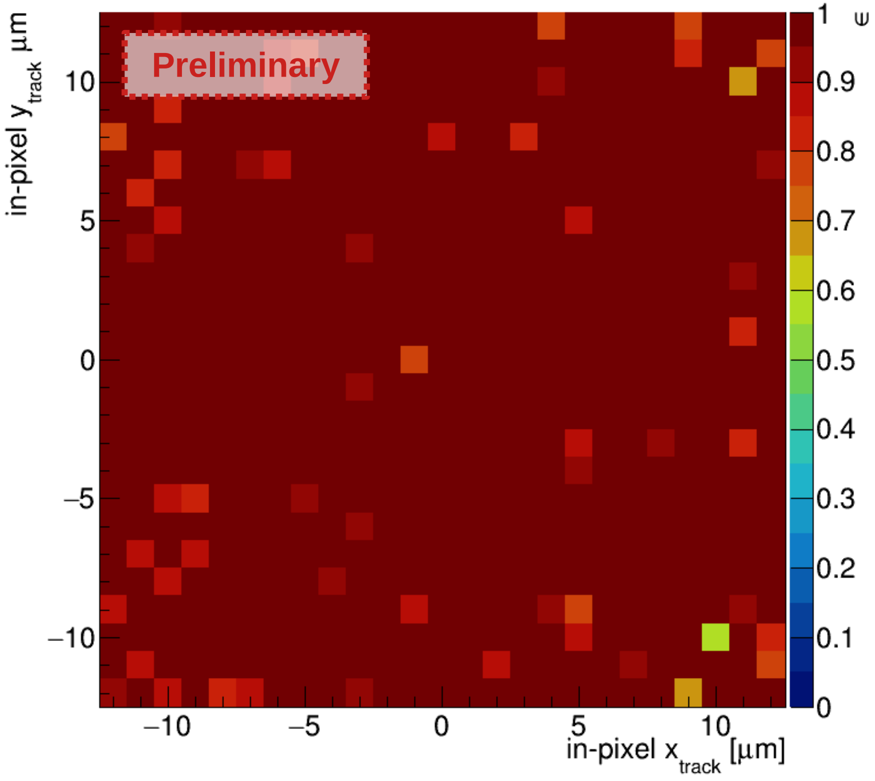
Simulation vs. Experiment

N-gap Layout

APTS
25 µm pitch
Bias = -4.8 V
Threshold = 200 e

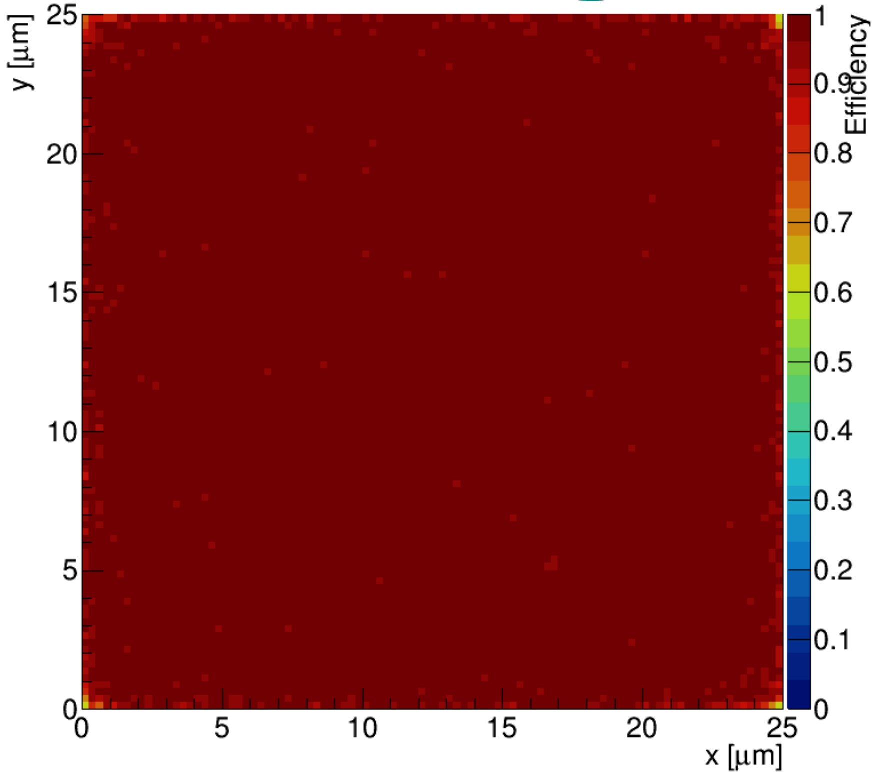
✔ Efficiency affected by inner structures of pixel?

Exp. Data



Simulation

Sentaurus TCAD



In-pixel Efficiency

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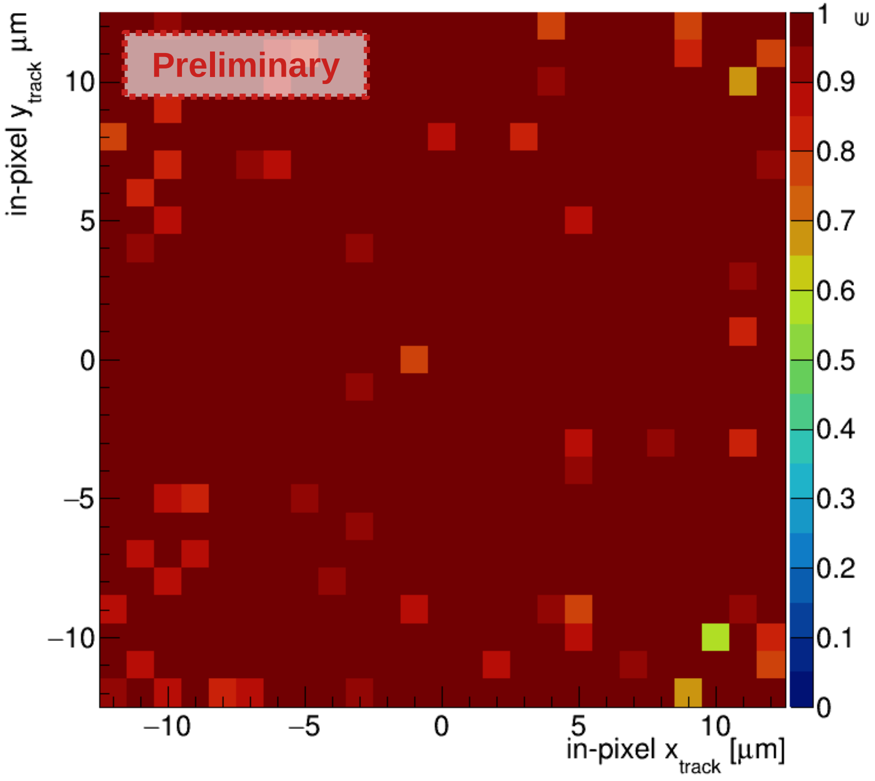
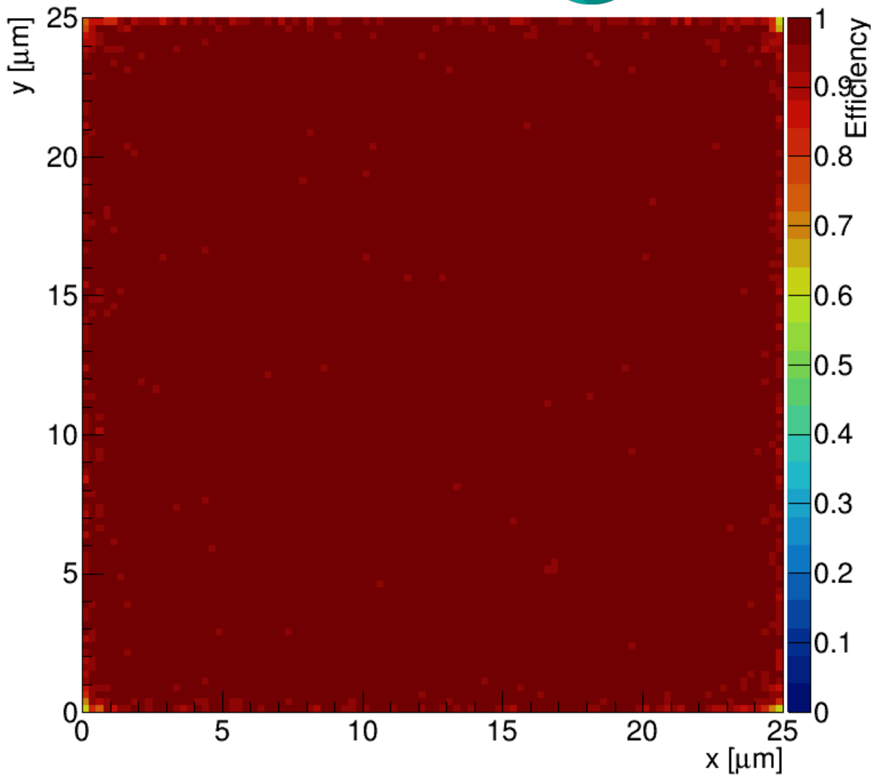
Simulation vs. Experiment

- ✔ Efficiency affected by inner structures of pixel?
- ✔ Fairly uniform in-pixel efficiency
- ✔ Similar trend in experimental data and simulation
- ✔ Difference due low statistics in measurements

Exp. Data



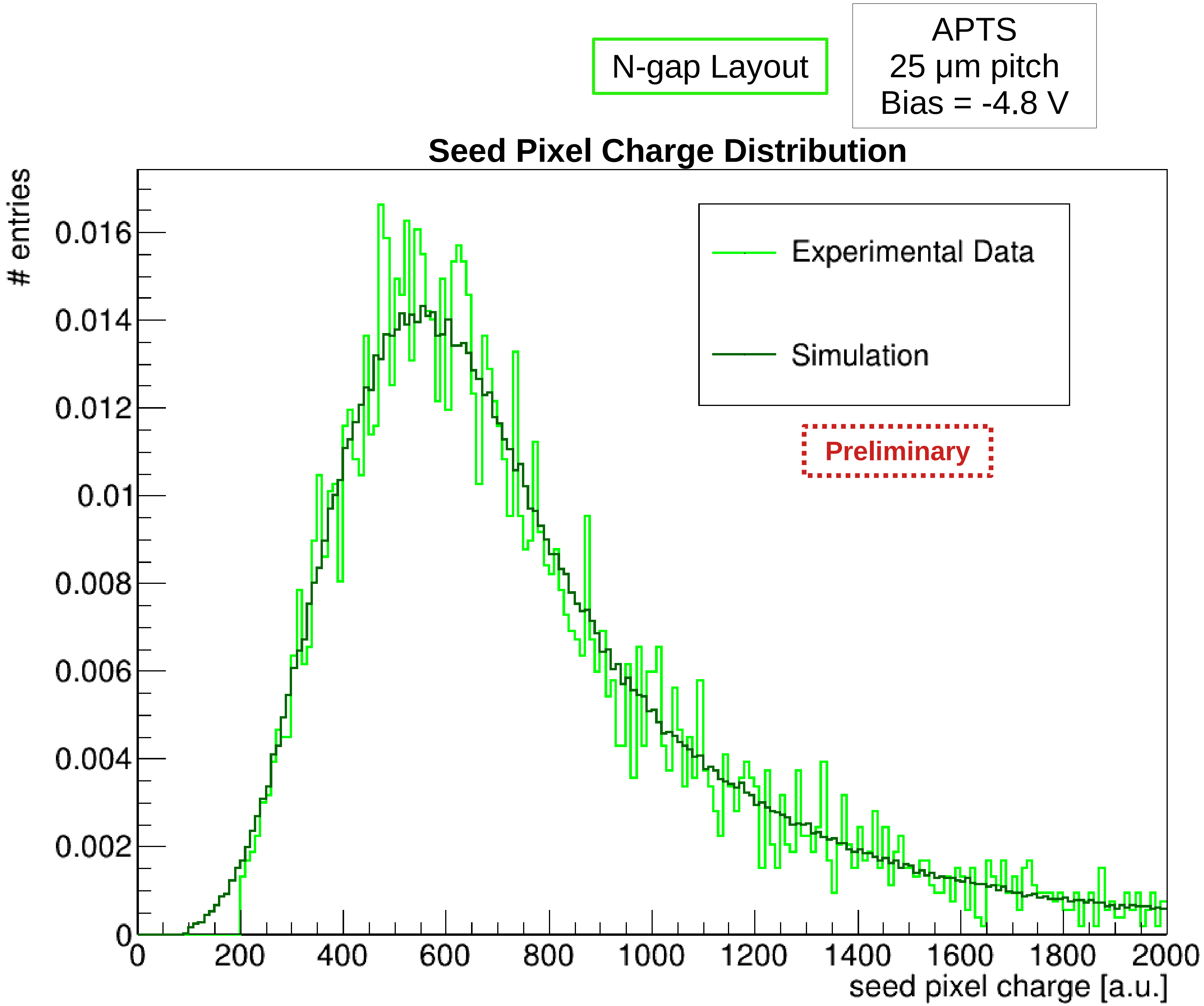
Simulation Sentaurus TCAD



Charge Distribution

Simulation vs. Experiment

- ✔ Seed pixel: pixel with highest collected charge per event
- ✔ Charge Distribution: Landau*Gaussian
- ✔ MPV ~ 550 e
- ✔ Similar trend in experimental data and simulation



Conclusions

- ✔ First development cycle of a MAPS in a 65 nm CMOS Imaging Technology
- ✔ Detector Layouts: standard, n-blanket and **n-gap**
- ✔ TCAD simulations using generic doping profiles have provided very useful insights for future sensor optimization
- ✔ Monte Carlo simulations produced results comparable with measurements
- ✔ Beam test of Analog Pixel Test Structure (APTS), thanks to the ALICE collaboration and EP R&D
- ✔ Preliminary detection efficiency and charge collection results
- ✔ TCAD + Monte Carlo Simulations and experimental results follow a similar trend
- ✔ **See other studies in the following talks by M. A. Del Rio Viera and S. Ruiz Daza!**

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Prospective Work

- ✔ More measurements → more statistics
- ✔ Continue analysis of test beam data
- ✔ More studies, including spatial resolution and timing
- ✔ Validate TCAD + Monte Carlo Simulations

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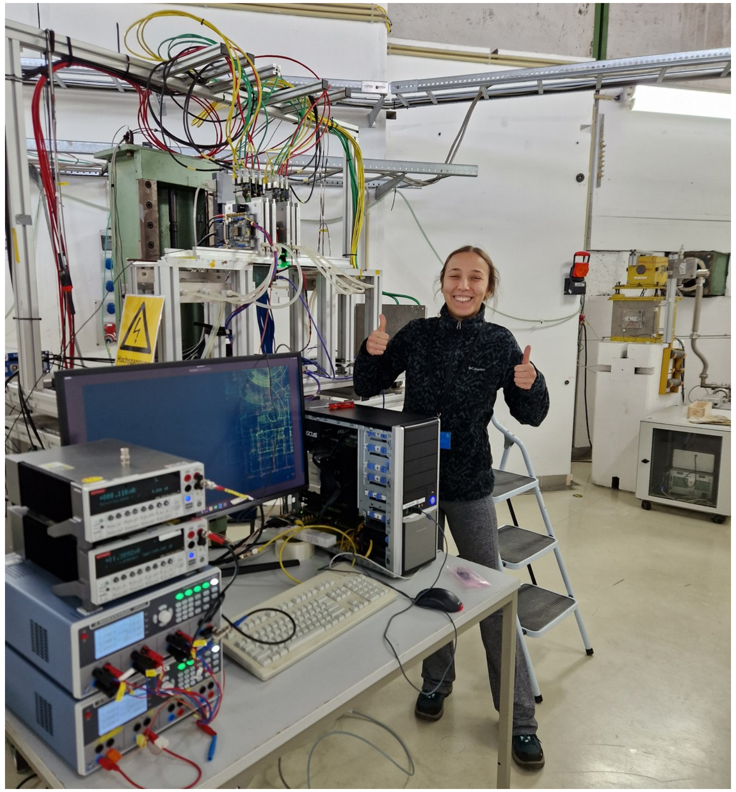

Back-up

Simulations

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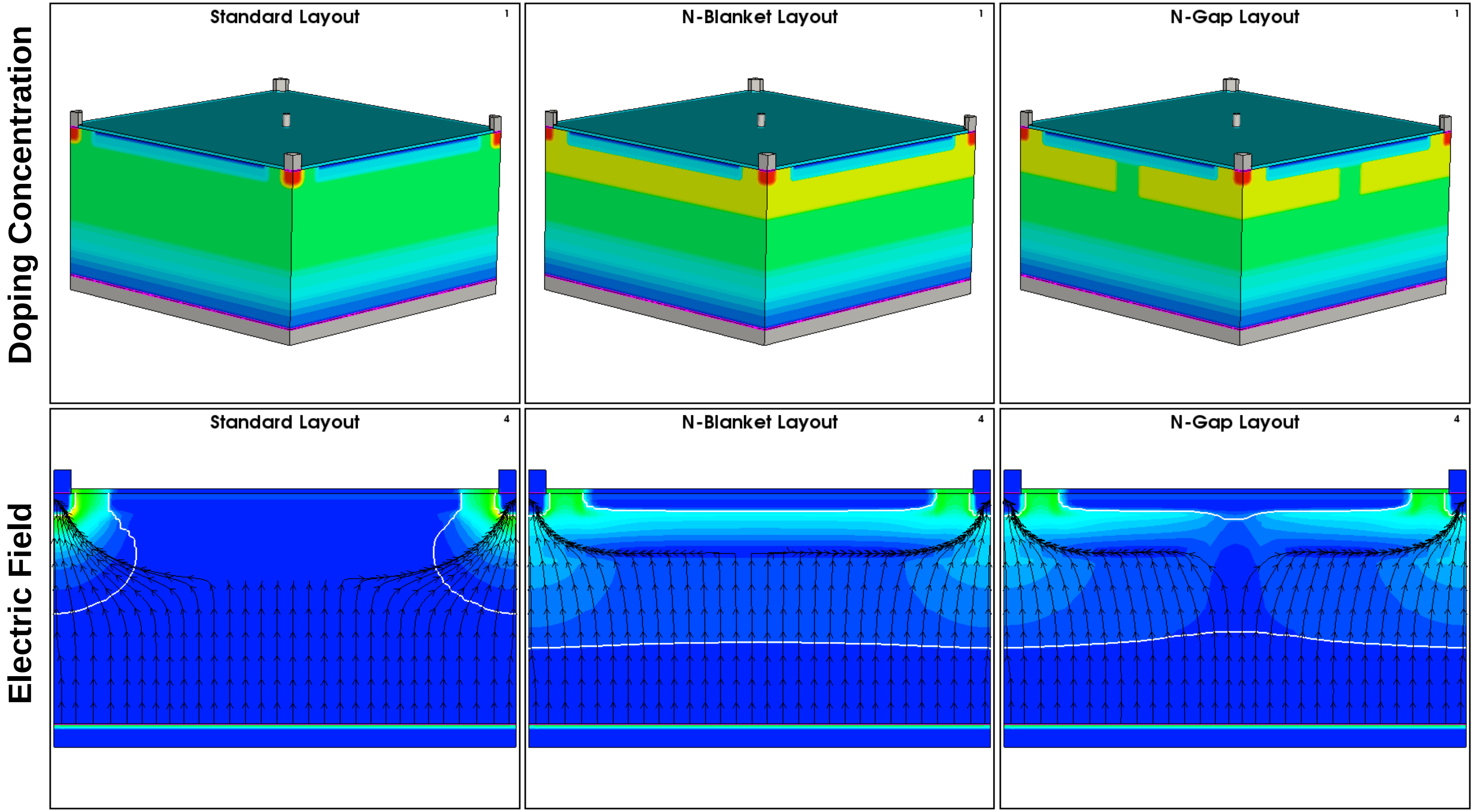


small depleted volume → - low efficiency - high charge sharing between pixels

larger depleted volume → - improvement in efficiency - impairment of resolution

higher electric field in pixel corners → - improvement in efficiency and charge collection time - impairment of resolution

Combining Tools

TCAD + Monte Carlo Simulations

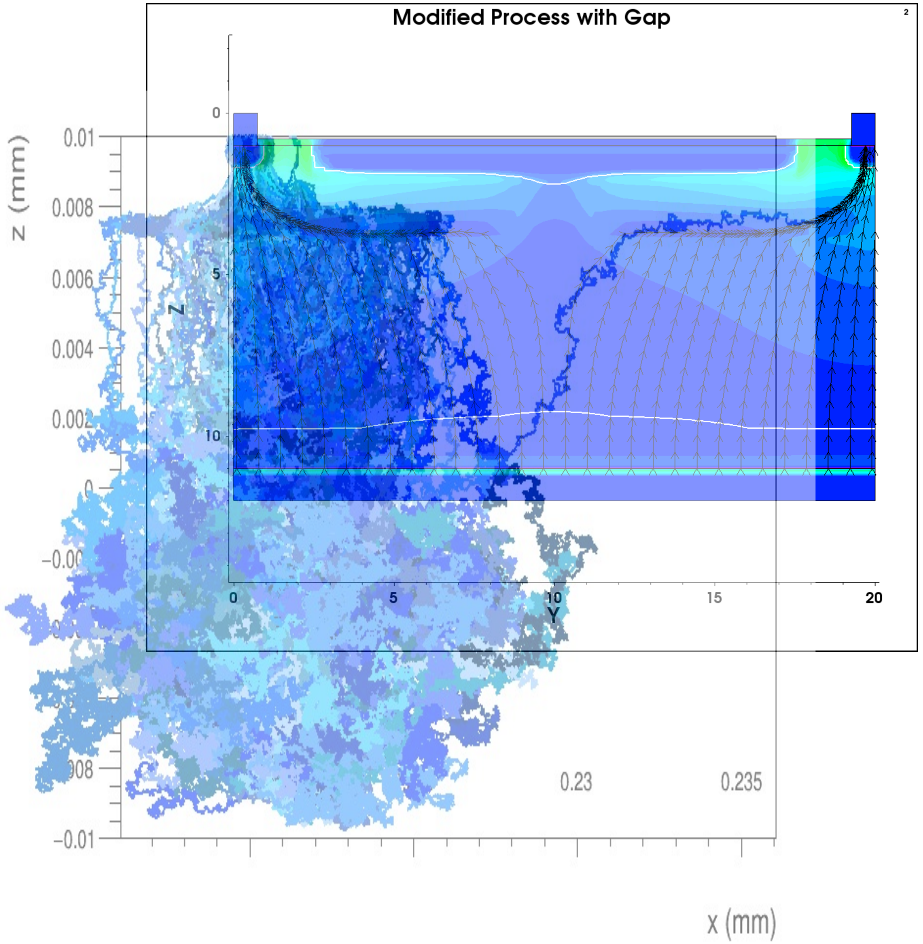
Performance parameters:

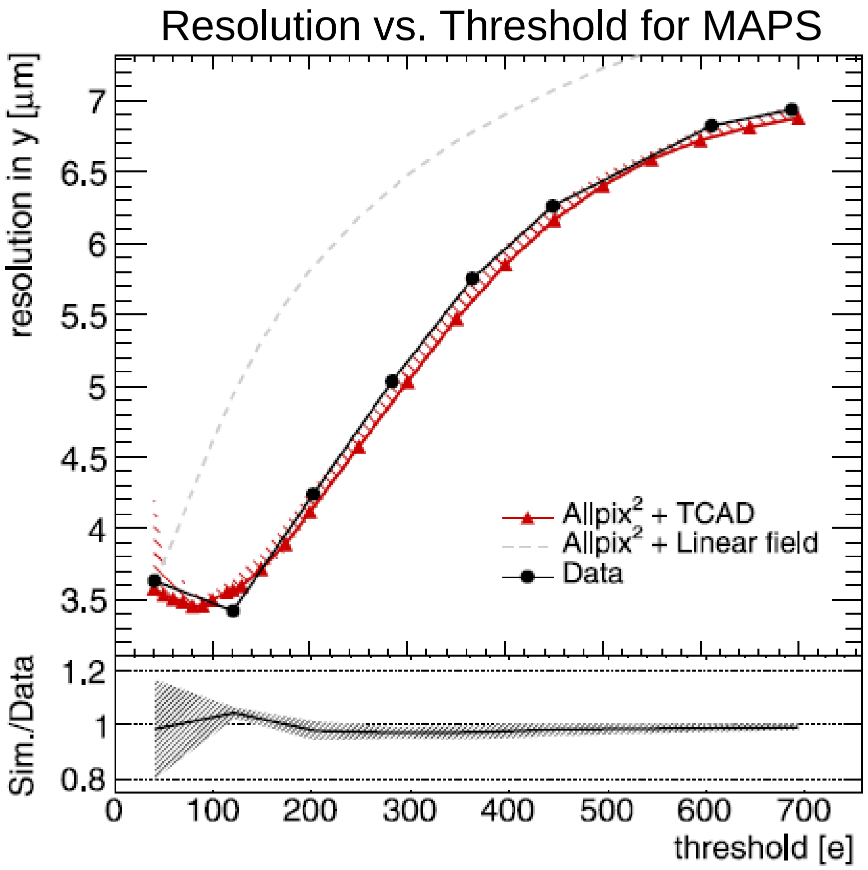
- Spatial resolution
- Timing resolution
- Detection efficiency

Why do we need to combine TCAD + Allpix^2?

Electric Fields:

- Linear
- Customized (TCAD)



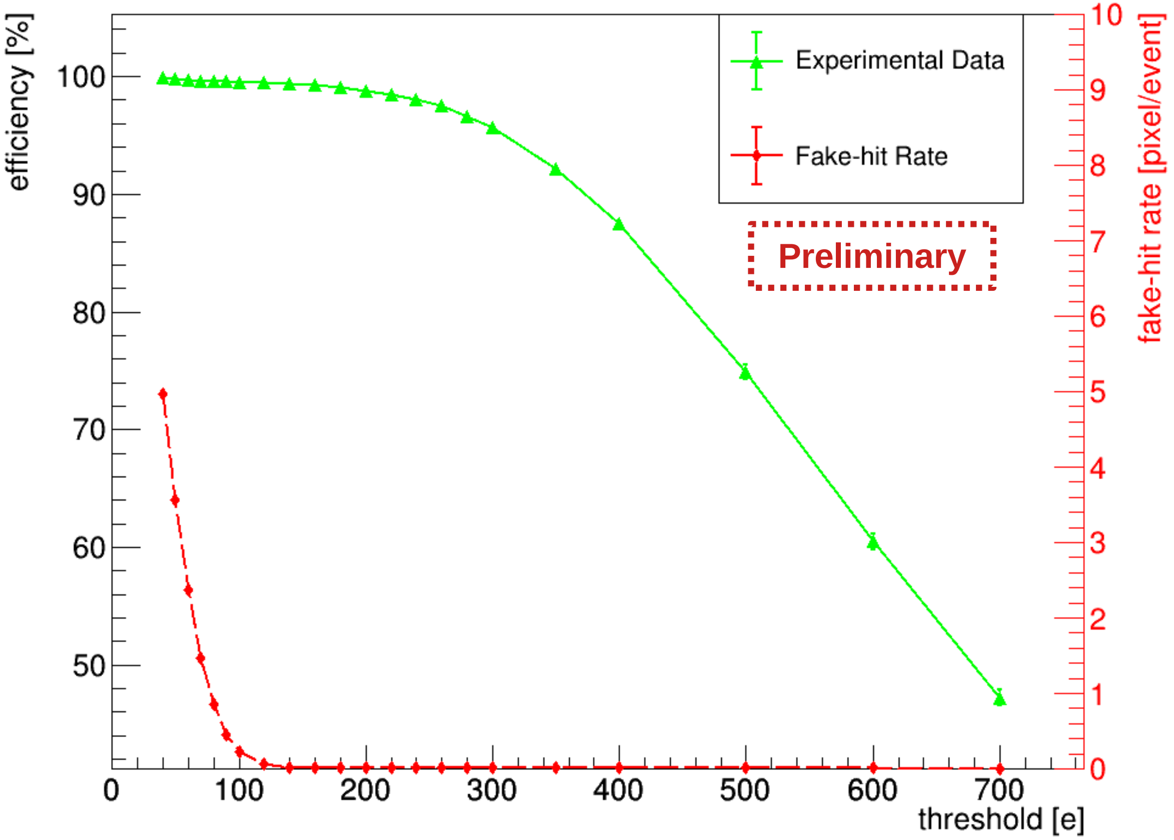


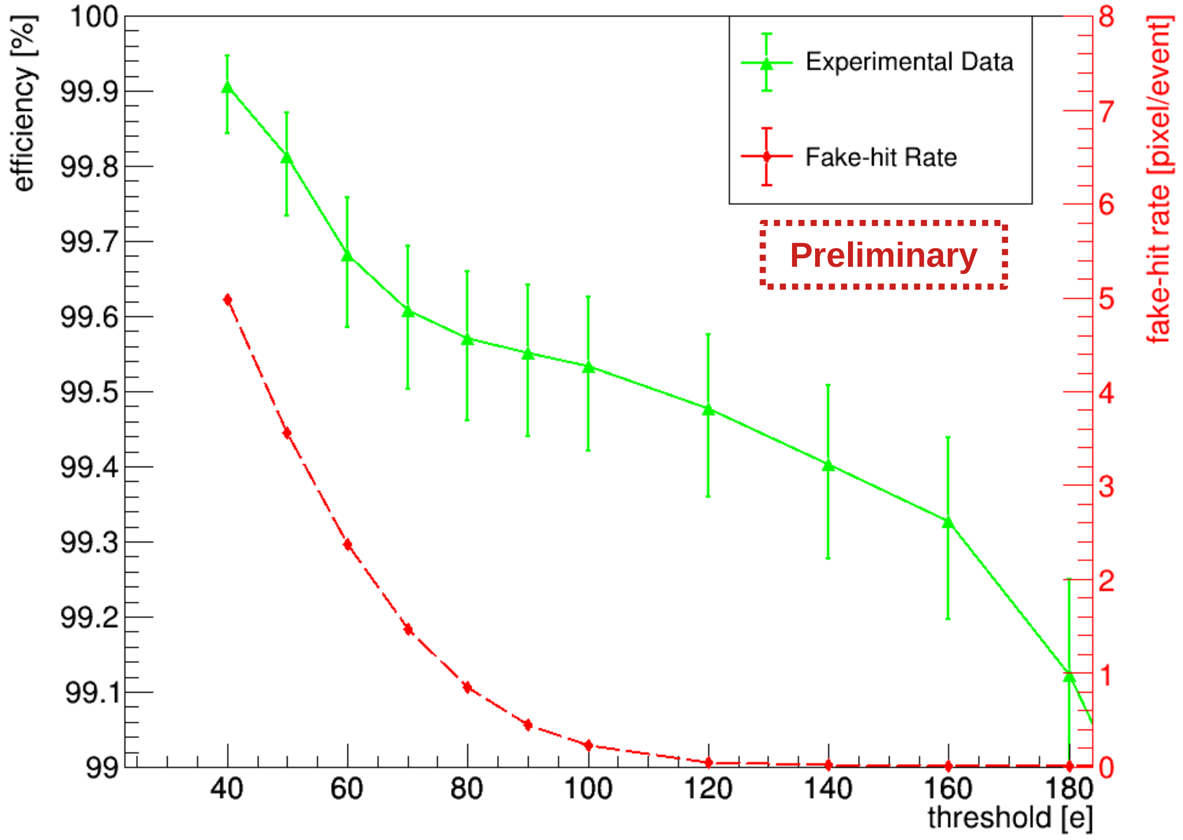
S. Spannagel et al.
https://doi.org/10.1016/j.nima.2020.163784

APTS Operational Parameters

- ✔ Samples: 19 (AF25), 24 (AF25B), 29 (AF25P)
- ✔ Pitch: 25 µm
- ✔ Type: standard, n-blanket and n-gap
- ✔ Split: 4
- ✔ V_{sub} = V_{pwell} = -1.2 V, -2.4 V, -3.6 V, -4.8 V (,-5.2 V only for sample 19)
- ✔ I_{reset} = 1 µA
- ✔ I_{biasn} = 20 µA
- ✔ I_{biasp} = 2 µA
- ✔ I_{bias4} = 546 µA
- ✔ I_{bias3} = 200 µA
- ✔ V_{reset} = 0.5 V

Preliminary Fake-Hit Rate

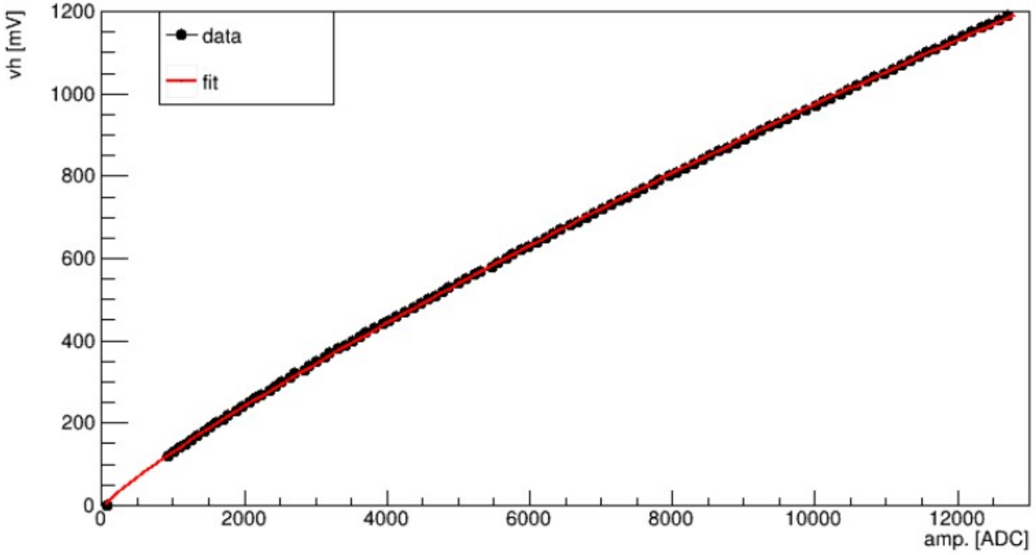


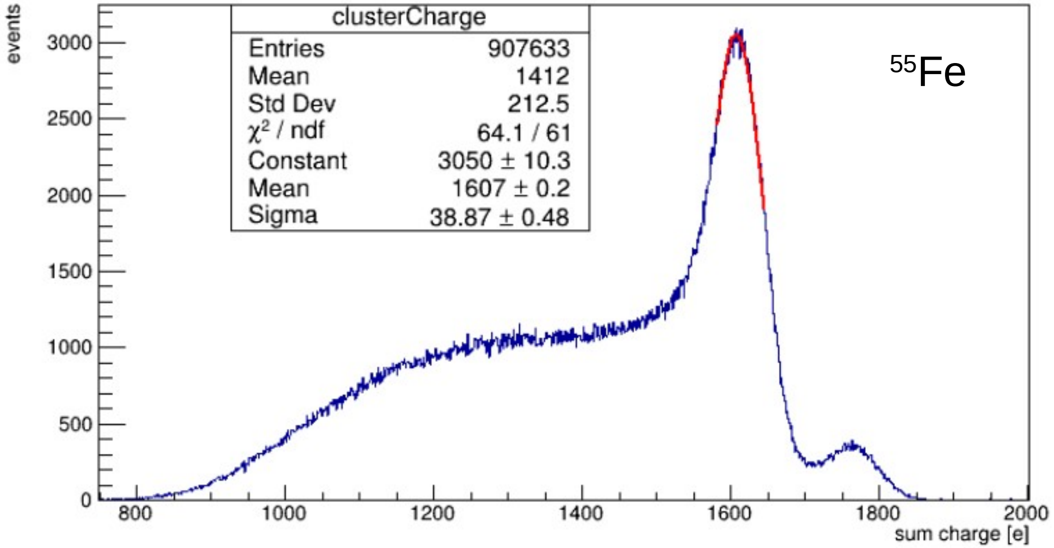


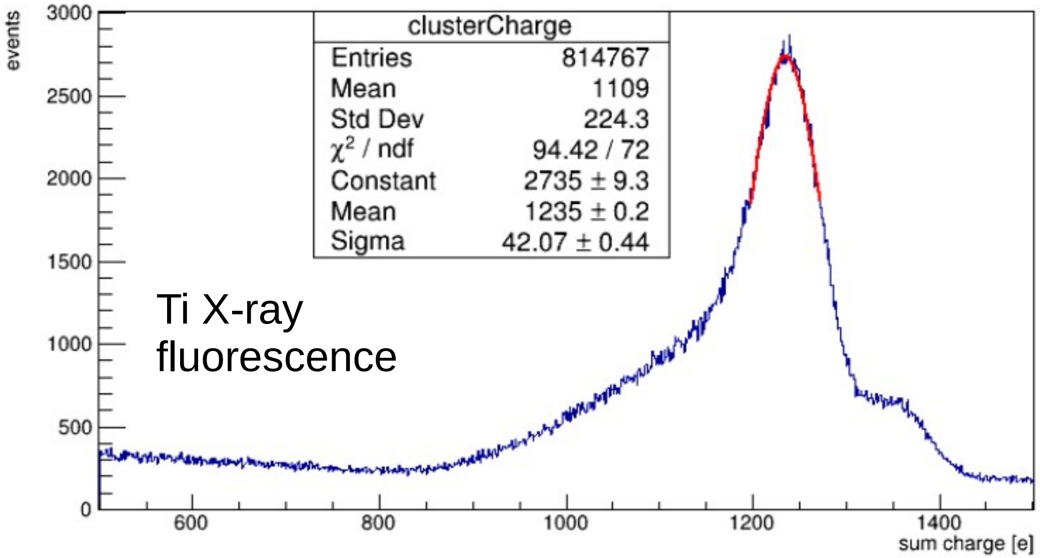
Calibration

- ✔ Test pulse measurements to characterize non-linearity and pixel-to-pixel variations
- ✔ Apply inverse gain curve from test pulse measurements (per pixel)
- ✔ Perform ^{55}Fe measurements to determine absolute calibration factor
- ✔ Check calibration with Ti X-ray fluorescence
- ✔ Calibration for all samples and combinations of bias voltage

F. Feindt

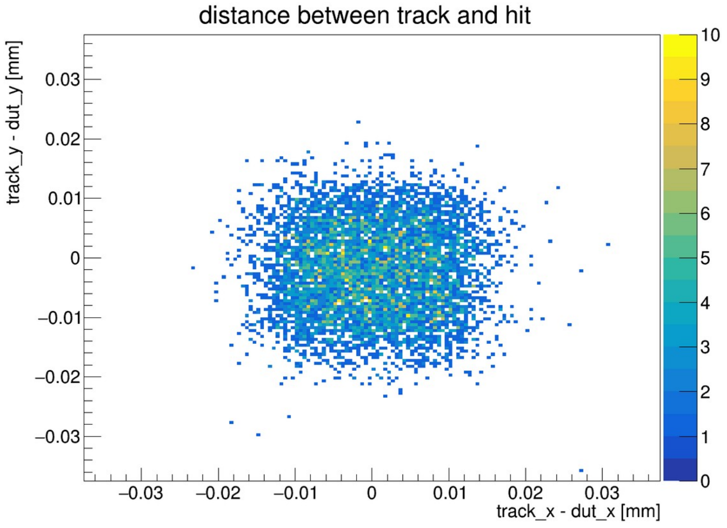


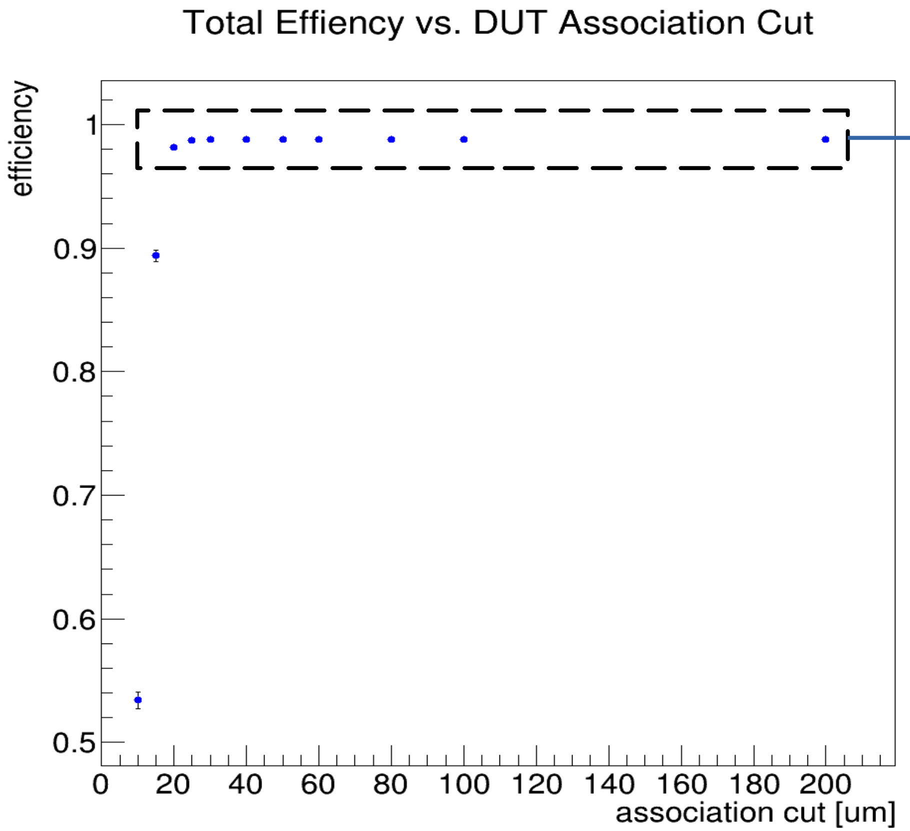


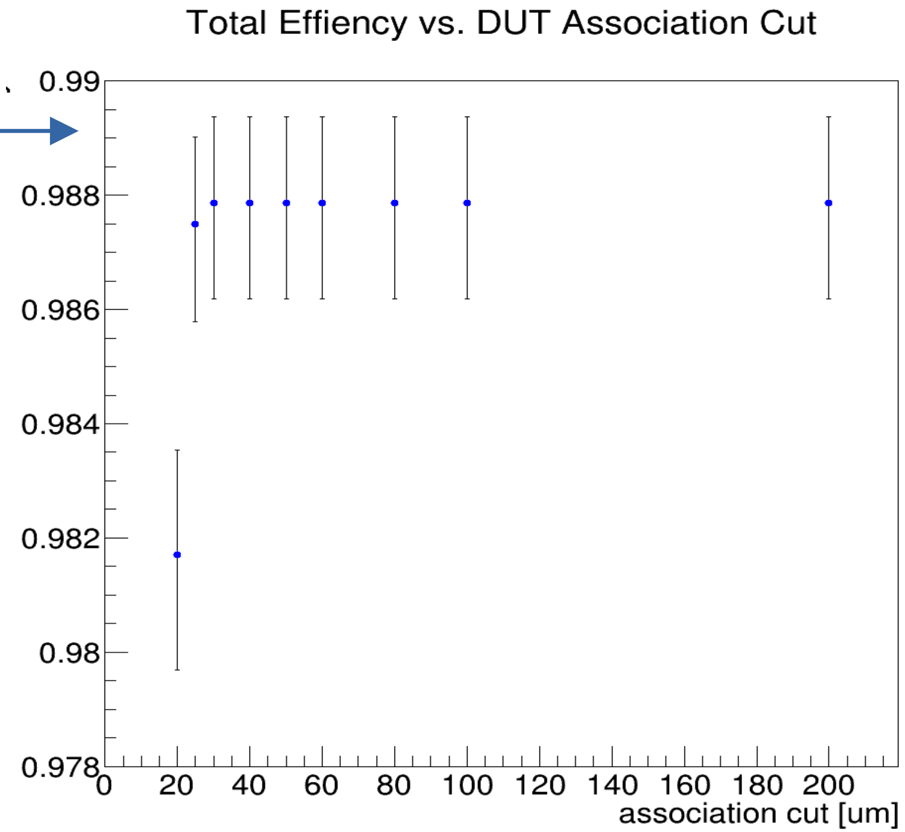


Selection Cuts

- A cut is performed to associate tracks to DUT clusters
- Chosen cut at 30 µm → covering beyond full pixel to take into account tracking uncertainties







Selection Cuts

- A cut at the sensor edge is performed to correct for the tracking uncertainties
- Chosen cut at 0.3 pixel fraction → more than 2 times the tracking resolution