Simulations and Performance Studies of a MAPS in 65 nm CMOS Imaging Technology

Adriana Simancas on behalf of the Tangerine Project at DESY and in collaboration with ALICE ITS3 and EP R&D at CERN

HSTD13

7 December 2023

Vancouver, Canada

The Tangerine Project

Towards Next Generation Silicon Detectors

Develop the next generation of silicon pixel sensors using novel technologies:

★ Vertex detector for future lepton colliders
★ Reference detector at DESY-II test beam

Performance parameters:

★ Material budget: ≤ 50 µm silicon
★ Spatial resolution: ≤ 3 µm
★ Time resolution: ~ ns

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CLIC FCC hh ee he ilc international linear collider DESY TEST BEAM.

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Monolithic Active Pixel Sensor (MAPS)

Science moving to CMOS commercial foundries
Advantages & Disadvantages:

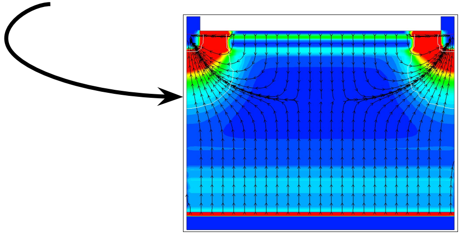
★ Profit from state-of-the-art technology
★ Reduce costs in large-scale production
★ Limited access to manufacturing process information

Introduction & Outline

Developing a new detector:

Part I

★ **Sensor Simulations:** predict sensor behaviour and test designs
  - Electric field distribution in sensor highly dependent on doping concentration and doping profiles
  - MAPS with a small collection electrode have highly complex electric fields



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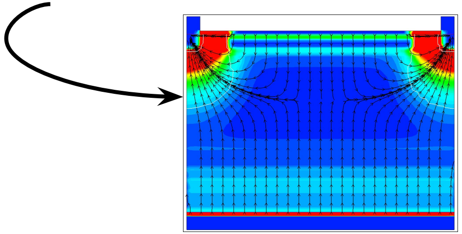

- ○ Simulations based on fundamental principles of silicon detectors and using generic doping profiles

★ **Prototype Testing**: characterize sensor under realistic conditions
- ○ Laboratory
- ○ Test-beams

Part II

Introduction & Outline

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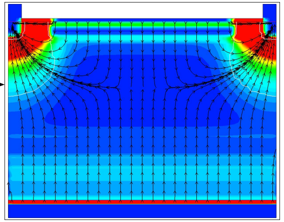

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★ **Prototype Testing**: characterize sensor under realistic conditions
  - Laboratory
  - Test-beams

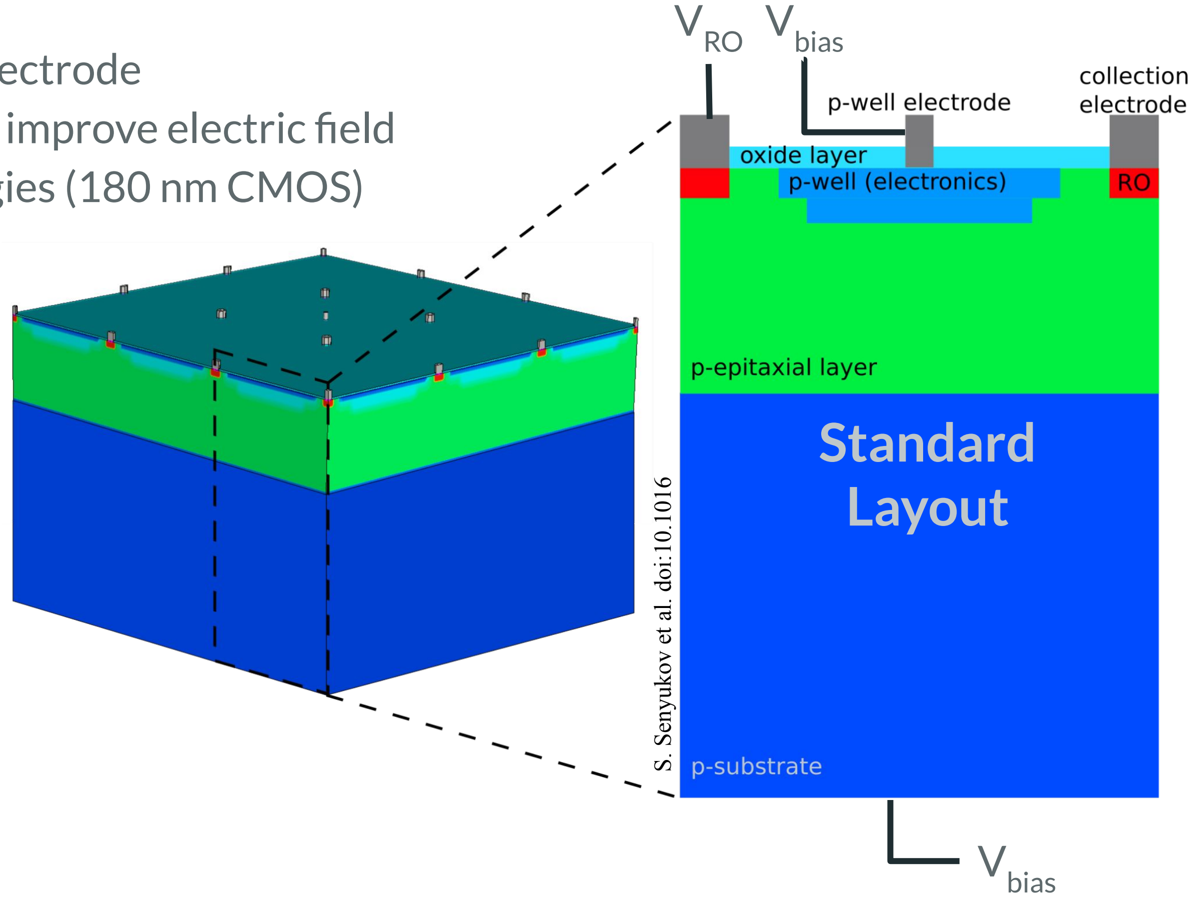
Part II

★ Comparison of simulations with experimental data

Part III

Sensor Design

- ★ MAPS with small collection electrode
- ★ Layouts with modifications to improve electric field
- ★ Already in previous technologies (180 nm CMOS)



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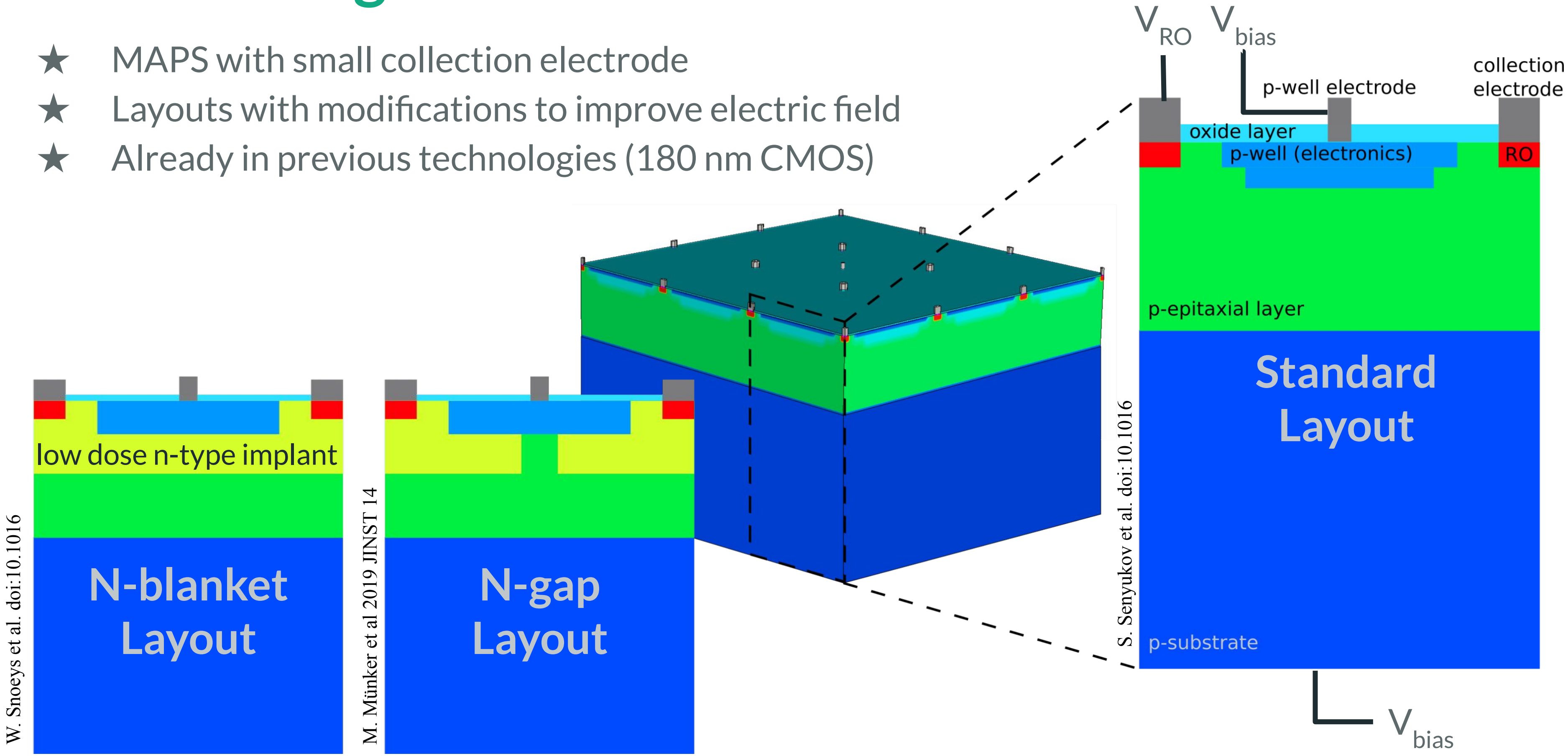


Part I: Sensor Simulations

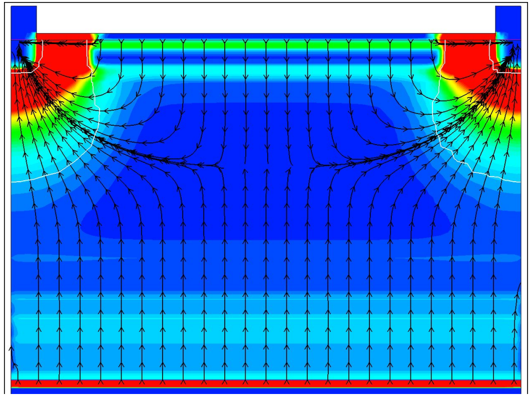
Sensor Simulation

Sentaurus TCAD

SYNOPSYS® Silicon to Software™

Technology Computer-Aided Design

★ Model sensor volume
★ Electric Fields: accurate and realistic
★ Observe sensor physical behaviour

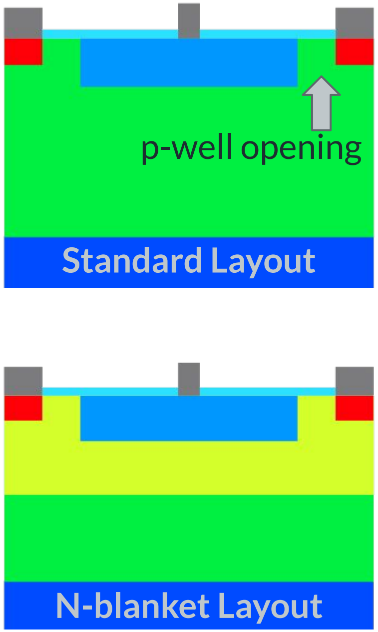


To take into account:

★ Avoid abrupt changes in electric field → **diffusion in doping concentrations** at interfaces
★ Minimize depleted volume inside p-well → must **shield electronics** from active sensor area
★ Charge carriers generated in sensor volume have to **reach collection electrode**
★ No conduction between different biased structures → **avoid punch-through**
★ Respect **limitations on the operating voltages** of transistors in readout electronics

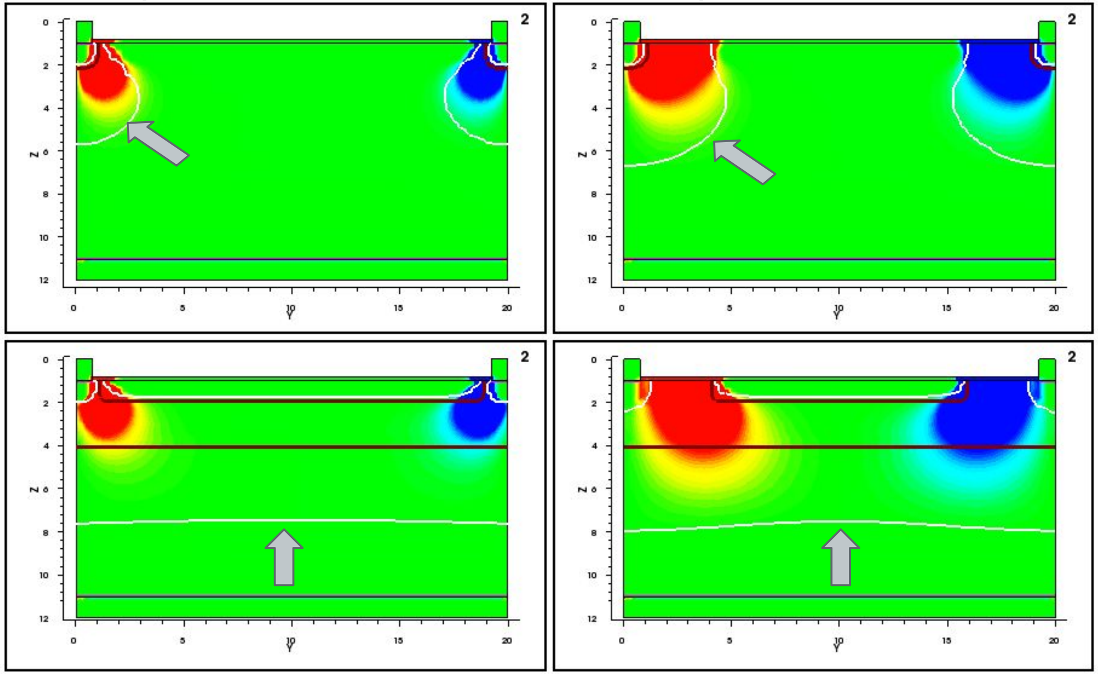
TCAD Simulations - Scans

★ Understand effect of design changes: p-well opening width
  ○ Impact on depleted volume (white line) and lateral electric field (red and blue regions)
  ○ Less significant for n-blanket layout



1 µm p-well opening

4 µm p-well opening



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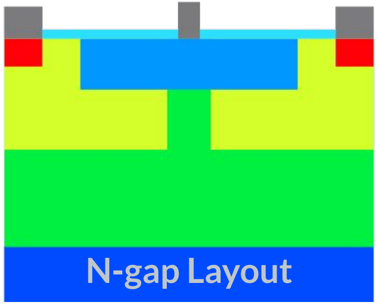
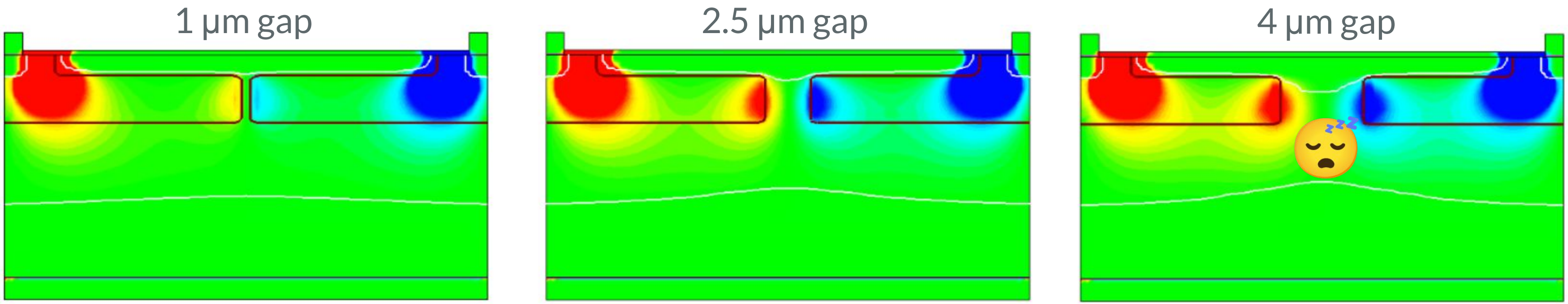


- ★ Optimize design and operation: n-gap size
  - Impact on lateral electric field (red and blue regions)
  - Compromise between strength of lateral electric field and position
  - Also constrained by layout rules of foundry process



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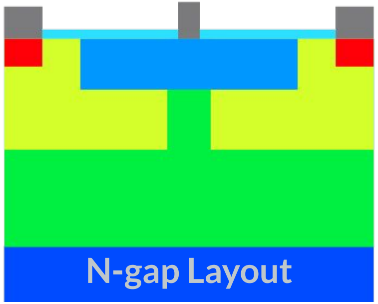

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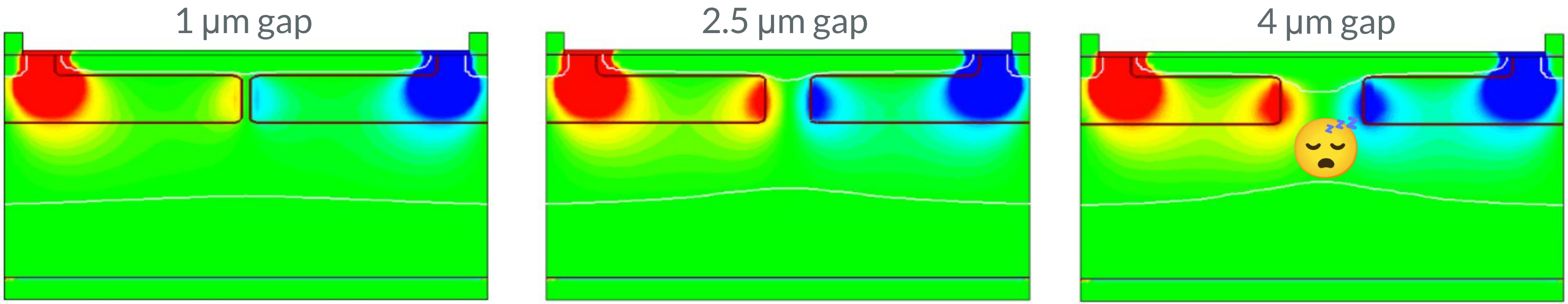
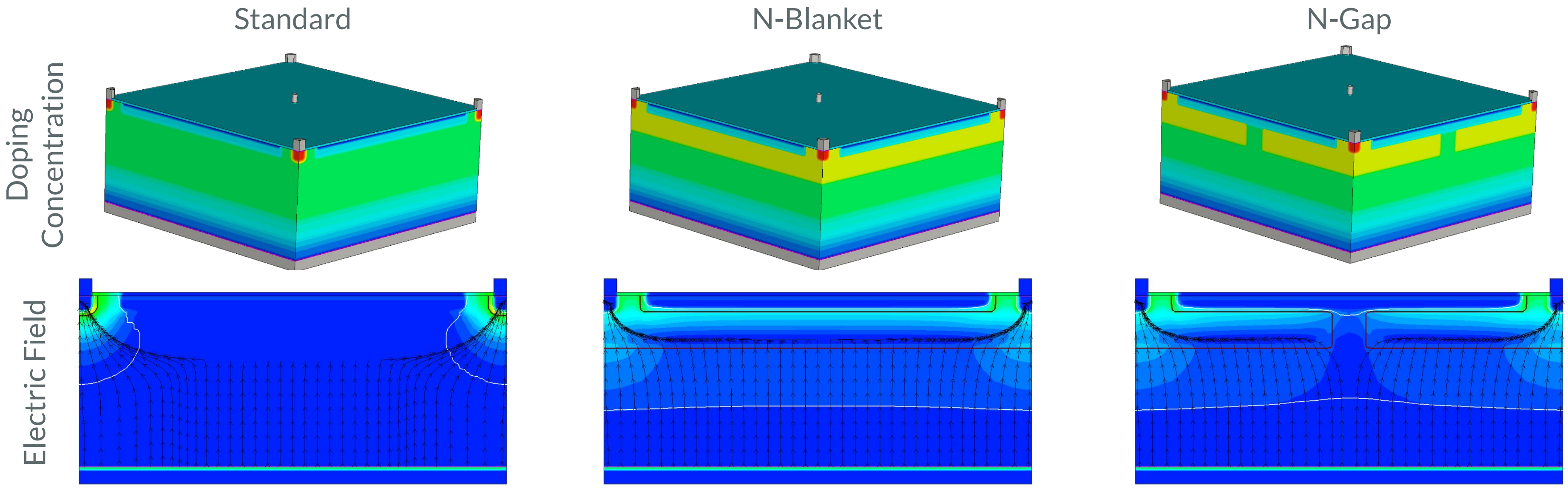


★ Finally, select parameters that reproduce expected physical behaviour (similar to previous studies)

★ Reminder: simulations based on fundamental principles of silicon detectors and using generic doping profiles

TCAD Simulations - “Final” Result



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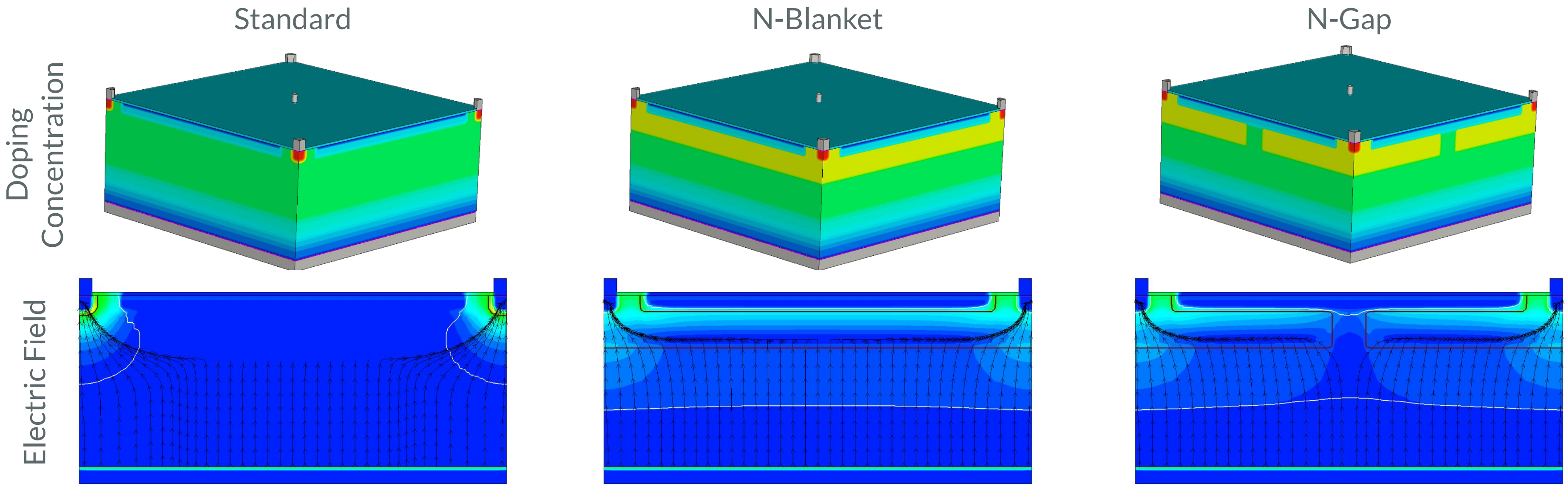

small depleted volume

⇩

- low efficiency
- high charge sharing between pixels

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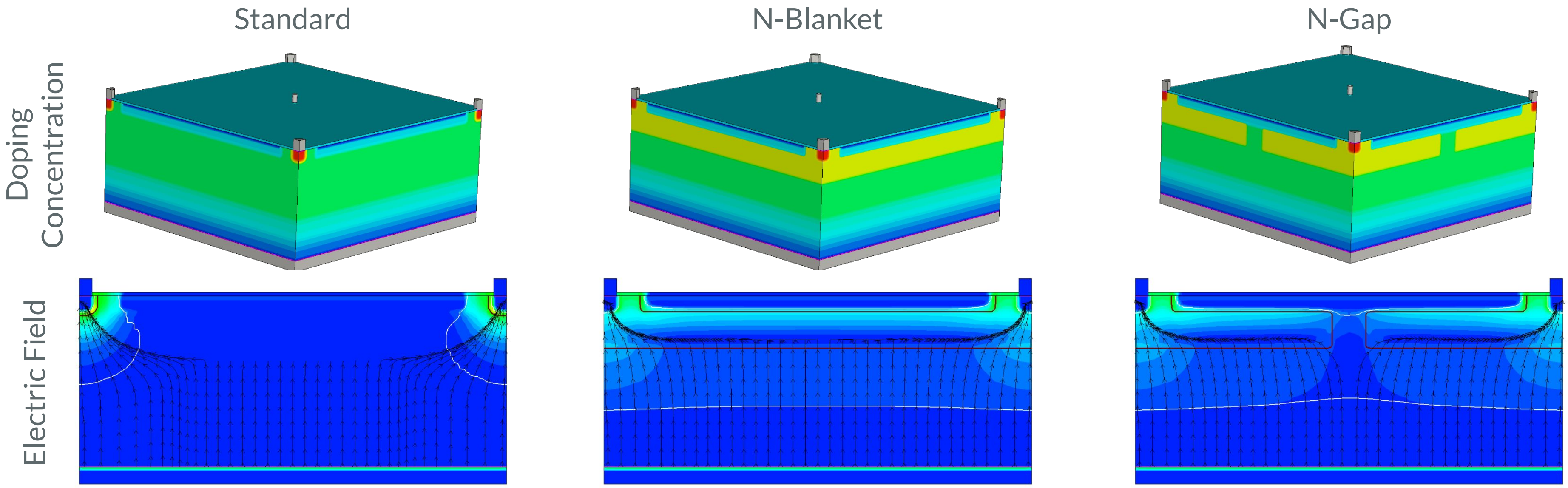

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larger depleted volume

⇩

- improvement in efficiency
- impairment of resolution

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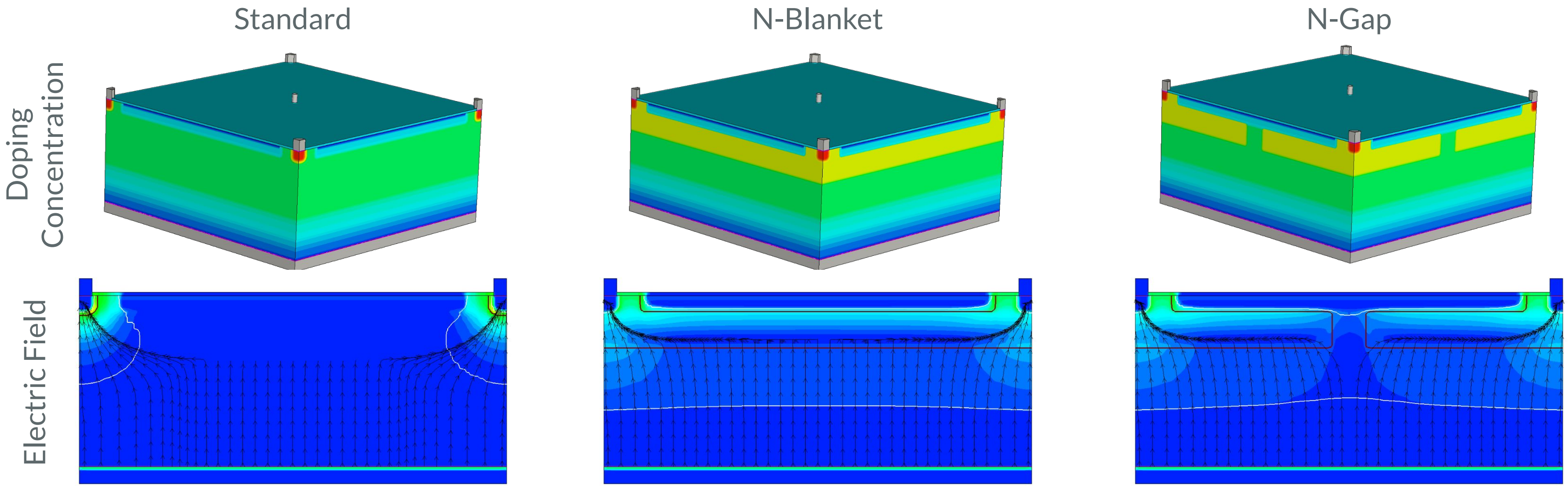


Standard: small depleted volume

⇩

- low efficiency
- high charge sharing between pixels

N-Blanket: larger depleted volume

⇩

- improvement in efficiency
- impairment of resolution

N-Gap: higher electric field in pixel corners

⇩

- improvement in efficiency and charge collection
- impairment of resolution

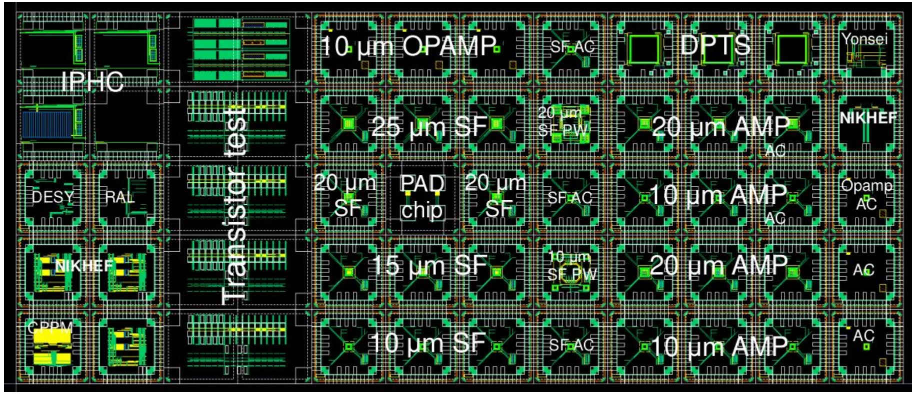
Part II: Performance Studies in Test-Beam

Prototypes

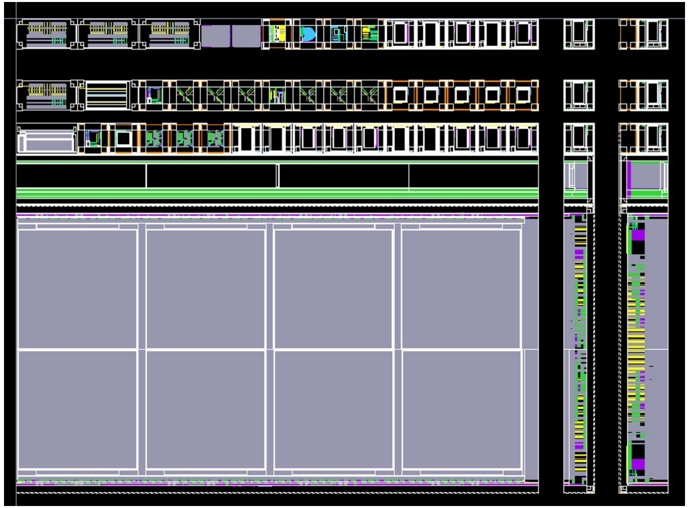
★ International collaboration for common submissions to foundry with 65 nm CMOS imaging process, coordinated by CERN

★ To date: two foundry submissions with several types of structures and designs

MLR1 (2021)
Multi-Layer Reticle



ER1 (2023)
Engineering Run



Prototypes

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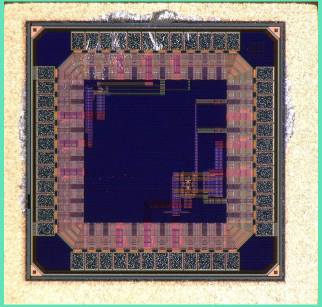

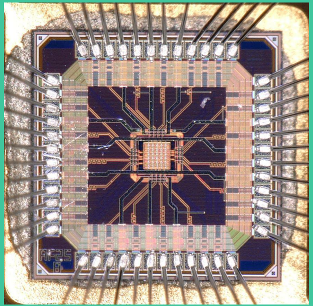

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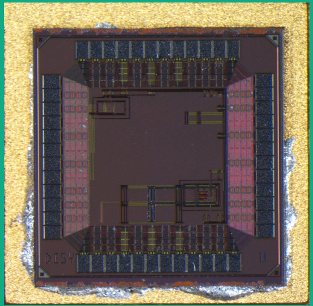

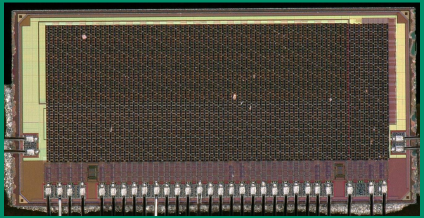

DESY Chip V1

- ★ Designed at DESY
- ★ CSA test structures
- ★ 2 × 2 pixel matrix
- ★ 16 μm pitch
- ★ Analog output

APTS

W. Deng et al.

- ★ Analog Pixel Test Structure
- ★ Designed at CERN
- ★ 4 × 4 pixel matrix
- ★ 15 - 25 μm pitch
- ★ Analog output with source follower (SF)

DESY Chip V2

- ★ Designed at DESY
- ★ 2 × 2 pixel matrix
- ★ 35 × 25 μm^2 pitch
- ★ In-pixel amplifier and discriminator

H2M

- ★ Hybrid-to-Monolithic
- ★ Designed at DESY, CERN and IFAE
- ★ 64 × 16 pixel matrix
- ★ 35 μm pitch
- ★ 4 acquisition modes

Prototypes

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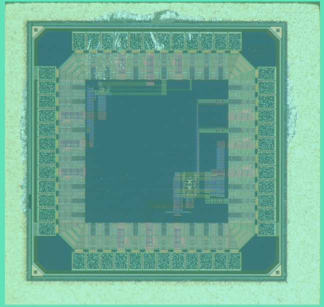

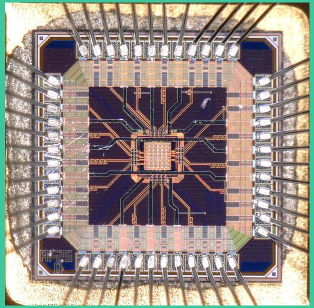

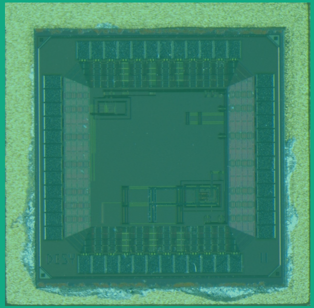

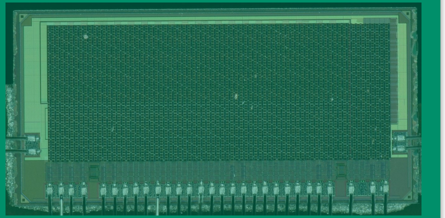

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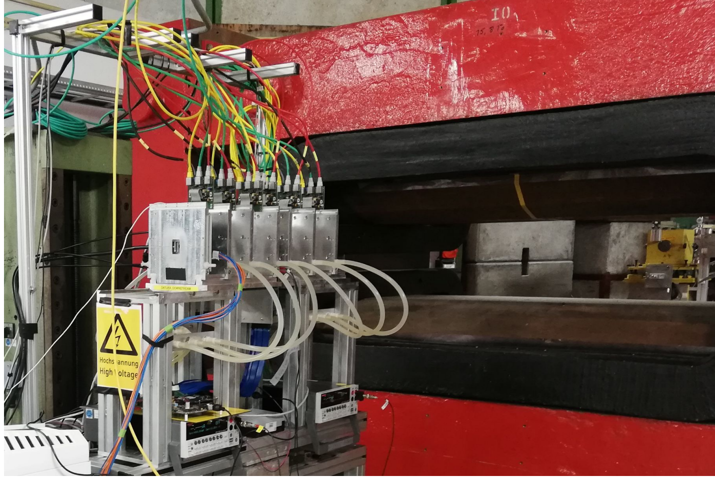
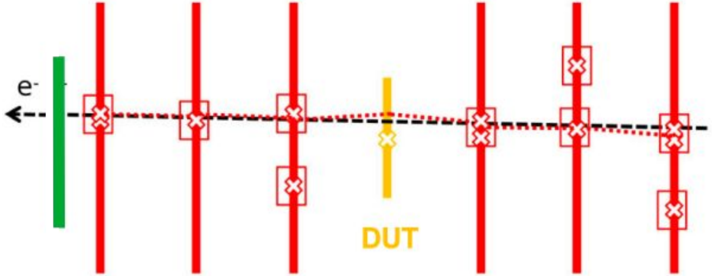
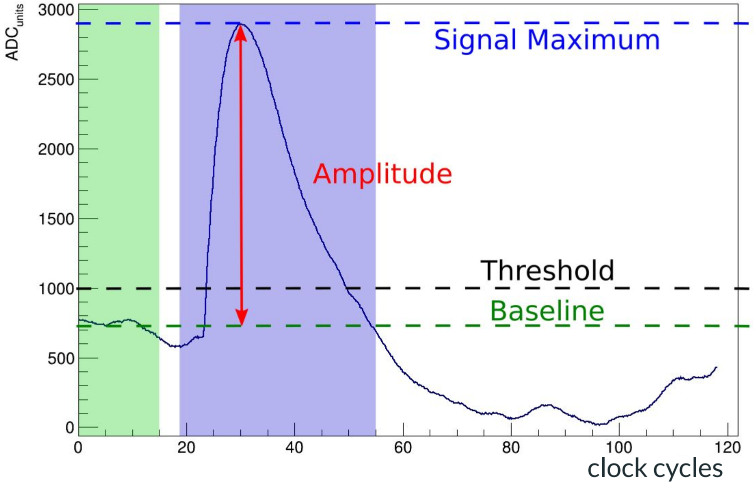
Test-Beam Setup

- ★ DESY II Test Beam Facility with 4 GeV electron beam
  J. Dreyling-Eschweiler et al.
- ★ MIMOSA26 Telescope H. Jansen et al.
- ★ Trigger plane with configurable ROI: TelePix (see L. Huth's talk)
  L.Huth et al.
- ★ DUT (Device Under Test): APTS
- ★ DAQ system based on Caribou (see F. Feindt's talk)
  T. Vanat
- ★ Corryvreckan framework (see L. Huth's talk) for track
  D. Dannheim et al.
  reconstruction and data analysis
- ★ Events defined as waveforms in DUT above threshold associated to tracks

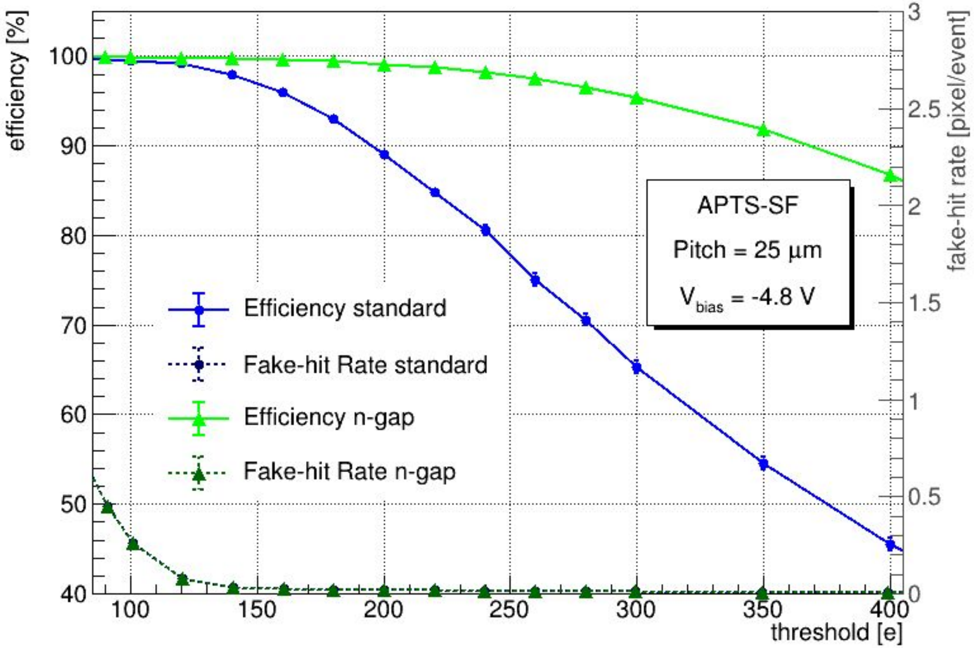






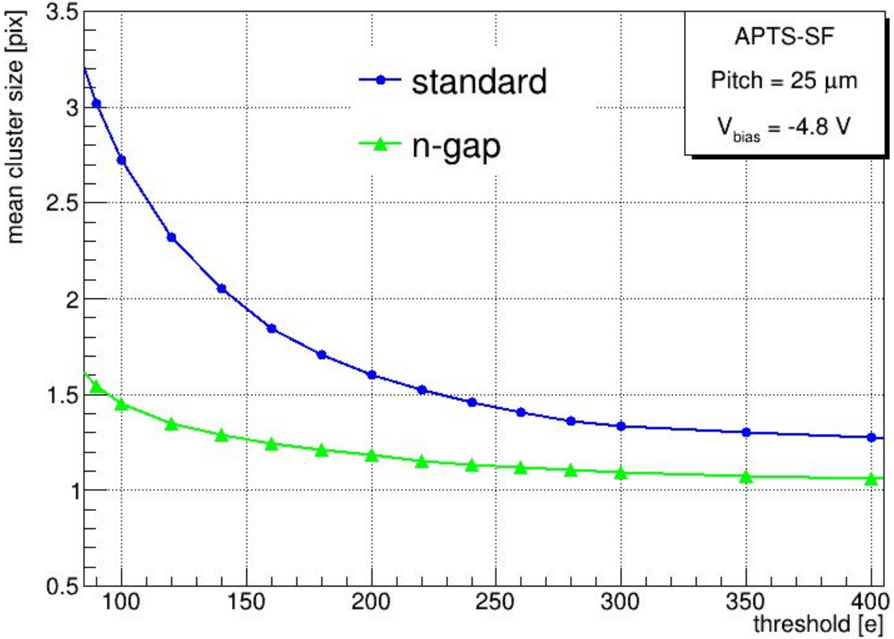
Test-Beam Results - Efficiency

★ Comparison of **standard** and **n-gap** designs
★ Efficiency reduced with higher thresholds
★ Higher overall efficiency for n-gap → larger depleted volume and reduced charge sharing



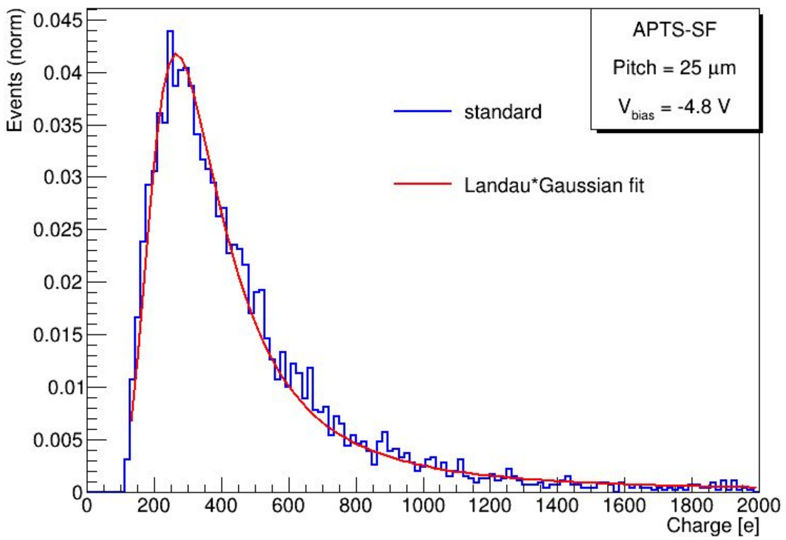
Test-Beam Results - Cluster Size

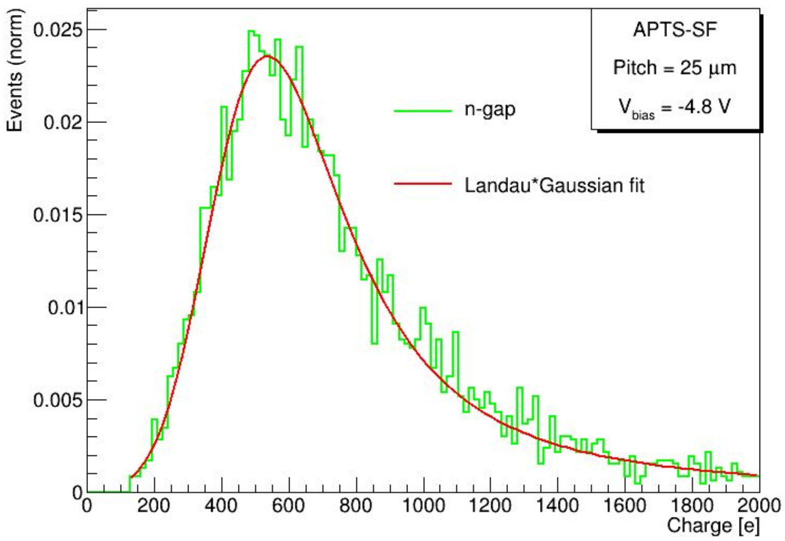
- ★ Cluster size reduced with higher thresholds
- ★ Higher overall cluster size for standard → more charge sharing



Test-Beam Results - Charge Distribution Seed Pixel

- ★ ADC units converted to electrons by x-ray fluorescence calibration
- ★ Landau*Gaussian Distribution → expected for thin sensors
  - MPV standard: 264 e ± 2 e
  - MPV n-gap: 496 e ± 4 e
- ★ More charge collected for n-gap → larger depleted volume





Part III: Simulation vs. Experimental Data

Combination of Simulation Tools

Sentaurus TCAD — SYNOPSYS® Silicon to Software™

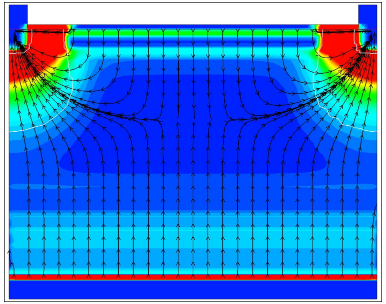
Technology Computer-Aided Design

+

Allpix^2: Monte Carlo Simulations for Semiconductor Detectors

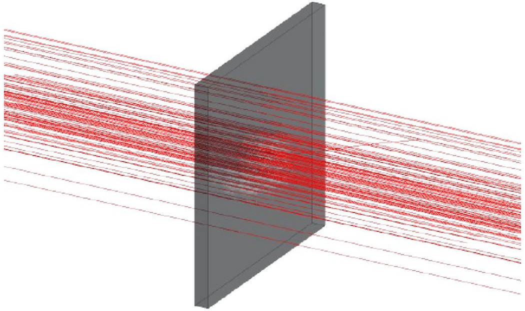
https://doi.org/10.1016/j.nima.2018.06.020

- ★ Model sensor volume
- ★ Electric Fields: accurate and realistic



- ★ Show sensor physical behaviour in **Part I**
- ★ Obtain electric fields to input in Monte Carlo simulations

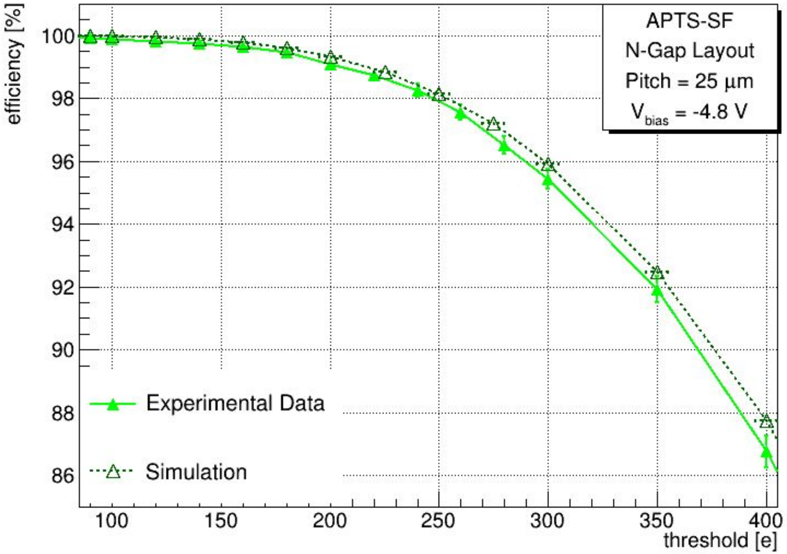
- ★ Simulate full response of detector
- ★ Particle Events: fast and high statistics

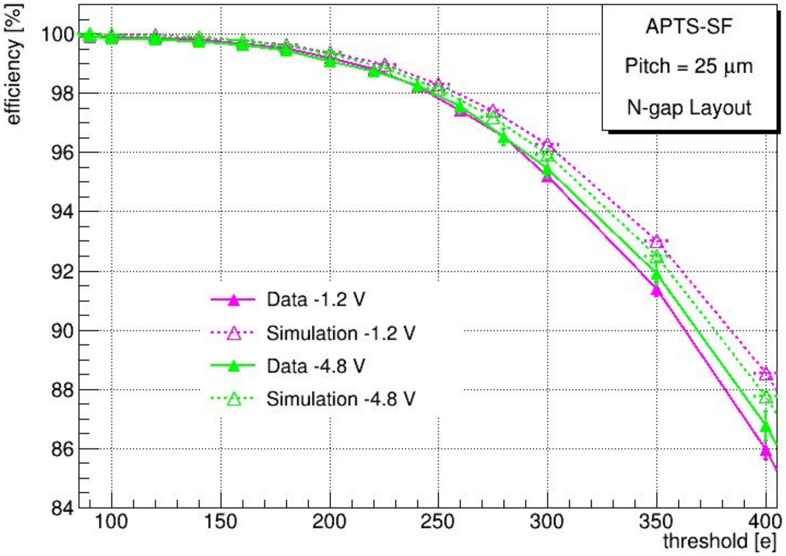


- ★ Obtain performance parameters
- ★ Compare to data in **Part III**

Simulation vs. Experimental Data - Efficiency

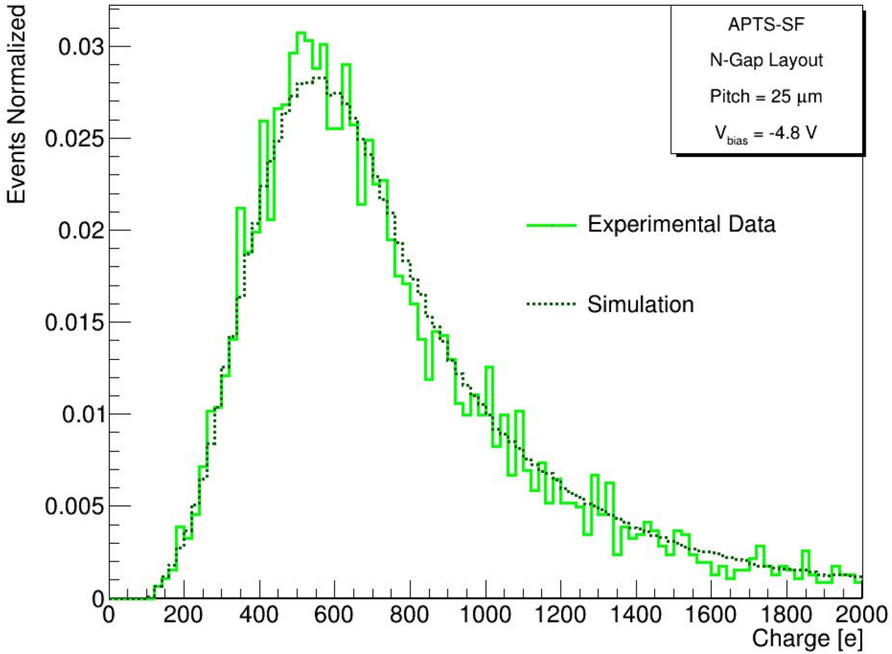
- ★ **N-gap** design
- ★ Experimental data compatible with simulations
- ★ Negligible changes at different bias voltages → similar trend for simulations
- ★ Error bars not final → only statistical uncertainties





Simulation vs. Experimental Data - Charge Distribution

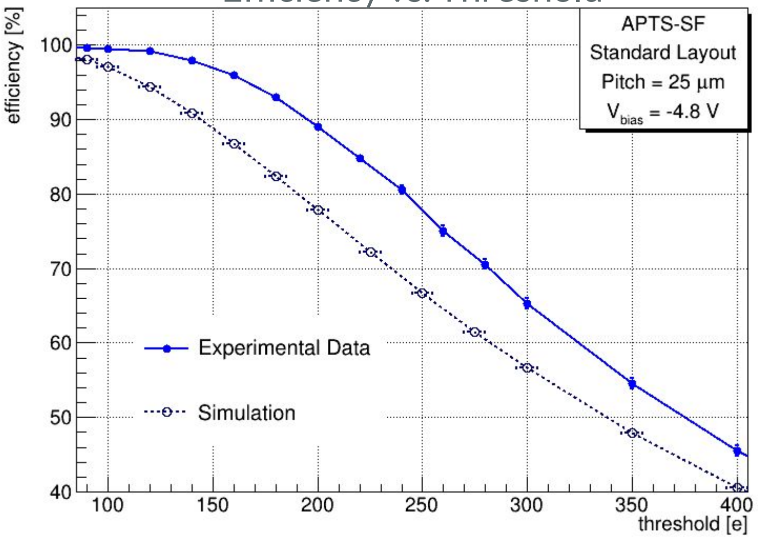
- ★ **N-gap** design
- ★ Charge distribution of the seed pixel
- ★ Experimental data compatible with simulations



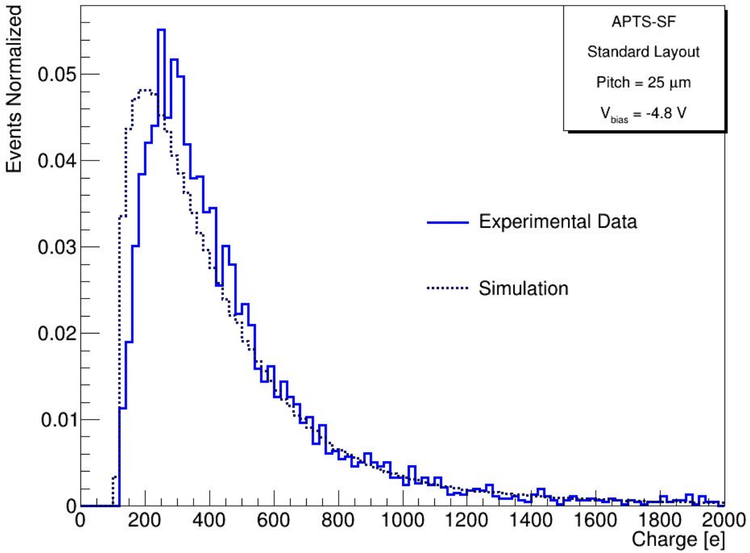
Simulation vs. Experimental Data - Outlook

- ★ **Standard** design → diffusion dominated → more sensitive to some parameters
- ★ Most performance values still don't match, but…
- ★ Gives hints on which parameters should be adjusted in simulations
  - ○ Substrate and/or epitaxial layer doping concentration
  - ○ Retracted deep p-well

Efficiency vs. Threshold



Seed Pixel Charge



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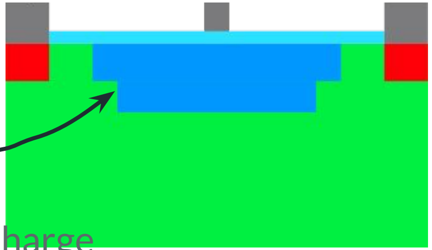
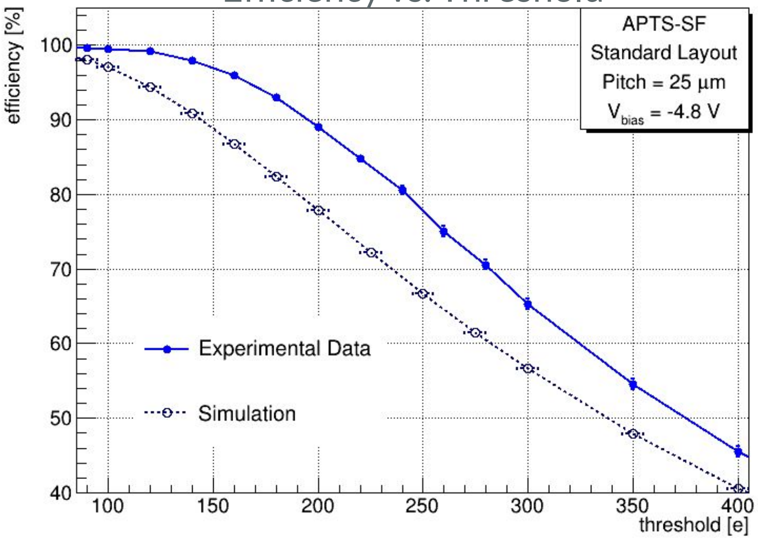


Efficiency vs. Threshold



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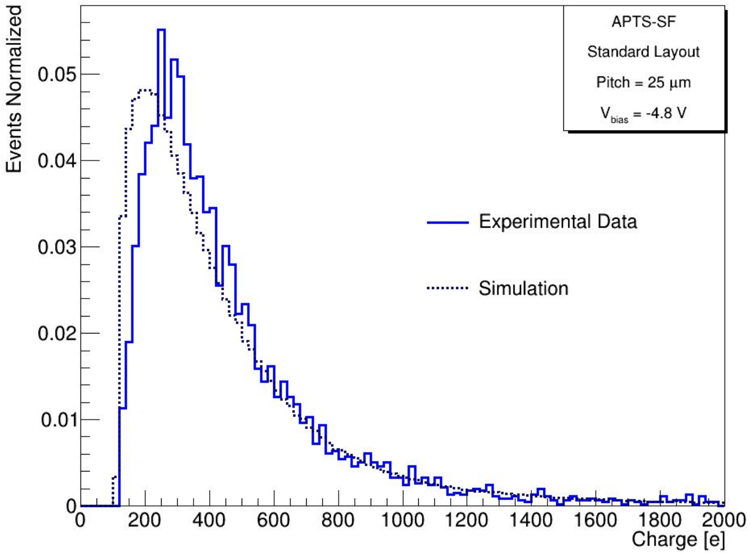

Summary & Conclusions

- ★ Simulation approach using generic doping profiles and semiconductor principles
- ★ Combination of TCAD + Monte Carlo simulation
  - ○ Provided very useful insights for future sensor optimization
  - ○ Produced results comparable with measurements
- ★ Beam test of Analog Pixel Test Structure (APTS)
  - ○ Compared performance of standard and n-gap designs
- ★ Some simulations and experimental results follow a similar trend
- ★ Some mismatch provides important feedback for simulation improvements

Outlook

- ★ More simulations on relevant parameters
- ★ Add uncertainties on simulation results
- ★ More measurements → more statistics
- ★ More studies, including spatial resolution and timing

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Thank you!

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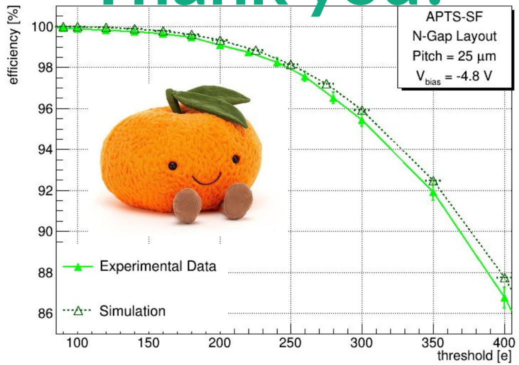
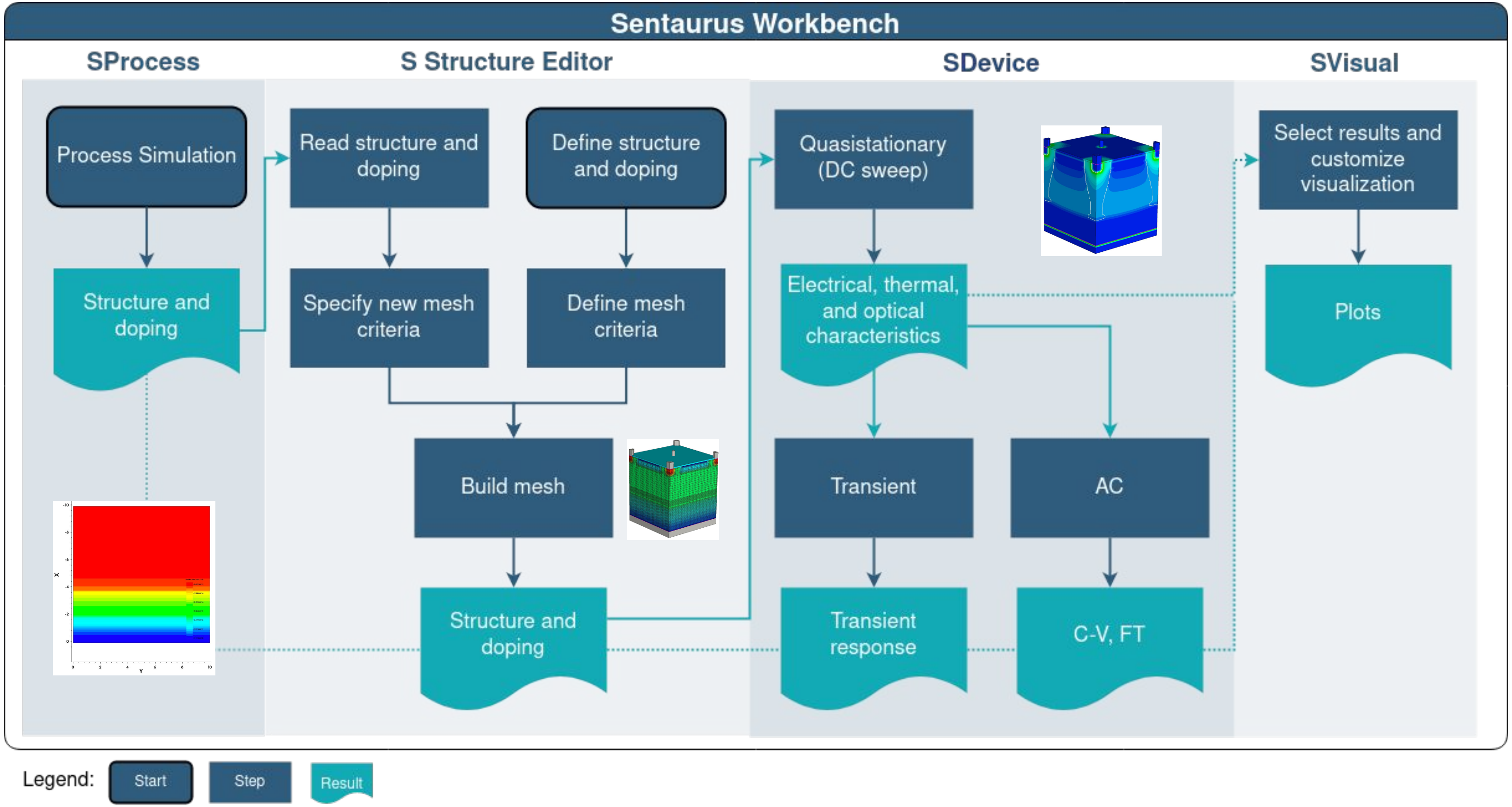


Back-up

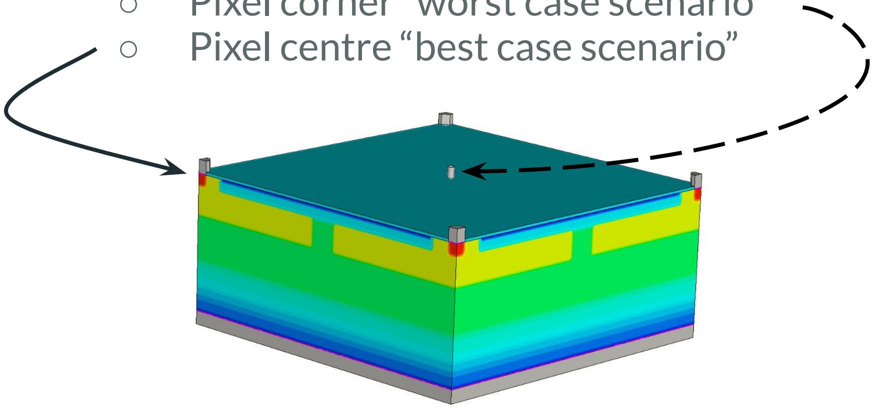
TCAD Simulation Workflow Example



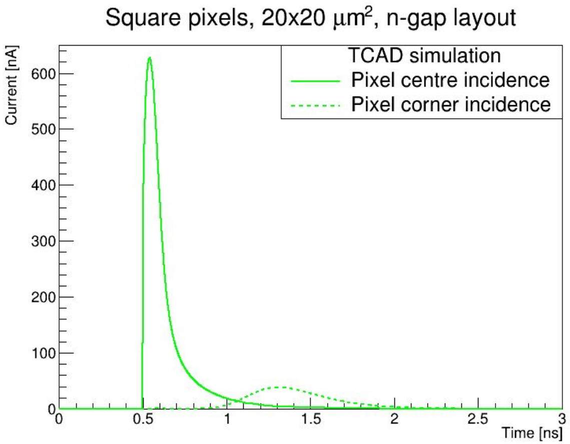
TCAD - Transient Simulations

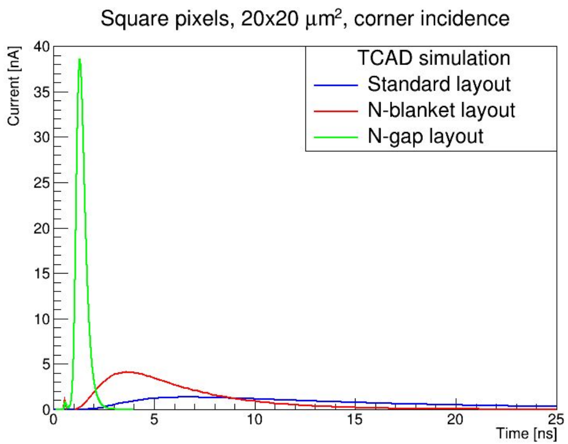
Time-dependent induced signal by MIP

★ MIP incidence comparison
  - Pixel corner "worst case scenario"
  - Pixel centre "best case scenario"

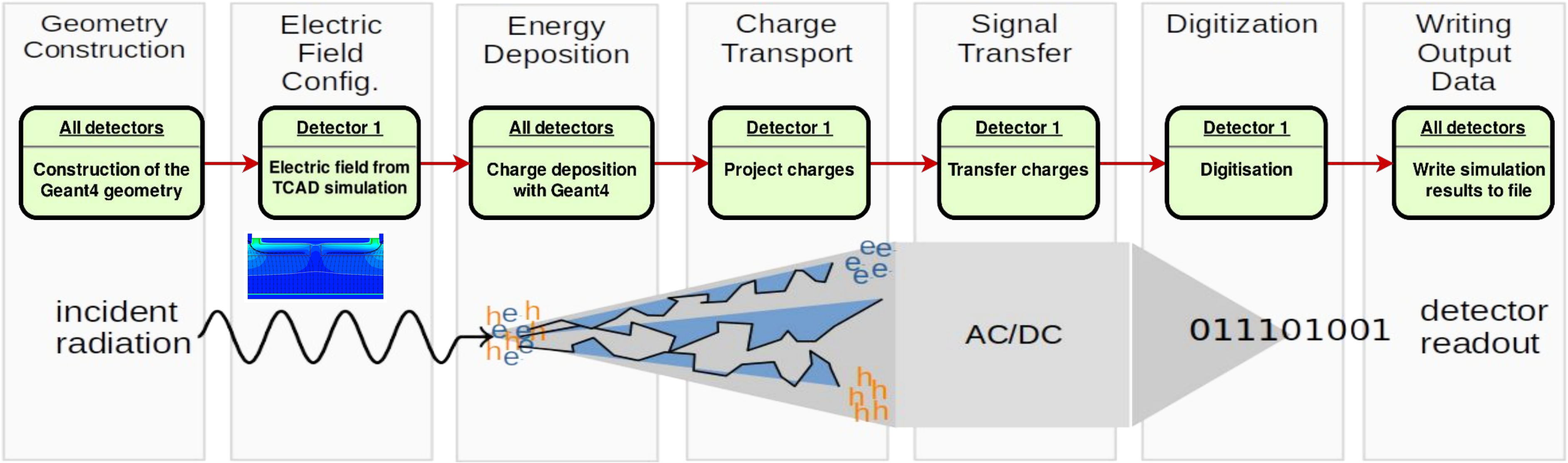


★ Layout comparison
  - Improvements brought on by modifications





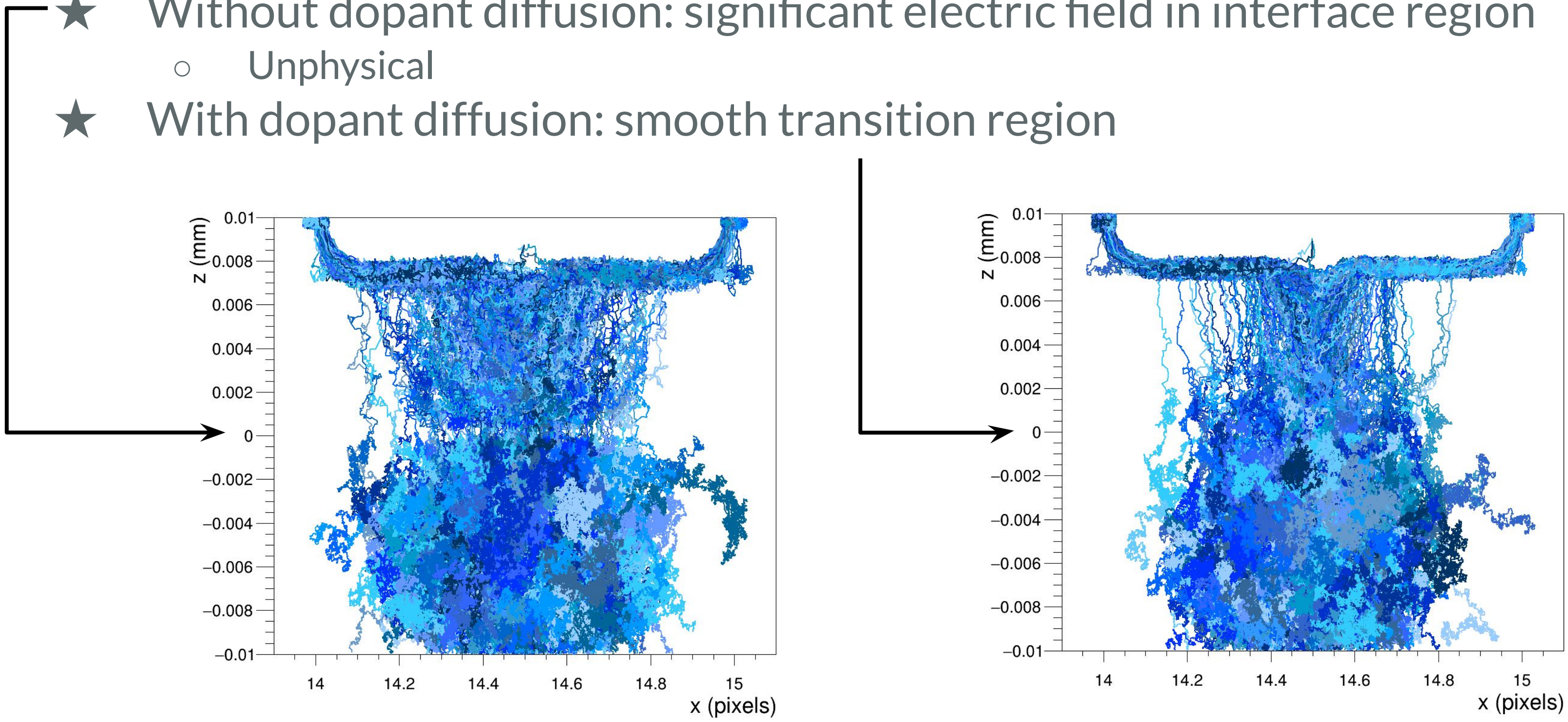
Monte Carlo Simulation Workflow Example



Monte Carlo Simulations - Diffusion

Comparing effect of electric field between substrate and epitaxial layer

- ★ Without dopant diffusion: significant electric field in interface region
  - ○ Unphysical
- ★ With dopant diffusion: smooth transition region

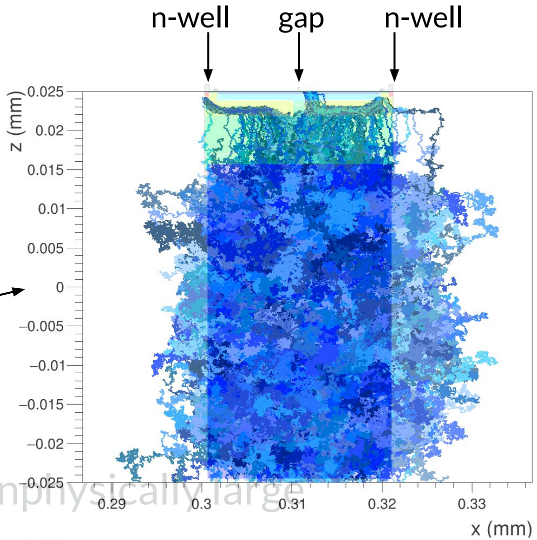


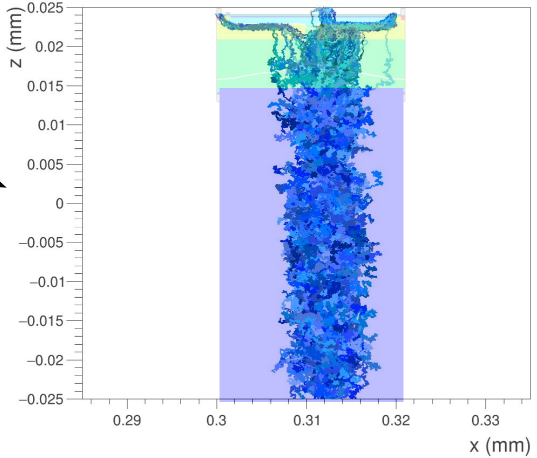
Monte Carlo Simulations - Mobility

Take into account important details…

E.g.: Mobility Models

- ★ Jacoboni-Canali (doping-independent)
  - Sufficient for low doping concentration
  - For high doping concentration (substrate) diffusion is unphysically large
- ★ Masetti-Canali (doping dependent)
  - Fit for high doping concentration



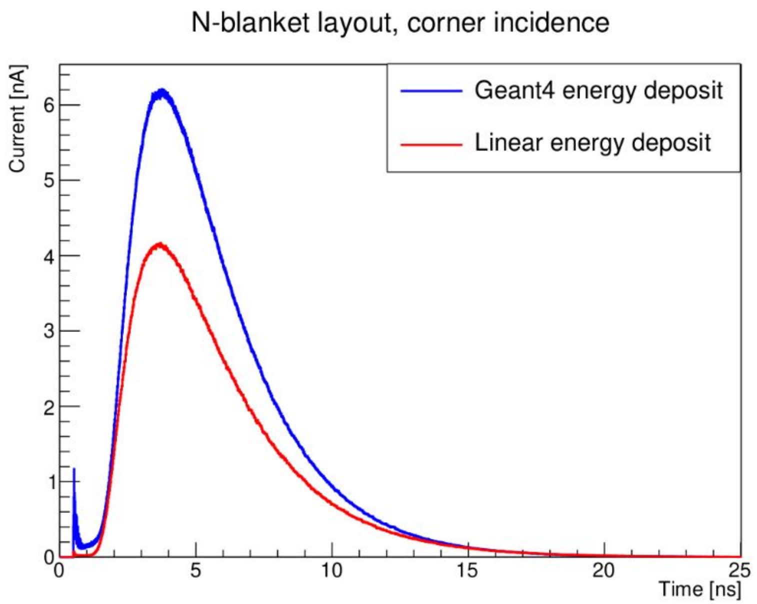


Monte Carlo Simulations - Energy Deposition

Transient simulations comparing:

- ★ Linear energy deposition (TCAD)
  - ○ Generates 63 electron-hole pairs per µm → most probable value
- ★ Geant4 (Allpix^2)
  - ○ Includes stochastic effects → takes into account all values from energy deposition distribution

Each signal is the average of 10 000 events, incident in the pixel corner



Monte Carlo vs. TCAD - Transient

See talk by M. A. D. R. Viera

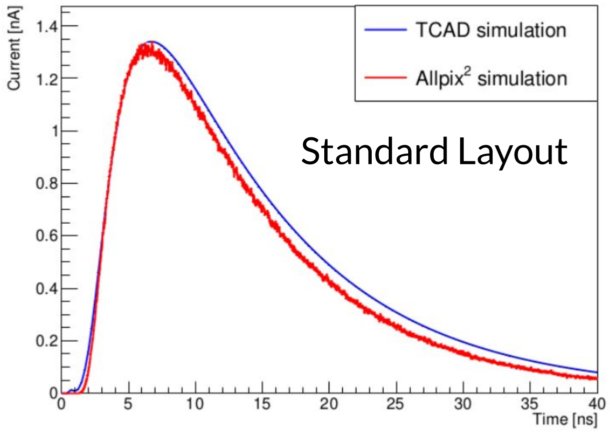
Electrostatic potentials from TCAD can be used to generate weighting potentials

→ Perform **transient simulations** with Allpix^2

- ★ Lower computational cost
- ★ Reproduce many events
- ★ Allows use of Geant4 energy deposition (see next slide)

Comparison Allpix^2 vs. TCAD:

- ★ Same settings for charge carrier creation and mobility
- ★ Results in general agreement

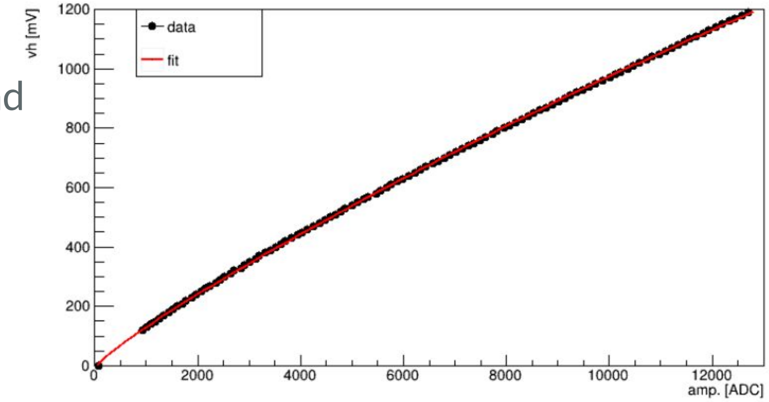


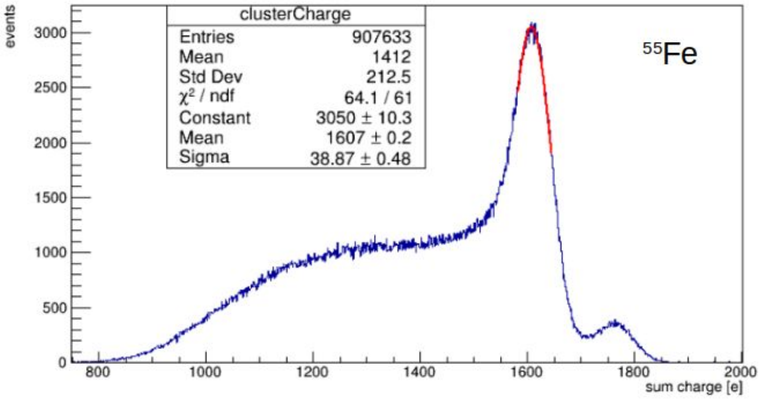
APTS Operational Parameters

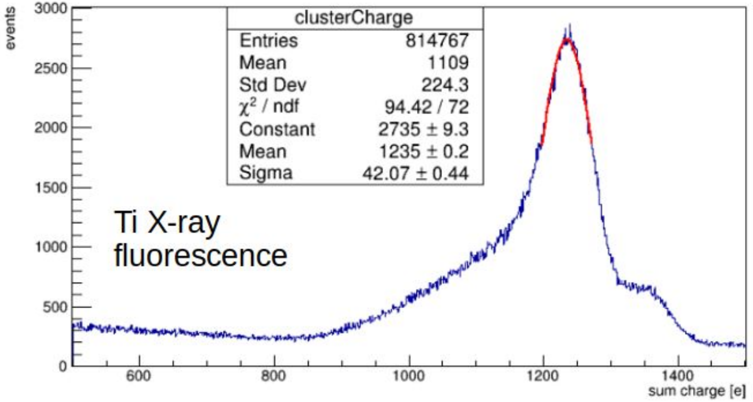
- ★ Samples: 19 (AF25), 24 (AF25B), 29 (AF25P)
- ★ Pitch: 25 µm
- ★ Type: standard, n-blanket and n-gap
- ★ Split: 4
- ★ Vsub = Vpwell = -1.2 V, -2.4 V, -3.6 V, -4.8 V (,-5.2 V only for sample 19)
- ★ Ireset = 1 µA
- ★ Ibiasn = 20 µA
- ★ Ibiasp = 2 µA
- ★ Ibias4 = 546 µA
- ★ Ibias3 = 200 µA
- ★ Vreset = 0.5 V

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

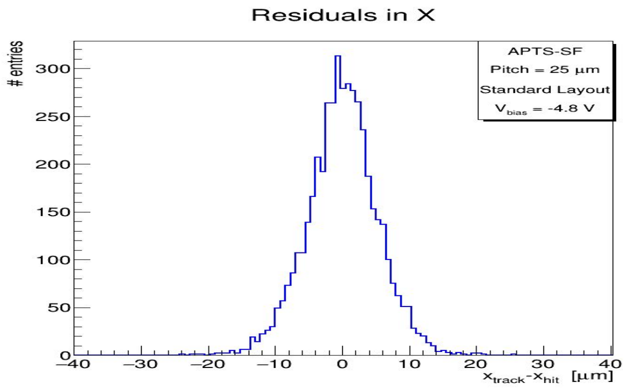


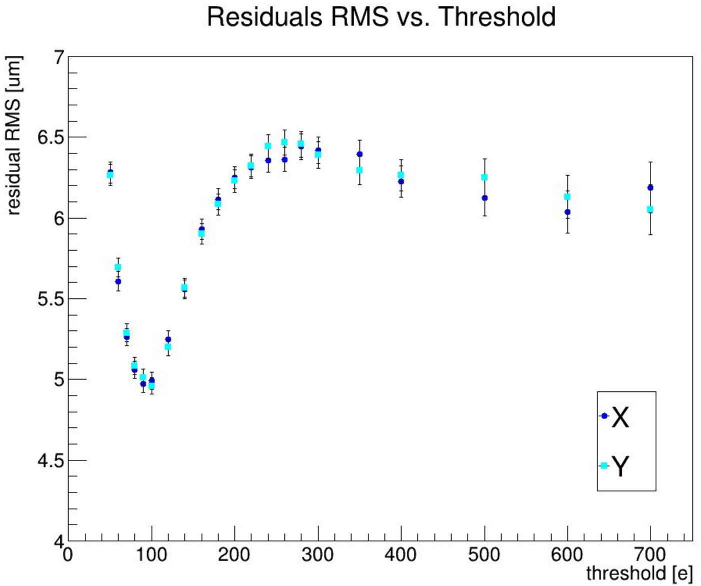


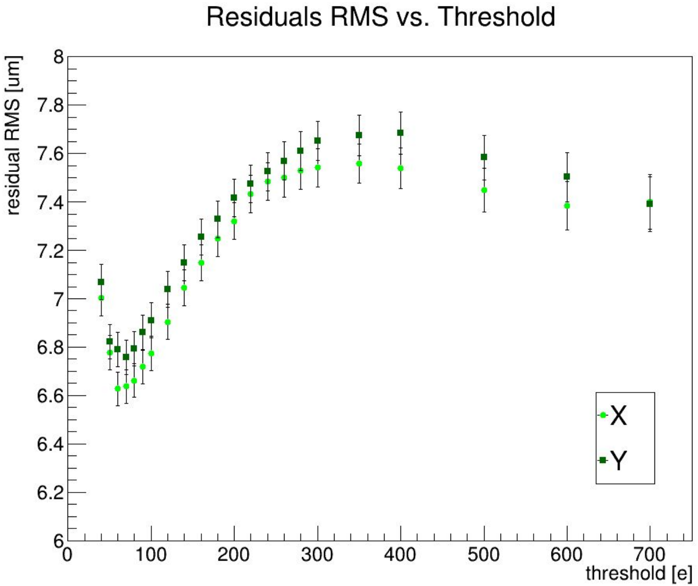


Spatial Residuals

★ Smaller residuals RMS for standard layout
→ better spatial resolution expected

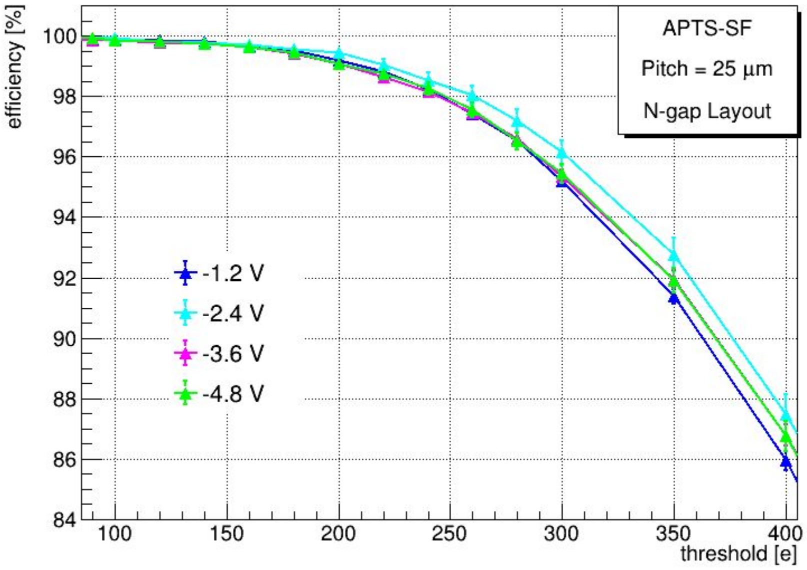


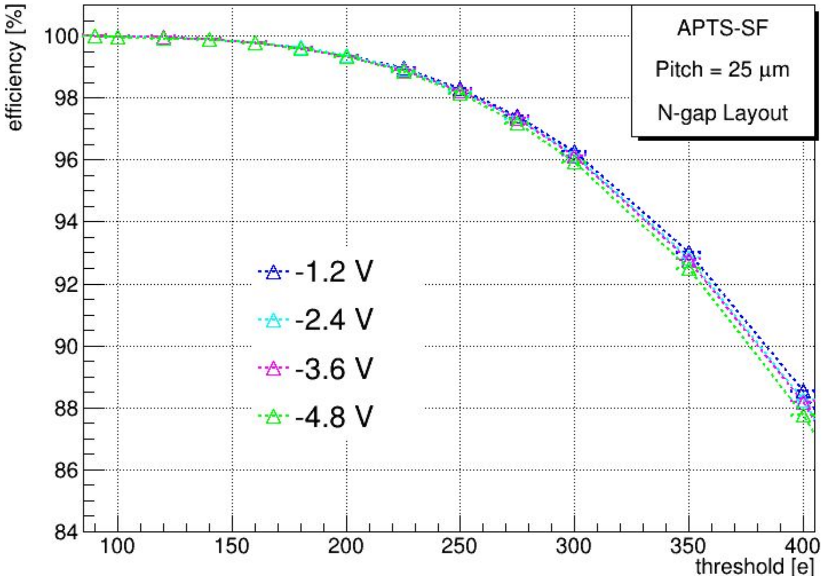




Simulation vs. Experimental Data - Efficiency

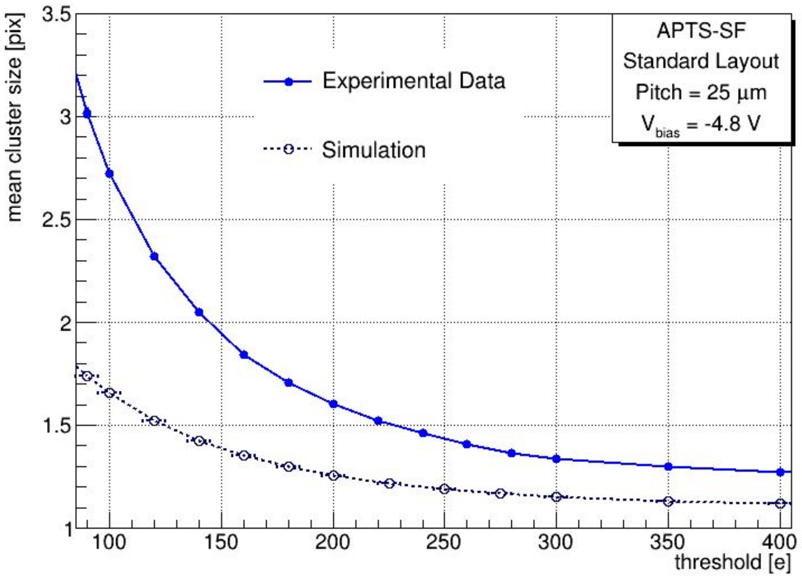
- ★ Experimental data compatible with simulations
- ★ Similar trend for different bias voltages

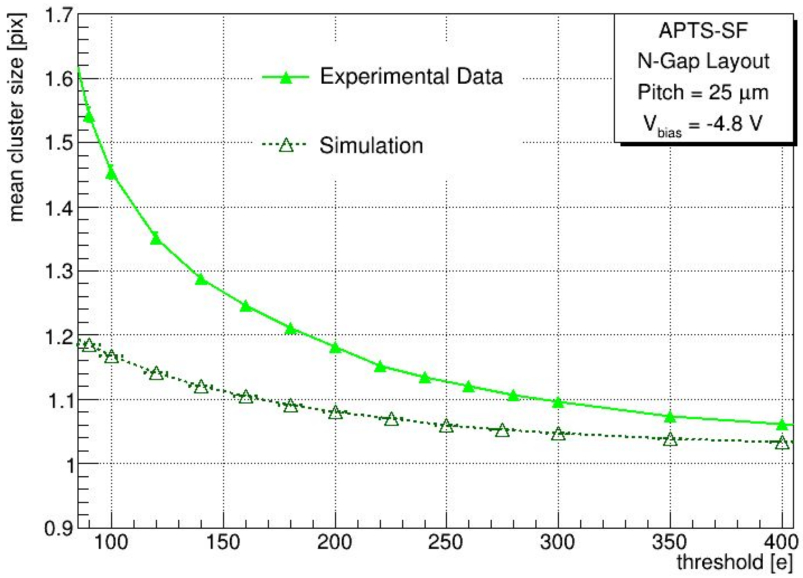




Simulation vs. Experimental Data - Cluster Size

- Cluster size mismatch
- Gives hints on which parameters should be adjusted in simulations
  - Substrate doping concentration





Time-dependent Alignment

- ★ During test-beam, DUT experienced a physical displacement over time due to temperature changes
- ★ Offline time-dependent alignment using Corryvreckan