Transient simulation of monolithic small collection electrode CMOS sensors in Allpix Squared

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2nd Allpix Squared User Workshop

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Outline

The sensor design

Transient simulation setup

Comparison to transient 3D TCAD

Comparison to test-beam data

Summary/Outlook

The sensor design

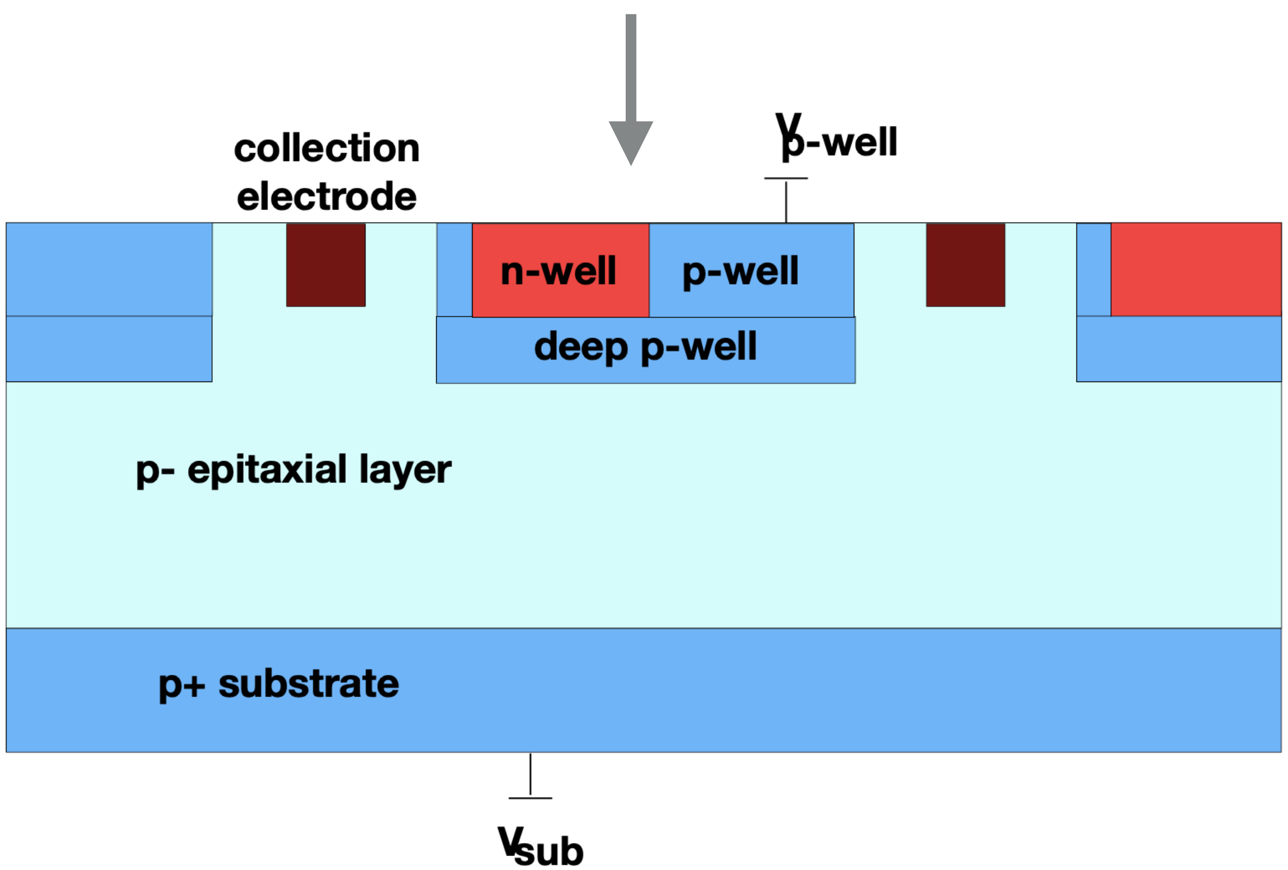
Monolithic silicon sensors

- Small material budget
- Reducing production costs/effort
- Large-scale production possibilities

Small collection electrode design

- Femto-Farad sensor capacitance
- Improving signal-to-noise ratio
- Reducing detection threshold
- Reducing power consumption

- On-chip CMOS electronics shielded by p-well in the active sensor volume
- P-well influences electric field and charge collection behaviour

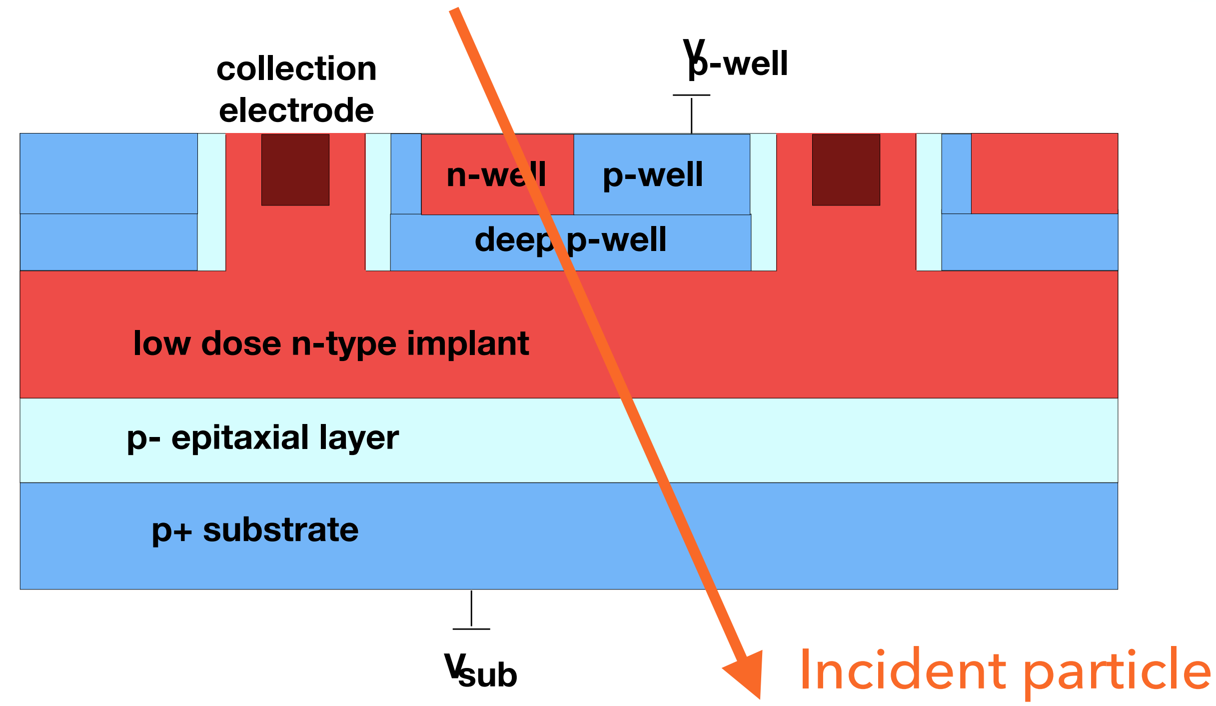


The sensor design

- Modified 180 nm CMOS imaging process (e.g. ALPIDE, (Mini-)MALTA, CLICTD,…)

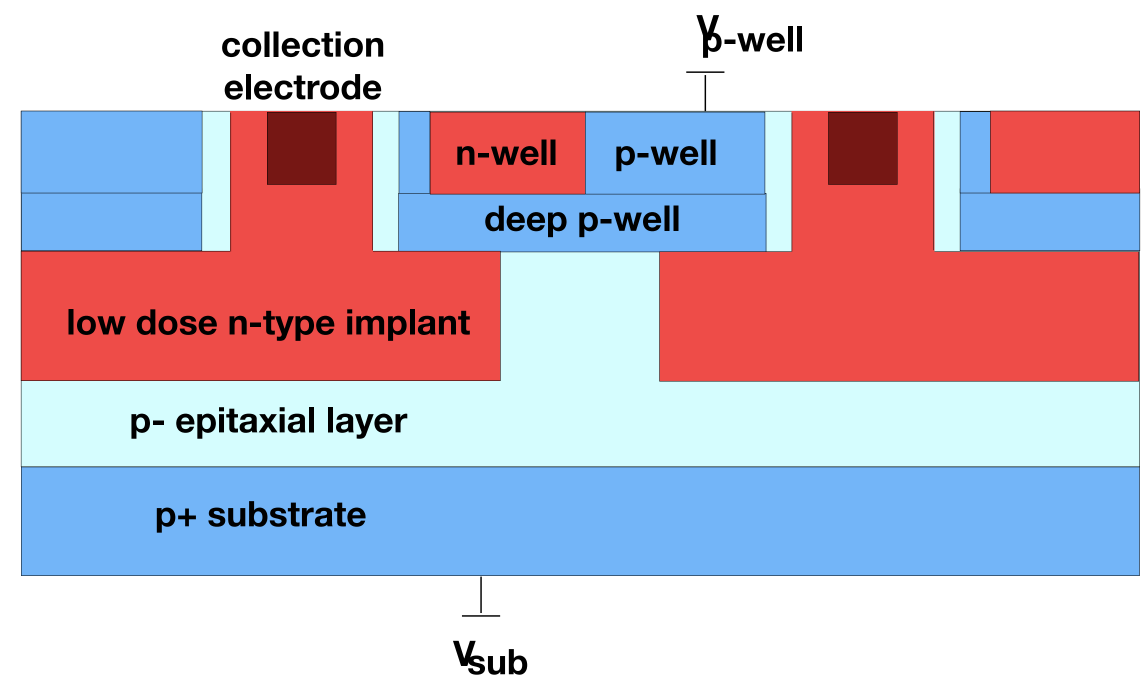
Adding deep low-dose n-implant

- Full lateral depletion of the epitaxial layer



Segmented deep low-dose n-implant

- Lateral doping gradient -> stronger lateral electric field
- Accelerated charge collection
- Reduced charge sharing
- Improved time resolution
- Higher radiation tolerance



JINST 14 (2019) C05013

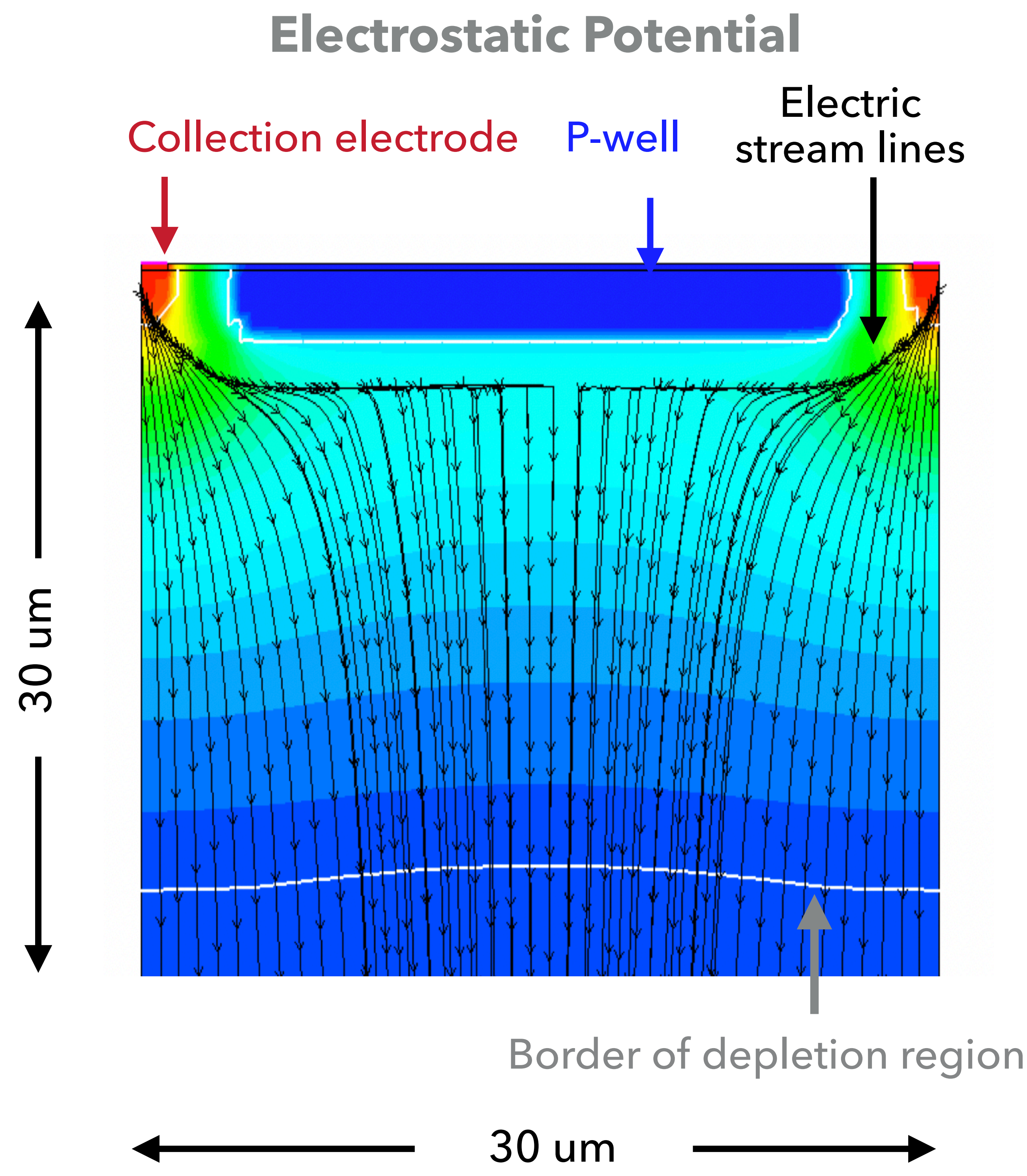
Simulation of sensors with a small collection electrode

- Complex non-linear field configurations due to small collection electrode design

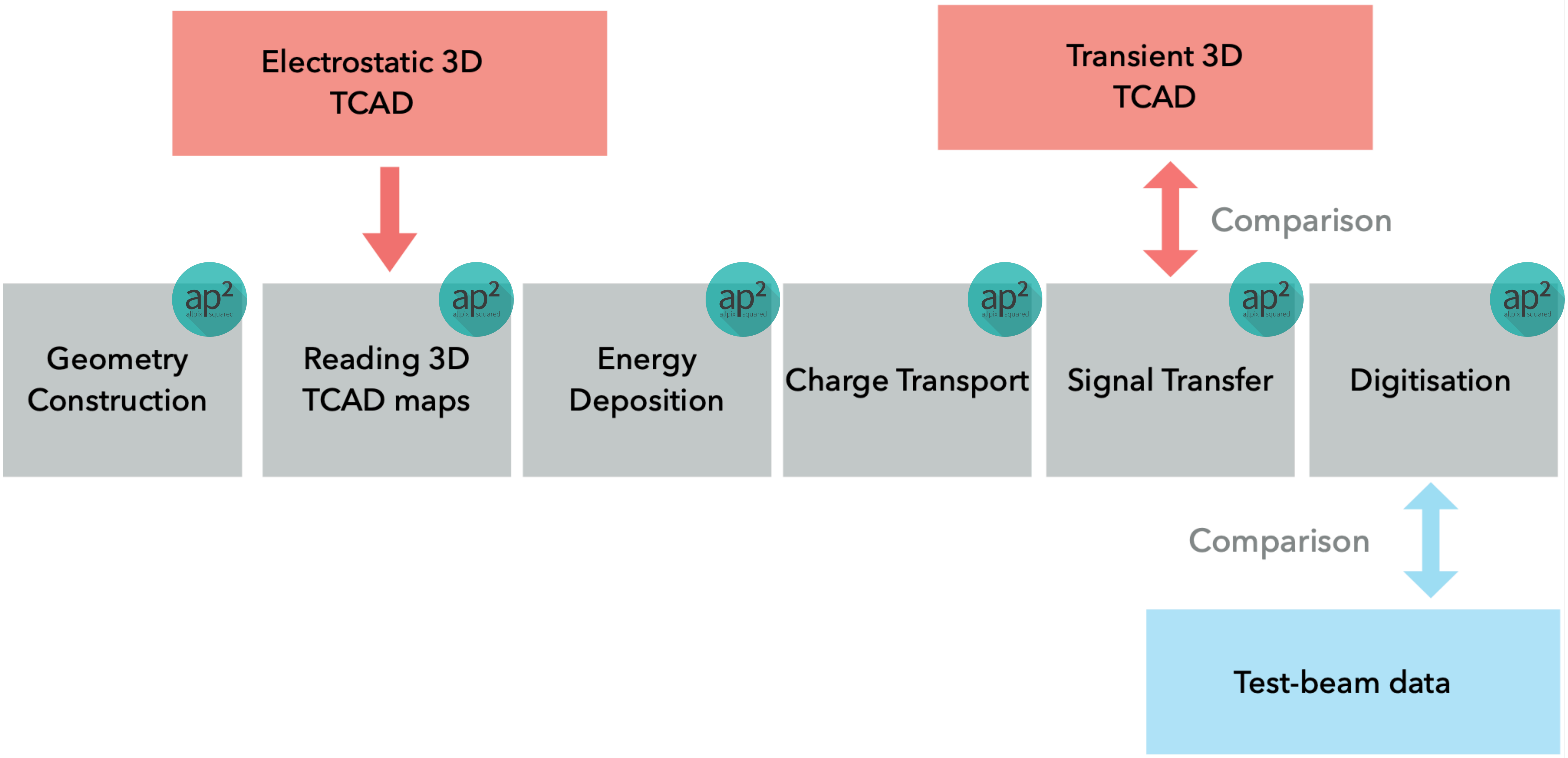
- Knowledge from planar sensors cannot be transferred

➡ Precise sensor modelling needed

- Field maps from electrostatic 3D TCAD simulations are imported into Allpix Squared



Simulation set-up



Reading field maps from 3D TCAD

- Maps computed with 3D TCAD are converted from an adaptive mesh to a regularly spaced mesh using the Mesh Converter tool

- They are imported using their respective Reader module

Doping profile

- Calculation of charge carrier lifetime
- Calculation of charge carrier mobility

Weighting potential

- Used to compute transient pulse

Electric field

- Used to compute drift of charge carriers in the sensor

```
[DopingProfileReader]
model = "mesh"
file_name = "inputDopingFile.init"
field_offset = 0.5 0.5

[WeightingPotentialReader]
model = "mesh"
file_name = "inputWeightingPotential.init"

[ElectricFieldReader]
model = "init"
file_name = "inputElectricFieldFile.init"
depletion_depth = 30um
field_offset = 0.5 0.5
```

Transient propagation

- Propagation taking drift and diffusion into account using the combined Masetti-Canali mobility model

- Charge carrier recombination based on the combined Auger and Shockley-Read-Hall model

- Induced charge on collection electrode is calculated using the Shockley-Ramo theorem

- The resulting transient pulses are used in the subsequent modules

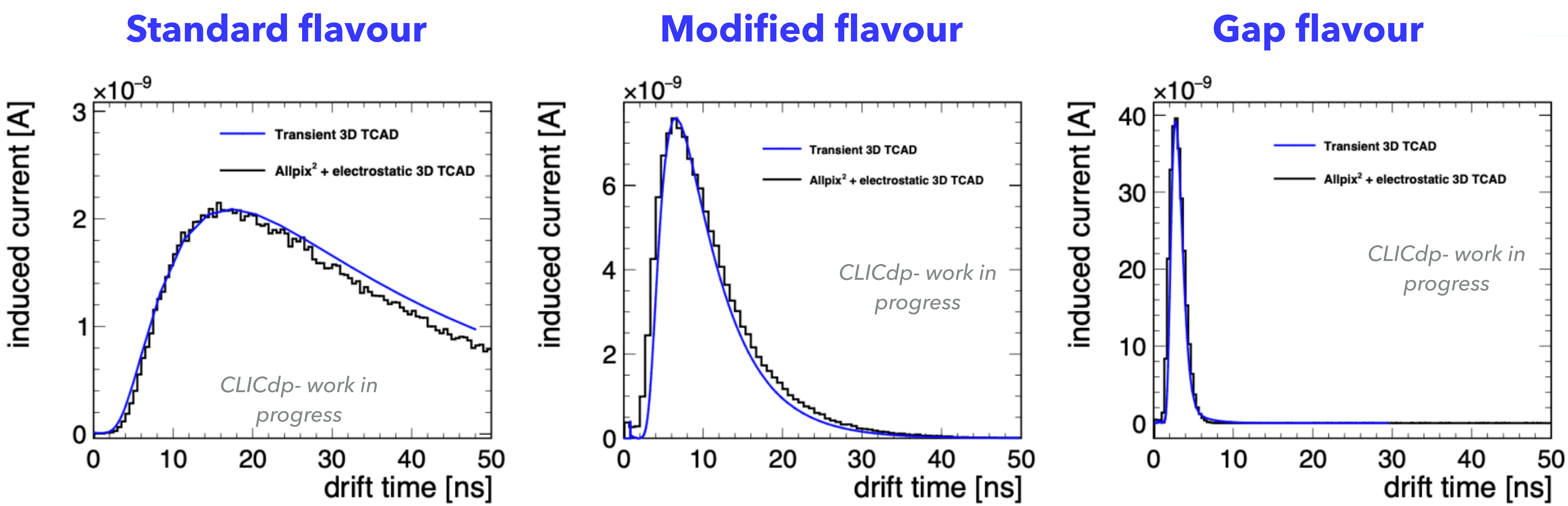
```
[TransientPropagation]
temperature = 293K
charge_per_step = 10
timestep = 0.0008ns
integration_time = 50ns
induction_matrix = 1,1
recombination_model = "srh_auger"
mobility_model = "masetti_canali"

[PulseTransfer]
output_plots = false
output_pulsegraphs = false
```

Comparison to transient 3D TCAD

- Charge injection along straight line at pixel corner (largest distance to electrode -> slowest charge collection expected)

- The transient pulse resembles the output obtained from transient 3D TCAD computations for all investigated pixel flavours

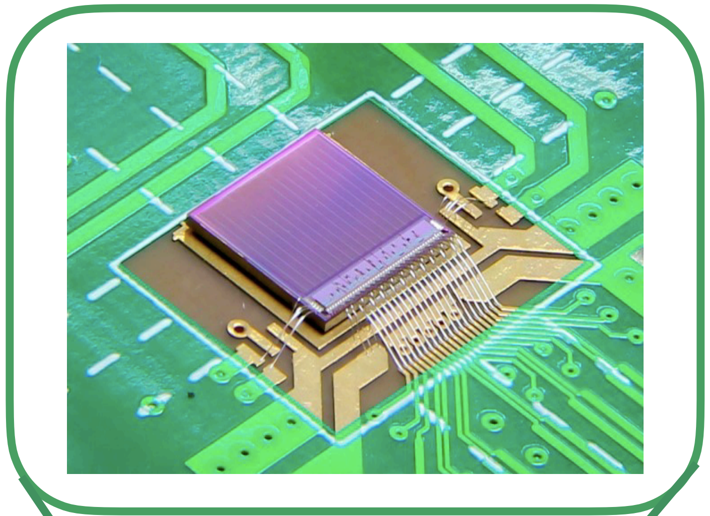


Comparison to test-beam data

The CLICTD technology demonstrator

- Fully integrated monolithic pixel sensor fabricated in modified 180 nm CMOS imaging process

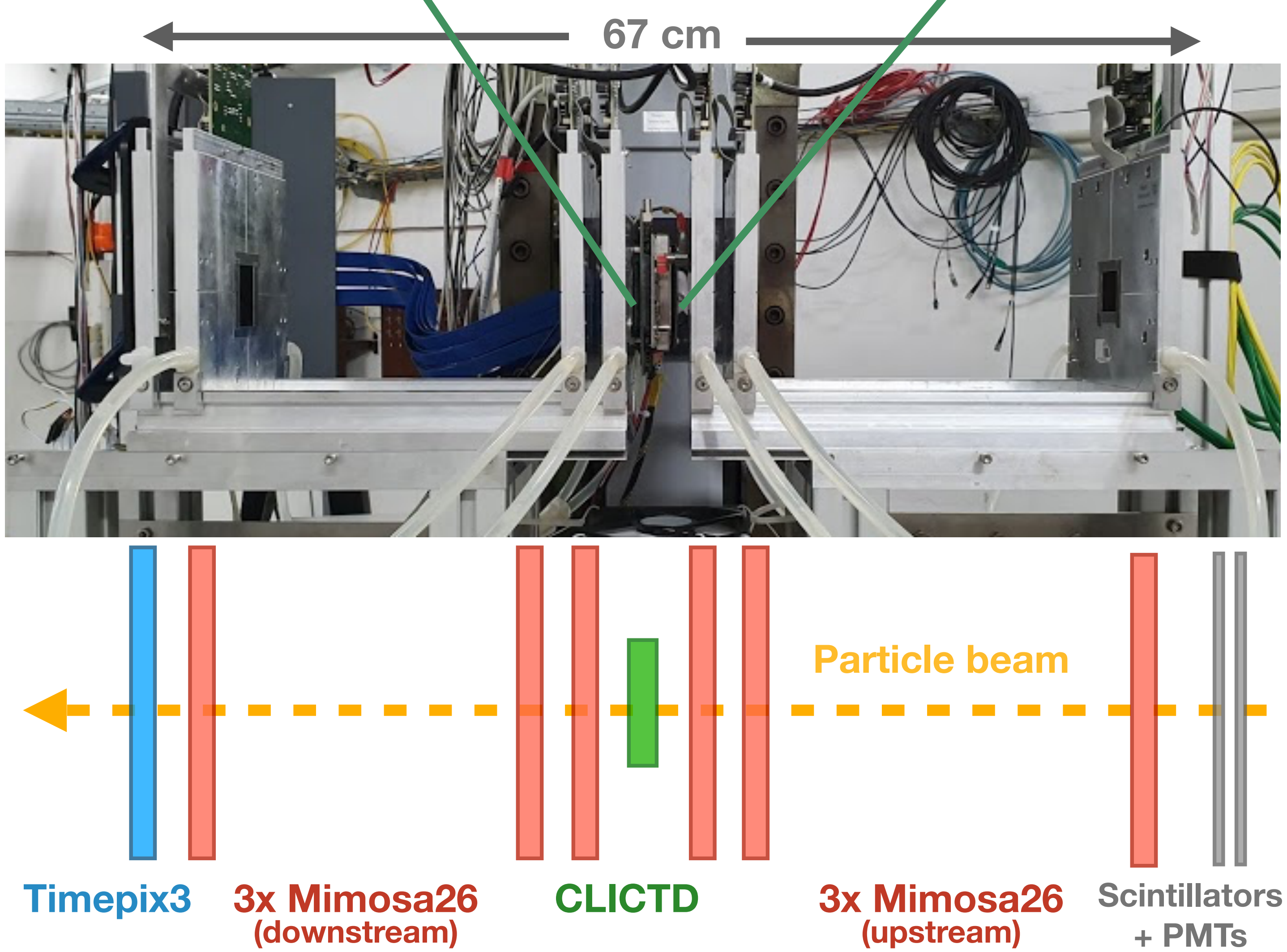
IEEE Tran. Nucl. Sci., August 2020
doi: 10.1109/TNS.2020.3019887



Test-beam at the DESY II Test Beam Facility

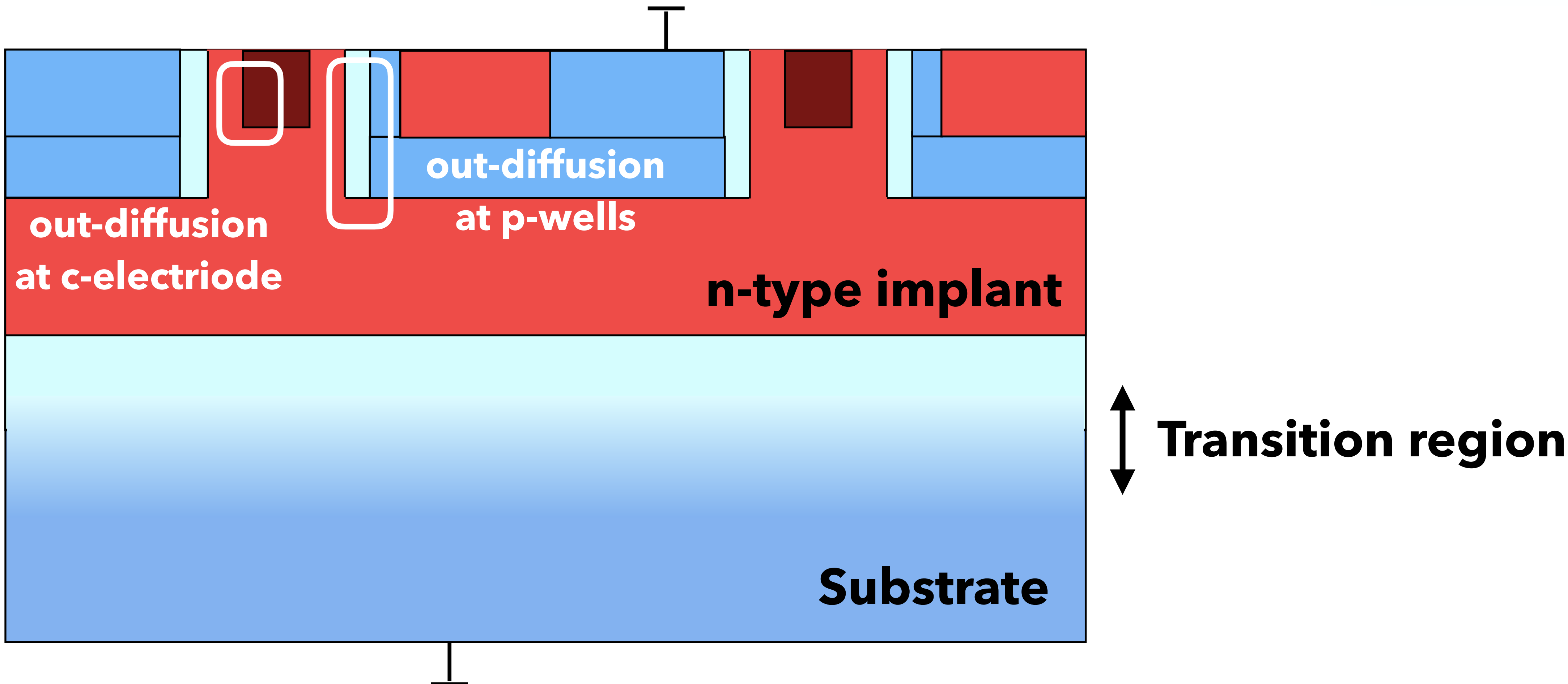
- 5.4 GeV electron beam
- MIMOSA-26 reference telescope equipped with TimePix3 plane for improved time reference

NIM A 1006 (2021) 0168-9002



The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

Systematic uncertainties

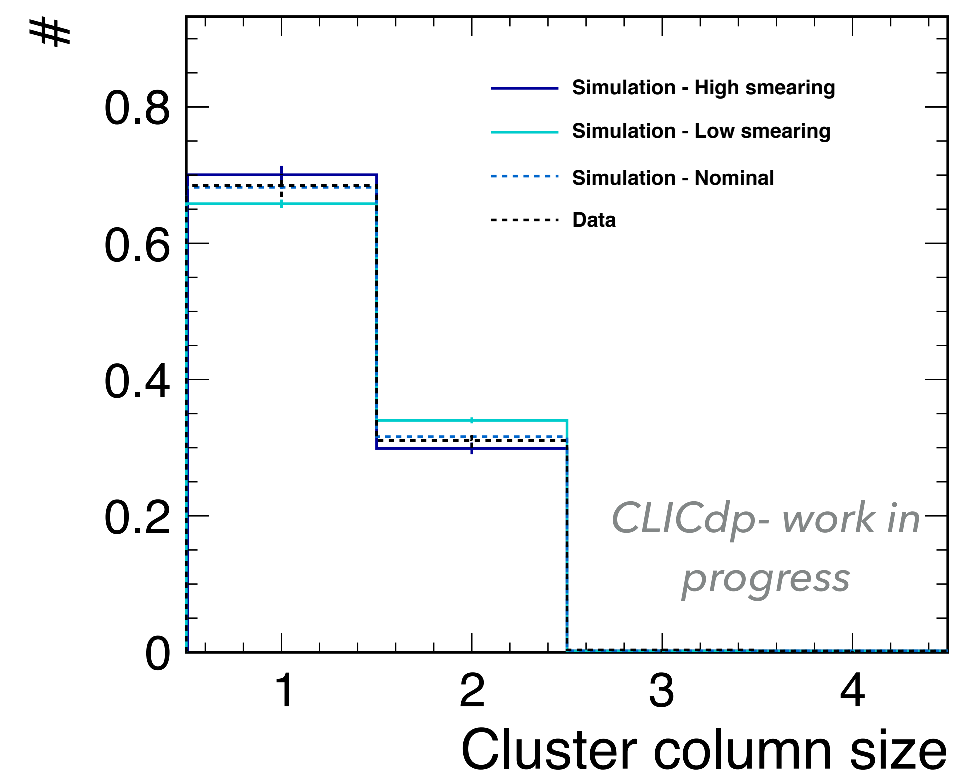


- Doping profiles are only known to a certain degree
- Introduces systematic uncertainties in the simulations (both 3D TCAD and Allpix Squared)
- Out-diffusion of three different implants was varied by a factor of 3 to quantify impact on cluster observables

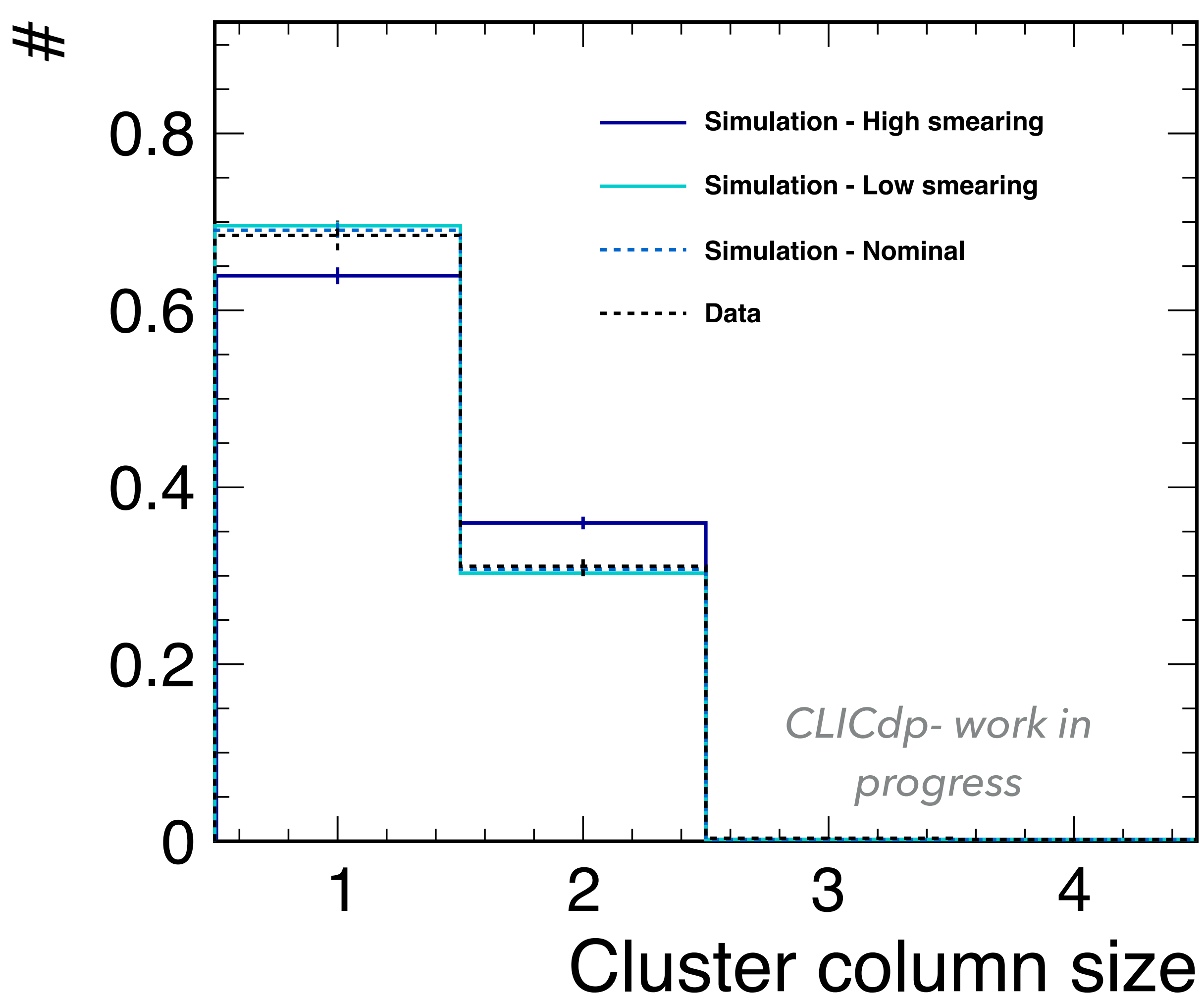
Systematic uncertainties

- In the following: only modified pixel flavour
- Non-linear impact on cluster size
- Sensor design needs to be optimised such that small variations in the doping profiles do not alter sensor performance significantly

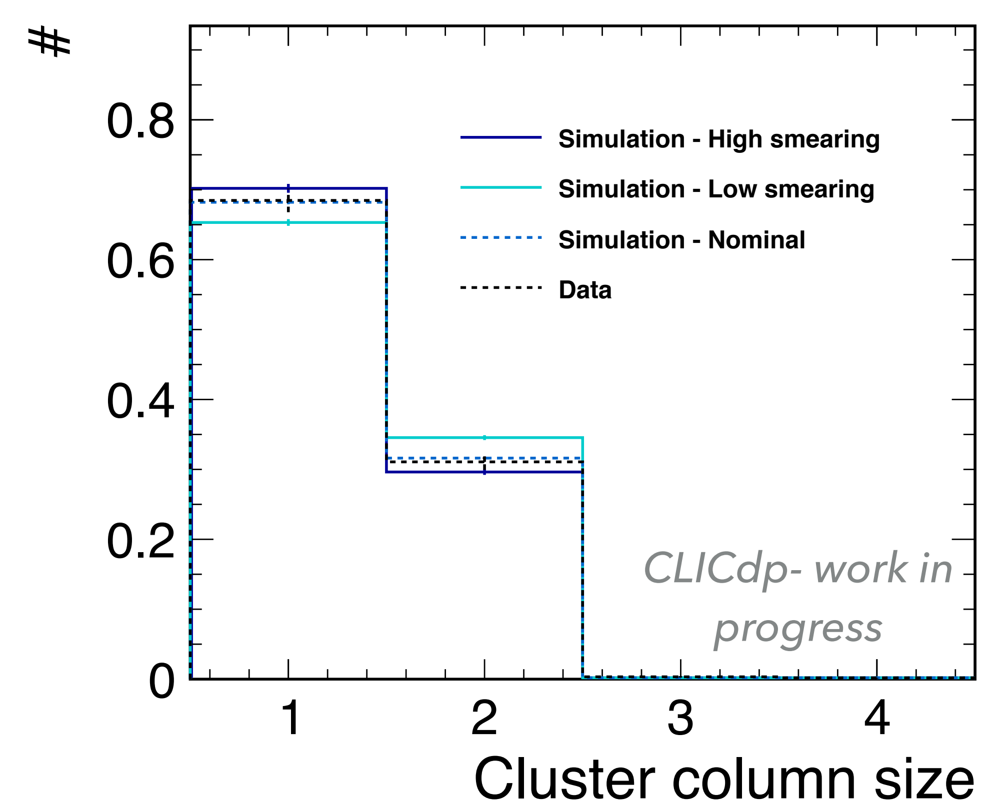
Transition region



P-well

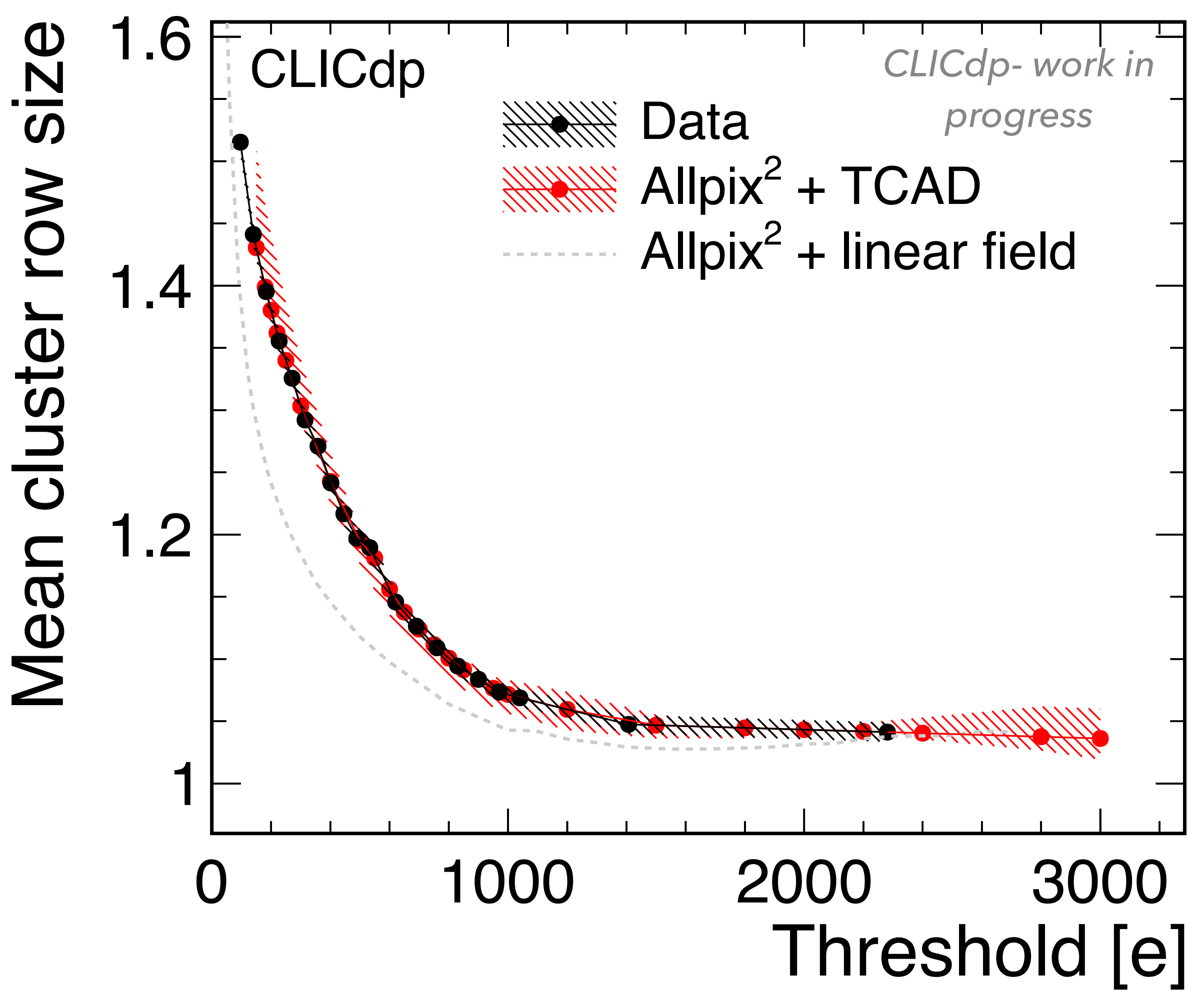


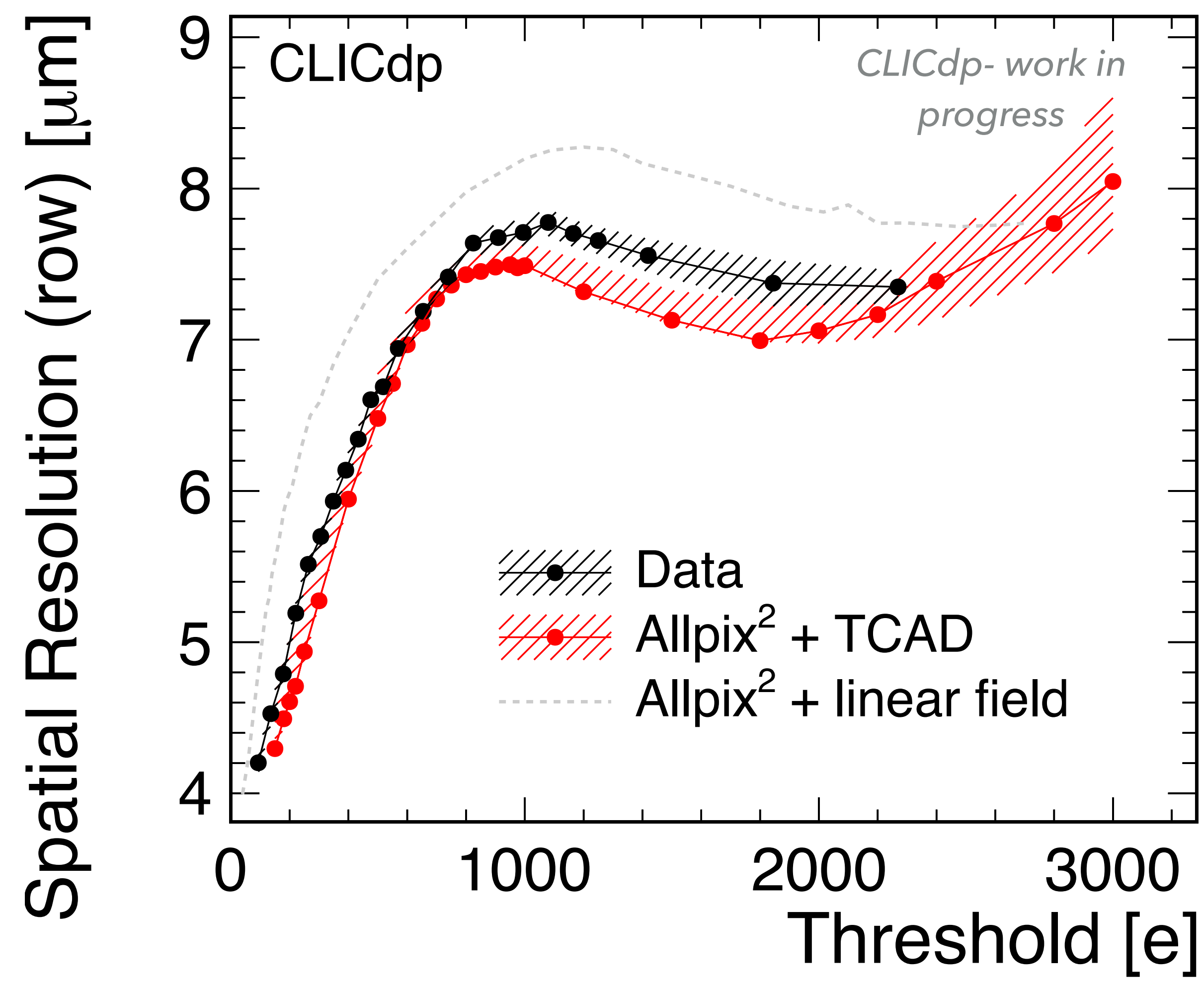
Collection electrode



Spatial resolution

- Band on data represents systematic uncertainties related to threshold calibration and test-beam reconstruction
- Band on simulation represents systematic uncertainties related to the doping profiles
- Simulation with linear electric field does not reproduce the data
- Good agreement using 3D TCAD combined with Allpix Squared



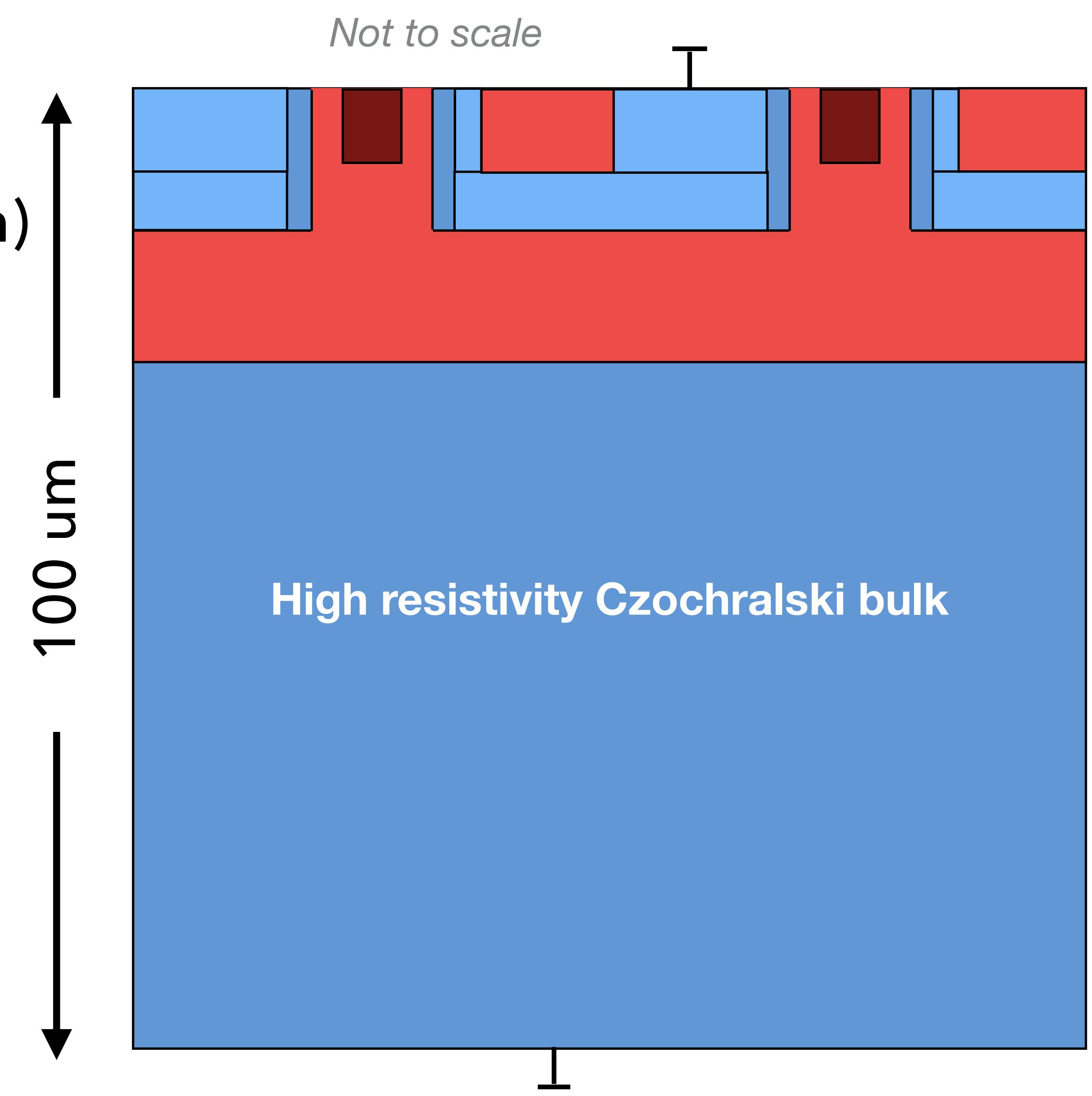


High-resistivity Czochralski material

- Limited thickness of epitaxial layer
- High-resistivity Czochralski (> 800 Ωcm) starting material allows for larger depleted volume

  NIM A 986 (2021) 164381

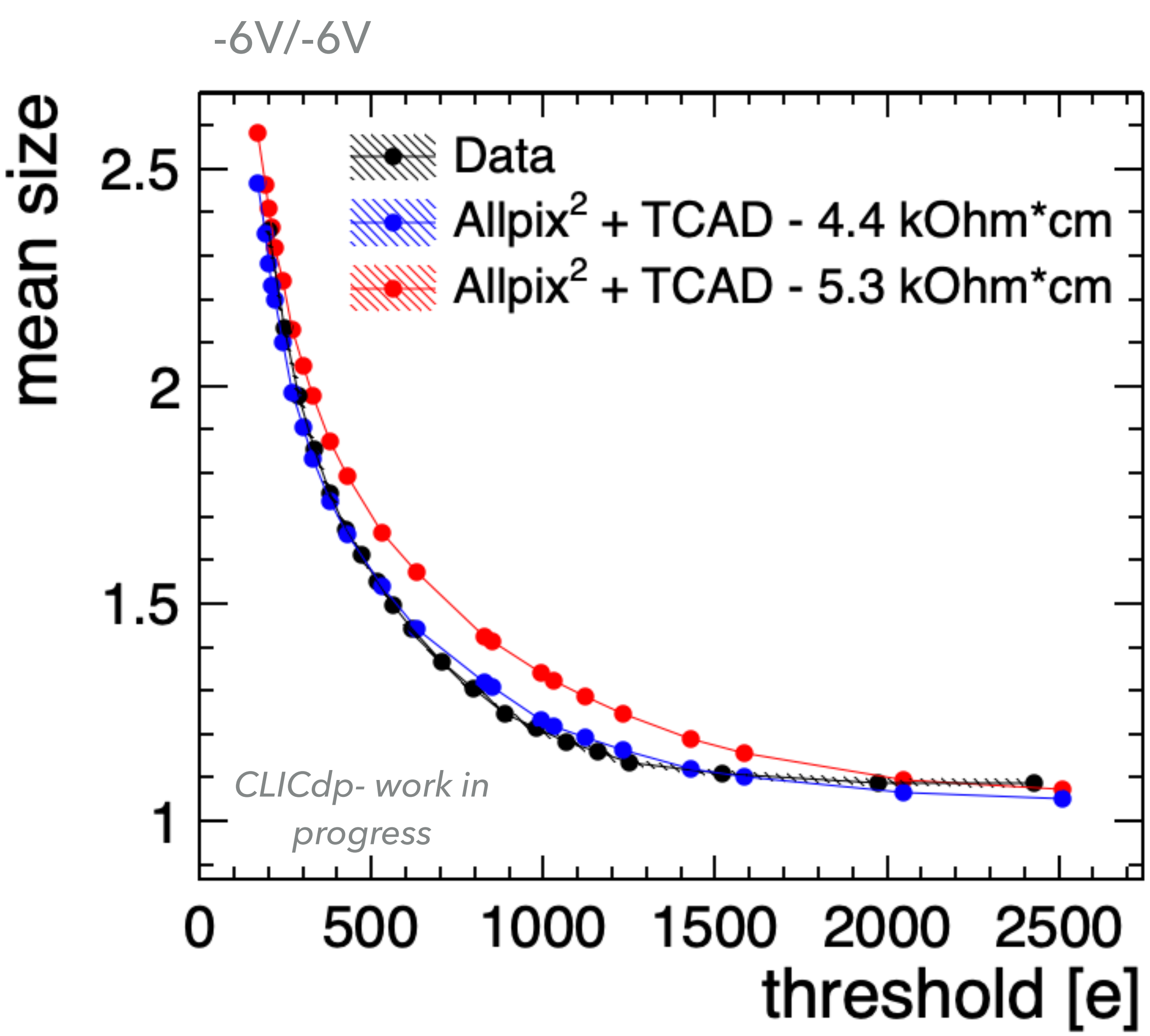
➡ Improved signal/noise ratio, larger cluster size (position resolution), larger efficient operation window

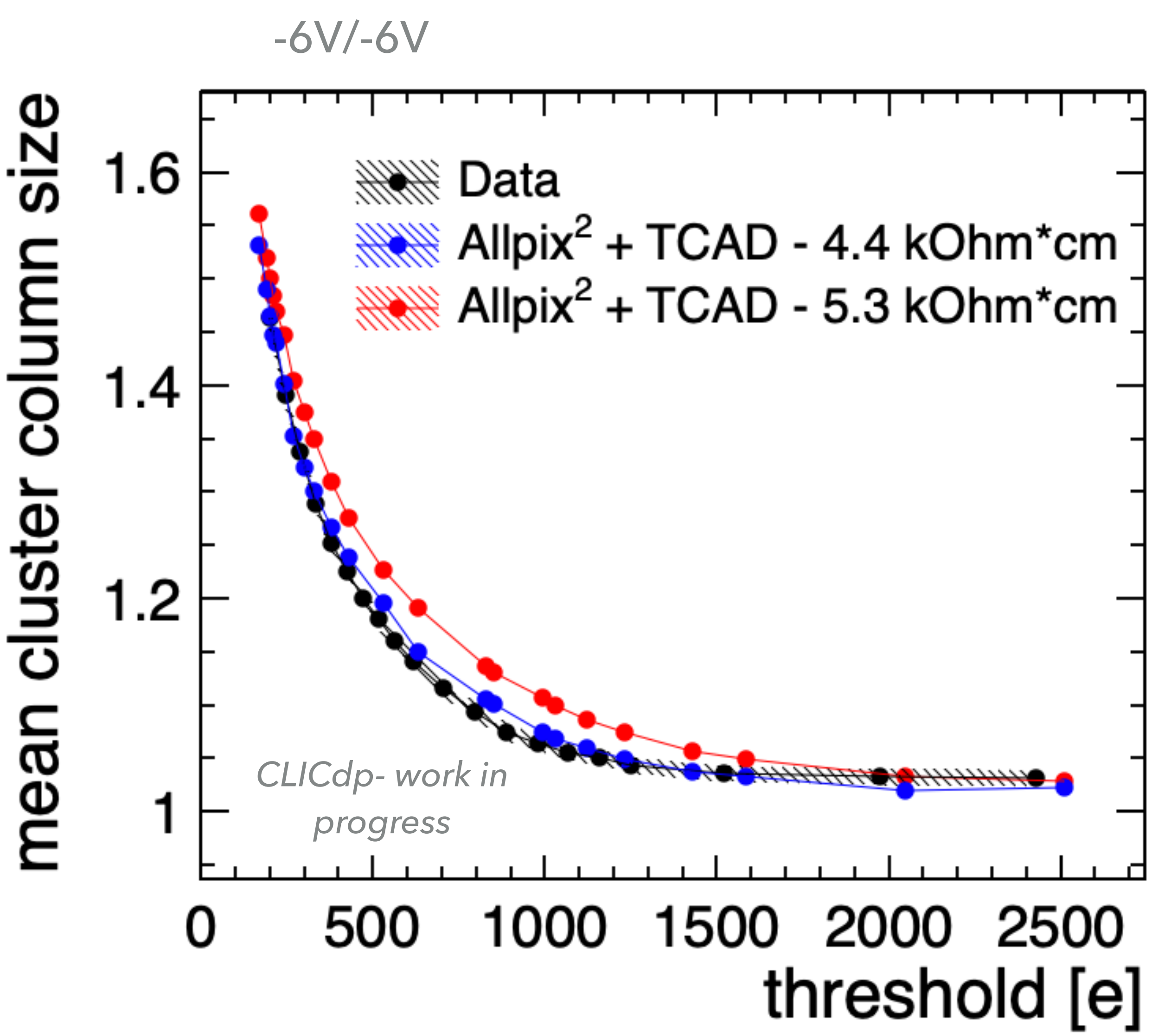


- High-resistivity Czochralski sample enables combination of small collection electrode with large depleted volume

Comparison to test-beam data

- Doping concentration of Czochralski substrate not precisely known -> additional source of uncertainties
- Comparison to data helps to confirm assumed resistivity
- Reconstruction and analysis of test-beam data currently on-going





Summary and outlook

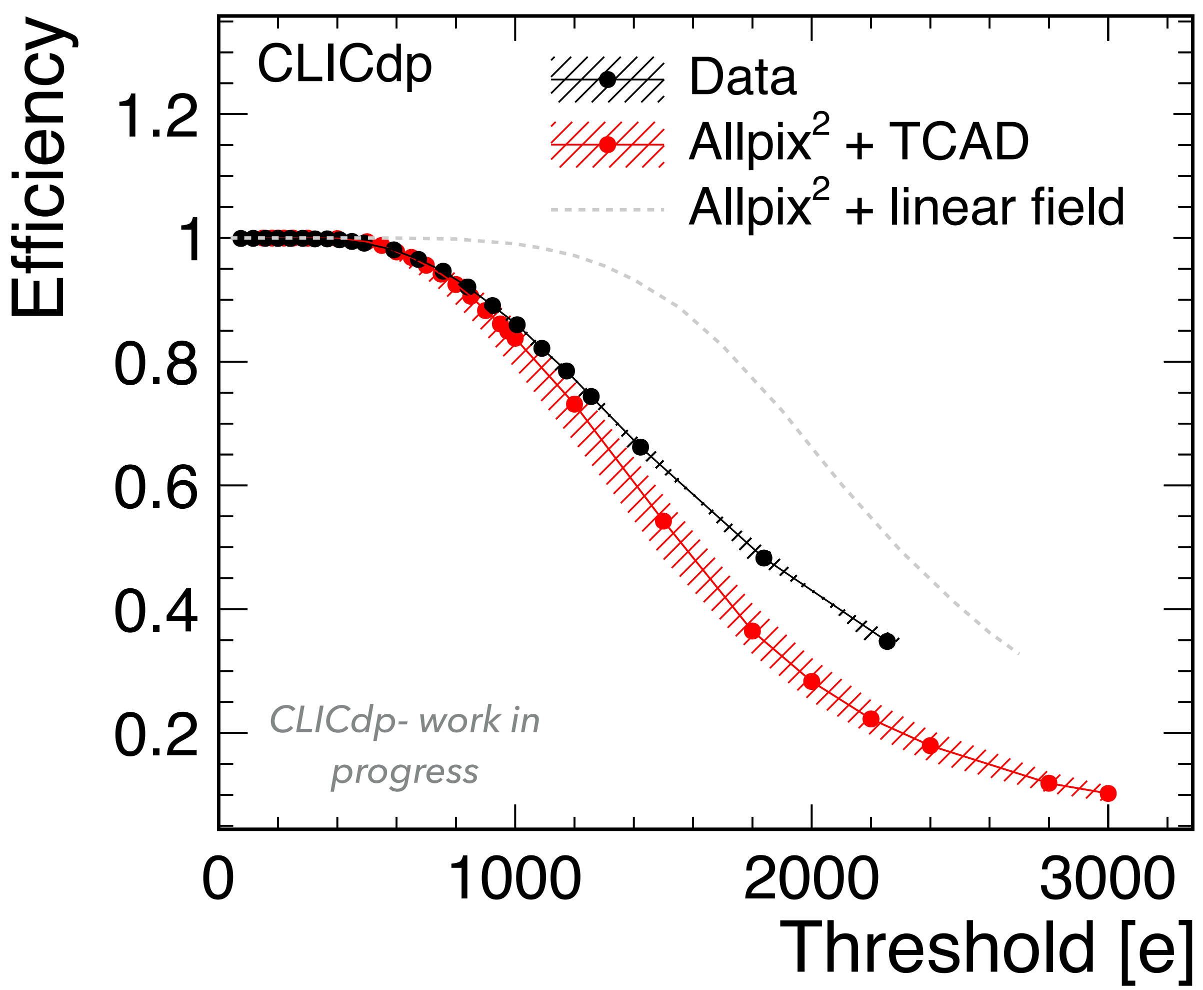
- Advanced simulation techniques required for complex sensor designs
- Simulations using electrostatic 3D TCAD and a MC framework allow for an accurate sensor modelling and high statistics
- Uncertainties are dominated by doping profiles of the pixel implants
- Good agreement over a wide parameter range
- Comparison between data and simulation for advanced starting materials on-going

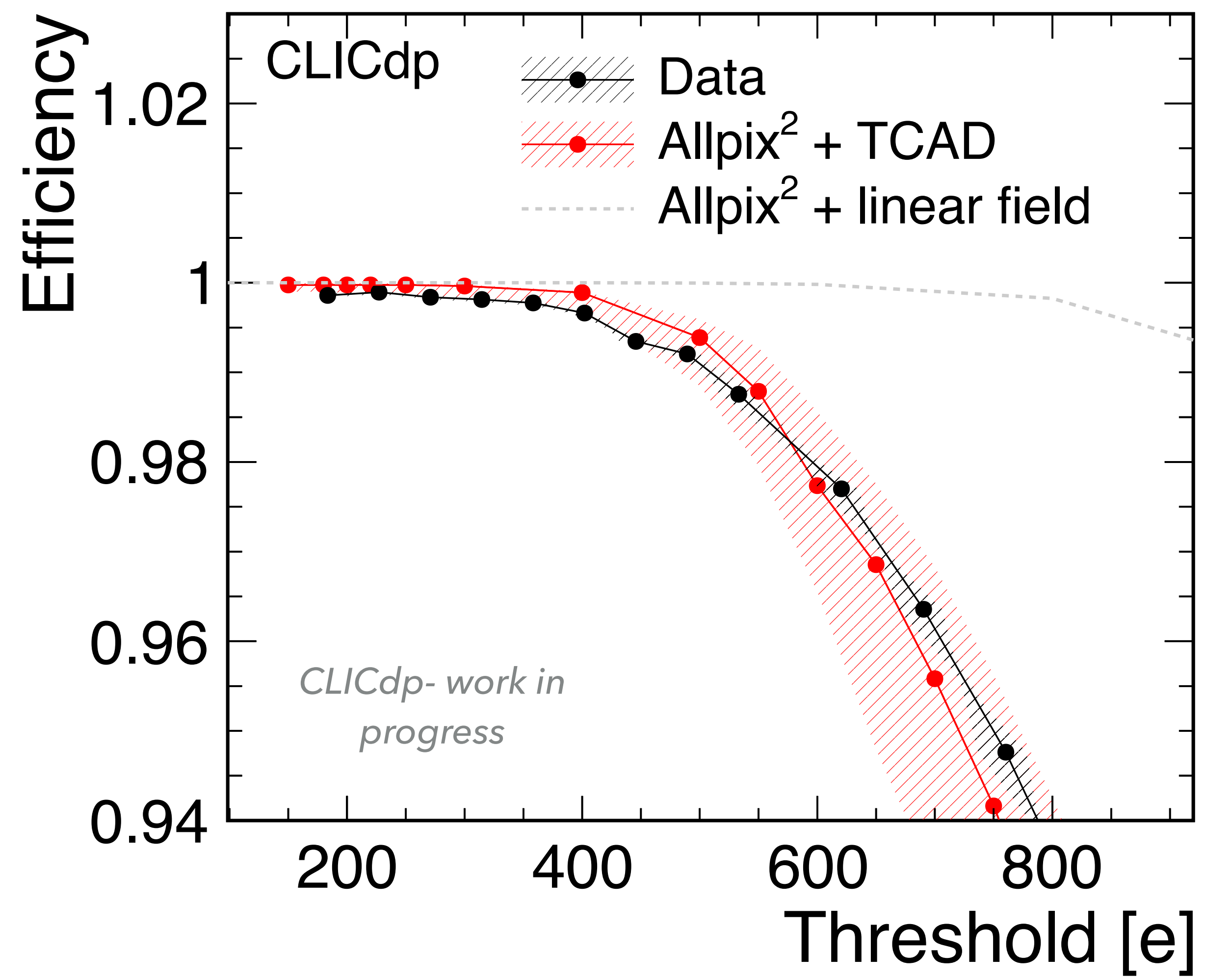
Thank you!

BACK - UP

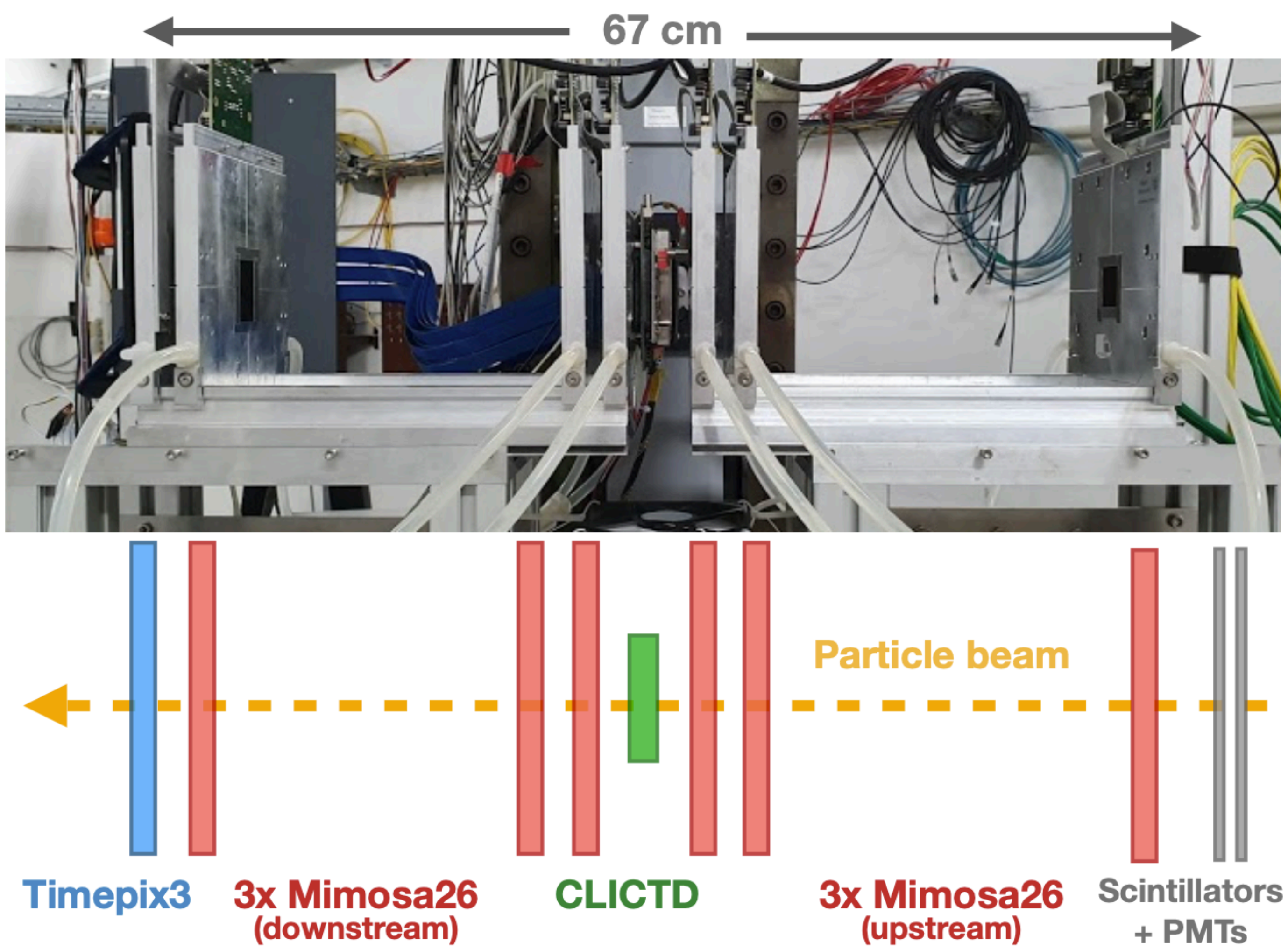
Hit detection efficiency

- Good agreement at low/intermediate detection thresholds
- Simulation with linear field clearly overestimates efficiency



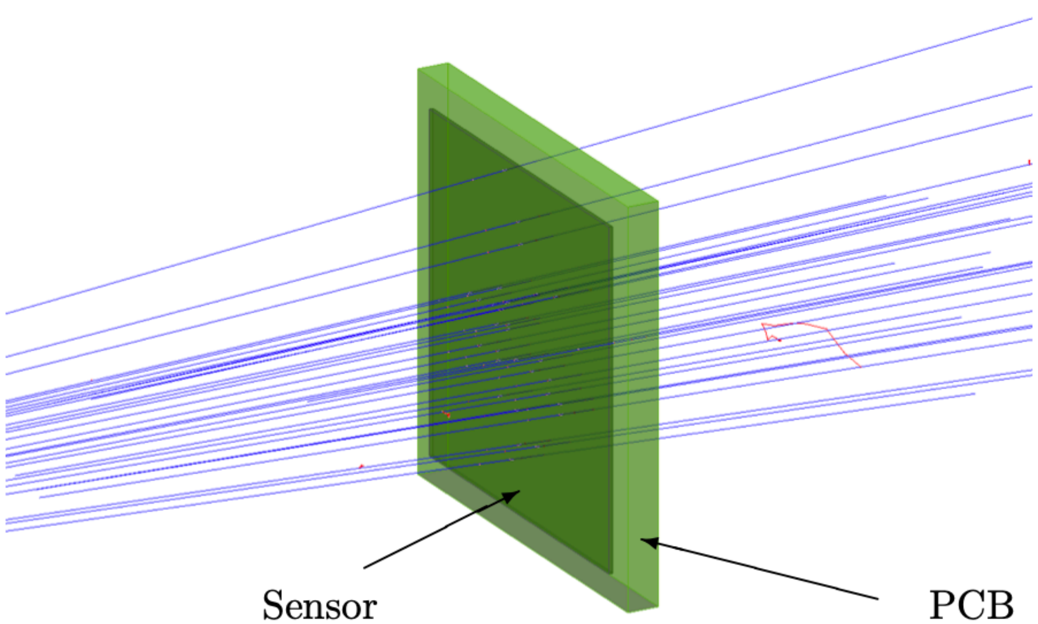


Comparison with data



Test-Beam set-up at DESY

- Beam: 5.6 GeV electrons
- 6 MIMOSA-26 + 1 Timepix3 sensor planes are used to form reference track
- Timepix3 sensor provides reference time-stamp (~ 1.1 ns)

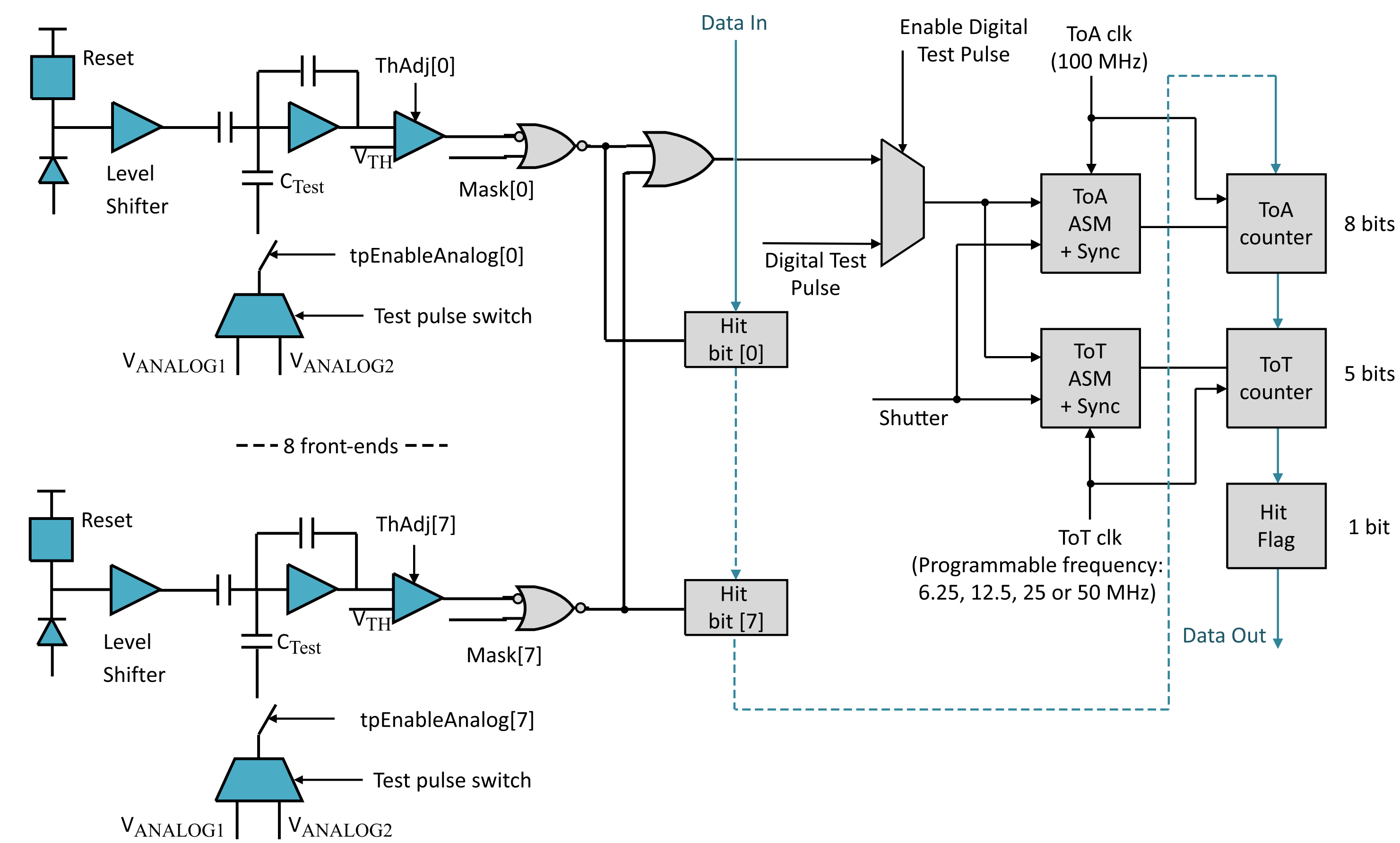


Simulation set-up

- Simulated beam particles : 5.6 GeV electrons
- Monte Carlo truth information used as spatial and timing reference (smeared with telescope resolution)

CLICTD - front-end design

- Detector channel consists of 8 sub-pixels (diode + analogue front-end)
- Channel pitch: 300 μm x 30 μm (16x128 channels)
- Collection electrode pitch: 37.5 μm x 30.0 μm
- Discriminator output of sub-pixels is combined in logic OR for ToT and ToA measurements
  (one ToT and ToA per channel)



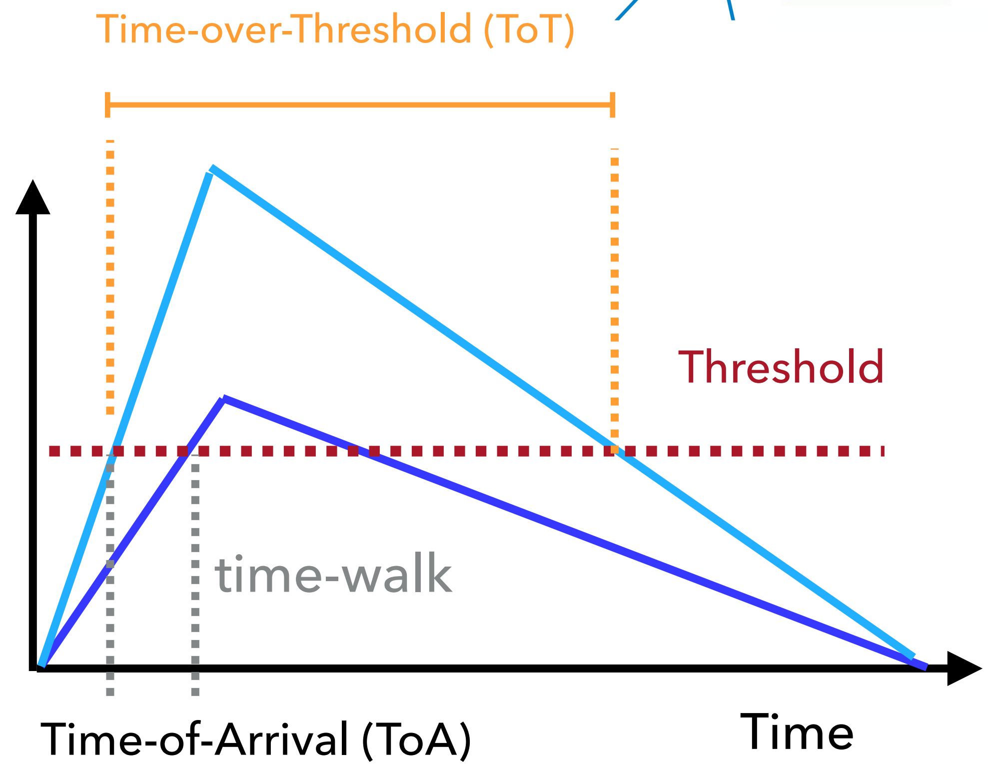
IEEE Trans Nucl. Science 67.10 (2020): 2263-2272.

➡ Save space for digital circuitry while maintaining small capacitance and fast charge collection

- 8-bit ToA (10 ns ToA bins) + 5-bit ToT (programmable from 0.6 - 4.8 μs)
  (combined ToA/ToT for every 8 sub-pixels in 300μm dimension)

Time resolution

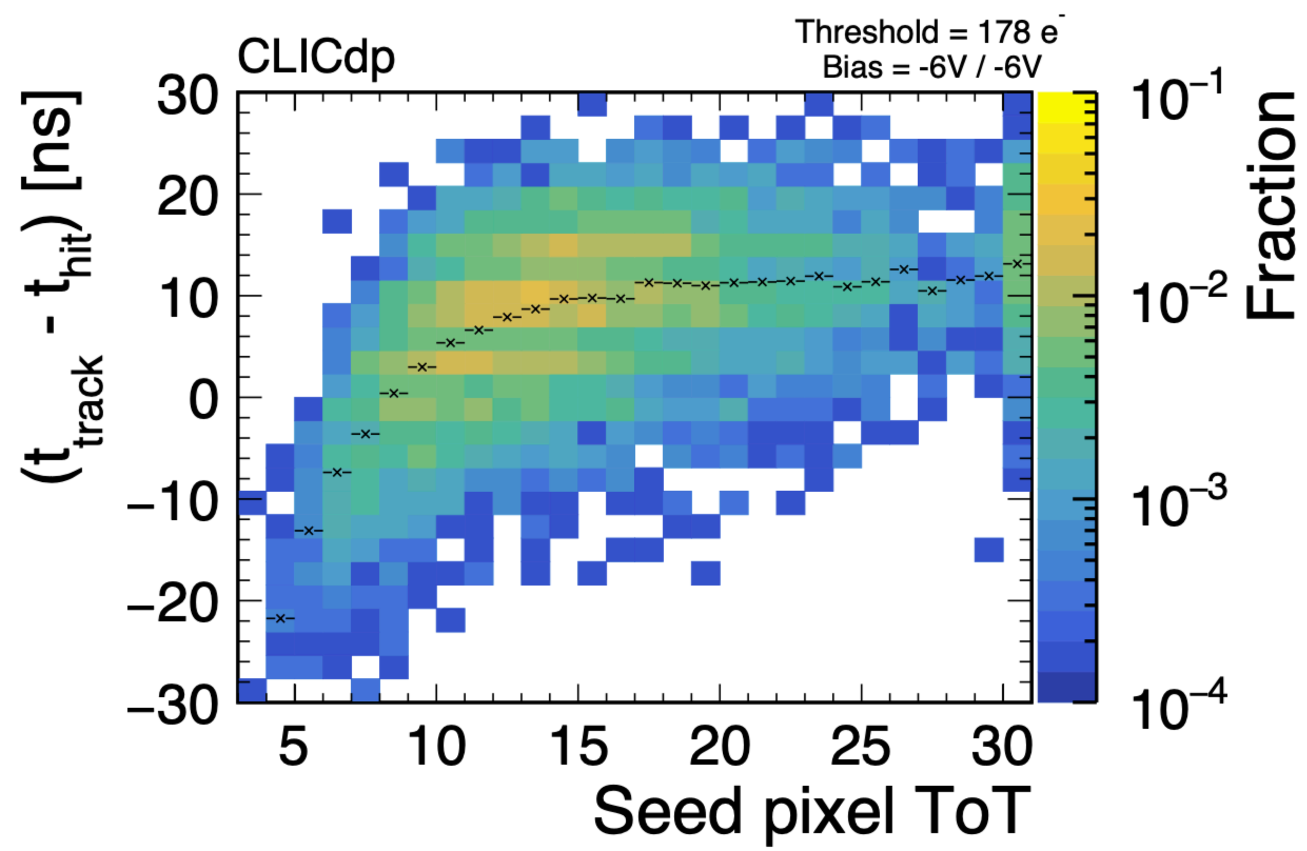
- Steeper slope for high signal heights (time-walk)
- Can be corrected offline by using charge information
- Time-of-Arrival (threshold crossing)/Time-over-Threshold (clock cycles above threshold) used to measure time/charge



Challenges in data

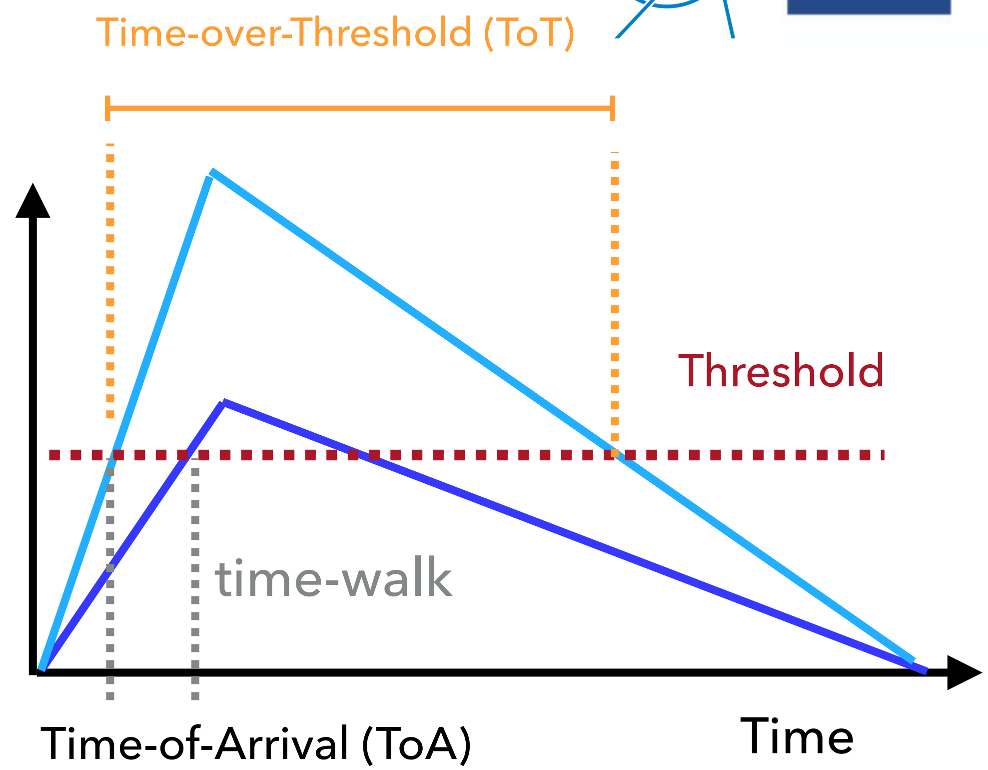
- Non-linear relationship between ToT and charge in physical units
  - Limited range of test-pulse signal
- Restricted charge measurement range (up to ToT 30)
- 100 MHz ToA clock limits time measurements
- Limited statistics: full matrix is used for obtaining correction factors

Data



Time resolution

- Simulation contains no front-end contribution (no time jitter) but only ideal sensor timing -> helpful to understand impact of sensor design on timing



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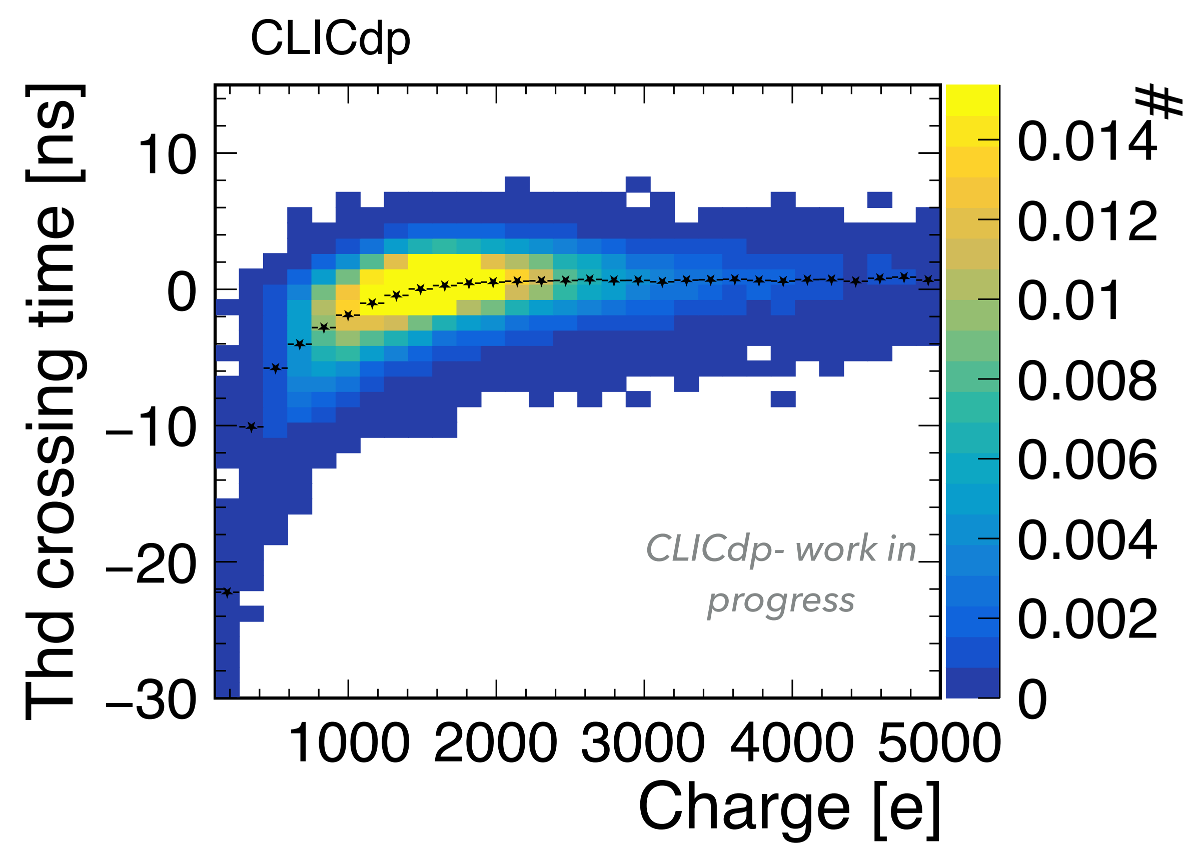
Simulation



Time resolution

- Reconstruction challenges in data can be largely overcome in simulation, which helps to study their impact on the final result
- Timing in data is dominated by front-end effects

➡ Direct comparison to simulation not possible

Simulations - After time-walk correction