Test-beam and simulation studies of the monolithic CMOS silicon sensor CLICTD

BTTB 2021

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On behalf of the CLICdp collaboration

Outline

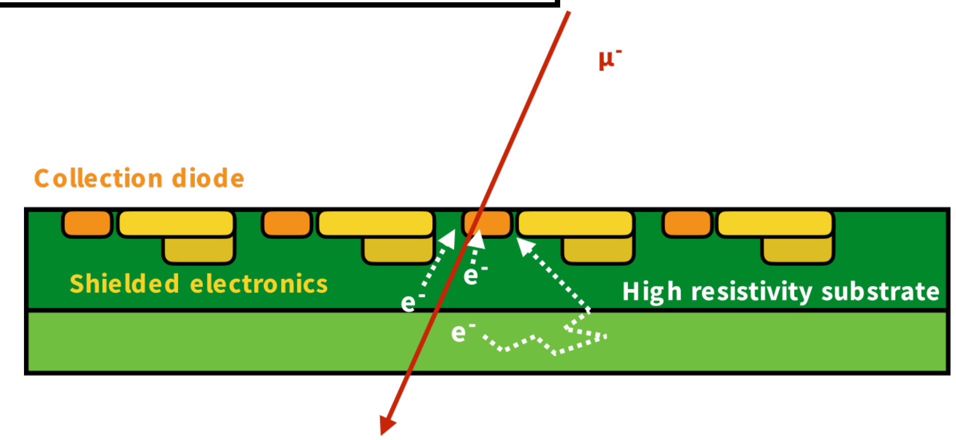
- The CLICTD sensor
- Test-beam rotation studies
- Simulation studies
- Summary and outlook

Motivation

Objective

Development and characterisation of detector technologies for future collider experiments (e.g. the Compact Linear Collider)

- Monolithic CMOS sensors with a small collection diode
  - No interconnects, reduced material budget, profiting from CMOS imaging industry
  - Low input capacitance thanks to small collection diode



Characterisation effort

- Detailed and precise test-beam measurements and simulations required
- Corresponding flexible tools (Caribou, AIDA telescope, EUDAQ2, Corryvreckan, Allpix-Squared, TCAD…) are necessary

The project is carried out in the framework of

The strategic CERN EP R&D programme

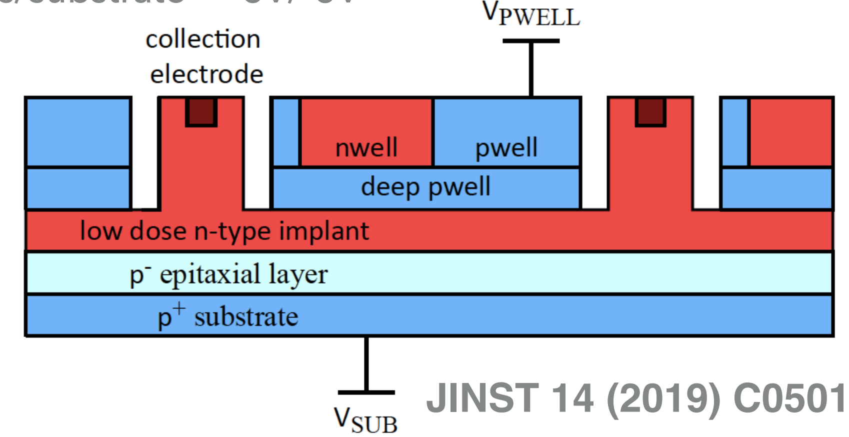
The CLICdp collaboration

The CLIC Tracker Detector (CLICTD)

Designed to meet the requirements of the CLIC Tracker

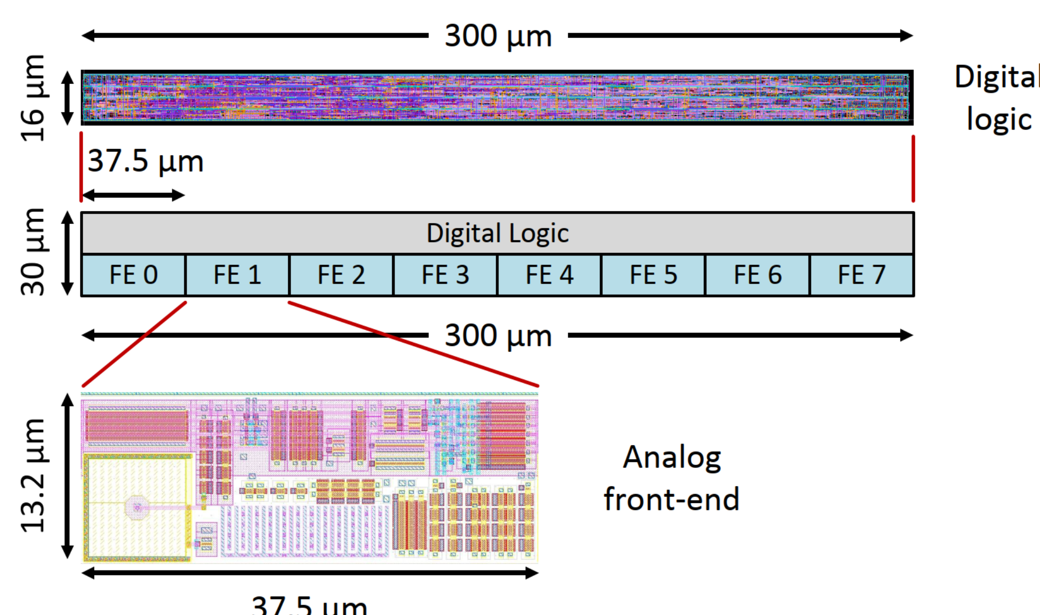
- Modified 180 nm CMOS imaging process with small collection diode
- Full lateral depletion in 30 µm epitaxial layer

Applied bias voltages to p-wells/substrate = -6V/-6V



JINST 14 (2019) C05013

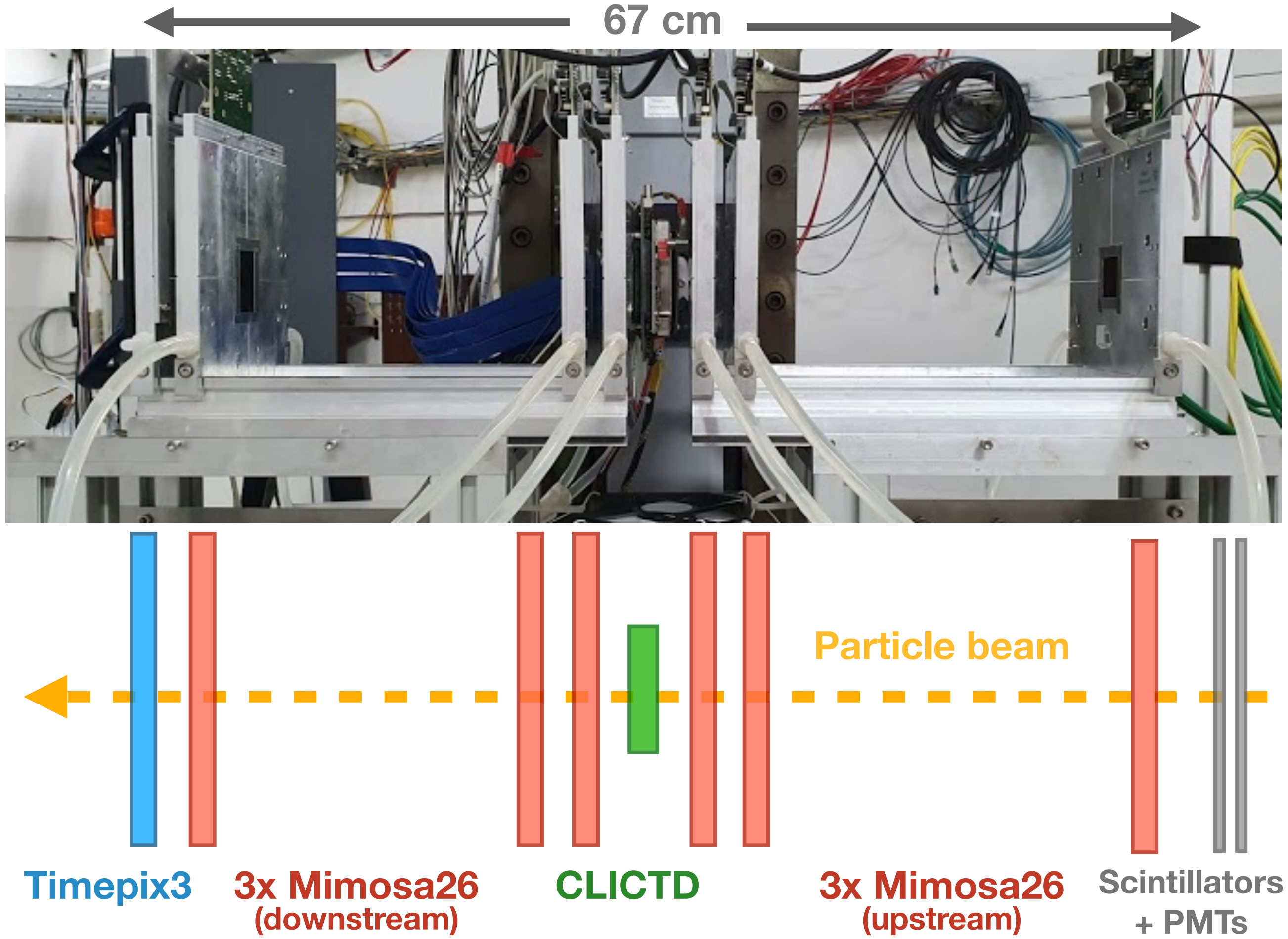
- Channel pitch: 300 µm x 30 µm (16x128 channels)
- Collection electrode pitch: 37.5 µm x 30.0 µm
- Detector channel consists of 8 sub-pixels (diode + analogue front-end)
  - Discriminator output of sub-pixels is combined in logic OR



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

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

Test-beam setup



- Test-beam measurements at the DESY II test beam facility

Big thank you to the DESY test-beam support team

- MIMOSA planes
  Track-position resolution at DUT: ~ 2 µm
- Timepix3 timing plane
  Timing resolution: ~ 1 ns
- AIDA TLU
  Triggers MIMOSA readout and provides global time reference
  See talk by Jens Kröger

- Device Under Test (DUT) CLICdp-Conf-2019-012
  Readout with Caribou versatile DAQ system
  See talk by Eric Buschmann
- Data acquisition framework
  Planes are read out and controlled using EUDAQ2

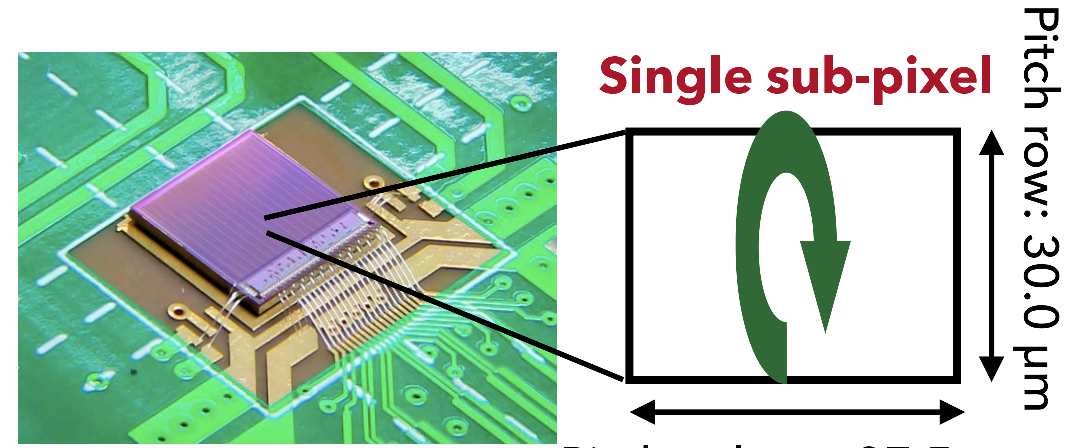
Test-beam rotation studies

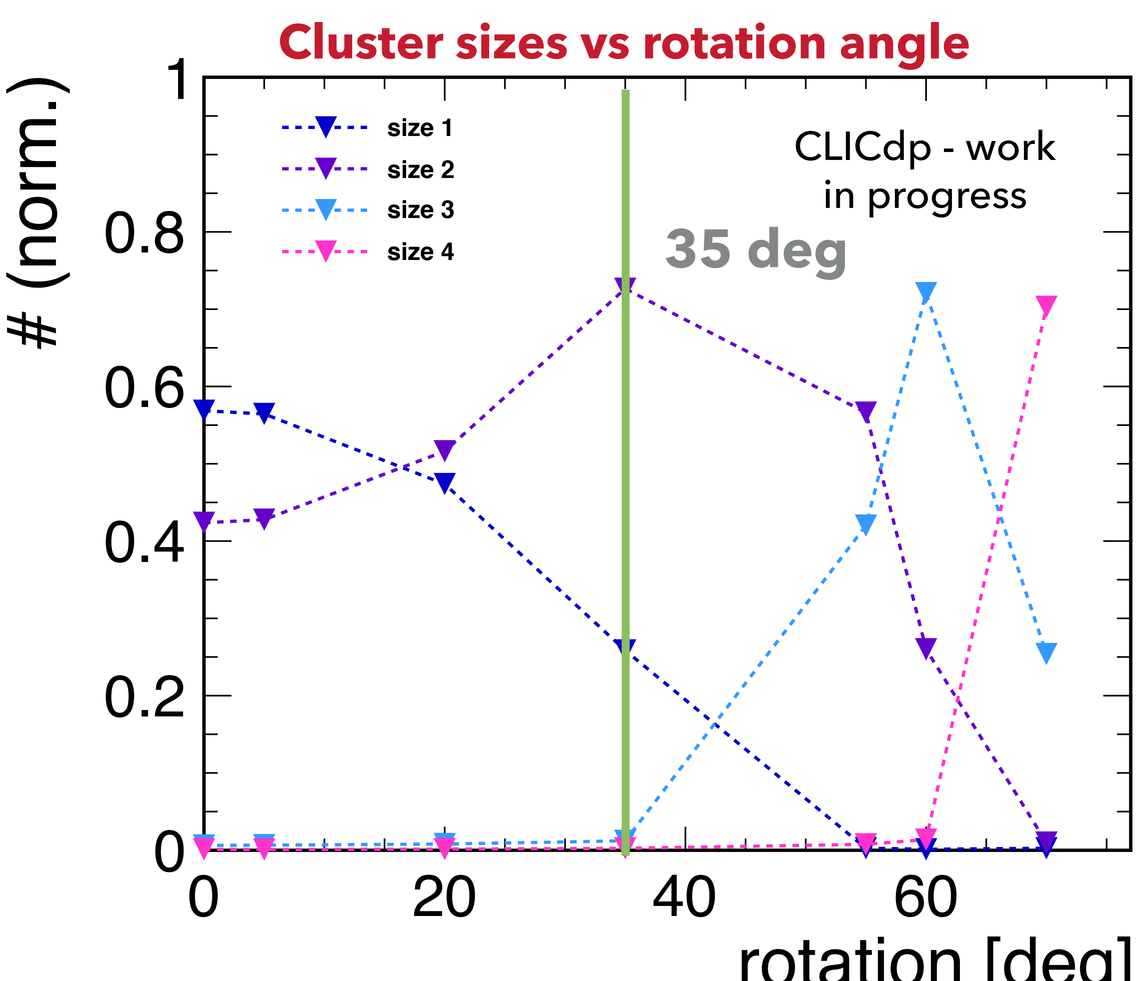
- Reconstruction and analysis with the Corryvreckan reconstruction framework **See tutorial by Jens Kröger**

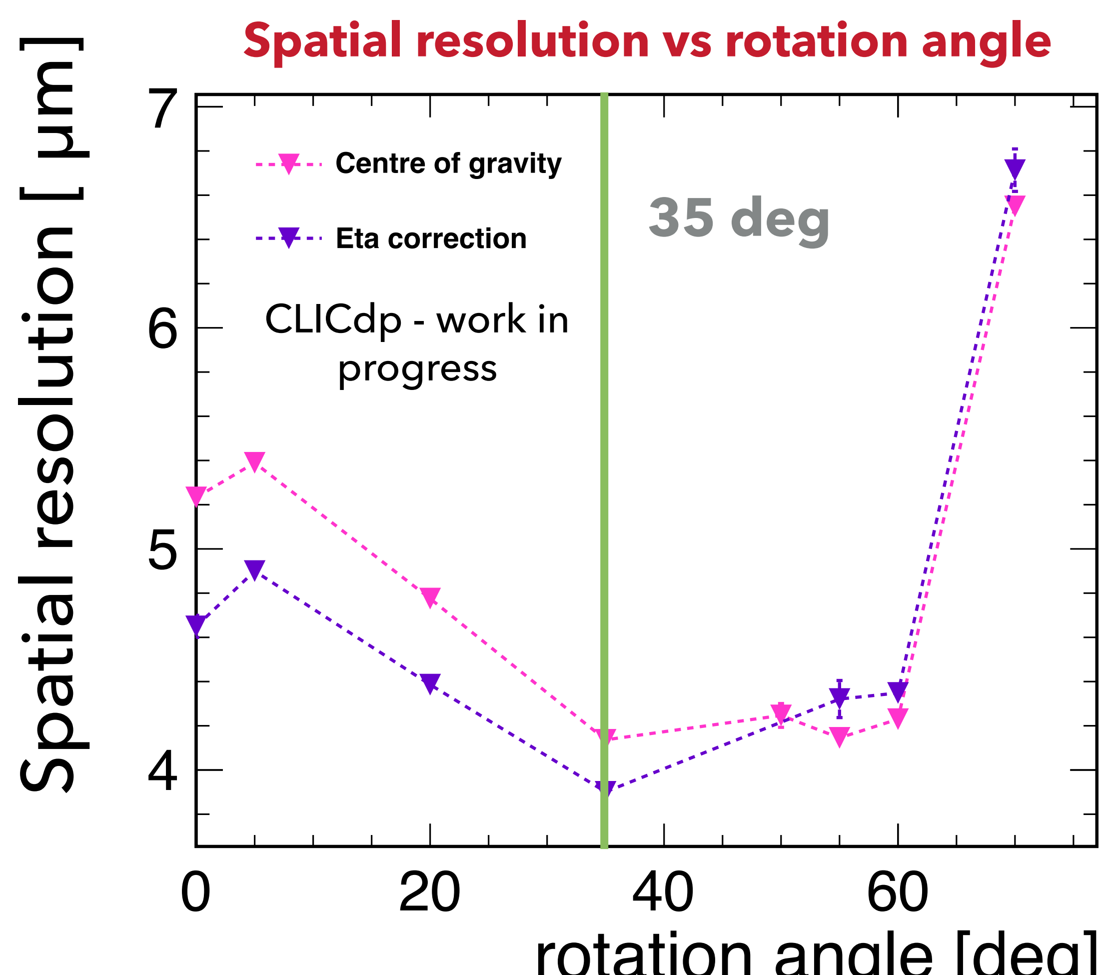
https://gitlab.cern.ch/corryvreckan/corryvreckan

- CLICTD is tilted in row direction
- Spatial resolution is best around 35 degrees where cluster size 2 is most prominent

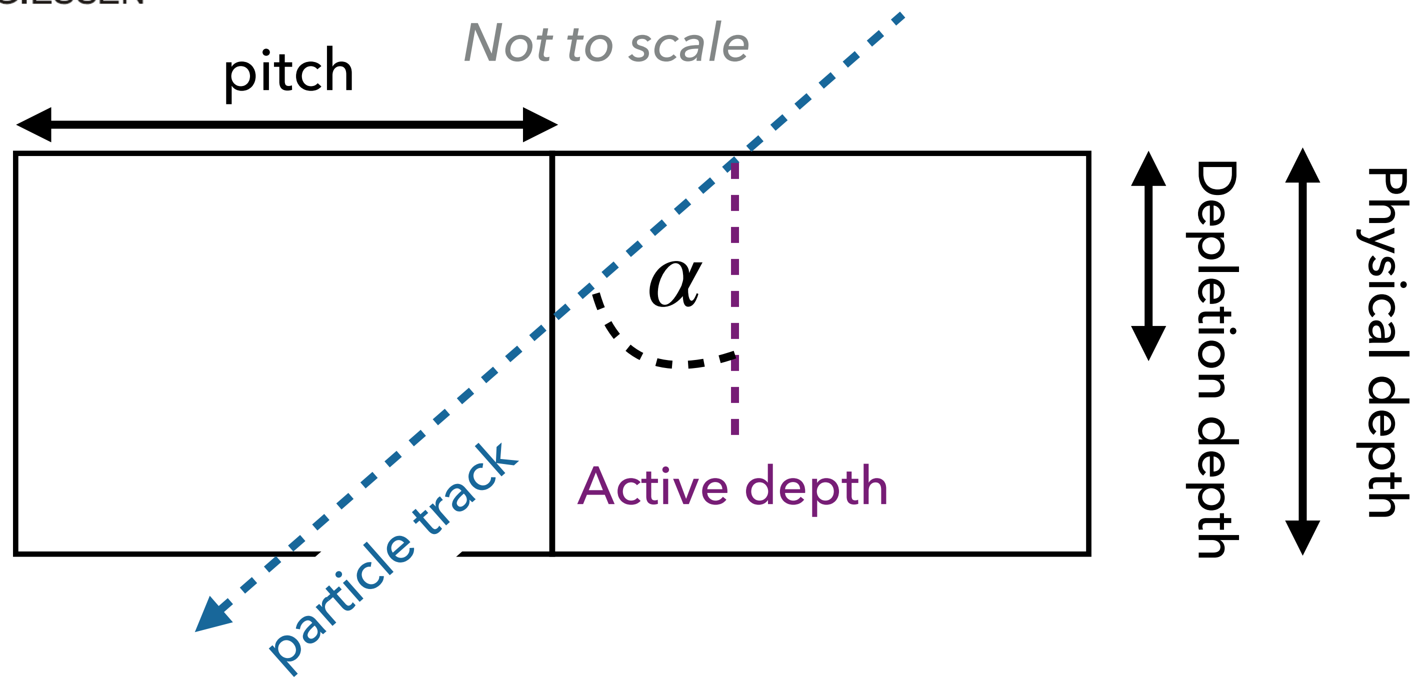
Cluster position reconstruction is still work in progress







Active depth from inclined tracks

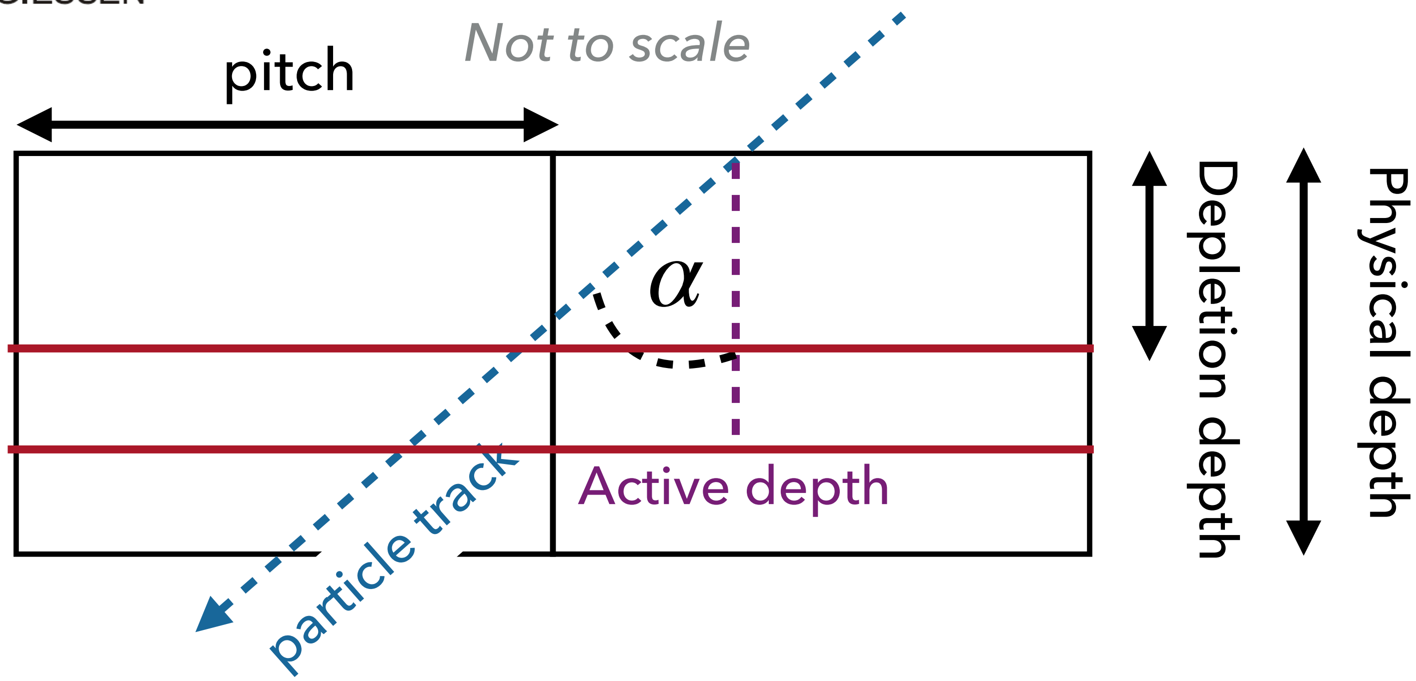


$$\text{size}_{\text{col}} = \frac{d_{\text{active}} \cdot \tan(\alpha)}{\text{pitch}_{\text{col}}}$$

- Complex non-uniform fields inside the sensor -> assumptions used for planar sensors do not necessarily hold
- Charge carriers below high-field depletion region can contribute to signal

- Charge carriers created within the active depth of the sensor contribute to the measured signal
- Active depth can be estimated by rotation-dependent cluster (column) size using a simple geometrical model
- Charge sharing by diffusion and threshold effects are not accounted for in this model

Active depth from inclined tracks



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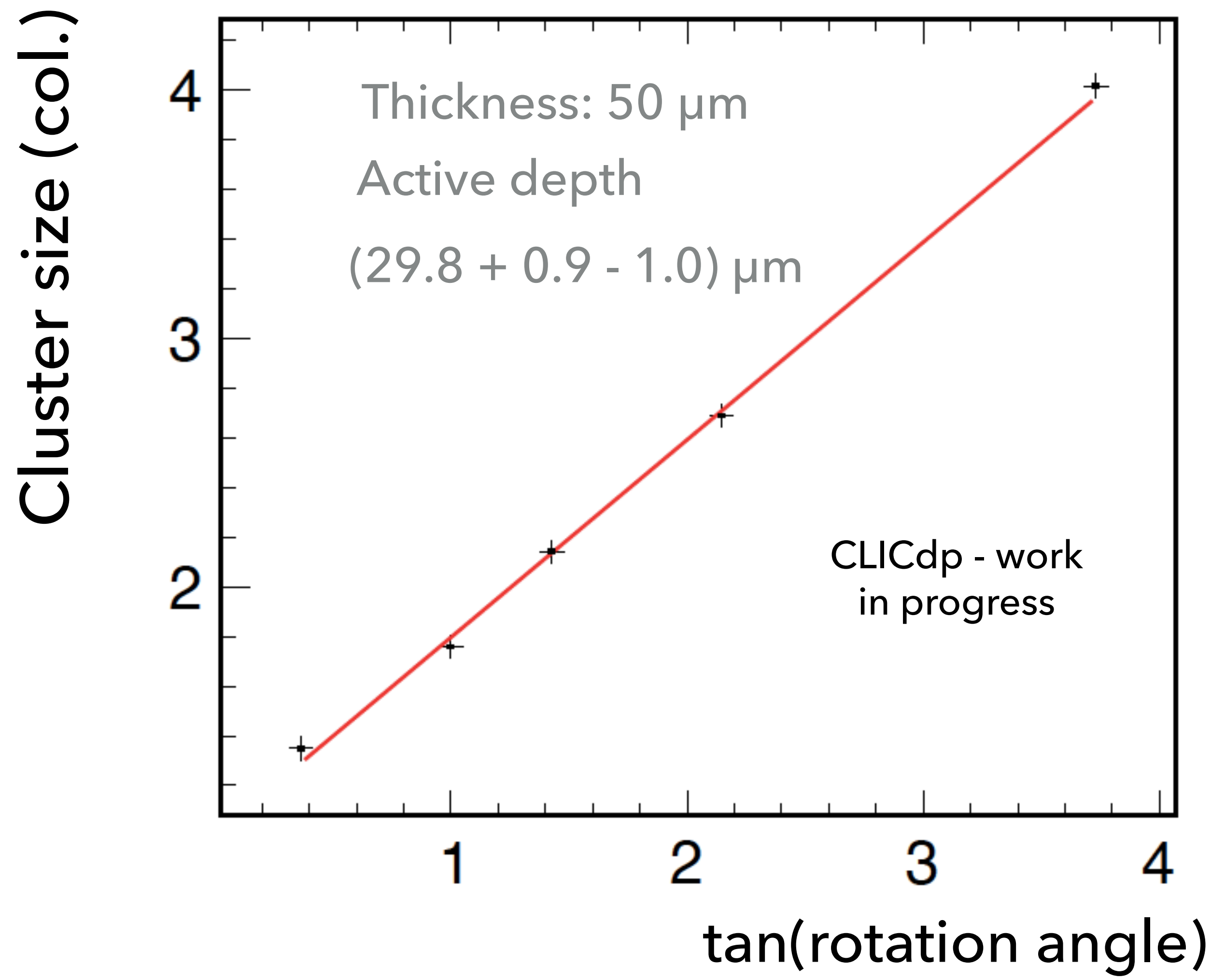


- Active depth of approximately 30 µm was found for assemblies with different thicknesses (50 µm - 300 µm)
- Thickness of epitaxial layer: 30 µm
- Expected depletion depth: 23 µm (estimated from 3D TCAD simulations) ➡ Contribution from non-depleted sensor region

Monte Carlo + TCAD simulations

- 3D TCAD simulation studies for monolithic CMOS sensors are crucial to optimise sensor design
  - Simulation of e.g. capacitance, leakage current, punch-through

- Optimised sensors can be evaluated by combining electrostatic TCAD and transient Monte Carlo simulations

- Stochastic effects, fluctuations, generation of secondary particles are included in the MC simulation

https://garfieldpp.web.cern.ch/garfieldpp

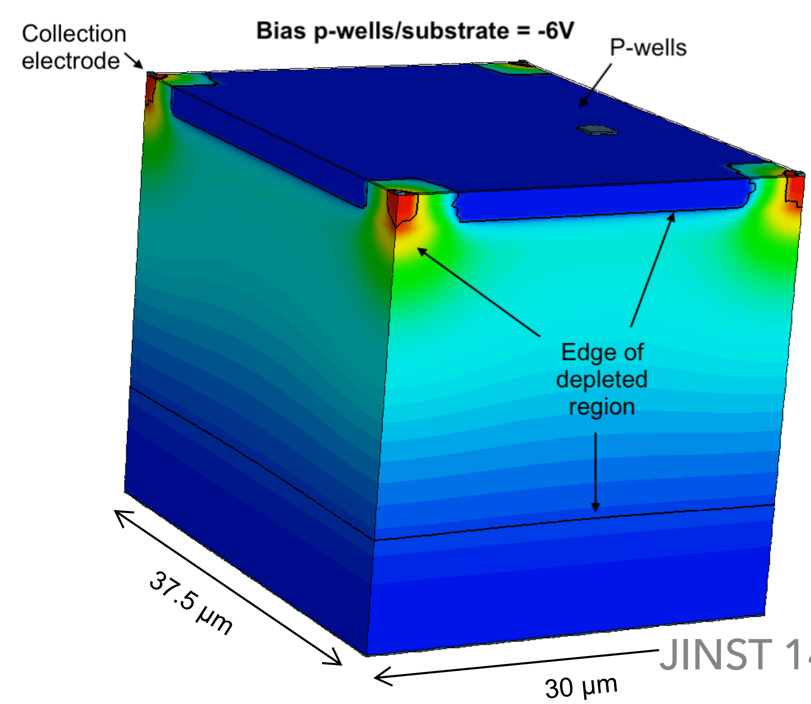
https://gitlab.cern.ch/allpix-squared/allpix-squared

Simulating monolithic CMOS sensors with small collection diode

- Complex non-uniform electric field

- Knowledge from standard planar sensors cannot be transferred -> simulations needed to design and evaluate new sensor concepts

Electrostratic potential from 3D TCAD



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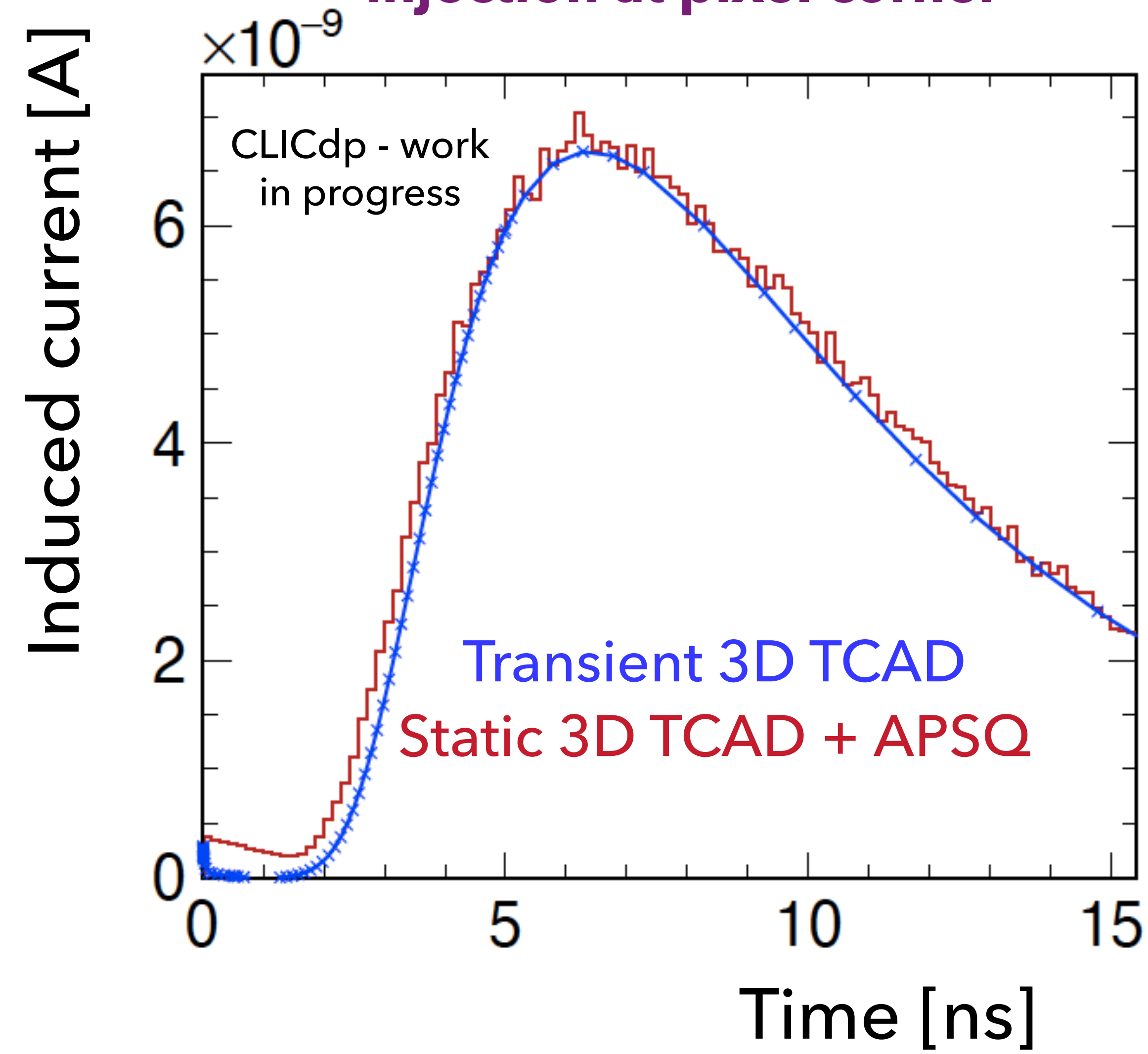
See talk/tutorial by Simon Spannagel

Simulation setup

- Full detector simulation from energy deposition until digitisation of signal
- Doping profile, weighting potential and electrostatic field maps are imported from electrostatic 3D TCAD simulation to
  - ensure precise field modelling
  - allow for accurate calculation of charge carrier lifetime, drift velocities, mobilities etc.
- Transient simulation with limited lifetime of simulated charge carriers (currently not in Allpix-Squared master branch yet)

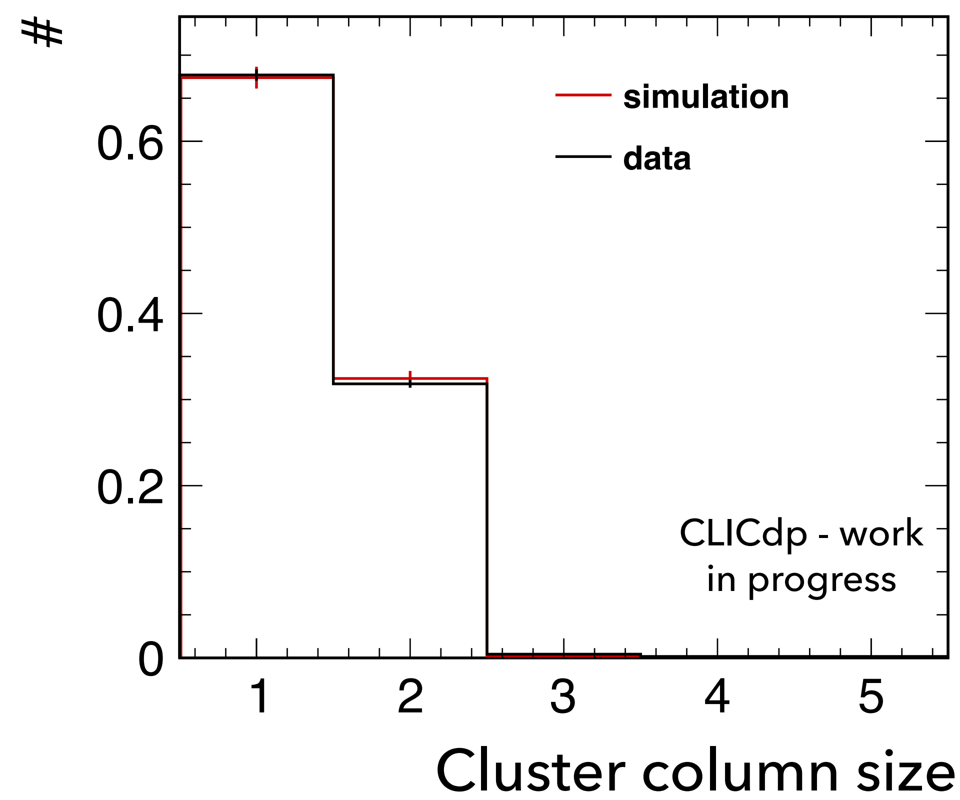
Transient pulse for charge injection at pixel corner

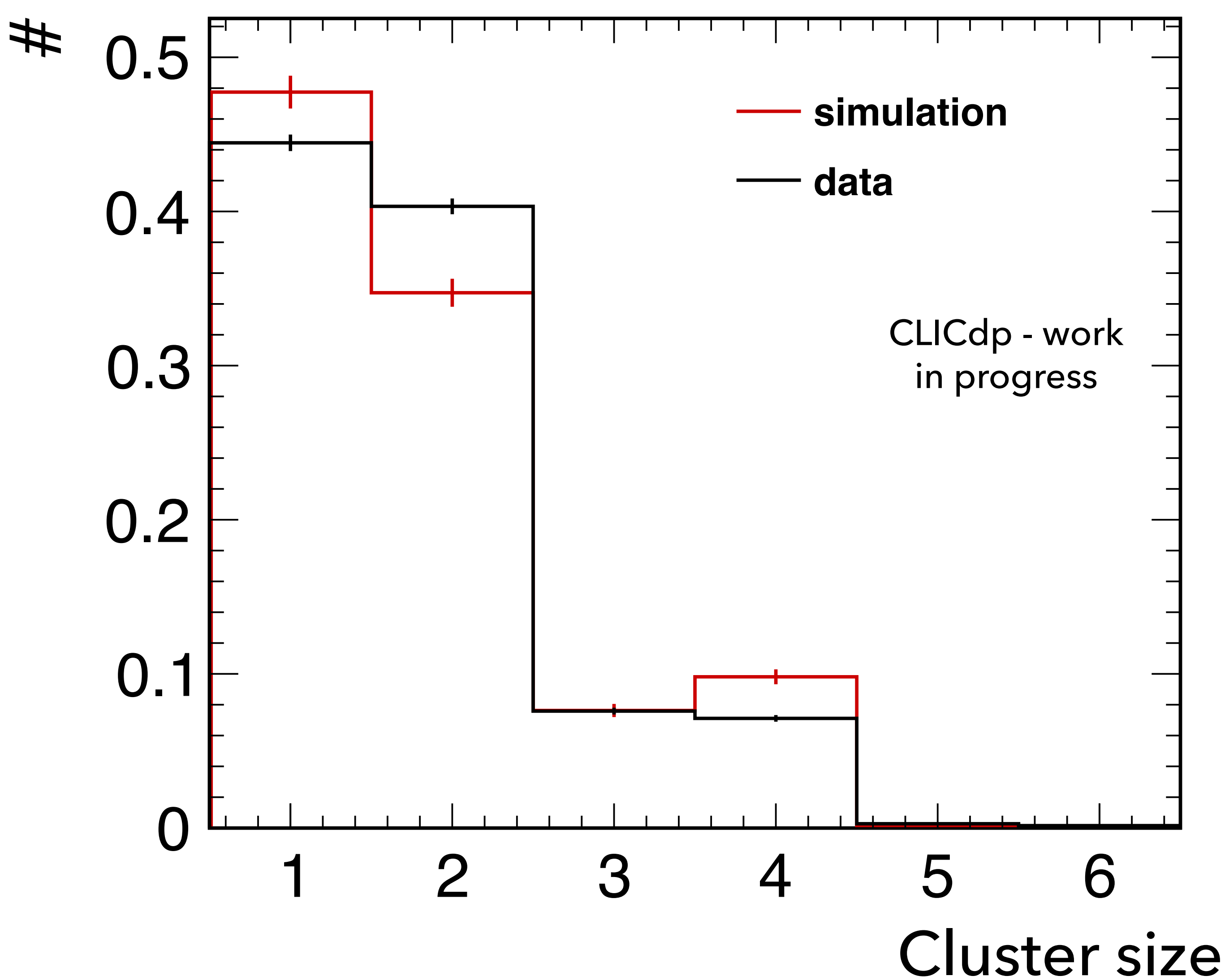


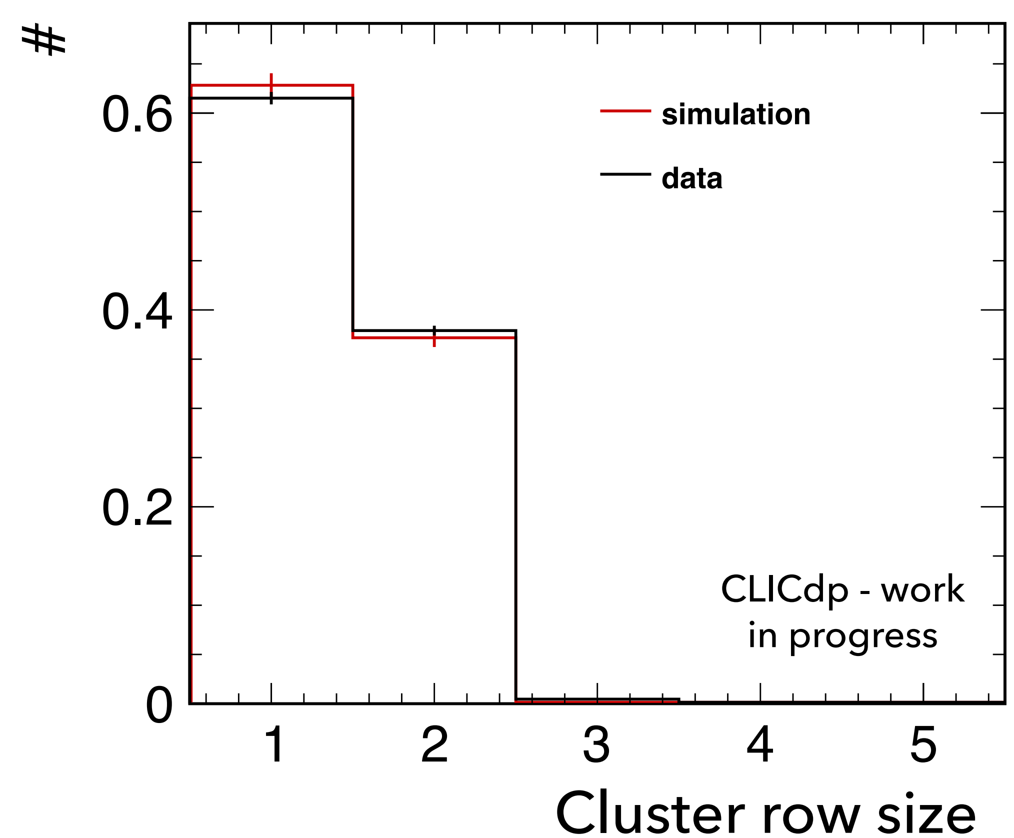
- Pixel flavour with continuous n-implant
- Detection threshold: 170 e
- Bias voltage of -6V/-6V at p-wells/substrate

Comparison against data - cluster size

- Cluster size is very sensitive to differences in charge sharing, charge carrier lifetime, etc.
- Simplifications and empirical models are required in some stages -> perfect agreement is not expected





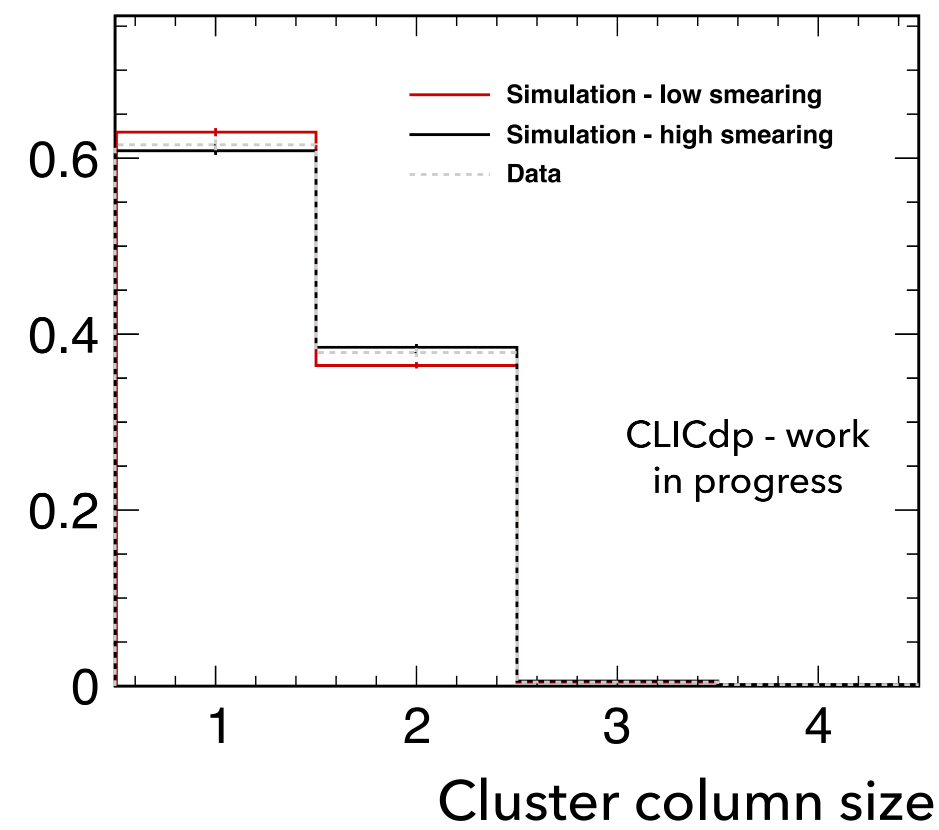


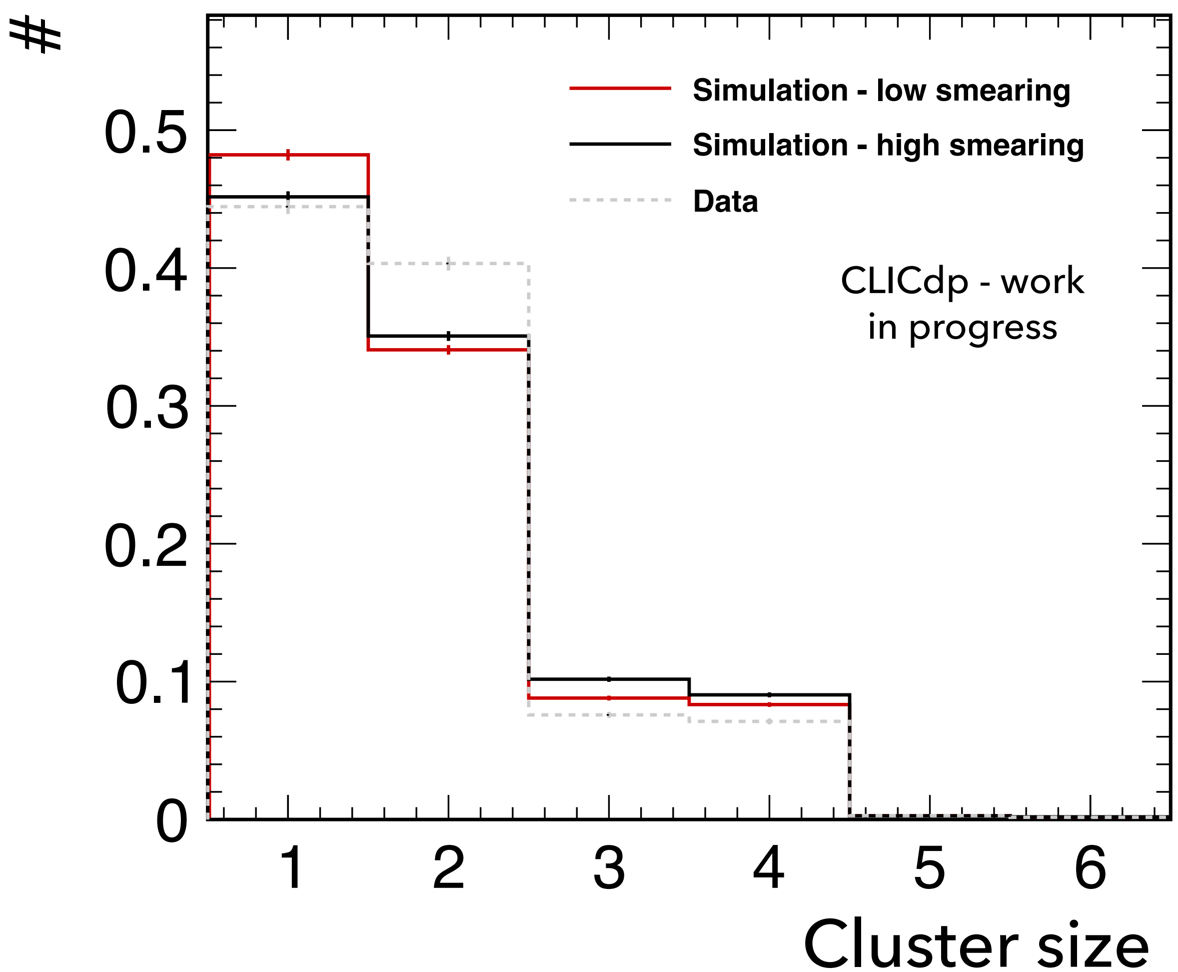
Doping profiles

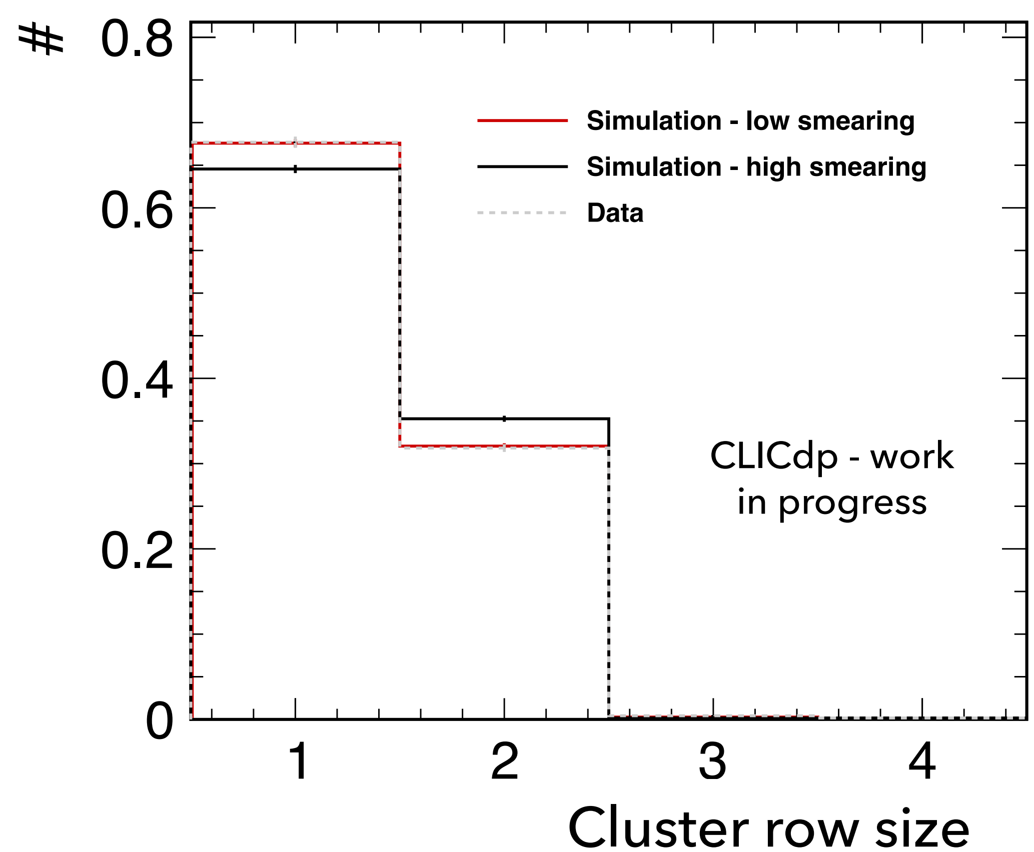
- What is the impact of uncertainties in the doping profiles on the charge sharing ?

- Higher lateral spread of the profile at the edge of the p-well implant (*p-well smearing*) leads to lower lateral electric field -> higher cluster size is expected

- <u>Uncertainties in the doping profiles have considerable impact on cluster observables</u>







Summary and Outlook

- CLICTD is a monolithic pixel sensor fabricated in a 180 nm CMOS imaging process
- Rotation studies were performed at the DESY II test-beam facility
    - spatial resolution of about 4 μm (at a rotation angle of 35 degrees)
    - active depth of about 30 μm
- Simulations combining 3D TCAD and Allpix-Squared provide an accurate sensor modelling and high simulation rate

➡Precise beam telescope + flexible data analysis + simulations tools are required for a detailed assessment of the sensor performance

Outlook

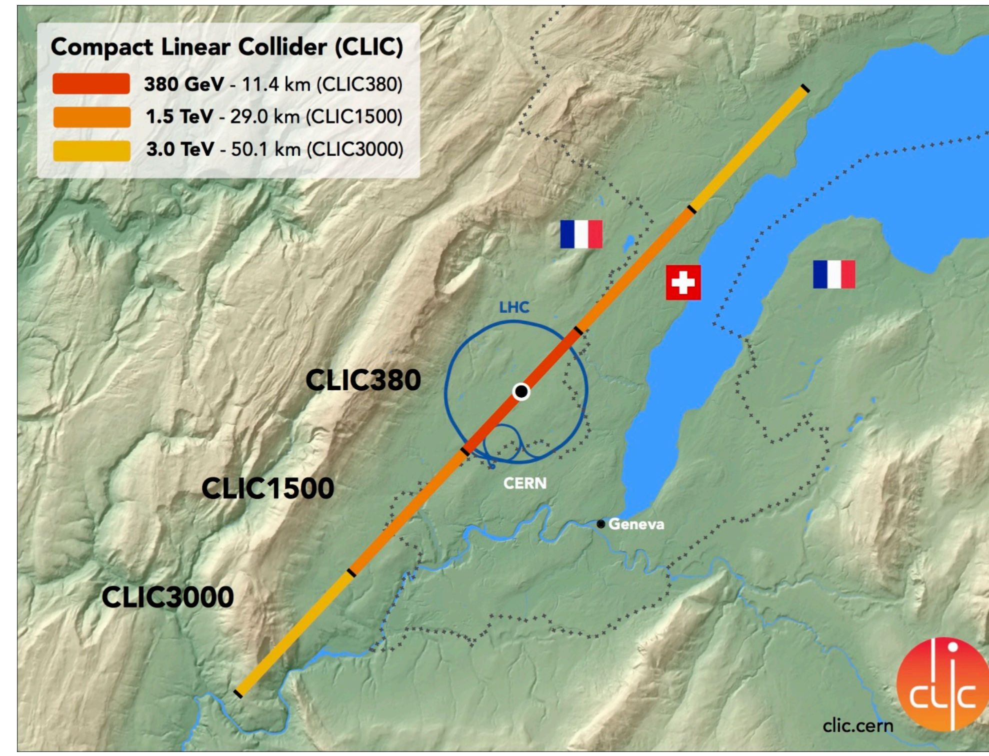
- CLICTD samples thinned down to 40 μm are currently under investigation
- 3D TCAD plus Allpix-Squared simulations for 65 nm CMOS process
- CLICTD samples on Czochralski wafer material will be studied

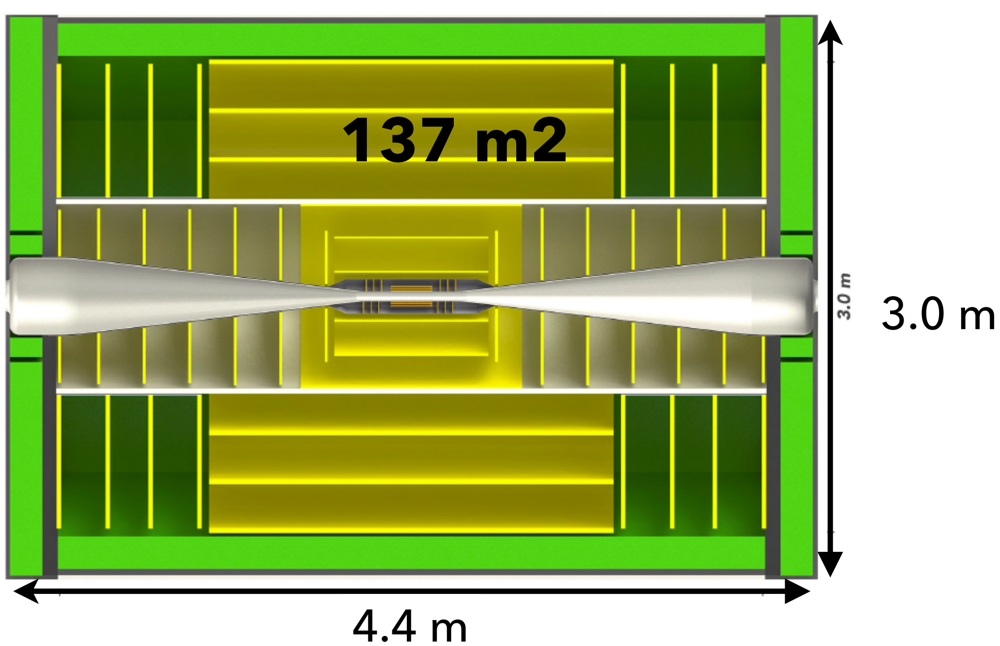
The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

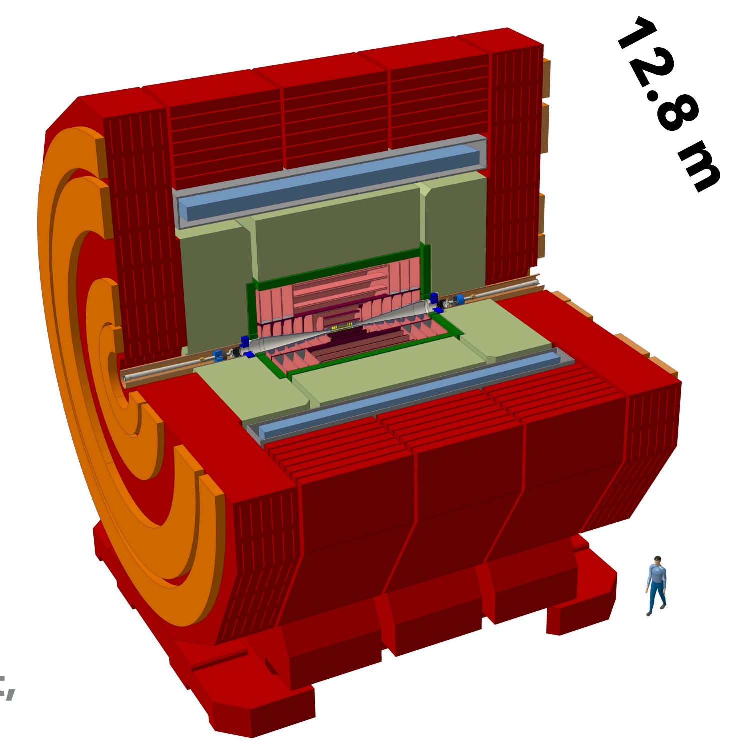
THE COMPACT LINEAR COLLIDER (CLIC)

- Concept for post-LHC linear electron-positron collider at CERN to be built in three energy stages (380 GeV -> 3 TeV)
- Monolithic silicon sensors are attractive candidates for large area, low-mass tracking detector foreseen for CLIC
- Requirements for tracking detector:
  - Single point resolution: 7 μm
  - Timing resolution: 5 ns
  - Material budget: ~1-2% X_0 per layer
  - Power consumption: < 150 mW/cm²





CLIC 2018 Summary Report, CERN-2018-005



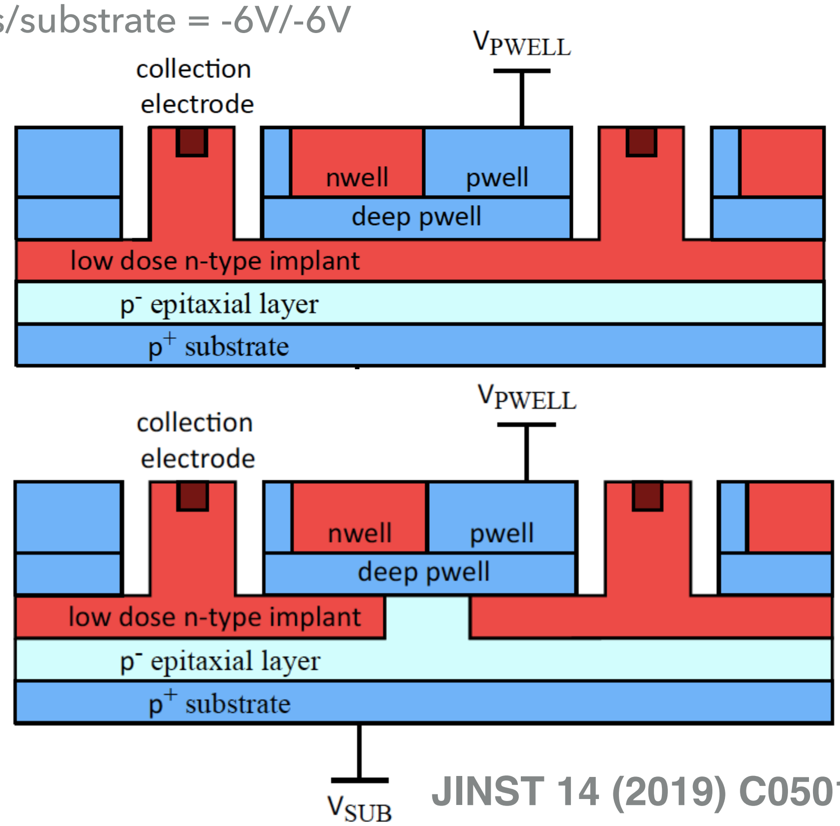
CLICTD Tracker chip

Designed to meet the requirements of the CLIC Tracker

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

- Modified 180 nm CMOS imaging process with small collection diode
- Full lateral depletion in 30 µm epitaxial layer
- Optional: Gap in n-type implant in one spatial direction:
  - Speed up of charge collection

Applied bias voltages to p-wells/substrate = -6V/-6V



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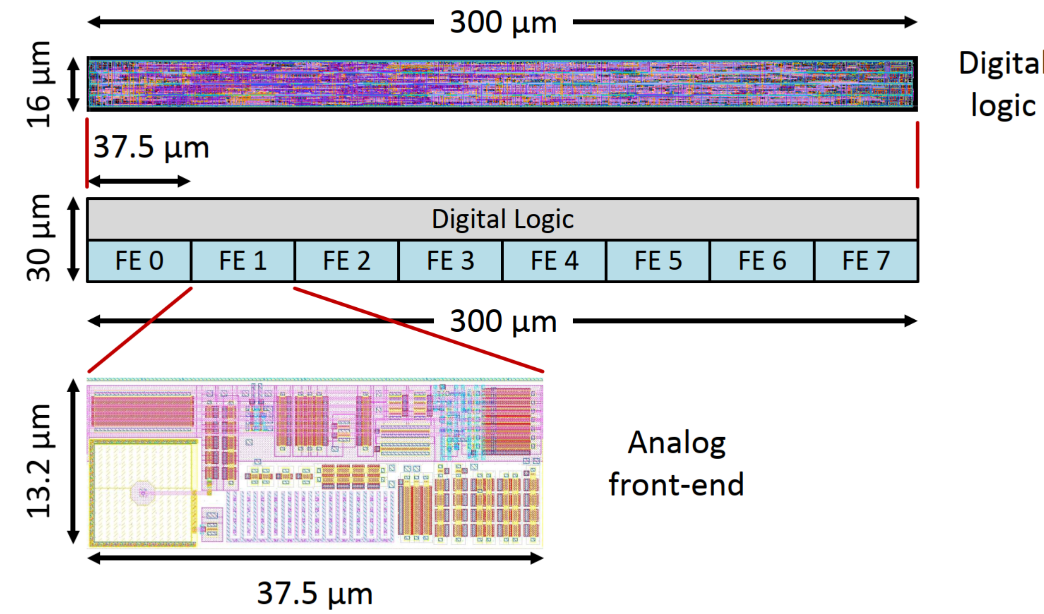

- Channel pitch: 300 µm x 30 µm (16x128 channels)
- Collection electrode pitch: 37.5 µm x 30.0 µm
- Detector channel consists of 8 sub-pixels (diode + analogue front-end) that are processed by a shared digital logic

  ➡ 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)

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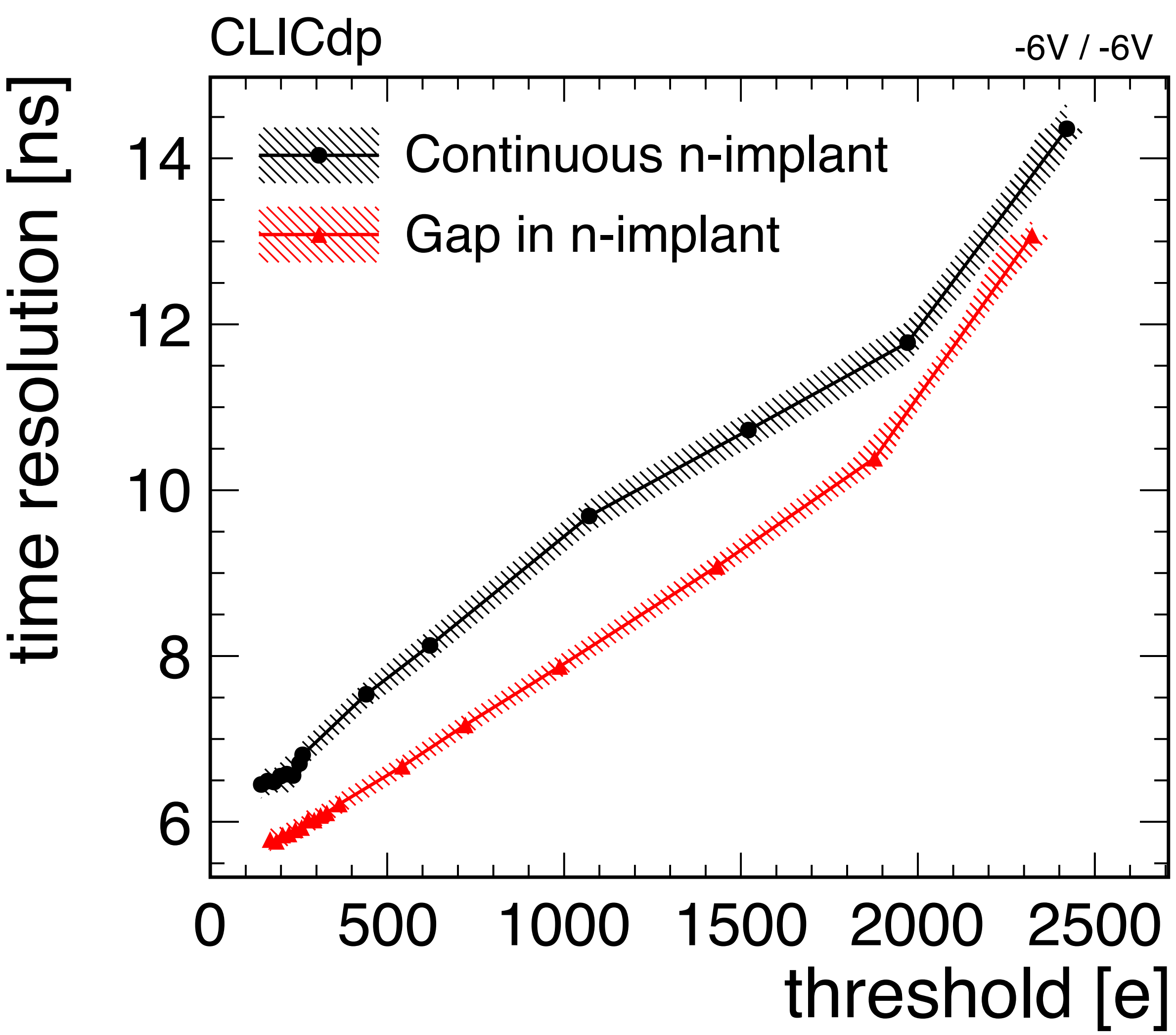
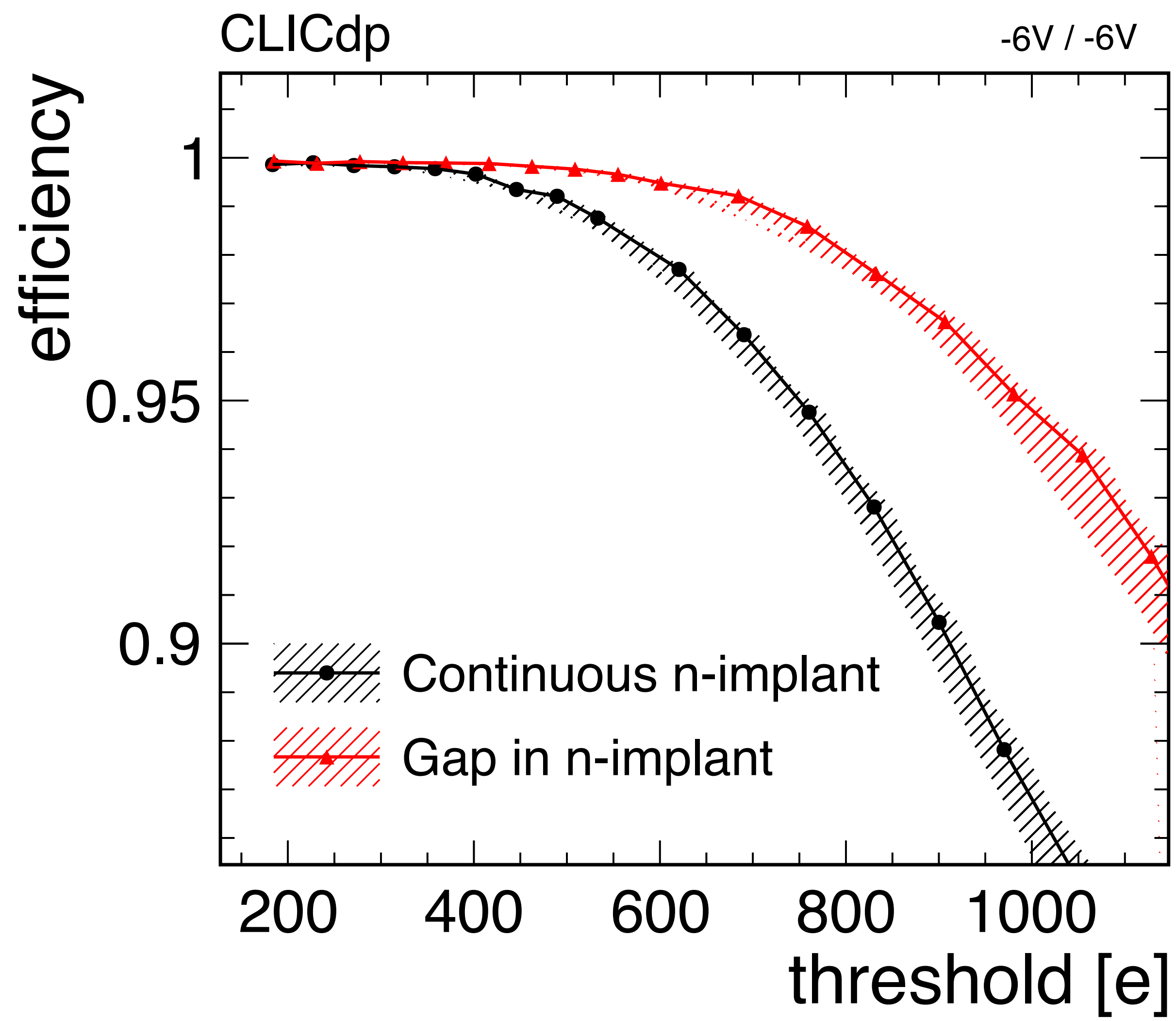
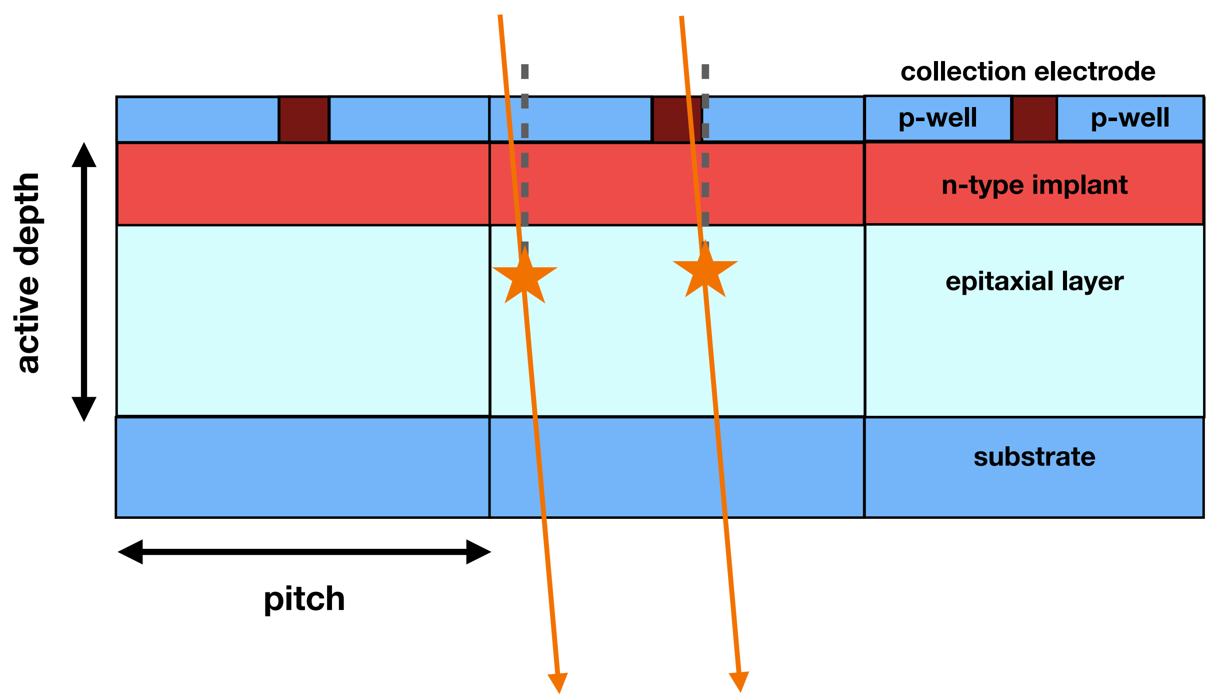
doi: 10.1109/TNS.2020.3019887

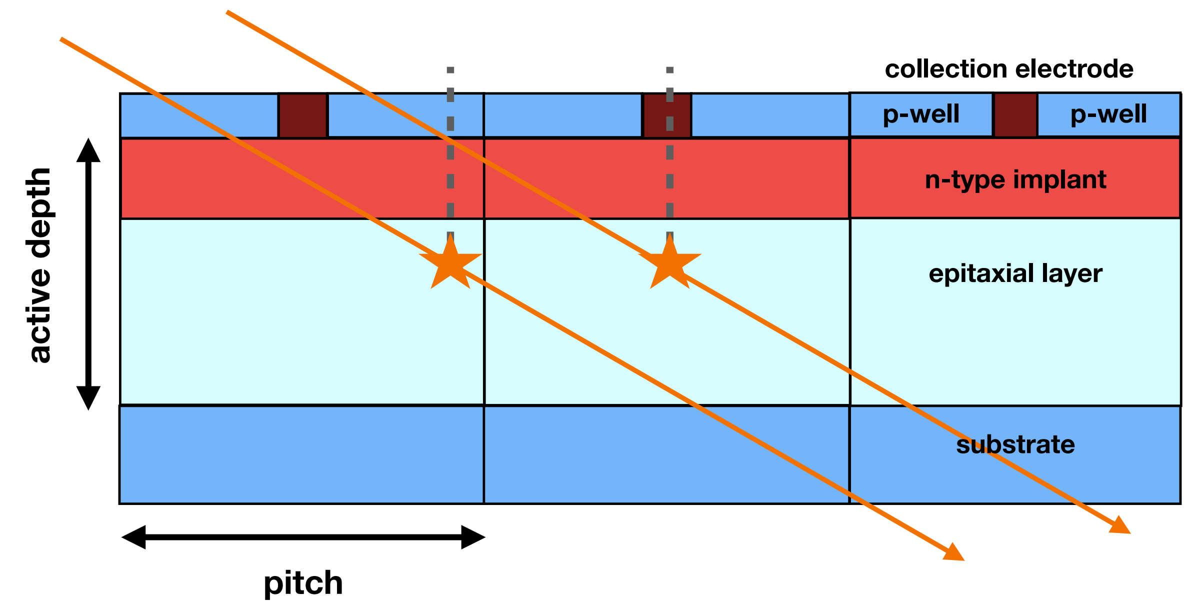
TEST-BEAM PERFORMANCE

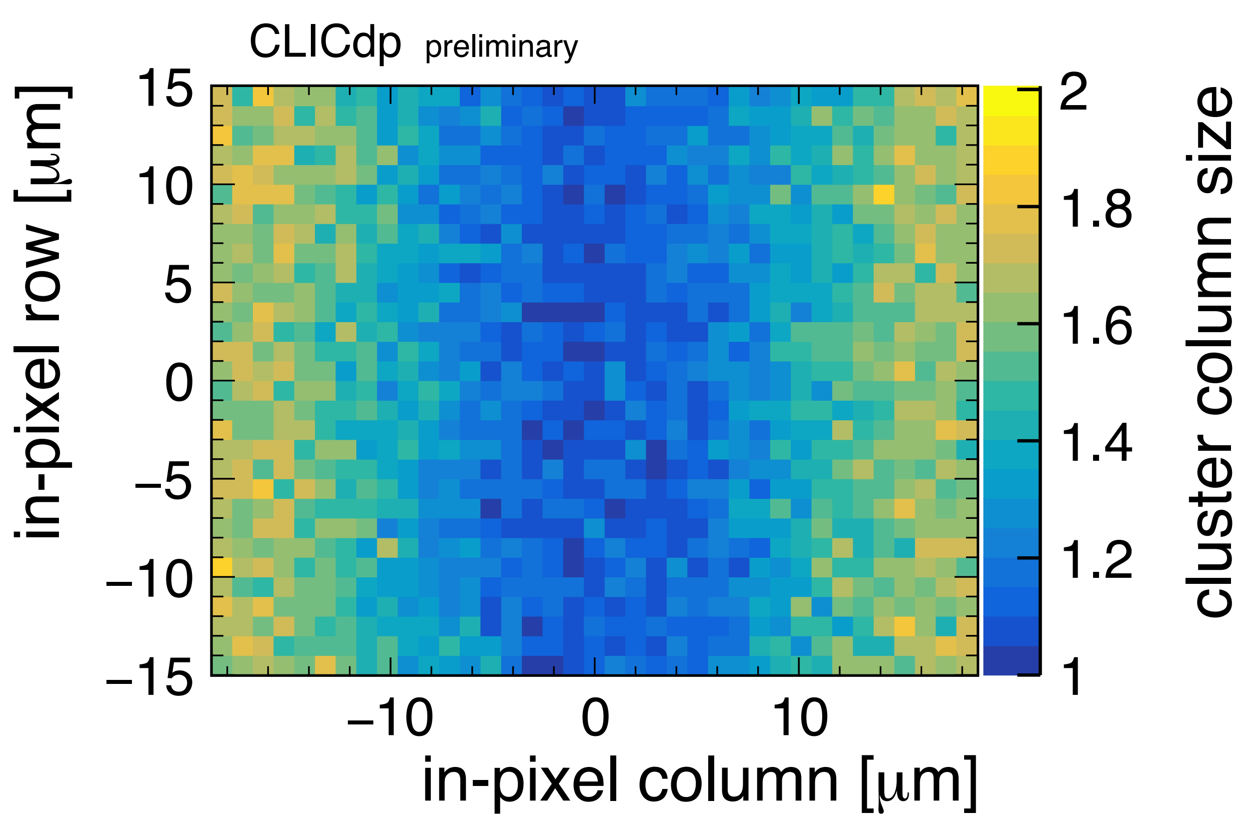


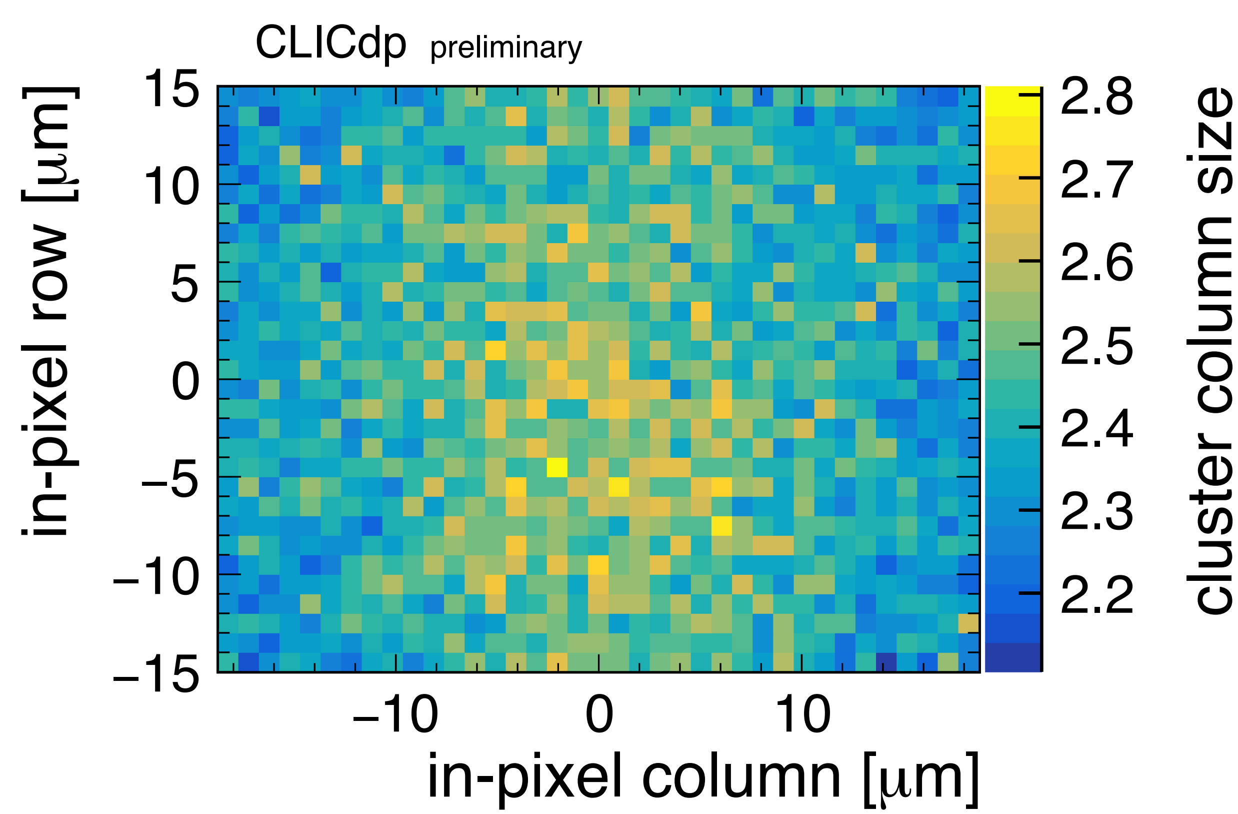


SPATIAL AND TIMING RESOLUTION



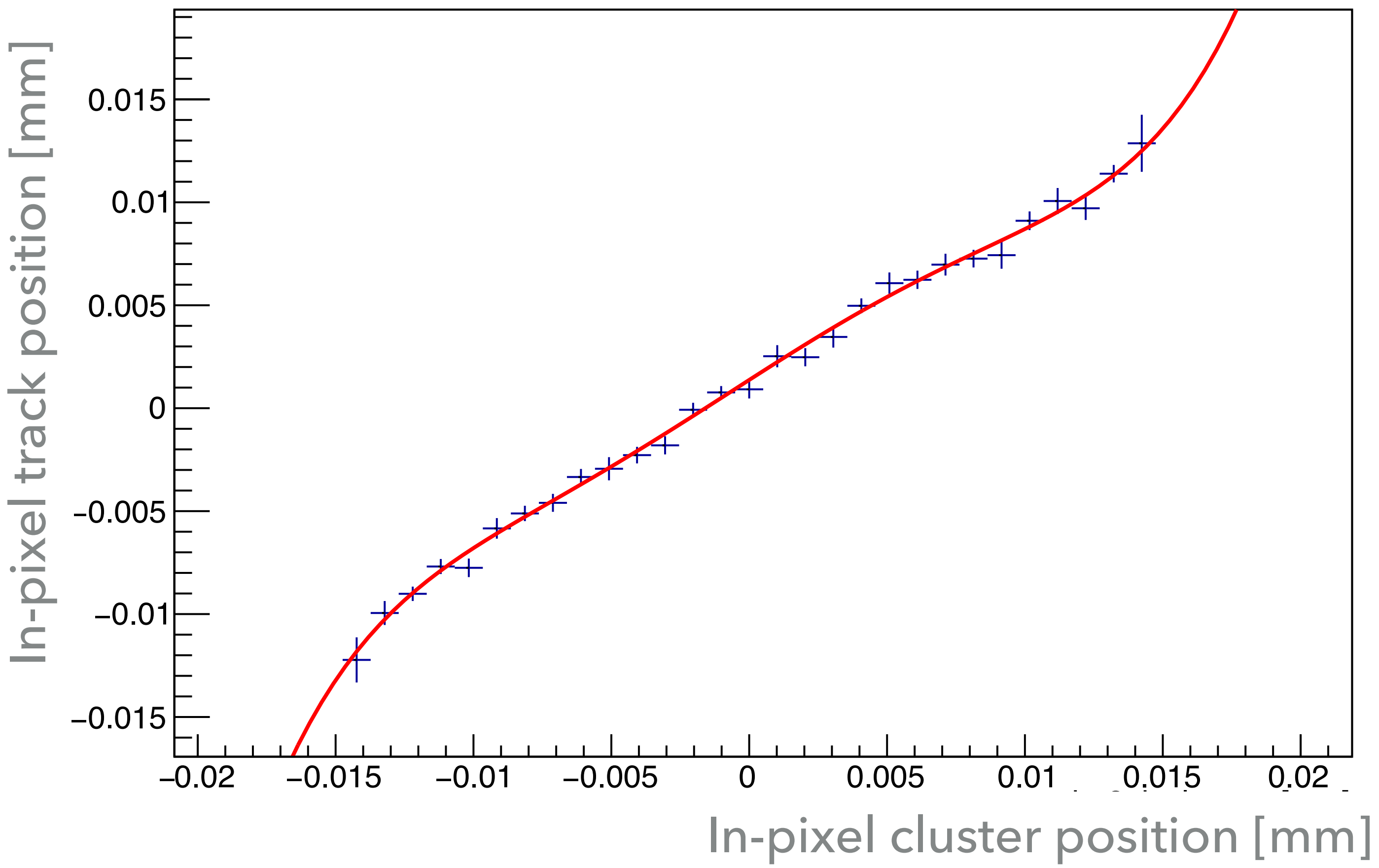






SPATIAL RESOLUTION

Eta function at 40 degree



Head-tail algorithm

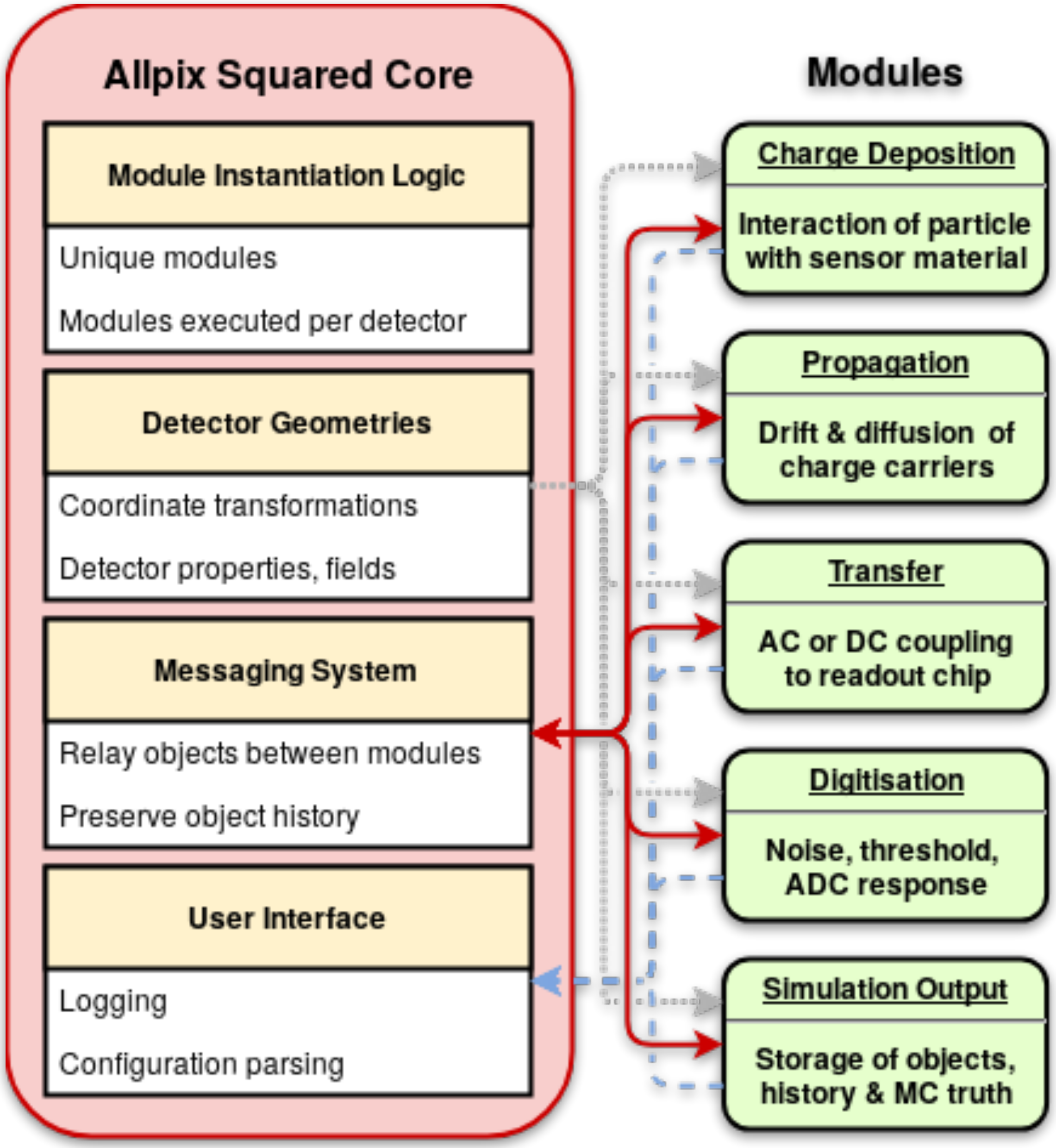
$$x_{\text{ht}} = \frac{x_{\text{head}} - x_{\text{tail}}}{2} + \frac{Q_{\text{tail}} - Q_{\text{head}}}{2Q_{\text{avg.}}}p.$$

Centre–of-gravity algorithm

$$x_{\text{cog}} = \frac{\sum_i Q_i x_i}{\sum_i Q_i},$$

THE ALLPIX-SQUARED FRAMEWORK

- Full detector simulation from energy deposition until digitisation of signal
- Infrastructure (core) is separated from physics (modules)
  - Simulation chain is built from individual modules (Plug & play concept)
- Static fields are imported from 3D TCAD simulations to ensure precise field modelling
- Validation of simulation with Investigator test-chip (developed within ALICE ITS upgrade) NIM A 964 (2020) 163784



NIM A 901 (2018) 164-172

THRESHOLD SCAN IN SIMULATION