Test-beam and simulation studies for the CLICTD technology demonstrator

a monolithic CMOS pixel sensor with a small collection diode

TIPP 2021

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On behalf of the CLICdp collaboration

International Conference on Technology and Instrumentation in Particle Physics

Outline

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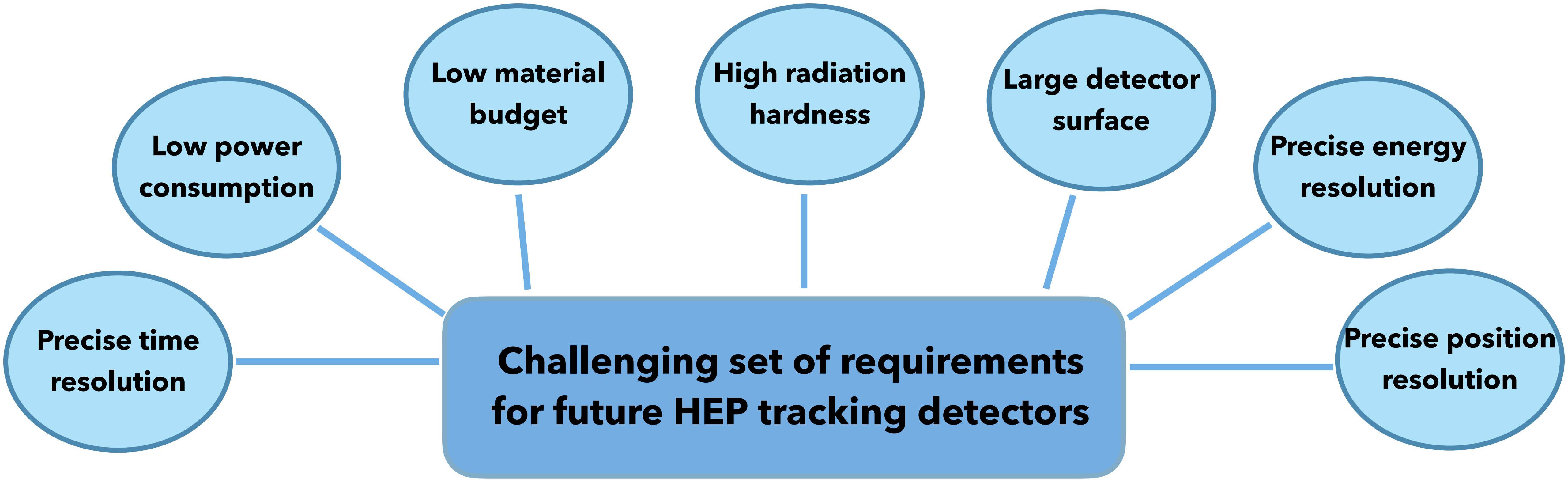
CERN EP R&D

Future tracking detectors for high-energy physics (HEP)

Tracking detector requirements for HEP experiments



- Monolithic silicon sensors are attractive candidates for large area, low-mass tracking detector (e.g. for CLIC)

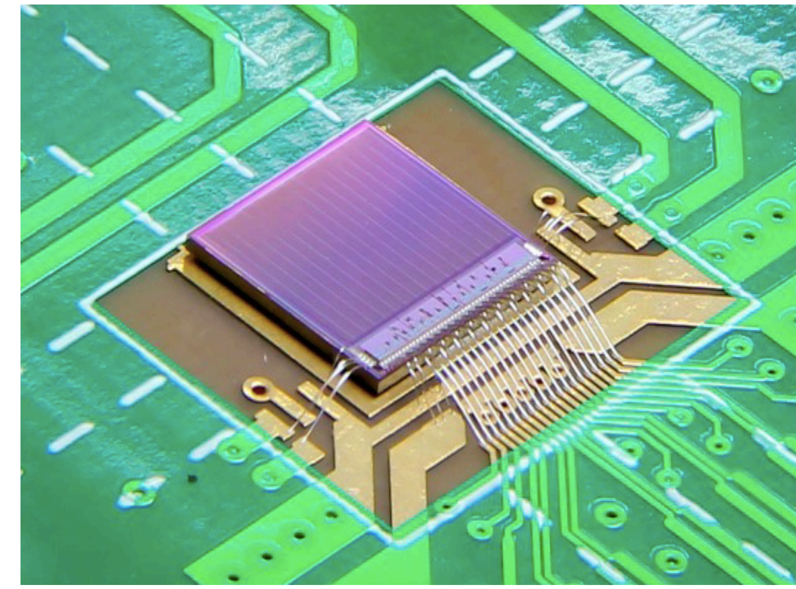
Requirements for CLIC tracking detector:

- Single point resolution: 7 µm (in direction perpendicular to the magnetic field)
- Timing resolution: ~5 ns
- Material budget: ~1-2% X_0 per layer
- Power consumption: < 150 mW/cm^2

Detector Technologies for CLIC, CERN-2019-001

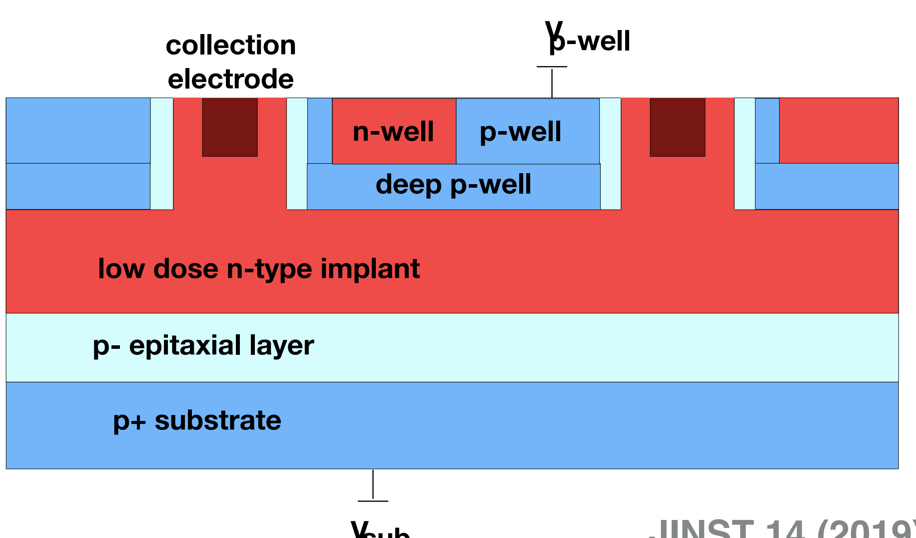
CLICTD - the sensor process

- The CLICTD technology demonstrator is a monolithic sensor with a small collection diode
- Fabricated in a modified 180 nm CMOS imaging process
- Full lateral depletion in 30 µm epitaxial layer
- Total sensor thickness: 300 µm (thinned down to 40 µm)
- Bias voltage of -6V applied to p-wells and substrate
- Design variant: Gap in n-type implant in row direction



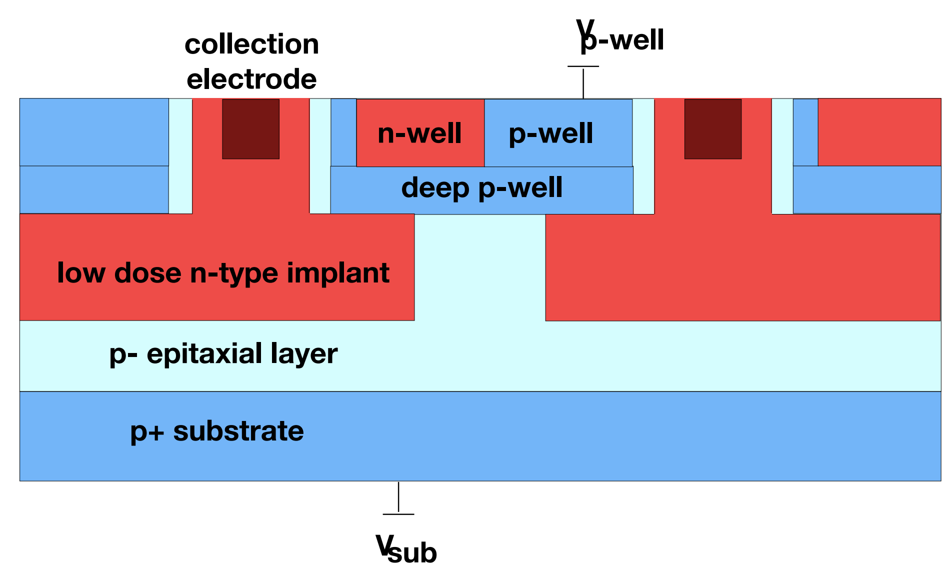
➡ **Speed-up of charge collection**

Continuous low-dose deep n-implant



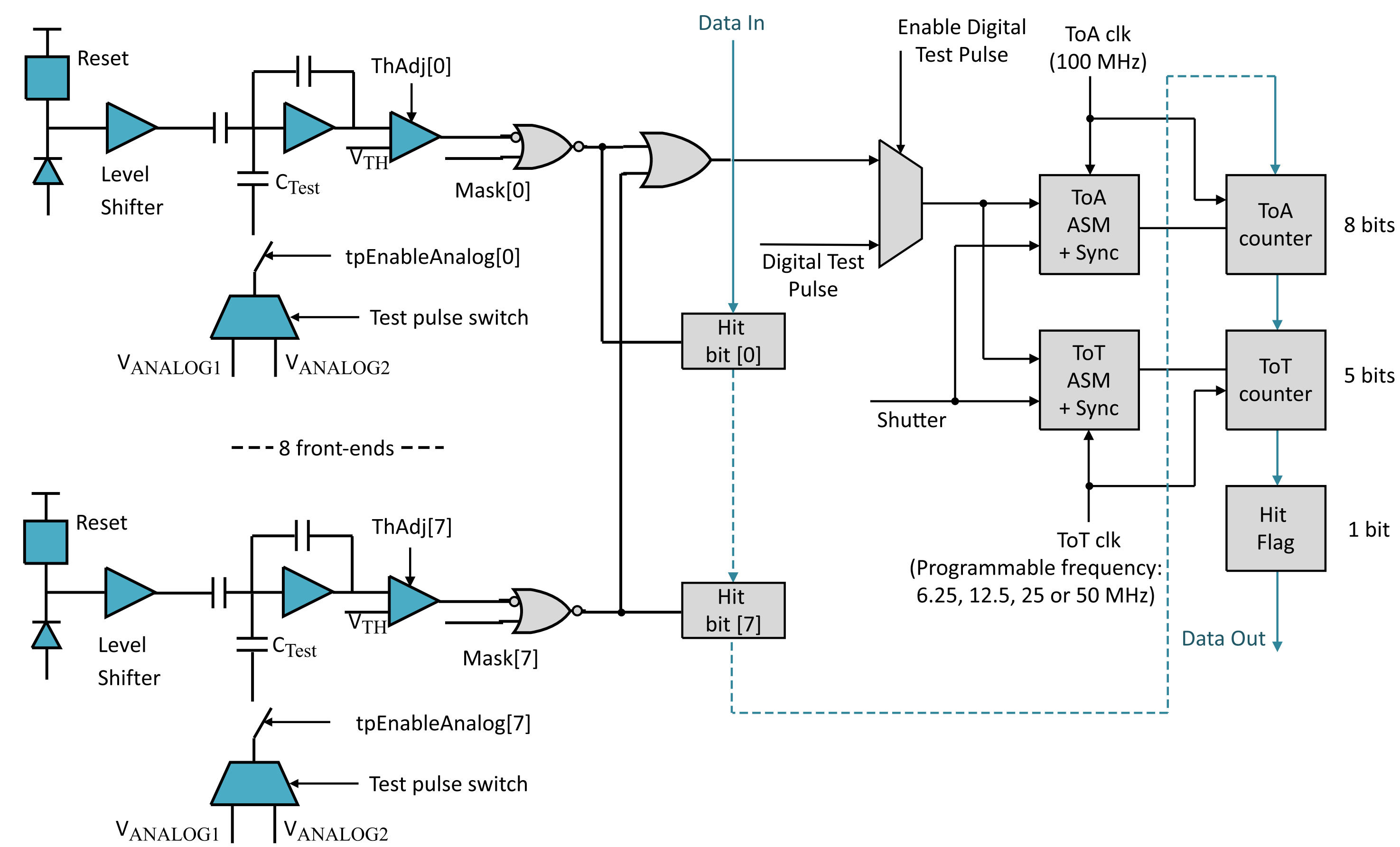
JINST 14 (2019) C05013

Segmented low-dose deep n-implant



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)

Test-beam setup

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

  Electron beam with 5.4 GeV

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)

- MIMOSA26 planes

  Track-position resolution at DUT: ~ 2 μm

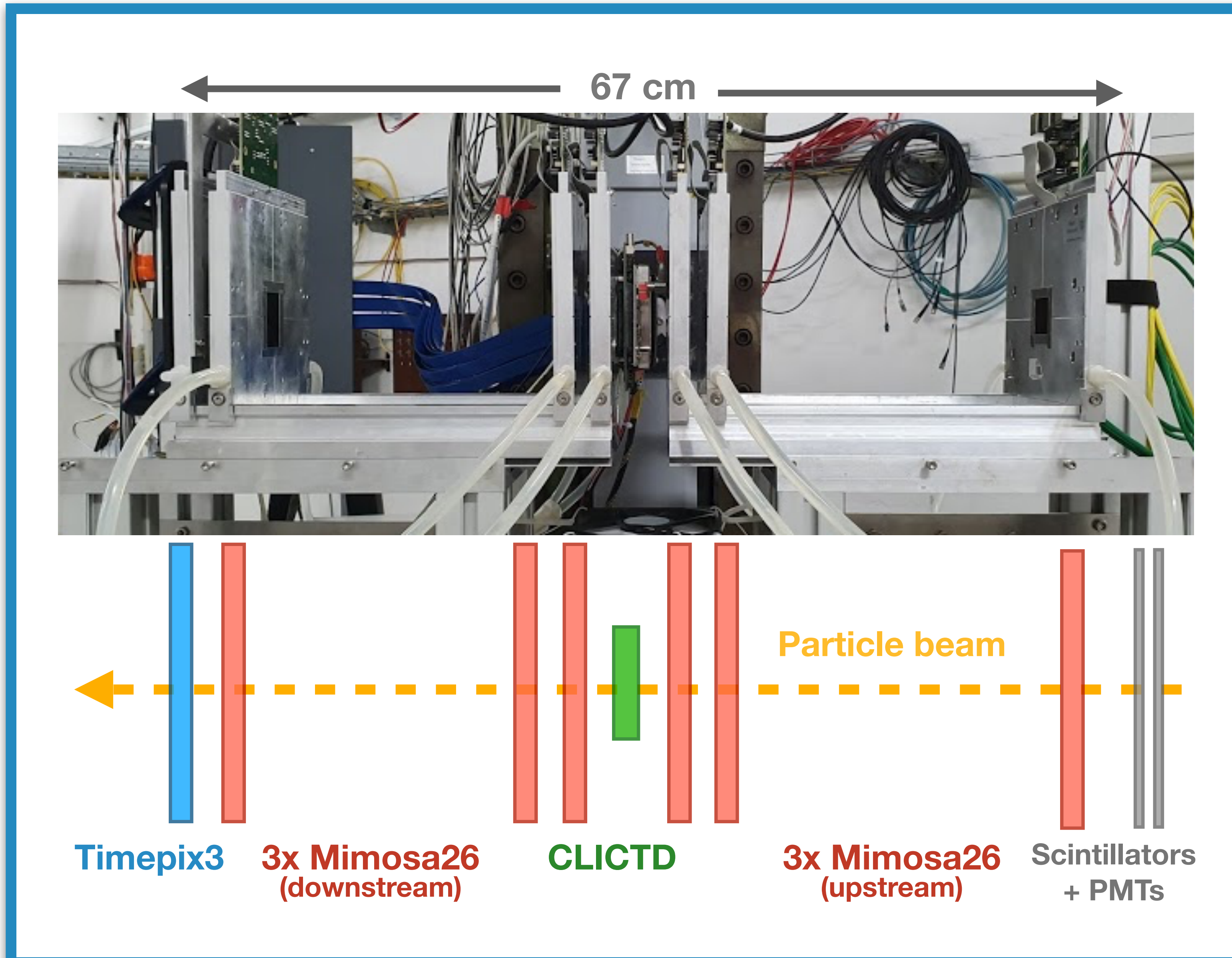
- Timepix3 track-timing plane

  Timing resolution: ~ 1 ns

- Device Under Test (DUT)

  Readout with Caribou versatile DAQ system

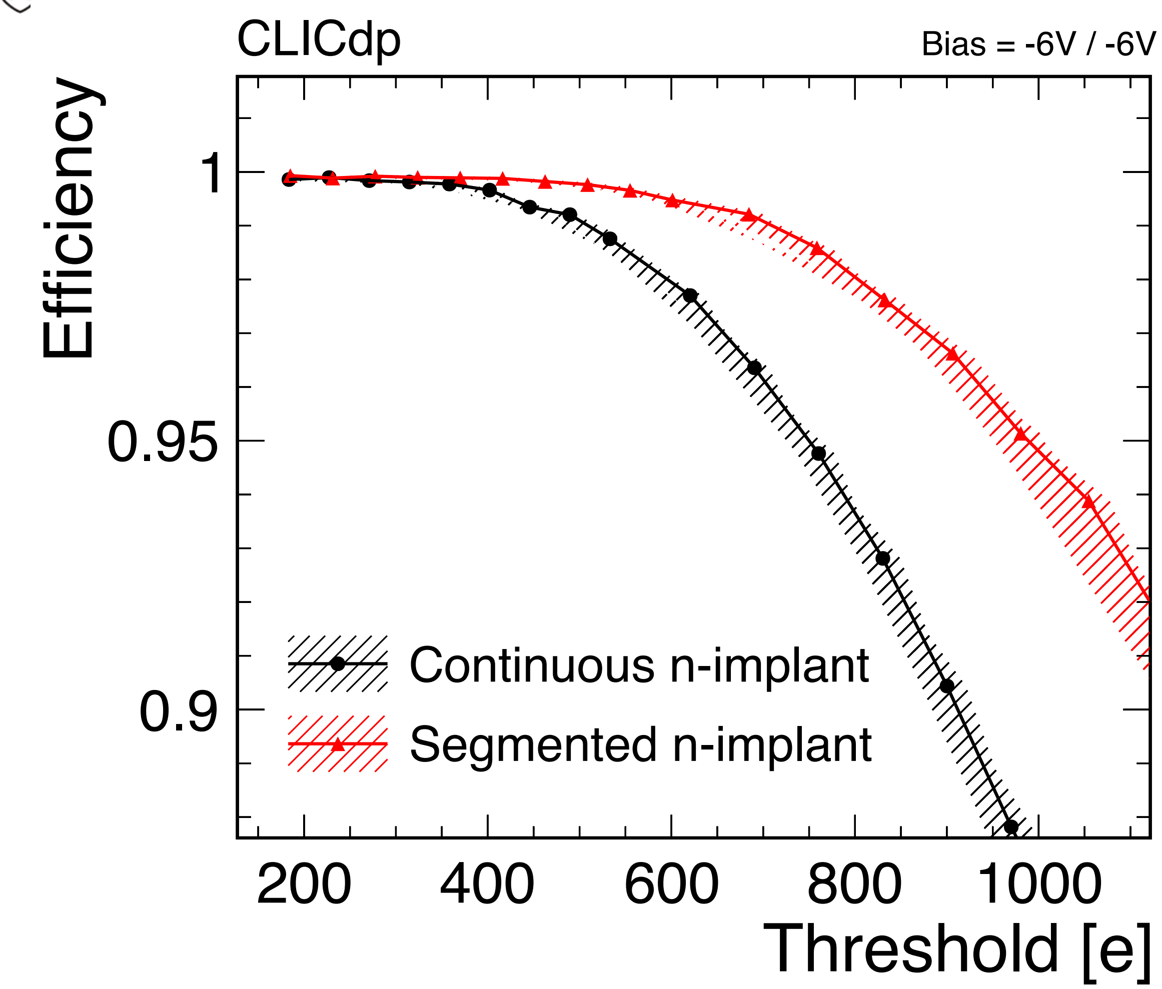
- Reconstruction and analysis

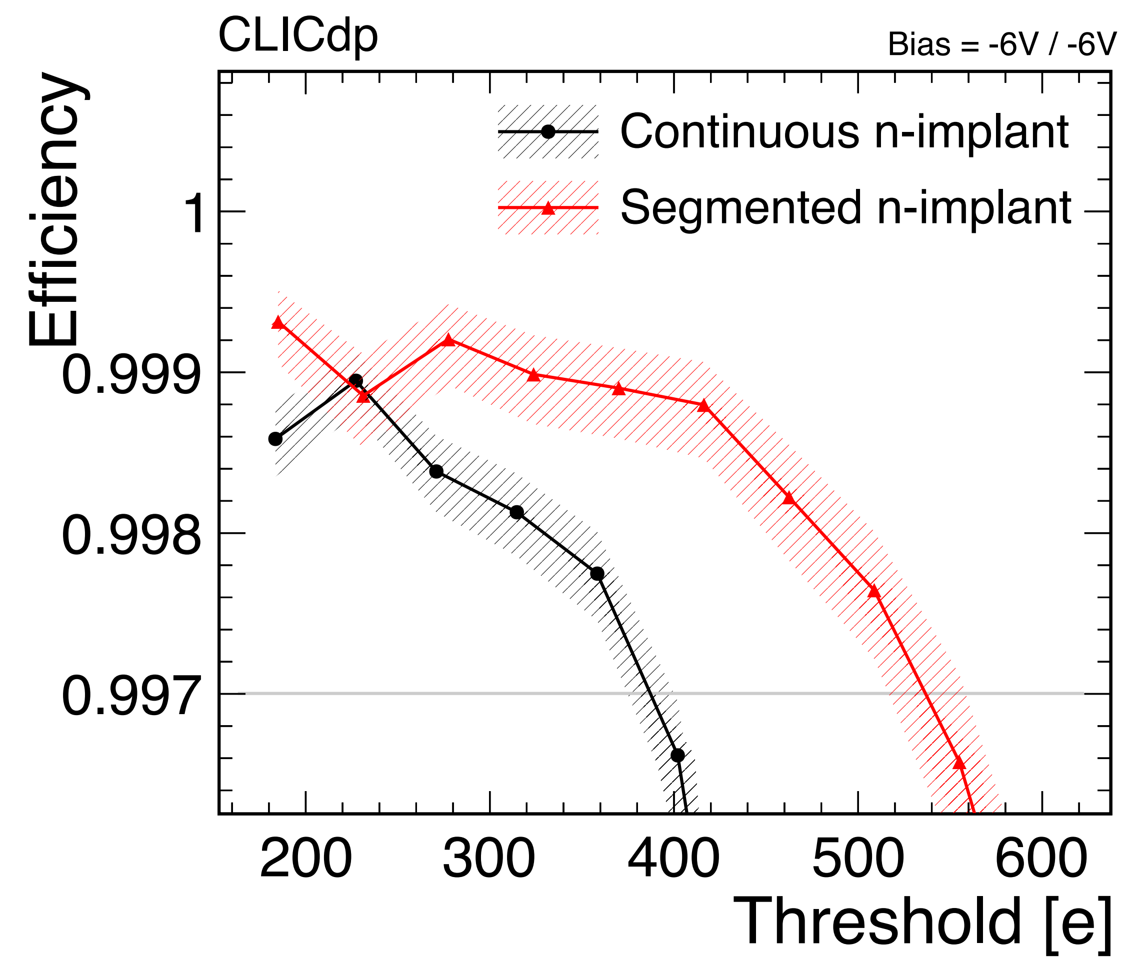


Corryvreckan reconstruction framework

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

Hit Detection Efficiency



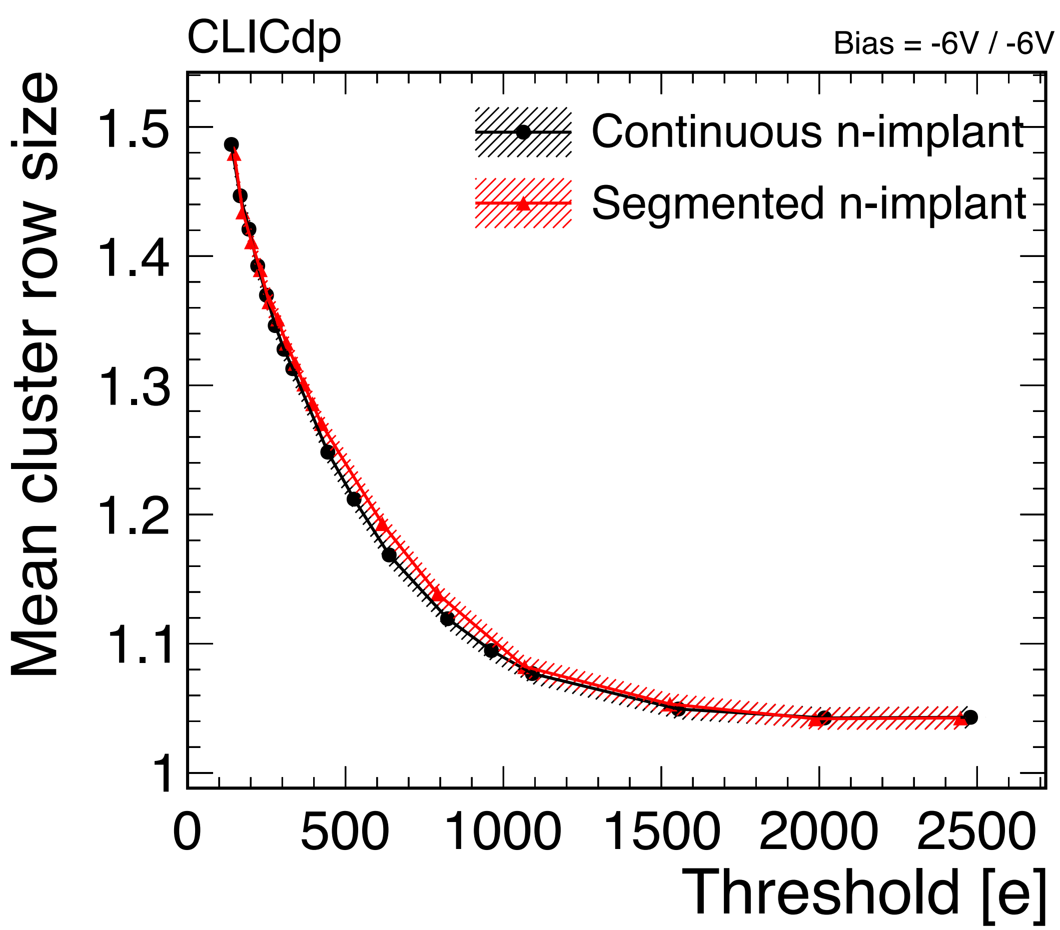


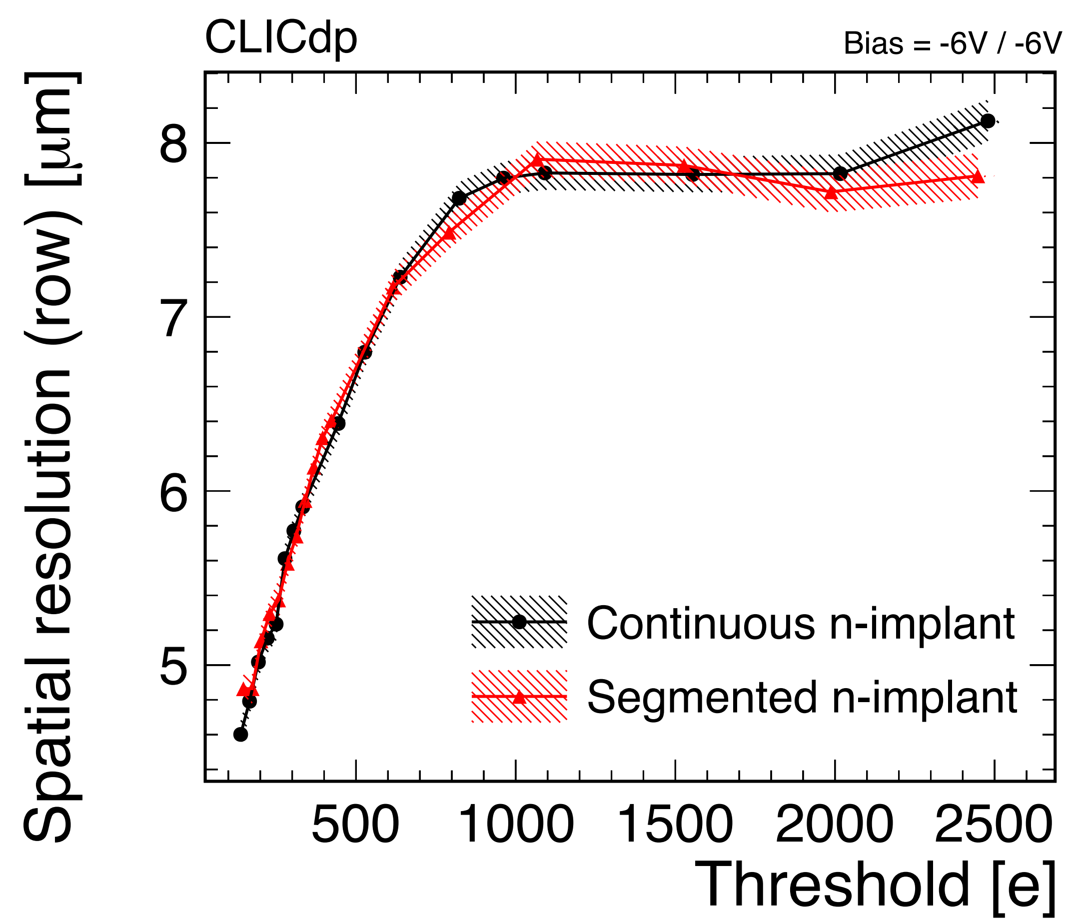
- Approximately 2000 e-/h+ pairs per MIP as expected from active depth of ~25 µm (according to simulations and rotation studies) **arXiv:2011.09389**
- Full efficiency (> 99.7%) for threshold range of several hundred electrons (efficient operation window)
- Reduced charge sharing for flavour with segmented n-implant leads to a higher seed signal which improves the efficiency for increasing thresholds

Position resolution

Row direction

- Cluster size in row direction remains unaffected since no segmentation was introduced
- Position reconstruction can be improved by charge interpolation
  - Cluster position calculated by centre-of-gravity algorithm
  - In row direction, an η-correction for non-linear charge sharing was applied
- Position resolution at nominal threshold (178 e) : ~ 4.6 μm





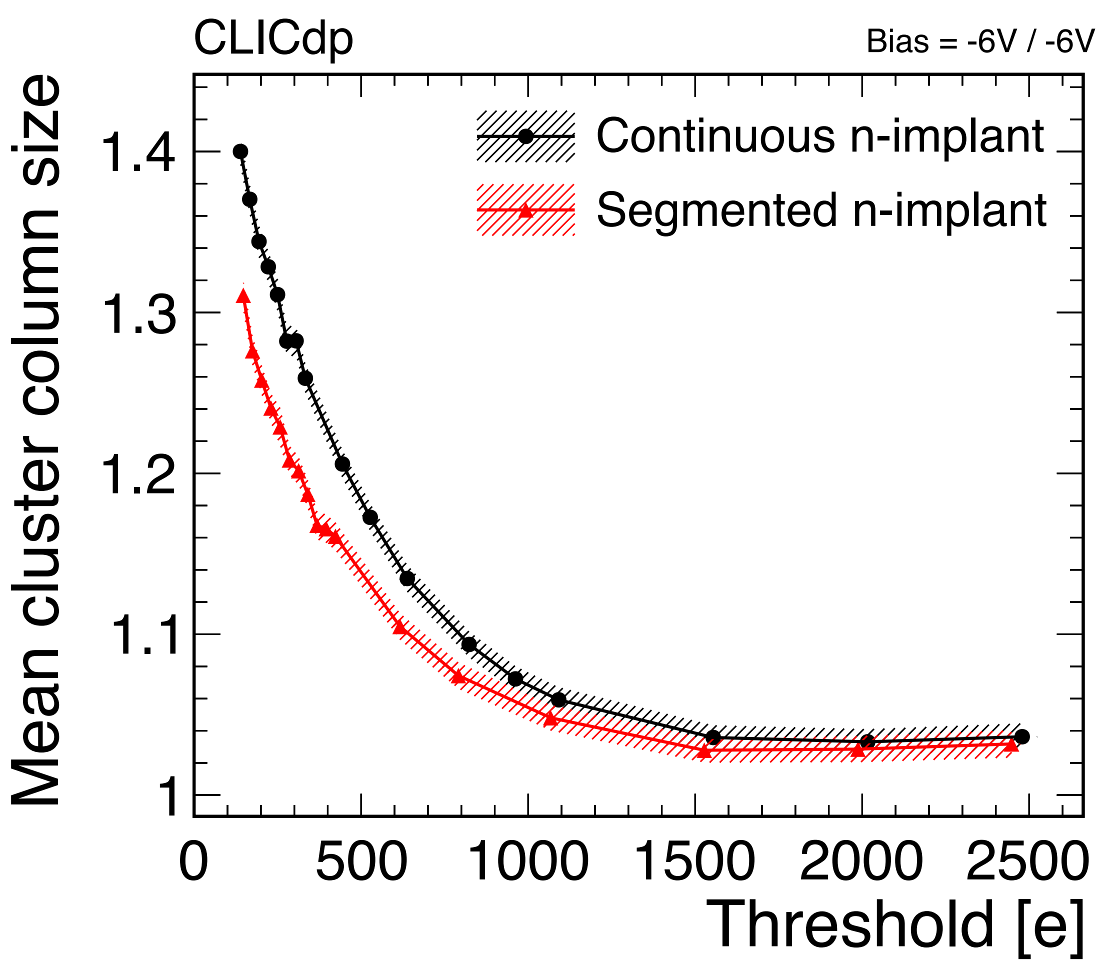
Position resolution

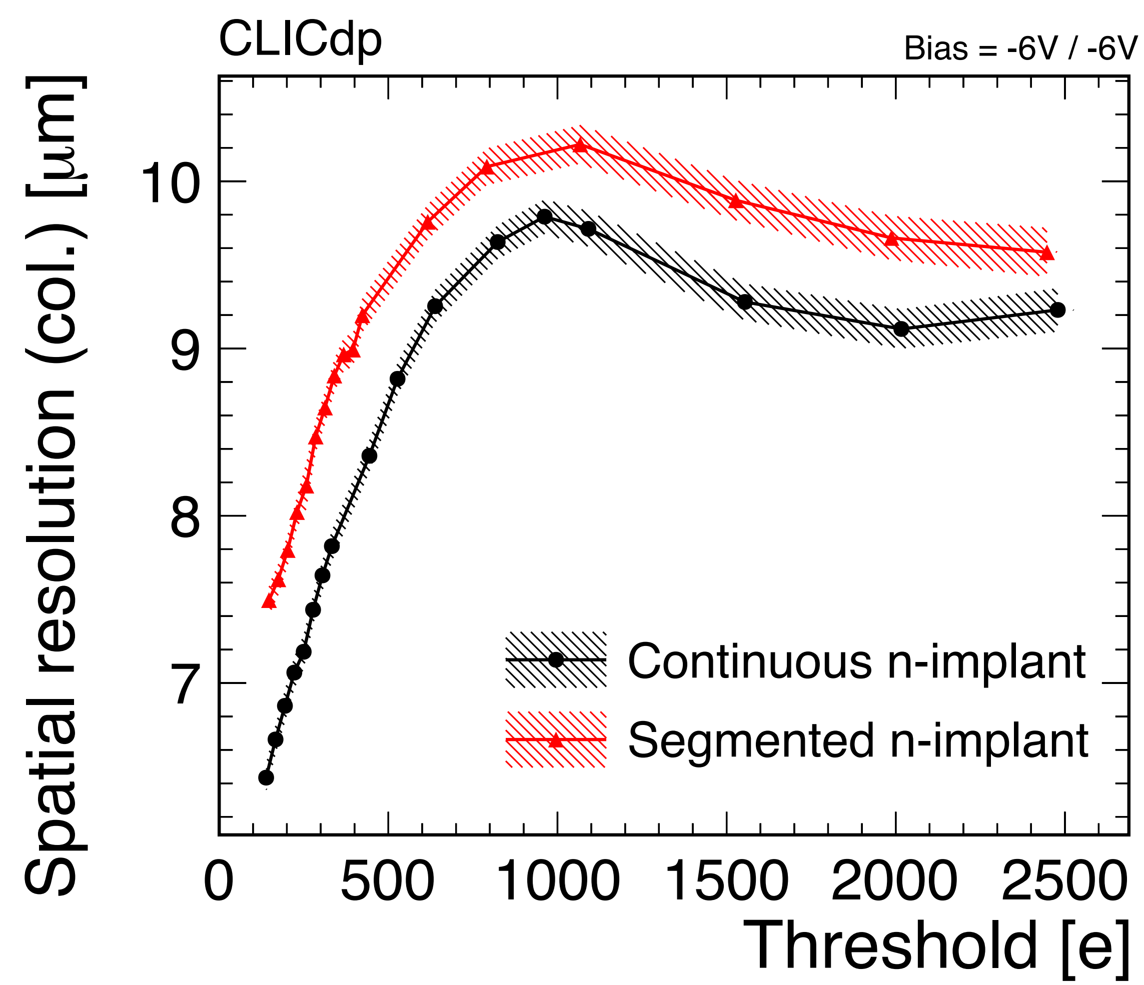
Column direction

- Reduced charge sharing for pixel flavour with segmented n-implant leads to a smaller cluster size in column direction

- Smaller cluster size in column direction for flavour with segmented n-implant leads to a degrading position resolution in this direction

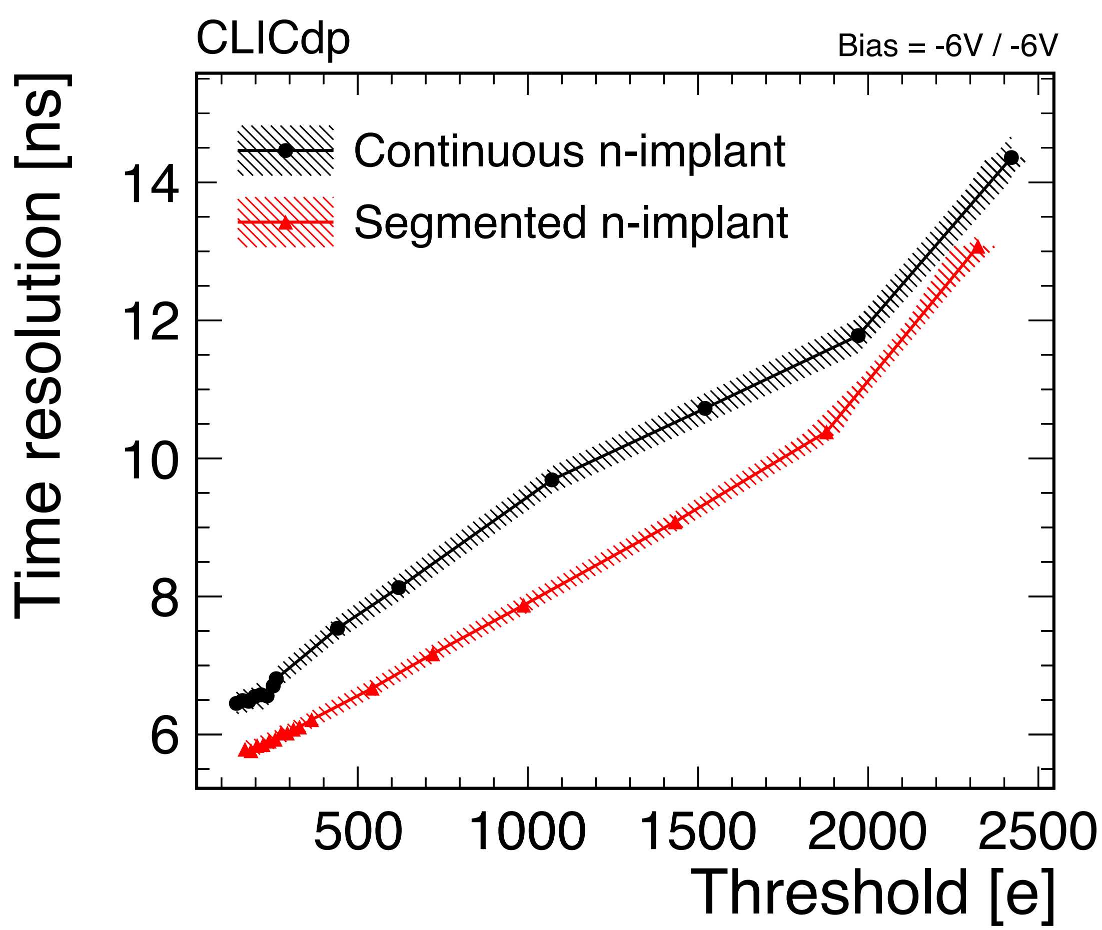
  (not relevant for momentum measurement in magnetic field)



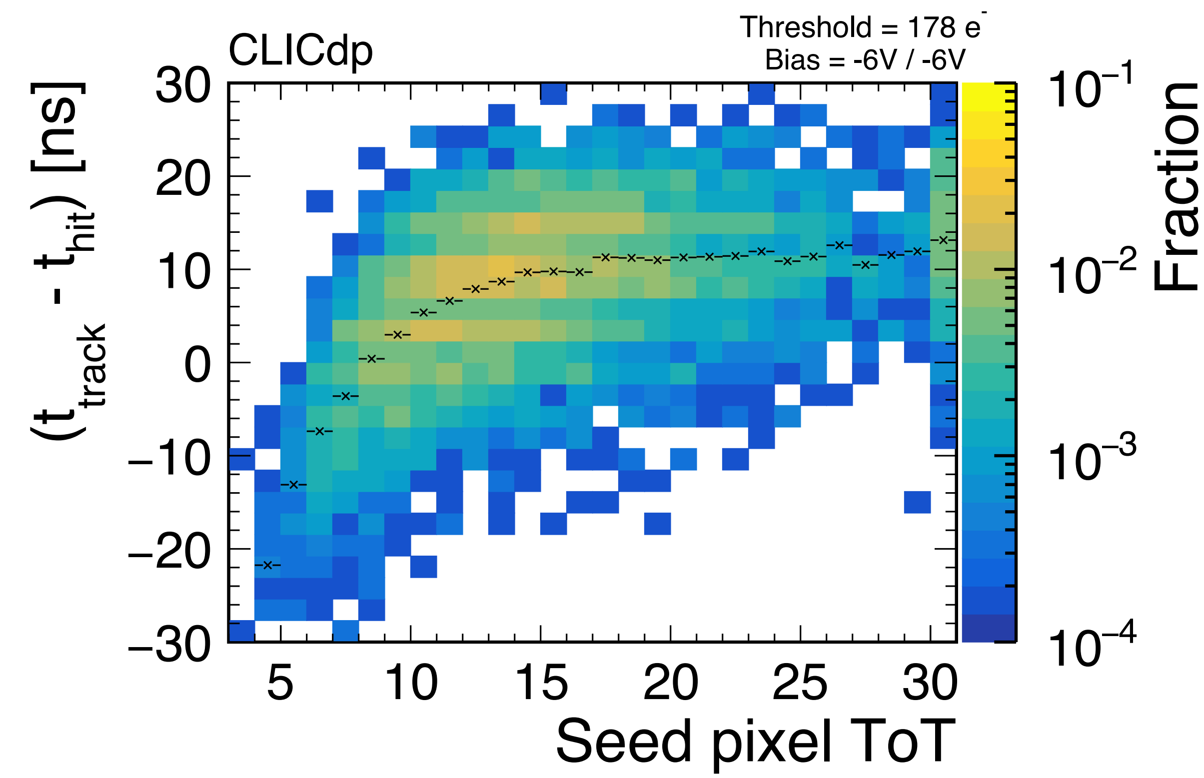


Time resolution

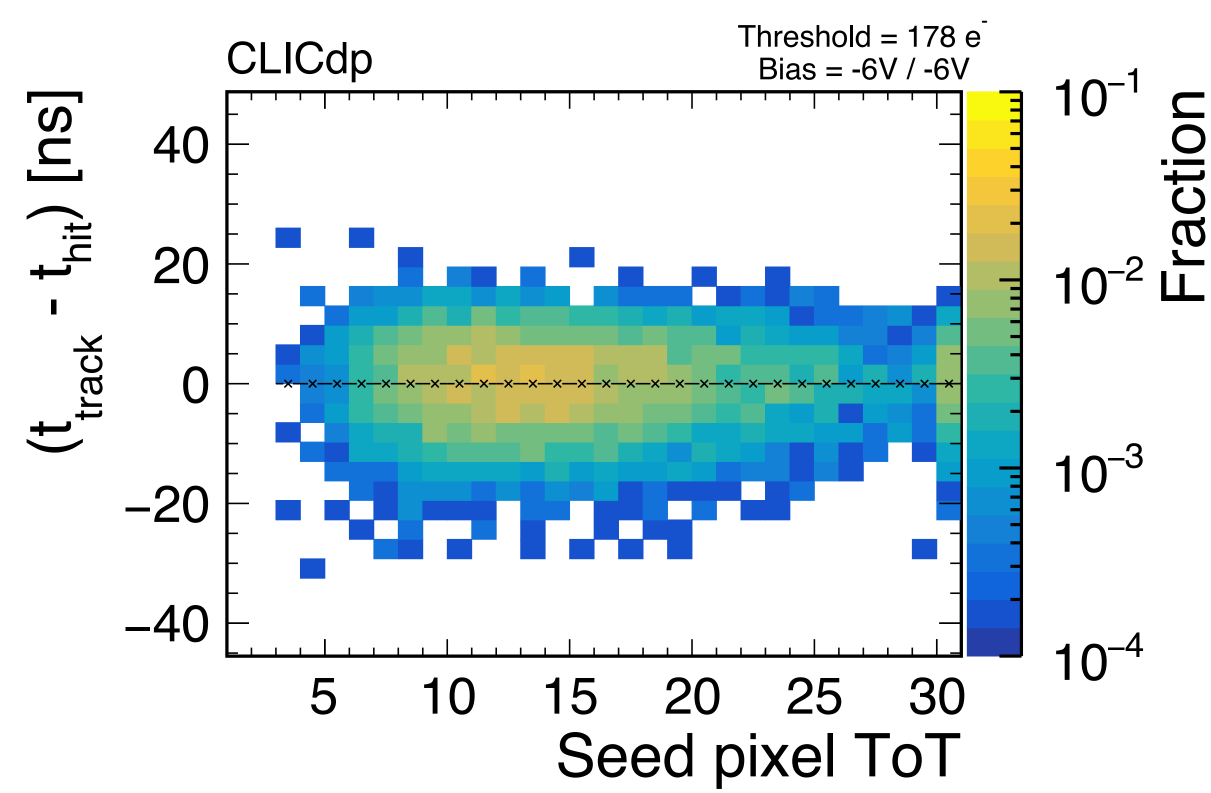
- Faster charge collection for flavour with segmented n-implant
- At nominal threshold (178 e) for the segmented n-implant: ~ 5.8 ns
  (telescope resolution unfolded)
- Laboratory measurements show that the time resolution is limited by the front-end



Before time-walk correction



After time-walk correction

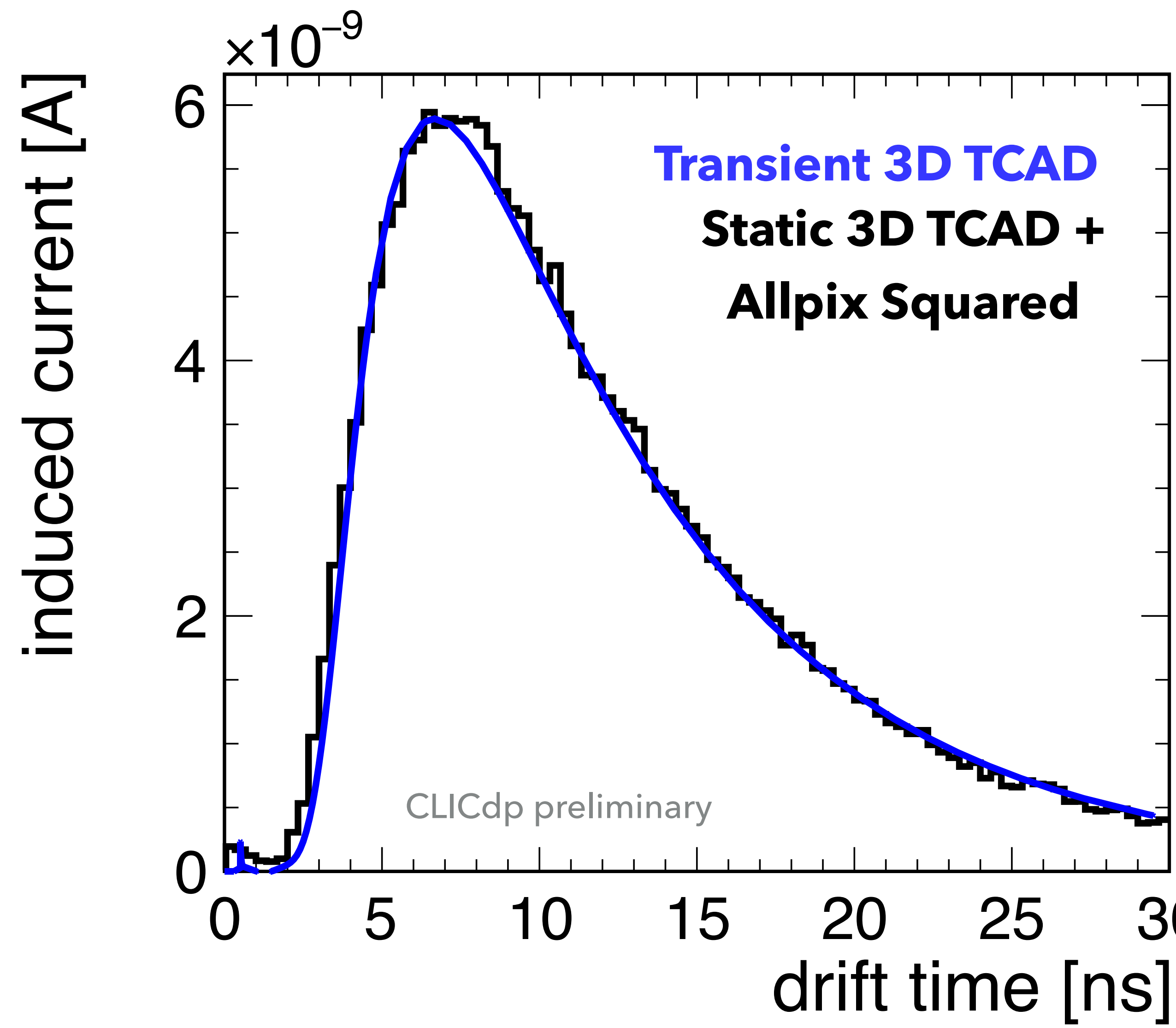


Combining 3D TCAD with MC framework

- Complex sensor structures require advanced simulation techniques
- Transient Monte Carlo (e.g. Allpix Squared or Garfield++) is combined with electrostatic 3D TCAD simulations
  NIM A 964 (2020) 163784
  - ✓ Accurate sensor modelling
  - ✓ Access to high statistics
- Allpix Squared framework: Full detector simulation from energy deposition until digitisation of signal NIM A 901 (2018) 164-172
- Transient pulses between transient 3D TCAD and static 3D TCAD + Allpix Squared (APSQ) are in good agreement with each other

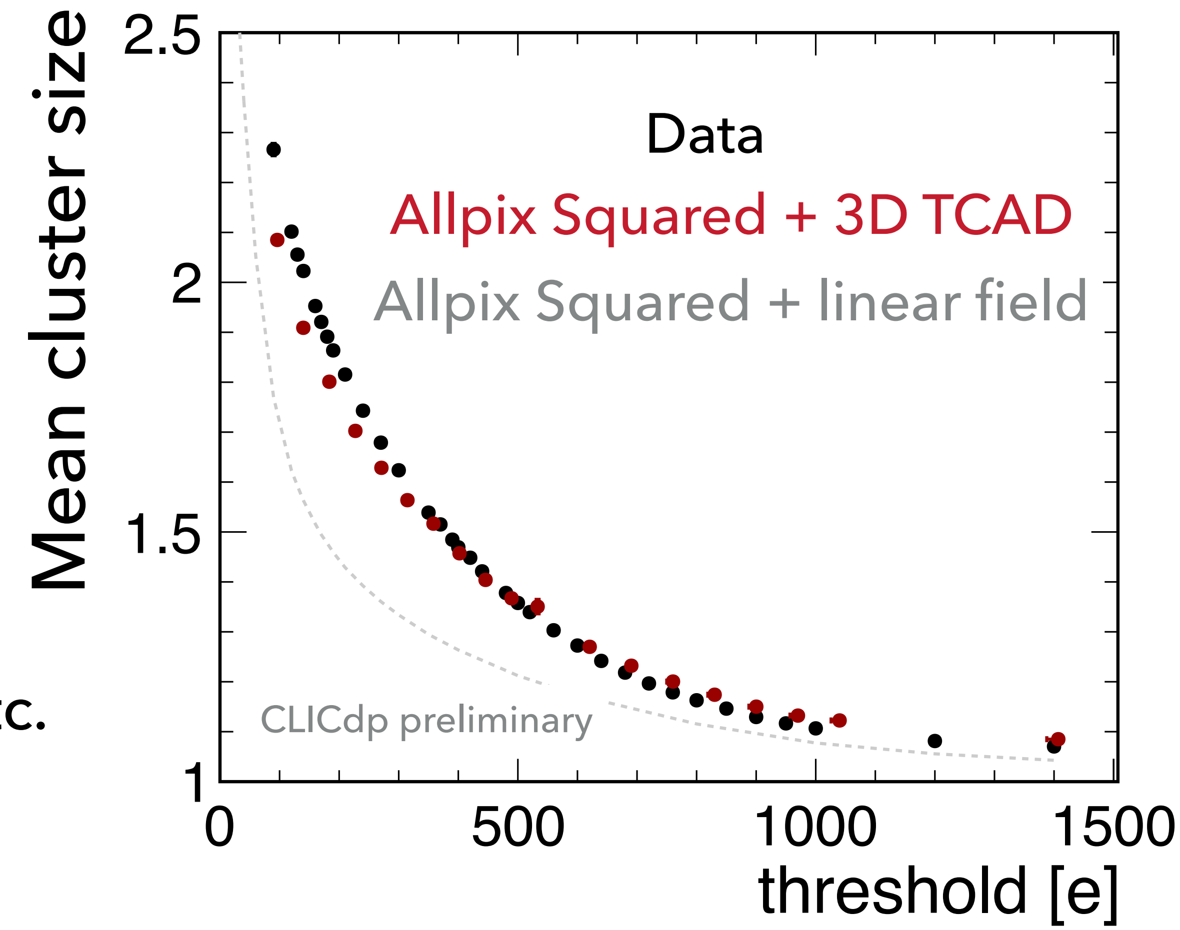
https://gitlab.cern.ch/allpix-squared/allpix-squared

Charge injection in pixel corner

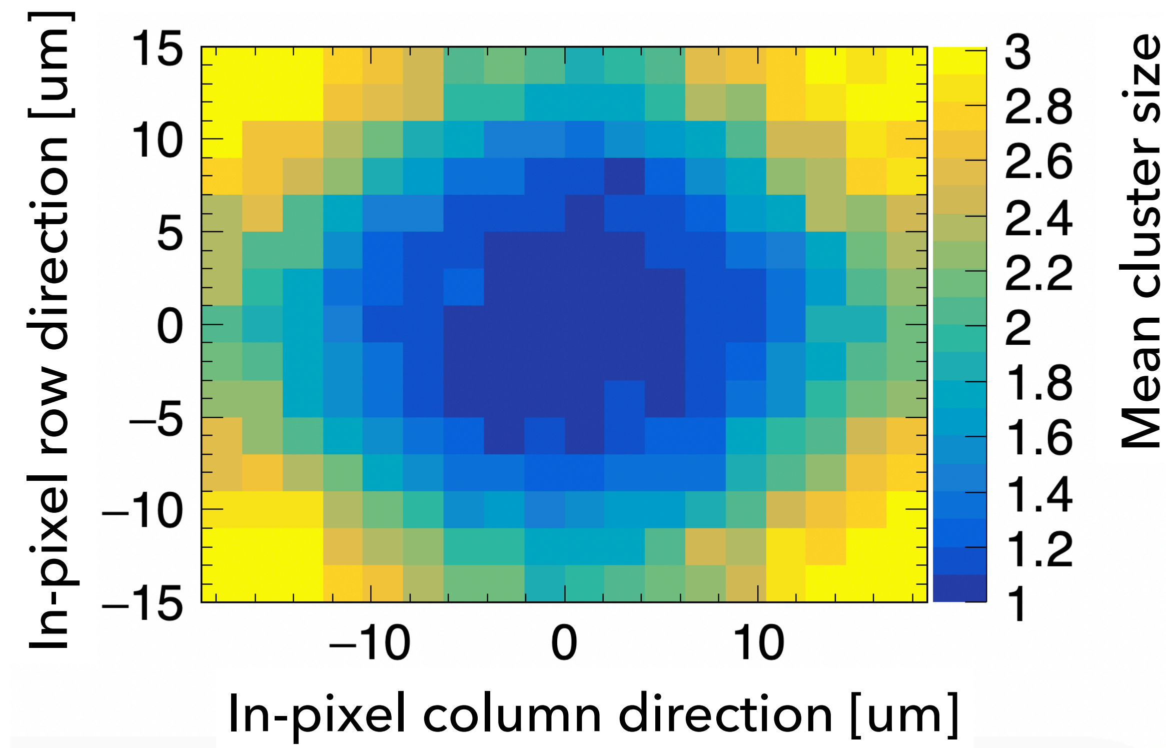


Comparison to data

- 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.

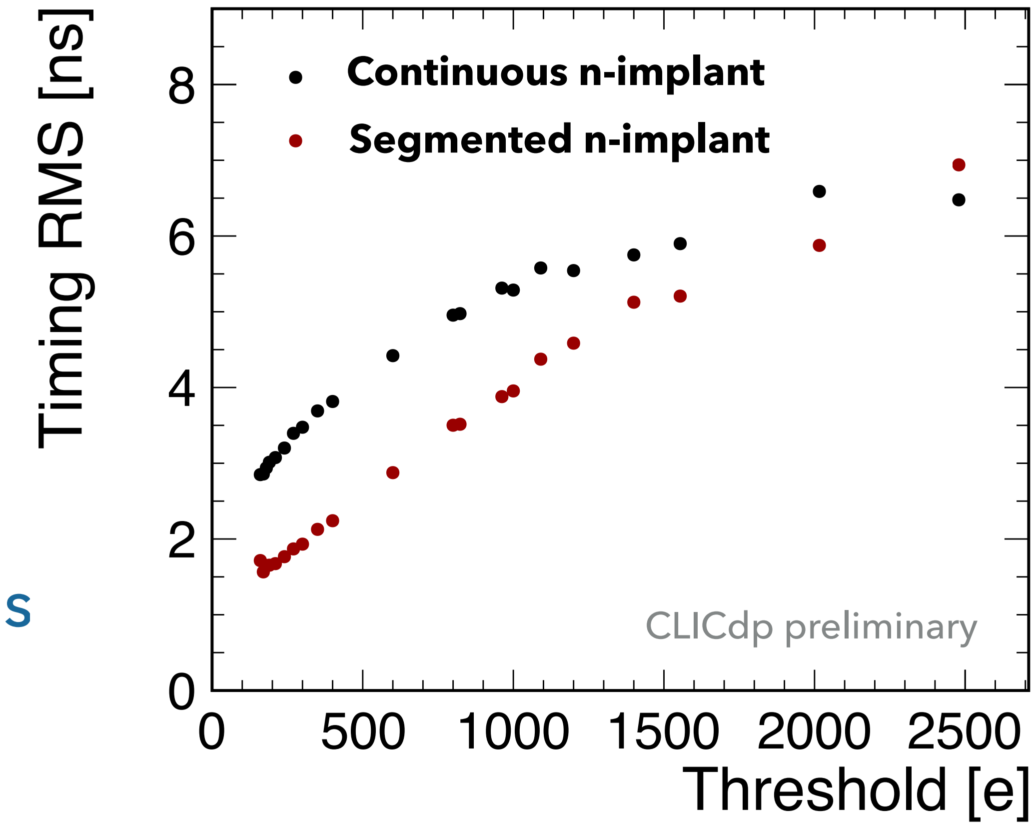


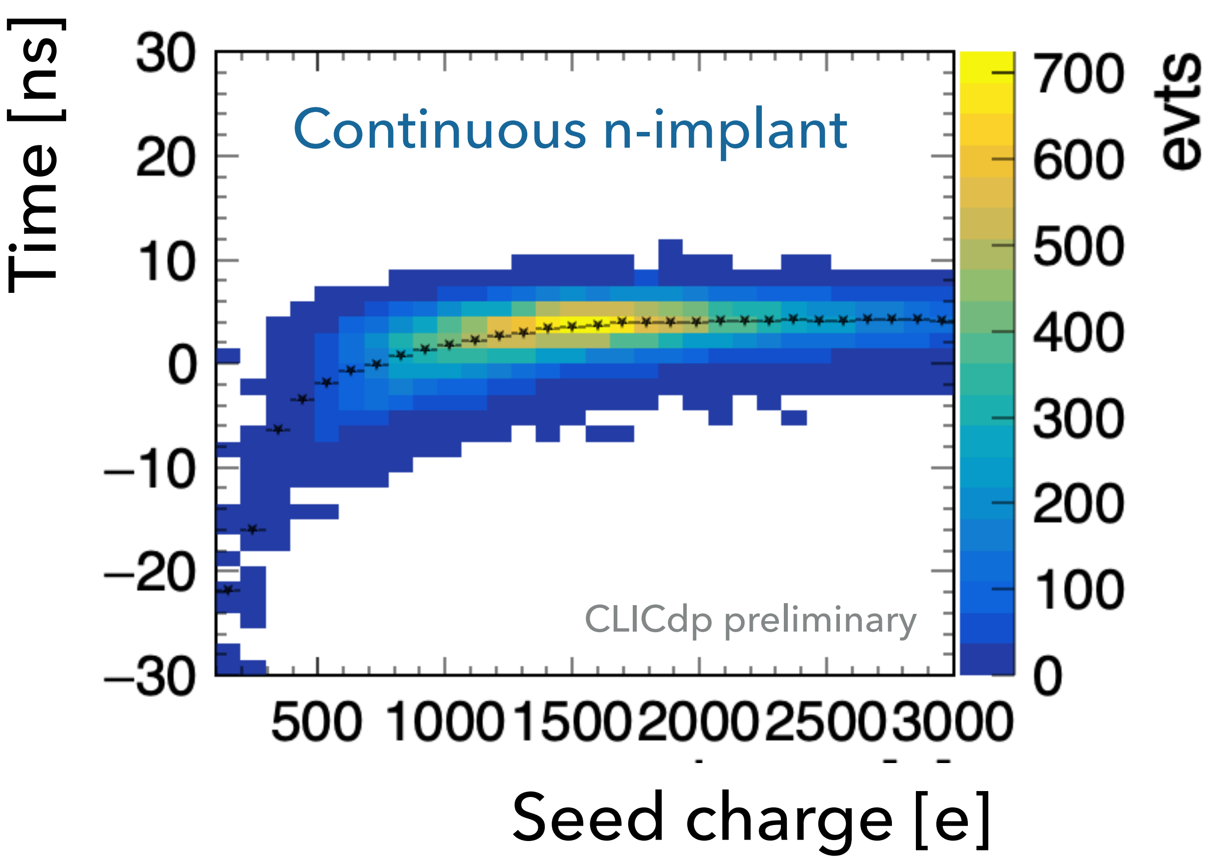
- High statistics simulations take stochastic nature of interaction between particles and silicon sensor into account
  - Observables can be studied as a function of in-pixel incidence position

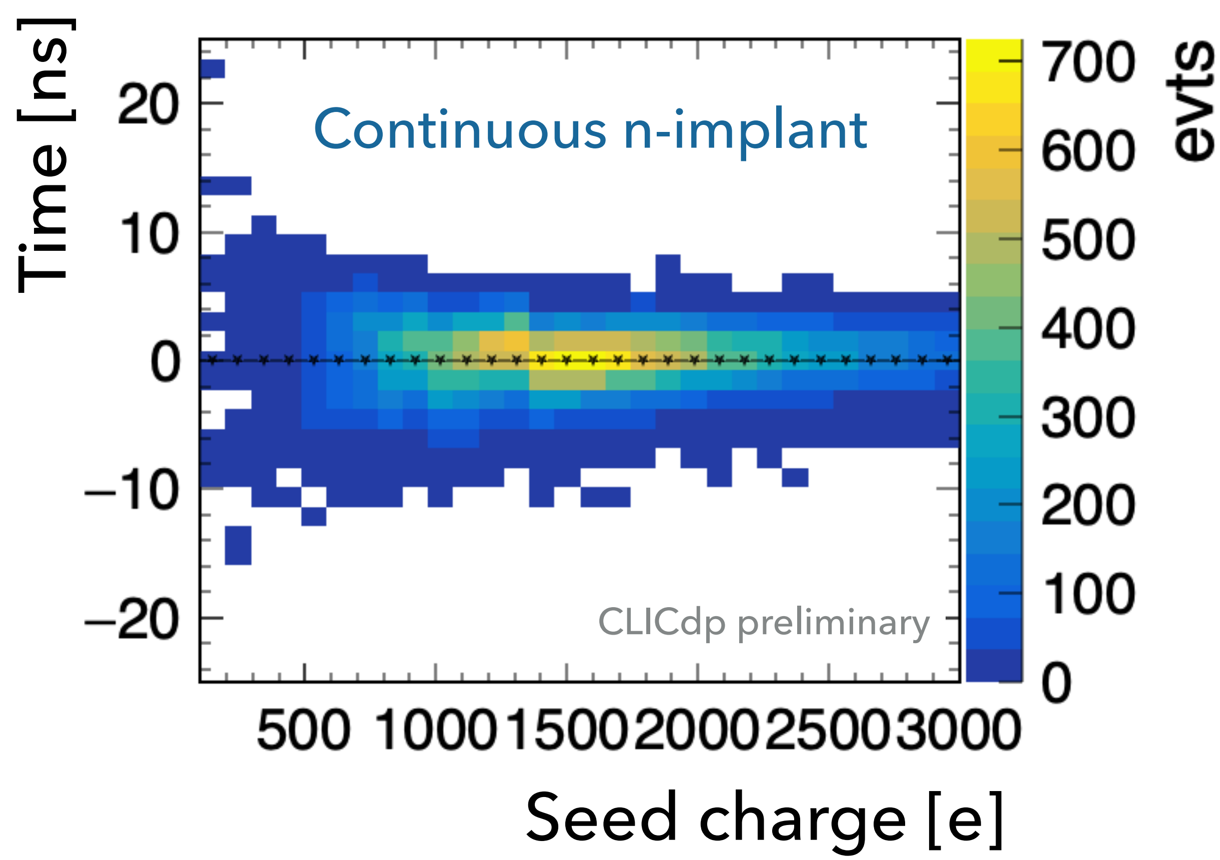


Time resolution in simulation

- In simulation: threshold-crossing time of signal is used to estimate sensor time resolution
- No simulation of front-end or electronics noise
- Time RMS after time-walk correction < 2 ns for segmented n-implant







CLICTD on Czochralski wafer

- Limited thickness of epitaxial layer (~ 30 µm)
- Thickness of Czochralski samples : 100 µm

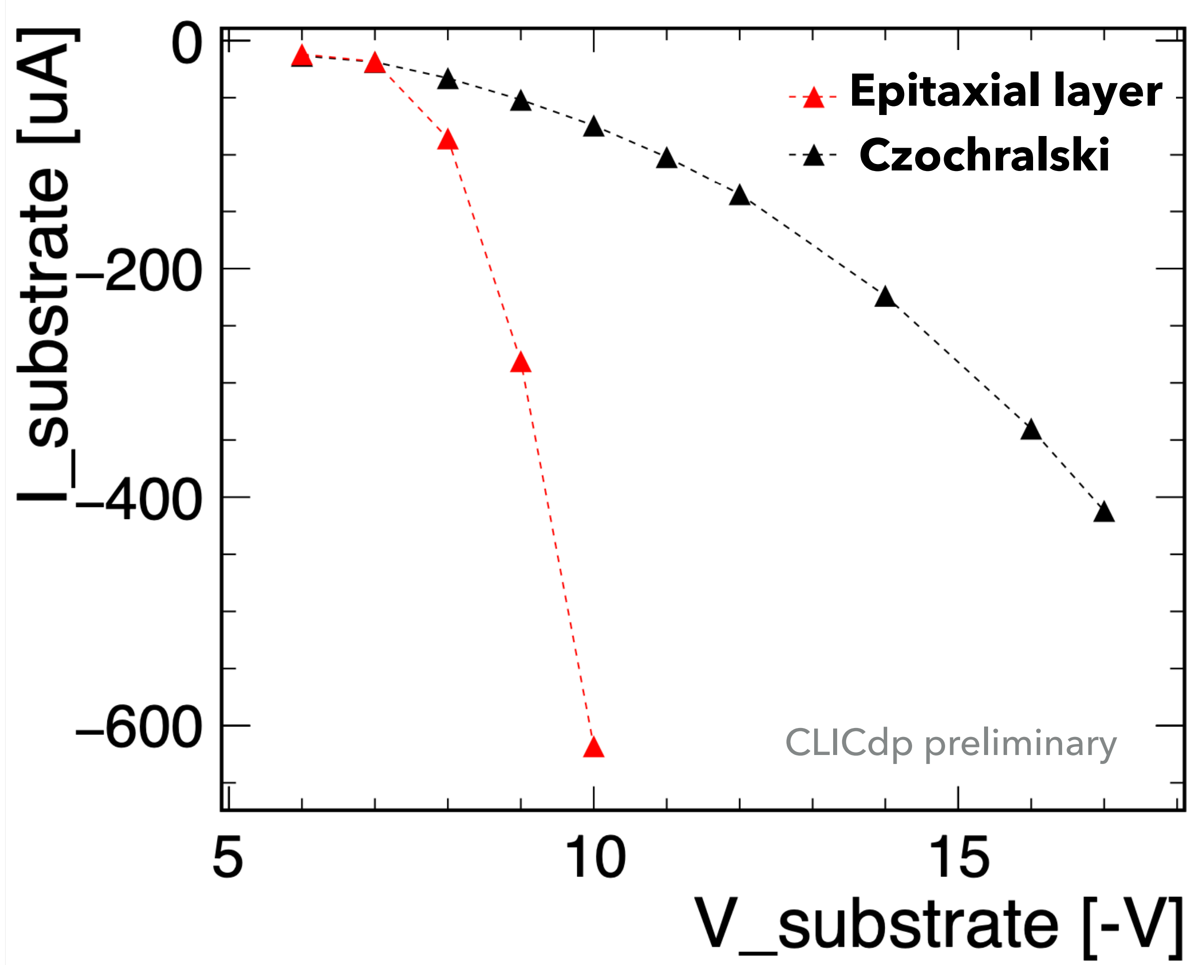
  ➡ High-resistivity Czochralski wafer (> 800 Ωcm) material allows for higher substrate voltages and a larger depleted/active volume

  NIM A 986 (2021) 164381

  - Larger cluster size -> improvement in position resolution expected
  - Improved signal/noise -> improvement in time resolution expected
  - Larger efficient operation range

Segmented n-implant

Bias voltage p-well: -6V



- Various different design parameters were produced and will be compared systematically
- Test-beam campaign foreseen for June 2021

Summary and Outlook

- CLICTD fulfils the main CLIC tracker requirements:
  - ✓ Position resolution (in row direction) : 4.6 μm
  - ✓ Time resolution (limited by front-end) : 5.8 ns
  - ✓ Full efficiency (> 99.7%) over threshold range of several hundred electrons

- 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

- Systematic test-beam studies of samples with different bulk material and thicknesses (down to 40 μm), using inclined tracks foreseen

Thank you for your attention

Back-up

References - Allpix Squared

Selected Applications

- **Detectors for HEP**
  - MAPS (CLICTD, ALICE, ARCADIA,…), RD53, ATLAS ITk Strips, …
- **NASA / Space Radiation Analysis**
- **ISS radiation monitor simulations**
- **Germanium X-ray detector (Synchrotron SOLEIL)**
- **Education / Outreach activities**
  - EDIT Detector School, Beamline for Schools 2019,…

Publications

NIM A 901 (2018) 164-172

NIM A 964 (2020) 163784

Website

https://cern.ch/allpix-squared

Repository

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

User Forum

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

User Manual

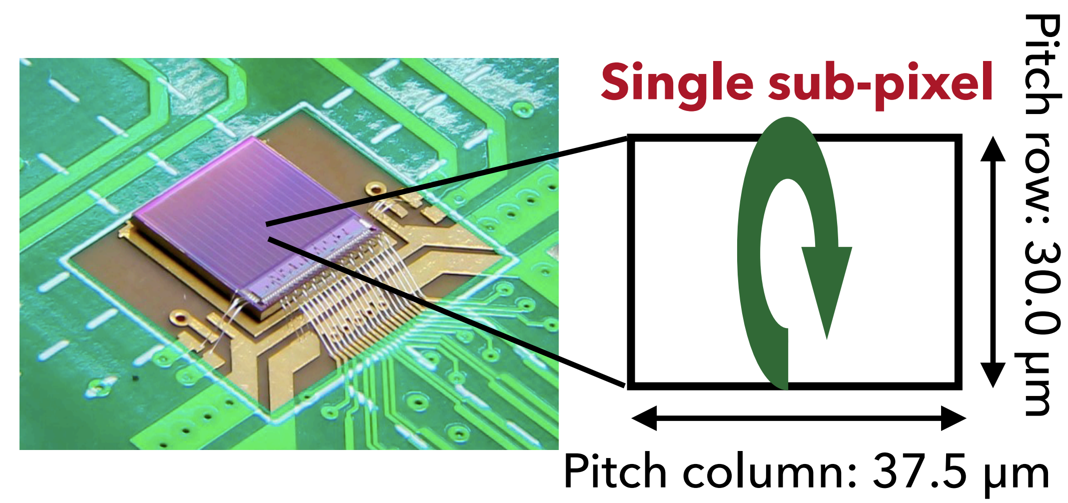
https://cern.ch/allpix-squared/usermanual/allpix-manual.pdf

Mailing list

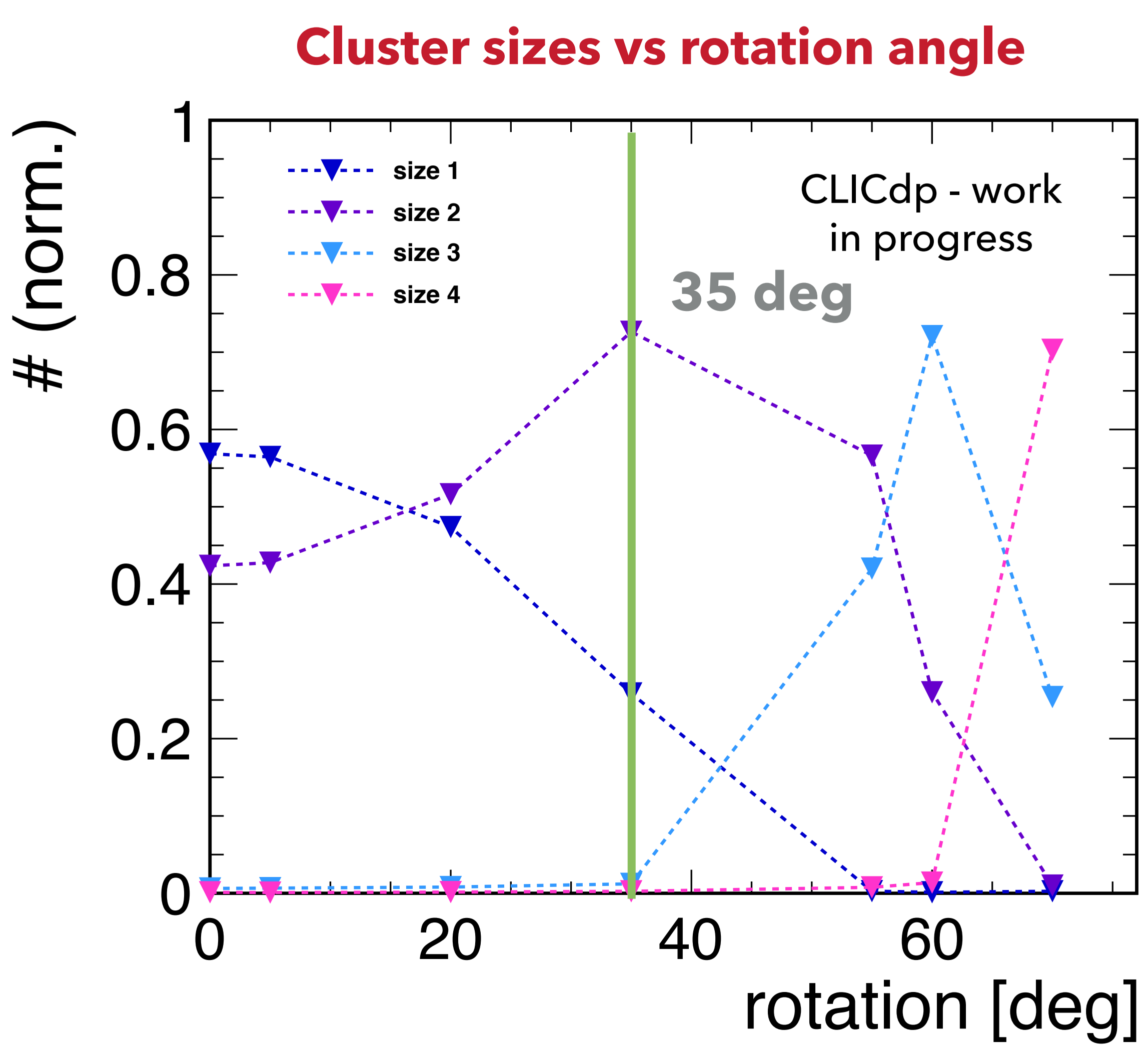
https://e-groups.cern.ch/e-groups/Egroup.do?egroupId=10262858

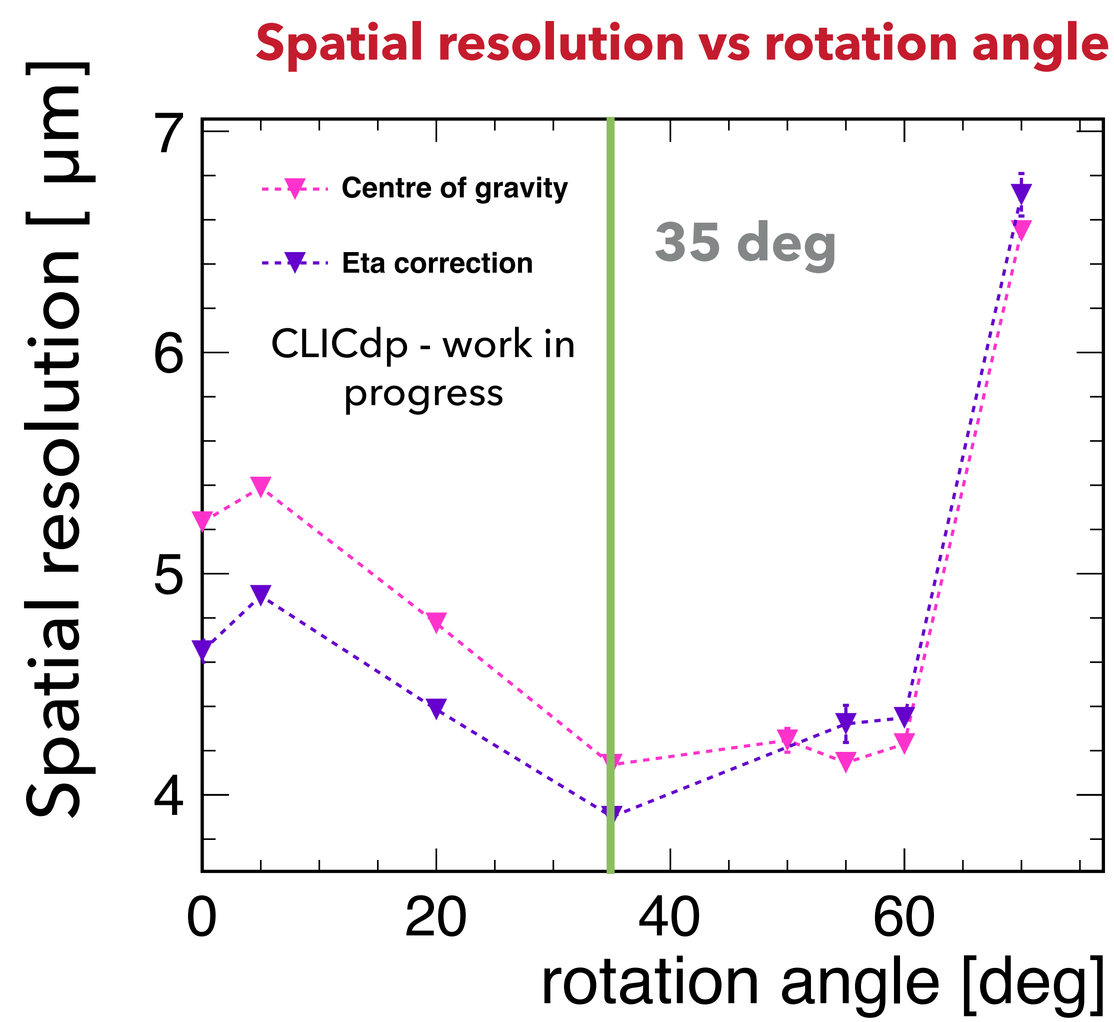
Inclined particle tracks

- 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

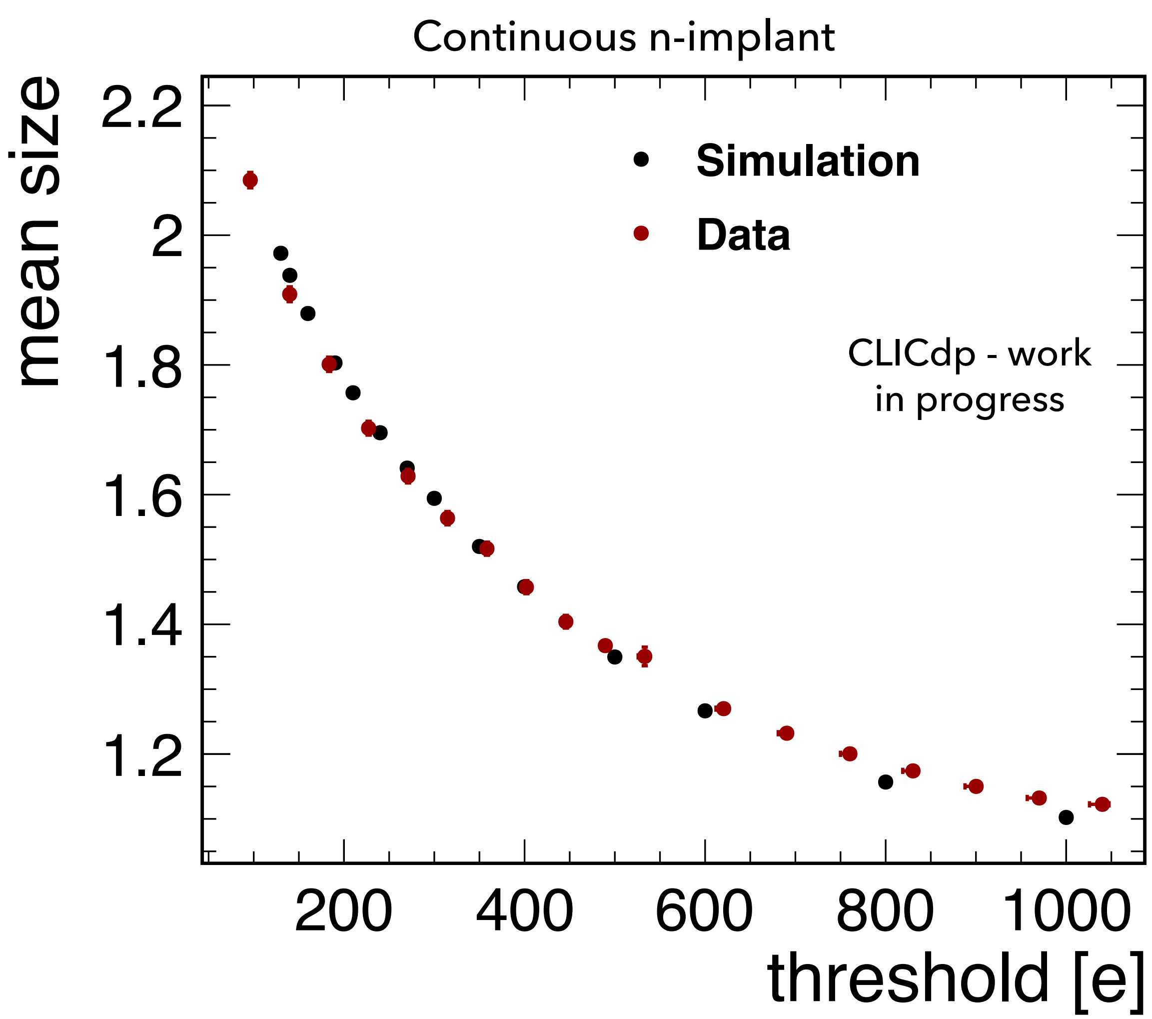


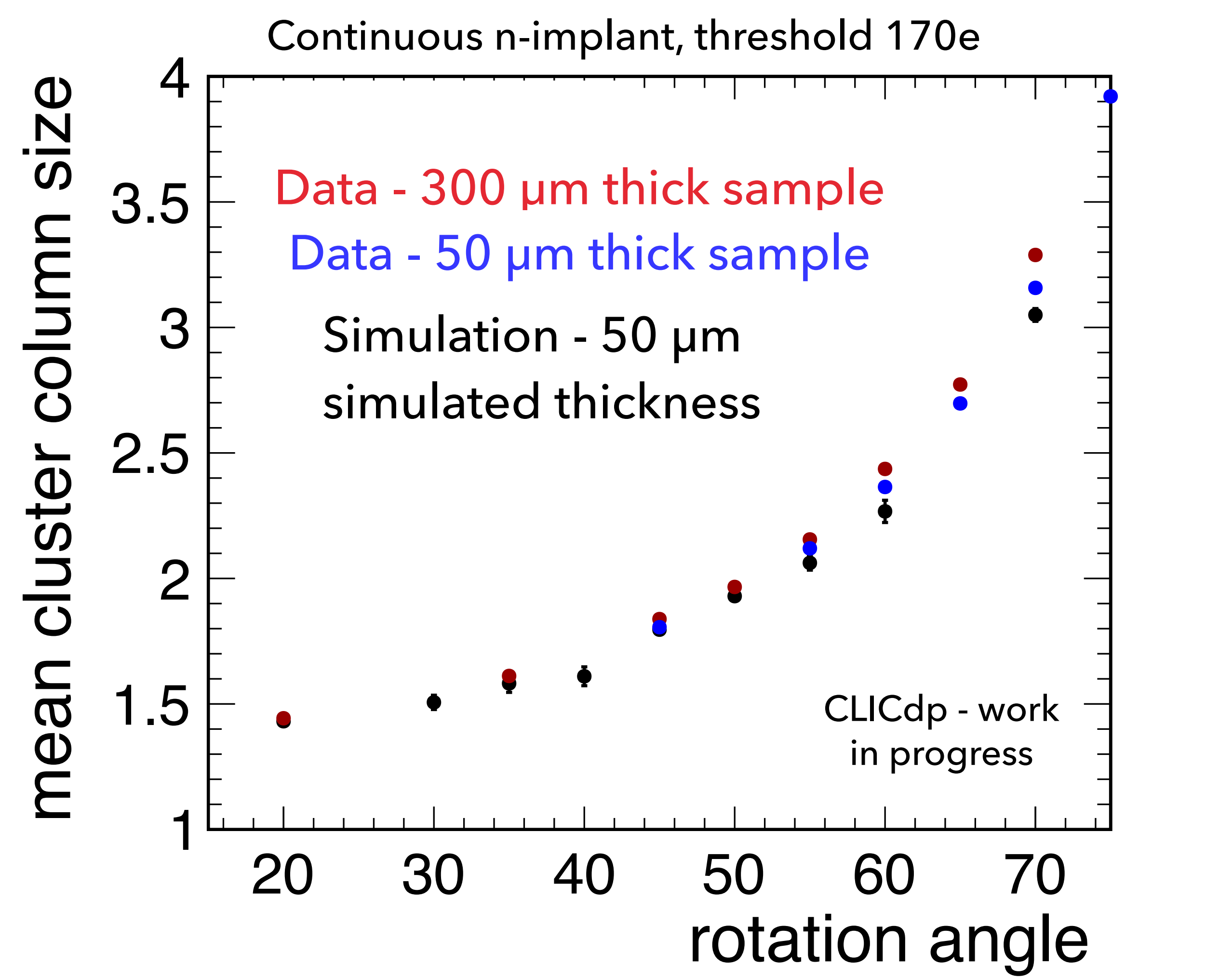


Comparison of simulation against data

- Cluster size is very sensitive to differences in electric field, charge carrier lifetime, etc.
- Uncertainties related to the doping profiles are currently investigated
- For high rotation angles, simulation gets more sensitive to charge carrier lifetime, mobility model, electric field, …

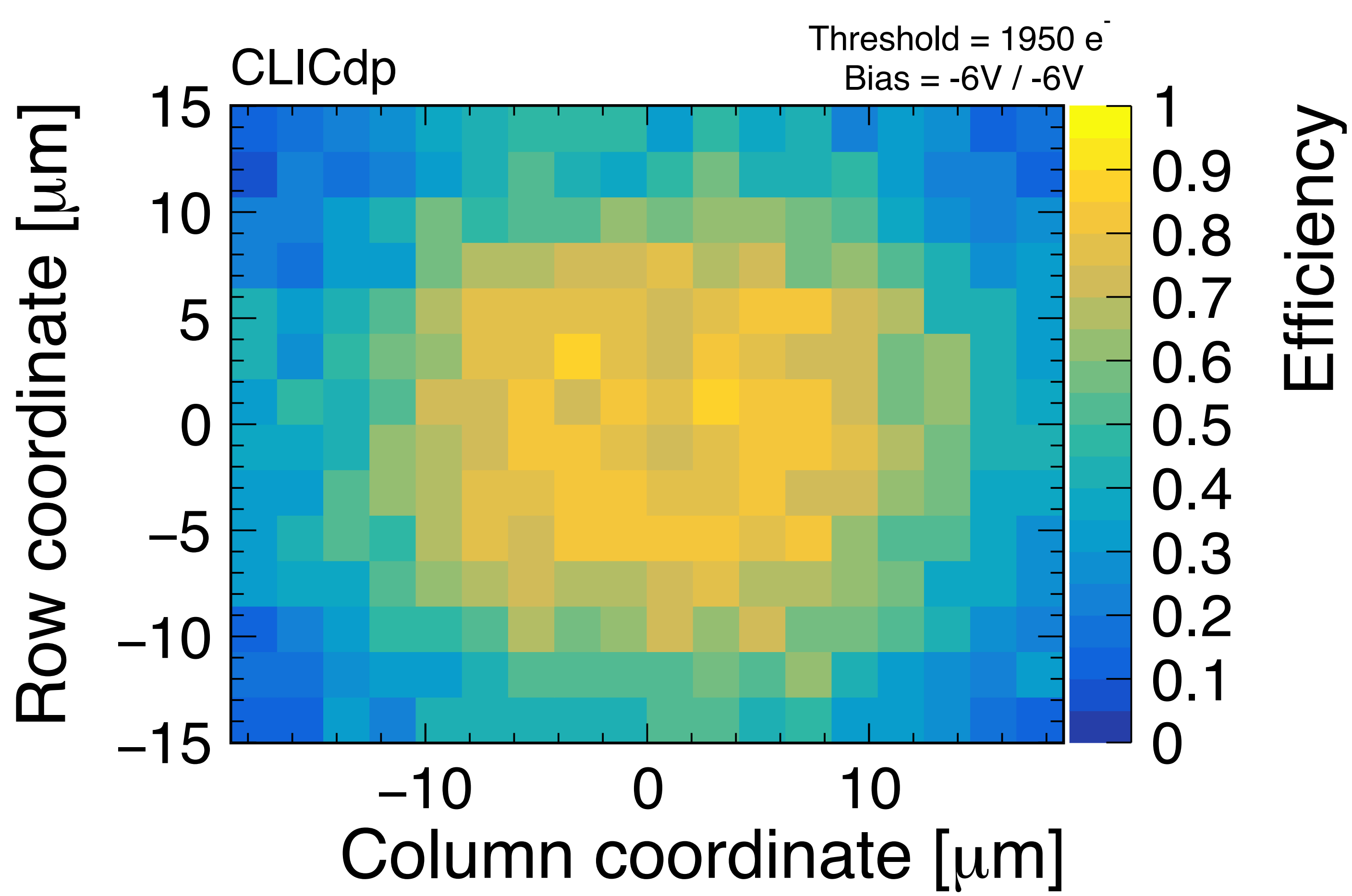
  ➡High accuracy of sensor modelling is needed



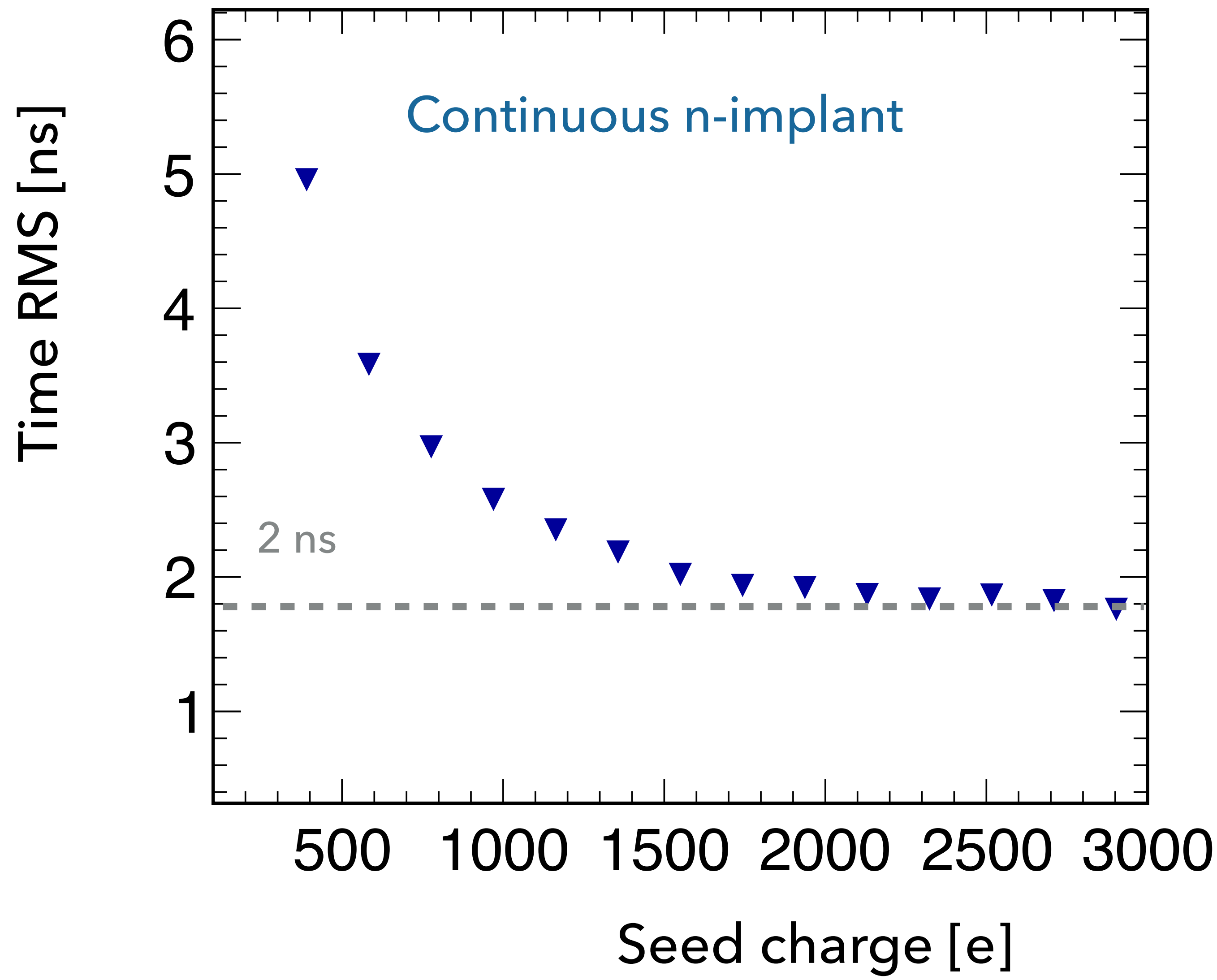


Efficiency

- Inefficient regions start to arise at the pixel edges due to the enhanced charge sharing
- The higher efficient operation window for the pixel flavour with segmented n-implant is especially relevant for sensors with thin active layers



Time resolution in simulation



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FUTURE TRACKING DETECTORS FOR HIGH-ENERGY PHYSICS (HEP)

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Table 3: Approximate requirements for the central tracking volume at the different collider experiments.

Exp. / Parameter	LHC	HL-LHC	SPS	FCC-hh	FCC-ee	CLIC 3 TeV
Fluence [$n_{eq}/cm^2/y$]	N x 10^{15}	10^{16}	10^{17}	10^{16} - 10^{17}	<10^{10}	<10^{11}
Max. hit rate [$s^{-1}cm^{-2}$]	100 M	2-4 G****)	8 G****)	20 G	20 M ***)	240k
Surface inner tracker [m^2]	2	10	0.2	15	1	1
Surface outer tracker [m^2]	200	200	-	400	200	140
Material budget per detection layer [X_0]	0.3%*) - 2%	0.1%*) - 2%	2%	1%	0.3%	0.2%
Pixel size inner layers [μm^2]	100x150-50x400	~50x50	~50x50	25x50	25x25	<~25x25
BC spacing [ns]	25	25	>10^9	25	20-3400	0.5
Hit time resolution [ns]	<~25–1k*)	0.2**)–1k*)	0.04	~10^{-2}	~1k ***)	~5

*) ALICE requirement **) LHCb requirement ***) At Z-pole running ****) max. output rate for LHCb/high intensity flavour experiments: 300-400 Gbit/s/cm^2

CERN-OPEN-2018-006