



Test-beam and simulation studies for the CLICTD technology demonstrator

a monolithic CMOS pixel sensor
with a small collection diode

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On behalf of the CLICdp collaboration

**International Conference on Technology
and Instrumentation in Particle Physics**

Outline

The CLICTD Sensor

Test-Beam Results

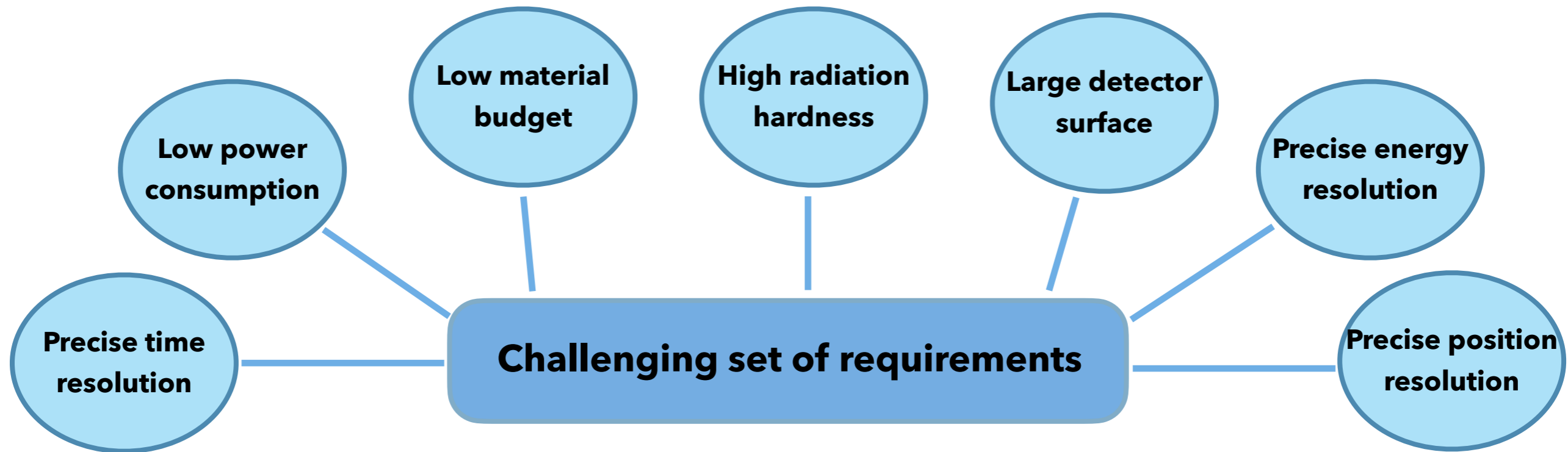
Simulation Studies

CLICTD on Czochralski

Summary/Outlook

Future tracking detectors for high-energy physics (HEP)

Tracking detector requirements for HEP experiments



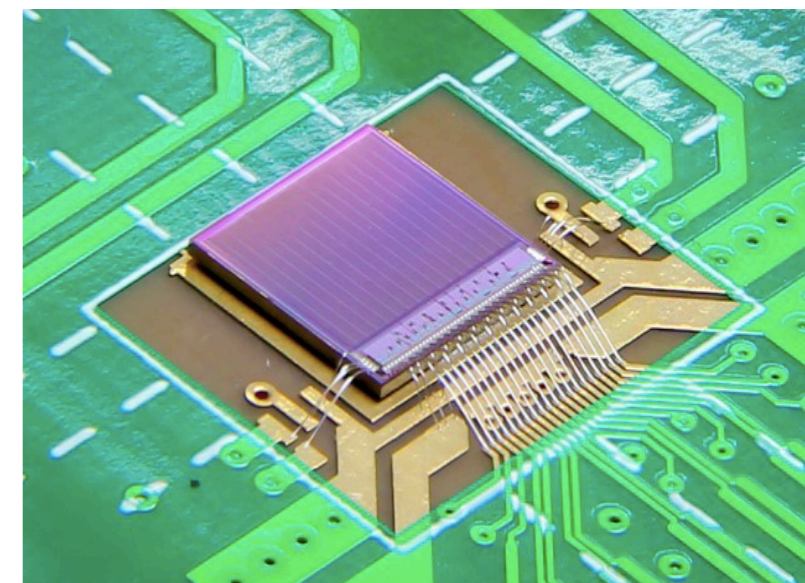
- Set of challenging requirements for silicon detectors foreseen for future HEP tracking detectors
- **Monolithic silicon sensors** are attractive candidates for **large area, low-mass tracking detector** (e.g. for CLIC)

Detector Technologies for CLIC, CERN-2019-001

Requirements for CLIC tracking detector:

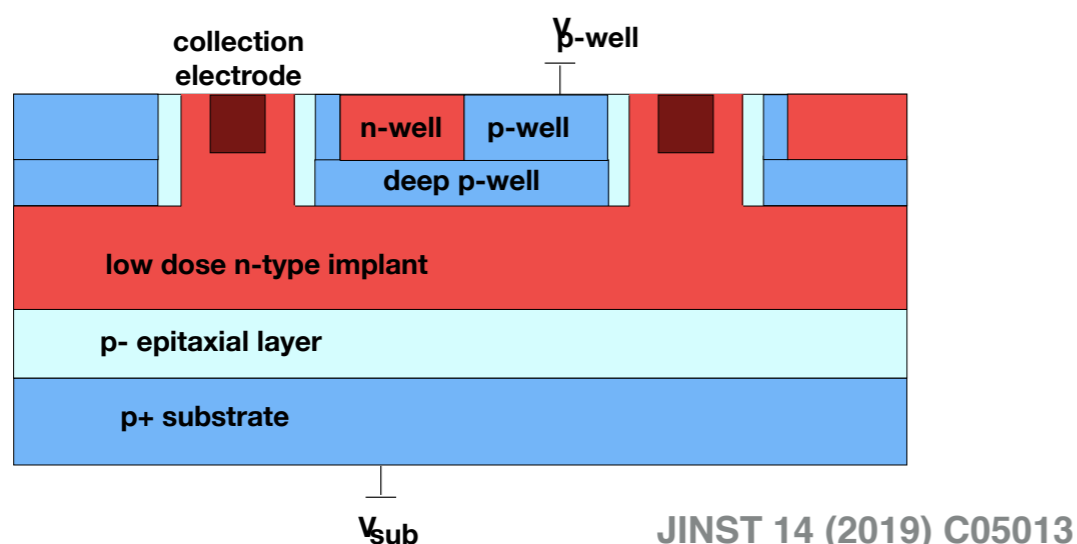
- Single point resolution: $7 \mu\text{m}$
(in direction perpendicular to the magnetic field)
- Timing resolution: $\sim 5 \text{ ns}$
- Material budget: $\sim 1\text{-}2\% X_0$ per layer
- Power consumption: $< 150 \text{ mW/cm}^2$

- 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**

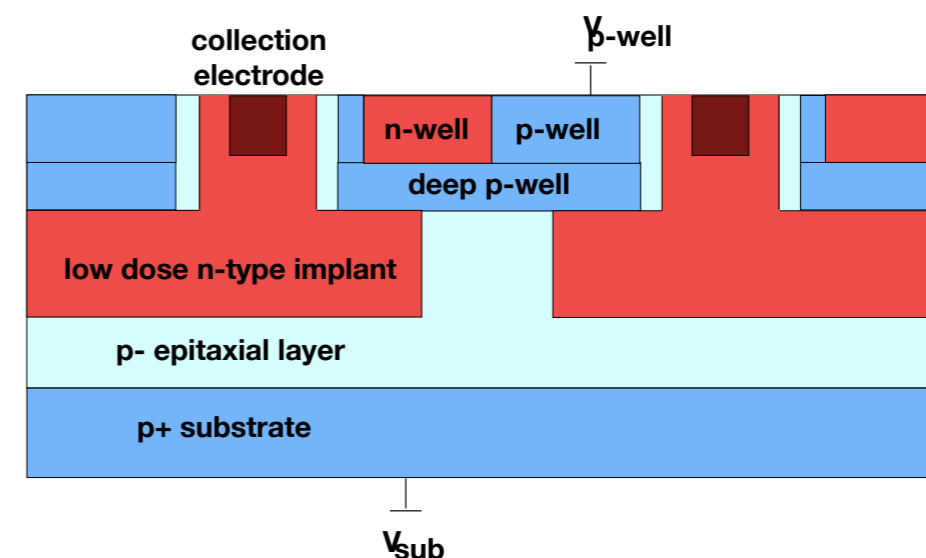


➔ Speed-up of charge collection

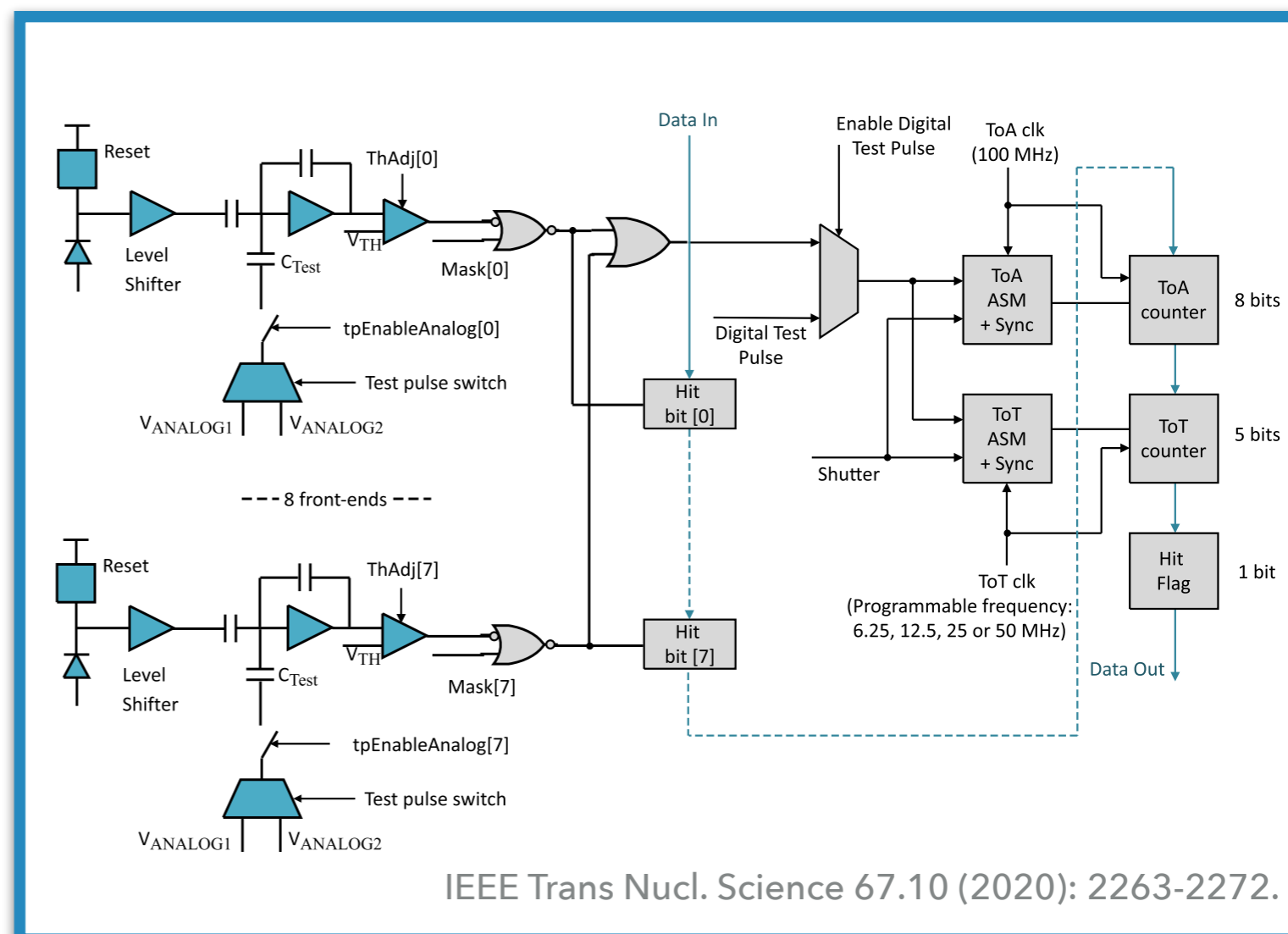
Continuous low-dose deep n-implant



Segmented low-dose deep n-implant



- 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 for ToT and ToA measurements (one ToT and ToA per channel)



➔ 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 300 μm dimension)

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

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)

Electron beam with 5.4 GeV

- MIMOSA26 planes

Track-position resolution
at DUT: $\sim 2 \mu\text{m}$

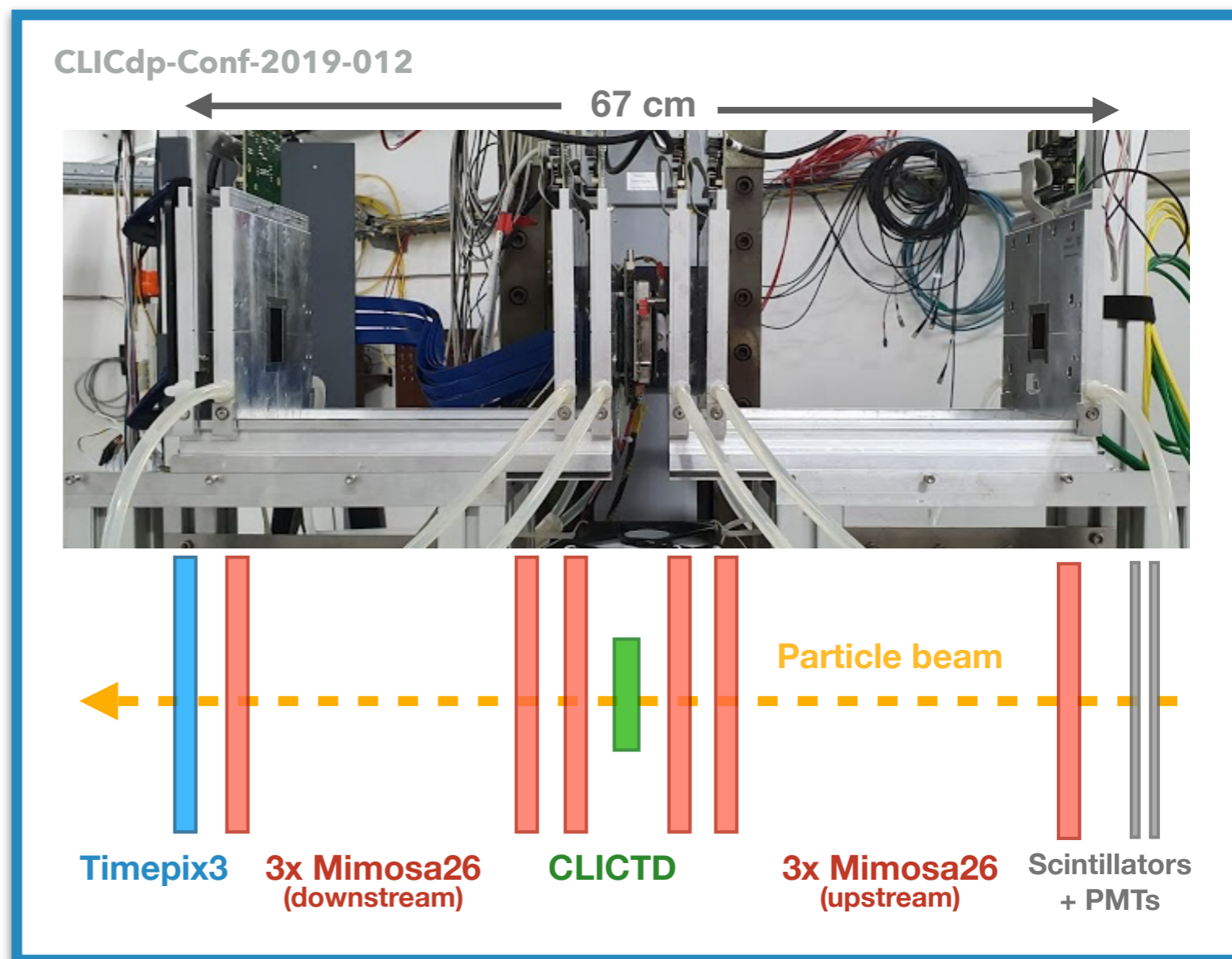
- Timepix3 track-timing plane

Timing resolution: $\sim 1 \text{ ns}$

- Device Under Test (DUT)

Readout with Caribou
versatile DAQ system

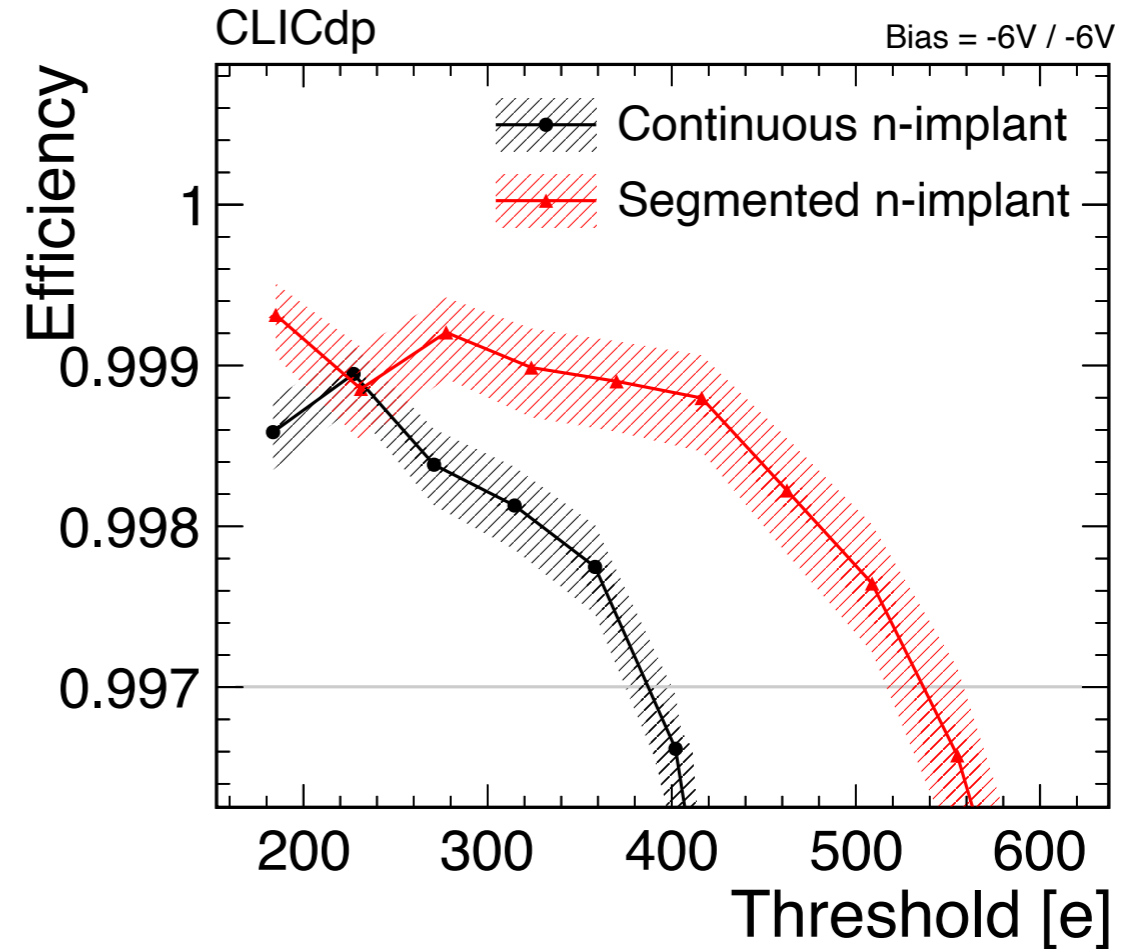
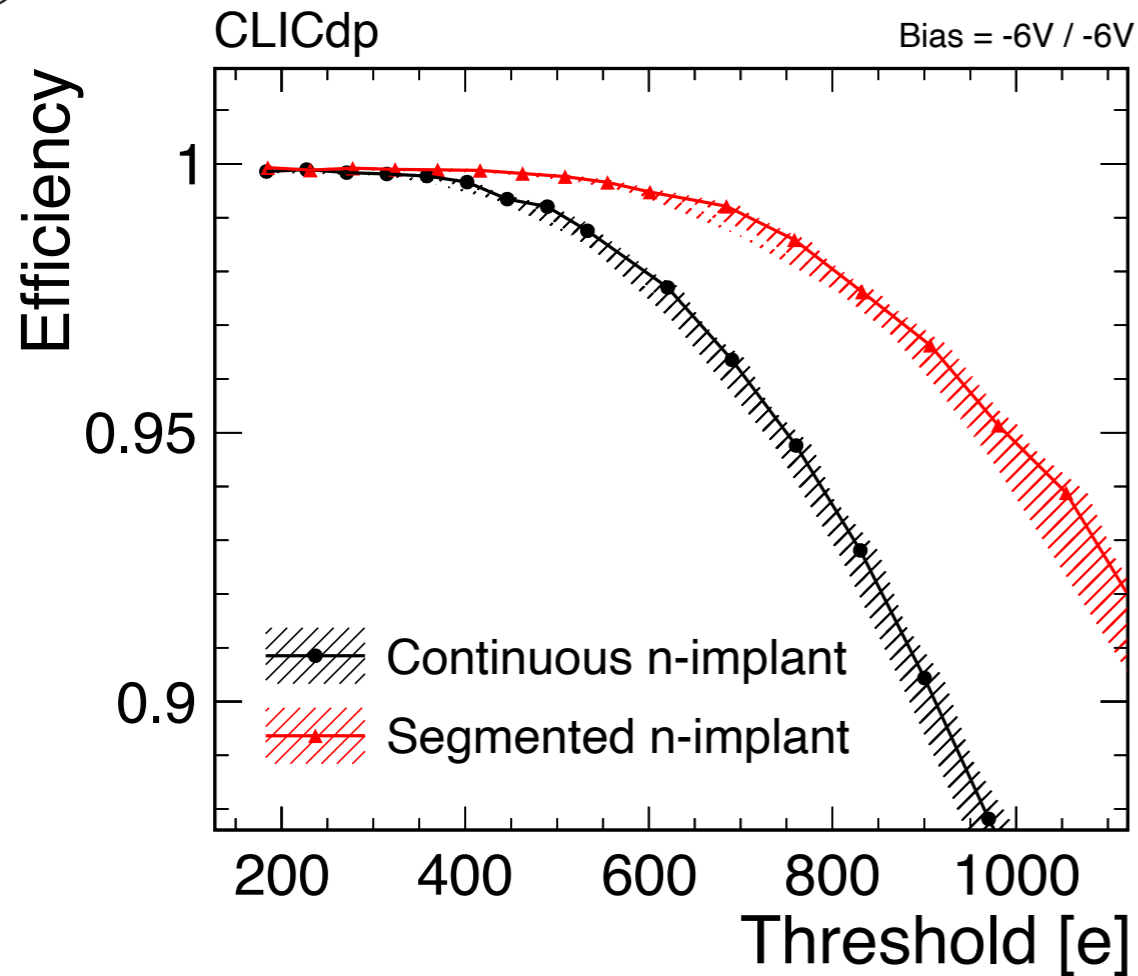
- Reconstruction and analysis



Corryvreckan reconstruction framework

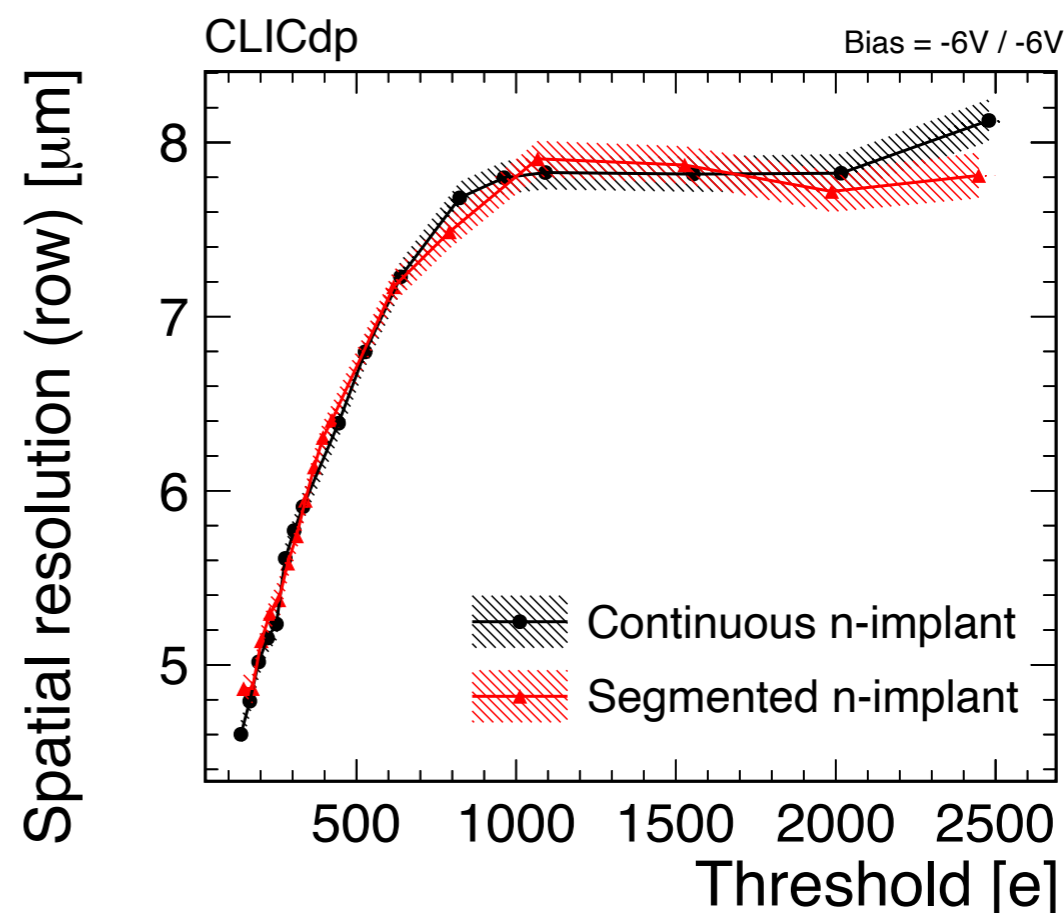
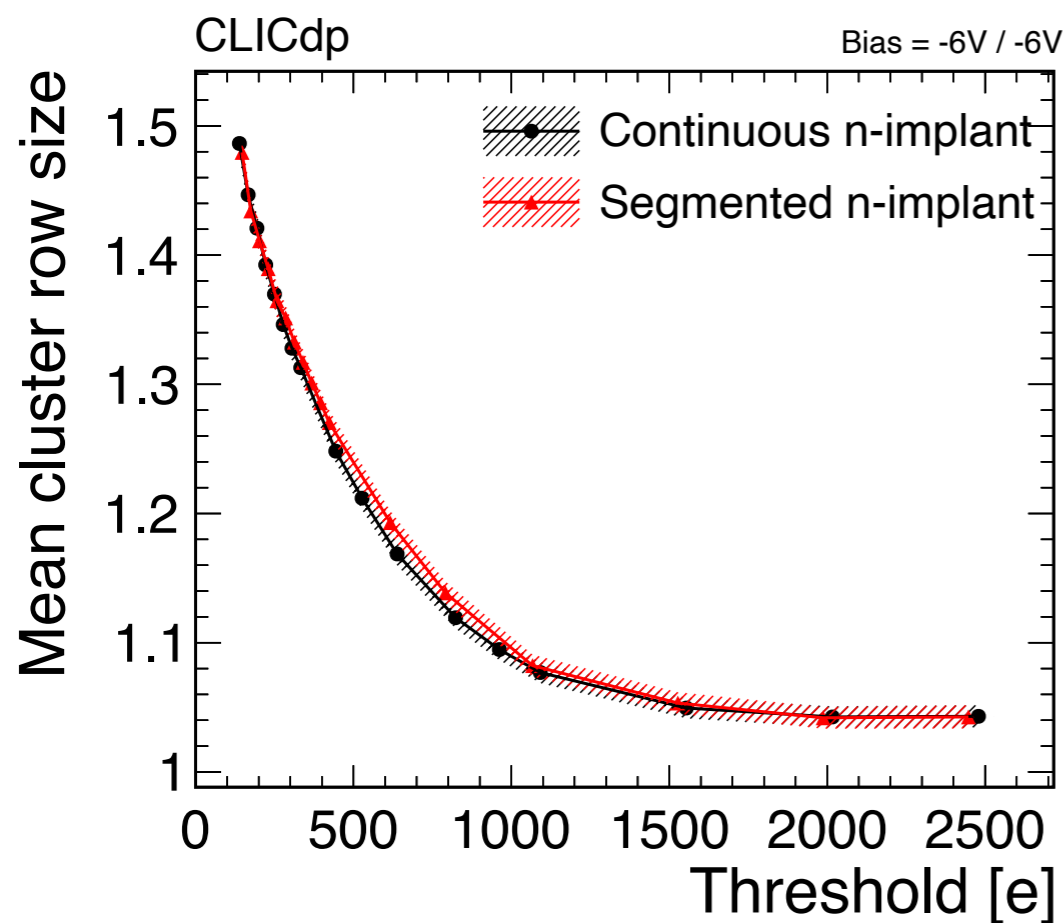


<https://gitlab.cern.ch/corryvreckan/corryvreckan>

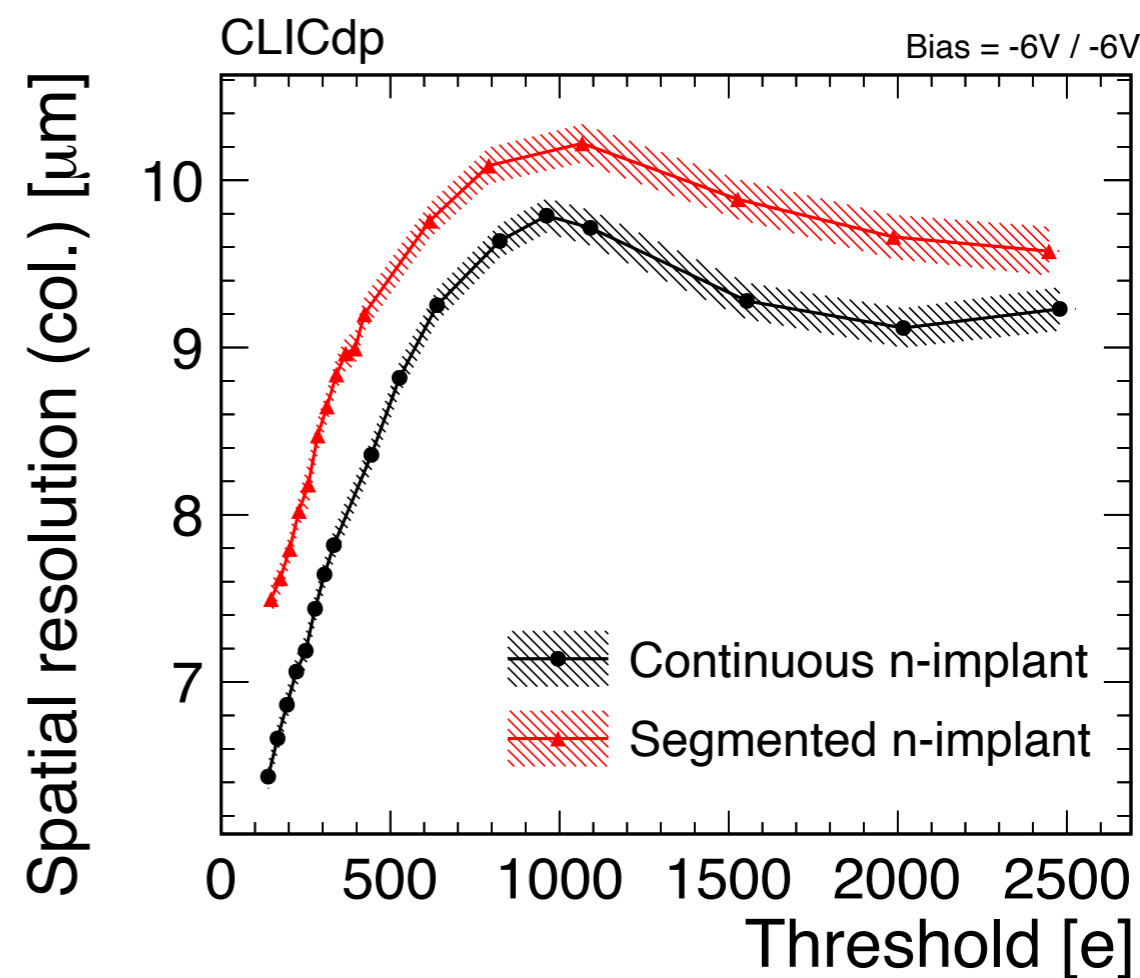
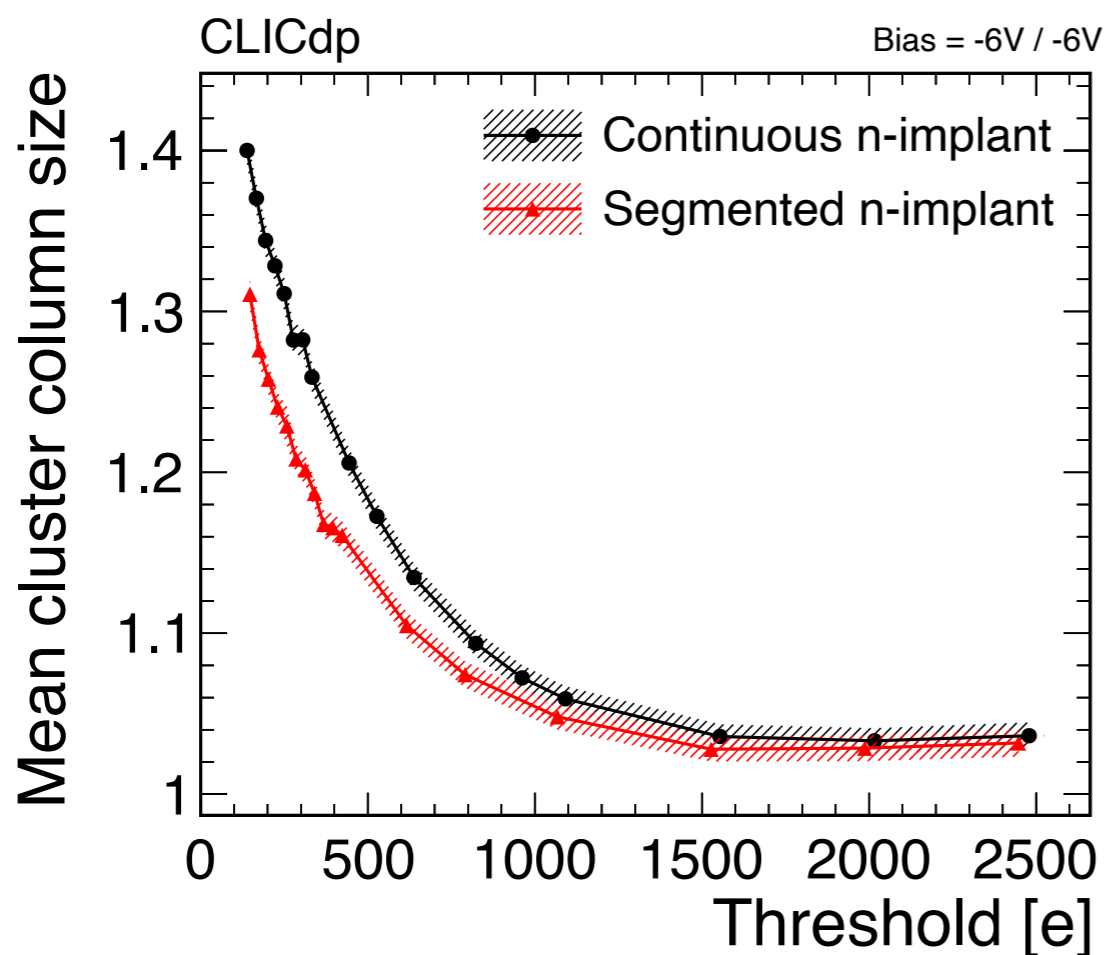


- Approximately 2000 e-/h+ pairs per MIP as expected from active depth of $\sim 25 \mu\text{m}$ (according to simulations and rotation studies) [arXiv:2011.09389](https://arxiv.org/abs/2011.09389)
- Full efficiency ($> 99.7\%$) for threshold range of several hundred electrons (efficient operation window)
- Reduced charge sharing for flavour with segmented n-implant leads to a higher seed signal which improves the efficiency for increasing thresholds

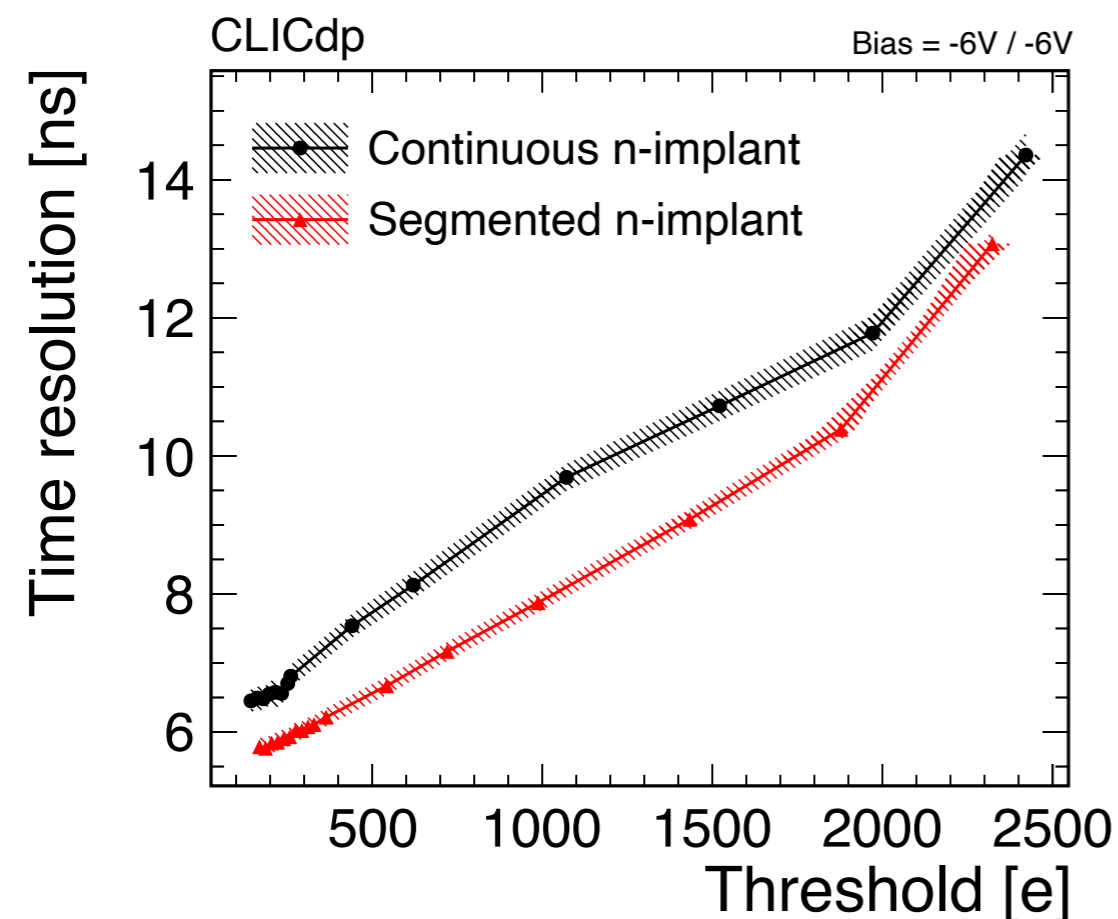
- Cluster size in row direction remains unaffected since no segmentation was introduced
- Position reconstruction can be improved by **charge interpolation**
 - Cluster position calculated by centre-of-gravity algorithm
 - In row direction, an η -correction for non-linear charge sharing was applied
-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



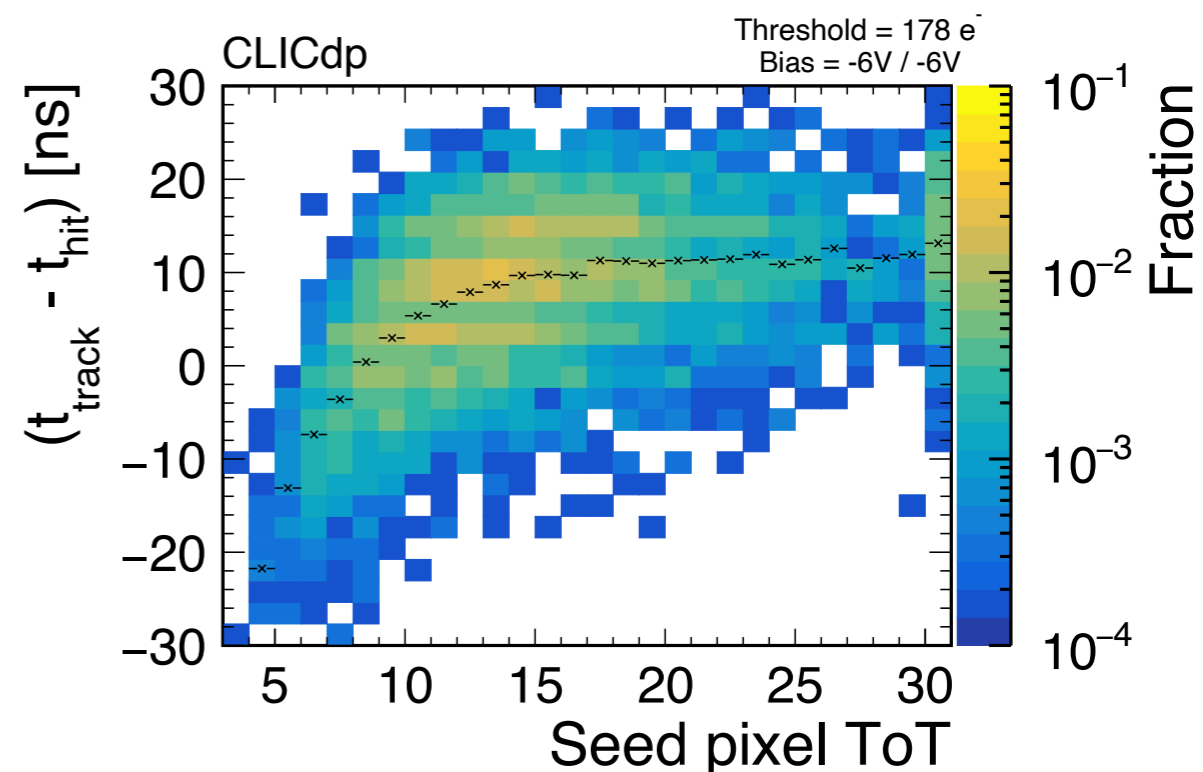
- **Reduced charge sharing** for pixel flavour with segmented n-implant leads to a **smaller cluster size** in column direction
- **Smaller cluster size** in column direction for flavour with segmented n-implant leads to a **degrading position resolution** in this direction
(not relevant for momentum measurement in magnetic field)



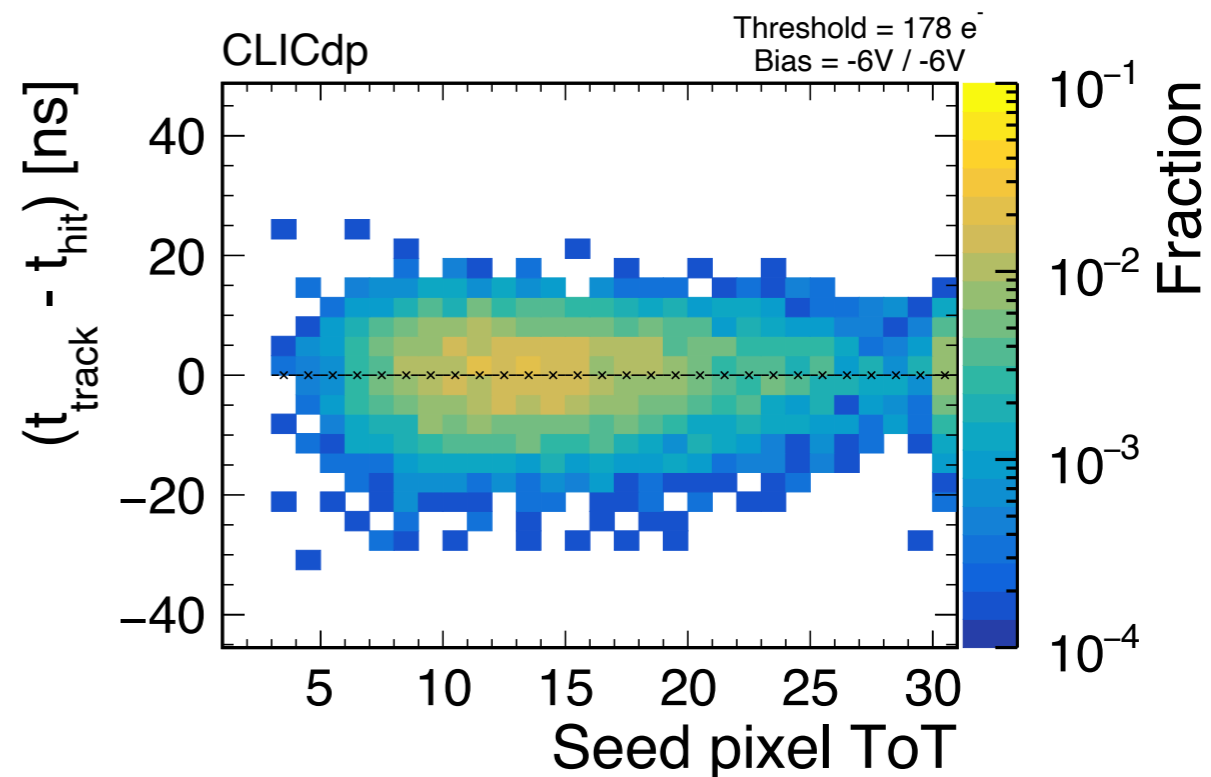
- Faster charge collection for flavour with segmented n-implant
- At nominal threshold (178 e) for the segmented n-implant: ~ 5.8 ns (telescope resolution unfolded)
- Laboratory measurements show that the time resolution is limited by the front-end



Before time-walk correction



After time-walk correction





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

- Complex sensor structures require advanced simulation techniques
- Transient Monte Carlo (e.g. Allpix Squared or Garfield++) is combined with electrostatic 3D TCAD simulations

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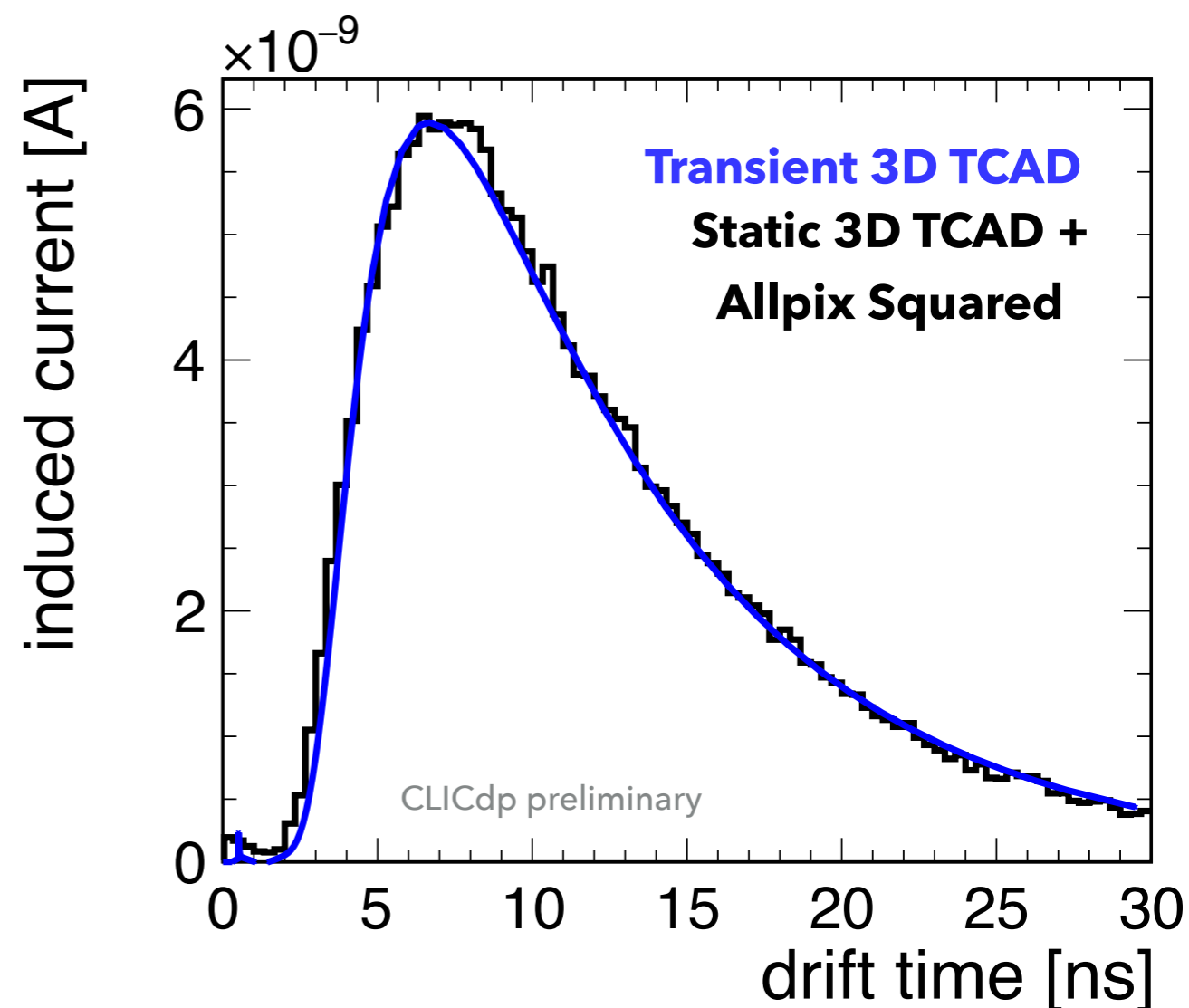
- ✓ Accurate sensor modelling
- ✓ Access to high statistics

- Allpix Squared framework: Full detector simulation from energy deposition until digitisation of signal

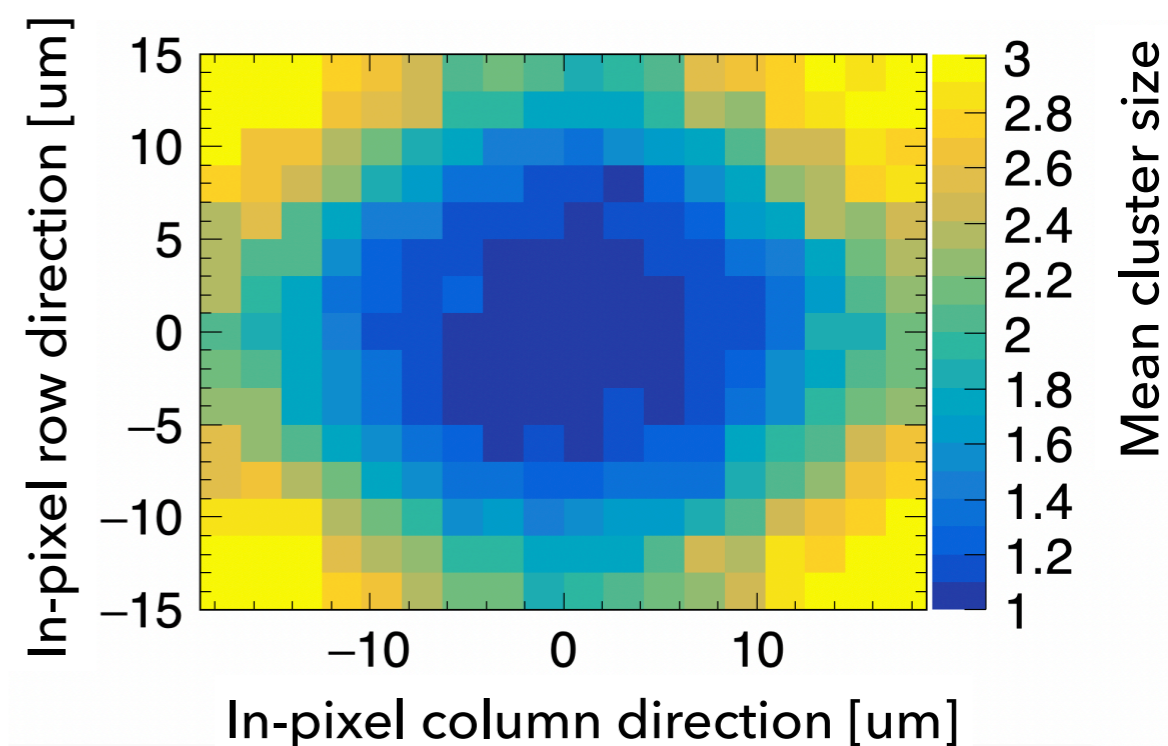
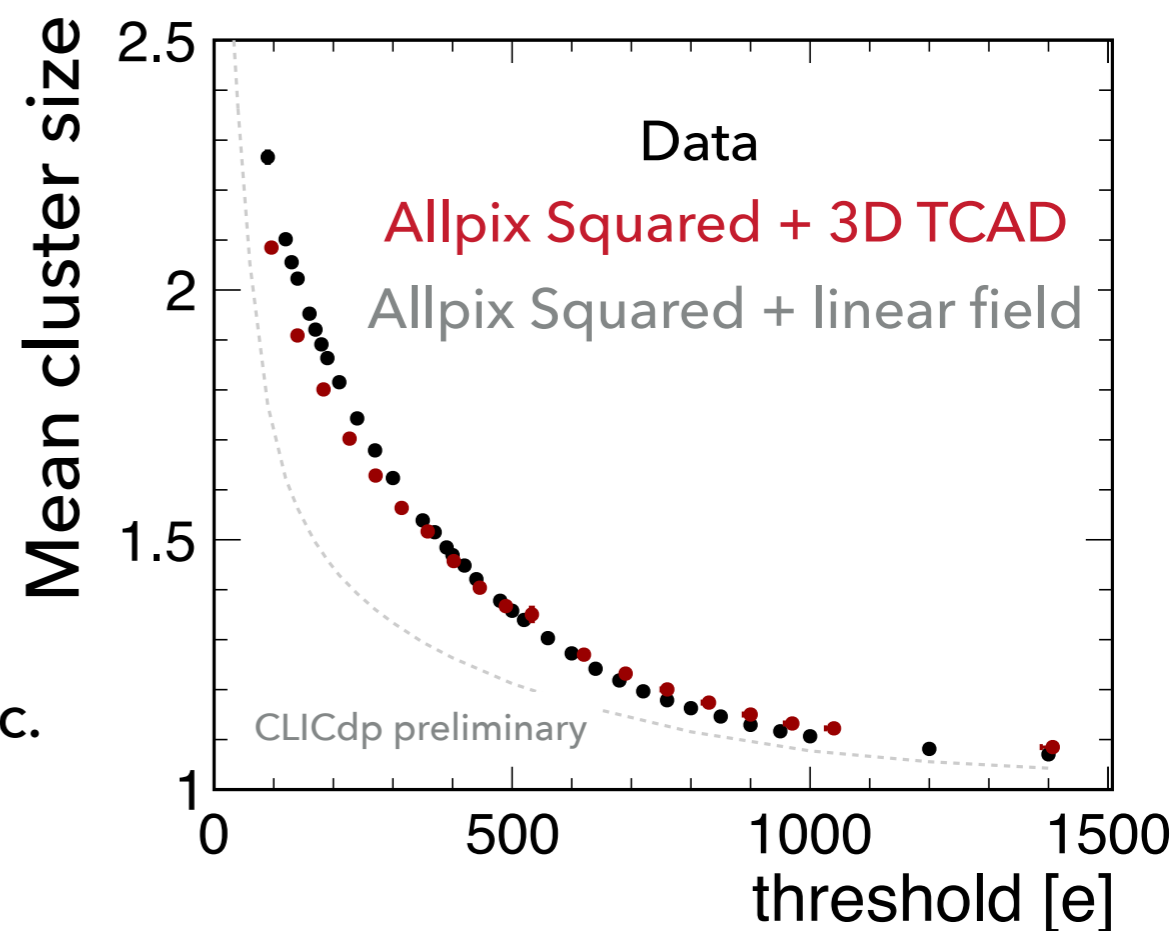
NIM A 901 (2018) 164-172

- Transient pulses between transient 3D TCAD and static 3D TCAD + Allpix Squared (APSQ) are in good agreement with each other

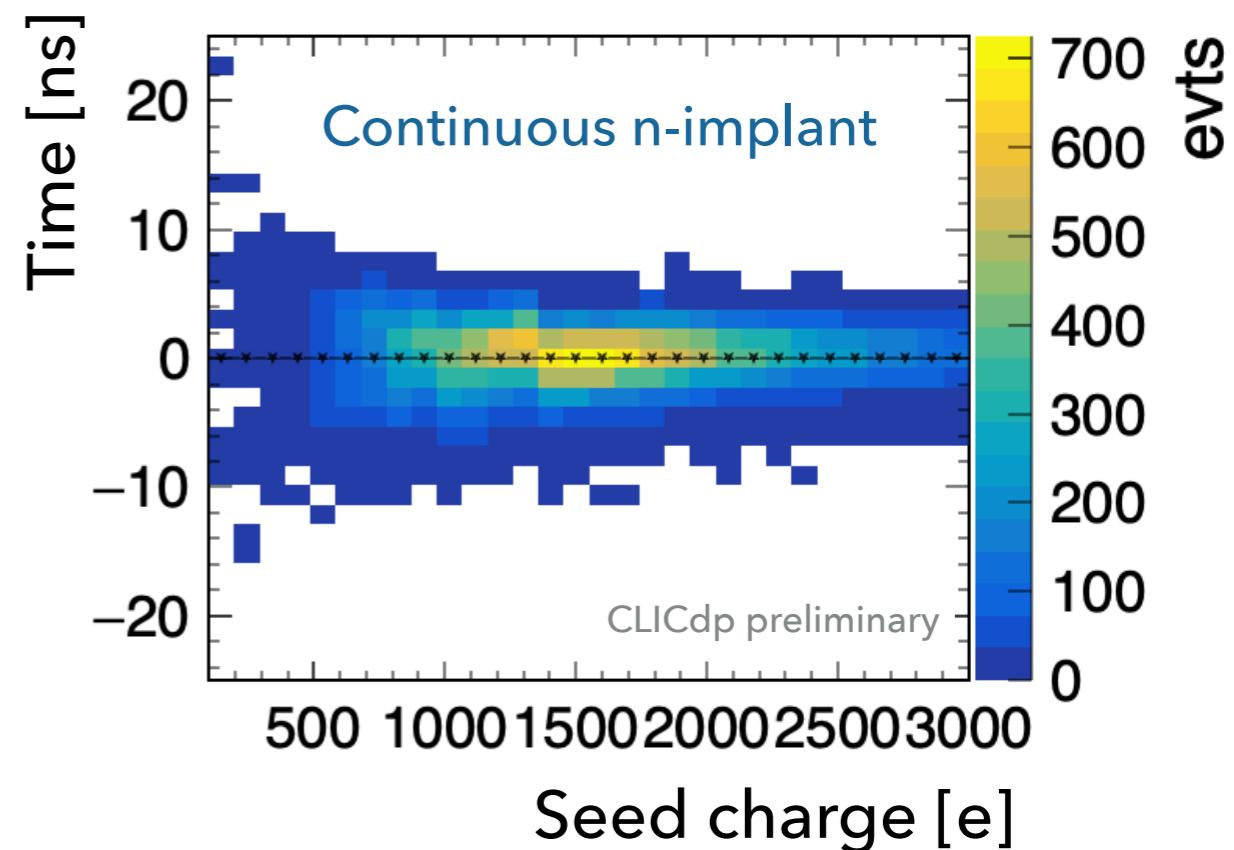
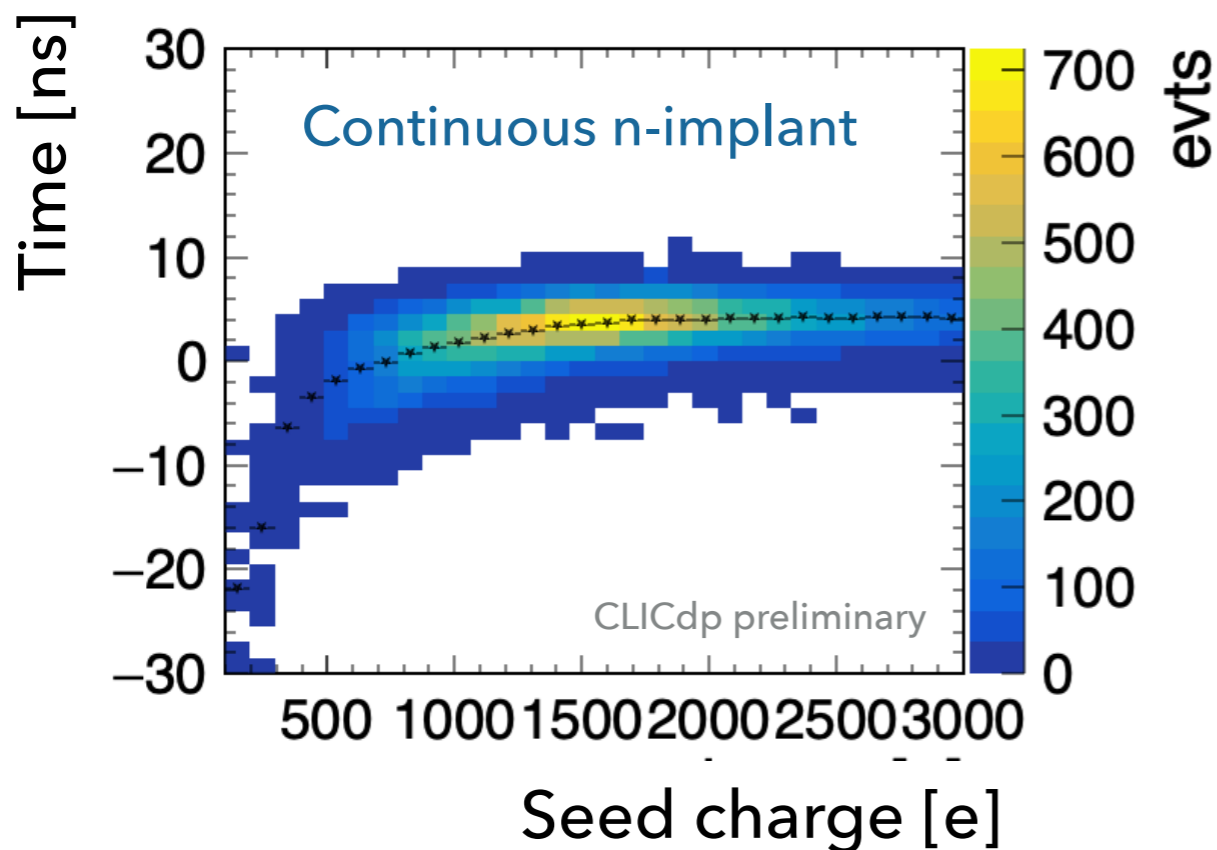
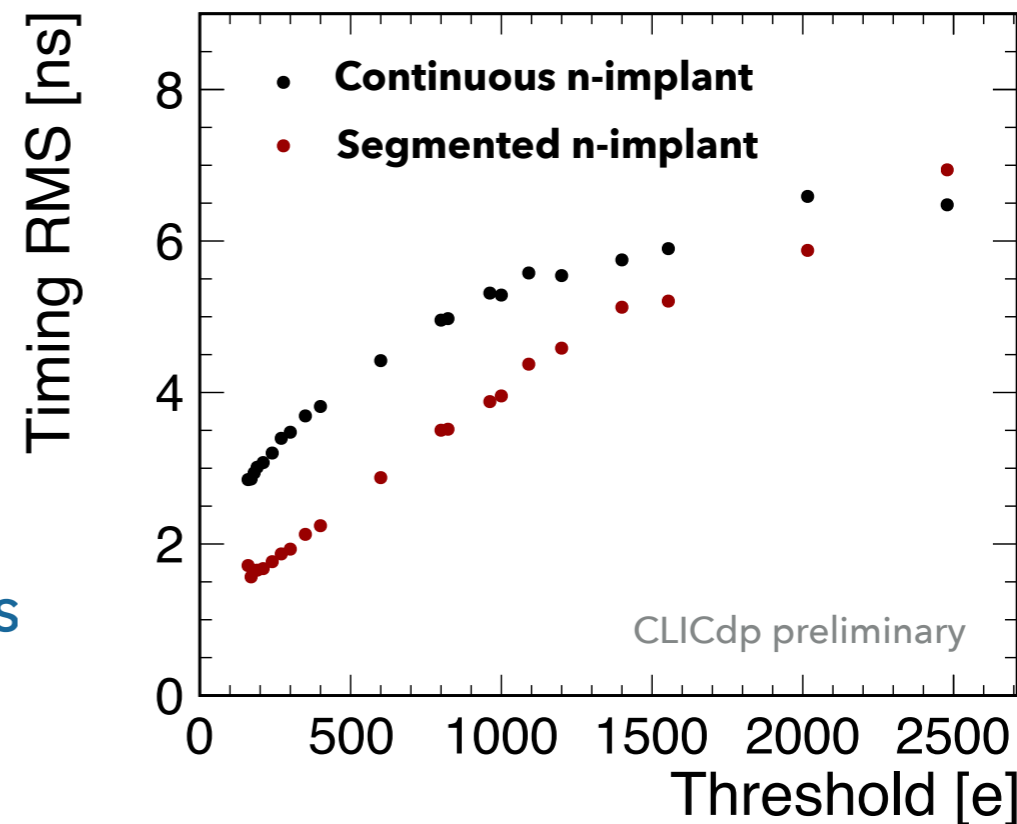
Charge injection in pixel corner



- 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



- 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



- Limited thickness of epitaxial layer ($\sim 30 \mu\text{m}$)
- Thickness of Czochralski samples : $100 \mu\text{m}$

➔ **High-resistivity Czochralski wafer**

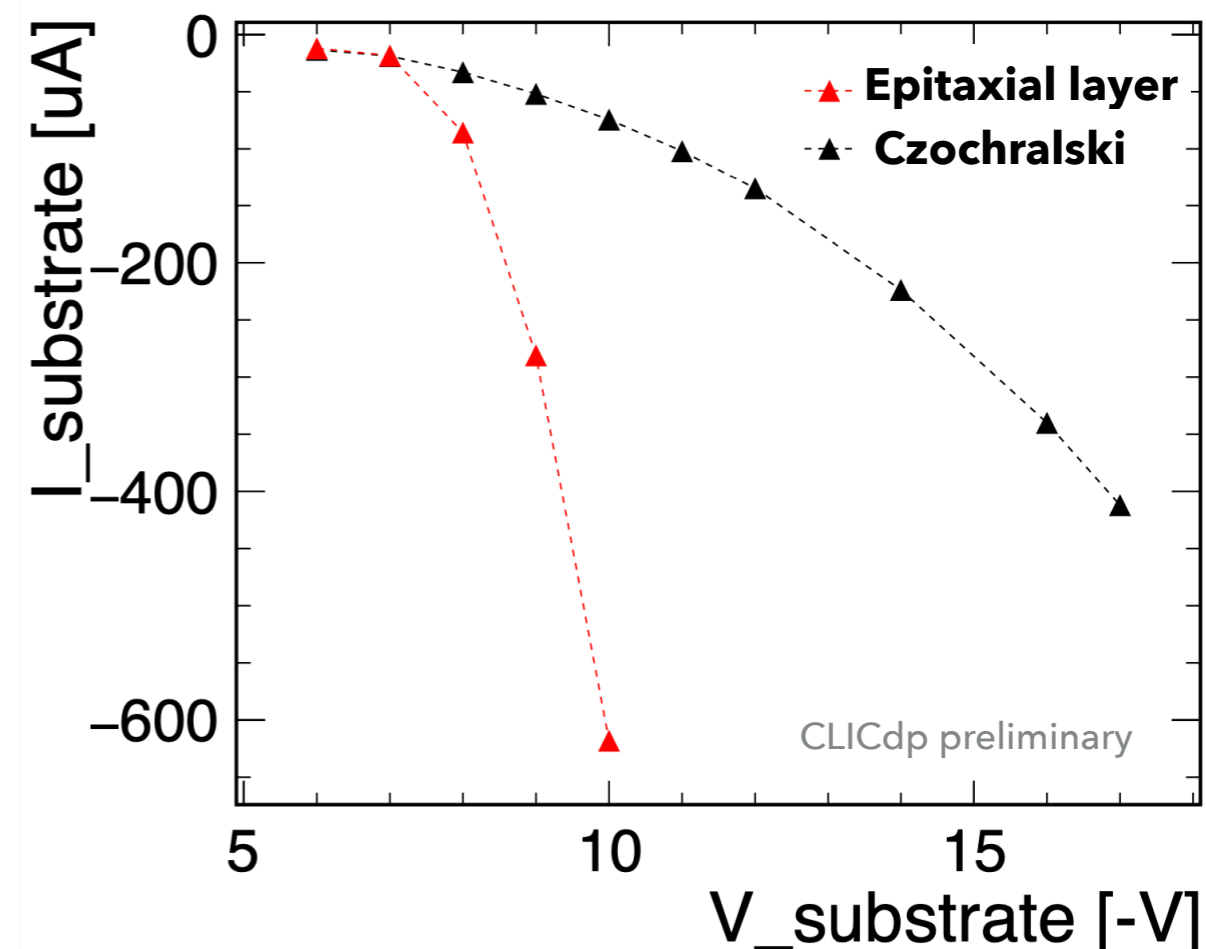
(> $800 \Omega\text{cm}$) material allows for higher substrate voltages and a larger depleted/active volume

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

Segmented n-implant

Bias voltage p-well: -6V



- 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



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

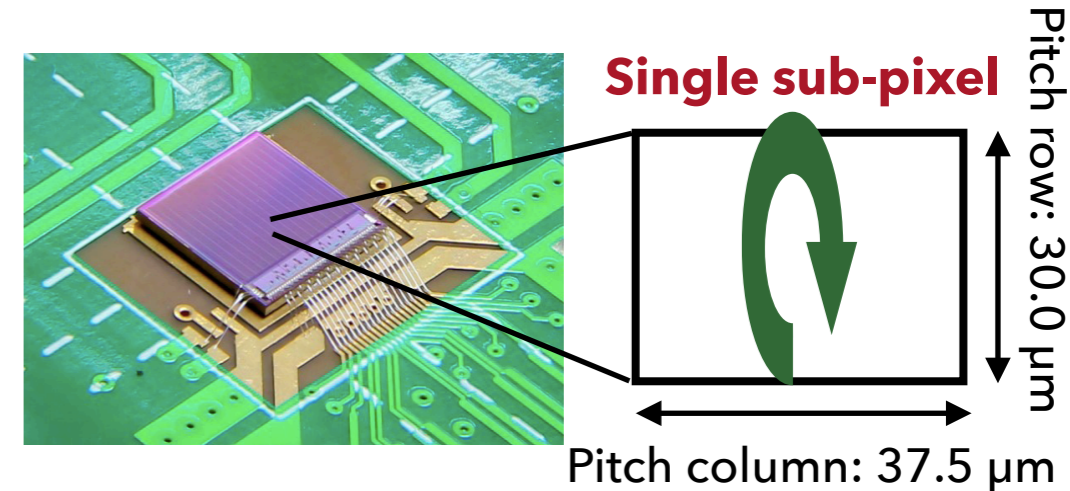
<https://cern.ch/allpix-squared/usermanual/allpix-manual.pdf>

Mailing list

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

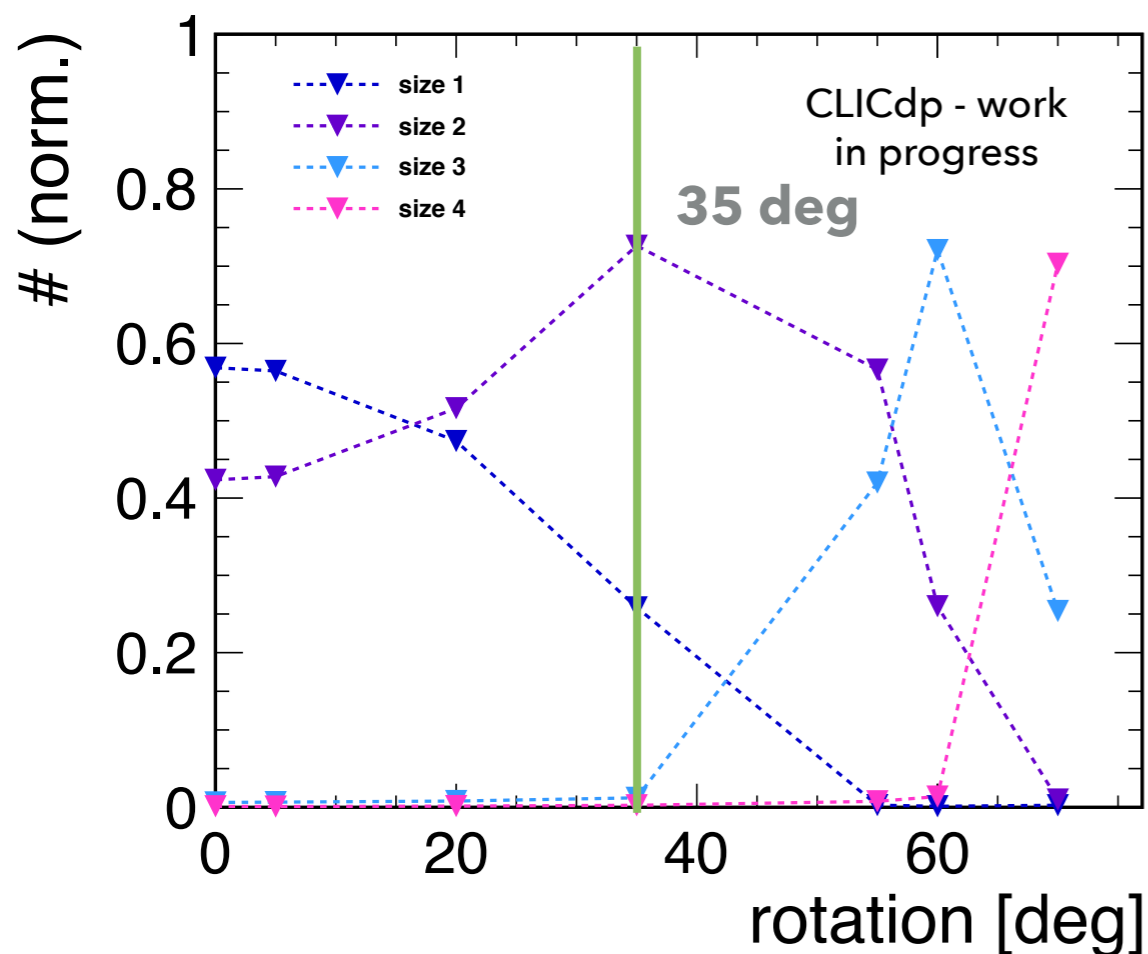
Inclined particle tracks

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

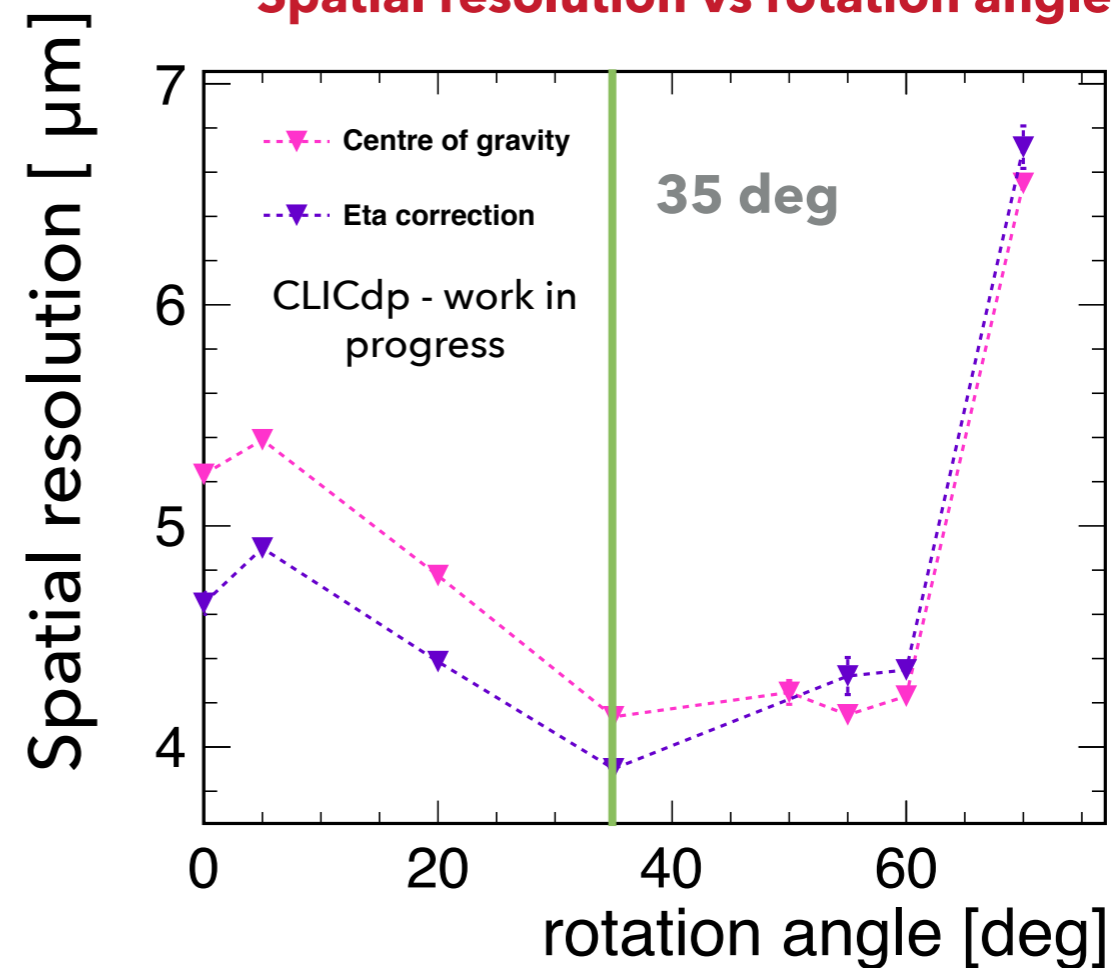


Cluster position reconstruction is still work in progress

Cluster sizes vs rotation angle

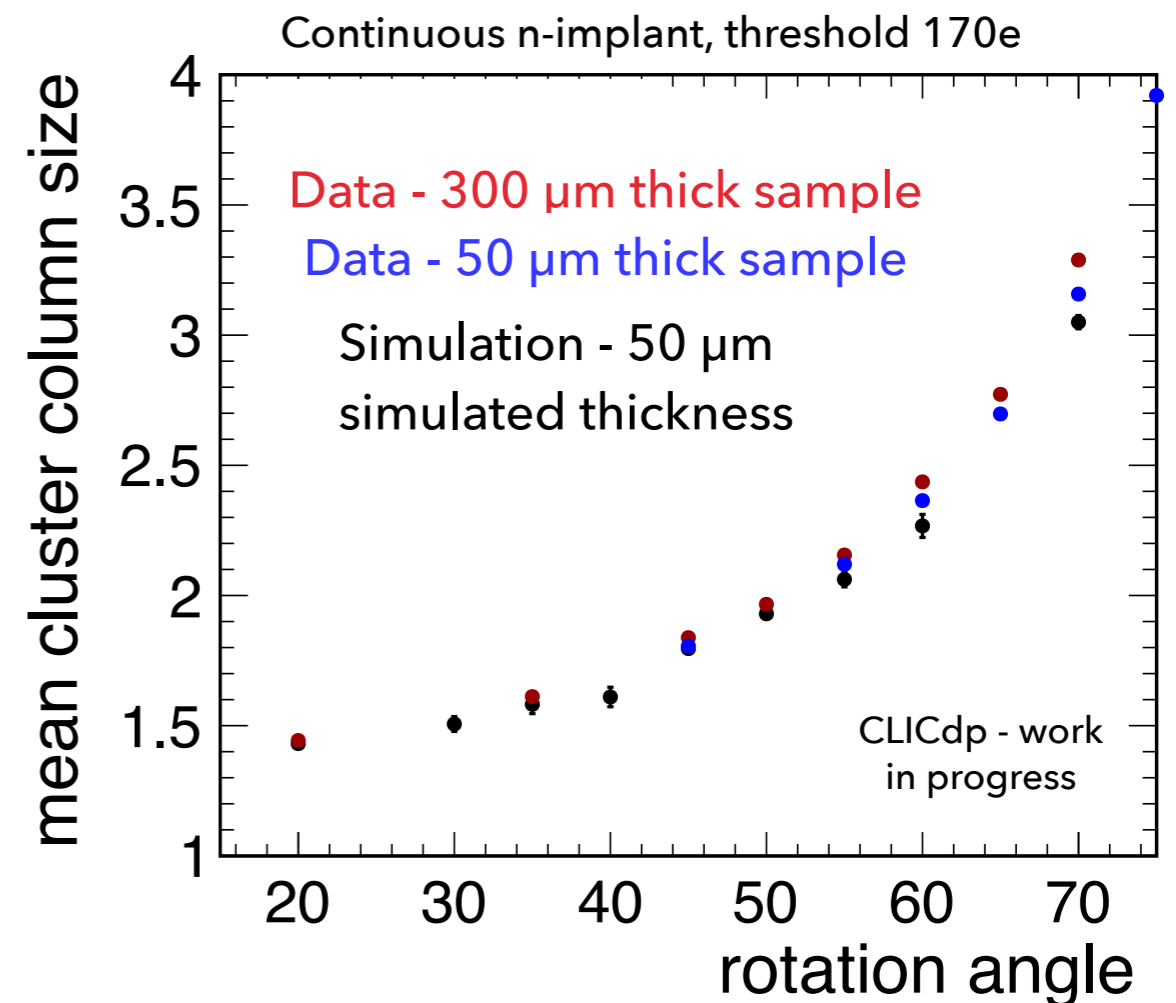
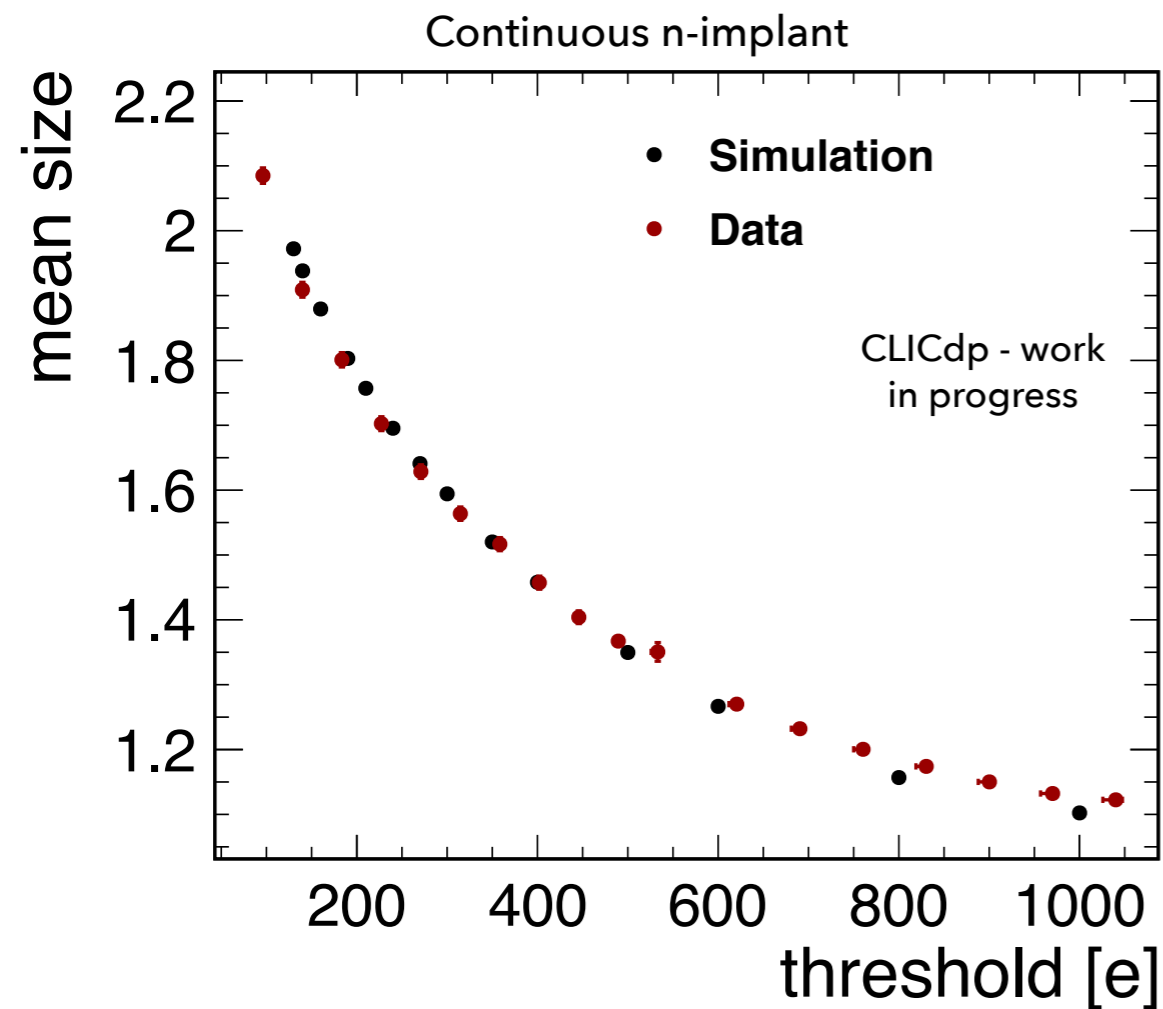


Spatial resolution vs rotation angle

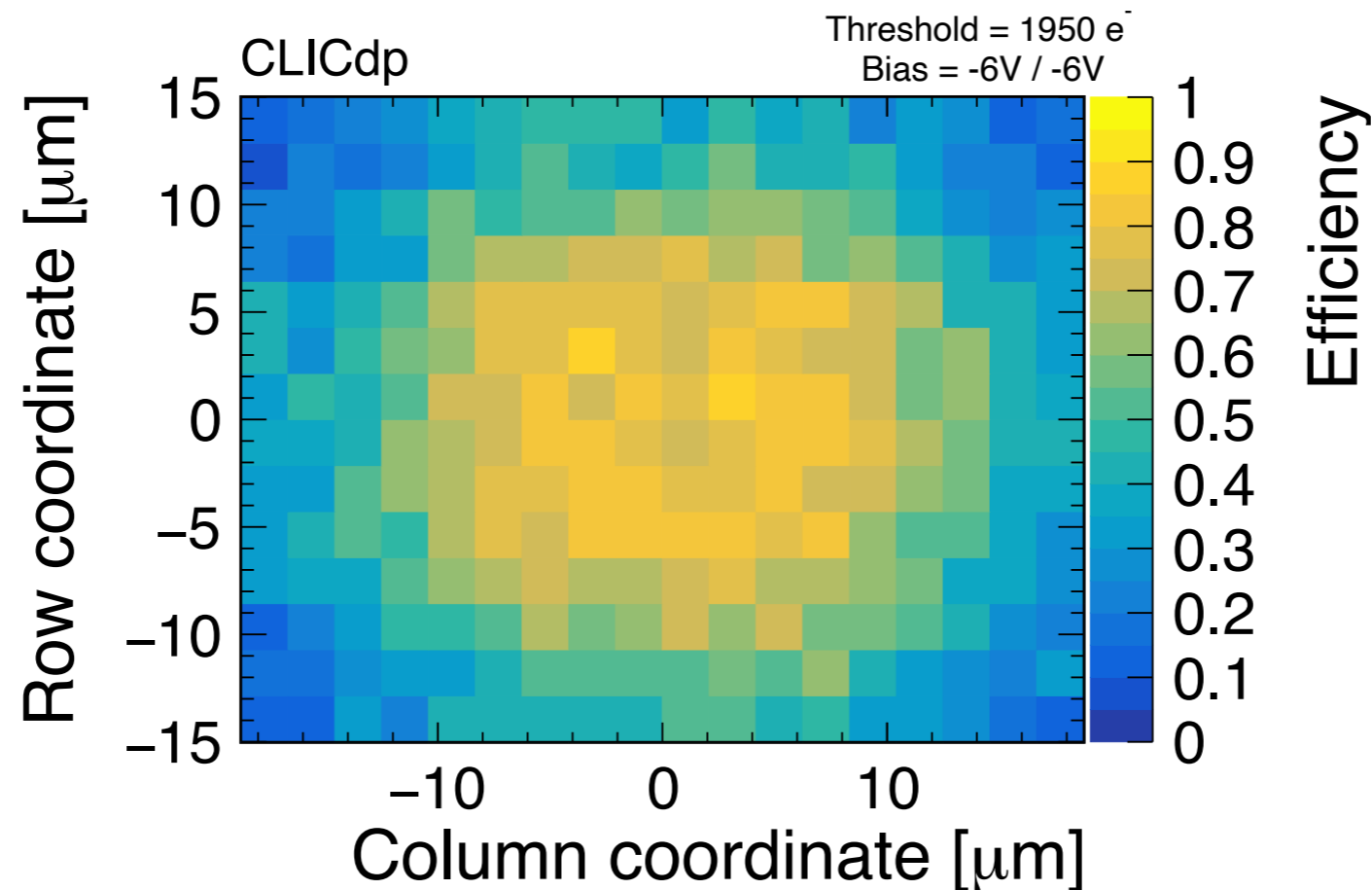


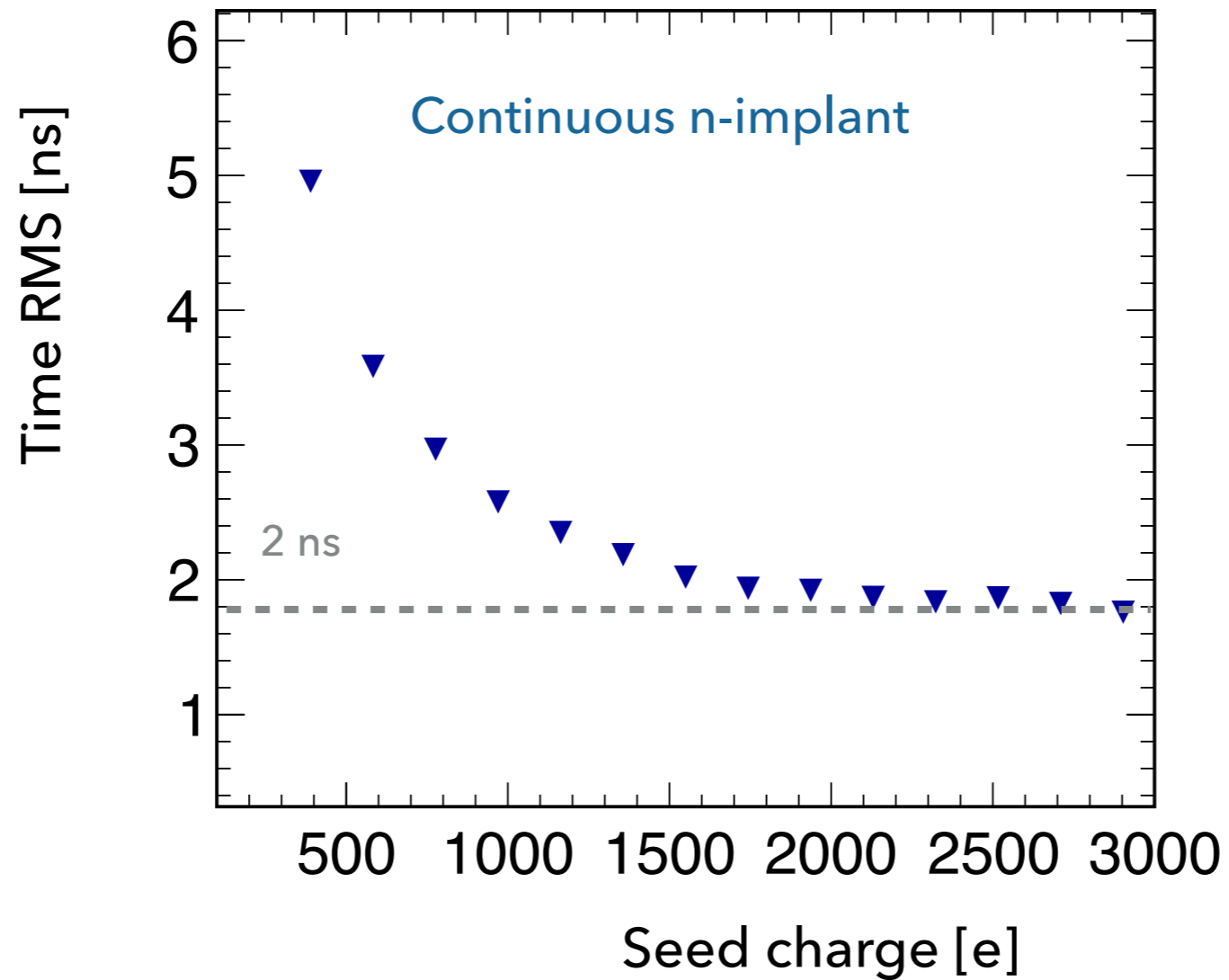
- Cluster size is very sensitive to differences in electric field, charge carrier lifetime, etc.
- **Uncertainties related to the doping profiles** are currently investigated
- For high rotation angles, simulation gets **more sensitive to charge carrier lifetime, mobility model, electric field, ...**

➔ **High accuracy of sensor modelling is needed**



- 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





FUTURE TRACKING DETECTORS FOR HIGH-ENERGY PHYSICS (HEP)

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

Exp.	LHC	HL-LHC	SPS	FCC-hh	FCC-ee	CLIC 3 TeV
Parameter						
Fluence [$n_{eq}/cm^2/y$]	$N \times 10^{15}$	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	$\sim 50 \times 50$	$\sim 50 \times 50$	25x50	25x25	$< \sim 25 \times 25$
BC spacing [ns]	25	25	$>10^9$	25	20-3400	0.5
Hit time resolution [ns]	$< \sim 25 - 1k^*)$	$0.2^{**)} - 1k^*)$	0.04	$\sim 10^{-2}$	$\sim 1k^{***)}$	~ 5

*) ALICE requirement **) LHCb requirement ***) At Z-pole running ****) max. output rate for LHCb/high intensity flavour experiments: 300-400 Gbit/s/cm²

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