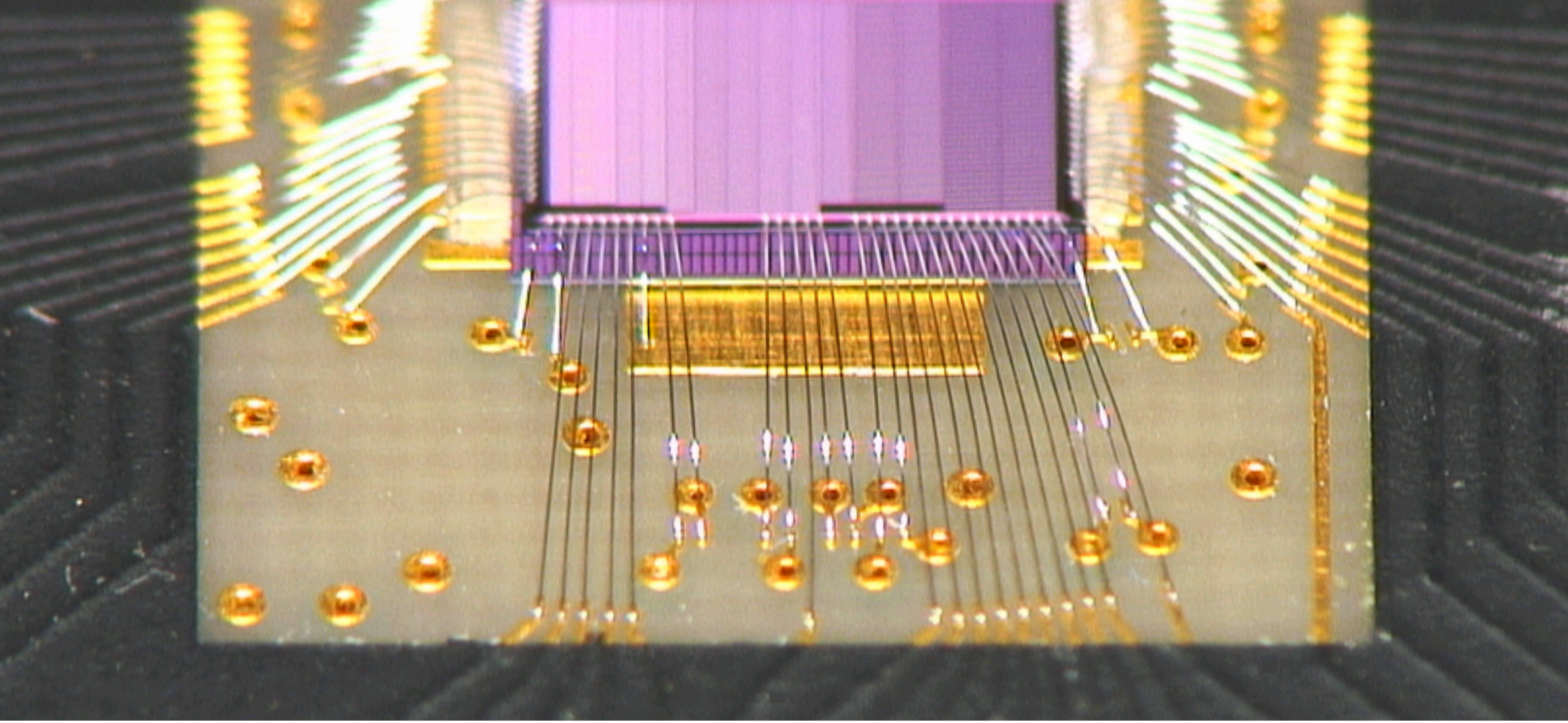


Integrated CMOS sensor technologies for the CLIC tracker

Magdalena Munker (CERN, University of Bonn)
On behalf of the CLICdp collaboration

International Conference on Technology and Instrumentation in Particle Physics 2017, Beijing

Bundesministerium für Bildung und Forschung

universitätbonn
Rheinische Friedrich-Wilhelms-Universität Bonn

CERN

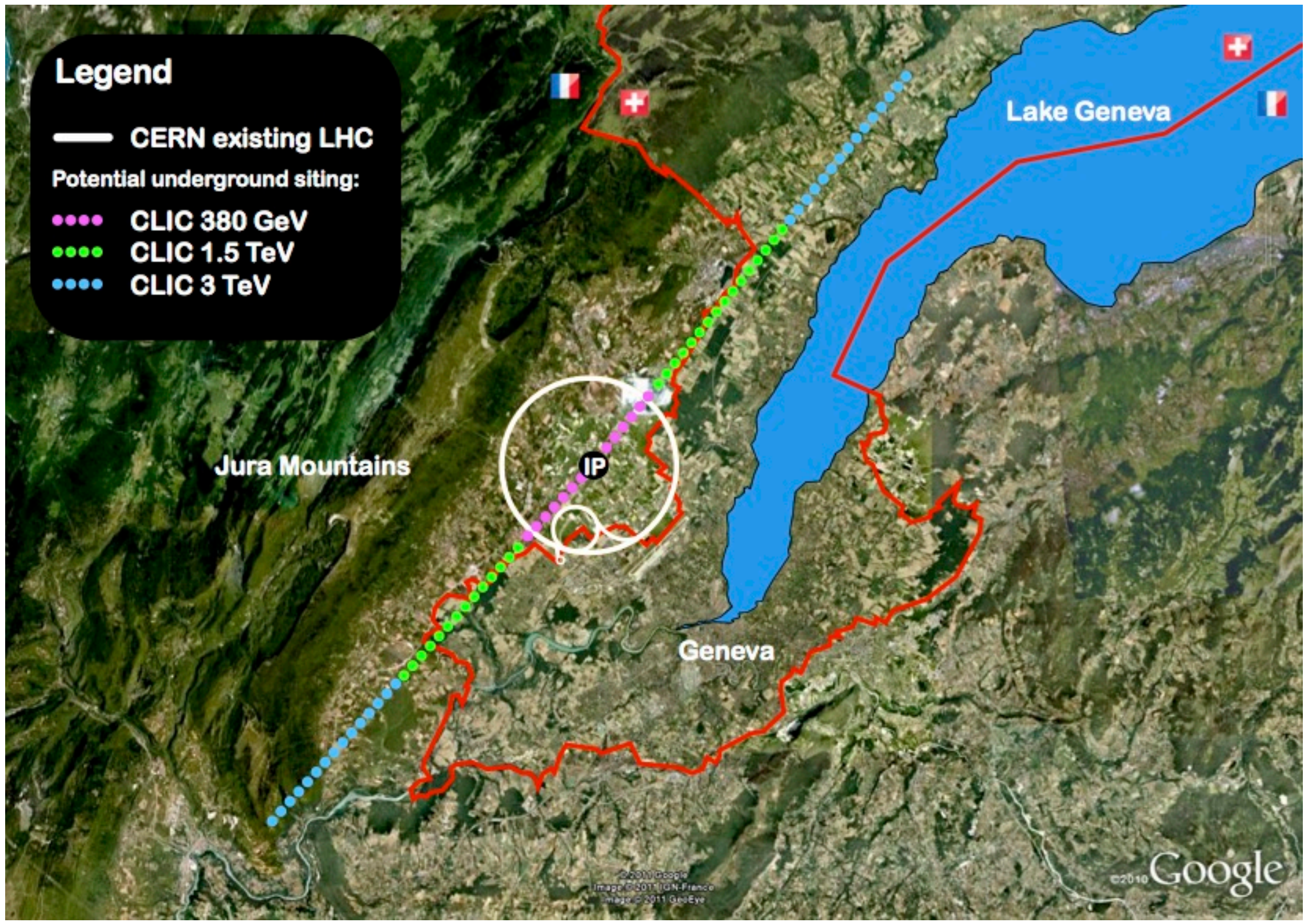
clic

Work sponsored by the Wolfgang Gentner Programme of the Federal Ministry of Education and Research

CLIC - the Compact Linear Collider

Possible multi-TeV linear e^+e^- collider in the post LHC phase at CERN:

CLIC layout:



3 TeV stage:

Bunch separation [ns]	0.5
# bunches / train	312
Train duration [ns]	156
Repetition rate [Hz]	50
Bunch size σ_x / σ_y [nm]	~ 45 / 1
σ_z [µm]	44

- High centre of mass energies up to 3 TeV
- Dense bunches to achieve high luminosity

➔ High background rates ➔ time-stamping of ~ 10 ns needed to reject background hits

- Note: significantly lower radiation levels of ~10^{11} neq/cm^2/y compared to hadron colliders

See talk by E. Sicking:
"Detector challenges for future high-energy e^+e^- colliders"

Integrated technologies for the CLIC tracker

<u>Physics needs & environment:</u>

Momentum resolution
$\sigma_{PT} / p_T^2 = 2 \cdot 10^{-5}$ / GeV

Suppression of high beam beam background occupancies

<u>Tracker requirements:</u>

7 µm single point resolution

~1% radiation length per layer

10 ns time stamping

<u>Technology choice:</u>

1. Highly granular / fine pitch
2. Thin / low material budget
3. Fast signal

See talk by A. Nurnberg:
"A vertex and tracking detector system for CLIC"

Needed:
Multi purpose technology

<u>Challenge to meet requirements simultaneously:</u>

Benefit from integrated CMOS technologies:

- No separate ASIC material: → Lower material budget
- No sensor-ASIC interconnect: → Large scale production ($100m^2$ CLIC tracker) → Finer pitch

Crucial for integrated CMOS technologies:

- Full depletion for fast and fully efficient operation

→ *Achievable with CMOS circuitry on High Resistivity HR epitaxial layer (epi)?*

The Investigator Chip (W. Snoeys, J. W. van Hoorne et. al.)

HR-CMOS process:

180 nm High Resistivity (HR) CMOS process, 15-40 µm thick epitaxial layer (1-8 kΩcm):

- Developed as part of ALPIDE development for ALICE ITS upgrade
- Fully monolithic ALPIDE chip developed in this process

Test-chip:

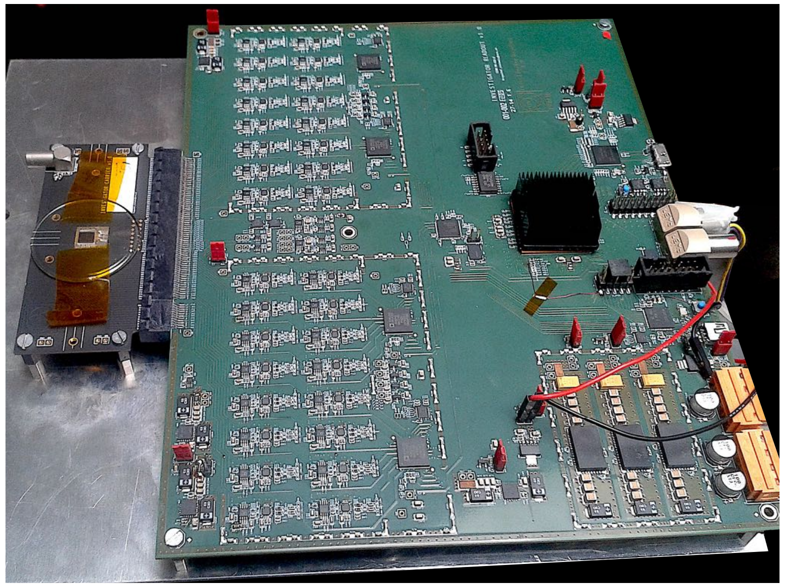
Various mini-matrices with different pixel layouts:

- Optimisation of pixel layout:
  - Minimising size of collection diode
  - → Minimise capacitance (~ fF)
  - Large signal/noise → fast timing (~ ns)

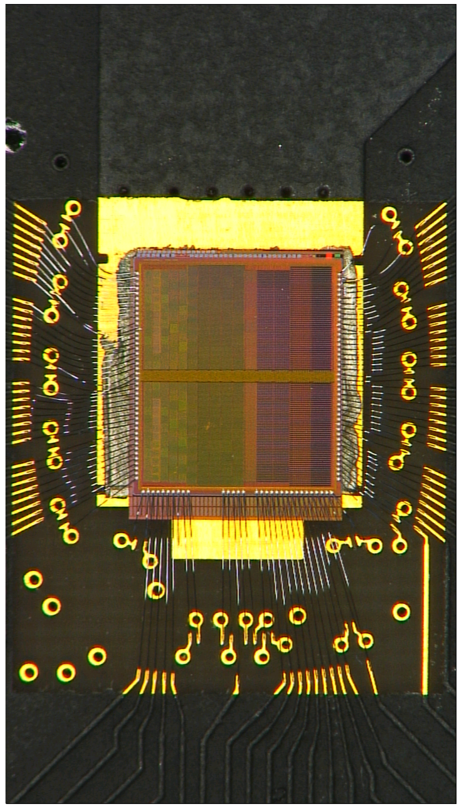
External readout board (*designed by K. M. Sielewicz*):

- 64 ADCs to read out full analogue waveform of 8 x 8 active pixel matrix
- 65 MHz sampling clock limits achievable timing resolution

Investigator & readout board:



Investigator:

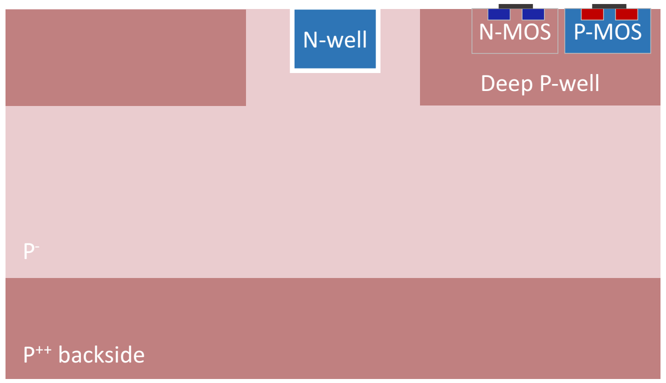


Two different submissions:

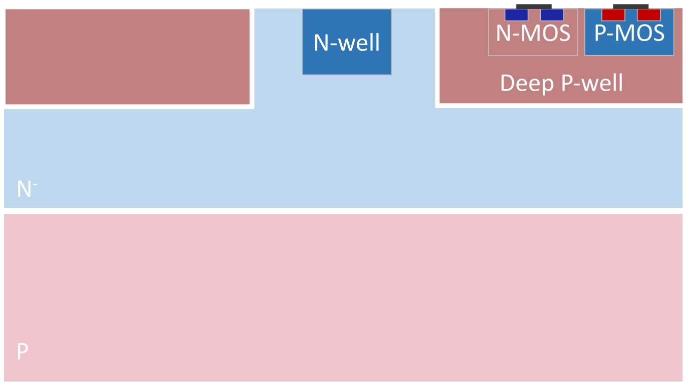
Changes in modified process to achieve full depletion:

- Better timing performance
- Radiation hardness

Schematic of process cross section of standard process:



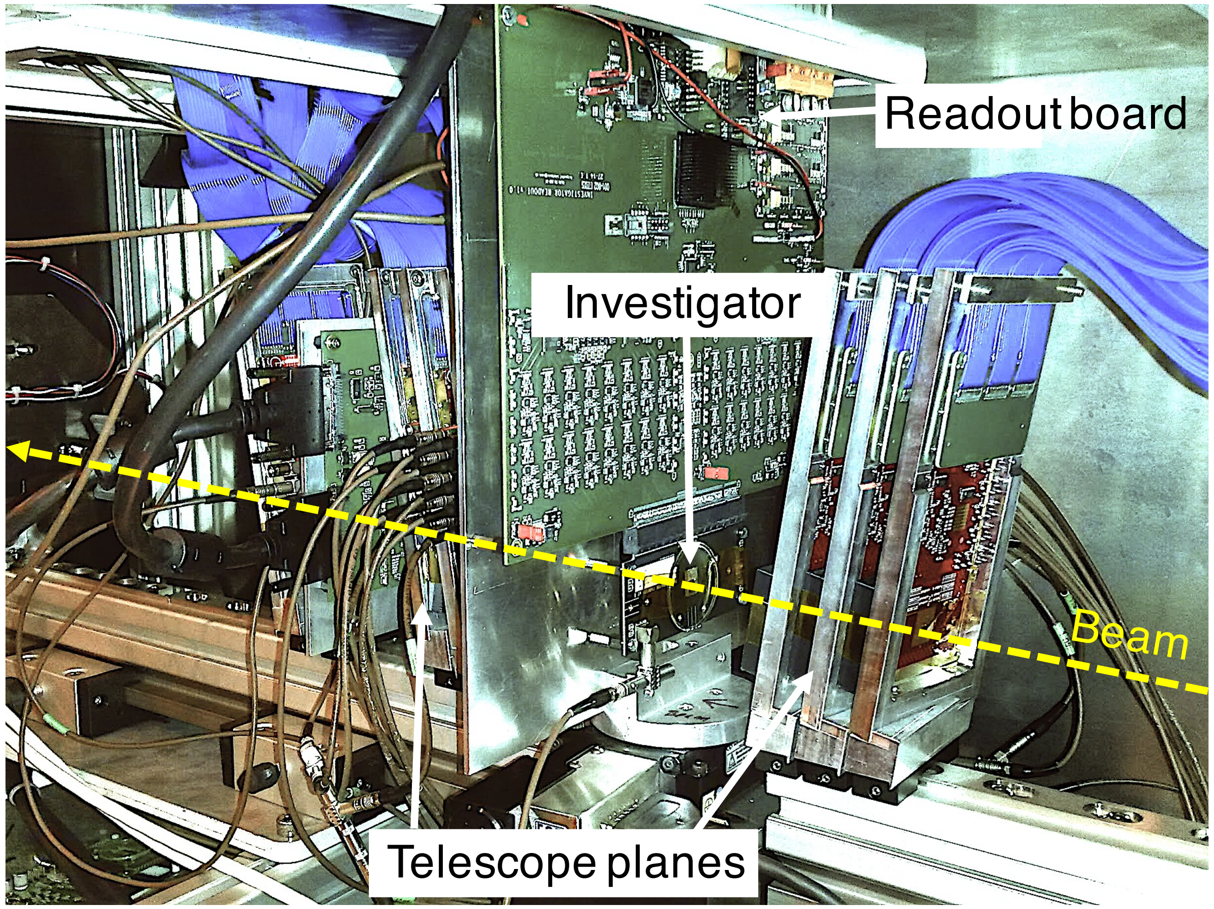
Schematic of process cross section of modified process:



Test-beam studies

Test-beam setup:

CLICdp Timepix3 telescope at SPS beam line:



- Timepix3 telescope:

  Excellent timing resolution ~ 1 ns:

→ Benefit for studies of fast Investigator timing

  Excellent track prediction resolution ~ 2 μm:

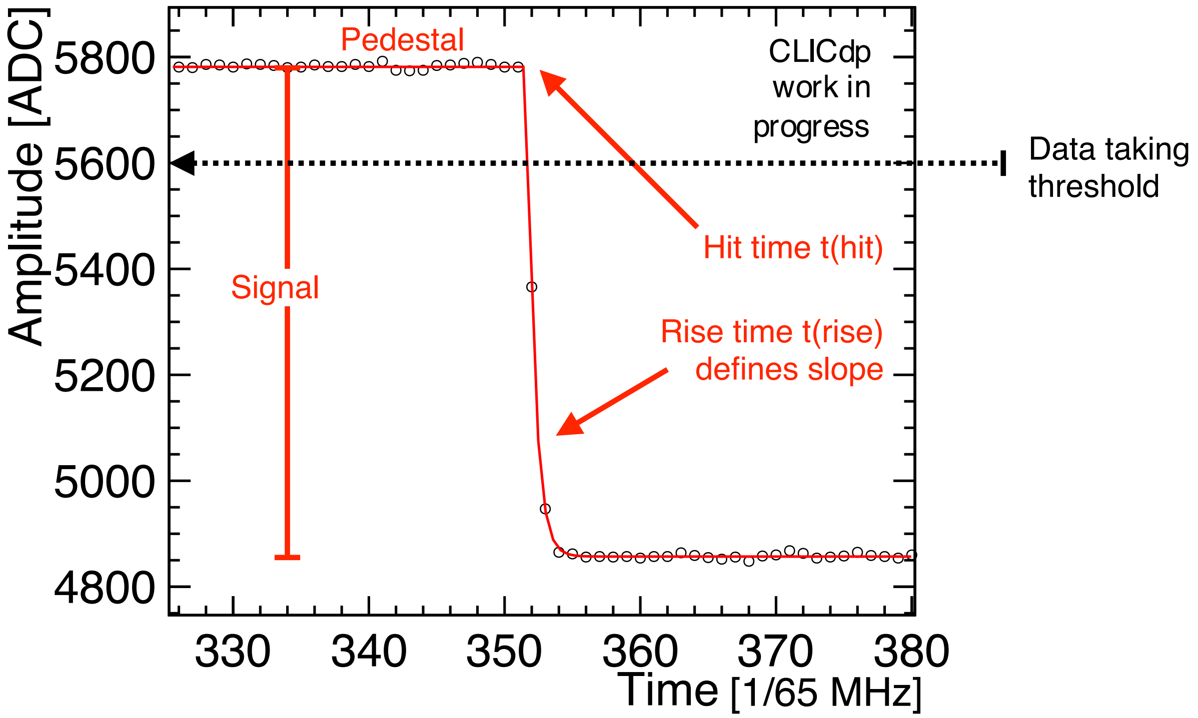
→ Benefit for sub-pixel performance studies for small pixel sizes of Investigator

Investigator data-taking & reconstruction:

If at least one pixel crosses a seed threshold:

- Full analogue waveform of all 8 x 8 active pixels read out
- Timestamp send to telescope planes for offline synchronisation

Example of single pixel waveform:



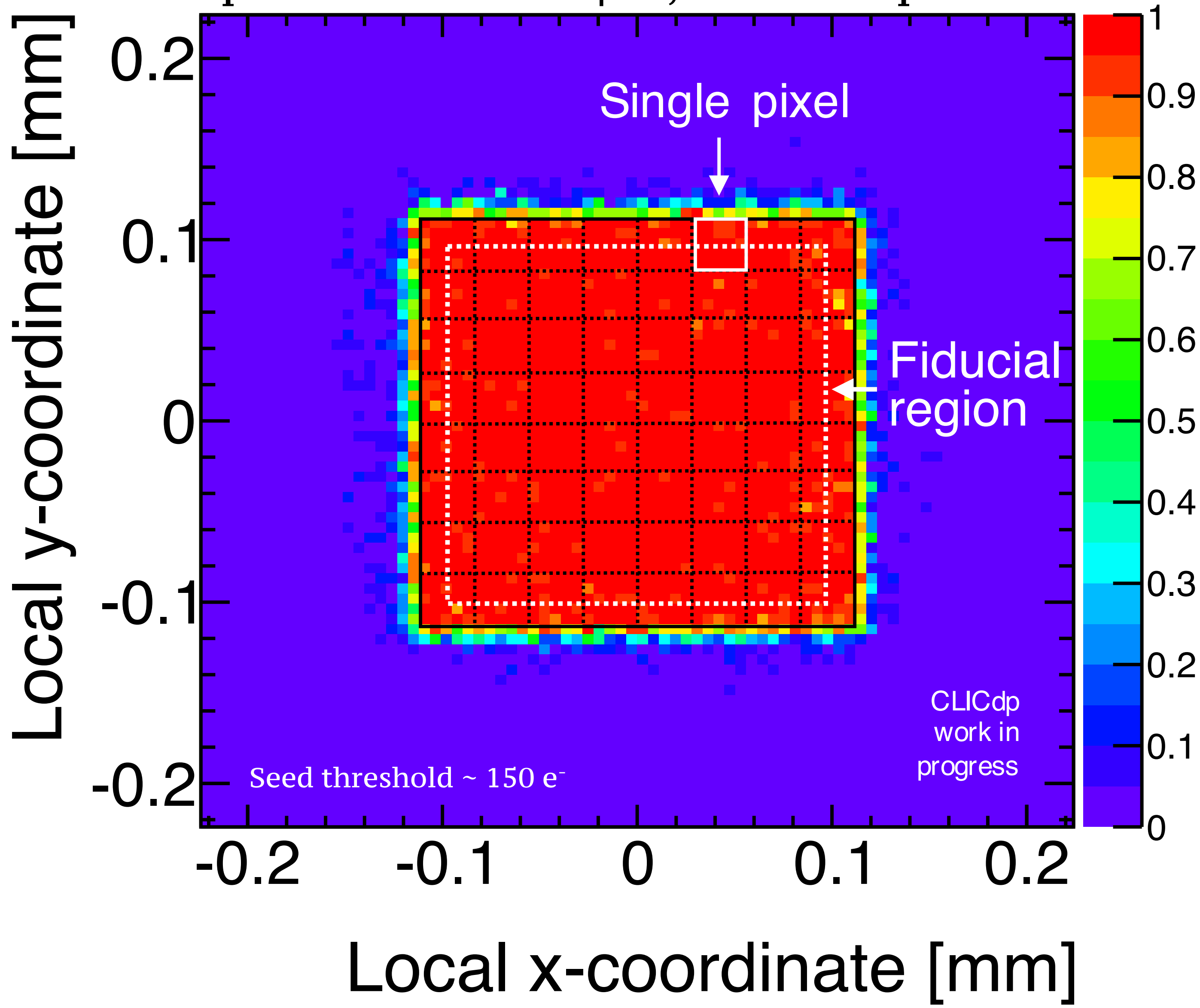
- Waveform reconstructed by exponential fit:

$$f(t) = \begin{cases} \text{Pedestal} & t \leq t(\text{hit}) \\ \text{Pedestal} + \text{Signal} * (e^{[t-t(\text{hit})]/t(\text{rise})} - 1) & t > t(\text{hit}) \end{cases}$$

Efficiency over pixel matrix / modified process

Efficiency over pixel matrix:

Pitch = 28 µm, bias voltage = 6 V,
epi thickness = 25 µm, modified process:



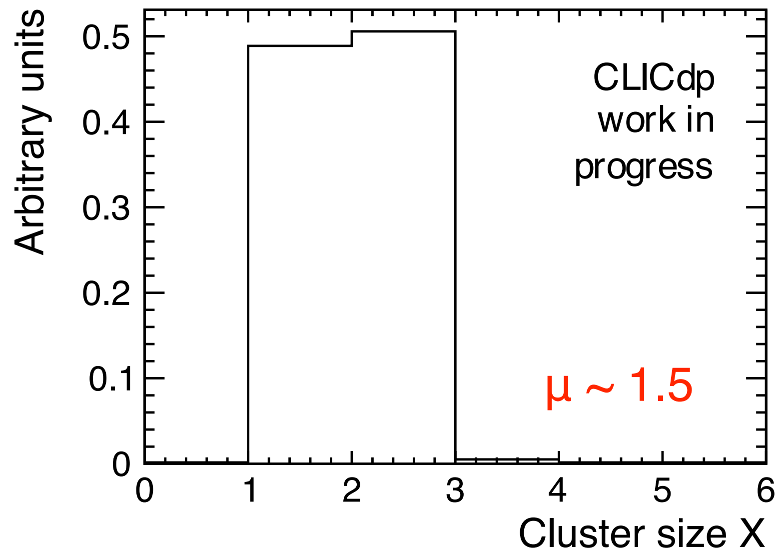
- Analysis of efficiency of standard process currently ongoing

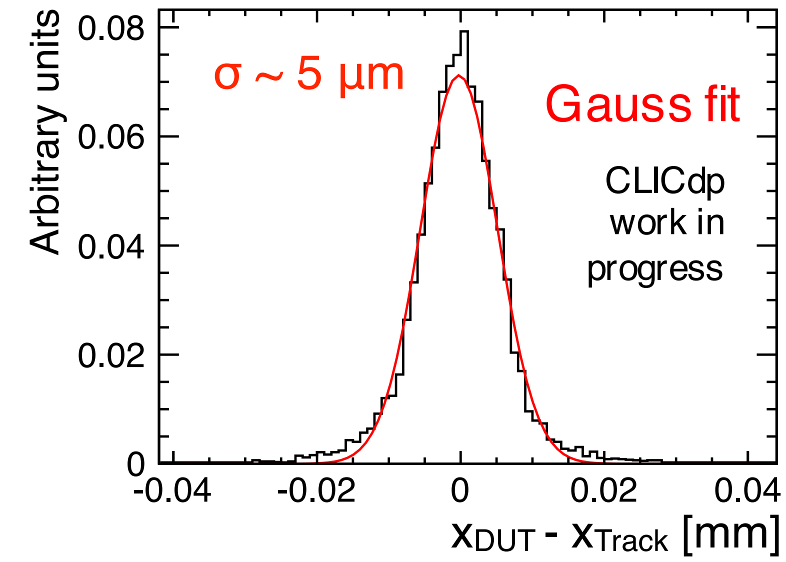
→ *Efficiency > 99 % over fiducial region* *(masking half of edge pixels to account for limited track precision)*

Cluster size & resolution / standard & modified process

Standard process:

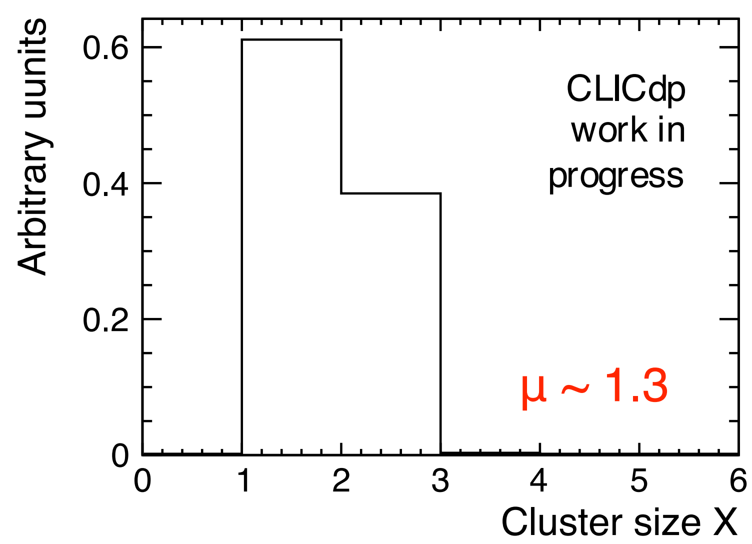
- Pitch = 28 μm
- Bias voltage = 6 V
- Epi thickness = 18 μm
- Neighbour threshold ~ 70 e^-

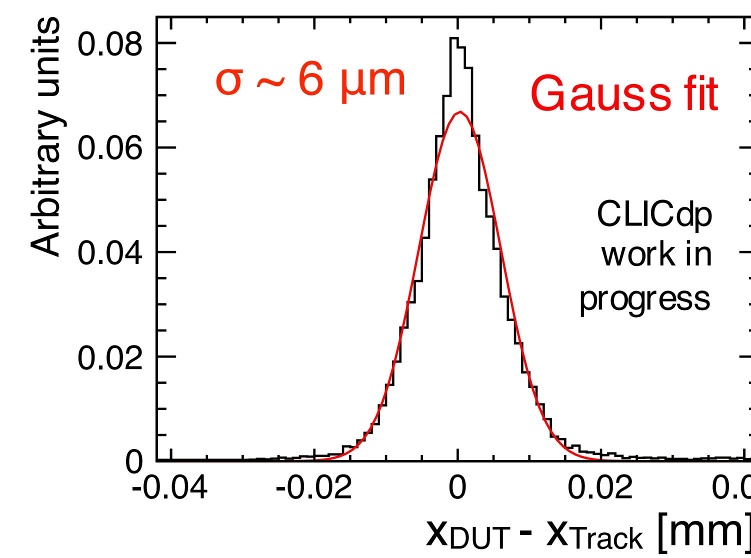




Modified process:

- Pitch = 28 μm
- Bias voltage = 6 V
- Epi thickness = 25 μm
- Neighbour threshold = 50 e^-





Despite thinner epi and larger threshold for standard process:

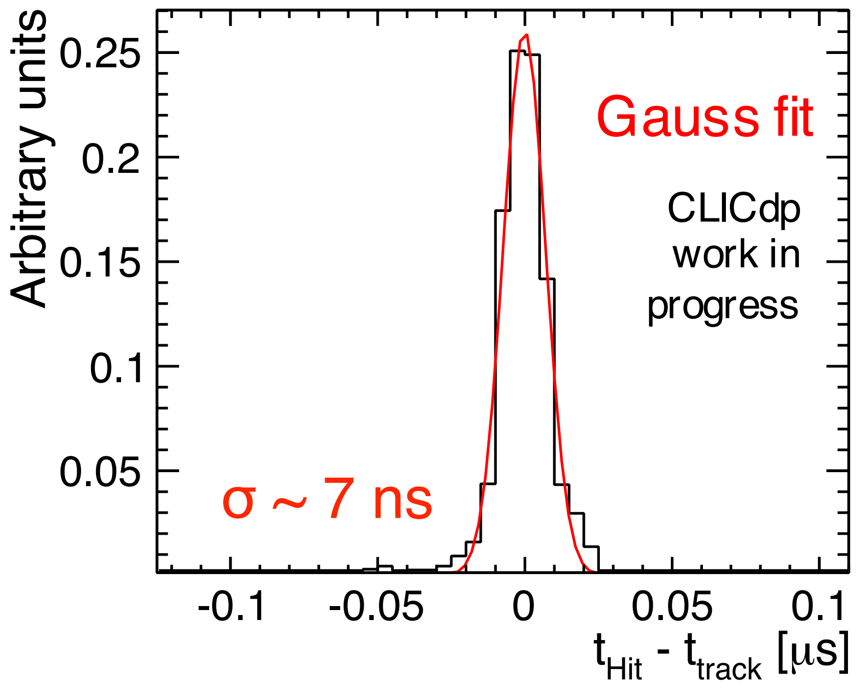
- Larger cluster size and better resolution, as expected from more diffusion

→ *Position resolution matching well requirement of 7 μm for CLIC tracker (t.b.c. with fully integrated chip).*

Timing / standard & modified process

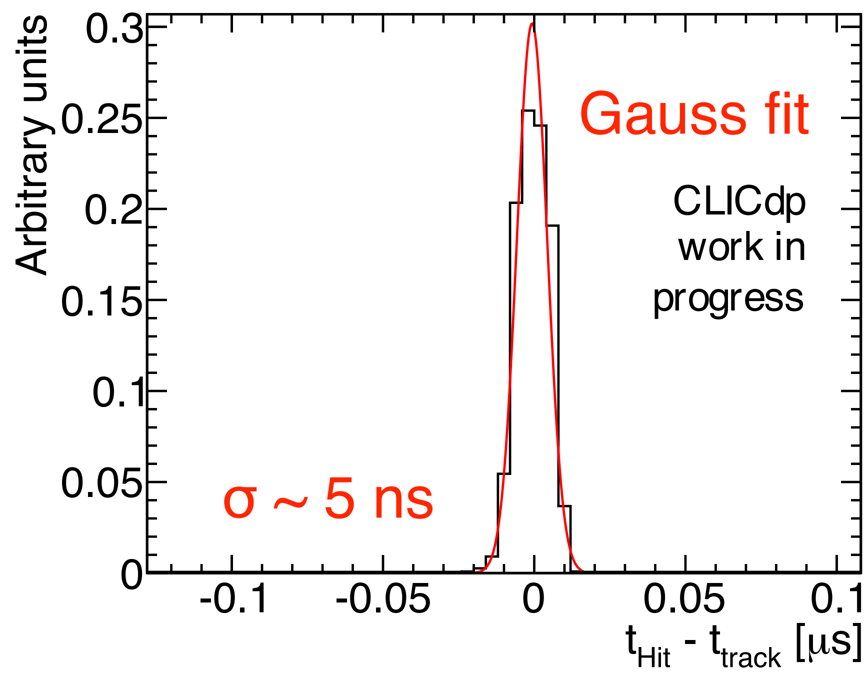
Standard process:

- Pitch = 28 µm
- Bias voltage = 6 V
- Epi thickness = 18 µm
- Neighbour threshold ~ 70 e⁻
- Seed threshold ~ 200 e⁻



Modified process:

- Pitch = 28 µm
- Bias voltage = 6 V
- Epi thickness = 25 µm
- Neighbour threshold = 50 e⁻
- Seed threshold ~ 150 e⁻

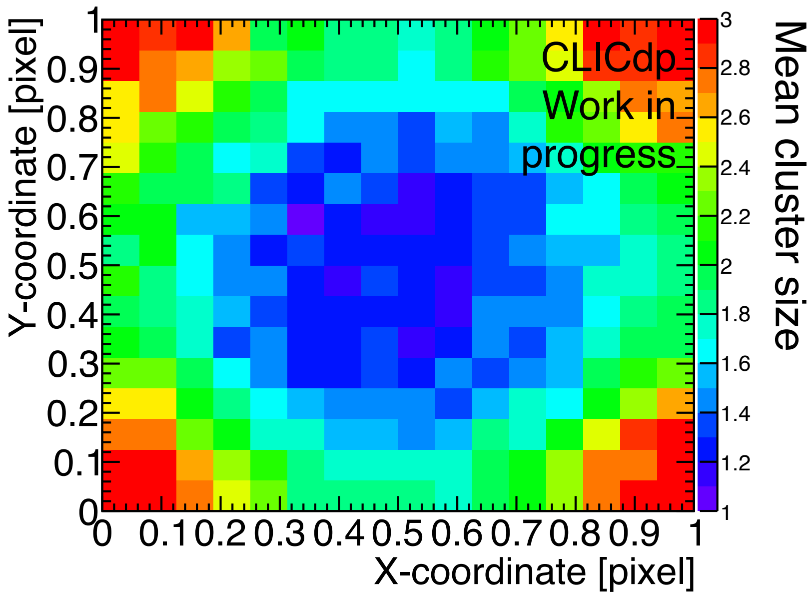


- Faster timing for modified process, as expected from full depletion
- Measured timing resolution limited by readout sampling frequency of 65 MHz

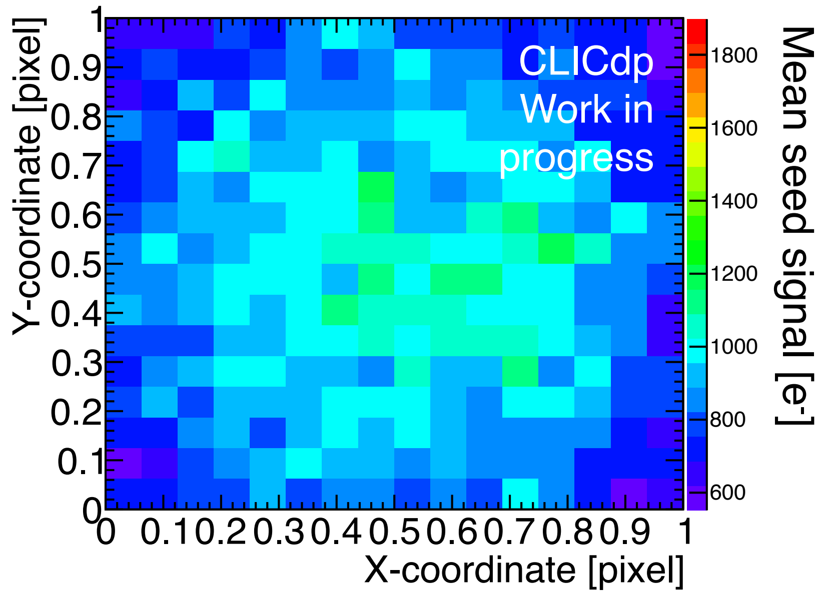
→ *Timing resolution matching well requirement of 10 ns for CLIC tracker (t.b.c. with fully integrated chip).*

Sub pixel studies / modified process

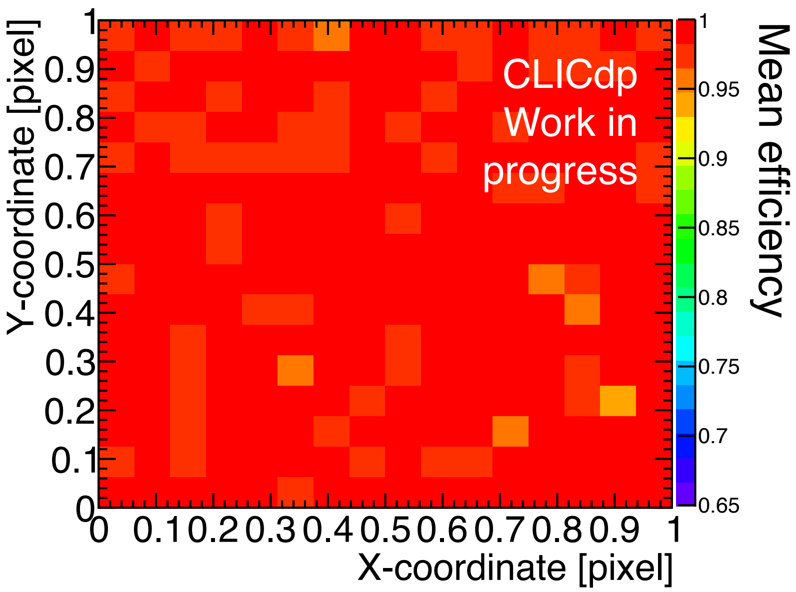
Mean cluster size in pixel cell:



Mean seed signal in pixel cell:



Mean efficiency in pixel cell:



- Results shown for modified process:

→ Pitch = 28 µm, epi thickness = 25 µm, bias voltage = 6V, neighbour threshold ~ 50 e^-

- More charge sharing in pixel edges and corners

→ Higher cluster size and Lower seed signal in pixel edges and corners

- Low seed threshold of ~ 150 e^- during data taking:

→ No significant efficiency loss in pixel corners

→ *Sub-pixel performance in qualitative agreement with expectations.*

Simulation

Simulation chain:

GEANT4 simulation:
- Energy that particle deposits while traversing the sensor.

↦

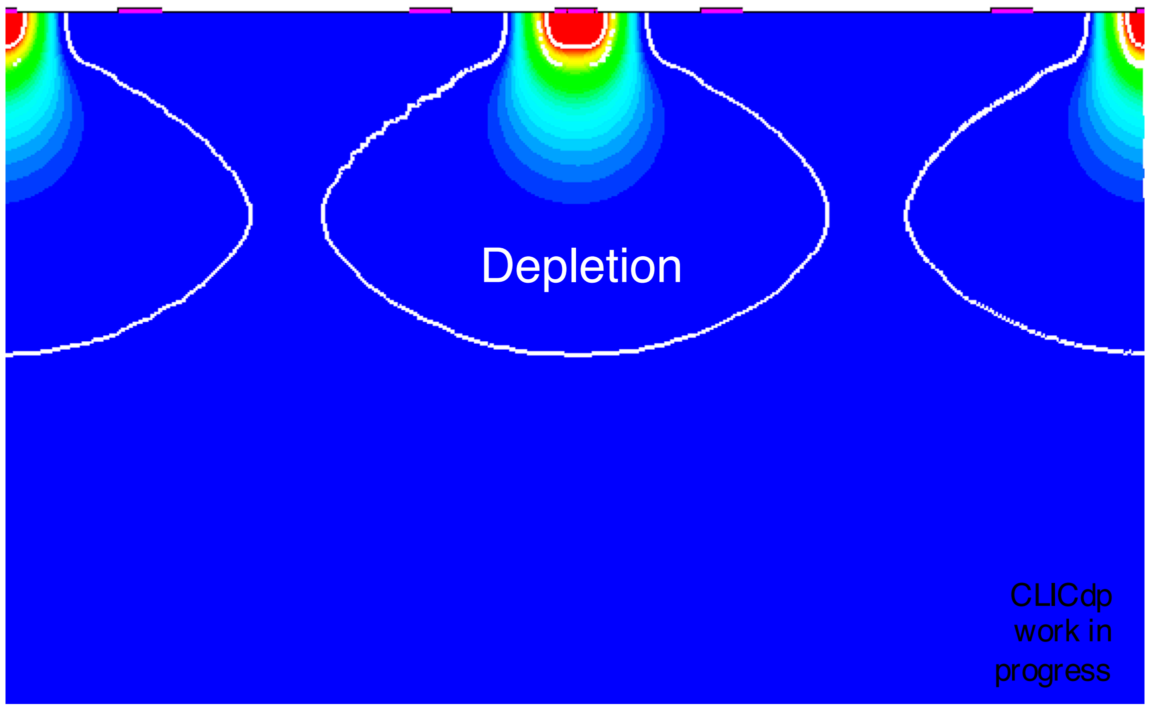
2-dimensional TCAD simulation:
- Simulate sensor geometry, doping and bias voltage application
- Transient simulation using particle with energy deposit from GEANT4

↦

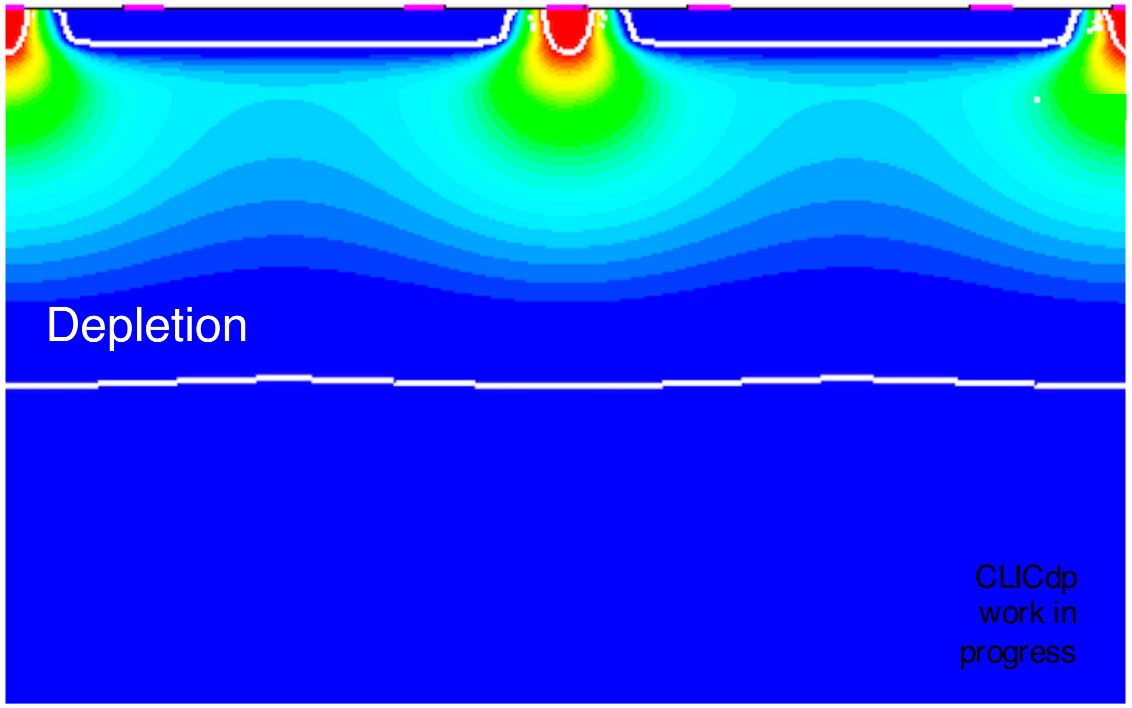
Fast parametric model:
- Energy fluctuations
- Threshold application
- Telescope resolution
- Reconstruction

TCAD simulation of standard & modified process:

Electrostatic potential for standard process:

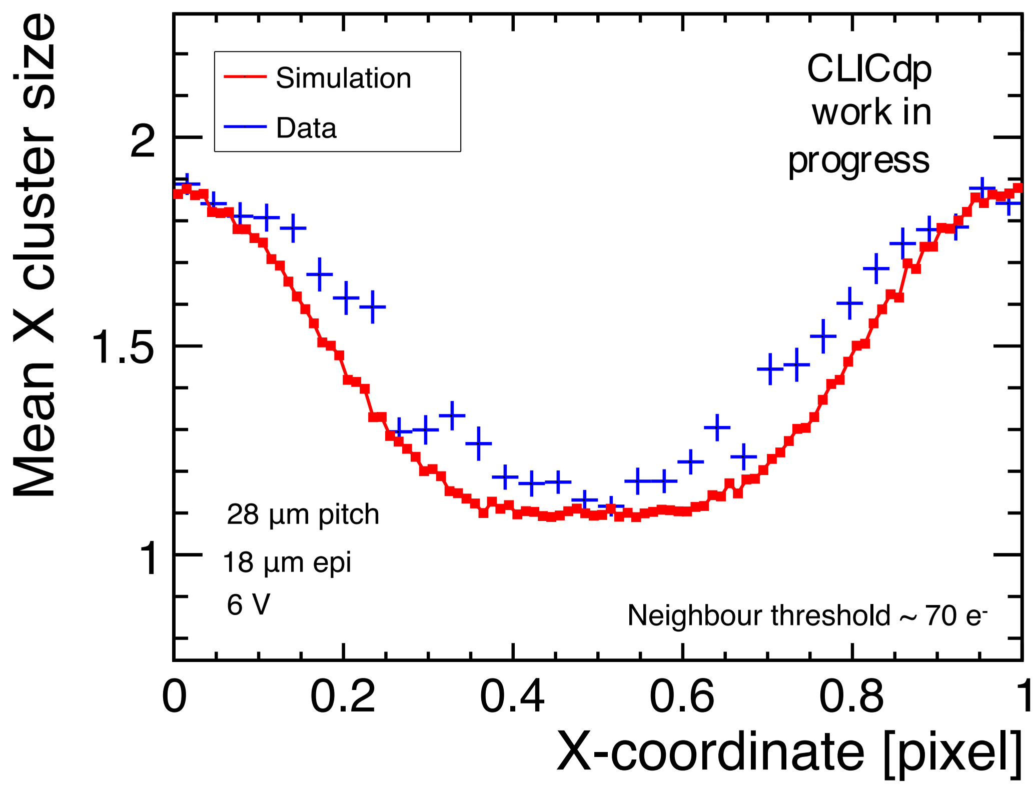


Electrostatic potential for modified process:

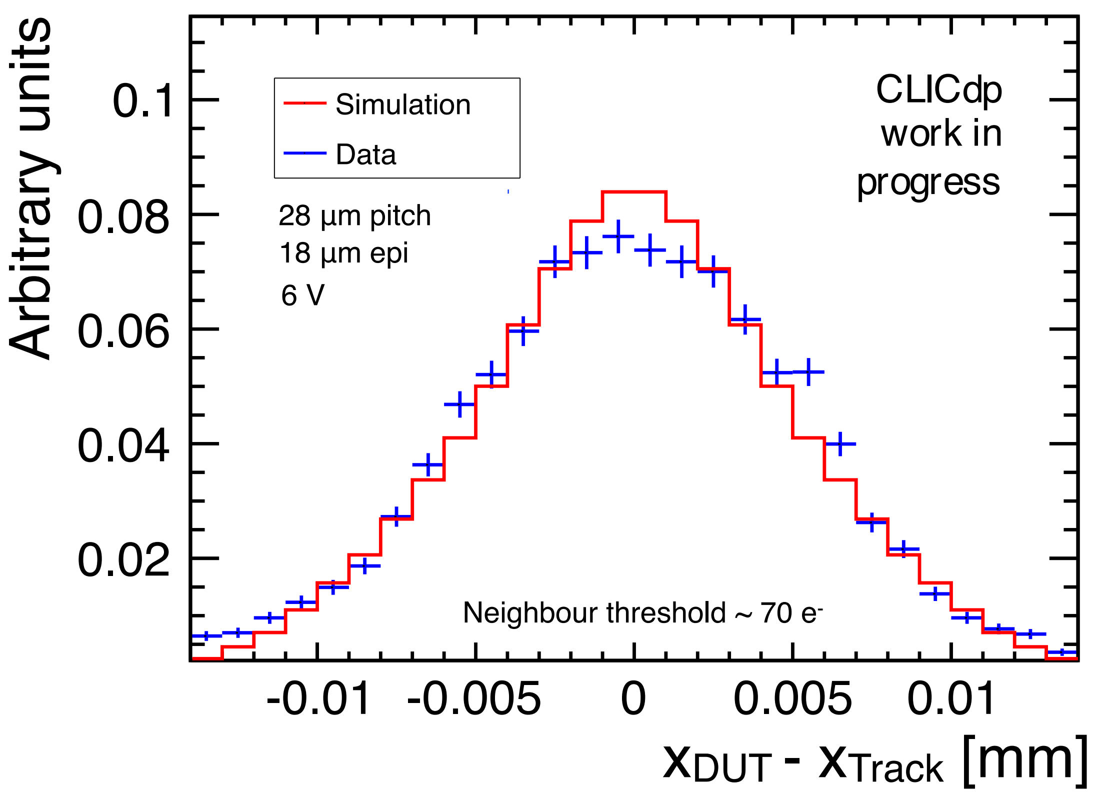


Comparison data - simulation / standard process

Mean X cluster size in pixel cell:



Residual in X-dimension:

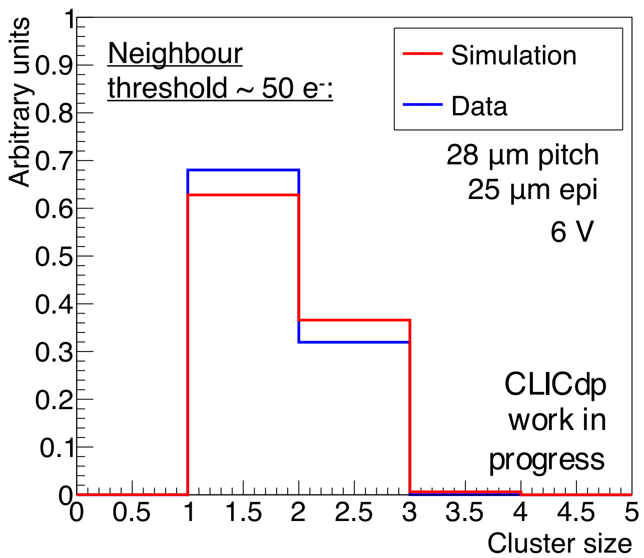


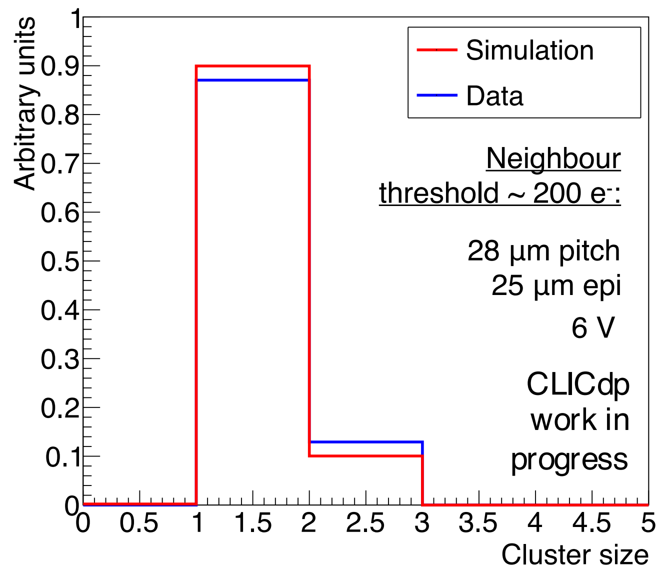
- ^{55}Fe- calibration applied to define threshold in simulation

  → *Excellent agreement between simulation and data on sub-pixel level.*

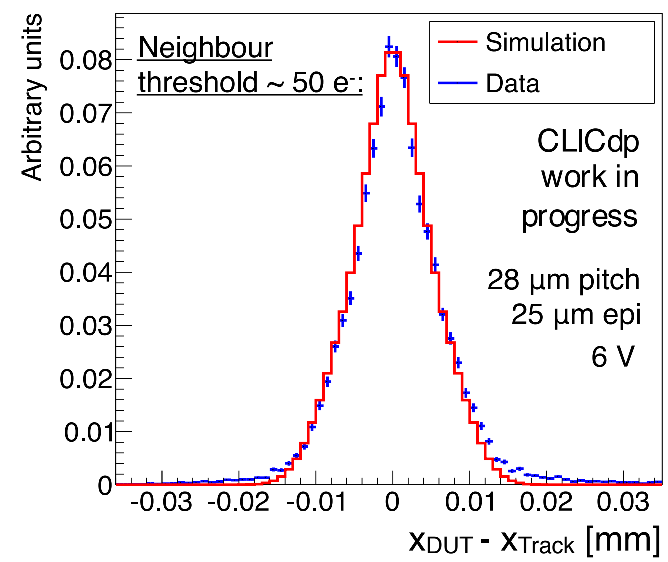
Comparison data - simulation / modified process

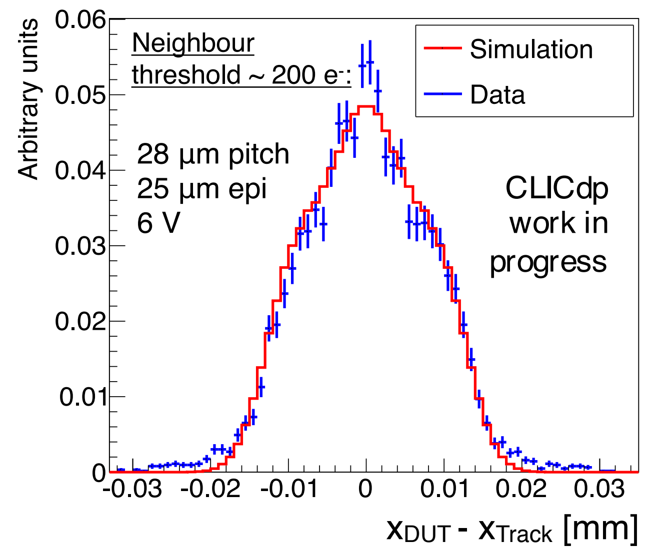
Cluster size distributions for different thresholds:



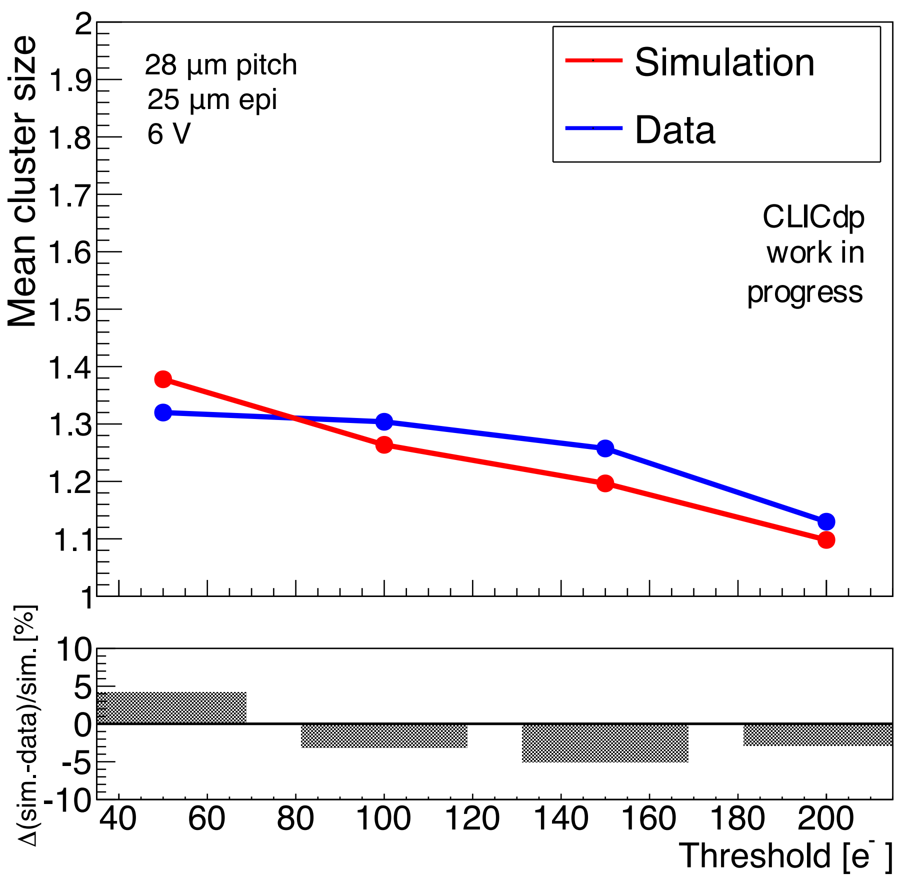


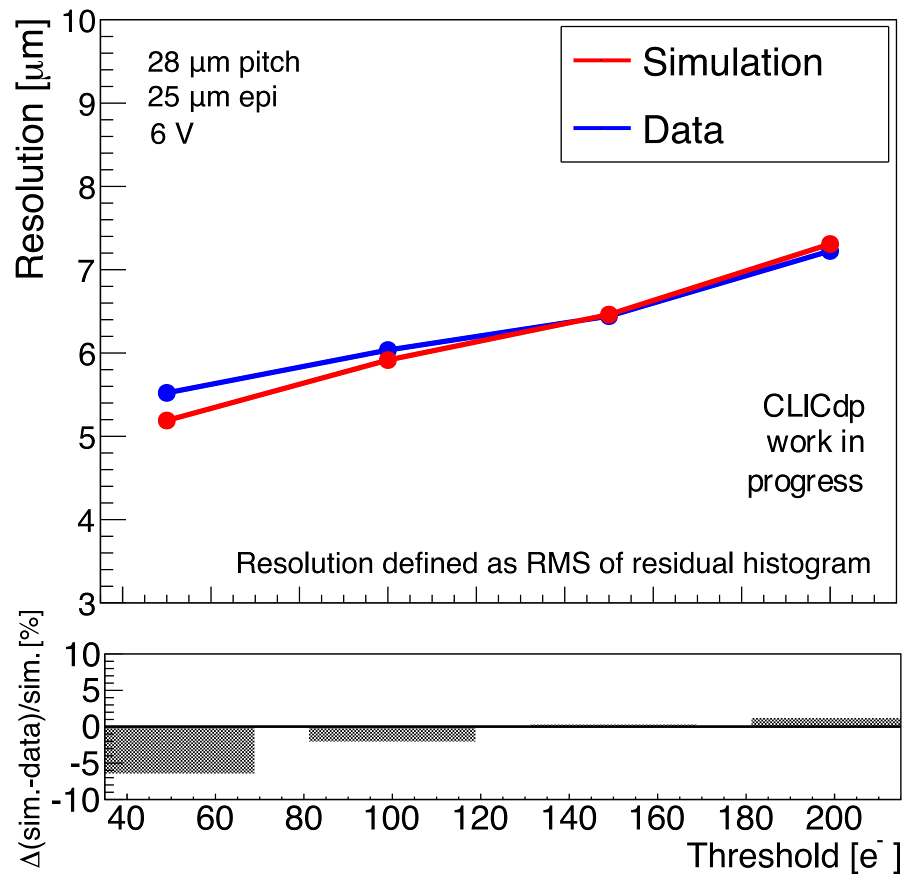
Residual distributions for different thresholds:





Mean cluster size & resolution for different thresholds:





- ^{55}Fe-calibration applied to define threshold in simulation
- Expected trend of lower cluster size and worse resolution visible in data & simulation

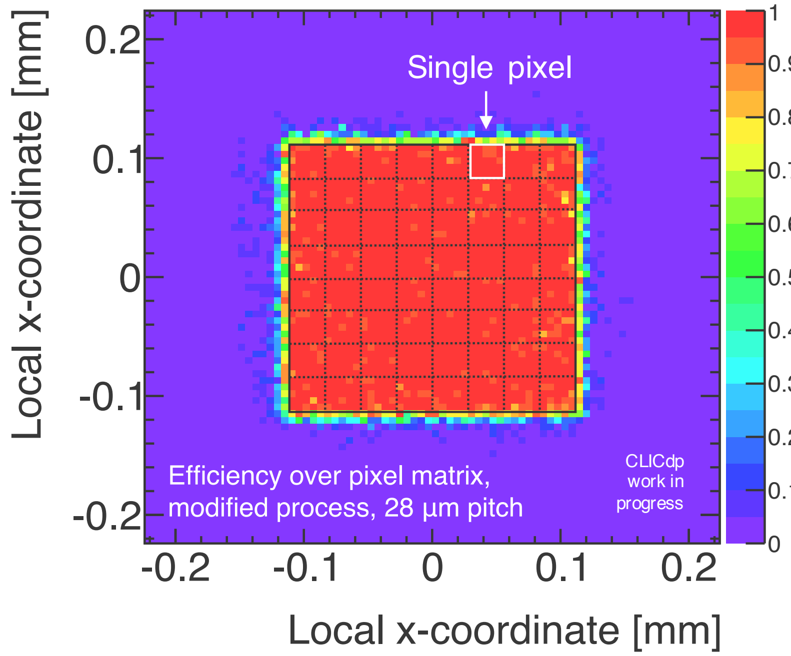
→ *Good agreement of data and simulation for different thresholds within a few percent.*

Summary

Study of Investigator HR-CMOS test-chip with respect to requirements for the CLIC tracker:

- Test-beam study of two different submissions standard & modified process
- Spatial and timing resolution matching requirements of 7 μm single point resolution & 10 ns time stamping for CLIC tracker:
    - *Single point resolution ~ 6 μm*
    - *Time resolution < 5 ns*
    - *Efficiency > 99%*

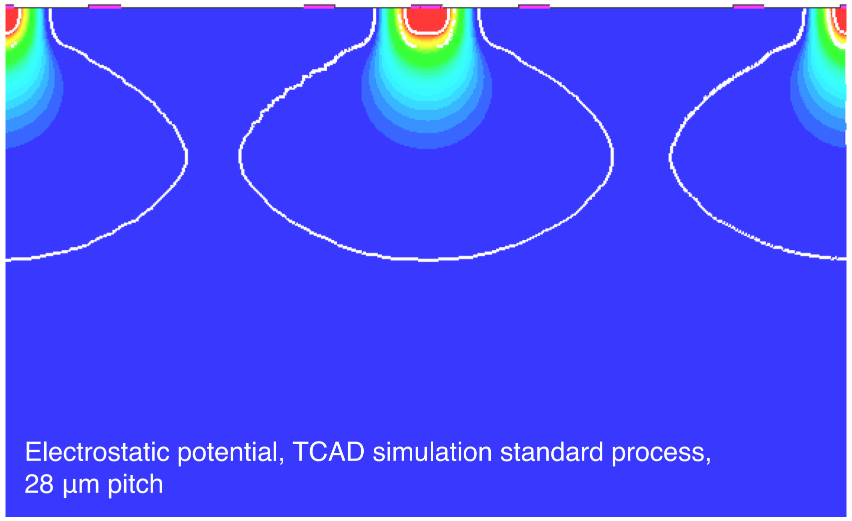
Modified process
28 μm pitch
(t.b.c. with fully integrated chip)

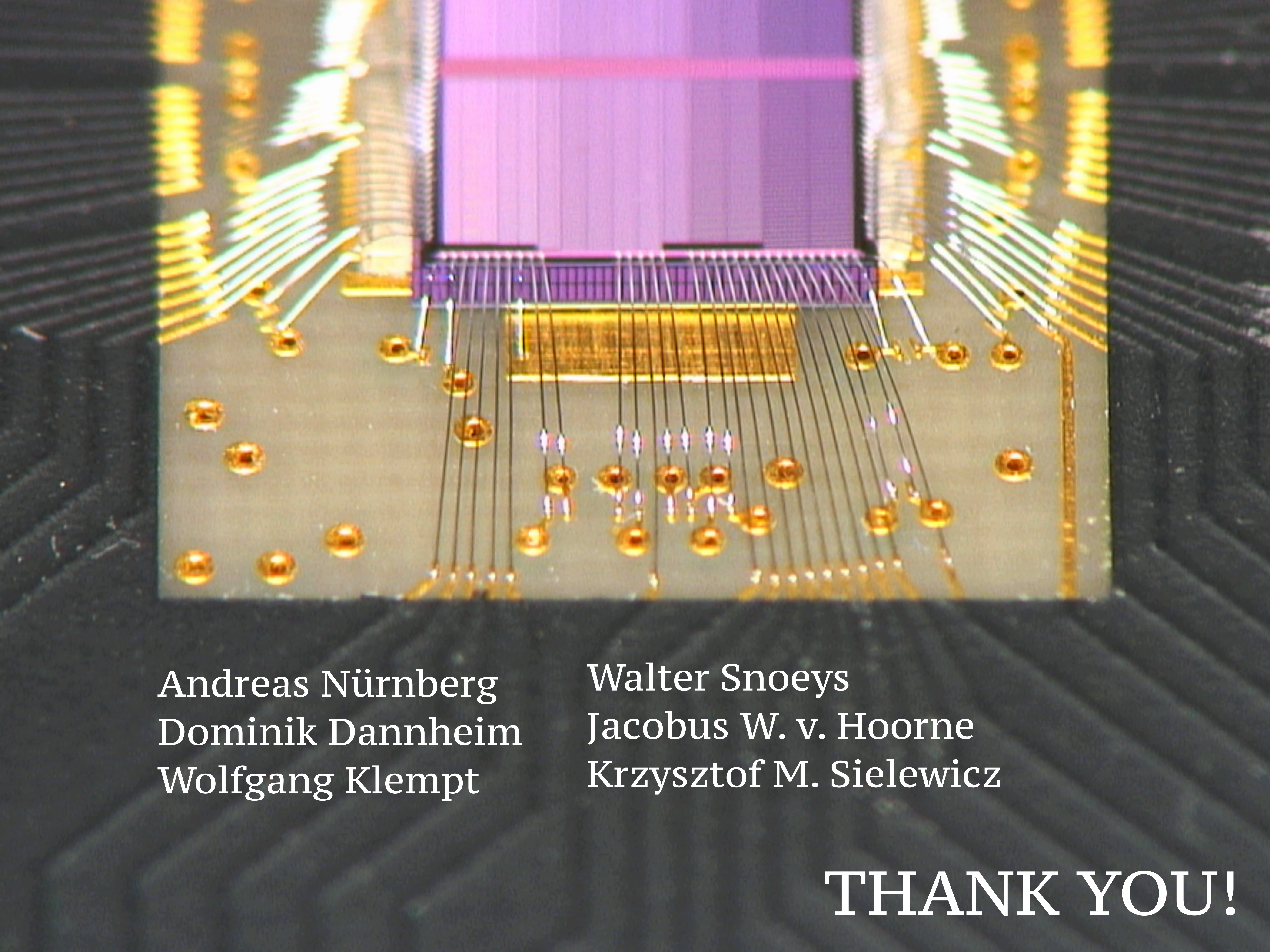


→ *Studies used as input for design of fully monolithic tracker chip for CLIC*
(see talk by A. Nurnberg: "A vertex and tracking detector system for CLIC")

Explore Investigator HR-CMOS technology:

- Detailed understanding of charge sharing on sub-pixel level
- Simulation of standard and modified process show agreement between simulation and data within a few percent *showing a good understanding of the studied technology*



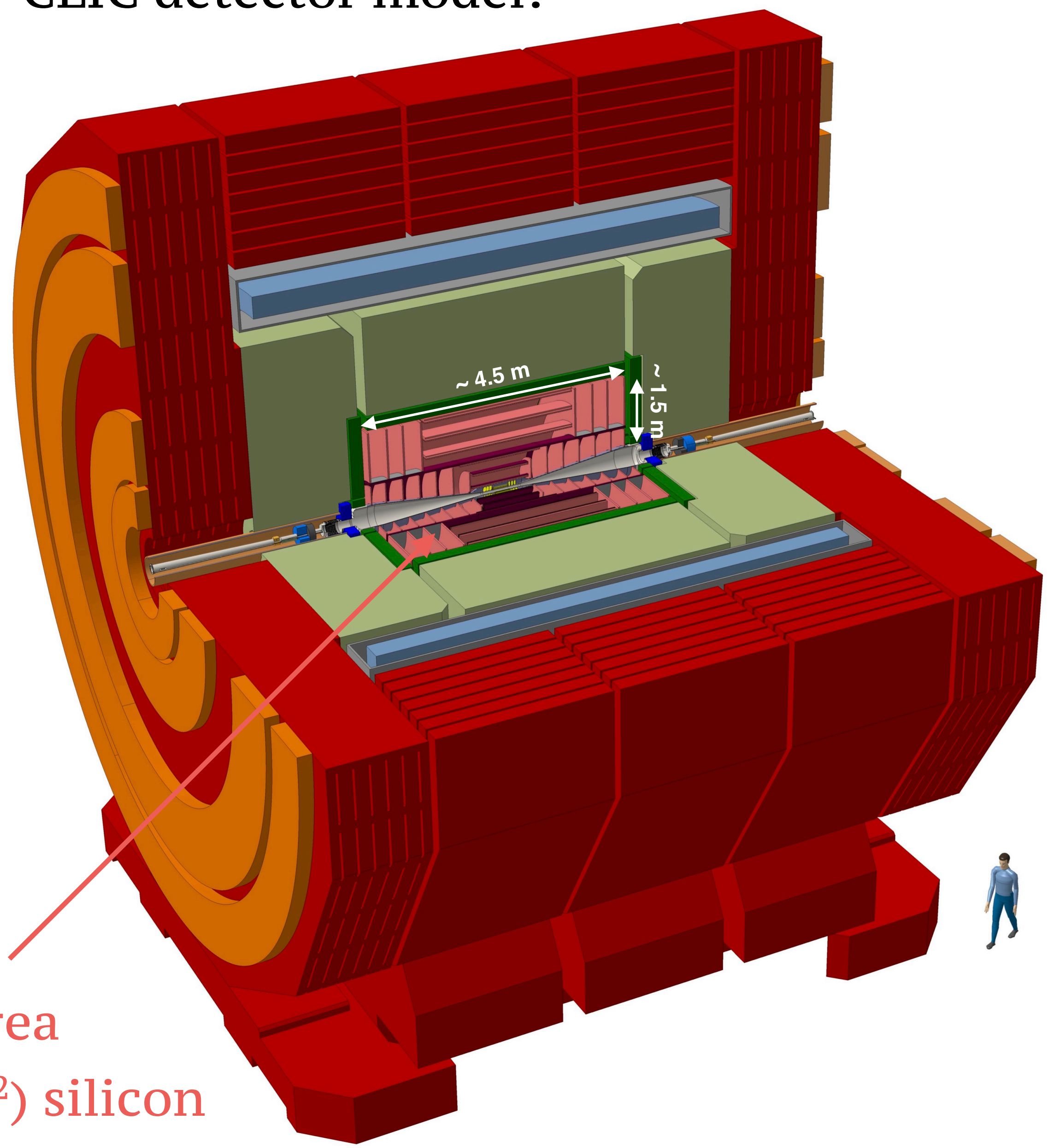

Andreas Nürnberg
Dominik Dannheim
Wolfgang Klempt
Walter Snoeys
Jacobus W. v. Hoorne
Krzysztof M. Sielewicz
THANK YOU!

The CLIC detector

CLIC detector for high precision measurements:

Physic aims		Detector needs
E.g. Higgs recoil mass, Smuon endpoint	→	Momentum resolution $\sigma_{P_T} / p_T^2 = 2 \cdot 10^{-5}$ / GeV
W/Z/H seperation	→	Jet energy resolution $\sigma E / E = 3.5\% - 5\%$
E.g. Higgs couplings (b/c-tagging)	→	Impact parameter resolution $\sigma_{r\varphi} \sim 5 * 15 / p \cdot \sin^{3/2}\Theta$ µm

CLIC detector model:



Tracker requirements:

Momentum resolution at high p_T	→	7 µm single point resolution
Momentum resolution at low p_T	→	~1% radiation length per layer
Reduce occupancies from beam-beam interactions	→	10 ns time stamping

Large area (~100m²) silicon tracker

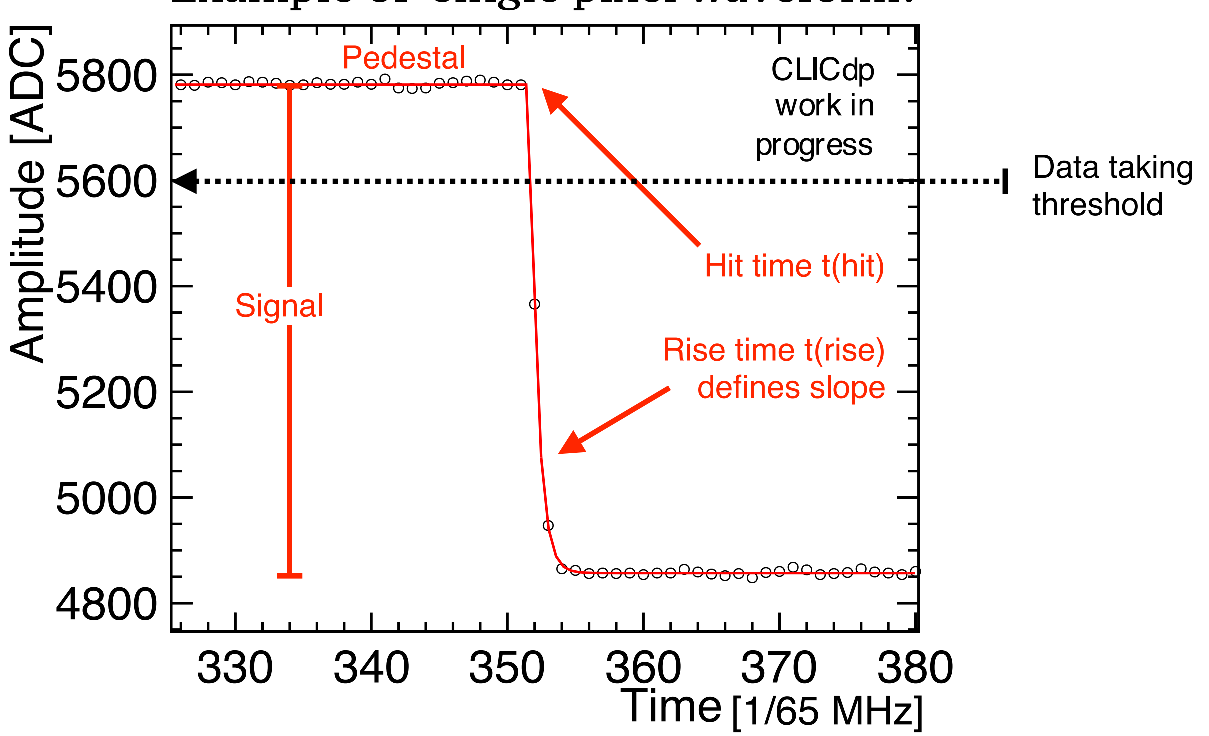
Analysis & definition of observables

Investigator event reconstruction:

- Signal defined as magnitude of amplitude drop
- Noise defined as RMS of fluctuation around pedestal
- Analysis cut on Signal/Noise > 5 for each single pixel
  (Note: higher data taking threshold corresponds to cut on seed signal while lower analysis cut corresponds to cut on neighbour pixel signal)
- Fit exponential function f(t) to waveform of each pixel to extract exact timing and signal:

$$f(t) = \begin{cases} \text{Pedestal} & \text{if } t \leqslant t_{Hit} \\ \text{Pedestal} + \text{Signal} \cdot (e^{-(t - t_{Hit}) / t_{Rise}} - 1) & \text{if } t > t_{Hit} \end{cases}$$

Example of single pixel waveform:



Further analysis cuts:

- Event size of 10 μs
- Distance track-Investigator hit position
  < 2 x pixel pitch
- Masking of half of edge pixels to avoid bias by edge effects due to limited tracking resolution and/or charge sharing