FASTPIX

Monolithic Pixel Sensor Demonstrator for sub-Nanosecond Timing in Future Vertex and Tracking Applications

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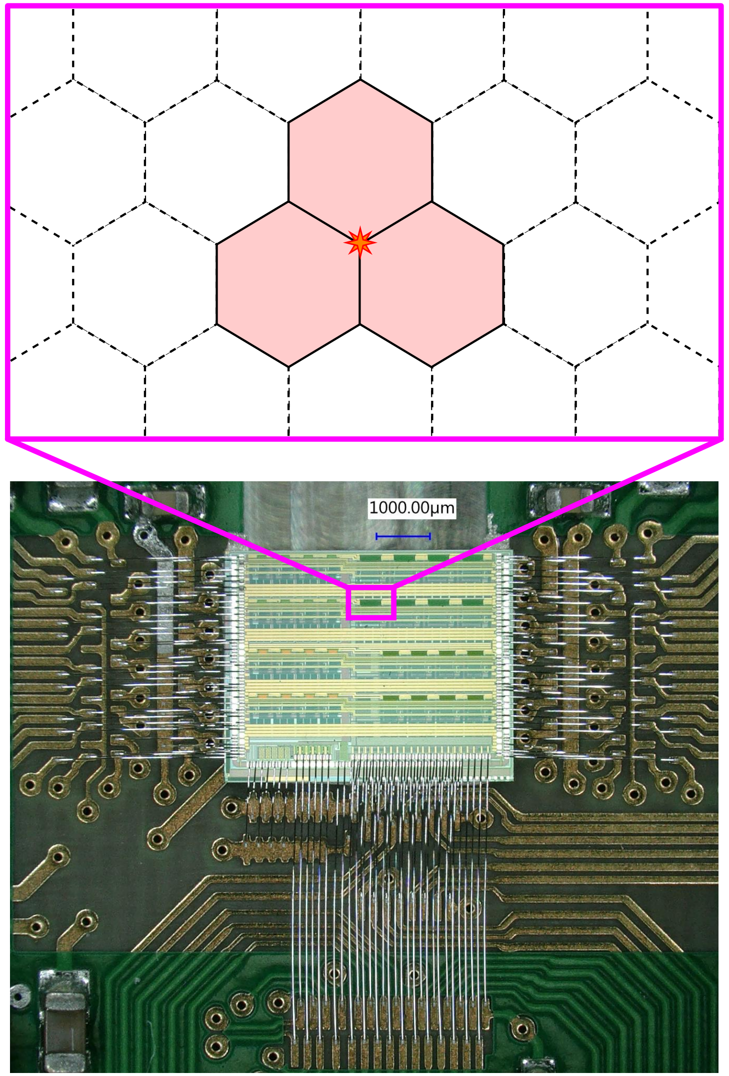
GENTNER DAY

26 April 2023

FASTPIX

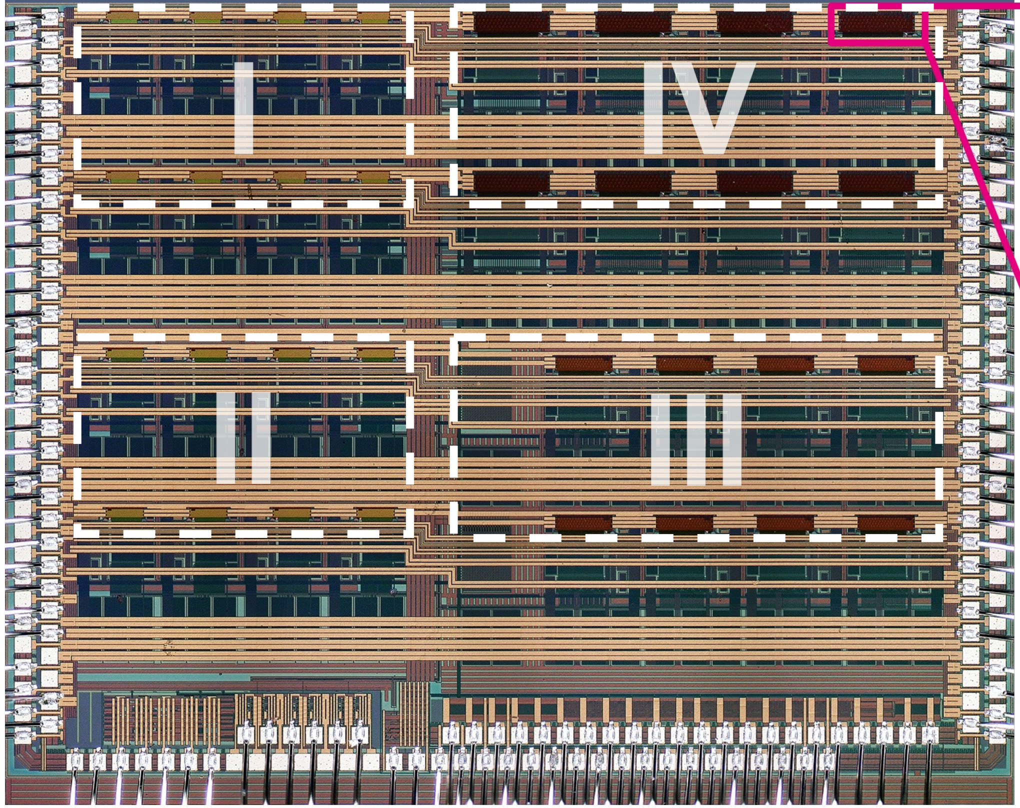
- **Monolithic pixel sensor demonstrator chip in modified 180 nm CMOS imaging process**
  - ➔ Hexagonal pixels with small, few fF capacitance collection electrodes
  - \+ Large signal-to-noise ratio in favor of detection efficiency and timing performance
  - – Non-uniform electric fields, time dependency on in-pixel particle incidence
- **Design variations aiming at charge collection optimization**
- **Target: excellent spatial and temporal resolution with high efficiency**
  - Future high-energy and high-rate particle collider experiments
  - Wide application range (e.g. spectroscopy, microscopy, medical applications)



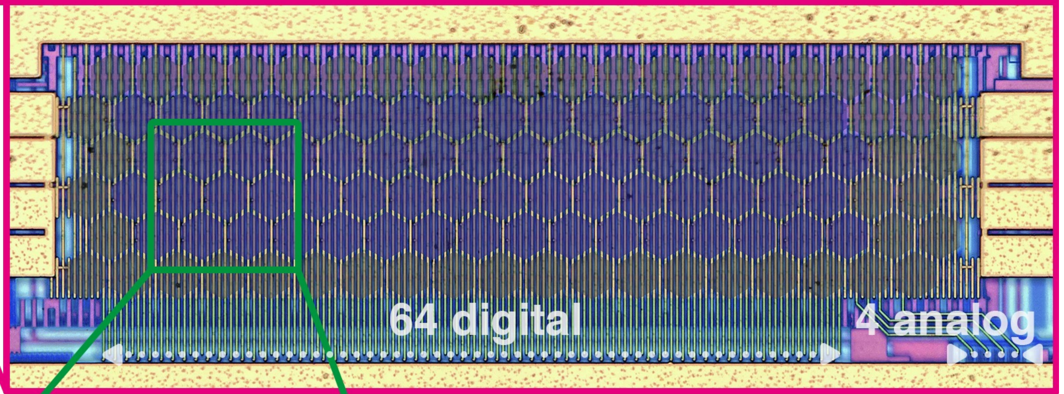
ATTRACT FASTPIX:
Sub-Nanosecond Radiation Tolerant CMOS Pixel Sensors

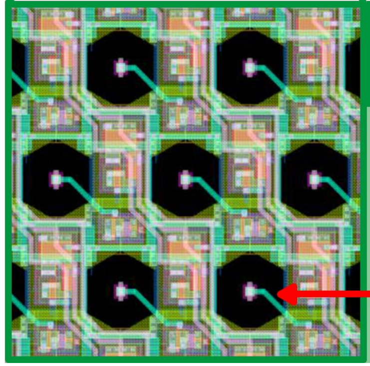
The Sensor

FASTPIX layout (5.3 x 4.1 mm²)



Pixel matrix layout, hexagonal grid 20μm





Pixel in the matrix

5 PMOS per pixel

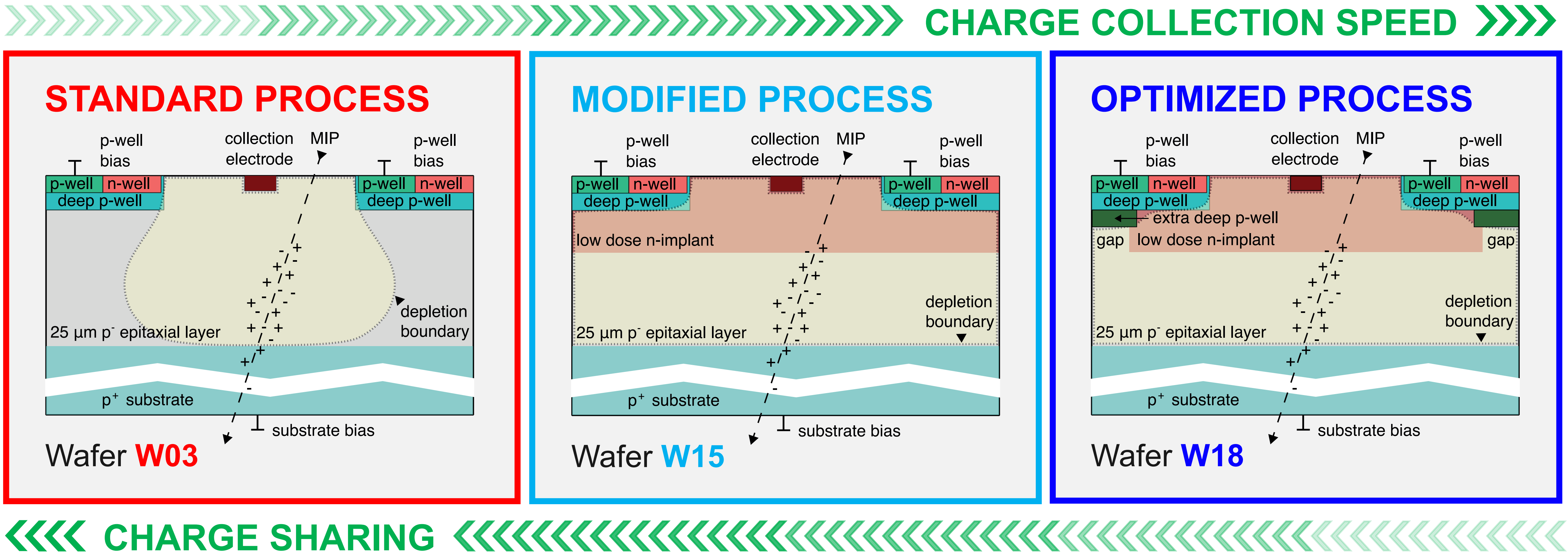
n-well electrode

➔ **Four groups with different pixel pitches:**
I: 8.66 μm, **II:** 10 μm, **III:** 15 μm, **IV:** 20 μm

➔ **Different design parameters implemented**
Collection electrode size, geometry of implant structures

The Pixel Cell

M. Munker *et al* 2019 *JINST* **14** C05013

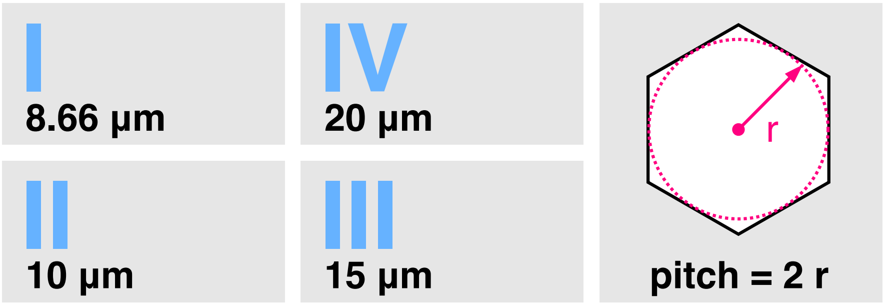


➔ **Process and design modifications for uniform depletion and accelerated charge collection**

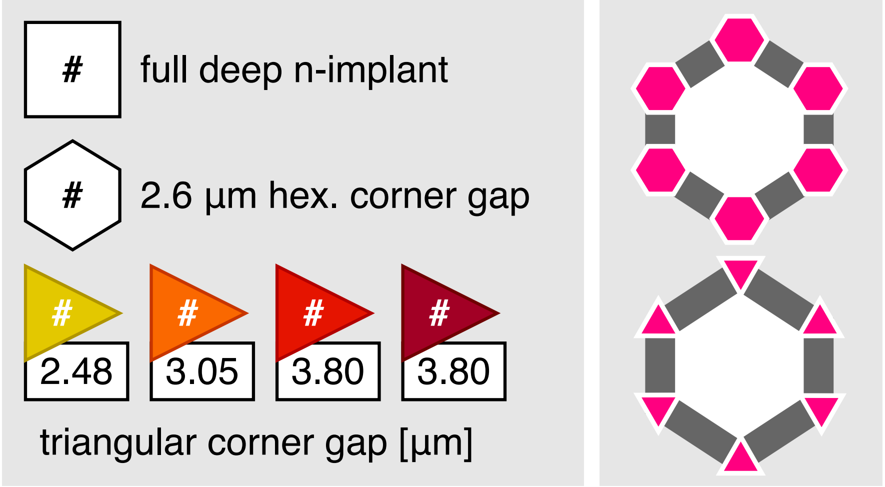
✚ **Add implant structures at pixel edge** ➔ shape electric field ➔ uniform acceleration of charge to collection electrode

Sensor Design Parameters in Optimized Process

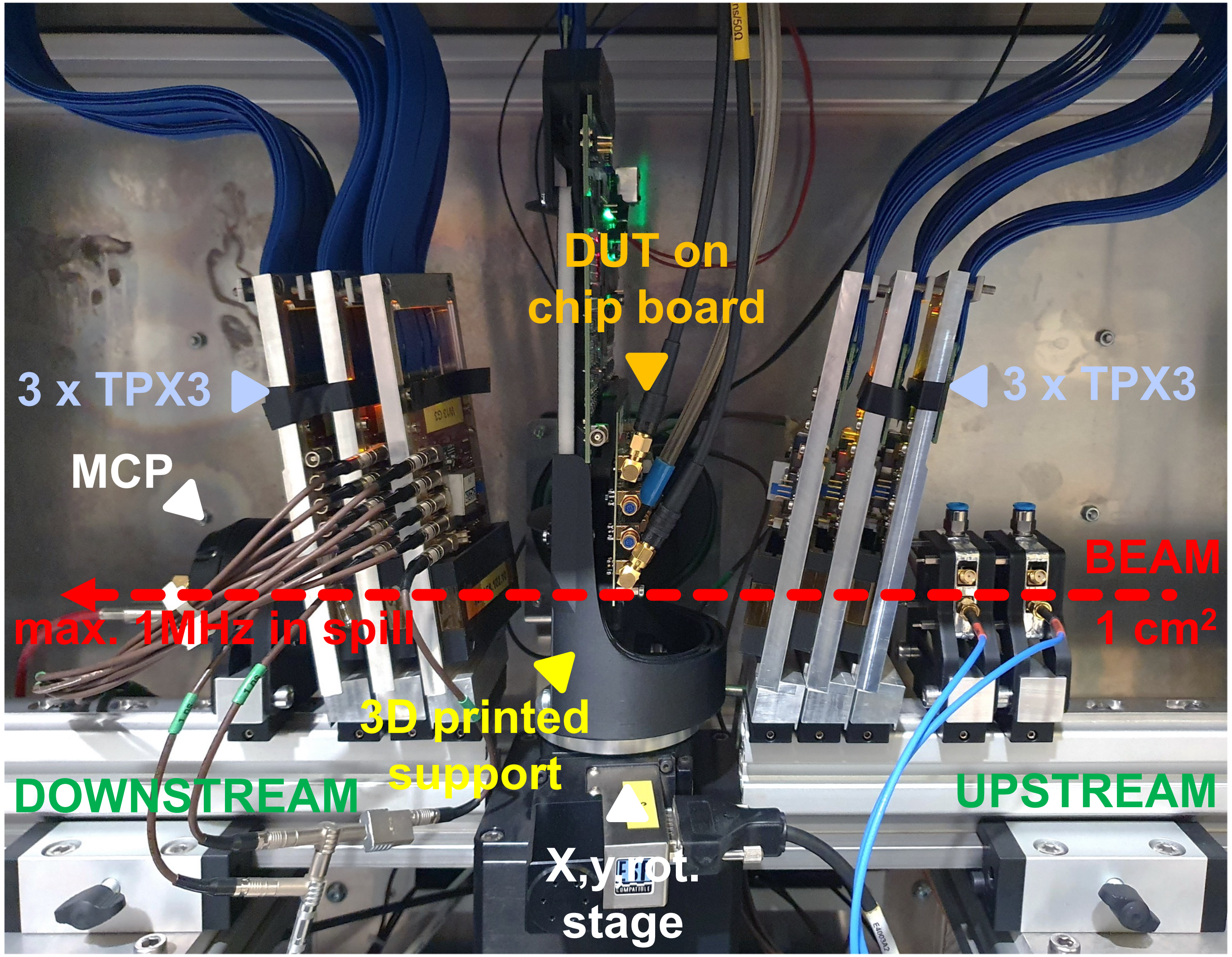
Pixel Pitch in Quadrants



Deep n-Implant Geometry



CLICdp Timepix3 Telescope Setup



- **CERN SPS North Area test beam on beamline H6 at 120 GeV/c pions**
- **DUT between upstream and downstream Timepix3 (TPX3) reference planes**
- **FASTPIX read out by Oscilloscope**

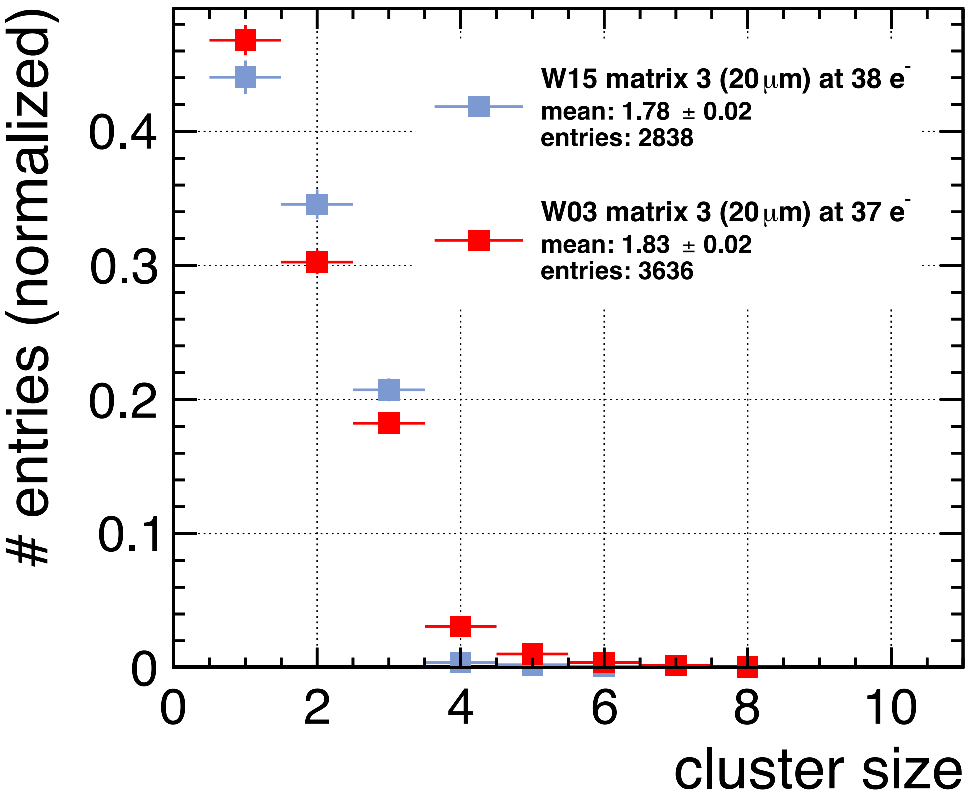
  … controlled by Caribou DAQ

  … connected to telescope DAQ

  - **FASTPIX:** -6V for substrate and p-wells
  - **Per 5 sec. spill ~ 1000k in telescope** yields ~ **0.5k** triggers **on matrix**
- **Microchannel Plate PMT (MCP-PMT) as time reference**

  ➔ ~ $\mathcal{O}$**(10 ps)** MCP-PMT timing precision

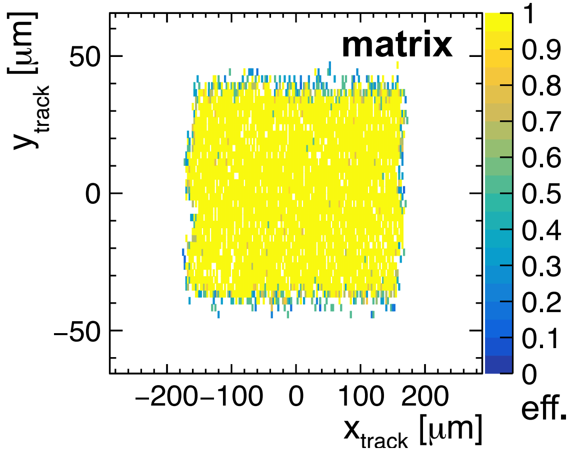
Cluster Size and Efficiency – 20 µm Pixel Pitch



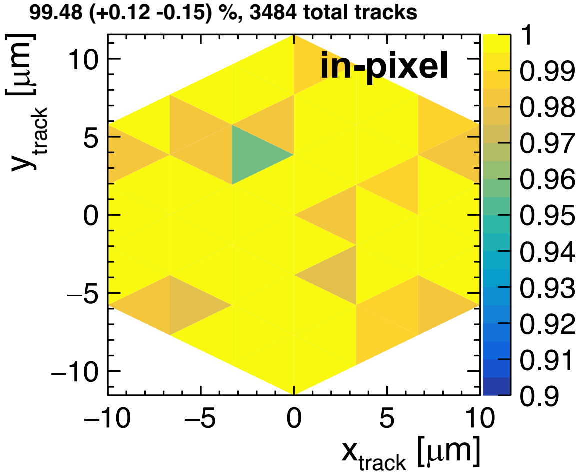
- **Standard W03** vs **Modified W15** for **20 µm** matrix
- **Fully efficient** operation, **threshold of 38 electrons** for both samples

➔ **No significant difference in cluster size or efficiency**

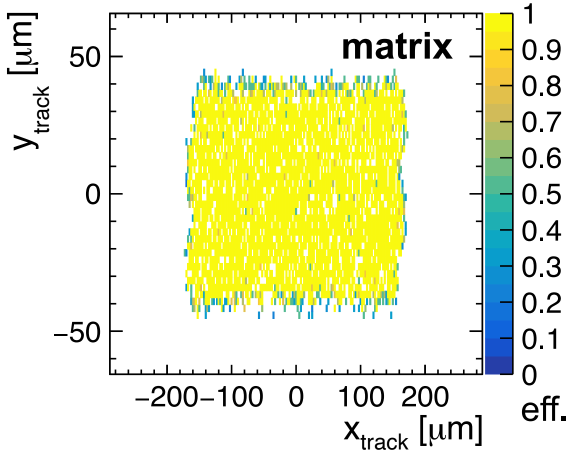
W03 #3 – 20 µm matrix



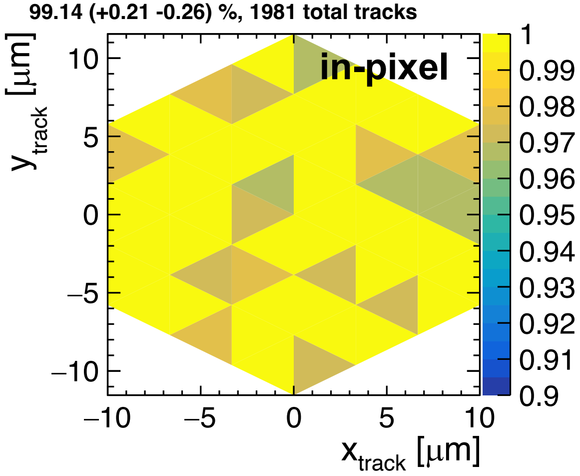
without deep n-implant



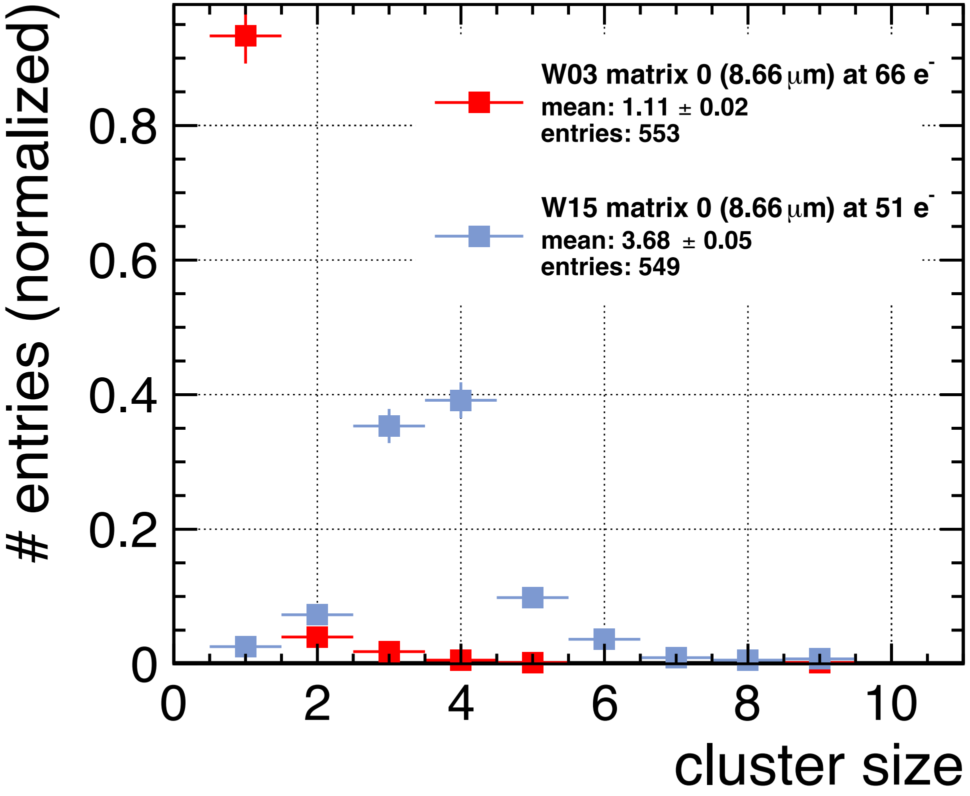
W15 #3 – 20 µm matrix



with deep n-implant

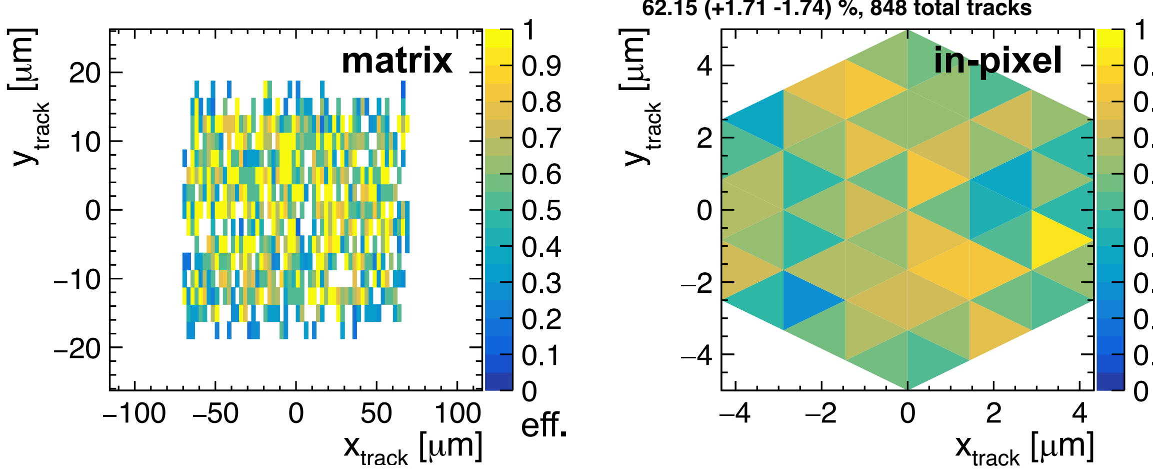


Cluster Size and Efficiency – 8.66 µm Pixel Pitch

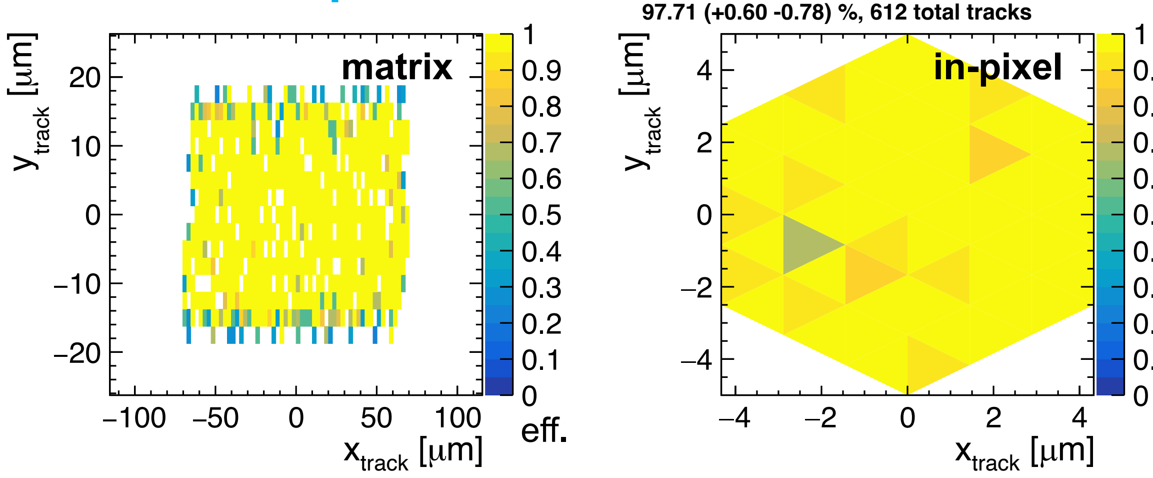


- ➔ **Standard W03** is **40% less efficient than Modified W15** for **8.66 µm pixel pitch**
- ➔ **Modified W15** has around **3 times higher mean cluster size**

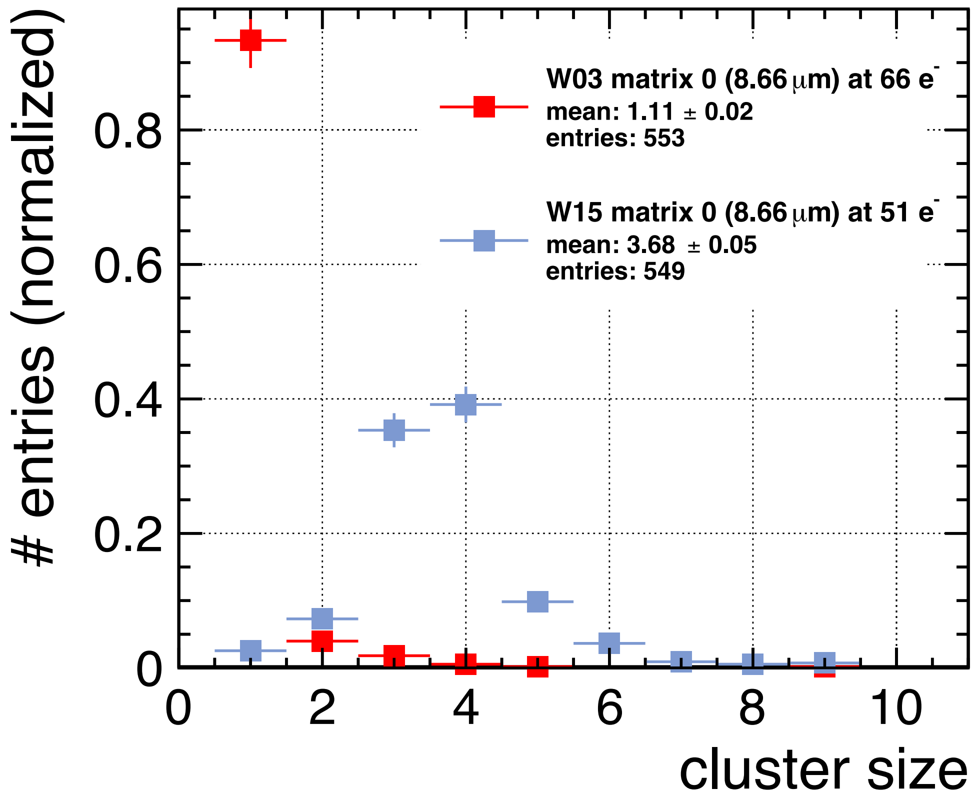
W03 #0 – 8.66 µm matrix | **without deep n-implant**



W15 #0 – 8.66 µm matrix | **with deep n-implant**



Cluster Size and Efficiency – 8.66 µm Pixel Pitch



➔ **Standard W03** is **40% less efficient than Modified W15** for **8.66 µm pixel pitch**

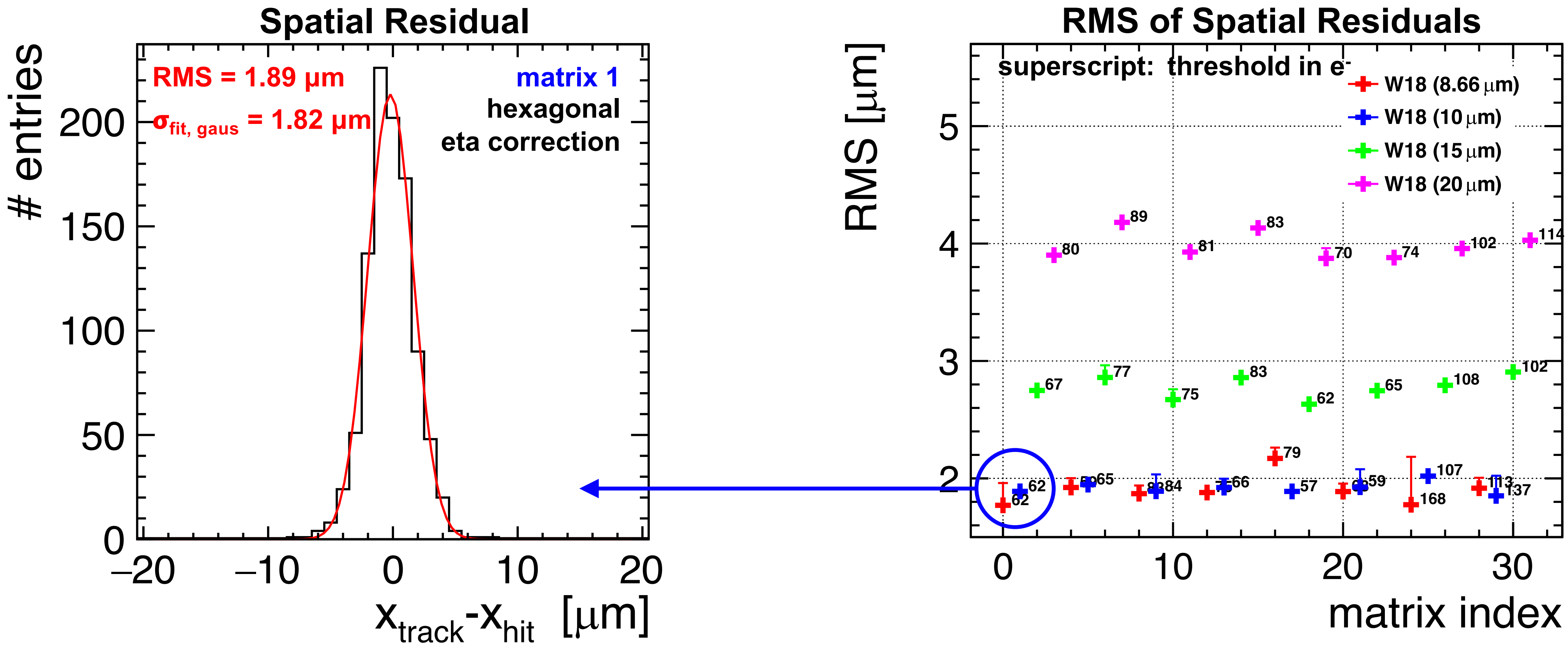
➔ **Modified W15** has around **3 times higher mean cluster size**

- **IF** full efficiency at the same threshold:
  - ➔ More charge sharing with **Standard W03**
  - ➔ Expected larger cluster size for **Standard W03** compared to **Modified W15**
- **BUT** small pitch causes:
  - ➔ Increased charge sharing
  - ➔ On average smaller signal on seed pixel
  - ➔ Signal more likely to stay below threshold
  - ➔ Hit and remaining pixels in the cluster remain undetected

➔ **Process modifications of Modified W15 help to contain the charge within single pixel**

➔ **More margin for efficient detector operation of small-pitch matrices**

Spatial Residuals for Optimized Process

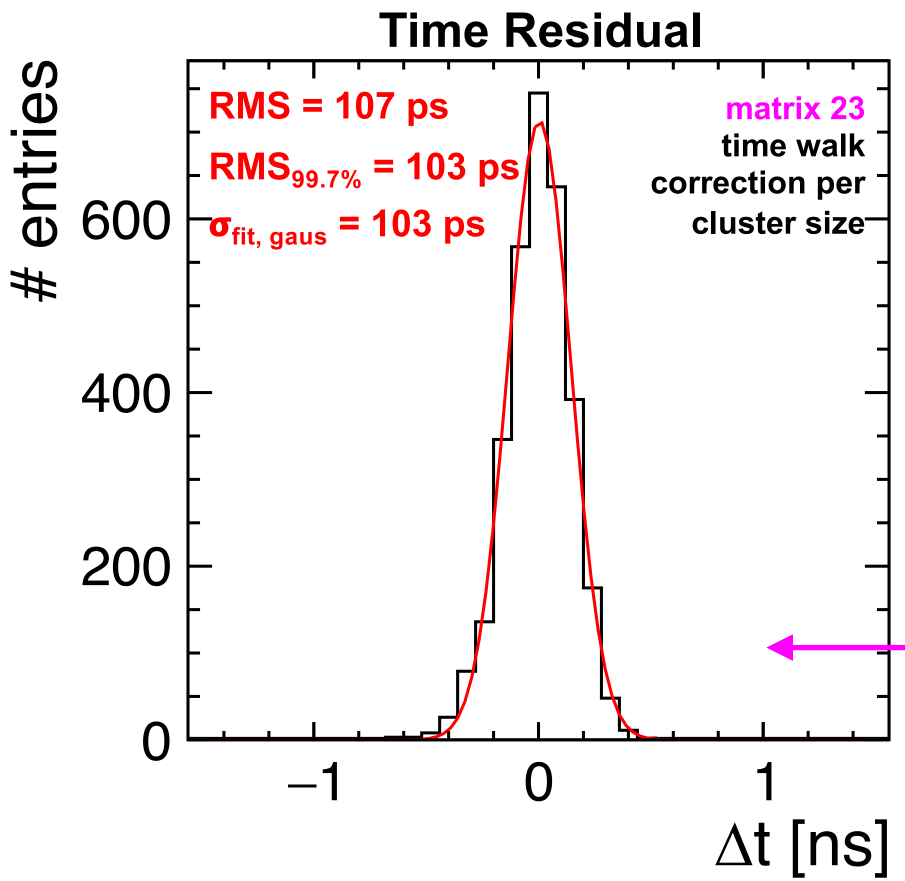


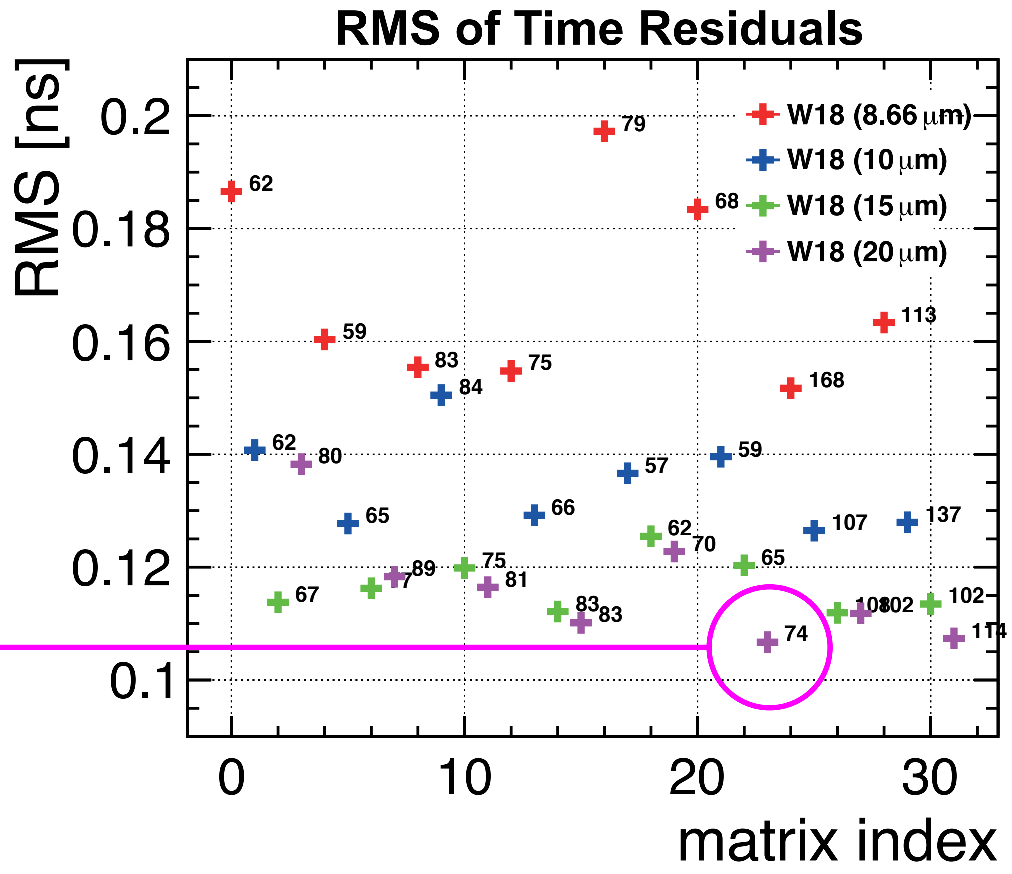
RMS of spatial residuals for all matrices between 1.9 µm and 4.3 µm

➔ **Smaller pitch ➔ lower RMS**

➔ **Spatial resolution down to 1 µm** after unfolding telescope tracking resolution of ~ 1.7 µm

Time Residuals for Optimized Process

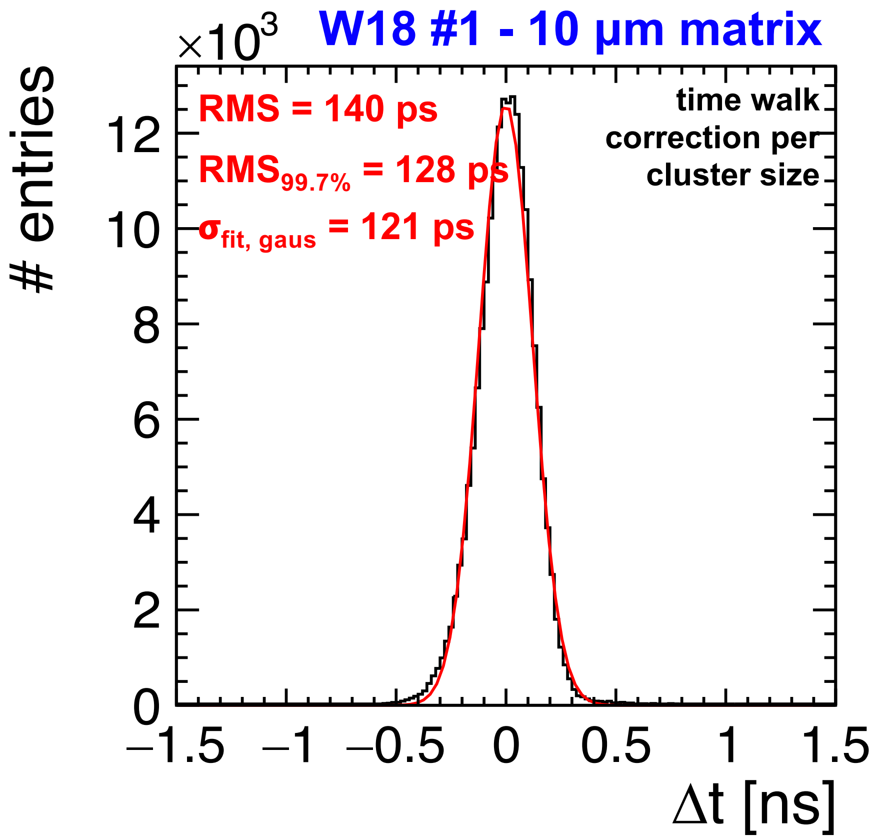


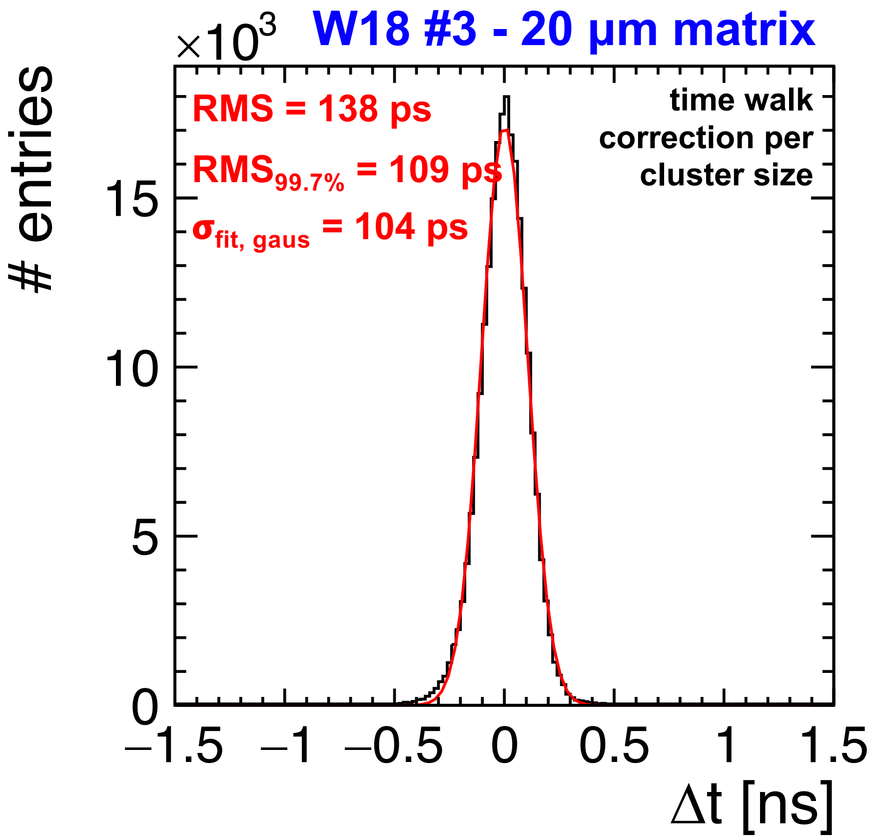


RMS of time residuals for all matrices between 100 ps and 200 ps

➔ **Larger pitch ➔ lower RMS:** smaller mean cluster size + more uniform lateral field ➔ larger share of signal collected by single pixel ➔ pos. influence on time resolution

Time Residuals for Optimized Process





Smaller pitch ➔ shorter drift distance but also **more charge sharing** and **larger cluster size**

➔ Deteriorated time resolution for the seed pixel ➔ better performance for larger pixel pitch

➔ **20 µm matrix** shows **15% better timing performance** compared to 10 µm matrix in optimized process

Summary & Outlook

- **Successful integration in existing Timepix3 telescope, reconstruction and analysis framework**
- **Process modifications are essential to maintain efficient operation for small pixel pitch**
- **FASTPIX reaches spatial resolution down to 1 µm**
- **FASTPIX reaches ~$\mathcal{O}$(100 ps) timing precision for optimized process**

NEXT STEPS

➔ Further improvements of reconstruction and analysis methodology

➔ Additional test beam campaigns focusing on measurement statistics and implications of angled tracks

Acknowledgements

- **ATTRACT**

  FASTPIX has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222.

- **AIDAinnova**

  This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA no 101004761.

- **CERN EP R&D**

  FASTPIX and connected testing efforts are part of the CERN EP R&D programme on technologies for future experiments.

- **German Doctoral Student Programme at CERN**

  This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA).

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Sensor Design Optimization Before FASTPIX

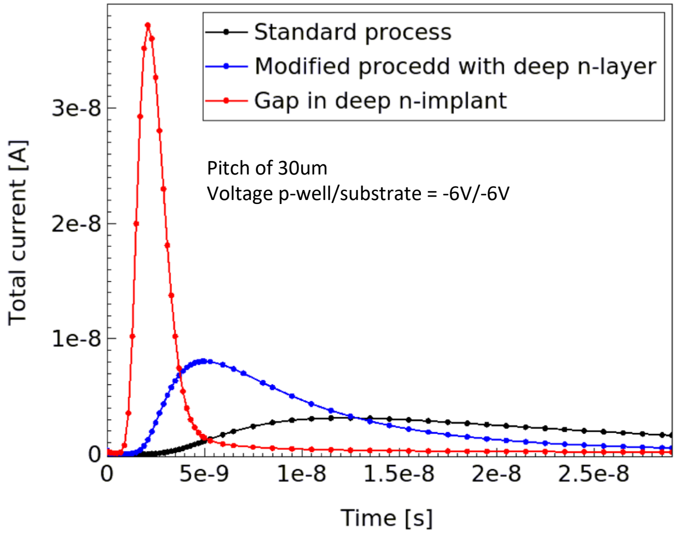
Slide taken from: M.Munker, iWoRiD 2021

Optimization performed with 3D Technology Computer Aided Design simulations (3D TCAD)

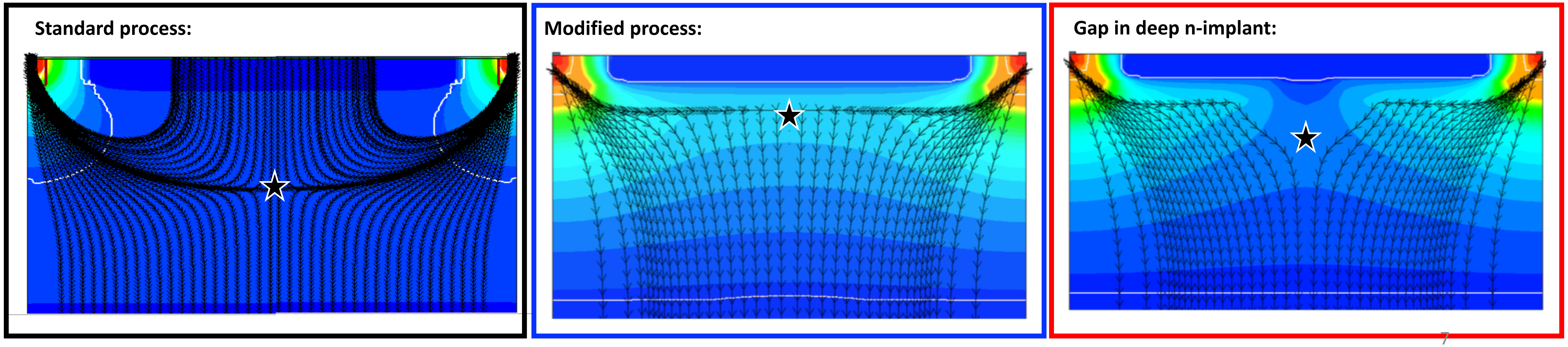
Fundamental challenges:

1. Increase and shape field significantly while maintaining small sensor capacitance
2. Limitations of circuitry on sensor and vice versa

Single pixel current pulse from transient 3D TCAD MIP simulation in pixel corner :

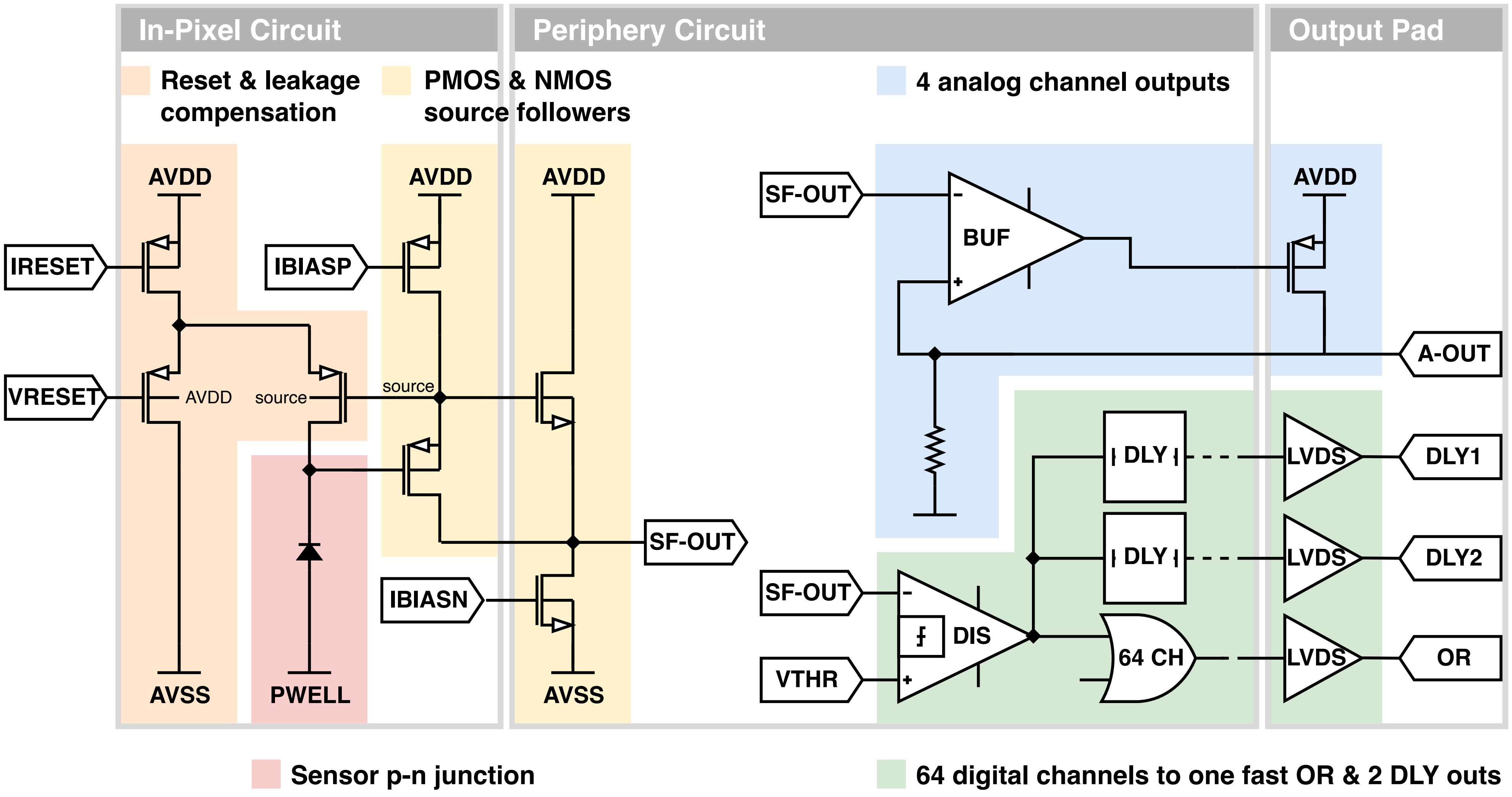


Electrostatic potential from 3D TCAD (color scale), streamlines (black arrows) and electric field minimum (star symbol):

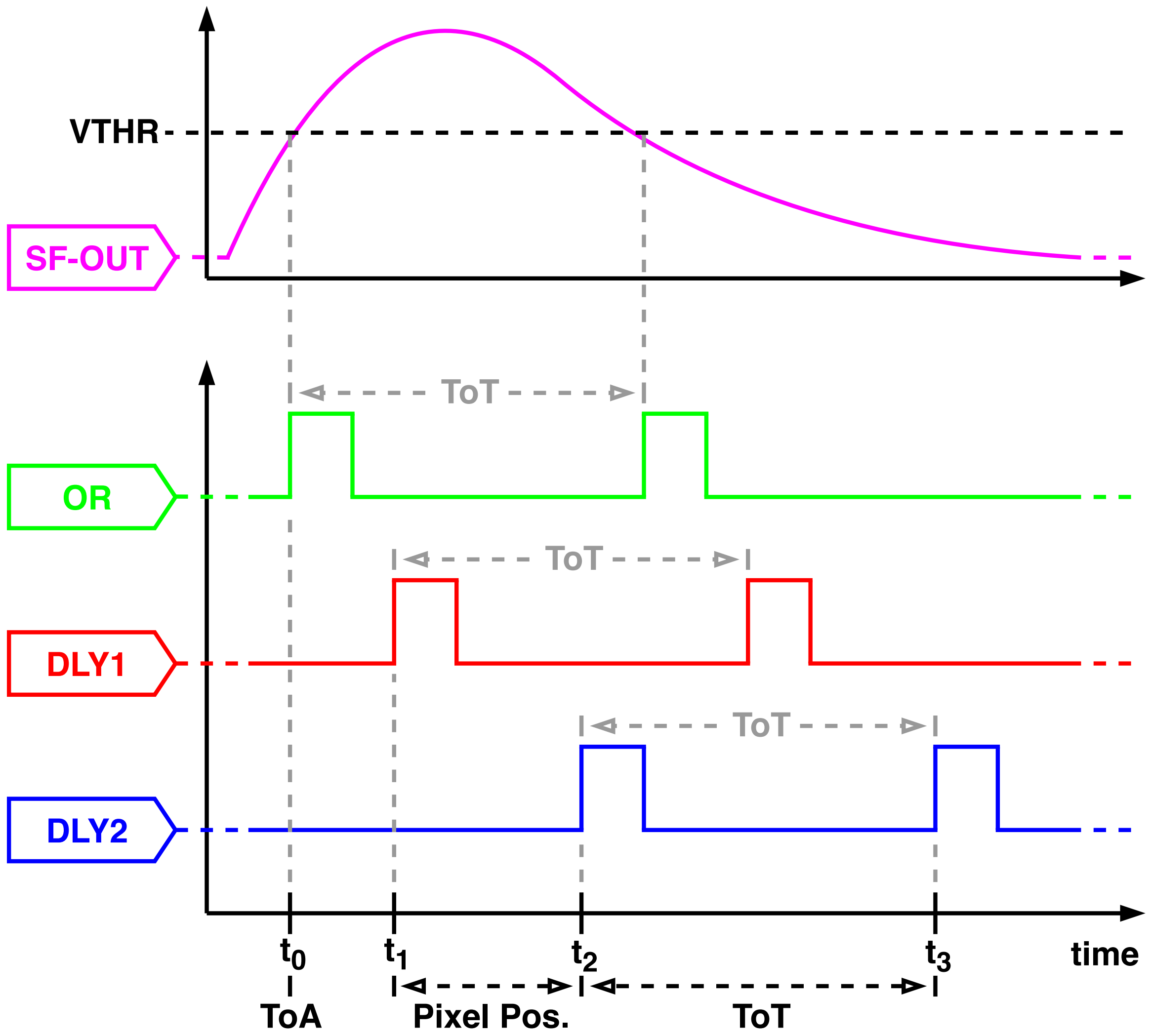


Pitch of 36.4µm, voltage p-well/substrate = -6V/-6V

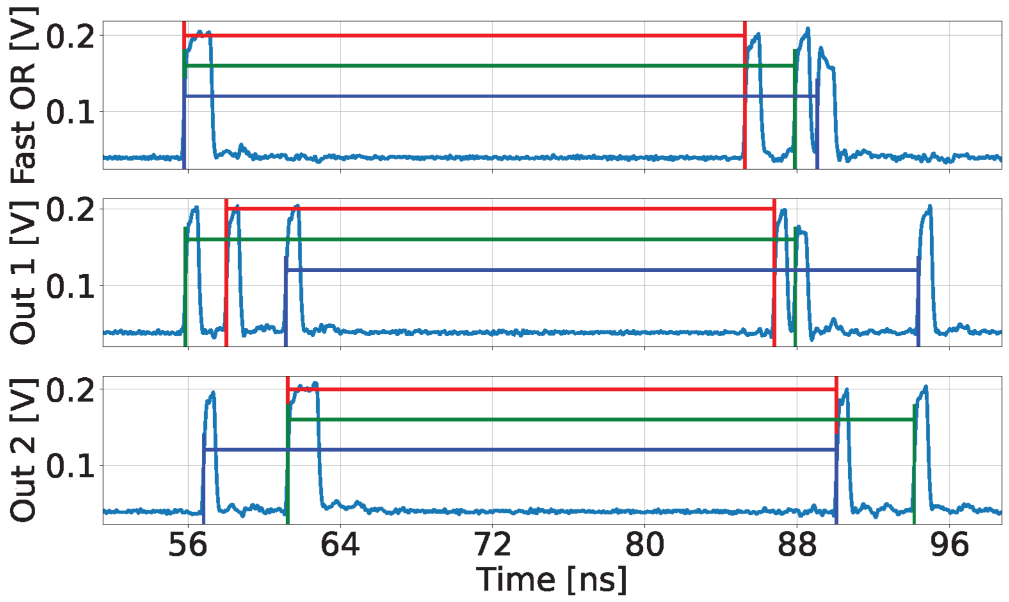
Frontend and Periphery



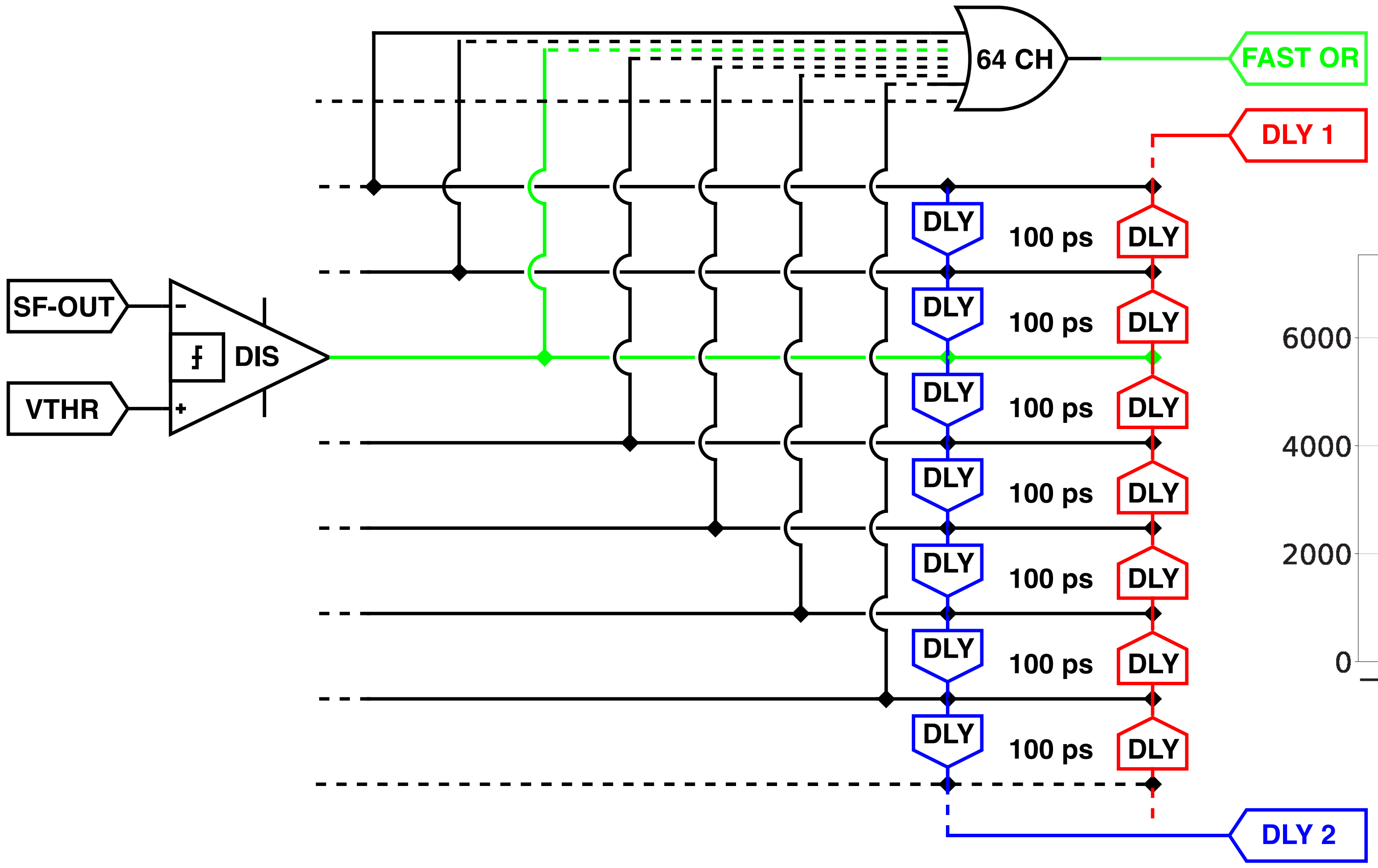
Readout Architecture (Digital Channels)

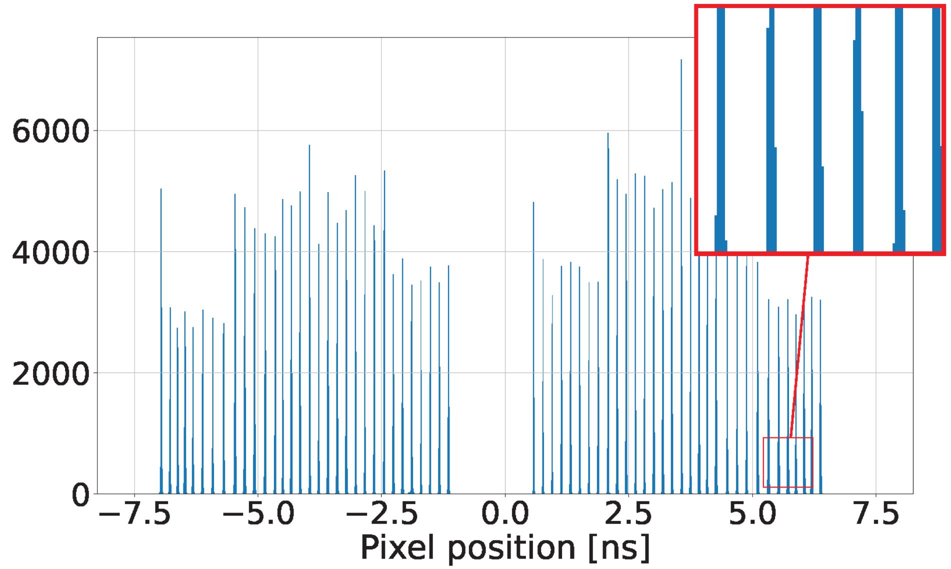


- Asynchronous readout with oscilloscope and off-chip processing
- Time-based position and time-over-threshold encoding on 3 channels: OR, DLY1, DLY2

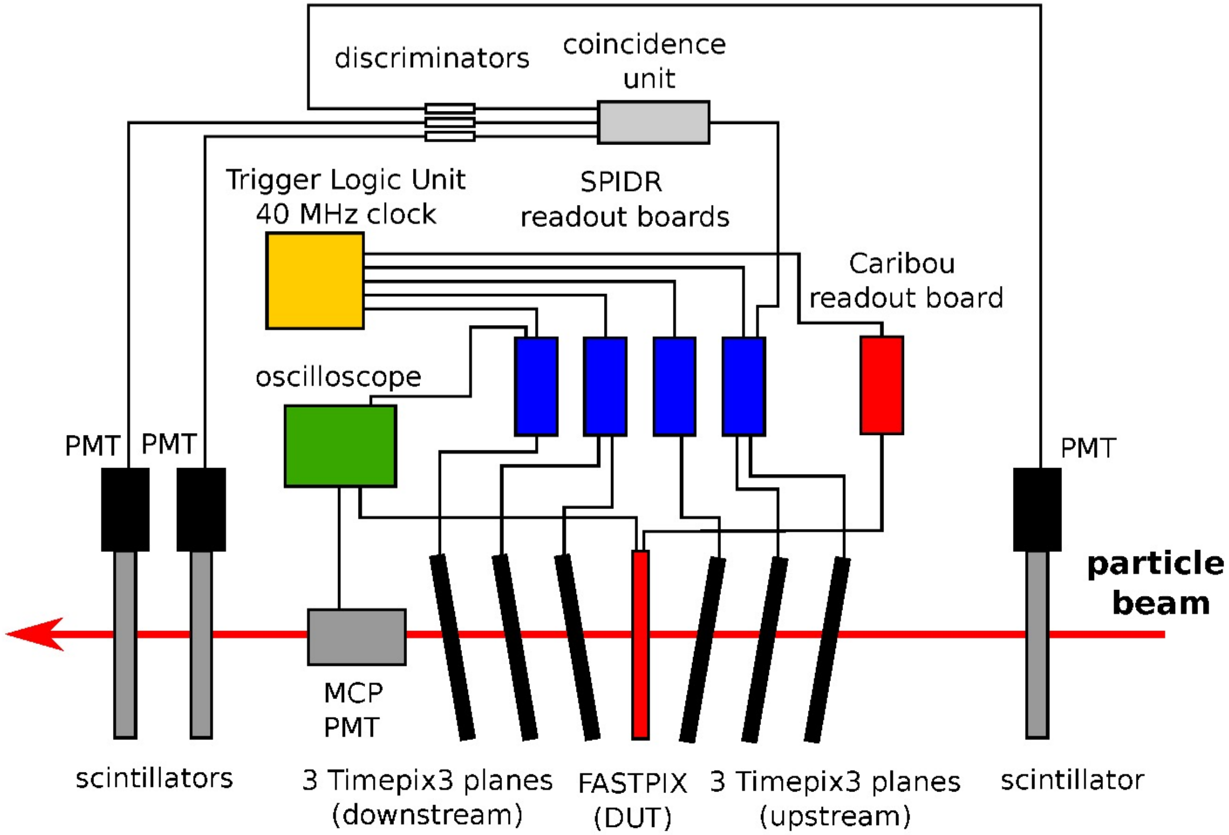


Readout Architecture





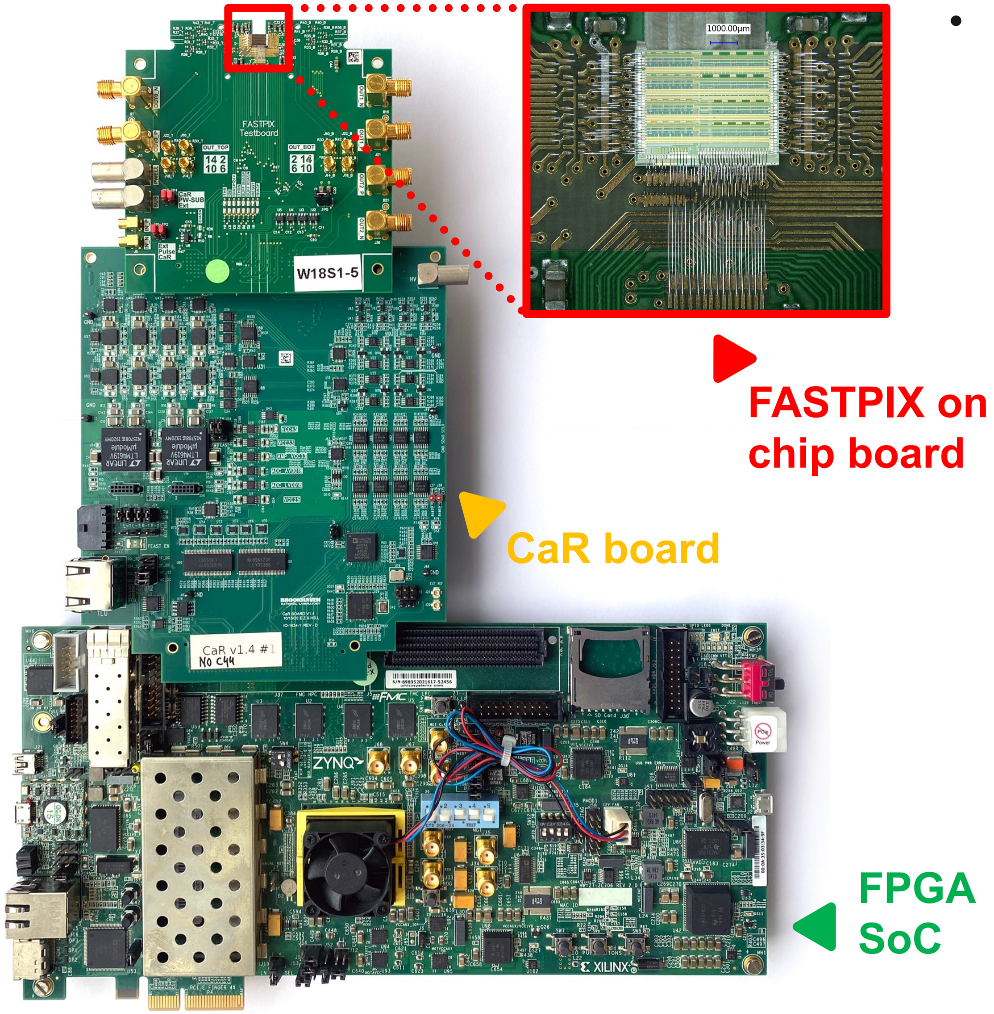
CLICdp Timepix3 Telescope Schematic



- **6 x Timepix3 connected to SPIDR readout boards**
- **Coincidence of Scintillator-PMTs is fed to TDC on a SPIDR board**

- **FASTPIX and oscilloscope controlled by Caribou and connected to telescope DAQ**
  - **FASTPIX** at -6V bias at substrate and p-wells
  - ➔ **Oscilloscope** triggers on **FASTPIX** fast **OR**
  - ➔ Triggers are fed to TDC on a **SPIDR board** for synchronization
- **Analysis with Corryvreckan reconstruction framework**
  - 2020 JINST 16 P03008
  - 2021 JPS Conf. Proc. 34, 010024
  - ➔ DLY calibration, raw data decoding scripts (C++)
  - ➔ Alignment, analysis in Corryvreckan
  - ➔ High-level analysis and plotting (Python, C++)

Readout and Measurement Setup



- **Caribou Data Acquisition System**

  Most recent publication by E Buschmann
  DOI 10.1088/1748-0221/18/02/C02005

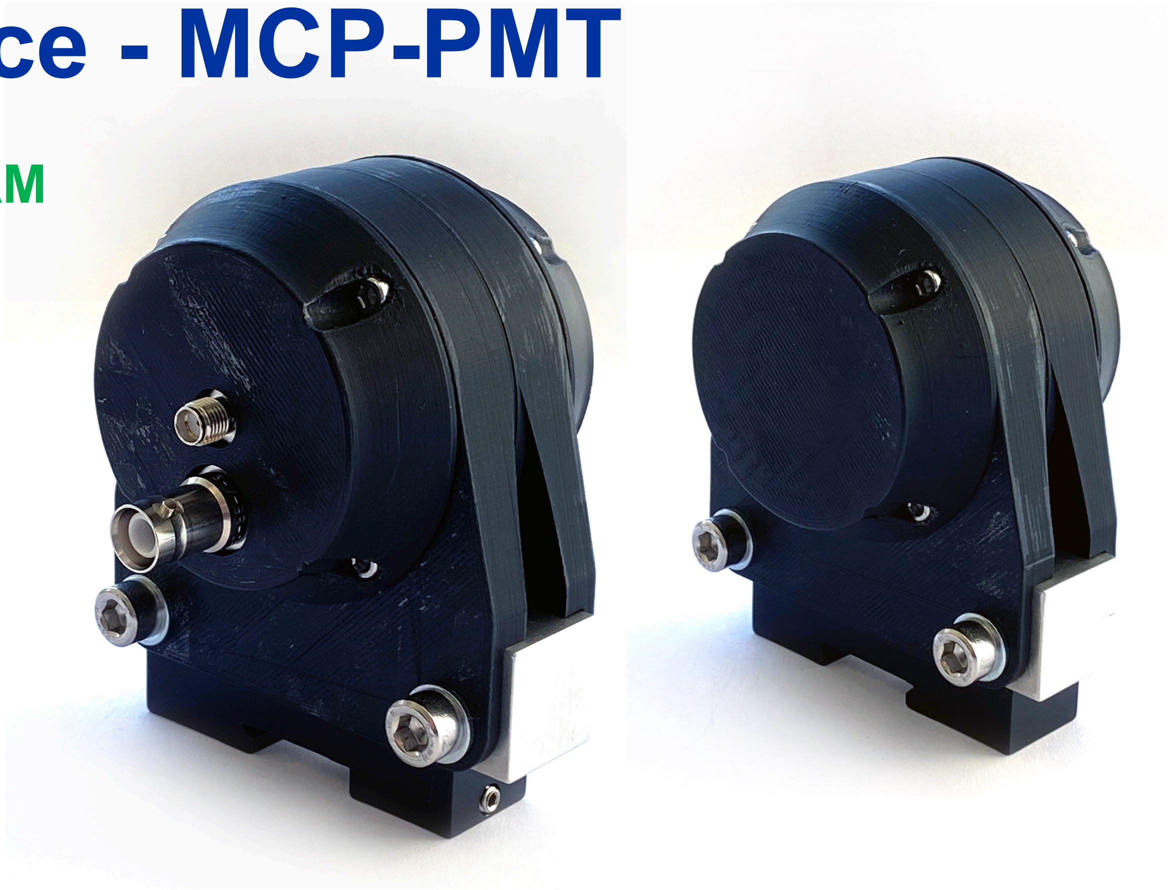
- **Stand-alone setup for initial laboratory tests and calibration**

  ➔ **FASTPIX chip board** contains wire-bonded detector, connects to readout system

  ➔ **CaR board** provides power, bias voltages and currents and configuration/control of detector

  ➔ **FPGA/SoC** runs Peary, the detector specific control firmware and data readout/processing software

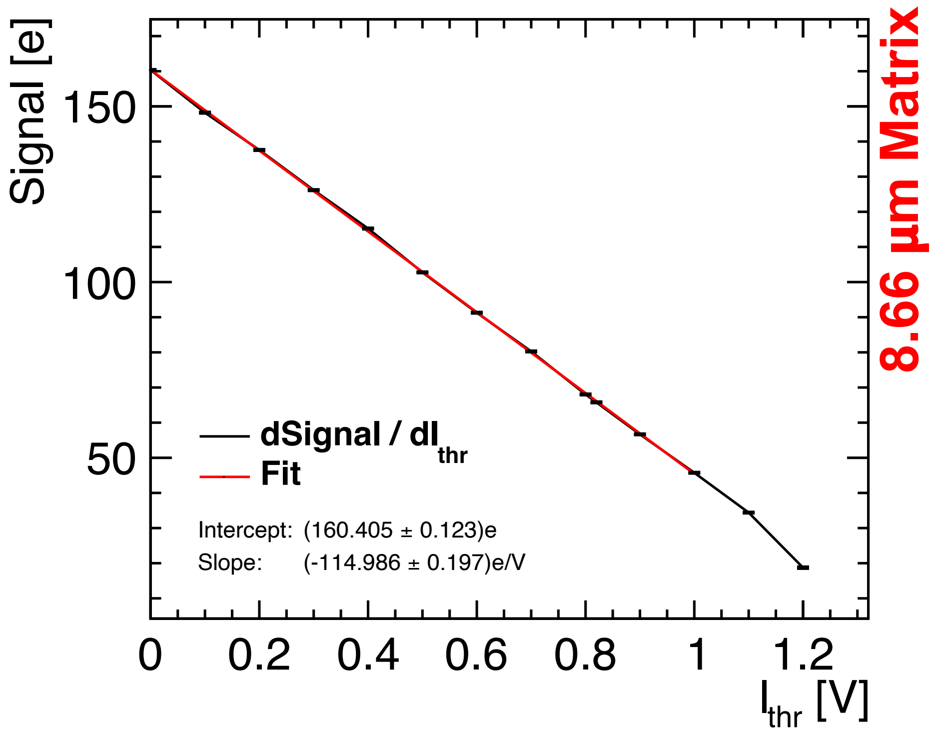
Independent Time Reference - MCP-PMT

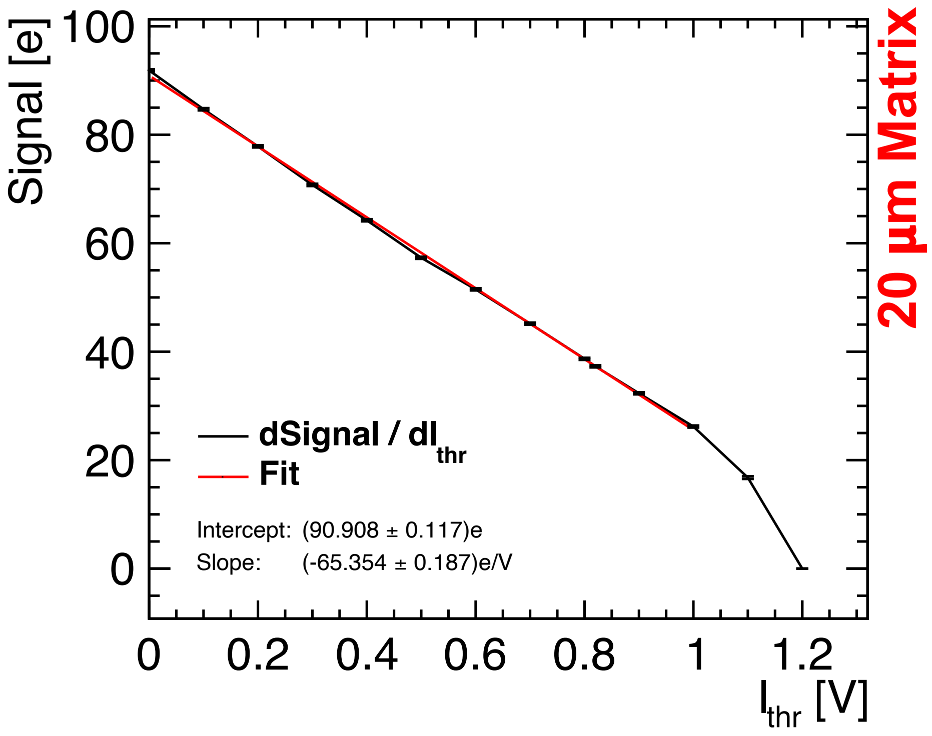


HAMAMATSU R3809U-50 CT1742

- Acceptance ~1 cm^2, expected resolution below 10 ps (see: J. Bortfeldt et al.)
- Built-in amplifier and bias-T circuit (V_{bias} = 2.6 kV) → Oscilloscope-based readout
- Custom 3D printed housing adapts to high-precision rails of telescope arms

Threshold Calibration with Test Pulses

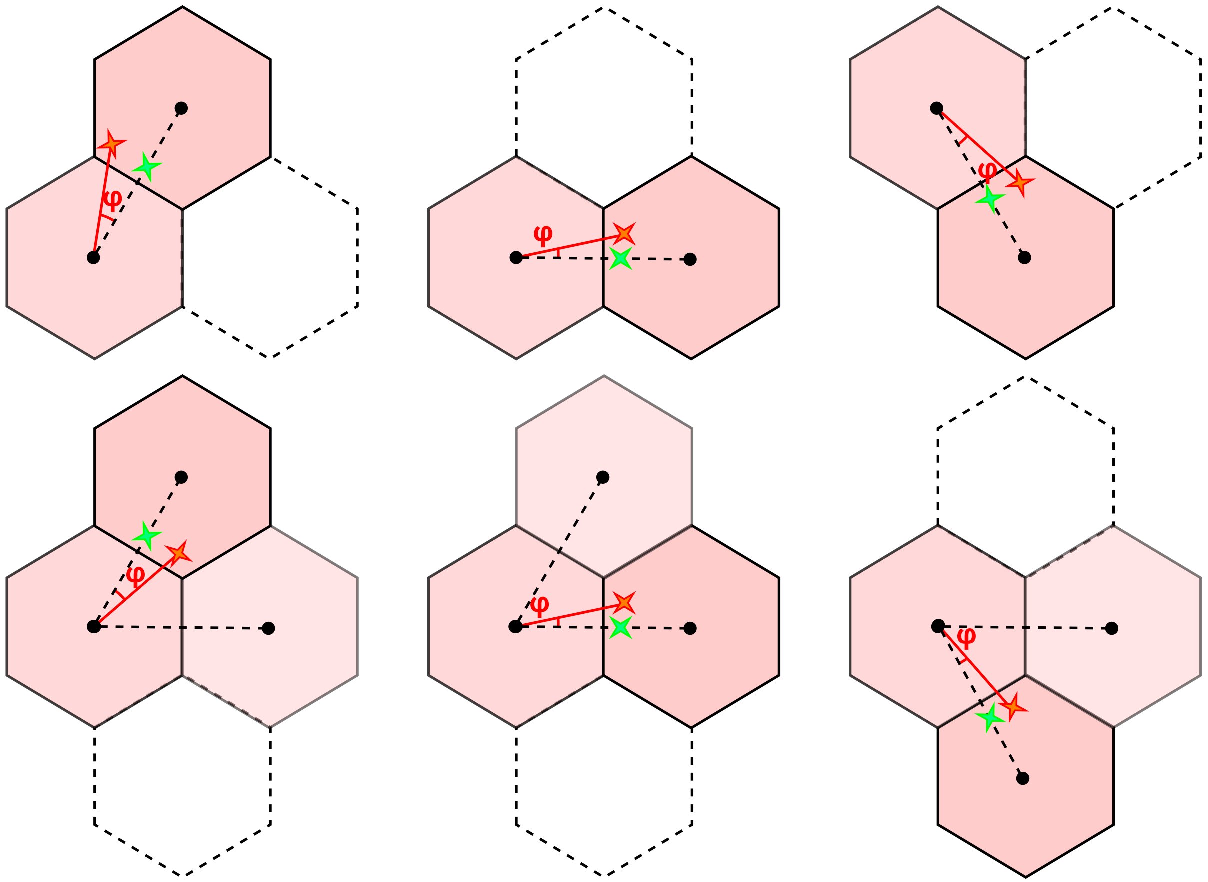




Signal in e^- is calculated using the design value of the test pulse capacitor

- Range follows approx. linear trend but fails to extend to higher electron-thresholds

Eta Correction for hexagonal pixels



Correction in radial coordinates (r,φ) account for different axes in hexagonal grid Håkan Wennlöf et al.

- **Reference position: Center of lowest, left-most pixel in cluster**
- **Algorithm for two-pixel clusters**

$$\Delta\varphi = \varphi_{\text{track}} - \varphi_{\text{cluster}}$$
$$r_{\text{track, projected}} = r_{\text{track}} \cdot \cos(\Delta\varphi)$$
$$phiDist_{\text{track, projected}} = r_{\text{track}} \cdot \sin(\Delta\varphi)$$

➔ No correction in angular direction

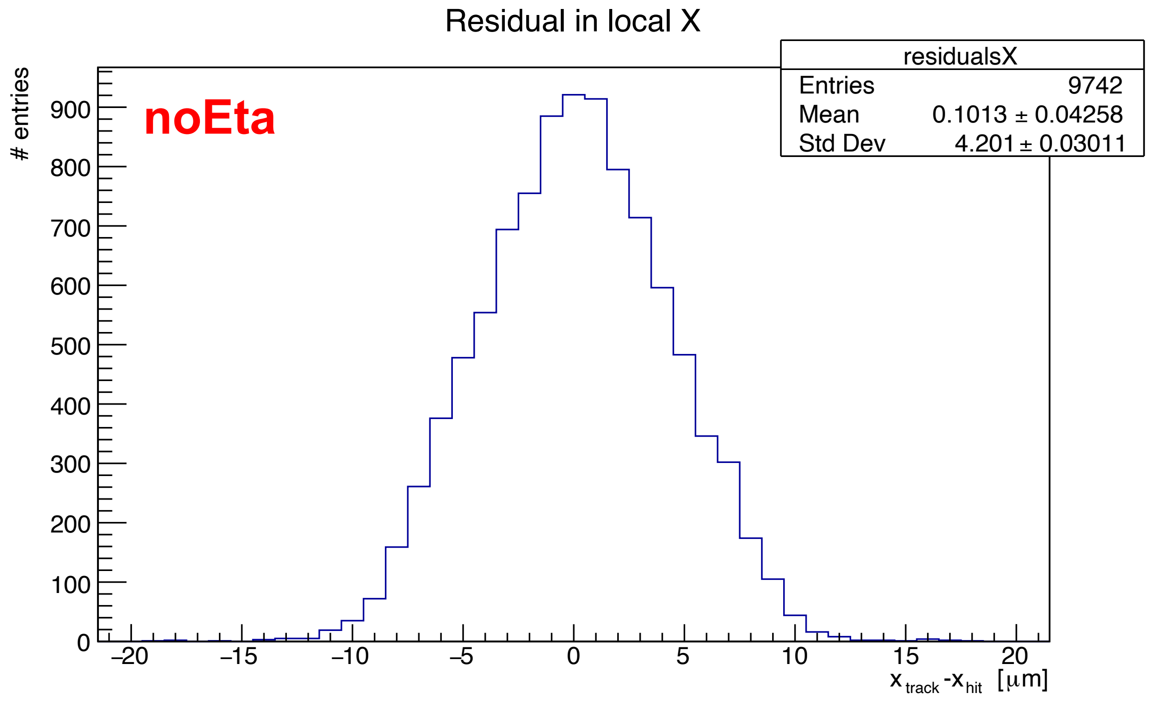
- **Algorithm for three-pixel clusters** similar in r

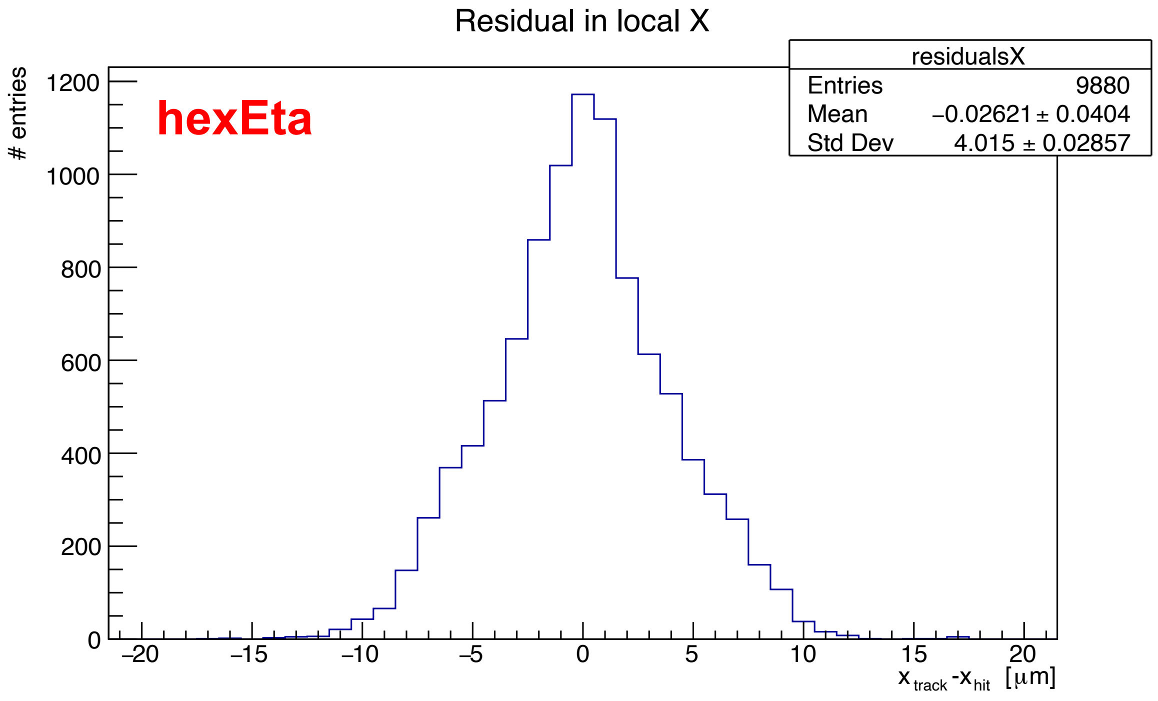
$$x_{\text{new}} = r_{\text{new}} \cdot \cos(\varphi_{\text{new}}) + x_{\text{reference}}$$
$$y_{\text{new}} = r_{\text{new}} \cdot \sin(\varphi_{\text{new}}) + y_{\text{reference}}$$

➔ Correction in angular direction possible

➔ Two possible **φ**-ranges: [-60°, 0°] & [0°, 60°]

Unbiased Residual in x – all cluster sizes – 20 µm

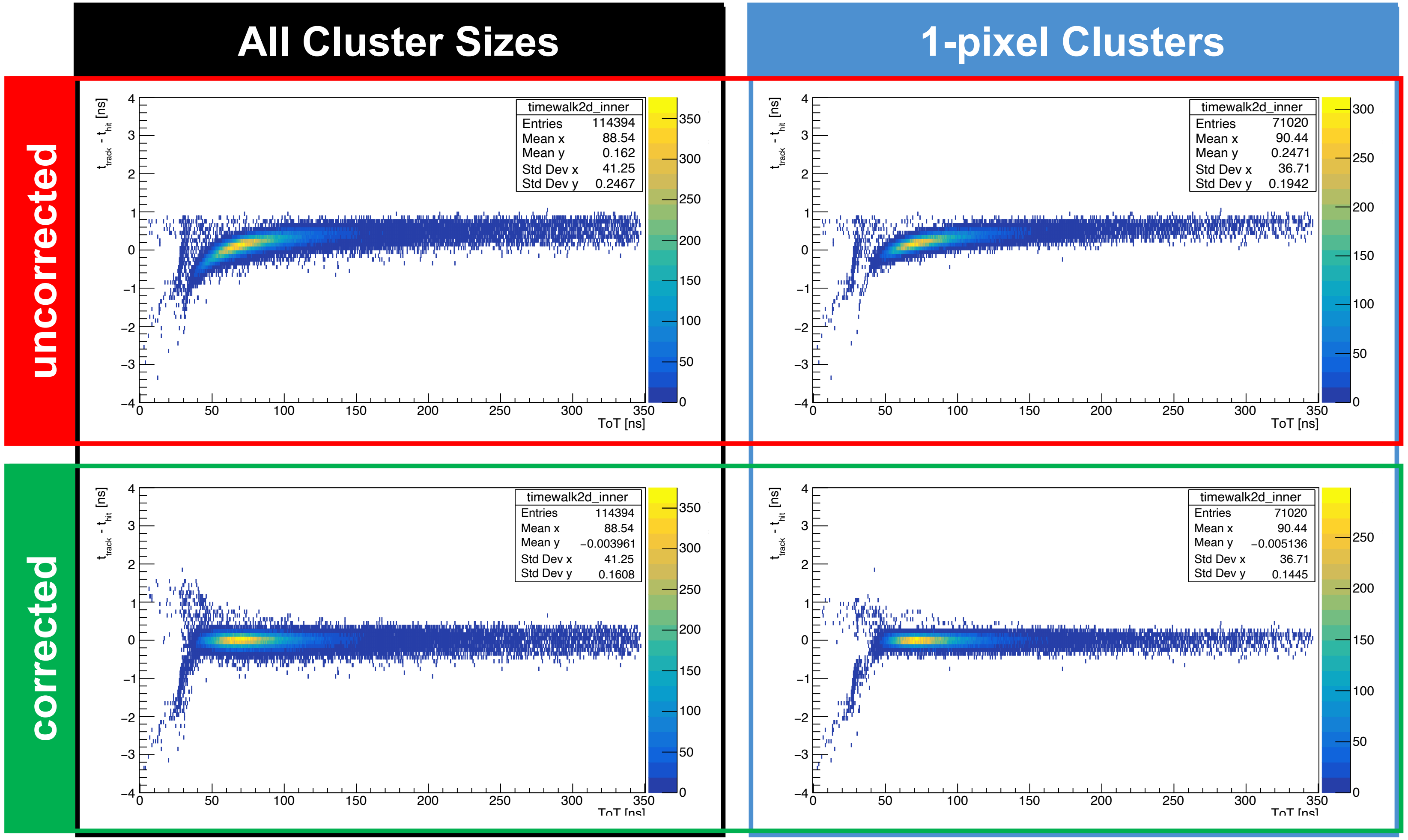




Unbiased residual in x – pixel pitch p_{CERN} = 20 µm ≡ p_{APSQ} = 23.1 µm

- Binary resolution approx.: $(20\ \mu m / 12^{1/2})_{CERN}$ = 5.8 µm ≡ $(23.1\ \mu m / 12^{1/2})_{APSQ}$ = 6.7 µm
- Telescope tracking resolution at DUT position: approx. 1.7 µm

Time Walk Correction – 20 µm Pixel Pitch



Correction shown for all cluster sizes and 1-pixel clusters in this example

- **Seed-pixel residuals over ToT** on pixel-by-pixel level
- **Correction method**

  Split data into two sets

  Set 1: obtain mean per ToT bin

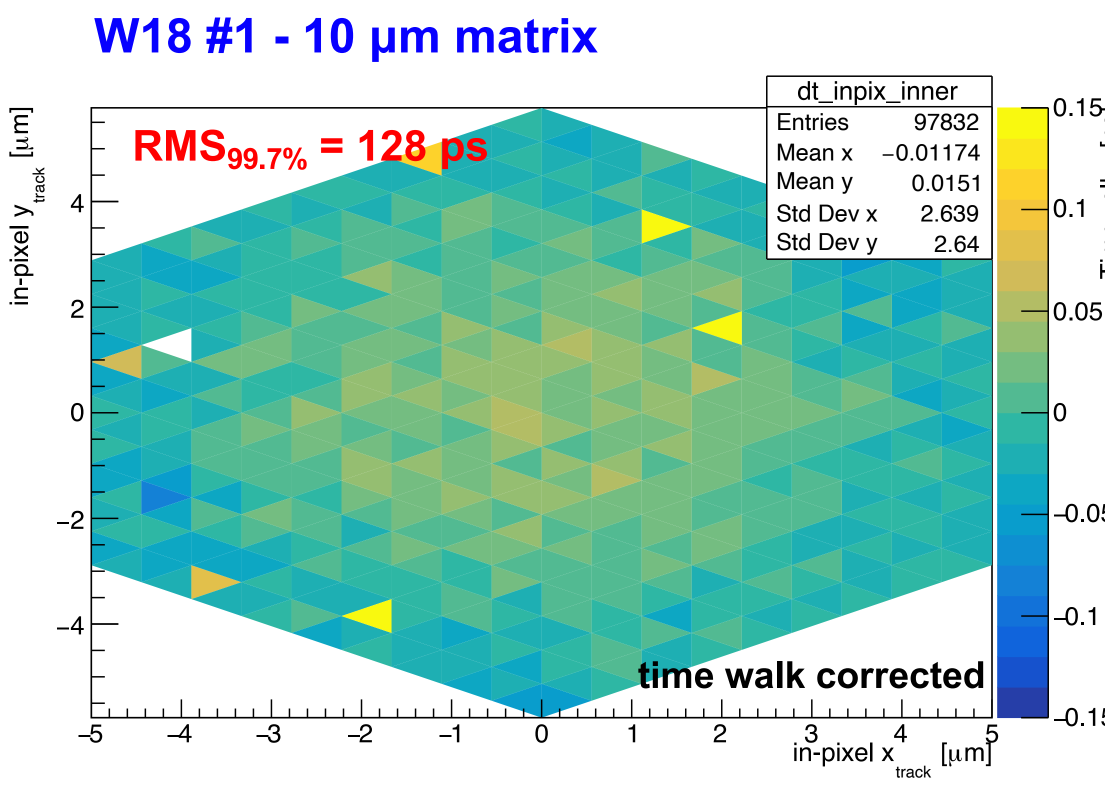
  Set 2: correct by subtracting mean of corresponding ToT bin from set 1

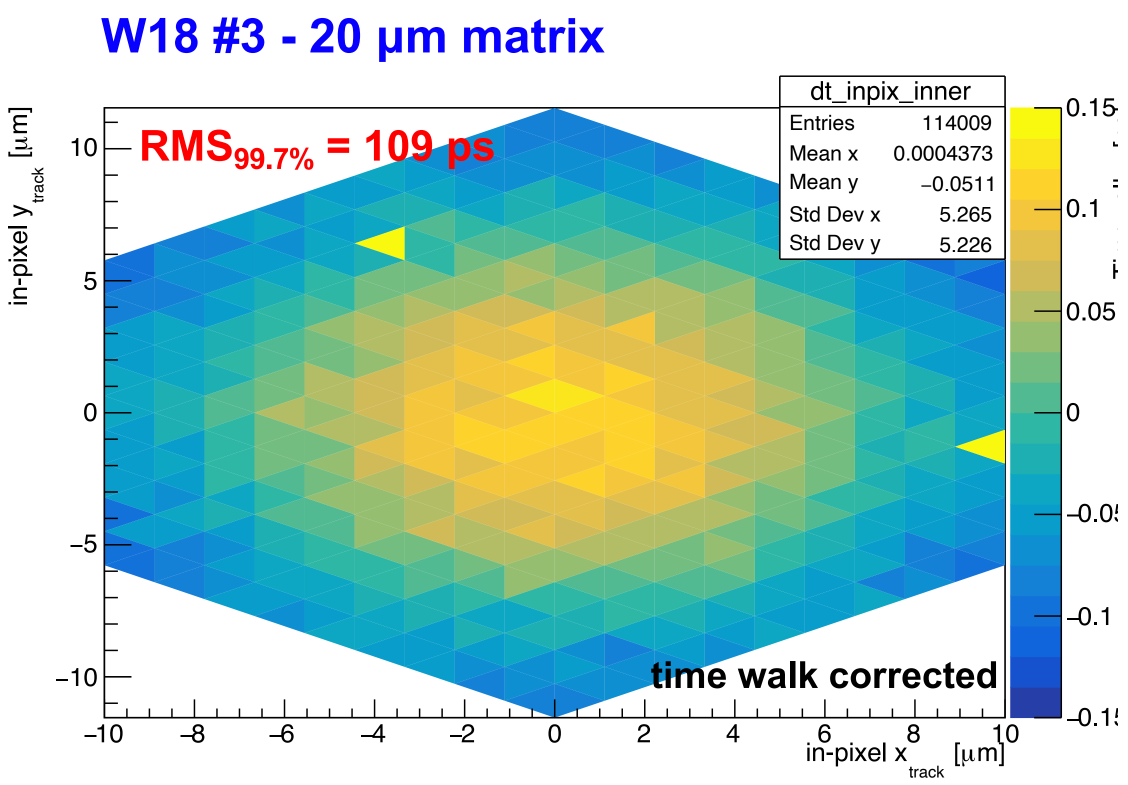
  Repeat vice versa
- **Correction per cluster size for 1-, 2-, 3-, 4-, ≥ 5-pixel clusters**

  Impacts on timing performance

  - Signal share collected in seed pixel
  - In-pixel particle incidence

In-Pixel Timing for Optimized Process





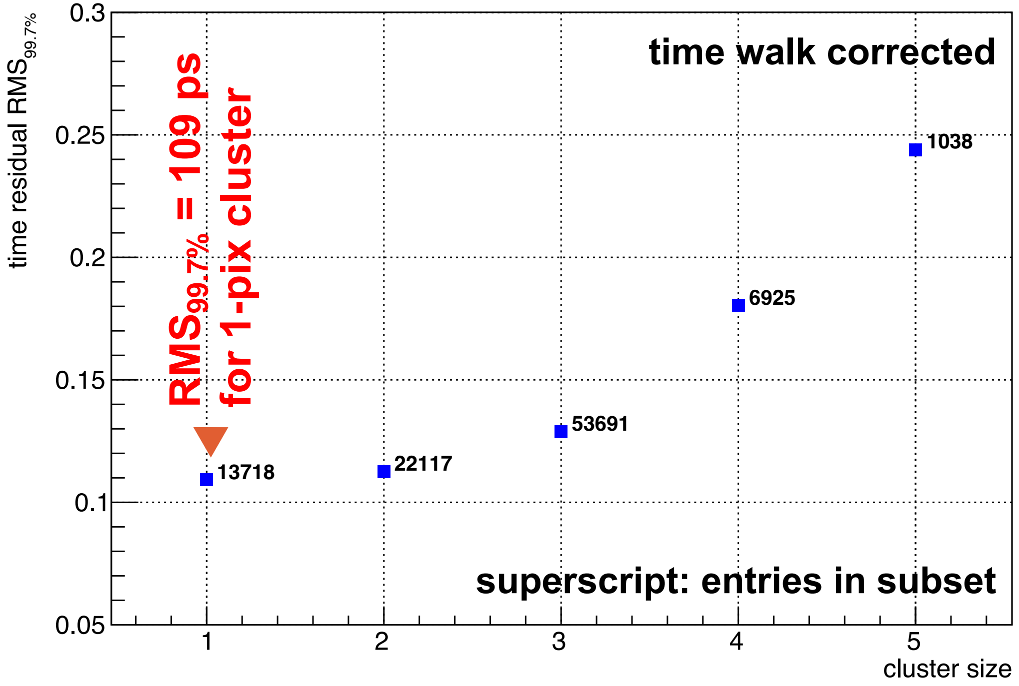
Smaller pitch ➔ shorter drift distance <u>but also</u> **more charge sharing** <u>and</u> **larger cluster size**

➔ Deteriorated time resolution for the seed pixel ➔ better performance for larger pixel pitch

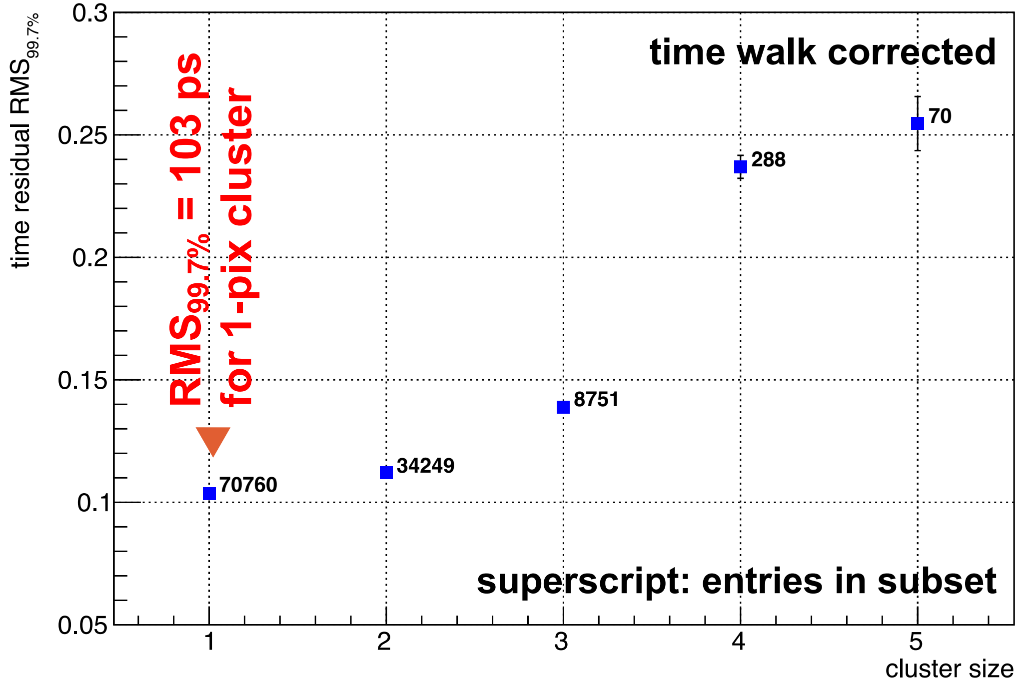
➔ **20 µm matrix** shows **15% better timing performance** compared to 10 µm matrix in optimized process

Time Residuals for Optimized Process

W18 #1 - 10 µm matrix



W18 #3 - 20 µm matrix



Larger cluster size ➔ more charge sharing ➔ deteriorated time resolution for the seed pixel

➔ Better performance for smaller cluster size

➔ **Timing precision of 103 ps in single pixel clusters** with 20 µm matrix in optimized process