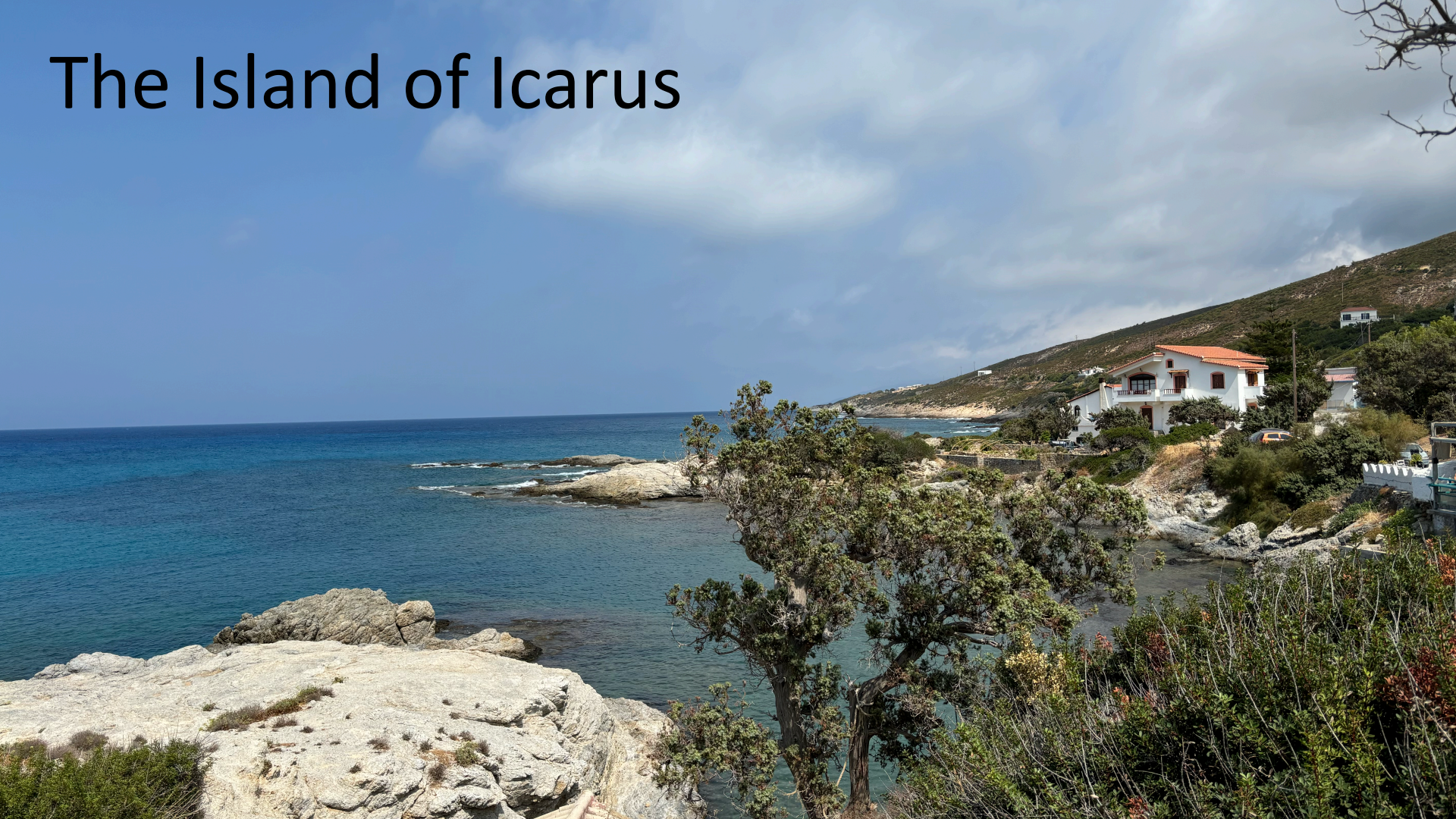
Testbeam results on 3D silicon sensors

A presentation for the FASTER summer meeting in Maastricht

The Island of Icarus




25 ps
Old fashioned sensor tech
Conventional electronics

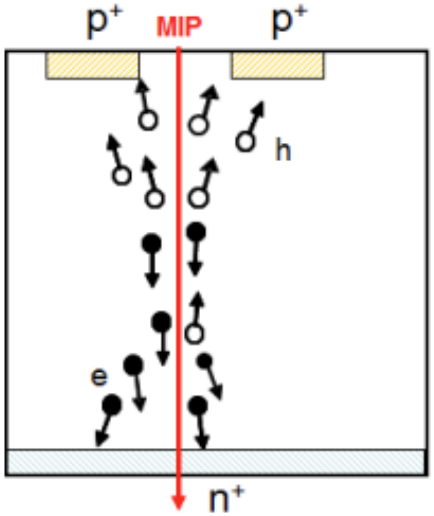

25 ps
Noise
Break down
slow
Material budget
Jitter
Trapping


25 ps
New fast-timing
technologies

Timing silicon detectors

The (g)old planar silicon sensors

- Silicon detectors are based on reverse biased p-n junctions
- Incoming charged particle create electron–hole pairs along its path
- In the presence of an electric field, these e-h pairs drift toward the electrodes, inducing current

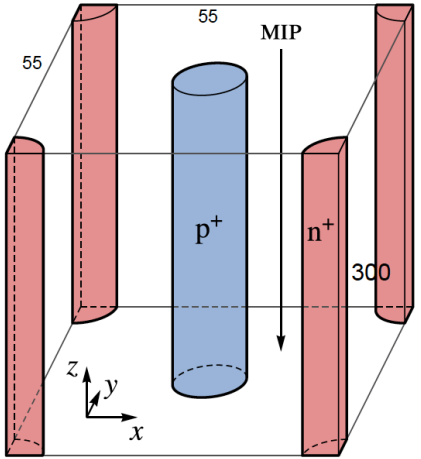


New fast timing sensor technologies

- LGAD
- 3D
- MAPS

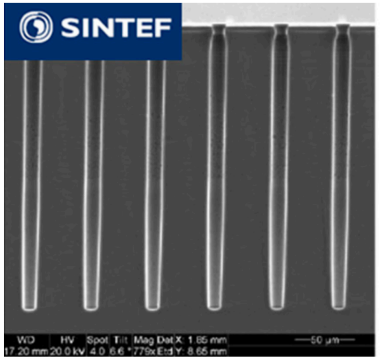
Social media photo…

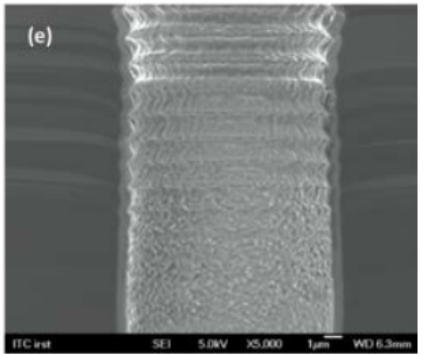
Basic Concept of 3D sensors



- The electrodes of 3D sensors penetrate the silicon bulk
- Electron-hole pairs drift perpendicular to track direction
- Wafer thickness decoupled from drift distance
  - Track length => signal amplitude
  - Drift distance => collection time

The reality…

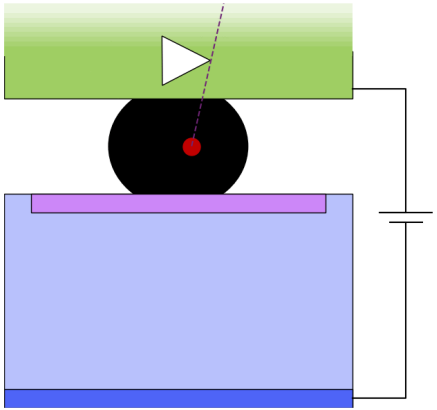




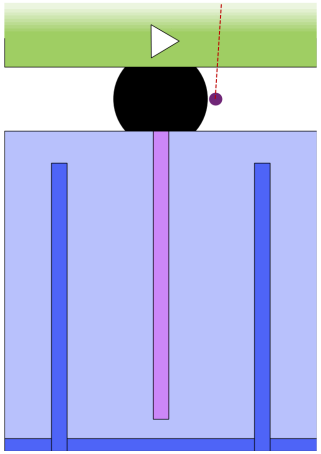
Planar vs 3D

Fast timing can be achieved with thin planar sensors.

However this results in smaller signal (e.g. not detected particles)

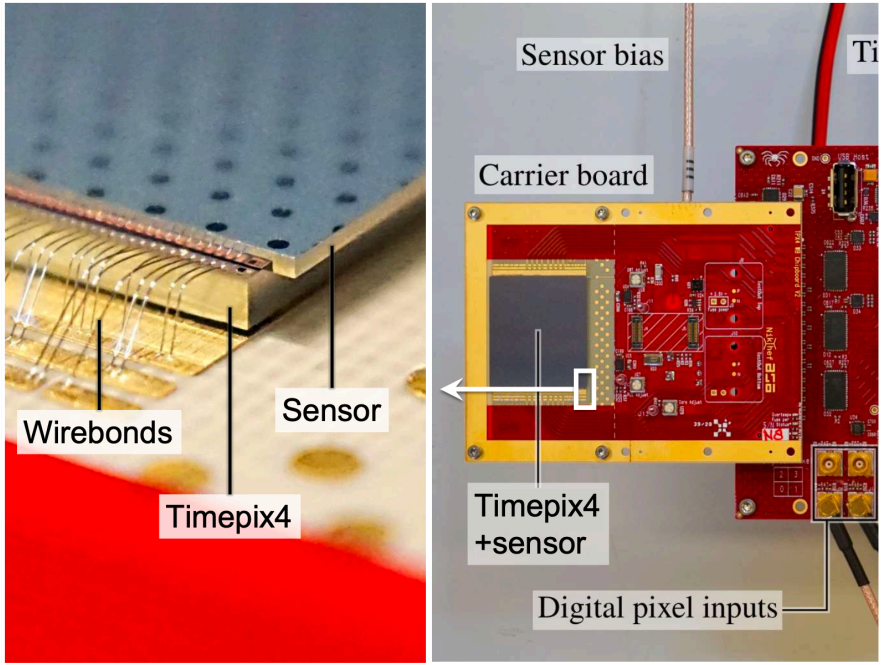


- **Increased signal-to-threshold ratio**
- **Radiation hard**
- **Reduced charge sharing**
- **Inefficient regions**
- **Production costs**

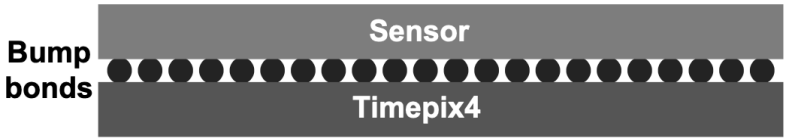


3D sensor on Timepix4

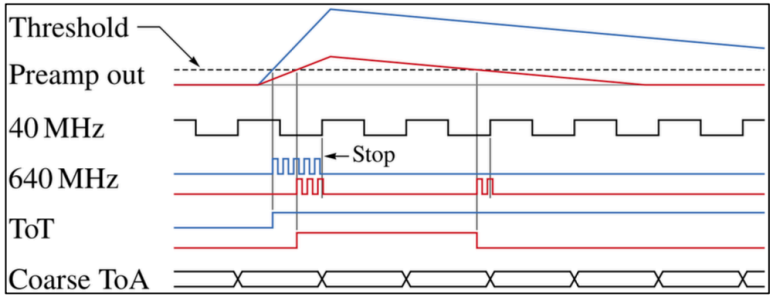
Timepix4 readout chip

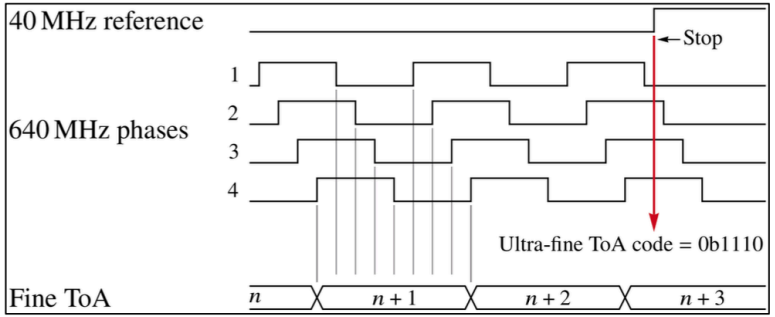


- Developed by CERN, Nikhef, and IFAE
- 448×512 pixels, $55 \times 55\ \mu m^2$ pitch
- Simultaneous measurement of time and charge deposition



Timepix4 time measurements





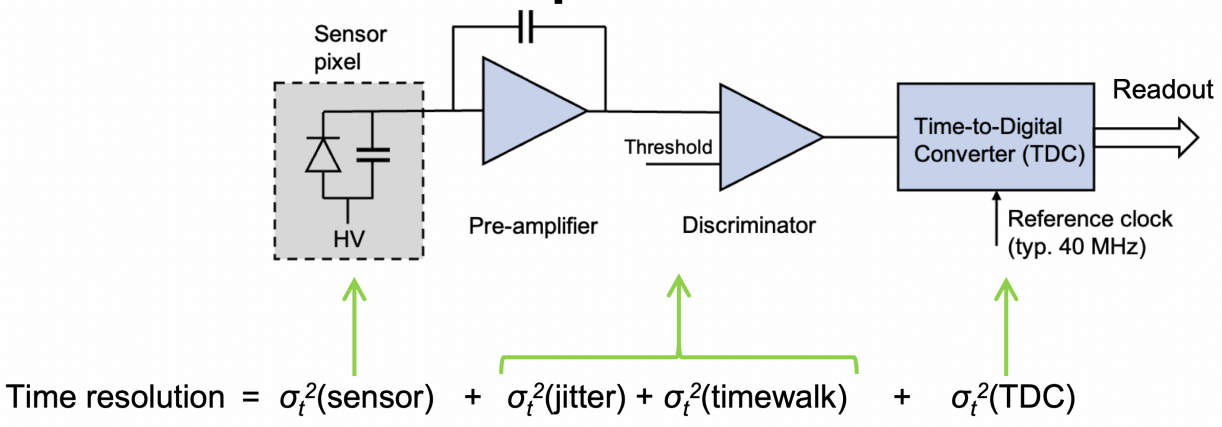
Timepix4 deploys 2 clocks to measure the time accurately:

- $40\ MHz$: Coarse ToA $\sim 25\ ns$
- $640\ MHz$ Voltage Control Oscillator (VCO): Fine ToA $\sim 1.56\ ns$
- 4 phase shifted VCOs: Ultra-fine ToA

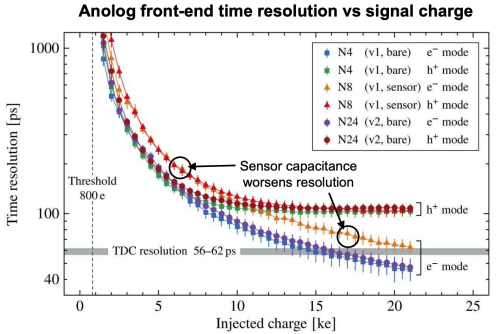
Time is binned in $195\ ps$ resulting in a *best possible time resolution* of:

$$\frac{195\ ps}{\sqrt{(12)}} \sim 56\ ps$$

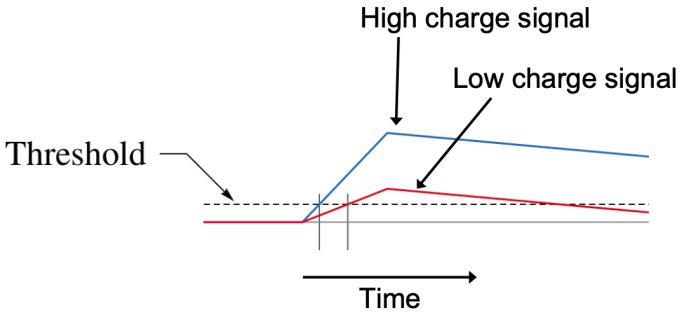
Time resolution components



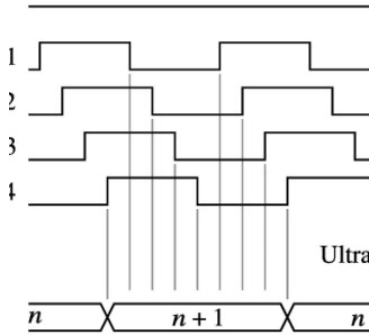
$\sigma(jitter) \sim 90\ ps$



$\sigma(tw)$: *correct*

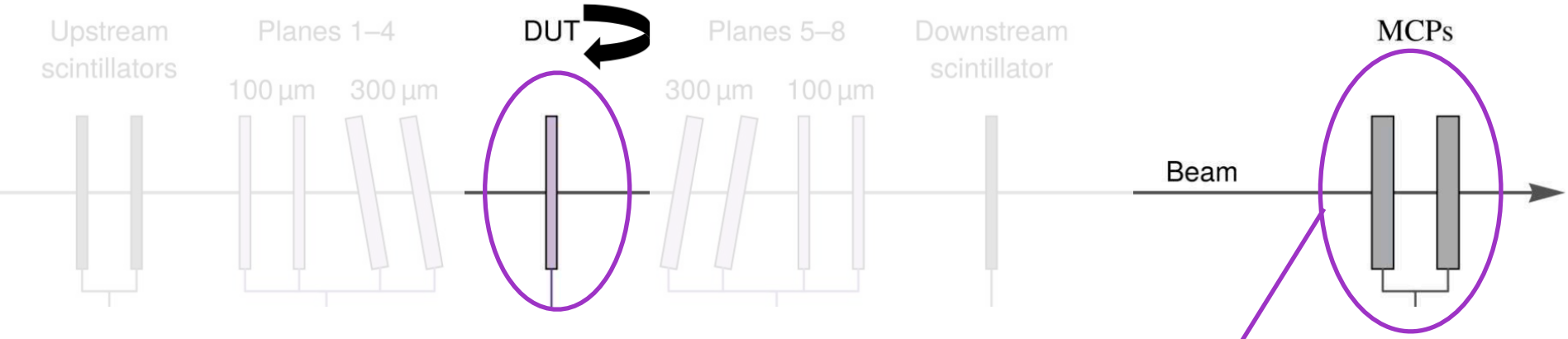


$\sigma(tdc) \sim 56\ ps$

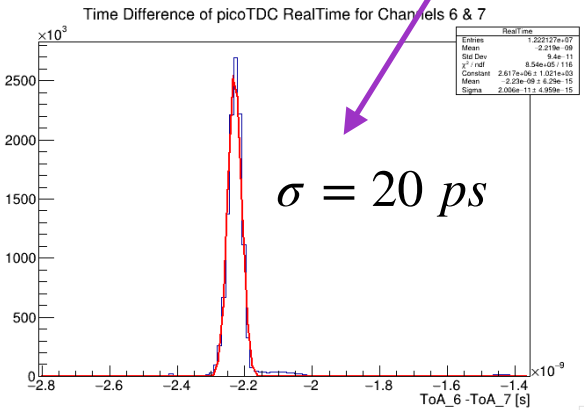


Time resolution of a 3D assembly using testbeam data

Testbeam setup



- 2 independent Micro Channel Plates (MCPs) with time resolution $\sim 14\ ps$ each (assuming they are identical)
- Combined MCPs time information is used as reference

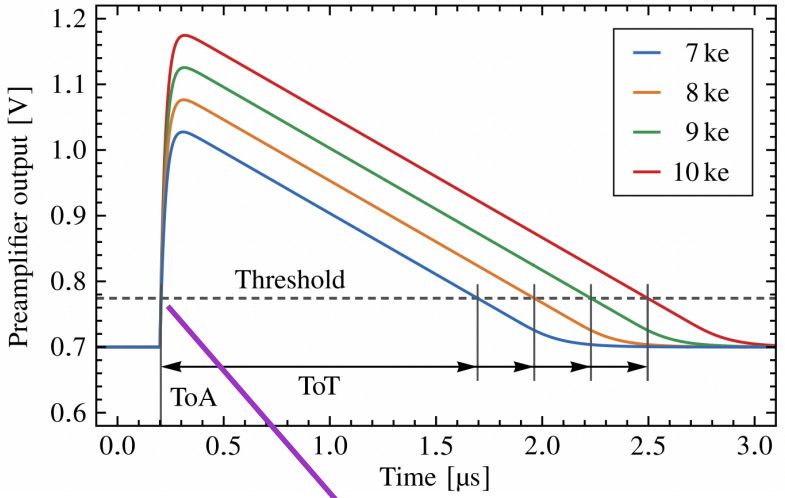


Timewalk corrections

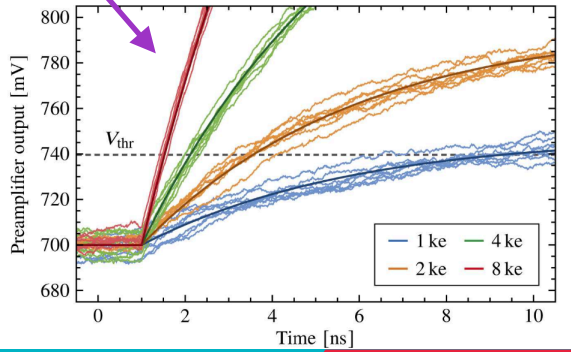
- Timewalk is the dependence of Time of Arrival (ToA) on the magnitude of the signal
- Time over Threshold (ToT) is a straight forward indication of signal amplitude
- ToT response for a certain amount of deposited charge differs per pixel.

  ➡Per pixel timewalk corrections are needed

Simulation! (not TPX4)



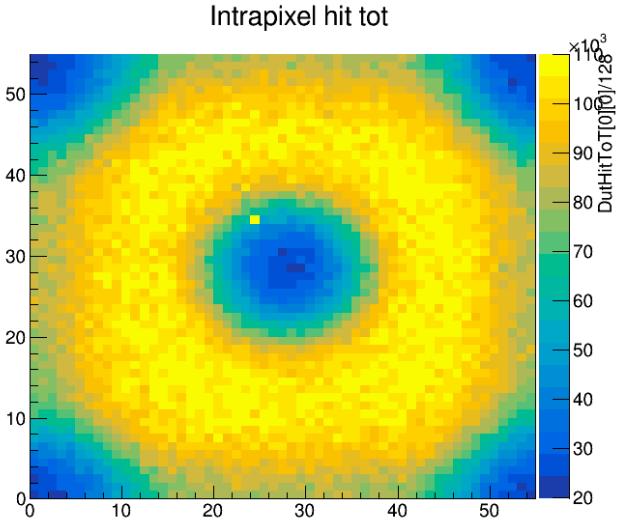
Simulation!



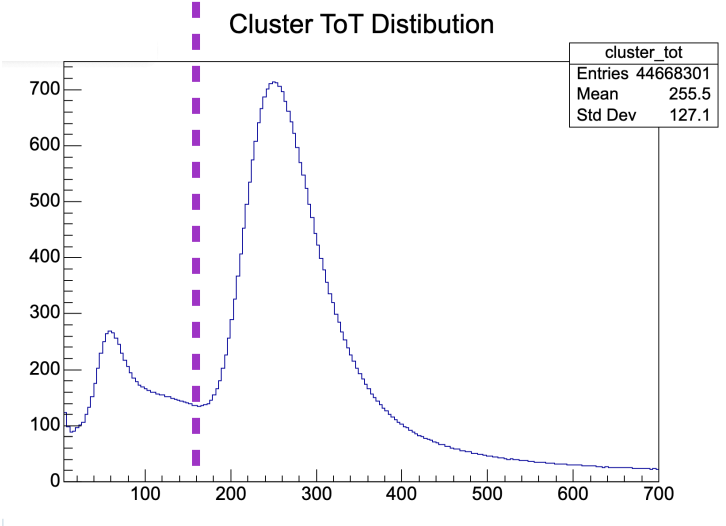
Timewalk corrections: Applied cut

For perpendicular incidence:

Smaller peak in lower cluster ToT values is explained by particles passed through the dead area of pillars therefore deposited less charge.

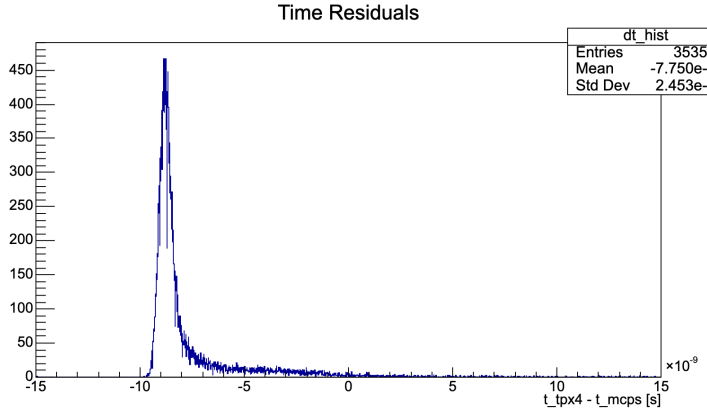


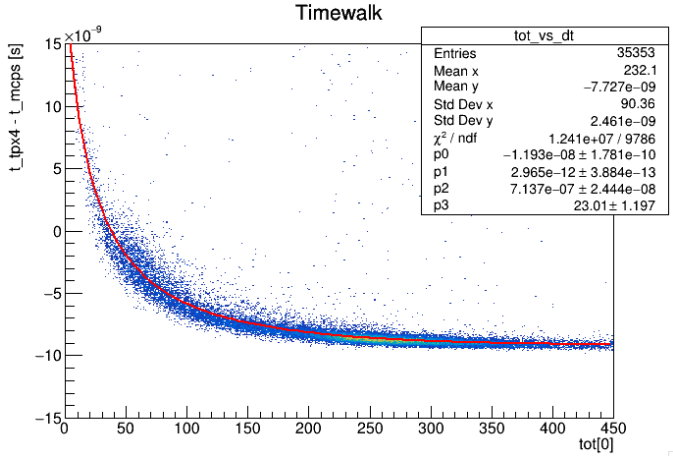
Cut: cl_tot>170

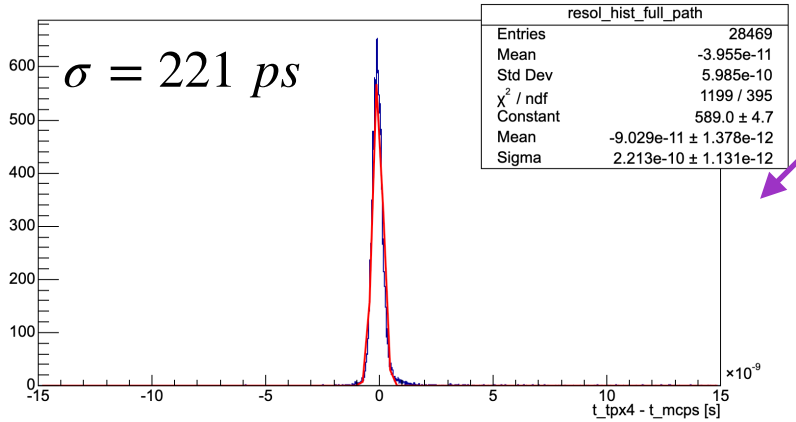


Timewalk corrections

Example pixel [199,306]:
Time resolution : 221 ps



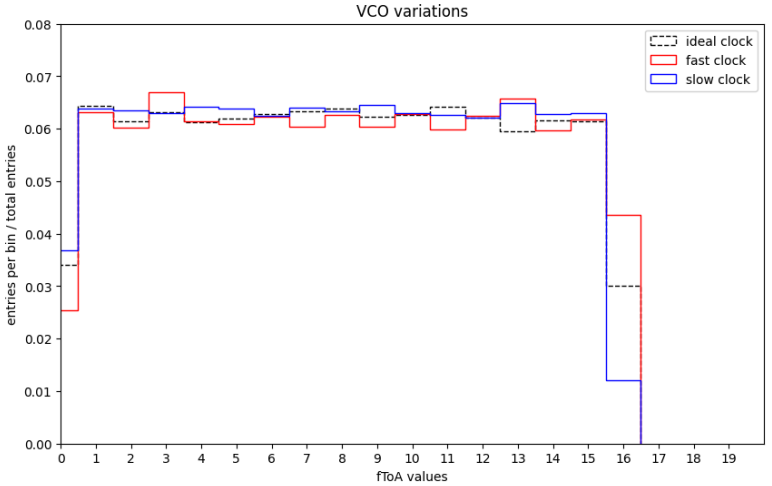


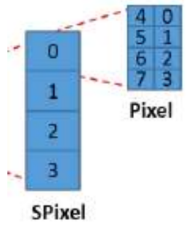


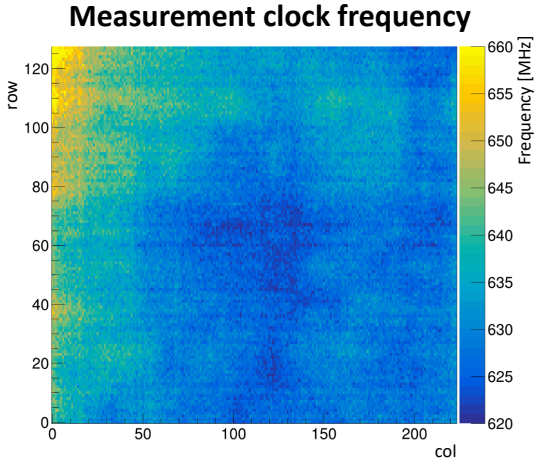
VCO corrections

- Superpixels have their own VCO, copies are not identical though
- Ideally, the $25\ ns$ are divided as:
  - ➡Bin 0 and 16 have half size by design
  - ➡Bin 1 to 15 should be equal to $1.56\ ns$
- Deviations of last bin from nominal size mean that the clock oscillates in a different frequency
- VCO frequency variations up to $6\ \%$ across TPX4 chip
- Per pixel VCO corrections are needed

Simulation!

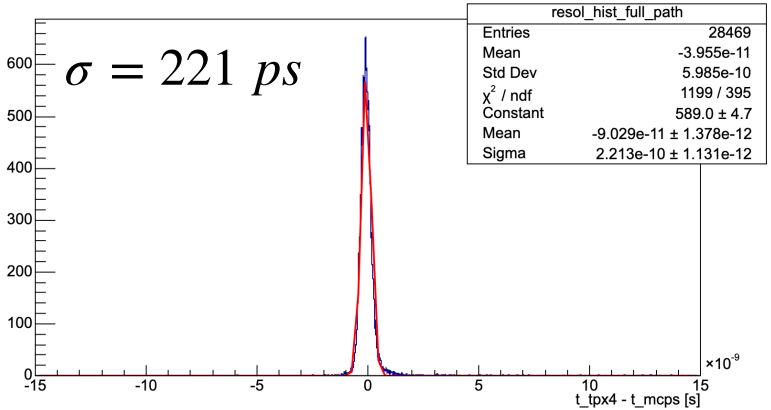


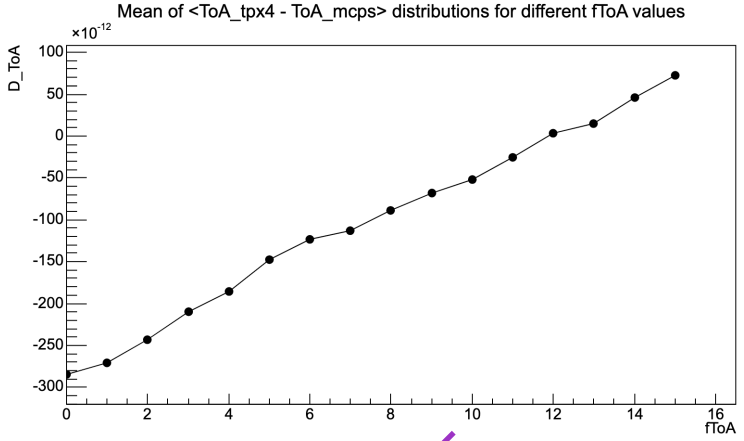


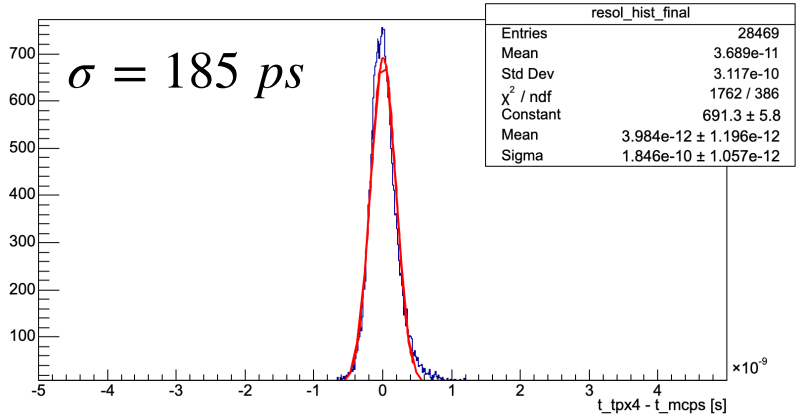


VCO corrections

Example pixel [199,306]:
Time resolution : 185 *ps*







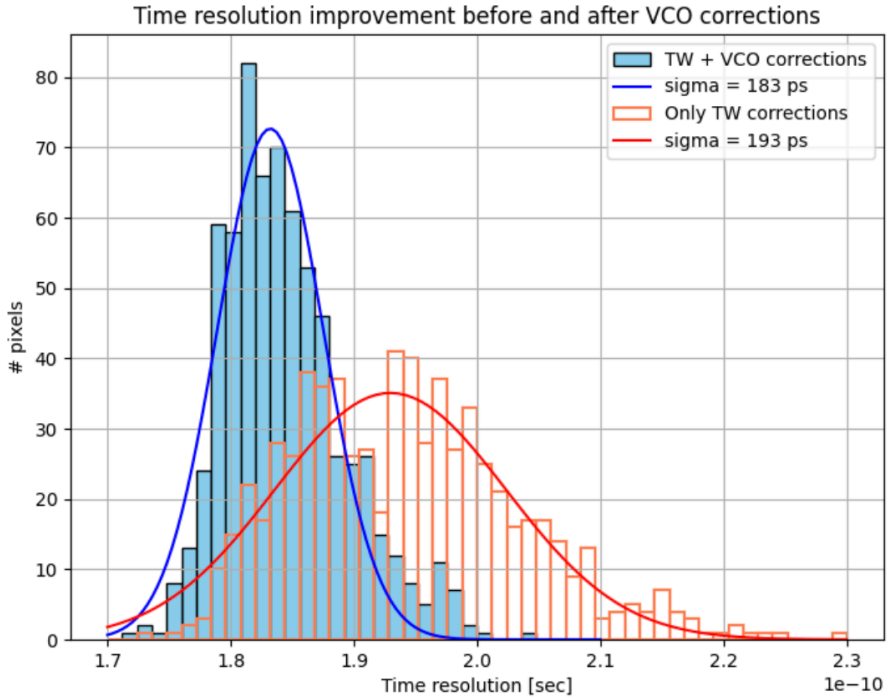
Sensor's performance

Repeating for all pixels with enough statistics (~ 700 pixels), time resolution is:

- $\sim 193\ ps$: after applying only timewalk corrections
- $\sim 183\ ps$: for combining time walk and VCO corrections

- Sensor resolution can roughly be estimated at:

$$\sigma_{sensor} \sim \sqrt{183^2 - 90^2 - 56^2} \sim 145\ ps \gg 25\ ps$$



Thoughts instead of conclusions

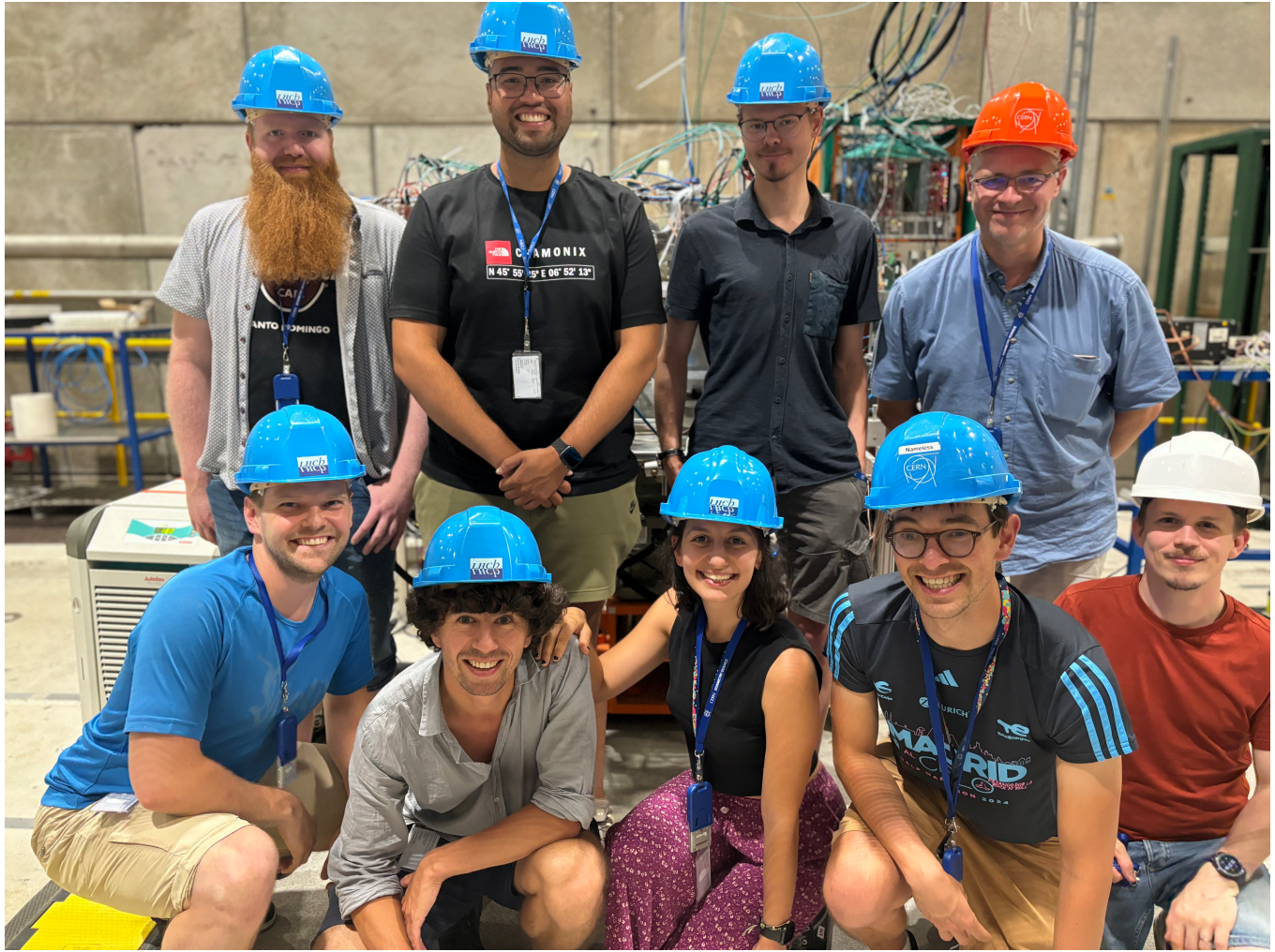
- Single pixel studies on 3D sensors show excellent fast-timing performance of 3D sensors. Design optimization is a work in progress.

- Our testbeam analysis of a full system 3D assembly reached a time resolution of $\sim 183\ ps$.

- With intrapixel studies we will investigate the efficiency as function of the intrapixel hit position

- New batch of 3D sensors with thinner pillars is coming.

THANK YOU !!

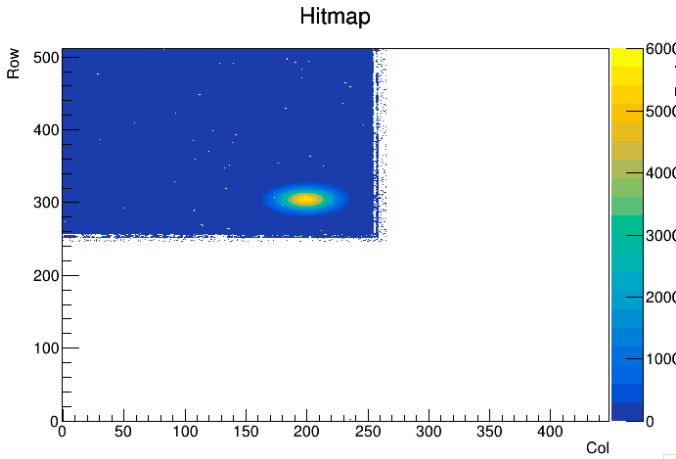


Questions ?

Backup

Details about 3D sensor used as DUT

- Sensor thickness = 300µm, pillar radius = 5µm , distance of pillar tip to opposite plane ~60µm
- Year of production ~ 2012
- Assembly N141, transplanted from Timepix3 to a Timepix4 chip
- Operated at 60V bias voltage, q=1 ke threshold
- Presented results from Run8152

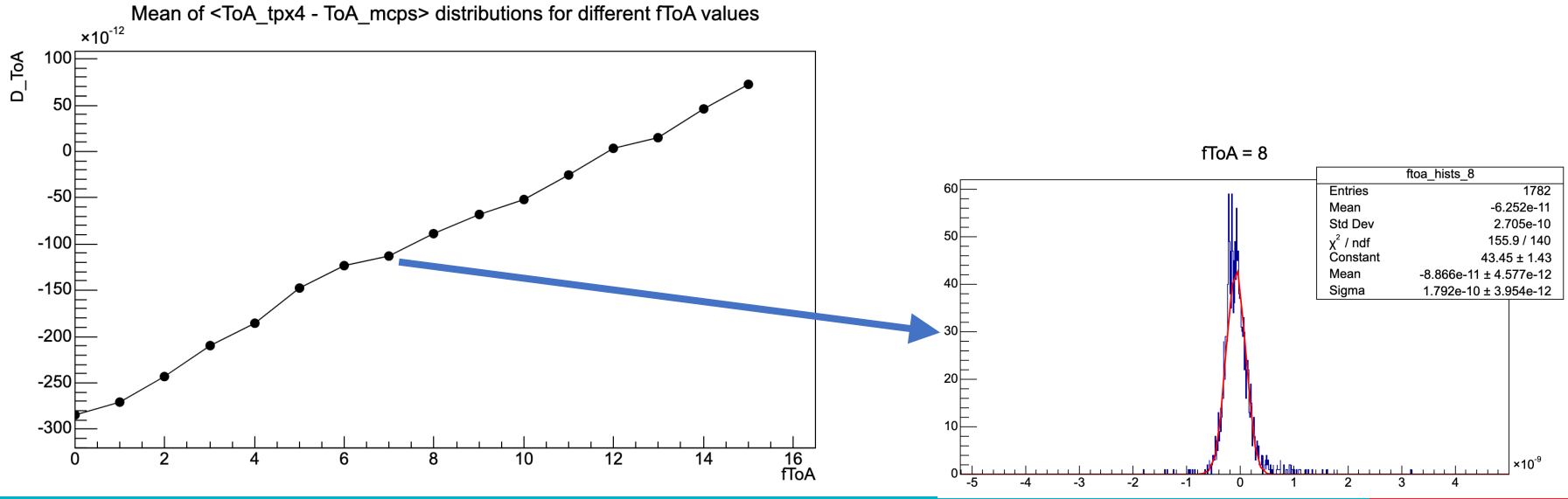


VCO corrections

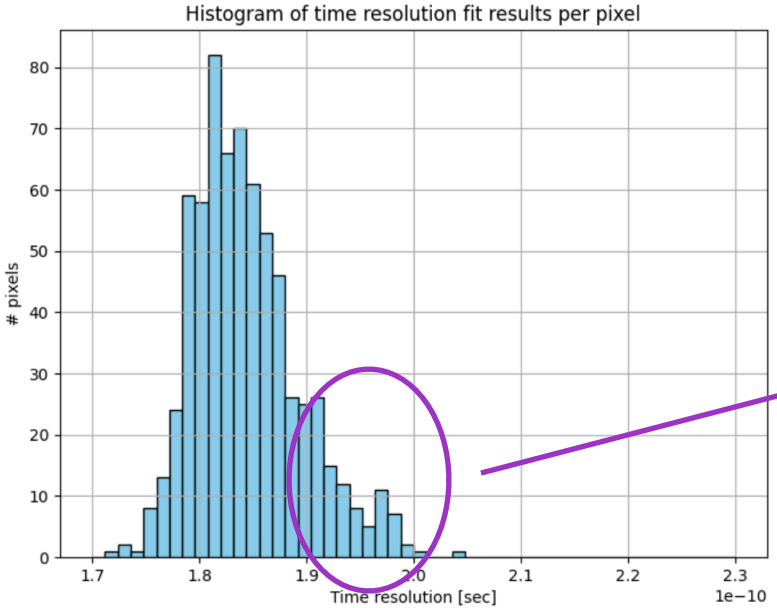
Reconstructed hit time:

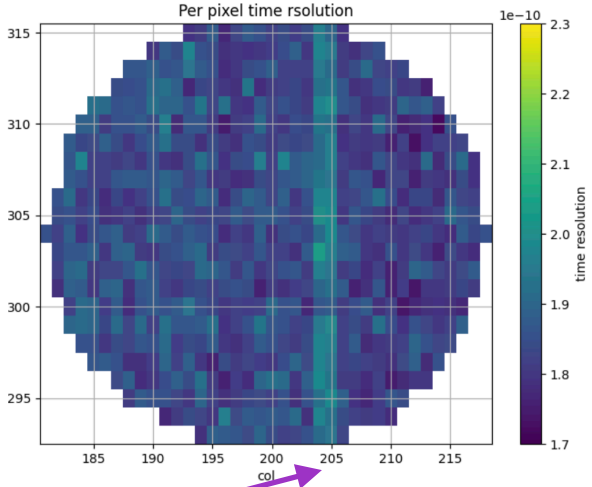
$$t_{hit} = cToA \cdot 25ns - a\frac{25ns}{16} fToA + O(2)$$

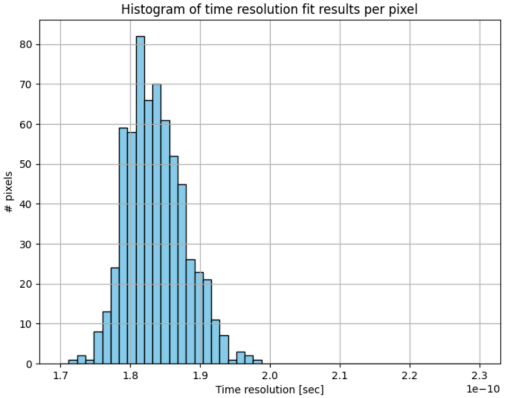
Where a : a correction factor that compensates VCO frequency variations.



Inefficient columns 204 & 205 ?





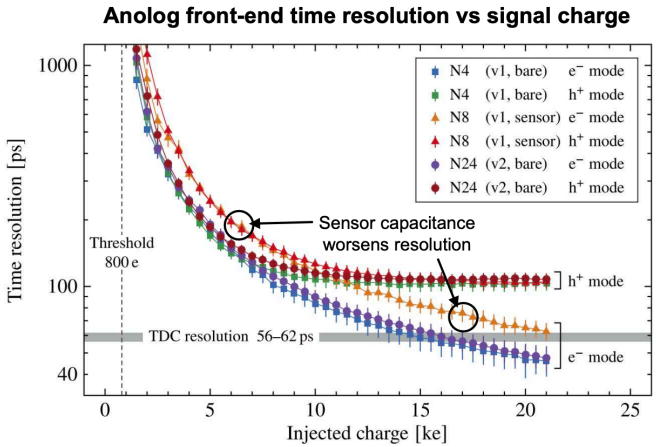


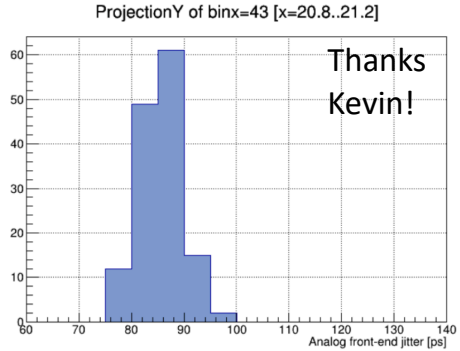
Front-end electronics resolution

Timepix4 is optimized for electron collection.

The tested 3D assembly is a hole collecting device.

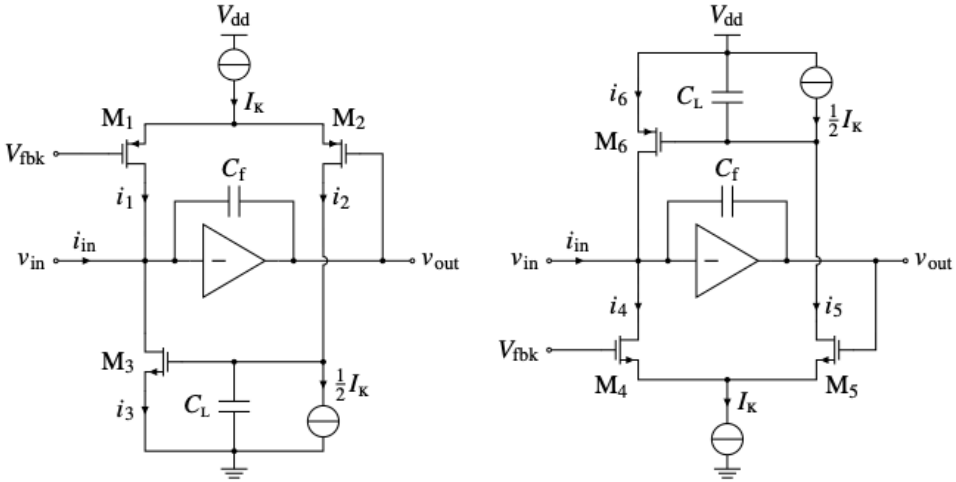
Front-end electronics $\sim 90\ ps$





Electron or Holes optimization circuit

- In equilibrium: Vfbk = Vout and i3 = Ik/2 +I_leak
- For dI in order to preserve Vfbk = Vout, we have: i3 = Ik/2 +I_leak +dI
- If dI>0 : i3>0 can compensate
- If dI<0: i3 can compensate up to dI=-Ik/2



Intrapixel drift time variations