Time is of the essence

Nikhef

FASTER Meeting

20th Sep. 2024

Working on Detector R&D

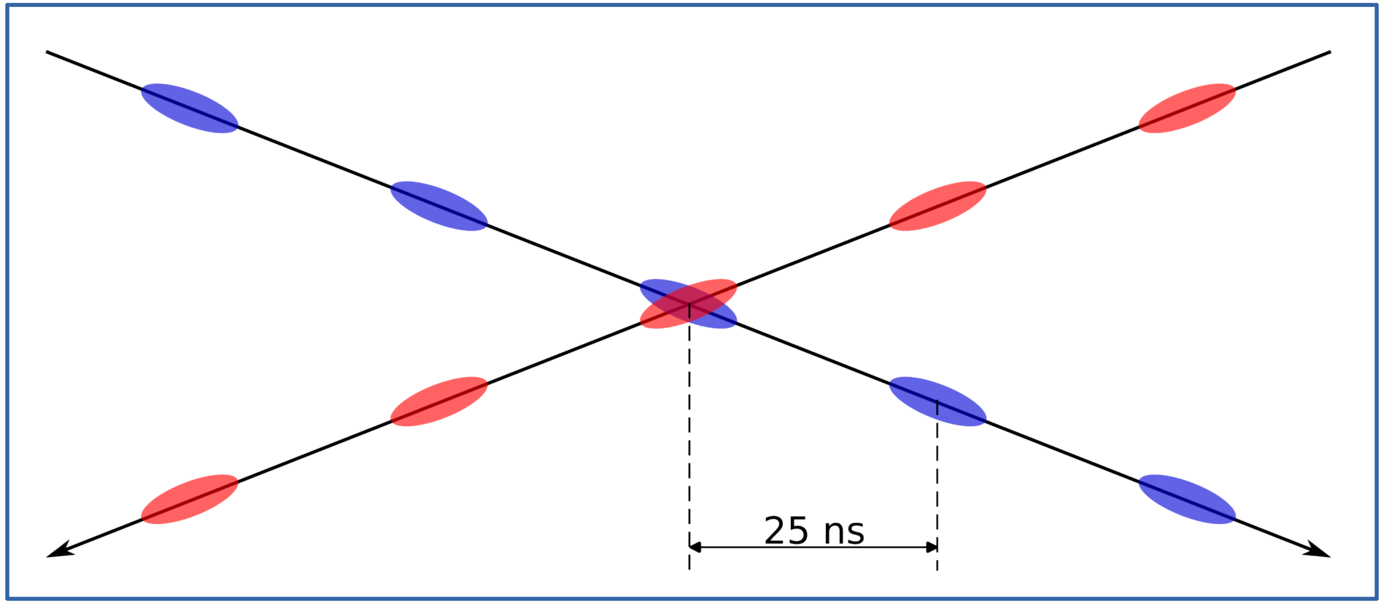
Fast timing, past

- Timing for Particle physics experiments was *ignored* for a long time
- Timing of currently installed LHC detectors
  - Bunch crossings need to be separable

    → 25 ns time resolution sufficient

Tab.: Specifications of Timepix3 and VeloPix. Taken from LHCb velo upgrade TDR (2013)

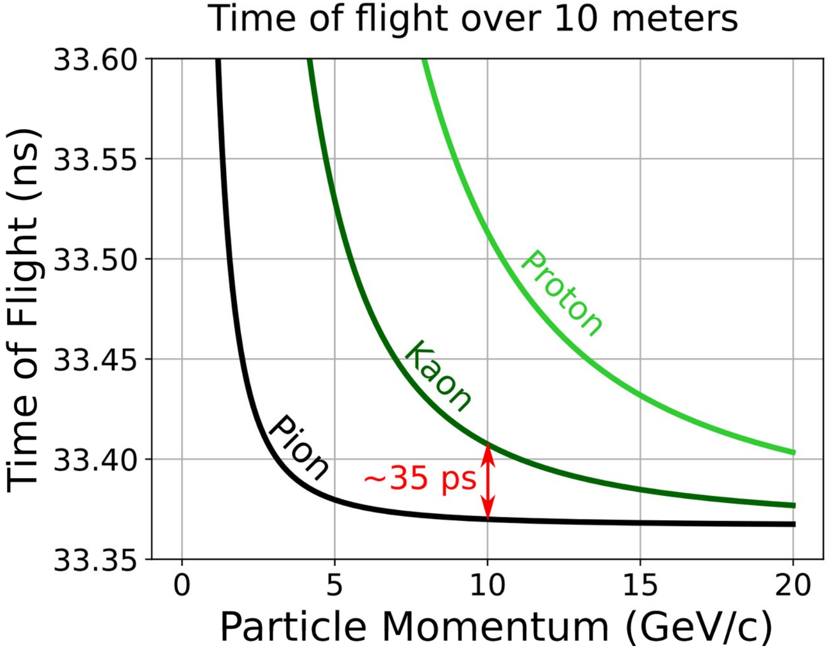
Specification	Timepix3	VeloPix
pixel dimension	$55 \times 55\ \mu m^2$	$55 \times 55\ \mu m^2$
matrix size	256×256	256×256
timewalk	< 25 ns	< 25 ns
Time over Threshold range	10 bit	6 bit (calibration mode only)
leakage current compensation (per pixel)	20 nA	20 nA
Time stamp resolution	1.6 ns	25 ns

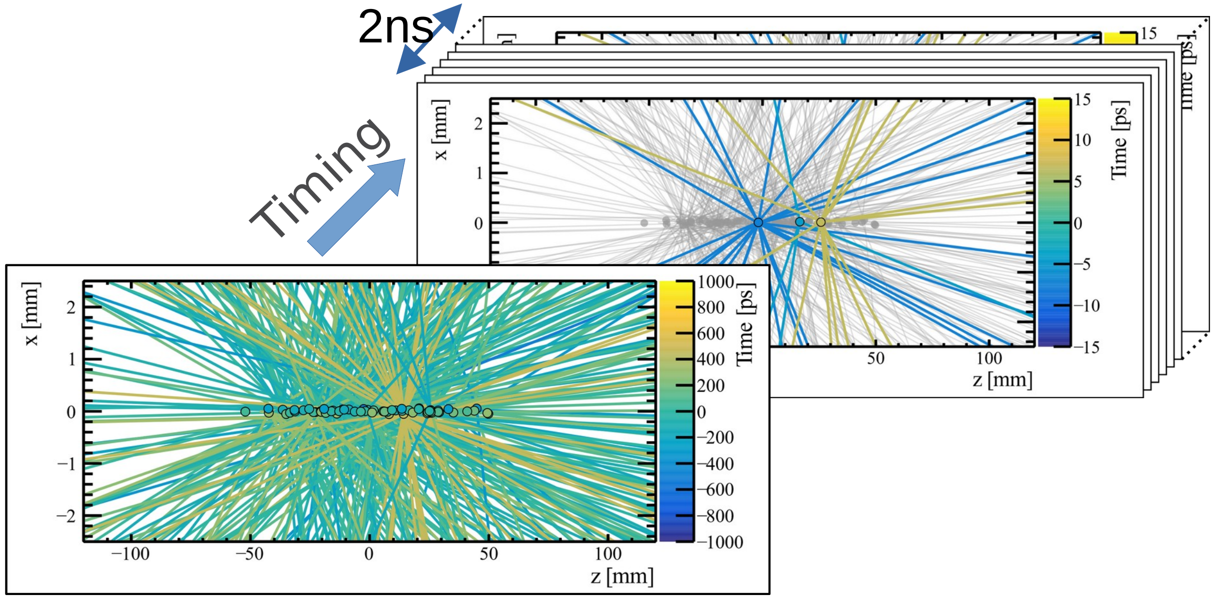


Fast timing, future

- Time as an important parameter to embed in the analysis
  - Time of Flight based particle identification
    - Further physics analysis
  - 4D-Tracking
    - Improved tracking performance
    - Reduced tracking complexity

→ **All require O(30 ps) time resolution**



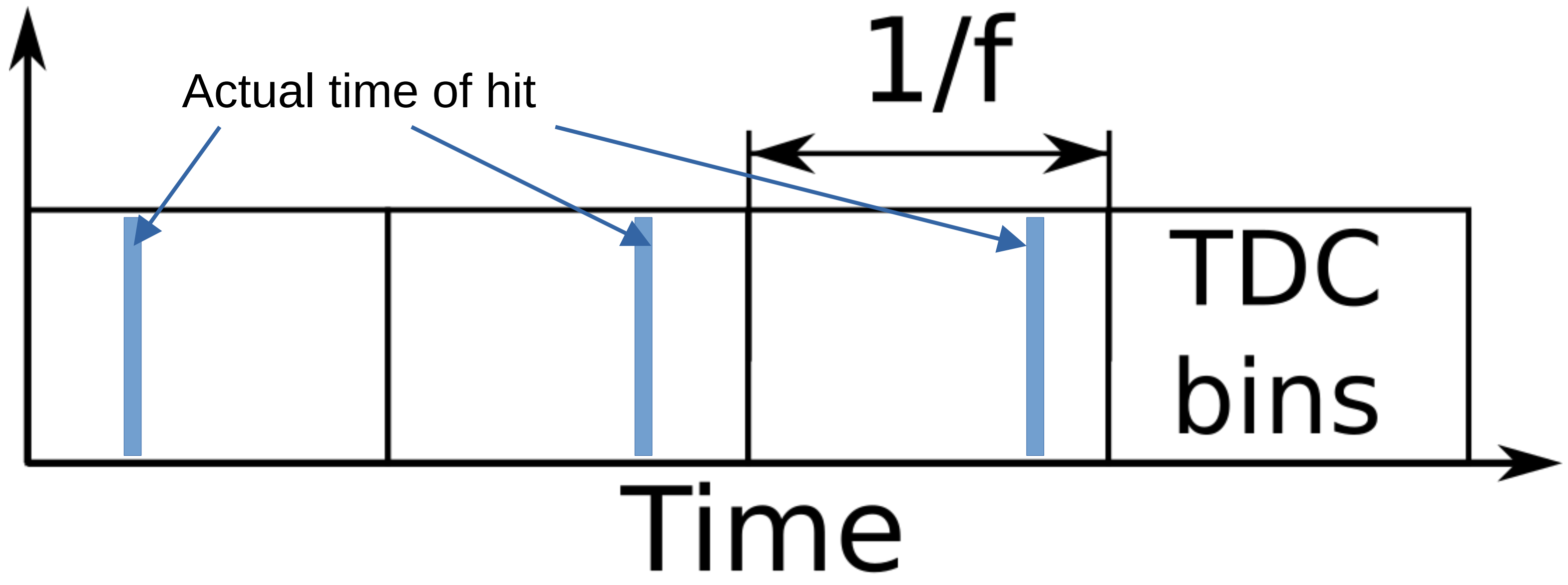


Contributions to time resolution

$$\sigma_t^2 = \sigma_{clock\text{-}global}^2 + \sigma_{clock\text{-}on\text{-}chip}^2 + \sigma_{TDC}^2 + \ldots$$

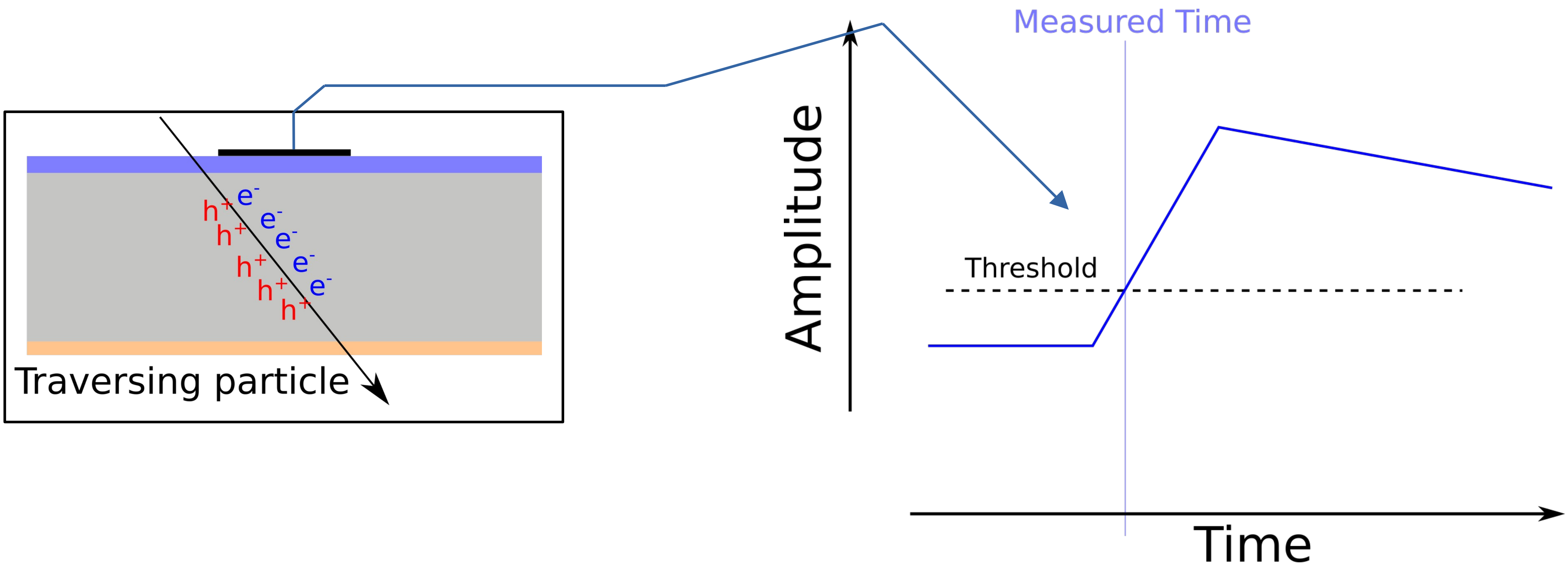
Inaccuracy of the clock and clock jitter

Time digitization error (binning error)



What is actually measured

- Measured is the time when a gathered charge signal crosses a threshold



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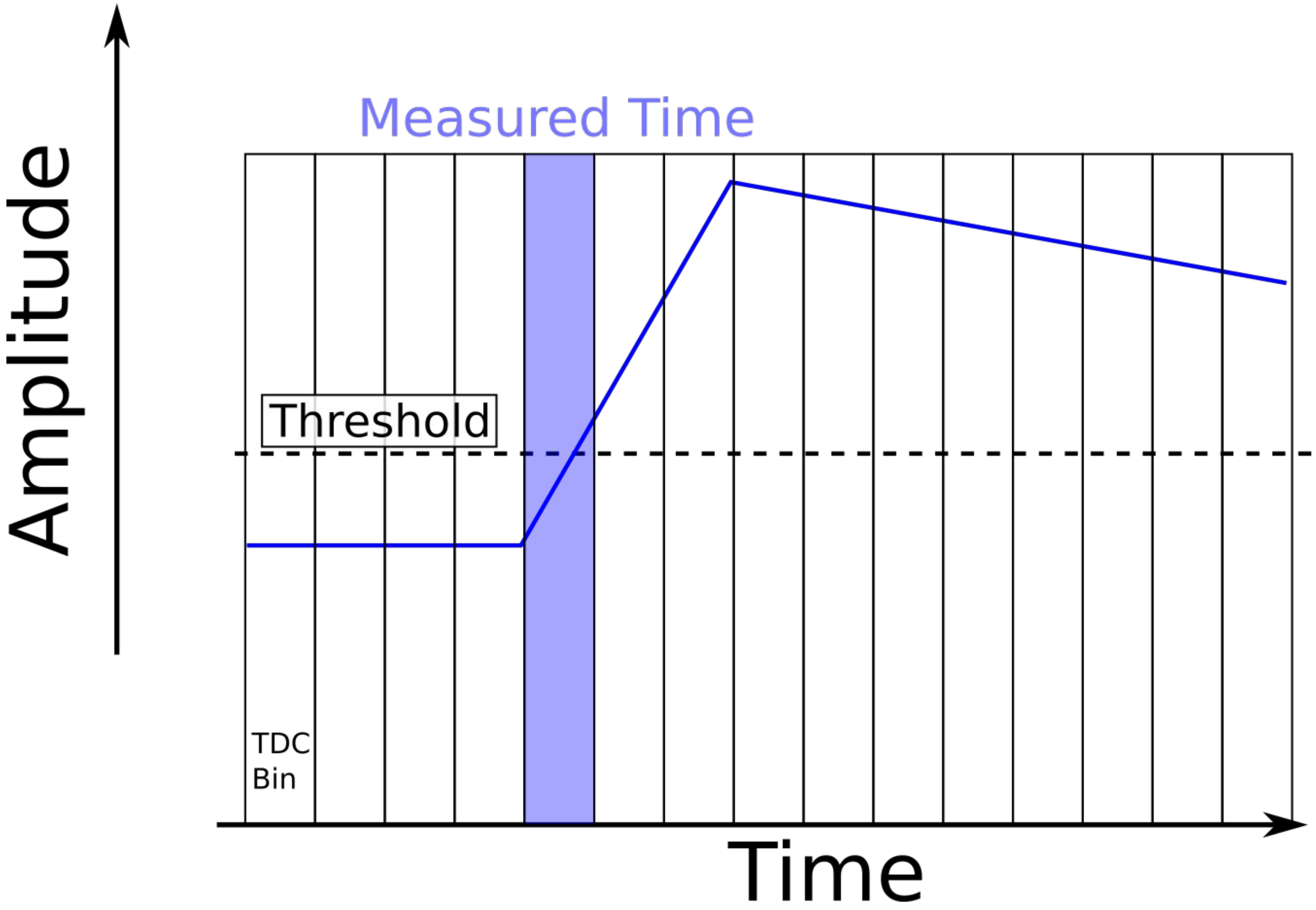
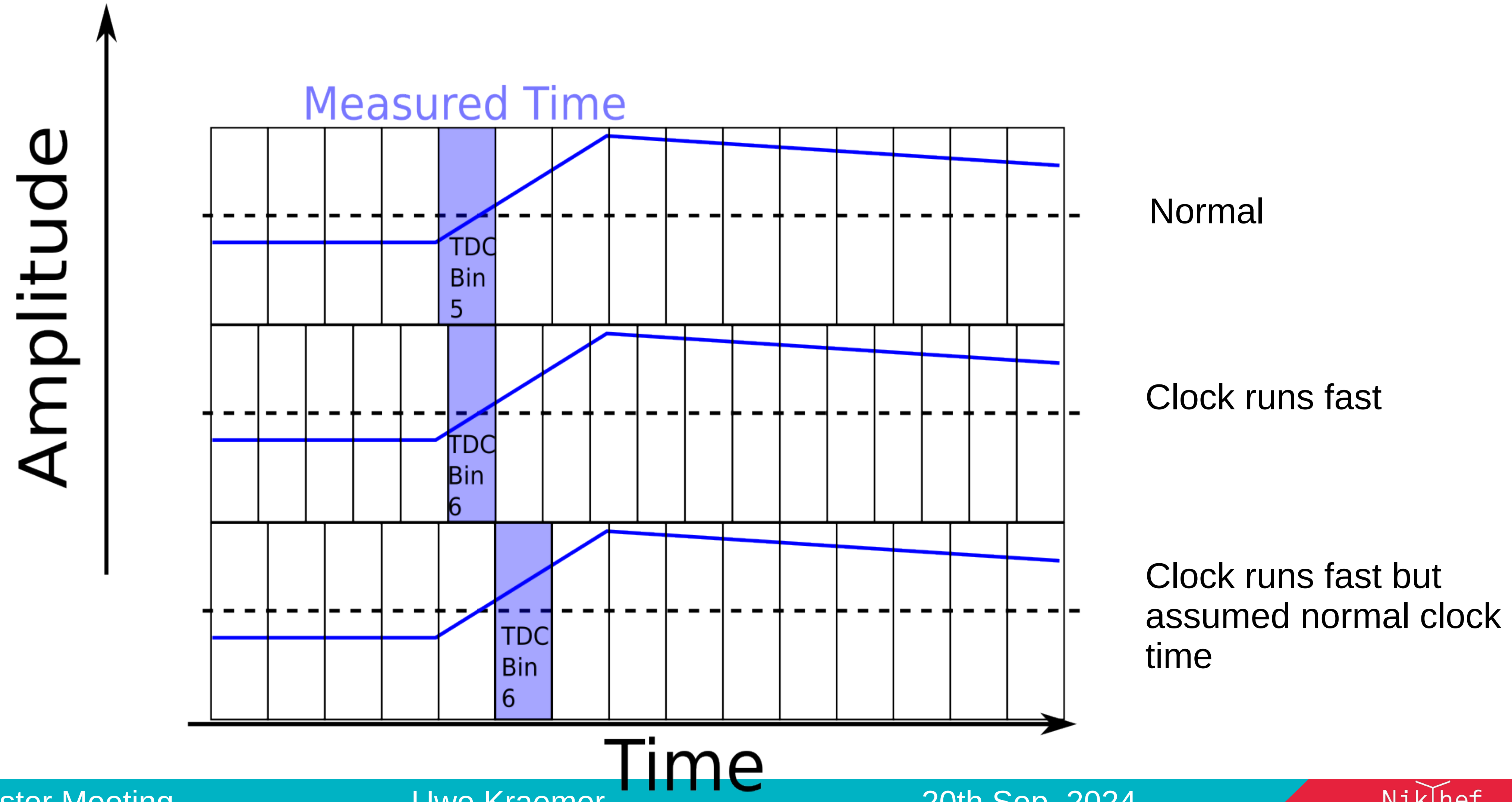


Contributions to time resolution

Can be partially corrected using large datasets

$$\sigma_t^2 = \sigma_{\text{clock-global}}^2 + \sigma_{\text{clock-on-chip}}^2 + \sigma_{\text{TDC}}^2 + \ldots$$



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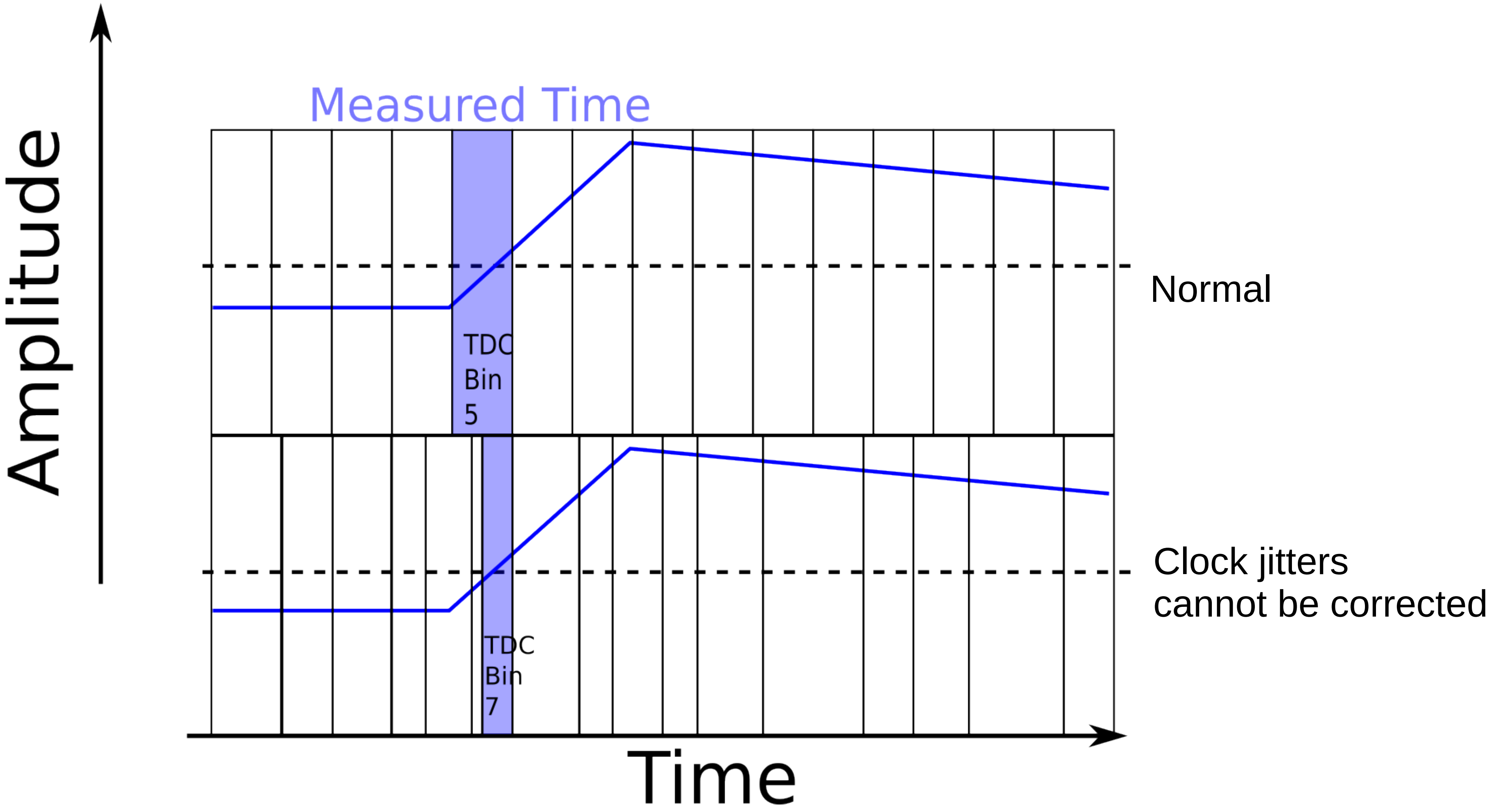
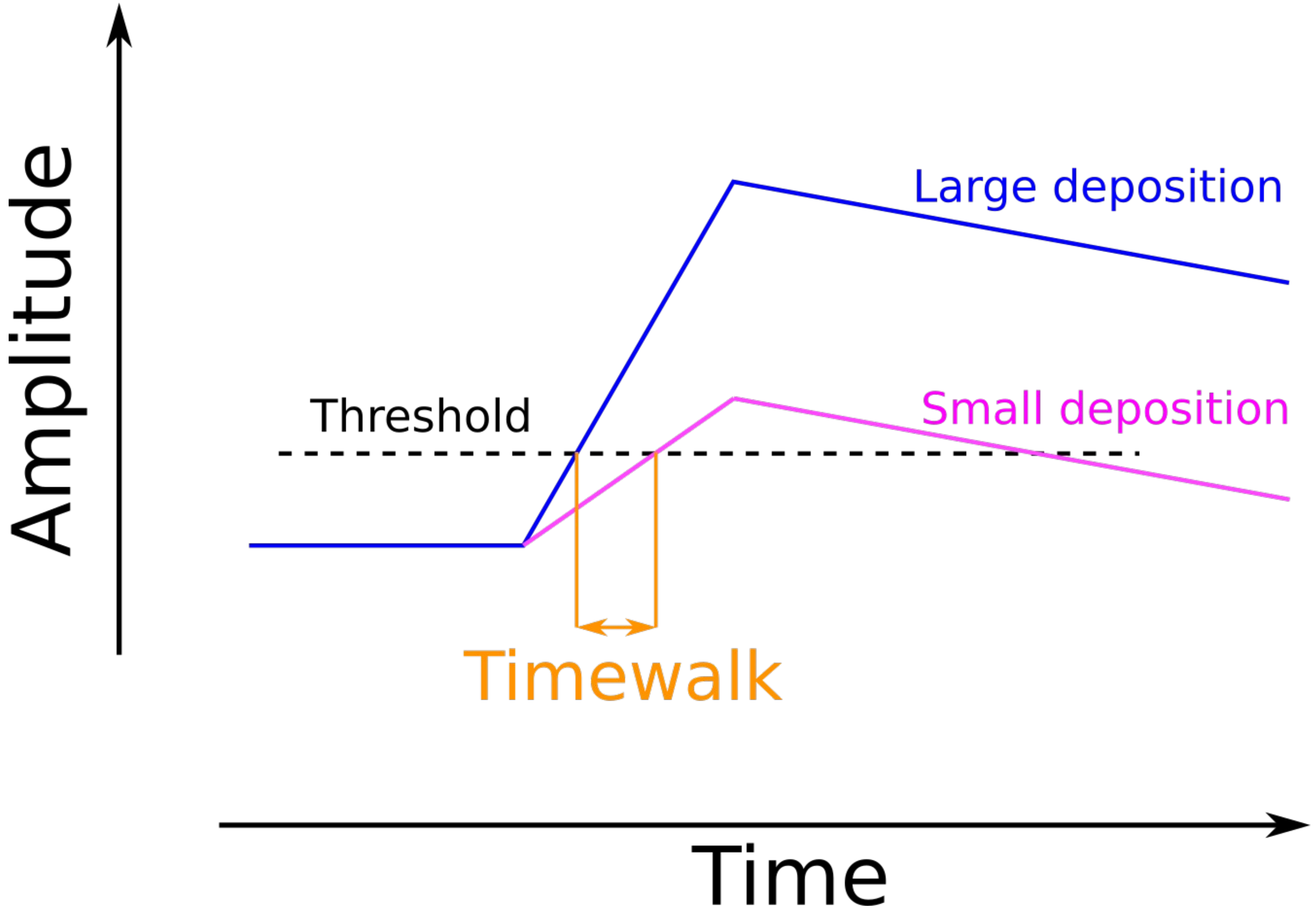


Contributions to time resolution

Can be corrected with charge measurement

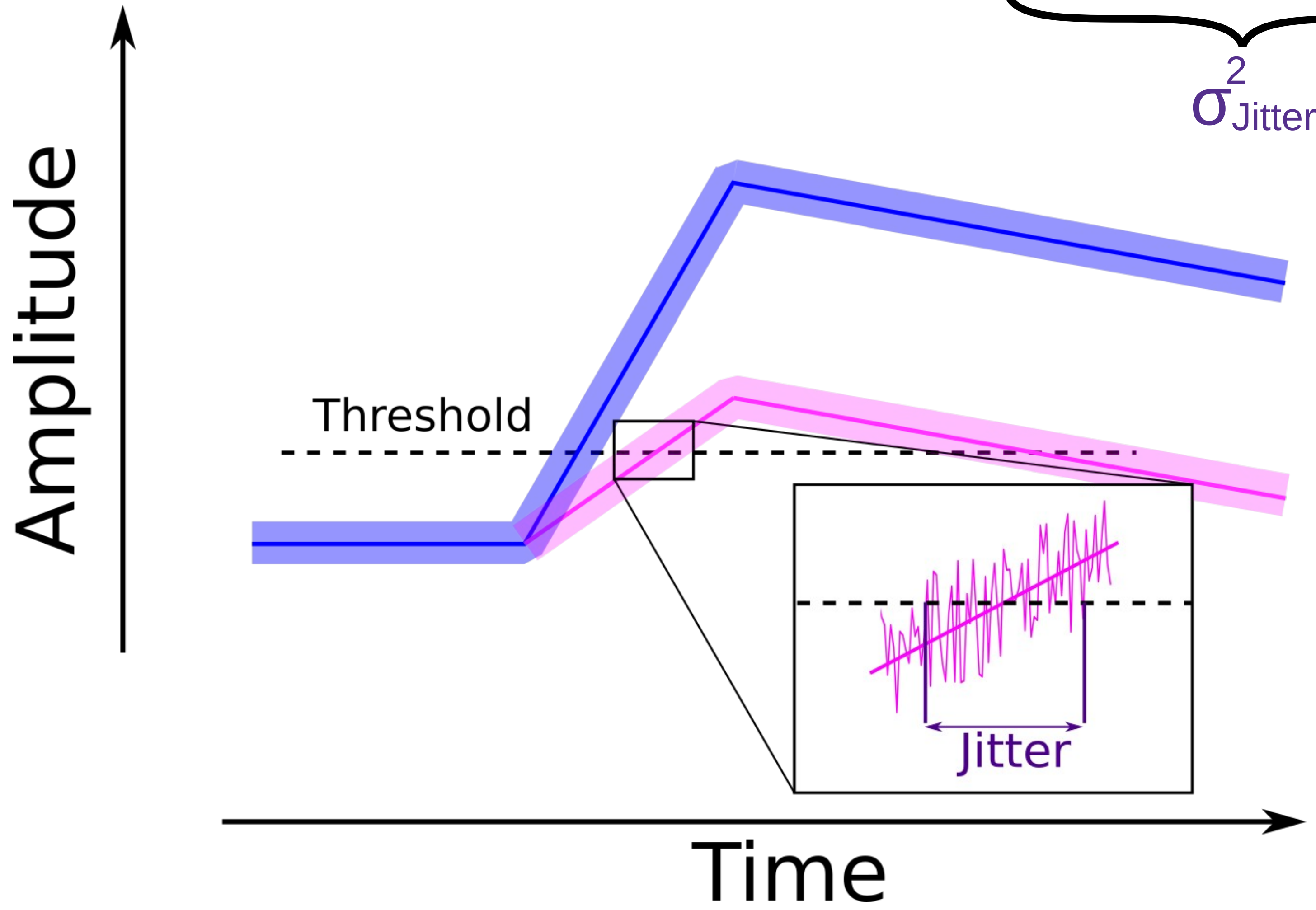
$$\sigma_t^2 = \sigma_{clock\text{-}global}^2 + \sigma_{clock\text{-}on\text{-}chip}^2 + \sigma_{TDC}^2 + \sigma_{Timewalk}^2 + \dots$$



Contributions to time resolution

$$\sigma_t^2 = \sigma_{\text{clock-global}}^2 + \sigma_{\text{clock-on-chip}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{Timewalk}}^2 + \underbrace{\sigma_{\text{Landau}}^2 + \sigma_{\text{Front-end}}^2}_{\sigma_{\text{Jitter}}^2}$$

Can be minimized by sensor geometry, capacitance etc.



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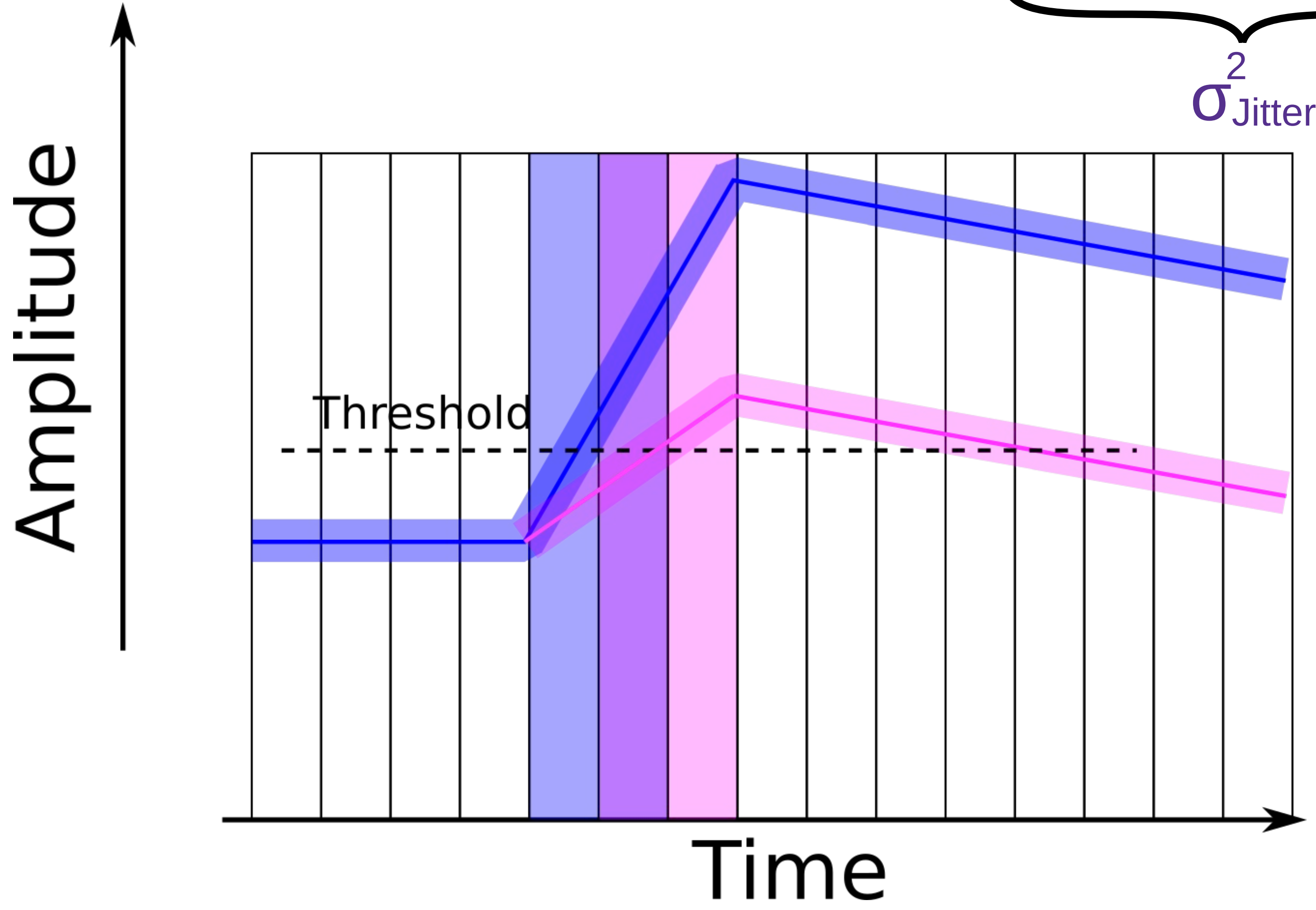
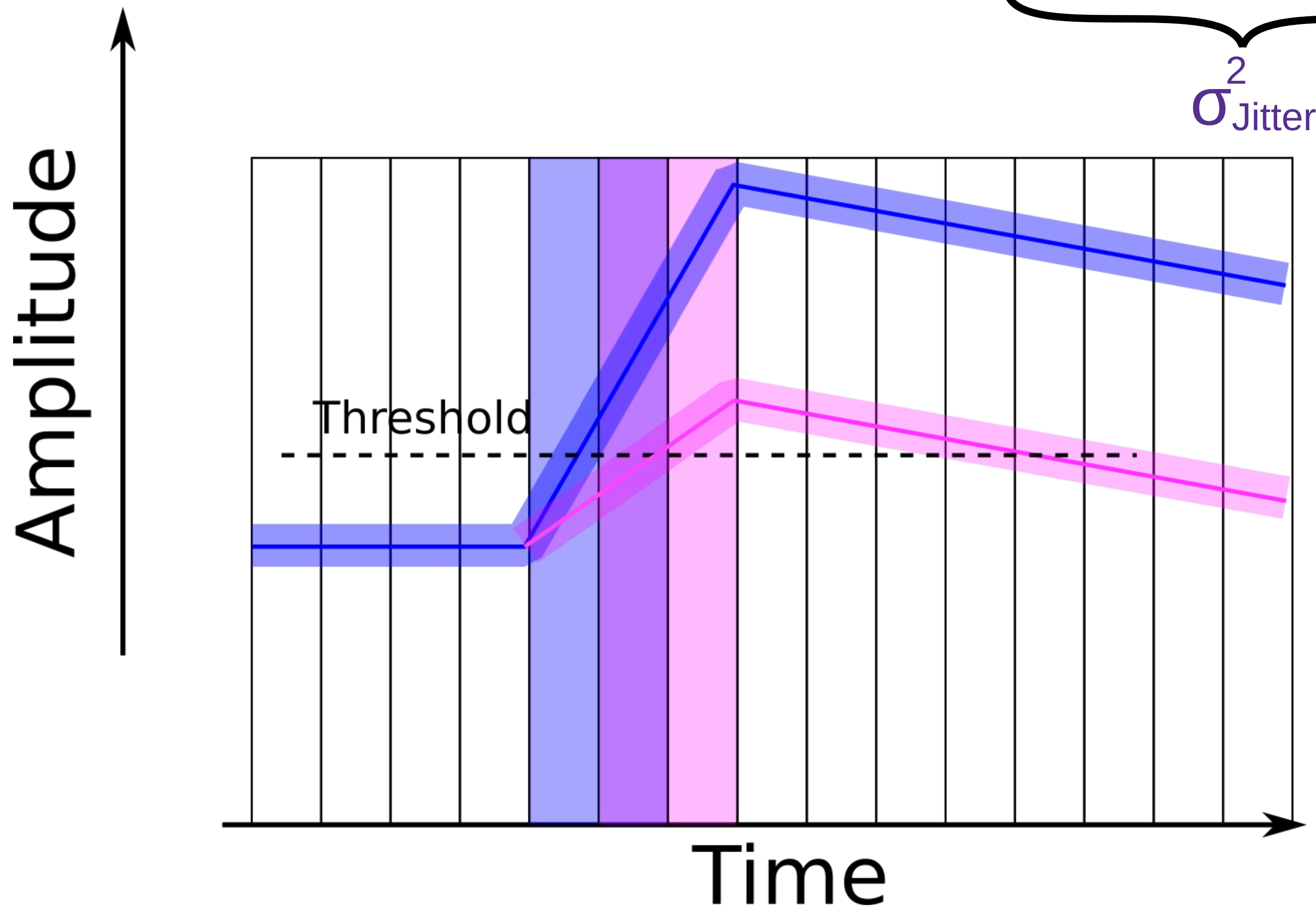


Contributions to time resolution

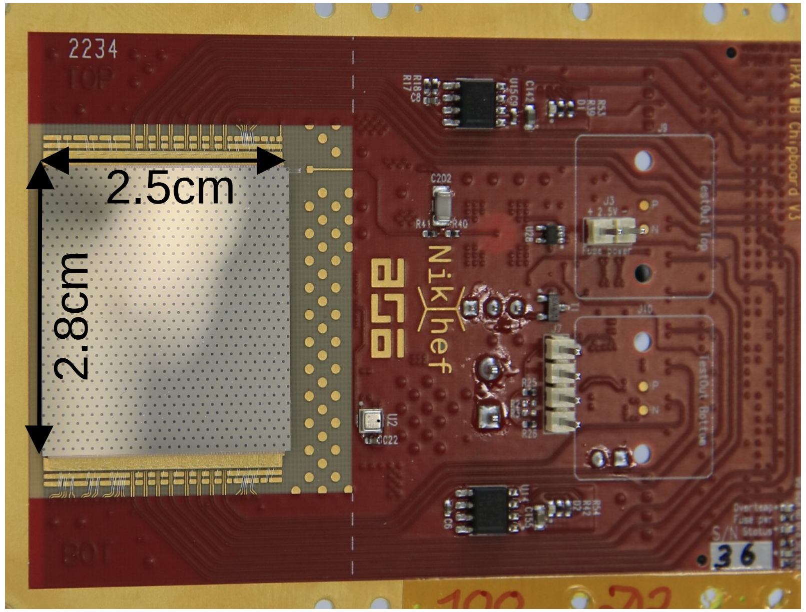
$$\sigma_t^2 = \sigma_{\text{clock-global}}^2 + \sigma_{\text{clock-on-chip}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{Timewalk}}^2 + \underbrace{\sigma_{\text{Landau}}^2 + \sigma_{\text{Front-end}}^2}_{\sigma_{\text{Jitter}}^2} \left(+ \sigma_{\text{Pixel-to-Pixel}}^2\right)$$



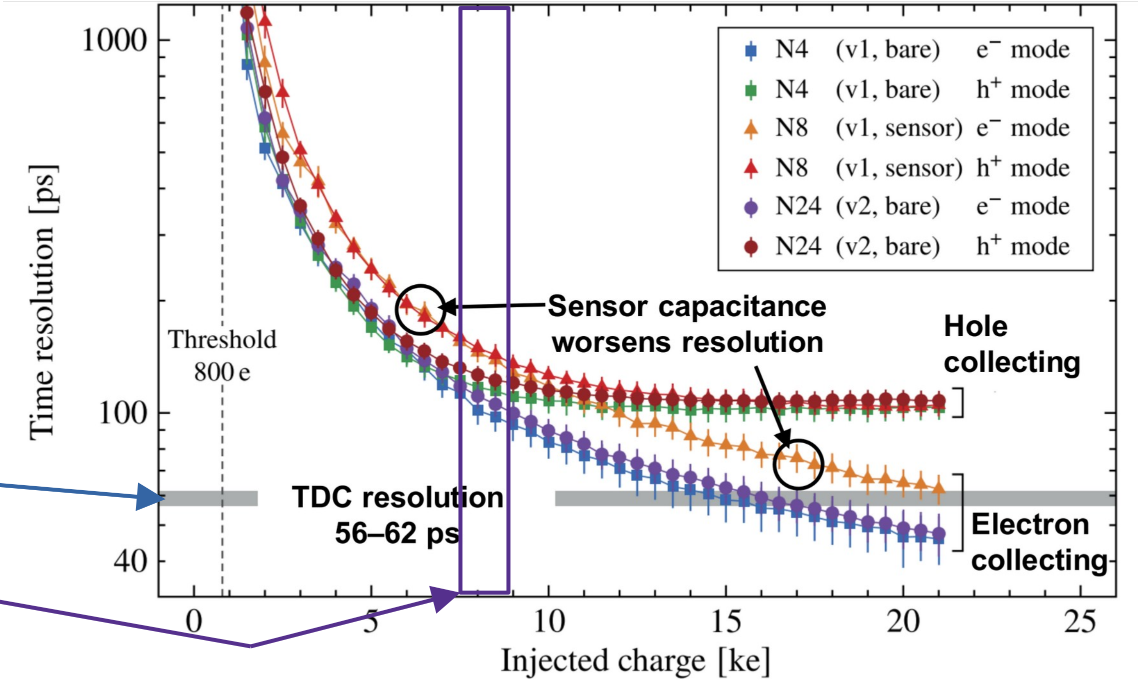
Removed through calibration, requires high statistics

Moving beyond digital limits

- Older ASICs
  - Timepix3 σ_{TDC} ~ 450 ps
- Newer ASICs
  - **Timepix4 σ_{TDC} ~ 62 ps**
- Next goal:
  - Picopix σ_{TDC} < 20 ps



- Impact of other contributions begin to be significant
  - Only capacitive load from sensor **$\sigma_{Front\text{-}end}$ ~ 100 ps**

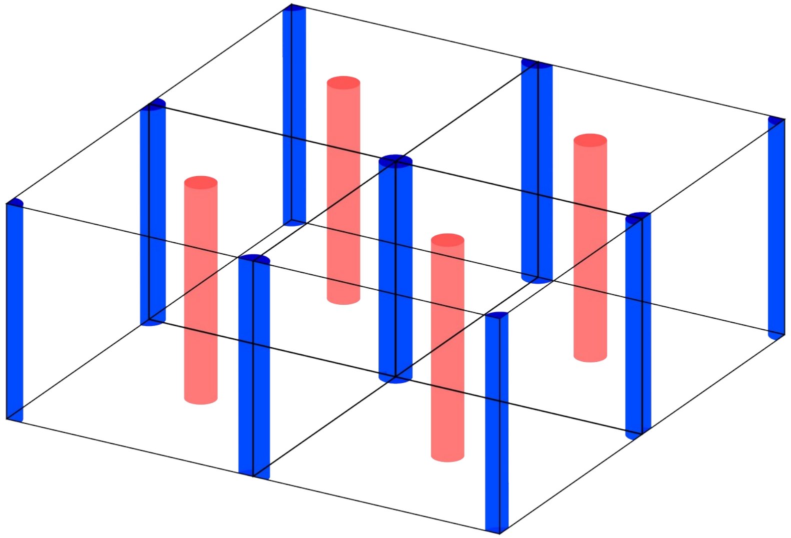


Improving Fast Timing

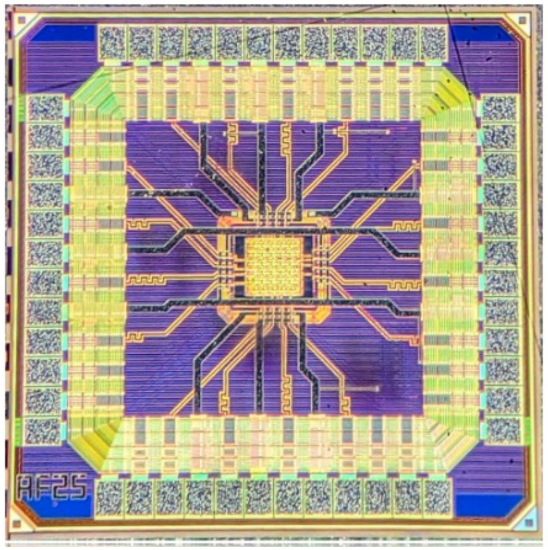
Different Approaches to Fast Timing Sensors

- Decision on what to improve/prioritize drives different sensor designs

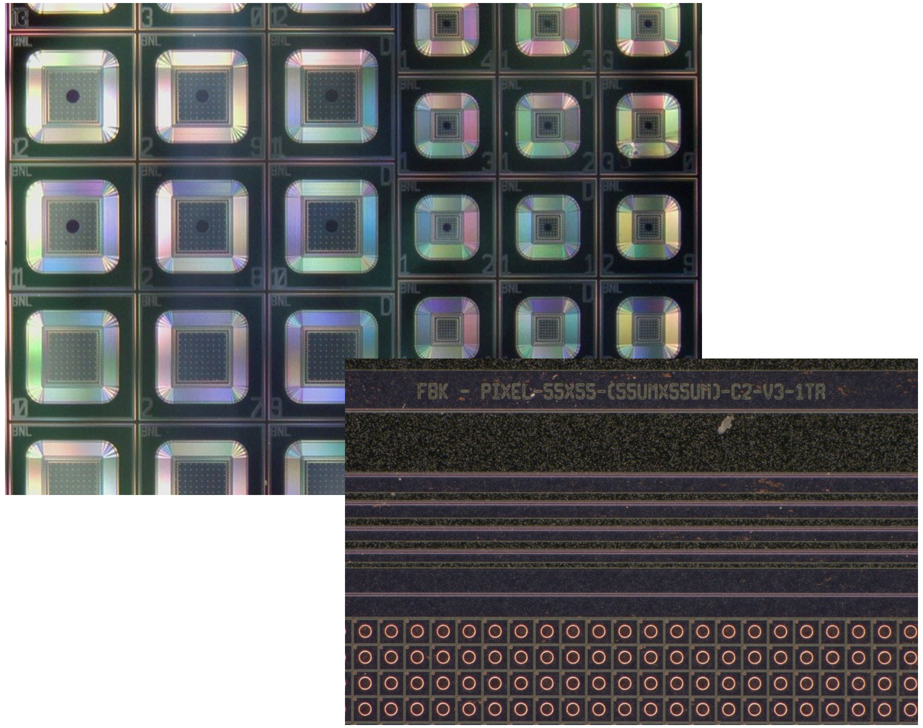
- 3D sensors
  - Large signal generation
  - ...



- Monolithic Active Pixel Sensors (MAPS)
  - Low capacitance
  - ...

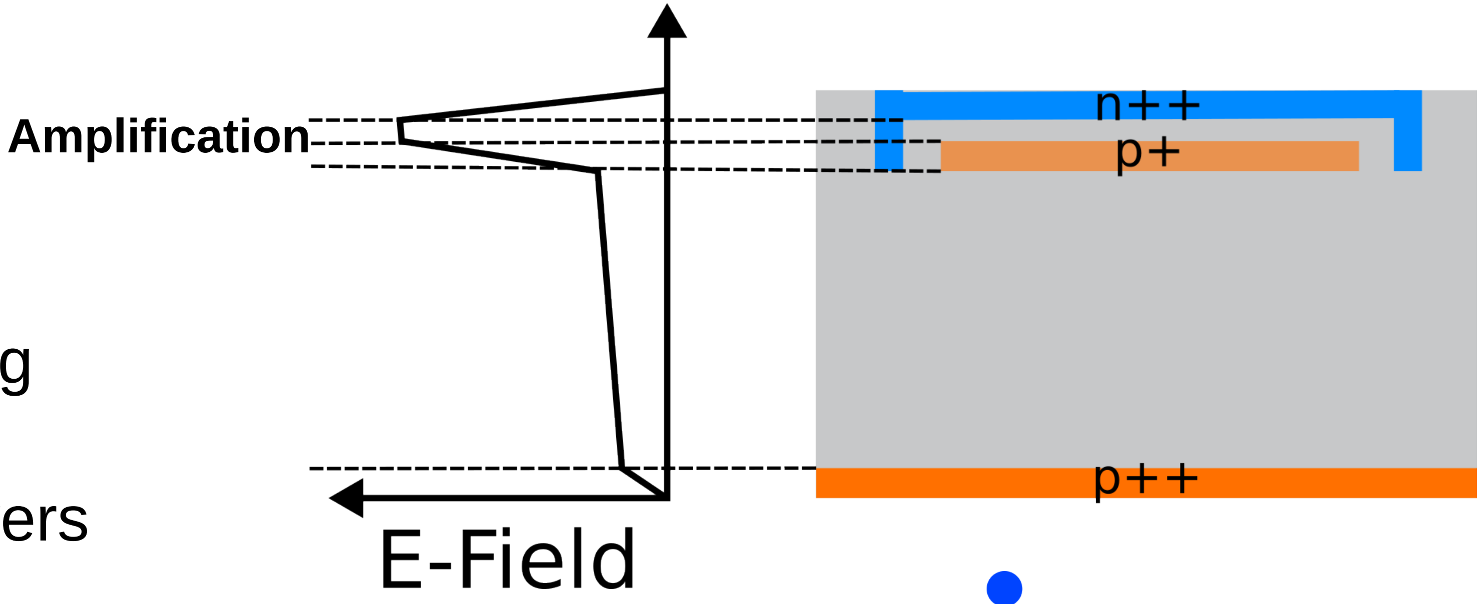


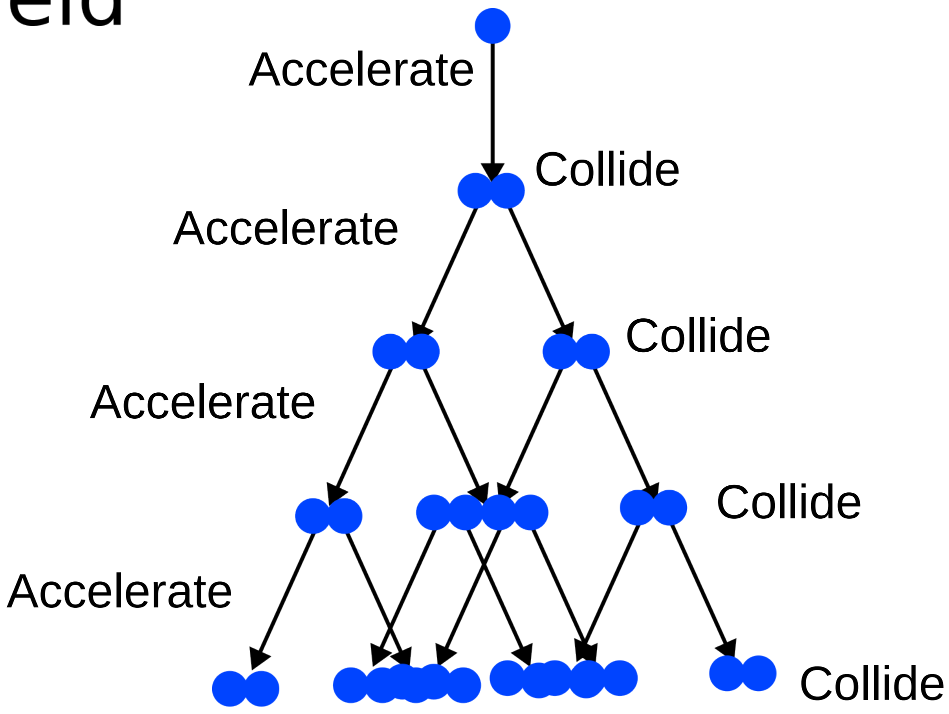
- Low Gain Avalanche Detectors (LGAD)
  - In-sensor amplification
  - ...



Gain in sensors

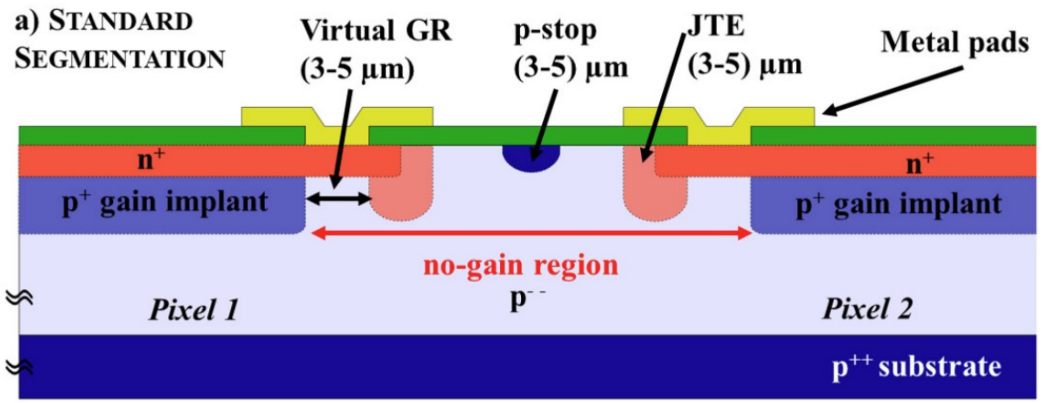
- Electron-hole pairs produced by collisions with charged particles
- Can we induce this with the drifting charge? Yes!
  - Adding specific highly doped layers produces a strong electric field
  - Electrons accelerate enough to produce more Electron-hole pairs via collisions
    - Cascading effect until field reduces
    - Position of layer, doping concentration etc. all influence gain
  - Low Gain Avalanche = O(10)





LGAD Pixel (Standard)

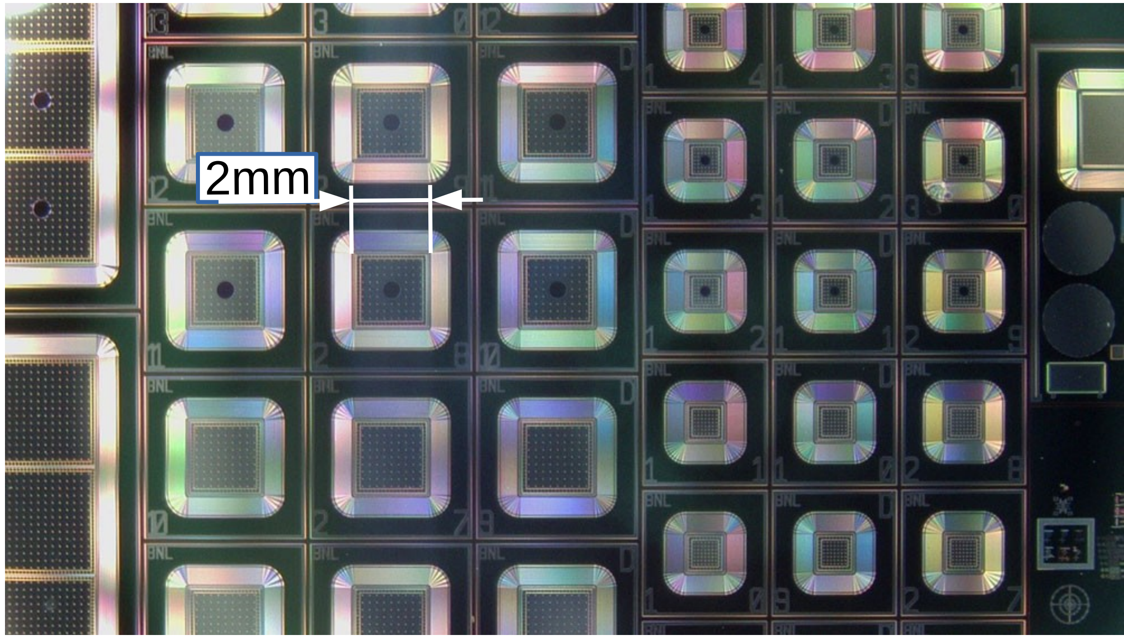
- Gain implants require electrical isolation and
  - Region without gain O(100 µm)
  - Large pixels to reach high fraction of active region (Fill Factor)



→ Large pixels with great timing

- Excellent for timing layers
- Insignificant spatial resolution

  → Not usable for 4D tracking

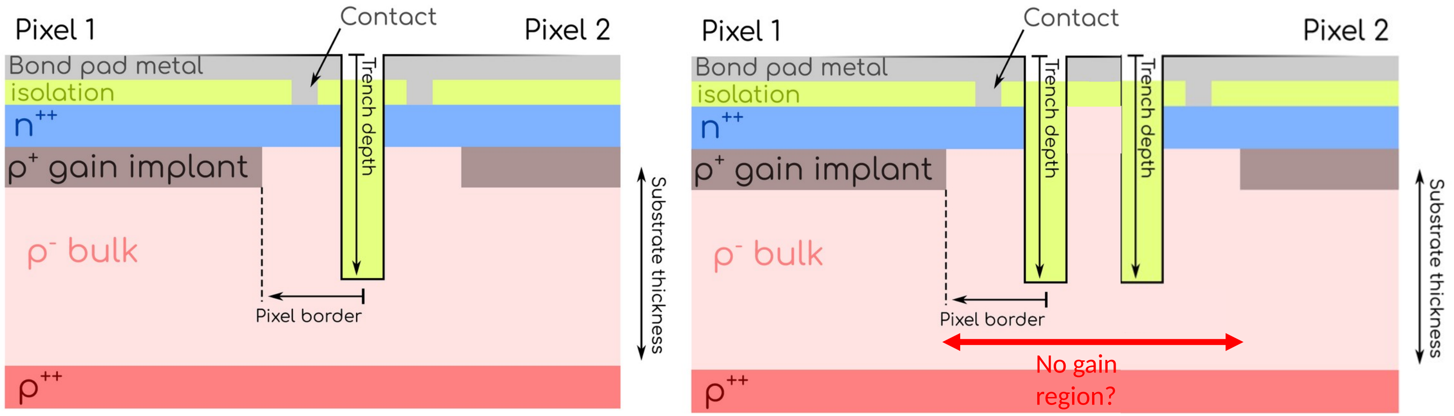


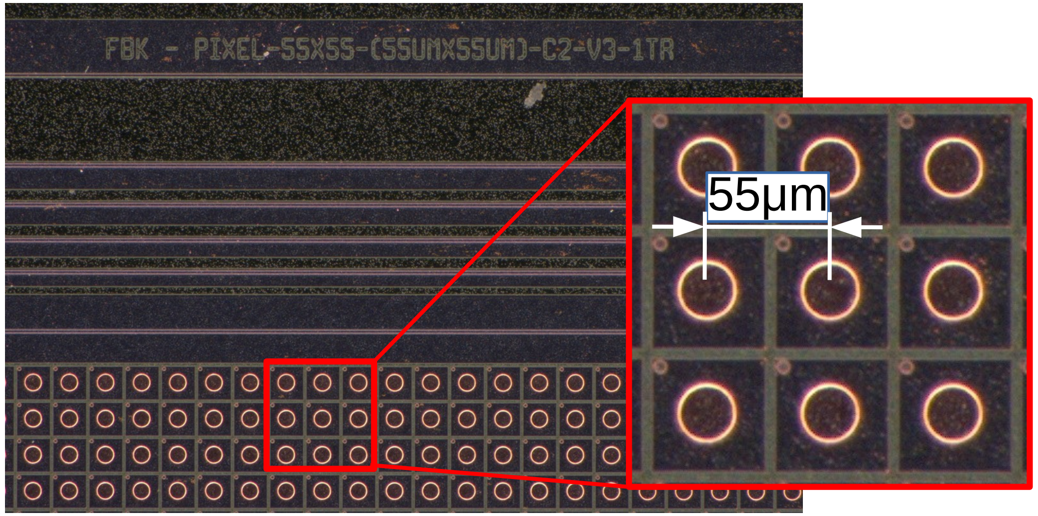
Can we make the isolation somehow smaller?

LGAD Pixel (Trenches)

- Cutting one or multiple gaps into silicon
  - Filled with silicon oxide as isolation
- Trench width and distance to gain implant ~ O(1µm)
  - Small pixels possible (55µm pitch)
- Devices installed on TPX4 ASIC.

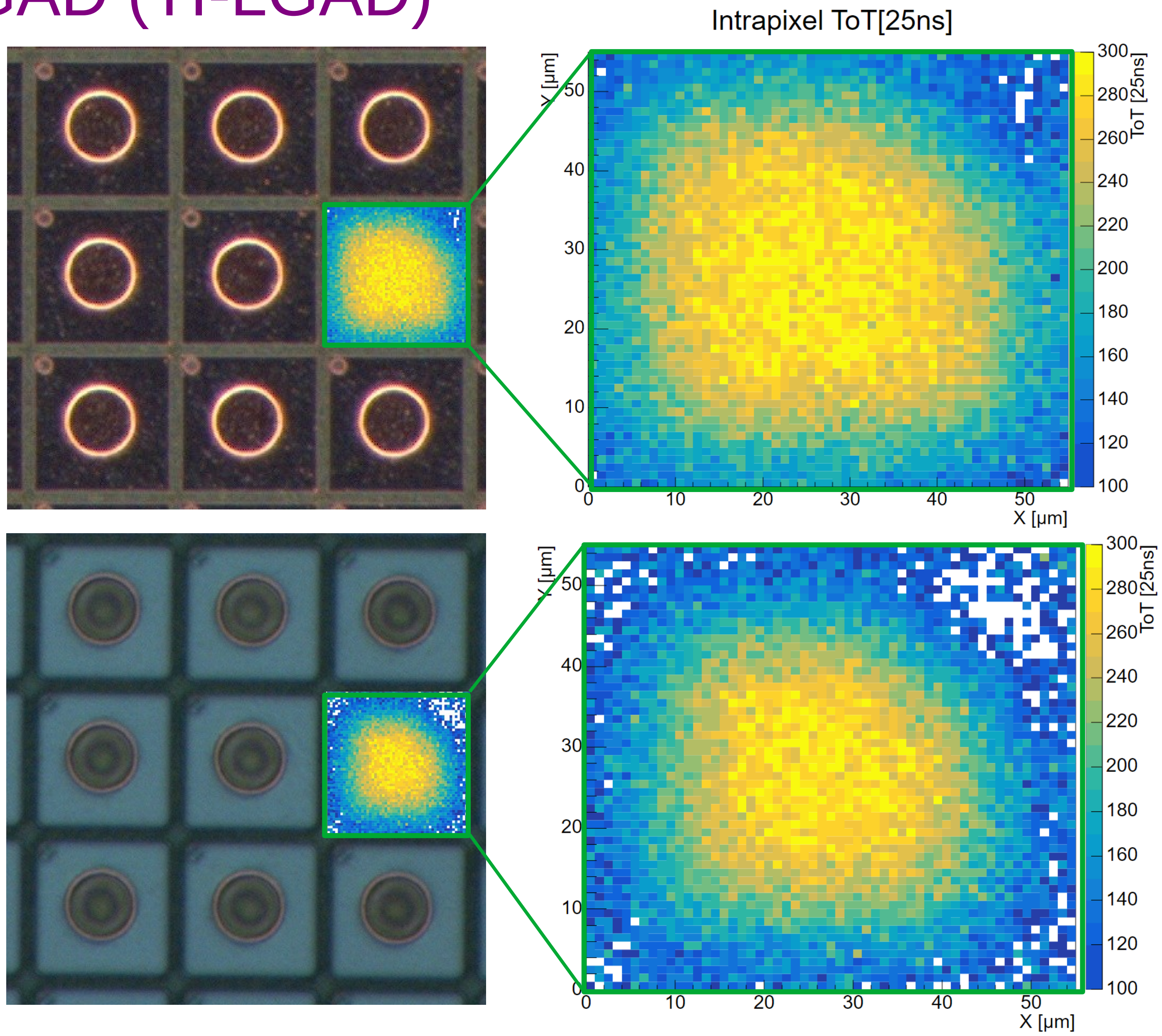
  → First small pixel LGAD with fully integrated readout





Testing of Trench-Isolated-LGAD (TI-LGAD)

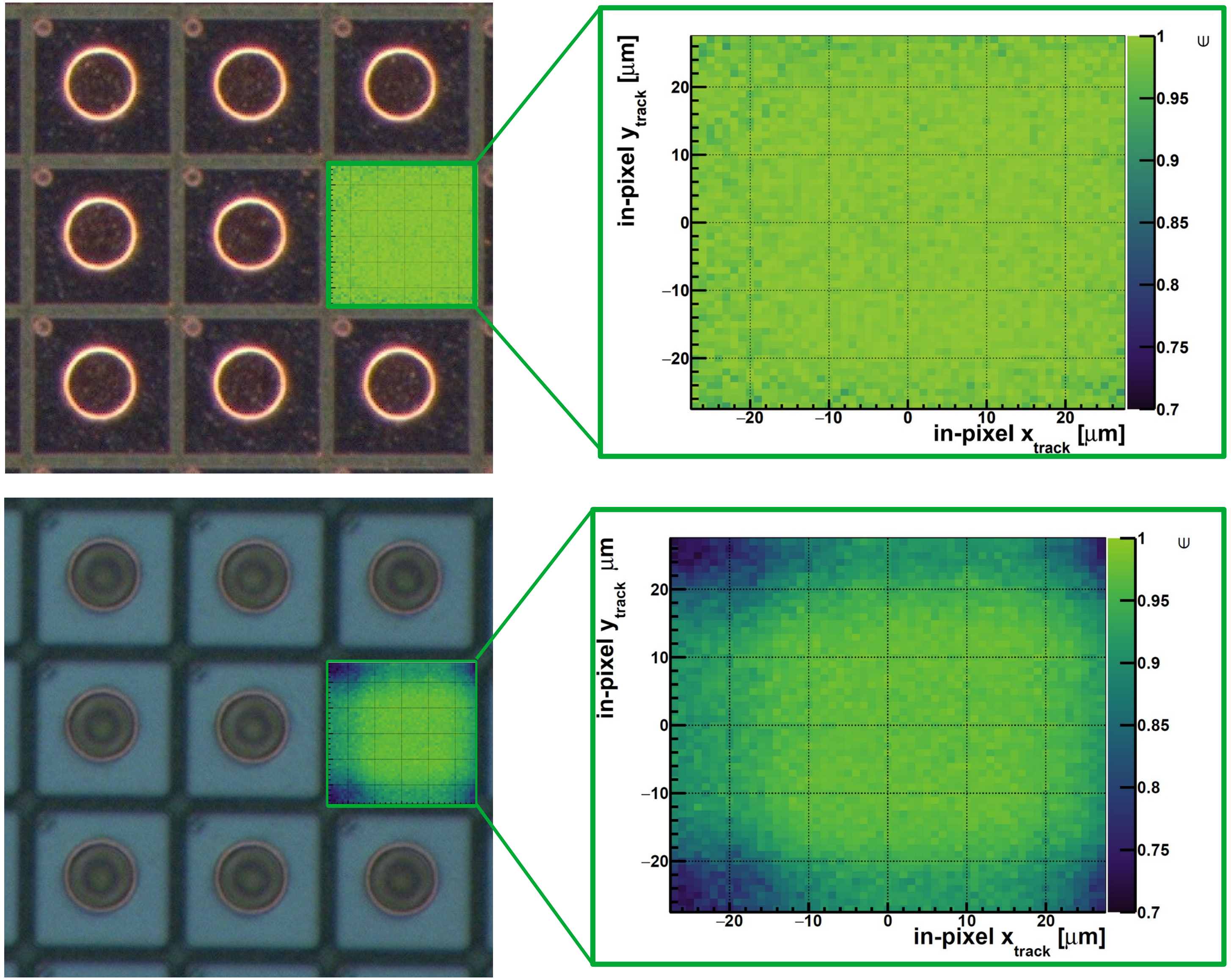
- Investigation into in-pixel structures
  - Area close to the trenches
- Both devices show reduced gain towards the edges



Testing of Trench-Isolated-LGAD (TI-LGAD)

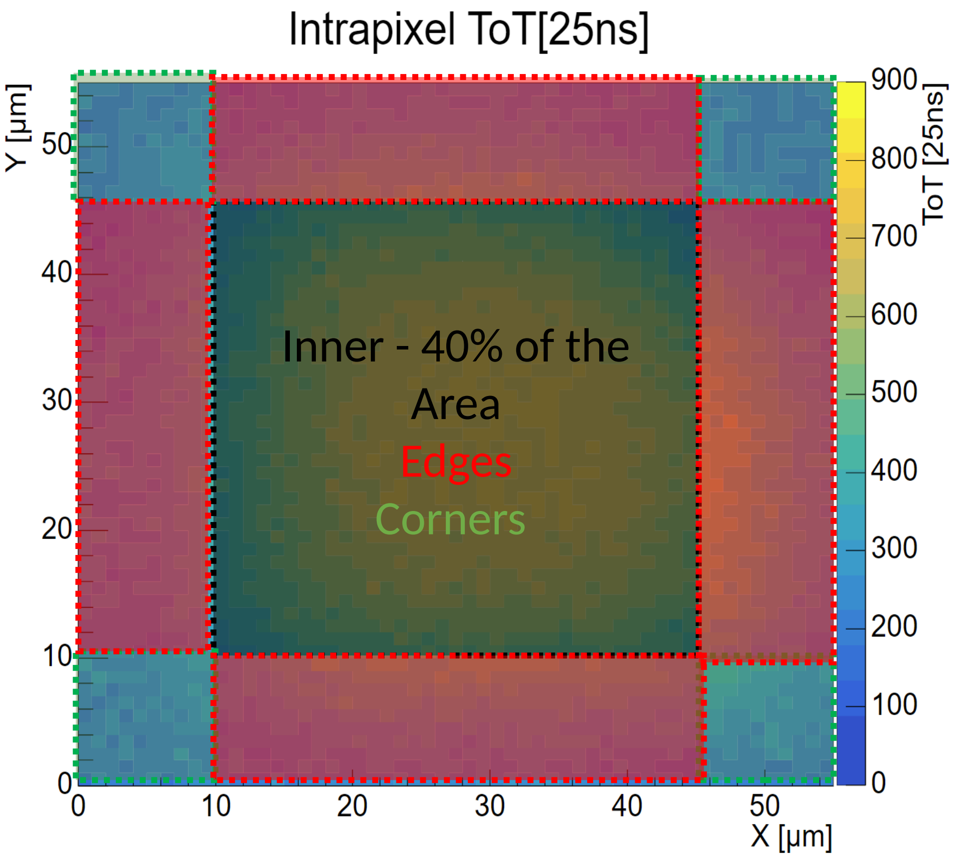
- Investigation into in-pixel structures
  - Area close to the trenches
- Both devices show reduced gain towards the edges
- Double trench device has efficiency drop in the corners

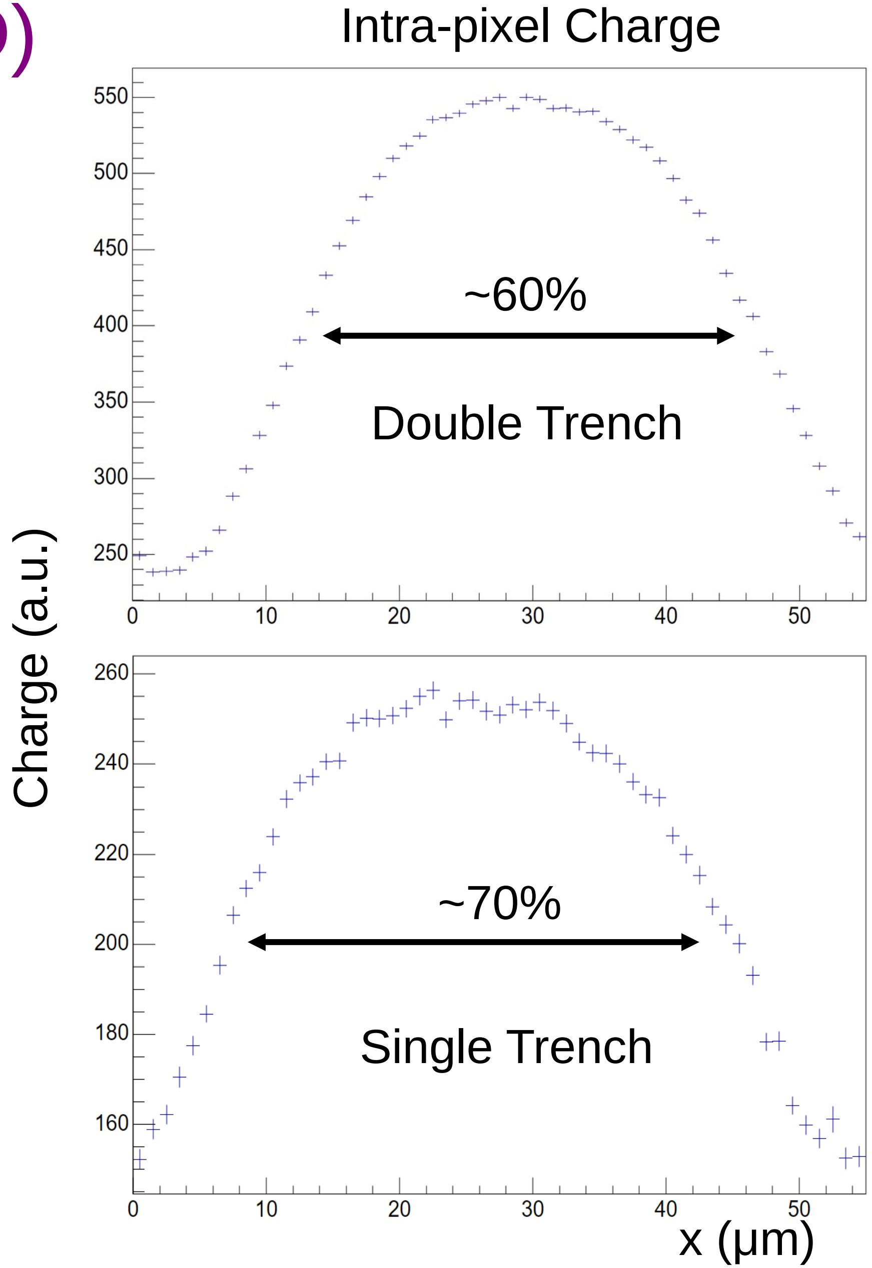
- Lowers effective Fill Factor and usable area to the center



Testing of Trench-Isolated-LGAD (TI-LGAD)

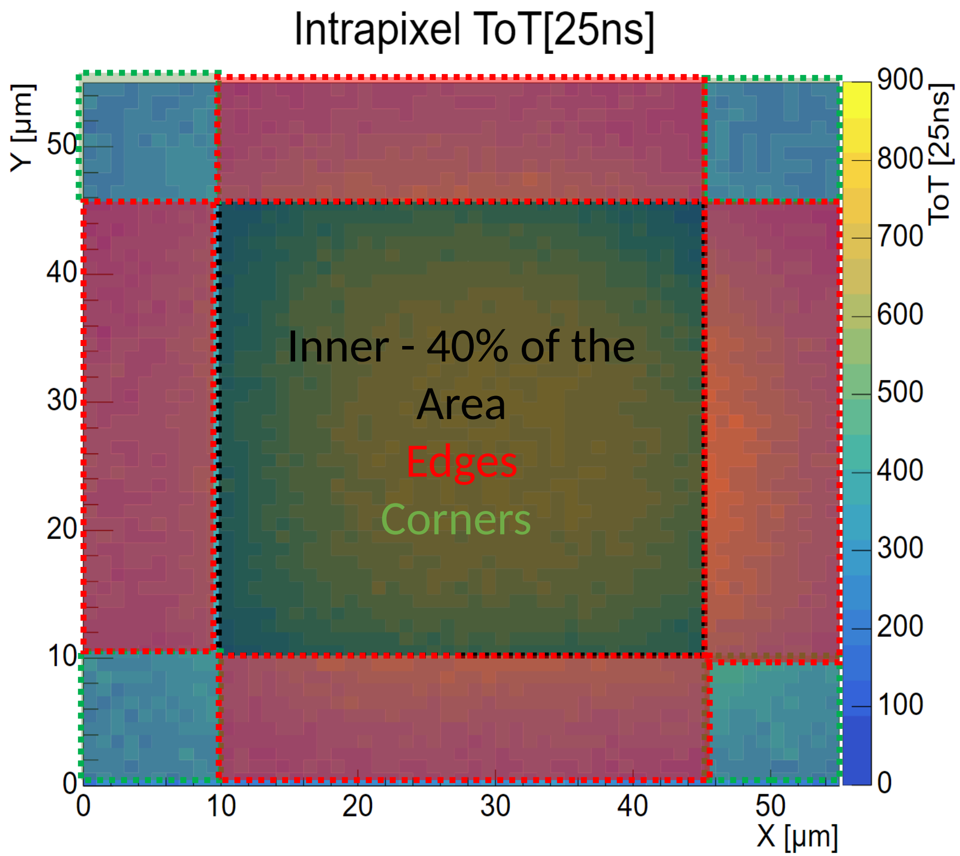
- Only 60/70% area with decent gain for (single/double trench)

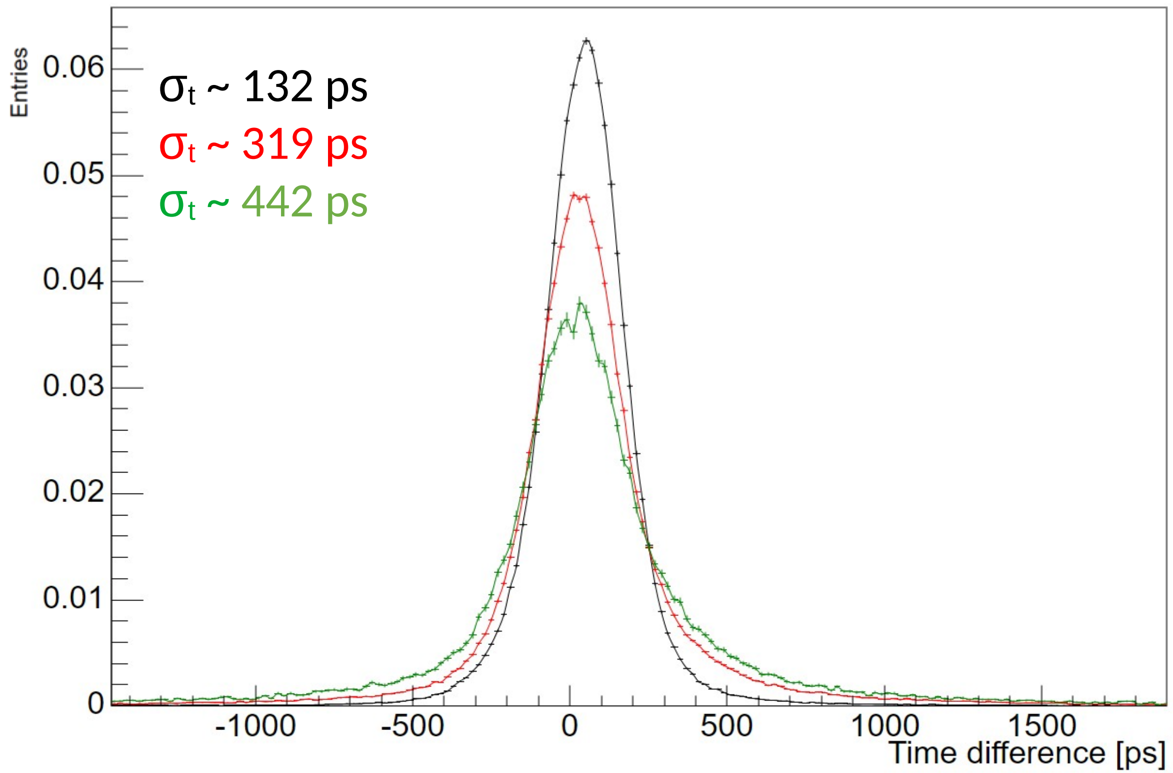




Testing of Trench-Isolated-LGAD (TI-LGAD)

- Time resolution varies a lot between the different areas inside the pixel
- Limiting data to the central area reaches a time resolution of **132 ps** before clock corrections for the double trench





Conclusion and Outlook

- Timing requirements have increased by ~1000.
- Timing itself has many aspects and levers for optimization that interplay with one another.

- Small pixel TI-LGAD can achieve excellent time resolution. Without clock correction O(130 ps) with full integration.
- Issues with gain towards pixel edges reduces effective area.
- Unexpected loss of efficiency for double trench device at the corners.
  - Hope to achieve sub 100 ps time resolution in central area.
  - Investigate and optimize area with good gain performance.

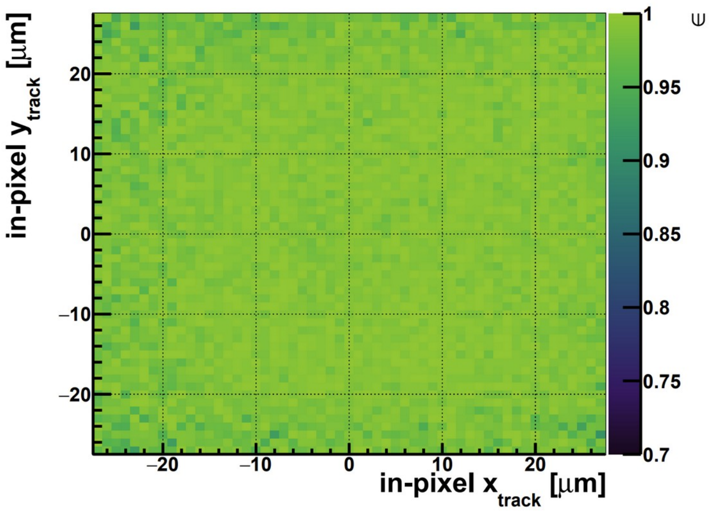
Backup slides

Trench comparison with planar

- Loss of efficiency in double trench not visible in single trench
- Also not visible in the planar sensor
- Unknown what causes this. Some ideas as to the cause, to be investigated

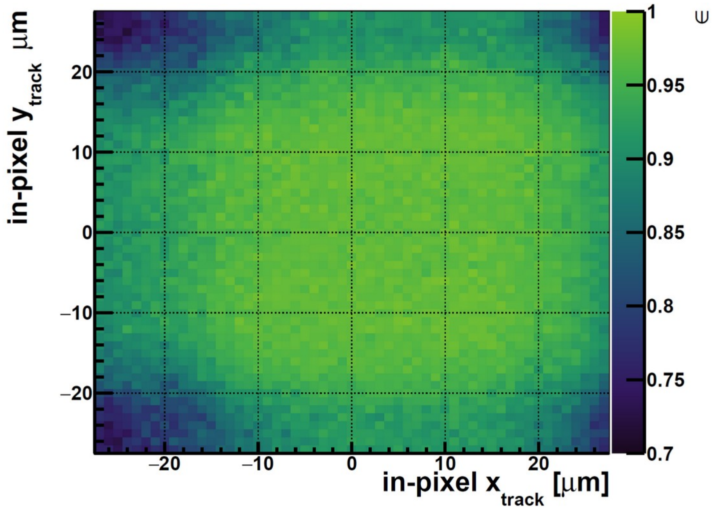
Single trench – 100V

Average ~ 97%



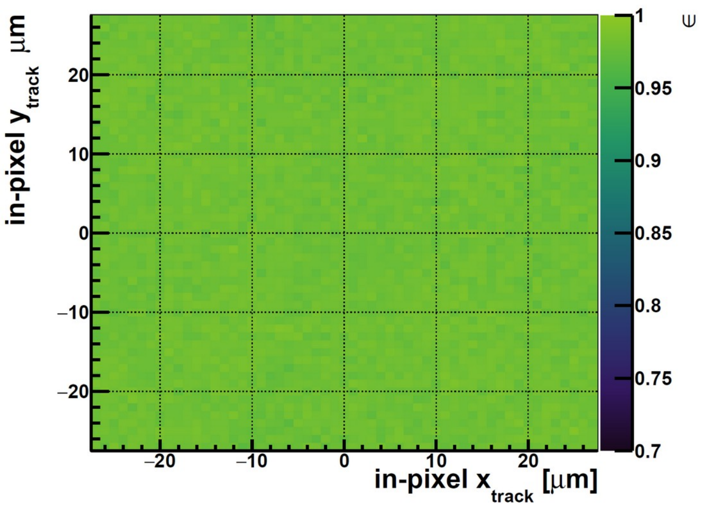
Double trench – 200V

Average ~ 93%



Reference 50 µm planar – 60V

Average ~ 97%



Signal rise time

- Jitter depends on front-end noise and therefore capacitance
- For the same amount of noise a fast rising signal is impacted less for its time resolution