Time is of the essence

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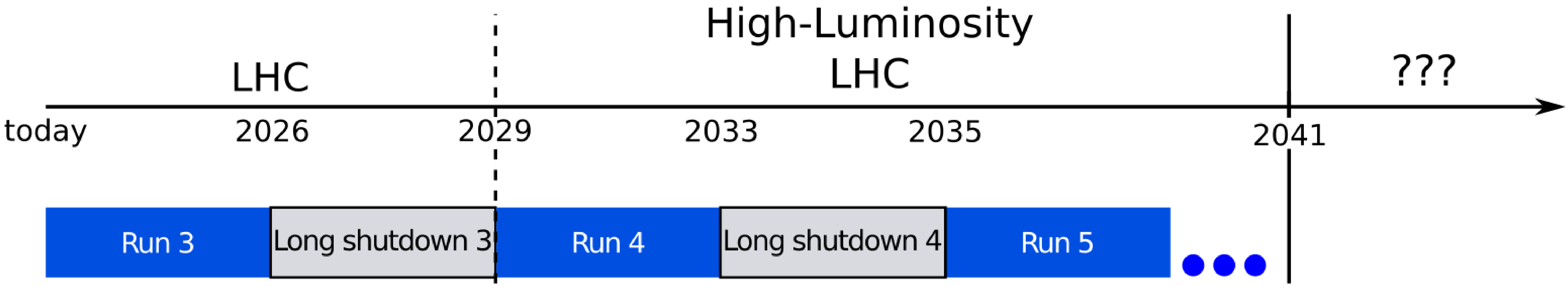
15th May 2023

Uwe Kraemer on behalf of the
Detector R&D Fast Timing Group

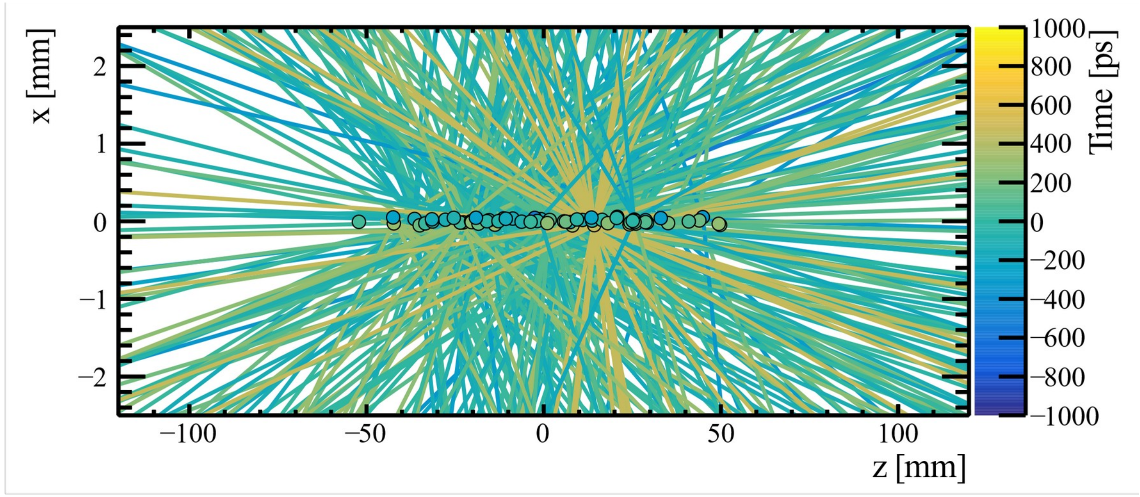
Detector R&D for the next accelerator

- Short term detector development
  - Driven by accelerator environment and physics case
- Long term detector development
  - Blue sky open development of future technologies



Time resolution

- Next future accelerator is the High-Luminosity upgrade of the LHC
  - More collisions per interaction window
  - Higher track densities
  - Higher amounts of radiation
- Track time resolution ~30 ps can resolve many of these issues → 4D Tracking



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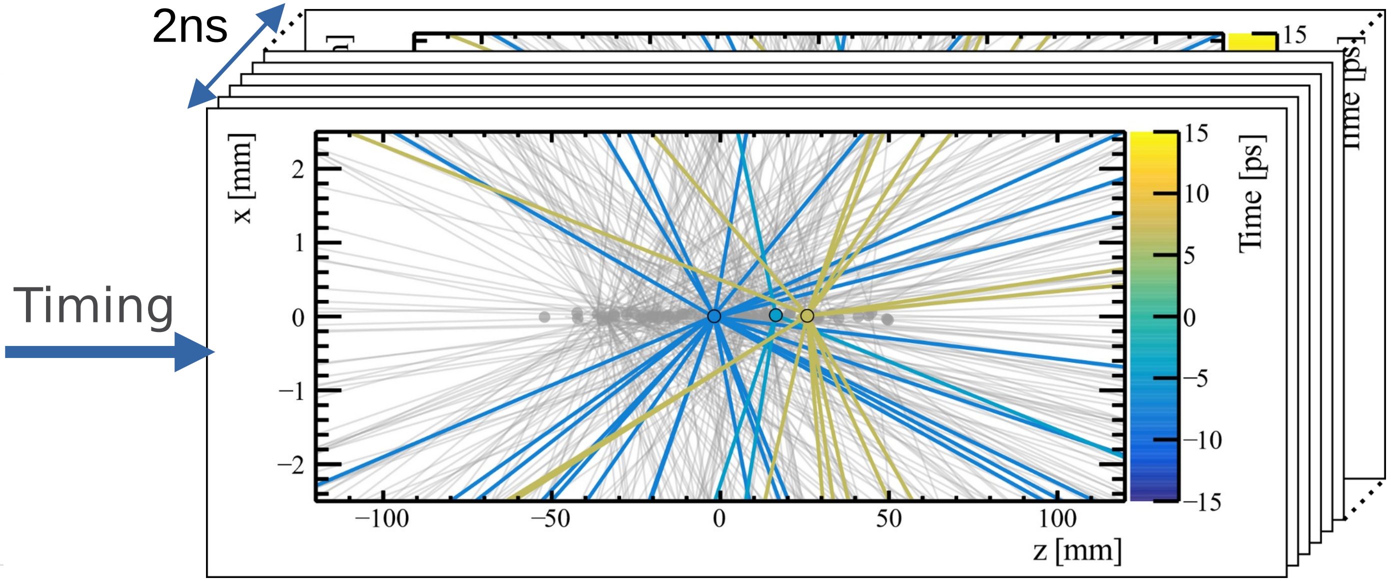

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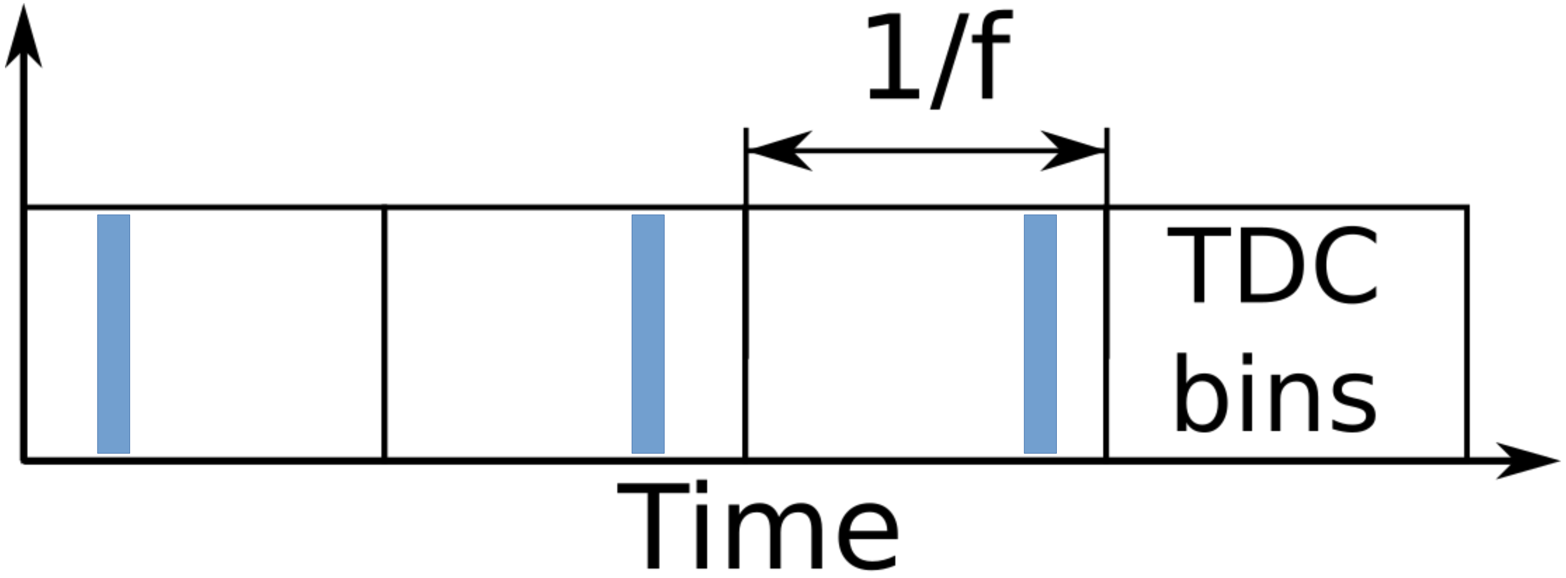
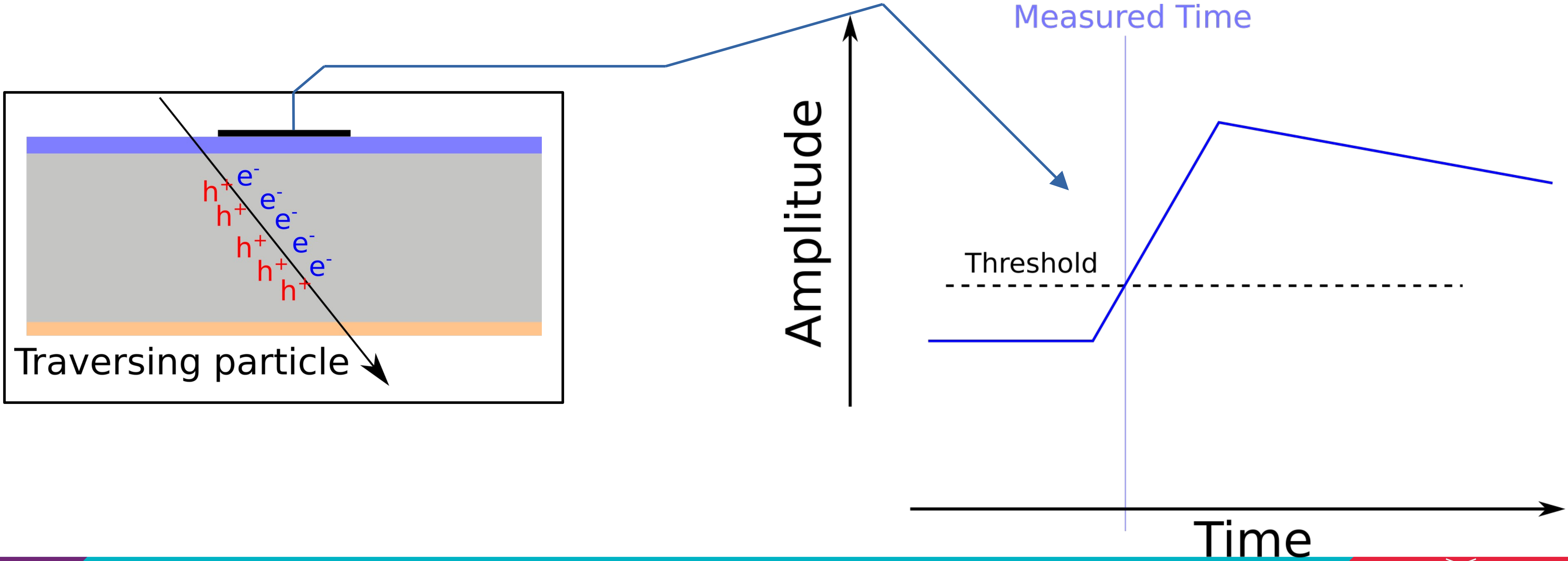
Contributions to time resolution

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



What is actually measured

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



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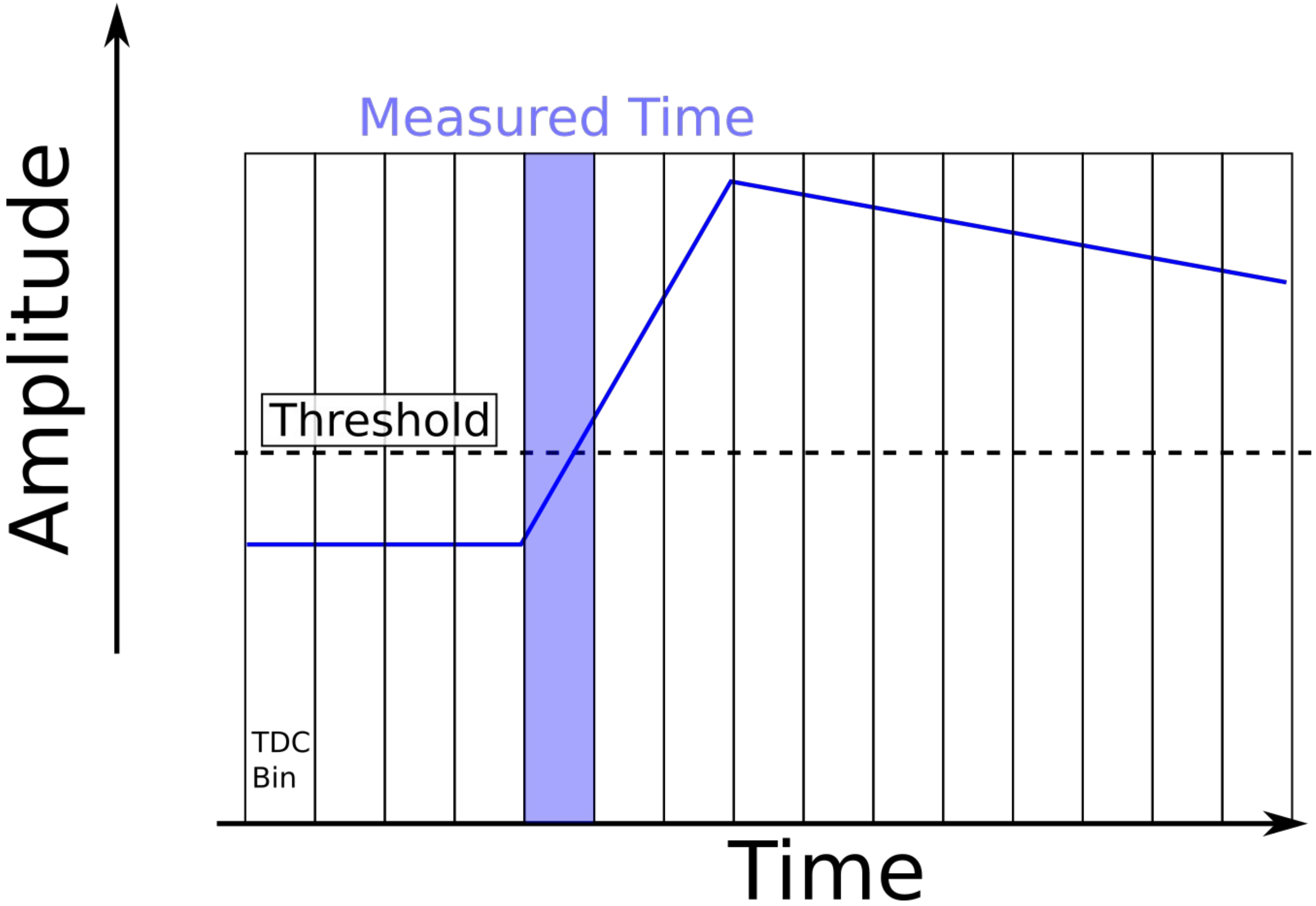

Contributions to time resolution

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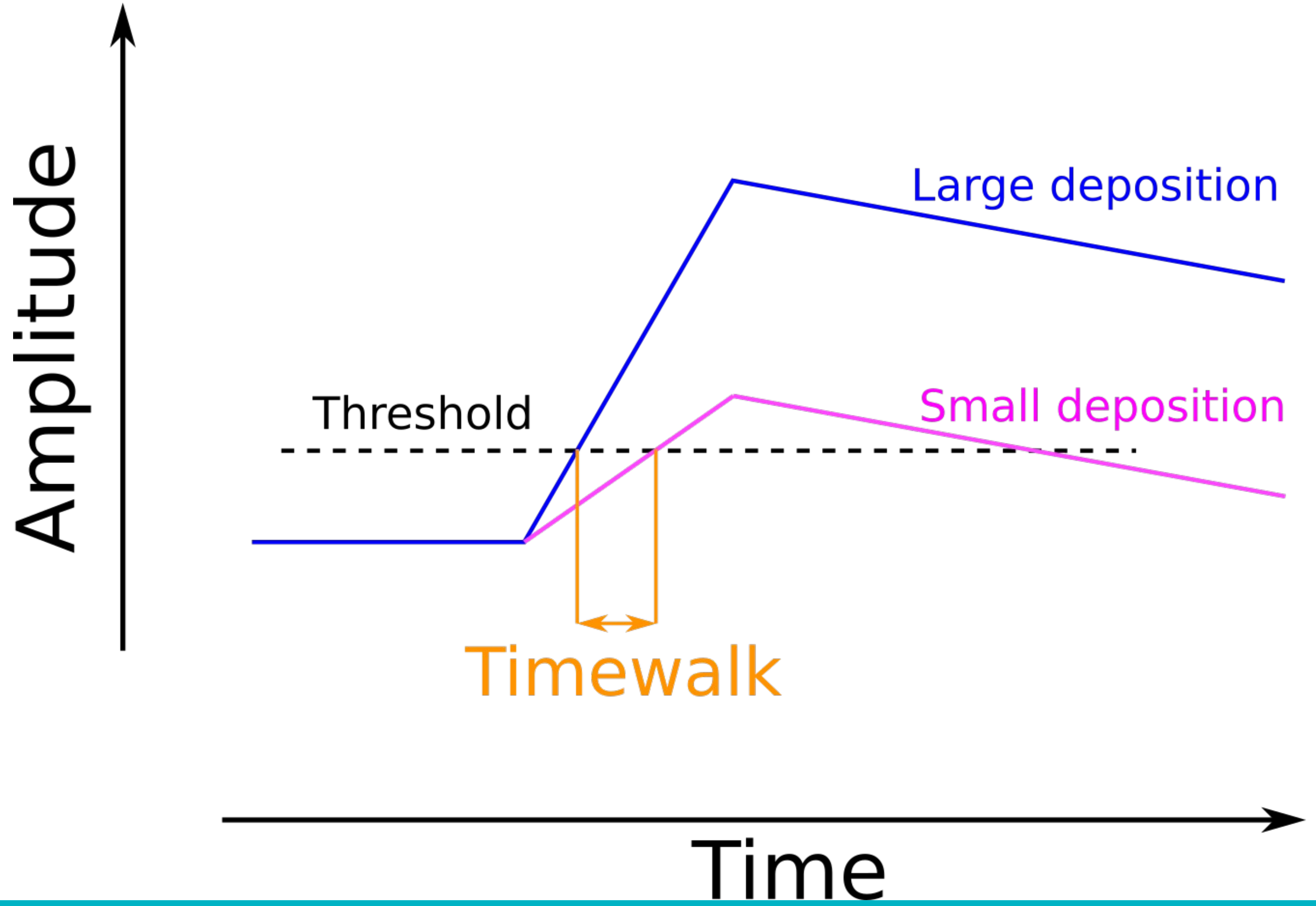
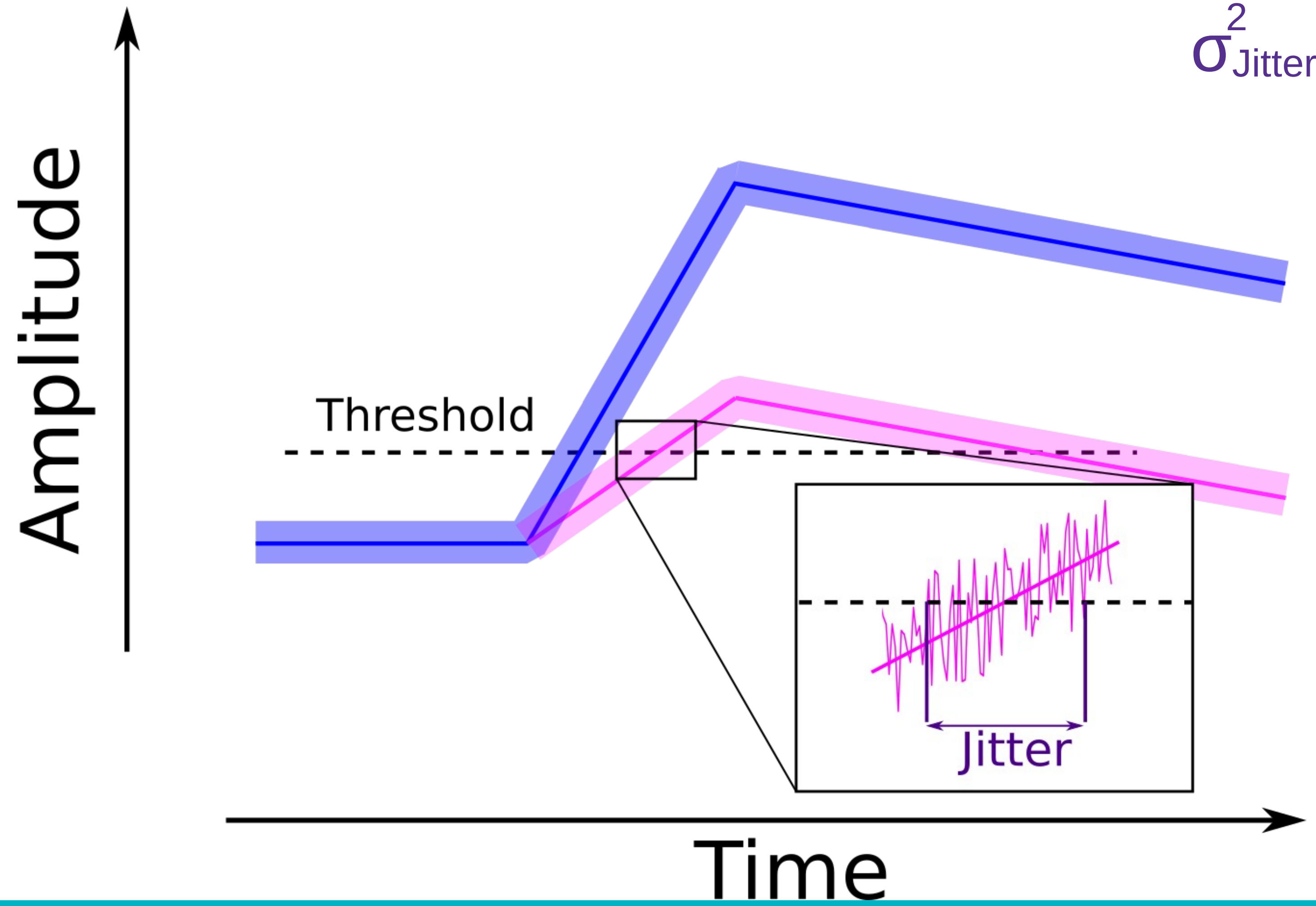


Contributions to time resolution

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



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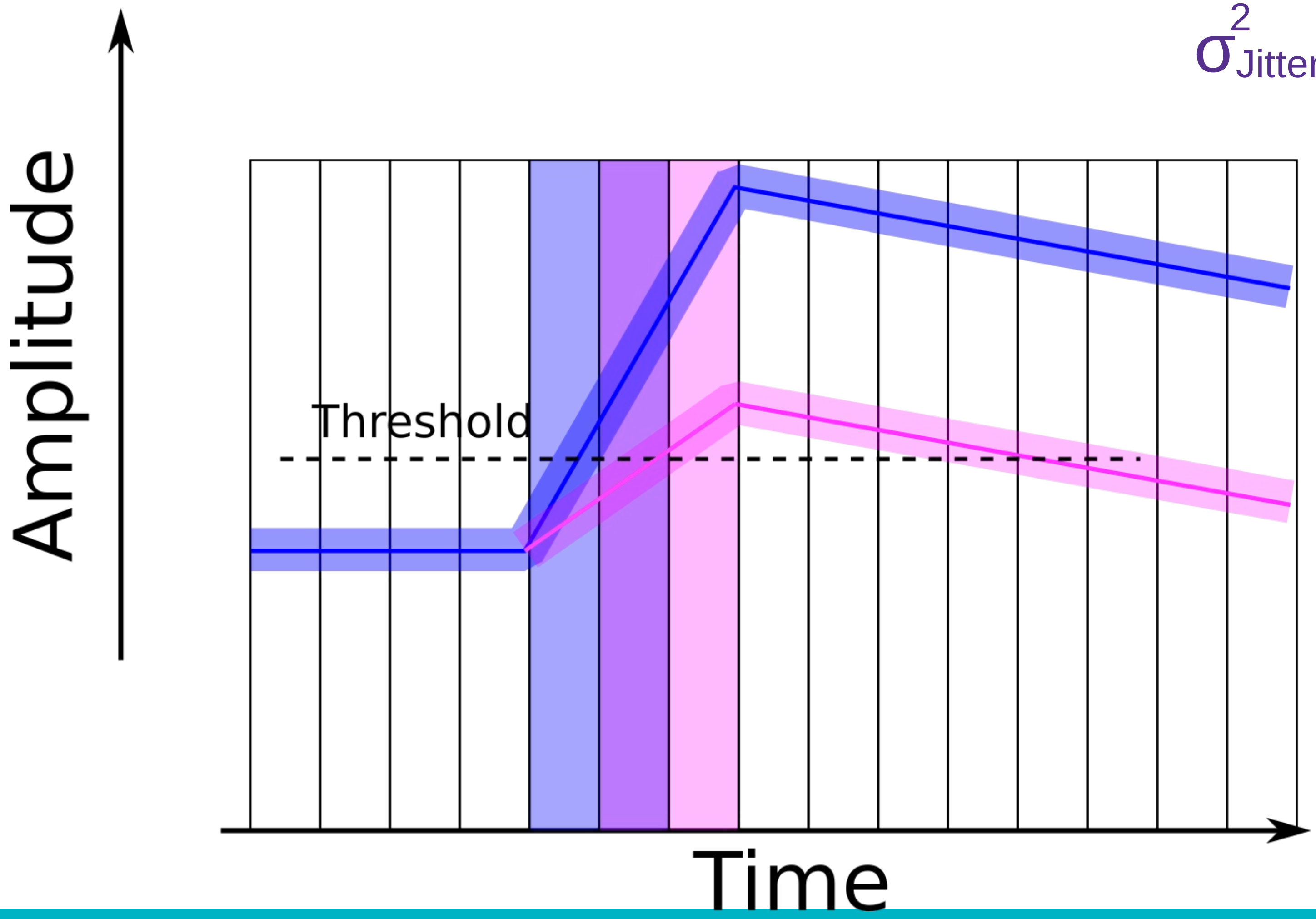
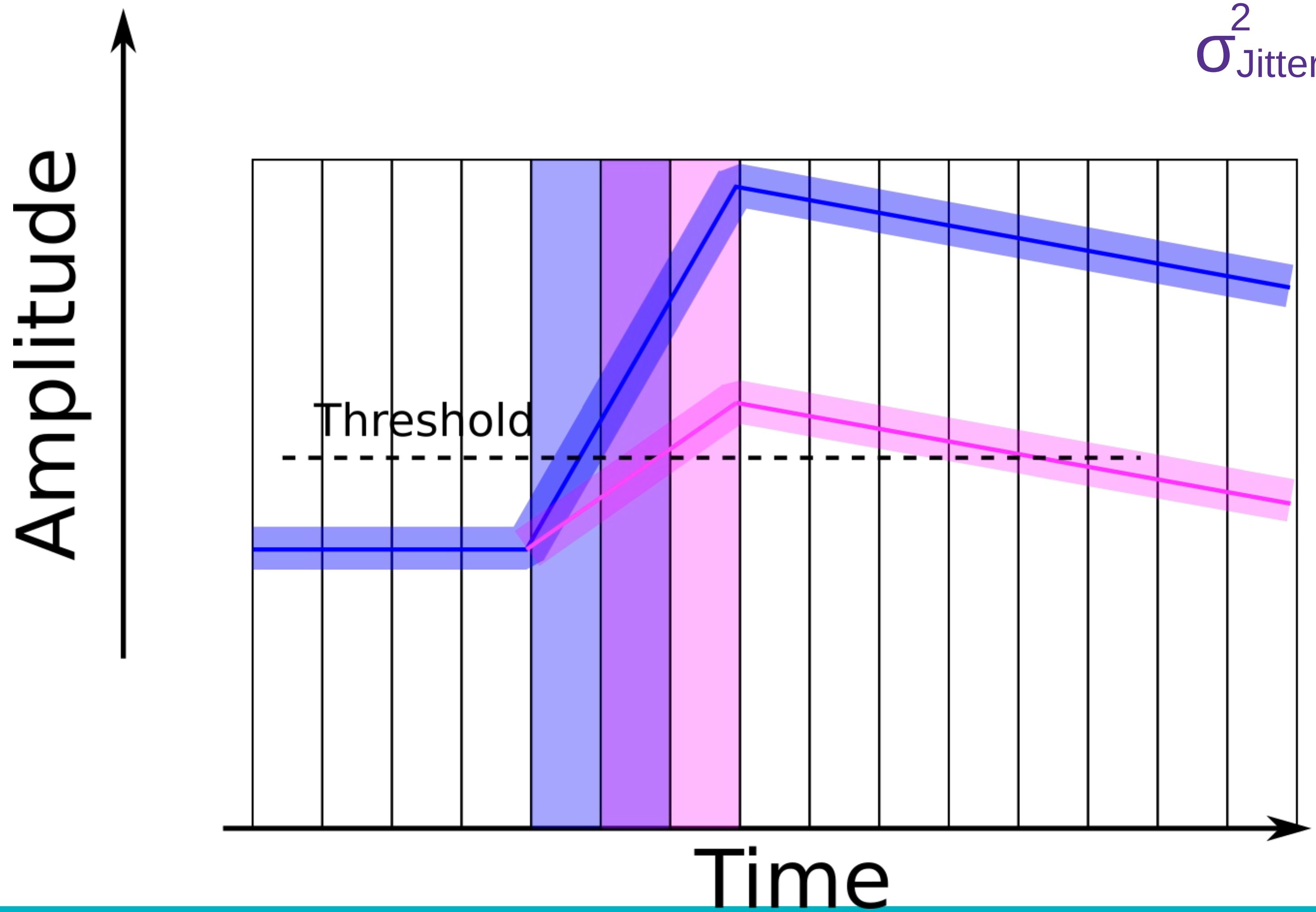


Contributions to time resolution

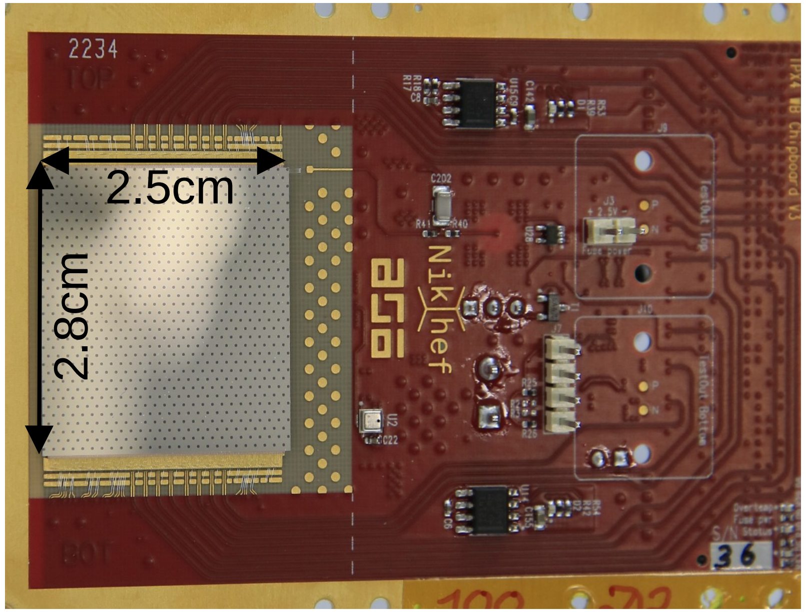
$$\sigma_t^2 = \sigma_{clock\text{-}global}^2 + \sigma_{clock\text{-}on\text{-}chip}^2 + \sigma_{TDC}^2 + \sigma_{Timewalk}^2 + \underbrace{\sigma_{Landau}^2 + \sigma_{Front\text{-}end}^2}_{\sigma_{Jitter}^2} (+ \sigma_{Pixel\text{-}to\text{-}Pixel}^2)$$

Removed through calibration, requires high statistics

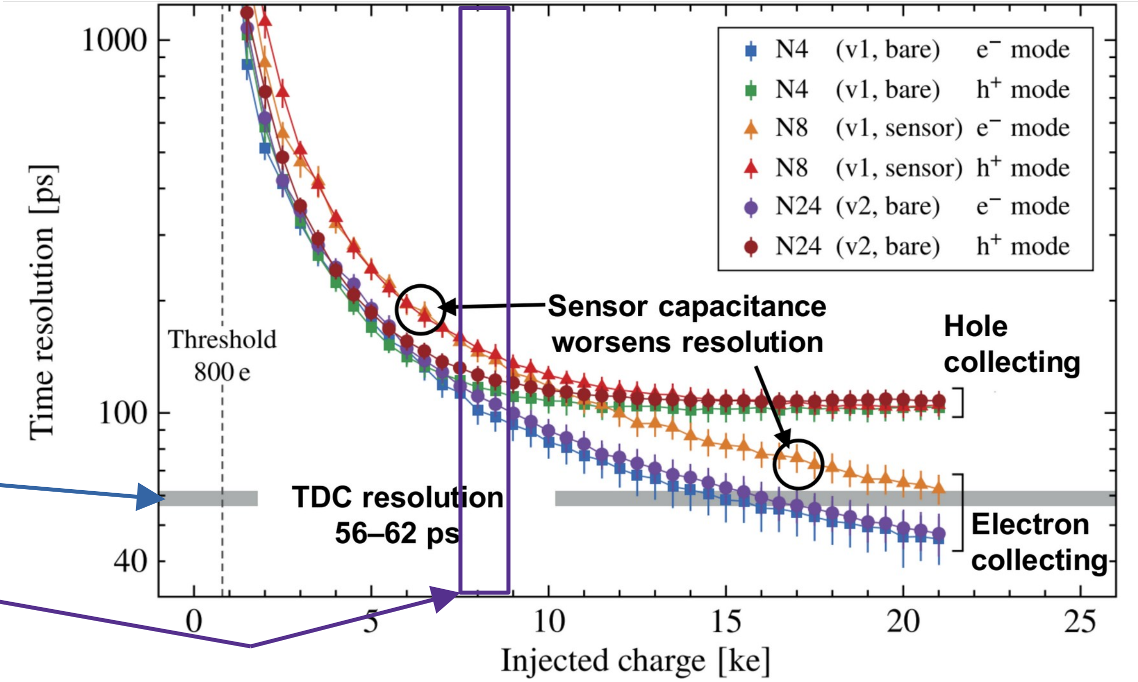


Moving beyond digital limits

- 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**

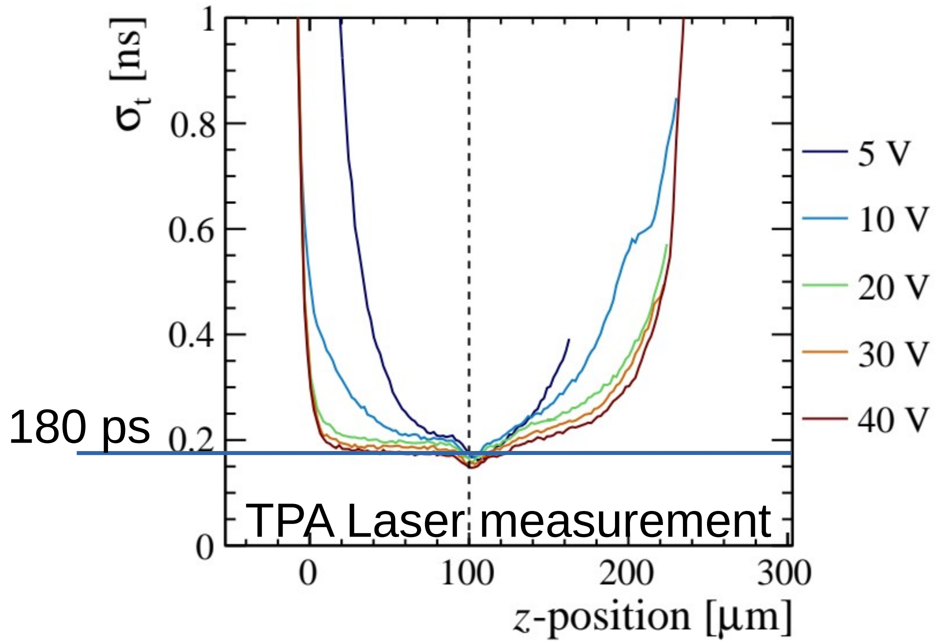


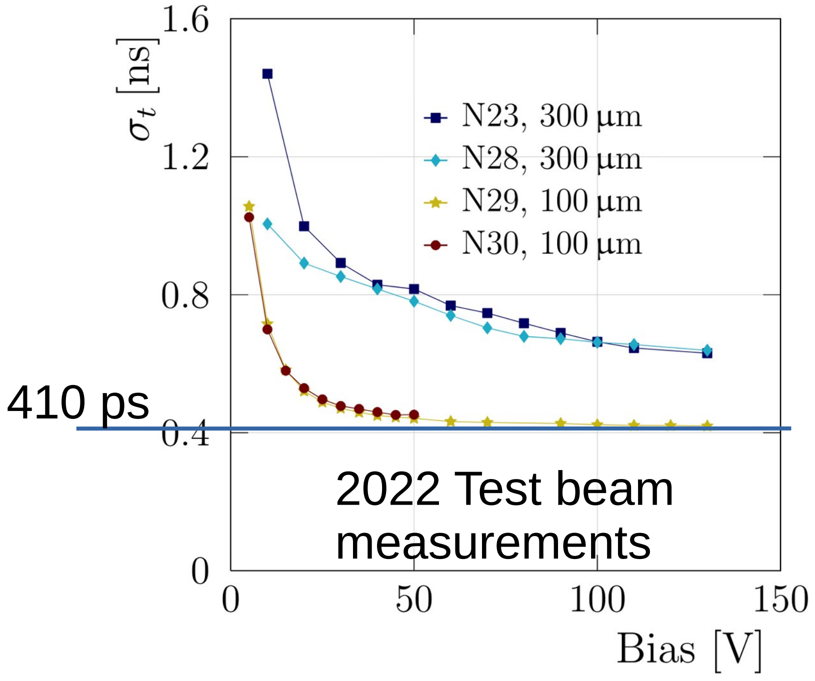
Moving beyond digital limits

- Single pixel measurement with charge induced in the sensor via TPA laser
  - $\sigma_t^2 = \sigma_{clock\text{-}global}^2 + \sigma_{clock\text{-}on\text{-}chip}^2 + \sigma_{TDC}^2 + \sigma_{Front\text{-}end}^2$
  - $\sigma_t = \sim 180$ ps

- Full chip measurement via test beam
  - $\sigma_t^2 = \sigma_{clock\text{-}global}^2 + \sigma_{clock\text{-}on\text{-}chip}^2 + \sigma_{TDC}^2 + \sigma_{Timewalk}^2 + \sigma_{Landau}^2 + \sigma_{Front\text{-}end}^2 + \sigma_{Pixel\text{-}to\text{-}Pixel}^2$
  - $\sigma_t = \sim 410$ ps

- Sensor type and structure start to play a major role





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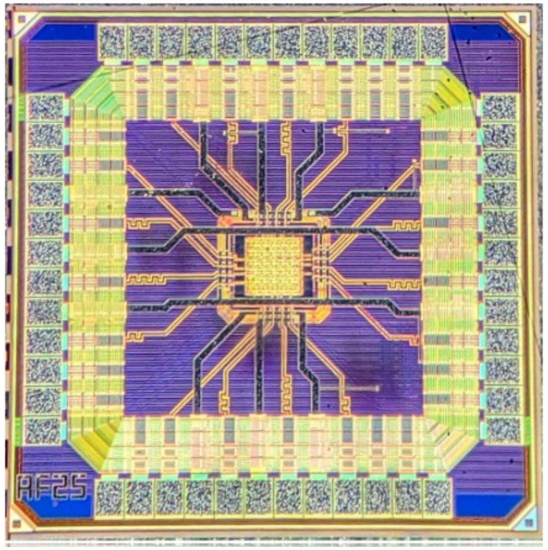
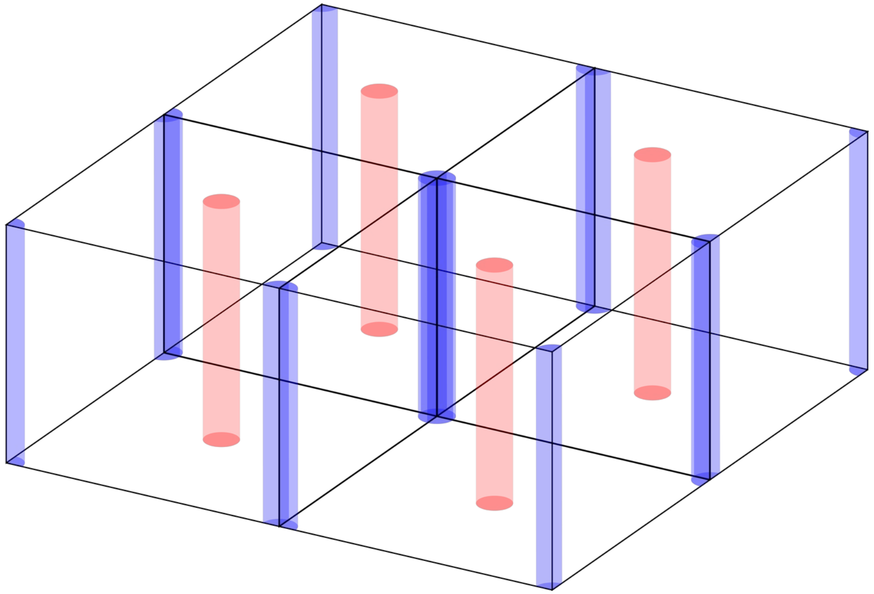
Beyond digital limits

- Different sensor structures under investigation
  - Monolithic Active Pixel Sensors (MAPS) for their fast charge collection and low capacitance
  - Low Gain Avalanche Diodes (LGAD) for their internal charge amplification
  - 3D sensors for their large signal generation and fast charge collection

ALICE APTS

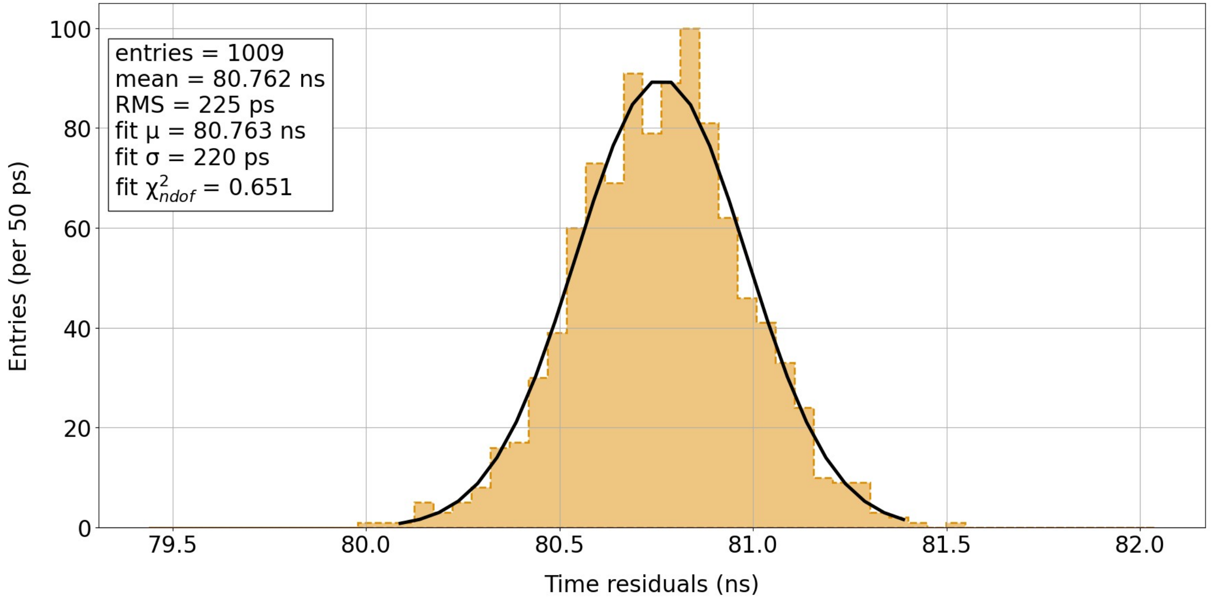


3D Silicon Sensor



ALICE MAPS

- Analog Pixel Test Structure (APTS) produced in different design structures
  - First tested standard process
    - $\sigma_{\text{Front-end}}$ ~ 220 ps with wide laser focused on pixel center



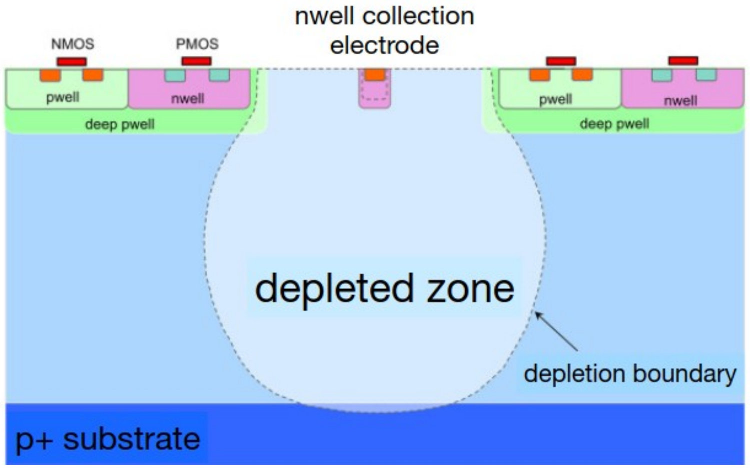


Fig.: Standard ALICE MAPS

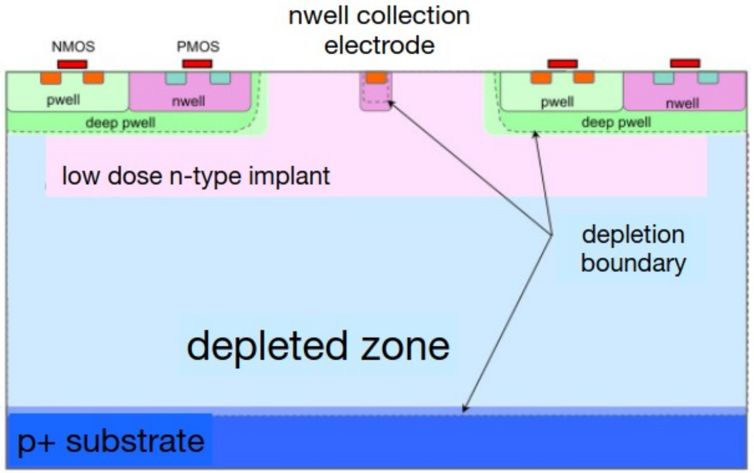


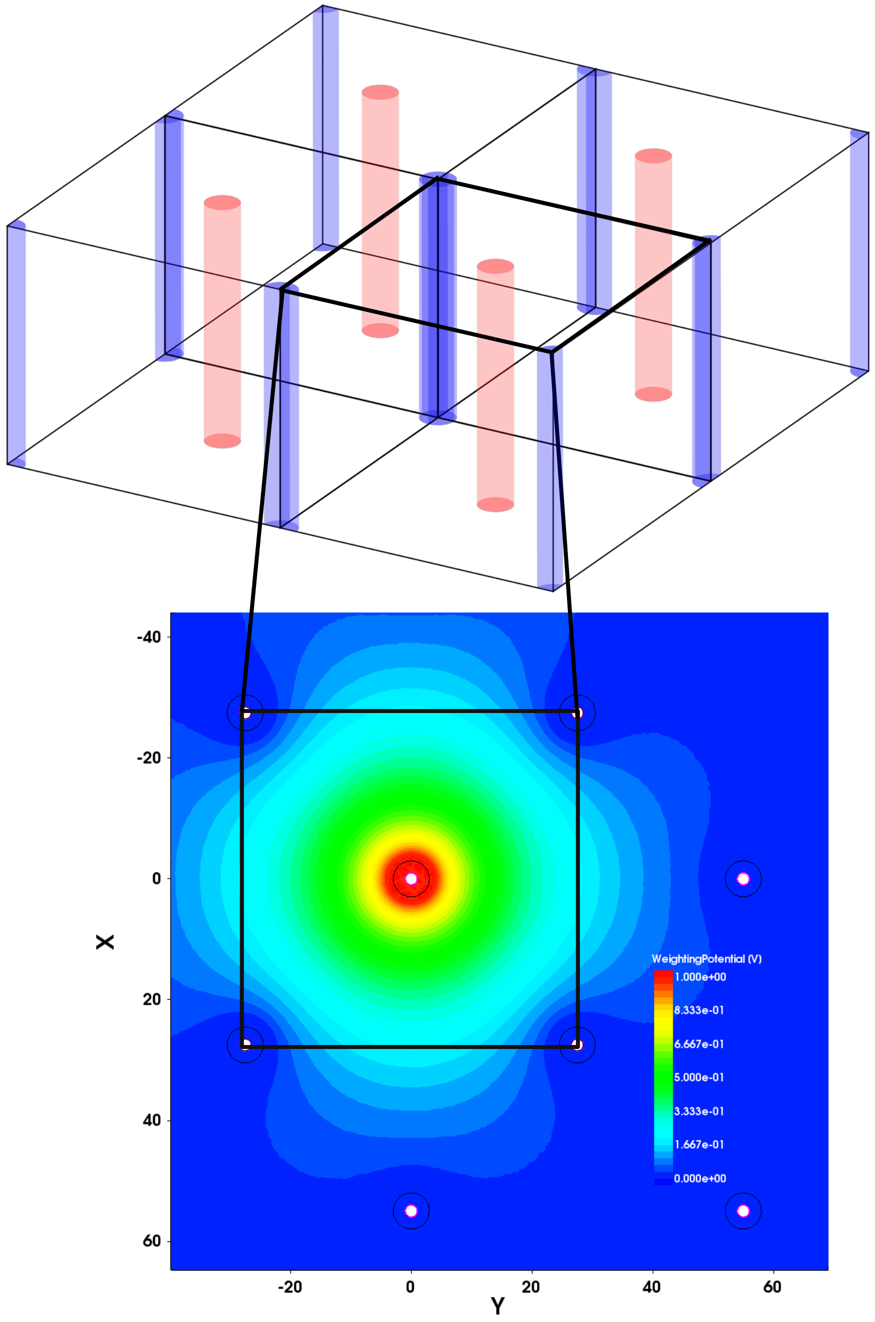
Fig.: Modified ALICE MAPS

  - Modified process
    - $\sigma_{\text{Front-end}}$ < 80 ps in whole pixel

3D Sensors and Simulations

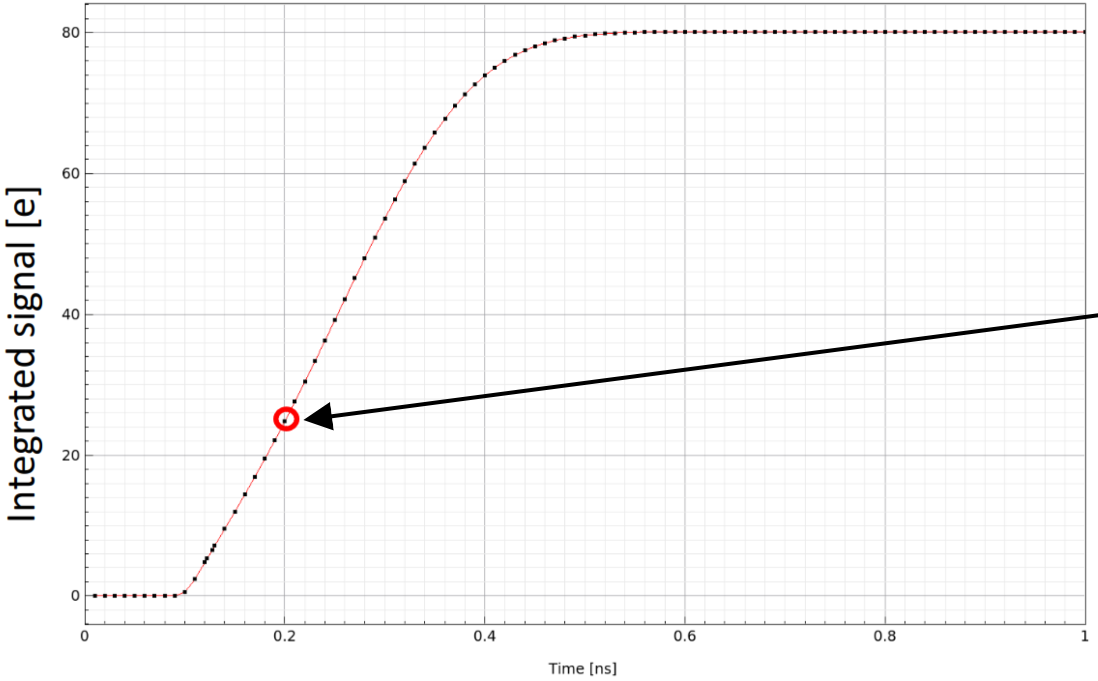
- 3D sensors:
  - Can be made thick as distance to electrodes doesn't depend on thickness
    - Fast charge collection
    - Large signal
  - More complex behavior with respect to track angle, charge sharing etc.

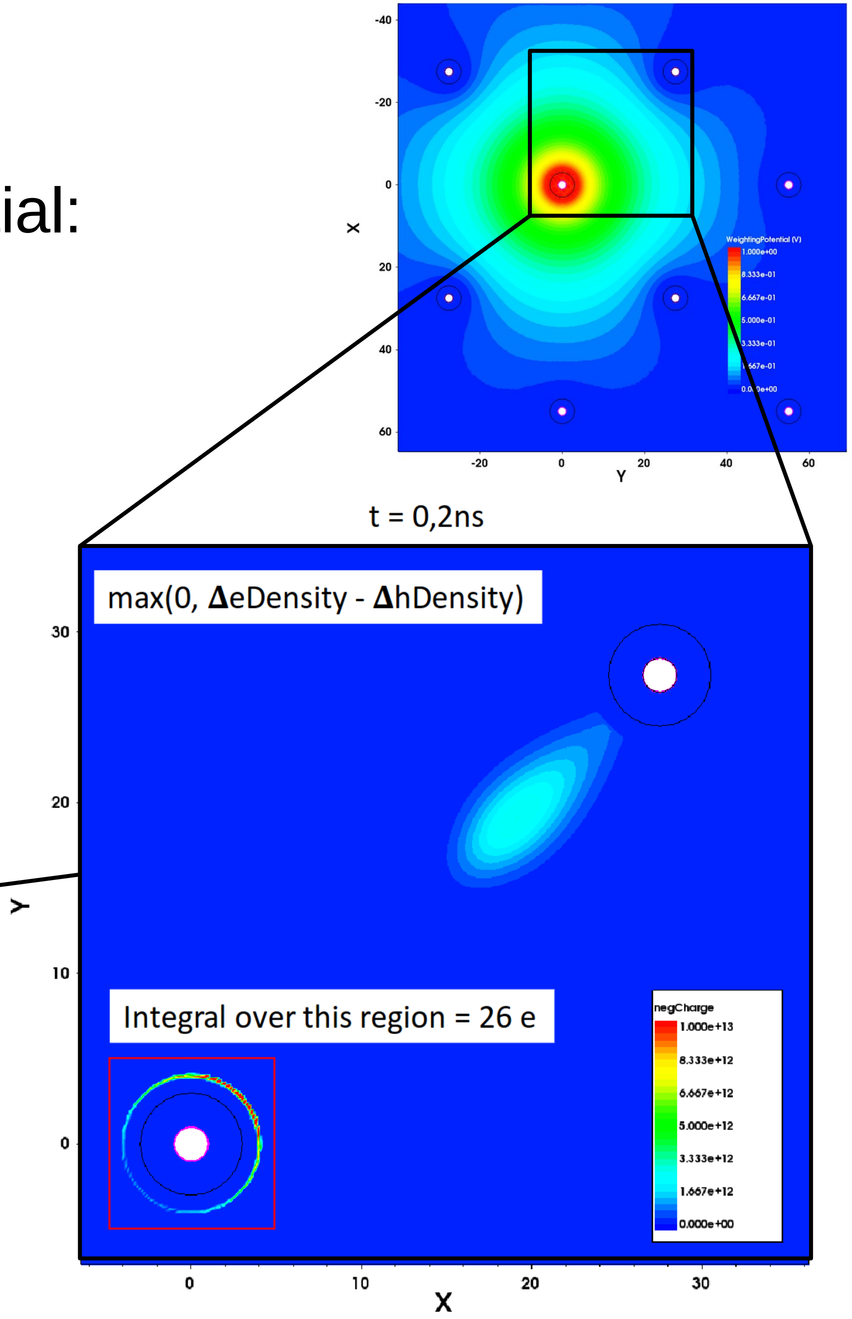
- Simulations allow for:
  - The modeling of complex structure
  - Investigation into single parameters to the overall time resolution
  - Verification laboratory and testbeam measurement



3D Sensors and Simulations

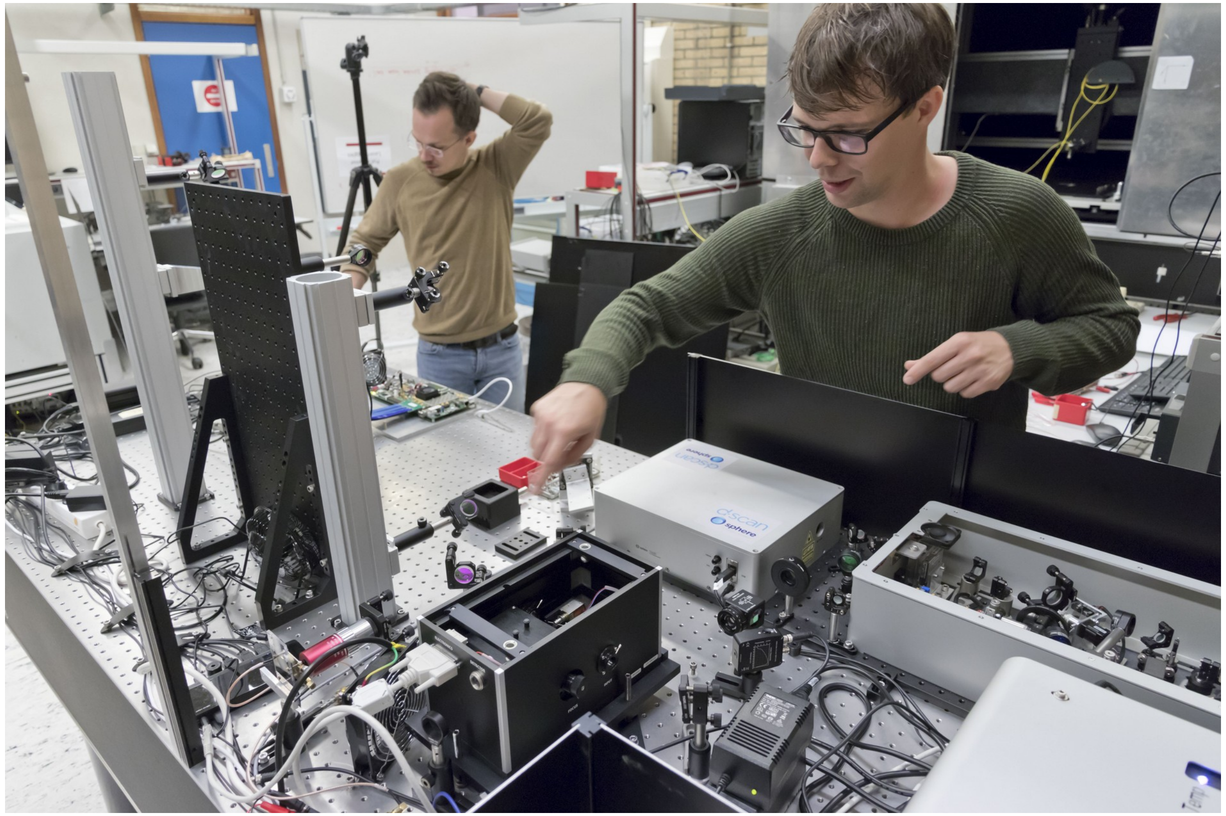
- Simulations of the sensor structures are essential:
  - Understanding system behavior
  - Verifying measurement results
  - Investigating potential design criteria





A tale of photon- and charged beams

Laser setups at the Nikhef Laboratories



Test beam measurements at CERN and DESY

Summary and Outlook

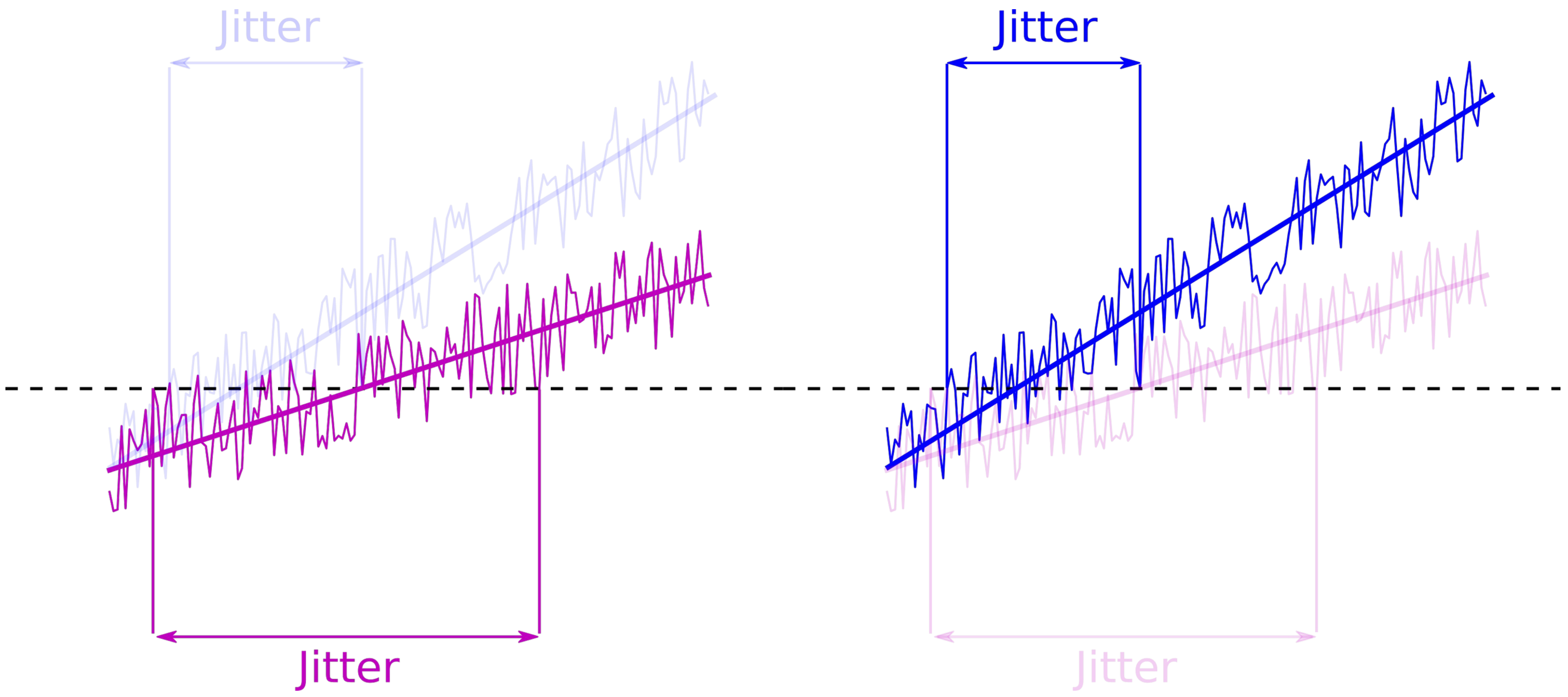
- Time resolution becoming essential for future collider experiments
- Time resolution is affected by both digital and analog components that all have interplay

- The Detector R&D group is working at the forefront of the fast timing efforts looking into many possible candidates for future technologies
- With the accepted FASTER proposal the efforts at Nikhef to produce detectors with the best possible time resolution will only be improved further

Backup slides

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



ALICE MAPS cont.

- Investigation of APTS structure concerning different settings