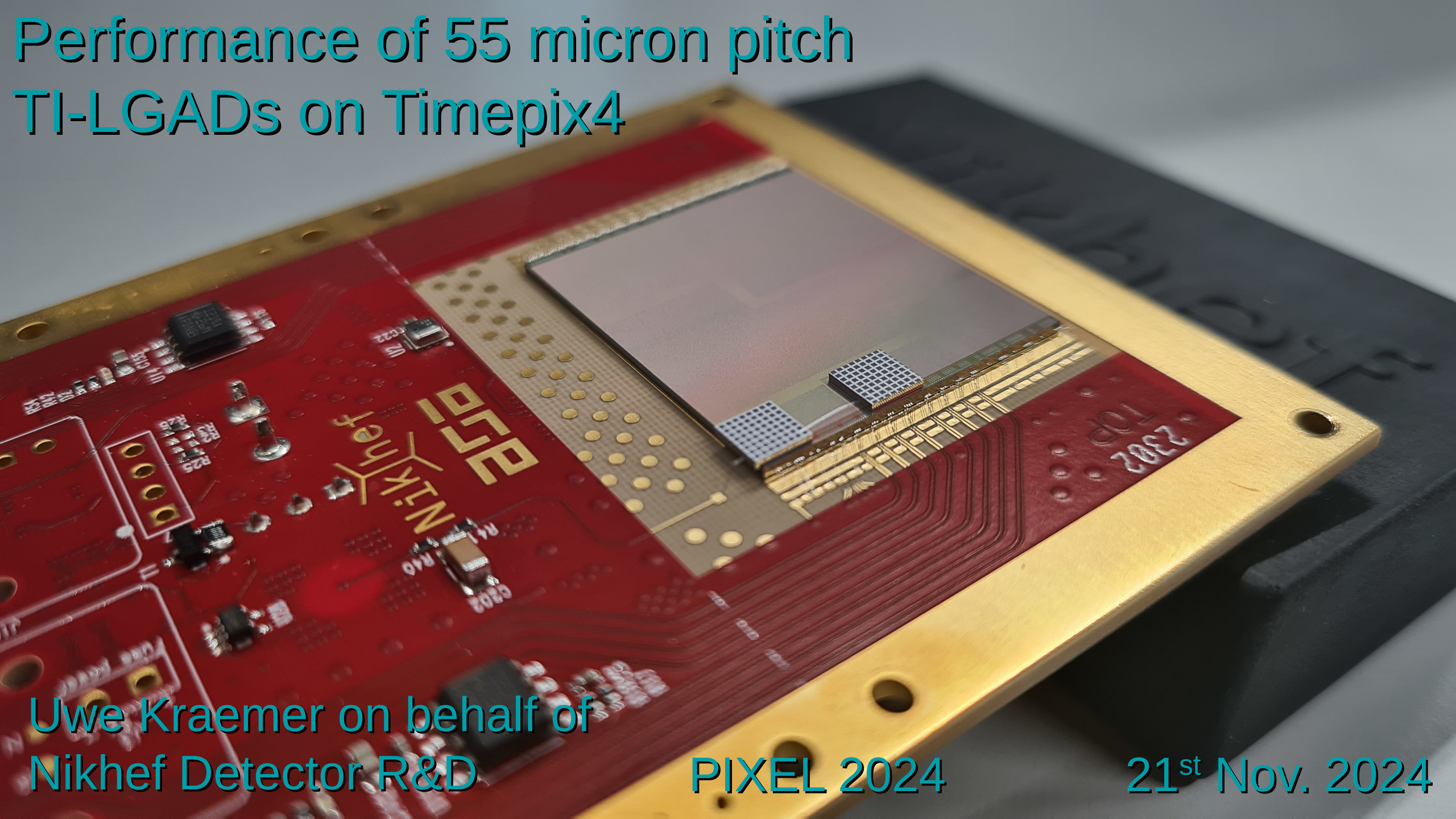
Performance of 55 micron pitch TI-LGADs on Timepix4



Uwe Kraemer on behalf of
Nikhef Detector R&D

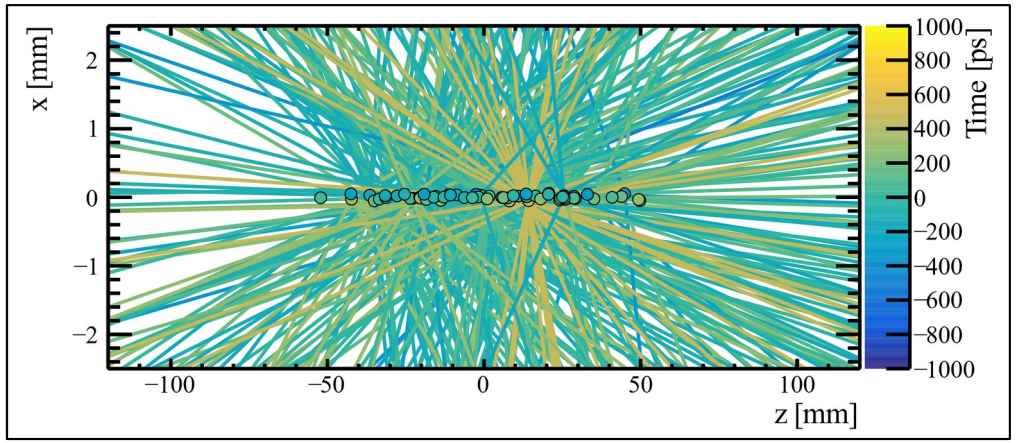
PIXEL 2024

21st Nov. 2024

4D-Tracking

- Future accelerators have an increasingly complicated tracking environment
- Time as an important parameter to embed in the analysis
  - Allows for Time of Flight based particle identification
  - Separation of tracks in time
    - Fewer tracks per event → Simpler analysis

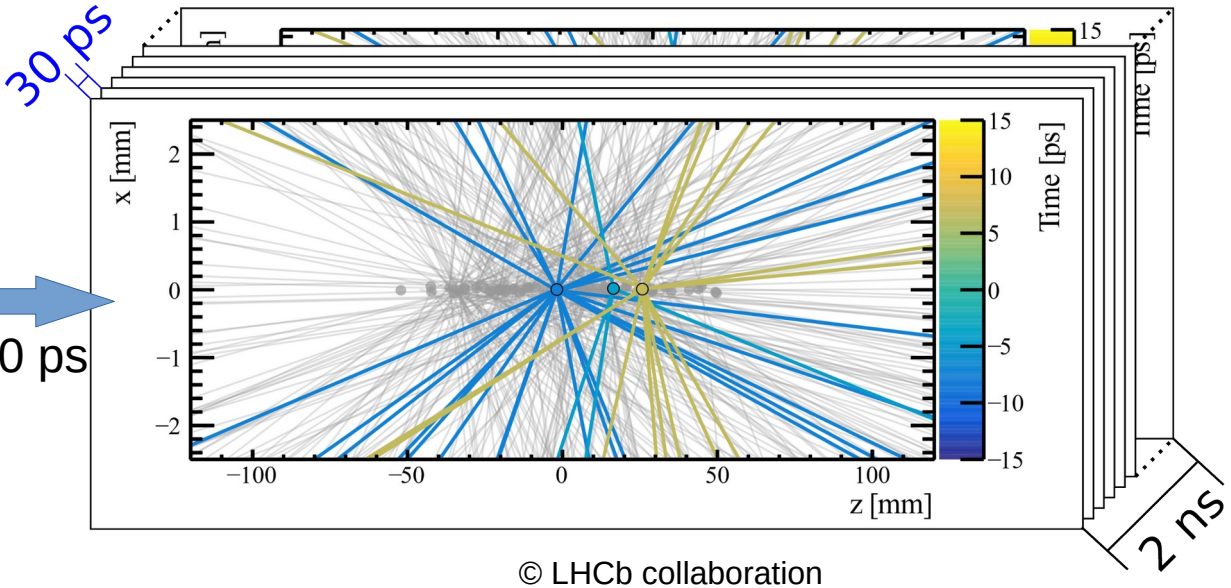
→ **Requires O(30 ps) time resolution**



© LHCb collaboration

Timing

2ns → 30 ps



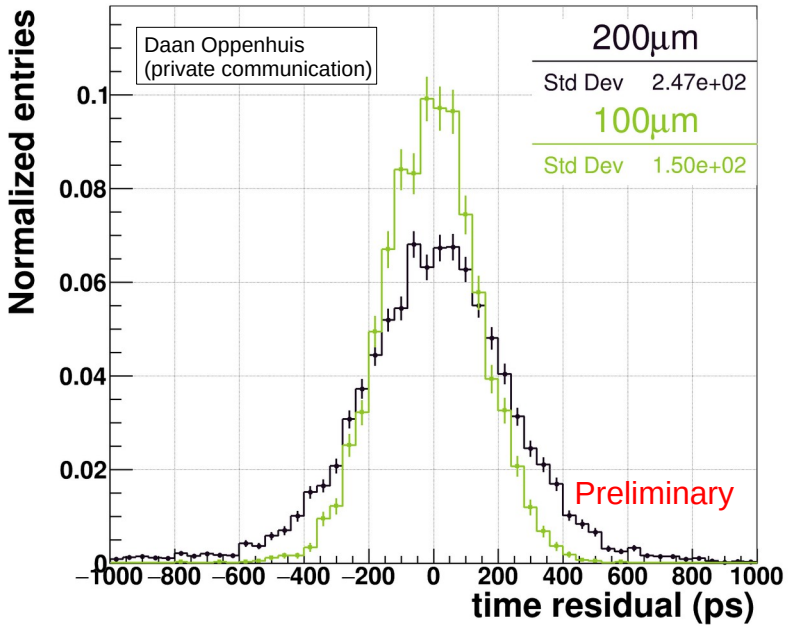
© LHCb collaboration

Reaching picosecond time resolution

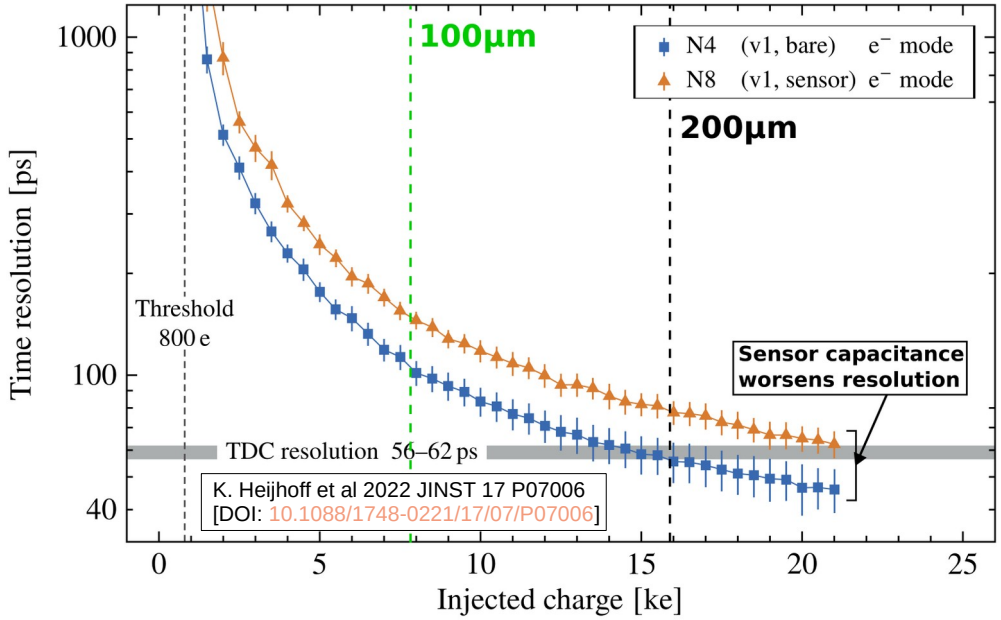
- Sensor only
  - Thin sensors → Better time resolution
    - 100 µm = 150 ps
    - 200 µm = 247 ps

- Front-end electronics
  - More charge → Better time resolution
    - 100 µm = 8000e^- = 150 ps
    - 200 µm = 16000e^- = 80 ps

Thin sensor + Lots of charge = **Gain**



Single pixel time resolution of planar sensors on TPX4 (Daan Oppenhuis)



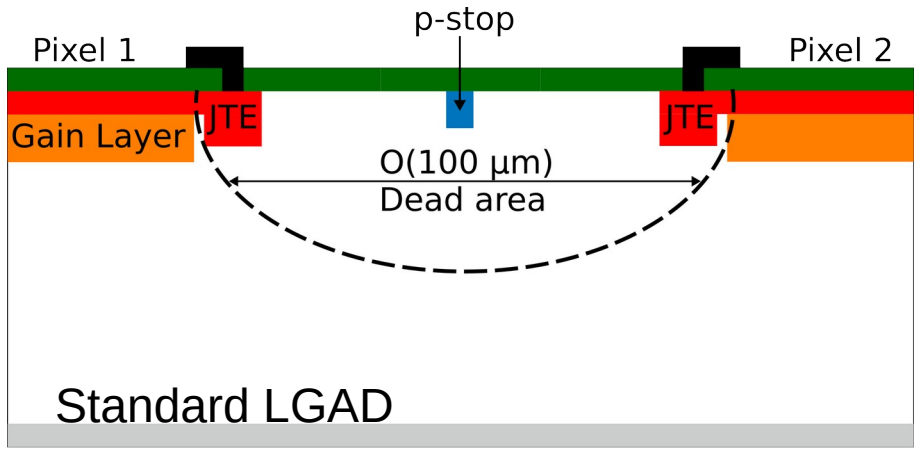
Mean time resolution of the TPX4 analog front-end versus injected charge

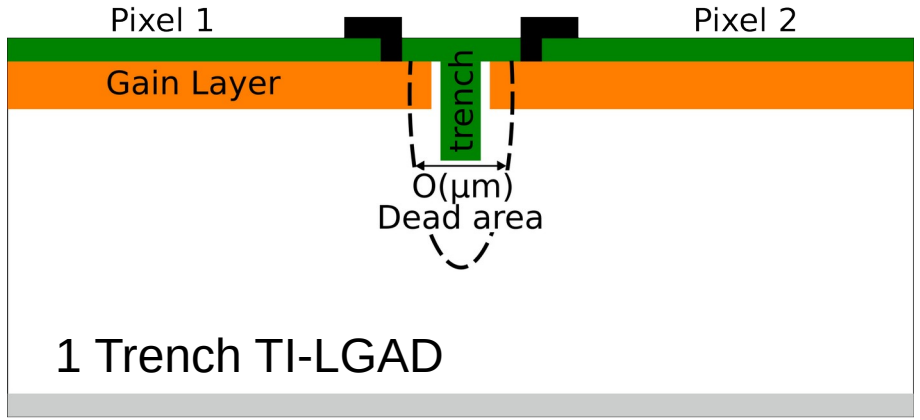
Low Gain Avalanche Detectors

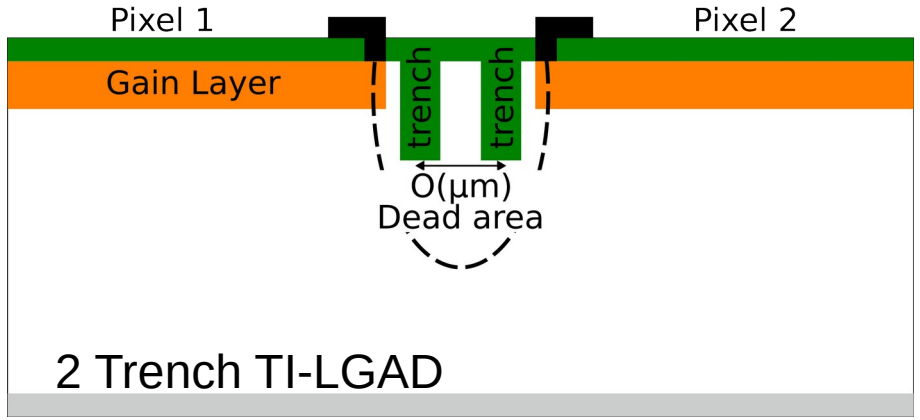
- Low Gain Avalanche Detectors (LGAD)
  - Controlled charge amplification within silicon sensor

- Standard LGAD
  - Junction Termination Extension (JTE)
    - Require large area → dead area
    - Pixel size ↔ Fill factor

- Trench Isolated LGAD (TI-LGAD)
  - JTE replaced by trench cut into silicon sensor
    - Smaller dead area
    - Small pixels with better fill factor

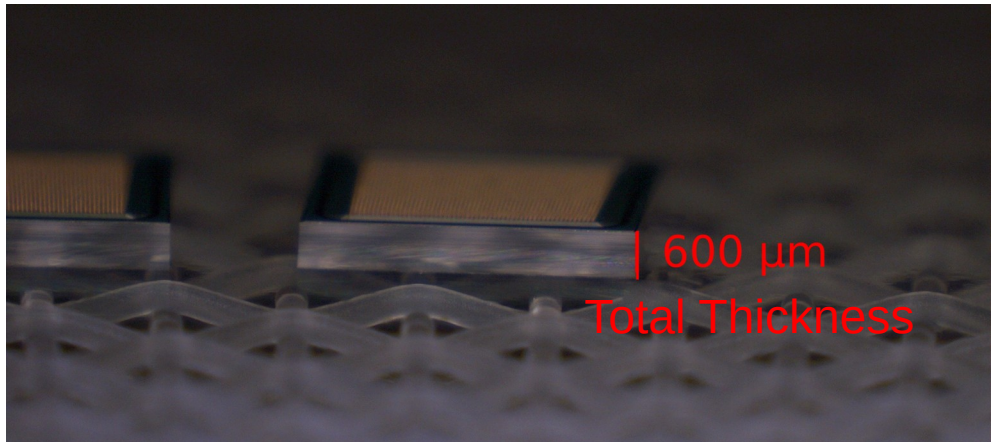






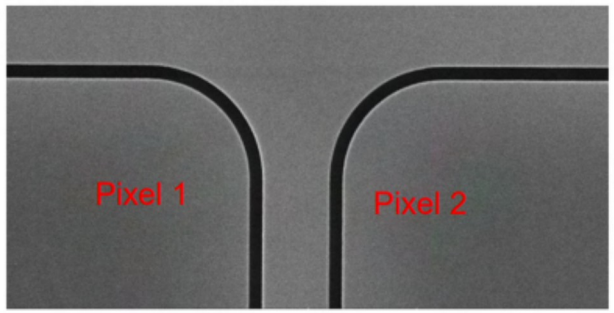
Small pitch TI-LGAD

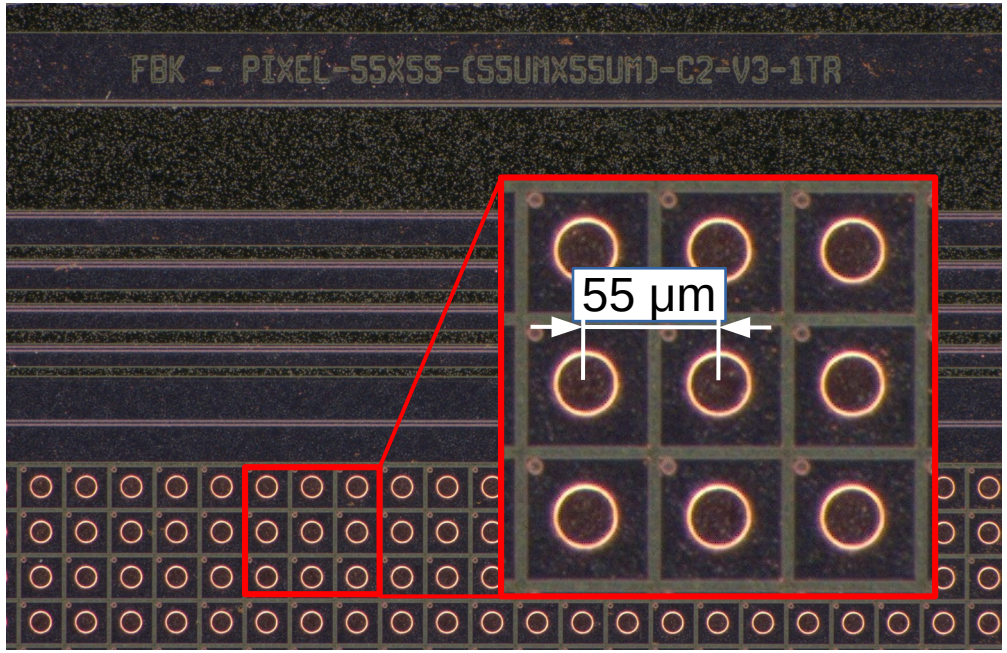
- Samples from RD50/AIDAinnova production
  - Produced by FBK
- 55 µm pitch TI-LGAD
  - 55 µm epitaxial thickness
  - Single and double trench
  - With and without gain layer



Single Trench

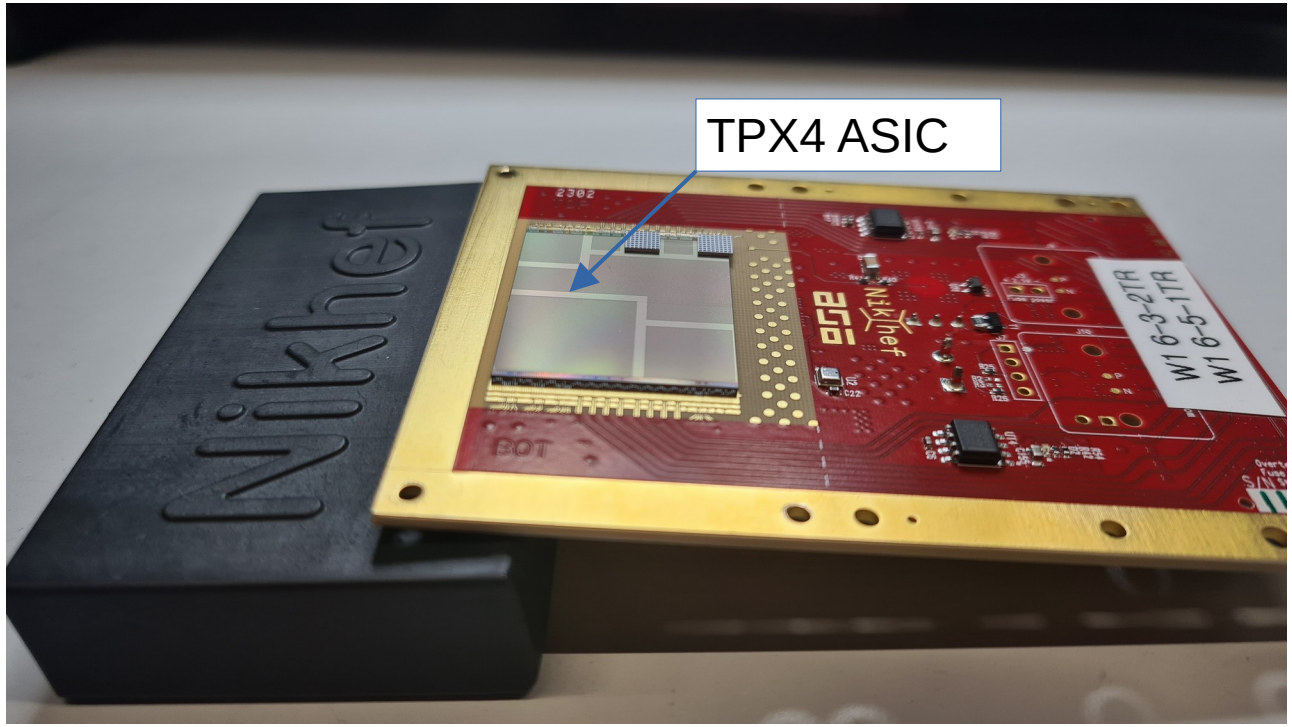
Double Trench





The Timepix4 readout ASIC

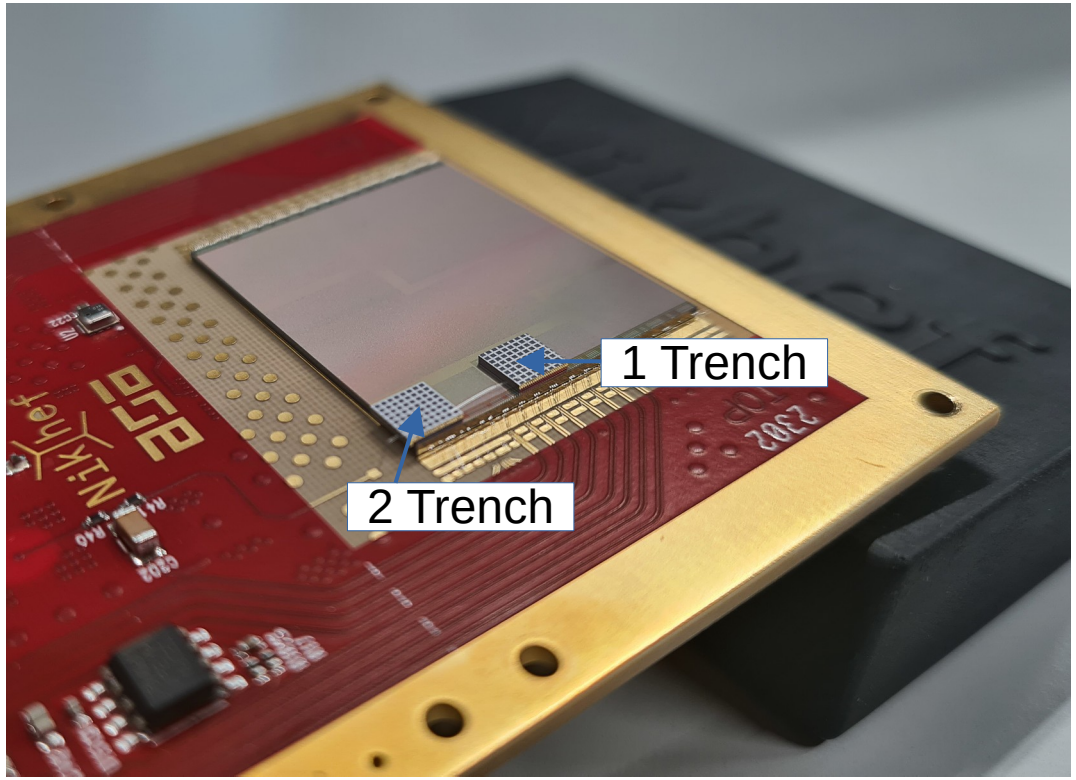
- Developed by CERN, Nikhef and IFAE
- 65 nm CMOS process
- 448x512 pixels
- 55 µm pitch
- Simultaneous measurement of
  - Time via Time of Arrival (ToA)
  - Charge via Time over Threshold (ToT)
- Time-bin size of 25ns/128 = 195 ps
  - Time to Digital Converter (TDC) resolution of 56 ps

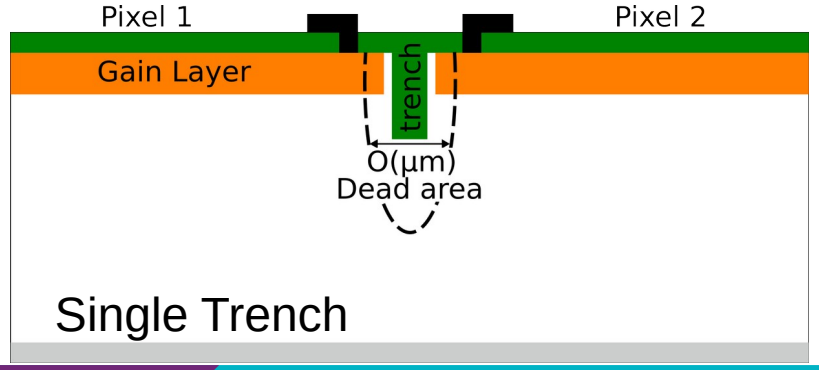


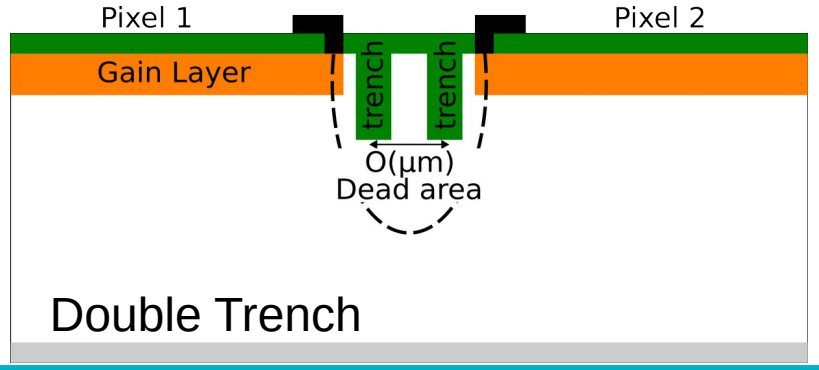
More details in the presentation from Kevin Heijhoff (https://indico.in2p3.fr/event/32425/contributions/142772/)

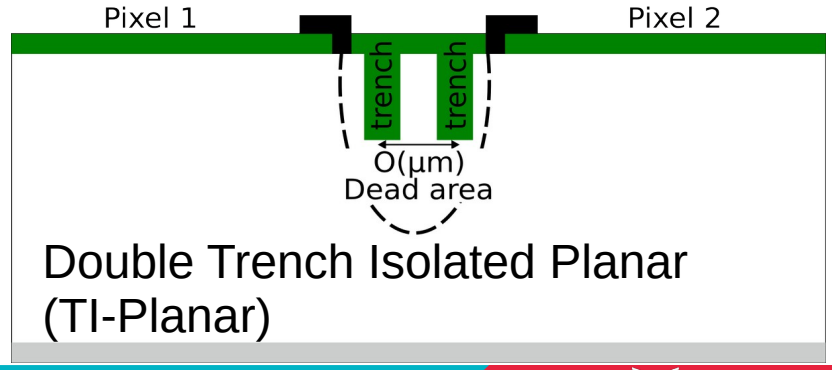
Timepix4 TI-LGAD assemblies

- Single trench
  - Only one functional assembly at 100V
- Double trench
  - Multiple assemblies above up to 100V
  - One assembly up to 200V
- Double trench isolated planar sensor (TI-Planar)
  - Same geometry as above, no gain layer
  - Assembly up to 200V
- 50 micron standard planar
  - Assembly up to 60V
- All operated at threshold = 1000e$^-$



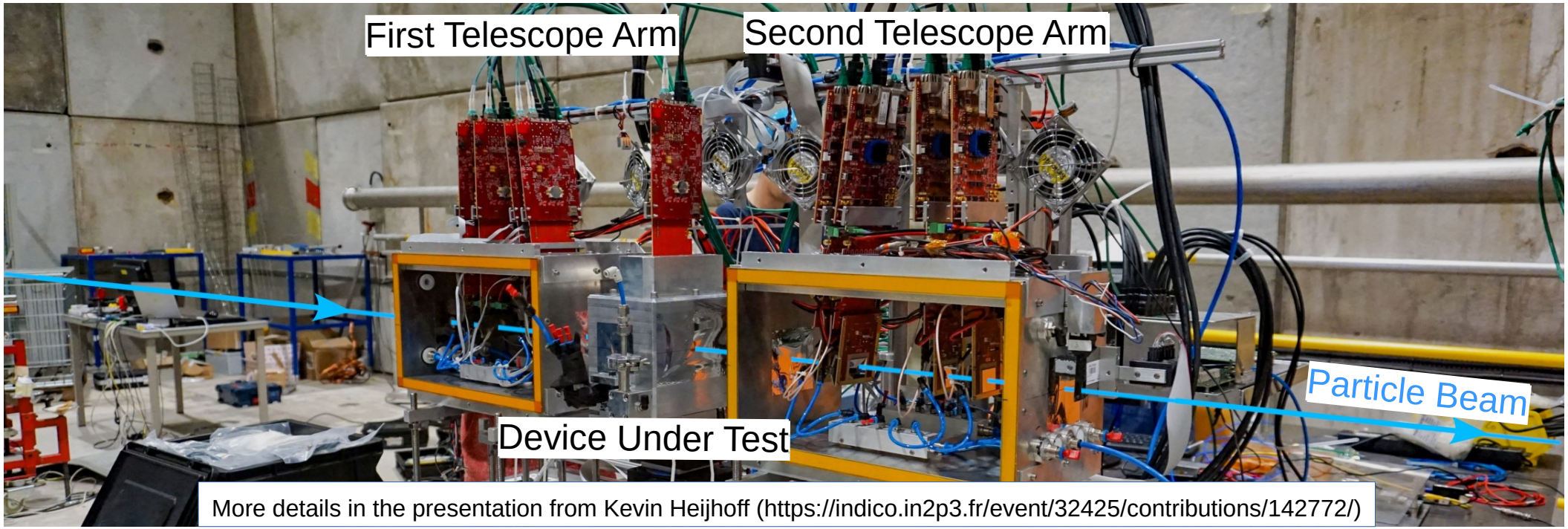






The test setup

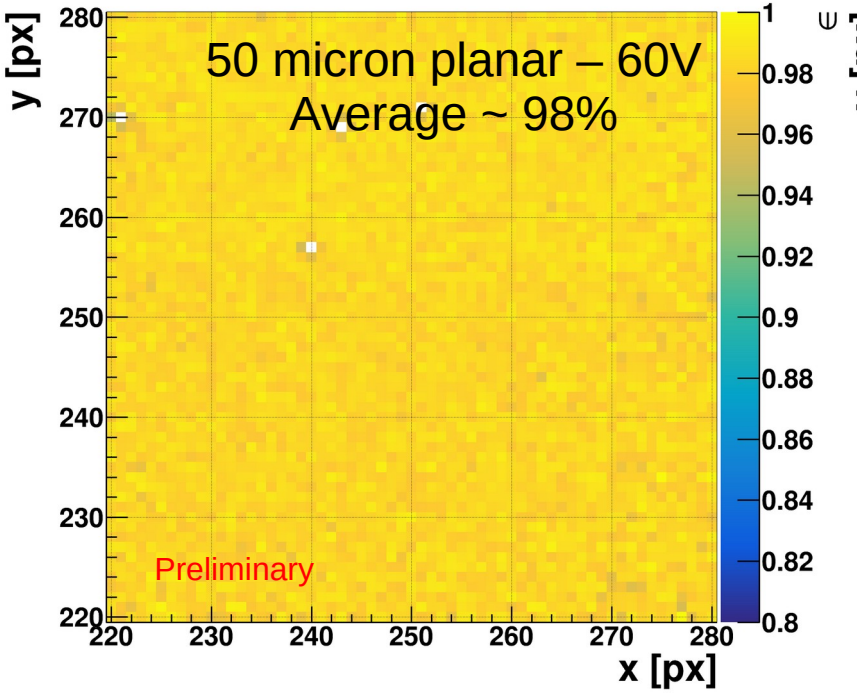
- Measurements performed at the CERN SPS area
  - 180 GeV particle beam
- Using 8 layer Timepix4 Telescope + Micro Channel Plates as reference detector
  - 2-3 µm spatial information
  - 12 ps resolution time reference
- Used to investigate efficiency and in-pixel performance using reconstructed tracks

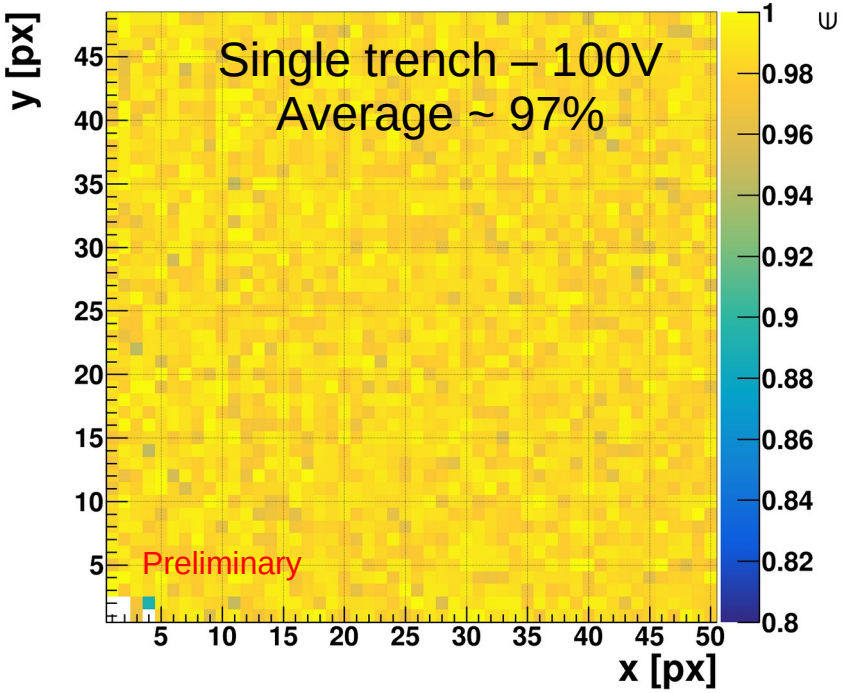


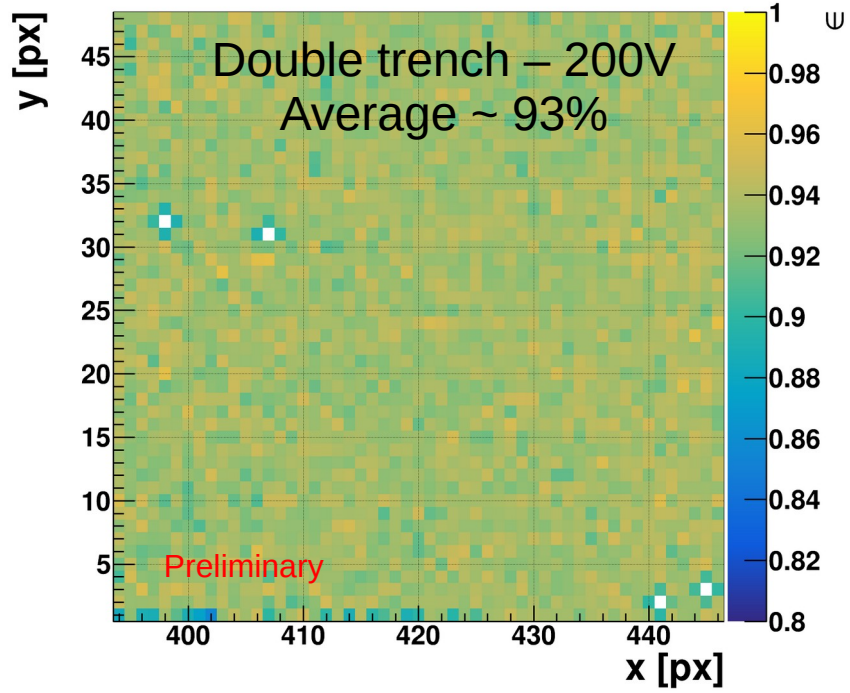
More details in the presentation from Kevin Heijhoff (https://indico.in2p3.fr/event/32425/contributions/142772/)

TI-LGAD Efficiency

- Masked pixels are considered inefficient and not taken out of efficiency calculation
- Single trench has similar efficiency to 50 micron planar
- Double trench efficiency is ~5% below the other two

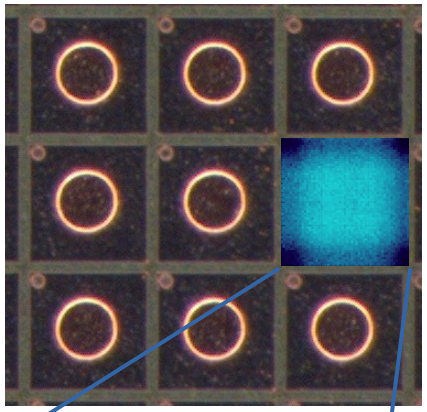


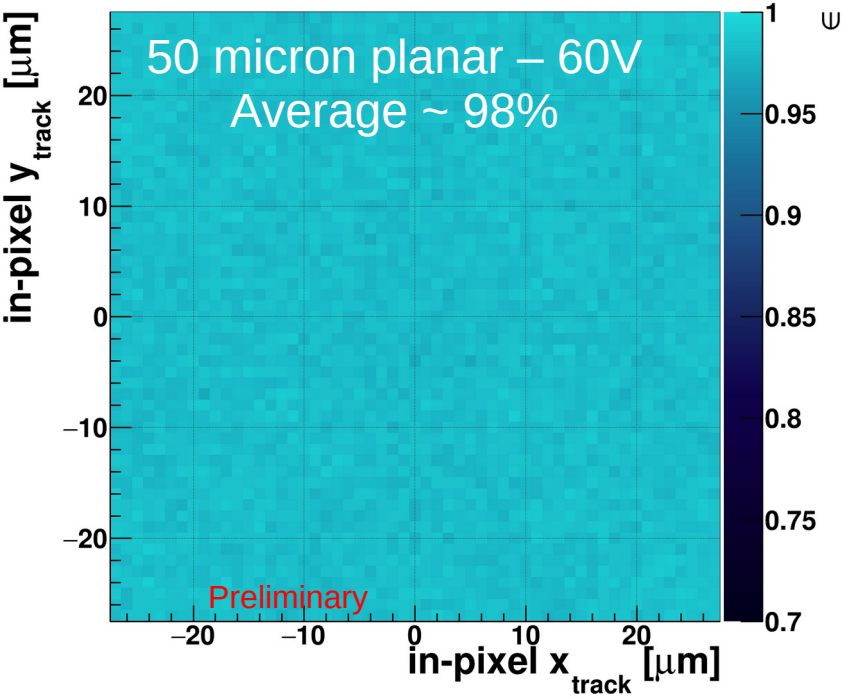


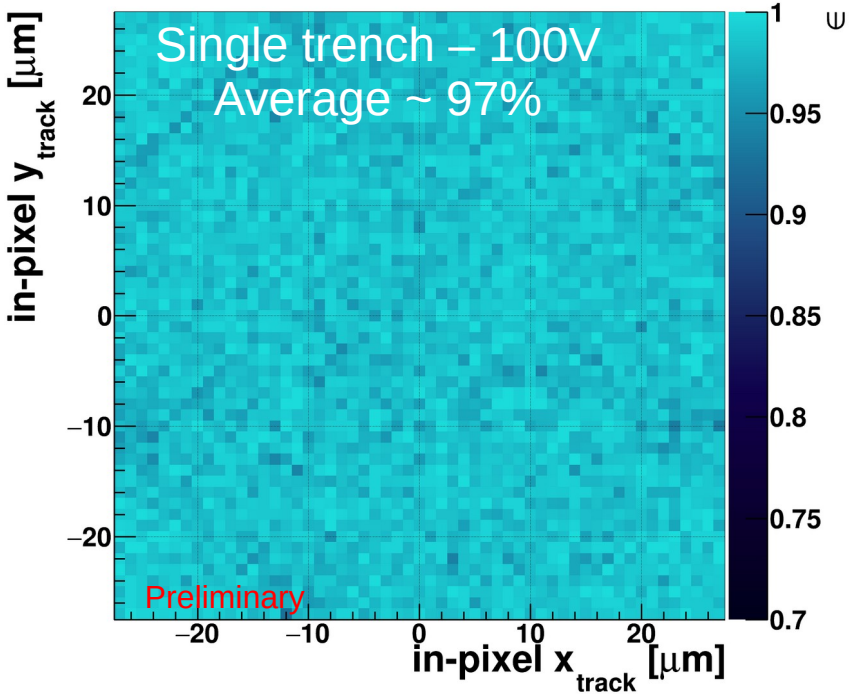


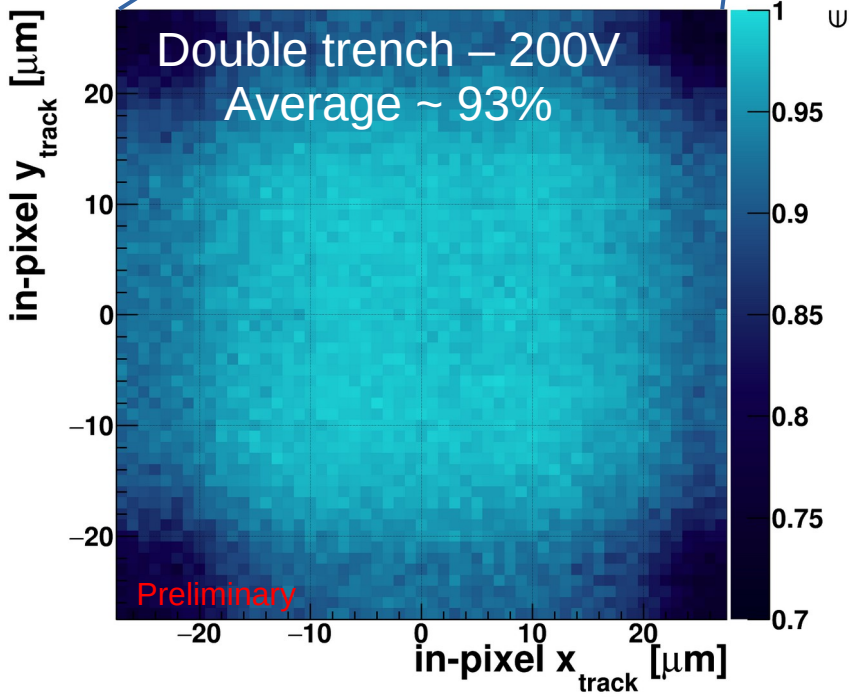
TI-LGAD in-pixel Efficiency

- Using reference track position as true in-pixel hit position
- No significant structures visible in the pixel in single trench
- 30% efficiency drop visible at the corners for the double trench



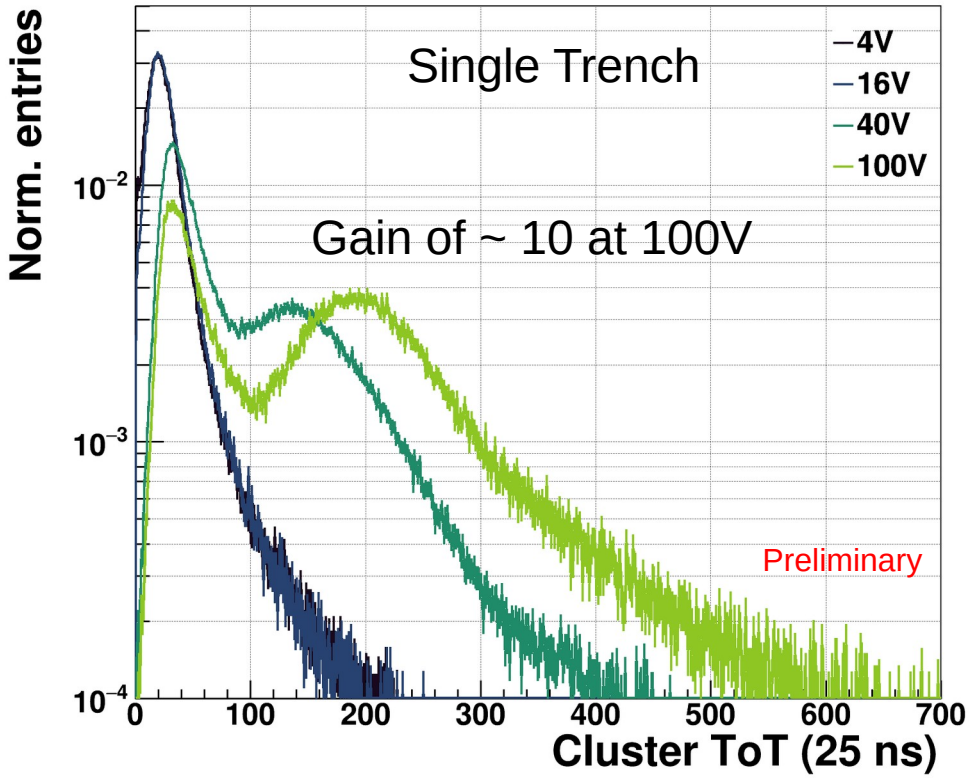


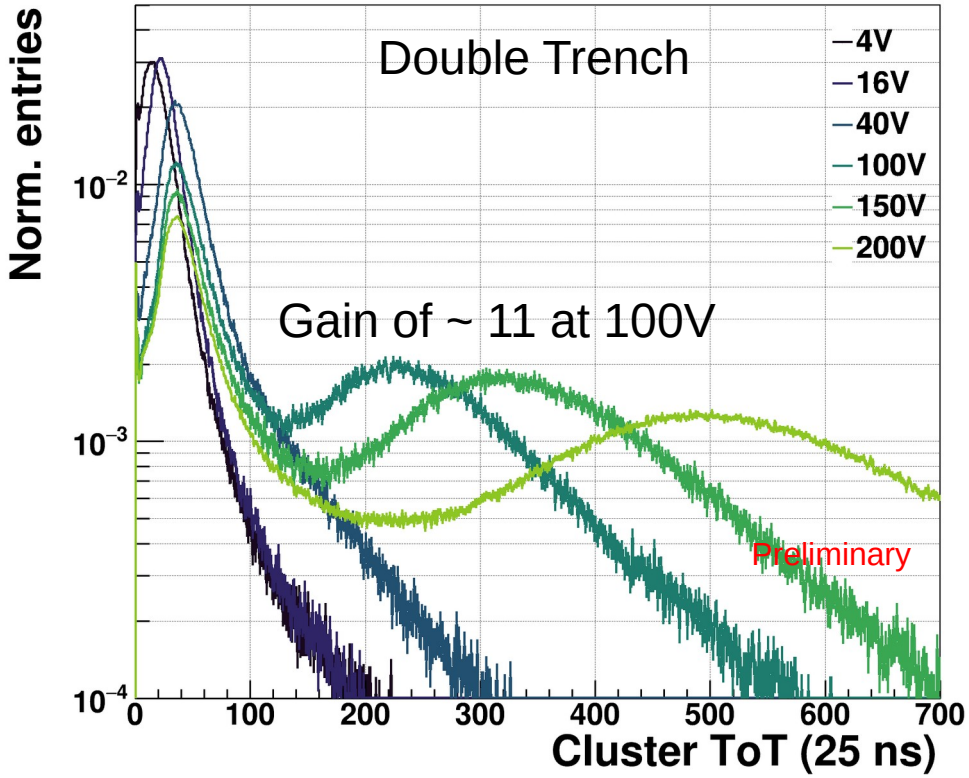




TI-LGAD cluster charge

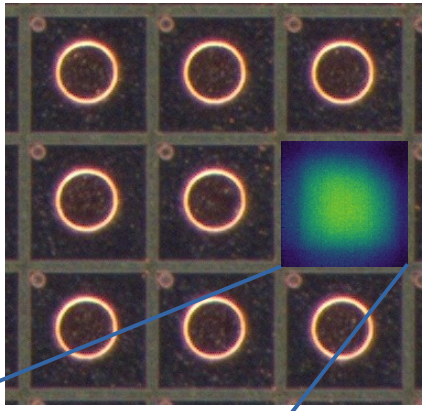
- Gain depends on applied voltage and doping concentration
  - Gain begins at 40V
- Gain steadily increases with applied bias voltage
- Significant no gain peak

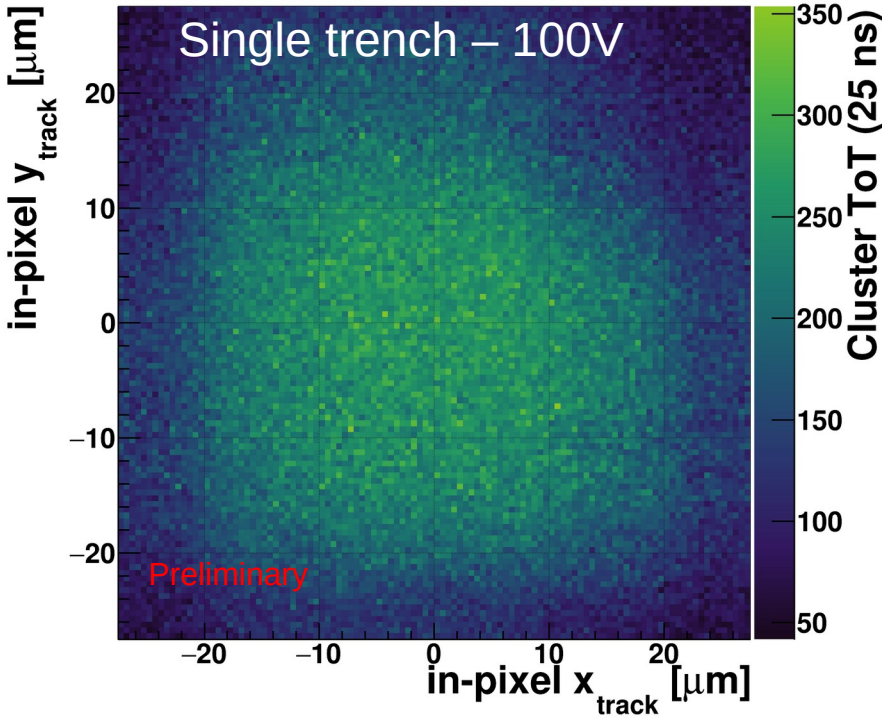


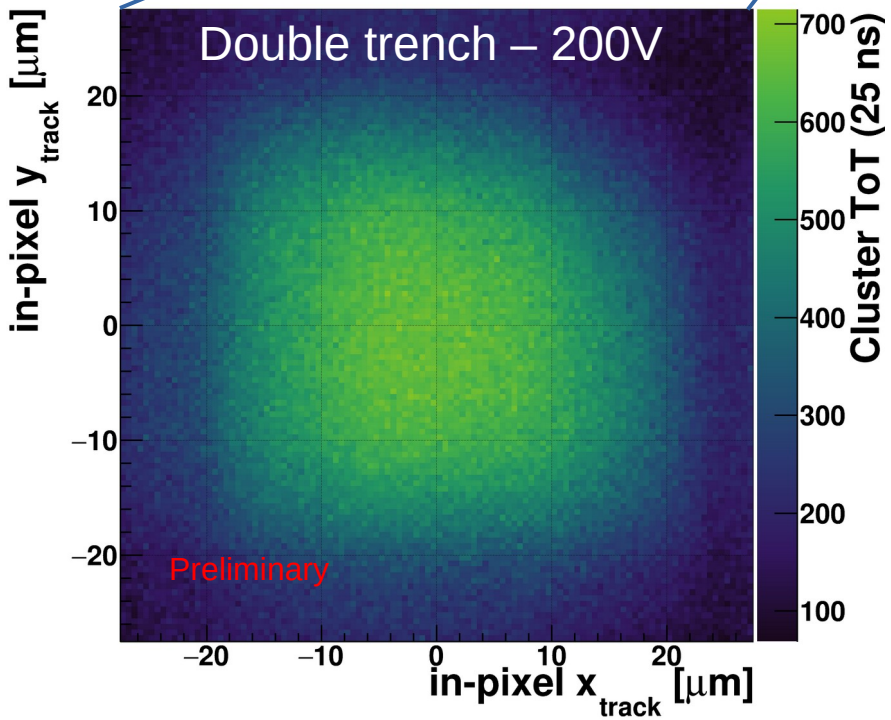


TI-LGAD in-pixel cluster charge

- Only central area has gain
- Area towards the edges has no gain (larger for double trench)
  → Issue for timing
- Non gain area present for both single and double
  → Cannot explain loss of efficiency in double trench relative to single



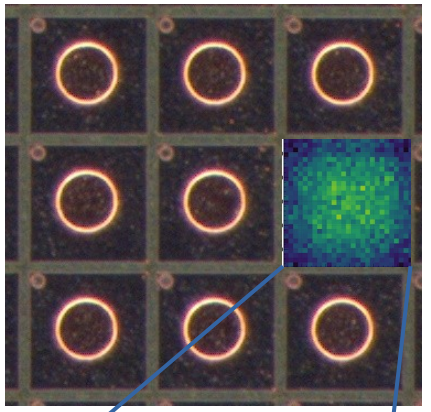


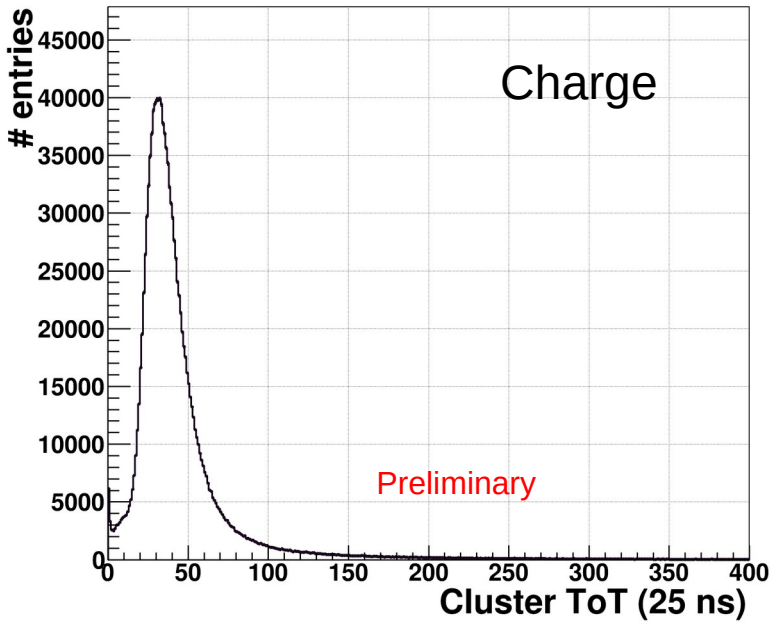


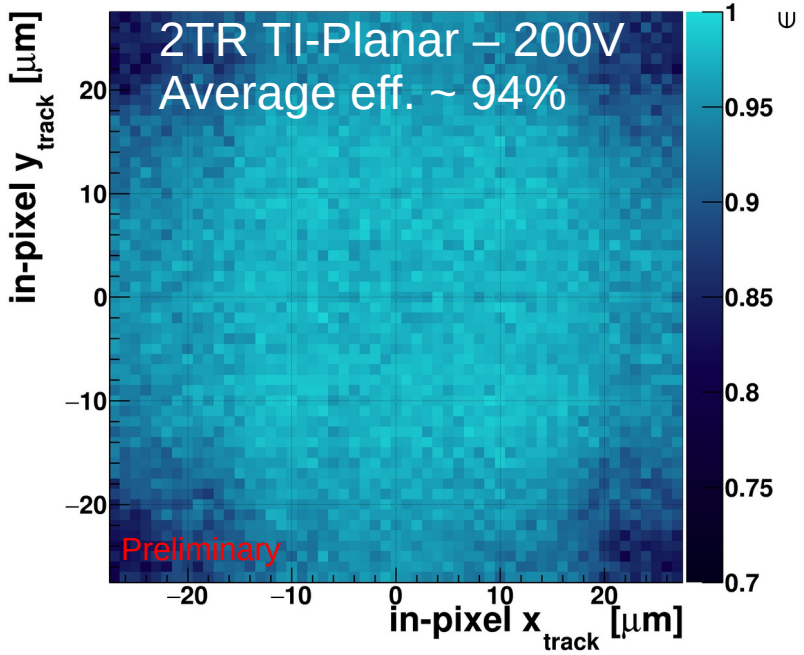
TI-Planar for comparison

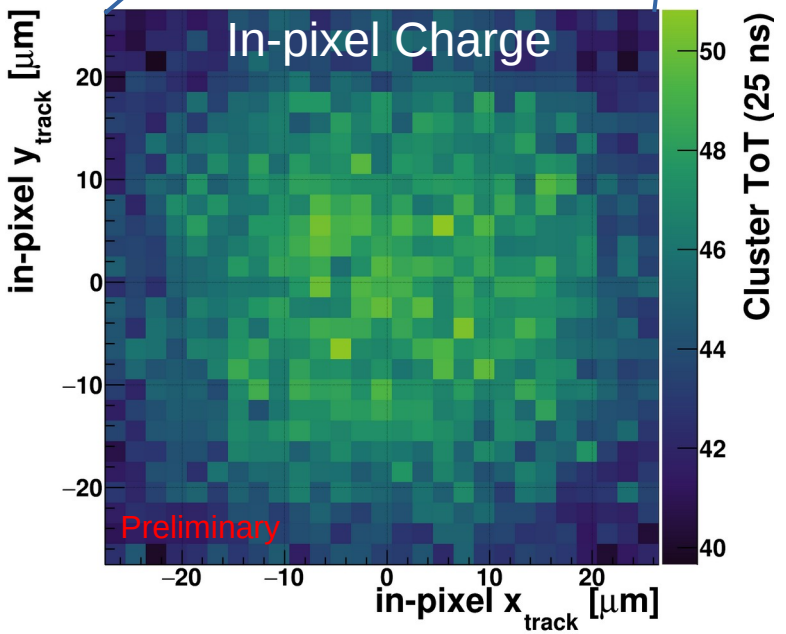
- Tested a trench-isolated planar
- Similar efficiency drop towards edges as visible in gain device
- Cluster charge towards the edges also drops

  → Reduced charge generation or charge loss due to trench structure



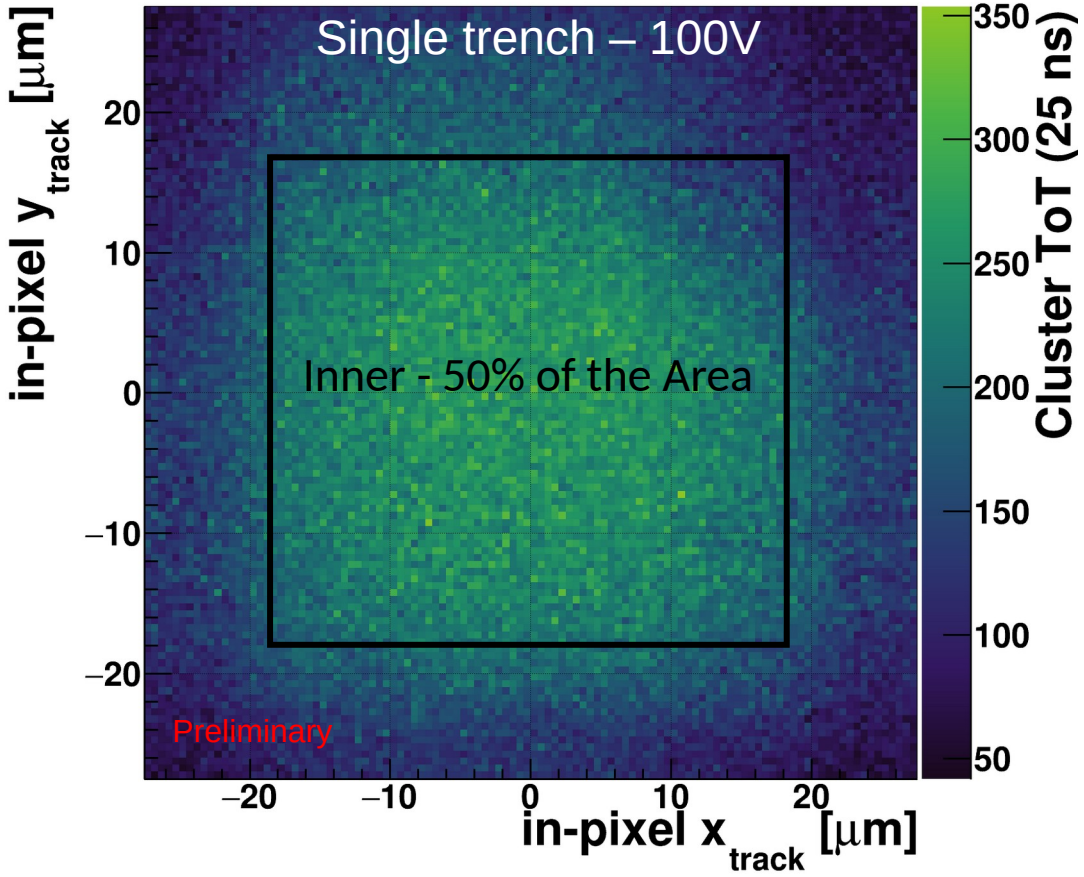


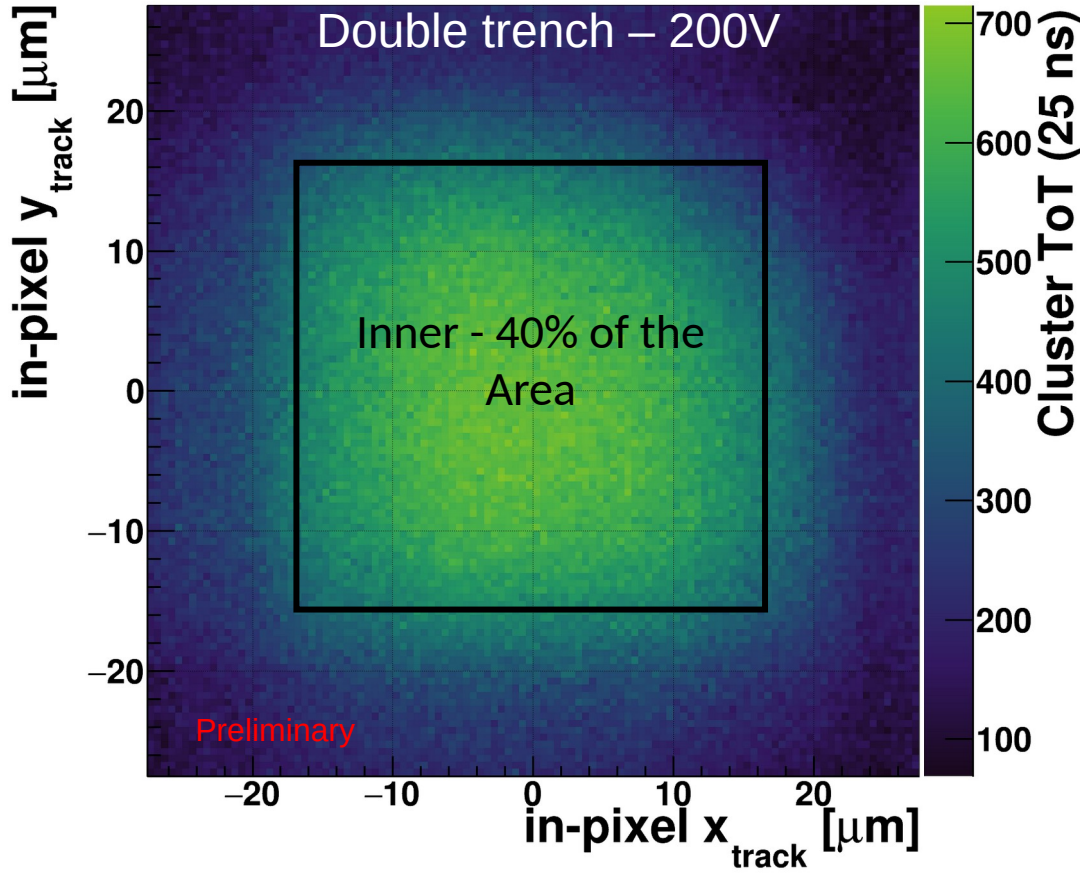




Time resolution of TI-LGAD on TPX4

- Only 40/50% of area with decent gain for single/double trench device
  - Effectively lowering efficiency for timing
- Need devices with different gain structure to improve effective area with gain





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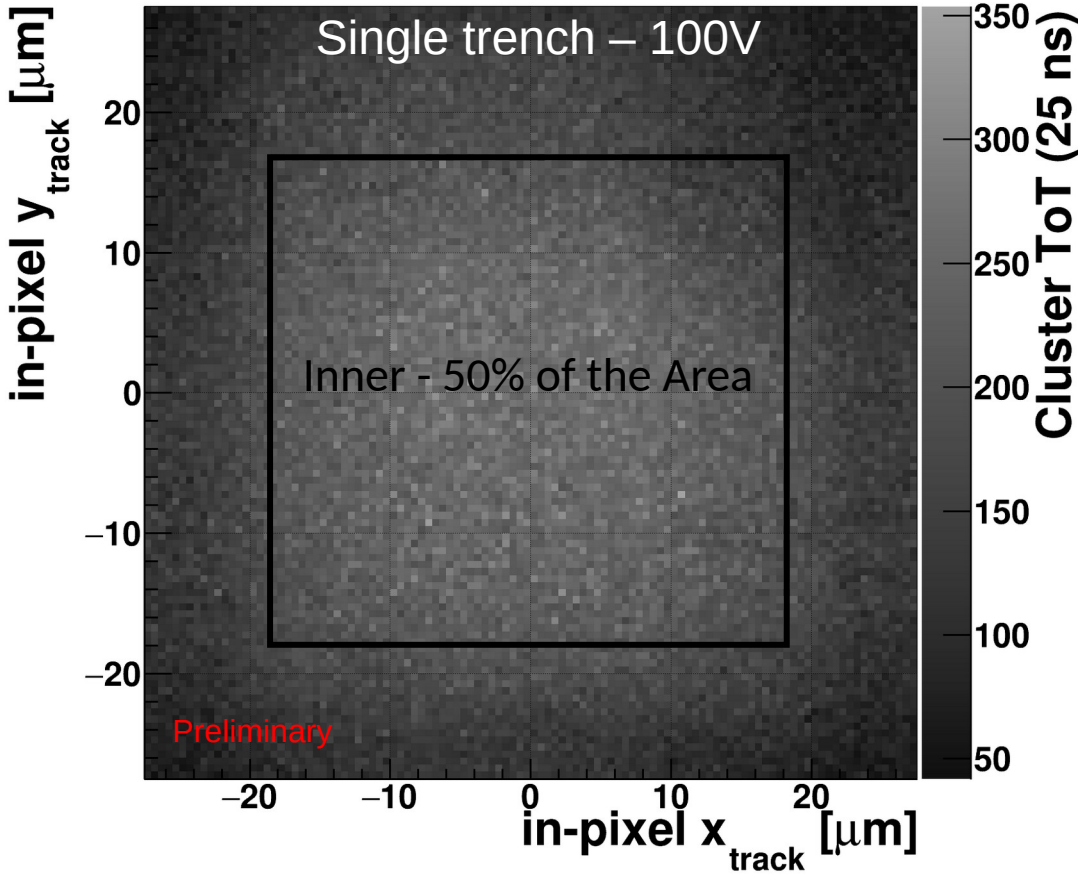
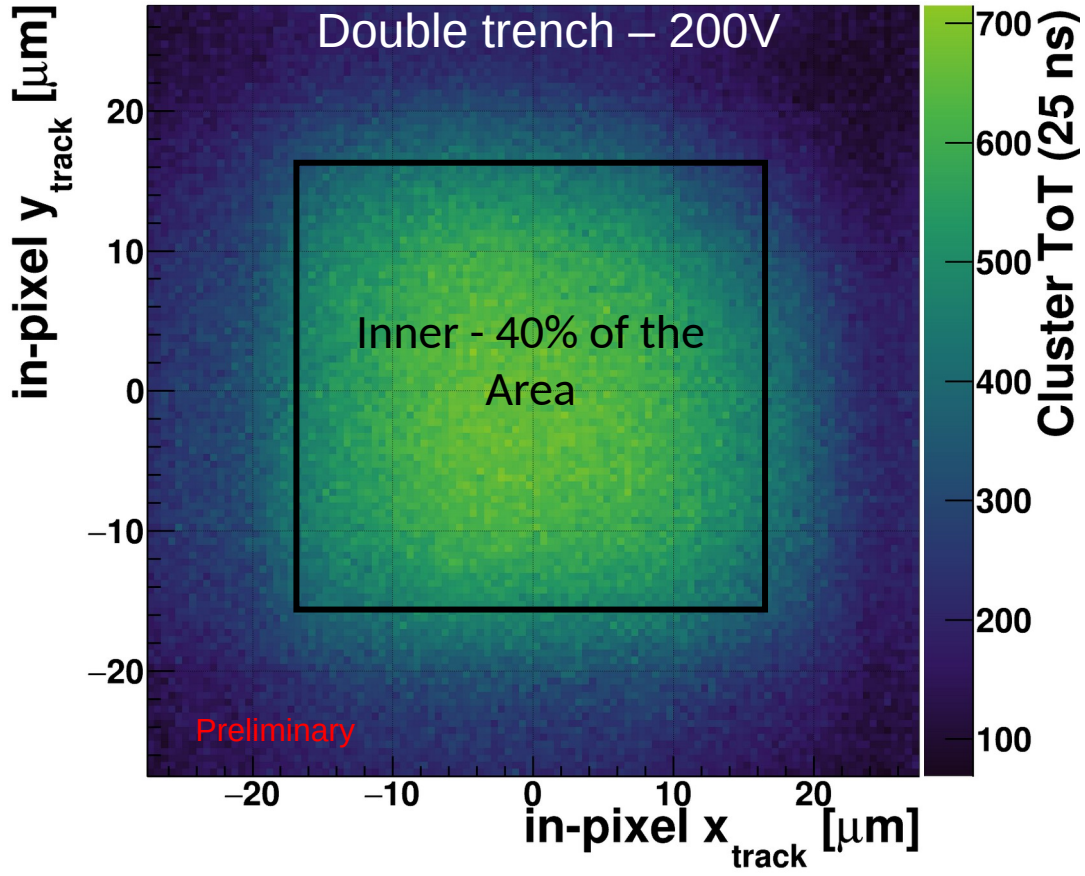
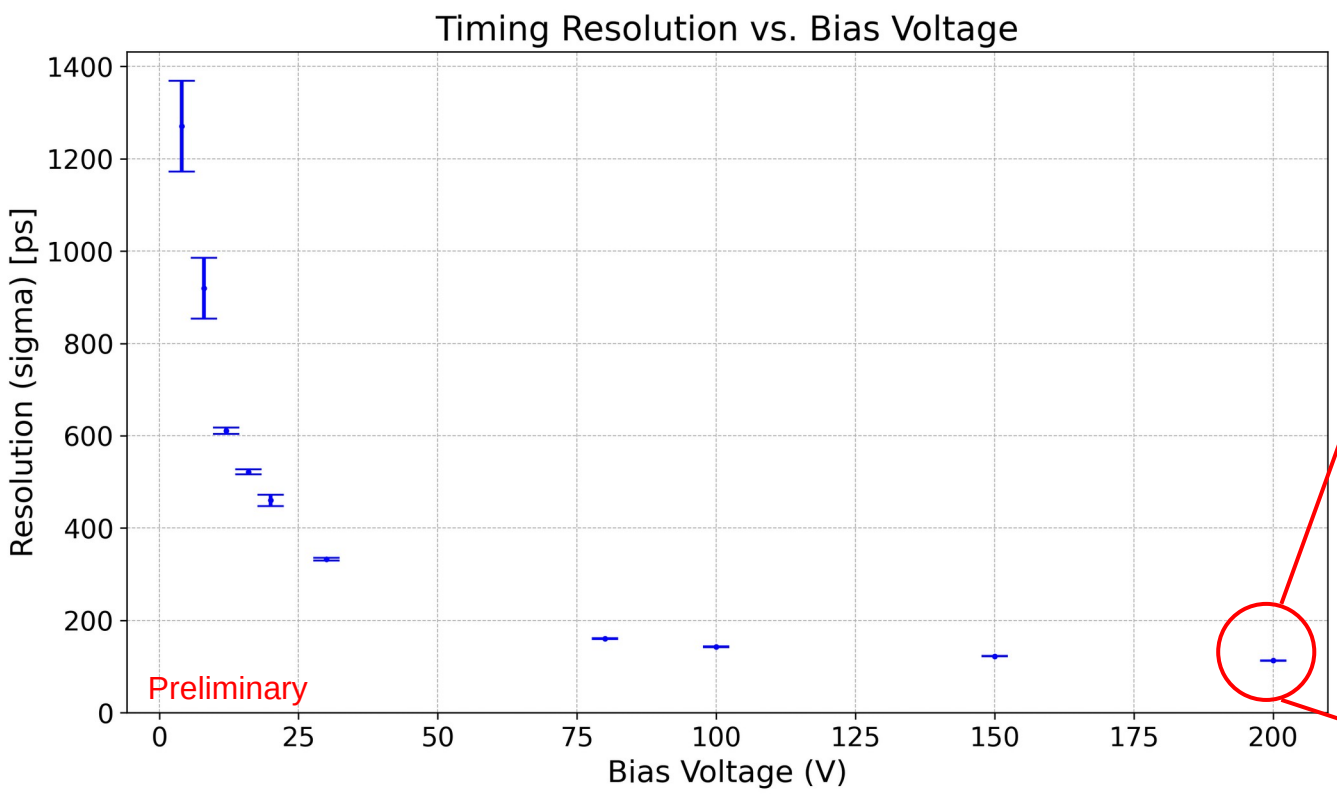
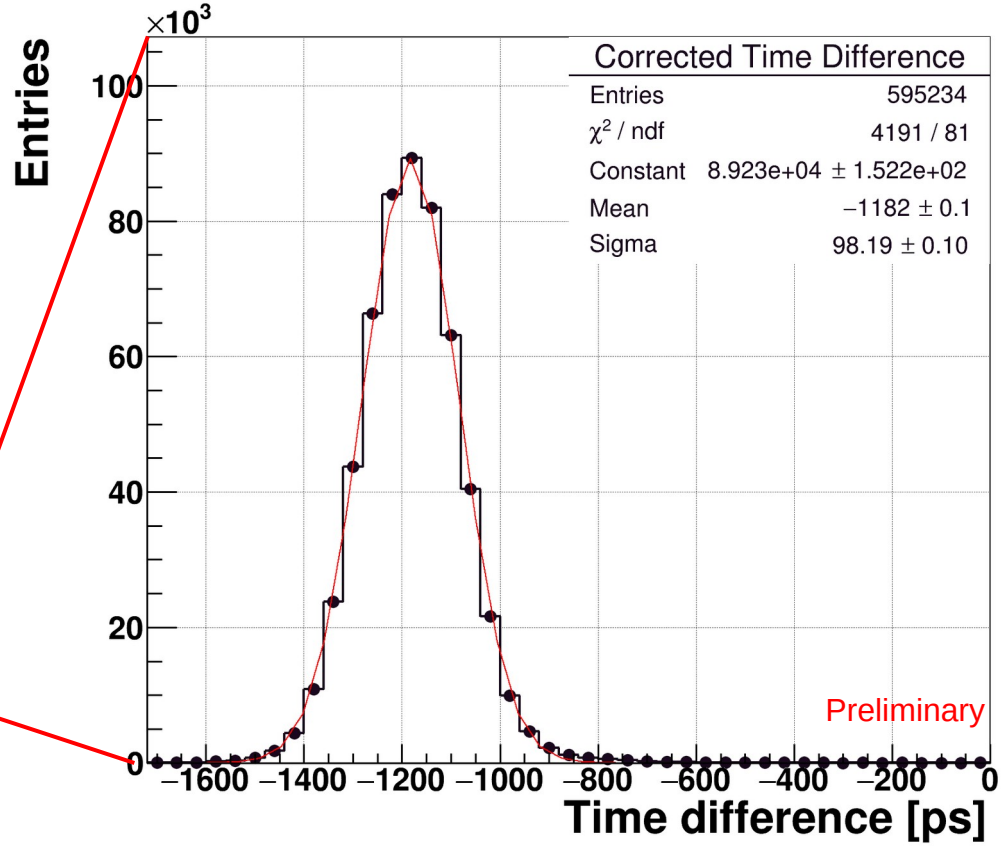




Time resolution of double trench TI-LGAD on TPX4

- Many corrections required for best possible time resolution
- Fully digitized time resolution of **98 ps** for central area of 55 µm pitch TI-LGAD





Conclusion and Outlook

- Achieved a below 100 ps time resolution using a fully integrated system

- Unexplained loss of efficiency for double trench
  - Not visible in 50 micron planar
  - Visible in double trench TI-Planar
- Issues with gain towards pixel edges
  - Need to modify process to increase active area

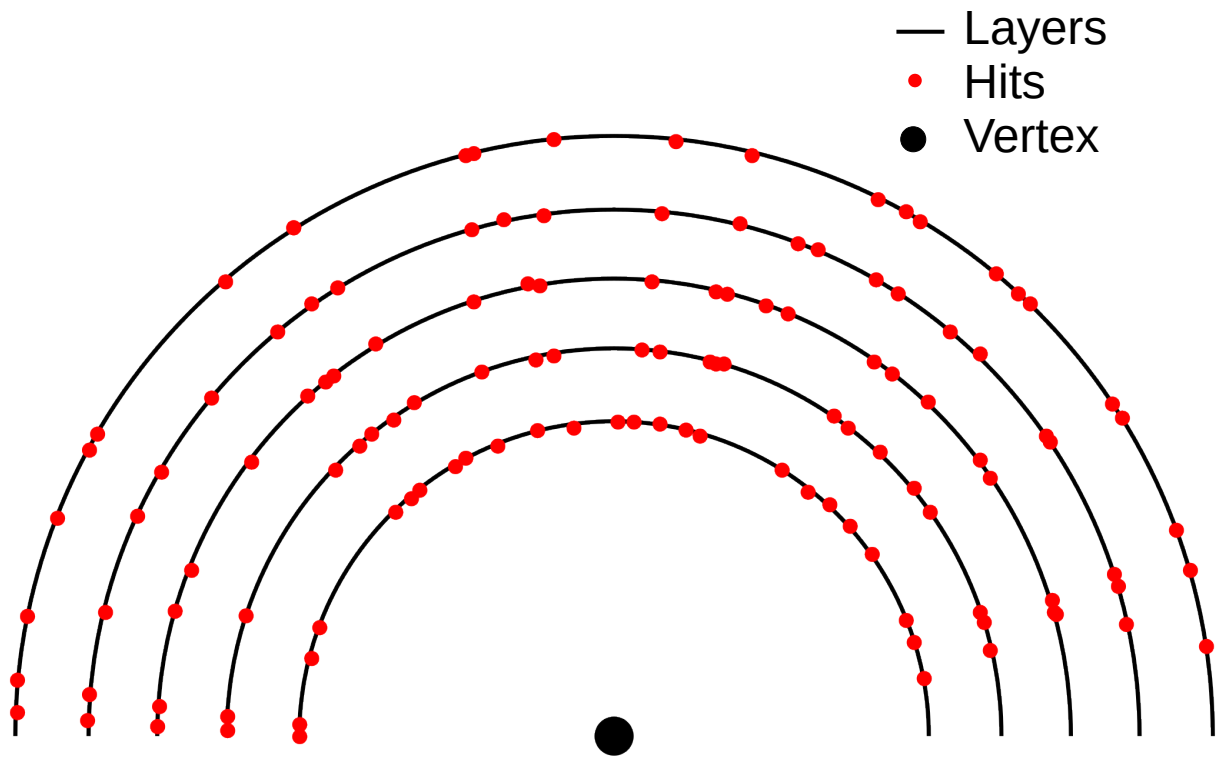
- New sensors are in the pipeline
- Working to complement results with Two Photon Absorption laser measurements

Backup slides

Tracking with high pile-up

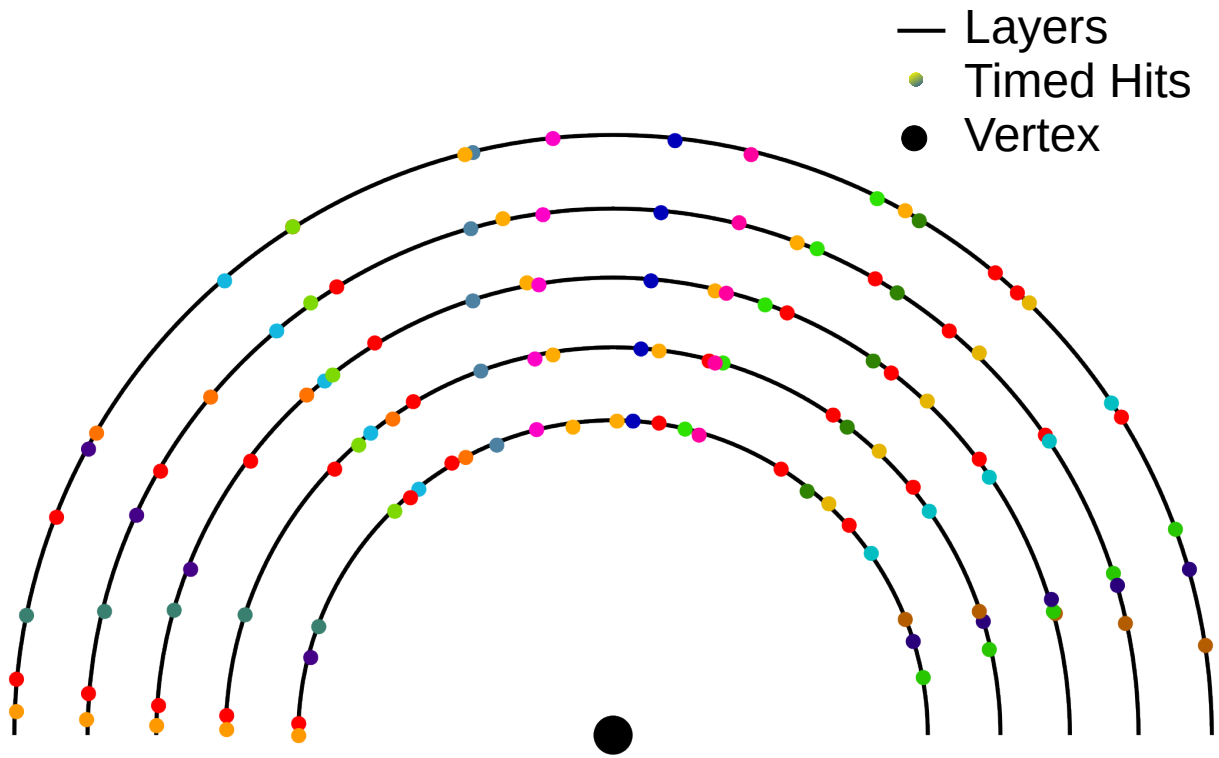
- We only see point hits on different layers
  - Need to combine to tracks

- High track density
  - Spatial separation of tracks starting to be insufficient
  - Large computational burden on tracking algorithm



Tracking with high pile-up

- We only see point hits on different layers
  - Need to combine to tracks
- High track density
  - Spatial separation of tracks starting to be insufficient
  - Large computational burden on tracking algorithm
- Timing as 4th tracking parameter
  - Extra degree for separation of tracks



Tracking with high pile-up

- We only see point hits on different layers
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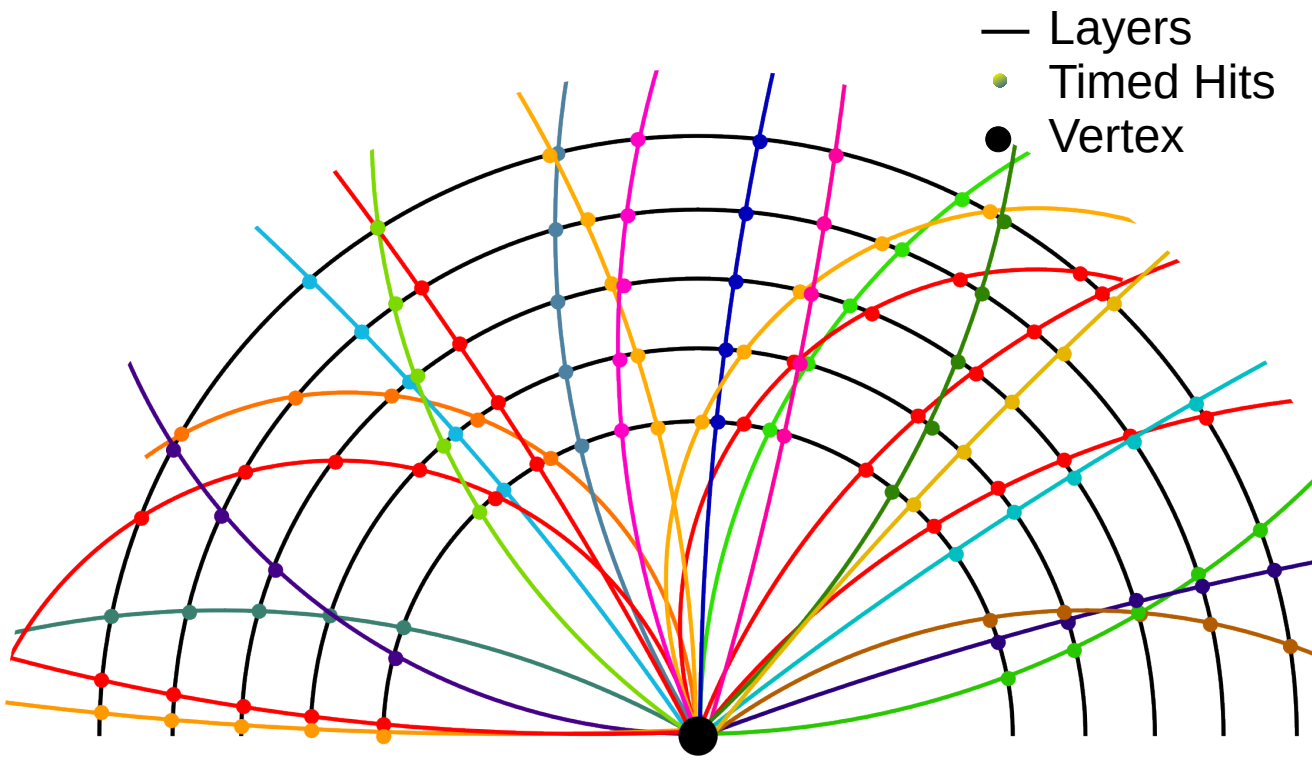
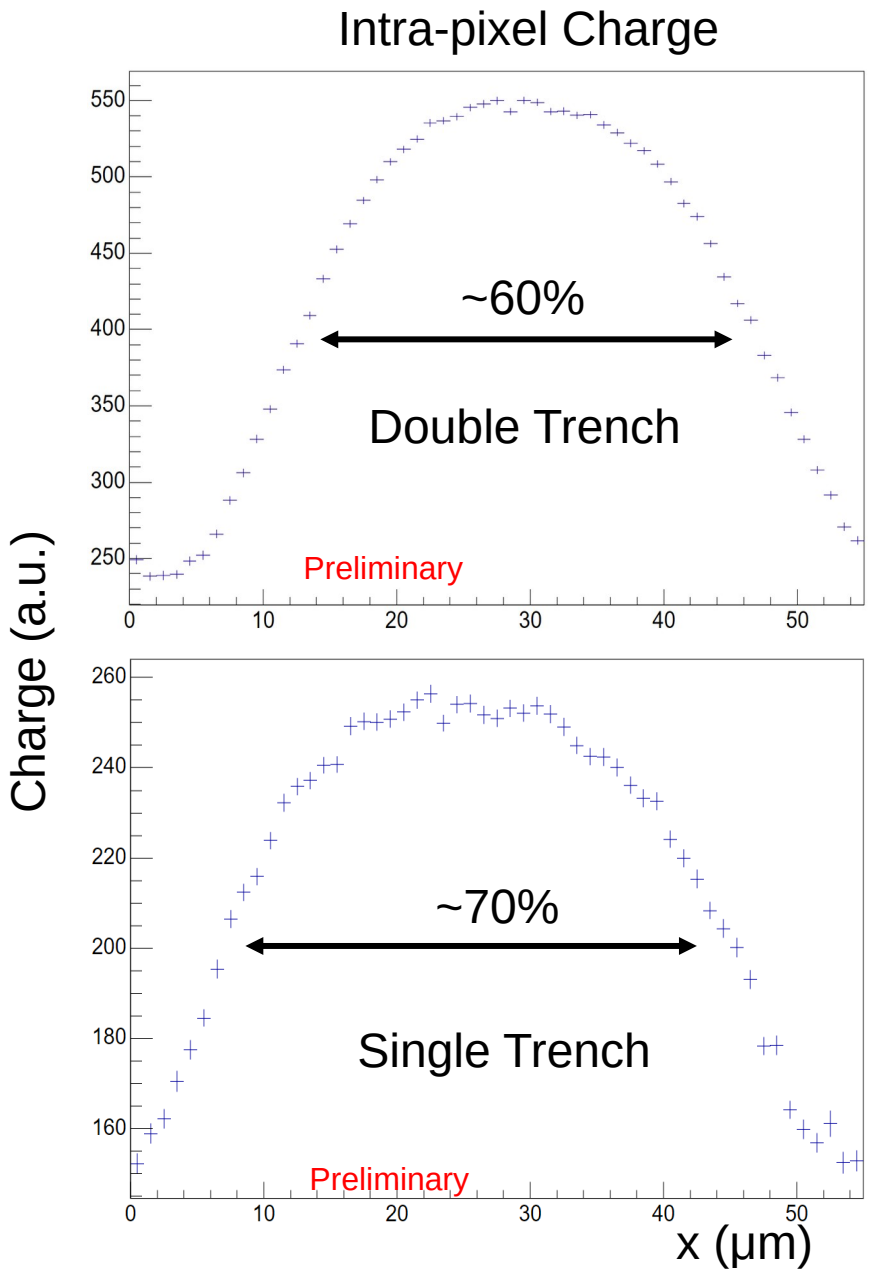


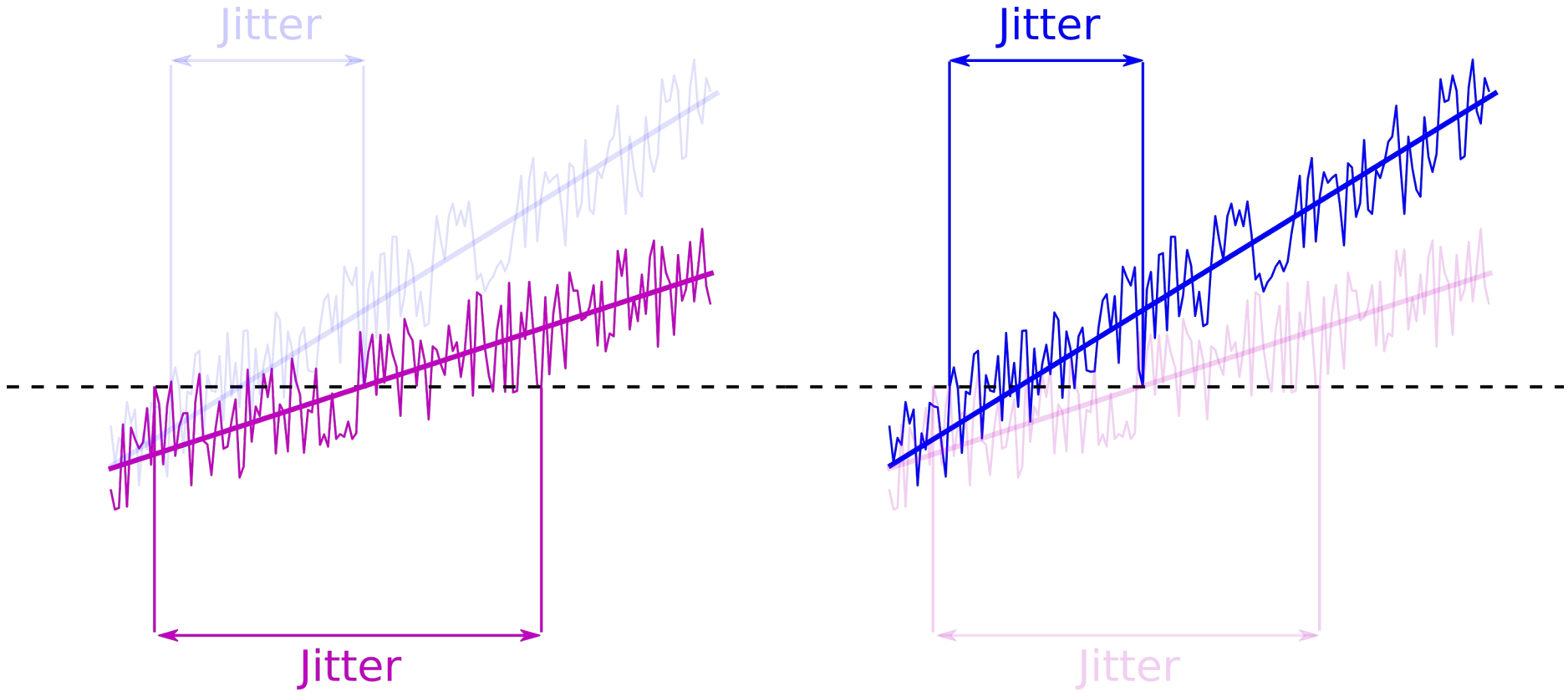
Effective area of TI-LGAD

- Area chosen based on half of maximum Gain



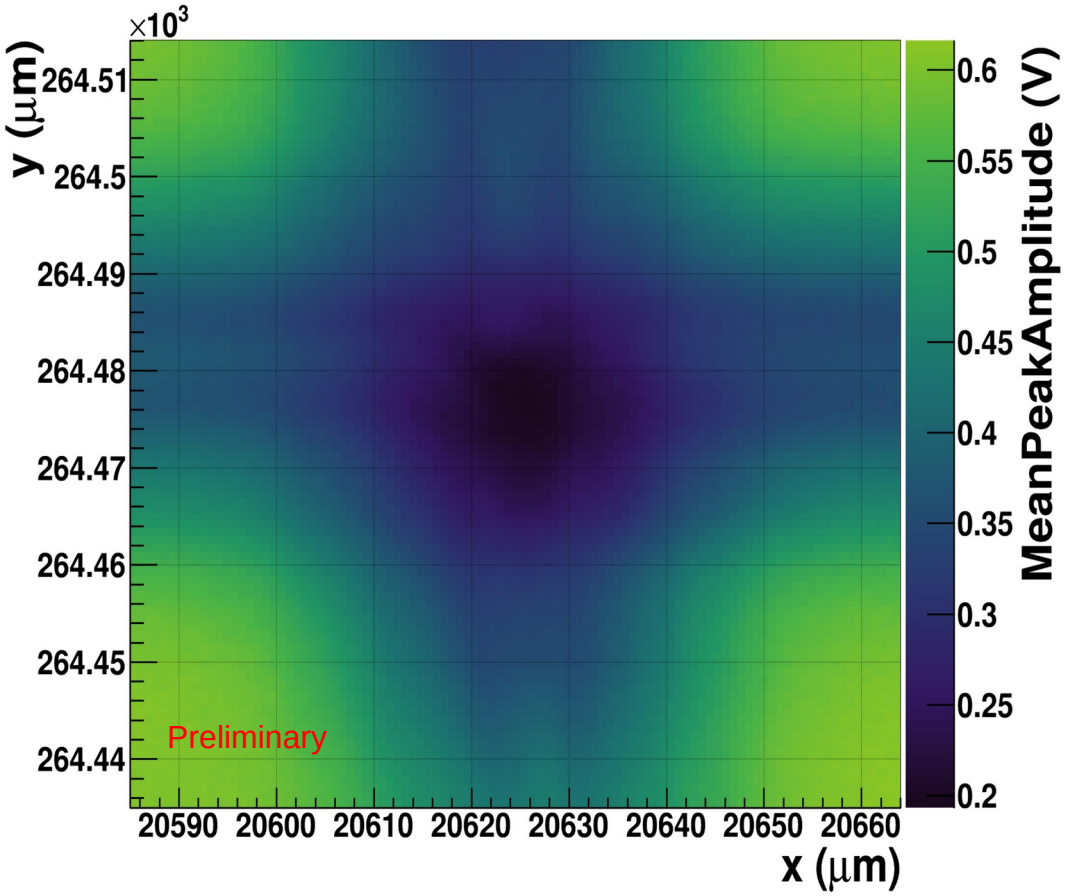
Signal rise time

- 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
- More signal typically equals faster rise time



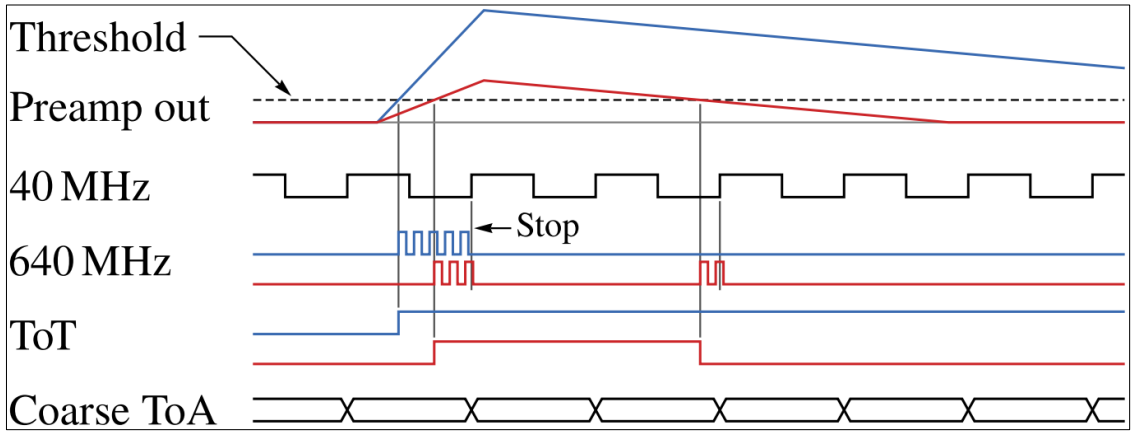
Bare TI-LGAD Laser measurement

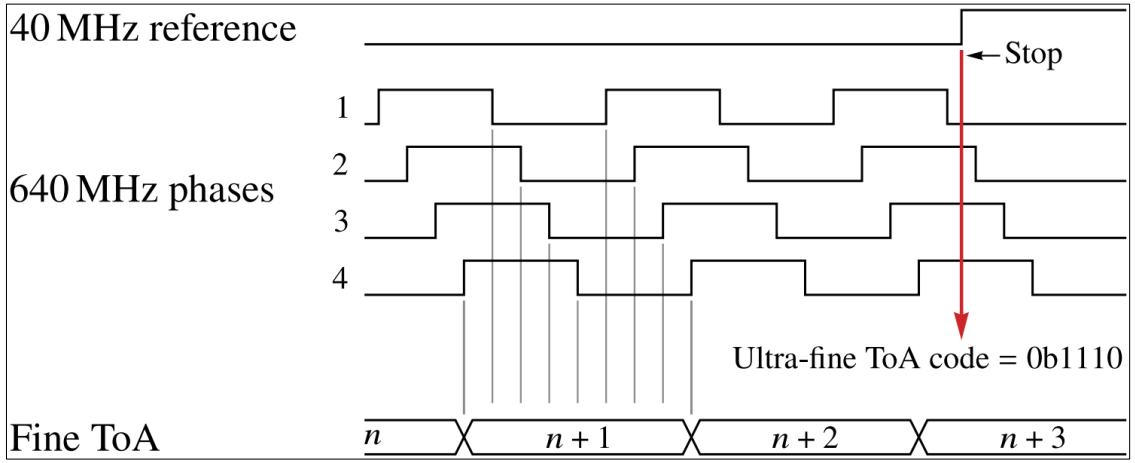
- Also performing verification of results with bare LGAD using laser setup
  - 4x4 matrix
  - 250x250 μm^2
  - Square laser opening on pixel corner
  - Analysis ongoing



Time measurement in TPX4

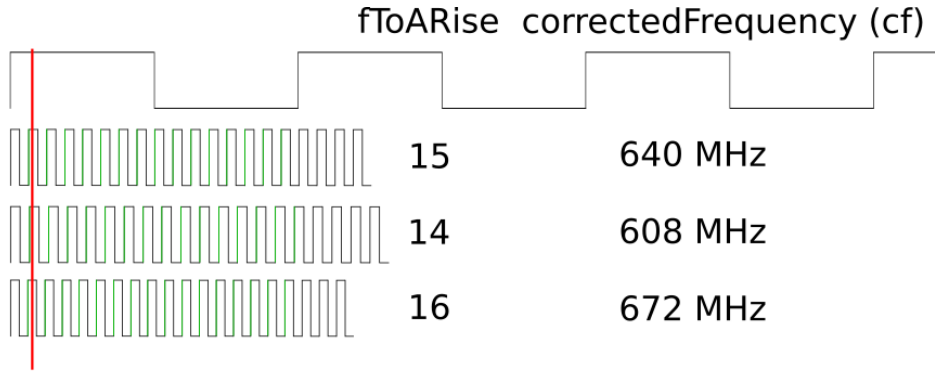
- Two clocks:
  - 40 MHZ
  - 640 MHZ VCO → FTOA
  - 4 Phases → 195 ps time bins → uFTOA
- Best possible time resolution = 56 ps
  - Requires detailed corrections
    - Pixel to pixel spread
    - Clock frequencies
    - Timewalk





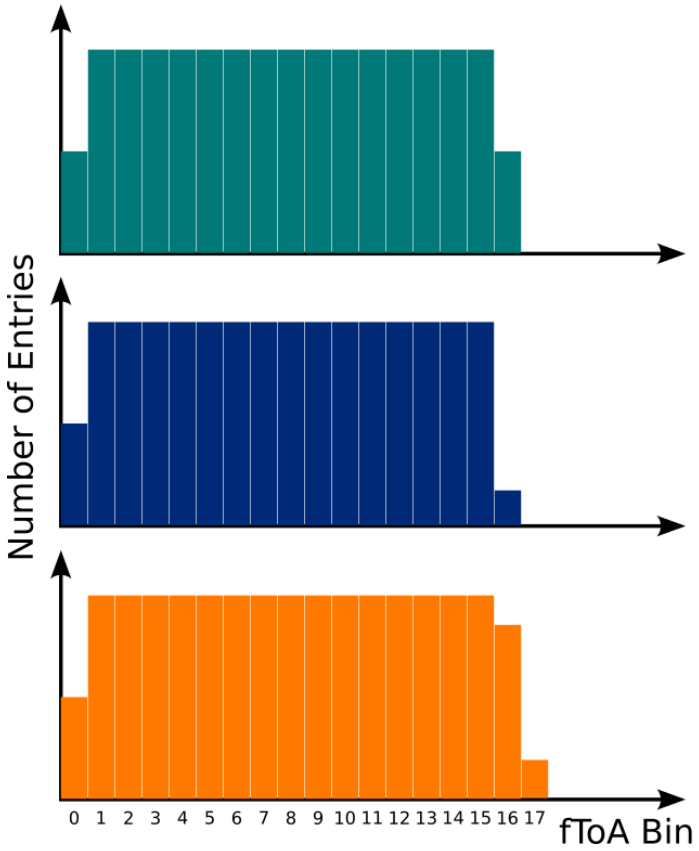
VCO corrections

- Each super pixel has their own clock
  - Variation in clock speed directly impacts time resolution
  - Needs to be corrected for each super pixel

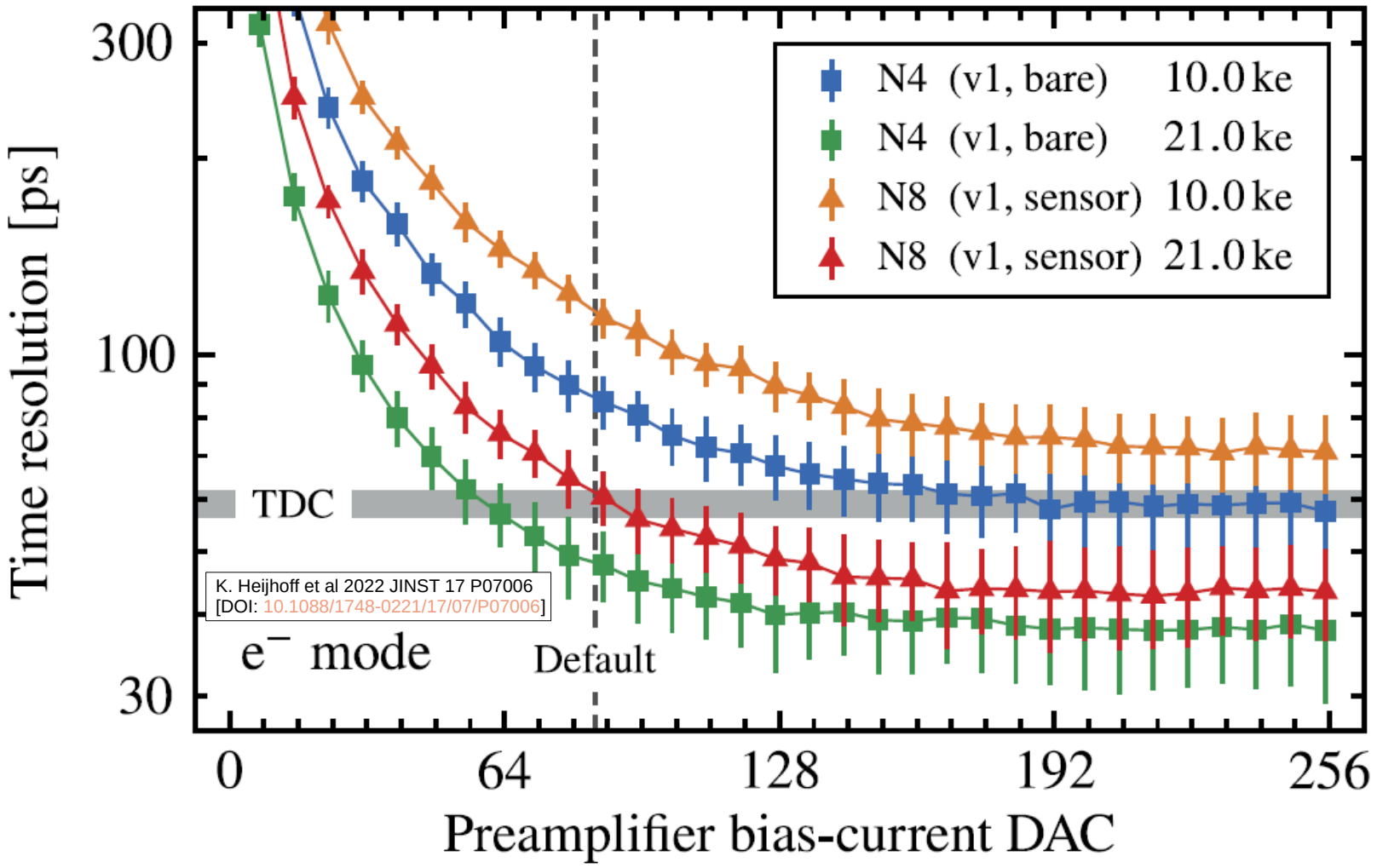


$t_{uncorrected}$ = ToA - ftoaRise*(1/640MHz)

$t_{corrected}$ = ToA - ftoaRise*(1/cf)

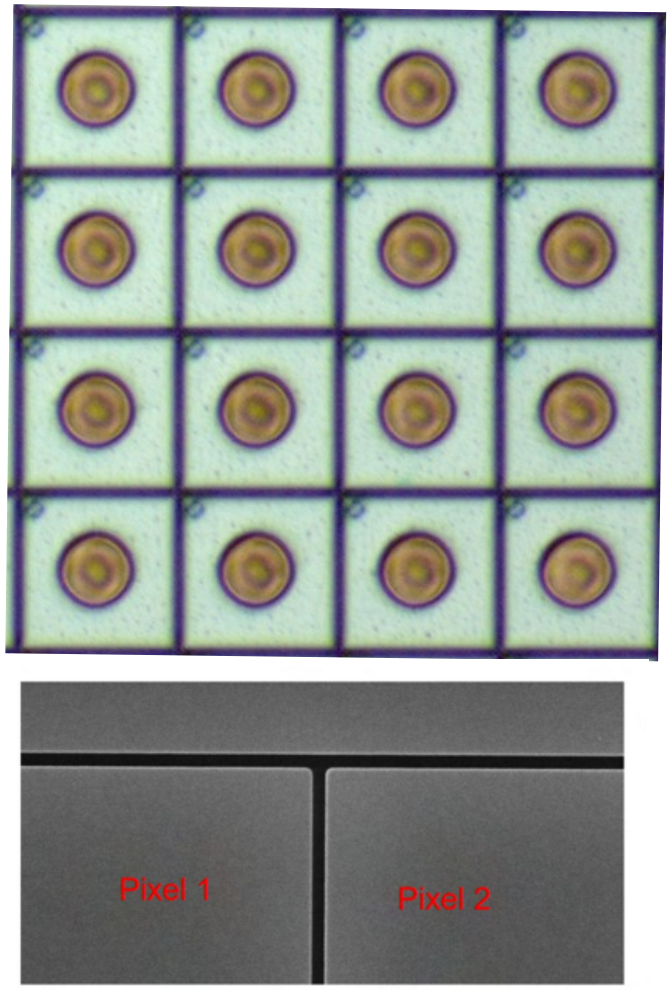


Relation between preamp current and time resolution



Single trench and double trench

Single Trench



Double Trench