Results from the Timepix4 Telescope

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BTTB12 — 17 April 2024

People involved

Testbeam crew

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IGFAE: Edgar Lemos Cid, Efrén Rodríguez Rodríguez
TU Dortmund: Elena Dall'Occo, David Rolf
University of Manchester/CERN: Tim Evans
University of Oxford: David Bacher, Rui Gao, Fernanda Goncalves Abrantes, Tommaso Pajero
University of Birmingham: Dan Johnson, Marcus Jonathan Madurai
University of Glasgow: Naomi Cooke, Aleksandrina Docheva

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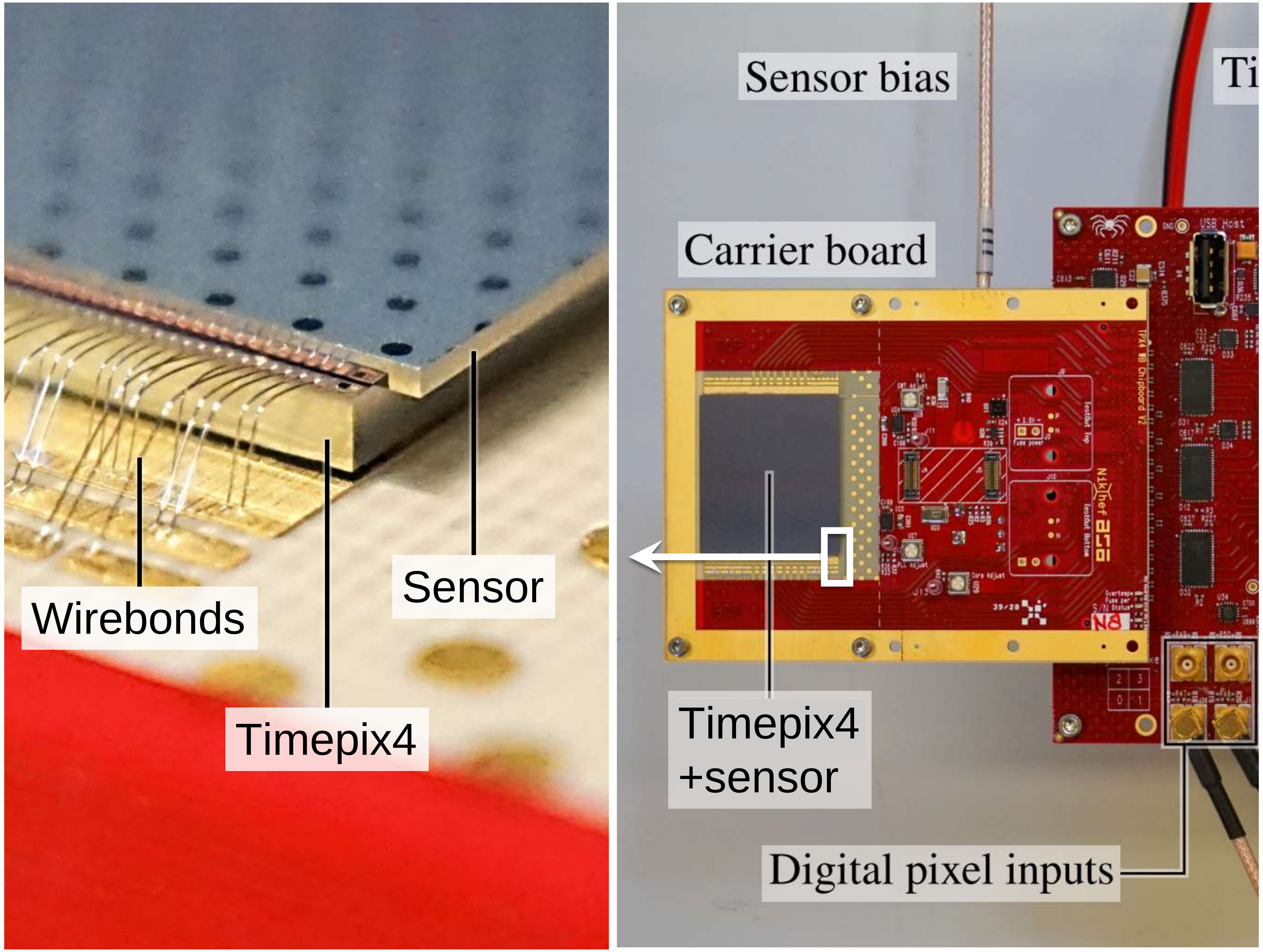
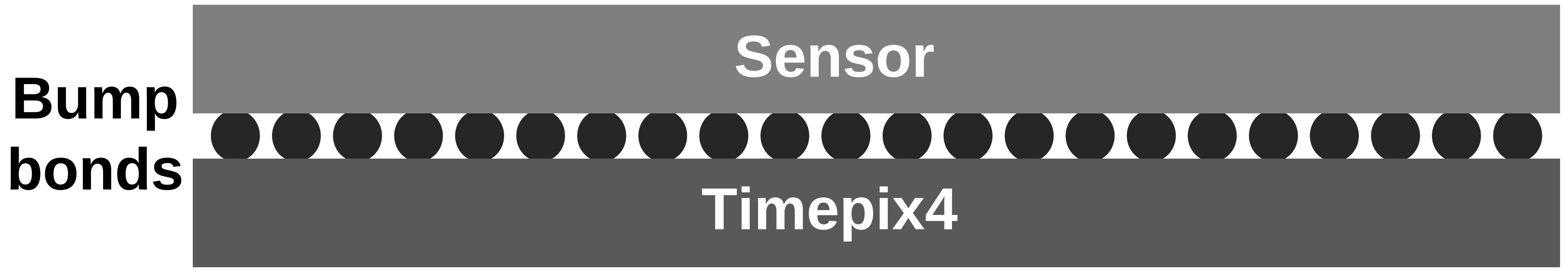
Timepix4: Hybrid pixel detector readout ASIC



Timepix4:

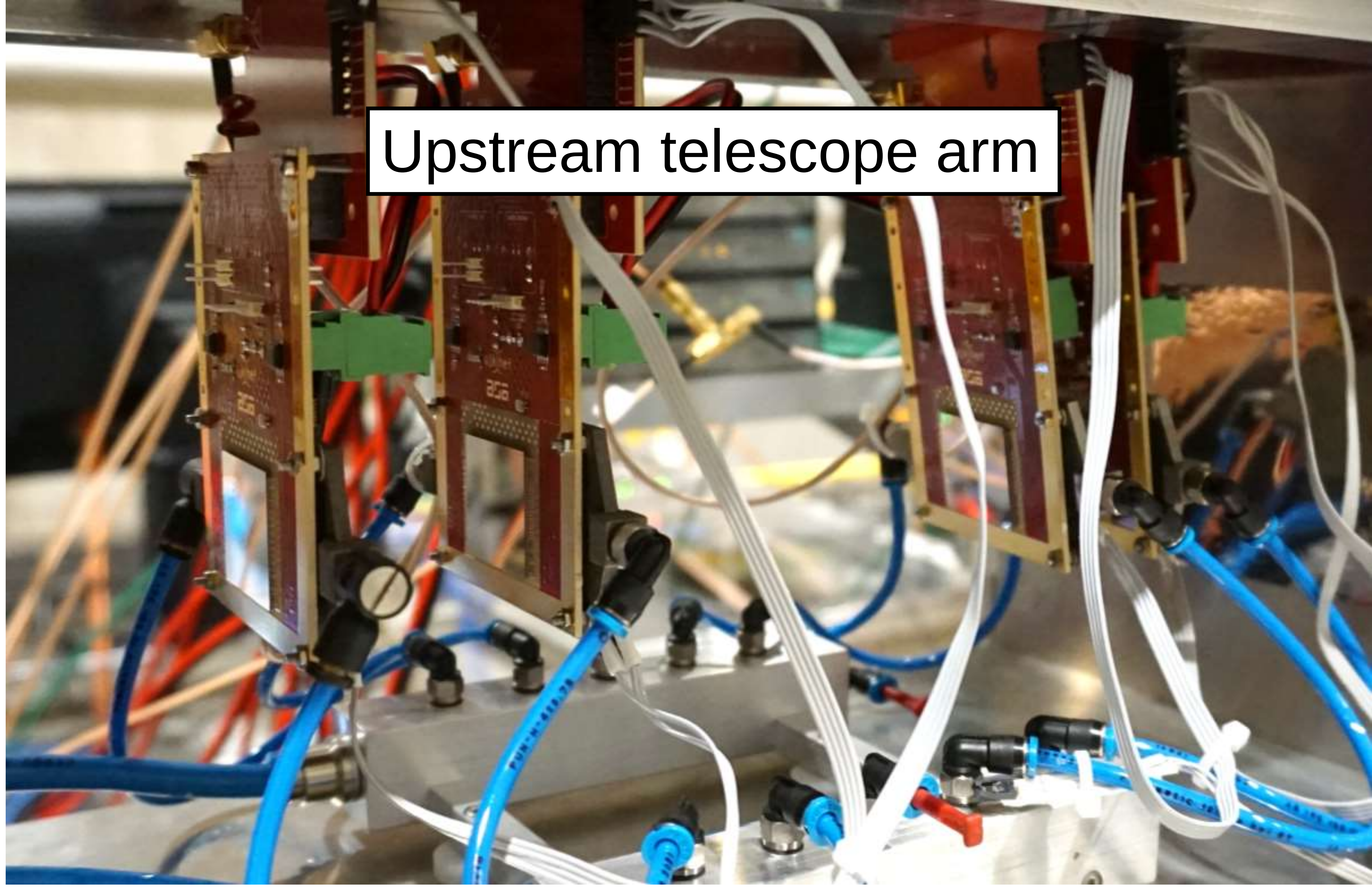
- Developed by CERN, Nikhef, and IFAE
- 448×512 pixels, 55×55 μm^2 pitch
- Simultaneous measurement of Time of Arrival (ToA) and charge deposition (by measuring Time over Threshold (ToT))
- Time-bin size of 25 ns/128 = **195 ps**



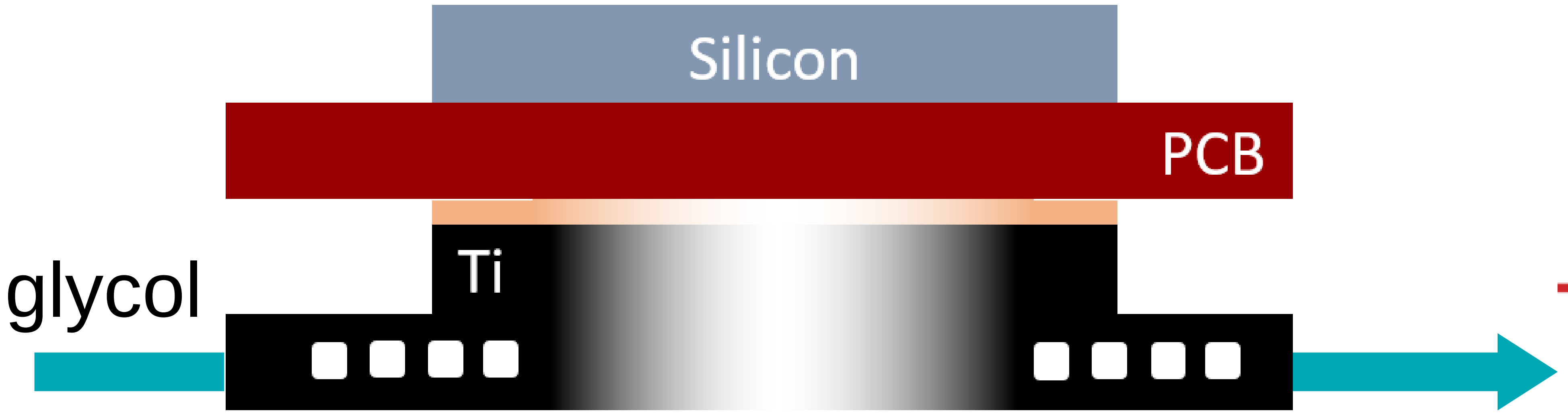
Telescope configuration

Plane assemblies (all Timepix4v2)

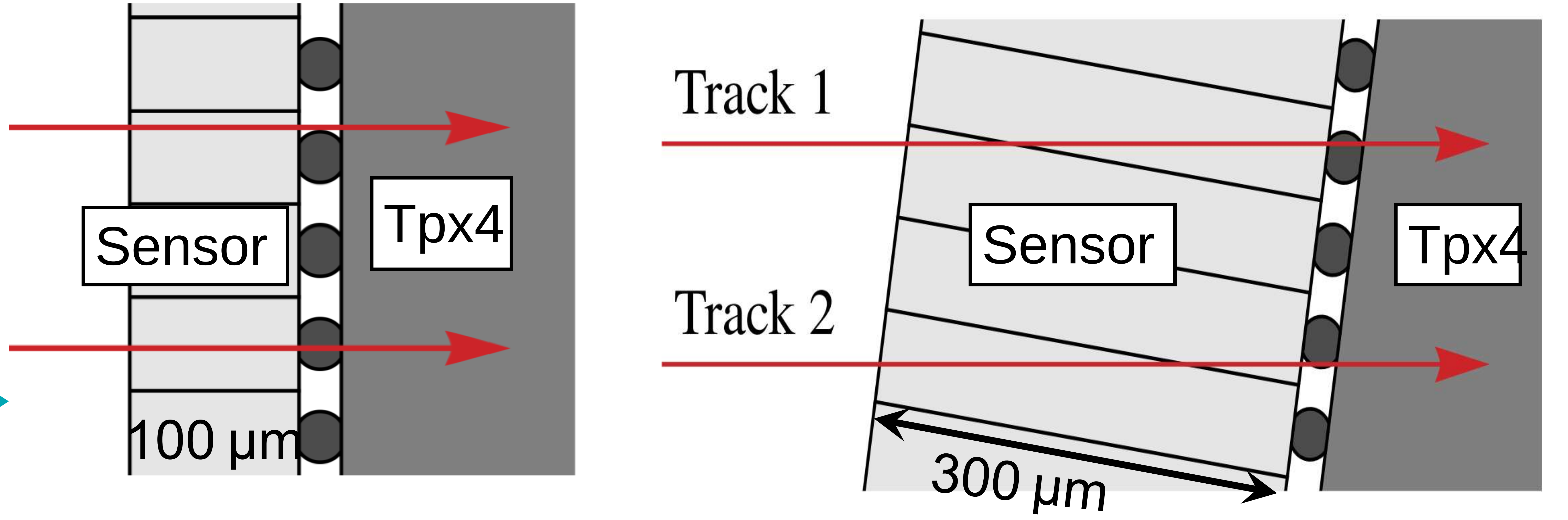
- Eight telescope planes with n-on-p planar silicon sensors:
  - 4 x 300 µm sensors for spatial resolution (angled)
  - 4 x 100 µm sensors for time resolution (perpendicular)
  - Sensor upgrades are anticipated (LGAD, 3D, …)
- Several DUT assemblies:
  - 50 µm, 100 µm, and 200 µm n-on-p planar silicon
  - 300 µm p-on-n
  - 2 x 250 µm iLGAD sensor 55 and 110 µm pitch
  - Cooled using glycol at 20 °C



Current cooling

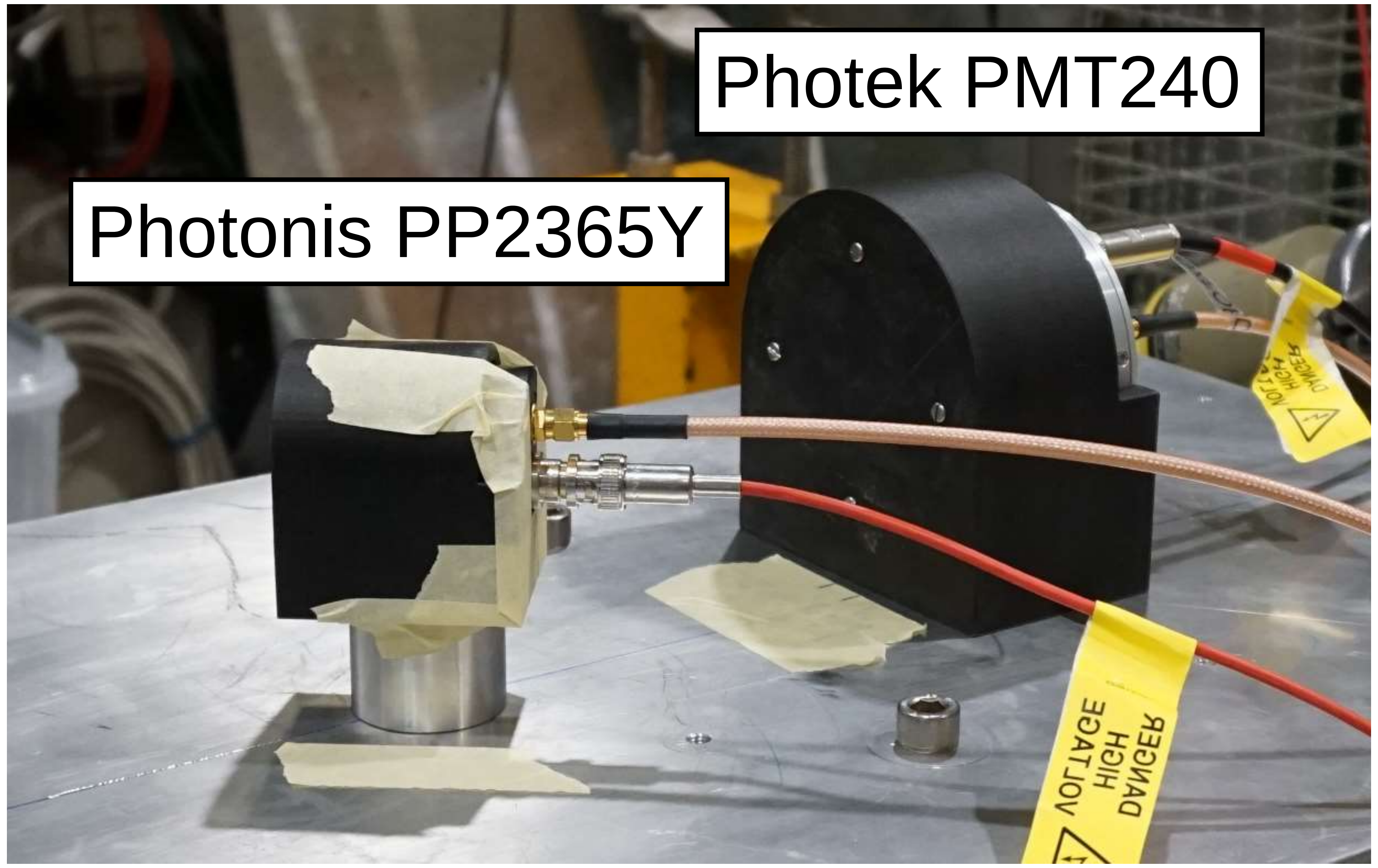


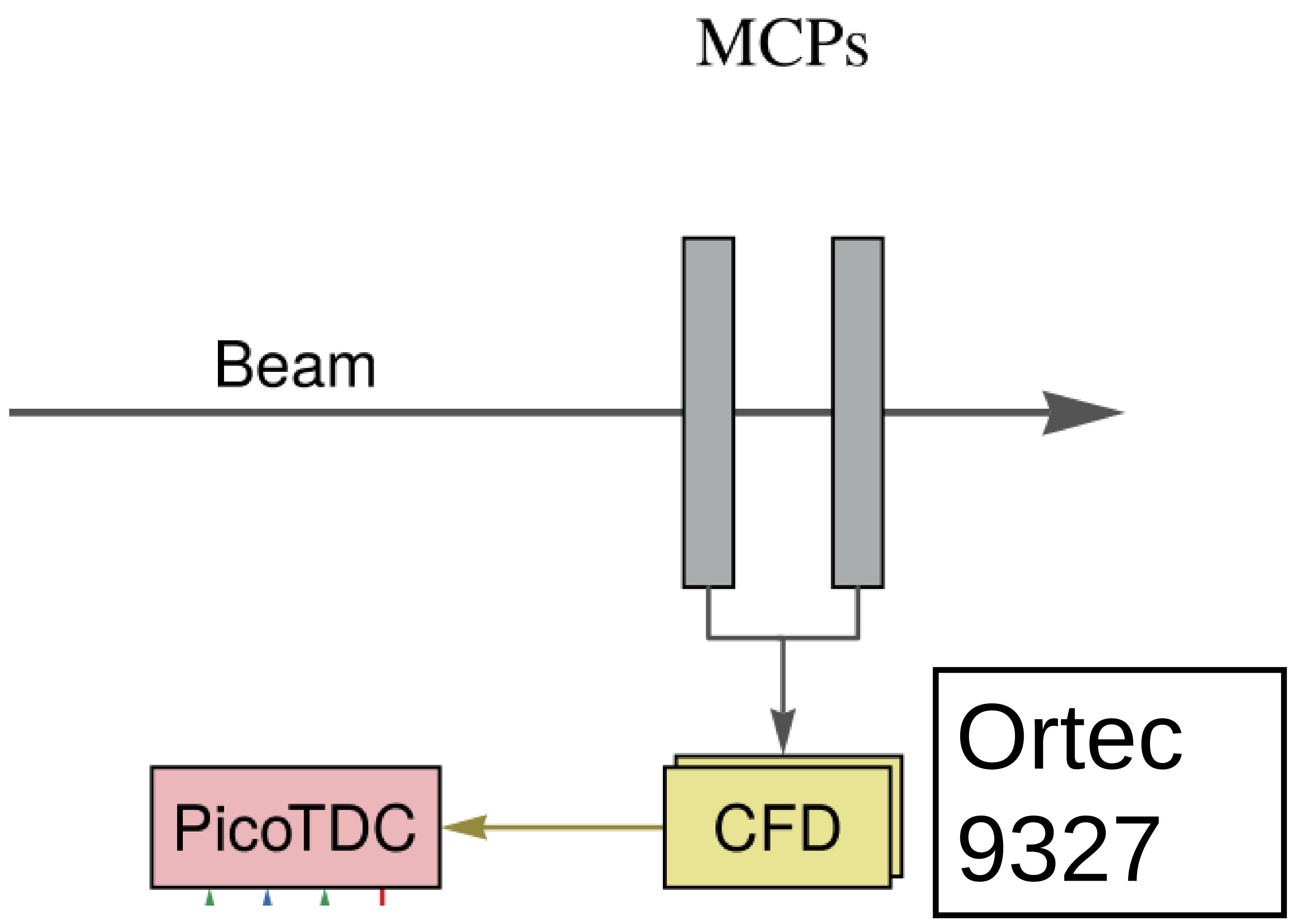
No Titanium in beam

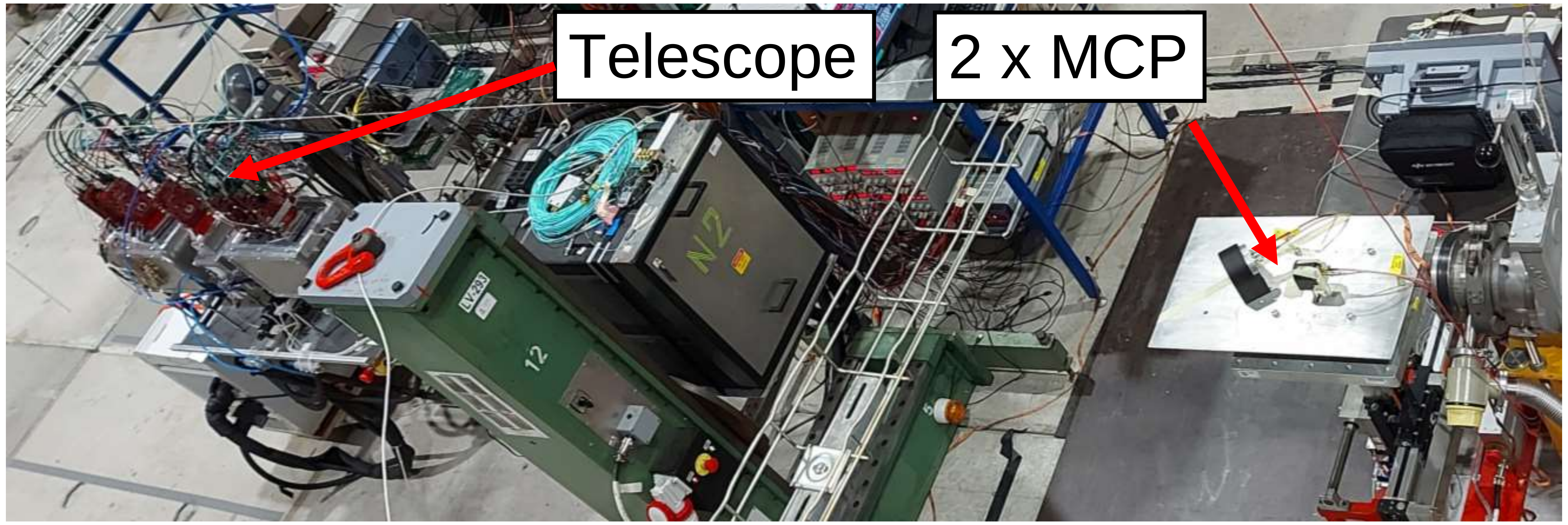


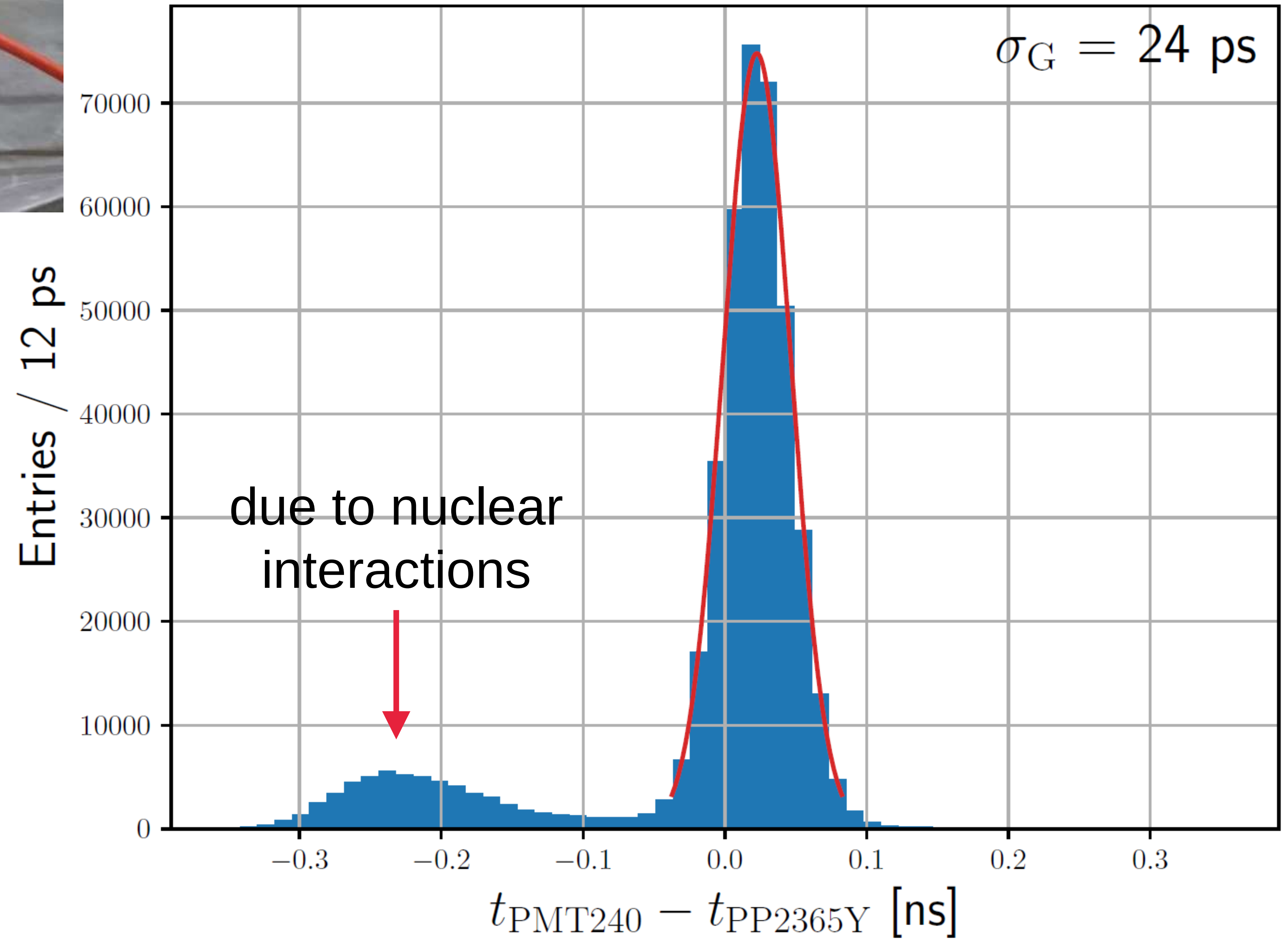
Microchannel plate (MCP) time reference

- Two MCPs provide precise time references to study timing performance of telescope
- Placed at the end/far downstream to not hinder other groups in same beam area (large material contribution)
- Combined MCP resolution: **12 ps**





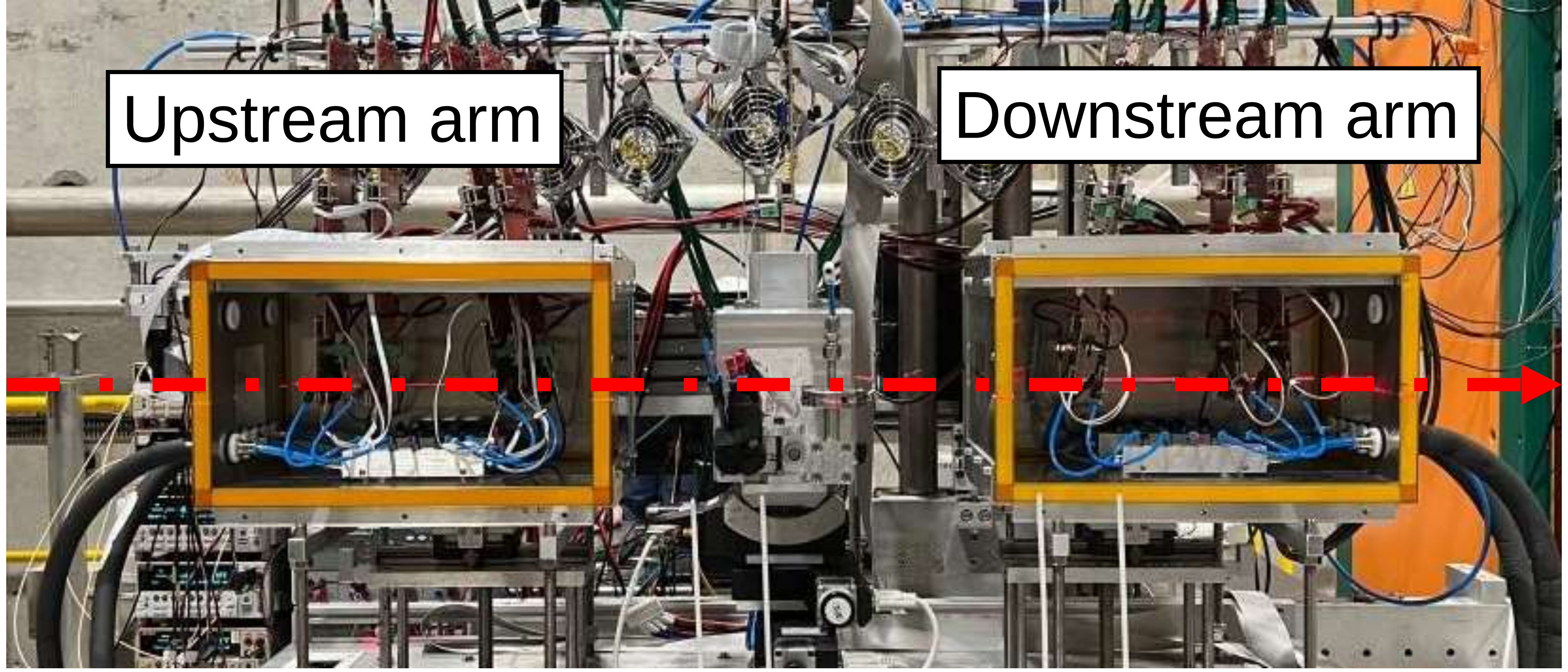




Hitmap 8 planes

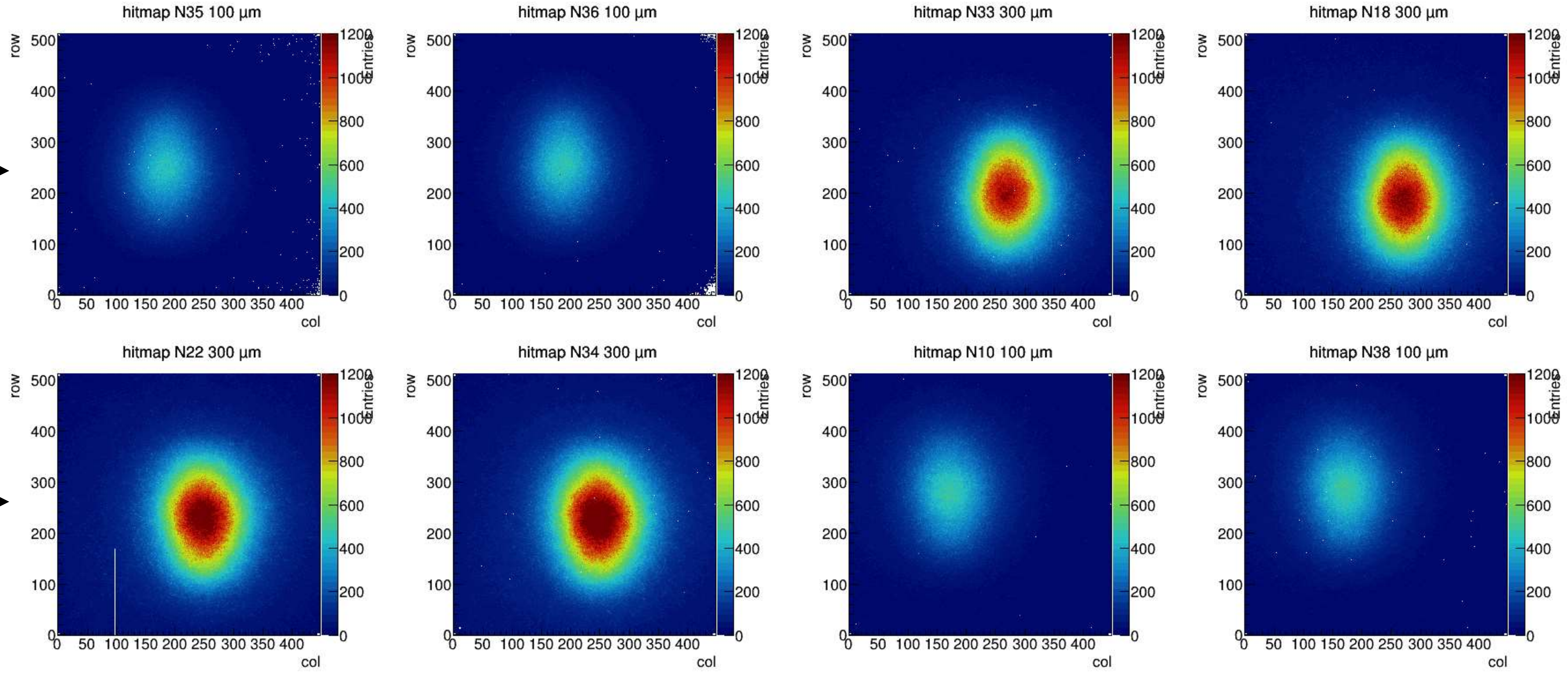
- H8 beamline at SPS / CERN
- 180 GeV/c mixed beam

- To optimize time and spatial resolution:
- charge calibration
- timewalk correction
- clock correction



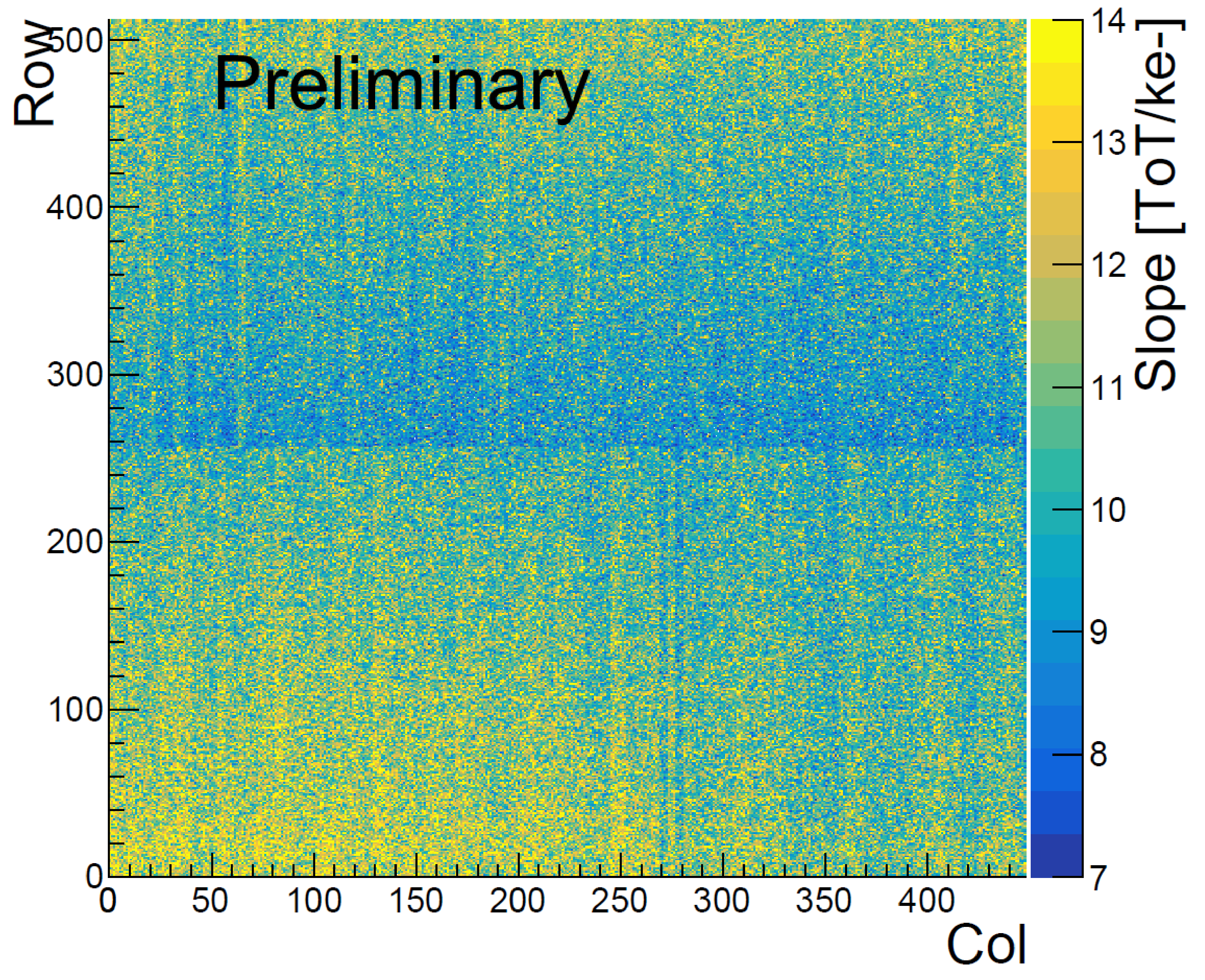
Upstream arm

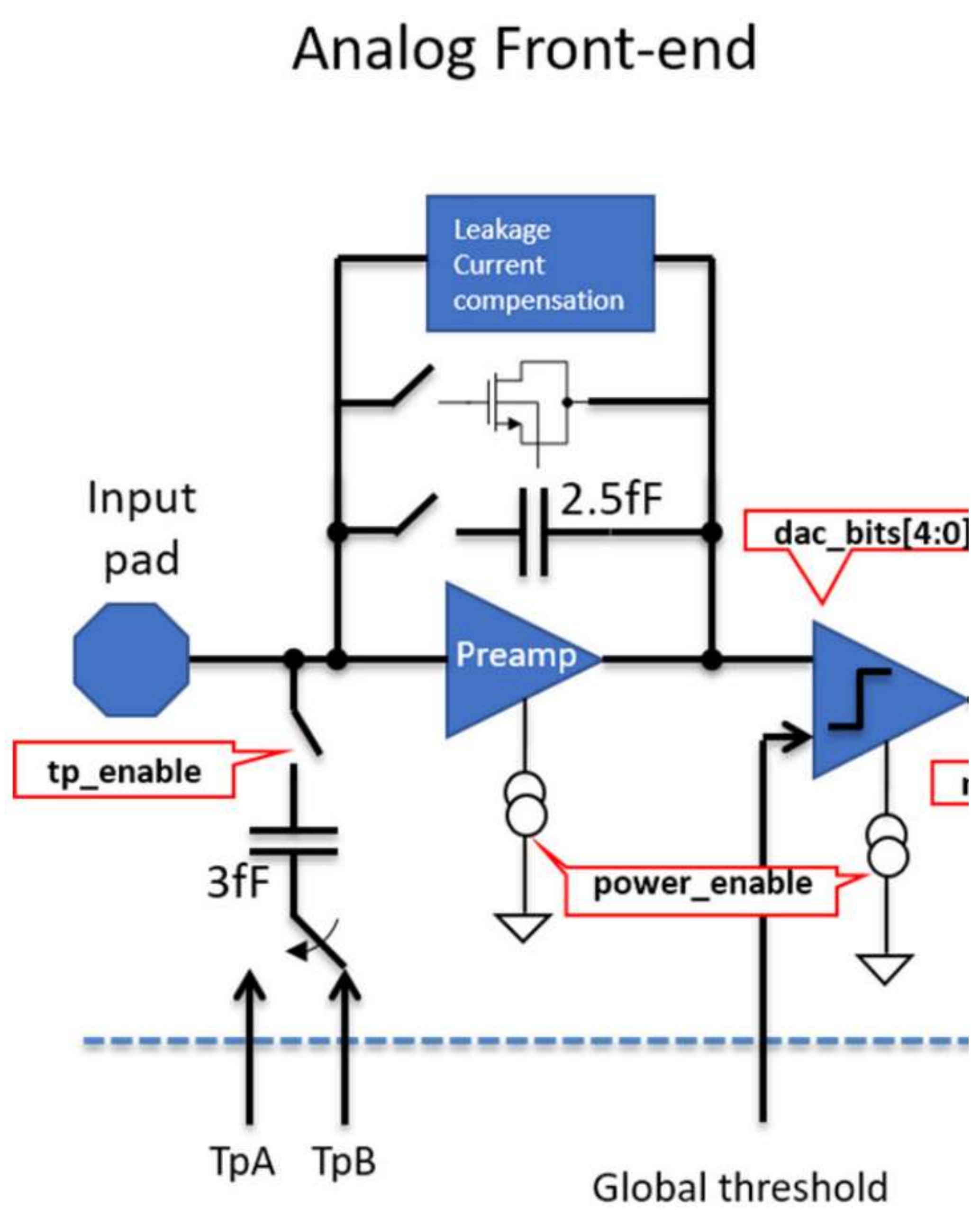
Downstream arm

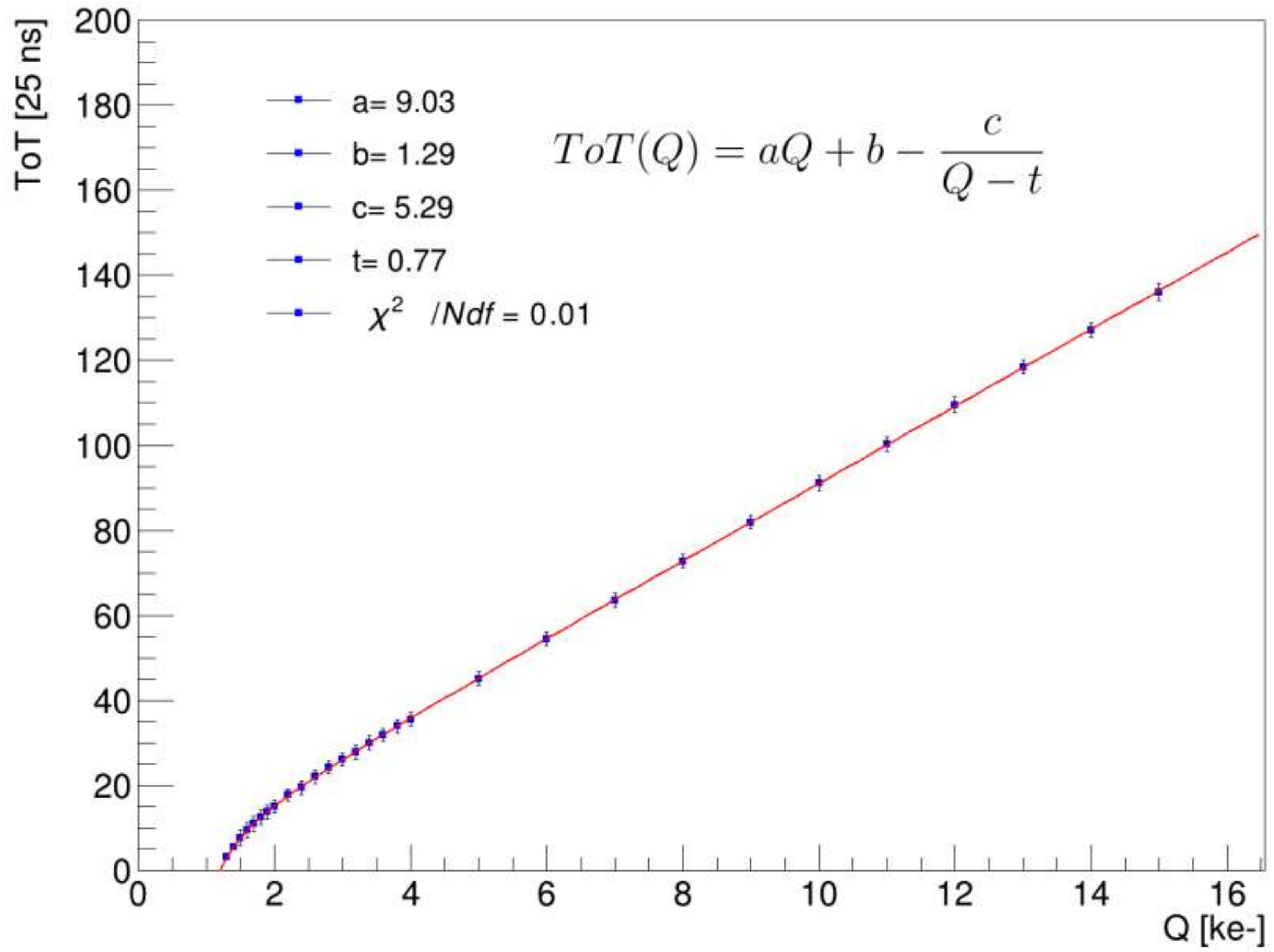


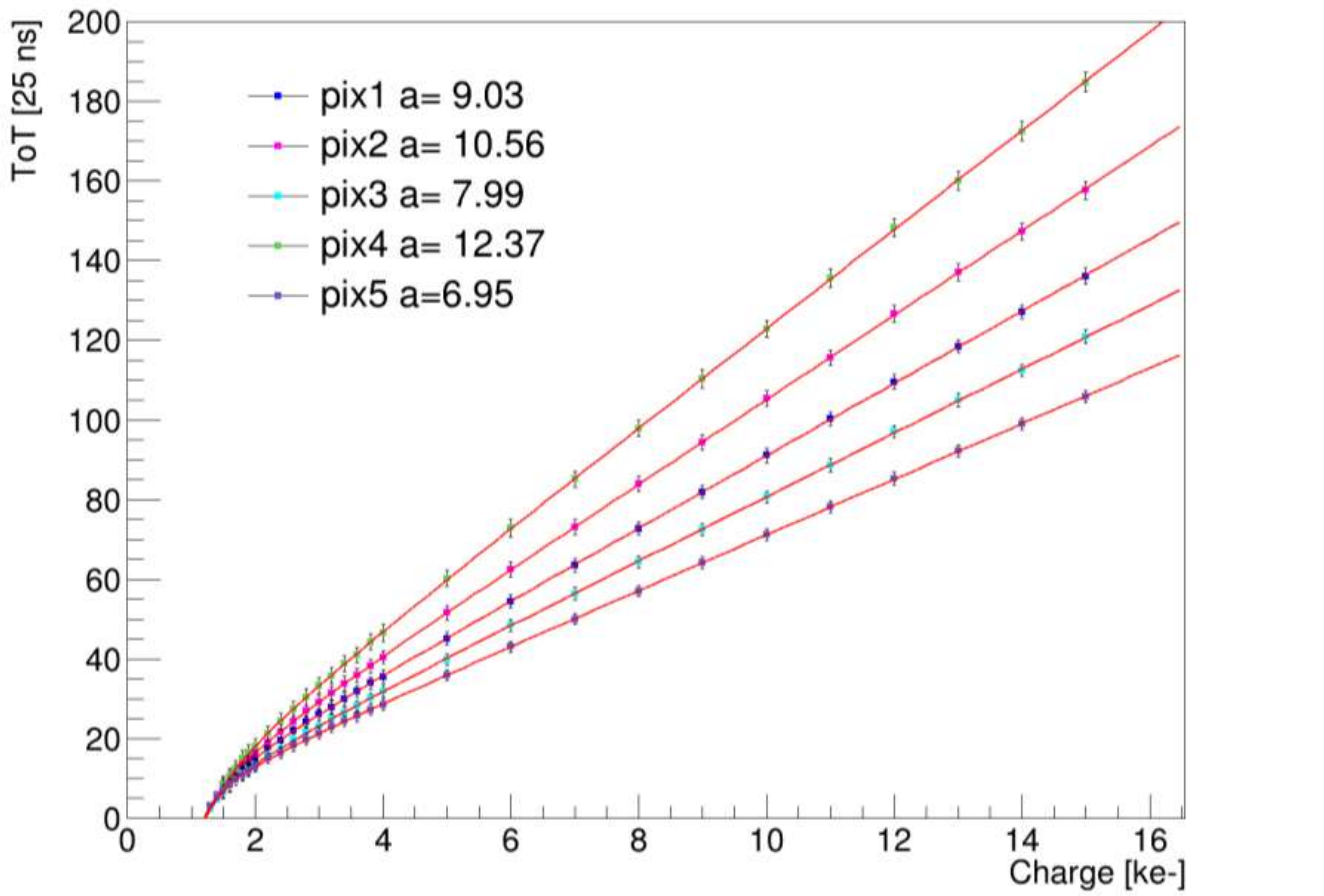
Charge calibration

- Per pixel calibration with test pulses
- Pixel to pixel ToT variation due to differences in discharge current
- Calibration needed to optimize spatial (and temporal resolution)



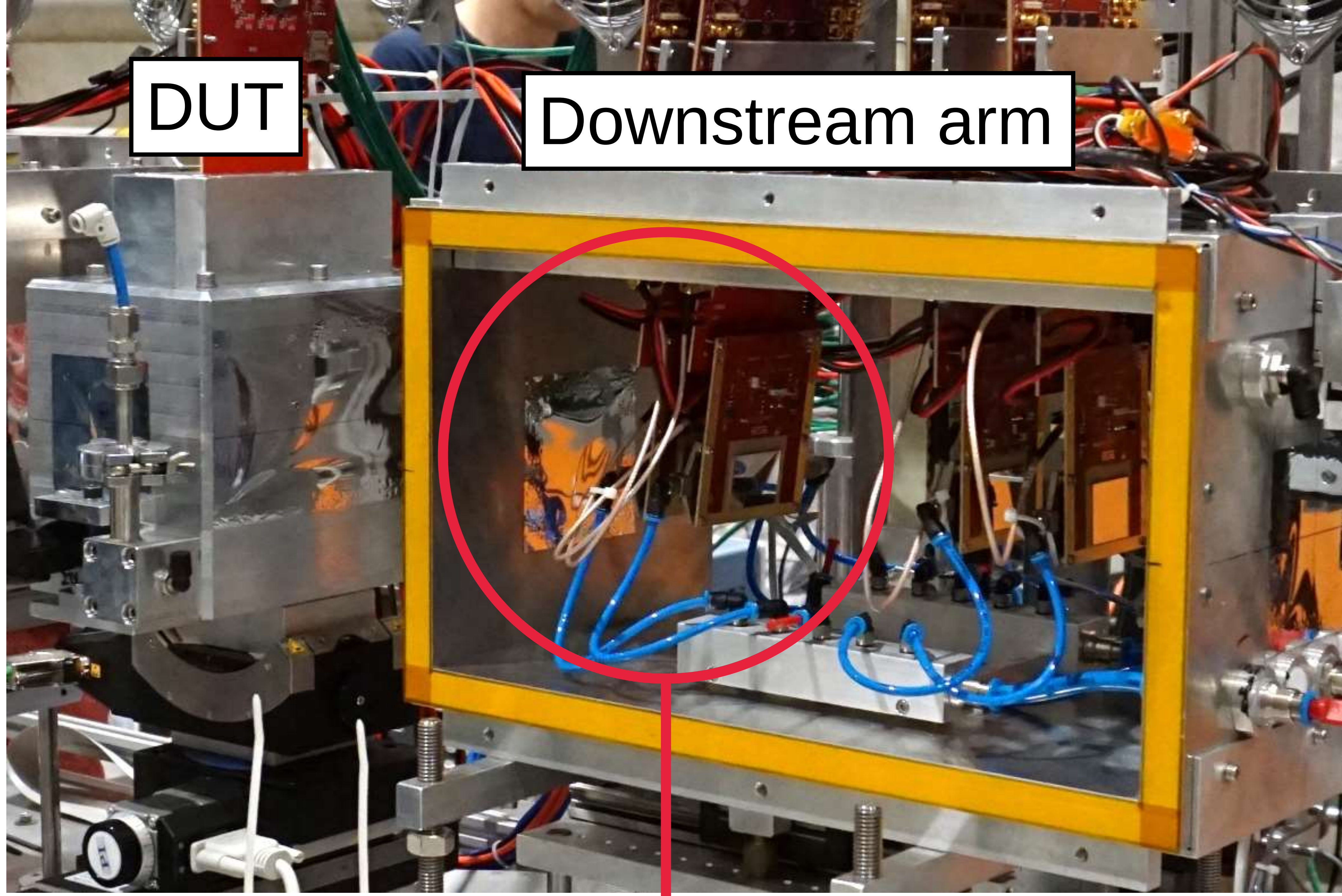


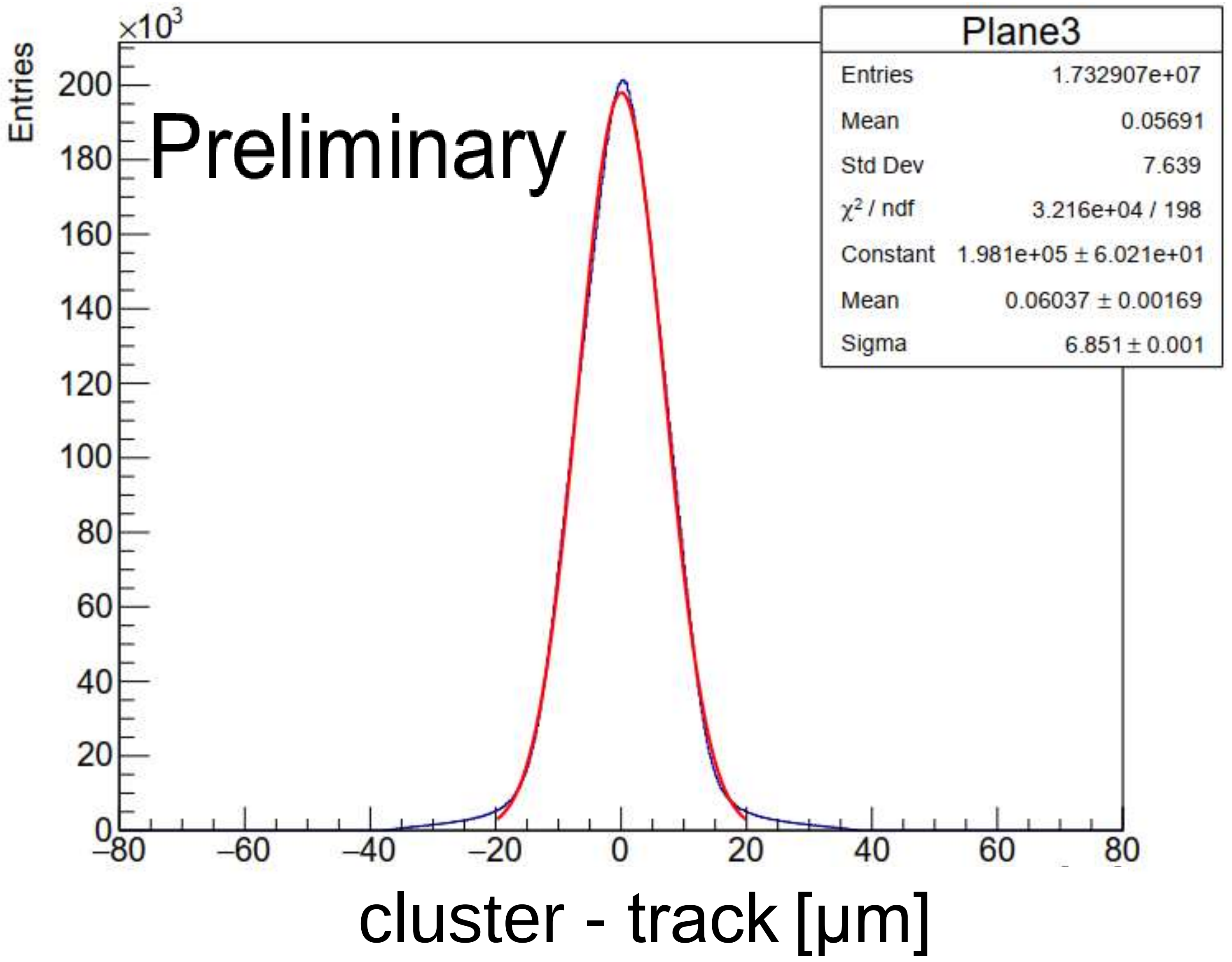


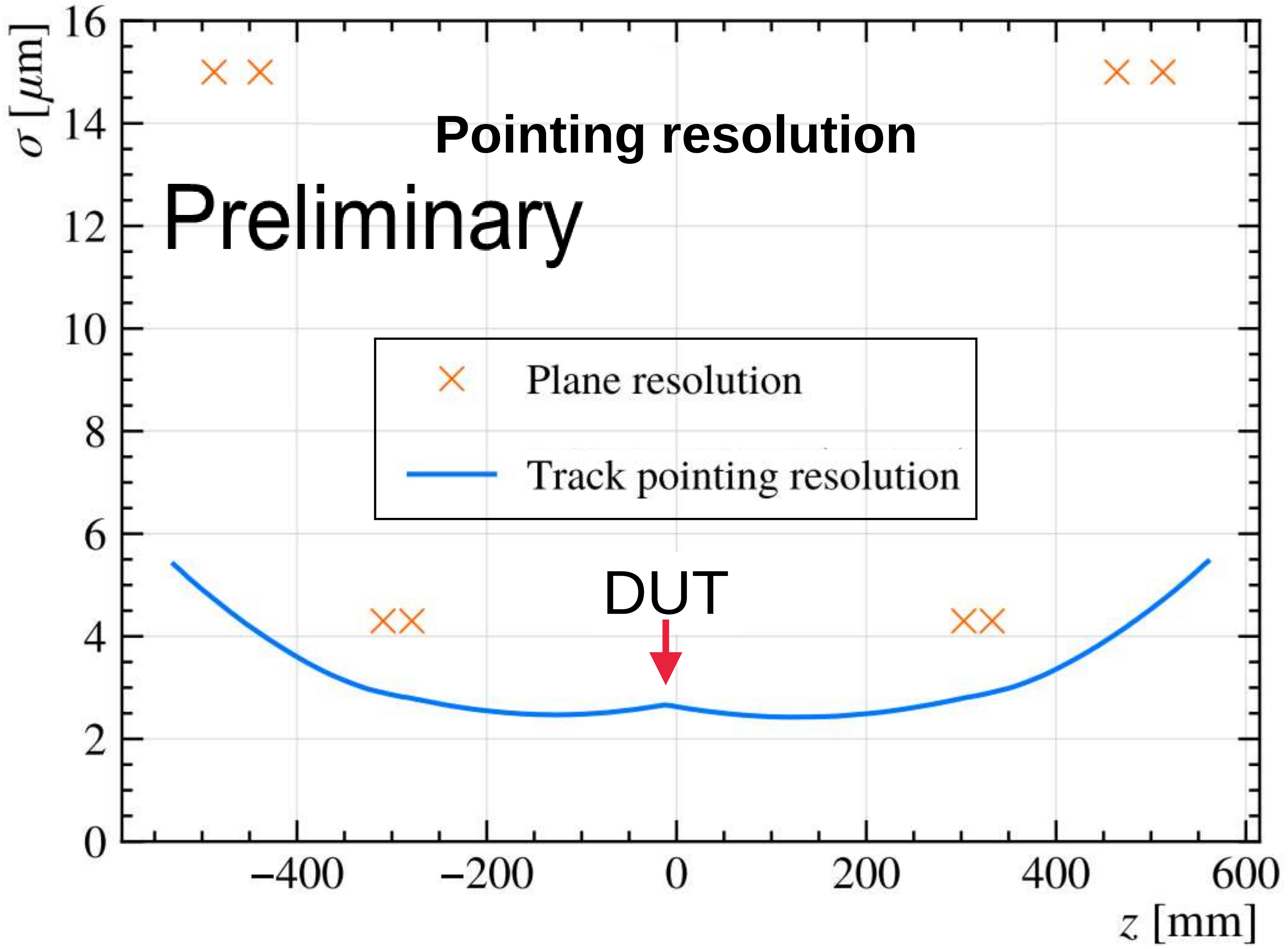


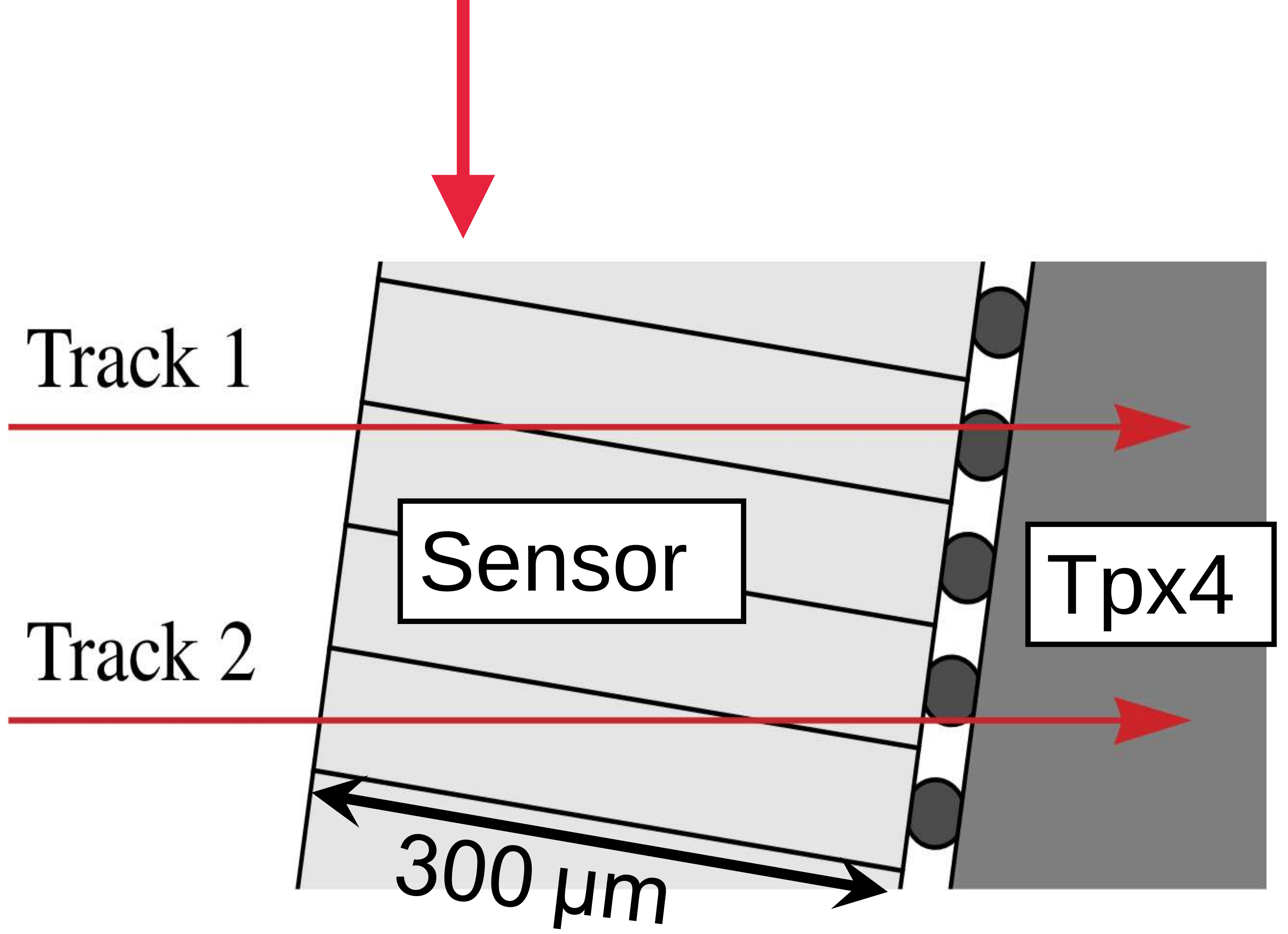
Spatial resolution

- Four innermost planes rotated 9° around x and y to enhance charge sharing between pixels
- Charge-weighted mean gives cluster position
- Single plane resolution: **4.3 µm**
- Pointing resolution at DUT: **2.7 µm** (Mixed hadron beam 180 GeV/*c*)
- Working on η corrections to improve spatial resolution



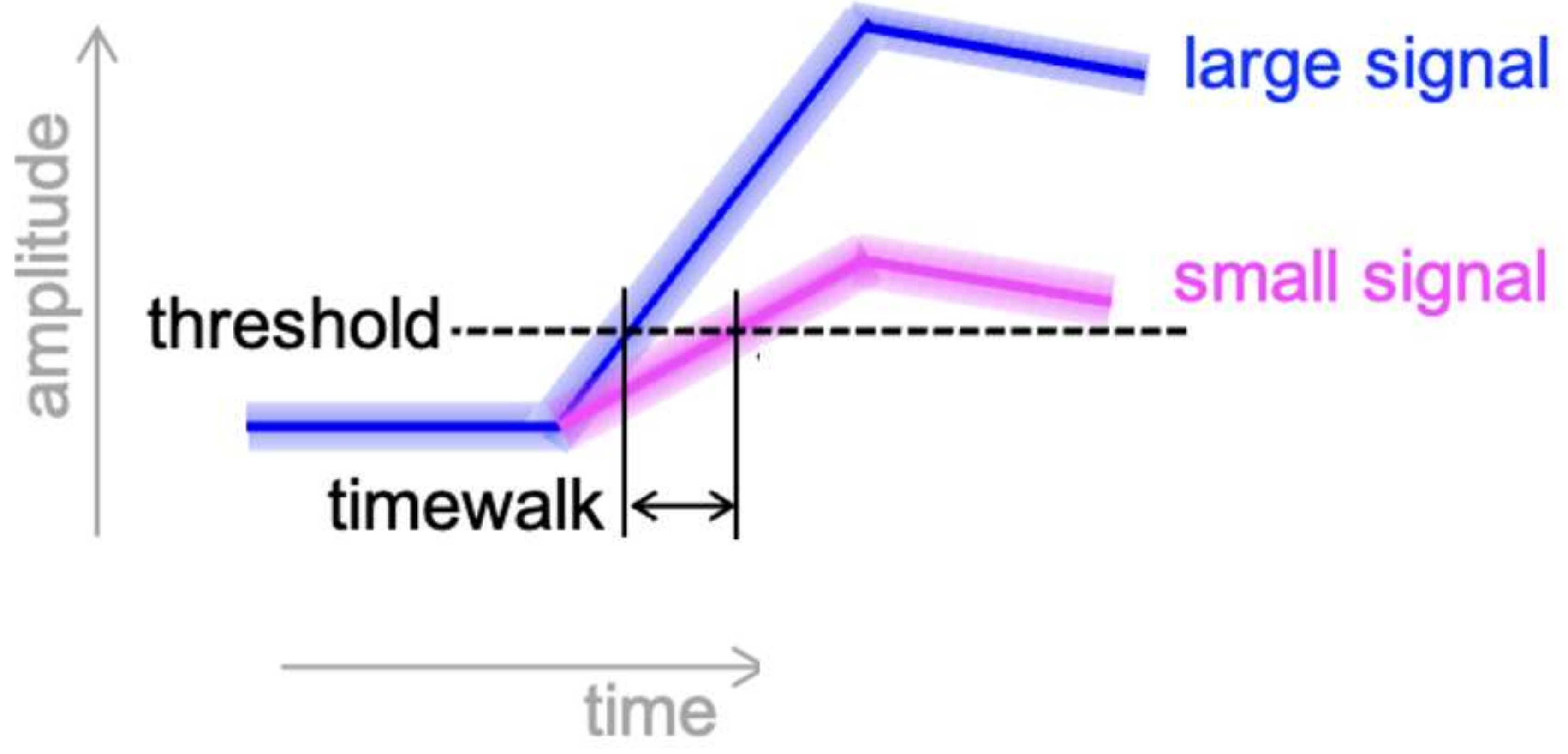


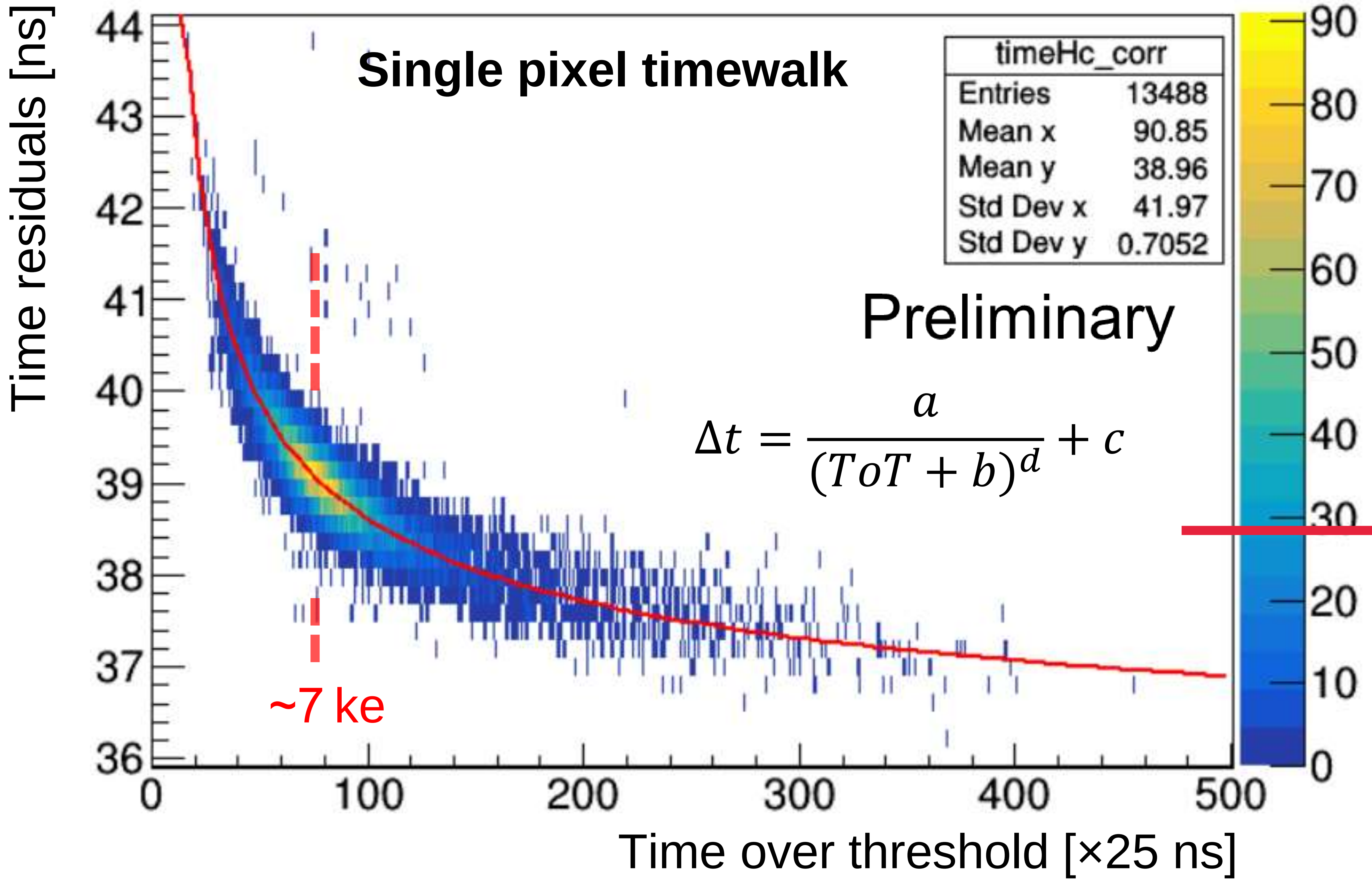


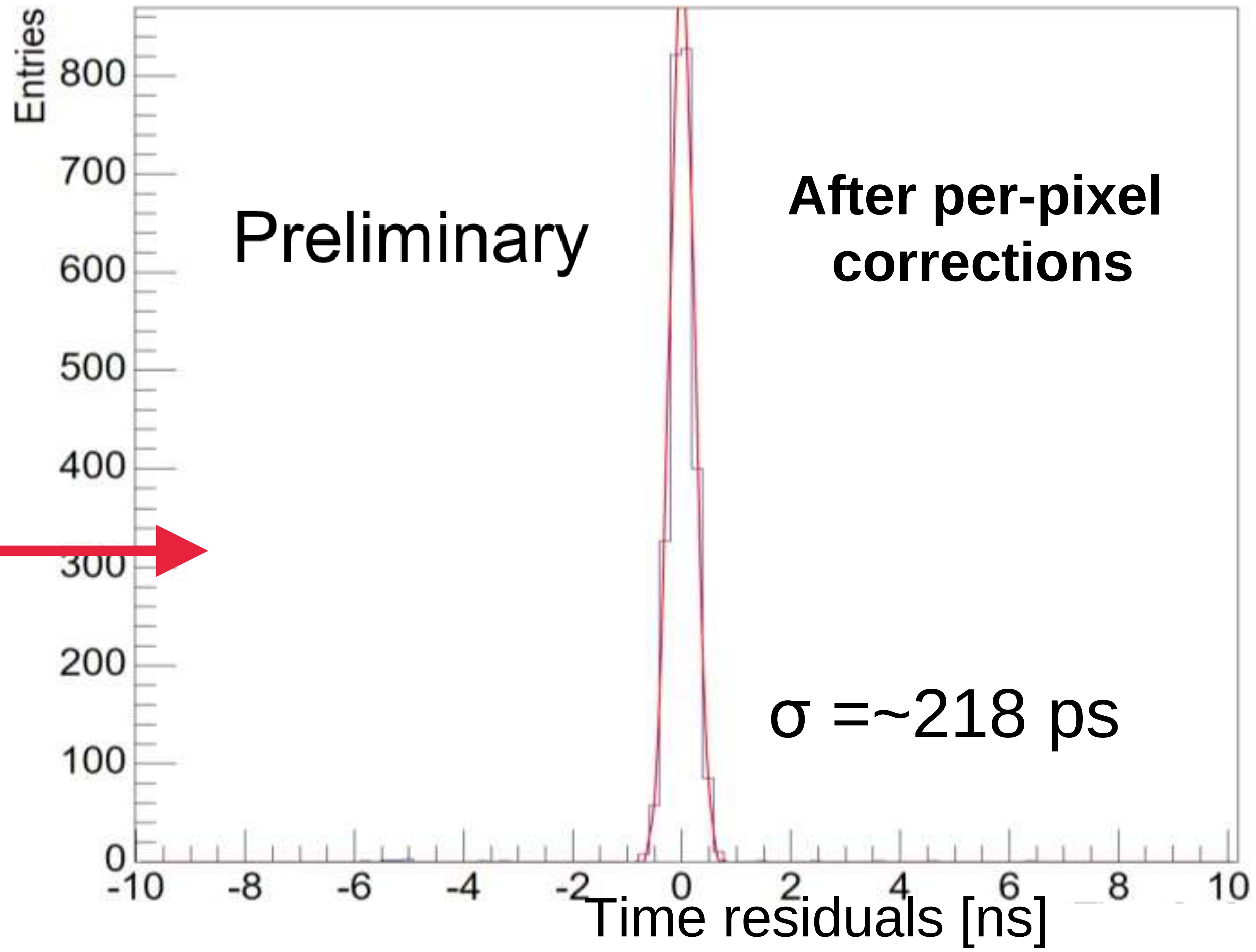


Time resolution

- Large signals cross threshold earlier than smaller ones
- Working on per-pixel timewalk corrections
- Current cluster-time resolution without Clock corrections: **~210-220 ps**

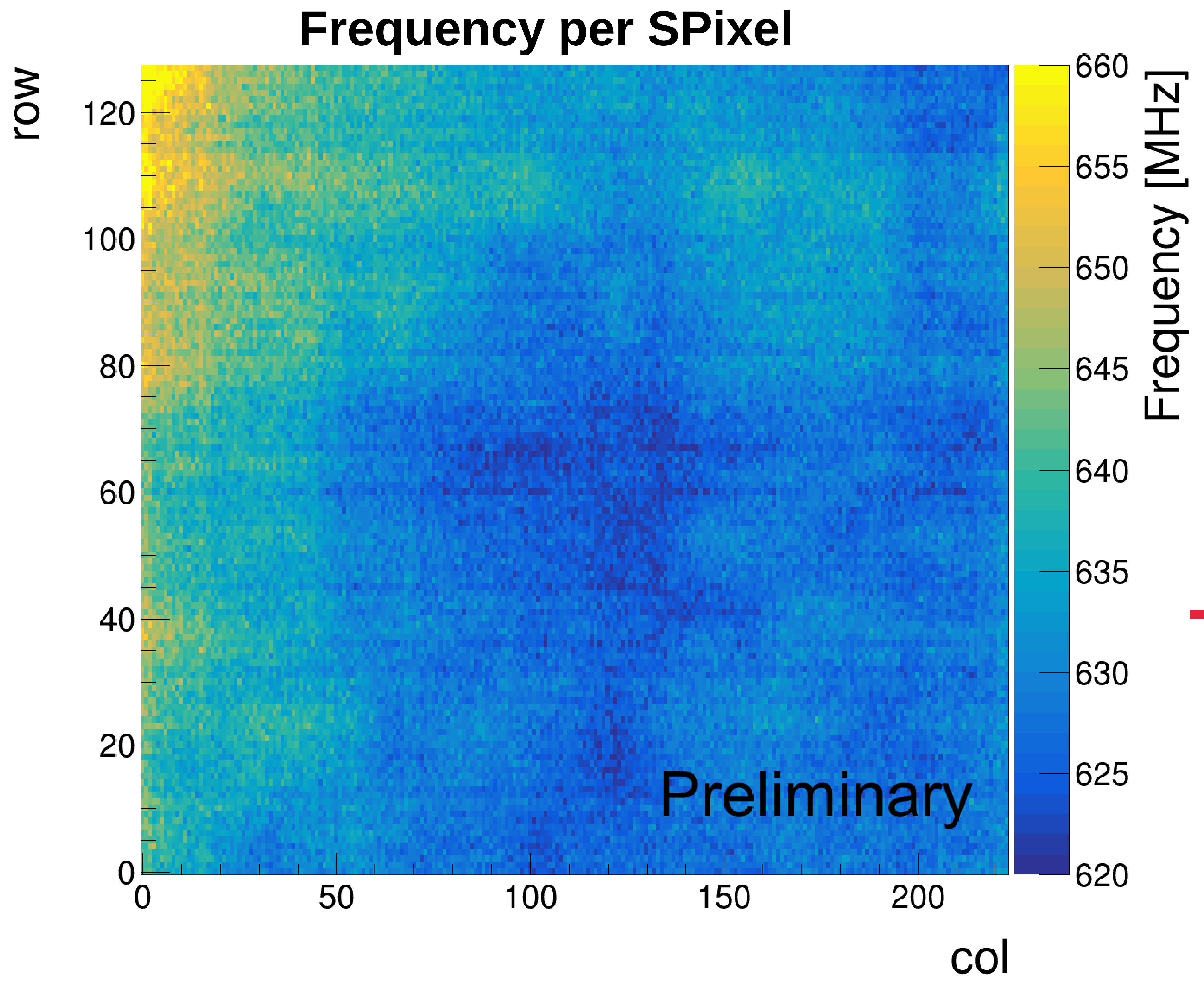


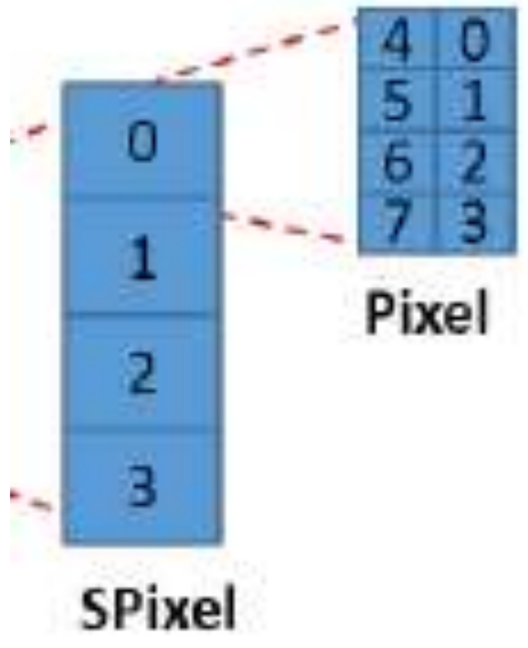


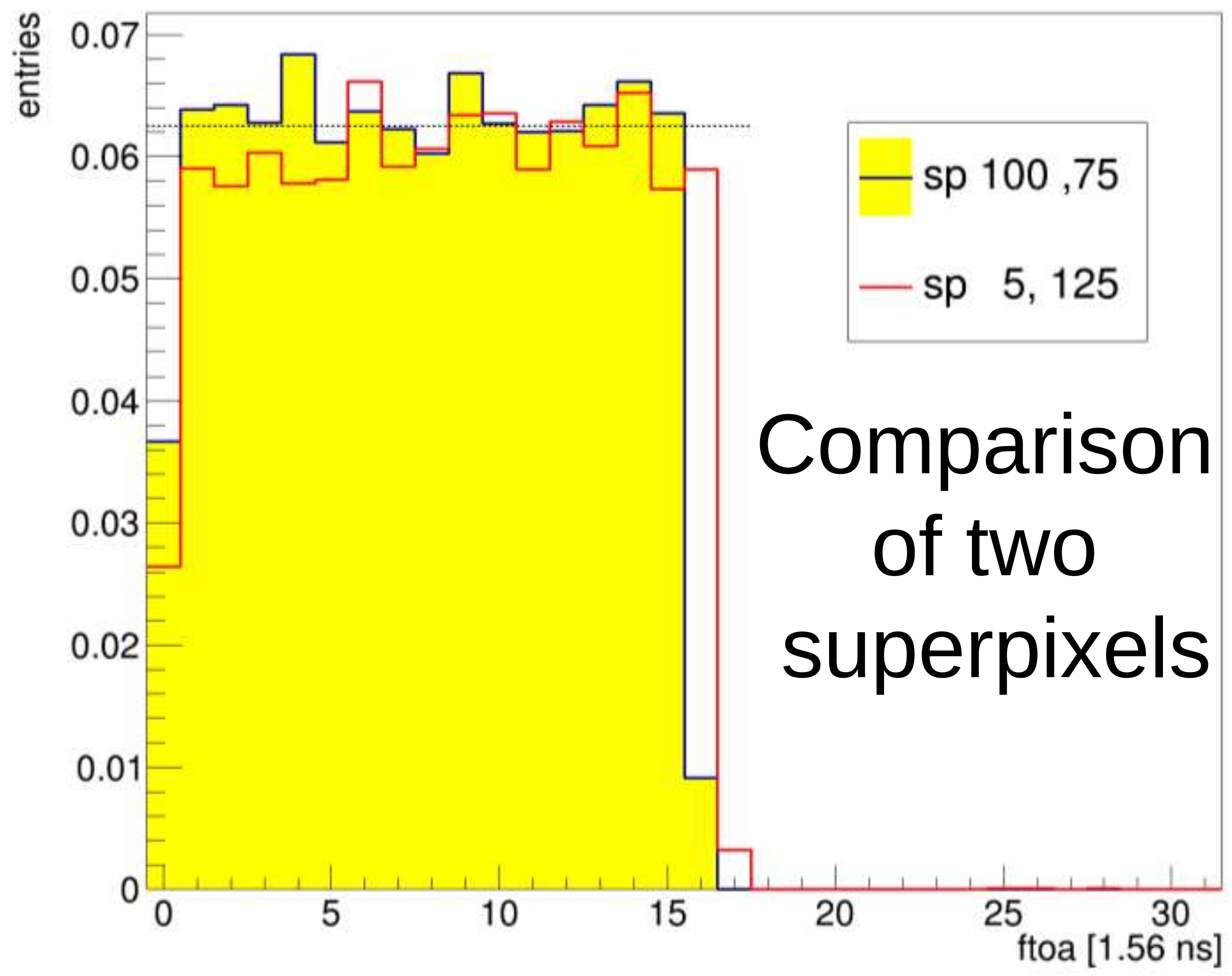


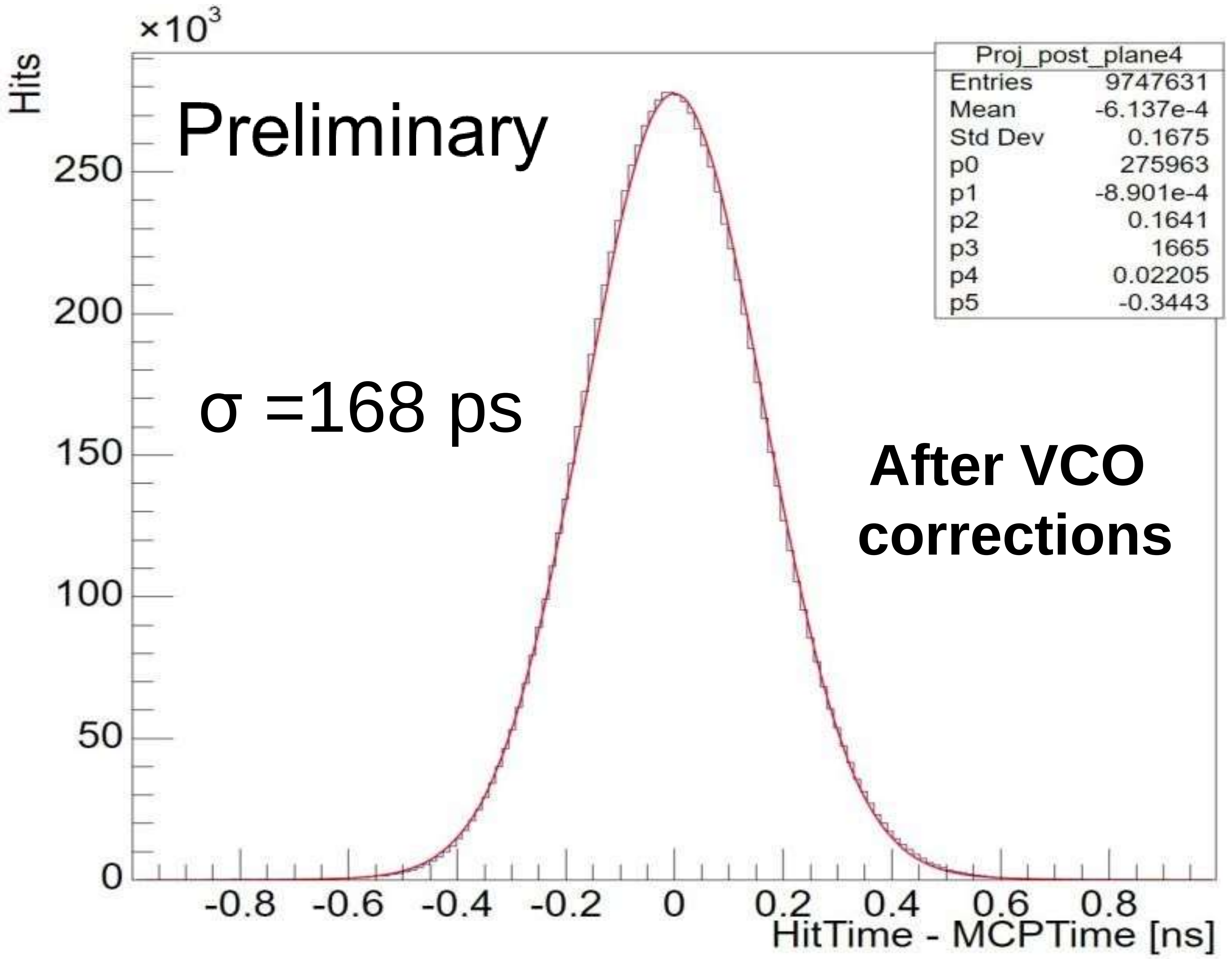
Time resolution

- ToA measurement with 640 MHz voltage-controlled oscillator
- Per superpixel VCO corrections
- After Timewalk+VCO corrections: **~168-185 ps**
- Track time: 4 × 100 µm orthogonal planes : **90 ps**



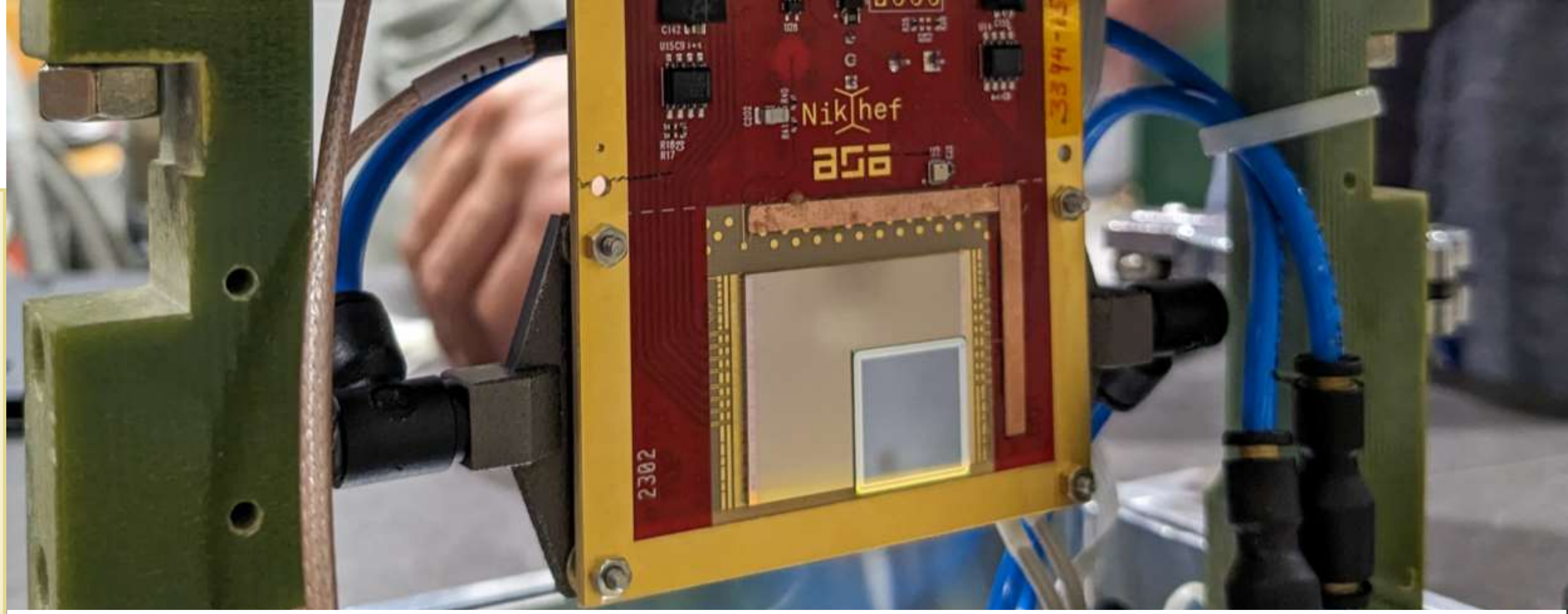


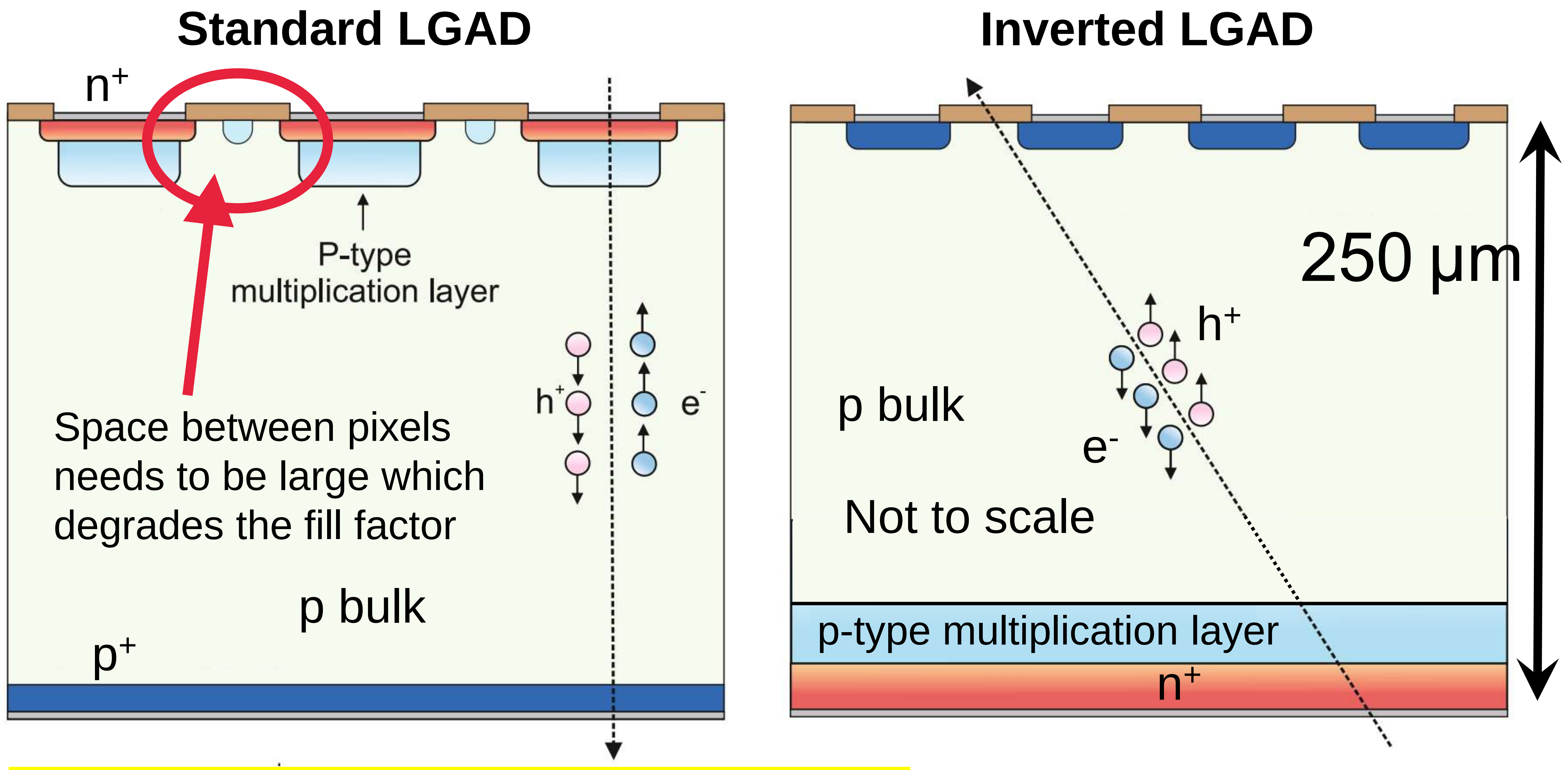




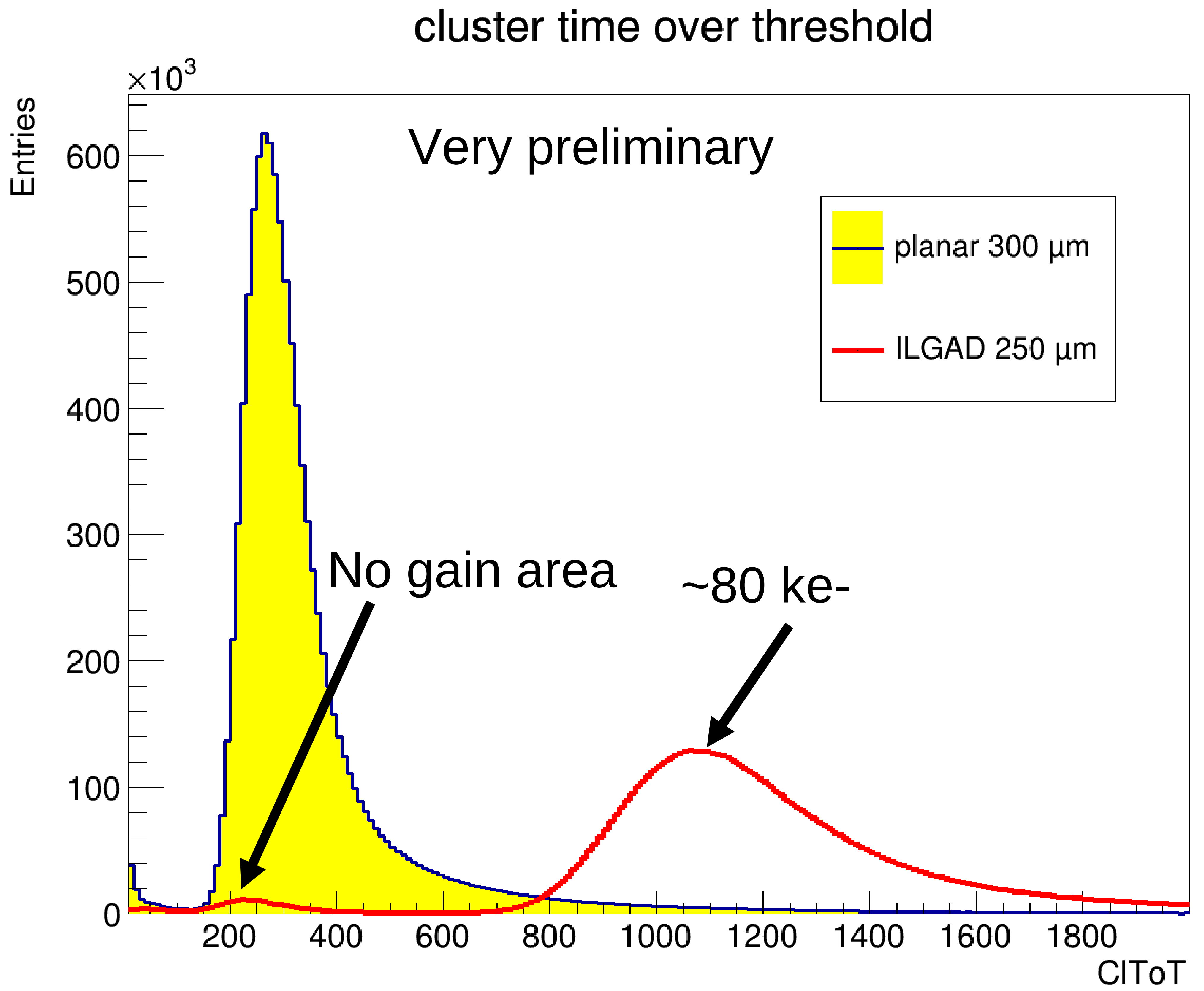
Inverted LGAD on Timepix4 as DUT

- Tested 250 µm thick iLGADs with 55/110 µm pitch (Tpx3 sized)
- Low-gain avalanche diodes (LGADs) use charge multiplication to deliver larger input signals
- Small pixel size cannot be achieved in standard LGAD technology (without losing efficiency)
- Inverted LGADs (iLGADs) solve this by placing the gain layer on the backside
- Sensors produced by Micron and provided by Glasgow



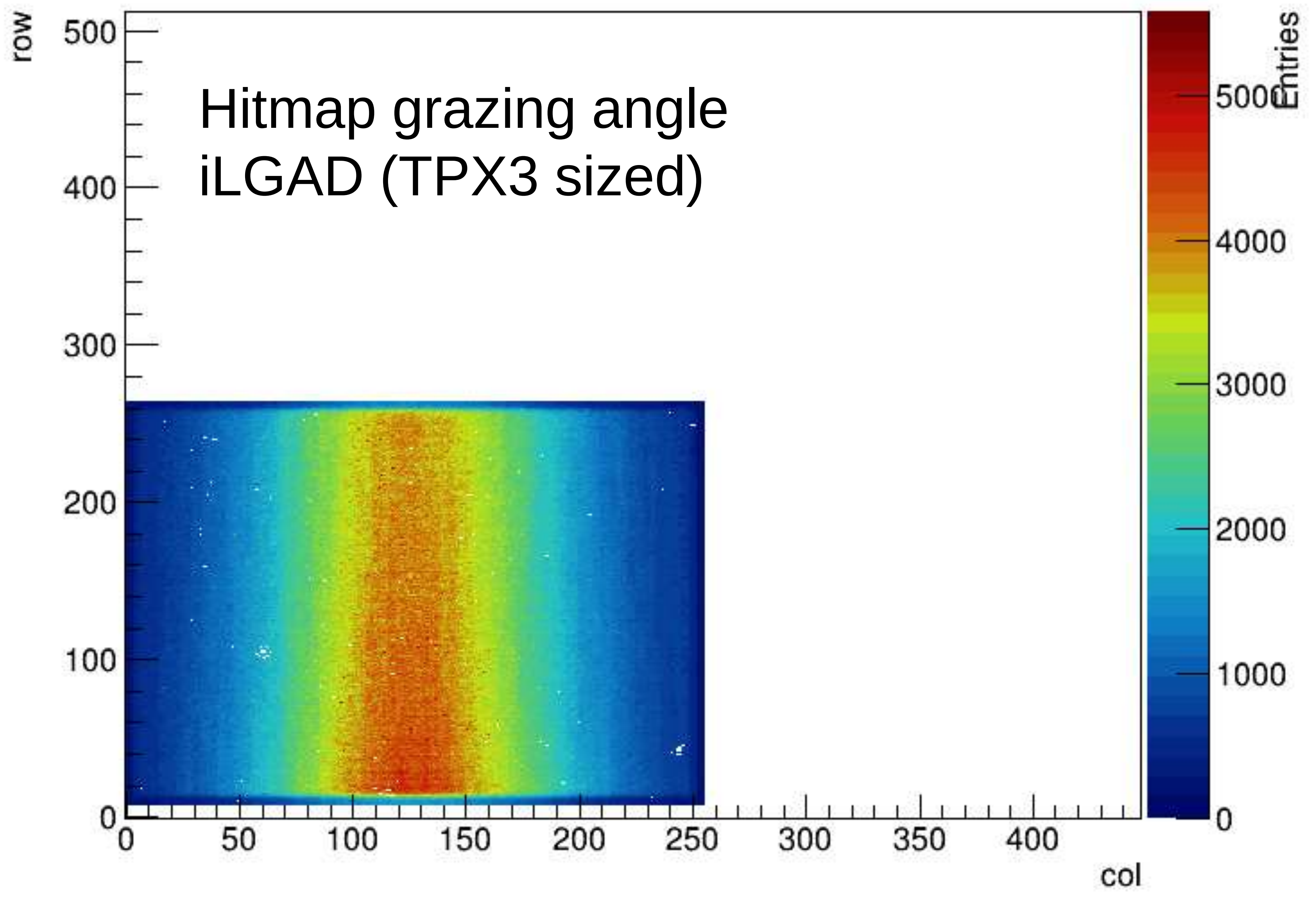


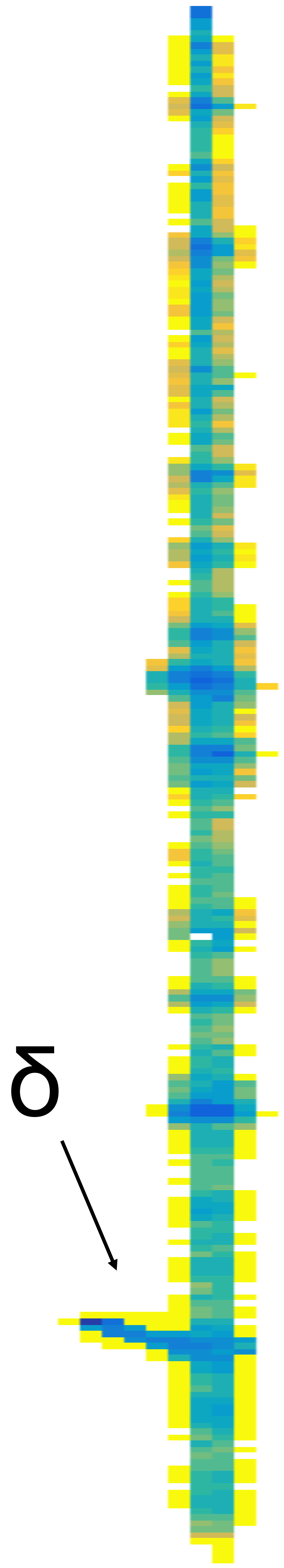
A. Doblas *et al Sensors* **2023**, 23, 3450 [DOI: 10.3390/s23073450]



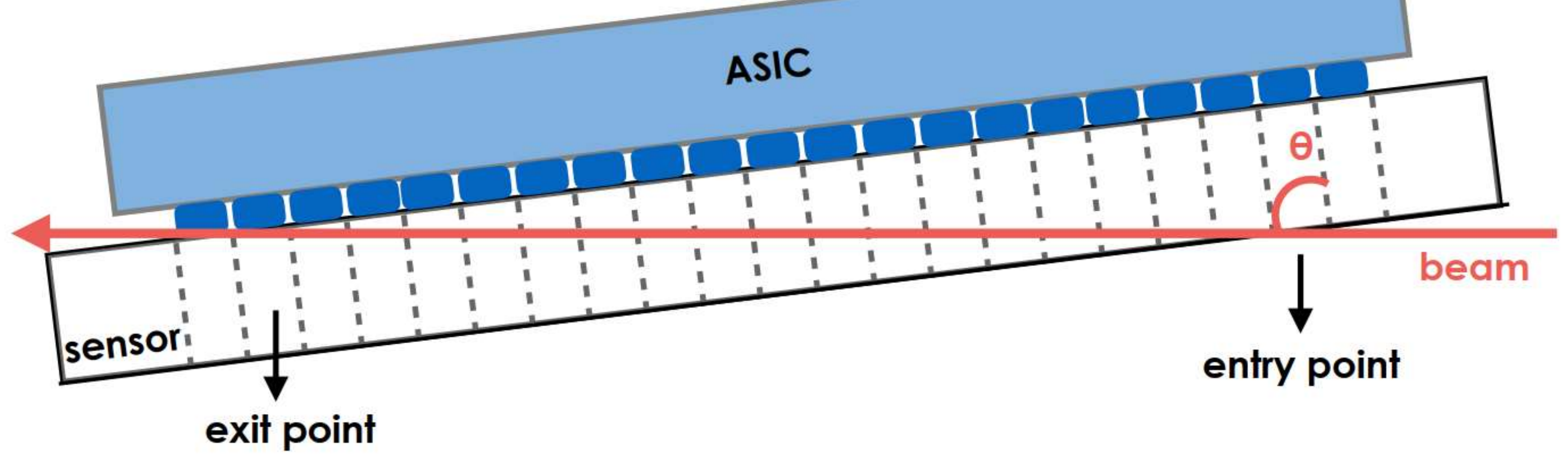
Grazing angle measurements

- Grazing angle measurement used to determine time resolution for different depth in the sensor
- Selection of clusters without δ-rays
- Average cluster time as time reference
- Operated at (too) low threshold

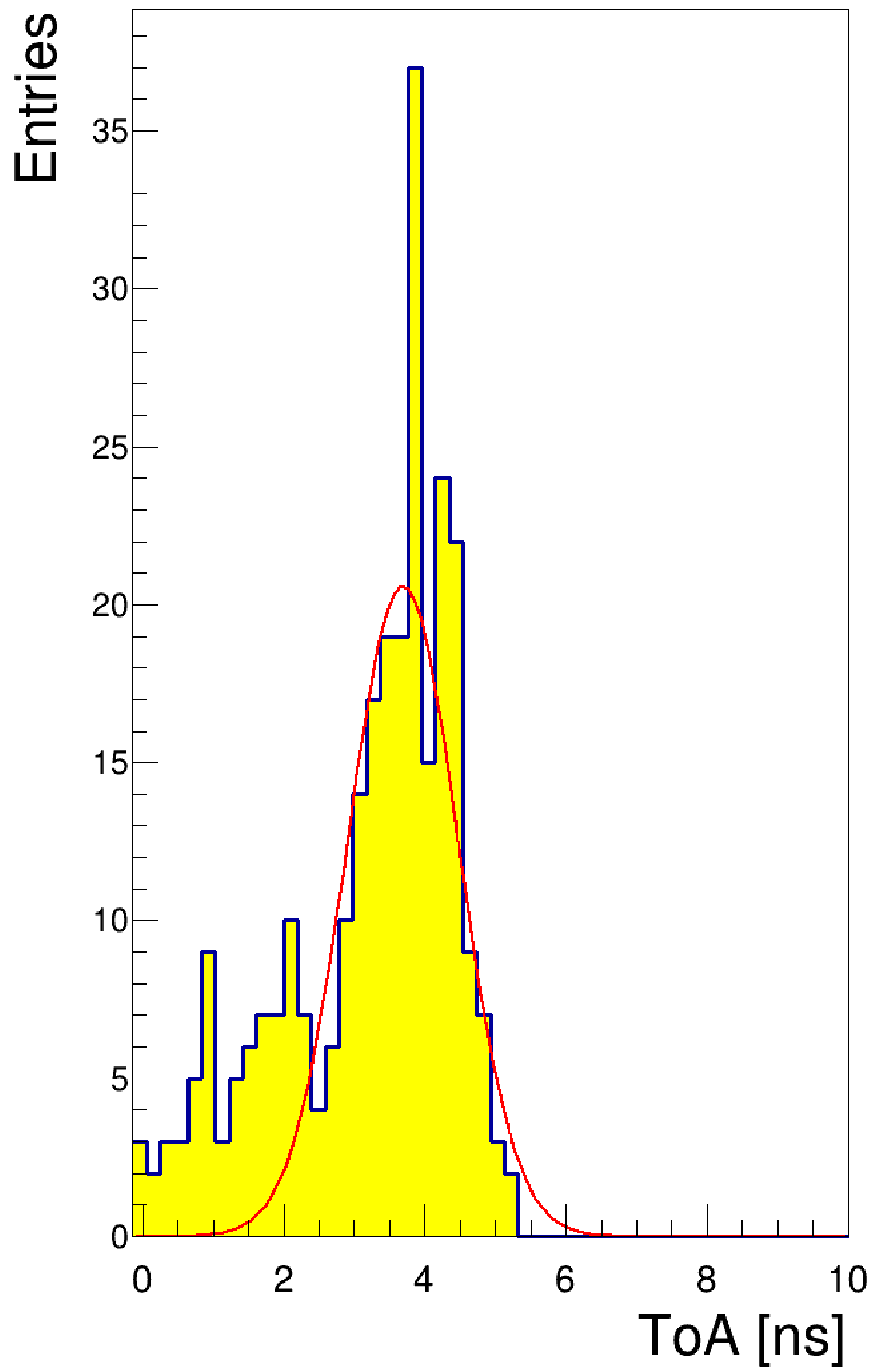


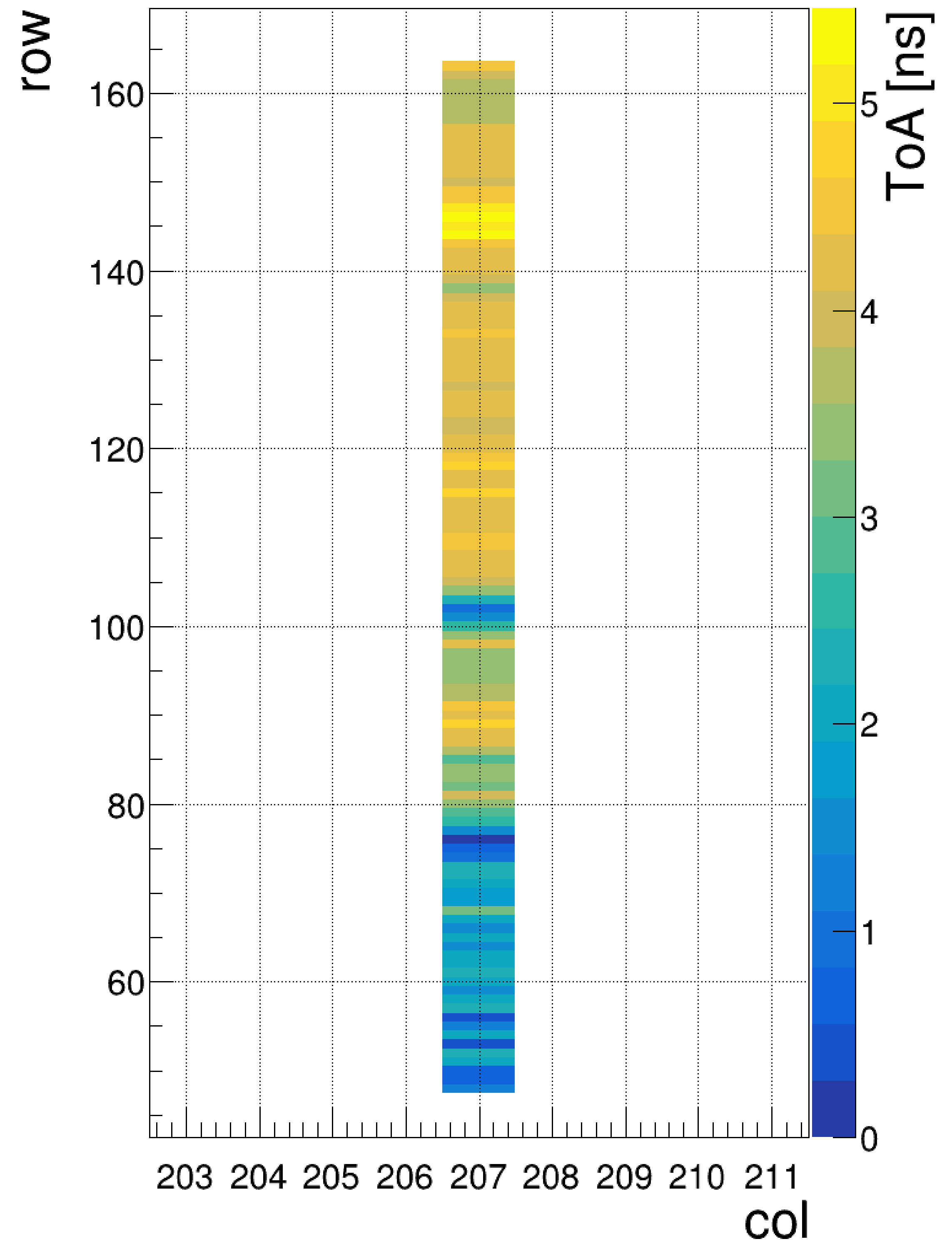


E. Dall'Occo et al 2021 JINST **16** P07035
[DOI: 10.1088/1748-0221/16/07/P07035]



ToA distribution of one cluster w.r.t. earliest hit

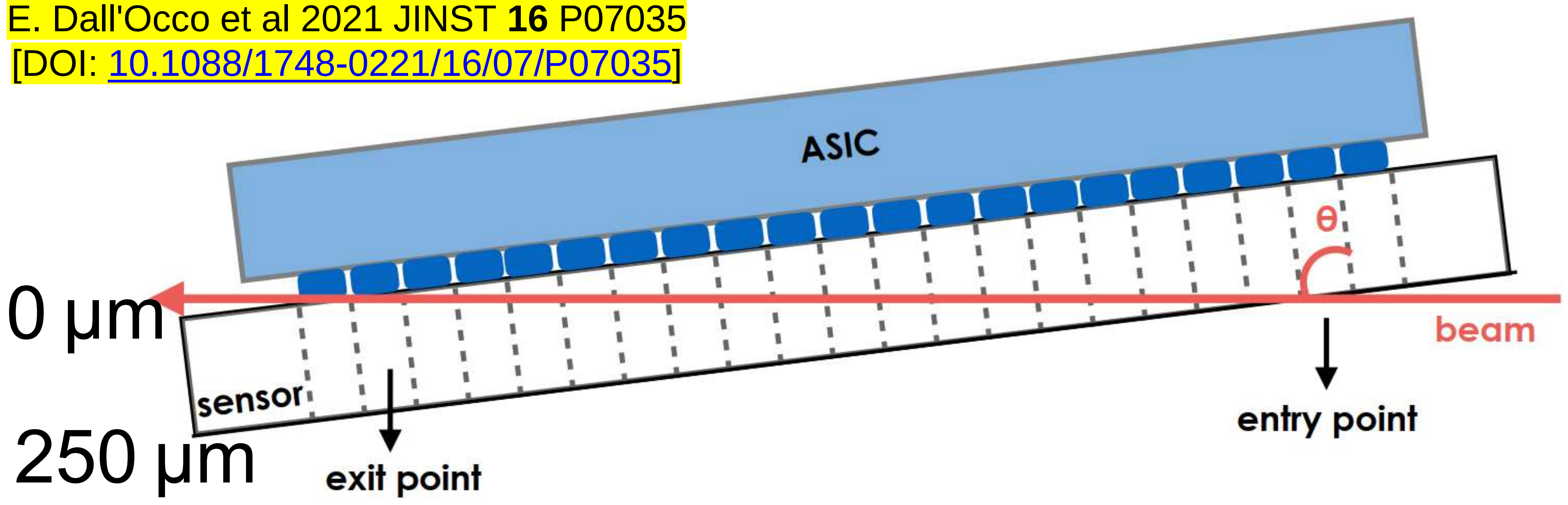


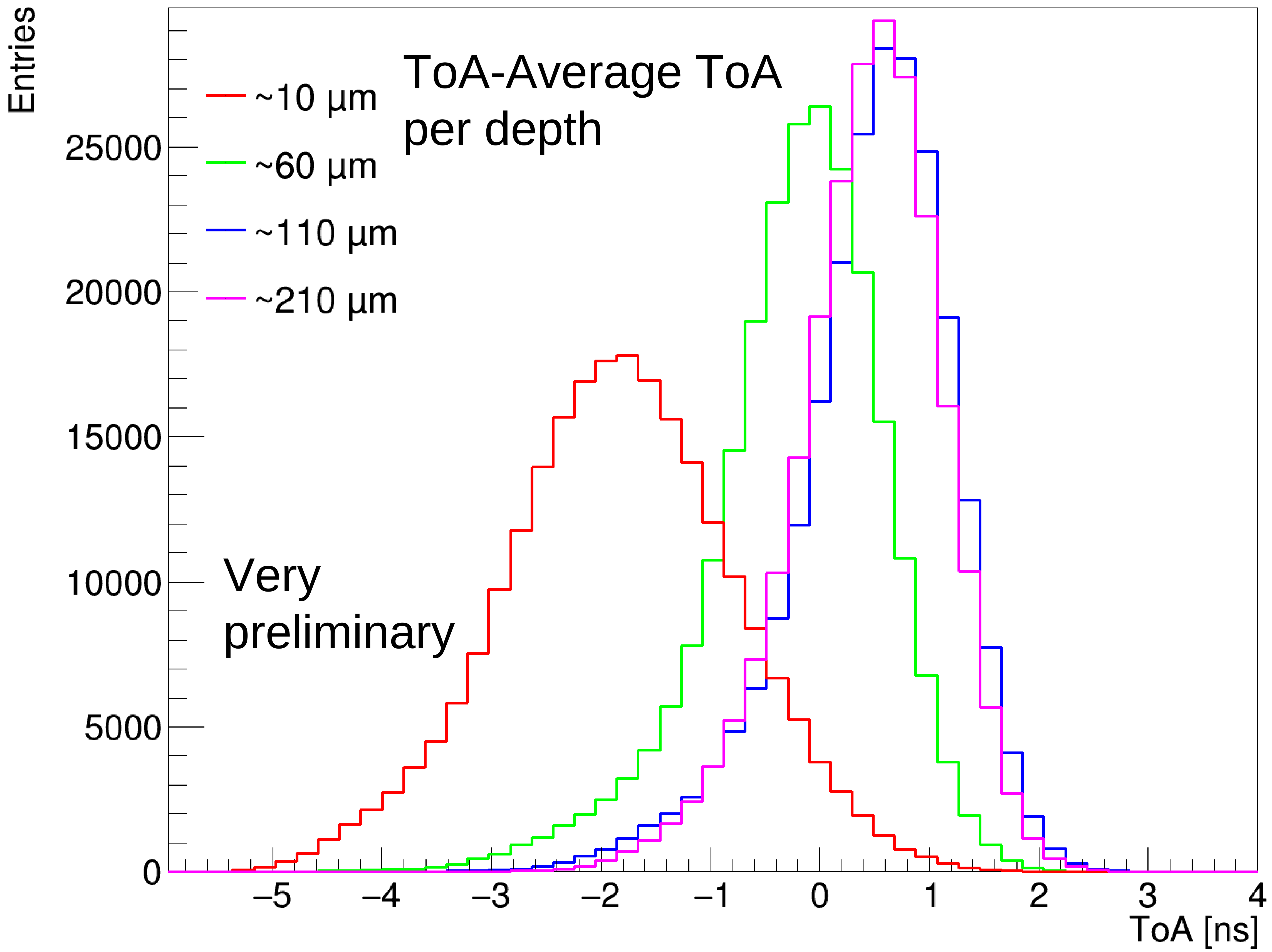


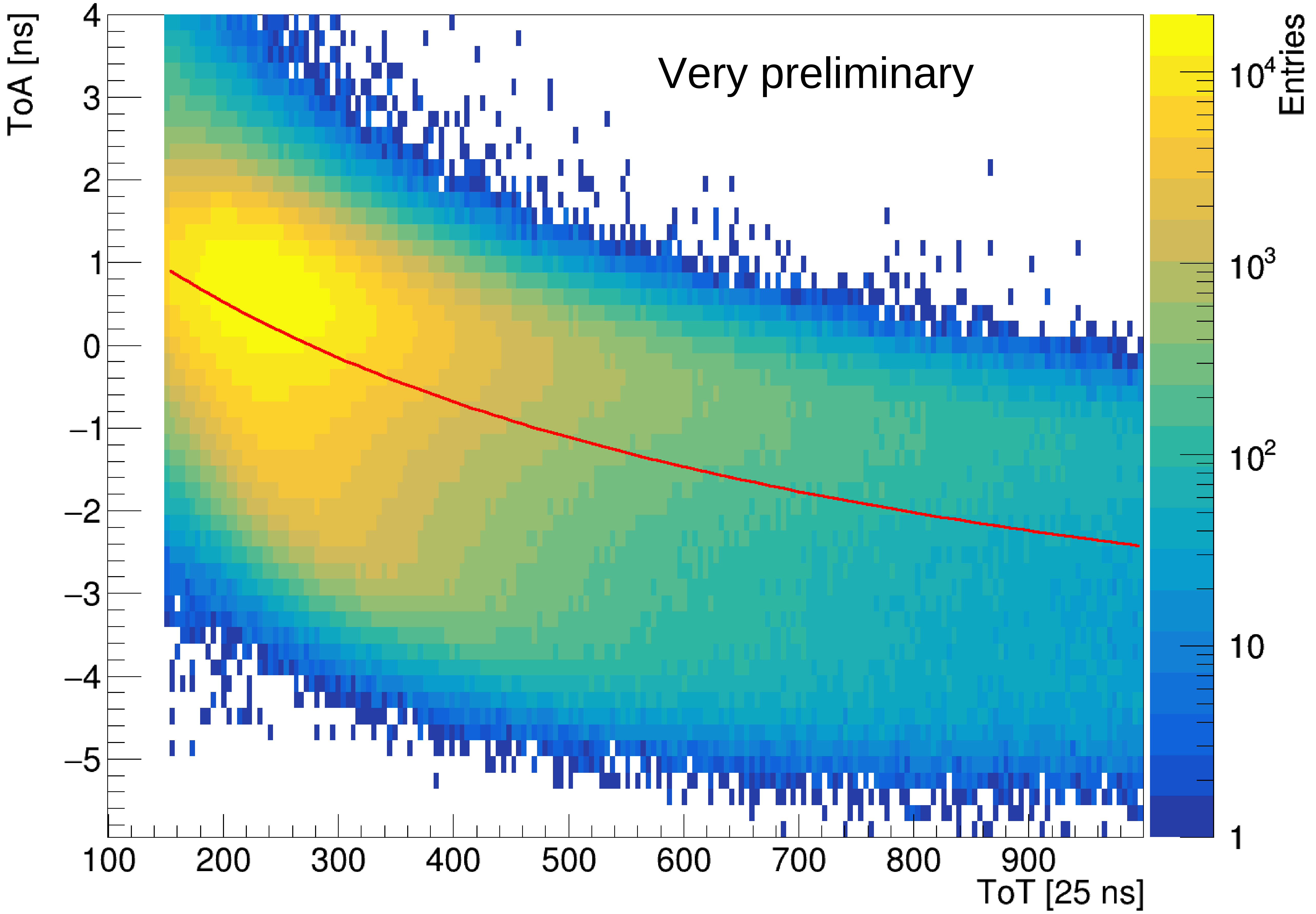
Timewalk

- Earlier signal close to read-out electrode
- Worse time resolution close to read-out electrode
- Multiple bands in timewalk curve
- Timewalk correction as function of depth

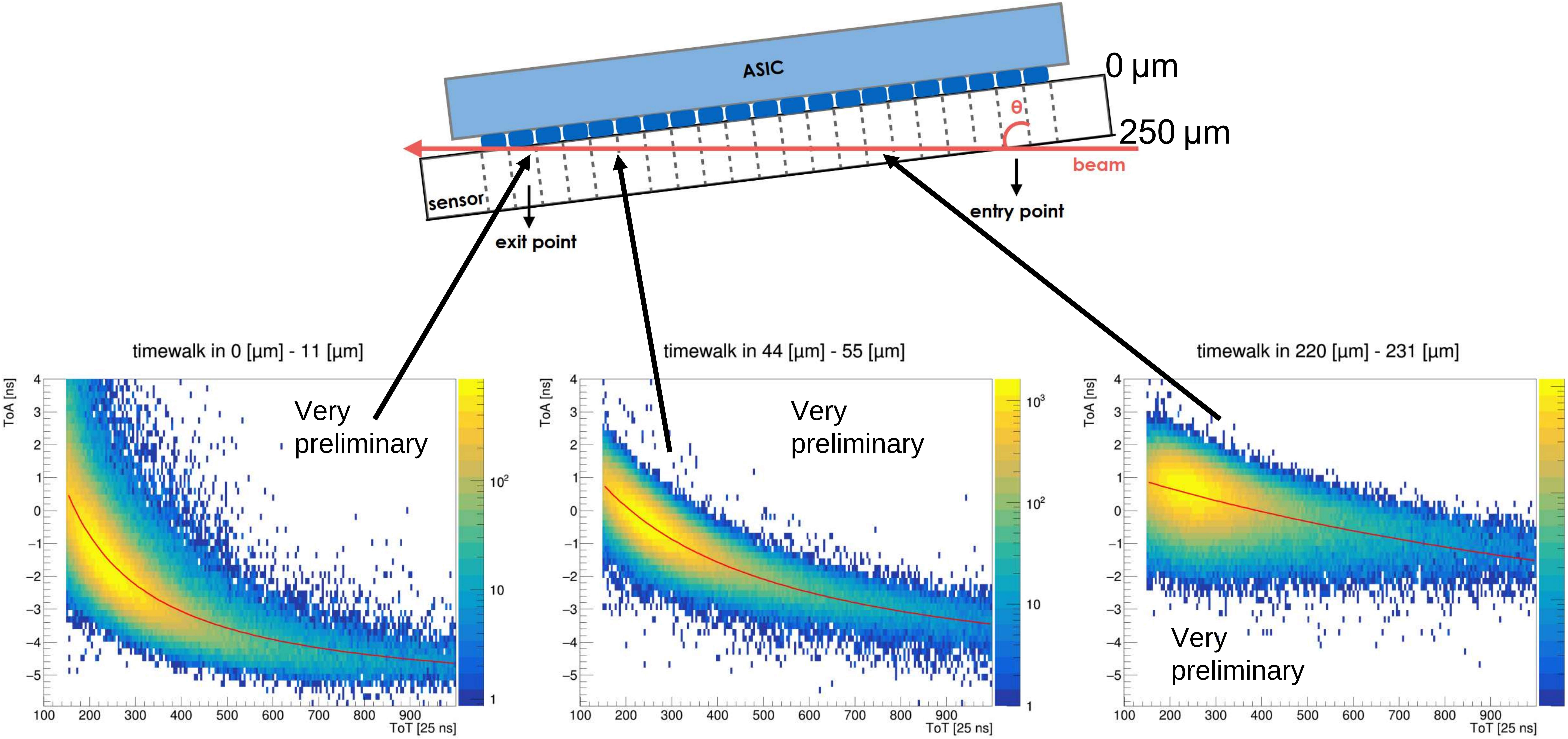
E. Dall'Occo et al 2021 JINST **16** P07035
[DOI: 10.1088/1748-0221/16/07/P07035]





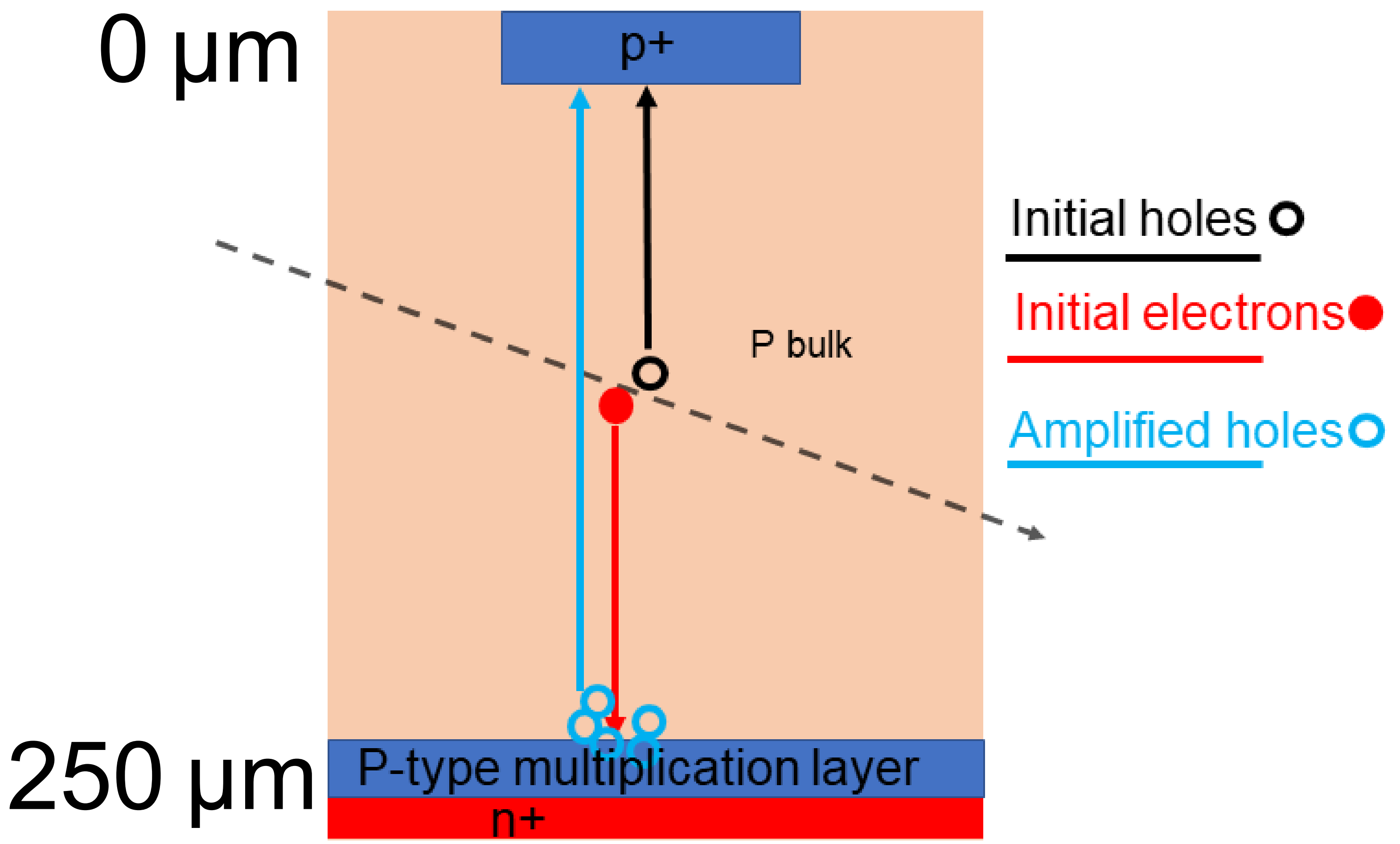


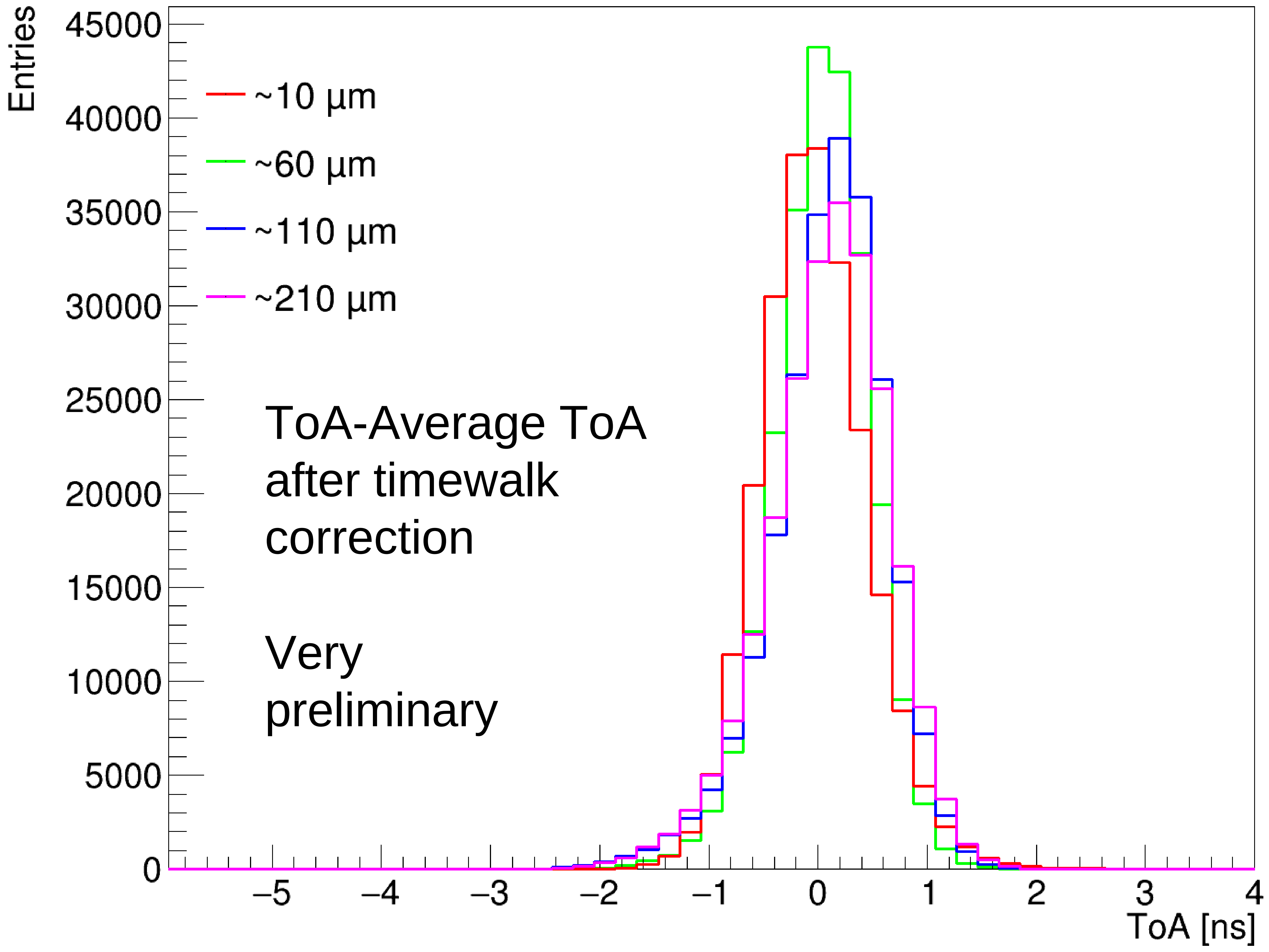
Timewalk correction per depth

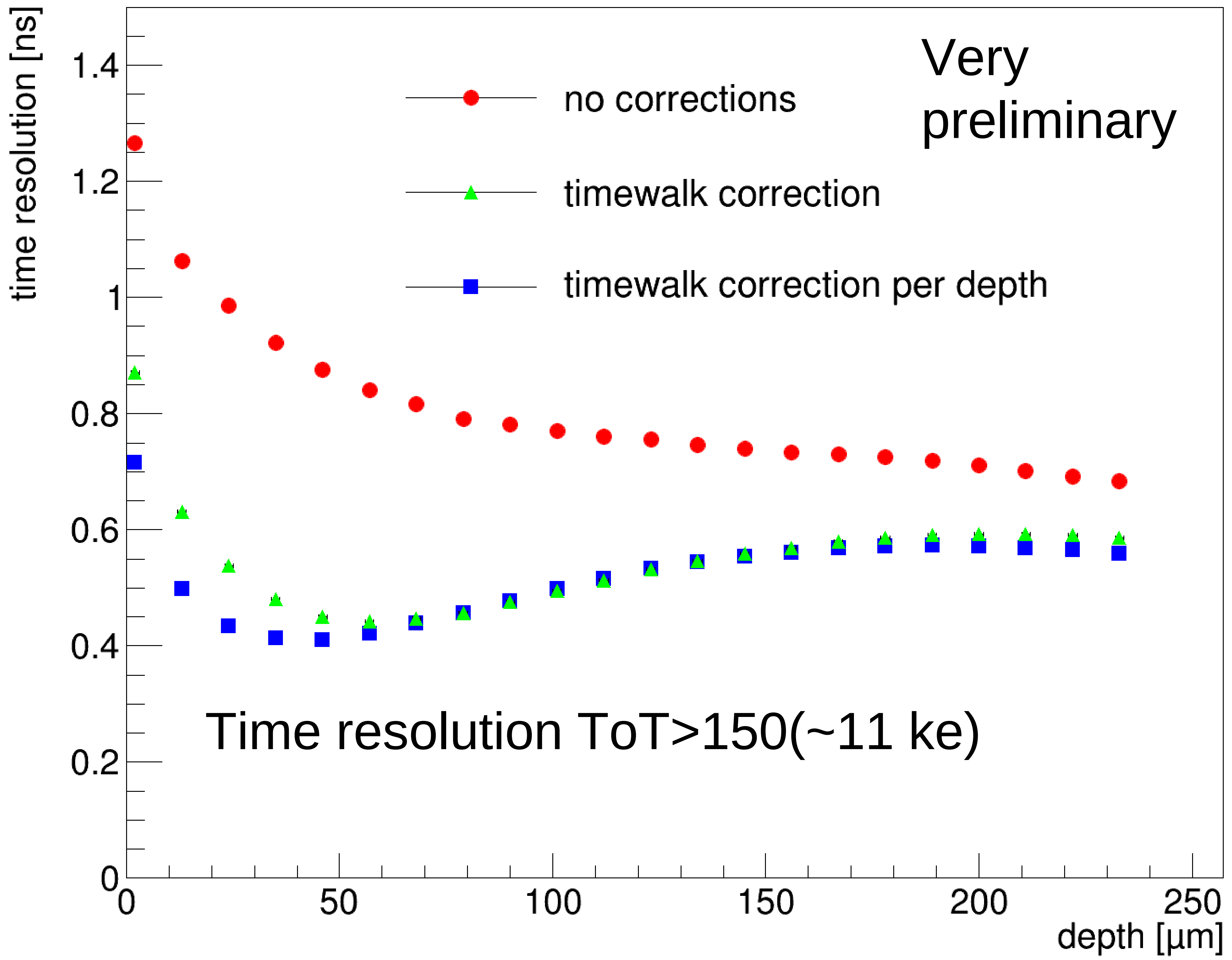


Time resolution as function of depth

- Timewalk correction has more effect close to read-out electrode
- Time resolution is best at 40 μm depth (at the moment)
- Improving timewalk corrections close to gain layer
- Working on comparison with MCP as time ref. (better resolution)





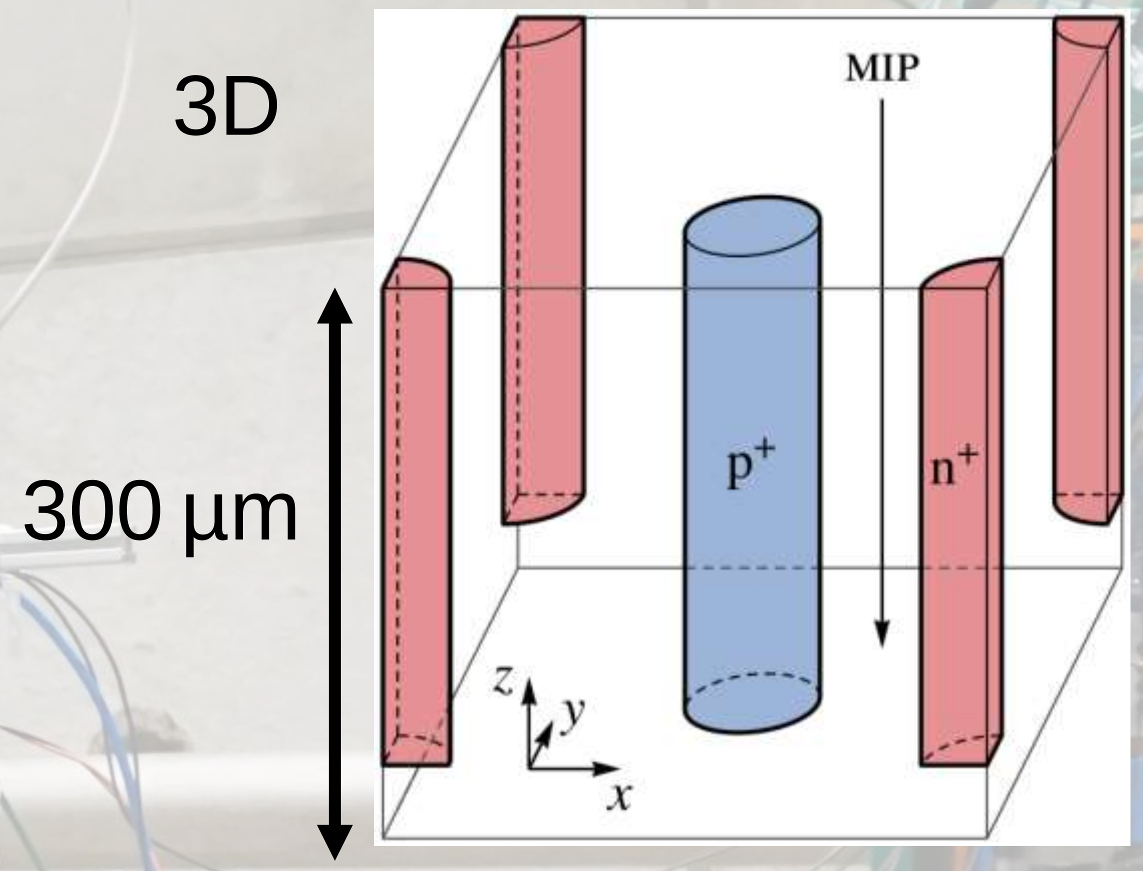


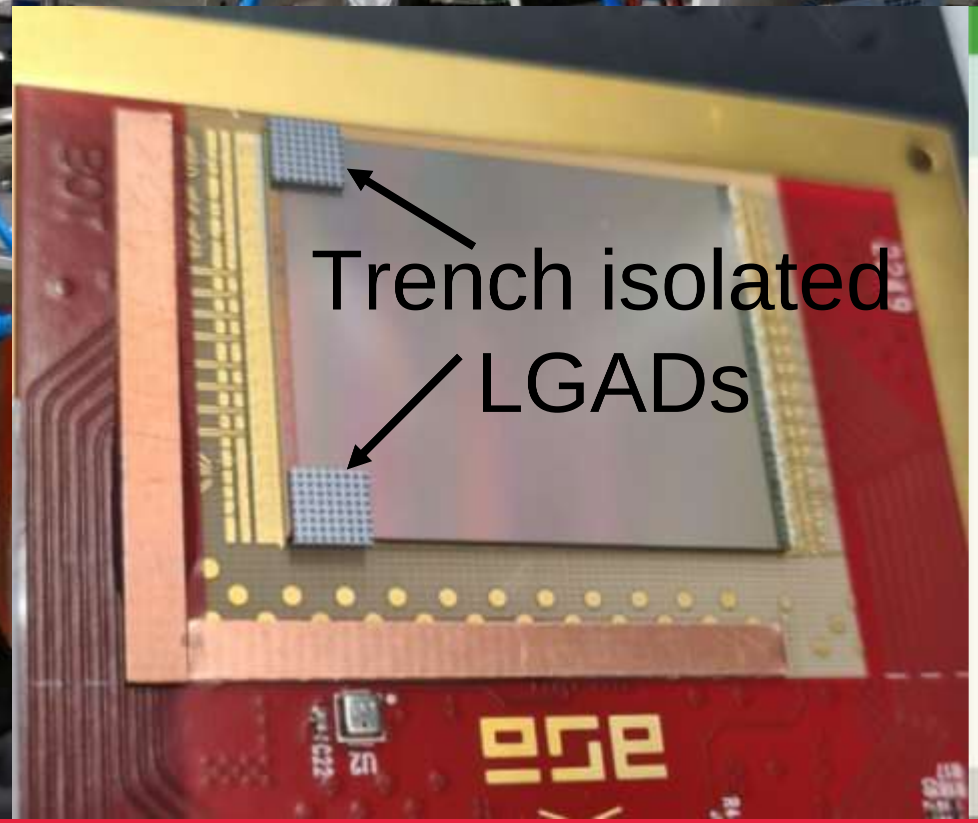
Future research

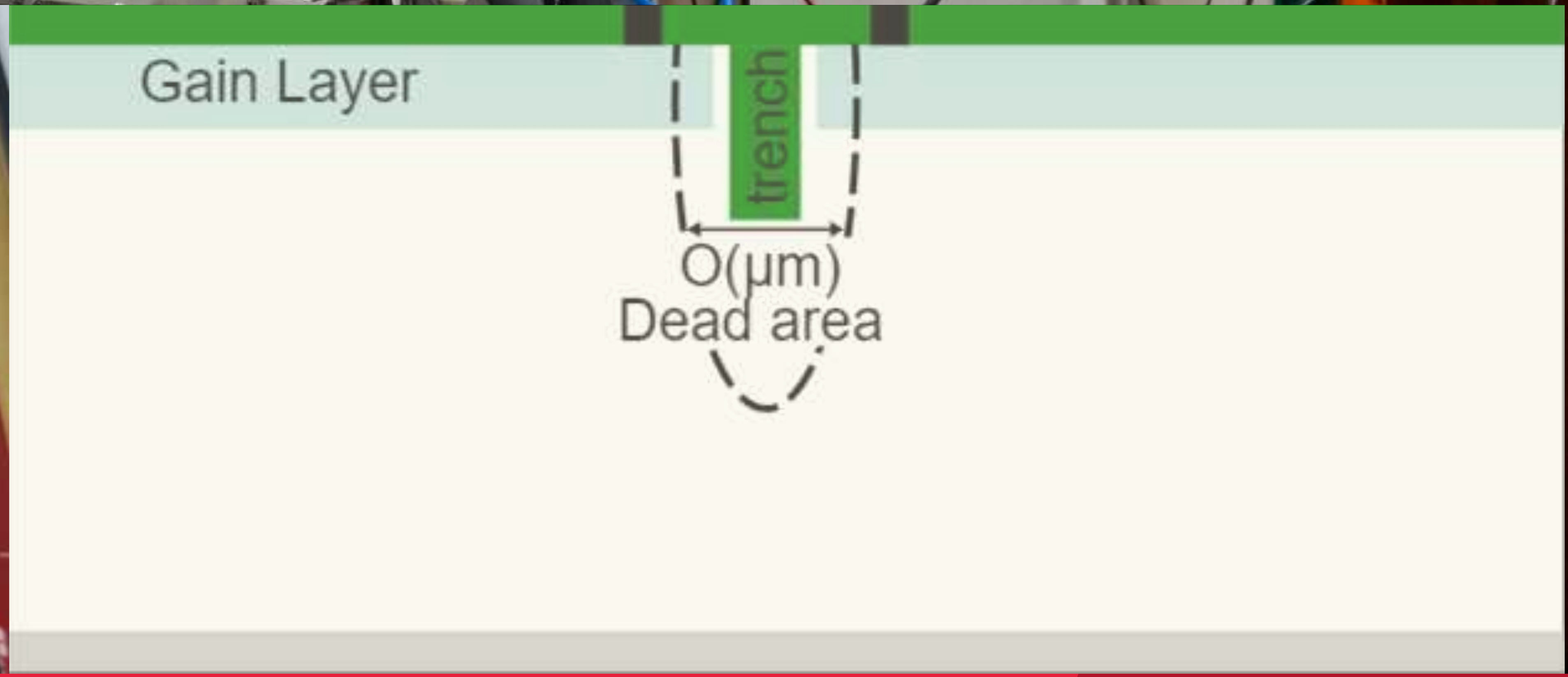
K. Heijhoff *et al* 2021 *JINST* **16** P08009 [DOI: 10.1088/1748-0221/16/08/P08009]

- **New sensors:**
- Focus will move from telescope to DUTs
- Probe larger parameter space of iLGADs (threshold, angle, voltage)

- New devices:
- Trench isolated LGAD (RD50 batch with 55x55 matrices, from FBK)
- 3D (two types, very old sensors from CNM + RD50 3D-DS timing from CNM)
- 300 um PiN devices (baseline for AIDAinnova timing layers, from CNM)
- AIDAinnova WP6 prototypes when available (TI-LGAD, iLGAD, 3D pillar & trench)







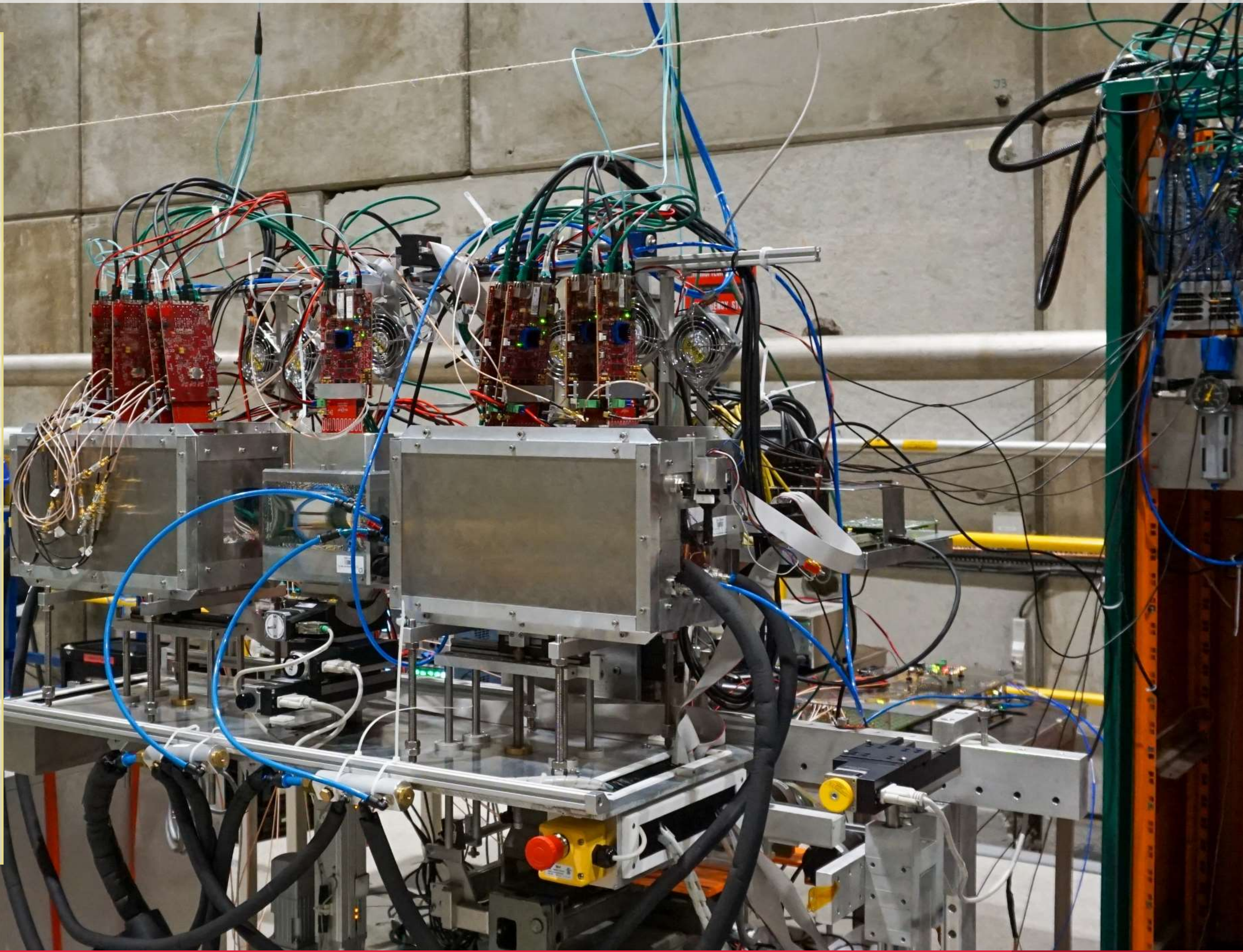
Conclusion

- Stable operation of complete telescope

- Continue to improve time/spatial resolution via additional corrections

- Current specifications:
- Spatial resolution: **2.7 µm**
- Cluster time resolution: **185-168 ps**
- Track time resolution (timepix4 only): **90 ps**
- MCP resolution: **12 ps**

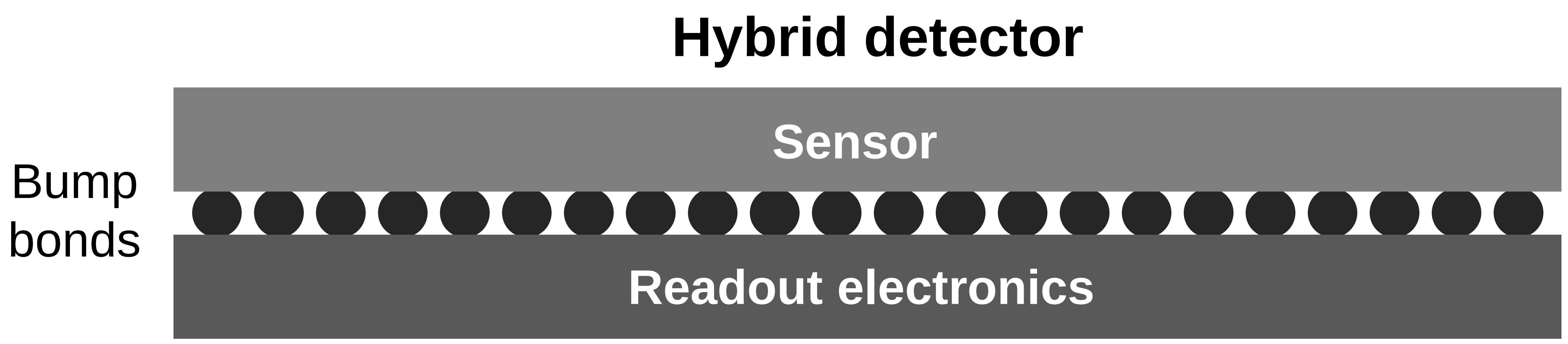
- Ready to move on to faster sensor technologies

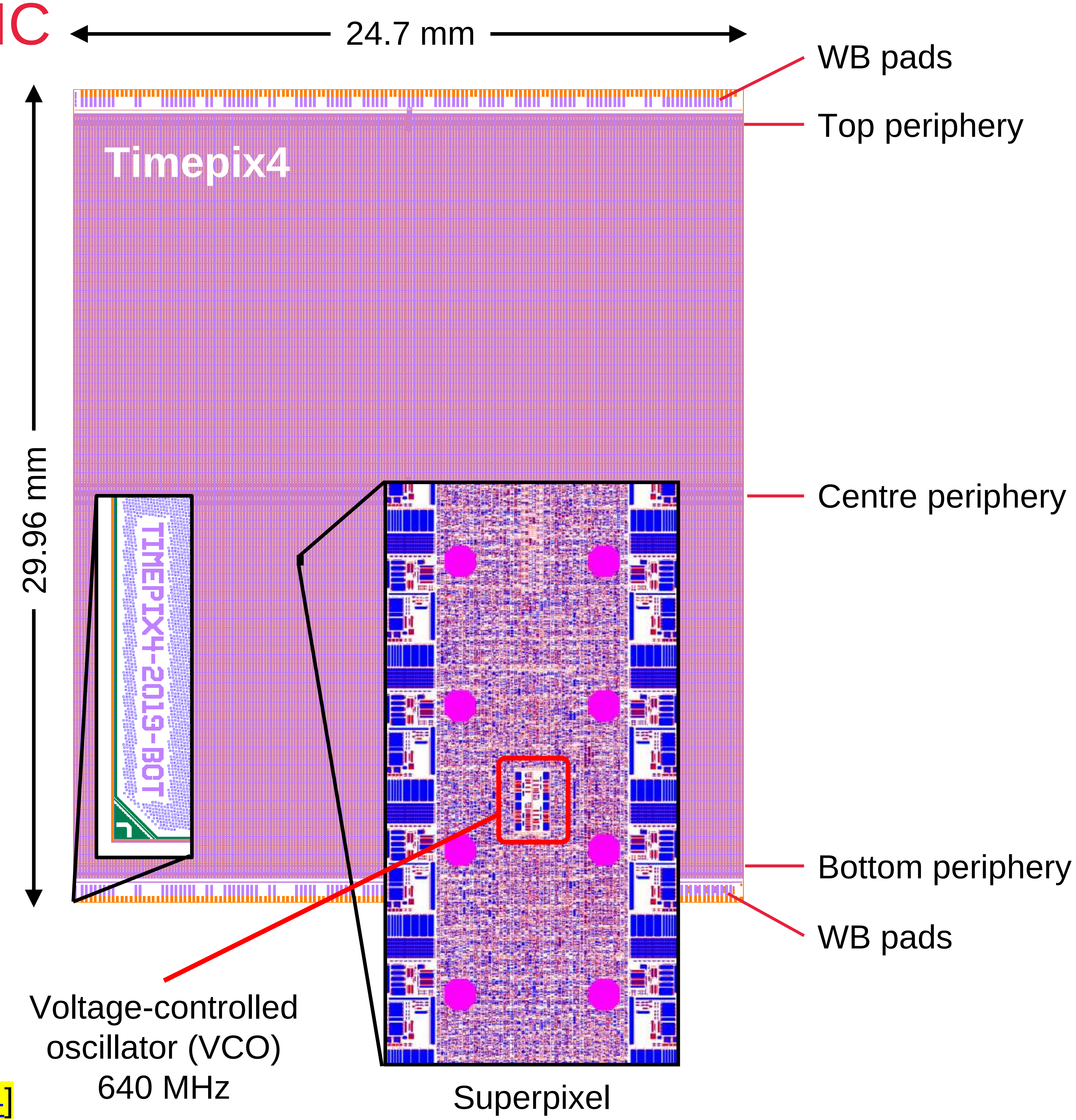


BACK-UP SLIDES

Timepix4: Hybrid pixel detector readout ASIC

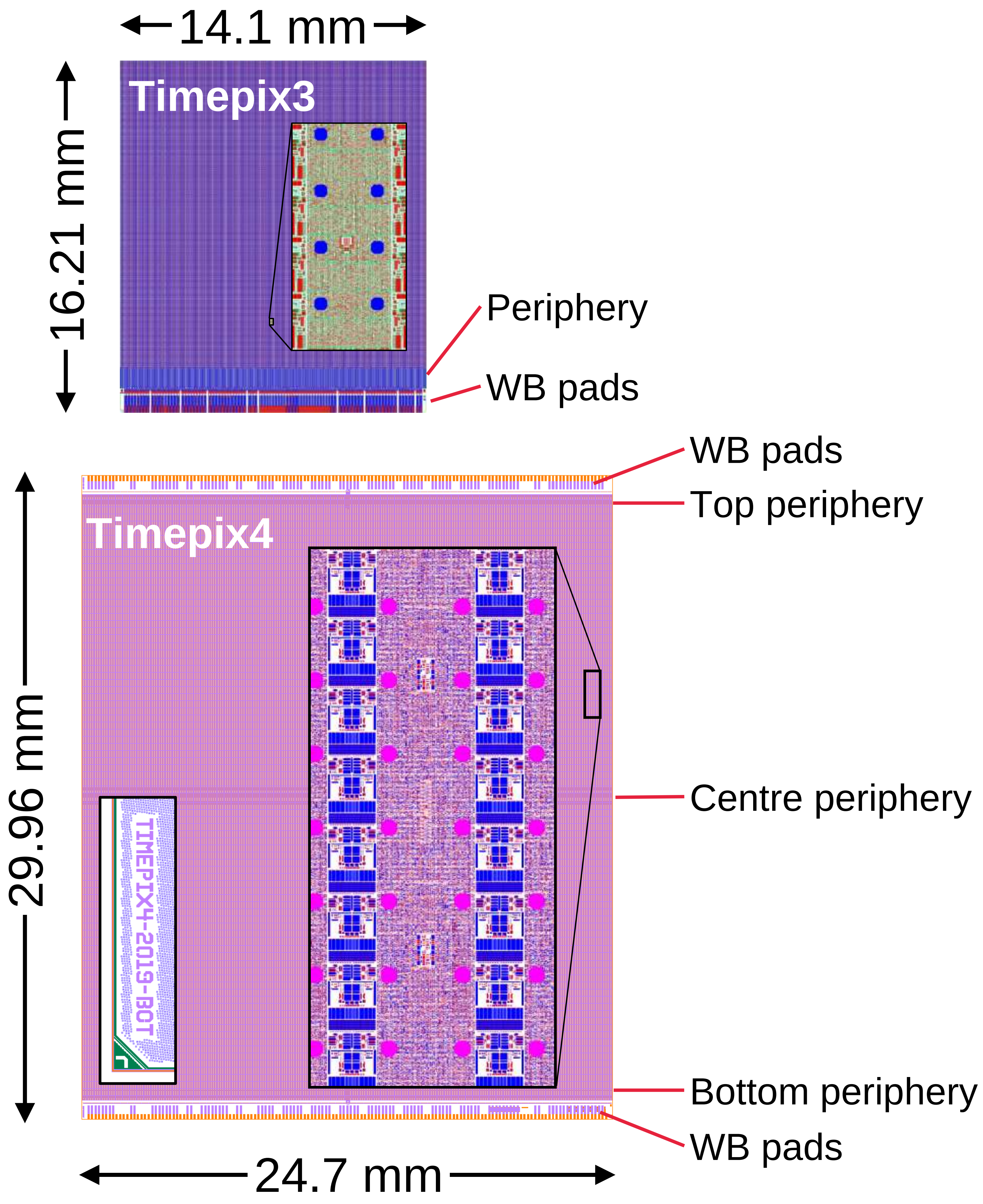
- Developed by CERN, Nikhef, and IFAE
- 65 nm CMOS
- 448×512 pixels, 55×55 μm^2 pitch
- Simultaneous measurement of time and charge deposition (by measuring time over threshold)
- Time-bin size of 25 ns/128 = **195 ps** (Timepix3: 1.56 ns)
- Max rate: 360×10^6 hits/cm^2/s (160 Gb/s for single chip)





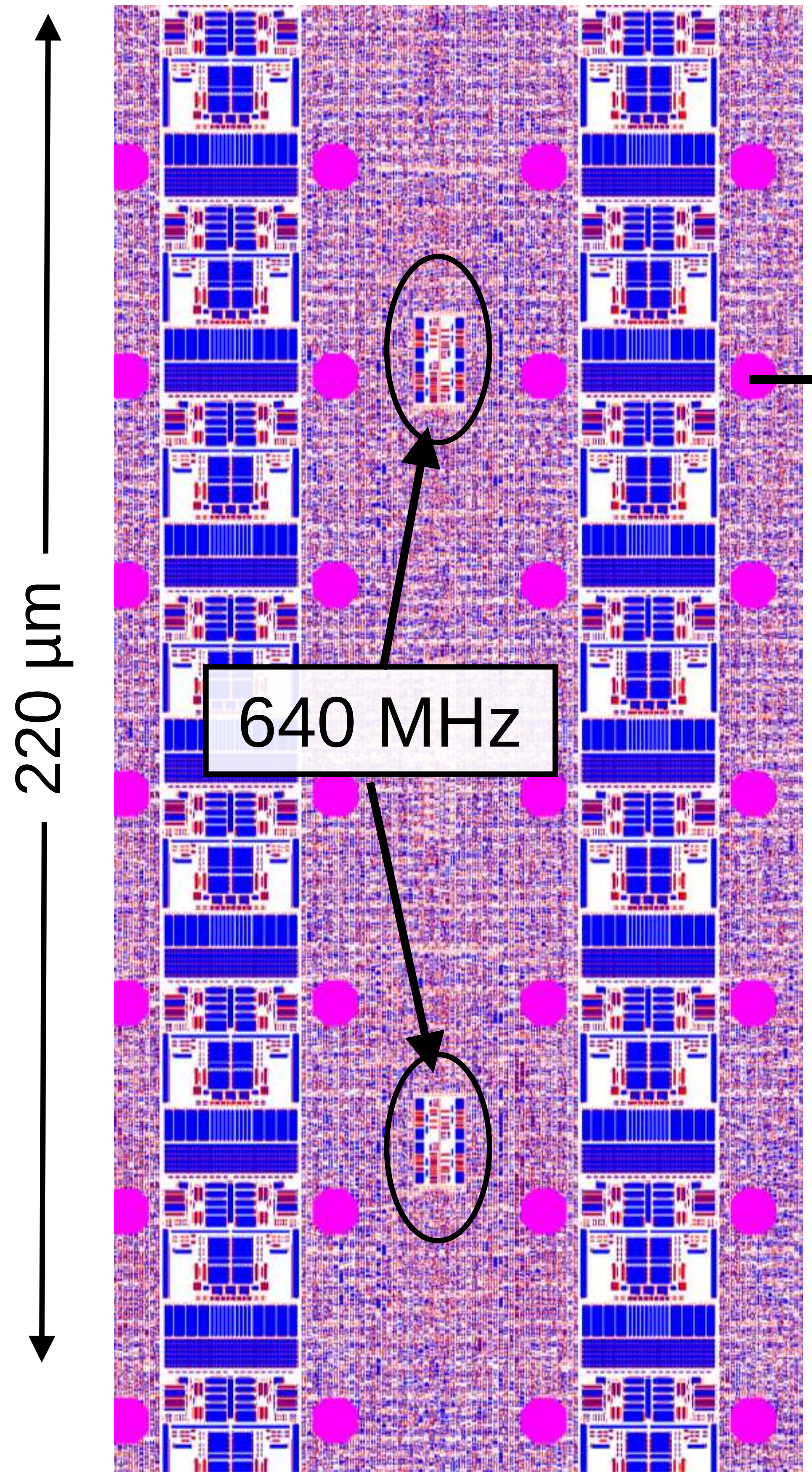
X. Llopart *et al* 2022 *JINST* **17** C01044 [DOI: 10.1088/1748-0221/17/01/C01044]

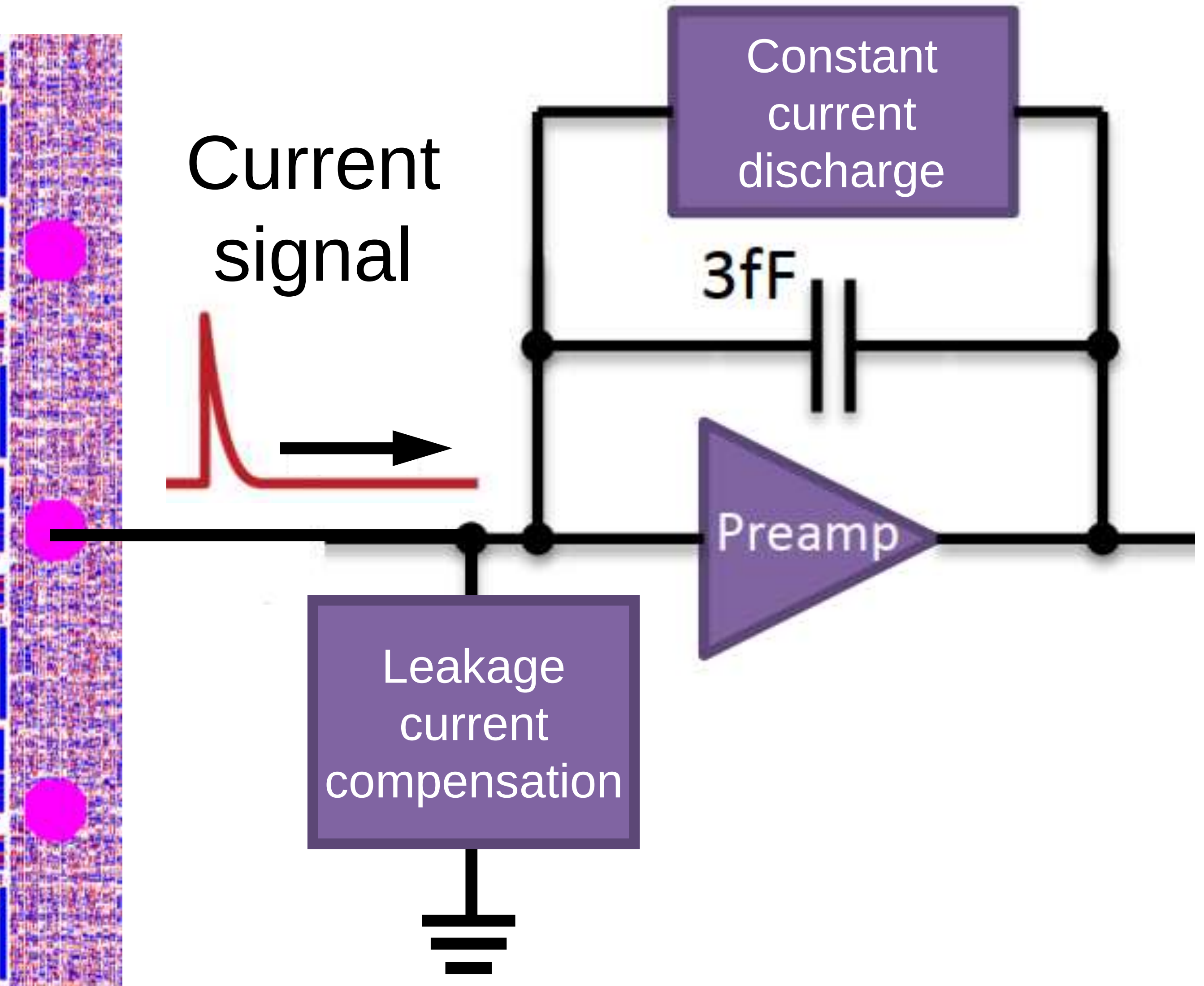
Timepix3 → Timepix4



			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	**3.5x**
Sensitive area			1.98 cm^2	**6.94 cm^2**	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	
		Max rate	0.43×10^6 hits/mm^2/s	**3.58×10^6 hits/mm^2/s**	**8x**
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	
		Max count rate	~0.82×10^9 hits/mm^2/s	~5×10^9 hits/mm^2/s	
TOT energy resolution			< 2KeV	< **1Kev**	
TOA binning resolution			1.56ns	**195ps**	**8x**
TOA dynamic range			409.6 µs (14-bits @ 40MHz)	**1.6384 ms** (16-bits @ 40MHz)	
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps** **(16x @10.24 Gbps)**	**32x**
Target minimum threshold			<500 e^-	<500 e^-	

Time measurement in Timepix4

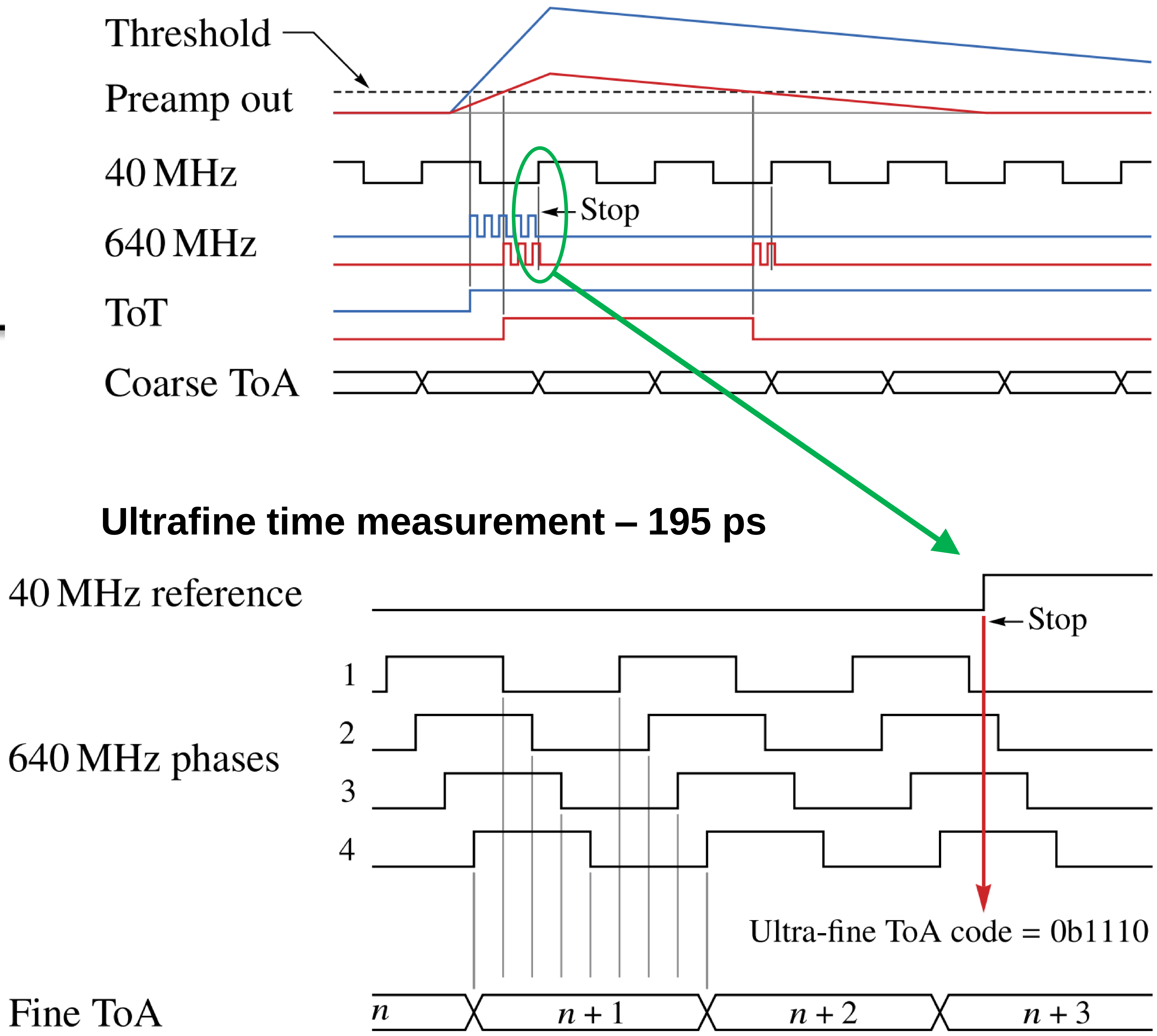




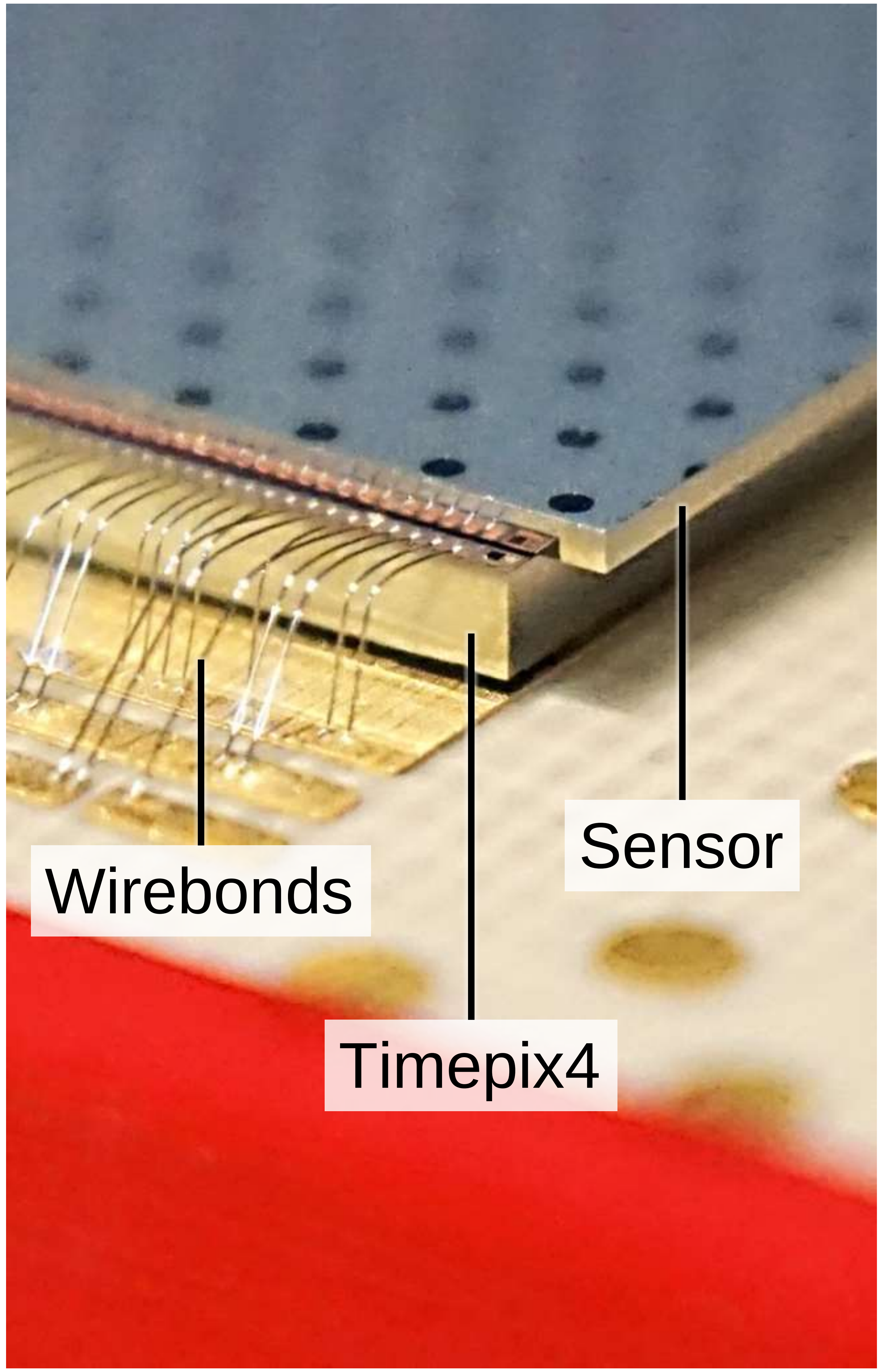
- Nominal TDC resolution: 195 ps/$\sqrt{12}$ = 56 ps
- Time over threshold (ToT) measures signal charge

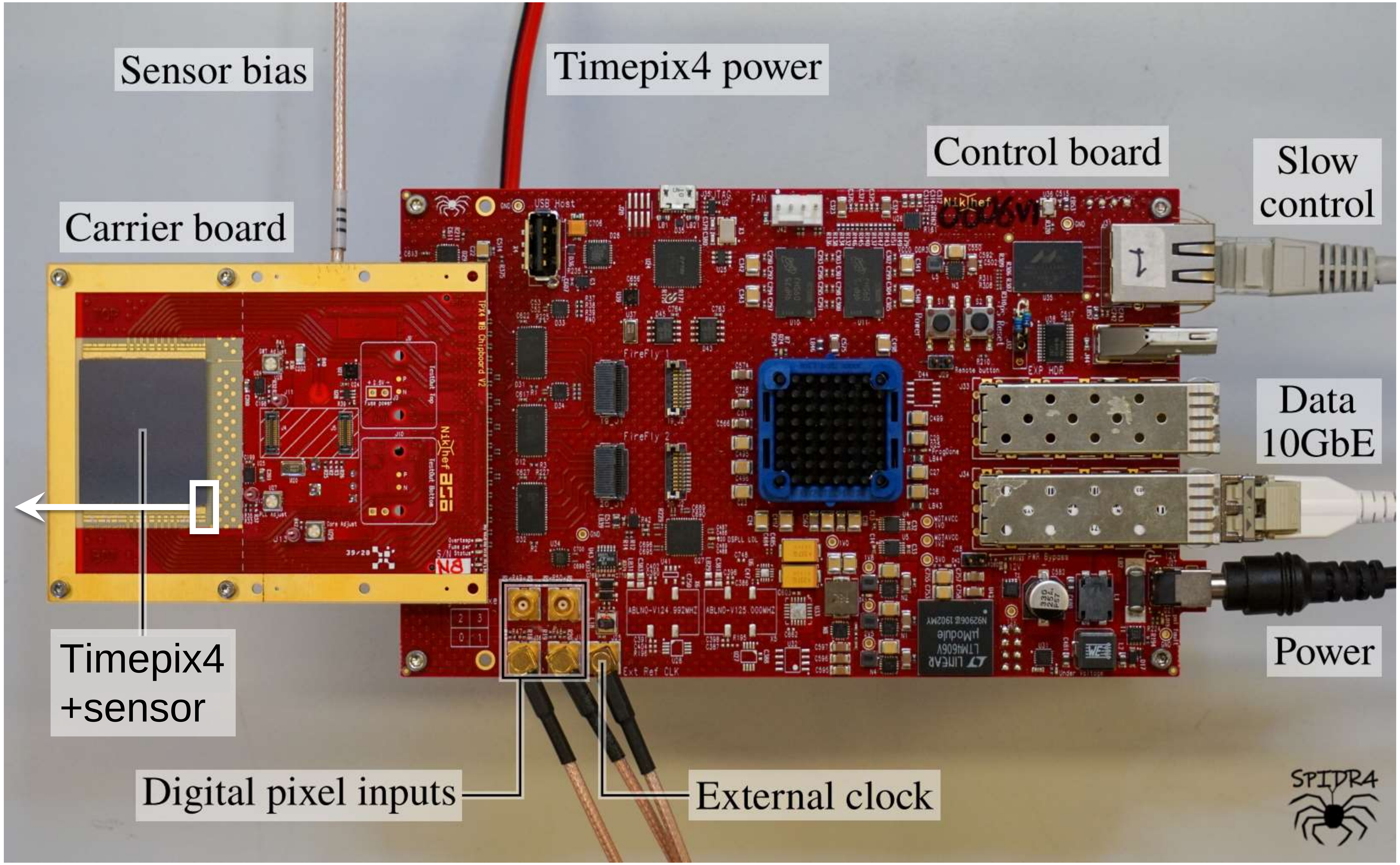
Coarse and fine time measurement – 40 MHz and 640 MHz

Ultrafine time measurement – 195 ps



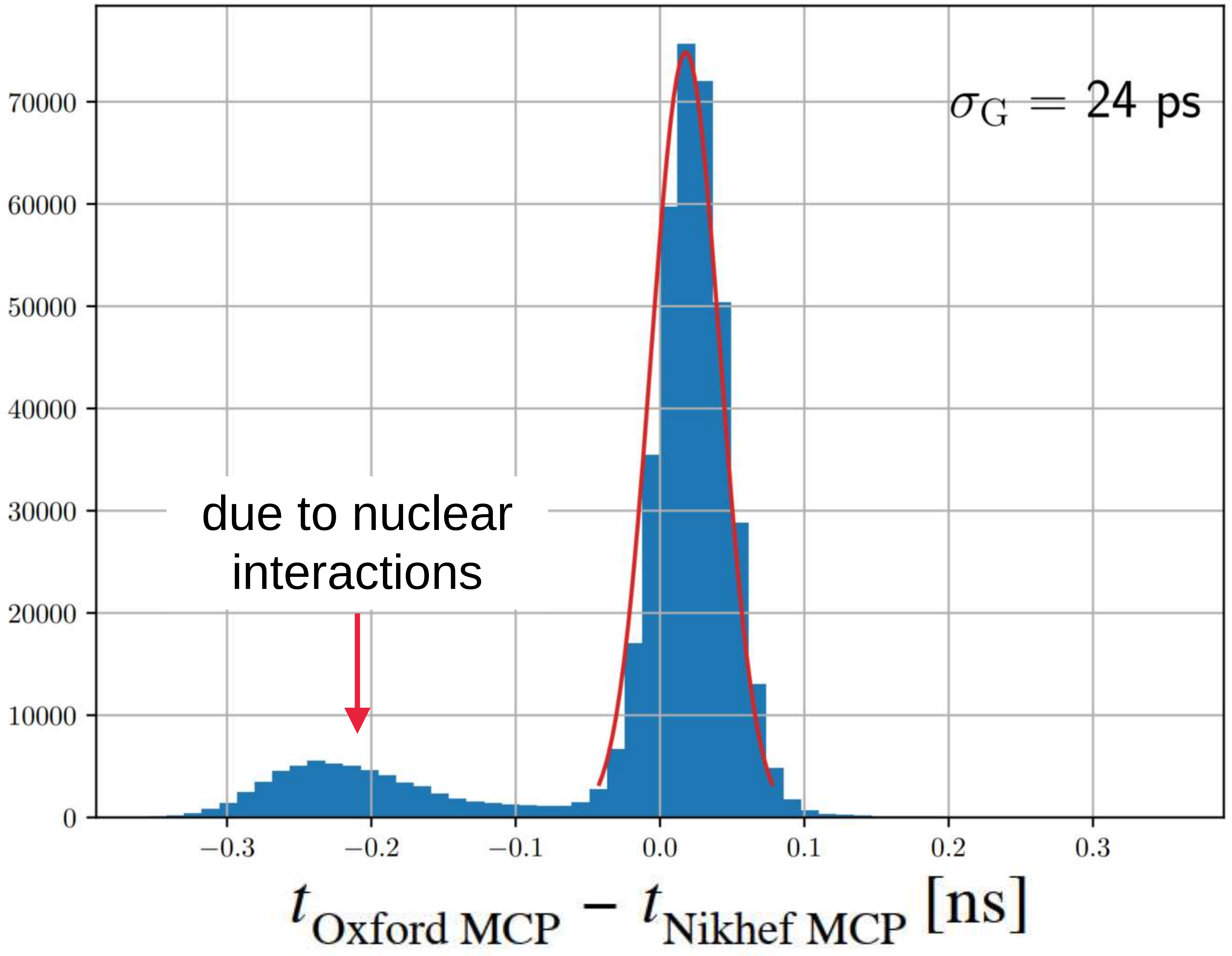
Speedy PIxel Detector Readout 4 (SPIDR4)

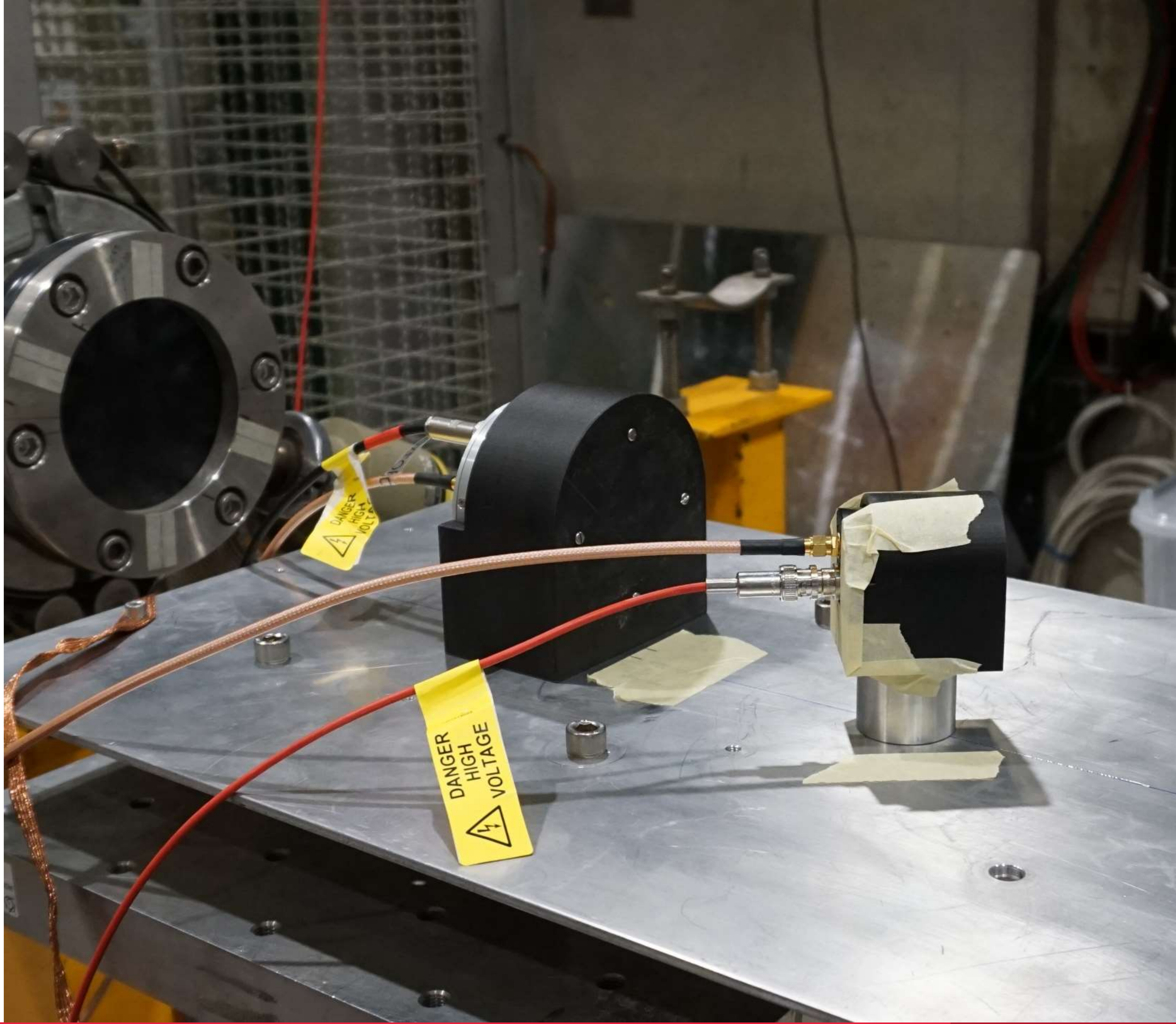




Micro channel plate detectors

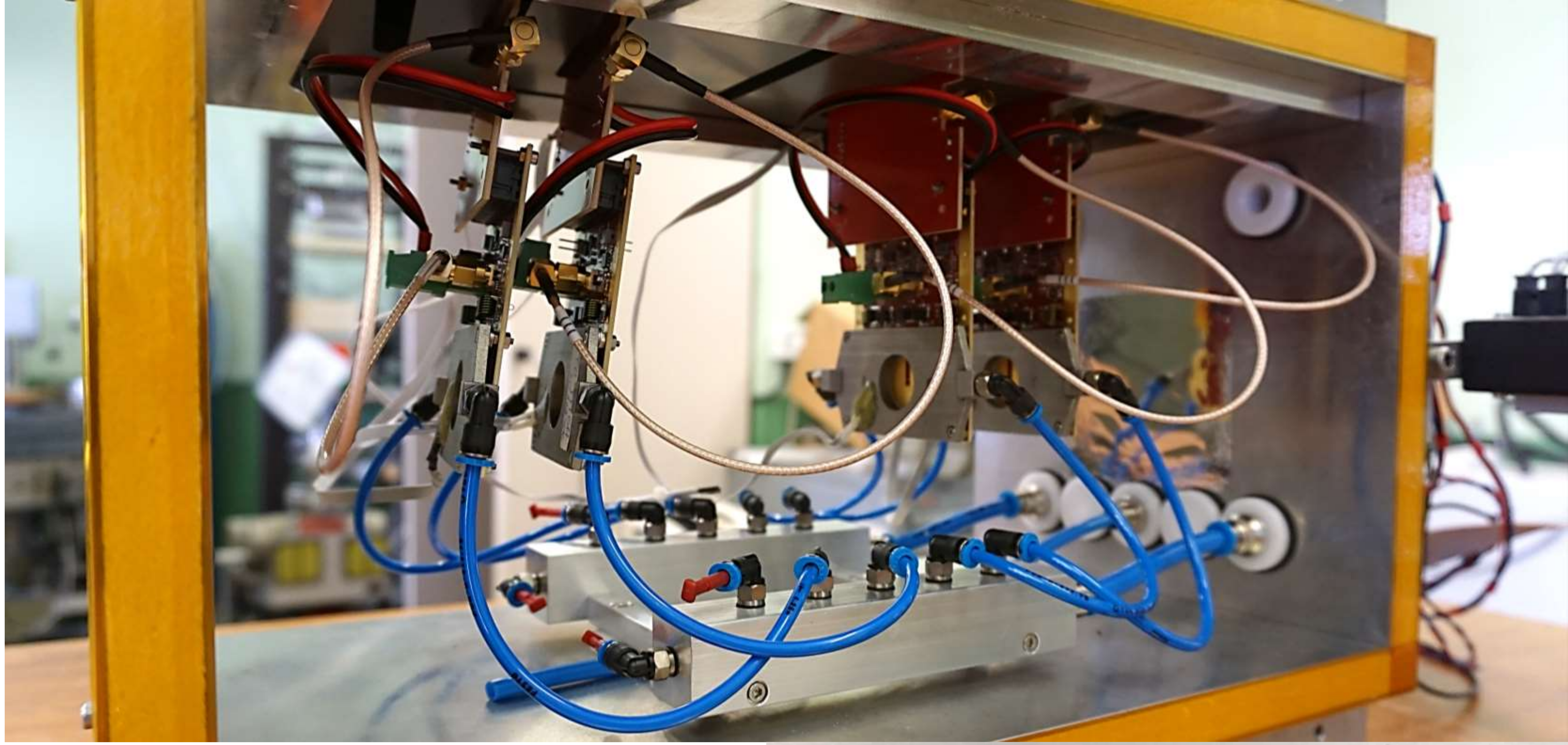
- Time reference to study telescope timing
- Considering installing Timpix4 plane to VETO events with nuclear interactions
- Current time resolution: 17 ps (single MCP)
- Combined MCP resolution: 12 ps



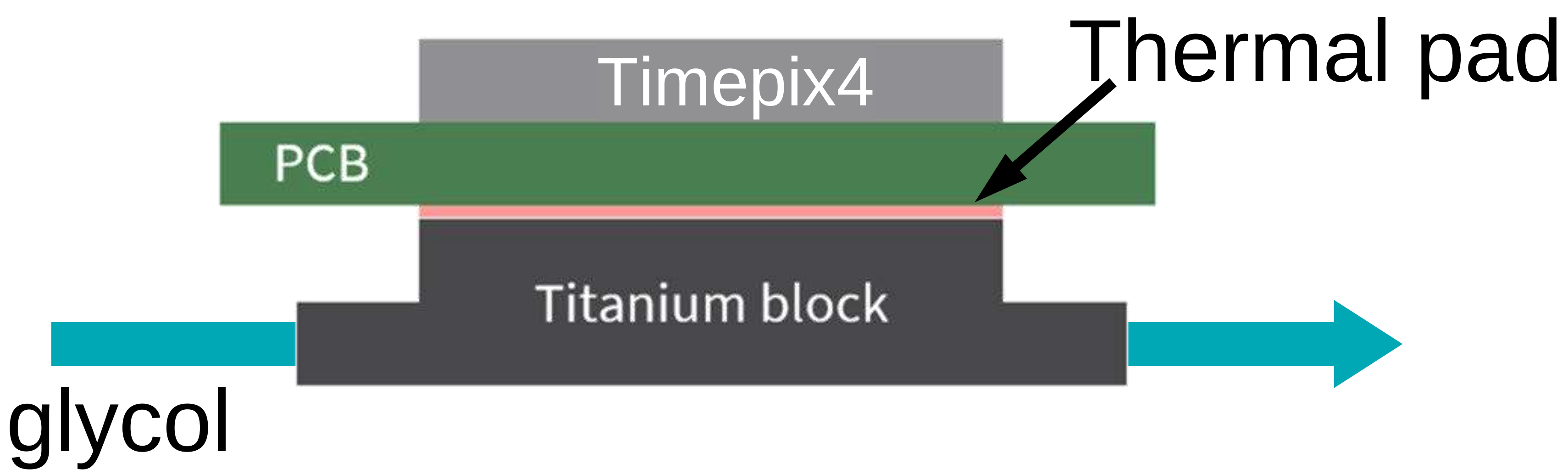


Assembly cooling

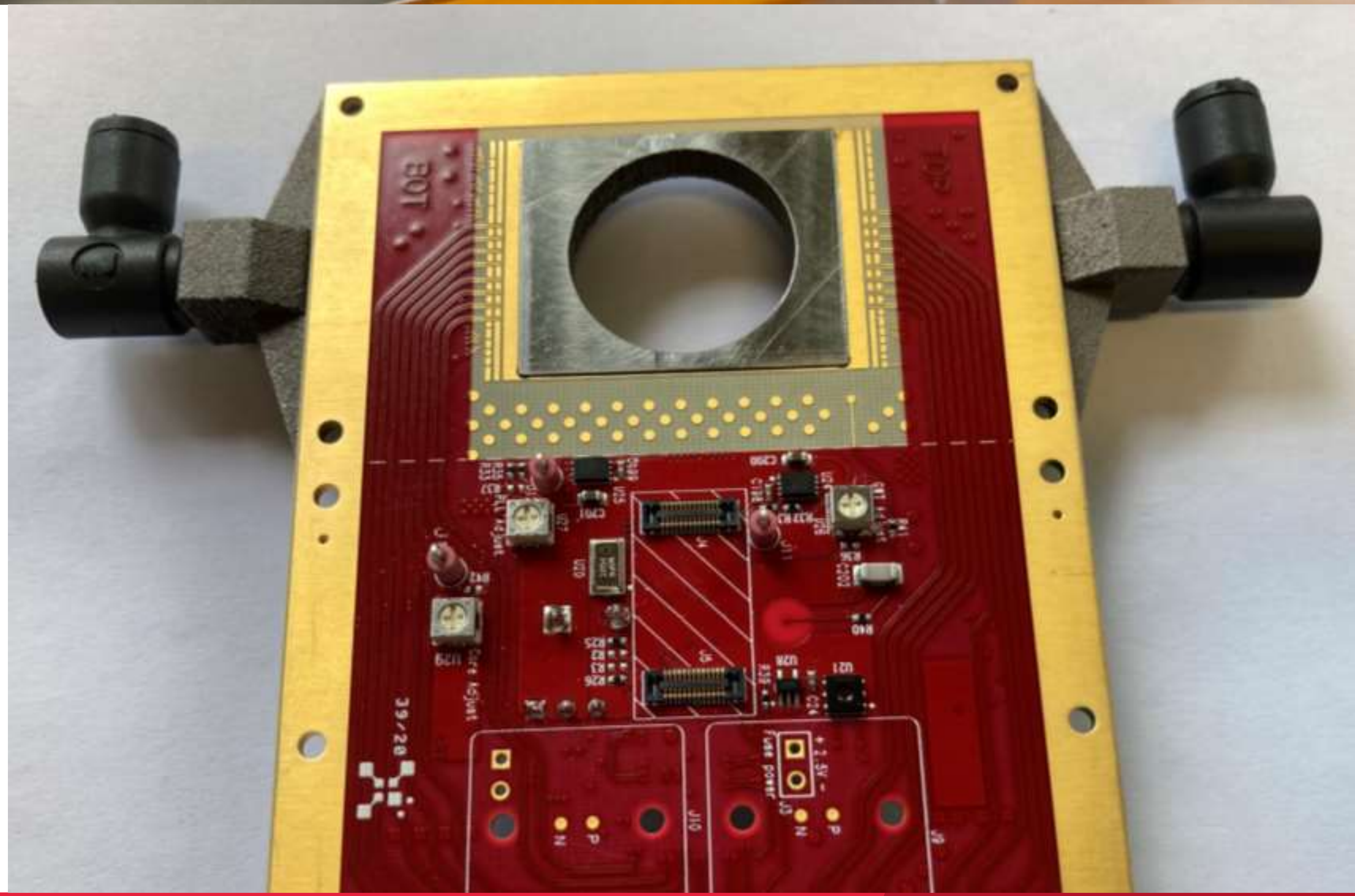
- All assemblies have a 3D-printed titanium cooling block
- Cooled using glycol at 20 °C
- Could go to –20 °C in the future
- Plan to mill PCB to have direct thermal contact with Timepix4



Current thermal interface



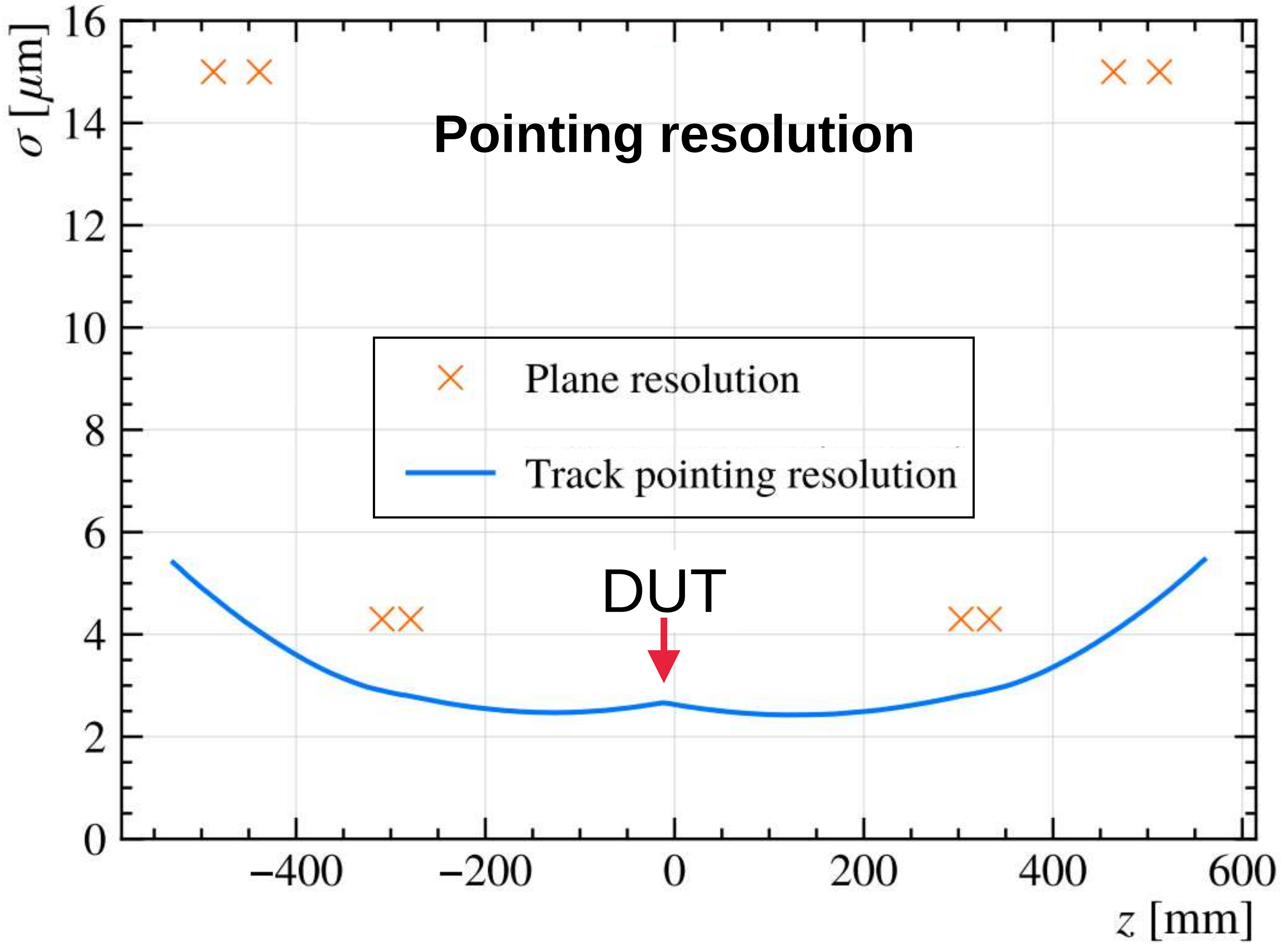
Future thermal interface

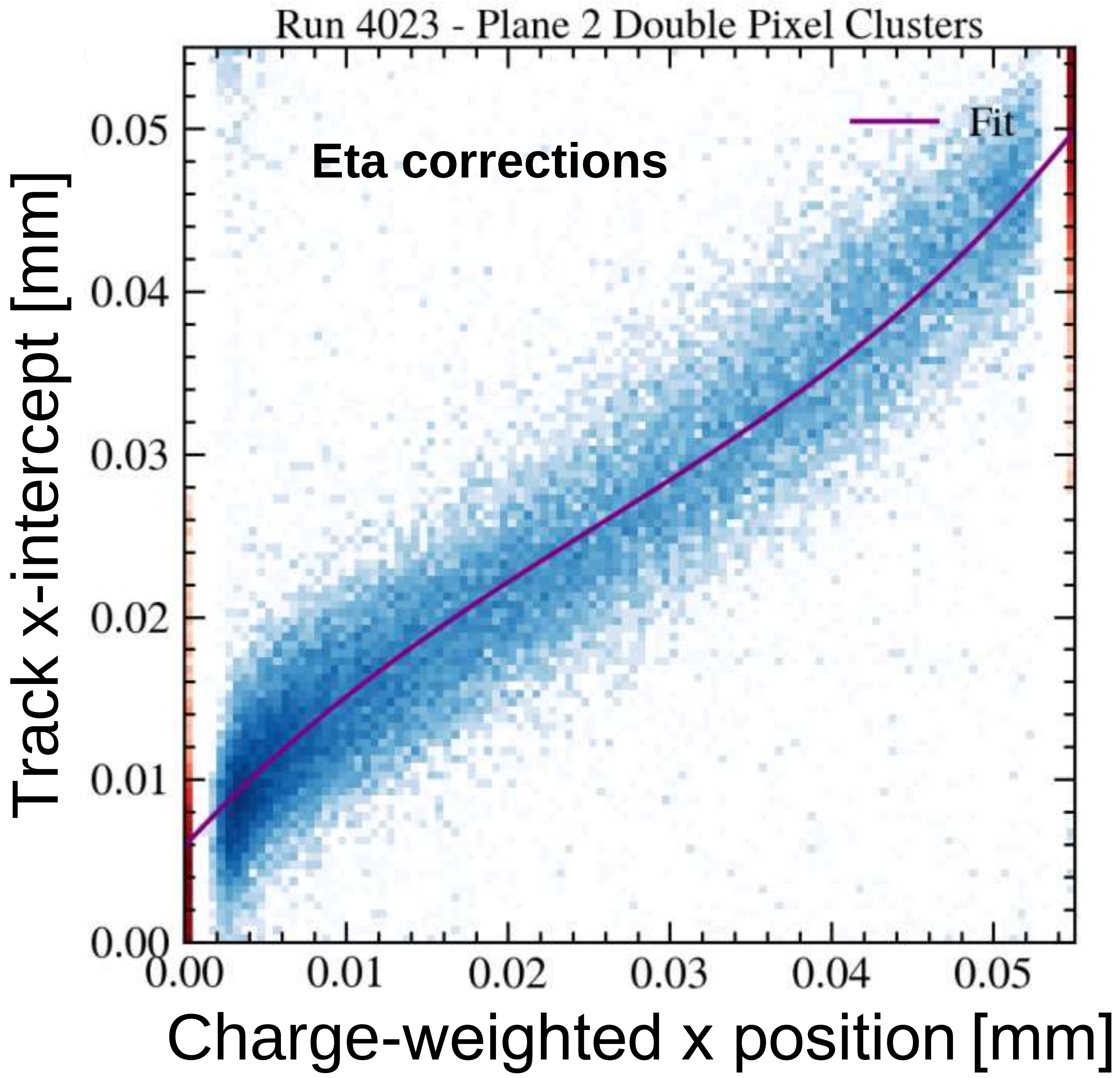


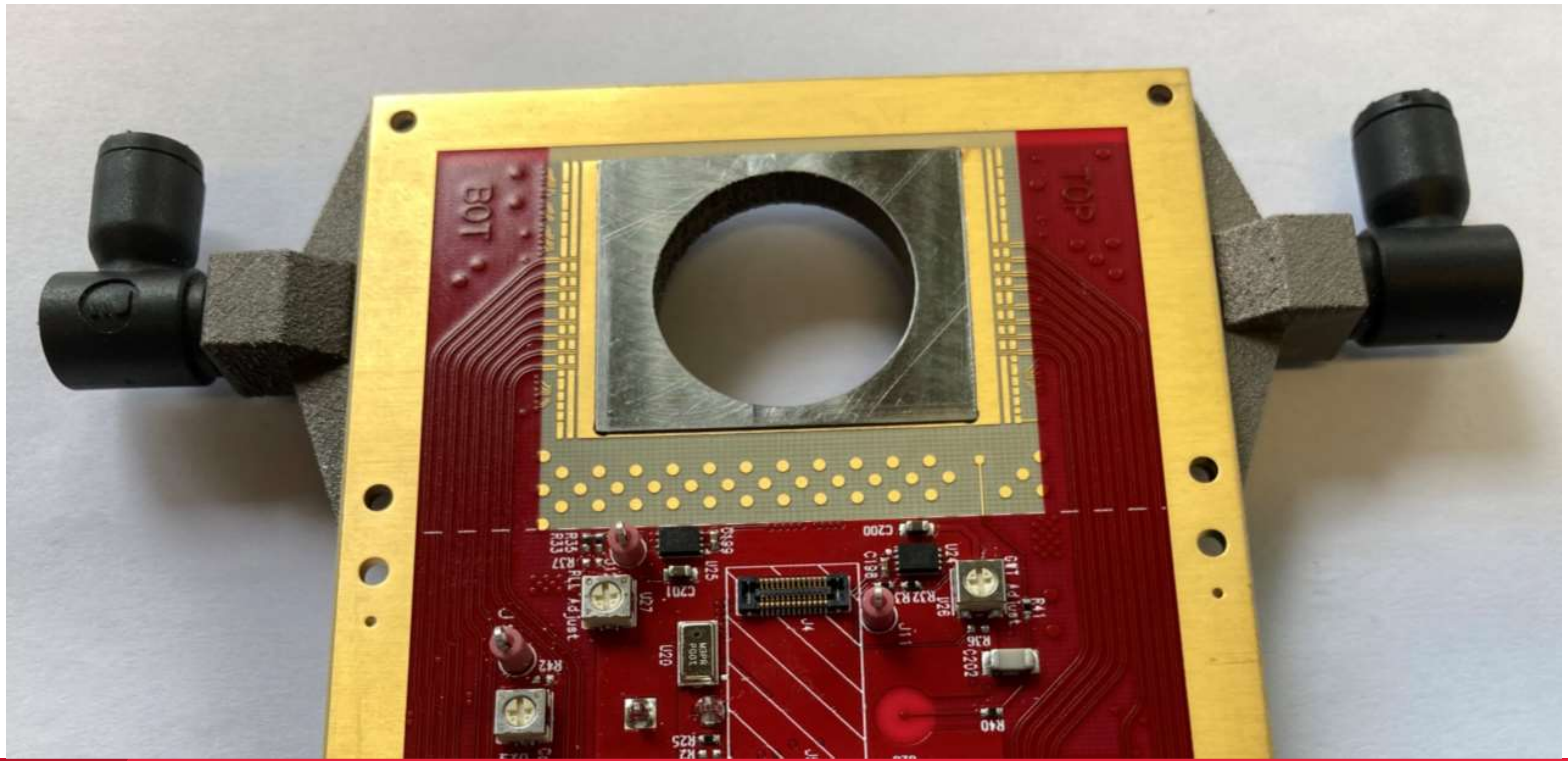
Track pointing resolution

- Pointing resolution at DUT: **2.7 µm** (Mixed hadron beam 180 GeV/*c*)
- PCB adds 1.8 %X_0 (ASIC + sensor adds 0.8–1.0 %X_0)
- Milling out PCB would improve resolution to **2.2 µm**
- Investigating "eta corrections" for nonlinear charge sharing
- Other possible improvements:
  - Move telescope arms further inward when possible
  - Operate 300 µm planes at lower detection threshold
  - Add additional planes

Scattering proportional to $\sqrt{x/X_0}\,[1 + 0.038 \log x/X_0]$



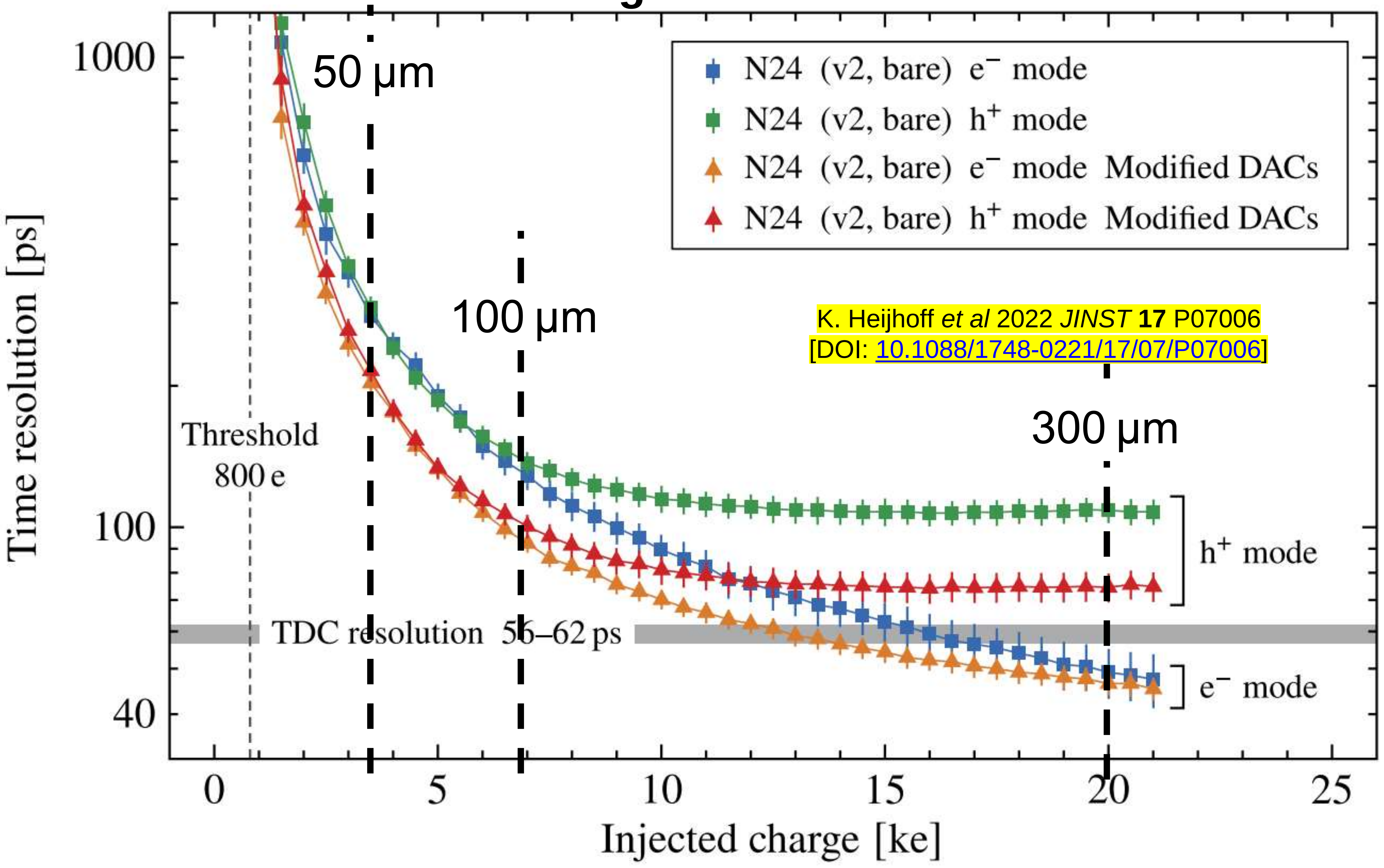




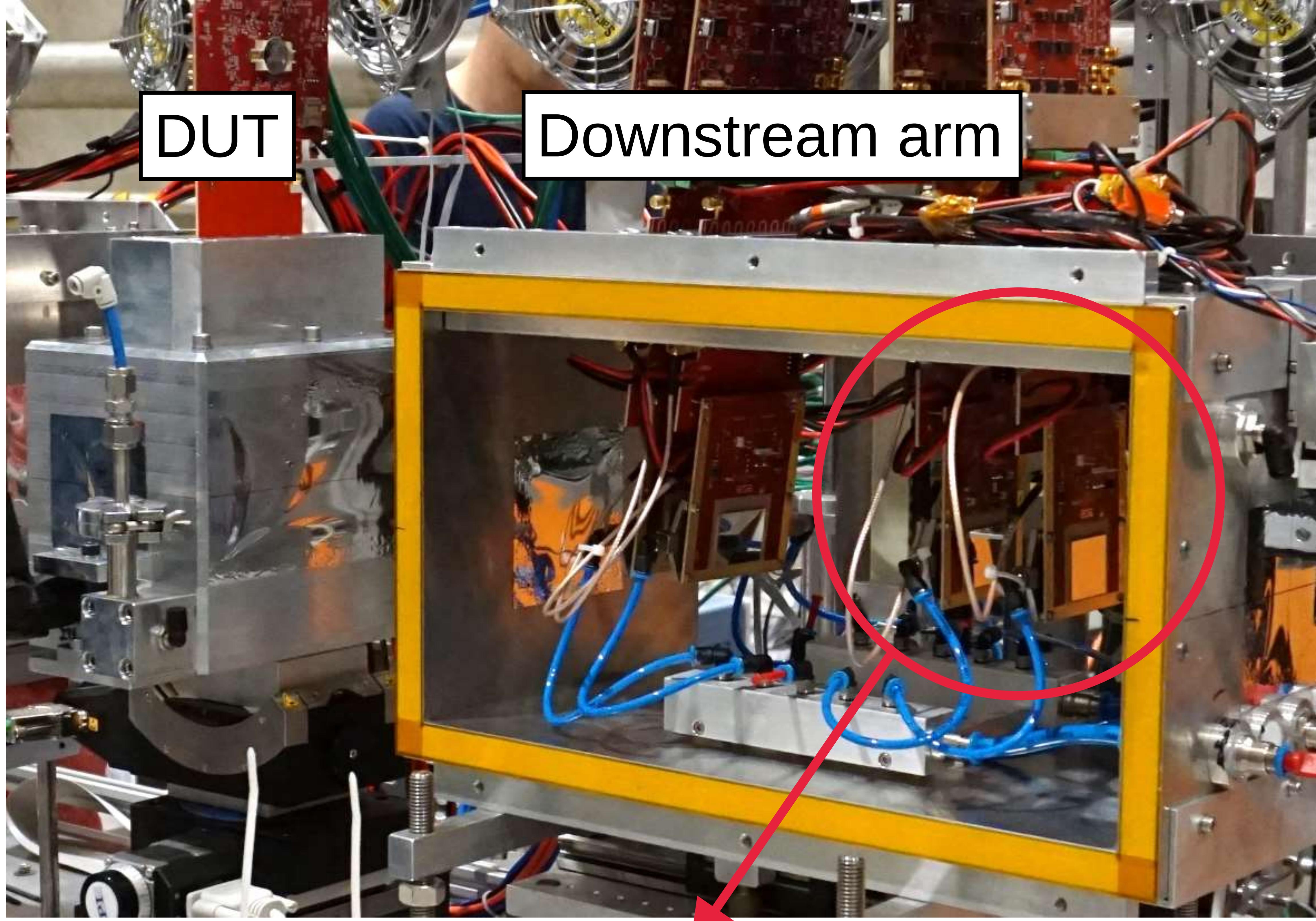
Time resolution

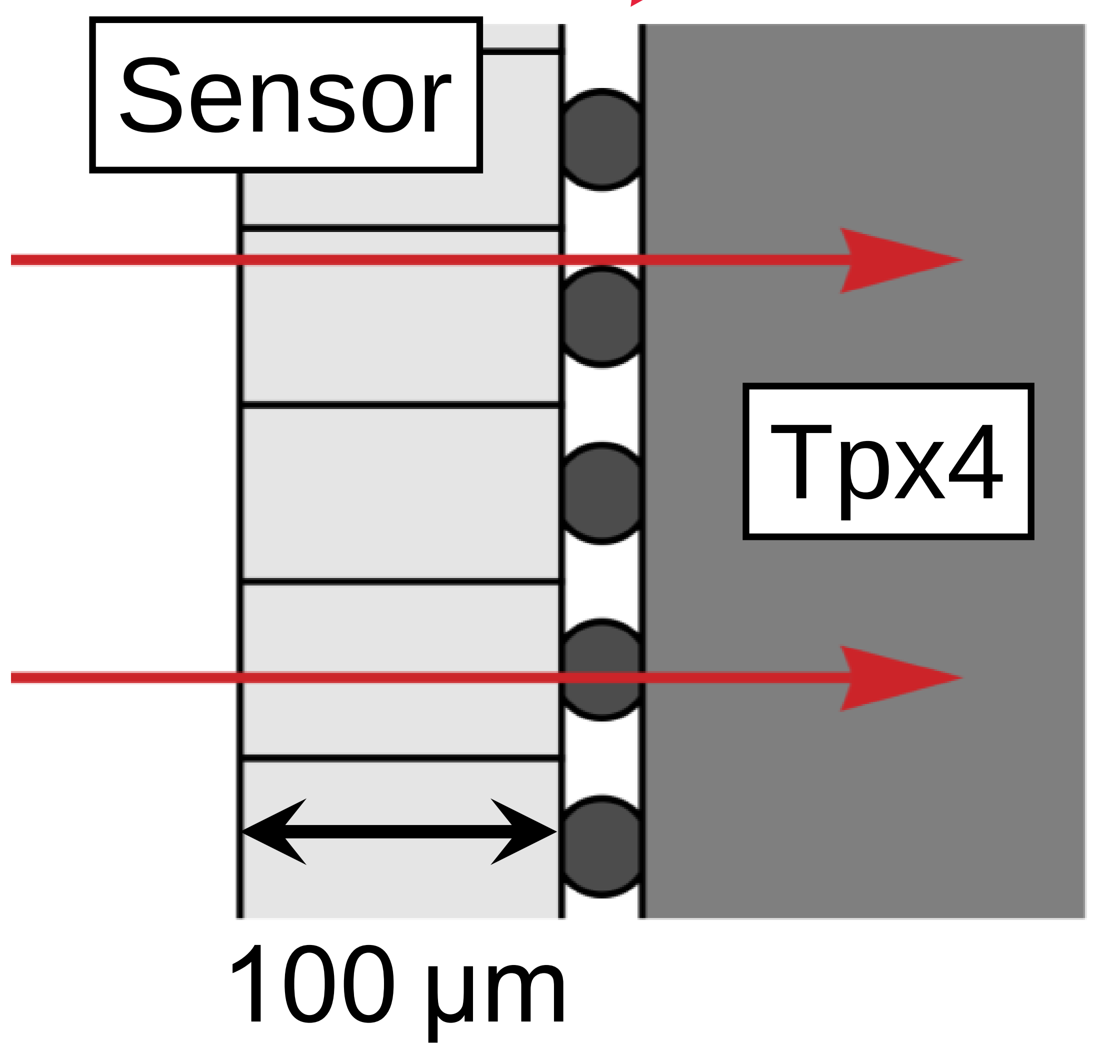
- Thin sensors reduce time errors due to Landau fluctuations
- Perpendicular to beam to maximise signal charge in single pixel
- Reduced signal size reduces analog front-end performance

Analog front-end resolution



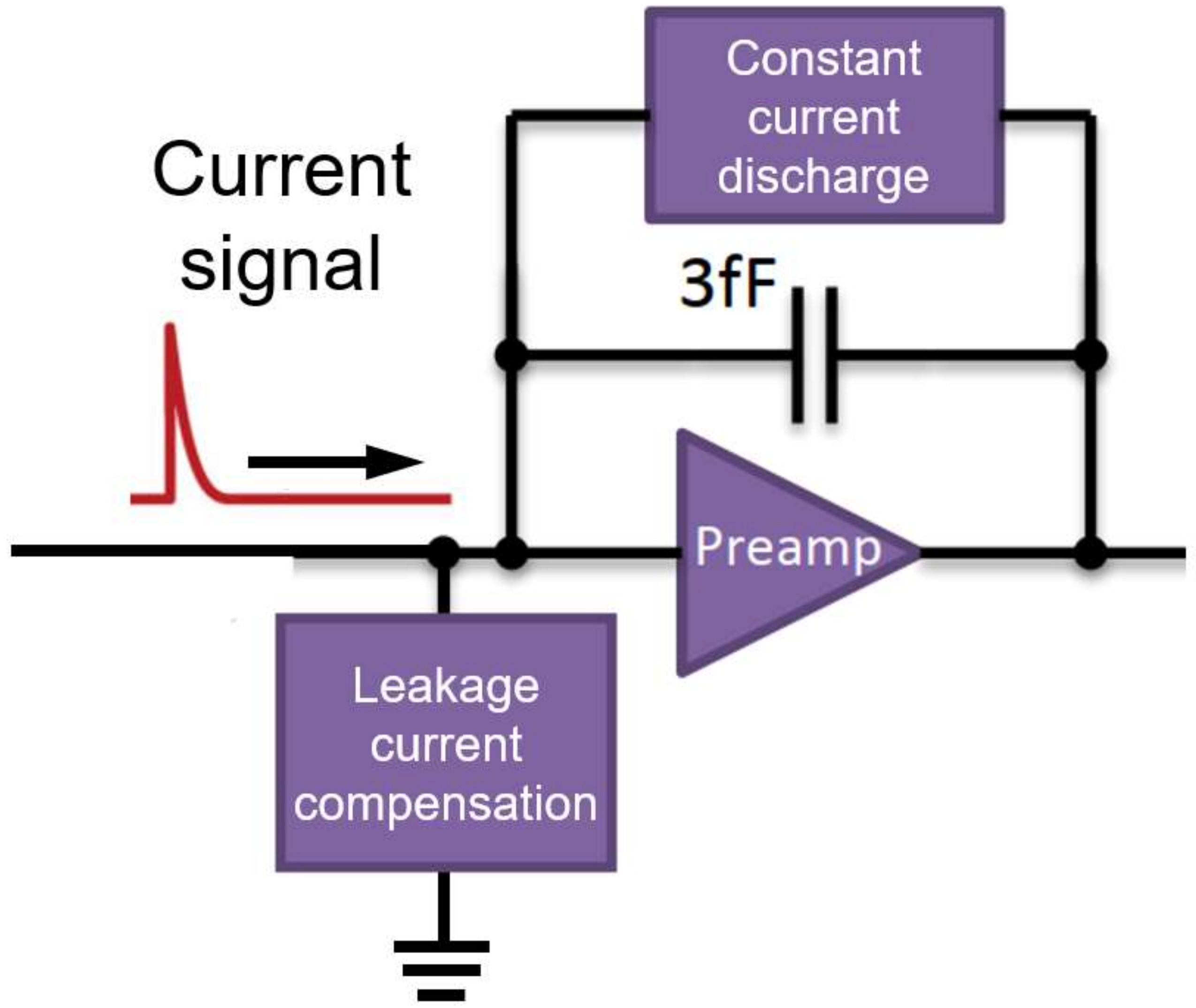
K. Heijhoff *et al* 2022 *JINST* **17** P07006
[DOI: 10.1088/1748-0221/17/07/P07006]

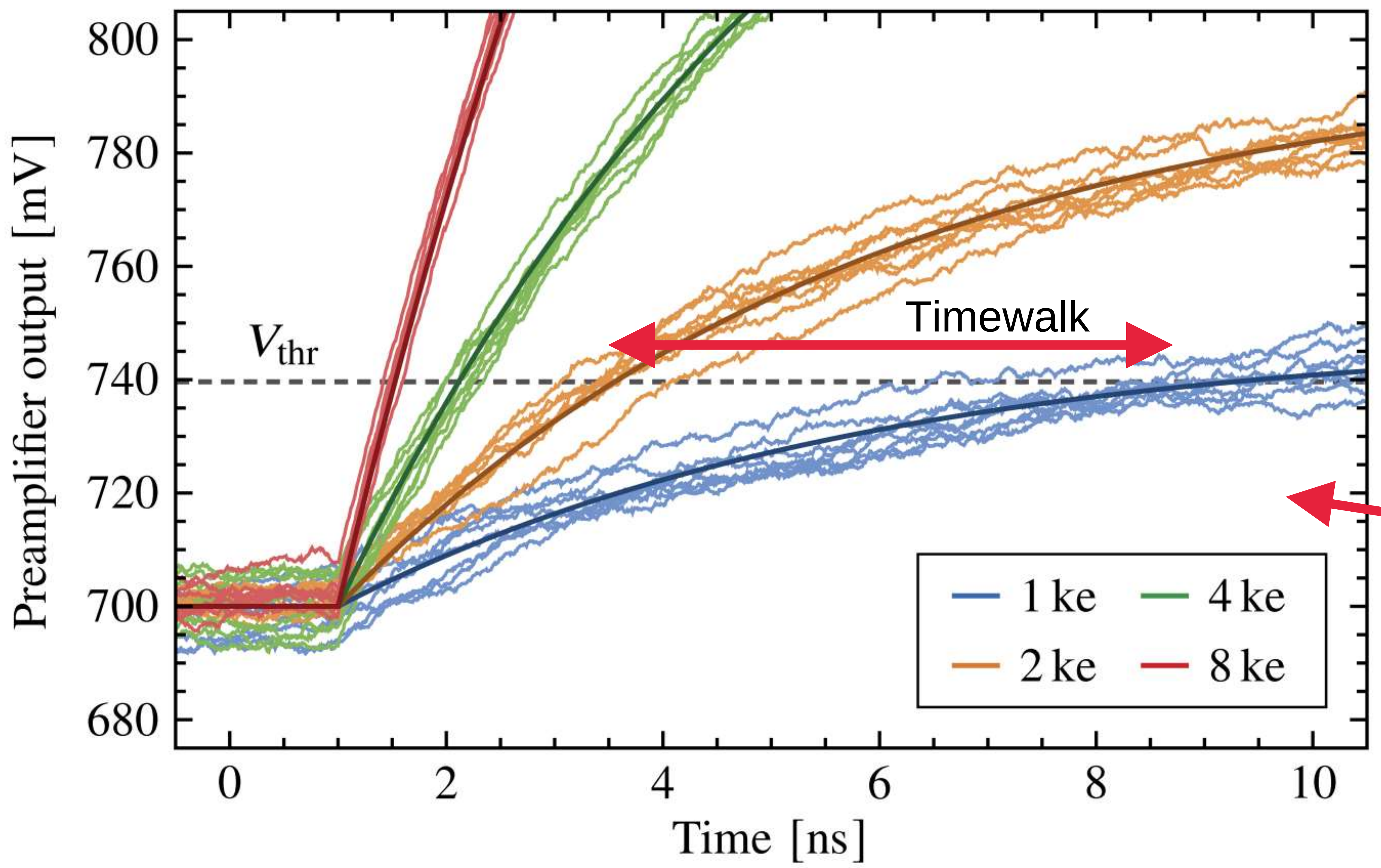


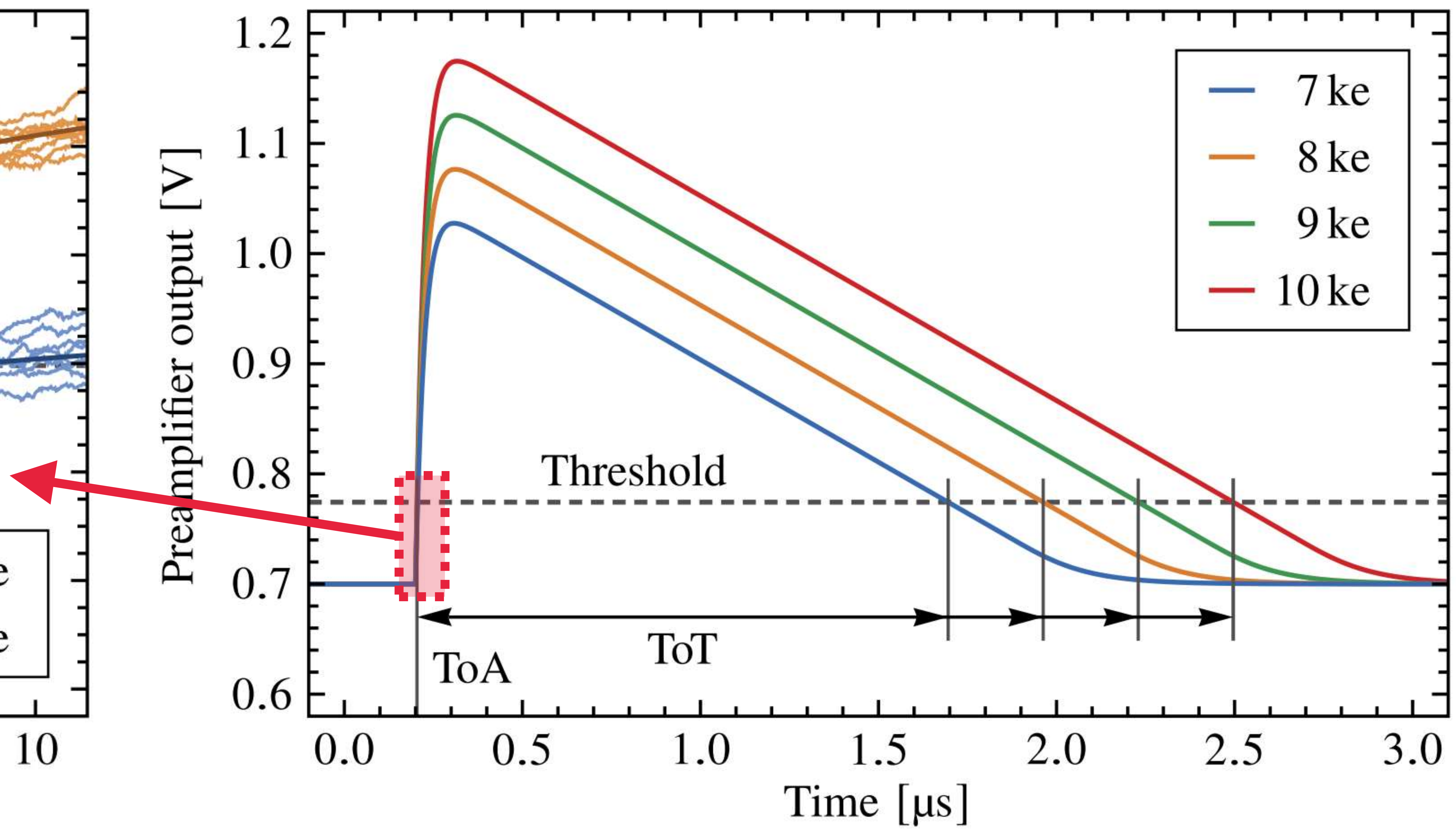


Timewalk

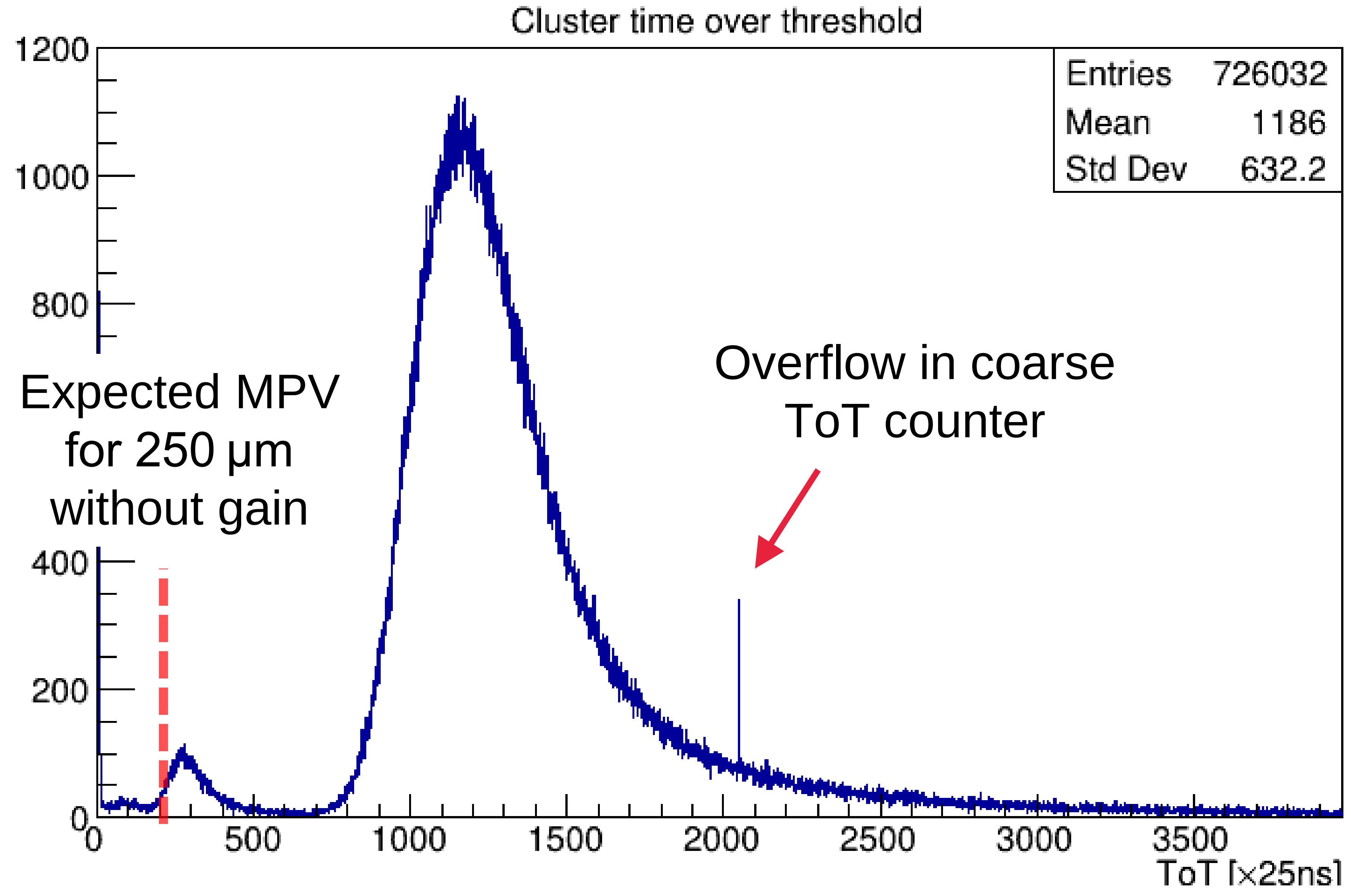
- Time measurement depends on signal size
- Preamplifier output has a fixed risetime
- Reduced signal size makes timewalk corrections crucial

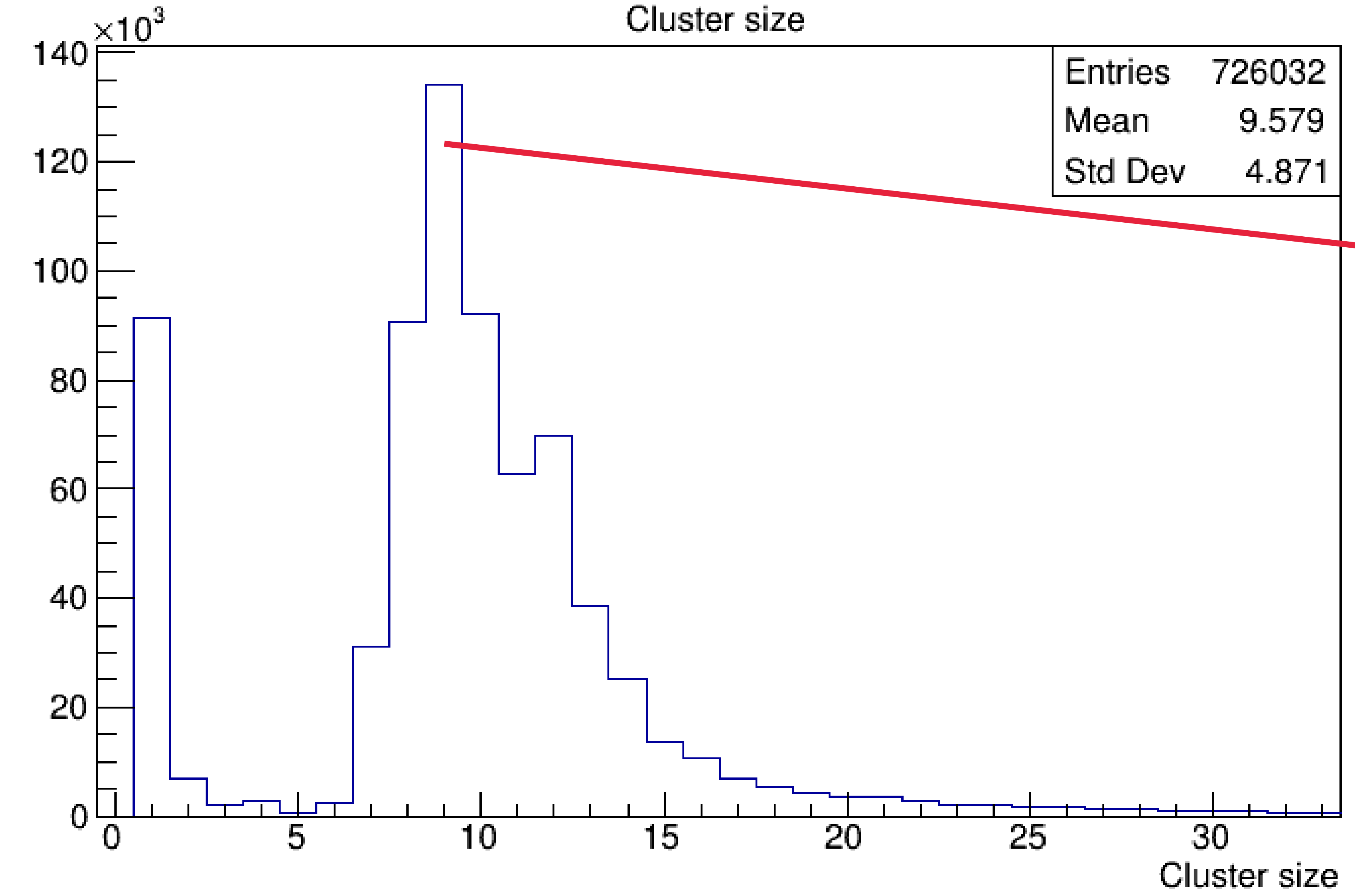




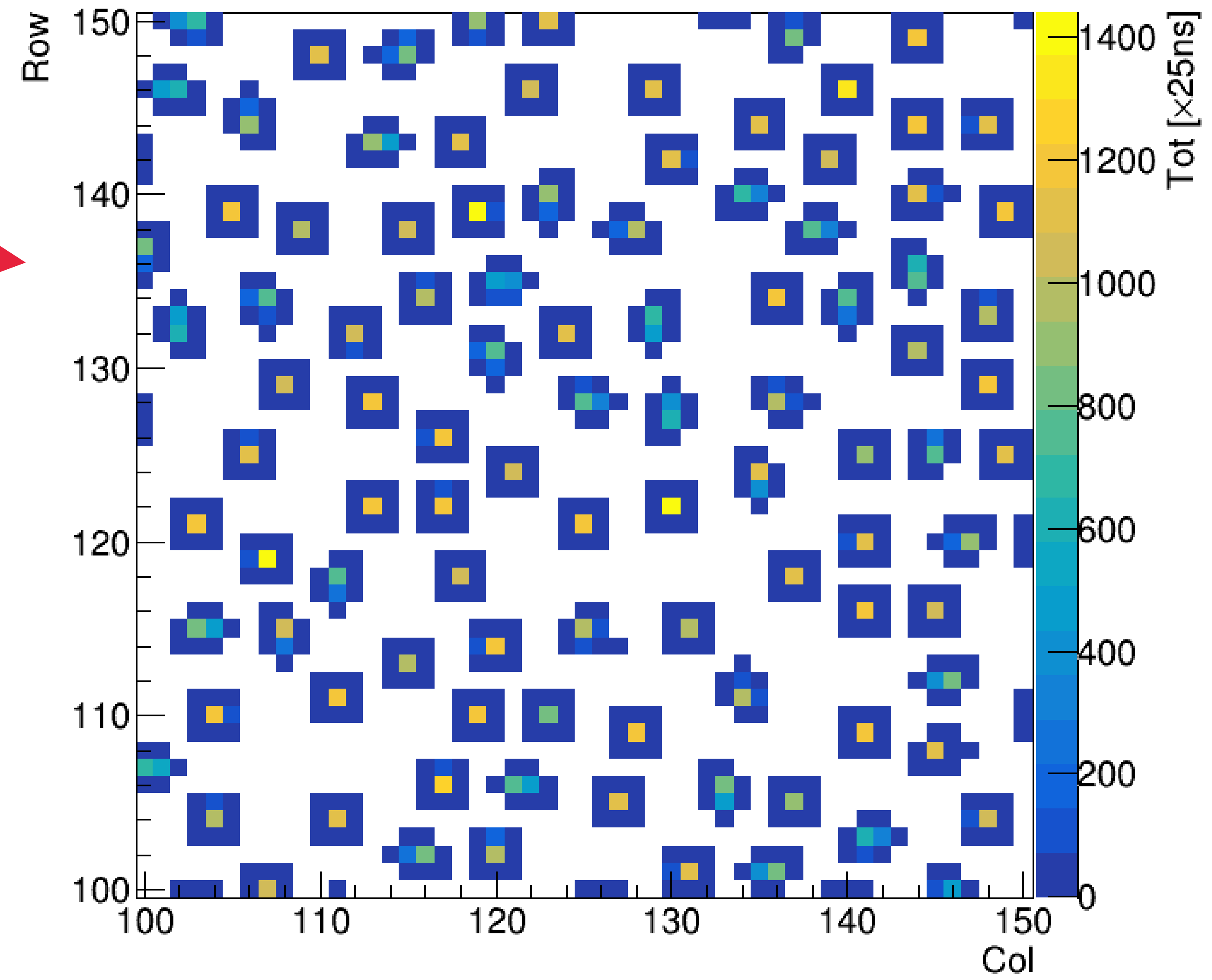


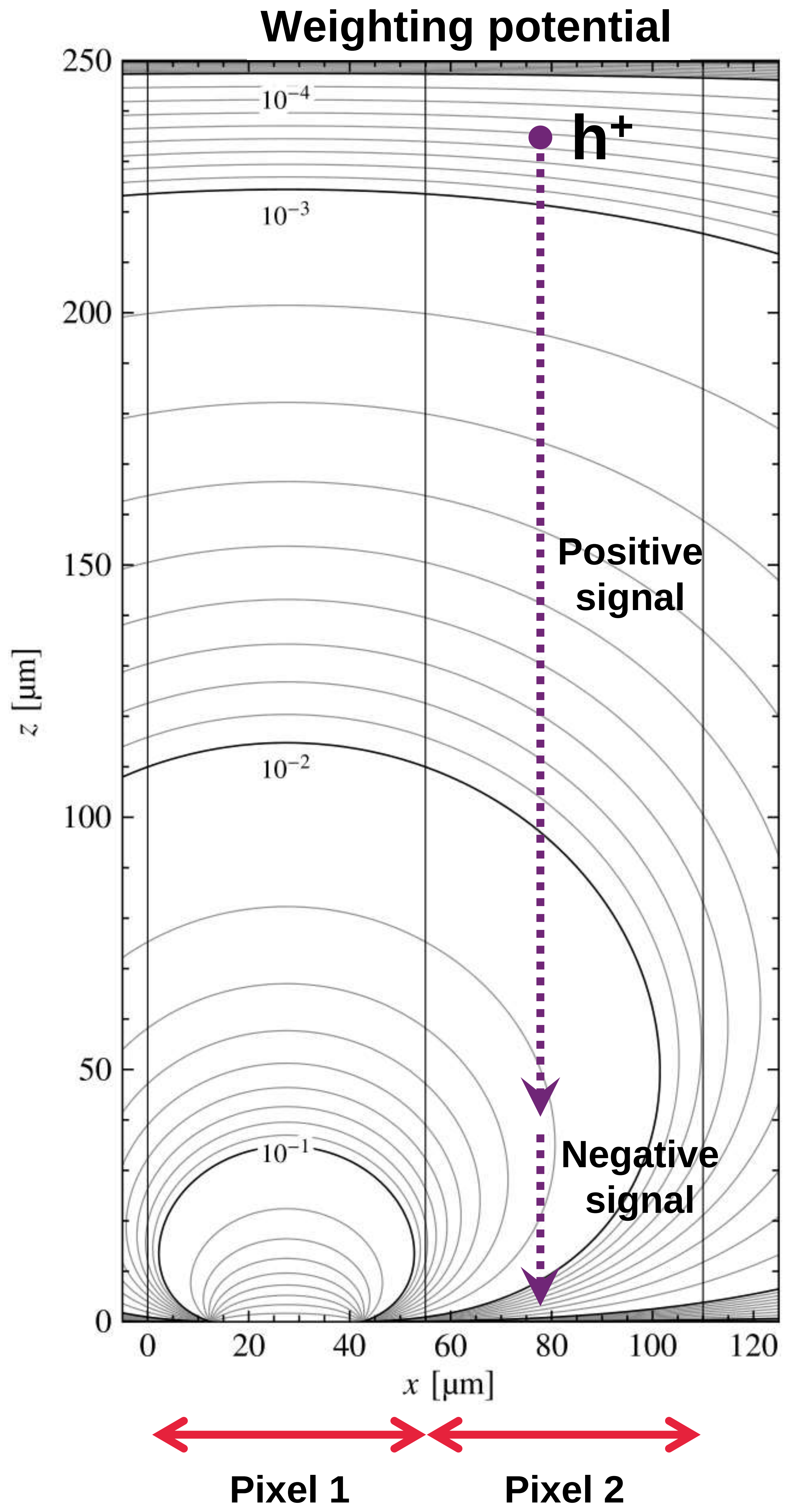
Inverted LGAD on Timepix4 as DUT (first glance)





- Analysis not yet started
- Large cluster size at perpendicular beam incidence
- Cluster have skirt of low-ToT hits (< 25 ns)
- We suspect due to bipolar signals in neighbouring pixels

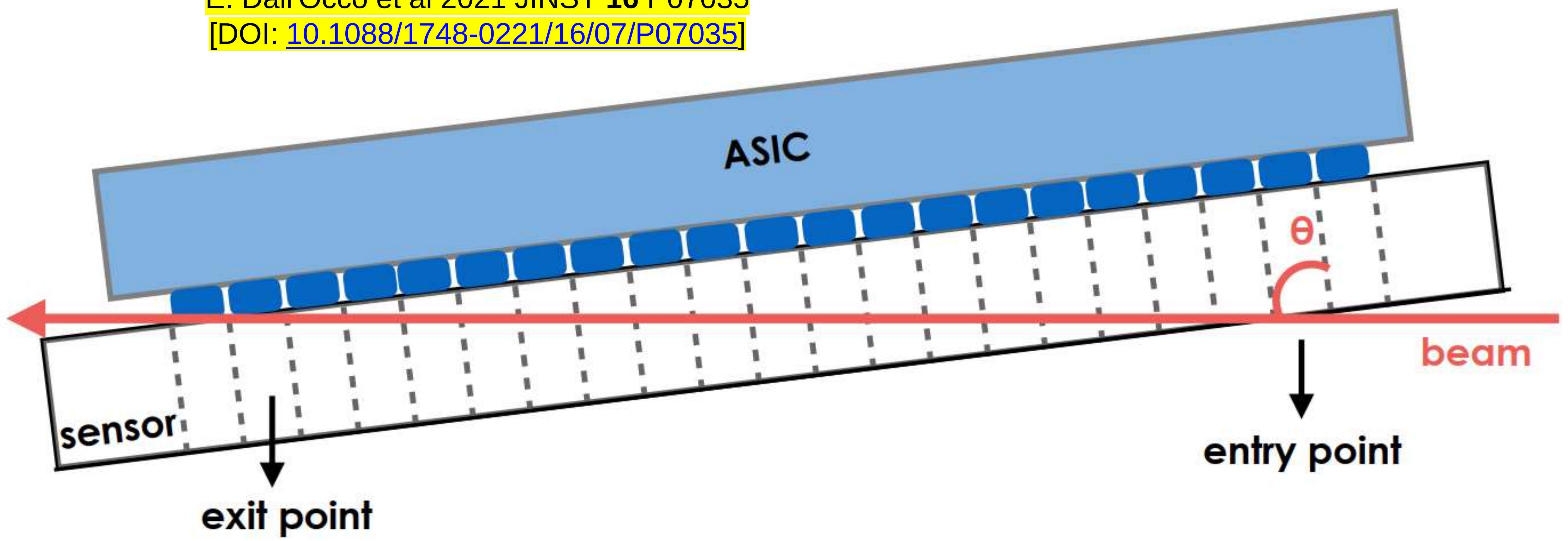


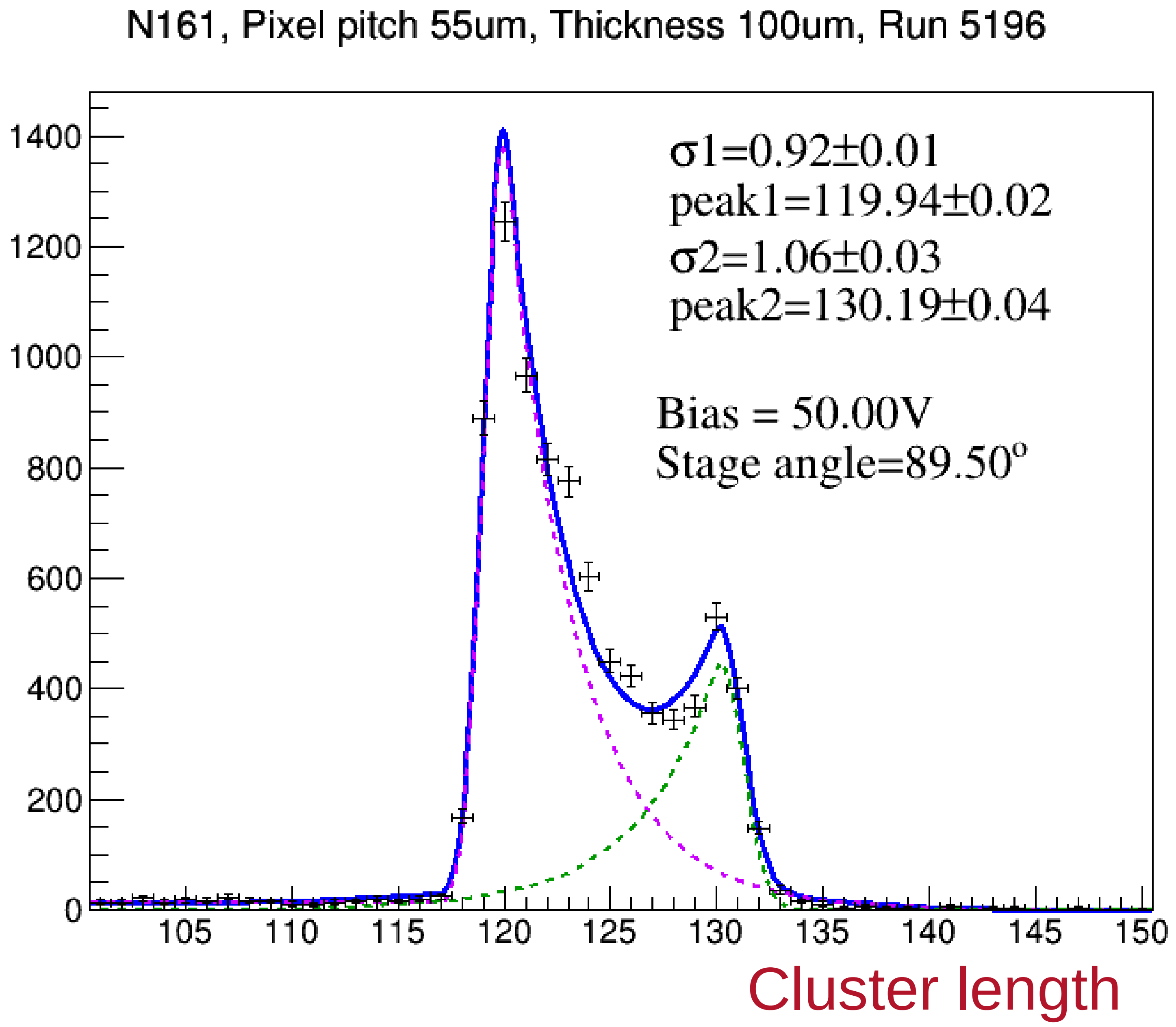


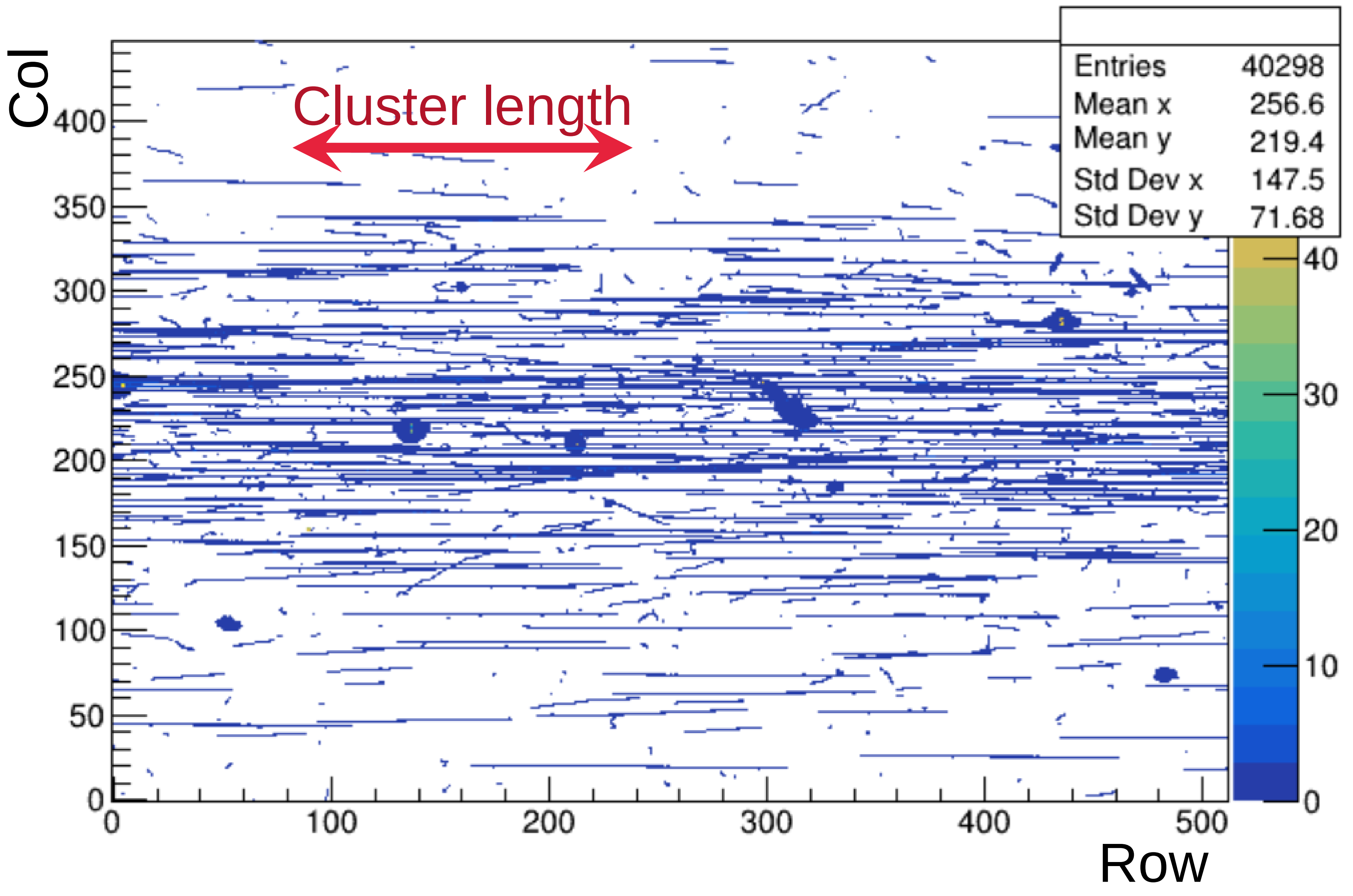
Grazing angle measurements

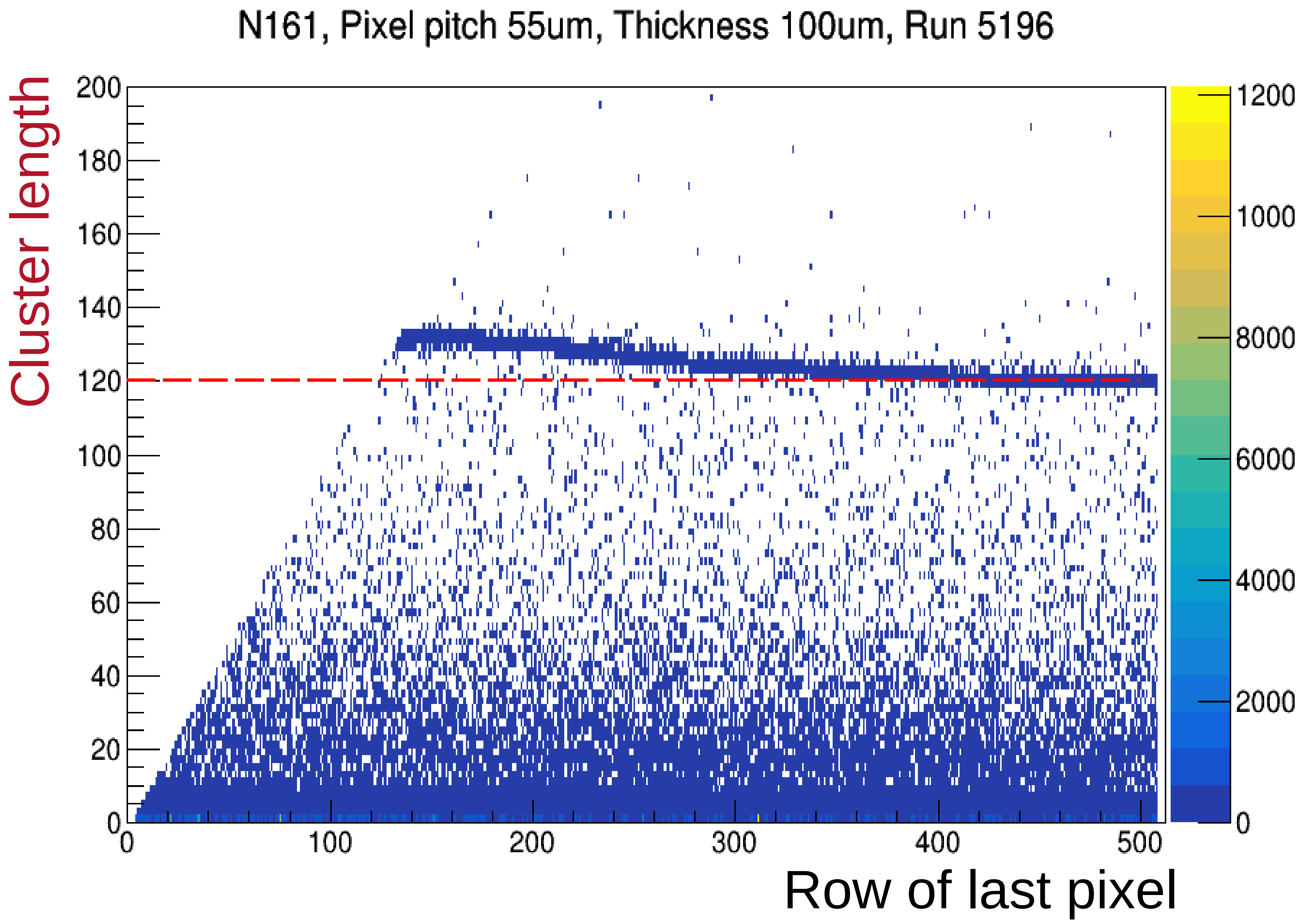
- Grazing angle measurements probe different depths of the sensor
- Can be used to determine thickness by measuring cluster length at various angles
- Sensors are thin, but not flat

E. Dall'Occo et al 2021 JINST **16** P07035
[DOI: 10.1088/1748-0221/16/07/P07035]

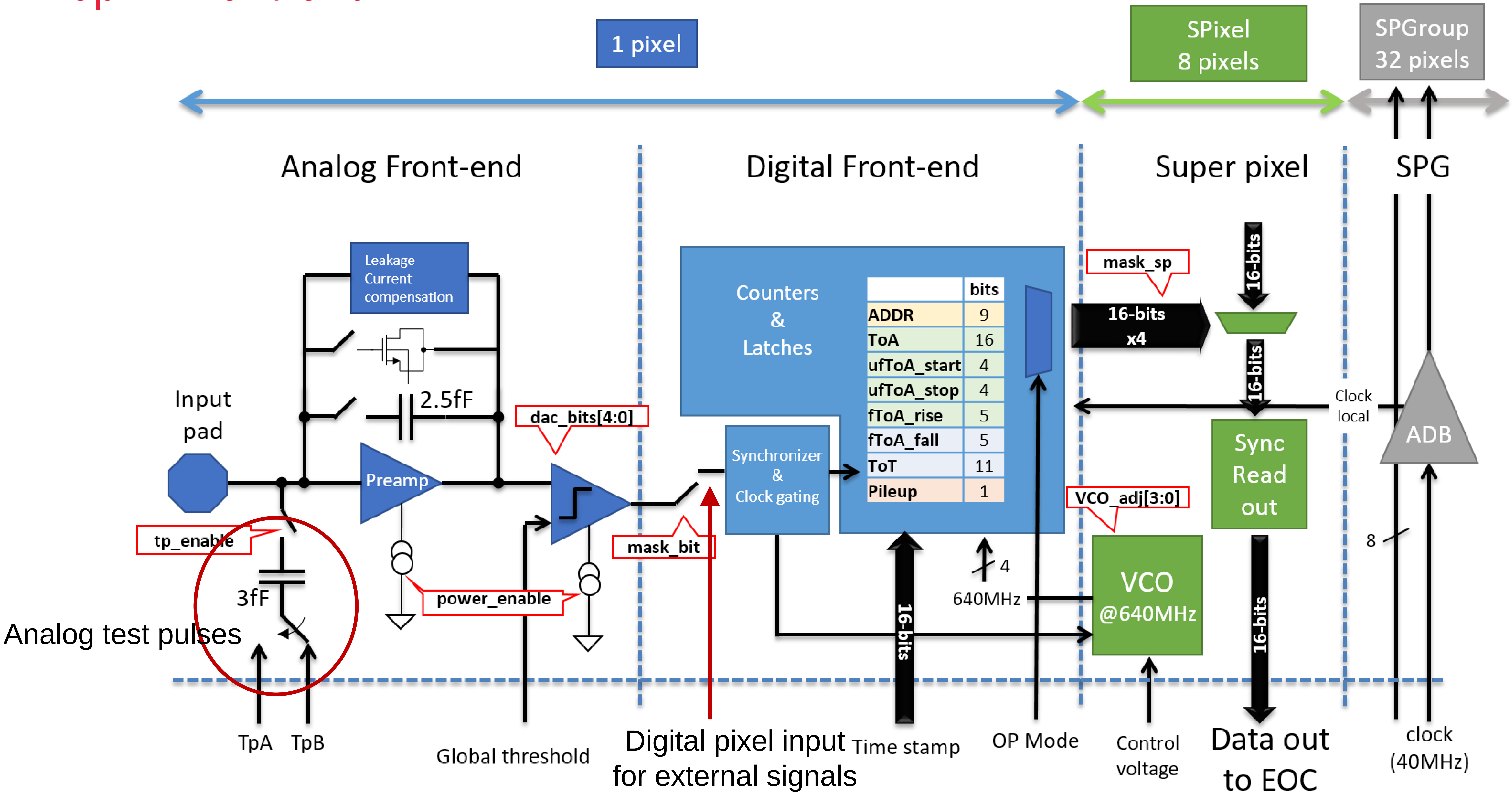








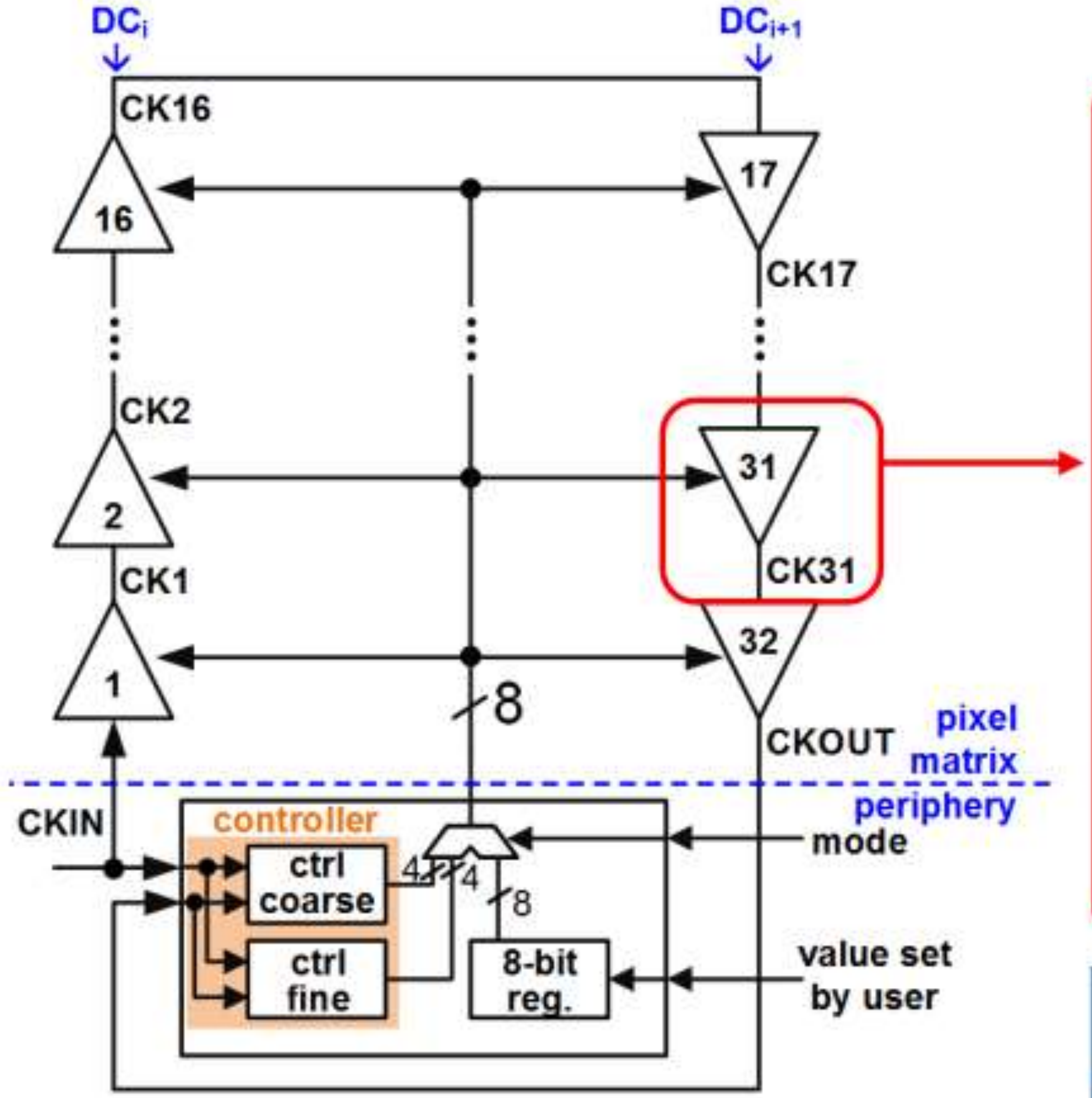
Timepix4 front-end

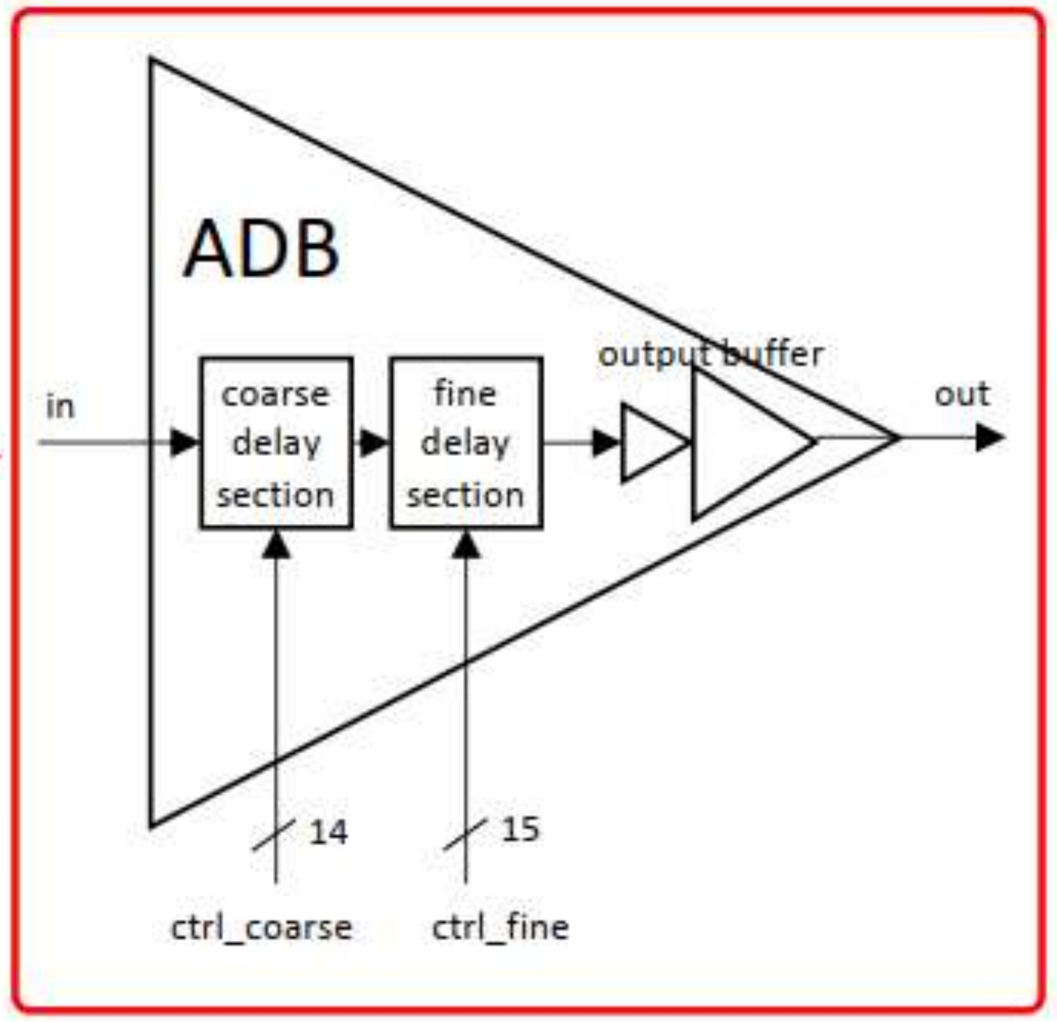


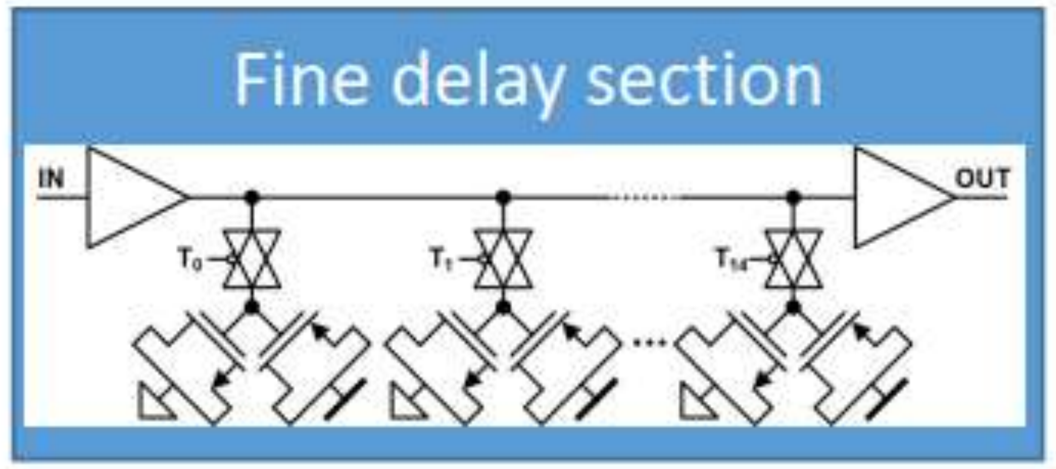
Clock distribution – Column digital locked look (DLL)

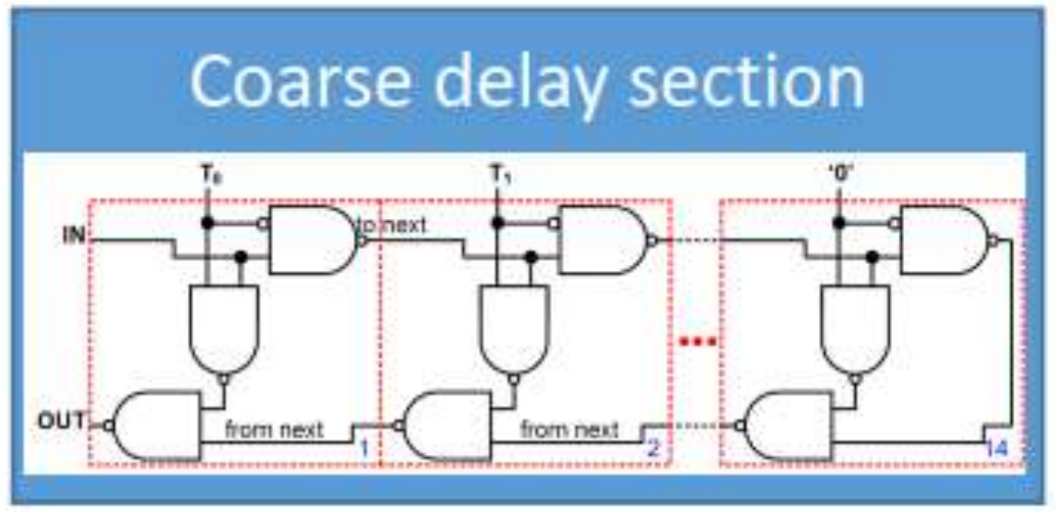
iWoRID 2018
X. Llopart et al 2019 JINST 14 C01024

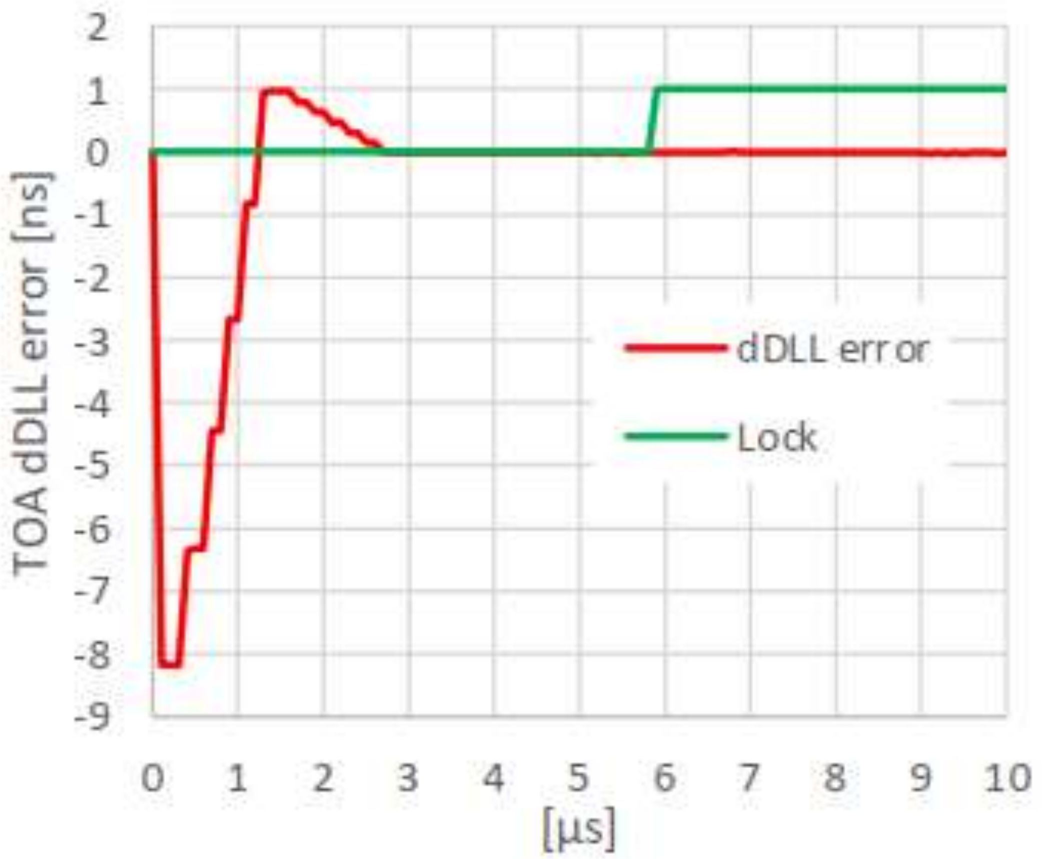
- The column DLL distributes the clock along the columns
- The adjustable delay buffers (ADBs) precisely define the clock phase in each pixel group
- Controller tunes the total delay to 25 ns
- Possible to set the delay manually
- Individual ADB stations can be bypassed

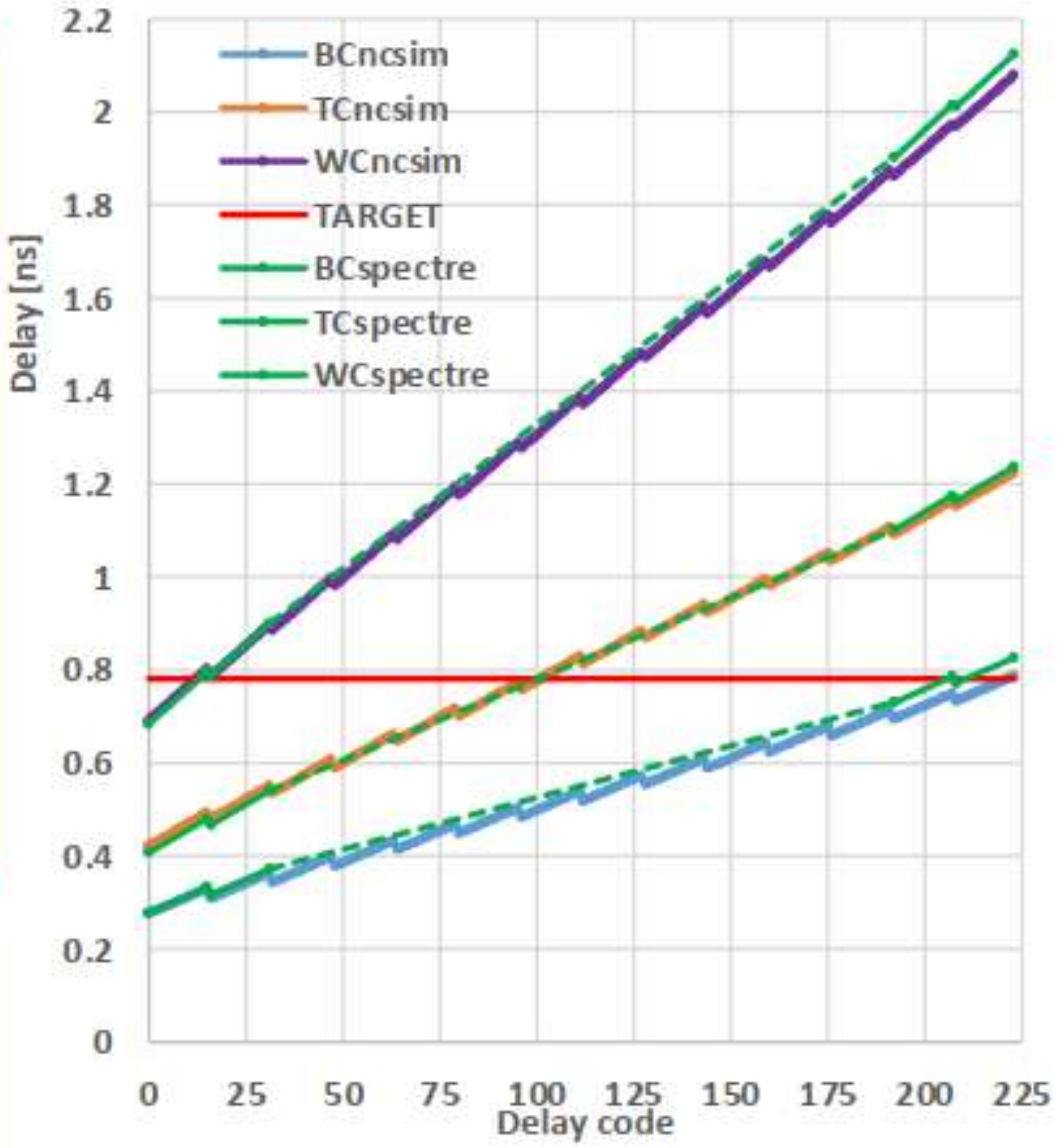










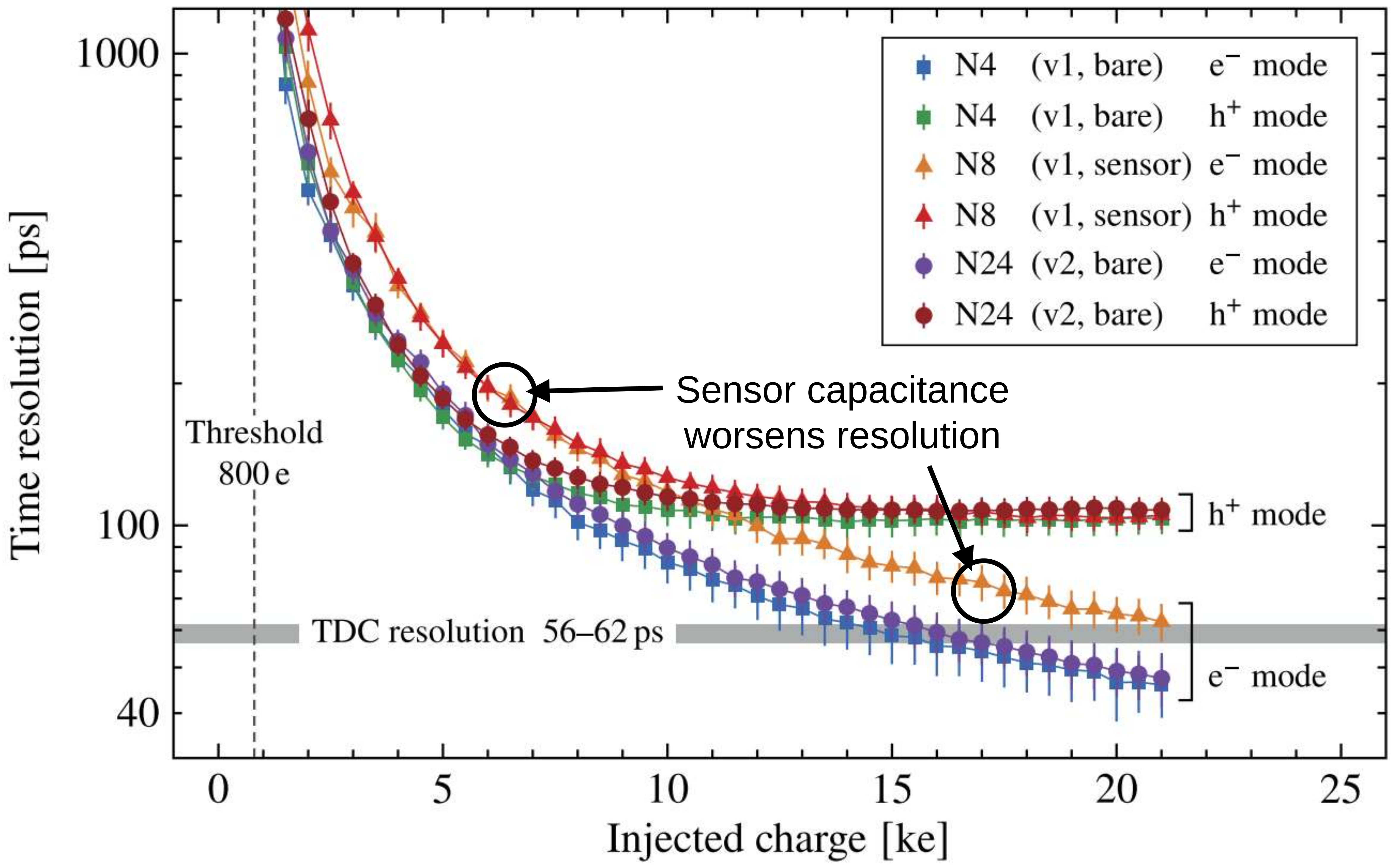


~22.7 mW/cm² to distribute a 40 MHz clock with a 100 ps_{rms}

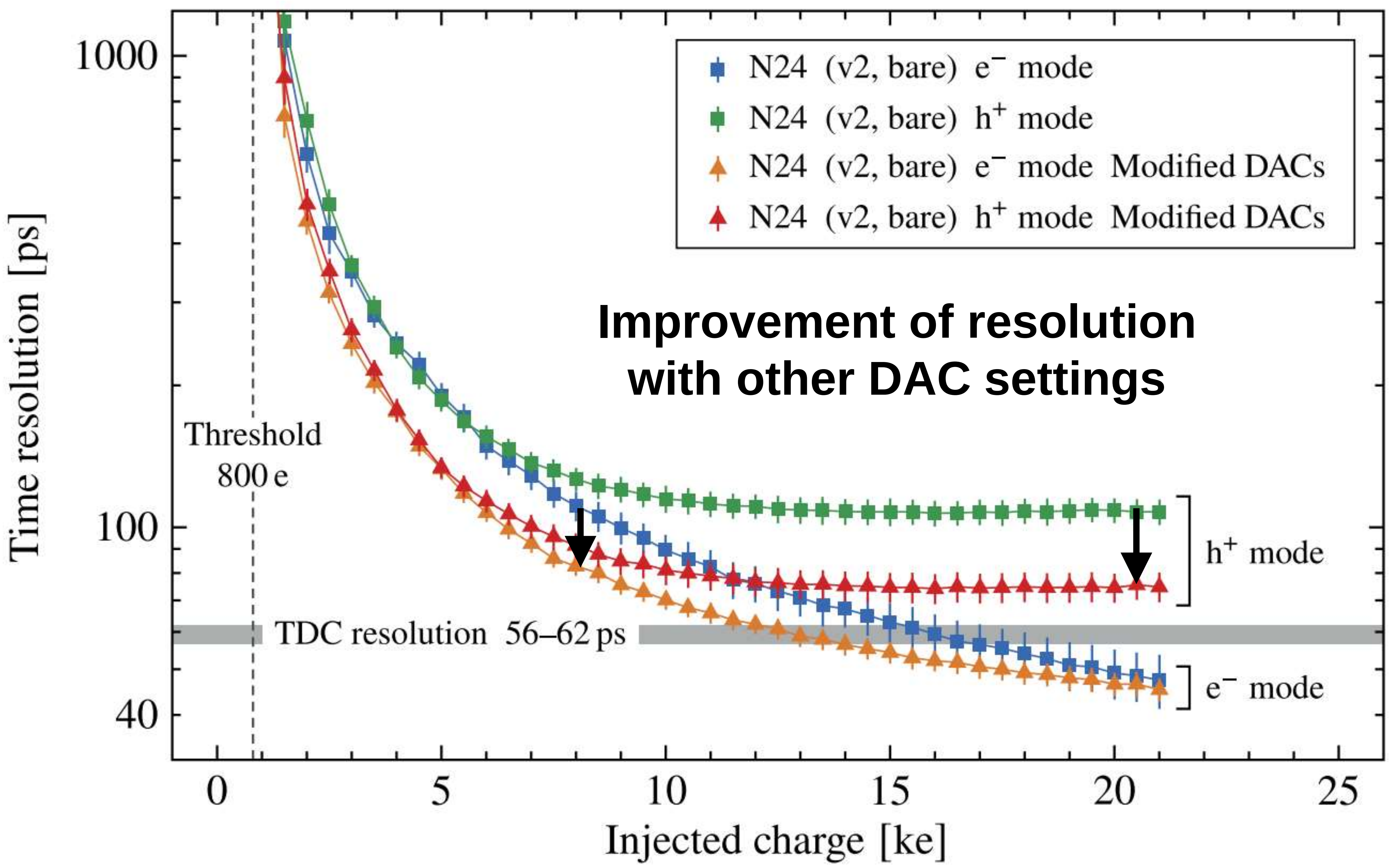
Timepix4 – Analog front-end jitter

- Time resolution in h⁺ mode limited to 75–105 ps depending on DAC settings
- Pixel capacitance decreases the time resolution
  (see R. Ballabriga *et al* NIM A 1045 (2023) 167489 [DOI: 10.1016/j.nima.2022.167489])

Anolog front-end time resolution vs signal charge



K. Heijhoff *et al* 2022 *JINST* **17** P07006 [DOI: 10.1088/1748-0221/17/07/P07006]

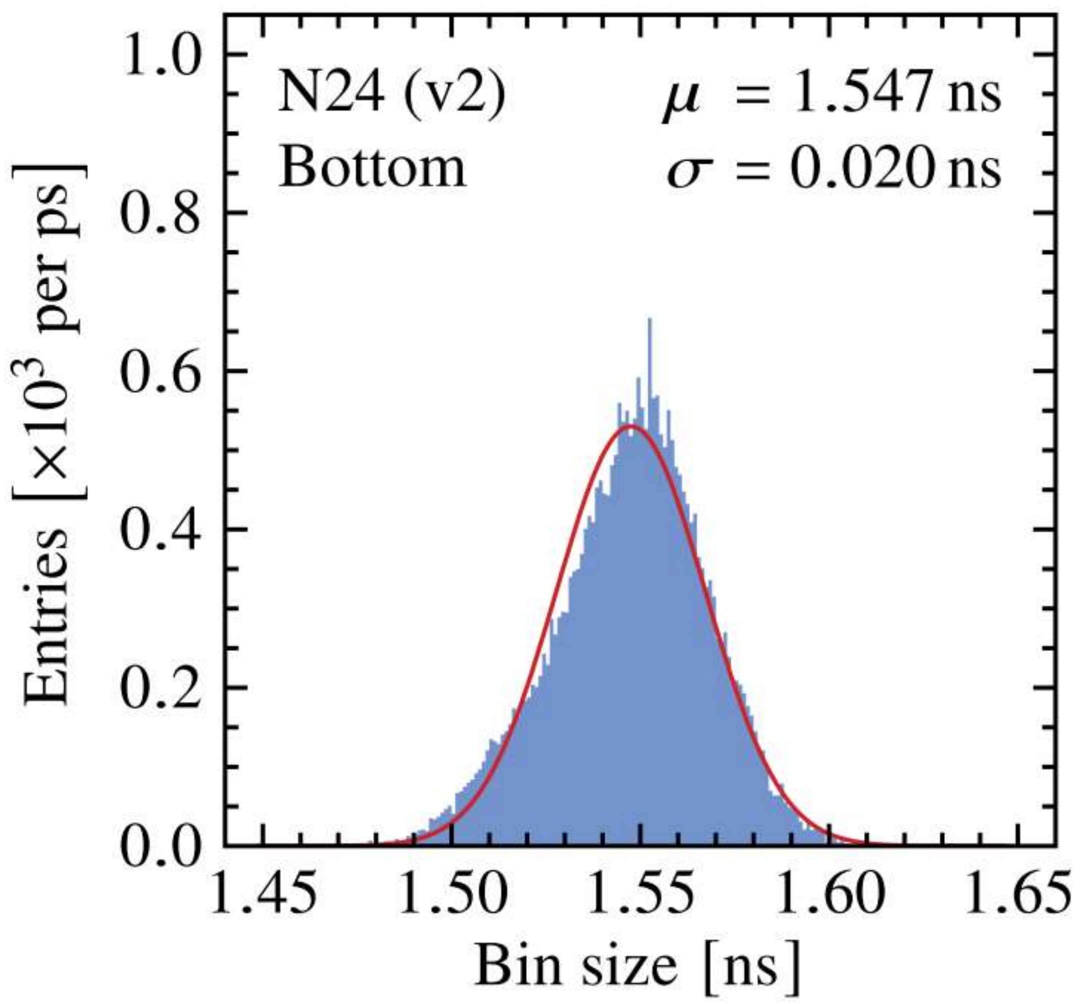


K. Heijhoff *et al* 2022 *JINST* **17** P07006 [DOI: 10.1088/1748-0221/17/07/P07006]

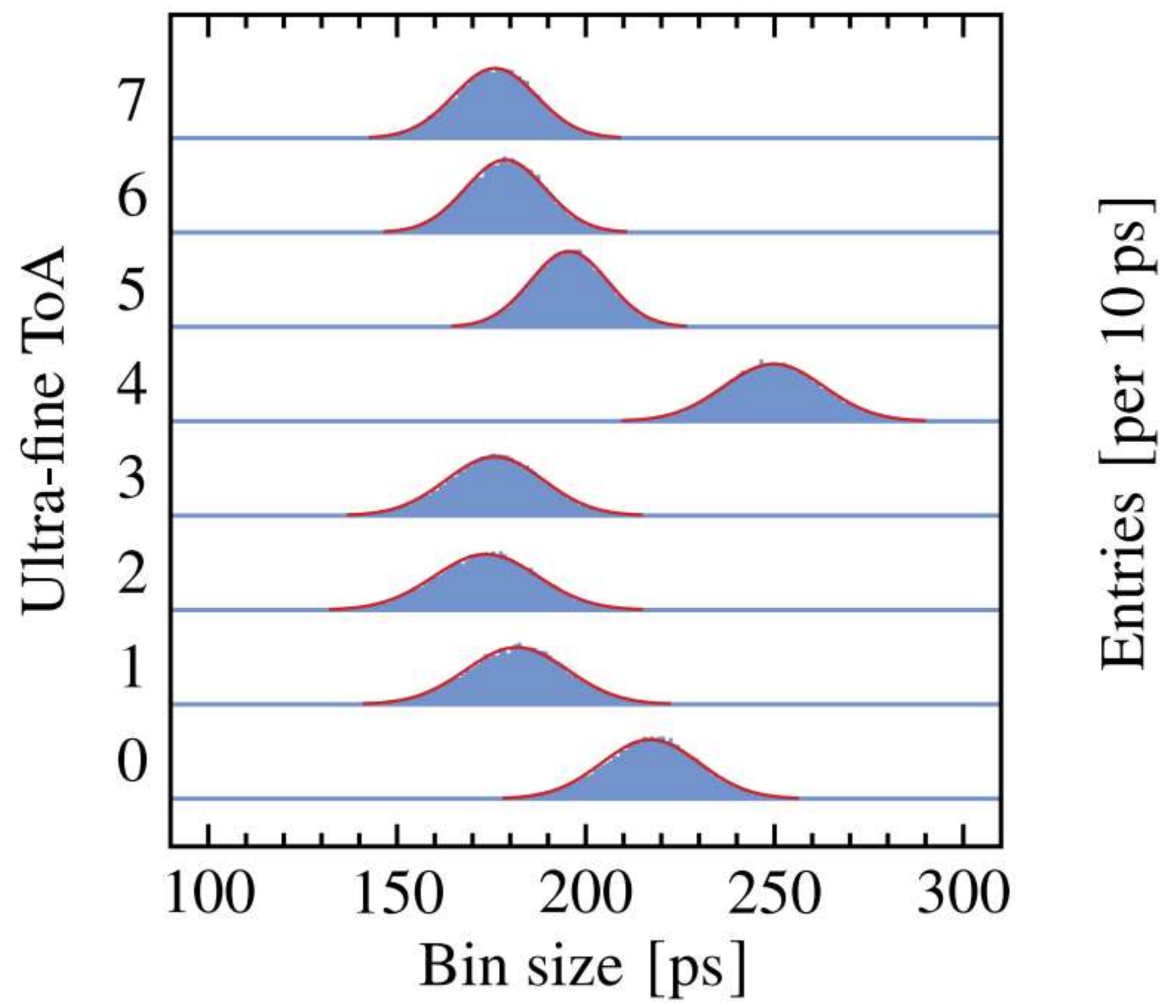
TDC resolution

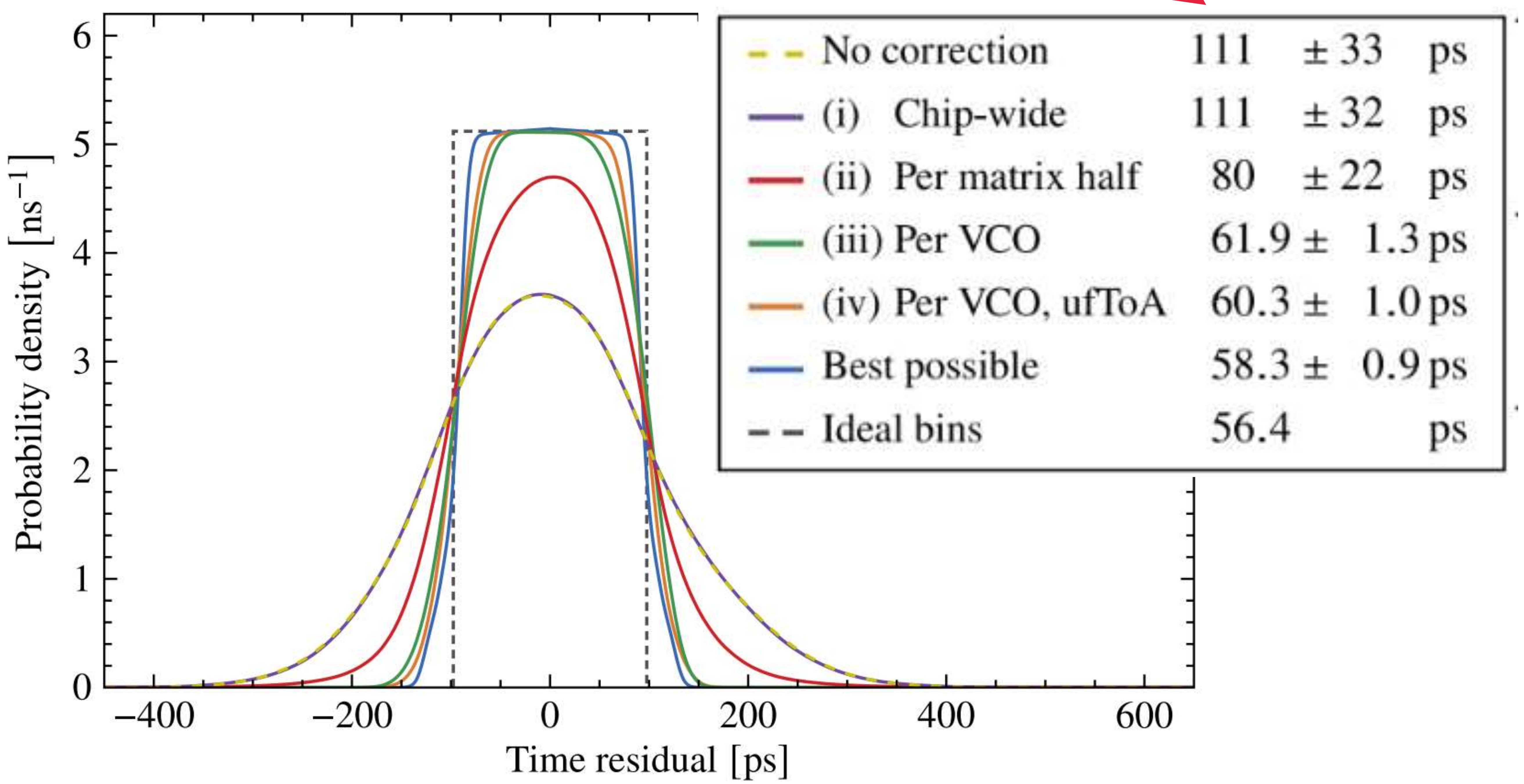
- Variation in the VCO frequency over the pixel matrix observed:
  Bottom half: 1.547 ns ± 20 ps
  Top half: 1.583 ns ± 14 ps
- Structure in ultra-fine time bins has a small impact on TDC resolution (few %)
- We have tried to predict the TDC resolution for correction methods of increasing complexity

Fine time bins (640 MHz)

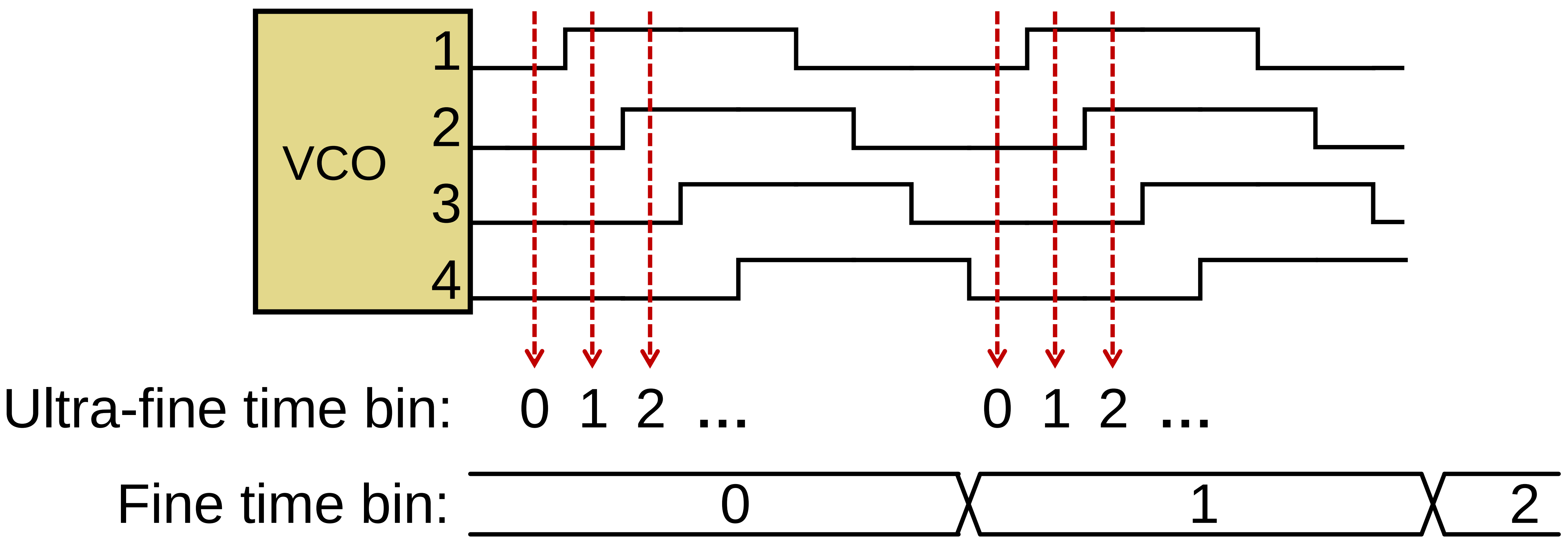


Ultra-fine time bins



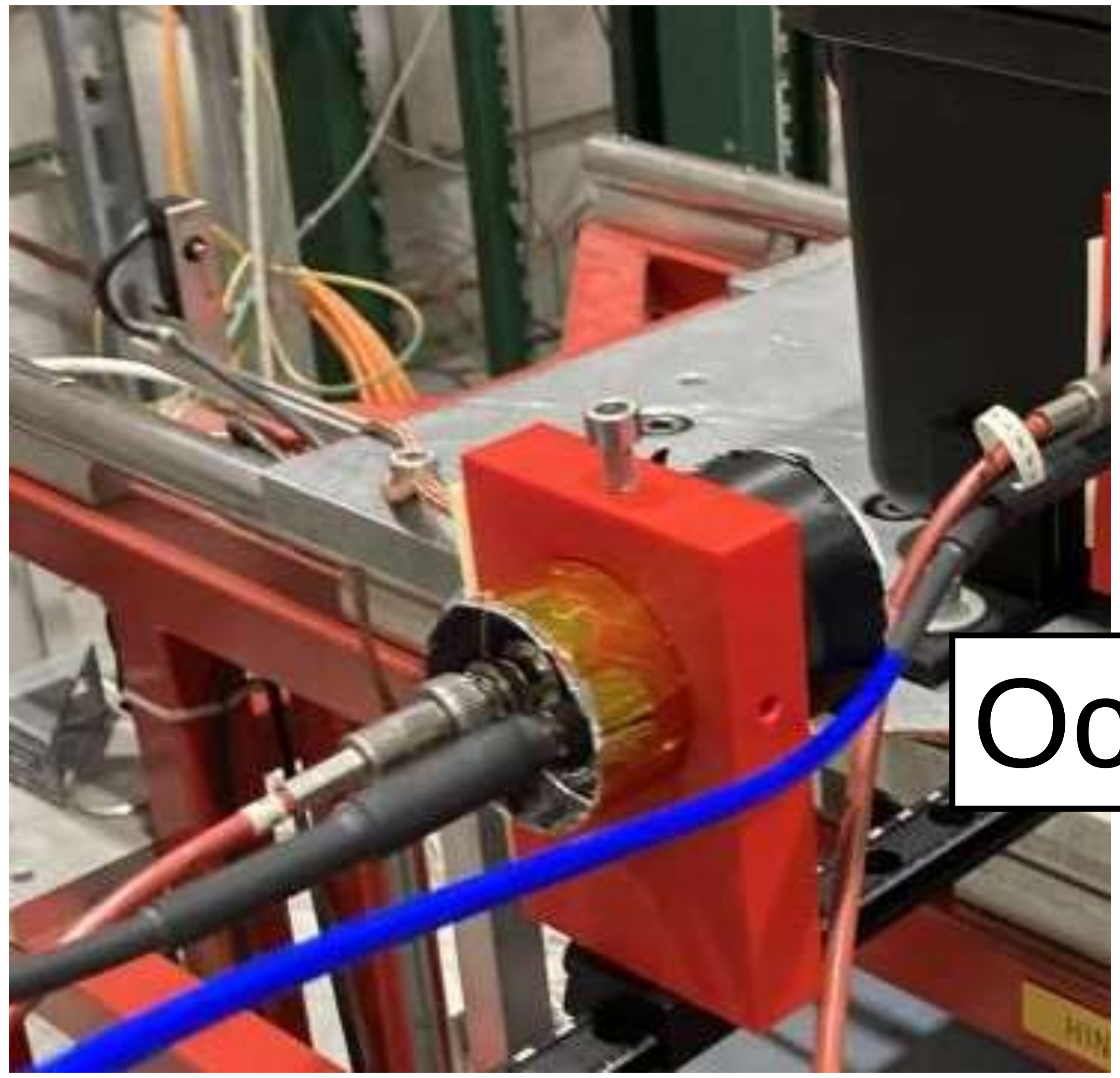


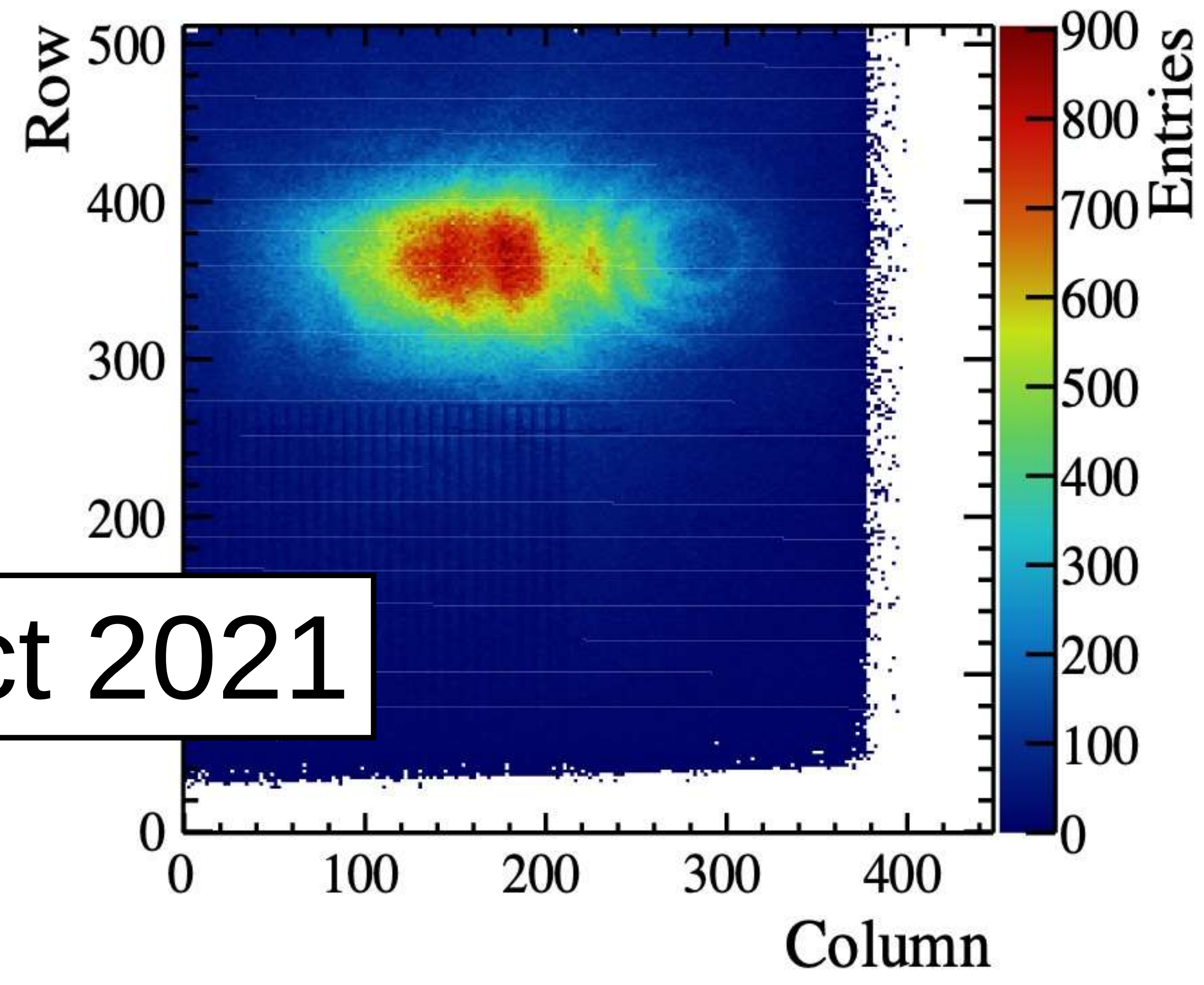
Phase shifted 640 MHz clocks

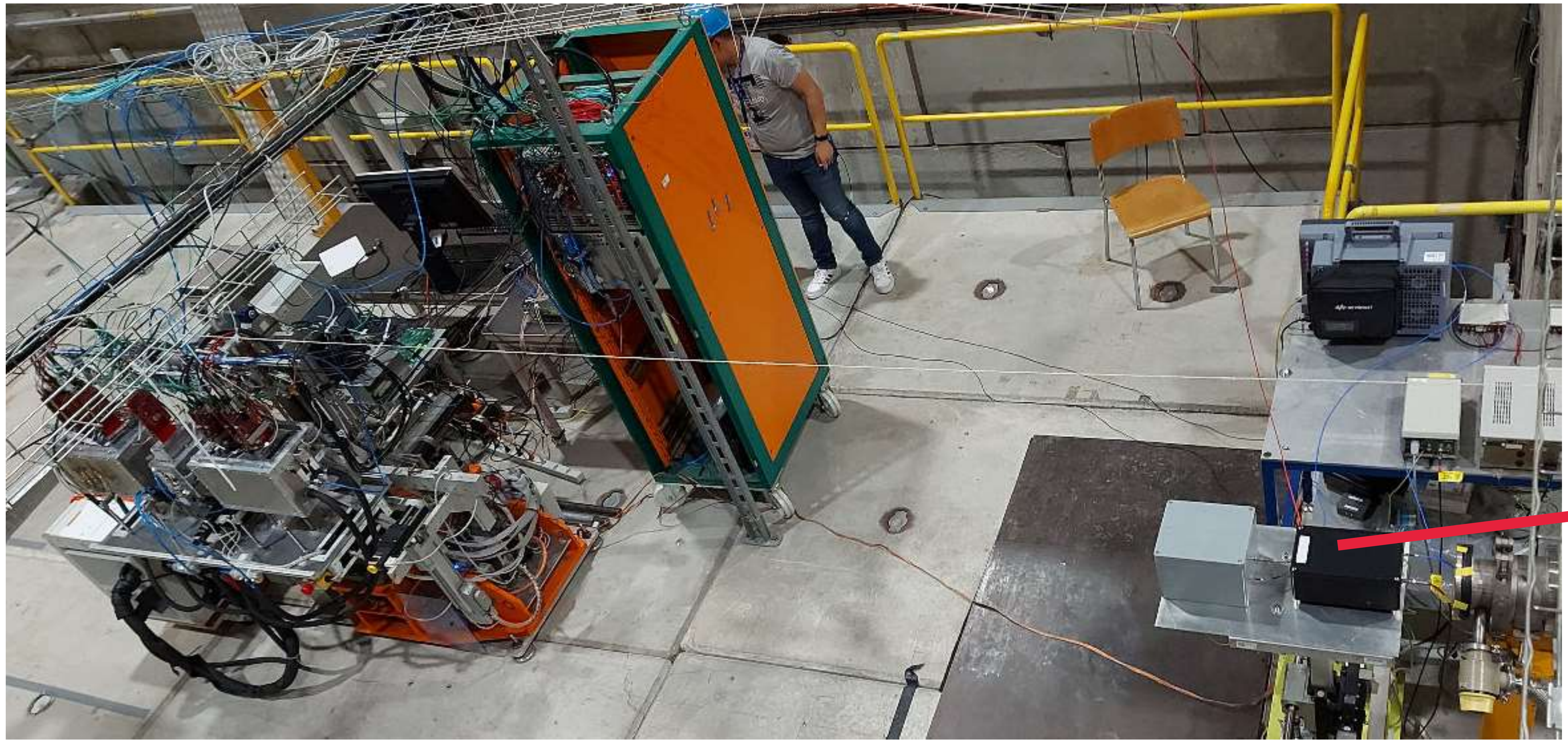


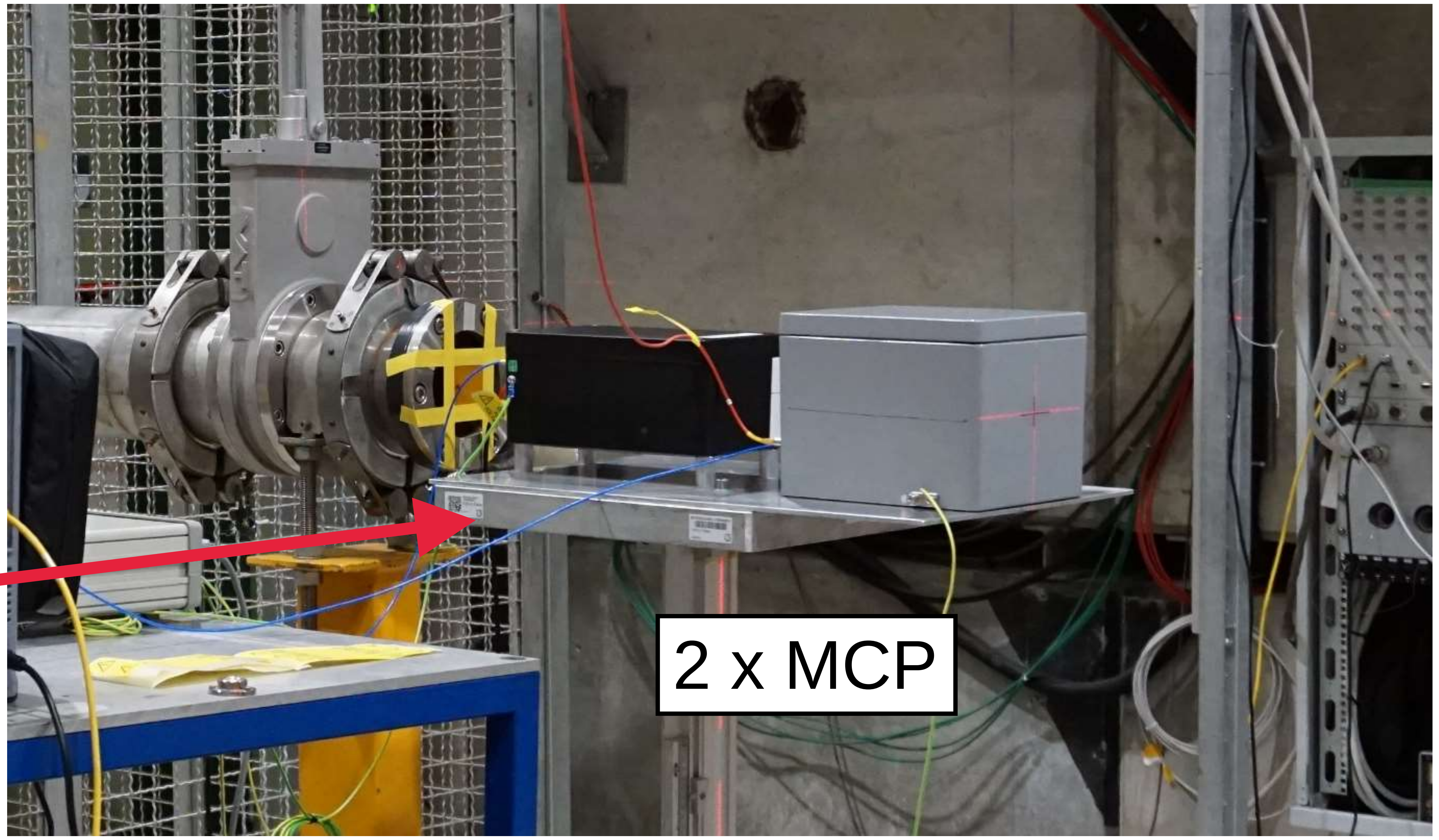
MCP time reference

- Two MCPs provide precise time references to study timing performance of telescope
- Placed at end to not hinder other groups in same beam area
- CFDs suffered from large signals due to nuclear interactions



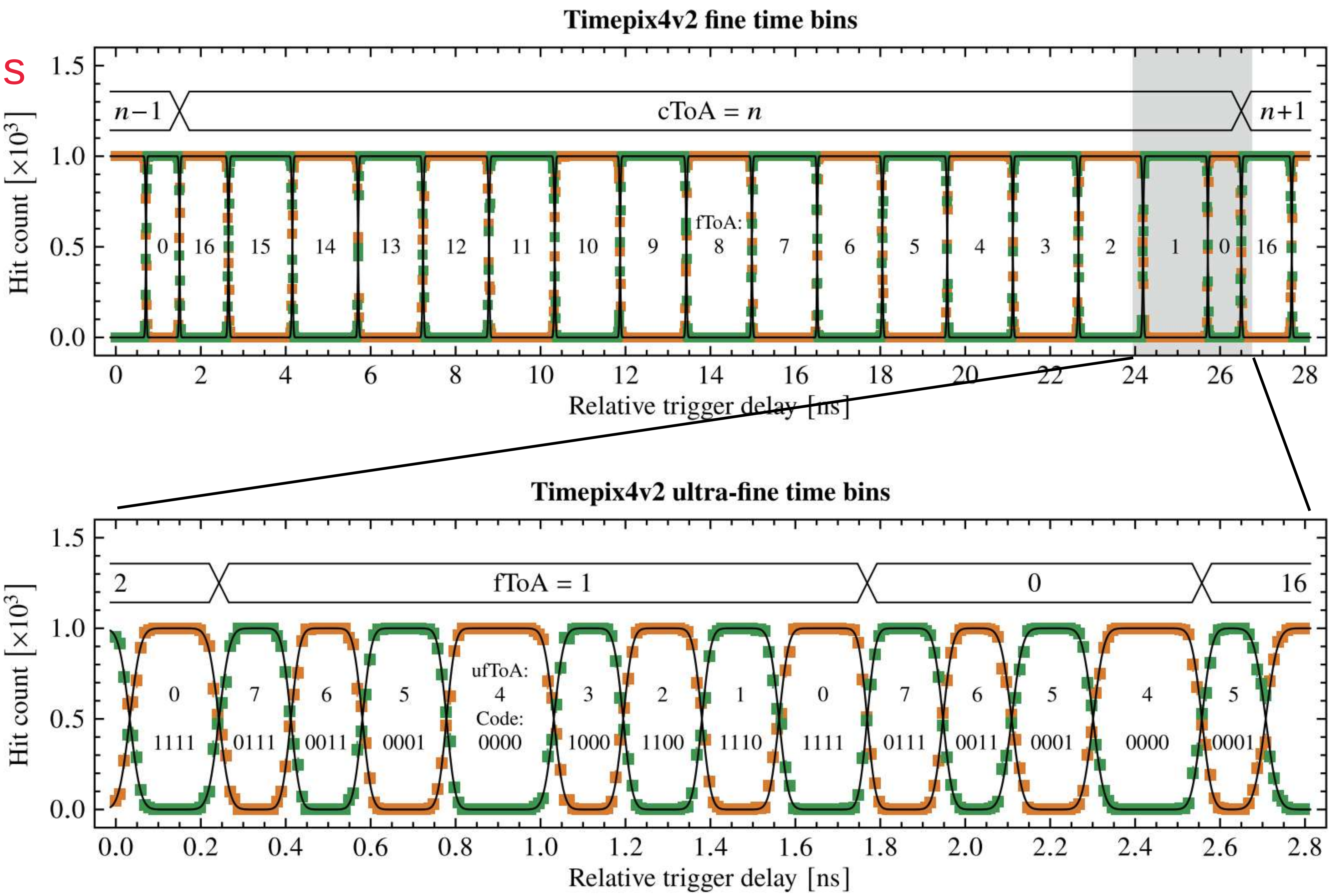






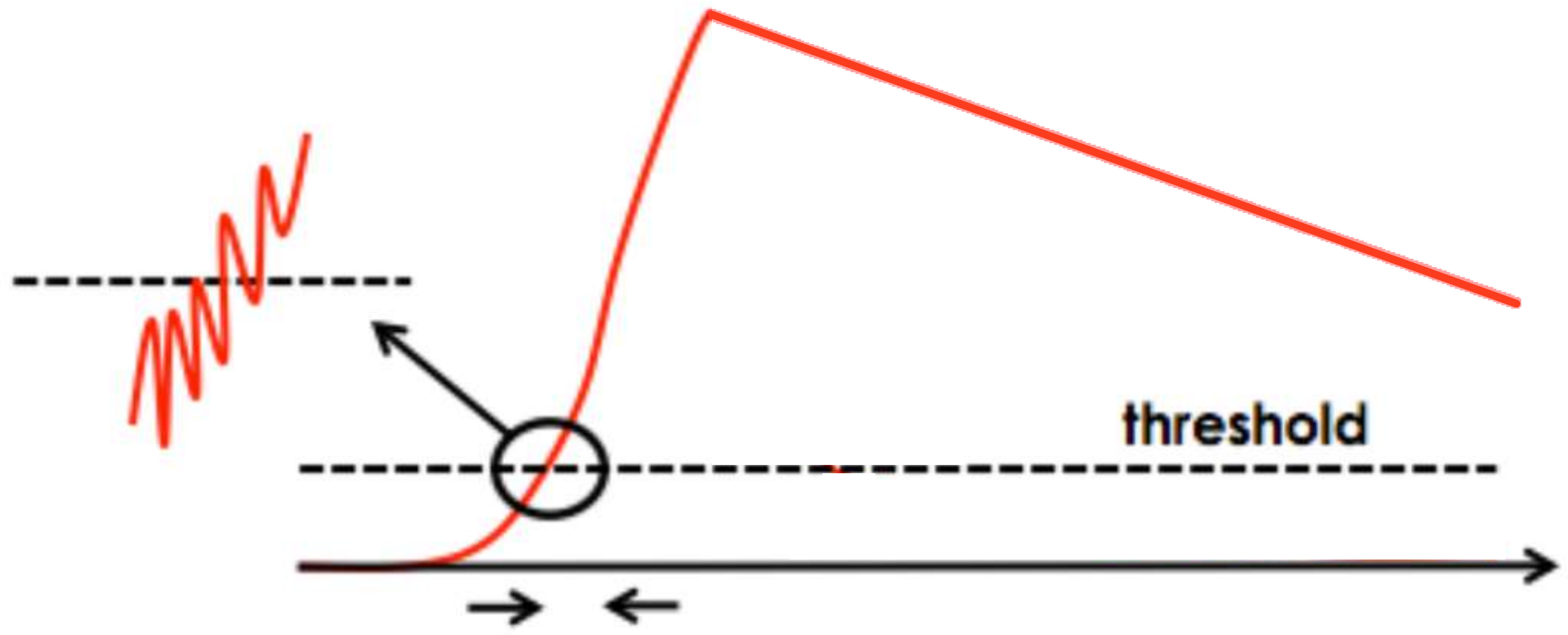
Timepix4 TDC bins

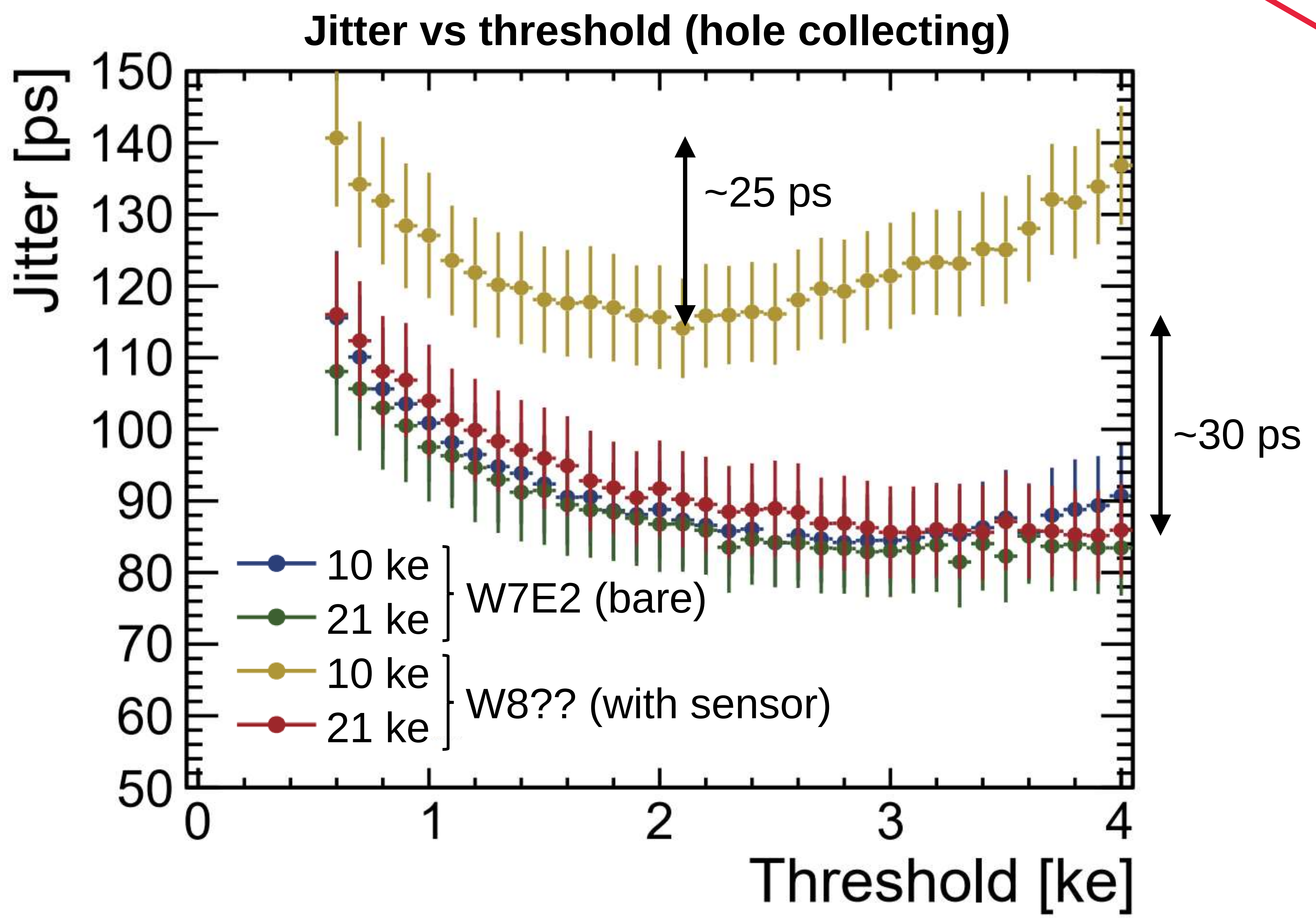
- Time bins measured using digital pixel inputs
- Timepix4v2

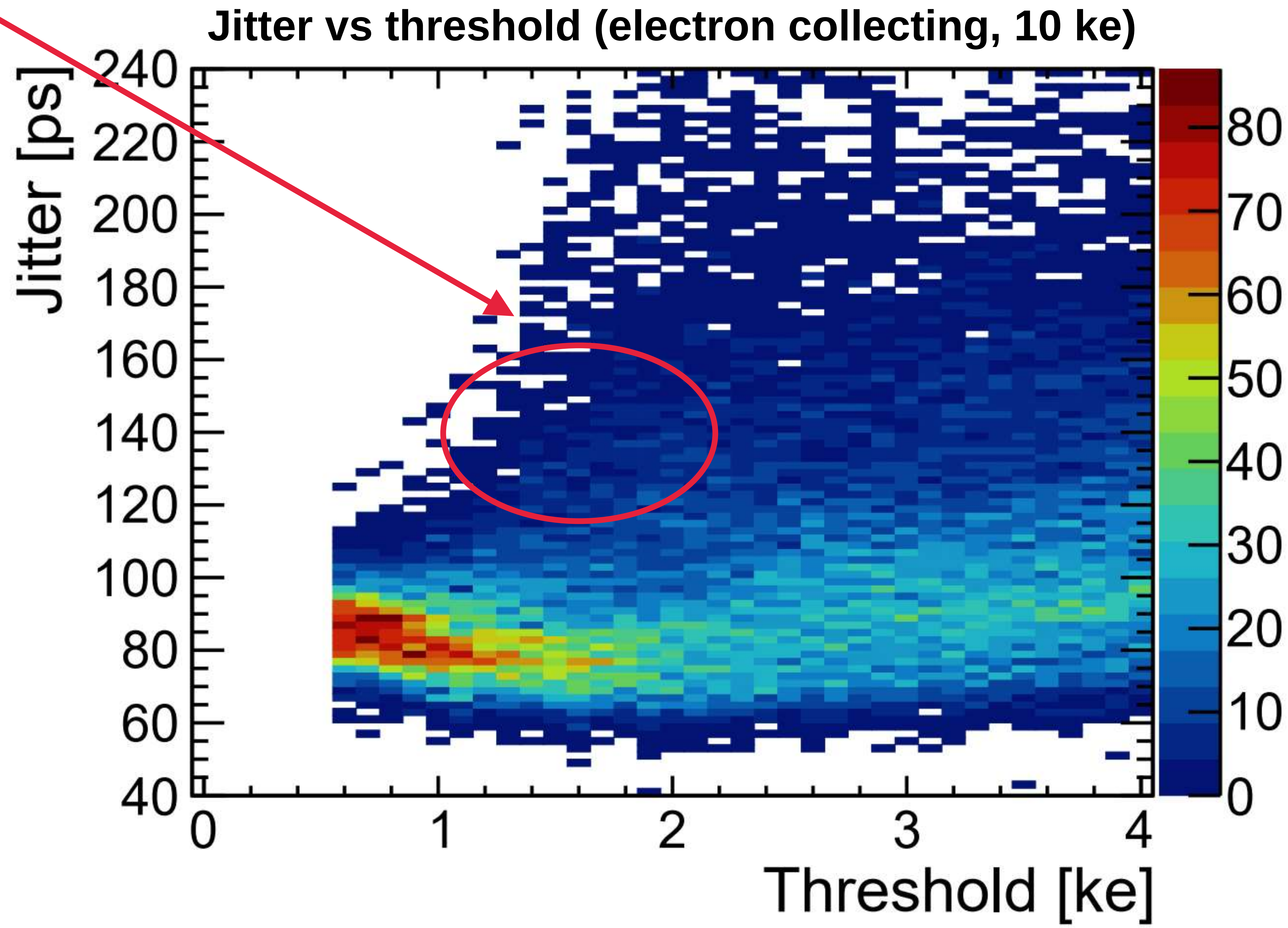


Timepix4 – Jitter vs threshold

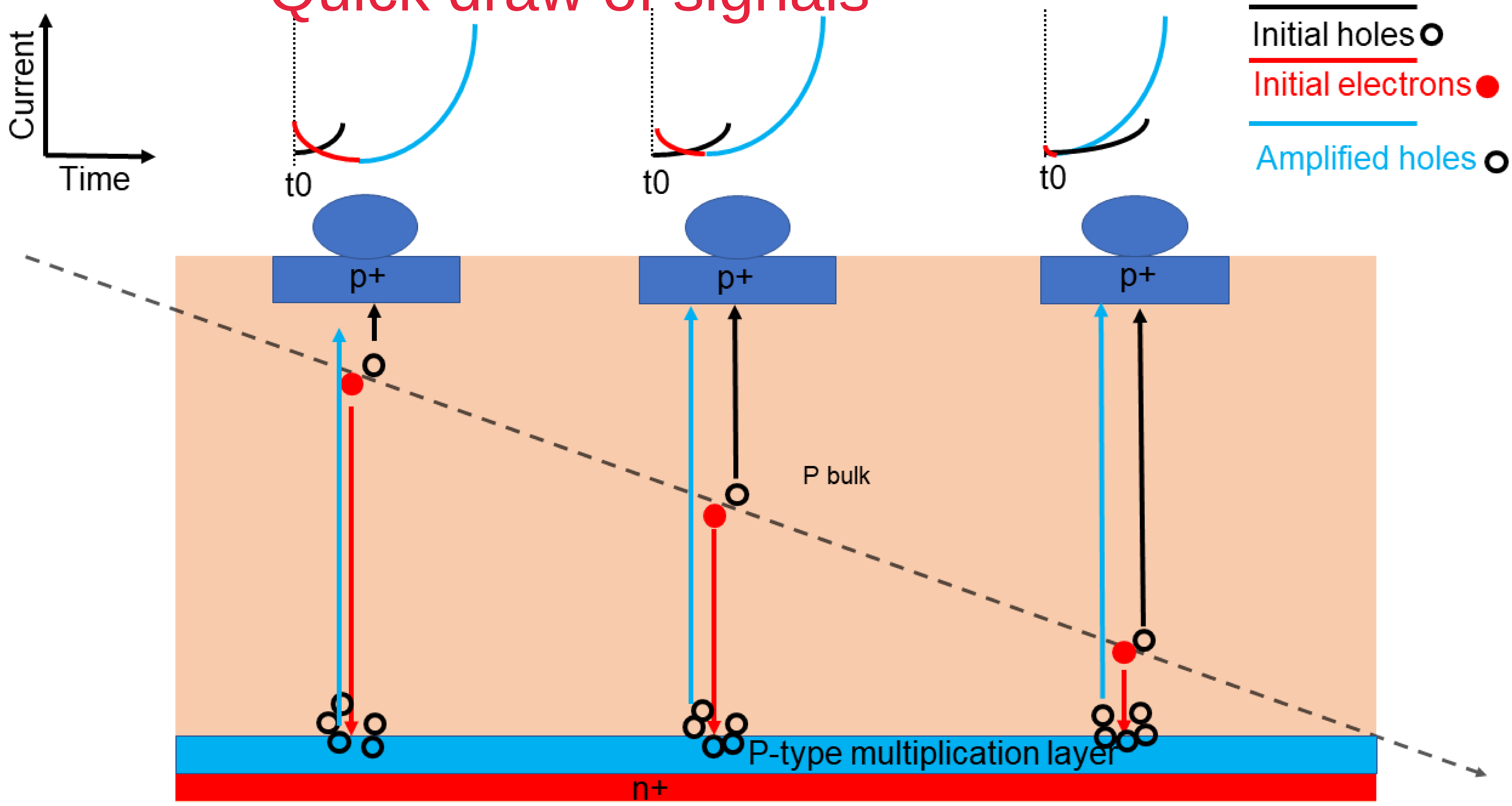
- Jitter depends on threshold
- Tail at high thresholds in electron-collecting mode not understood







Quick draw of signals



Charge calibration with test pulses

- ToT for a test pulse charge of 15 ke