New Results from Timepix4 at the SPS

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on behalf of the Timepix4 Telescope group

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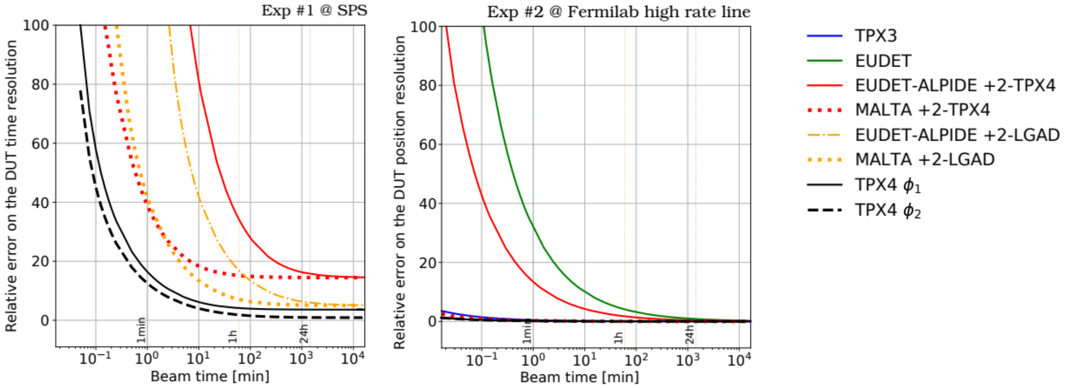
Timepix4 Telescope

- Success Timepix3 based **beam telescope** -> **upgrade** using Timepix4
- Main improvement (and challenge): **better track time resolution**
  - Timepix3 telescope achieved ~O(300) ps after long and careful tuning

K. Heijhoff *et al.*, 'Timing performance of the LHCb VELO Timepix3 Telescope'

- Timepix4 based beam telescope will be used for characterization of novel sensors (in view of LHC upgrade programmes)
- Timepix4 based telescope was constructed:

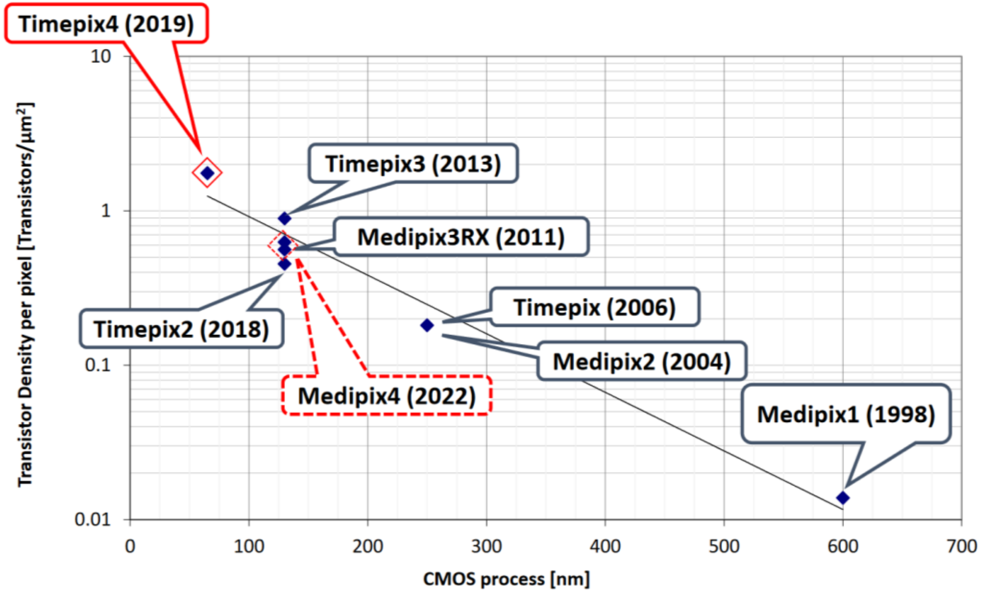
  Main aim was to see first tracks in Timepix4 in July 2022 and get closer to a final telescope in October 2022



Comparison of the beam time needed by the various telescope options to reach a given relative uncertainty on the measurement

Timepix3 -> Timepix4

- The temporal resolution [1] from Timepix3 yielded an extremely clean clustering and track reconstruction [2] .
- The Timepix4 [3] has 8 times finer TDC and can lead to a real-life 4D tracking device.
    - Can we achieve 20 ps on a track?
- The TPX4 also has a much higher data rate allowing even faster Characterisation of devices [4] – the future 4D detectors need a lot more data!
- **Timepix4 based tracker was constructed for several testbeam campaigns: October (2021), July (2022), October (2022)**

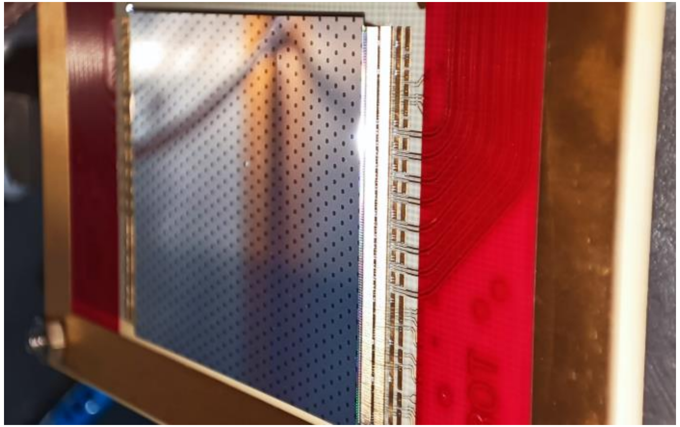


Xavi Llopart Cudie, "Timepix4, a pixel detector readout chip with sub-200 ps timestamp binning", CERN Detector Seminar 11th February 2022

Timepix4 ASIC

https://indico.cern.ch/event/1121147
X. Llopart et al 2022 JINST 17 C01044

			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	TOT and TOA	
		Event Packet	48-bit	64-bit	33%
		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	6x
TOT energy resolution			< 2KeV	< **1Kev**	2x
Time resolution			1.56ns	**195.3125ps**	8x
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	≤163.84 Gbps (16x @10.24 Gbps)	32x
Target global minimum threshold			<500 e^-	<500 e^-	



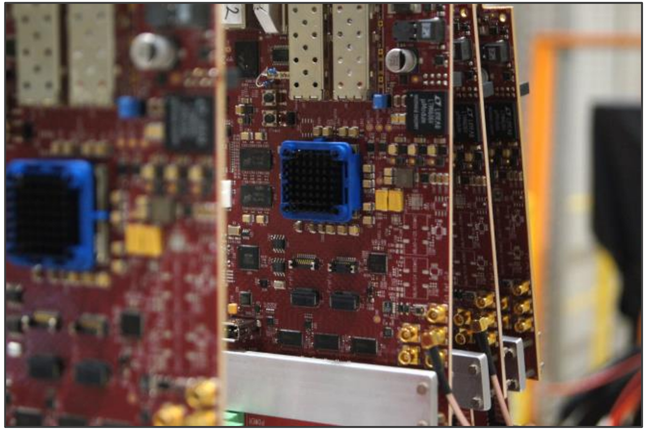
Timepix4v2 with 100µm sensor n-on-p in the testbeam setup (July 2022)

Limitations Timepix4v1 and outlook Timepix4v2

Timepix4v1: **problem** with the **VCO** (voltage controller oscillator) -> the frequency is too high

- Leads to **stability problems** in the chip
- Parameter variations over the chip remain
- Issue expected fixed in **Timepix4v2**

~1/2 of the world's supply of SPIDR4

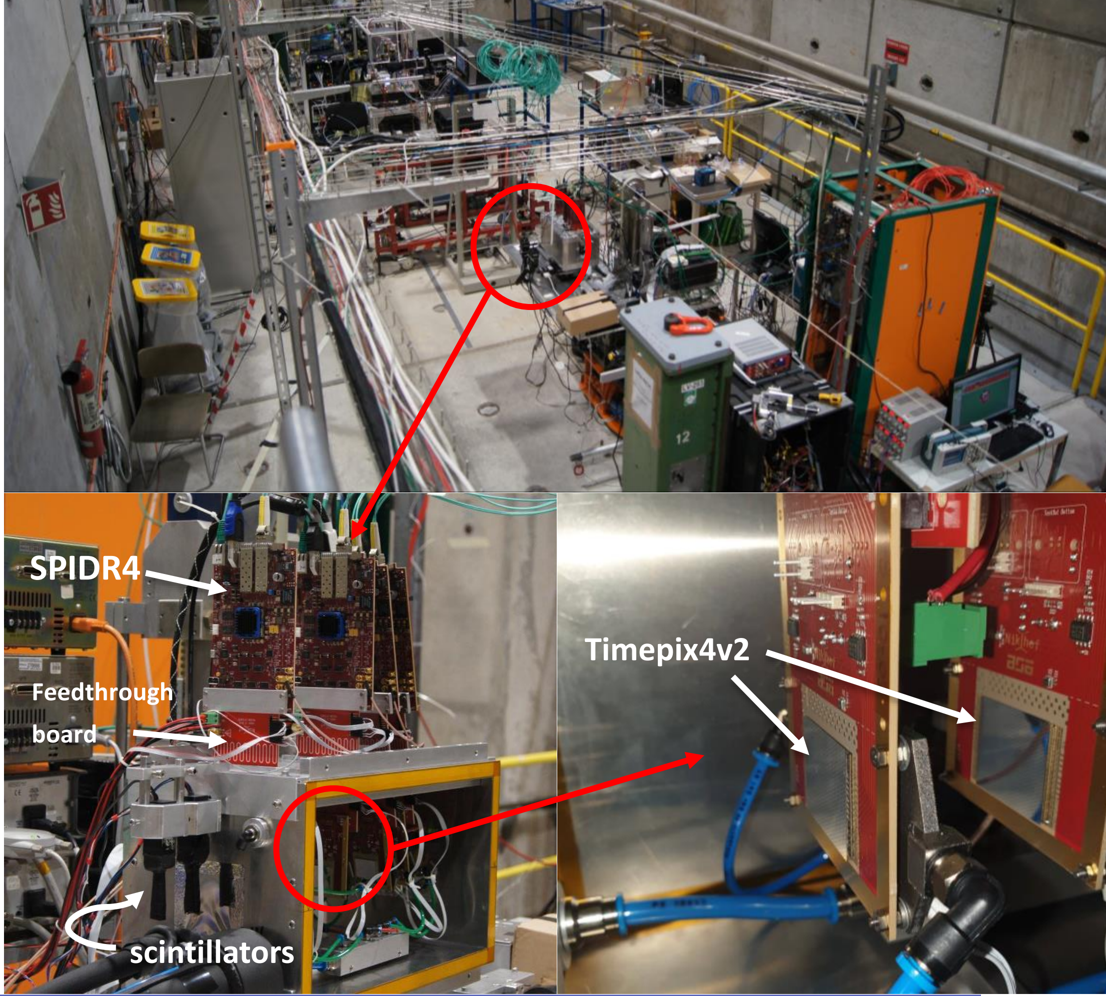


For **Timepix4v2** telescope

- New supply of SPIDR4 -> Increased number of planes
- Test stability and full telescope configuration
- Timing and spatial resolution studies:
  - Angle, bias, threshold and pre-amp scans

Testbeam facilities

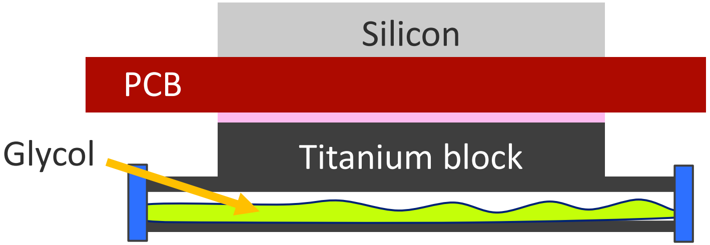
- H8 beamline at SPS / CERN
- 180 GeV/c mixed beam
- Mostly pions (K, p)

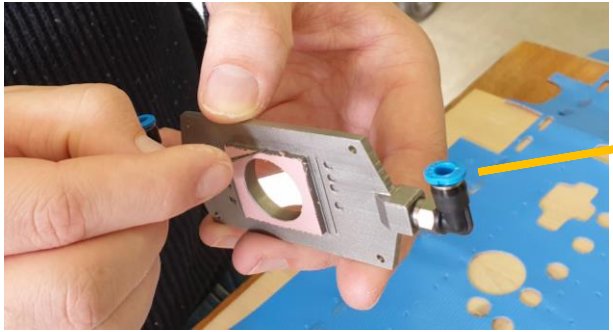


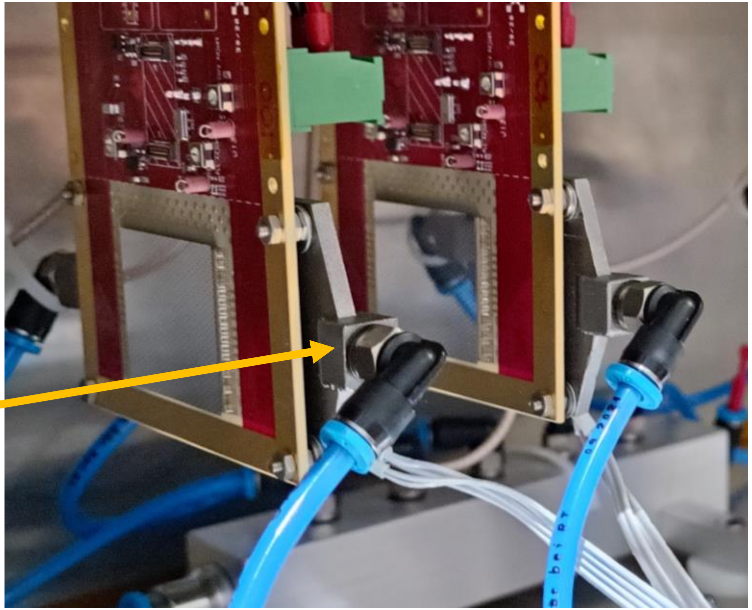
Assemblies and chipboards

- 10 assemlies :
  - Telescope: 4 x 100 µm (timing) and 4 x 300 µm (spatial) All sensors are n-on-p
  - 1 x 50 µm as DUT
  - 1x 300 µm p-on-n (backup sensor)
- All chips/PCBs attached to 3D printed titanium cooling block
- Glycol used to cool chips to about room temperature – ready to go colder

Cooling and interface



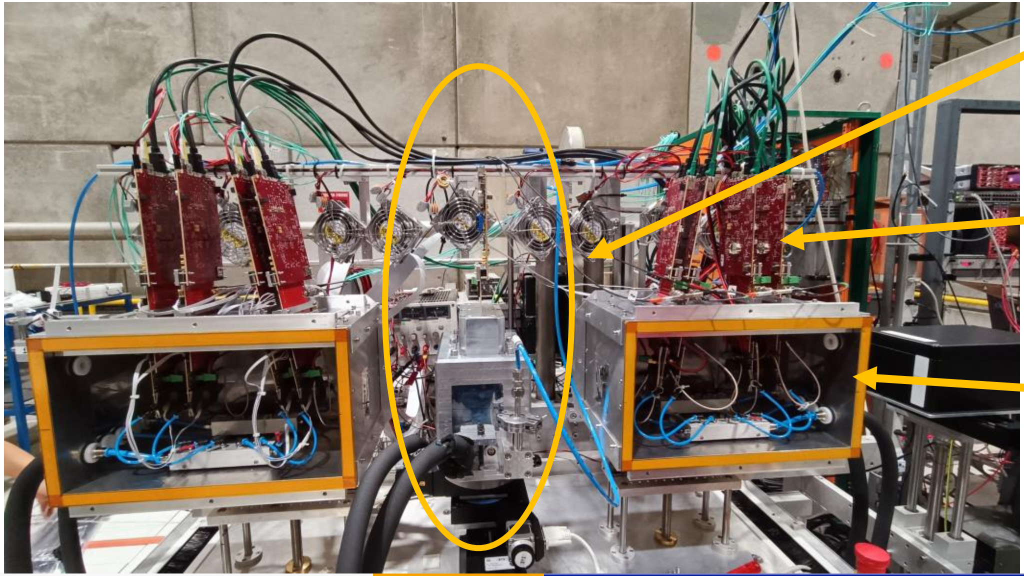




Telescope configuration

8 tracking layers with Timepix4v2 ASICs with sensors from Advacam:

- 4 with 300 µm n-on-p sensors, at 9º pitch/yaw angle for better spatial resolution
- 4 with 100 µm n-on-p sensors, at 0º angle for better time resolution
- 3 Scintillators + constant fraction discriminators & MCP (MicroChanel Plate) + PicoTDC as reference timing
- 50 µm n-on-p sensor as DUT (Device Under Test), in motor stage for angle studies

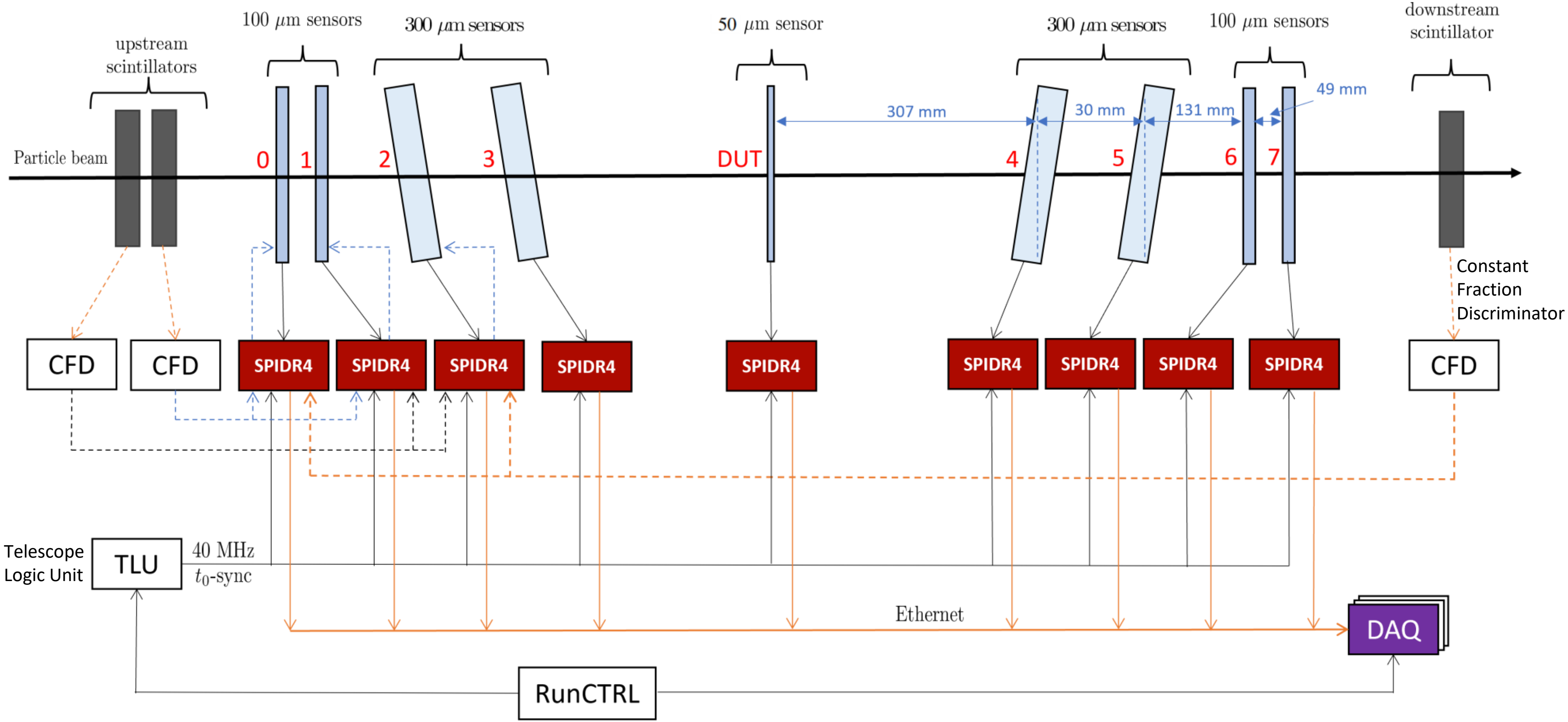


DUT assembly with motion stage

Read out by 9 SPIDR4 systems:
10 Gbit ethernet via fibre

Timepix4 assemblies in gas-tight and light-tight enclosure:
Allows operation at low(er) temperatures (better time resolution)

Schematic view



Last testbeam campaign events

Initially 8 working planes + unstable 50 µm DUT

Power supply spike left us with 7 planes + DUT:

- Data taking with this configuration for temporal and spatial resolution on all sensors

Replacement of unstable 100 µm with a 300 p-on-n

Replacement DUT for a telescope plane for angle studies, 50 µm not included in telescope due to stability issues:

- Final running configuration: 6 planes telescope + DUT
- DUT was swapped with both kind of sensors for angle studies

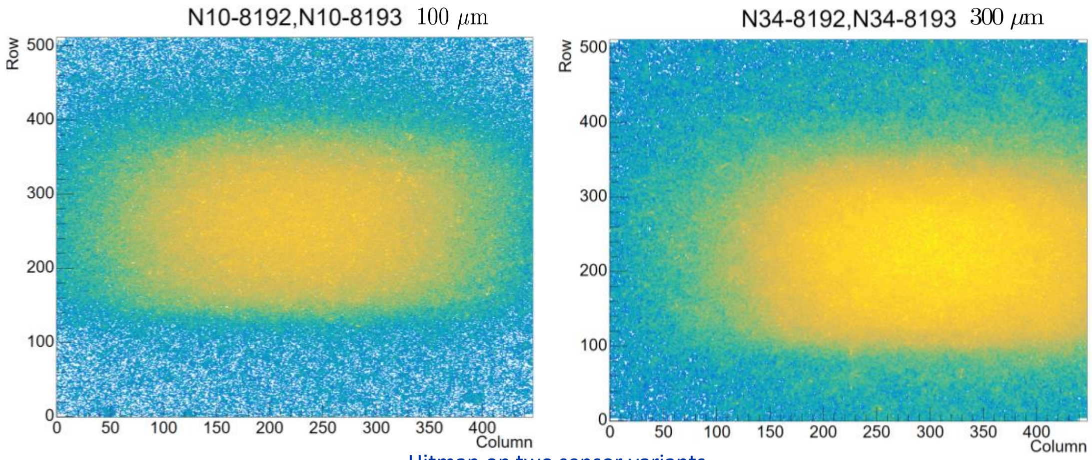
Lost of data from plane 1 due to broken hard drive

- Data available for most of the campaign: 5 planes telescope + DUT

This is still an improvement from previous testbeams and getting closer to the full working telescope!

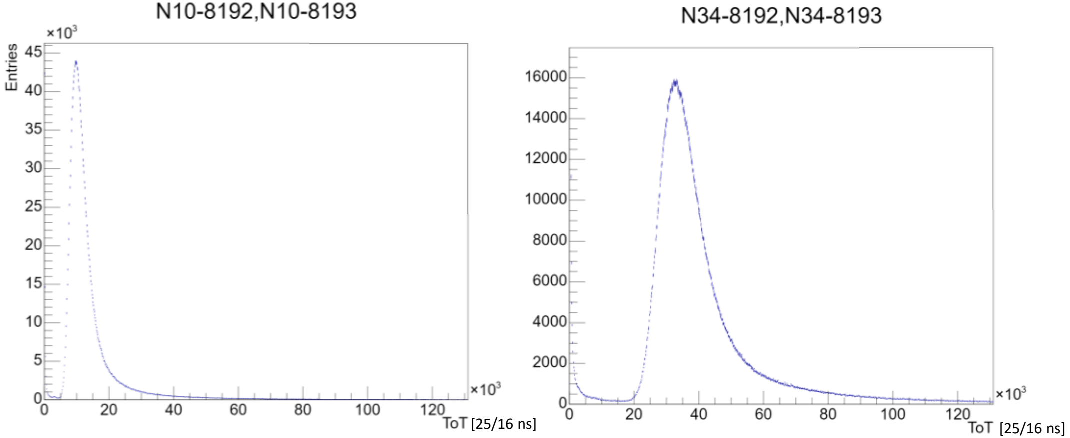
Data Analysis and Results

- Online monitoring to check for performance
- ToT and hitmap look “as expected”
- Offline and online analysis using the LHCb’s Kepler framework.



Hitmap on two sensor variants

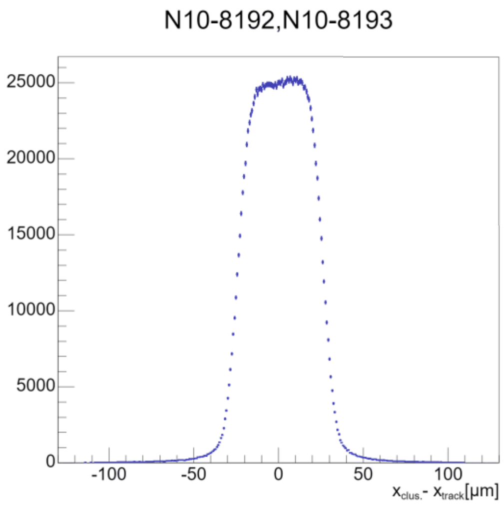
Cluster TOT distribution for the two sensor variants



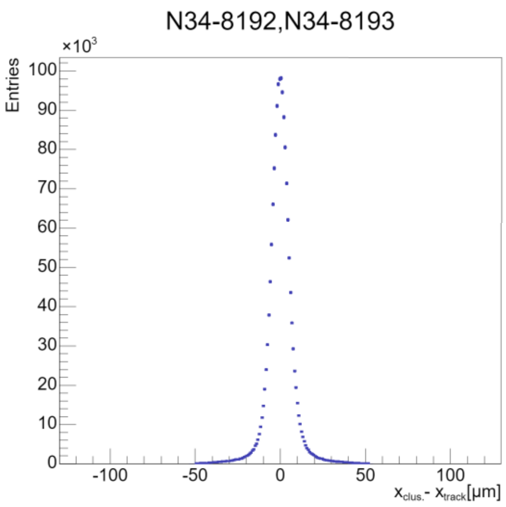
Spatial Residuals

- Unbiased residuals, measured extrapolating tracks made with the rest of the detectors for each run
- 6 planes working for this examples:

  3 x 300 µm & 3 x 100 µm
- The pointing resolution is not subtracted from these values, hence the huge differences



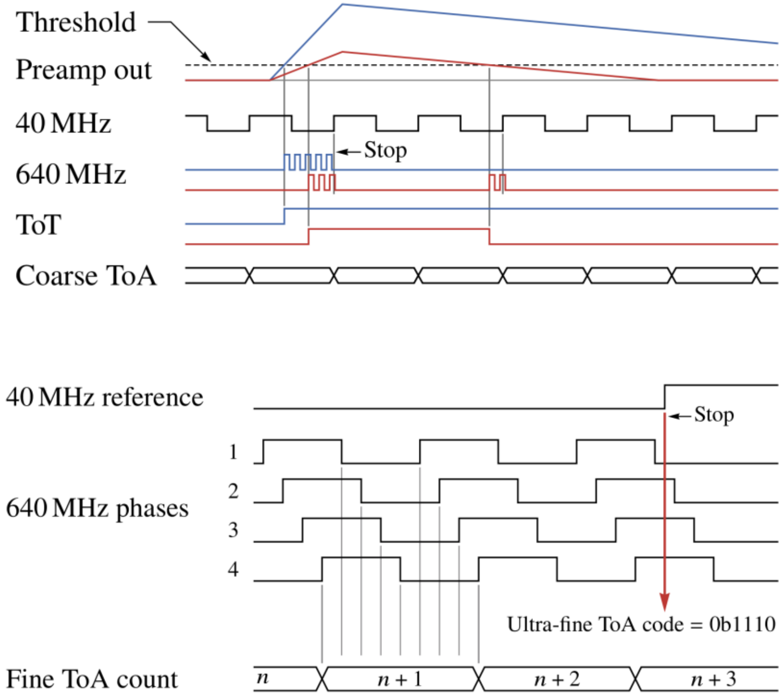
100 µm sensor
Residual dominated by sensor pitch of 0º (not by telescope: 3 thick sensors used in track reconstruction)



300 µm sensor
Residual is mix of sensor and Telescope (only the remaining 2 thick sensors used in track reconstruction)

Temporal measurement

- Base clock of **40 MHz**
- **Hit starts 640 MHz ring oscillator**
  - 1.56 ns bins
  - Count # clock cycles (like in Tpx3)
  - Oscillator shared by 8 pixels in superpixel
- Oscillator is stopped by first rising edge of 40 MHz clock
- In addition the internal state of ring oscillator is captured → 195 ps bins



Time measurements: TPX4v1 vs TPX4v2

- TPX4v1 oscillator ~25% too fast -> 21 FToA bins instead of 16
- TPX4v2 oscillators run at (almost) the design frequency -> Issue fixed in Timepix4v2: 16 fToA bins, as expected

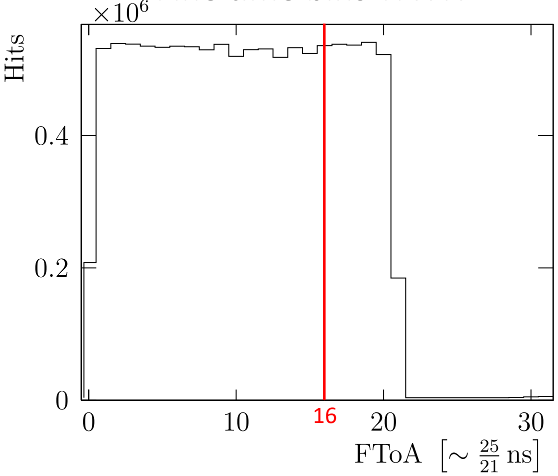
Actually 17 bins, as first and last bin are half the size

Correction factors are still necessary:

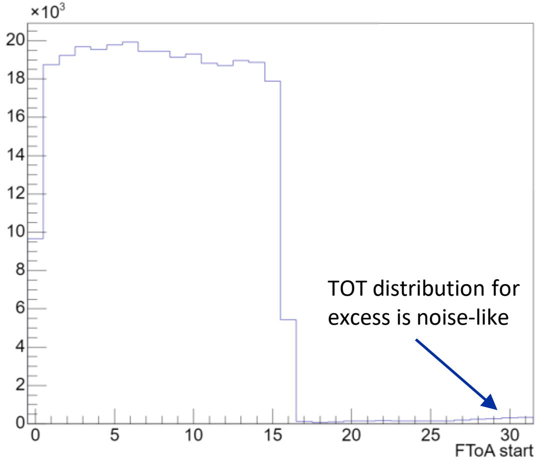
•Small VCO frequency deviations can still worsen the time resolution because of accumulative errors

•Ultrafine time bins not equalized yet

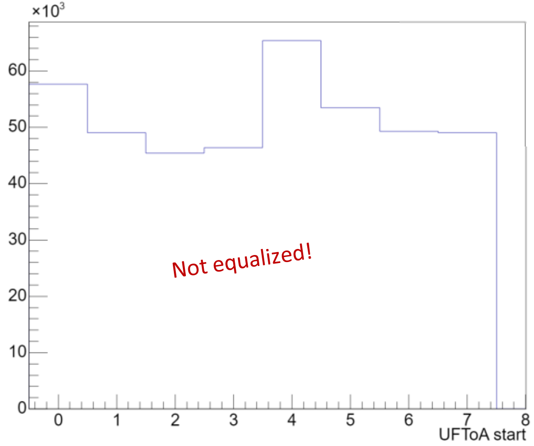
Fine time bins TPX4v1



Fine time bins TPX4v2

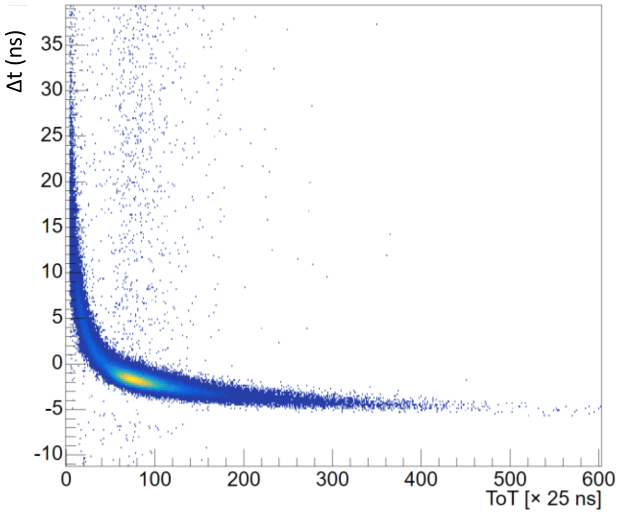


Ultrafine time bins

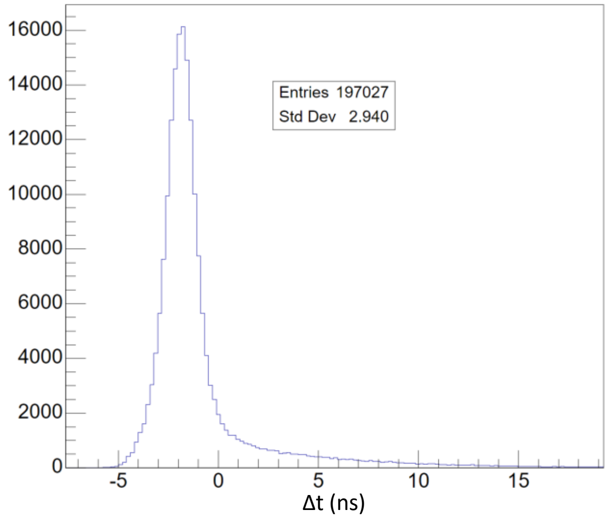


Time resolution

- Time reference = Scintillator : initial value for time resolution (example 100 µm perpendicular plane)
  - Where $\Delta t = t_{scintillator} - t_{hit}$

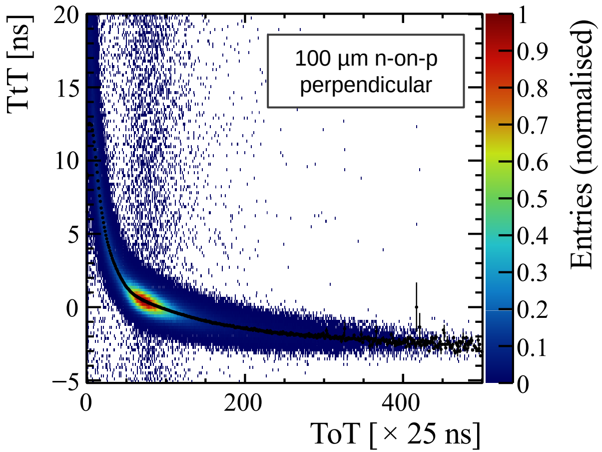


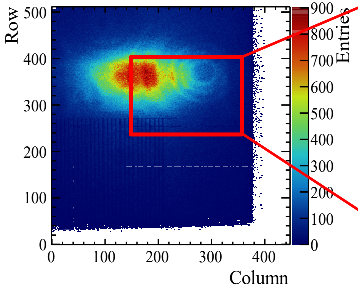
- Projecting the values to the Y axis we can see the time resolution distribution with a raw resolution before any corrections of ~O(3) ns

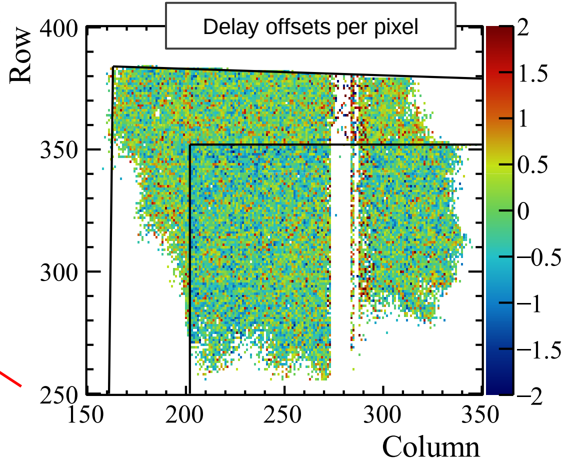


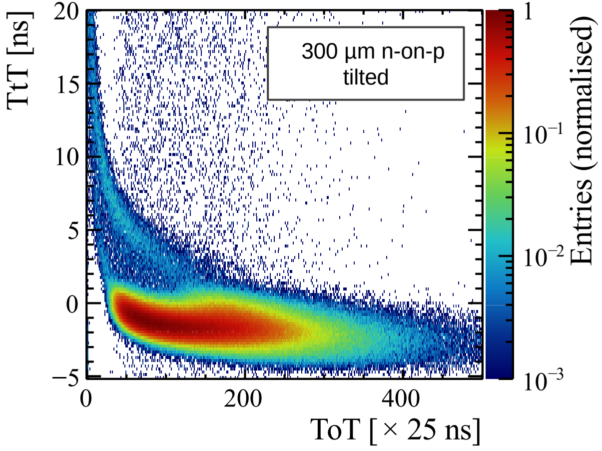
Temporal corrections Timepix4v1

- Timewalk correction applied using Time-to-Threshold (TtT) measurements
  - **Track based timewalk** correction for tilted sensors
- Delay **offsets** per-pixel corrected
- Planned for final telescope: **per-VCO bin** delay correction
  - Needs substantial statistics









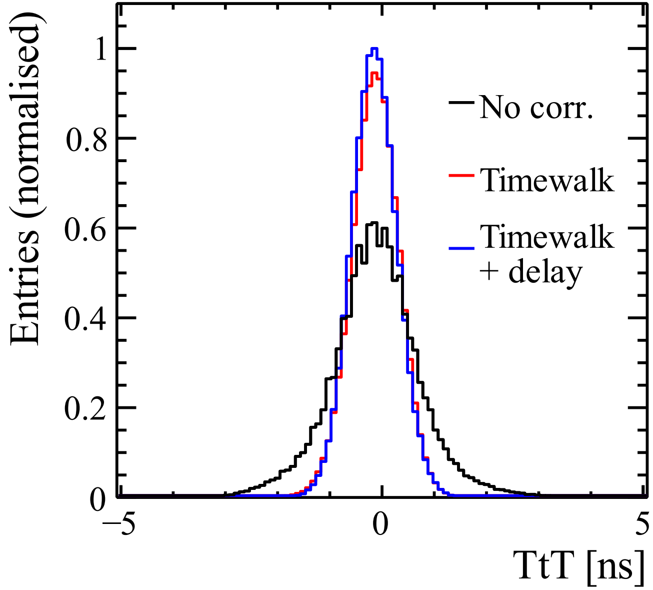
See K. Heijhoff et al., 2020 JINST 15 P09035 for detailed information on track based timewalk and pixel-to-pixel variation corrections

Corrected time resolution (single plane Timepix4v1)

- An example of the corrections:
  - 100 µm n-on-p @ 50 V

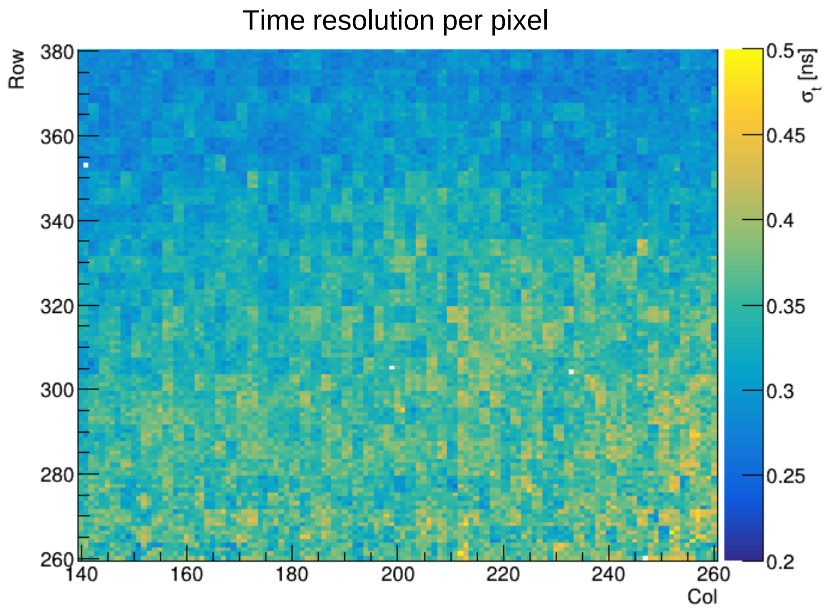
Corrections:	σ_t [ps]
None	789
Timewalk	450
Timewalk + delay offset	439

- **Final goal**: find the best operating condition for **all planes** individually
- Due to lack of time not done for Timepix4v1
- **Best track resolution,** for 4 plane TPX4v1 telescope**,** at nominal threshold and highest bias voltage: **340 ps**



Time resolution variations Timepix4v1

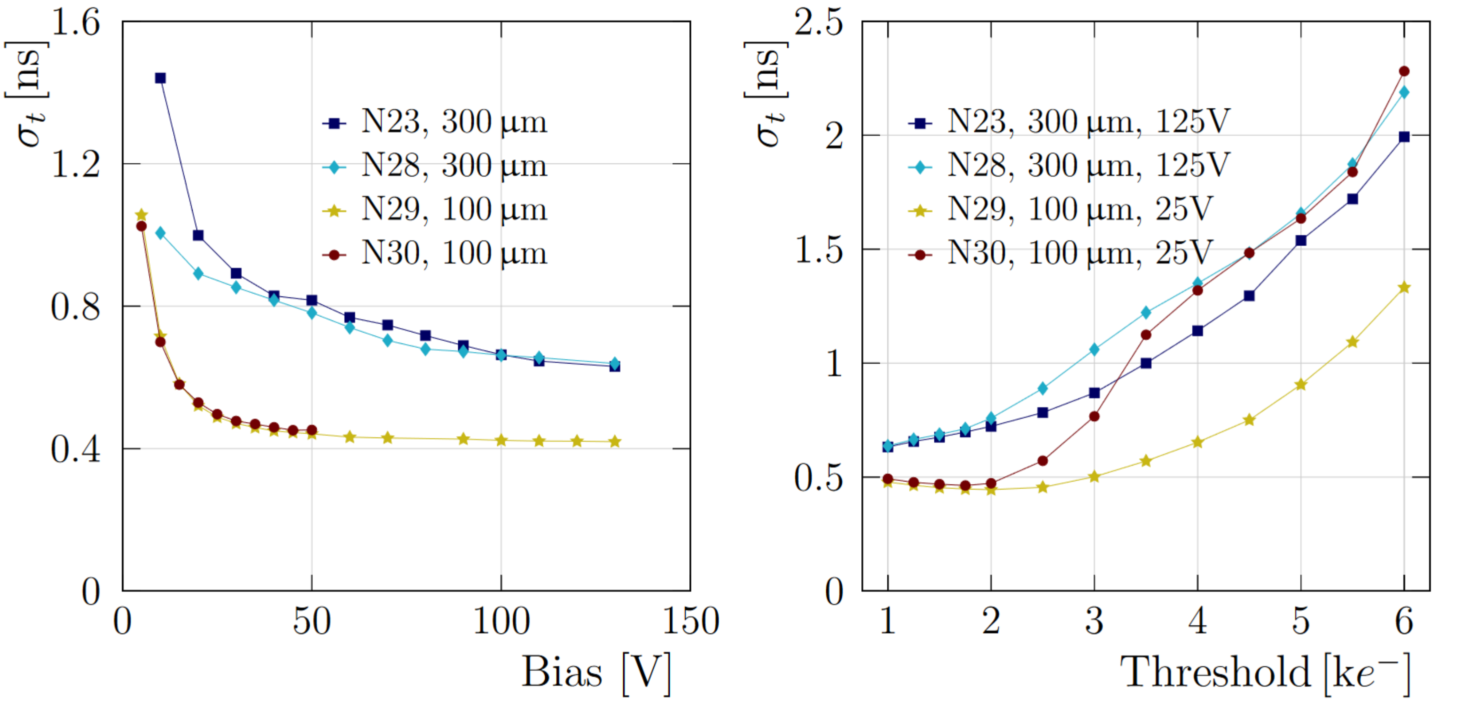
- **Variation** of **time resolution** observed over the matrix
  - From 250 ps to 450 ps over half the chip
- Most likely related to **VCO issue** from Timepix4v1
  - Investigation started, and planned to look at the response of Timepix4v2
- Good hope that **Timepix4v2** will **not have** (or drastically reduced) this variation



Time resolution Timepix4v1

K. Akiba *et al.*, 'Reconstruction of charged tracks with Timepix4 ASICs', *Journal of Instrumentation*, vol. 18, no. 02, p. P02011, Feb. 2023.

Left (right): time resolution of the four telescope planes from 2021 testbeam as a function of the bias voltage (threshold)



Data and analysis plans with 2022 data

Several scans have been performed

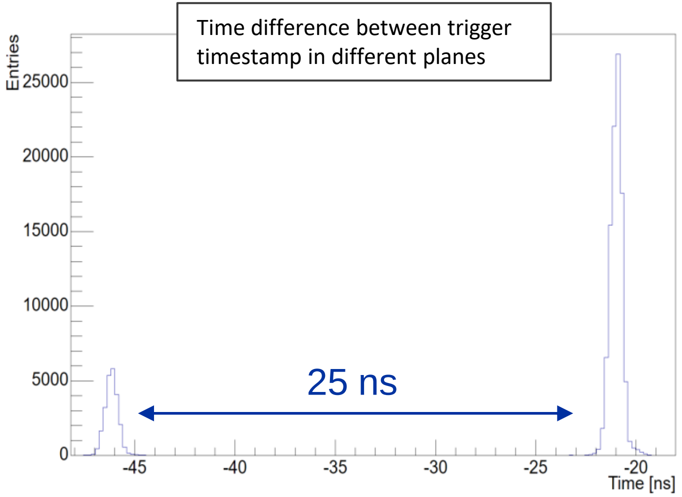
- As DUT
  - Scans over: bias, threshold, Vpreamp and agle
    - 300 µm p-on-n
    - 50 µm n-on-p
    - 100 µm n-on-p
  - 2D scan over bias and angle for a 100 µm n-on-p
- As telescope planes
  - Scans over: bias, threshold and Vpreamp
    - 100 µm n-on-p
    - 300 µm n-on-p

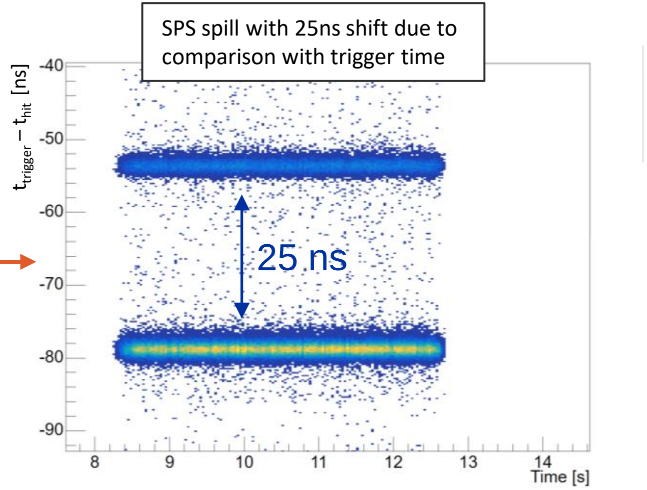
Analysis plans

- Time resolution studies on 50 µm, 100 µm and 300 µm
- Spatial resolution studies on 300 µm
- Telescope configuration for resolution improvement
- Improve time resolution with PicoTDC data from scintillators and MCP

Problems encountered so far

- Shift between planes of 25 ns (equivalent to 40 MHz timepix4 clock)
- Delay offsets per pixel (study ongoing on matrix delay structure)
  - Effect visible after timewalk correction (possible due to delay in matrix edge)





Summary for Timepix4 telescope

Results from Timepix4V1 sensor scans published

Recently performed a beam test with 8 Timepix4v2 sensor planes + DUT

- Stable system for most sensors
- At first glance the data looks good and makes sense
- First tracks with full Timepix4v2 telescope reconstructed
- Very preliminary spatial and time resolution numbers

Analysis ongoing, and planning on:

- Improve the time resolution of reference signal: MCPs + PicoTDC < 20 ps ?
- Studies on different telescope configurations for resolution optimization

Getting ready for a full, and stable, 8 planes telescope this year

People directly or indirectly involved in 2022 test beam

Test beam crew:

Nikhef: Robbert Geertsema, Kazu Akiba, Kevin Heijhoff, Martin van Beuzekom, Daan Oppenhuis

CERN: Victor Coco, Raphael Dumps, Wiktor Byczynski

IGFAE: Efrén Rodríguez Rodríguez, Edgar Lemos Cid

Dortmund university: Elena Dall'Occo, David Rolf

Manchester University/CERN: Tim Evans

Oxford University: Tommaso Pajero, Rui Gao, Fernanda Goncalves Abrantes

And of course people from the Timepix4 and SPIDR4 design teams in general and especially: Xavi, Vladimir, Bas, Vincent, Henk, Martin F.

Thank you for your attention

Questions?

Backup

Tpx3/Tpx4

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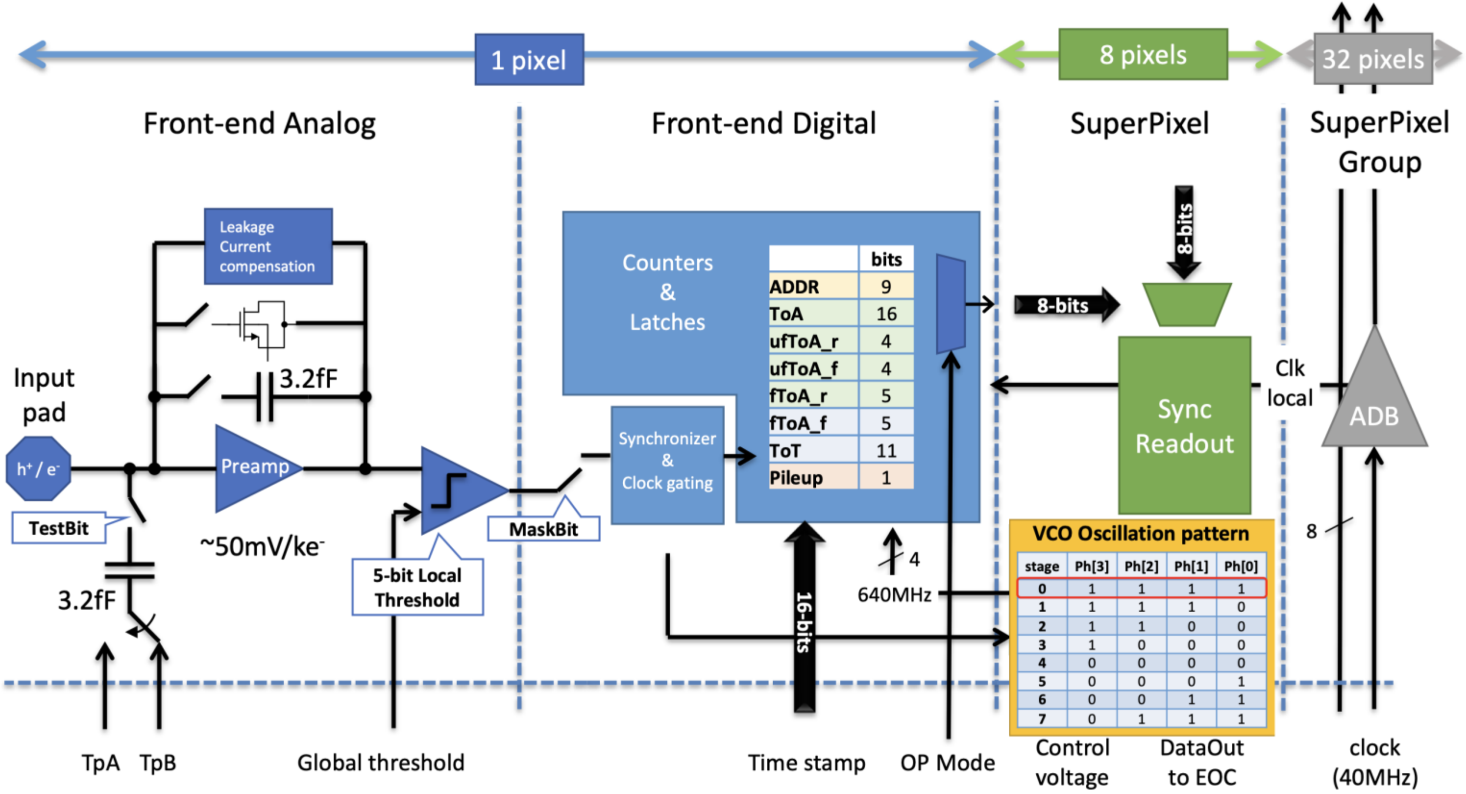
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)
		Max count rate	~0.82 x 10^9 hits/mm^2/s	~5 x 10^9 hits/mm^2/s
TOT energy resolution			< 2KeV	< **1Kev**
TOA binning resolution			1.56ns	**195ps**
TOA dynamic range			409.6 μs (14-bits @ 40MHz)	**1.6384 ms** (16-bits @ 40MHz)
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps (16x @10.24 Gbps)**
Target global minimum threshold			<500 e^-	<500 e^-

Timepix4 pixel architecture



stage	Ph[3]	Ph[2]	Ph[1]	Ph[0]
0	1	1	1	1
1	1	1	1	0
2	1	1	0	0
3	1	0	0	0
4	0	0	0	0
5	0	0	0	1
6	0	0	1	1
7	0	1	1	1

Timepix4 versions

Q4 2019

Timepix4v0

Full mask engineering run

6 wafers received

Chip is operational

1) Excess noise coupling from peripheries to FE
2) 640 MHz clock in edge peripheries
3) VCO not oscillating at nominal frequency

Q3 2020

Timepix4v1

4 BEOL masks changed

Small test VCO chip

6 wafers received

1) Improved RDL shielding in peripheries
2) 640MHz in peripheries recovered

1) VCO not oscillating at nominal frequency

Q2 2021

Timepix4v2

4 FEOL + 4 BEOL masks changed

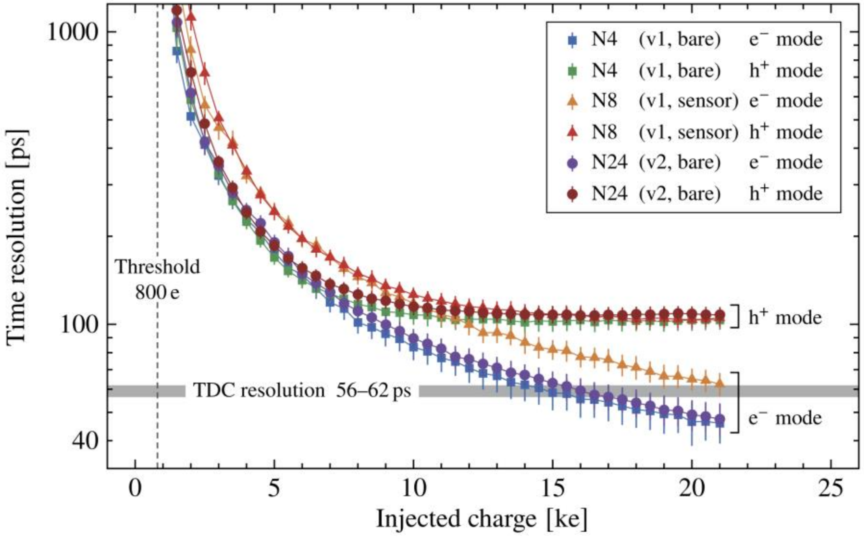
19 wafers received

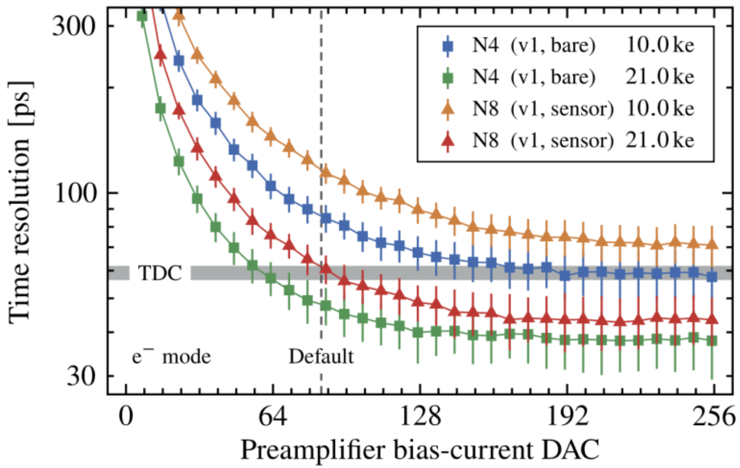
1) TDC and High speed links working as expected
2) Further improvement in RDL shielding in peripheries

Chip at its final version

Time resolution of analog front-end, lab measurement (Timepix4v1)

- Timepix4 suited for electron and hole collecting sensors
- Optimized for electron-collecting mode

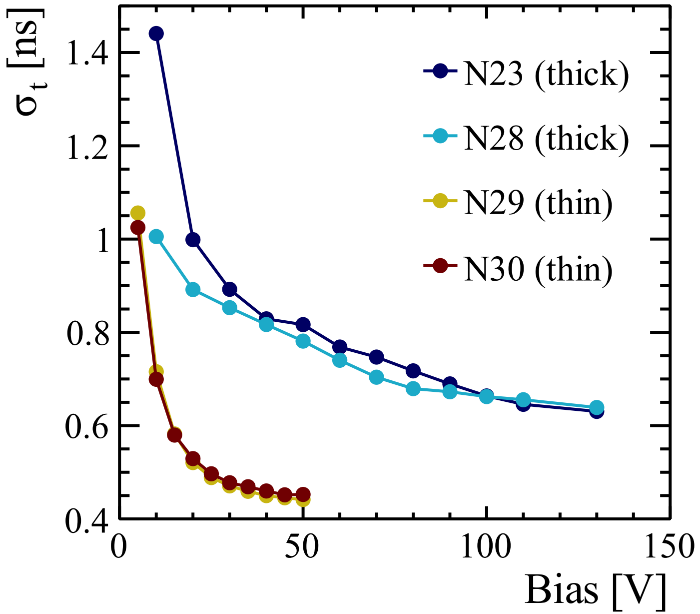




- Front-end time resolution depends on settings
- (Somewhat) better time resolution can be achieved at the cost of power

Time resolution vs bias voltage (Timepix4v1)

- Current configuration does **not** allow to **change** the bias for each plane **separately**
- Currently only a bias scan:
  - Thick (300 µm sensor) tilted
  - Thin (100 µm sensor) perpendicular
  - **Best time resolution** found at **highest bias voltages**
- Bigger contributions might obscure further improvements for the thin sensors



Time drift between planes Timepix4v1

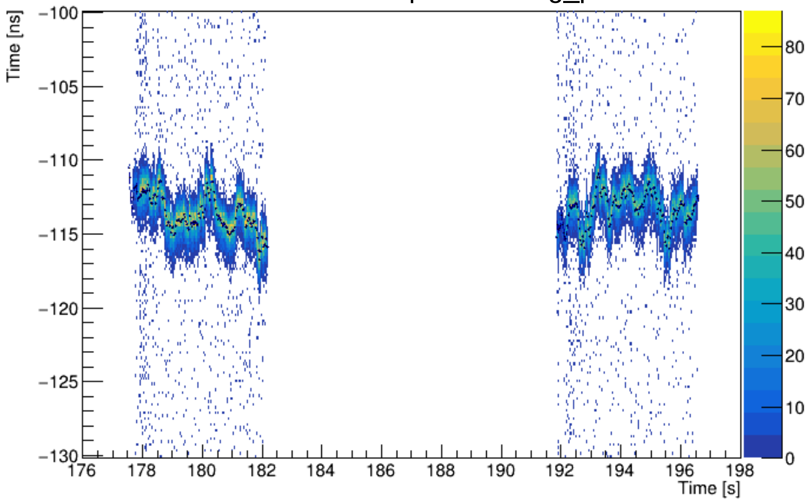
Scintillator hit timestamped by one plane, hits from other plane

Observed time drift of ns between different planes; change at millisecond scale

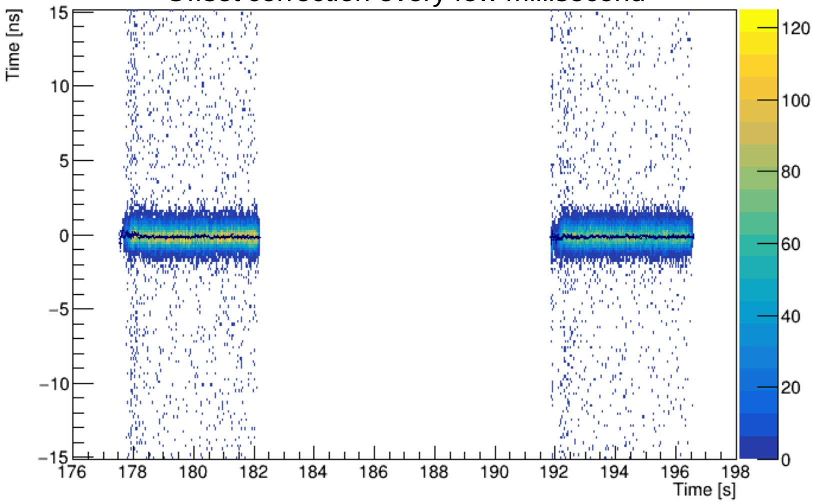
Seems to be caused by clock jumps, and the response of the SPIDR4 PLLs

Still under investigation, but clearly need to improve clock stability & distribution

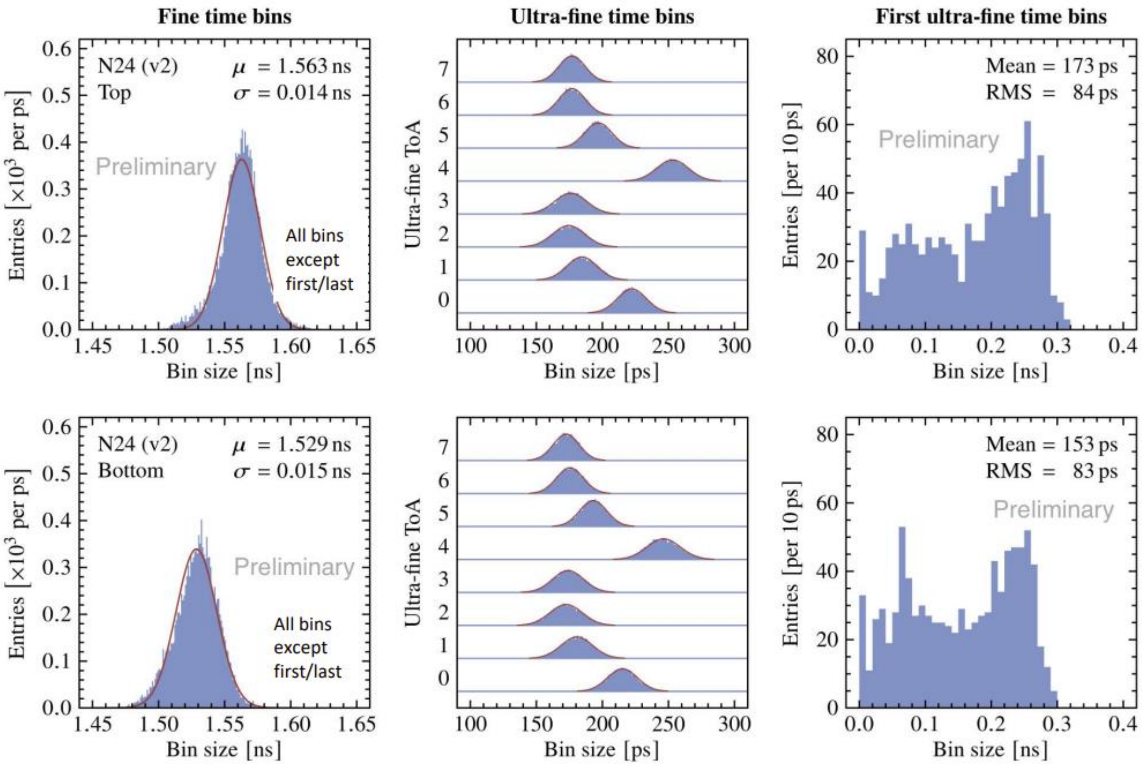
Time difference hits plane0 – trig_plane1



Offset correction every few millisecond



Timepix4v2: fToA and ufToA distributions



- Data from top and bottom row superpixels
- Mean fToA bins size close to expectation
- Small standard deviation
- Difference between top and distributions is small
- But nonetheless corrections will make a difference for the time resolution

Why corrections are required

K. Heijhoff, et al. "Timing performance of the Timepix4 front-end". *Journal of Instrumentation* 17. 07(2022): P07006.

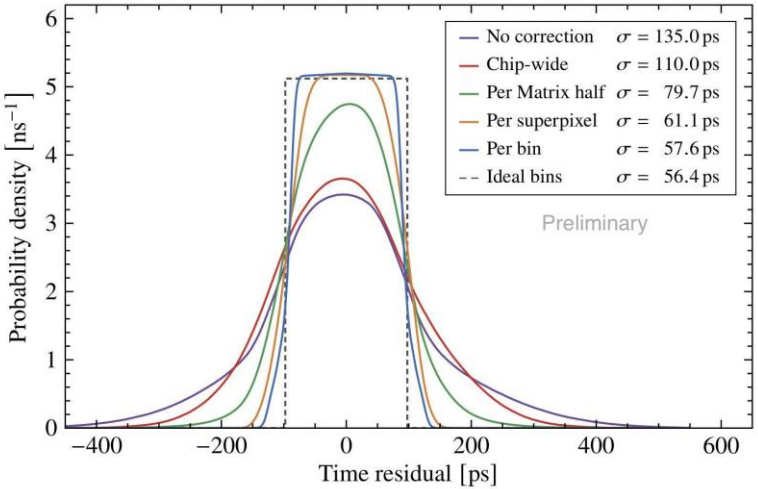
- Time of arrival is calculated with:

$$t_{\mathrm{hit}} = \left(\mathrm{cToA} - \frac{\alpha}{16}\,\mathrm{fToA} - \frac{\alpha}{128}\,\mathrm{ufToA}\right) 25\,\mathrm{ns} + \Delta t_{\mathrm{pixel}}$$

  - Where α is a per pixel correction factor
  - And Δt_{pixel} is time offset of pixel, which is assumed to be calibrated out

- Chip-wide, per half and per superpixel corrections are worth the effort

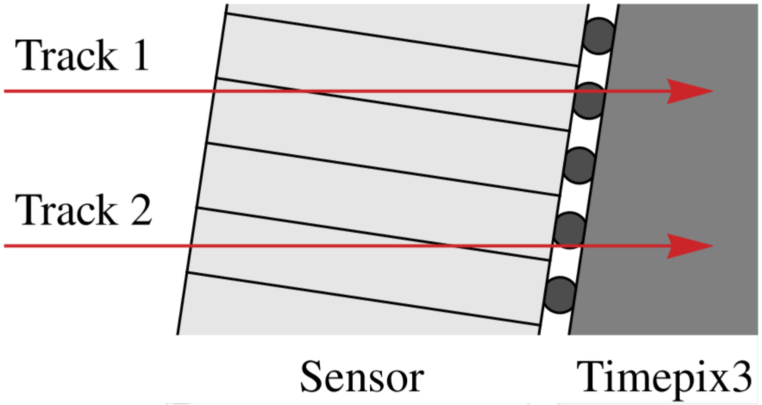
- Per bin corrections will only give only ~6 % improvement
  - While the number of correction parameters increases by a factor 8, 64, or even 1024

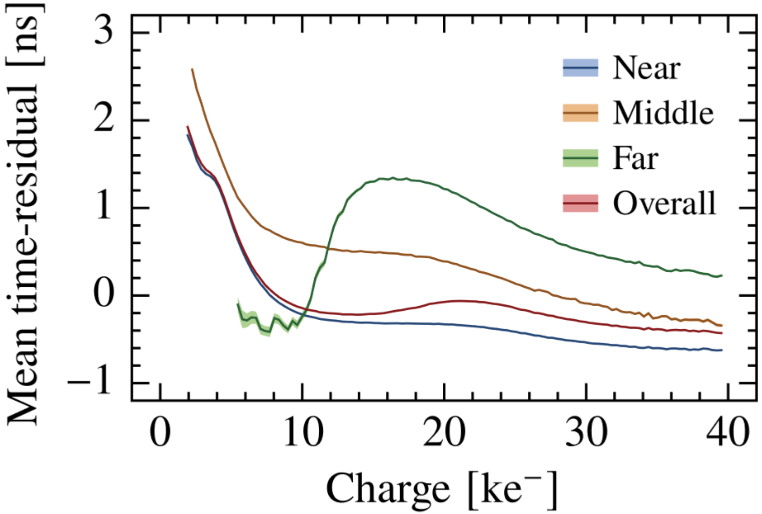


(i) no correction: $\alpha \rightarrow 1$,
(ii) chip-wide: $\alpha \rightarrow \alpha_{\mathrm{chip}}$,
(iii) per matrix half: $\alpha \rightarrow \alpha_{\mathrm{bottom/top}}$,
(iv) per superpixel: $\alpha \rightarrow \alpha_{\mathrm{superpixel}}$,
(v) per time bin: $\alpha \rightarrow \alpha_{\mathrm{bin}}$.

Track based timewalk correction

For detailed information see K. Heijhoff et al., 2020 JINST 15 P09035





Alignment results