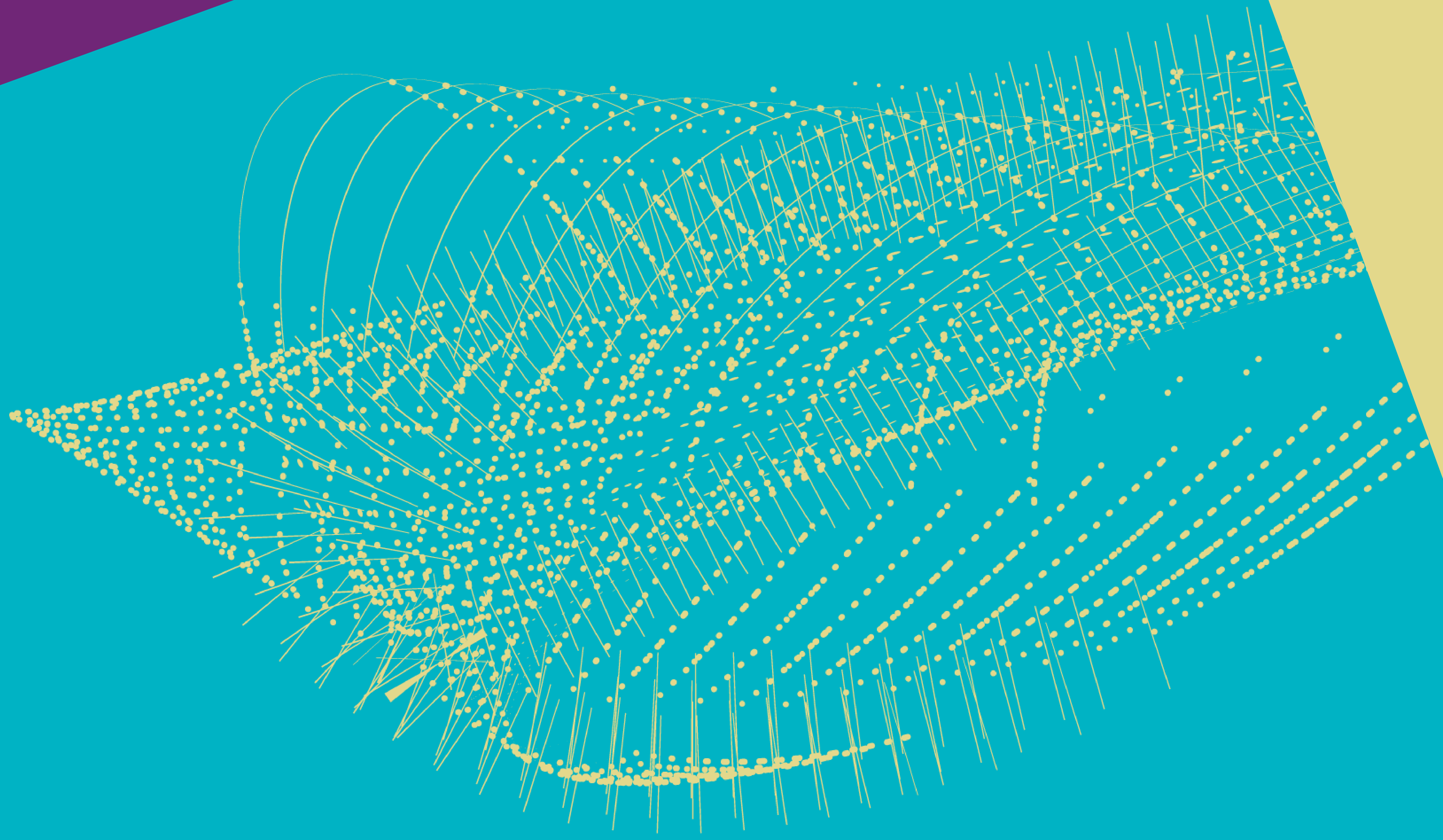
Kevin Heijhoff



Timepix3 Telescope Temporal Resolution Studies

IEEE NSS MIC
Manchester 2019

Introduction

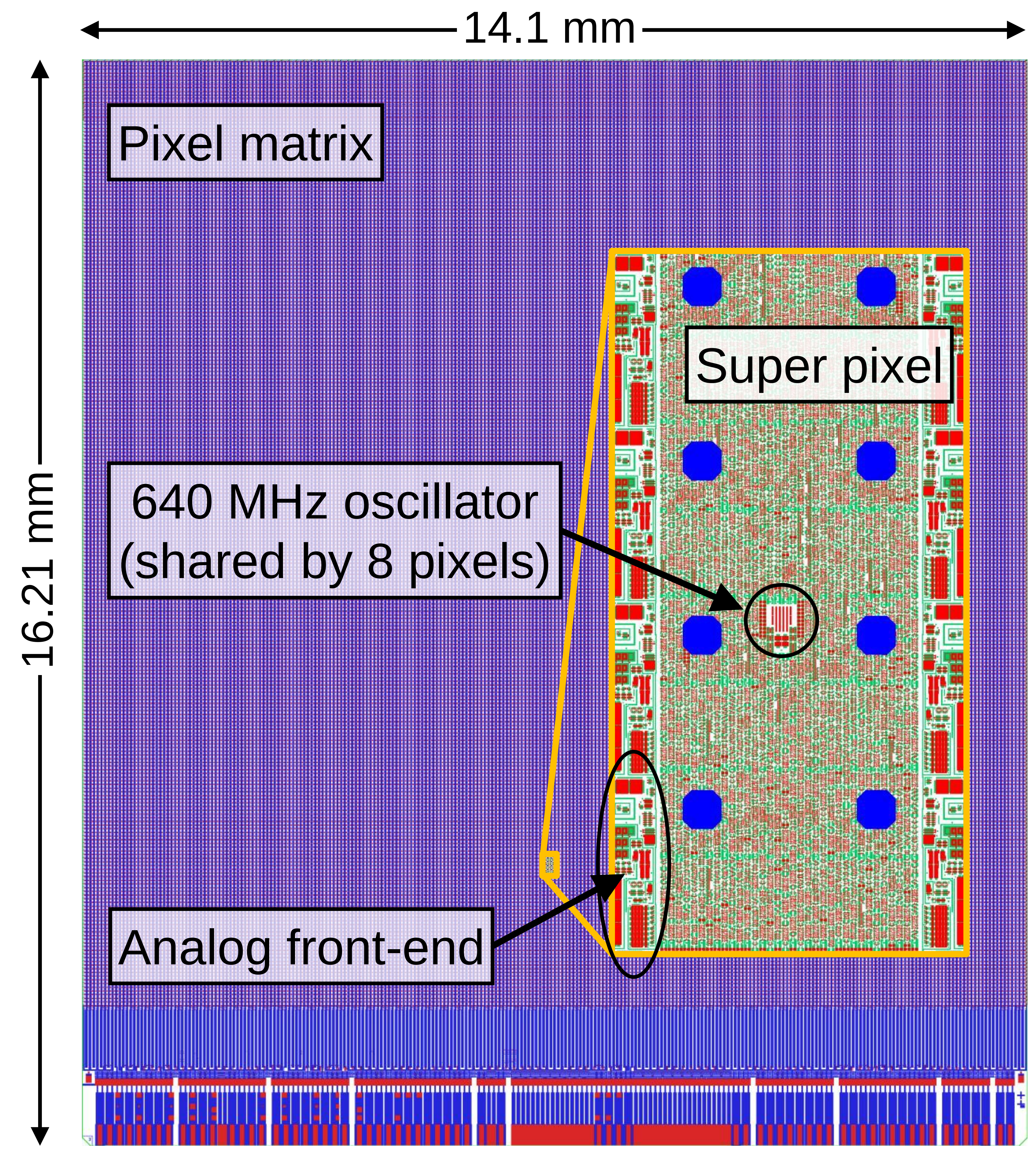
- Timepix3 Telescope built to perform detailed studies of LHCb VELO Upgrade prototypes
  - Optimised for spatial resolution
  - Timing mainly used for pattern recognition

- Future upgrades in view of 4D tracking at high rate
  - Need good temporal- and spatial resolution

- While “waiting” for Timepix4, study systematics and limits of Timepix3 telescope
  - What is the track time resolution?
  - Can we improve it? → Need to understand systematics

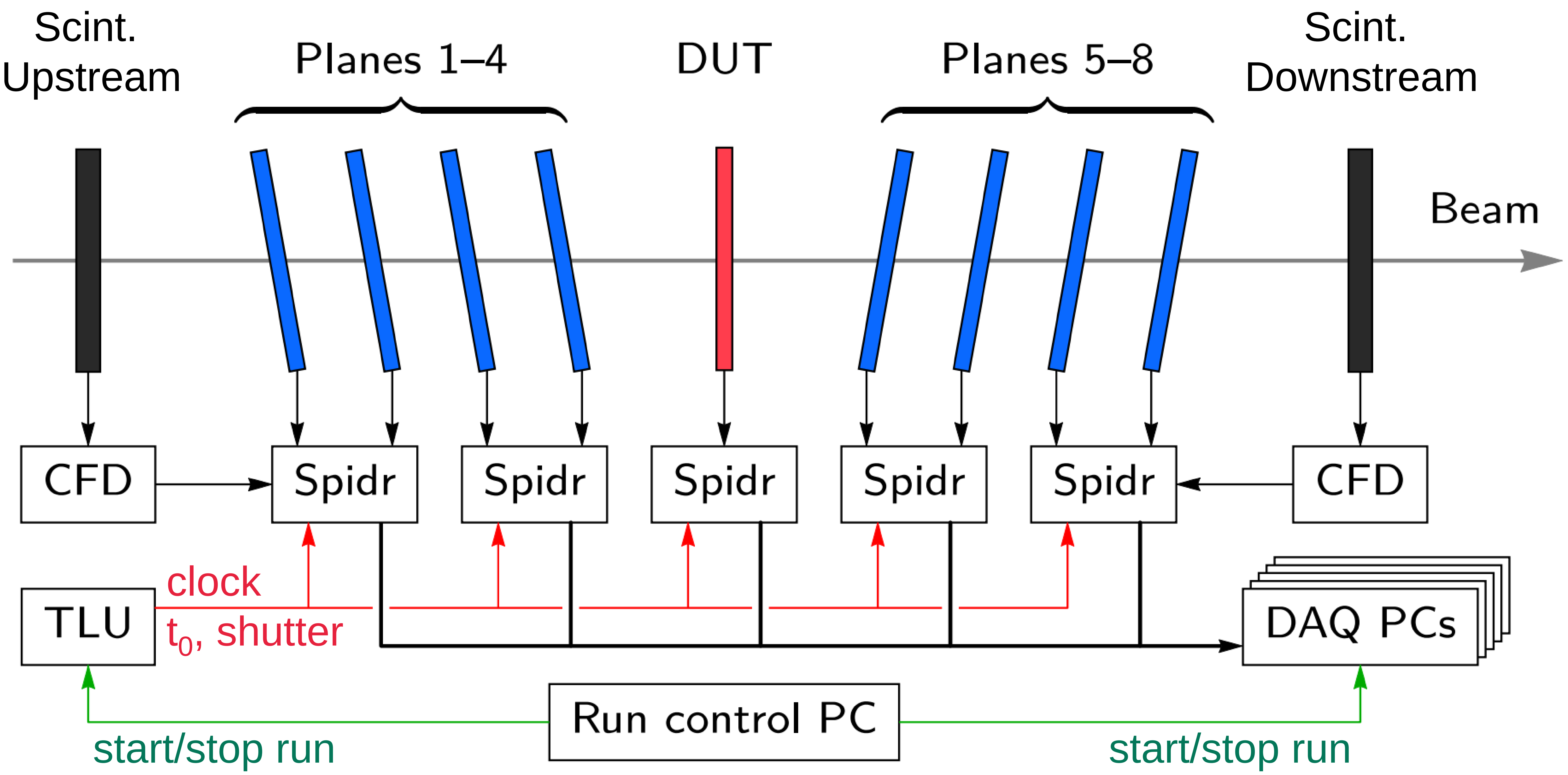
Timepix3 ASIC

- 256×256 Matrix, 55 µm pitch
- Simultaneous measurement of time and charge deposition
- Time-bin size of 25 ns/16 ≈ **1.56 ns**
- 130 nm CMOS
- From 2013



Timepix3 telescope

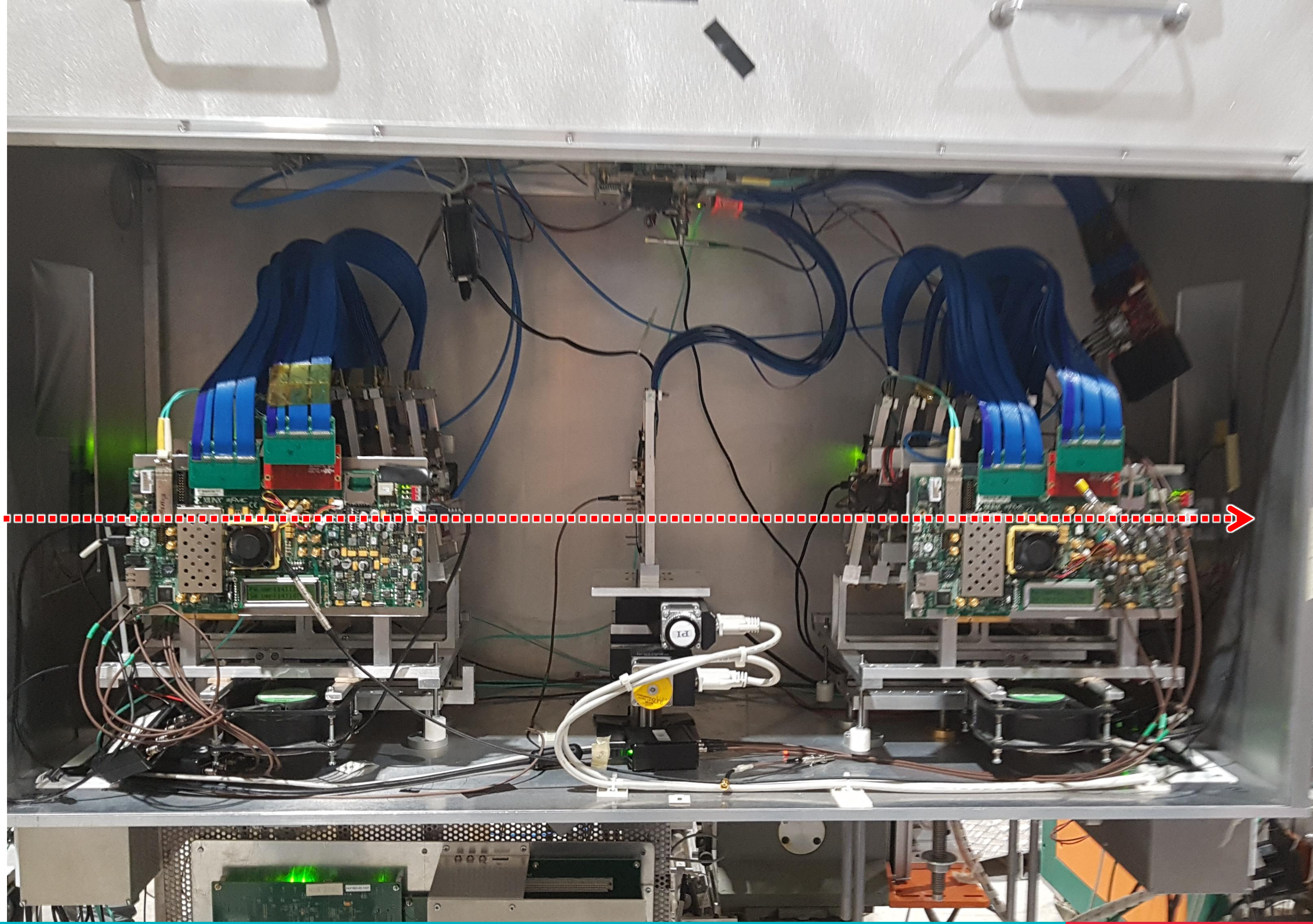
- Eight layers Timepix3 with 300 µm p-on-n Si at 200 V
- Scintillators provide a reference time
- Constant fraction discriminators (CFDs) reduce timewalk effects
- All planes run on a common 40 MHz clock

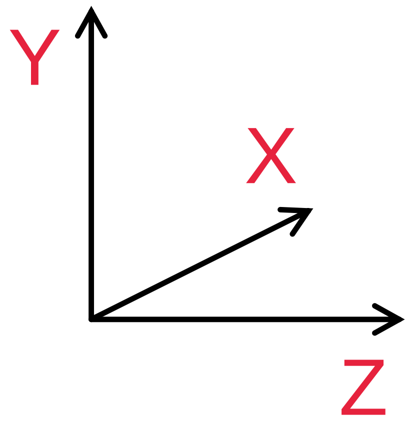


Timepix3 telescope

- Planes rotated in X and Y to optimise spatial resolution

- Pointing resolution at DUT (device under test):
  $\sigma_x = 1{,}69(16)\ \mu\text{m}$
  $\sigma_y = 1{,}55(16)\ \mu\text{m}$





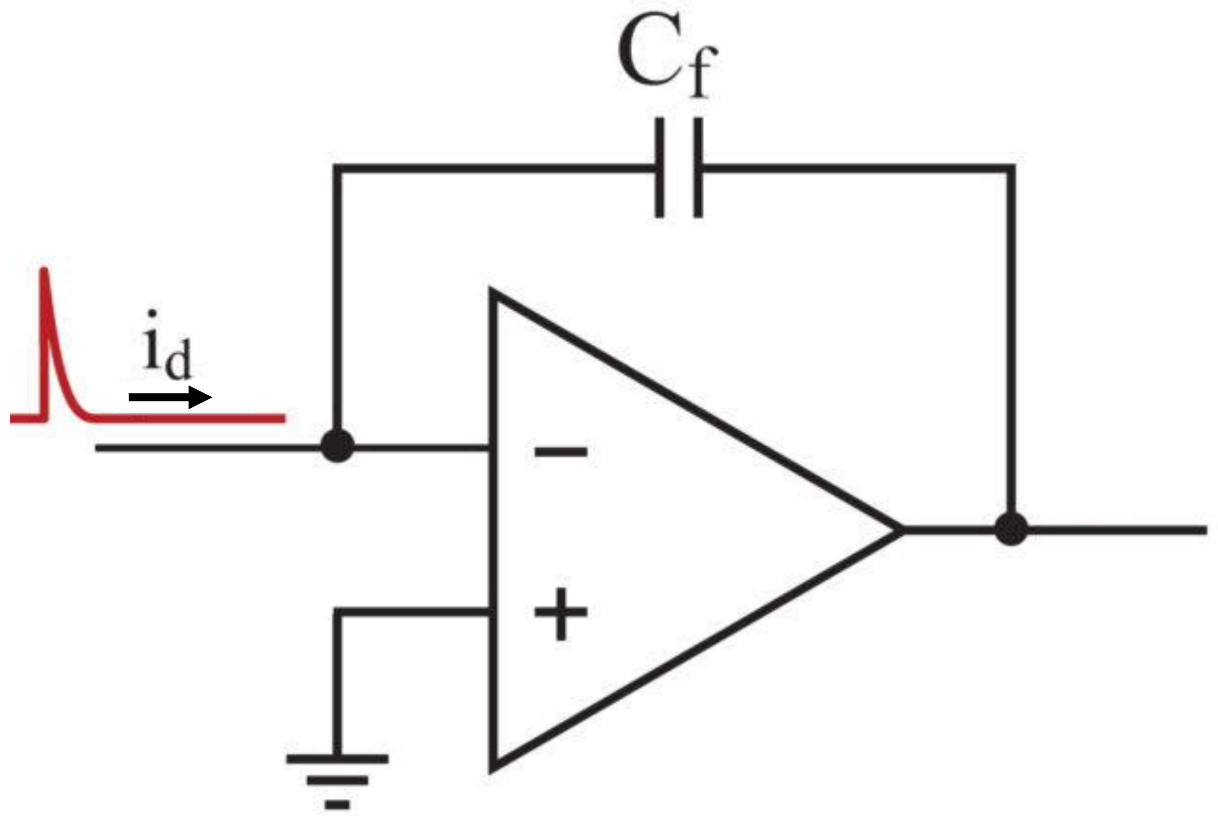
LHCb VELO Timepix3 telescope
K. Akiba *et al* 2019 *JINST* **14** P05026
DOI: 10.1088/1748-0221/14/05/P05026

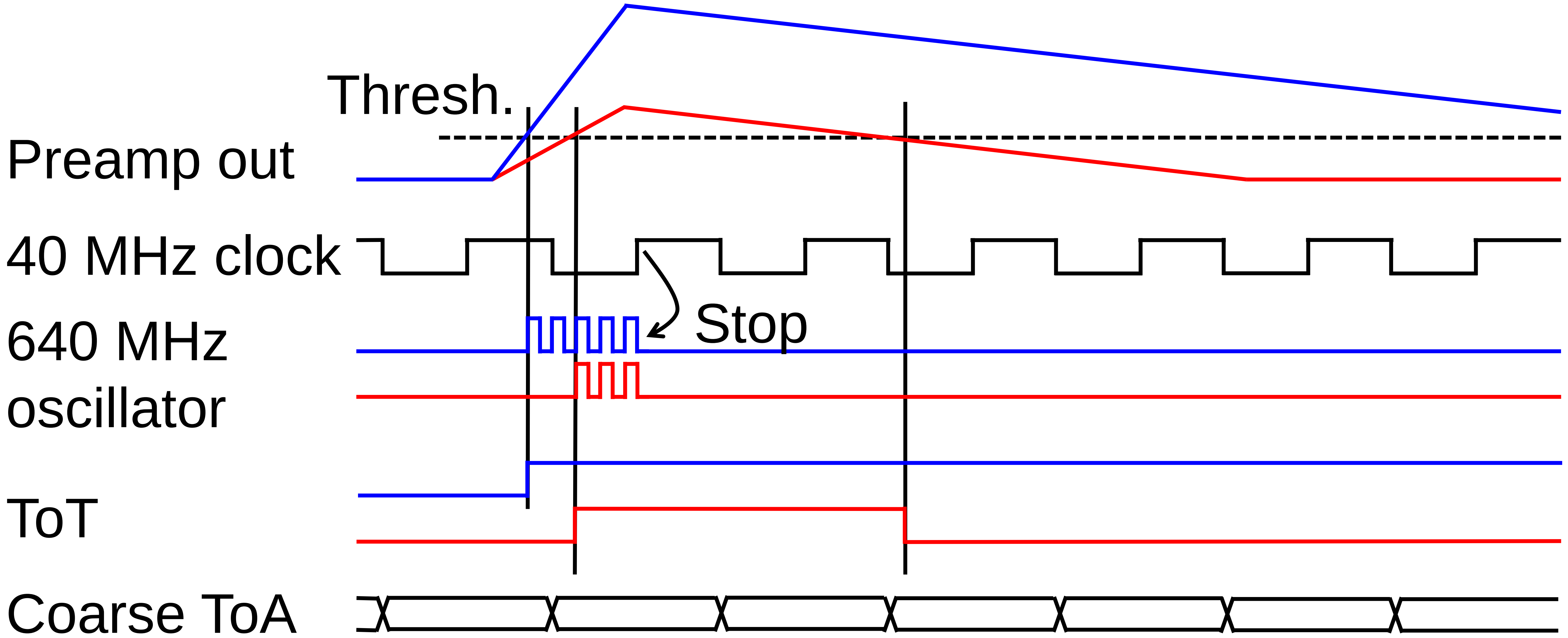
Timepix3 time measurement

- 640 MHz oscillator
  - Started by discriminator
  - Counted until 40 MHz rising edge
- **1.56 ns** time bins for time-of-arrival (**ToA**)
  - bin/$\sqrt{12}$ = 451 ps TDC resolution (in addition to front-end jitter)
- Time-over-threshold (**ToT**) measures the input charge of the signal
  - Uses 40 MHz: 25 ns bin size

Systematic effects

- Timewalk from charge fluctuations
- Variations in the 640 MHz oscillator
  - Start-up time
  - Frequency





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Time resolution without corrections

- Resolution from covariance of residuals w.r.t. two uncorrelated references (the scintillators):

$$\sigma(t) = \sqrt{\mathrm{var}(t - t_{\mathrm{real}})} \equiv \sqrt{\mathrm{cov}\left(t - t_{\mathrm{up}}, t - t_{\mathrm{down}}\right)}$$

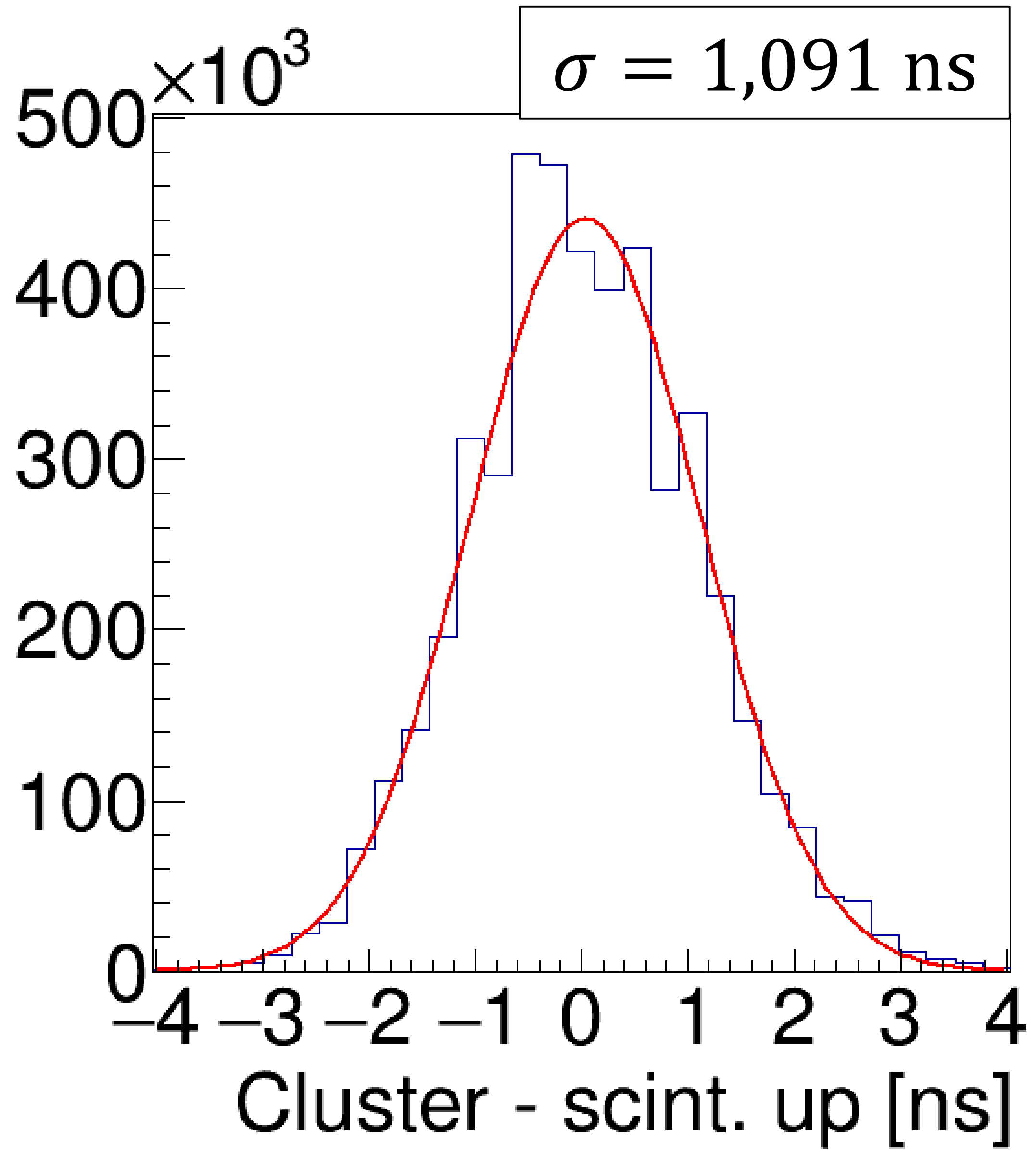
- Scintillator resolution:
  Upstream: ~390 ps ← CFD not properly tuned
  Downstream: ~190 ps ← All residual plots are w.r.t. this scint.

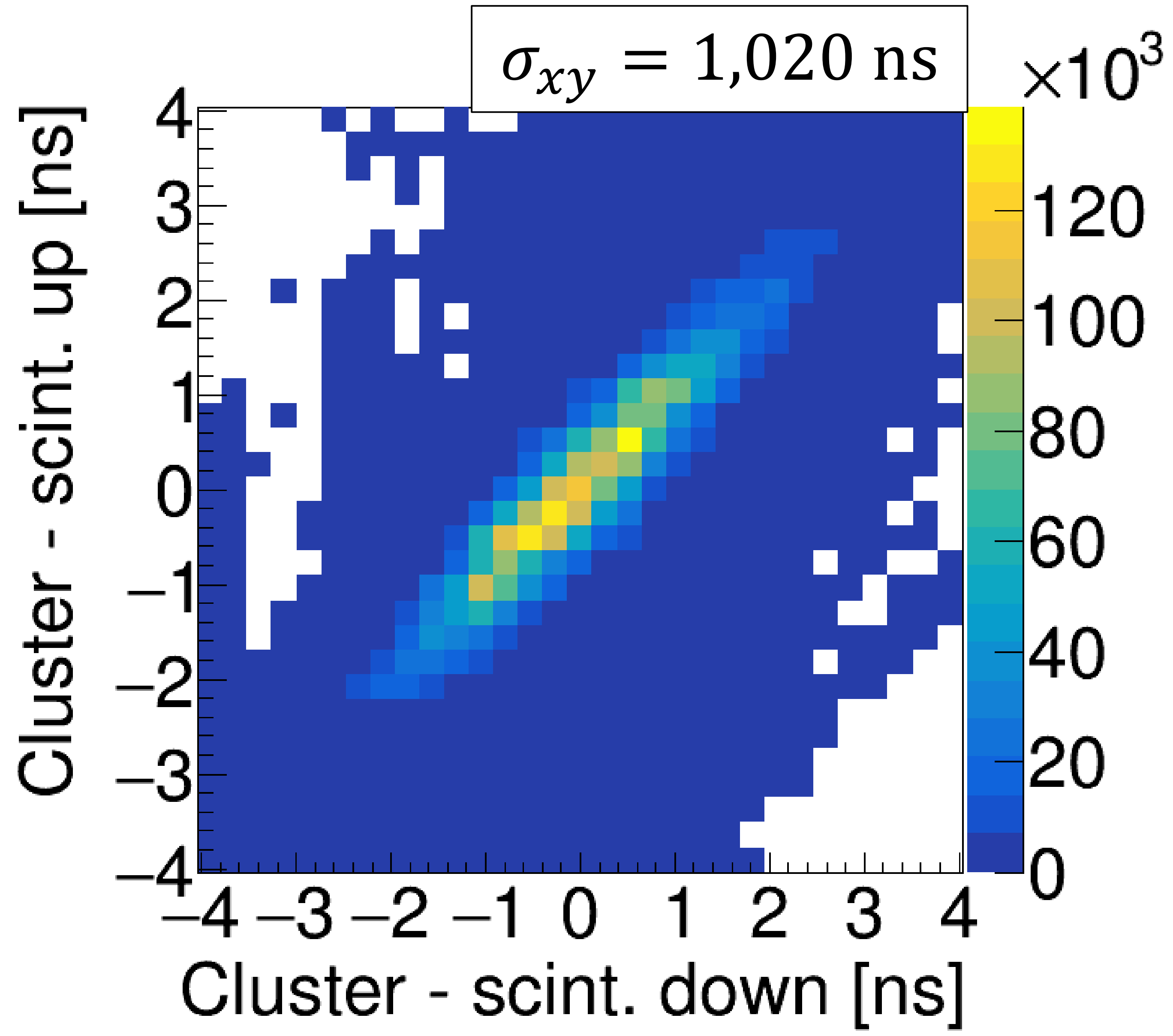
- Cluster time (earliest hit in cluster) resolution: $1\ \mathrm{ns}$

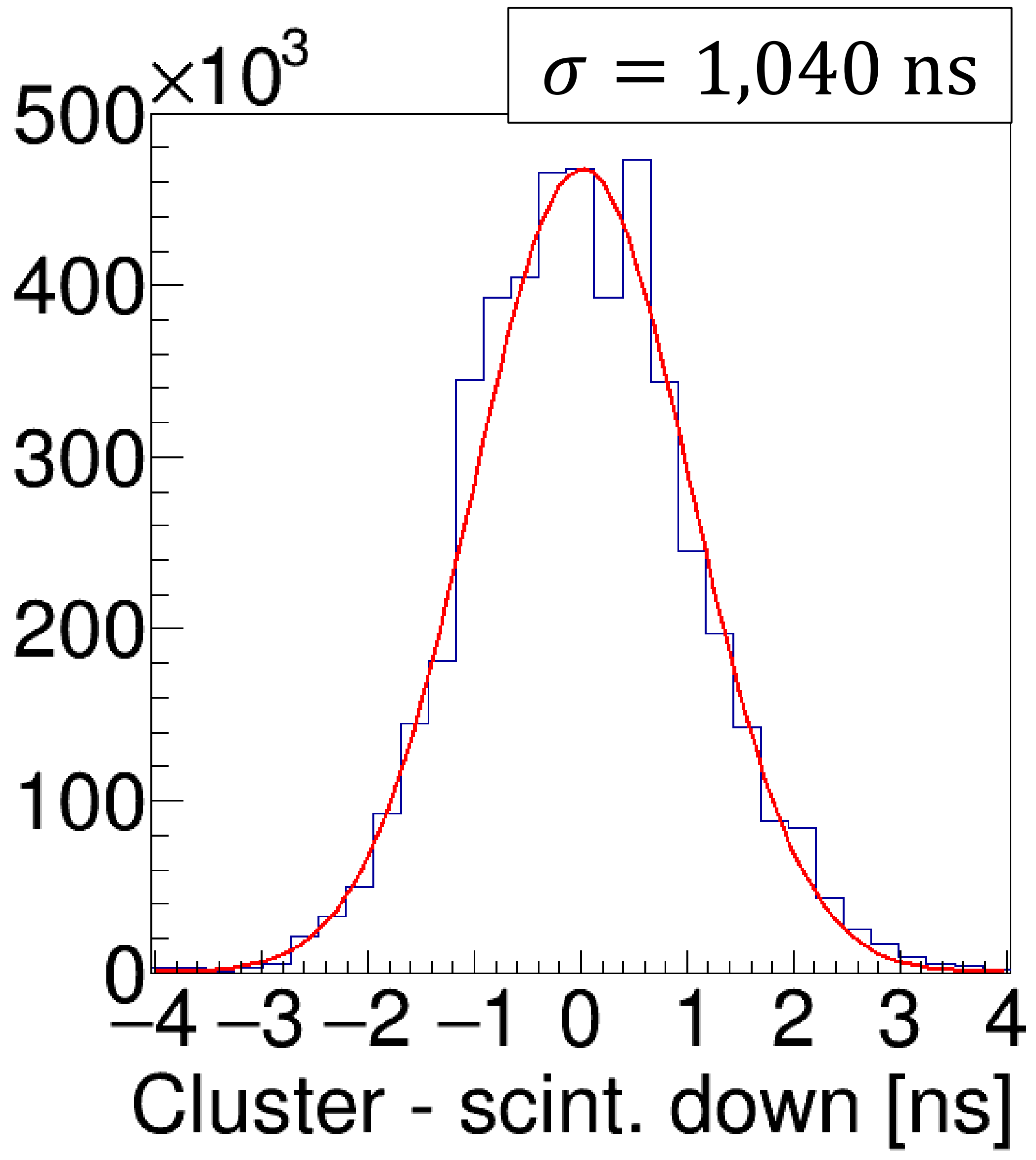
- Track time resolution: $450\ \mathrm{ps}$

- For uncorrelated measurements, would expect $\frac{1\ \mathrm{ns}}{\sqrt{8}} = 350\ \mathrm{ps}$

  ↖ 8 telescope planes







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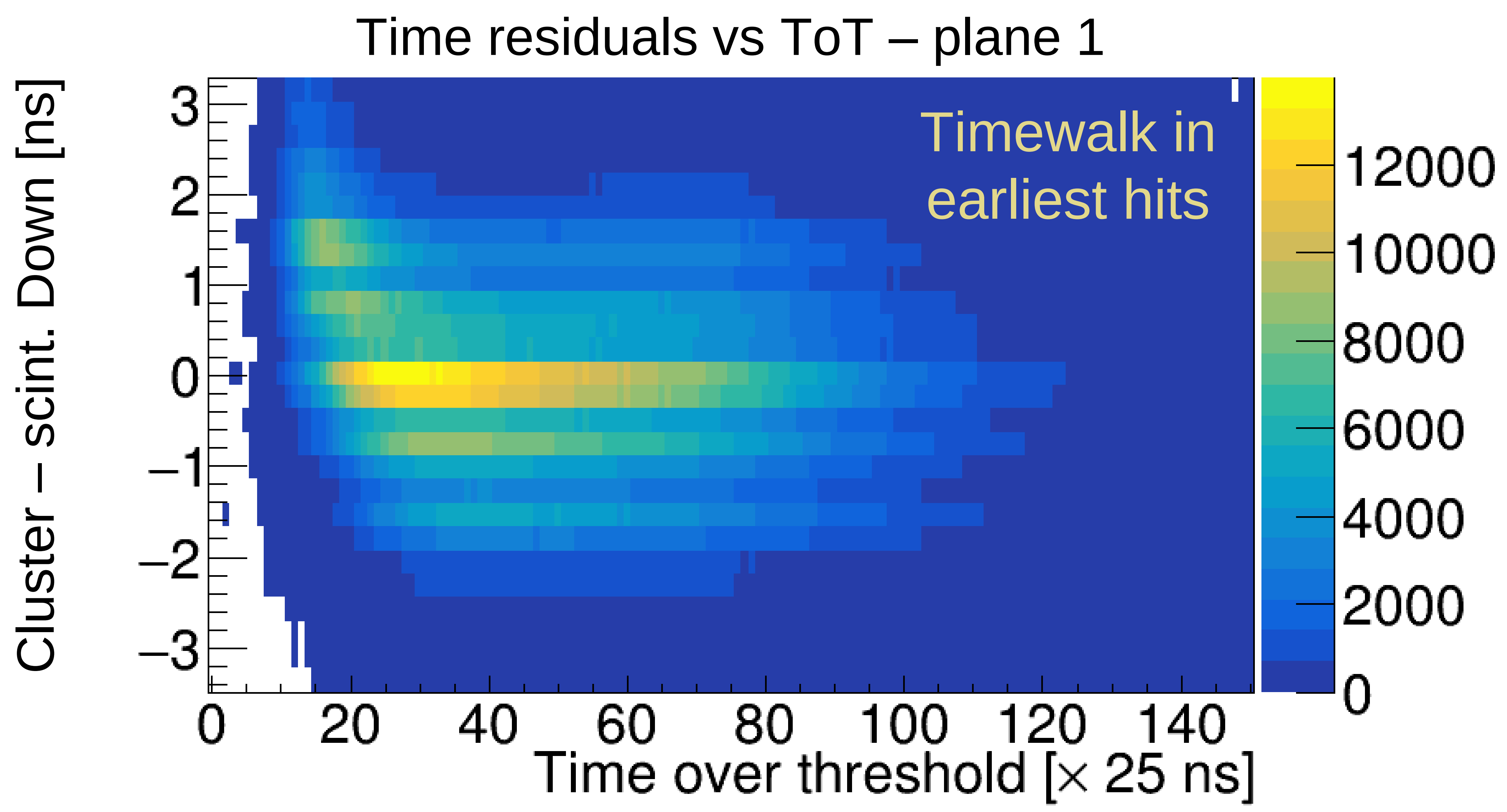
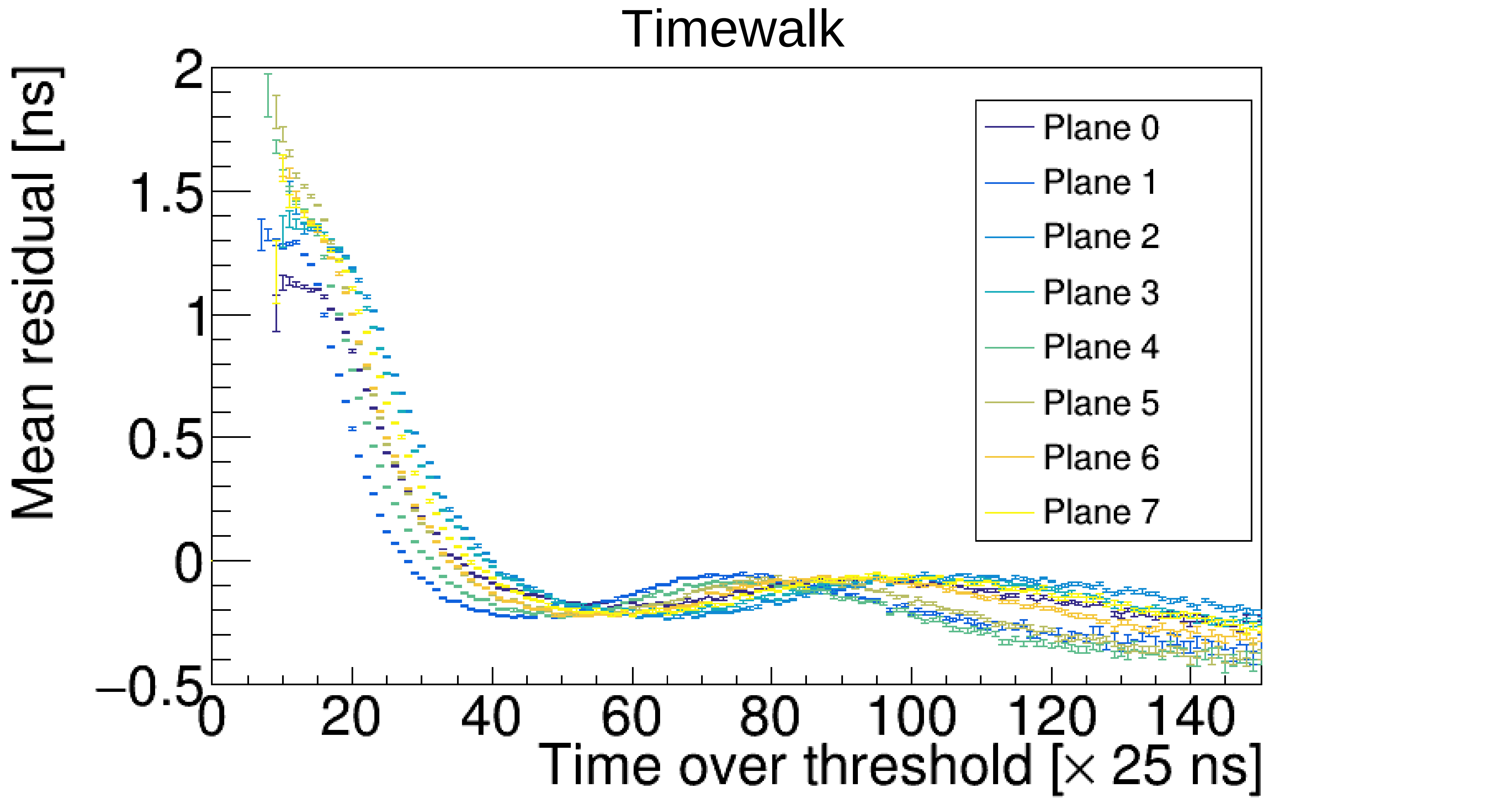
Timewalk

- Cluster time set by earliest hit in cluster: cuts out most timewalk
- Atypical timewalk curve
- Correction Improves track resolution:

$$\sigma(\text{track}) = 450 \text{ ps} \rightarrow 440 \text{ ps}$$





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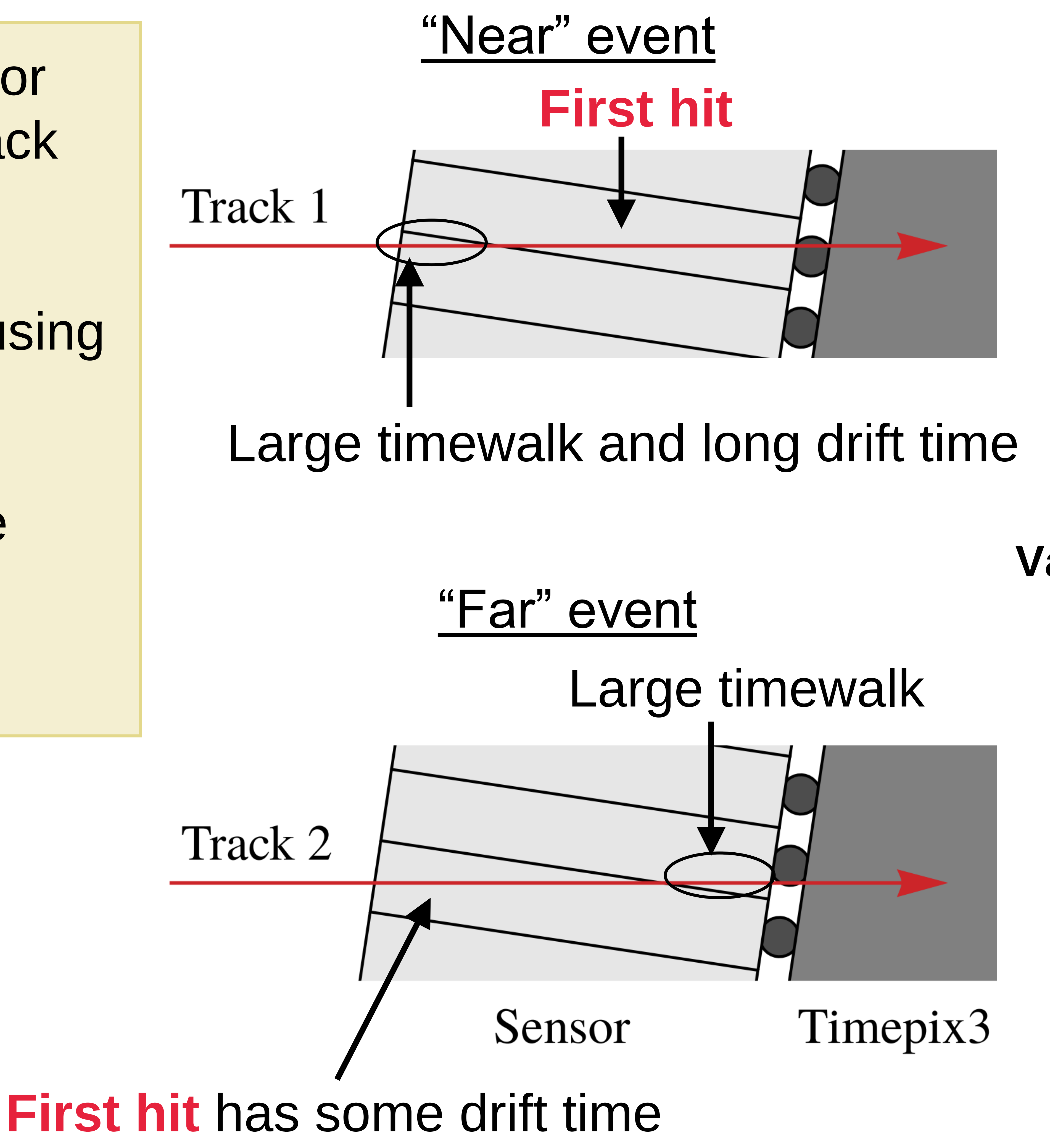
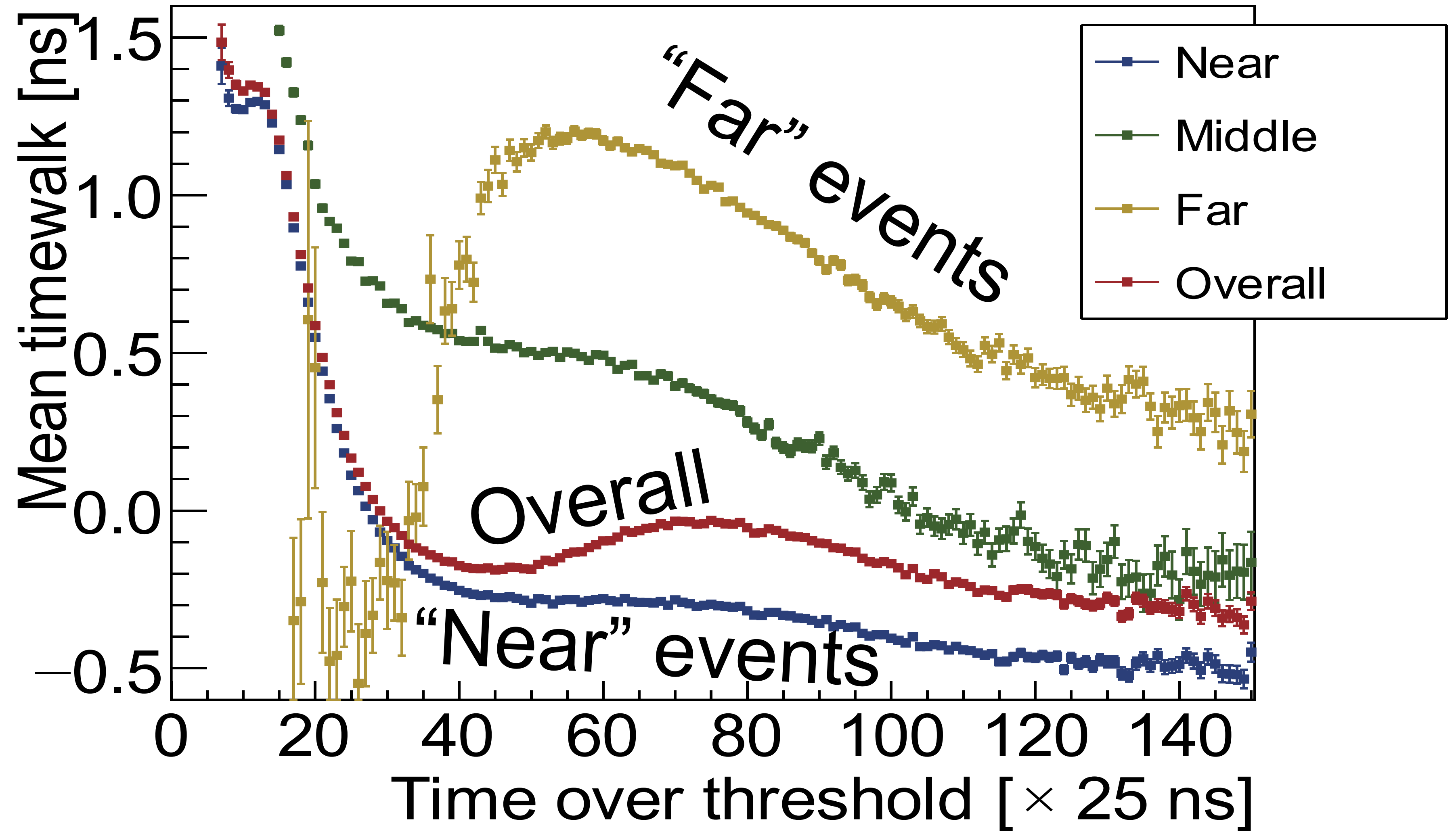
Timewalk and track topology

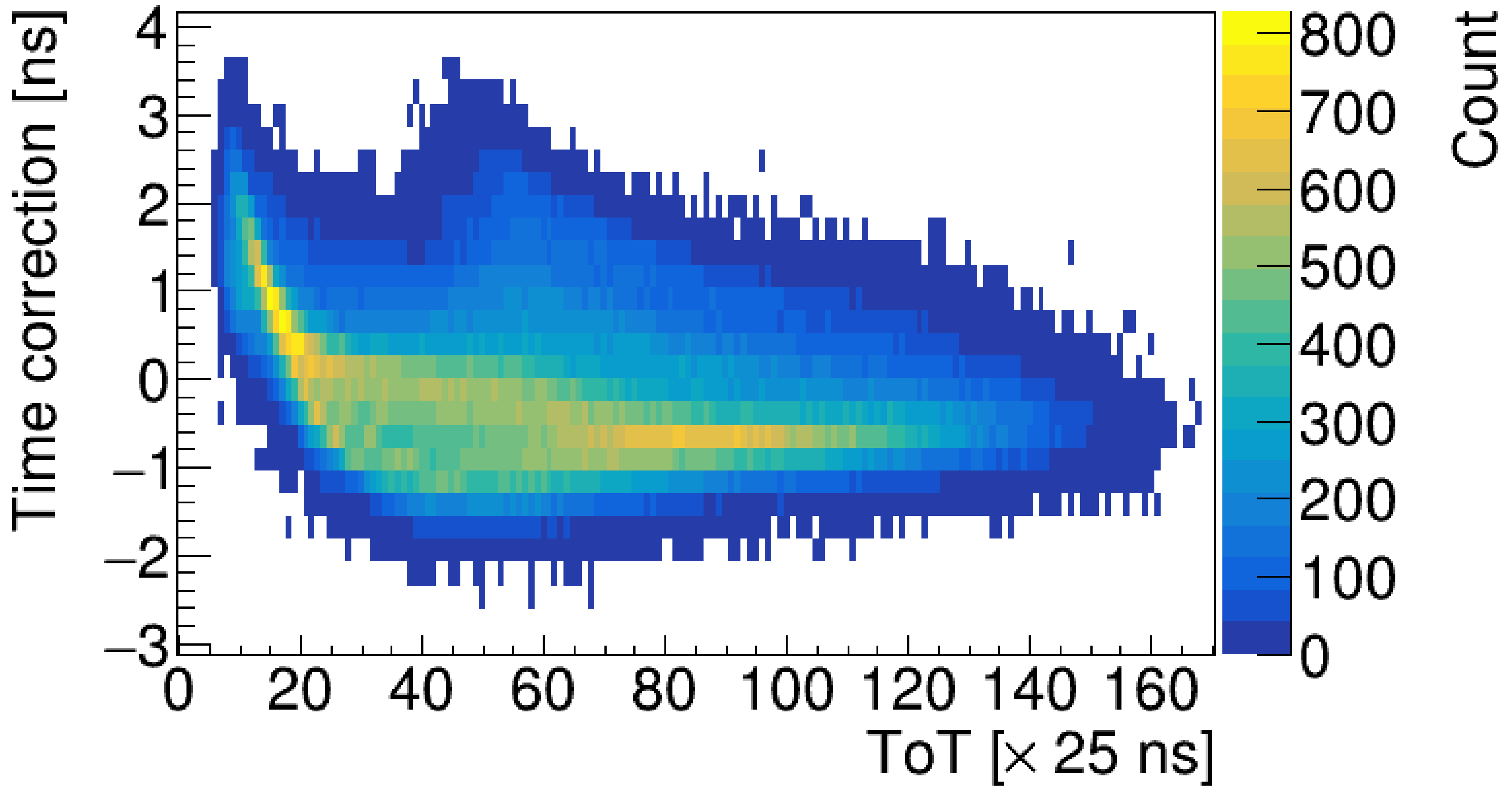
- Timewalk and sensor effects mixed by track topology
- Correct for this by using the track intercept
- Improves track time resolution:

  450 ps → 380 ps





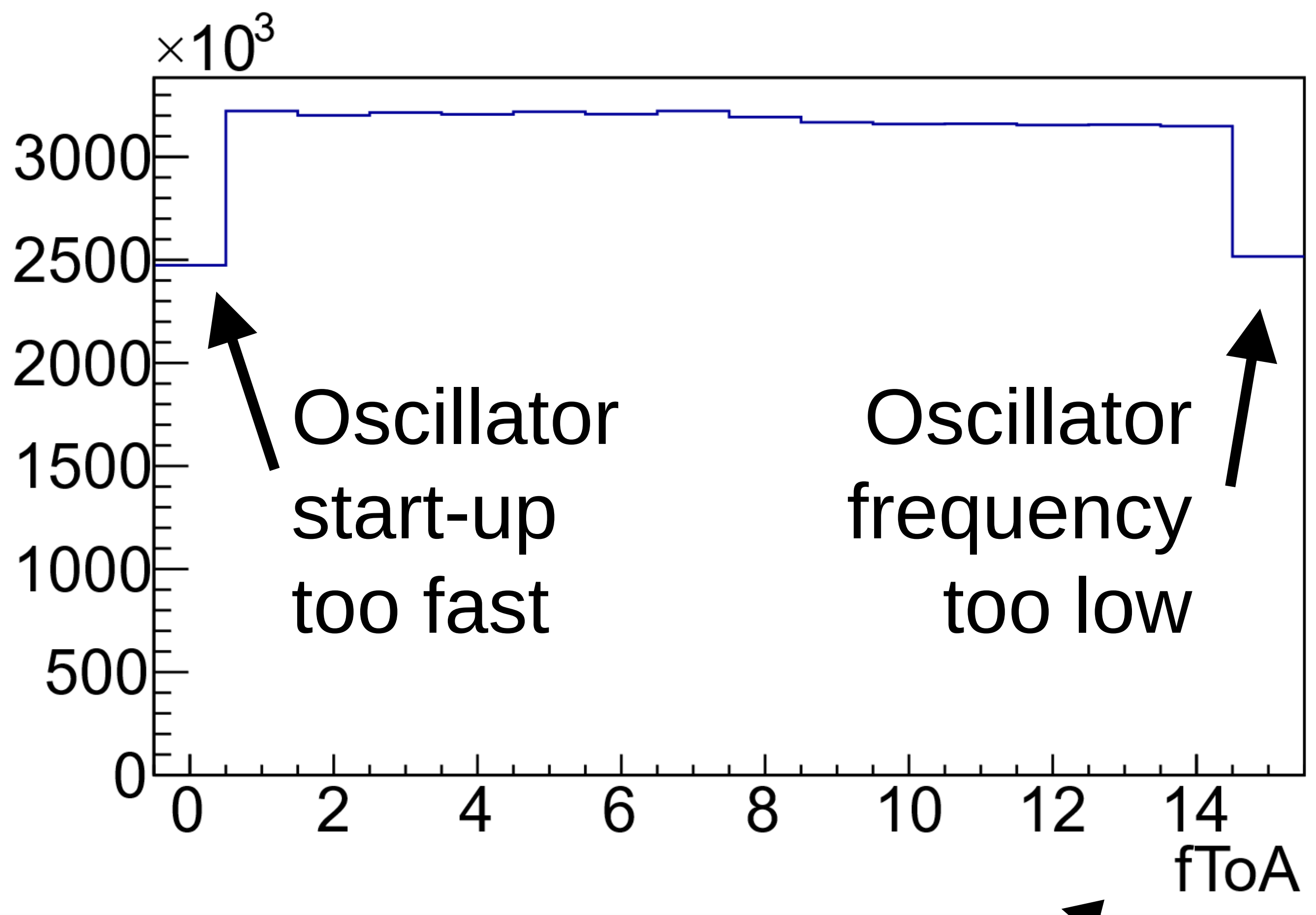
Variation in time corrections throughout a pixel – Plane 1

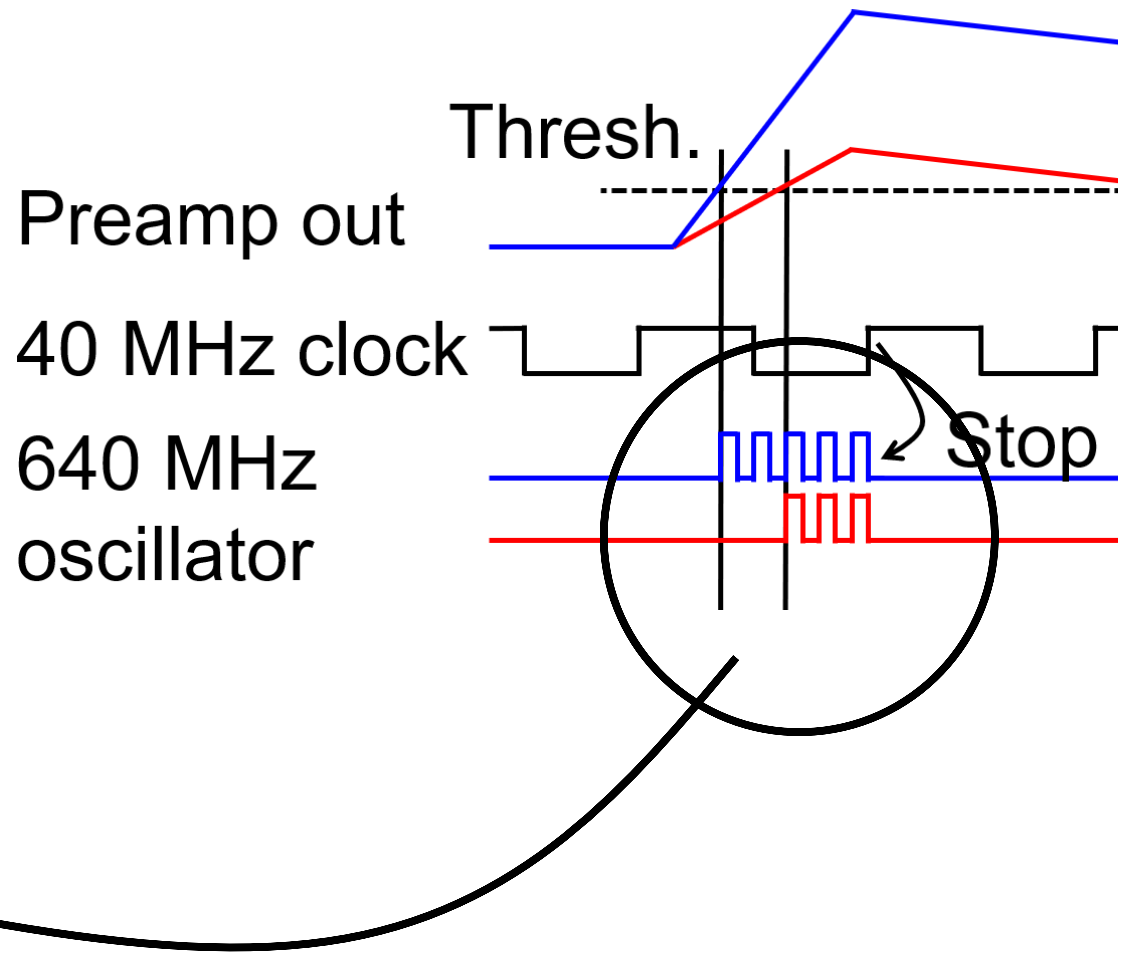


Pixel matrix systematics

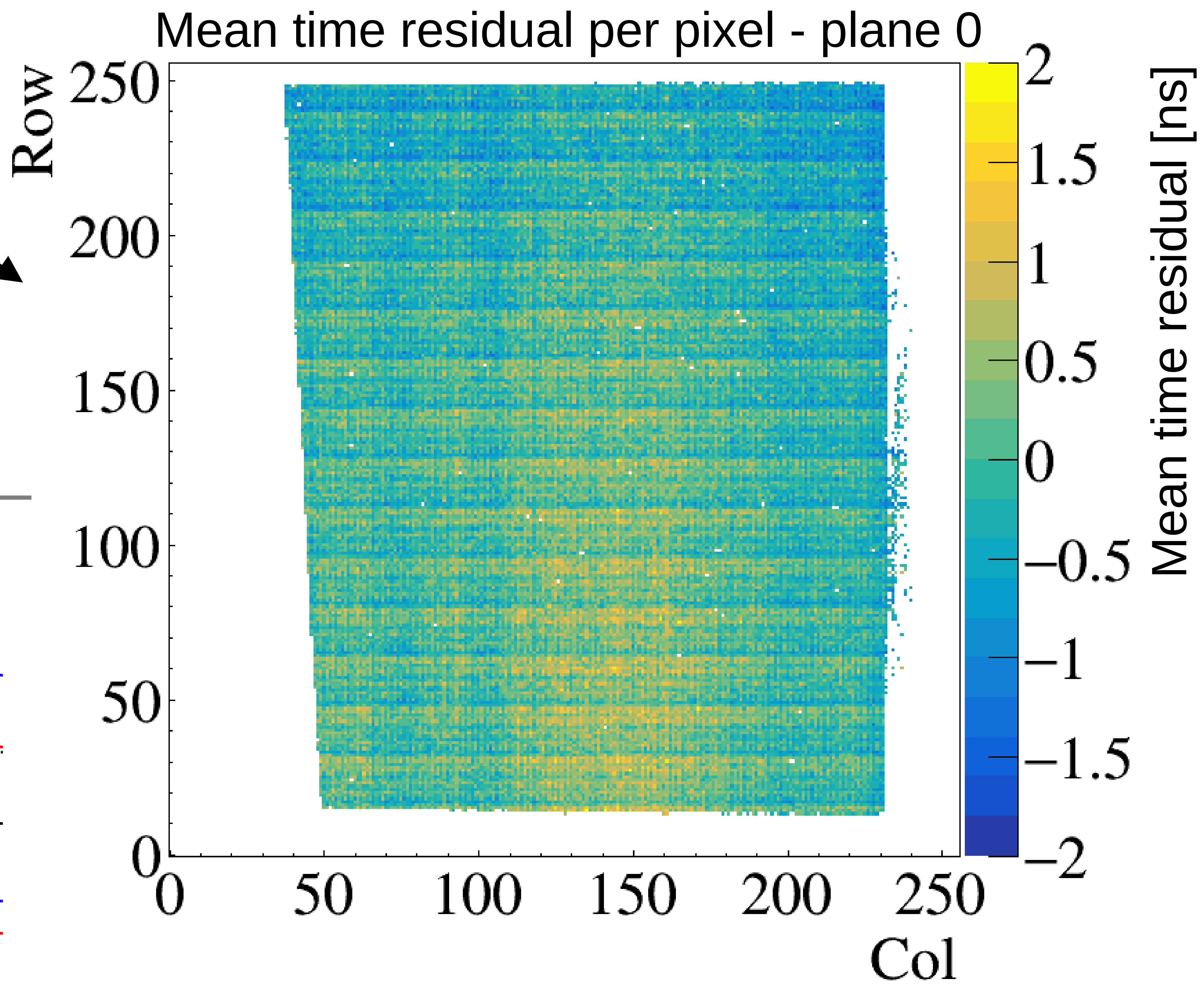
- The mean time residual varies over the pixel matrix
- Possible origins:
  - Clock distribution gives row structure
  - Differences in propagation delay between pixels and (shared) fast oscillator
  - Power distribution over the chip

- We apply one additional correction for each fToA bin





Histogram number of counts



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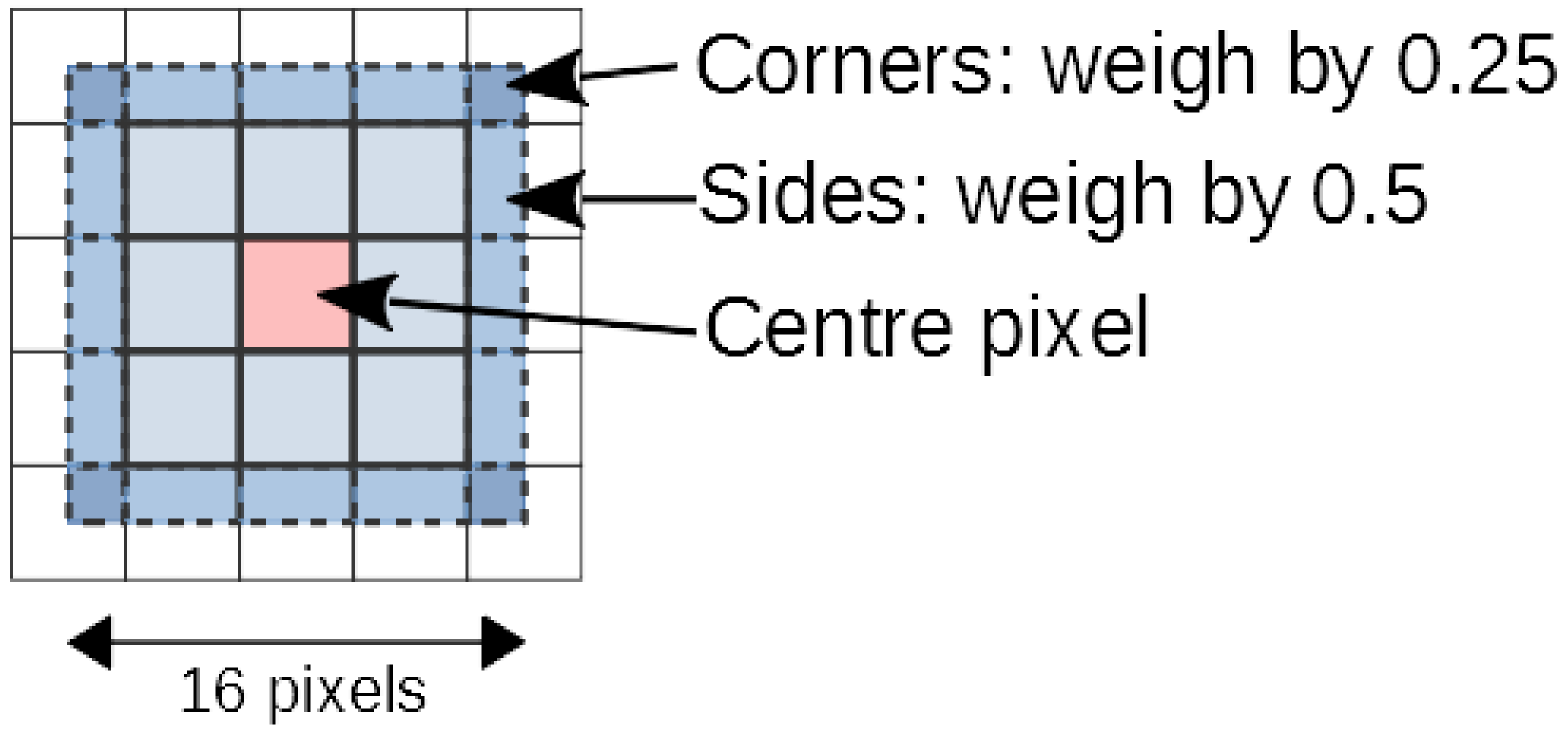
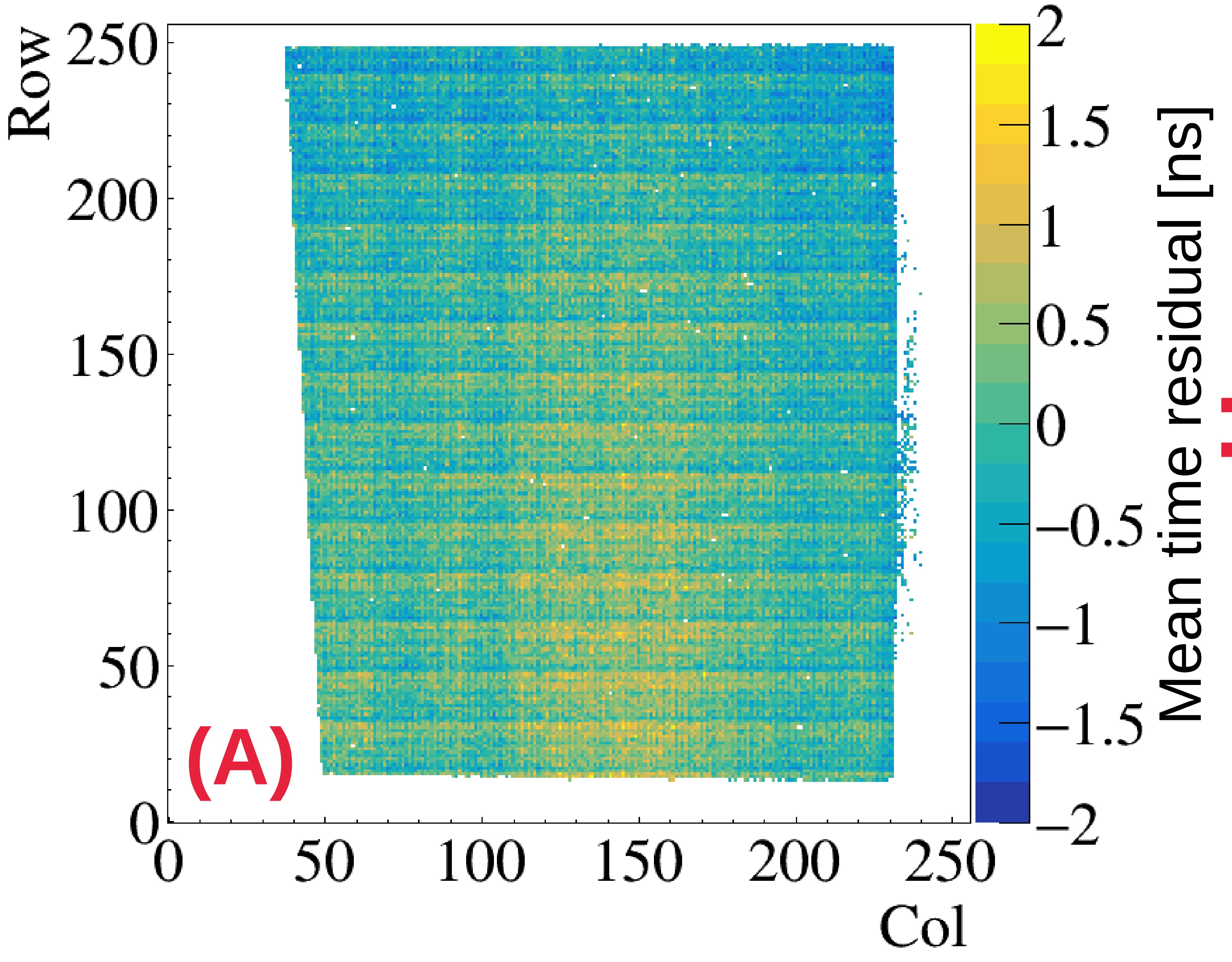
Decomposing pixel matrix systematics

- Quick method to separate per-pixel time offsets:
  1. Calculate mean of 16×16 pixels of (A) to get (B)
  2. Subtract (B) from (A) to get (C)





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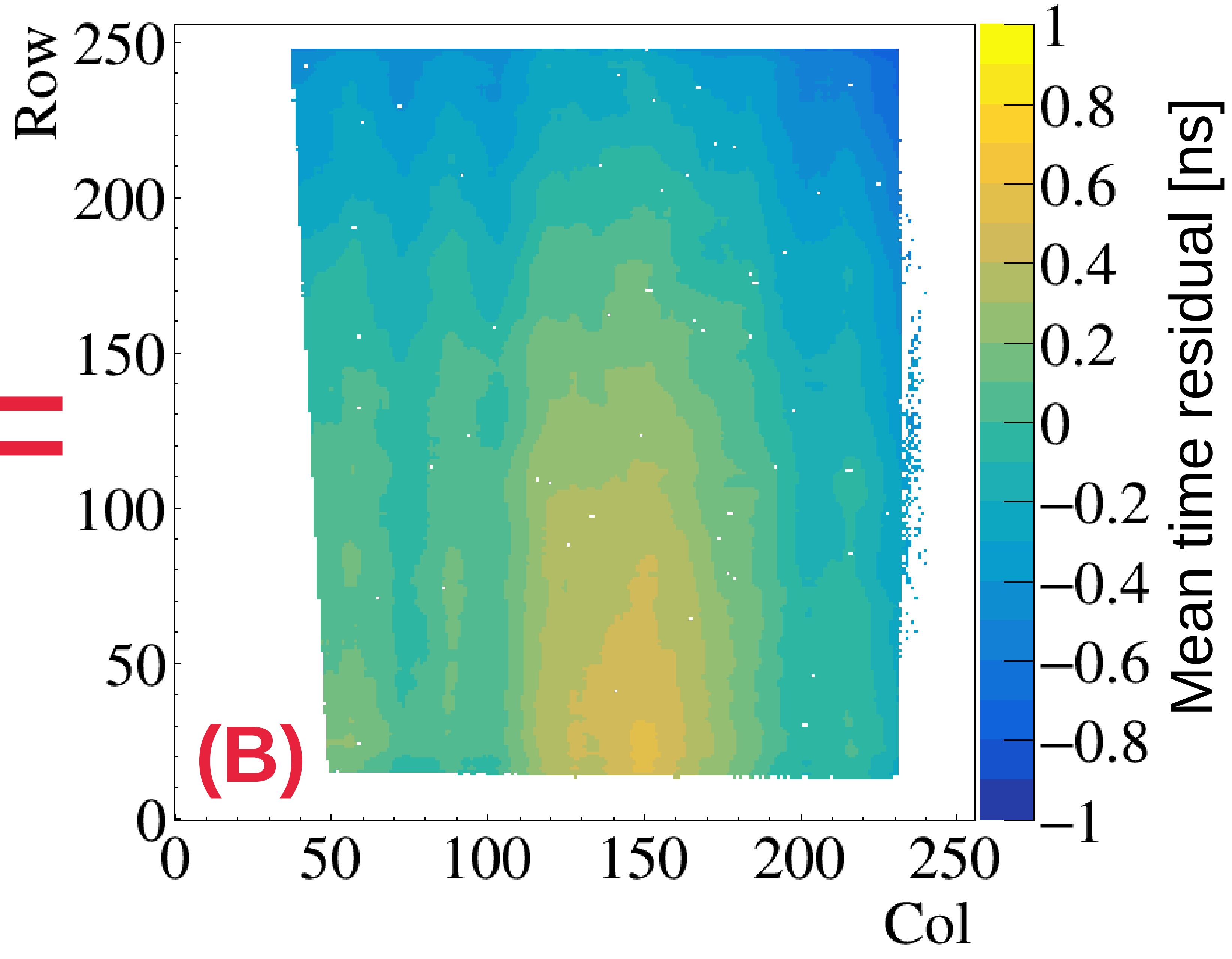

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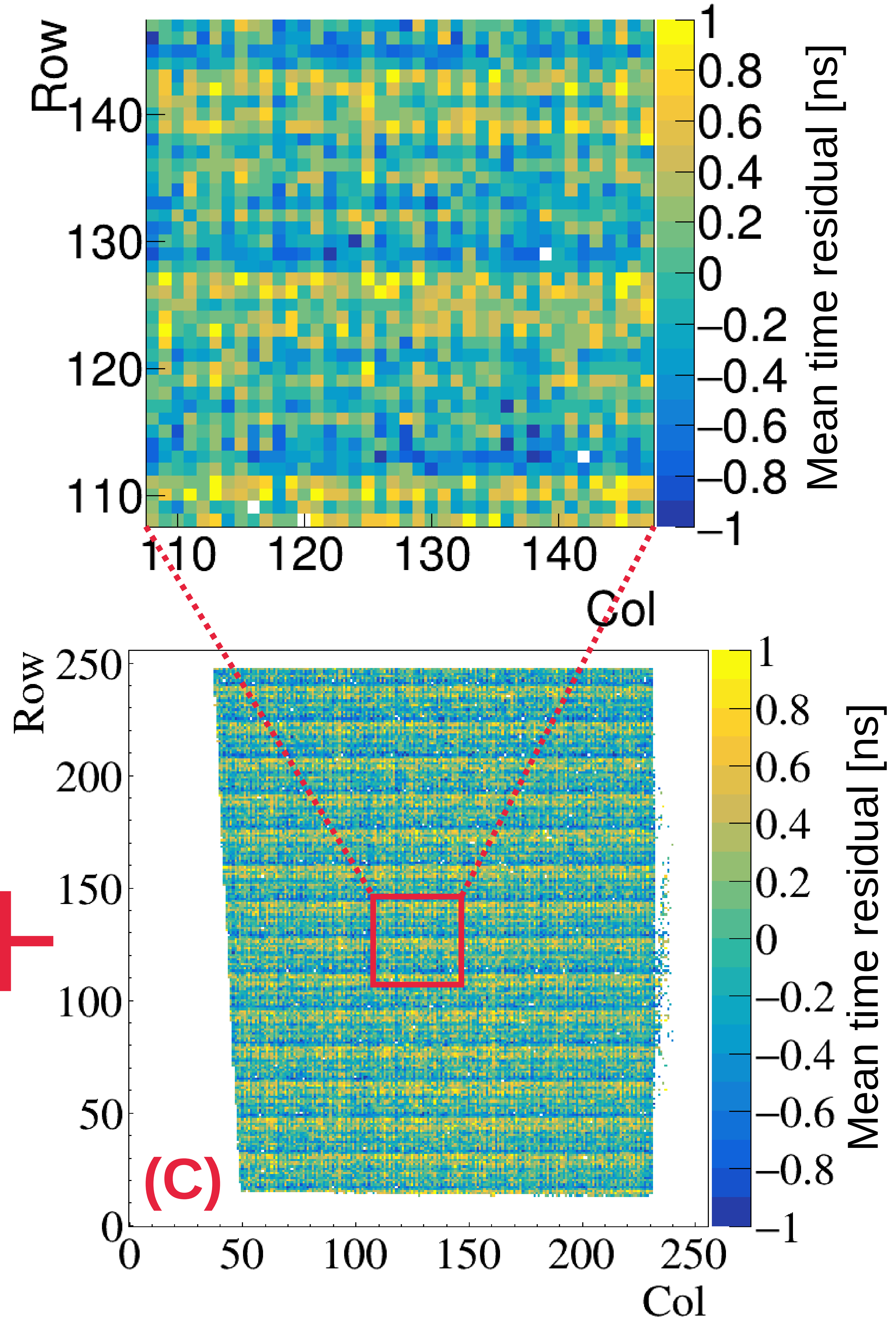
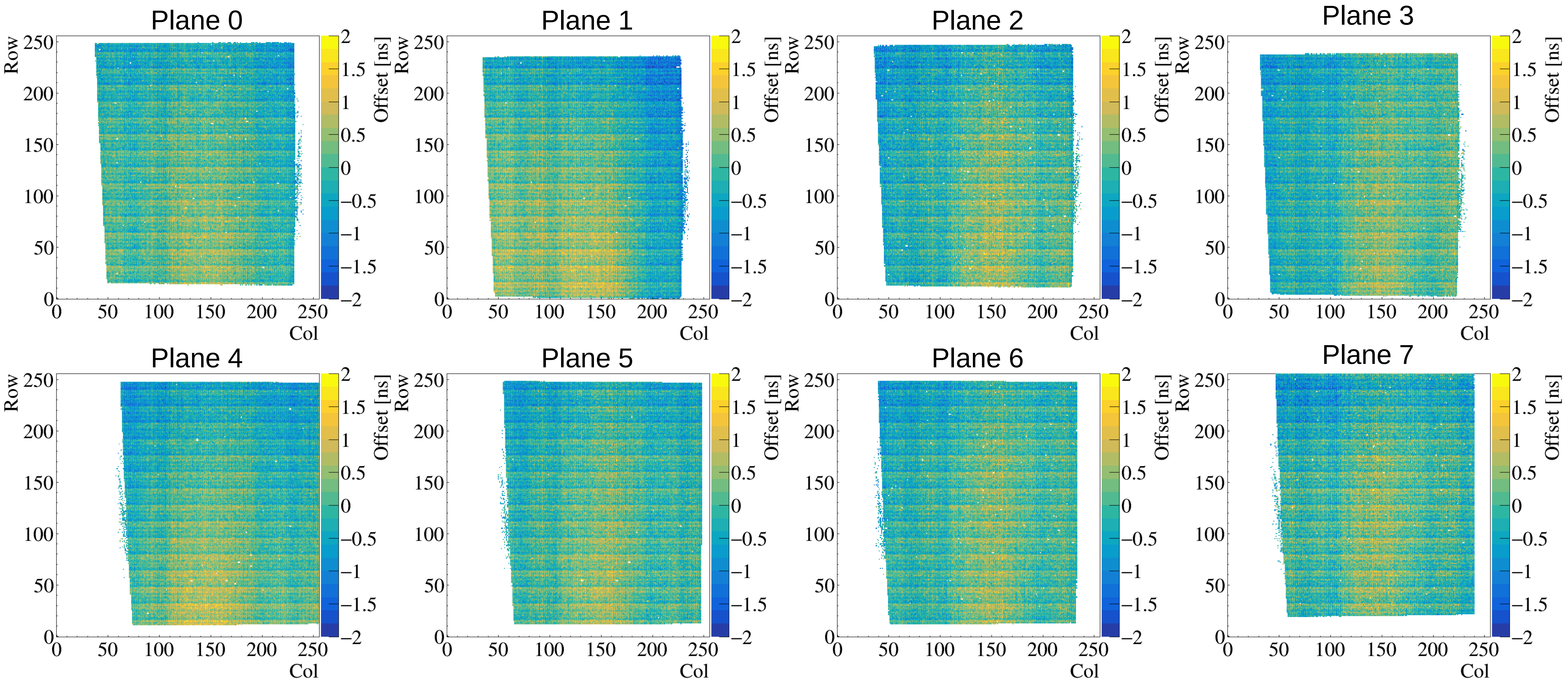


Pixel matrix systematics



- All planes show a similar structure, but there are differences
- Each plane needs its own per-pixel correction

Time resolution after all corrections

- Corrections improve the time resolution:

$$\sigma(\text{cluster}) = \quad 1\ \text{ns} \rightarrow 646\ \text{ps}$$
$$\sigma(\text{track}) \quad = 450\ \text{ps} \rightarrow 271\ \text{ps}$$

- Probably still affected by sensor effects:

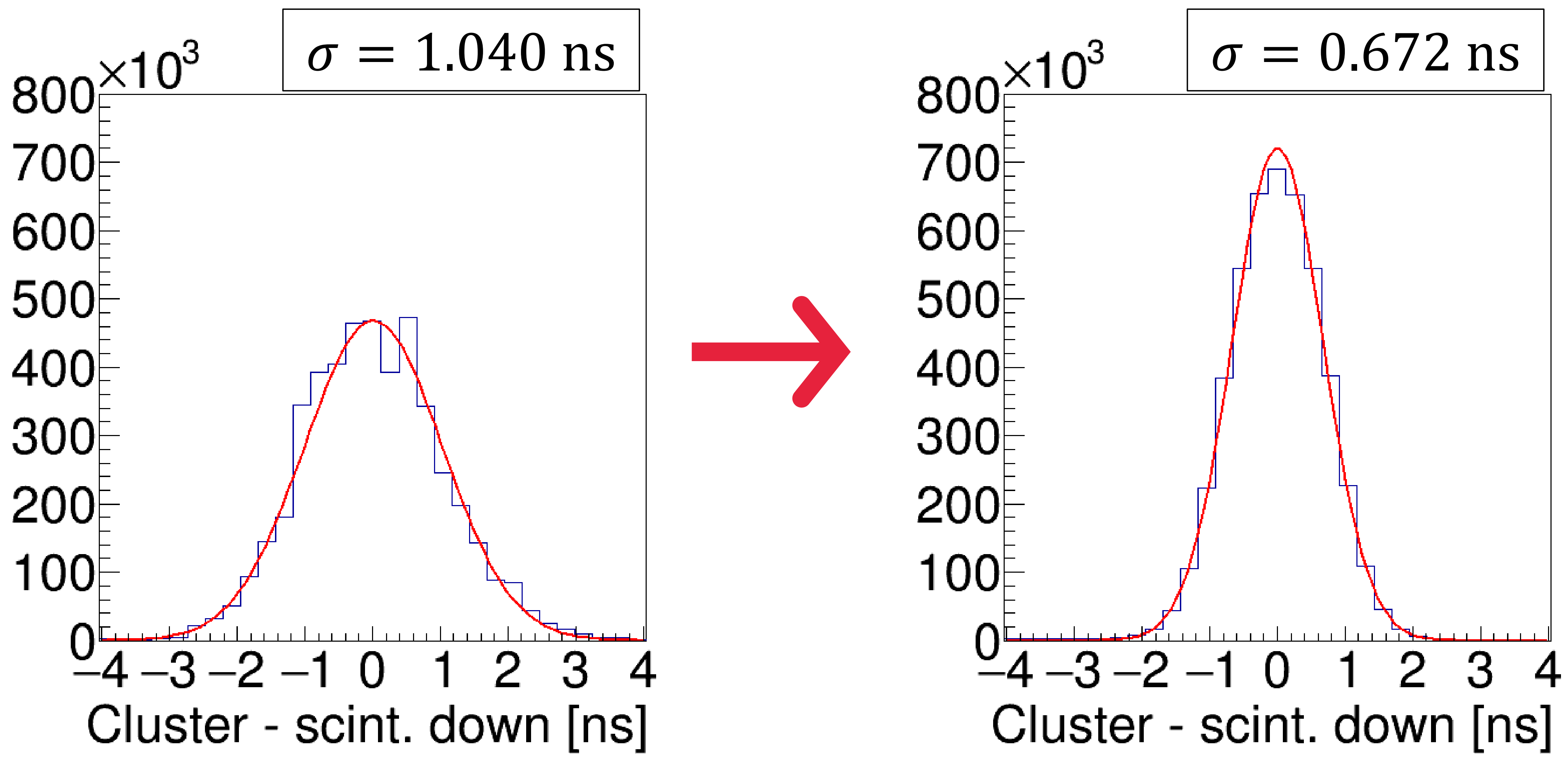
$$646\ \text{ps} \ominus 451\ \text{ps} = 463\ \text{ps}$$

↑

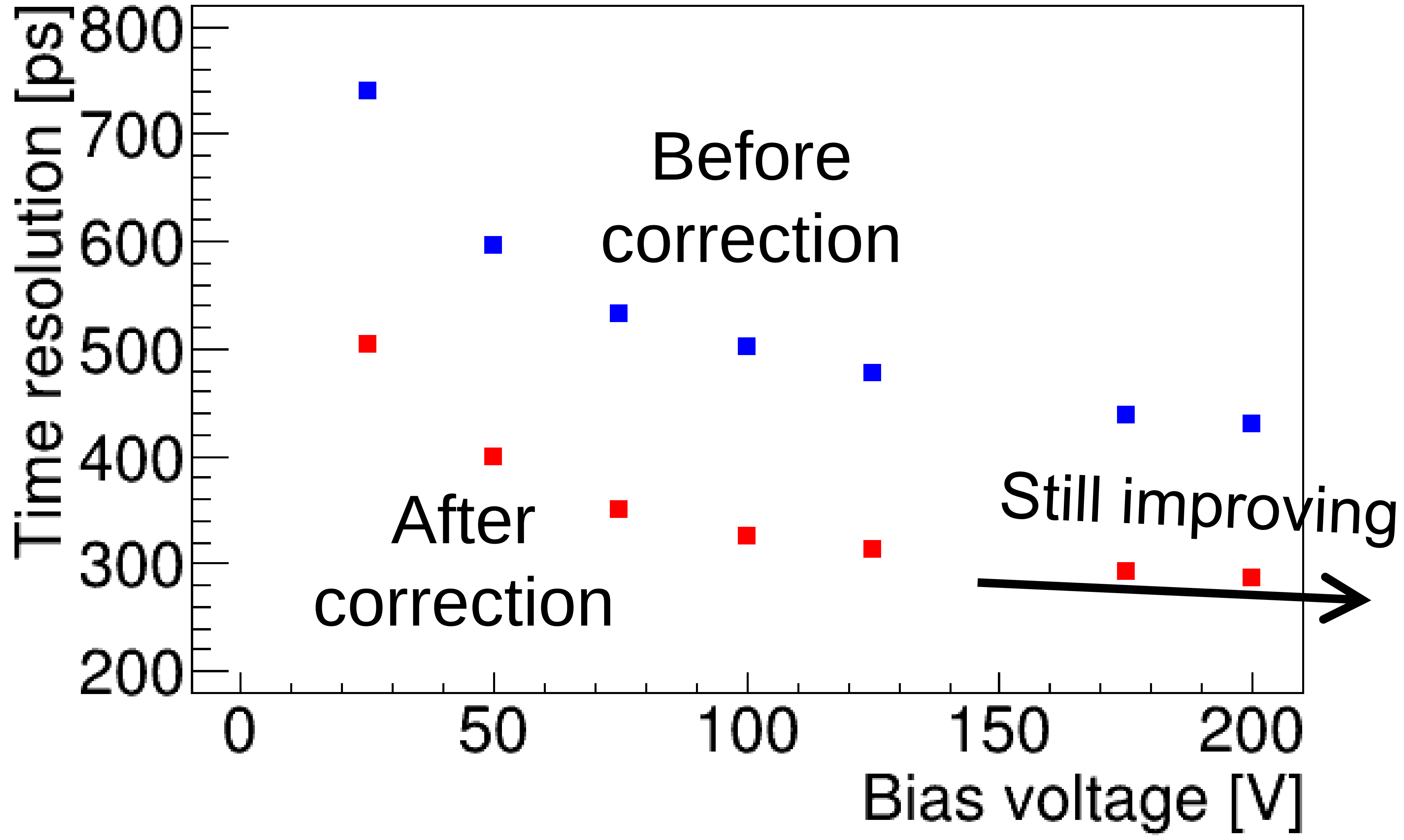
Time binning
Contribution $1.56\ \text{ns}/\sqrt{12}$

- Bias scan also indicates that (residual) drift-time effects still affect resolution

Cluster time residuals before and after all corrections



Track time resolution



Fast sensors on Timepix3

Thin planar 50 µm[1)]
- Short drift distance
- Less charge → more timewalk
- Small pixel implant → time resolution varies inside pixel

- Overall resolution: **845 ps (715 ps)**
- Selecting best hits: **588 ps (377 ps)** (Centre of pixel, Q>5ke⁻)

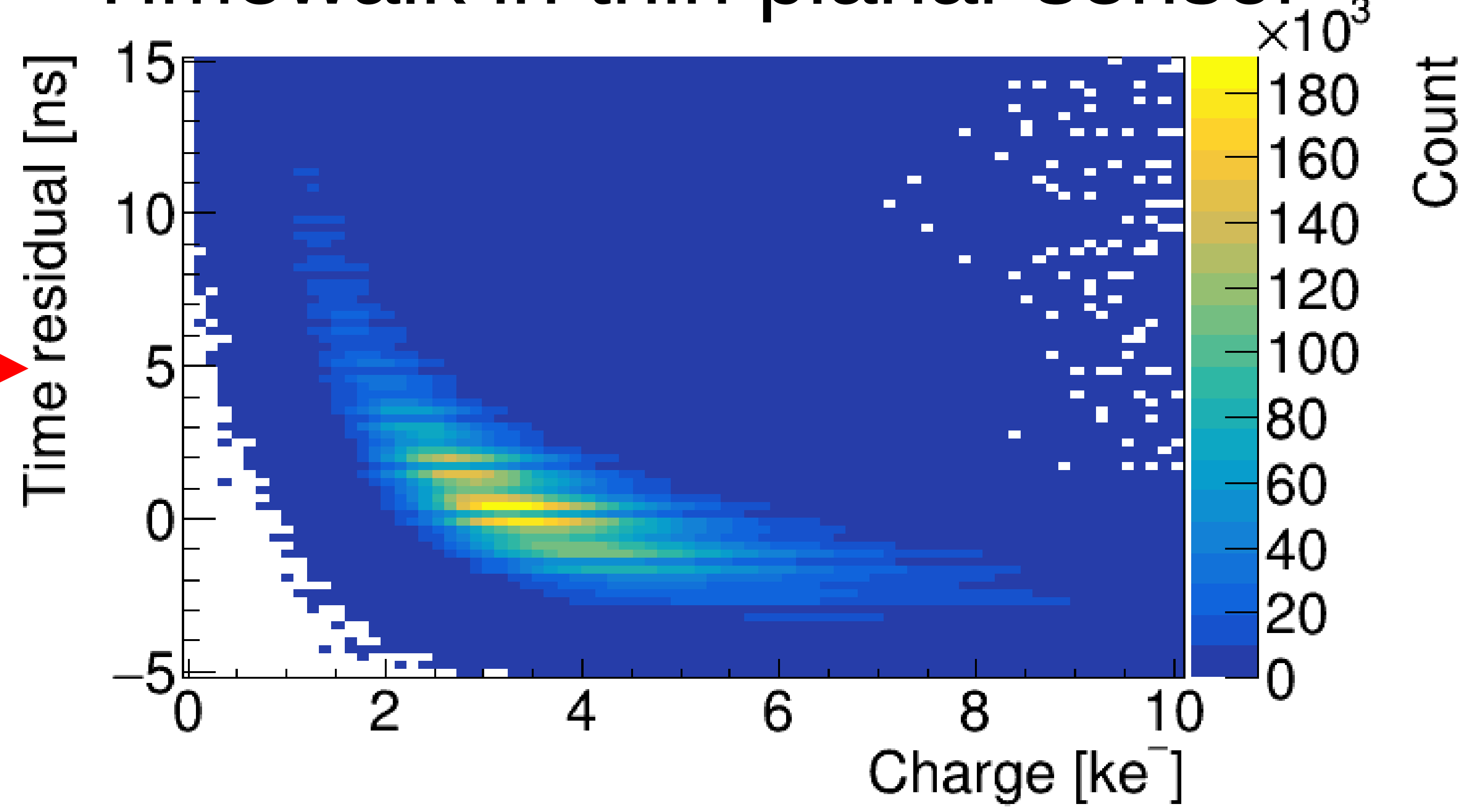
3D sensor[2)]
- Short drift distance
- Plenty of charge

Without 451 ps TDC contribution

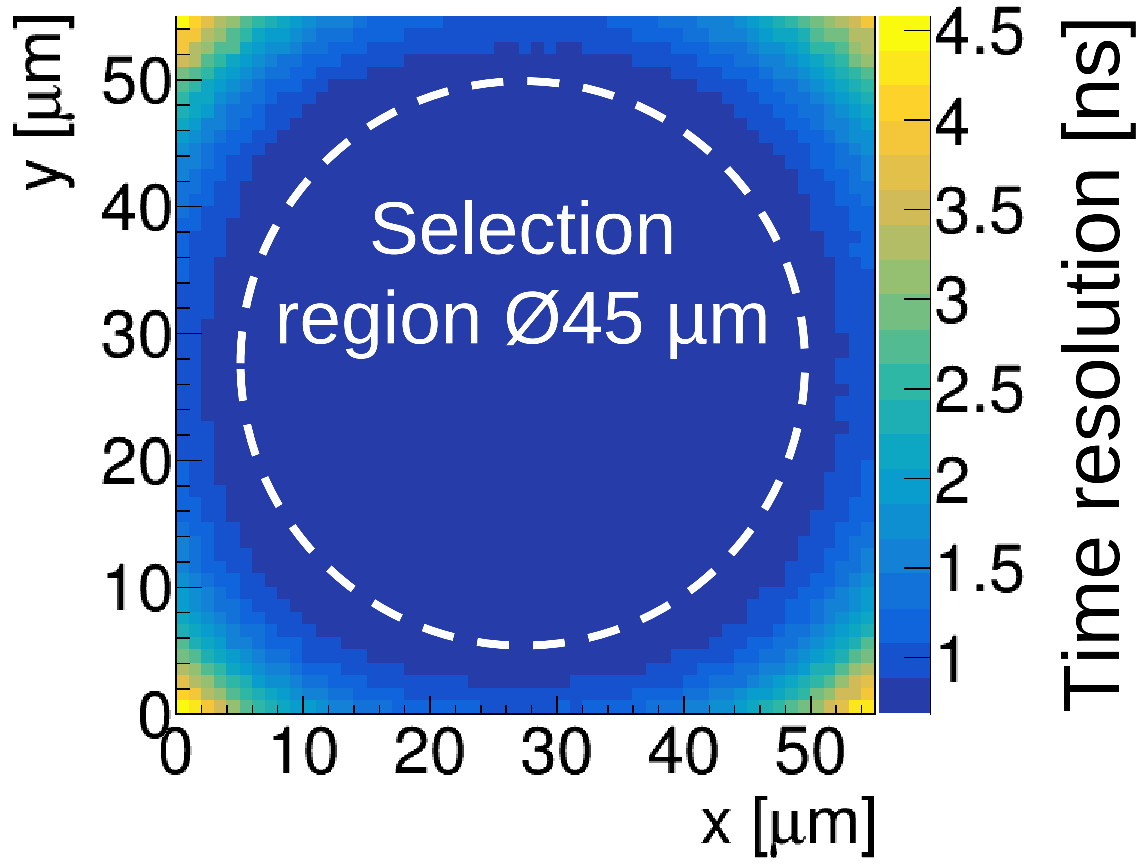
- Overall resolution: **746 ps (594 ps)**
- Selecting best hits: **590 ps (380 ps)** (Cluster size 1, Outside pillars, Q>16ke⁻)

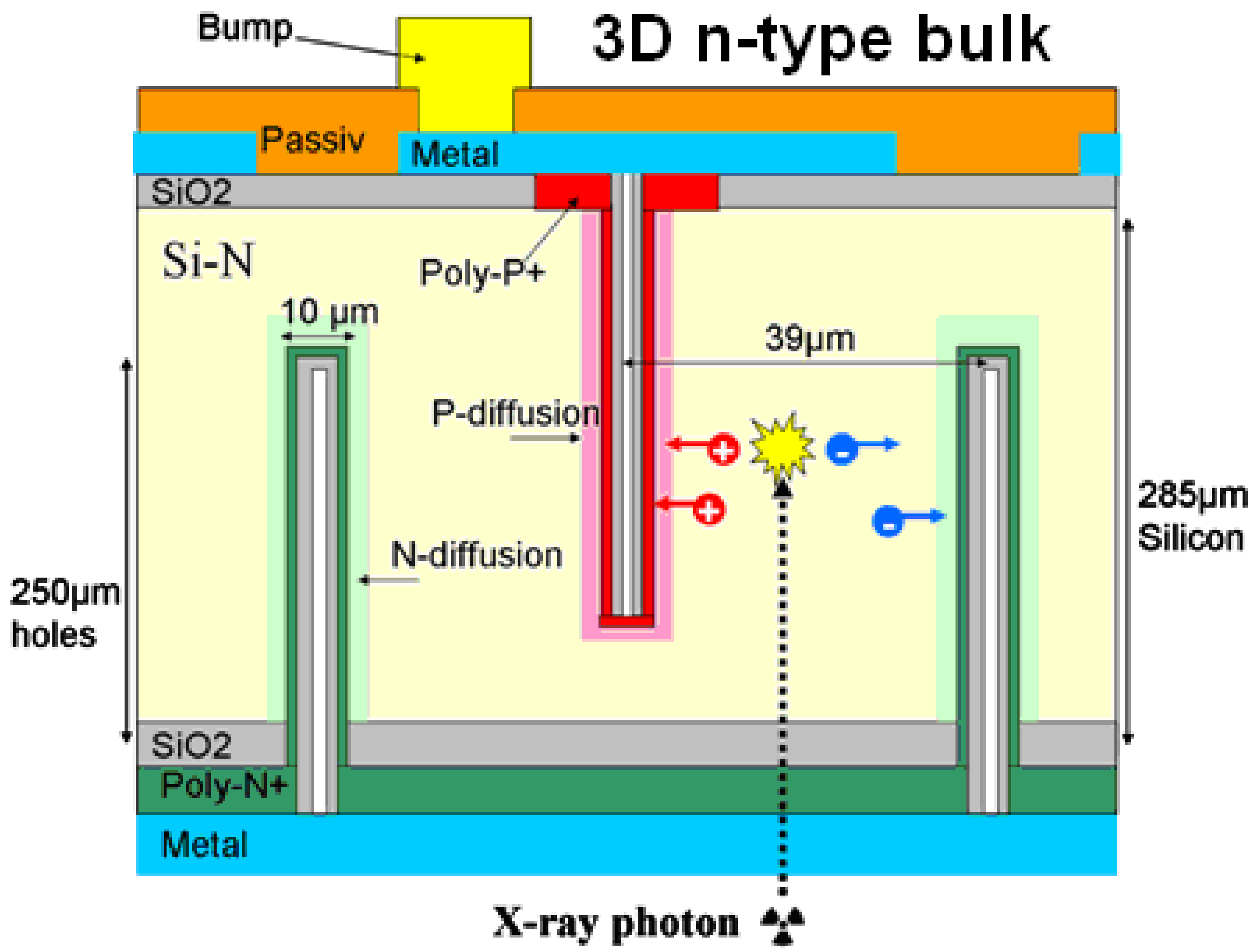
- Timepix3 limiting the resolution
- Bias voltage limited by breakdown

Timewalk in thin planar sensor

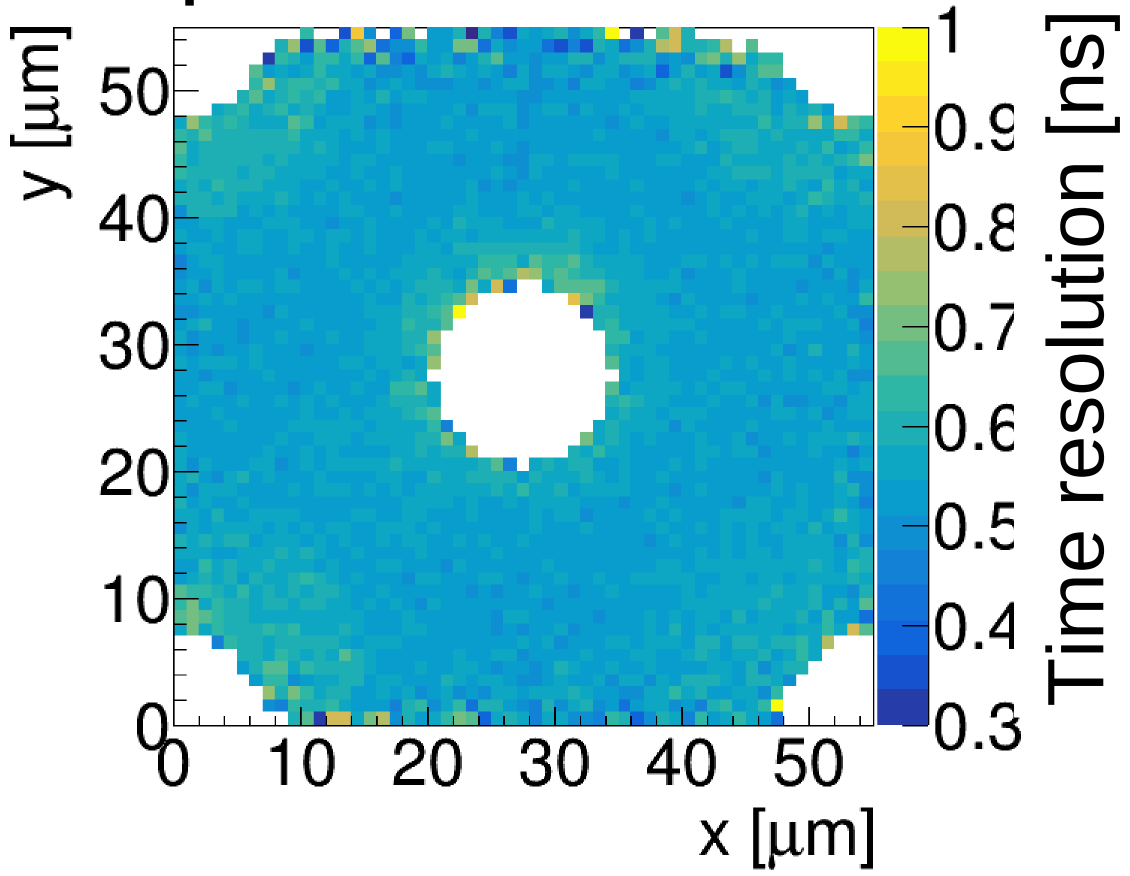


Intrapixel time resolution





Intrapixel time resolution



Sensor	Manufacturer	Type	Thickness	Depletion voltage (V)	Bias voltage (V)
Thin planar	Advacam	p-on-n	50 µm	15–20	90
3D	CNM-IMB	n-type bulk	285 µm	20	60

1) Thanks to D. Dannheim, CLICdp
2) Thanks to Richard Bates

Conclusion

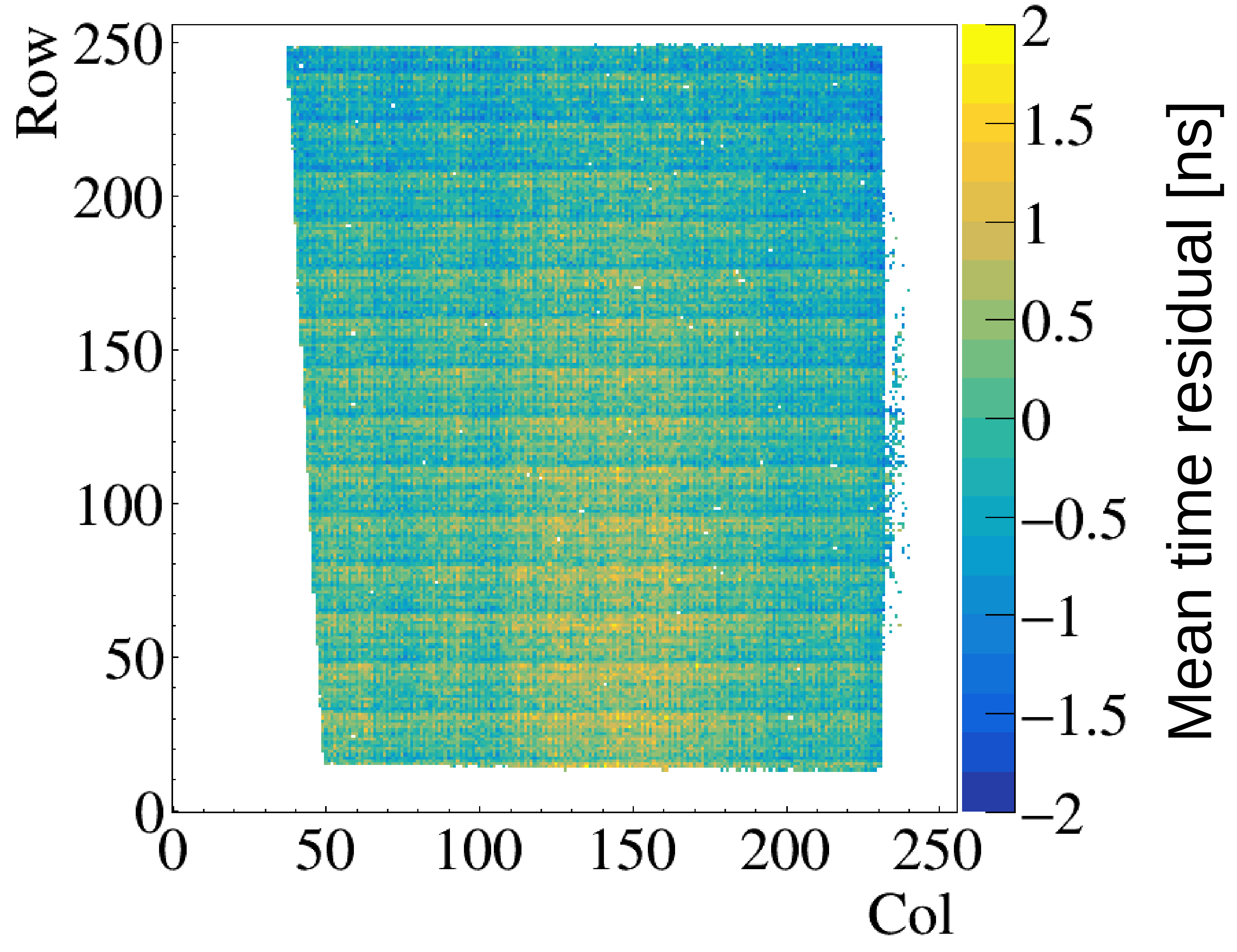
- We showed that we can improve the cluster/track time resolution by correcting systematic effects:

$$\sigma(\text{cluster}) = \quad 1\text{ ns} \rightarrow 646\text{ ps}$$
$$\sigma(\text{track}) \quad = 450\text{ ps} \rightarrow \mathbf{271\ ps}$$

← Current best time resolution of the telescope

- Understanding systematics of large scale systems will become more important for next generation devices.
- Unfortunately Timepix3 telescope time resolution not sufficient to study fast sensors

Mean time residual per pixel - plane 0



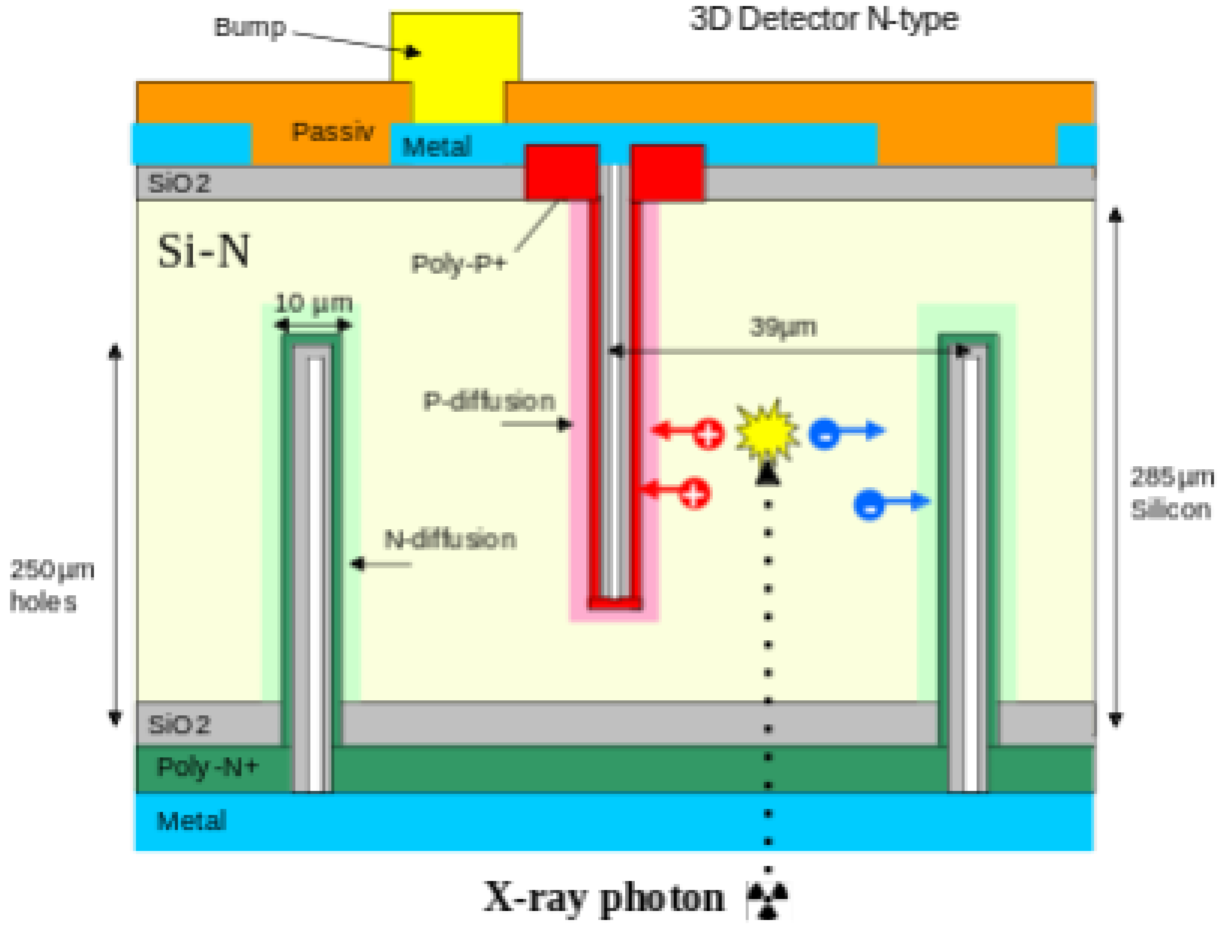
What is next?

- Analysis of more testbeam data of fast sensors*:
  - Thin planar 50 µm
  - 3D sensor

  These sensors are suboptimal
- TCAD simulations of fast sensors
- Timepix4! Better time measurement: **1.56 ns → 200 ps bins**

*Measured resolution limited by Timepix3

3D sensor



Backup slides

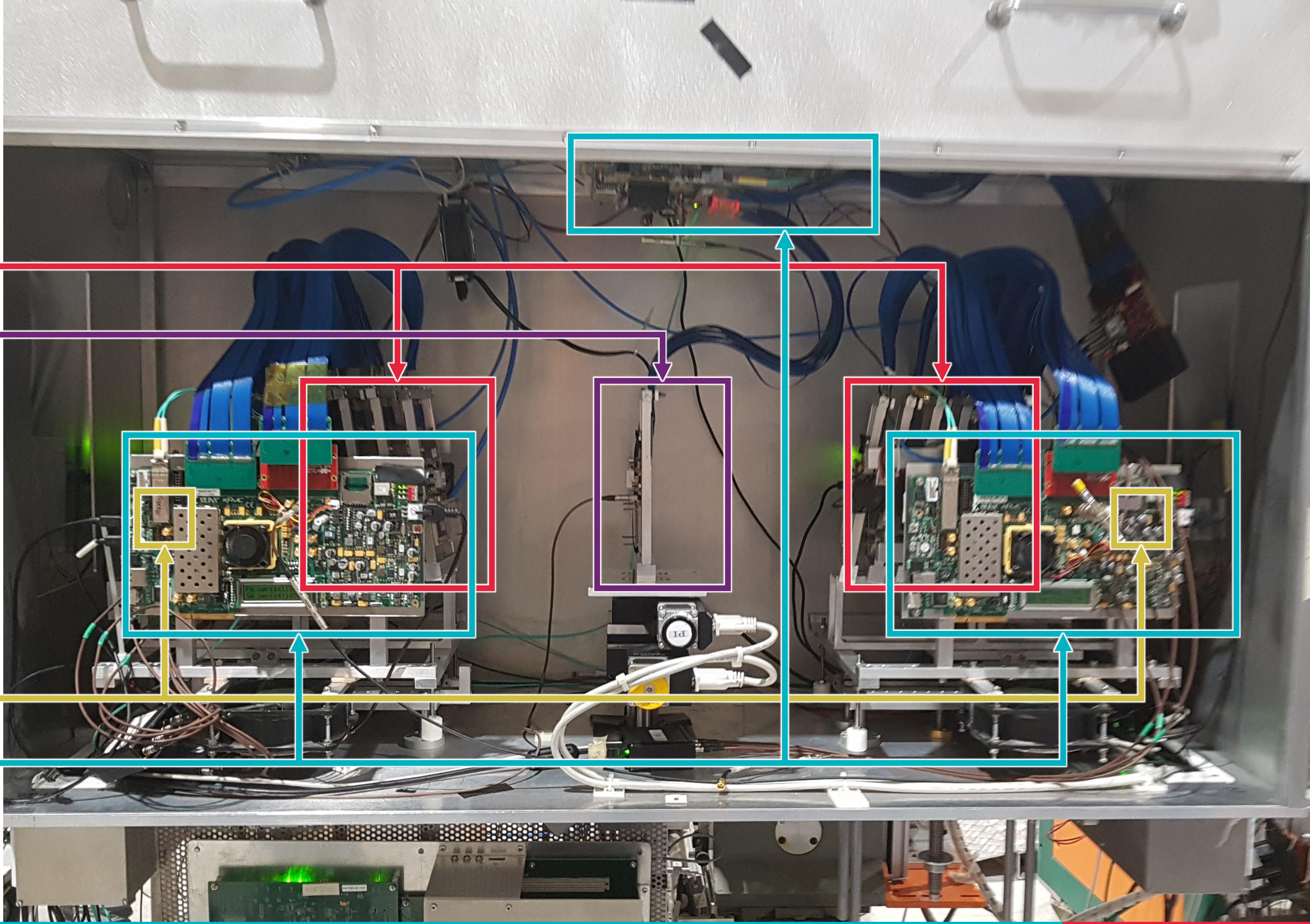
Timepix3 telescope

4+4 Tpx3 planes

DUT

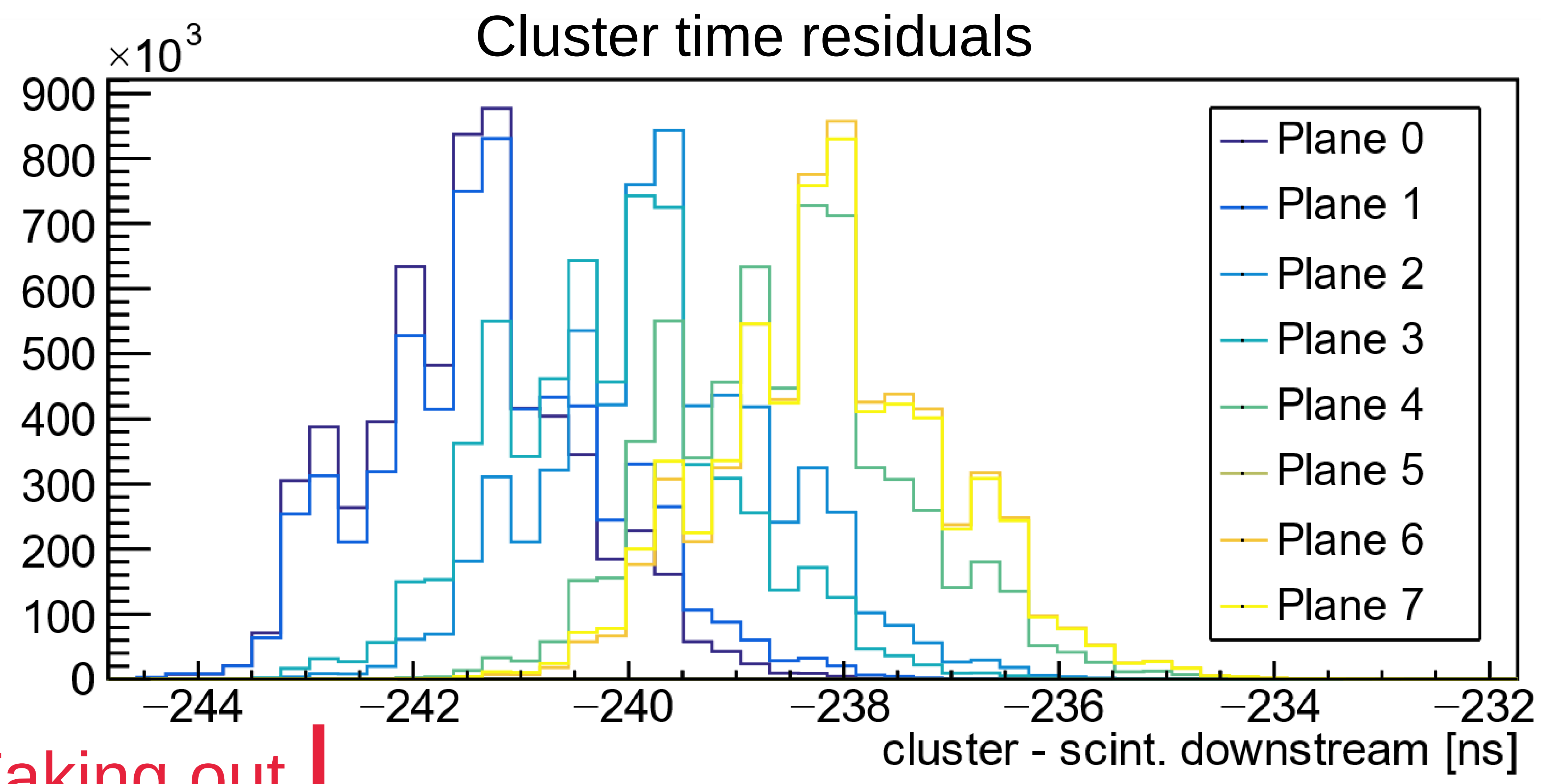
Beam scintillators

2+2+1 SPIDRs

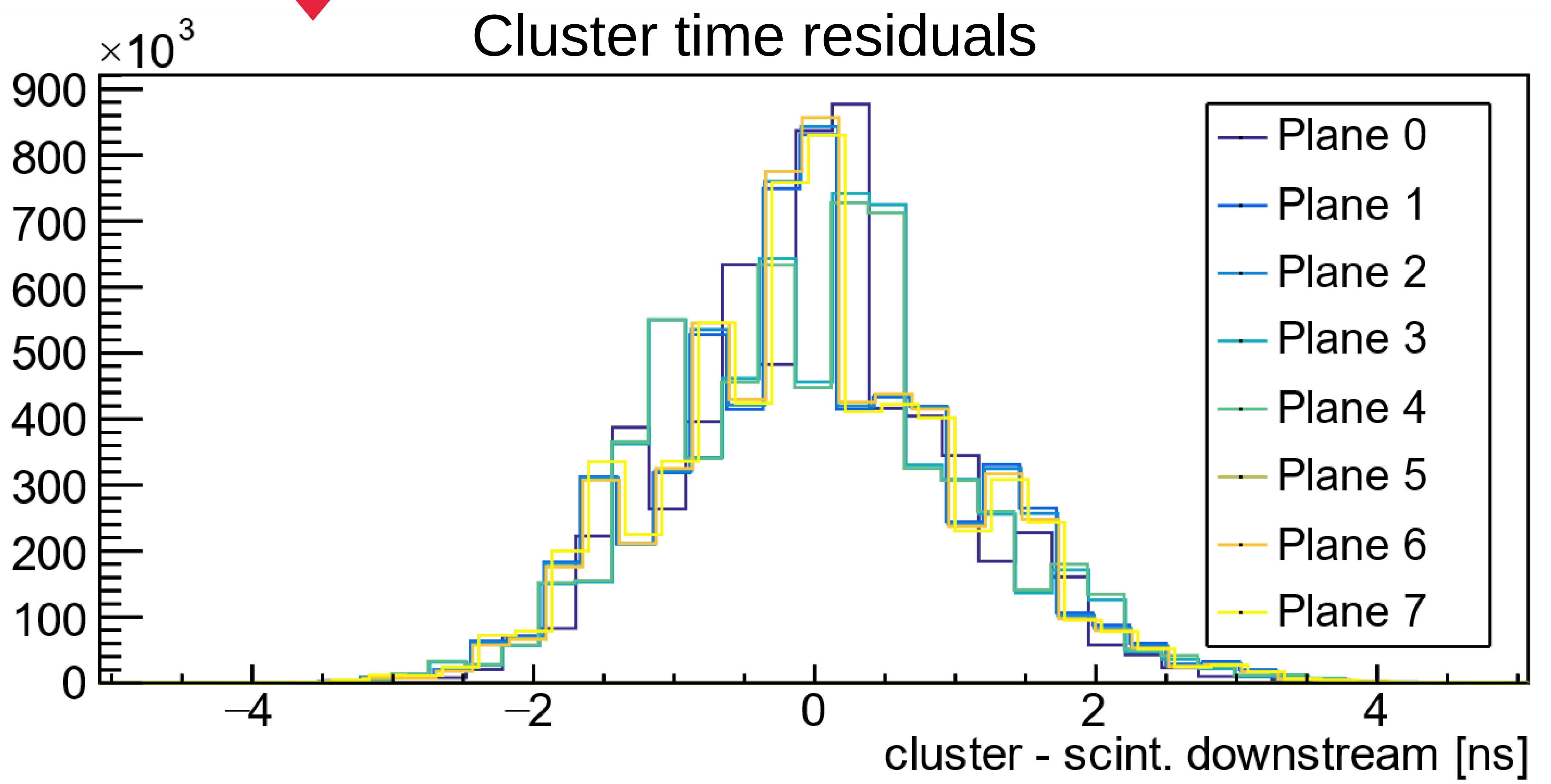


Cluster- and track time residuals

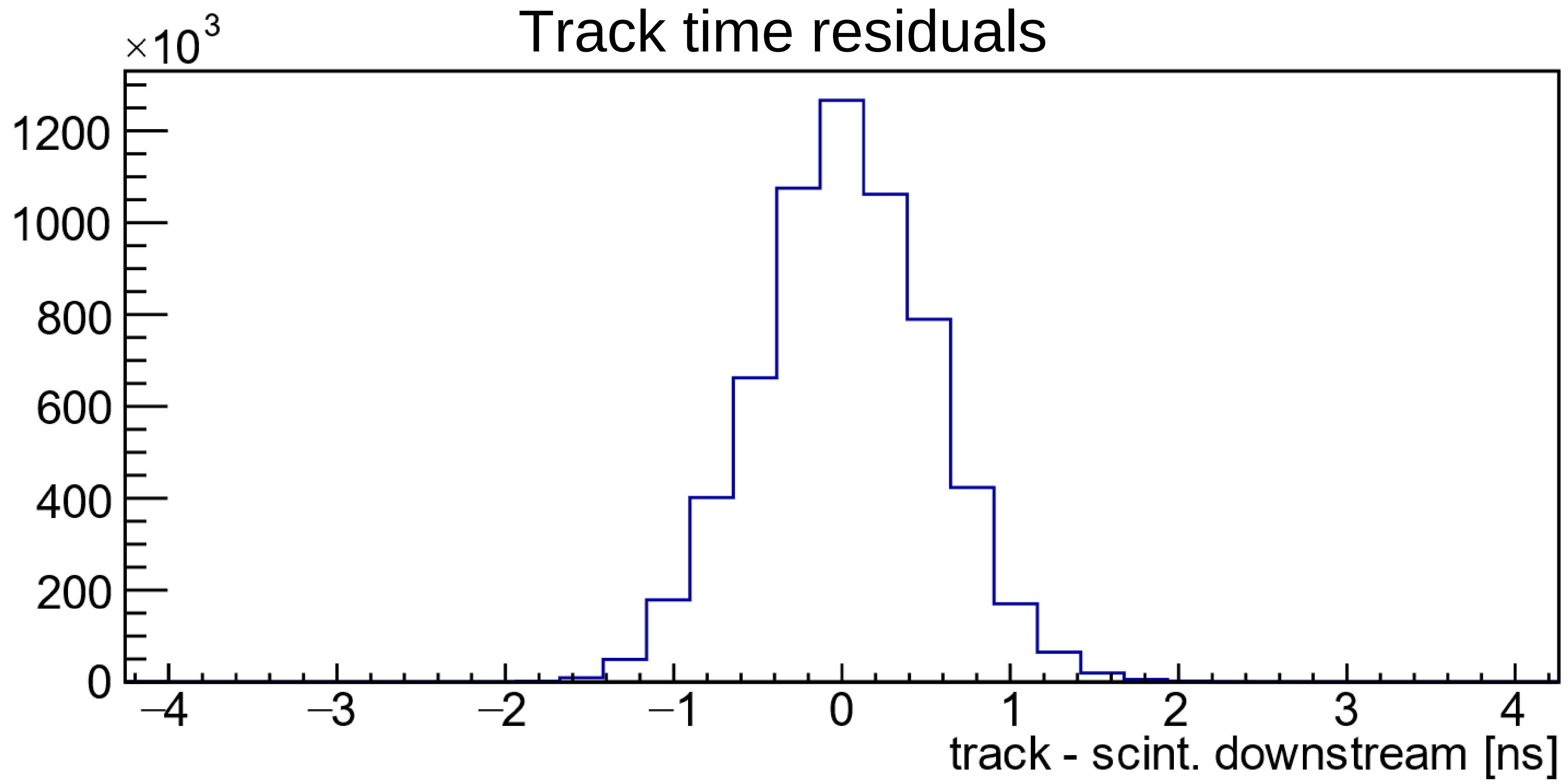
- Earliest hit in a cluster defines the cluster time
- We calibrate out the mean offsets
- We require a cluster on each telescope plane to form a track
- Track time is mean of cluster times



Taking out offsets



Track time



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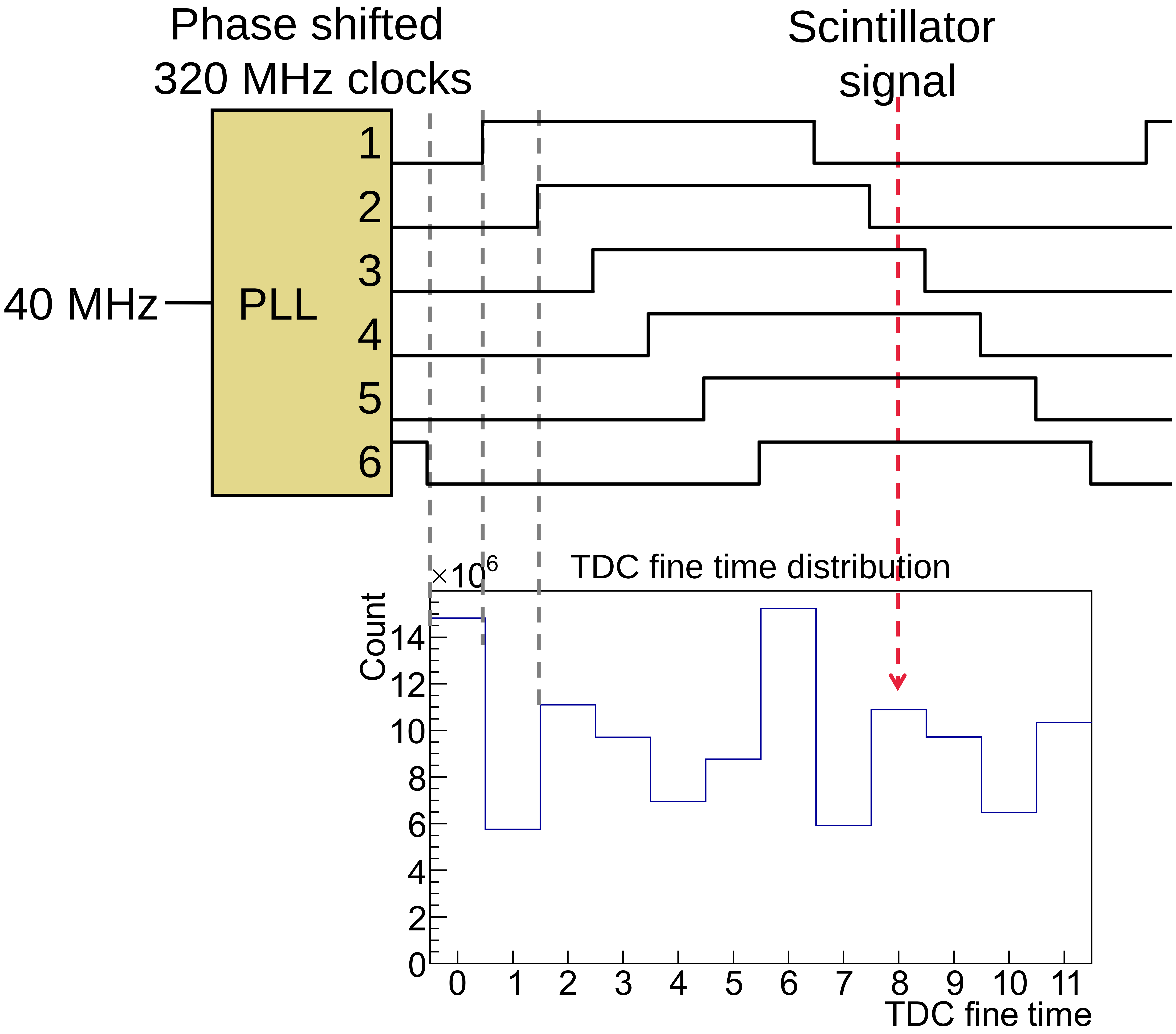
Beam scintillators

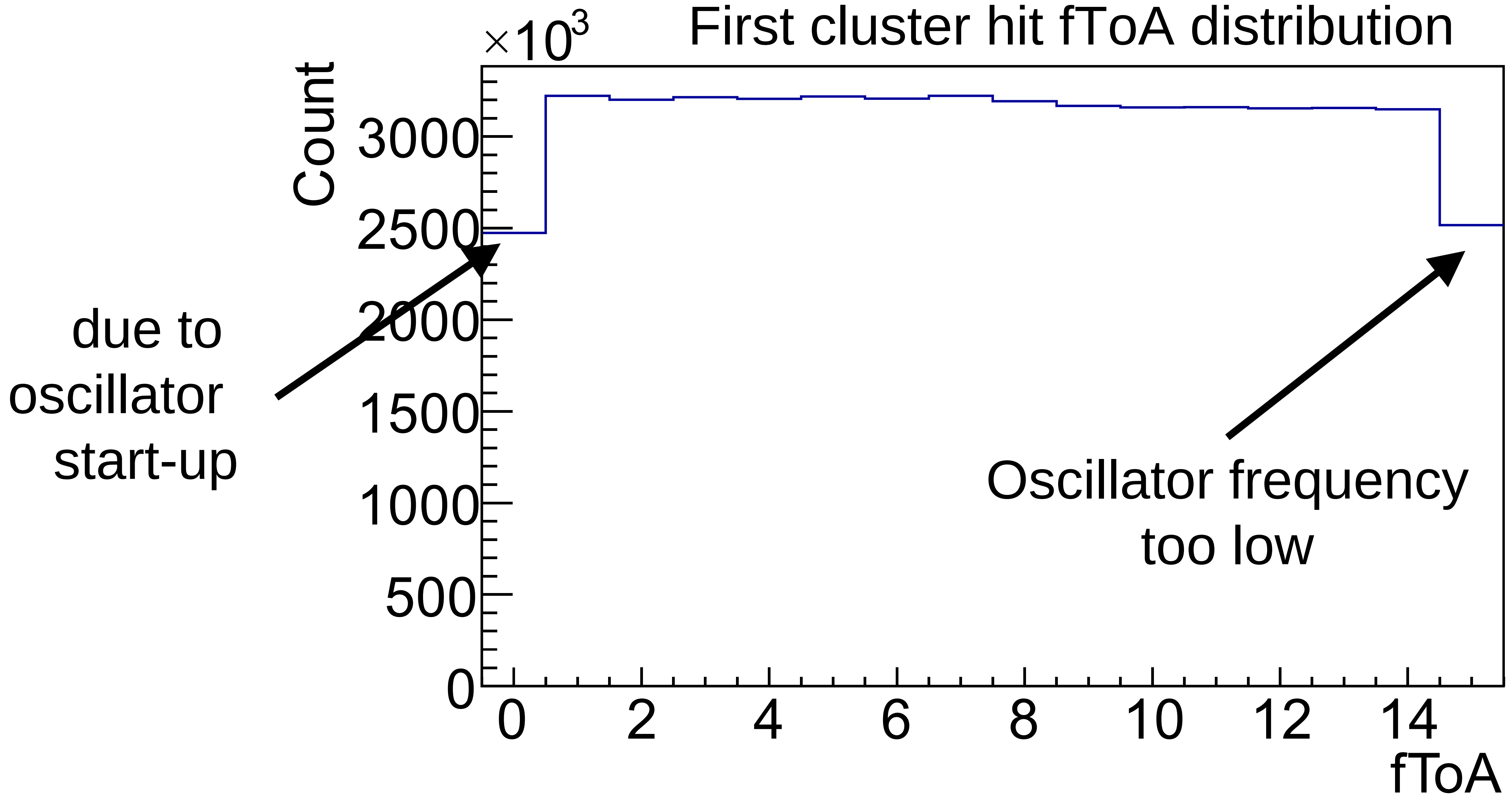
- TDC on SPIDR provides timestamp
- Phase shifted clocks make 12 time bins in 320 MHz period: 3.125 ns / 12 ≈ **260 ps**
- Measured scintillator resolution:
  Upstream: ~390 ps
  Downstream: ~190 ps
- Upstream CFD not properly tuned
- Time bins vary in size: Adds about 15 ps to the time bin resolution:

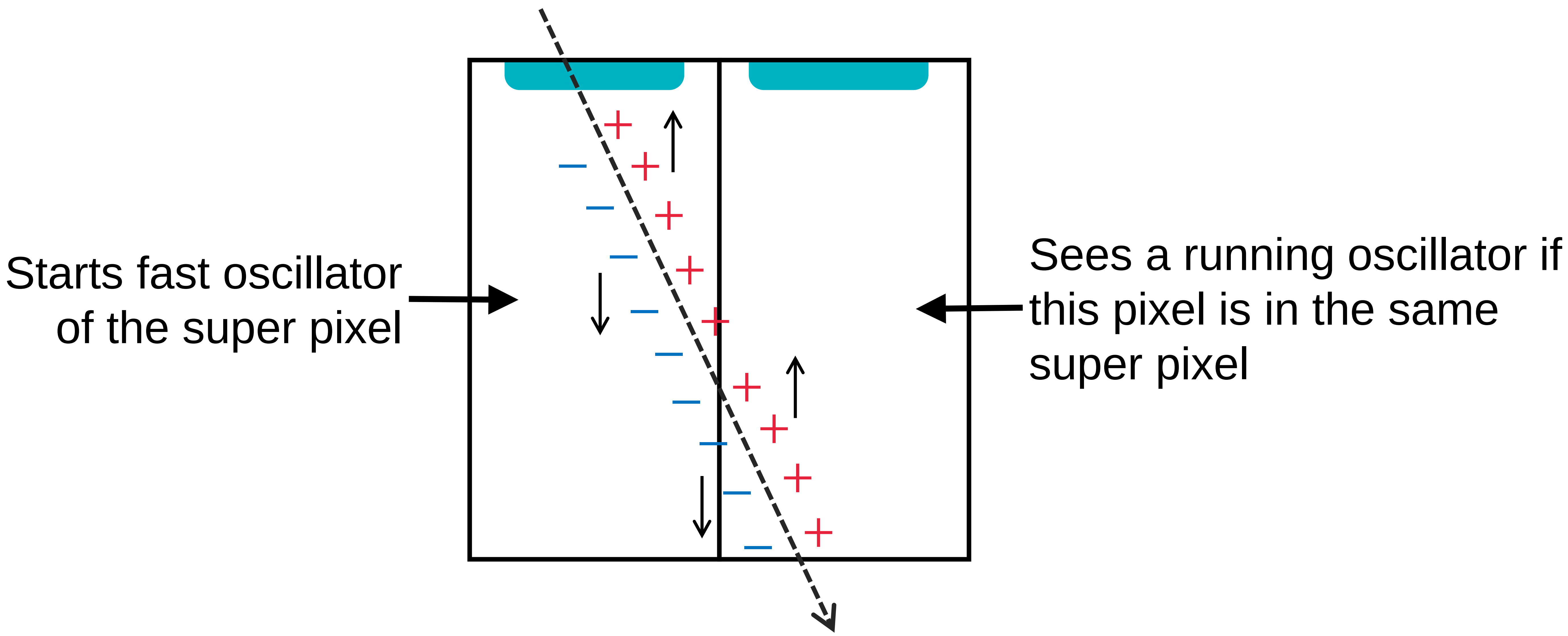
$$\sigma(\text{bin}) = \frac{260\ \text{ps}}{\sqrt{12}} \approx 75\ \text{ps} \ \rightarrow\ 90\ \text{ps}$$

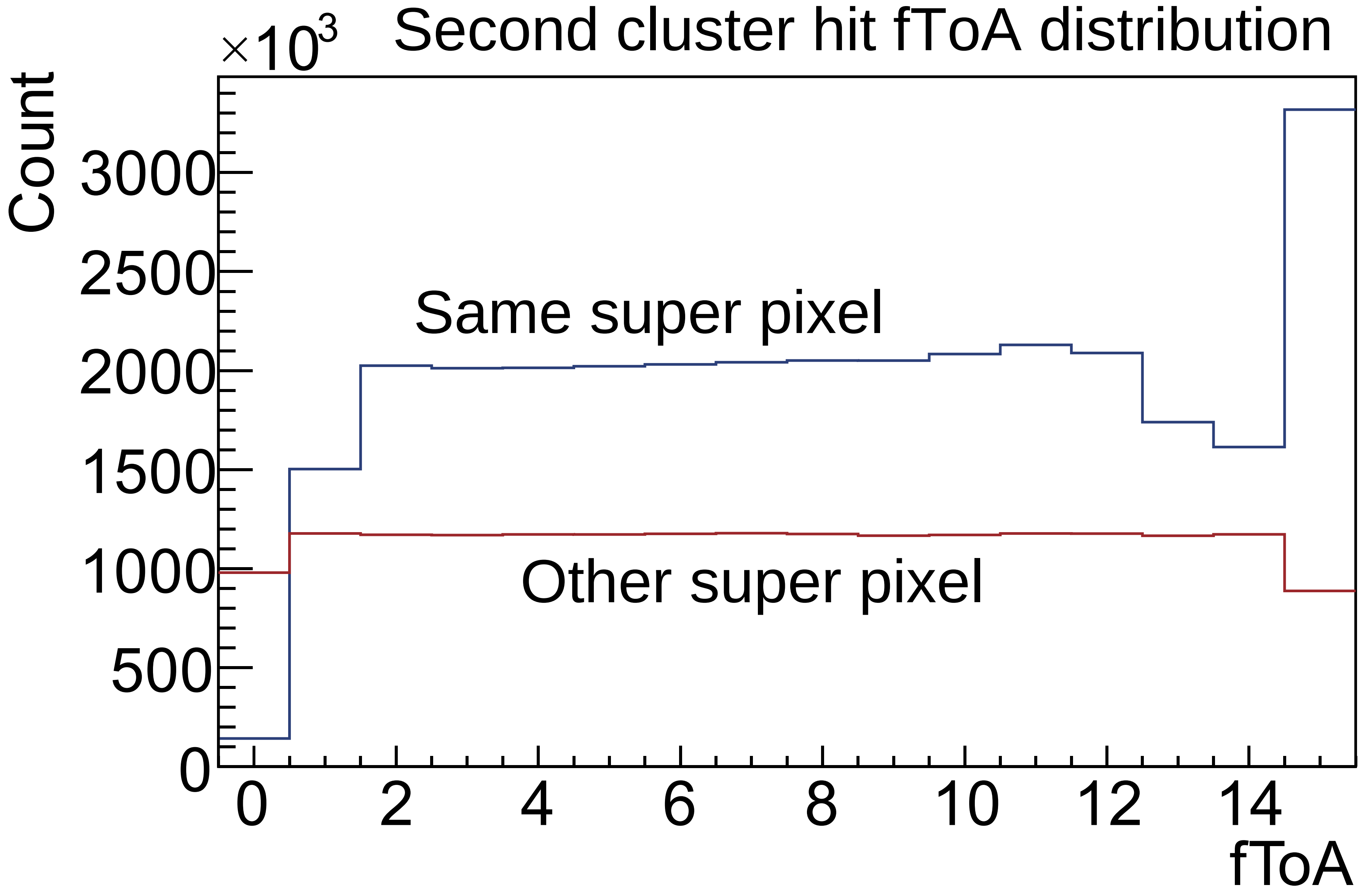


Pixel time-bin nonuniformity

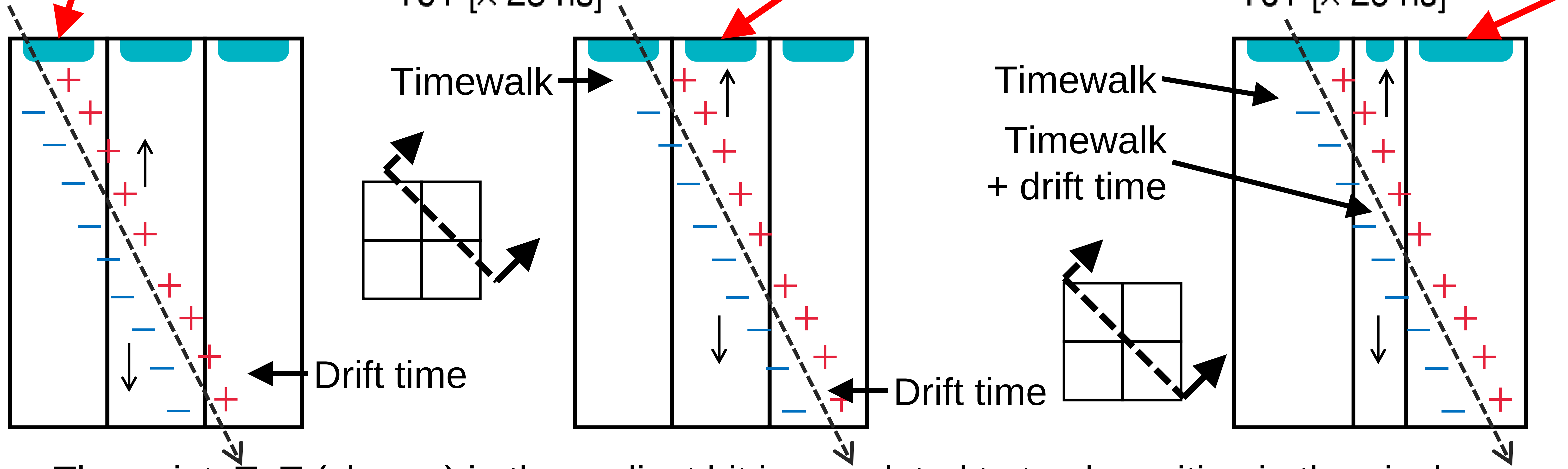
- First and last time bins have different size
- fToA counts to 1 too quickly, but counts too slowly to reach 15
- Second hit *in same super pixel* encounters an already running oscillator

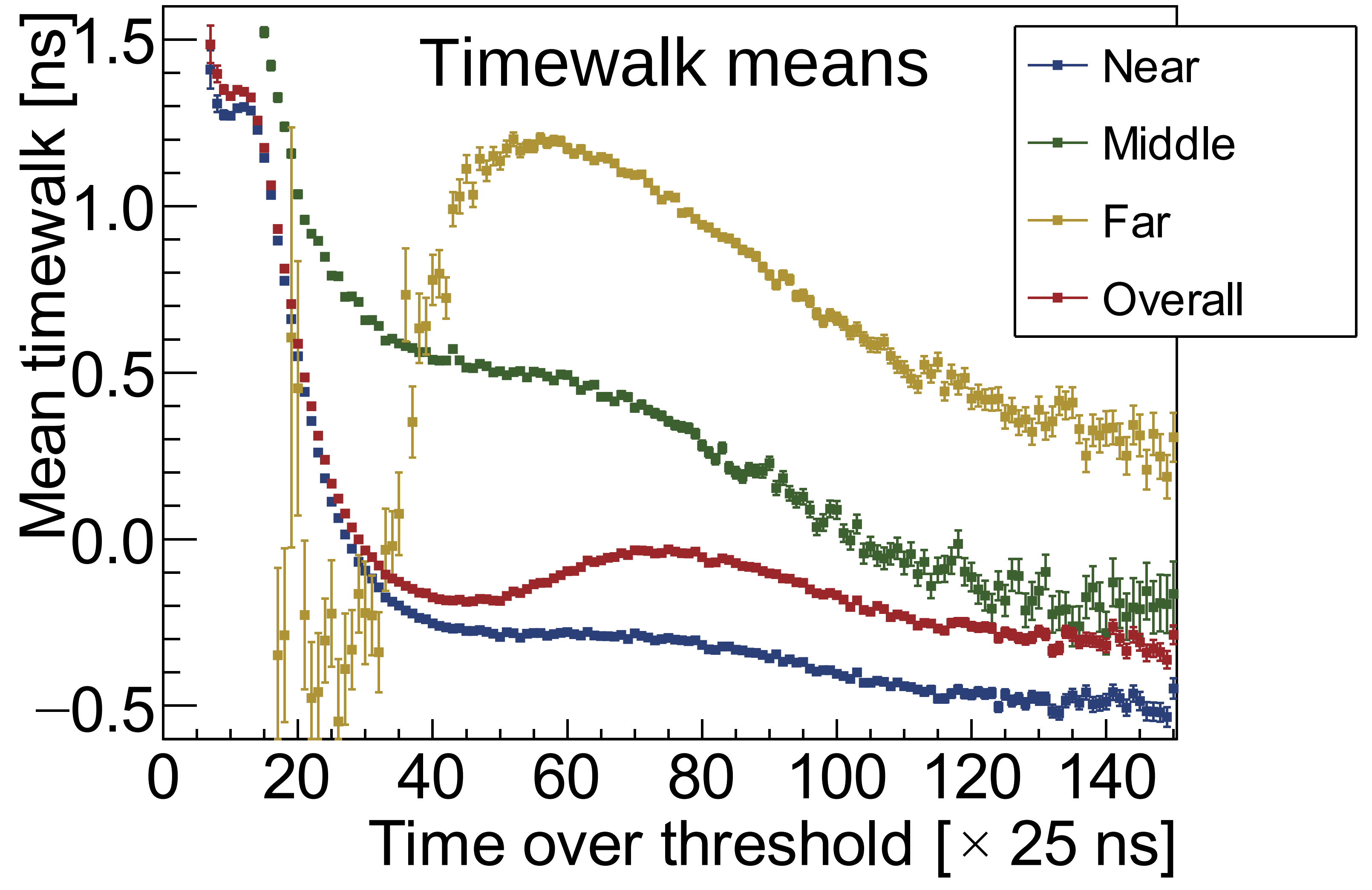






Timewalk and track geometry



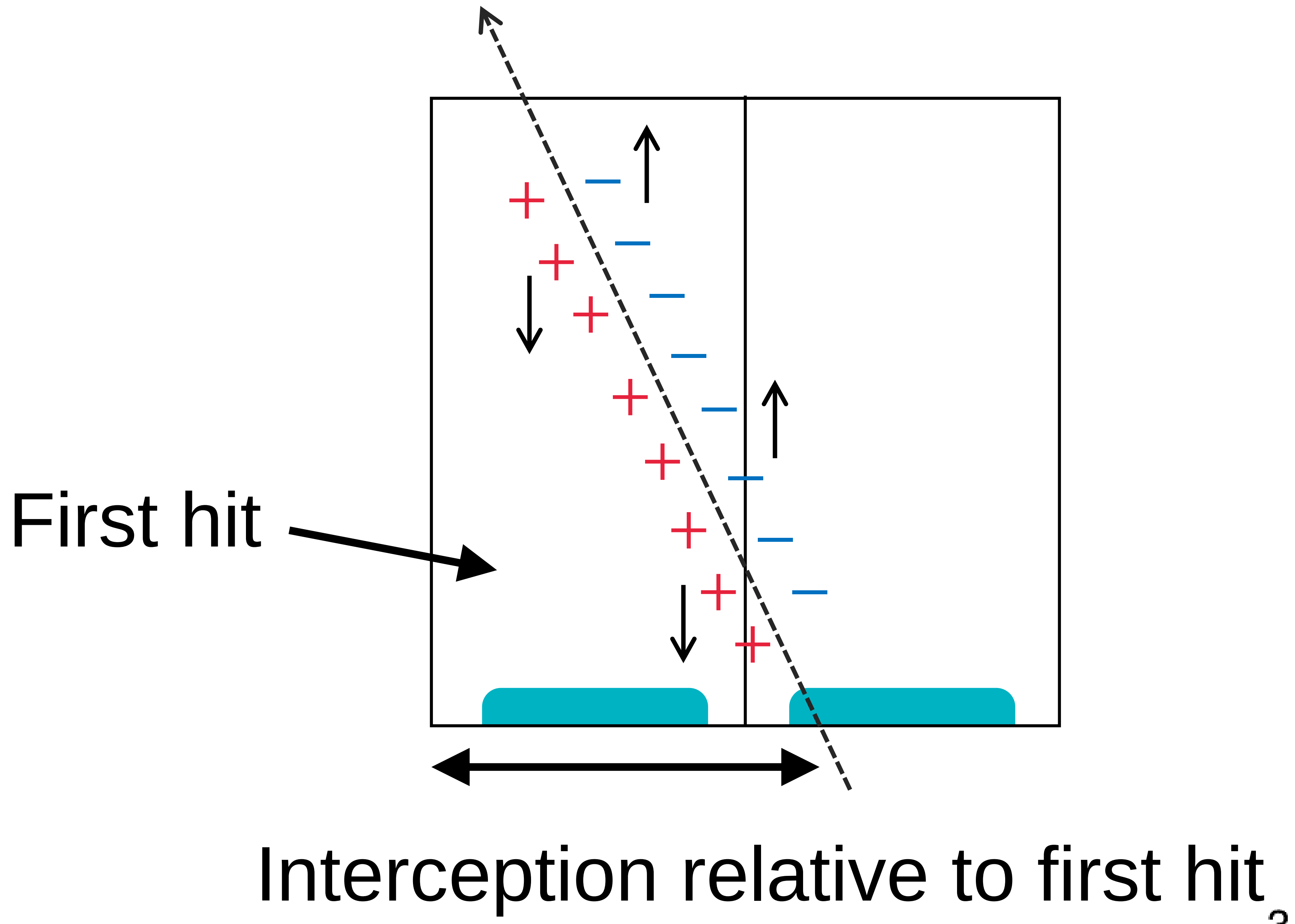


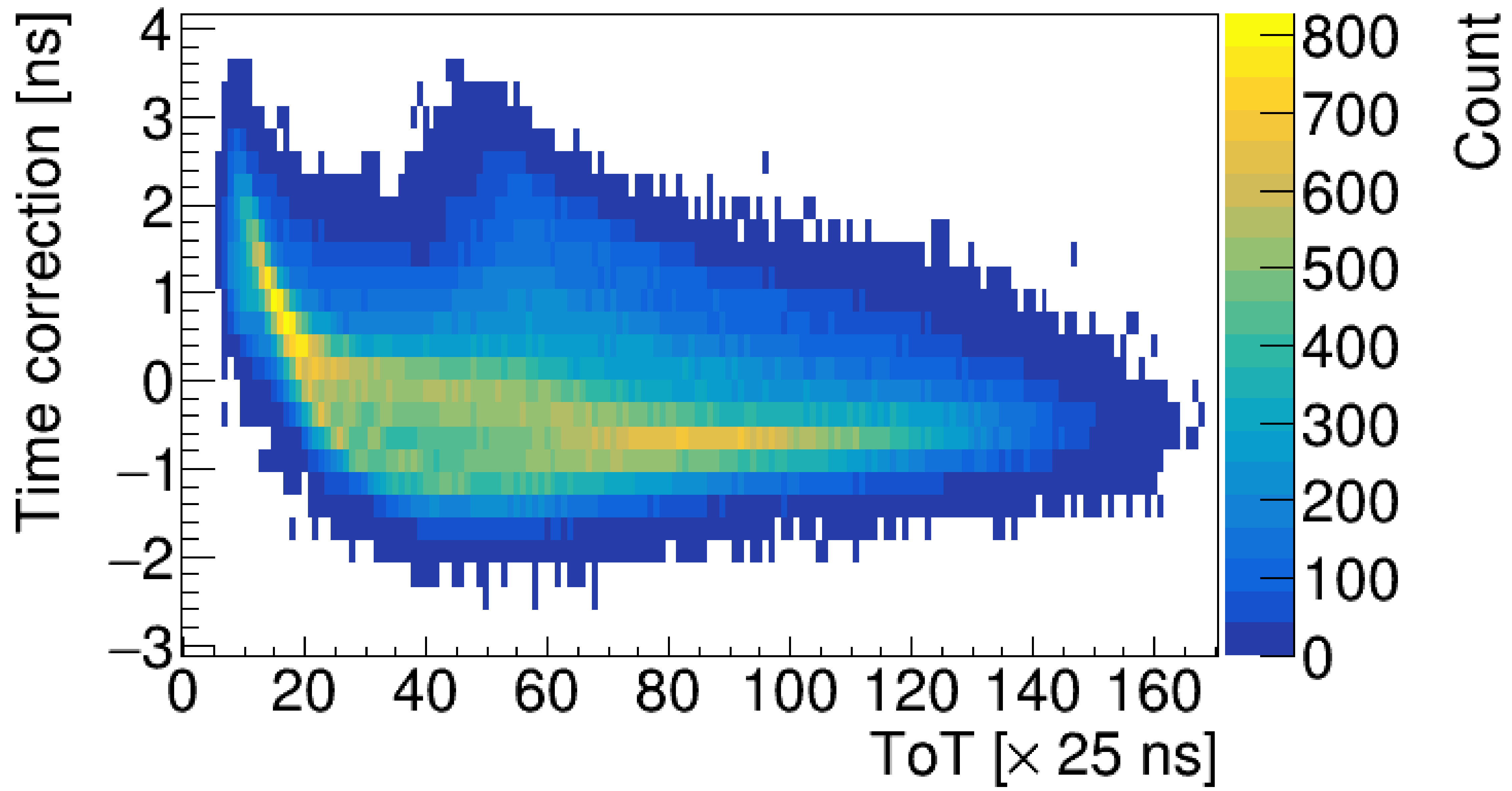
- The point: ToT (charge) in the earliest hit is correlated to track position in the pixel so we also see sensor effects (drift time, signal induction)

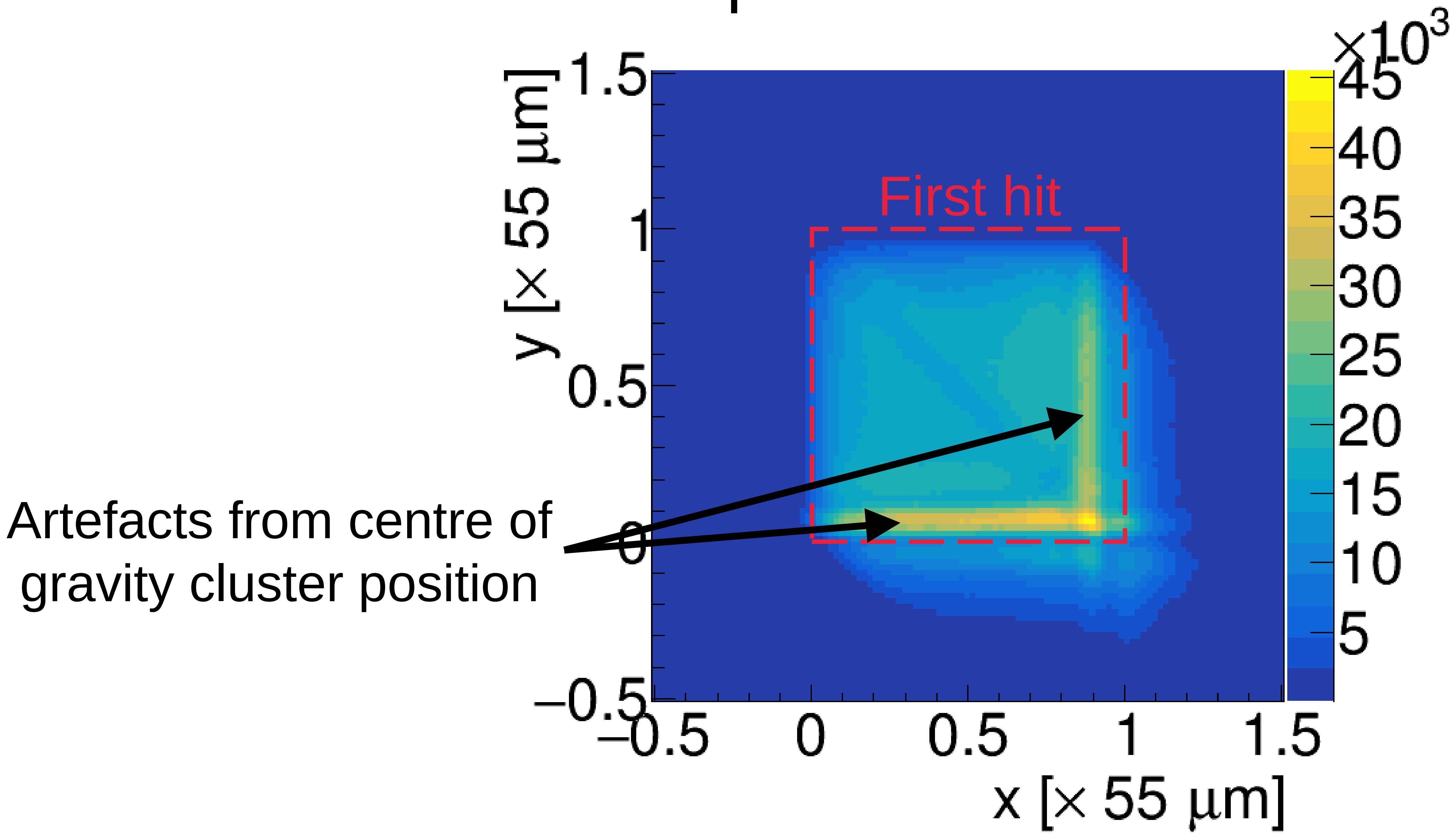
Timewalk and sensor correction

- Bin data on **both** track interception and charge and determine the time offset of each bin
- Correction varies depending on track interception
- Improves track time resolution:

$$\sigma(\text{track}) = 450 \text{ ps} \rightarrow 380 \text{ ps}$$







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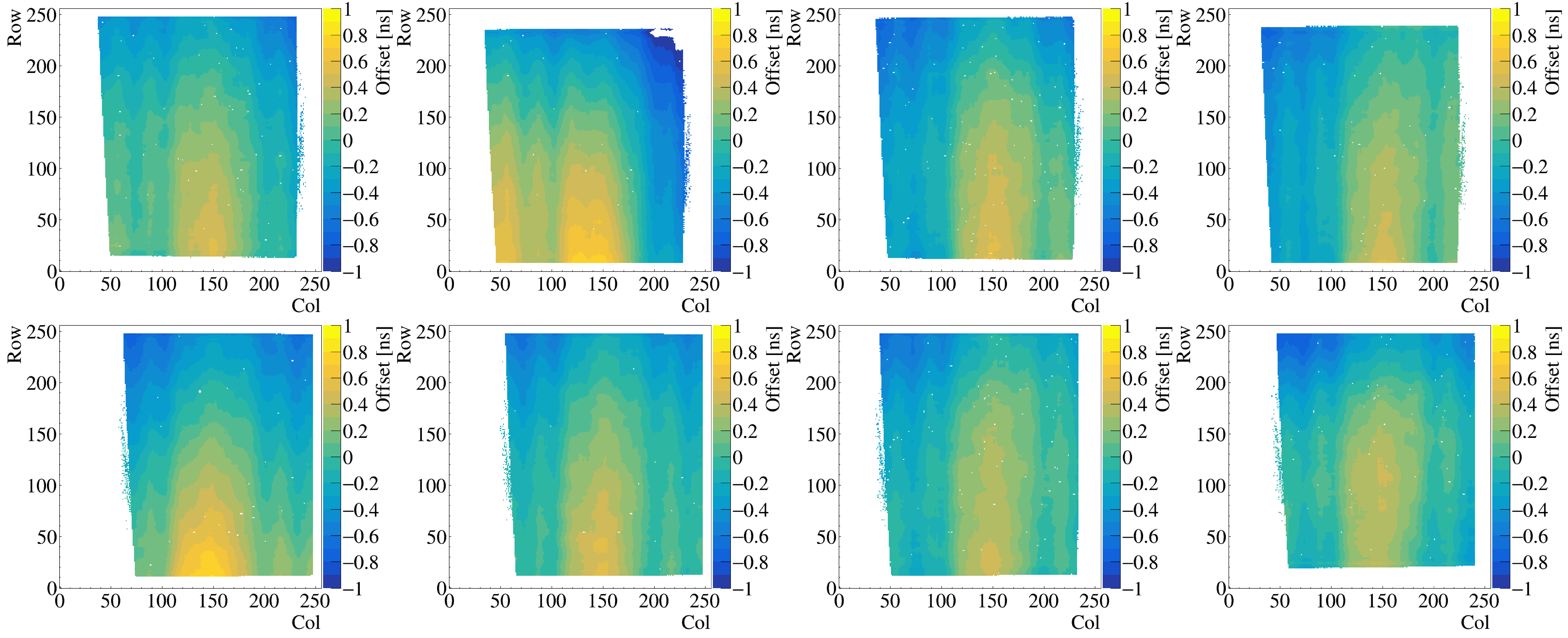
Decomposing per-pixel time offsets



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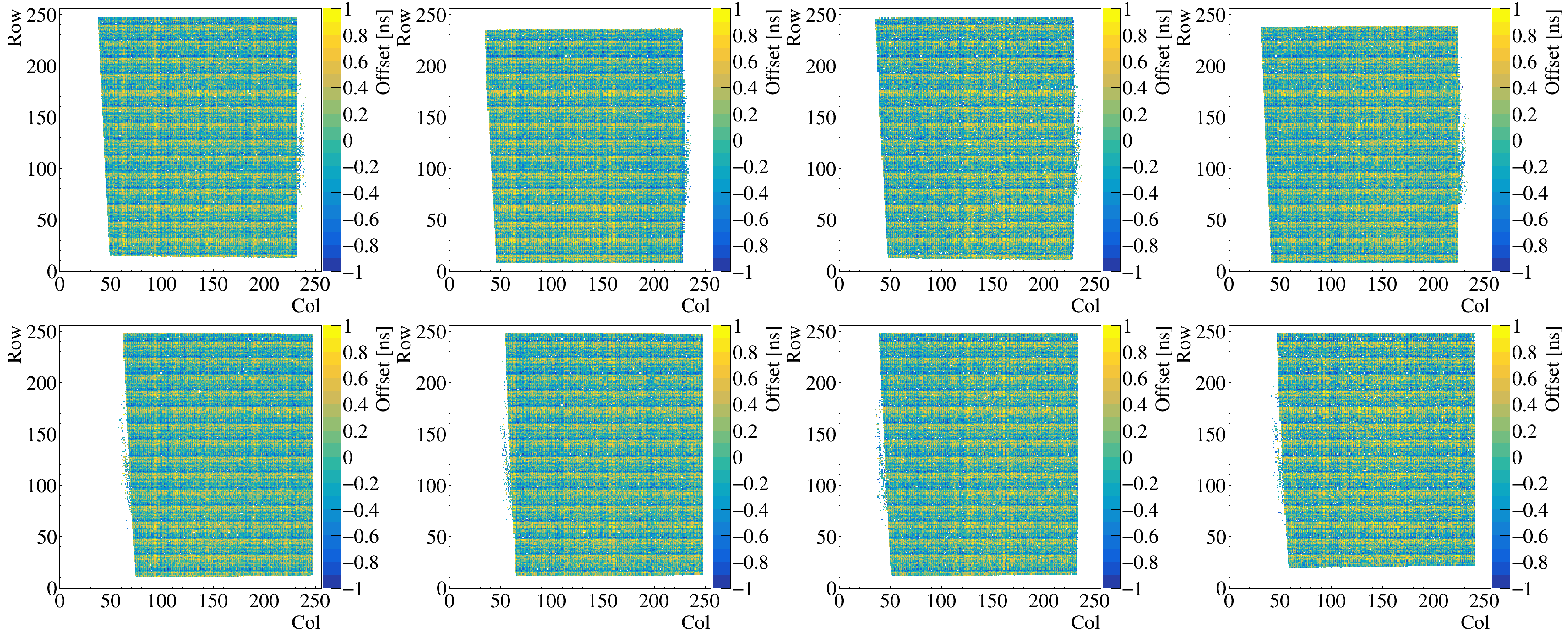
Decomposing per-pixel time offsets

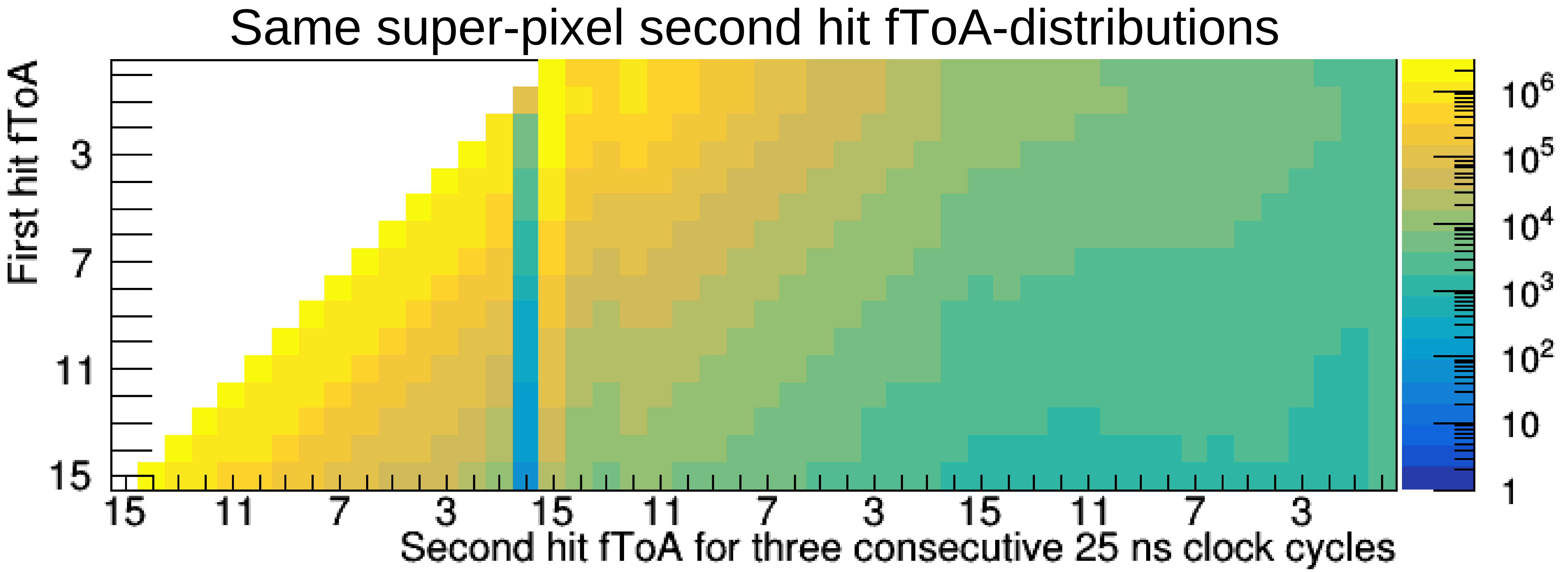


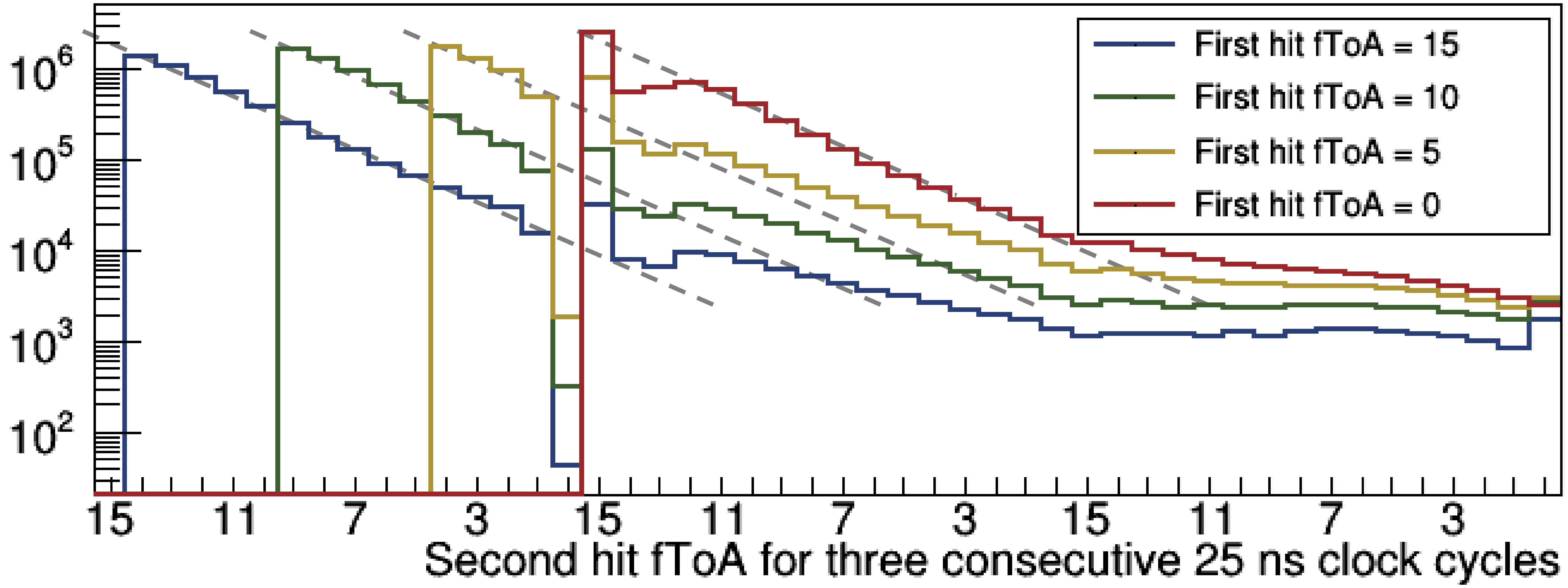
Pixel time offset and fToA distribution

- Late pixels have low fToA=15 count
- Early pixels have low fToA=0 count

Second hit fToA distribution

- Second hit fToA distribution should be independent of first hit fToA except for an overall shift
- Second hits that should have fToA=0 overflow into the next 25 ns cycle and get fToA=15





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