Recent Results From The Timepix4 Telescope

TREDI Workshop 20-22nd February 2024

Federico De Benedetti, on behalf of Timepix4 telescope group

TIMEPIX4 TELESCOPE

Timepix3 telescope:

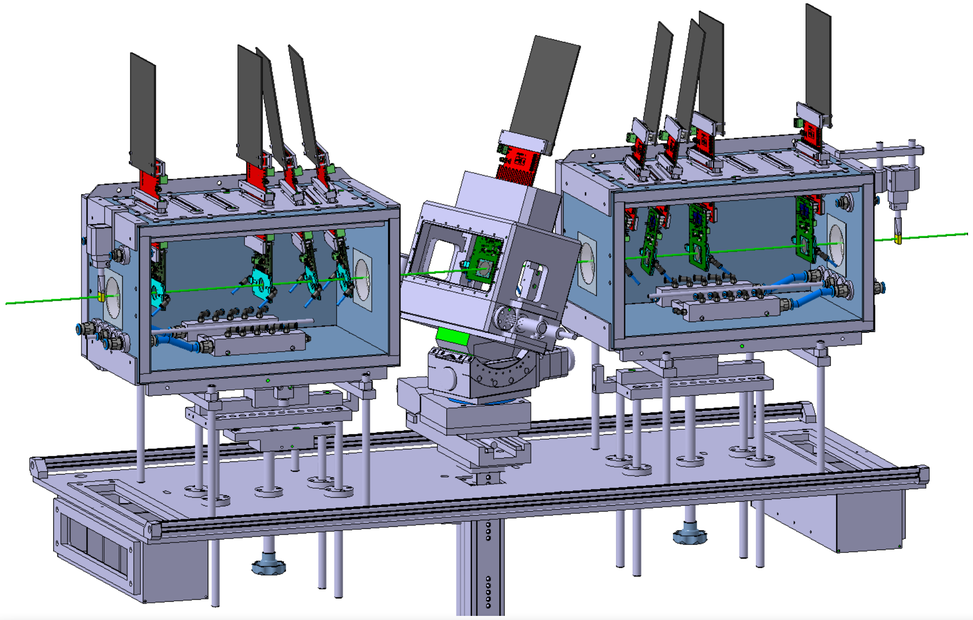
- Achieved 1.6 μm pointing resolution at DUT, 236 ps track time resolution

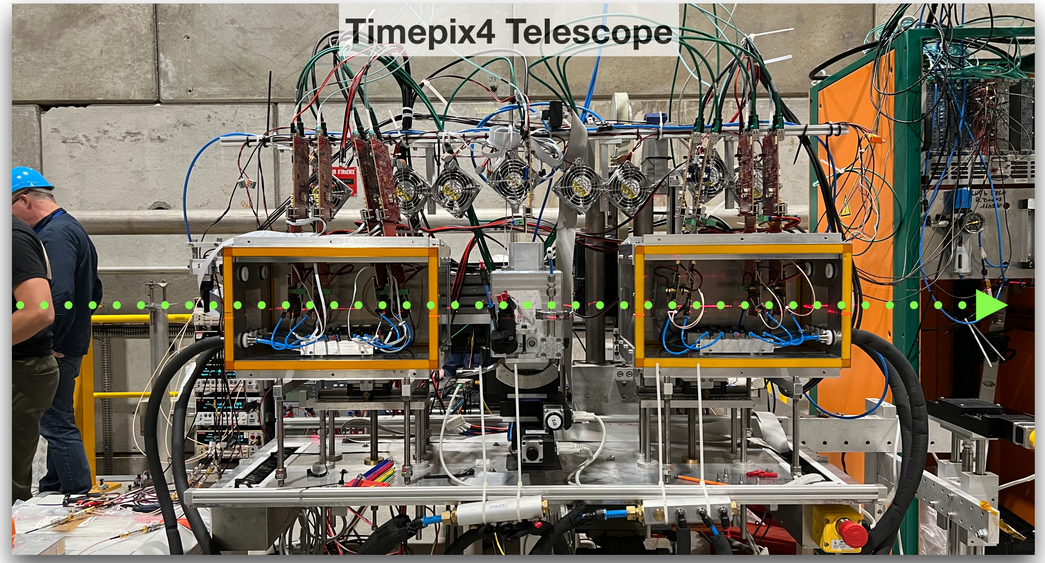
K. Akiba et al 2019 JINST 14 P05026, K. Heijhoff et al 2020 JINST 15 P09035

Timepix4 telescope goals:

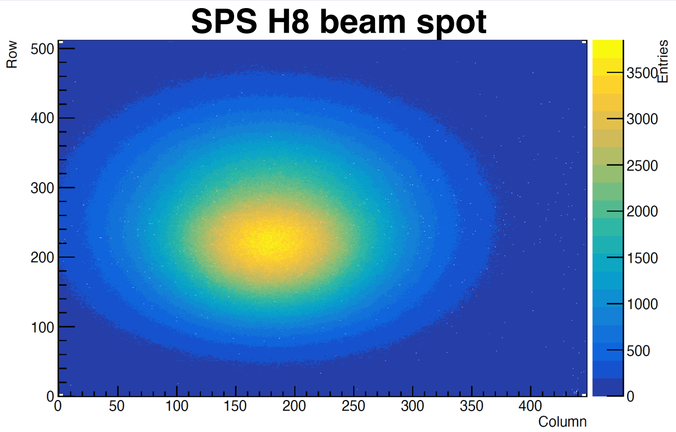
- Intrapixel characterization of sensor + ASIC assembly
- Proof of concept of a 4D tracker
- ~2 um pointing resolution at DUT
- Track time resolution combined with MCPs
- High track rate operations

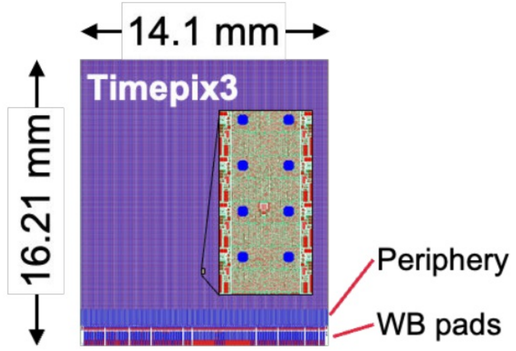
- Two arms of 4 planes each
- DUT plane in the center
- Can translate and rotate up to grazing angle
- MCP-PMTs for time reference downstream

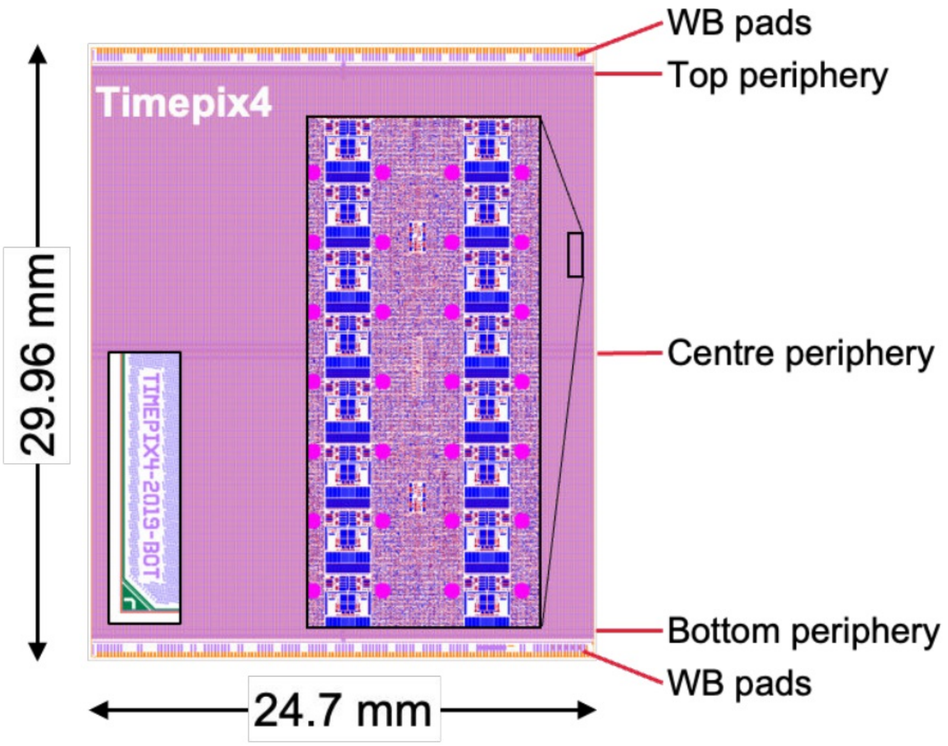




TIMEPIX4 CHIP



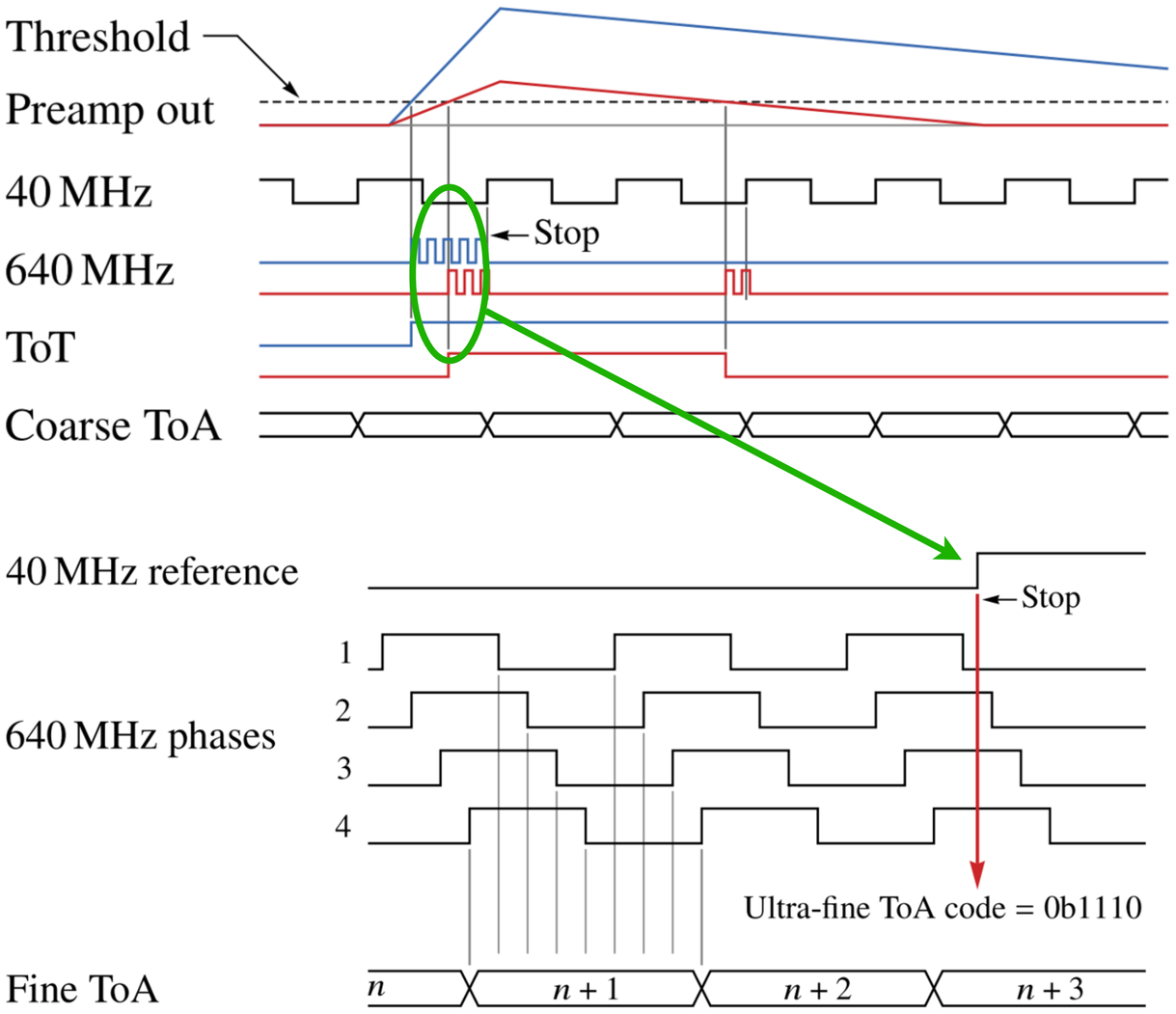


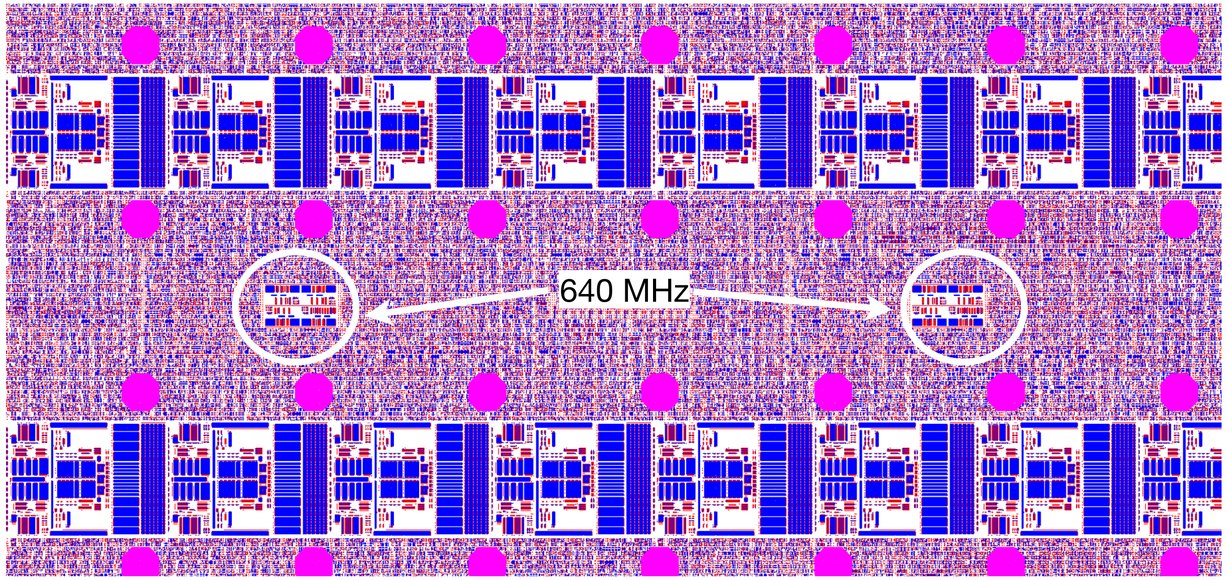


			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	3.5x
Sensitive area			1.98 cm^2	**6.94 cm^2**	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	
		Max rate	0.43x10^6 hits/mm^2/s	**3.58x10^6 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 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**	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^-	

TIMEPIX4 TDC

X. Llopart et al., JINST 17 (2022) 01, C01044

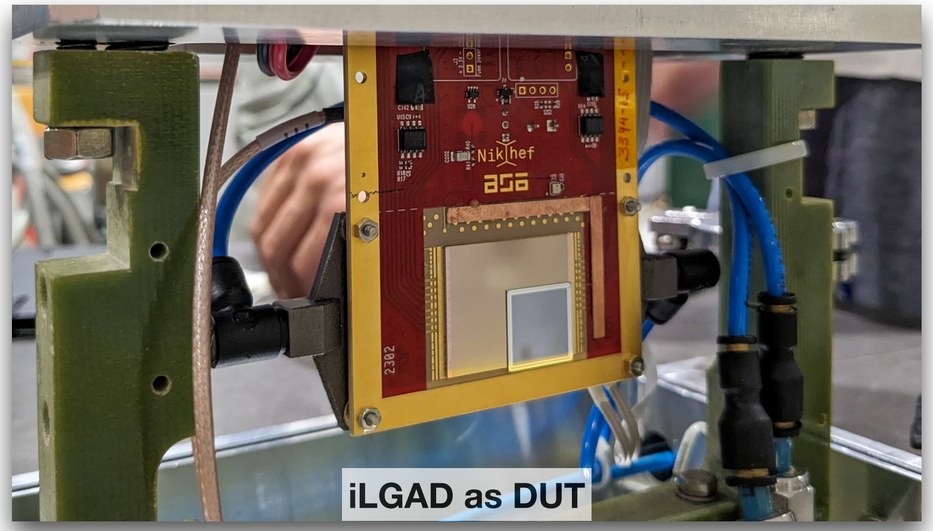




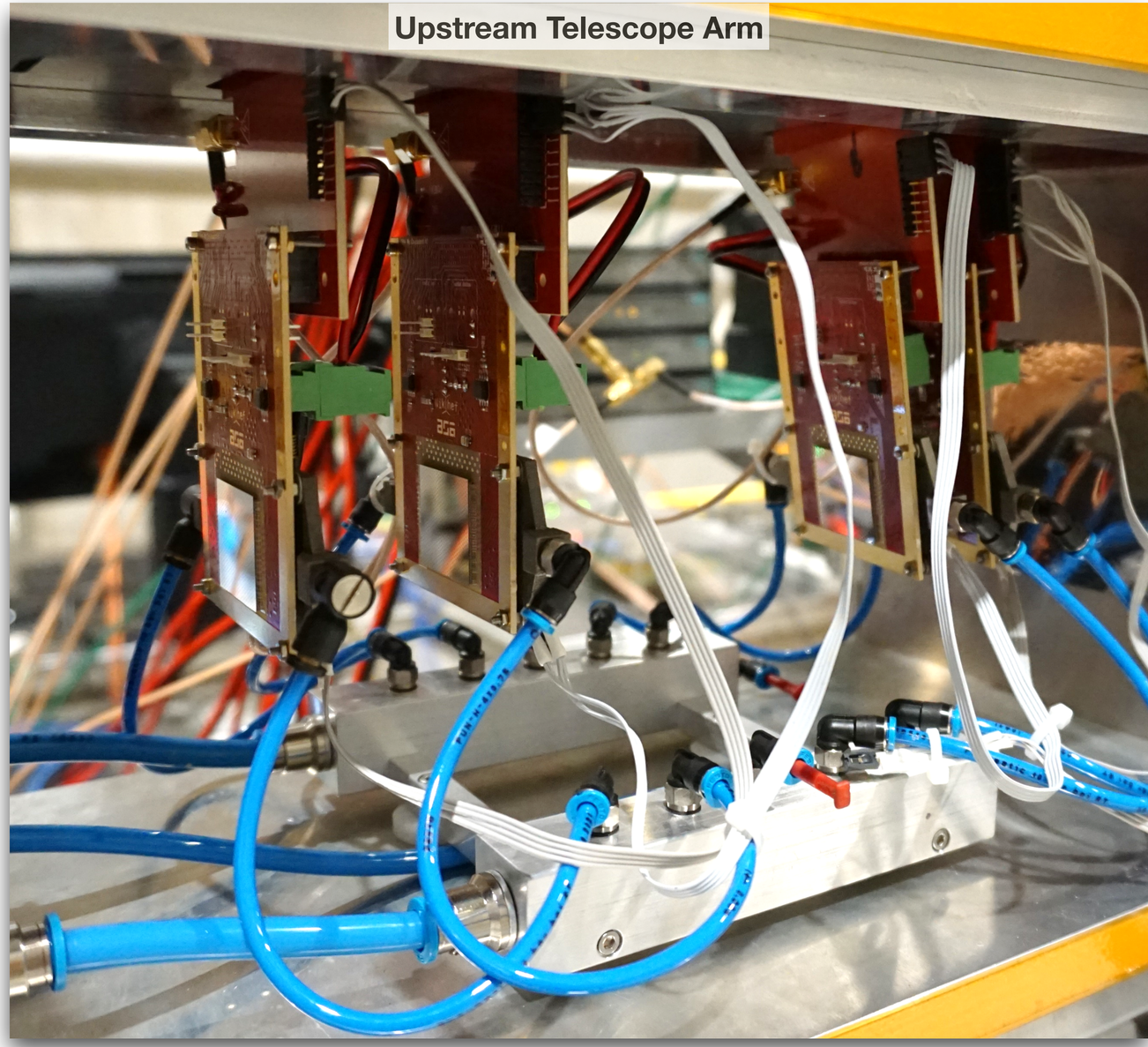
- Base clock of 40 MHz (ToA)
- Hit starts 640 MHz voltage-controlled ring oscillator (VCO)
  - 1.56 ns bins (fToA)
  - shared by 2x4 pixels (“superpixel”)
  - stopped by first rising edge of 40 MHz clock
- Status of 4 phase-shifted instances of VCO is latched at 40 MHz rising edge
- Nominal TDC resolution (ufTOA) is 195 ps/√(12) = 56 ps

TELESCOPE PLANES

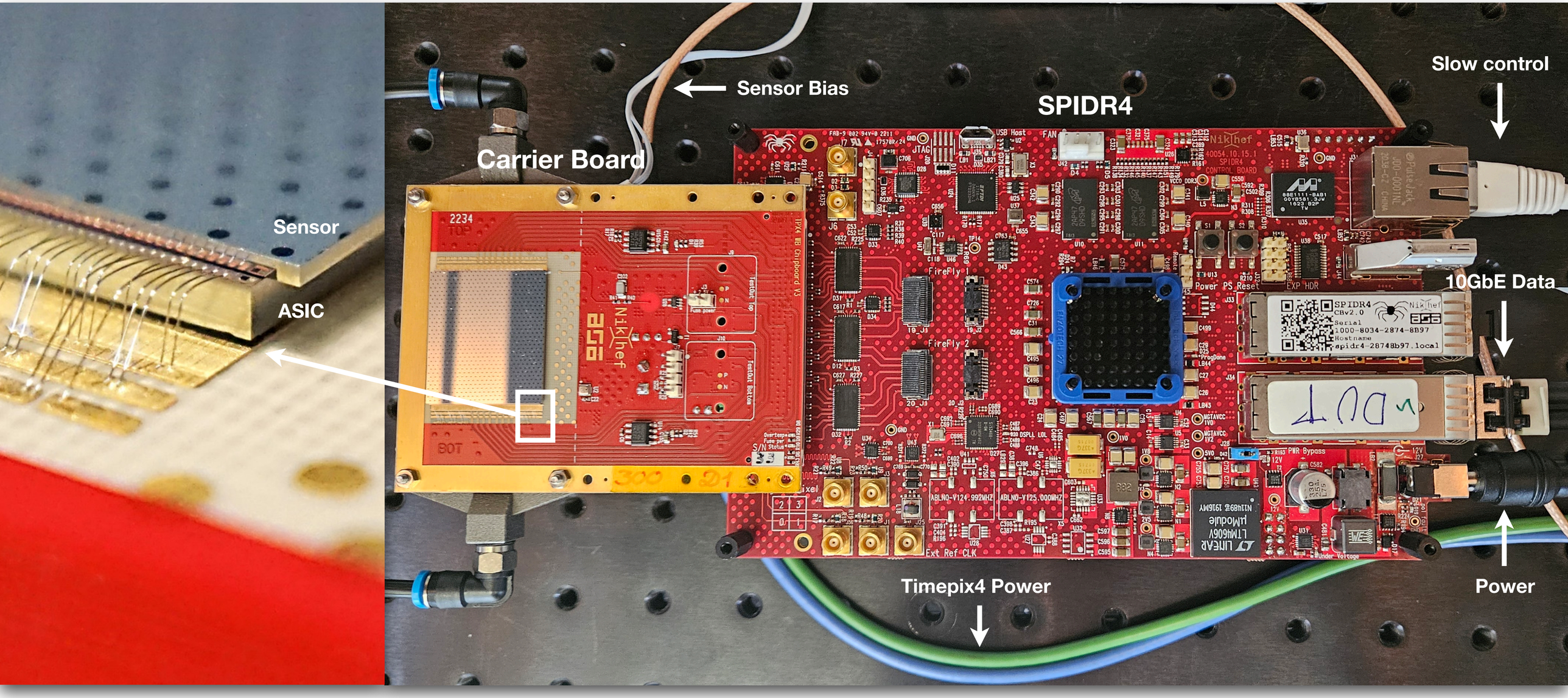
- Eight telescope planes with n⁺-on-p planar silicon sensors:
  - 4 x 300 µm sensors for spatial resolution (angled 9°)
  - 4 x 100 µm sensors for time resolution (perpendicular)
- Several DUT assemblies
  - 50 µm, 100 µm and 200 µm n+-on-p planar silicon
  - 300 µm p⁺-on-n planar silicon
  - 2 x 250 µm iLGAD sensors with 55 µm and 110 µm pitch (Timepix3 sized)
- All bump-bonded to Timepix4 V2 ASICs



iLGAD as DUT

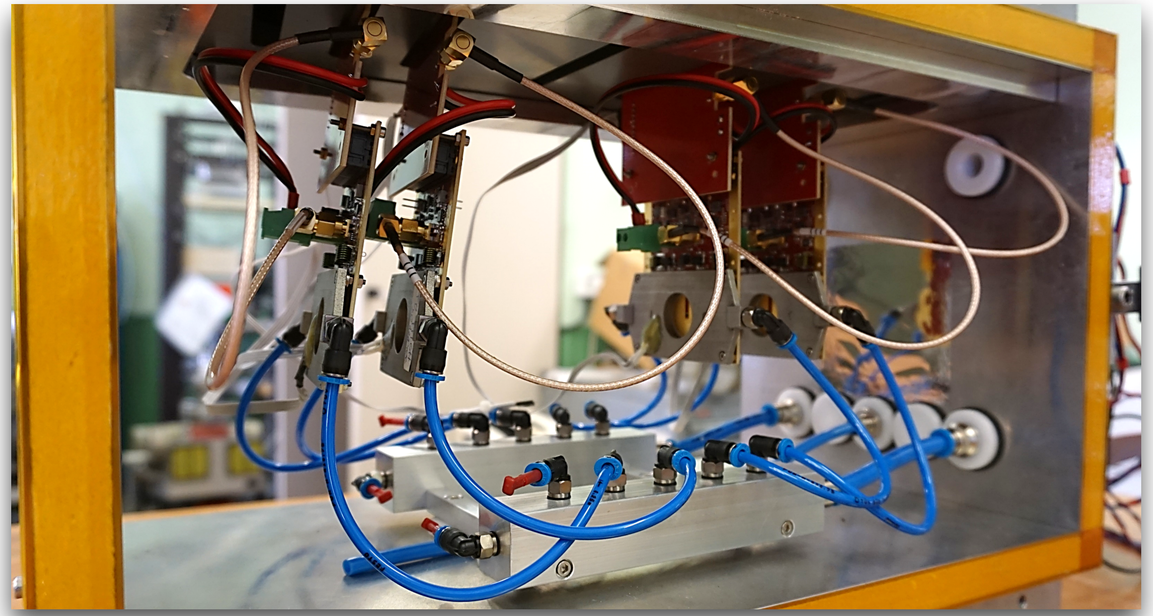

Upstream Telescope Arm

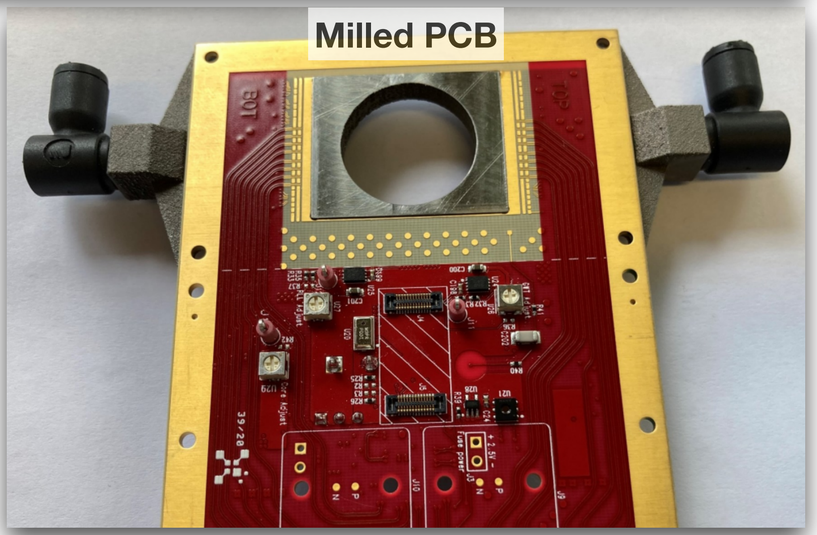
Speedy PIxel Detector Readout 4 (SPIDR4)



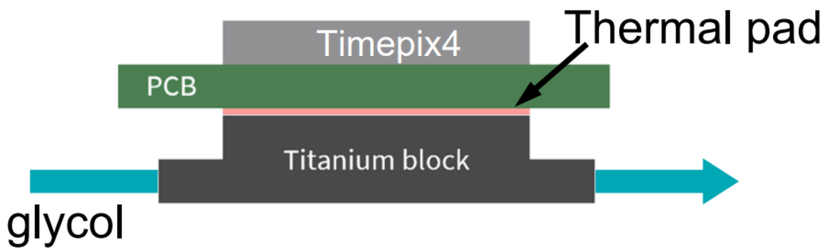
TELESCOPE COOLING

- All assemblies have a 3D-printed titanium cooling block in contact with the PCB
- Cooled using a chiller with glycol at 20 °C
- Possible to go down to –20 °C in the future (especially in the DUT)
- Temperature and humidity monitoring
- Telescope box flushed with N2
- Plan to mill PCB to have direct thermal contact

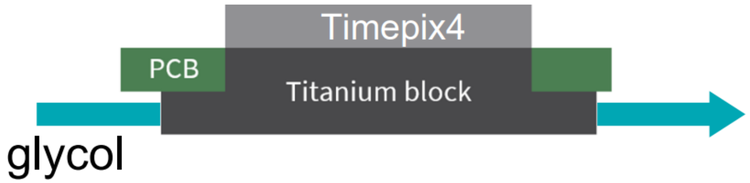




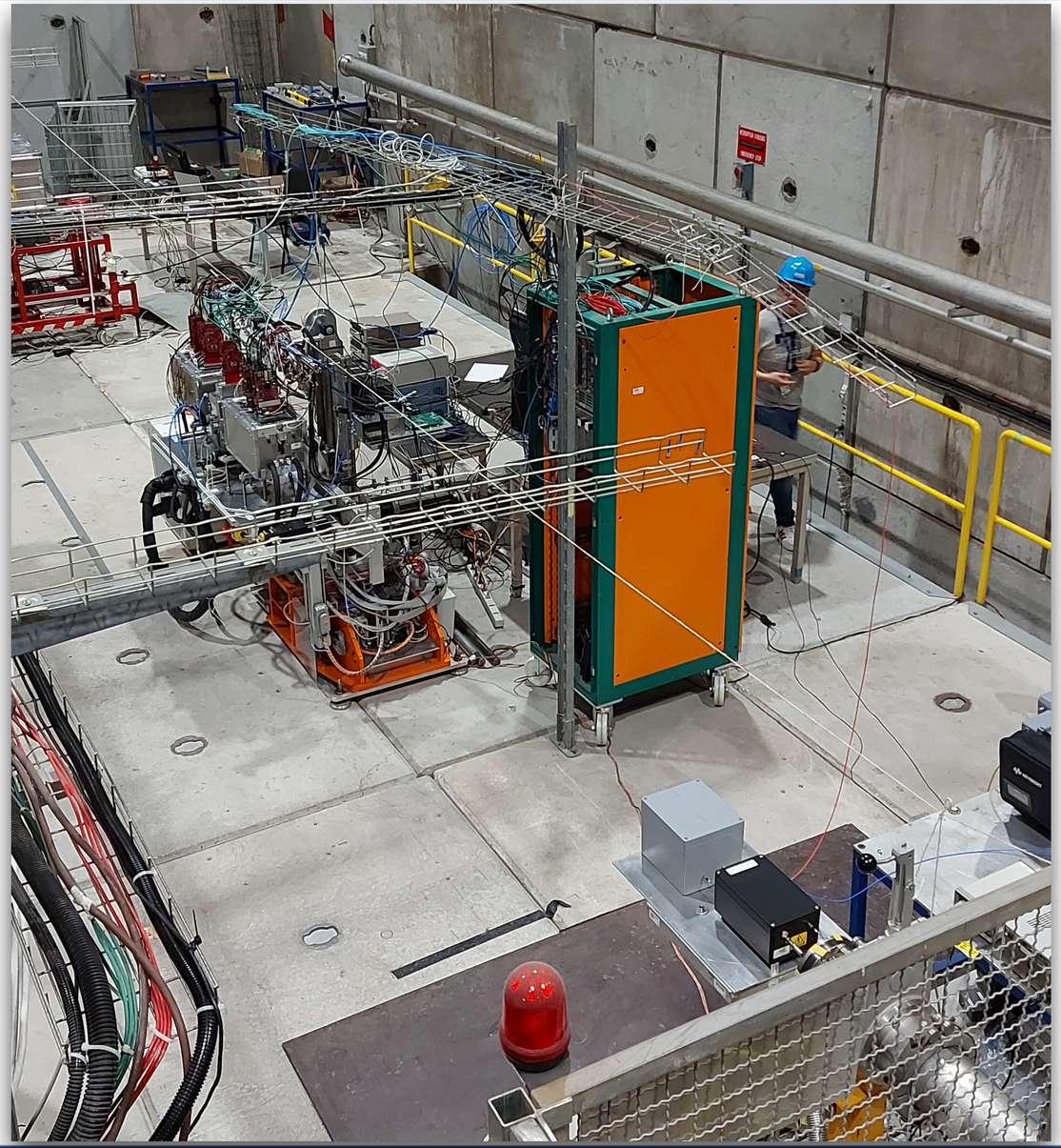
Current thermal interface



Future thermal interface

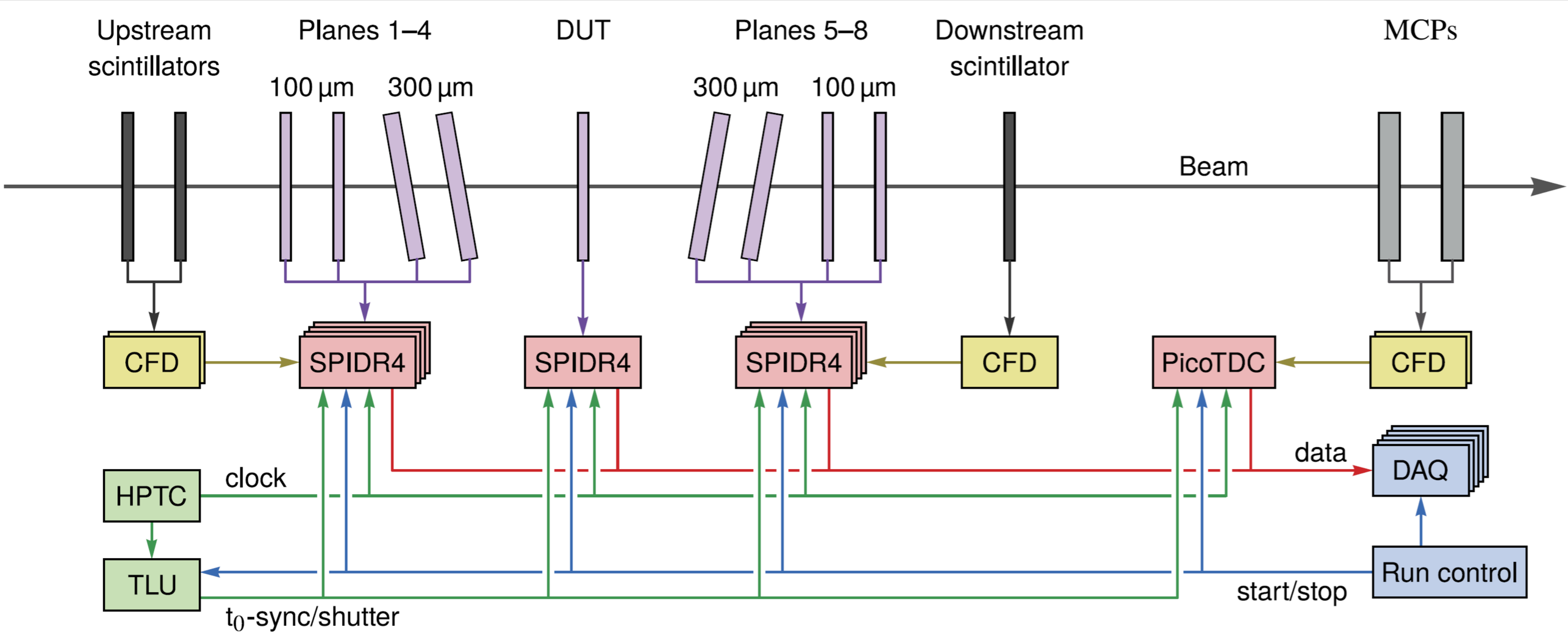


SPS CONFIGURATION



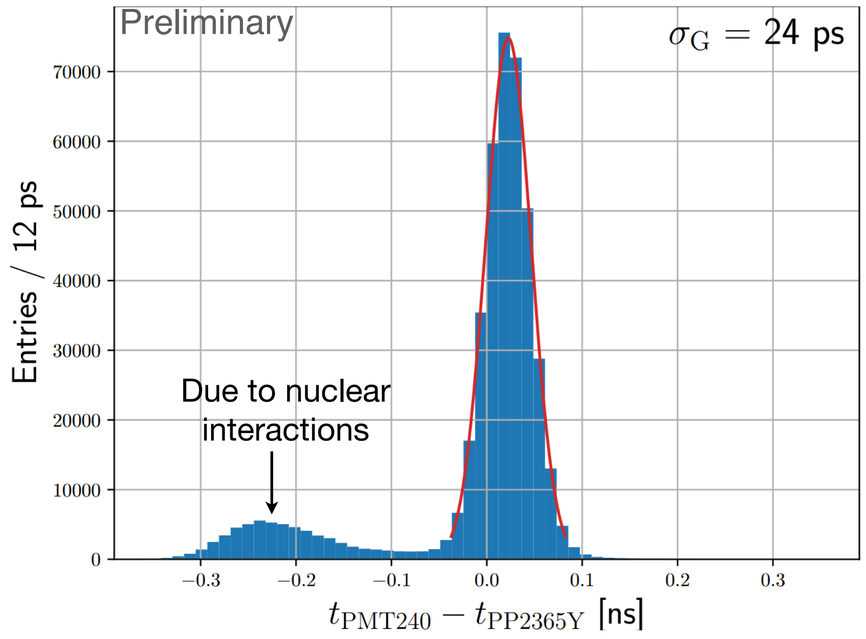
- Telescope installed at H8 beamline at SPS
- 180 GeV mixed hadron beam
- MCP-PMTs downstream of all other detectors to minimize the disturbance due to high material budget
- ~3 data-taking campaigns per year since 2022

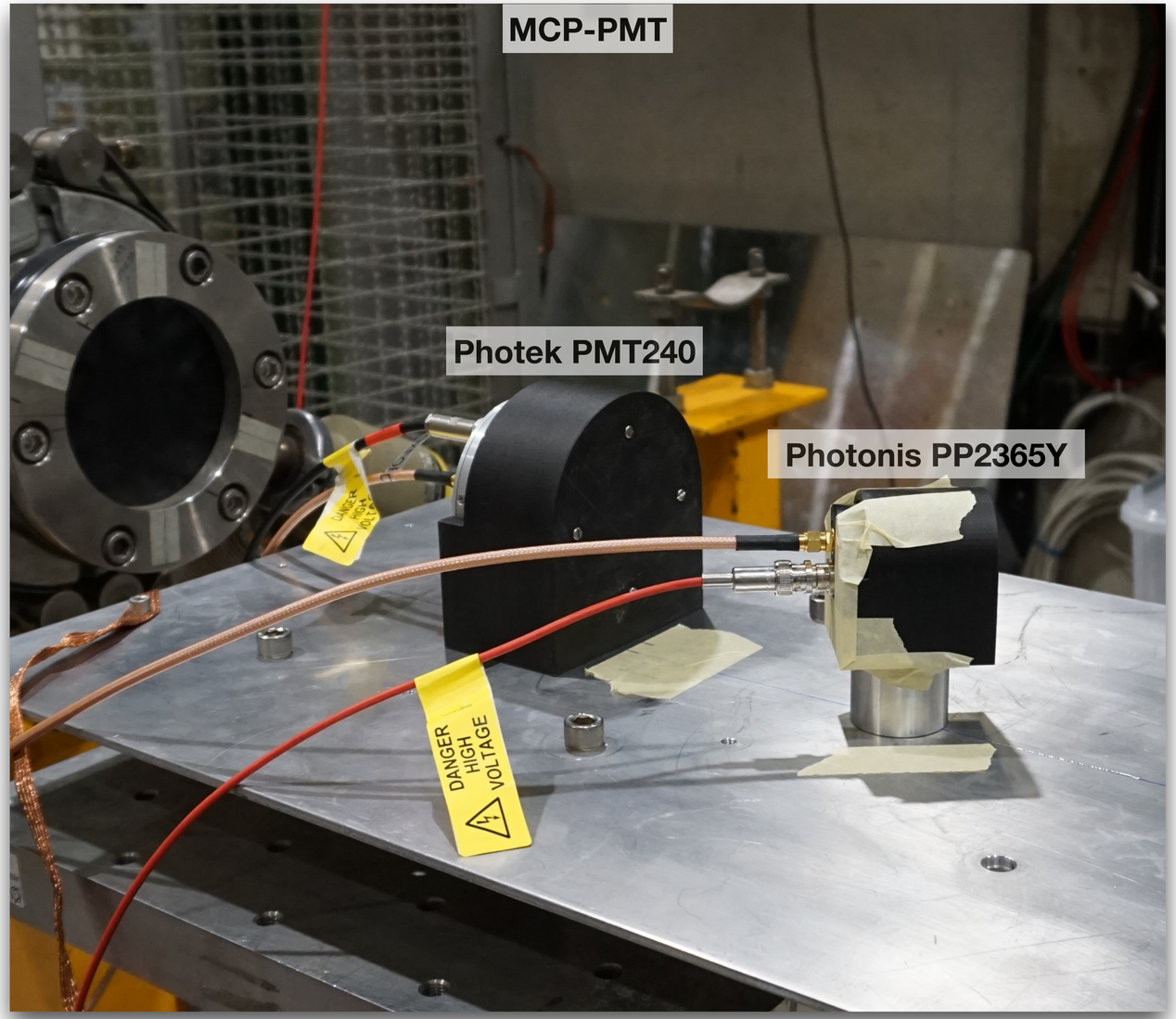
TELESCOPE CONFIGURATION



MCPs TIMING REFERENCE SYSTEM

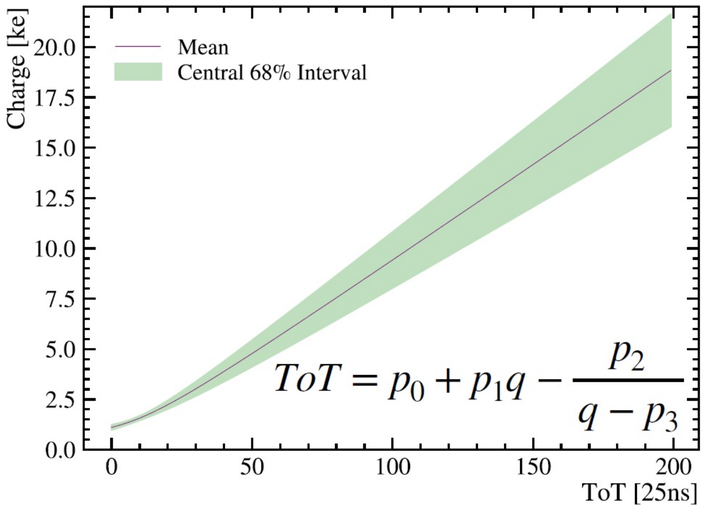
- Two microchannel plate photomultipliers (MCP-PMT) in coincidence
- CFD through Ortec9327, digitisation by PicoTDC
- Considering installing Timpix4 plane to VETO events with nuclear interactions
- Current time resolution: 17 ps (single MCP)
- Combined MCP resolution: 12 ps

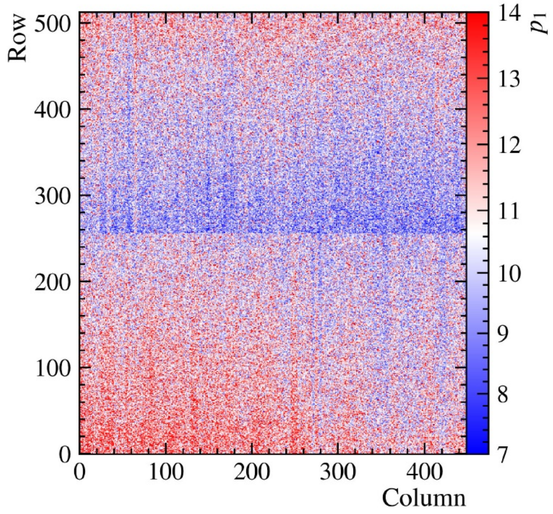


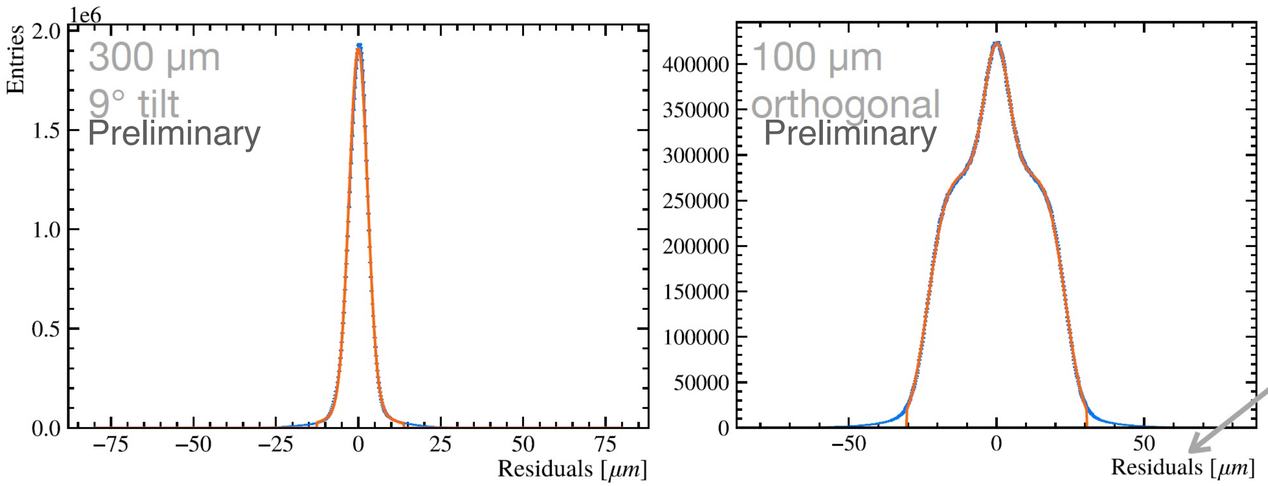


SPATIAL RESOLUTION

- Pixel size 55 μm × 55 μm
- Four innermost planes rotated 9° around x and y to induce charge sharing between pixels
- Charge-weighted mean gives cluster position
- Optimal resolution achieved by using only clusters with width less or equal than 2
- ToT-to-charge calibration from test pulses in the laboratory
- η corrections applied to all planes
- Nominal per-plane resolution:
  - 3.6 µm (300 µm tilted sensors, 98% central interval)
  - 14.1 µm (100 µm orthogonal sensors, 98% central interval)

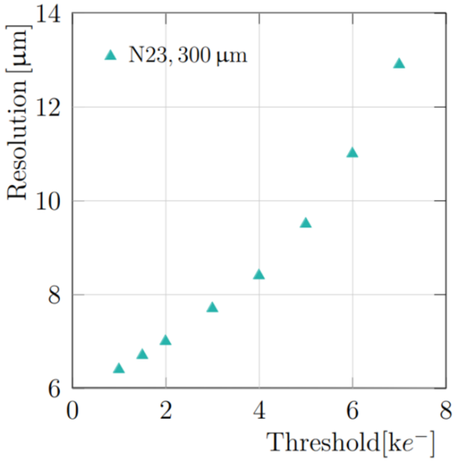


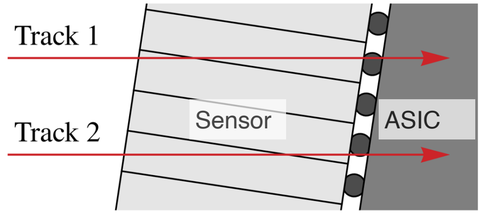




Cluster-track

K. Akiba et al 2023 JINST 18 P02011



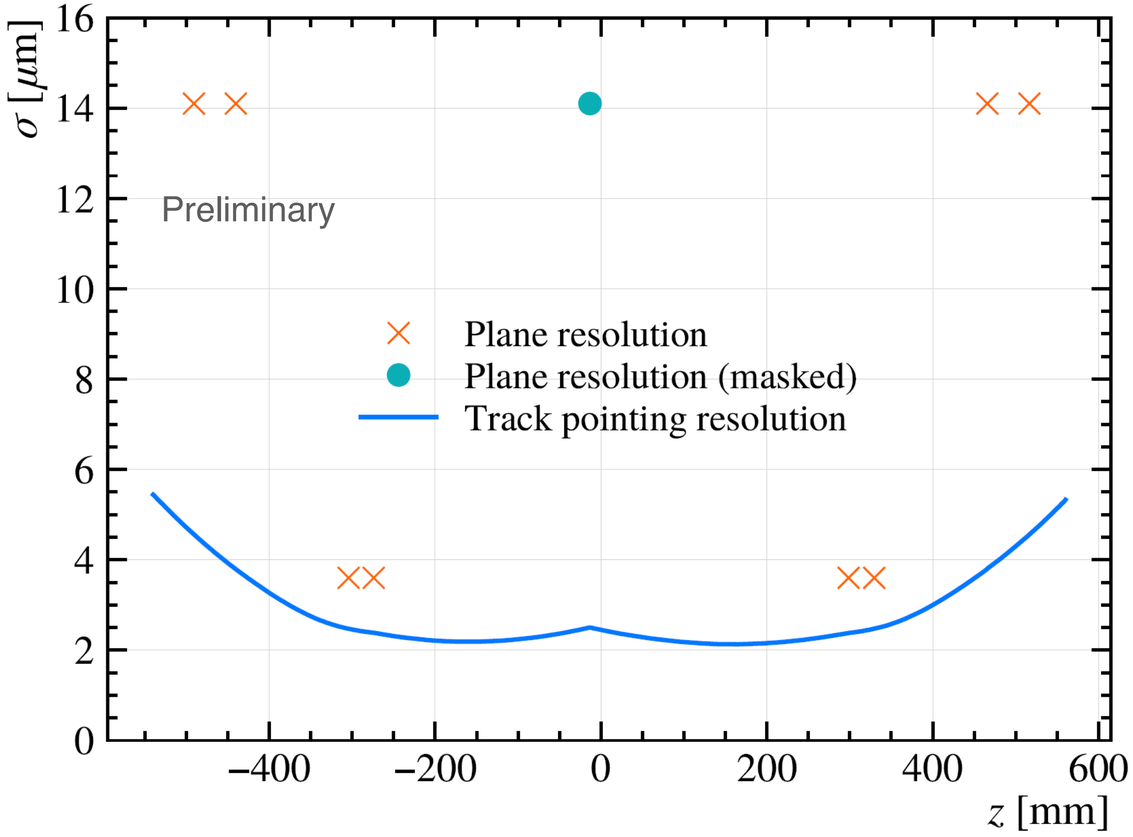


TRACKING POINT RESOLUTION

- Resolution driven by the four innermost planes (300 µm, tilted)
- Pointing resolution at DUT: 2.5 µm
- Material budget per plane:
  - ASIC + sensor → 0.7–1.0% X_0
  - PCB → 1.8–2.4% X_0

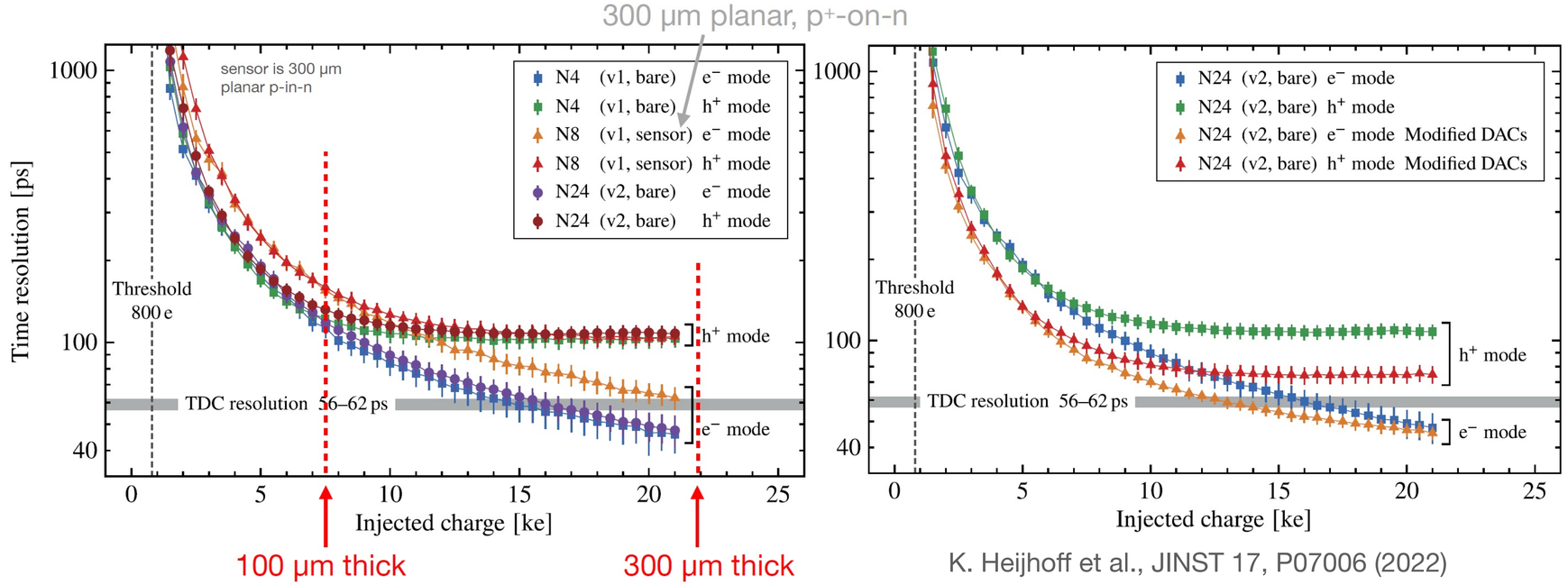
Possible improvements:

- Milling the PCBs would reduce pointing resolution to ~2.0 µm
- Increase the number of 300 µm planes
  - Need 8 × 300 µm for ~1.6 µm pointing resolution
- Move telescope arms further inwards if possible
- Operate Timepix4 at lower threshold

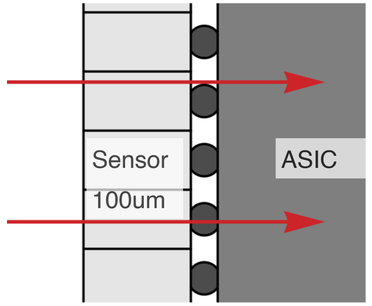


TIME RESOLUTION

- Thin sensors have better weighting field and reduce timing errors
- Reduced signal size reduces analog front-end performance
- Perpendicular beam incidence maximizes signal charge in single pixel
- Pixel capacitance worsens the time resolution
- Modifying the DACs settings increasing the preamplifier bias current improves the resolution at the price of 15–20% increase of power usage

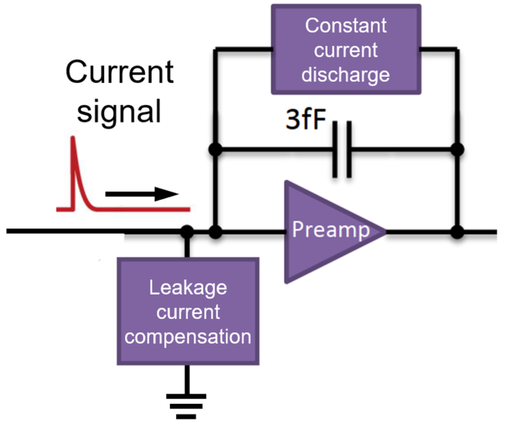


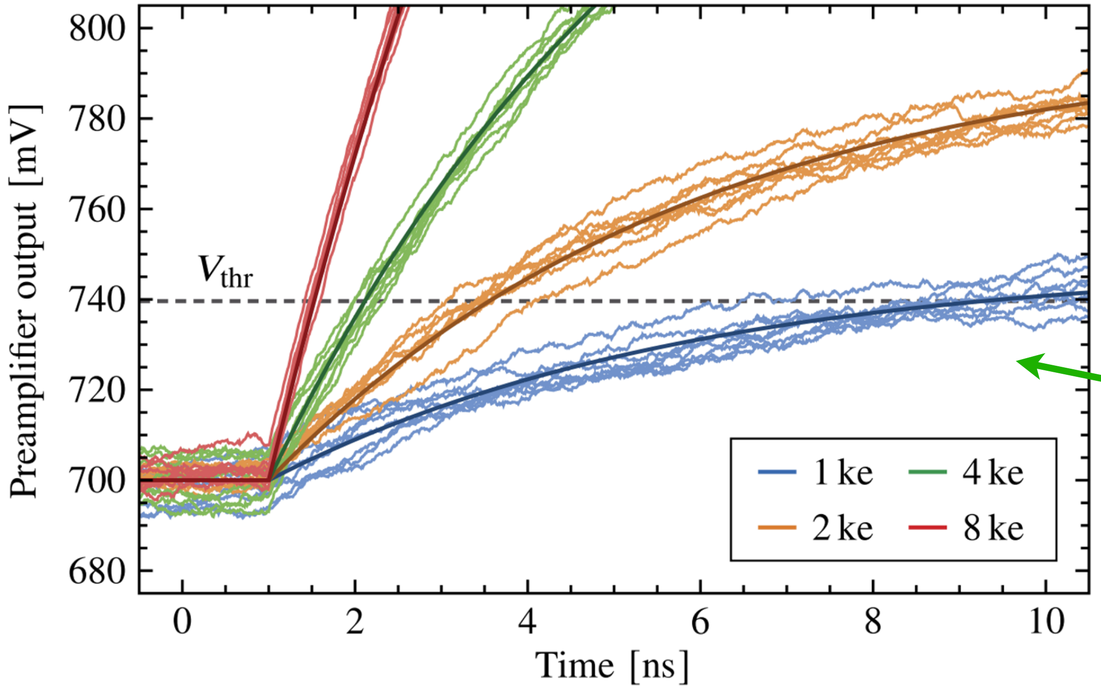
K. Heijhoff et al., JINST 17, P07006 (2022)

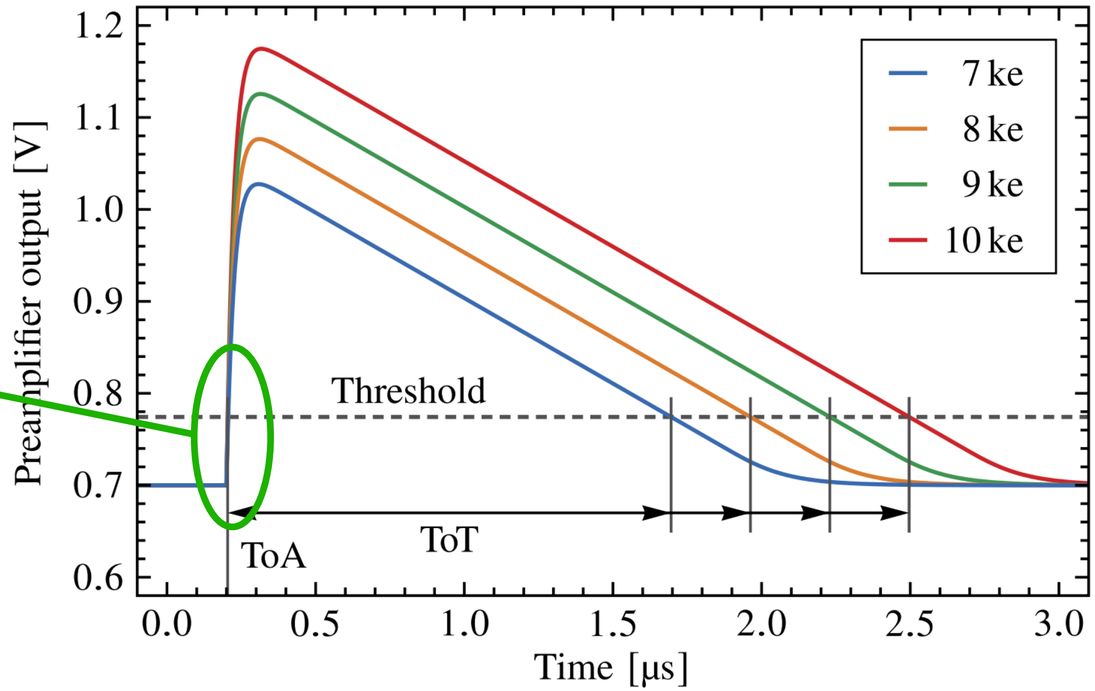


TIMEWALK

- Time measurement depends on signal size
- Reduced signal size makes timewalk corrections crucial

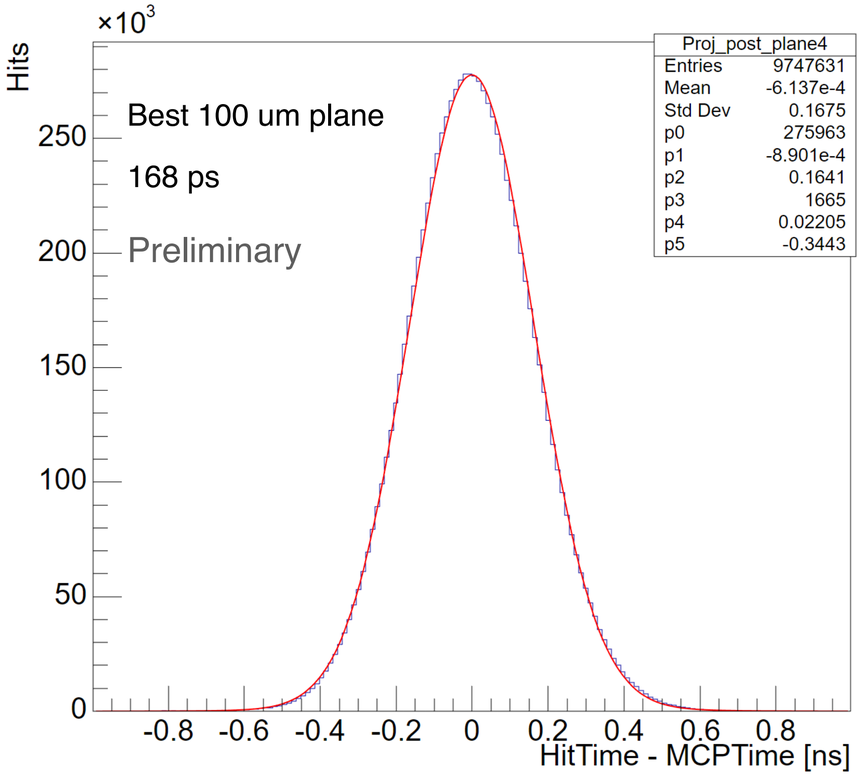


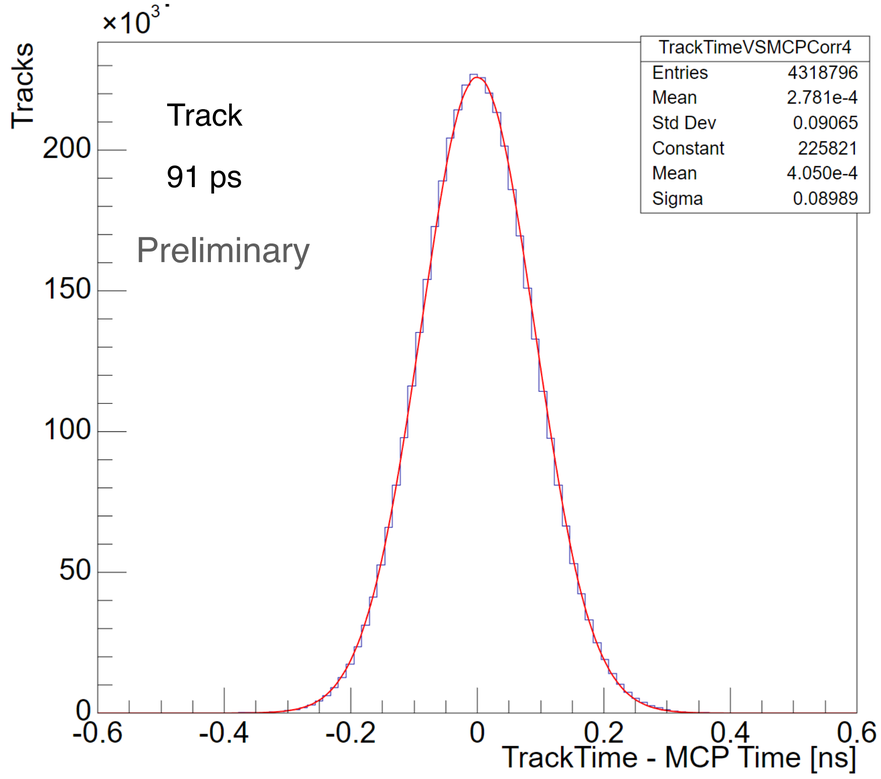




TIME RESOLUTION

- Working on per-pixel timewalk corrections
- Corrections for variations of VCO
- Current cluster-time resolution: ~170 to 185 ps
- Track-time resolution with 4 planes: ~90 ps





CONCLUSIONS

- Timepix4 telescope is operational in stable conditions and commissioned. It is ready to test faster sensor technologies
- Up to 200 kHz track rate (limited by SPS H8 intensity)
- 2.5 μm pointing resolution (will be improved by milling the PCBs and adding new 300 μm tilted planes)
- 12 ps time resolution (very sensitive to material distribution upstream of the MCP-PMTs)
- Current timing track performance down to $\sigma_t \sim 90$ ps (4×100 μm orthogonal planar sensors)
- No correlations from clock distribution etc. pinpointed
- Studies of first DUTs (planar sensors + i-LGADs) are ongoing
- Plenty of data to be analyzed

PEOPLE INVOLVED

Test beam crew

- *Nikhef*: Kazu Akiba, Martin van Beuzekom, Tjip Bischoff, Robbert Geertsema, Kevin Heijhoff, Daan Oppenhuis, Ganrong Wang
- *CERN*: Federico De Benedetti, Wiktor Byczynski, Victor Coco, Raphael Dumps, Morag Williams, Edgar LemosCid
- *IGFAE*: Efrén Rodríguez Rodríguez
- T*U 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

And acknowledgements to everyone making this possible, including

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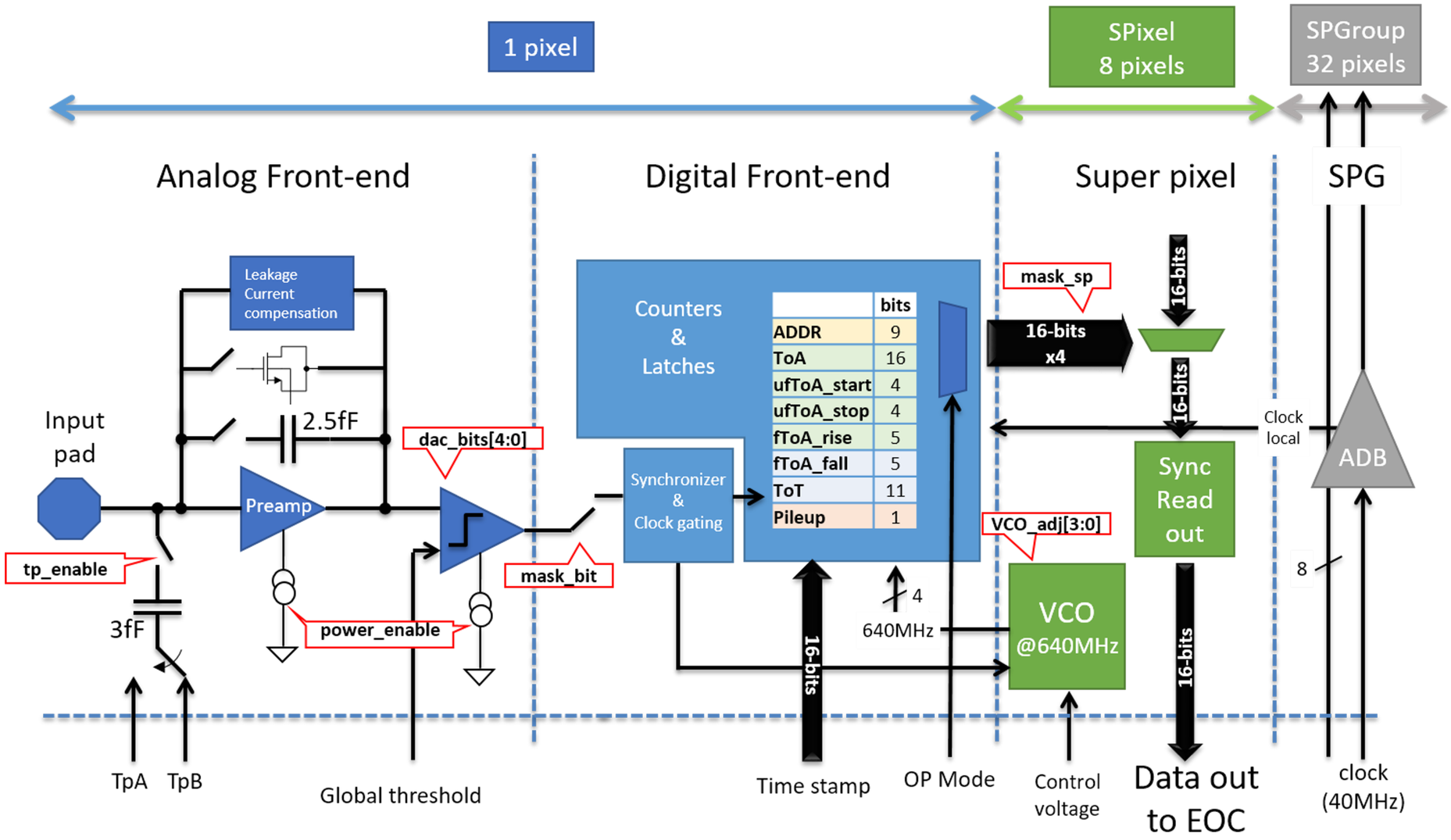
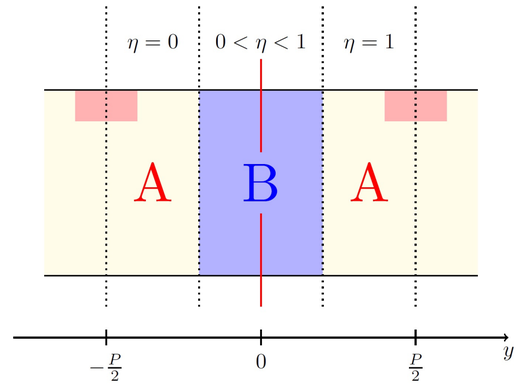
BACKUP

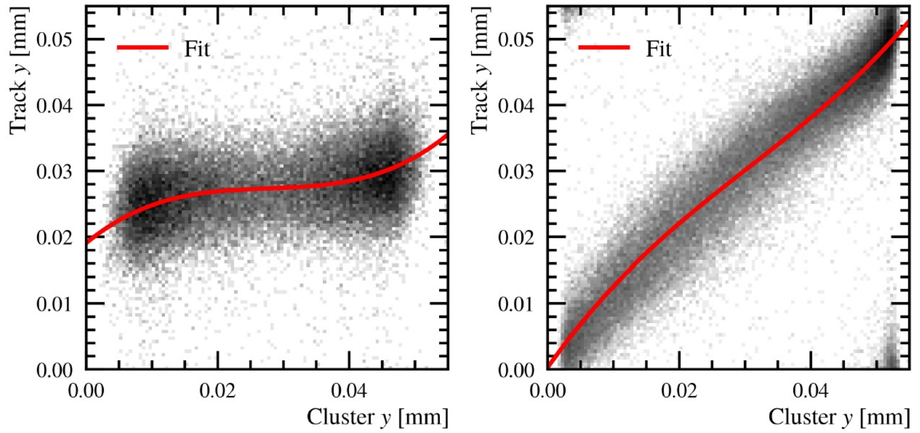
TIMEPIX4 FRONT END

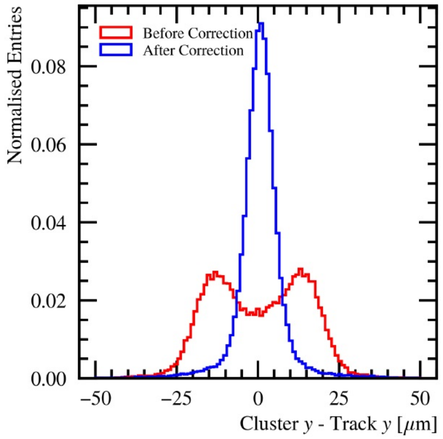


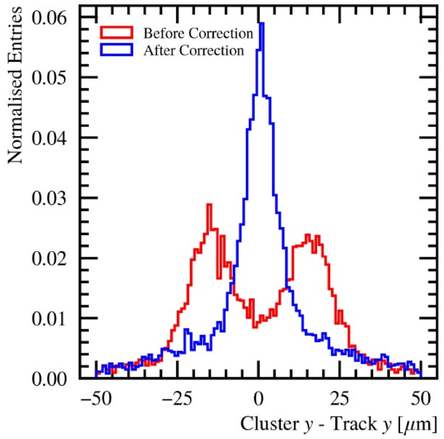
η CORRECTIONS

- Charge sharing is non-linear → bias in position reconstruction
- Charge asymmetry for multi-pixel clusters: η = (QL – QR)/QL

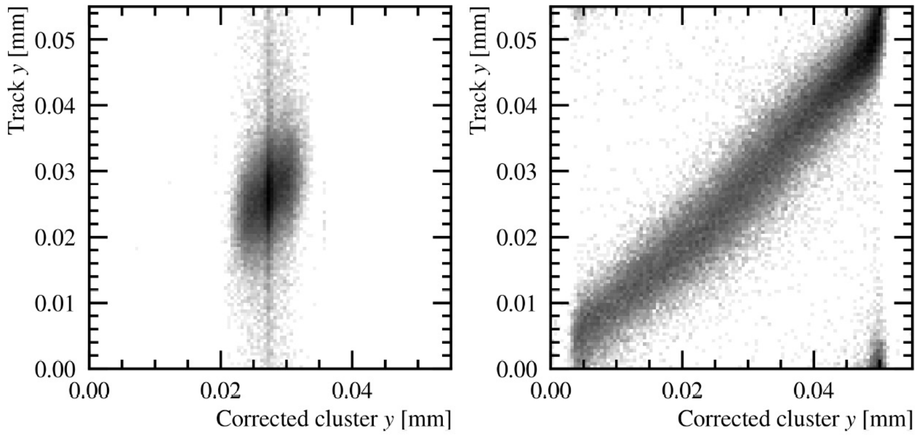


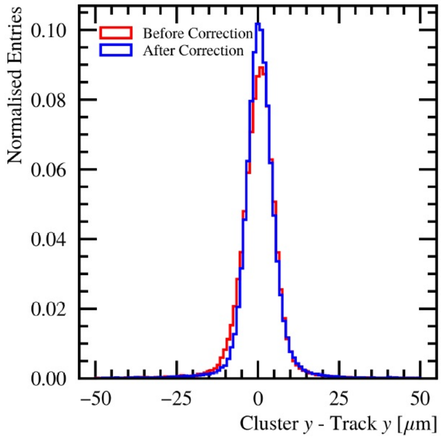


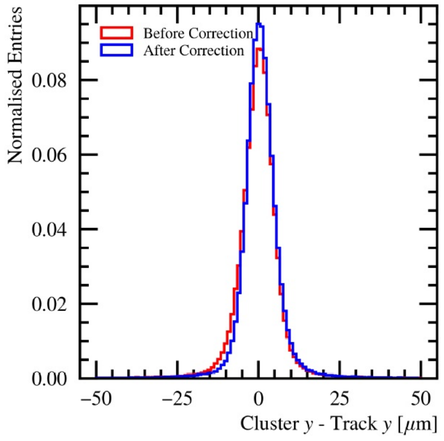




100 µm







300 µm