Development of hybrid single-photon detector based on microchannel plates and the Timepix4 ASIC

J.A. Alozy[a], R. Ballabriga[a], N.V. Biesuz[b], R. Bolzonella[b,c], M. Campbell[a], V. Cavallini[b,c], A. Cotta Ramusino[b], **M. Fiorini**[b,c], E. Franzoso[b], M. Guarise[b,c], X. Llopart[a] , S. Okamura[b,c], M. Panconesi[b], G. Romolini[b,c], A. Saputi[b]

[a] CERN [b] INFN Ferrara [c] University of Ferrara

Phose2023 – Workshop on Photodetectors and Sensors for PID and NP searches

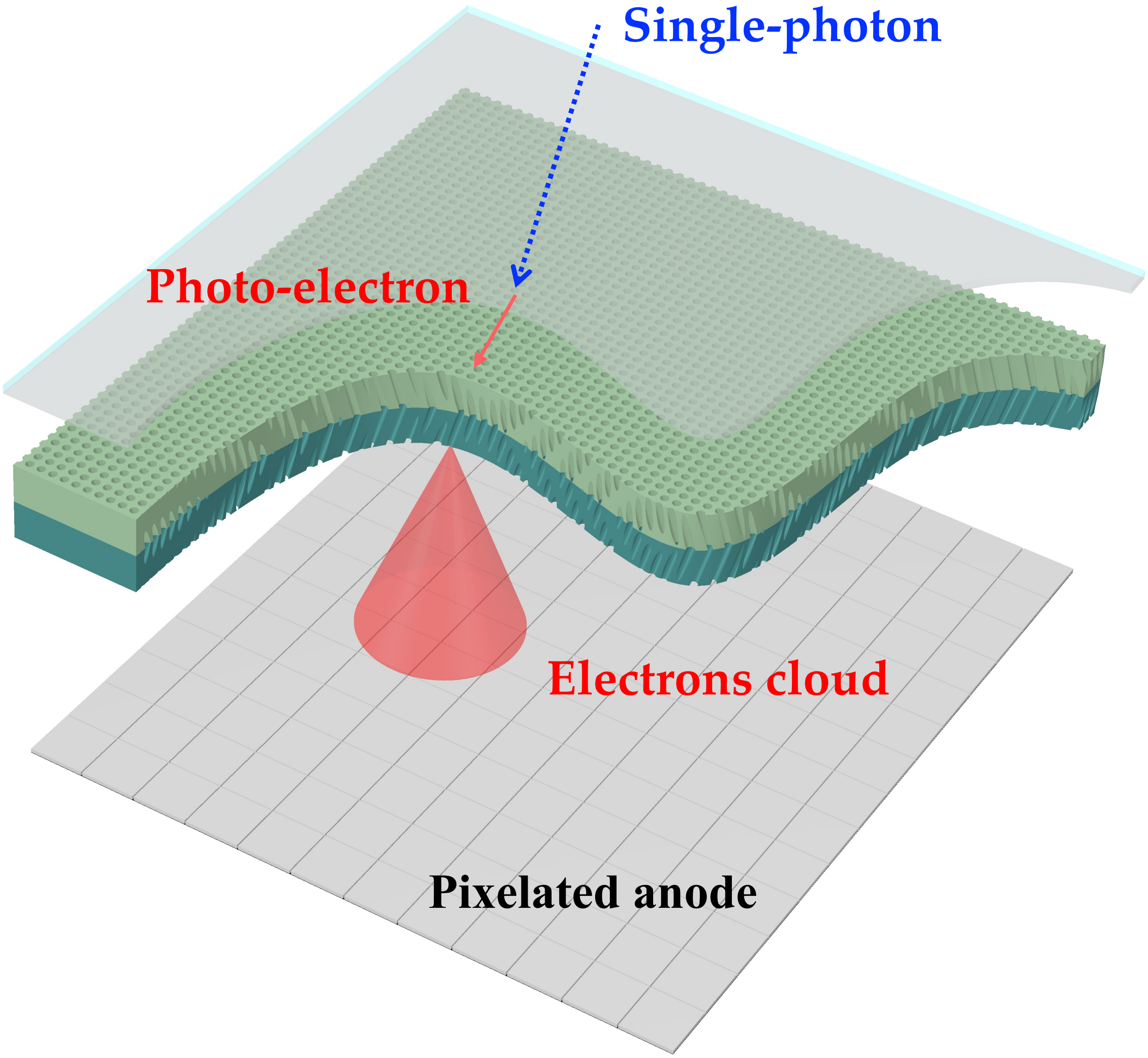
CERN, November 22nd 2023

Project goal and detector concept

- Development of a new photodetector with large active area able to measure single photons with simultaneous excellent timing and spatial resolution, with a low noise level at room temperature
- Detector based on a "hybrid" concept:
  - Vacuum detector; photocathode with high QE in the region of interest
  - Proximity-focusing geometry
  - Micro-channel plate (MCP) amplification
  - Silicon ASIC embedded inside vacuum tube
  - Reference: JINST 13 C12005 2018

Target time resolution	<100 ps r.m.s.
Position resolution	5-10 μm
High-rate capability	10^9 hits/s
Low dark count rate at room T	~10^2-10^3 counts/s
Large active area	7 cm^2
High channel density	0.23 millions

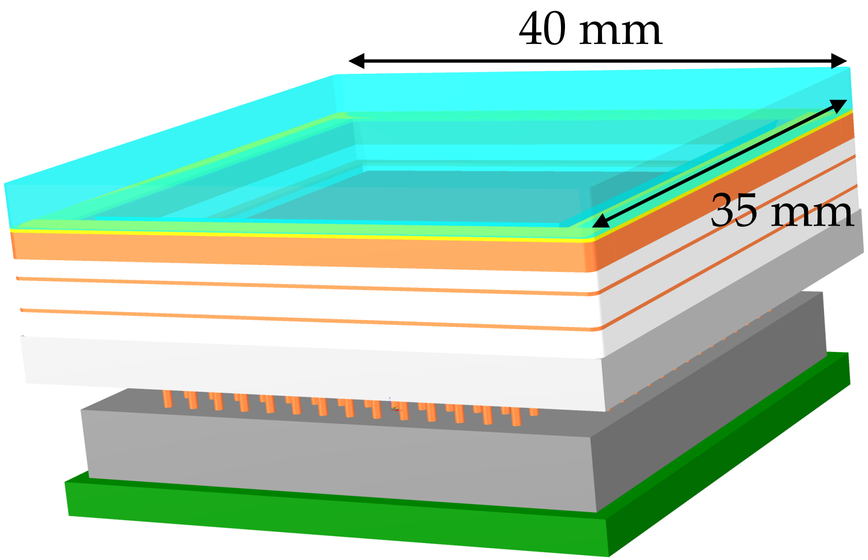
Detector concept

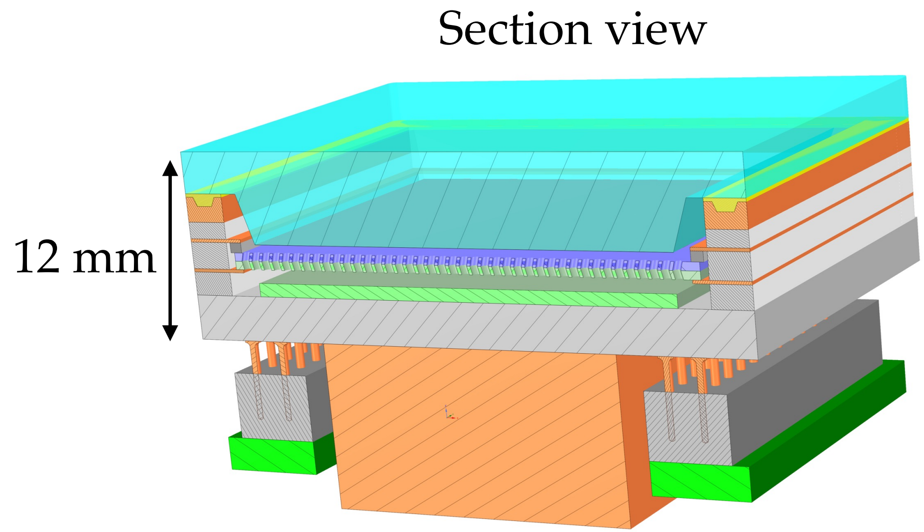


- Entrance window + photocathode
- Microchannel plate stack (chevron)
- Pixelated anode
  - Electron cloud spread over a number of pixels
  - **55μm × 55μm** pixel size
  - **0.23 M pixels** measuring arrival time and duration of input signals
  - **7 cm^2** active area
  - Up to **2.5 Ghits/s**
  - Local signal processing

Hybrid detector assembly

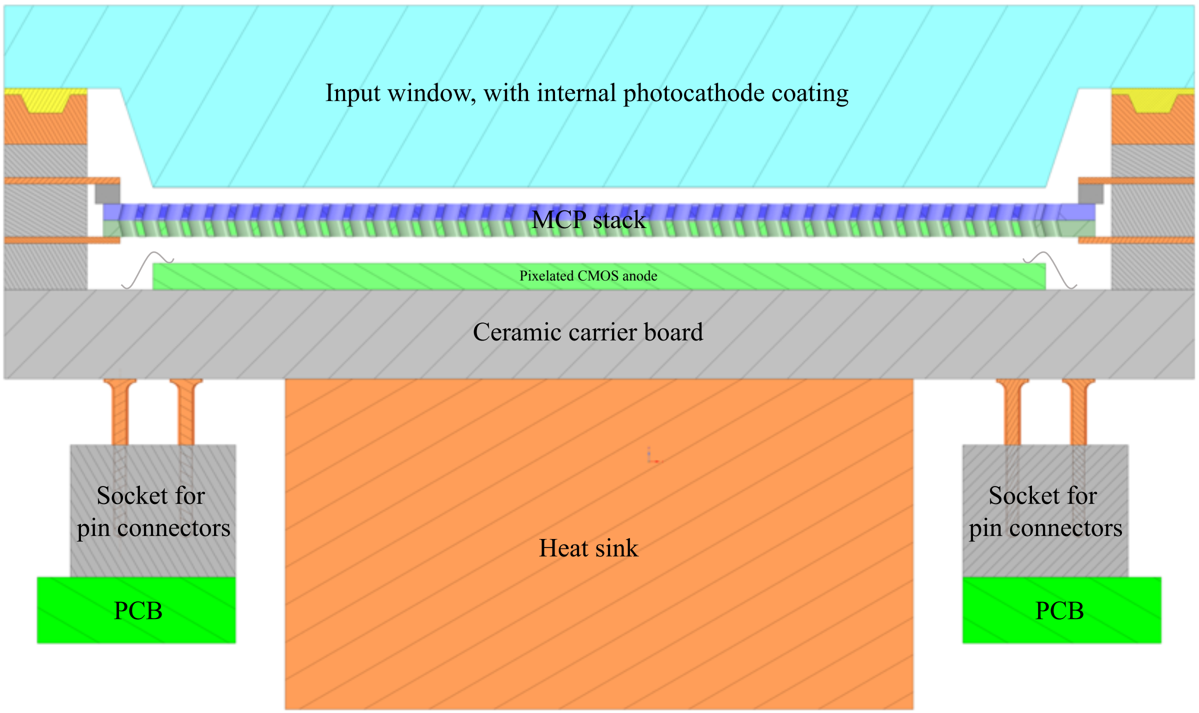
3D structure: detector rendering





- Vacuum-based detector
  - Assembly of many components under high vacuum (~10^{-10} mbar)
  - High-speed connections through pins in ceramic carrier board
- Heat sink for stable detector operation (~5 W heat removal)
- Carrier printed circuit board (PCB)
  - Socket for detector pins, regulators and high voltage
  - Connected to FPGA-based read-out and DAQ via 16 × 10 Gbps links

Detector geometry



- Shortest photocathode-to-MCP distance preserves impact position information
- Optimized MCP-to-anode distance spreads the electron cloud over a number of pixels

Pixelated anode

- Timepix4 ASIC in 65nm CMOS **silicon pixel technology**
  - Developed and produced by the Medipix4 Collaboration for hybrid pixel detectors
- Charge sensitive amplifier, single threshold discriminator and TDC based on Voltage Controlled Oscillator
  - 4-side buttable (TSV)
  - Data-driven and frame-based read-out

Technology			**CMOS 65 nm**
Pixel Size			55 μm × 55 μm
Pixel arrangement			4-side buttable 512×448 (0.23 Mpixels)
Sensitive area			6.94 cm² (2.82 cm × 2.46 cm)
Read-out Modes	Data driven	Mode	TOT and TOA
		Event Packet	64-bit
		Max rate	358 Mhits/cm²/s
TDC bin size			**195 ps**
Readout bandwidth			≤163.84 Gbps (16× @10.24 Gbps)
Equivalent noise charge			50-70 e⁻
Target global minimum threshold			<500 e⁻

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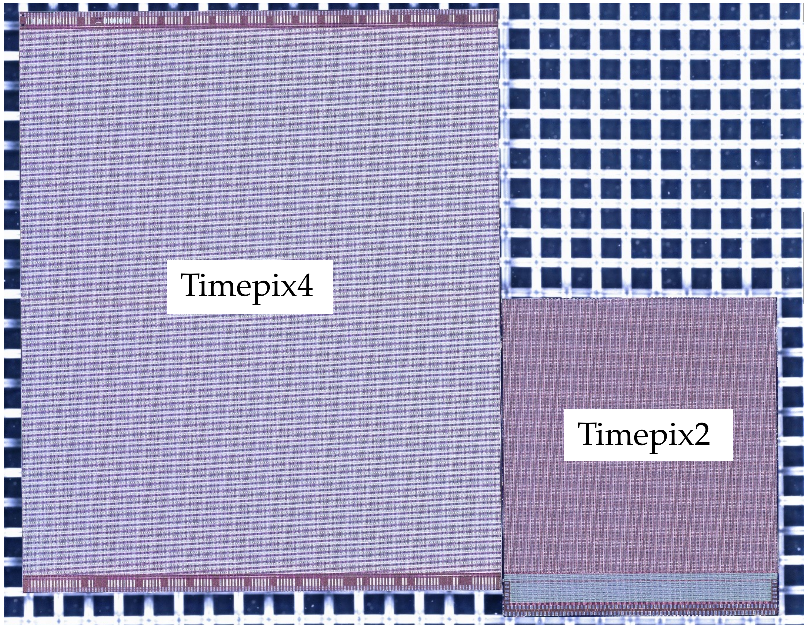
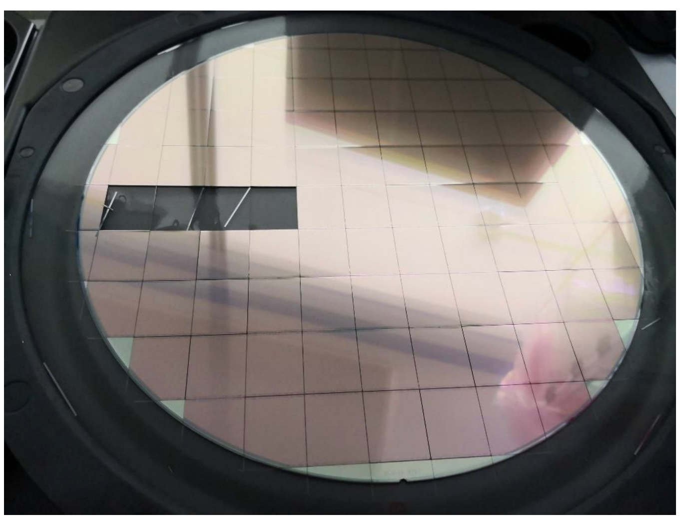
The Timepix4 ASIC



- 65 nm CMOS (TSMC)
- ASIC productions:
  - Timepix4_v0 (Q1 2020)
  - Timepix4_v1 (Q4 2020)
  - Timepix4_v2 (Q4 2021)
  - Timepix4_v3 (Q1 2023)



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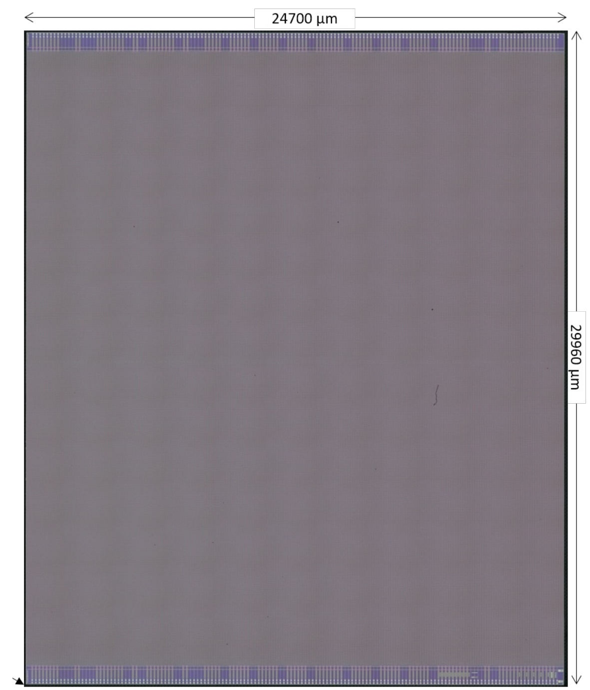
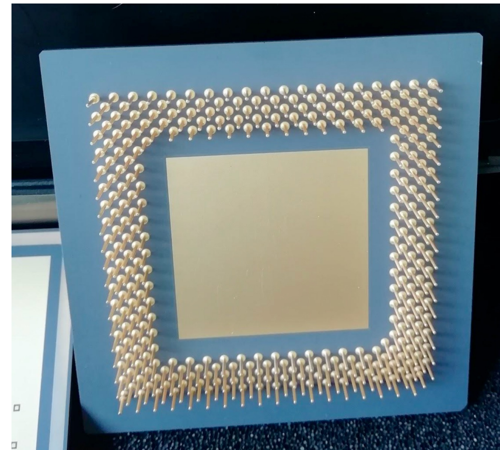


Ceramic carrier

- Dedicated testbed for electrical and mechanical tests
- Electrical design critical due to 10 Gbps lines
- First qualitative electrical measurements on existing devices (loop-back) plus signal integrity simulations
  - PGA not limiting factor per se
  - Requires careful pin placement
  - Low pin density
- Main contributions to signal degradation
  - Parasitic capacitance
  - Aluminium oxide multilayer PCB
  - Pads (wire-bond and pin pads)



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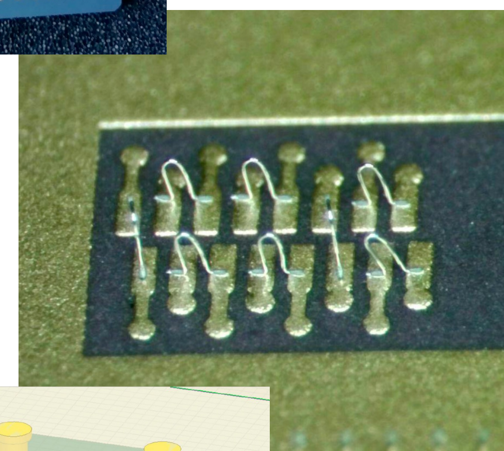
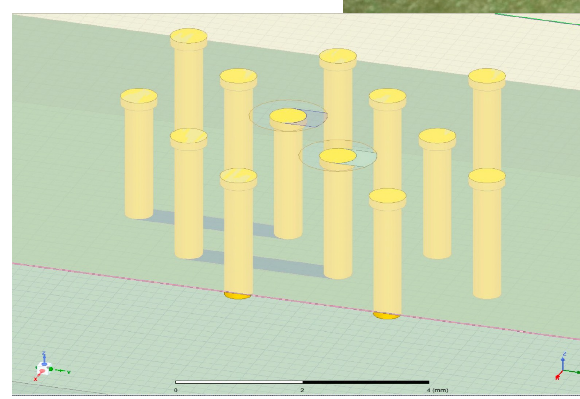
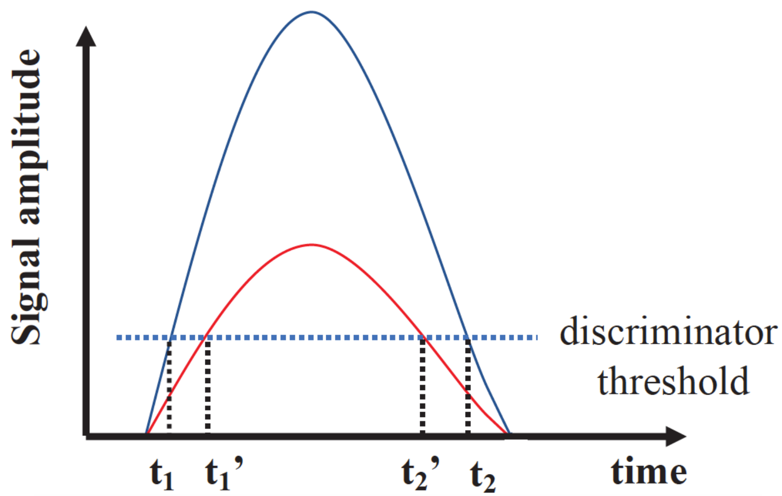




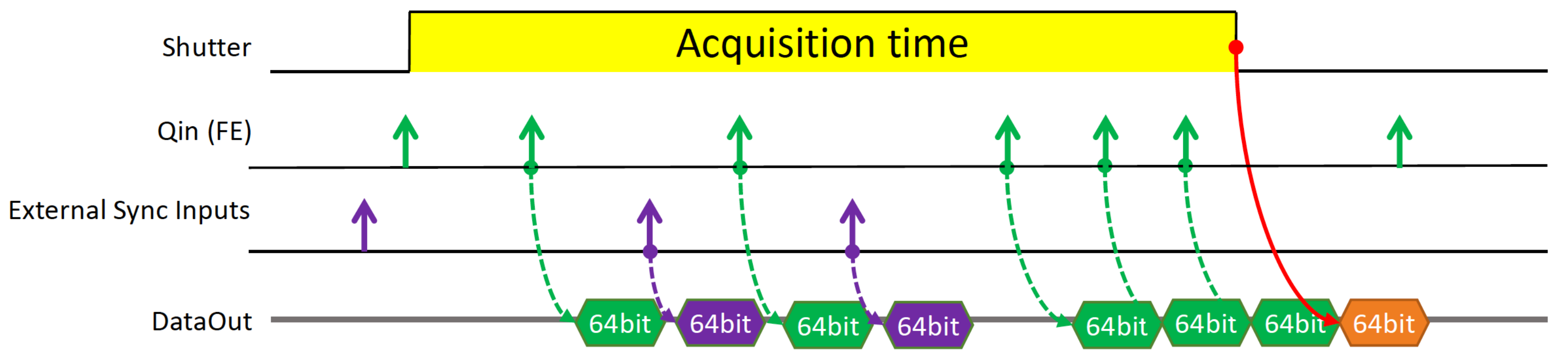
Timepix4 hit data

- Measures arrival time (t_1) and Time-over-Threshold ($ToT=t_2-t_1$)
  - TDC bin size: 195 ps (56 ps r.m.s. resolution per pixel)
- Electron cloud spread over a number of pixels → cluster
- Use ToT information (proportional to the charge in a pixel) to:
  - Correct for time-walk effect in every pixel
  - Improve **position resolution** by centroid algorithm
    - Go from $55\mu m/\sqrt{12} \sim 16\mu m$ down to **~5µm**
  - Improve **timing resolution** by multiple sampling
    - Many timing measurements for the same photon → **few 10s ps**



Timepix4 data-driven read-out

- Zero-suppressed continuous data-driven
  - Output bandwidth from 40 Mbps (2.6 Hz/pixel) to 160 Gbps (10.8 KHz/pixel)
- 4 external inputs to synchronize/align external signals with data



SPEC: Packet specifications ToA/ToT				
Name	Width	MSB	LSB	Bits
Top	1	63	63	[63:63]
EoC	8	62	55	[62:55]
SP	6	54	49	[54:49]
Pixel	3	48	46	[48:46]
ToA	16	45	30	[45:30]
ufToA_start	4	29	26	[29:26]
ufToA_stop	4	25	22	[25:22]
fToA_rise	5	21	17	[21:17]
fToA_fall	5	16	12	[16:12]
ToT	11	11	1	[11:1]
Pileup	1	0	0	[0:0]

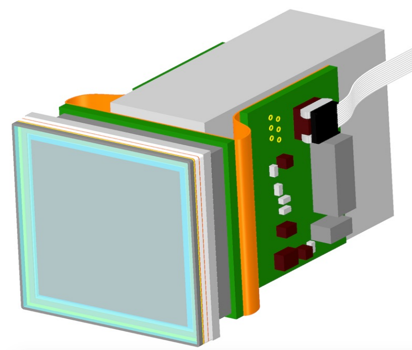
Address: 18 bits

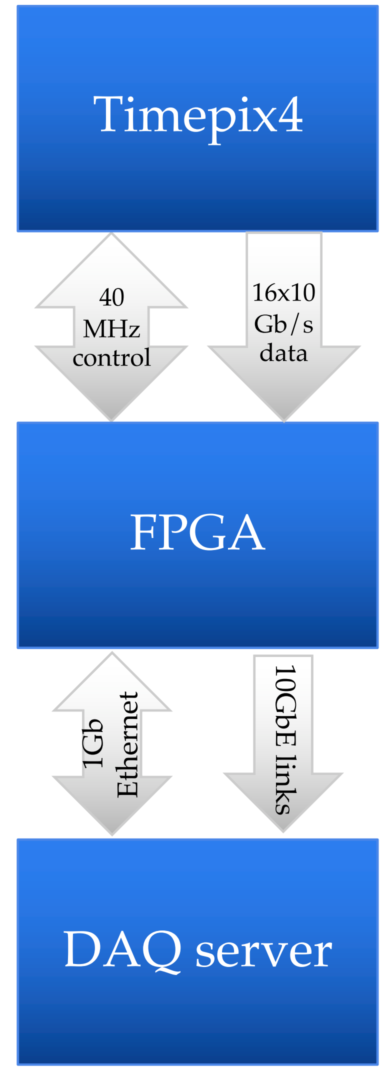
Time: 29 bits

Energy: 21 bits

Electronics and DAQ

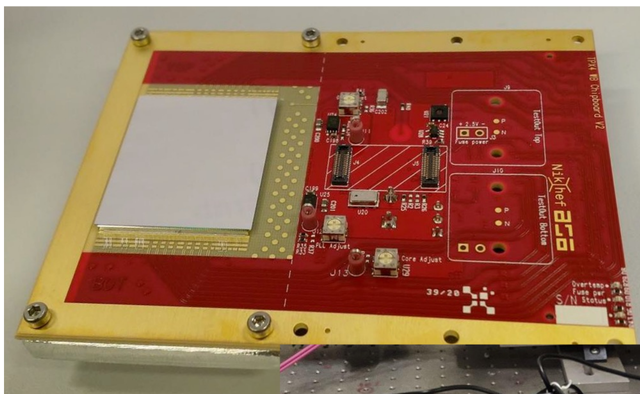
- On-detector electronics
  - Timepix4 ASIC
  - Electro-optical transceivers link the ASIC to an FPGA-based board for the exchange of configuration (slow control) and the collection of event data
  - Regulators, etc.
- Off-detector electronics
  - FPGA far from detector
- The FPGA performs serial decoding and sends the data to a PC for data analysis and storage using fast serial data links

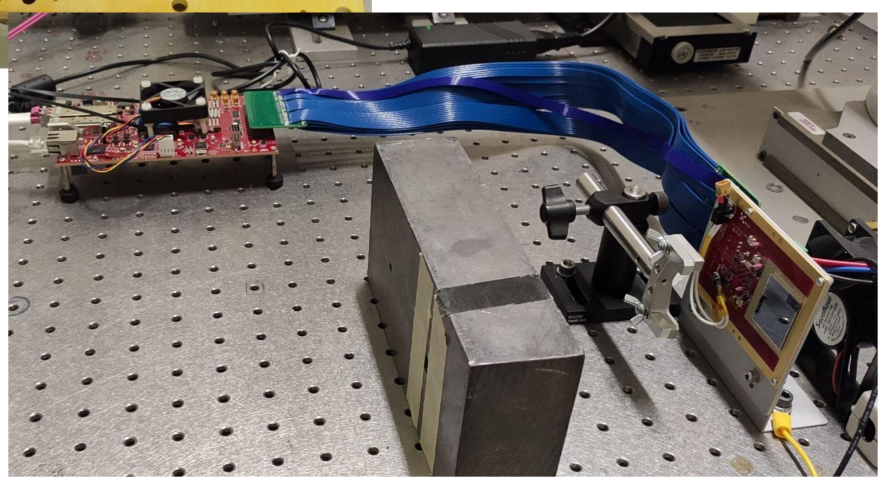


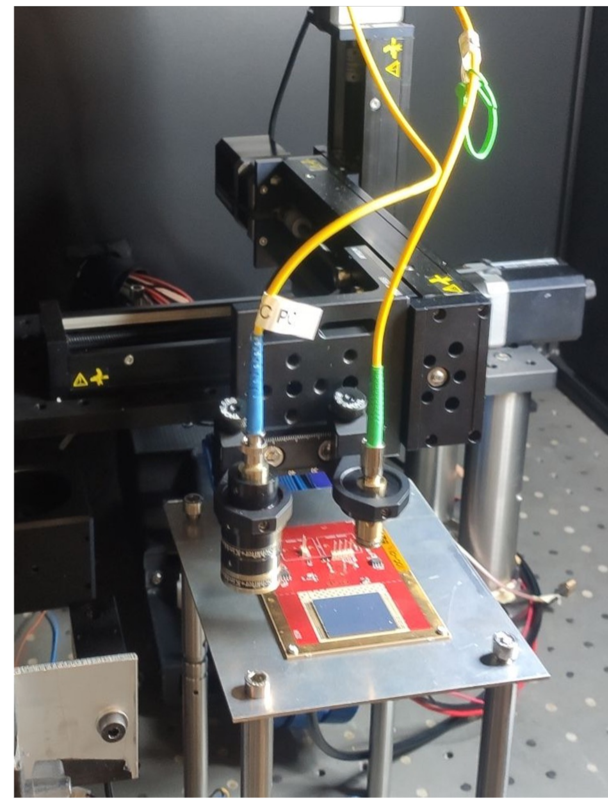


Current test system

- Timepix4 bump-bonded to silicon sensors (300μm and 100μm)
- SPIDR4 FPGA read-out system and sensor carrier board
  - Developed by Nikhef Medipix4 group
- Dedicated DAQ system working now with 1 Gbps interface

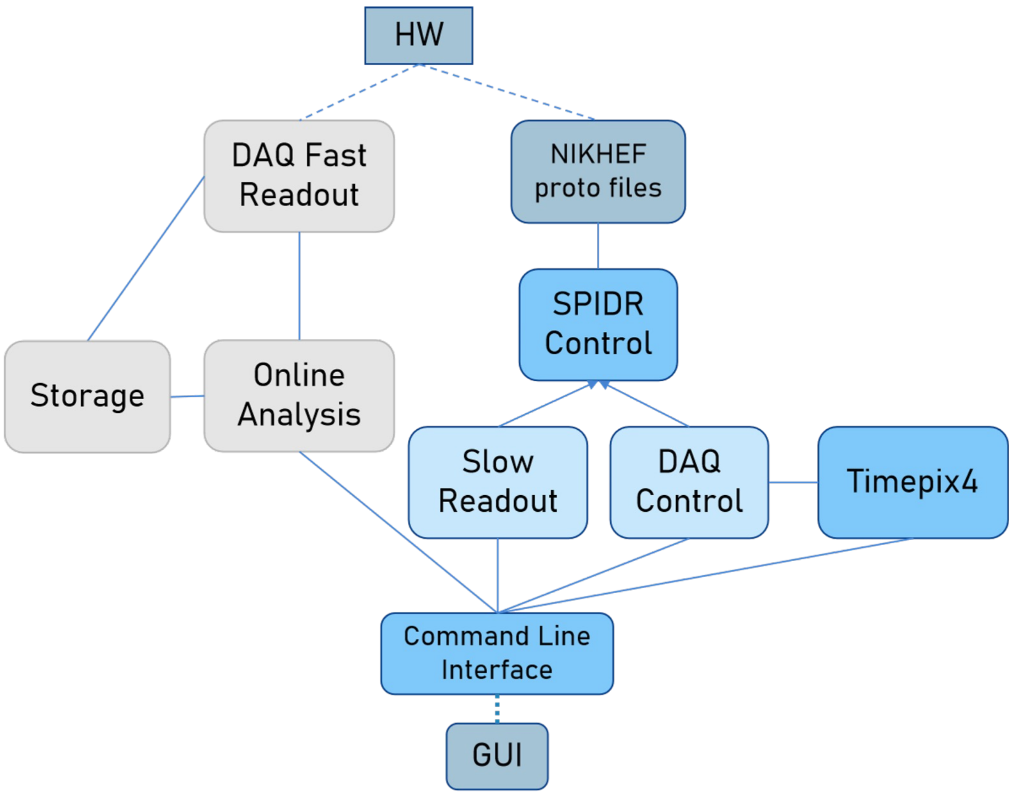






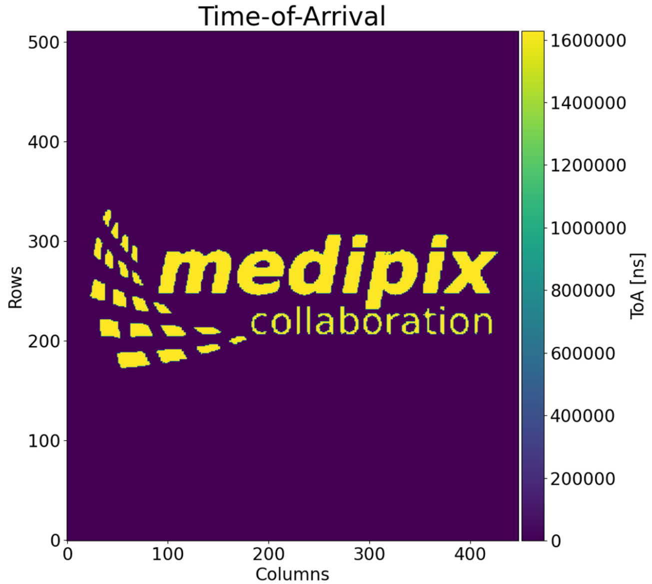
Software

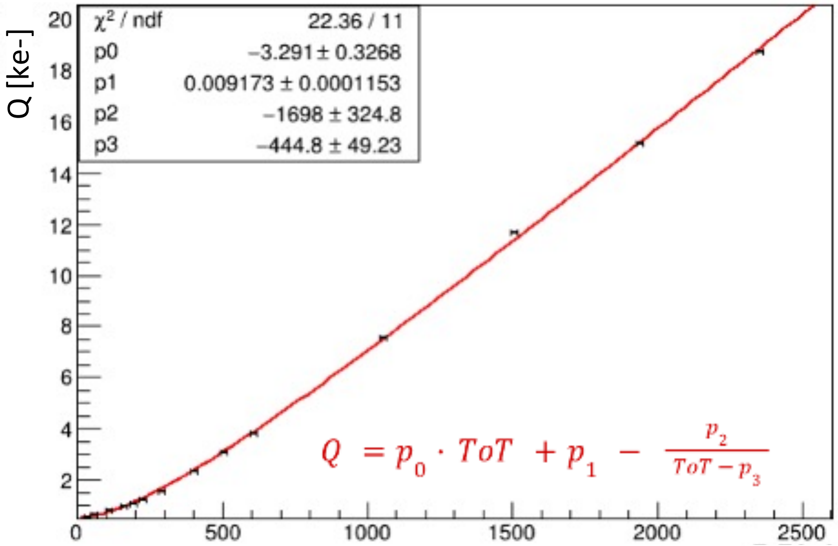
- Dedicated software
- C++ based
  - Low-level
  - Object-oriented
- Readout and Control in unique CLI
- Read and Write register functions
- Application Programming Interfaces for Timepix4
- Packets decoder
- Open source



Measurements with Timepix4

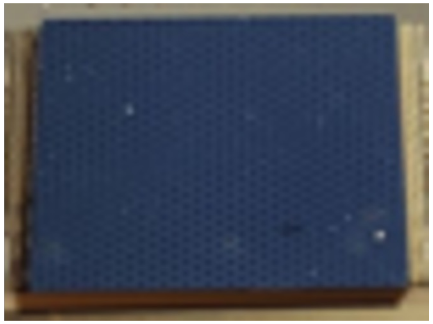
- Digital test pulse:
  - Correct patterns, number of pulses and ToA-ToT
- Analog test pulse:
  - Per-pixel ToT calibration through test pulse over the whole pixel matrix
  - Calibration validated using radioactive sources
- Radioactive sources measurement:
  - Density based clustering (DBSCAN)
  - ToT-charge calibration
- Laser measurement:
  - Timing resolution

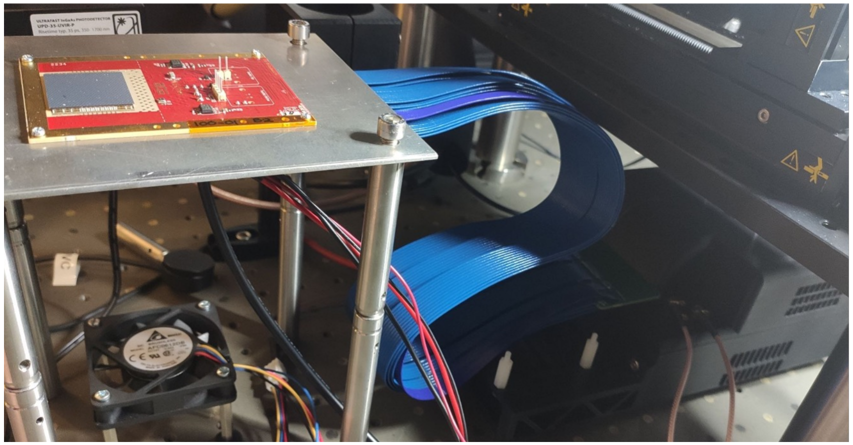


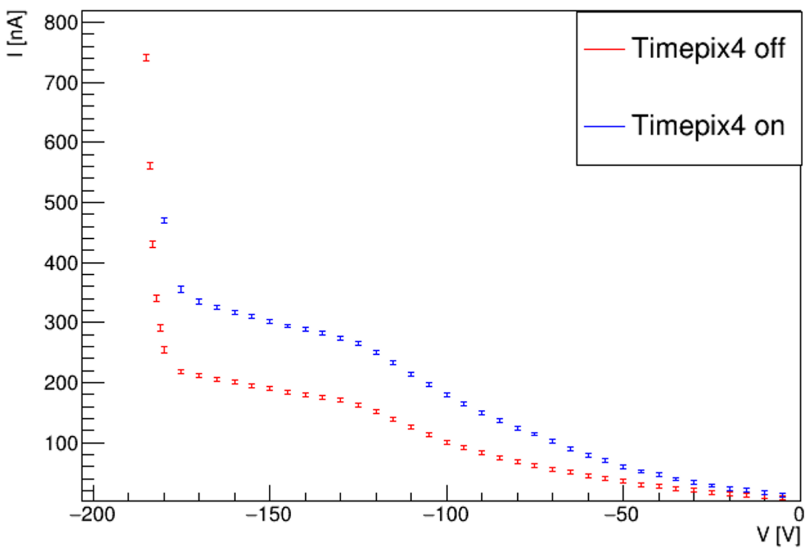


Timing resolution measurements (1)

- SPIDR4 control board
- Timepix4_v2 bonded to a 100 μm n-on-p Si detector
  - Metallization with holes pattern
  - Thanks to V. Coco, M. Van Beuzekom et al. (LHCb Velo group)

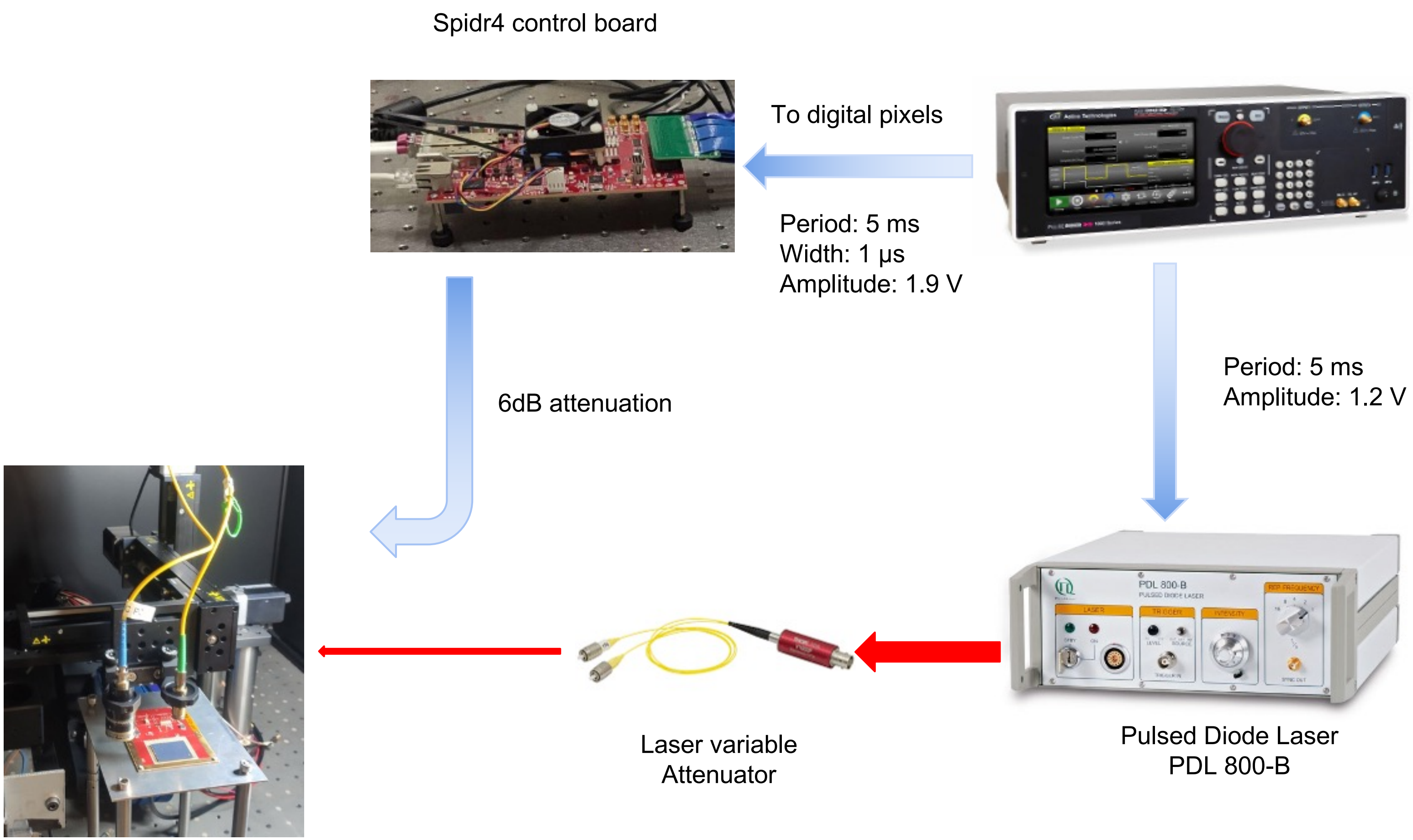






Timing resolution measurements (2)

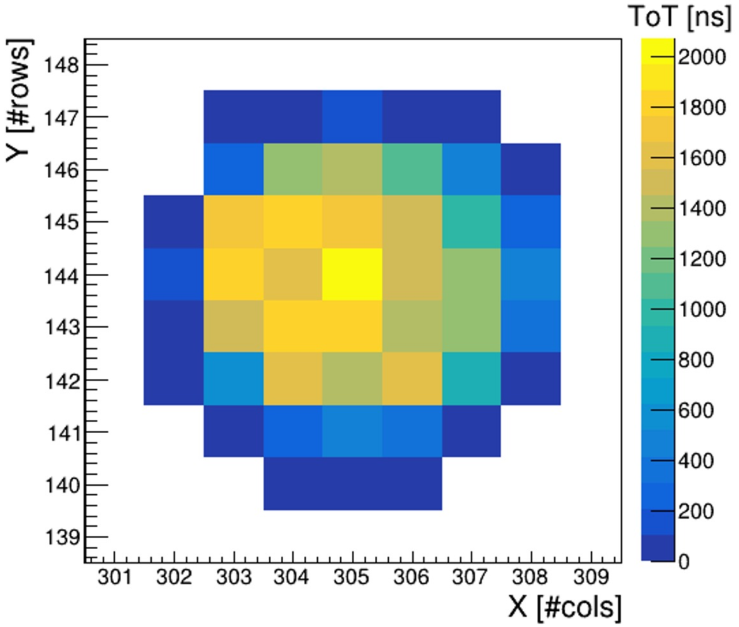
- Waveform generator: input signal to digital pixels + laser trigger
- Laser: 1060 nm + variable attenuator
- Linear translation stages: 3D position regulation with μm precision



Timing resolution measurements (3)

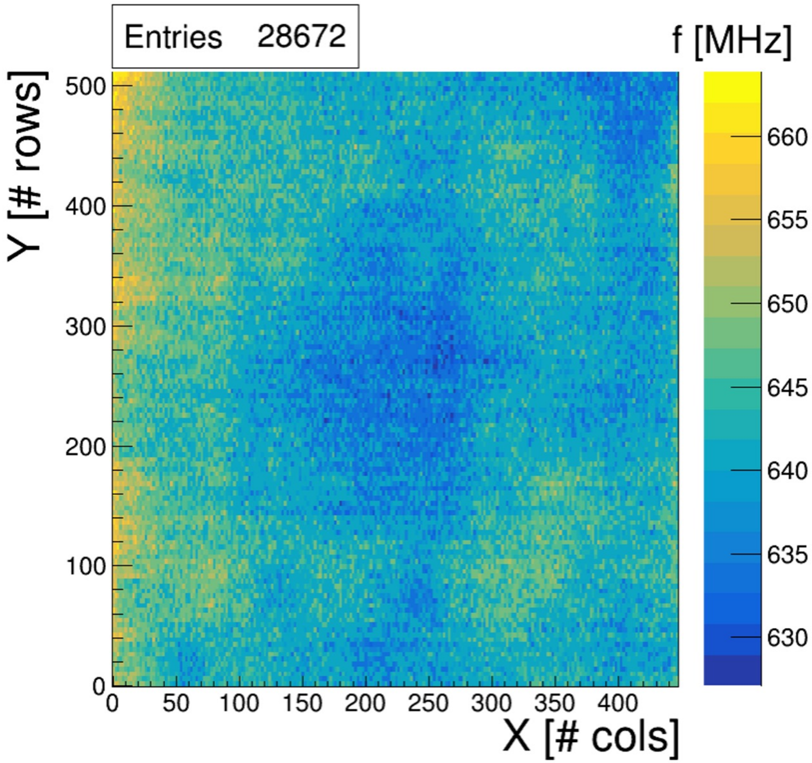
- Laser focused using micro-collimator:
  - σ = 1.4 pixel = 77 μm

- Laser spot in fixed position for all presented measurements



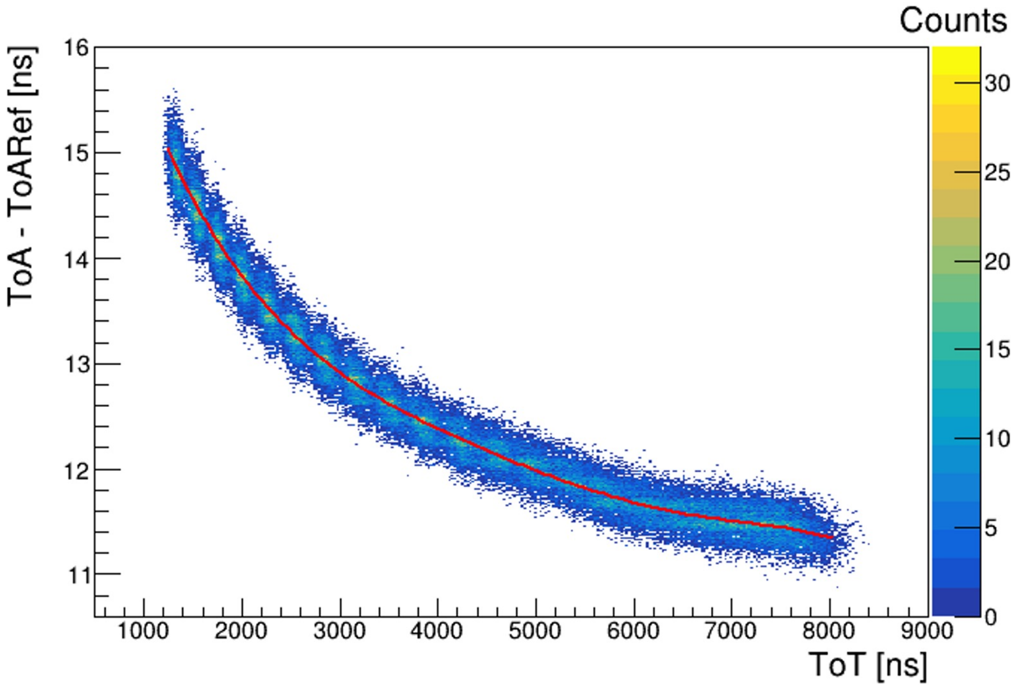
Timing resolution measurements (4)

- VCO of different pixels oscillate with different frequencies
- Finer ToA bins generated with different width
- ToA and ToT measurements heavily affected by this effect
- Internal test pulse tool exploited to calibrate VCO frequencies for the whole matrix (~28.7k VCO)



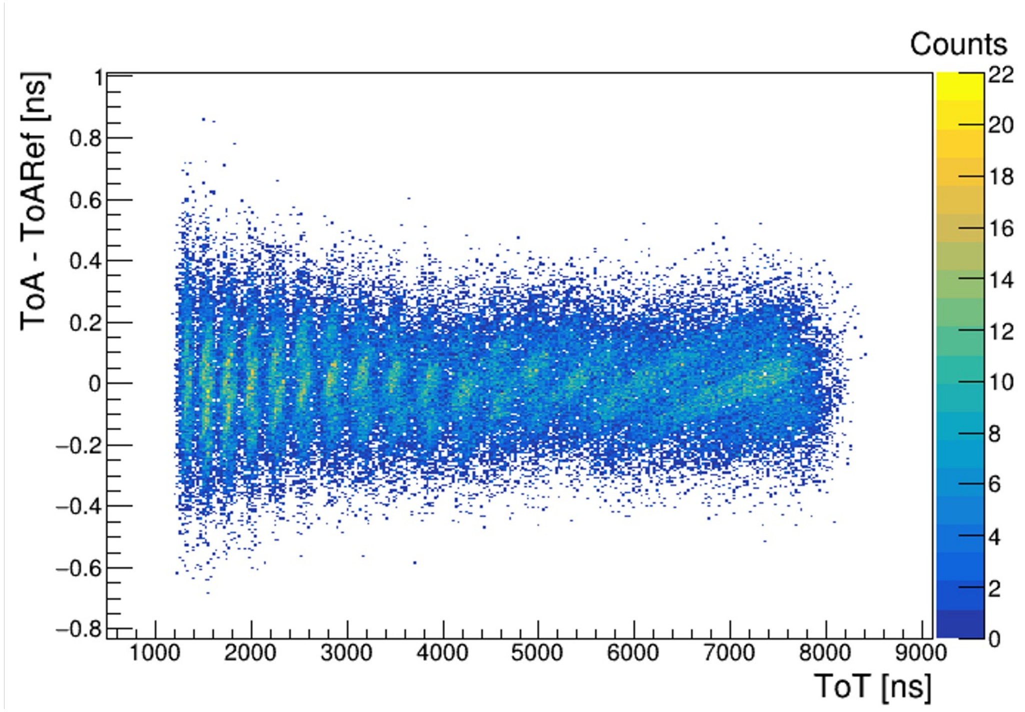
Timing resolution measurements (5)

- Single pixel timing resolution
- Measurements using variable laser attenuation, populating a wide ToT range on each pixel
- Different time walk trends on different pixels
- Time walk corrected separately on each pixel



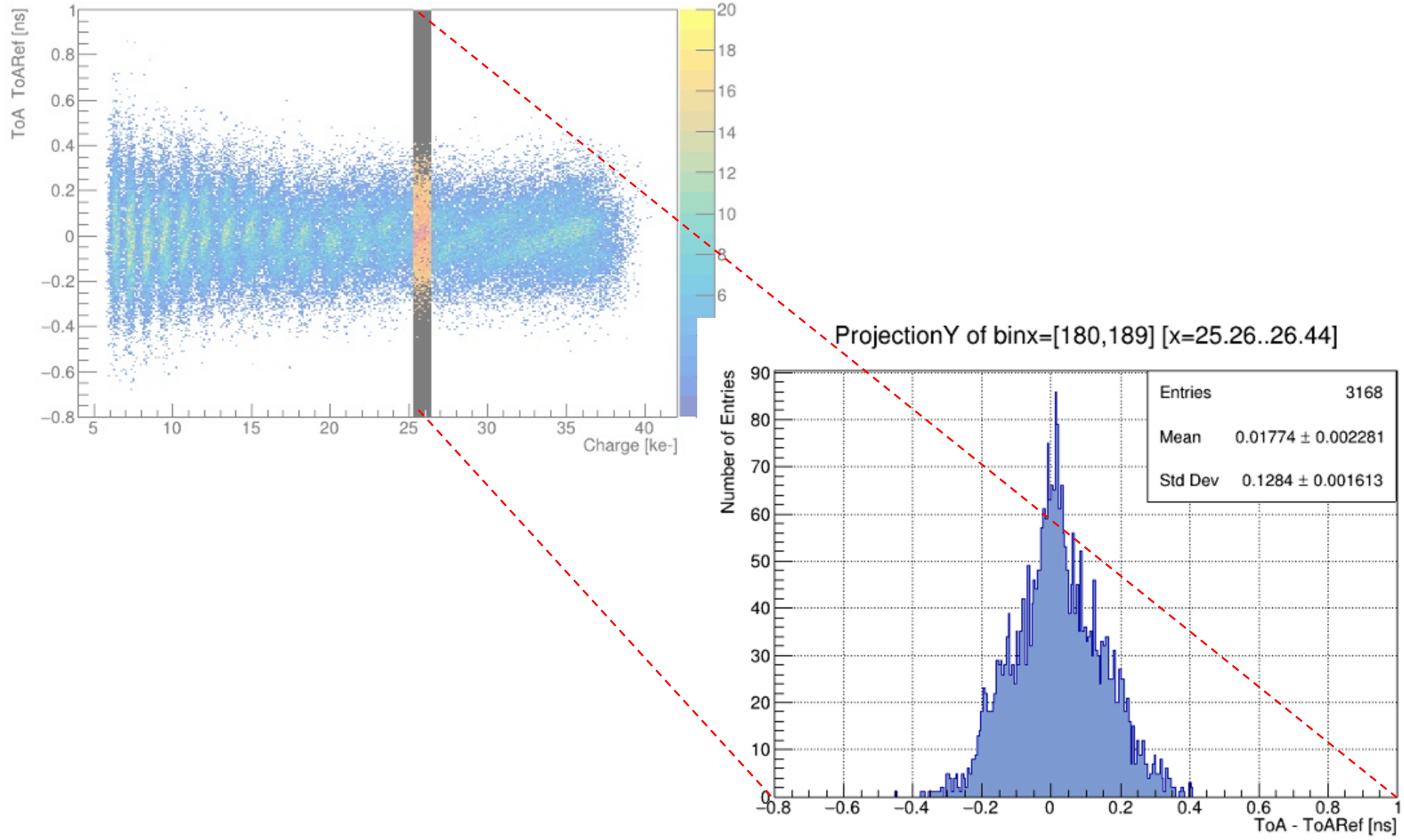
Timing resolution measurements (6)

- Single pixel timing resolution
- Measurements using variable laser attenuation, populating a wide ToT range on each pixel
- Different time walk trends on different pixels
- Time walk corrected separately on each pixel



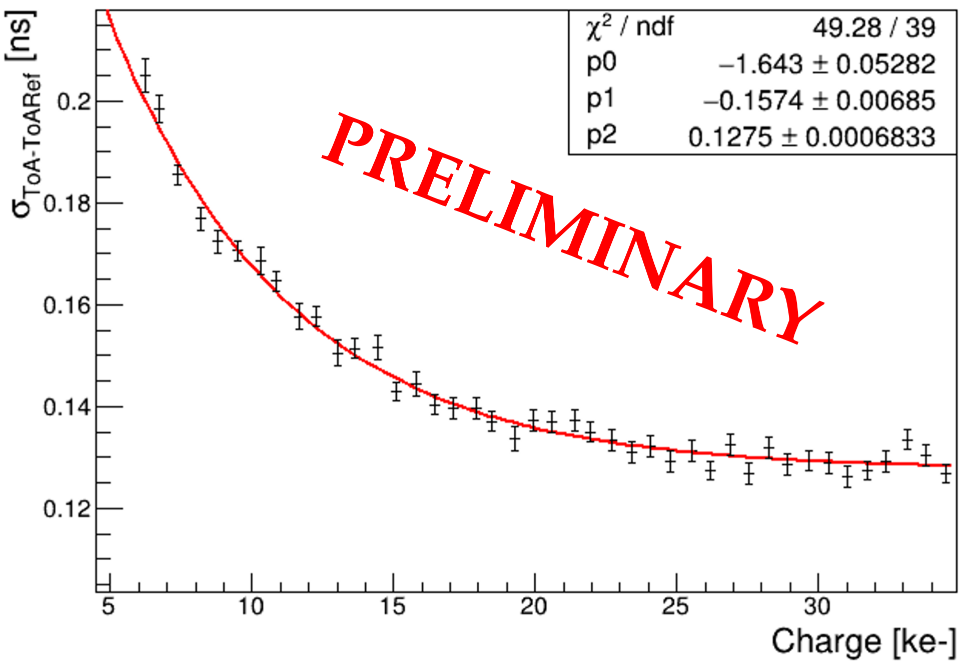
Timing resolution measurements (7)

- ToT vs charge calibration applied to each pixel
- Distribution divided into "vertical" slices, each one selecting a narrow range of charge
- Timing resolution values extracted for each slice



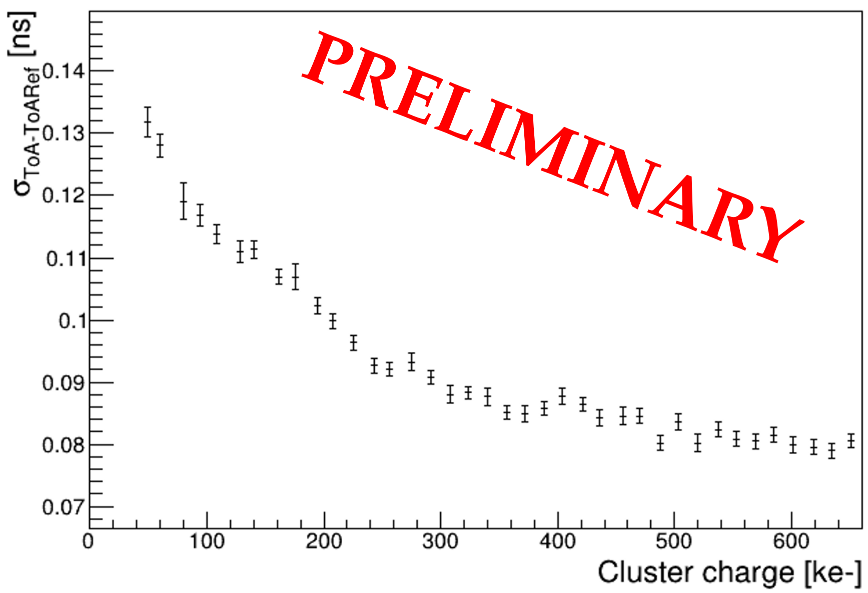
Timing resolution measurements (8)

- Single pixel timing resolution
- Distribution of timing resolution as a function of injected charge
- For the pixel [305,144], where the laser is focused, the standard deviation saturates at 128±1 ps rms
- Subtracting the contribution of the reference TDC (60 ps), a resolution of 111±1 ps rms is obtained



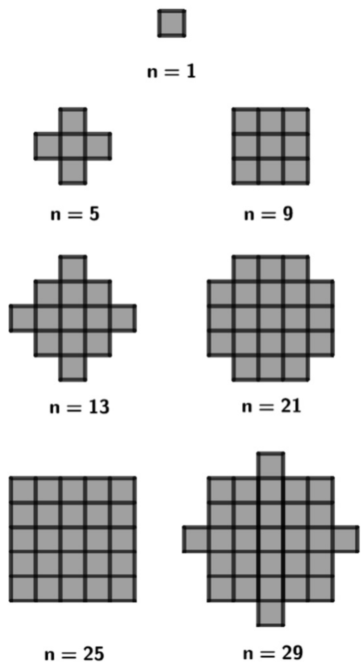
Timing resolution measurements (9)

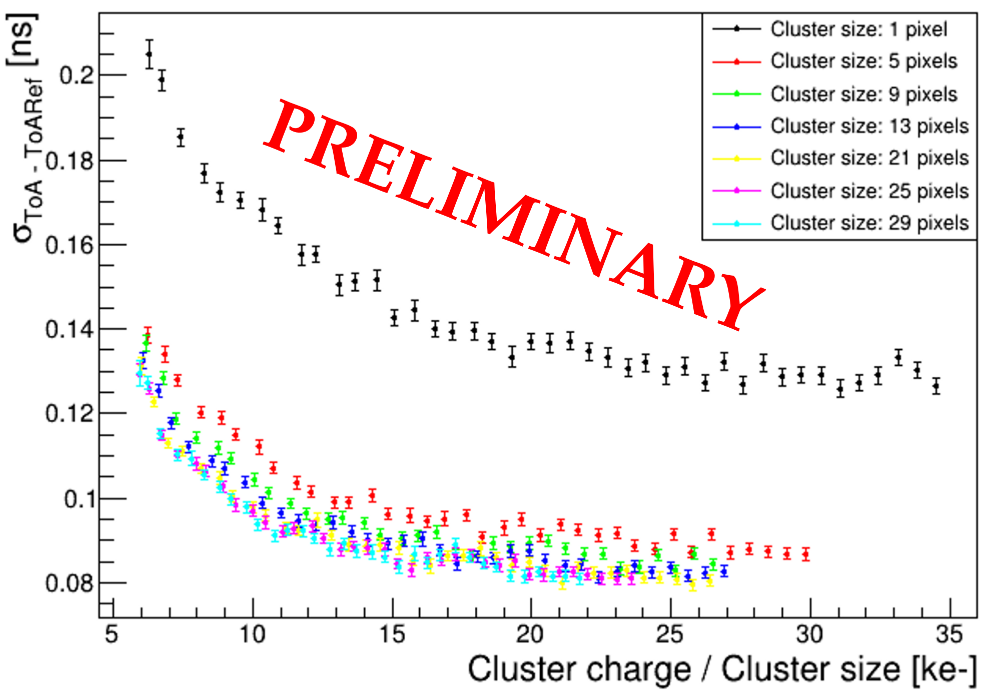
- For each cluster:
  - weighted average of ToA using charge as weights
  - cluster charge computed
- Timing resolution dependence on cluster charge:
  - best result: $\sigma_{ToADiffAvg}$=79 ± 1 ps rms
- Timing resolution subtracting reference TDC contribution:
  - σ_{ToAAvg}=49 ± 1 ps rms



Timing resolution measurements (10)

- Offline "variation of cluster size": consider shells of pixels within the same physical cluster
  - Large improvement in the resolution from 1-pixel clusters to 5-pixels clusters
  - Small or negligible improvement increasing further the cluster size





Outlook

- A "hybrid" MCP-PMT is under development
  - Funded by European Research Council (G.A. No. 819627)
  - Demonstrator based on existing full-scale ASIC (Timepix4 developed by Medipix4 Collaboration for hybrid pixel detectors)
  - Complete integration of sensor and electronics
    - On-detector signal processing, digitization and data transmission with large number of active channels (~230 k pixels), with limited number of external interconnections (~200)
  - Full exploitation of both timing and position resolution of a MCP
- Future improvements for use in HEP harsh environments
  - Radiation hardness
    - Use rad-hard-by-design ASIC (plus rad-hard serializers)
  - High rate capability and detector lifetime
    - Improve current MCP technology
  - Timing resolution
    - Use ASIC with smaller TDC bin size and lower front-end jitter


THANK YOU
FOR YOUR ATTENTION
500
400
300
200
100
0
0
50
100
150
200
250
300
350
400

Application: LHCb RICH Upgrade II

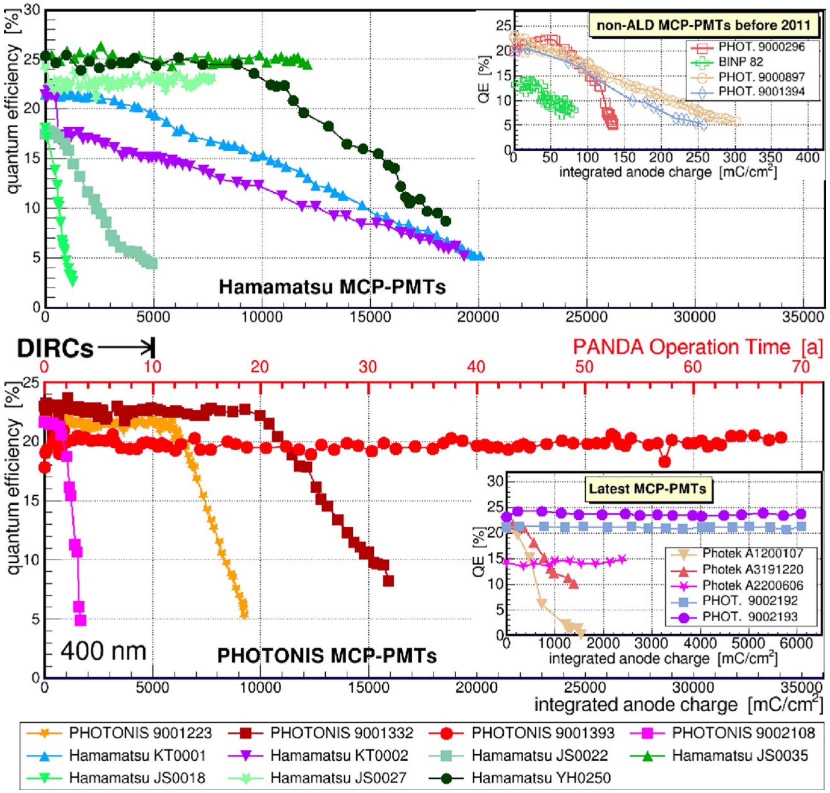
- Current detectors not adequate for RICH in the HL-LHC environment (need granularity ~1 mm, time resolution <100 ps)
- Advantage of the proposed device for future RICH detectors:
  - 5-10 μm position resolution → the pixel size contribution to the Cherenkov angle resolution becomes negligible
  - High granularity (55 μm × 55 μm) and rate capabilities (2.5 Ghits/s) crucial in applications with large detector occupancies
  - <100 ps resolution per single photon excellent handle for pattern recognition and time-association of the individual photons
  - Negligible detector-related background at room T
  - Robust in magnetic fields
  - Longer lifetime compared to standard applications due to low gain
  - On-detector signal processing and digitization with large number of active channels (~230 k pixels), with limited number of external interconnections (~200)

Radiation hardness

- For the LHCb Upgrade II we expect, in the RICH region:
  - ~2 Mrad TID, ~3×10^{13} 1 MeV n_{eq}/cm^2, ~1×10^{13} HEH/cm^2
- Advantages of the proposed detector:
  - Optical window made of "silica" glass
    - No degradation of window transmittance
  - 65 nm CMOS front-end technology
    - Resistant to >100 Mrad Total Ionising Dose
    - Triple Modular Redundancy not implemented in Timepix4
      - Single Event Upset mitigation: refresh configuration registers
  - FPGA-based back-end electronics far from detector region
    - Signals are digitized inside the vacuum tube
    - Use radiation hard components on-detector (transceivers, etc.)
- Future improvements
  - Use VeloPix2 (PicoPix) ASIC (30 ps TDC, rad. hard by design)

MCP-PMT limitations

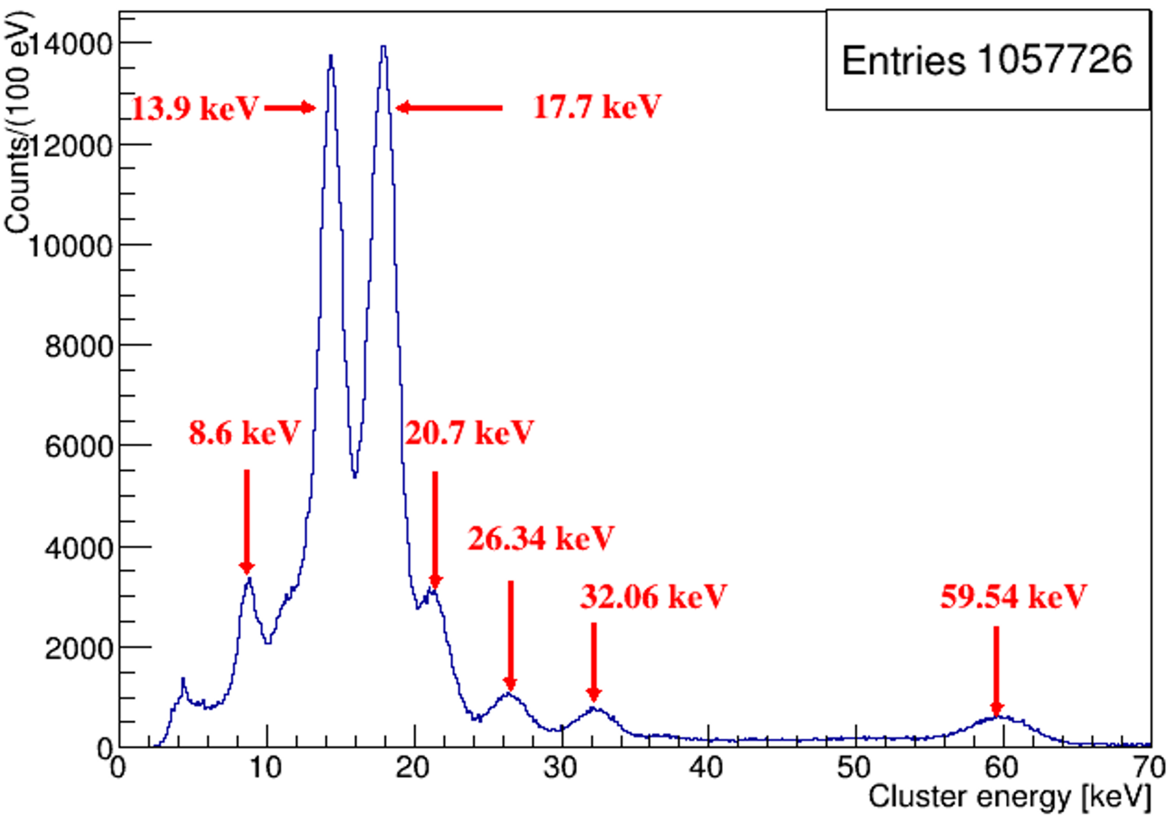
- MCP-PMT lifetime limited by the integrated anode charge, which leads to a strong QE reduction
  - From 0.2 C/cm² to >30 C/cm² in recent years thanks to ALD
- With the expected photon hit rate (~10 MHz/mm²), assuming a 10^4 gain (very conservative), and an operation of 10 years with 25% duty cycle we have:
  - Total IAC ~120 C/cm²
  - Anode current density ~2 μA/cm²
- ALD coating is based on the deposition of resistive and/or secondary emissive layers (could tune MCP properties)
  - Reported adverse effects on saturation current on some model with ALD
- Strong R&D to find the best "recipe" is needed



D. Miehling et al., NIM A 1049 (2023) 168047

ToT Vs Q calibration

- Validation with radioactive sources(^{137}Cs and ^{241}Am superimposed spectra)



PicoPix project

- PicoPix is intended to be a "realistic" demonstrator chip for a future upgrade of the LHCb Velo project (Velopix2)
  - Main requirement is time resolution < 30 ps rms
  - Other very challenging requirements (pixel size, radiation hardness, power, bandwidth, etc.)
- There is a limit on time resolution that are achievable for small pixels with limited power
- High-speed links in 28 nm (CERN EP R&D WP6)
  - lpGBT (10 Gbps) → DART28 (>26 Gbps)

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Velopix2

- Initial requirements on Velopix2 from LHCb

	Requirement	scenario S_A	scenario S_B
	Pixel pitch [μm]	≤ 55	≤ 42
	Matrix size	256×256	335×335
Priority	Time resolution RMS [ps]	≤ 30	≤ 30
	Loss of hits [%]	≤ 1	≤ 1
	TID lifetime [MGy]	> 24	> 3
	ToT resolution/range [bits]	6	8
	Max latency, BXID range [bits]	9	9
	Power budget [W/cm^2]	1.5	1.5
	Power per pixel [μW]	23	14
	Threshold level [e^-]	≤ 500	≤ 500
	Pixel rate hottest pixel [kHz]	> 350	> 40
	Max discharge time [ns]	< 29	< 250
	Bandwidth per ASIC of 2 cm^2 [Gb/s]	> 250	> 94

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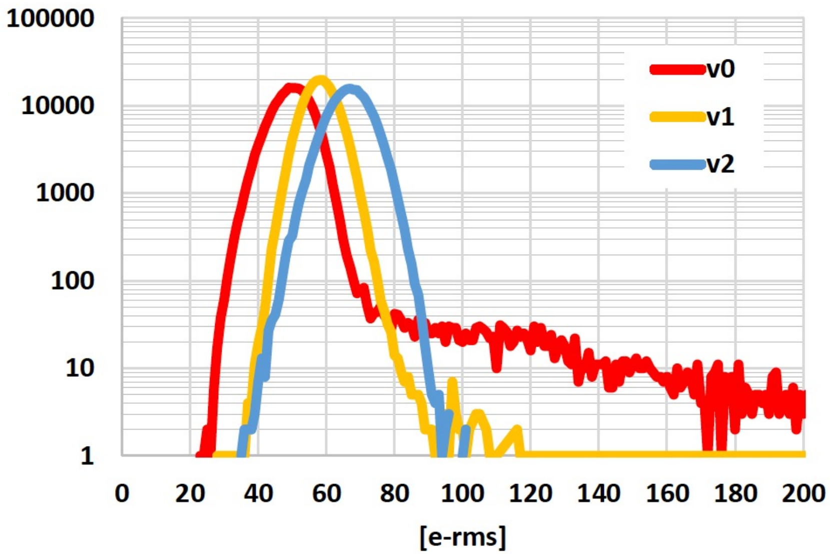
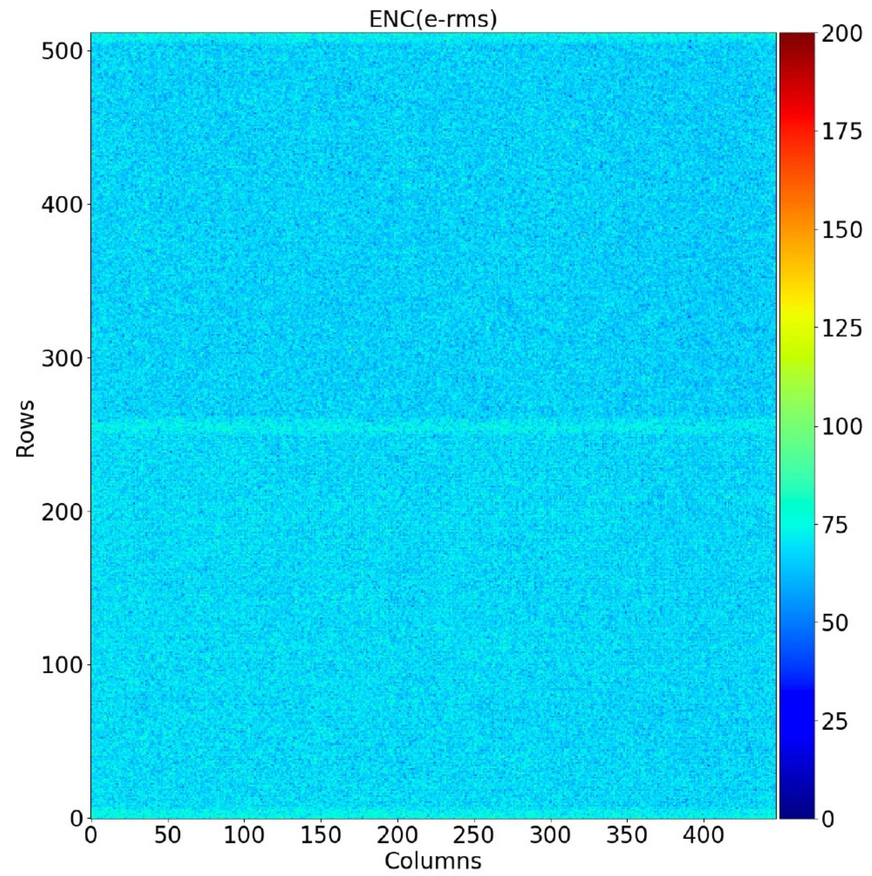
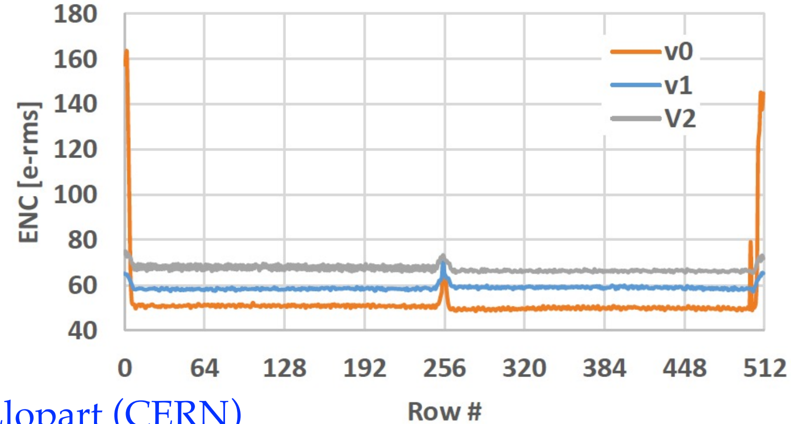
Challenging! doable

Timepix4 noise

- Equivalent Noise Charge (ENC) for v0, v1 and v2





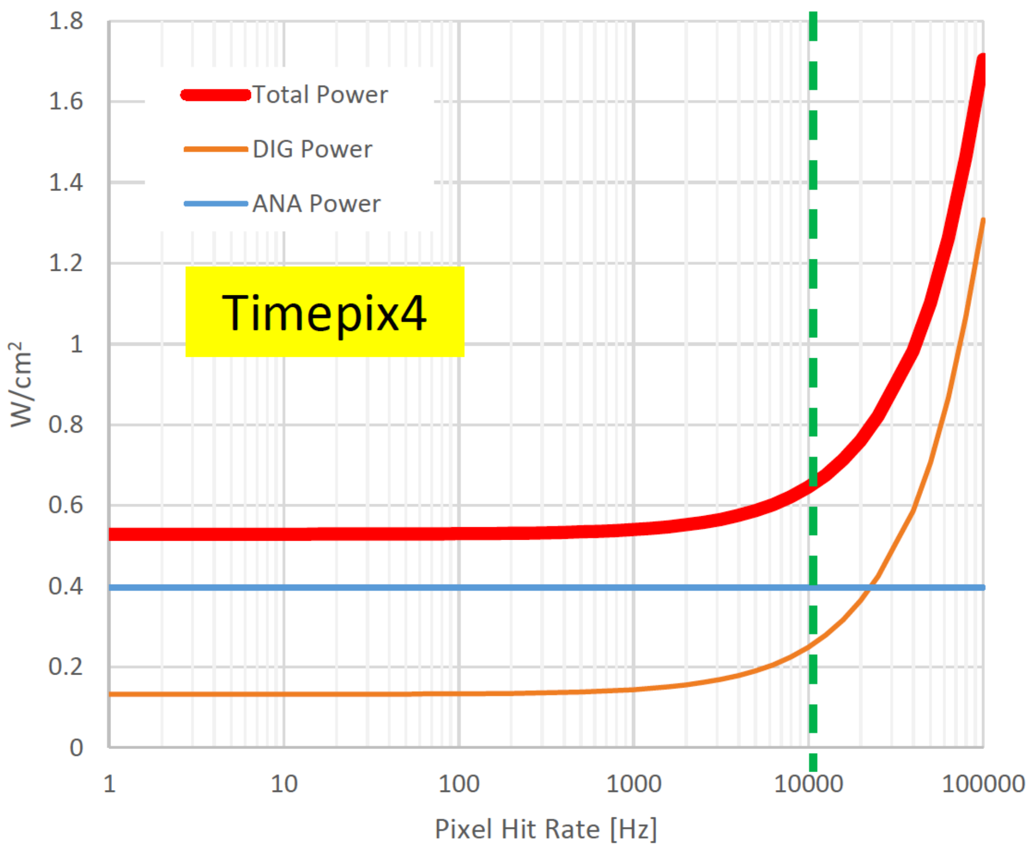


With a Si sensor the noise slightly increase ~3e⁻ / pixel

X. Llopart (CERN)

Power consumption and cooling

- Timepix4 power consumption (~5 W)
- Goal: stable operation with 20 °C inside the vacuum tube
  - Cold "finger" attached to ceramic carrier



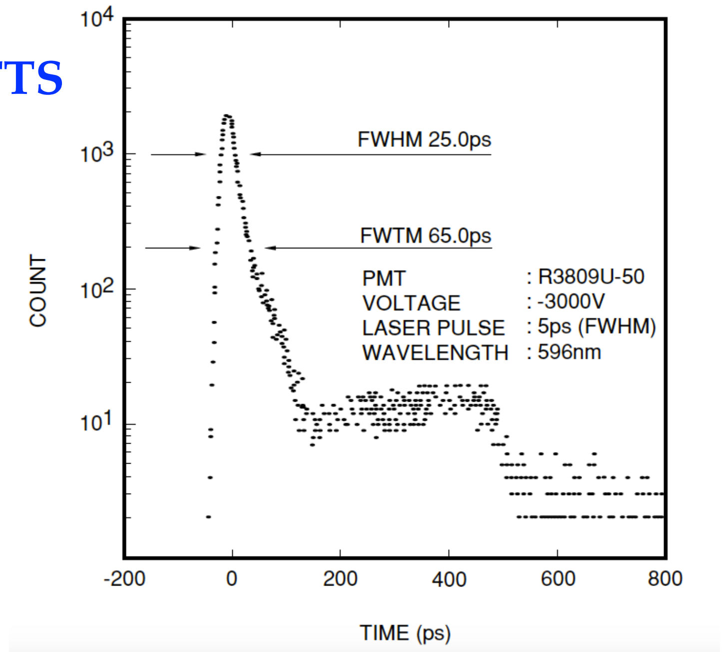
X. Llopart (CERN)

Time resolution contributions

$$\sigma_{time} = TTS \oplus \sigma_{front-end} \oplus \sigma_{TDC}$$

- Contributions:
  - TTS (Transit Time Spread) of electrons: 25 ps FWHM
  - Front-end: <30 ps for input charge >10^4 e^-
  - TDC contribution: 56 ps (195 ps bin size/√12)
- Time resolution for **1 pixel**: **70 ps**

TTS



Front-end