Innovative hybrid photodetector based on the Timepix4 ASIC as pixelated anode

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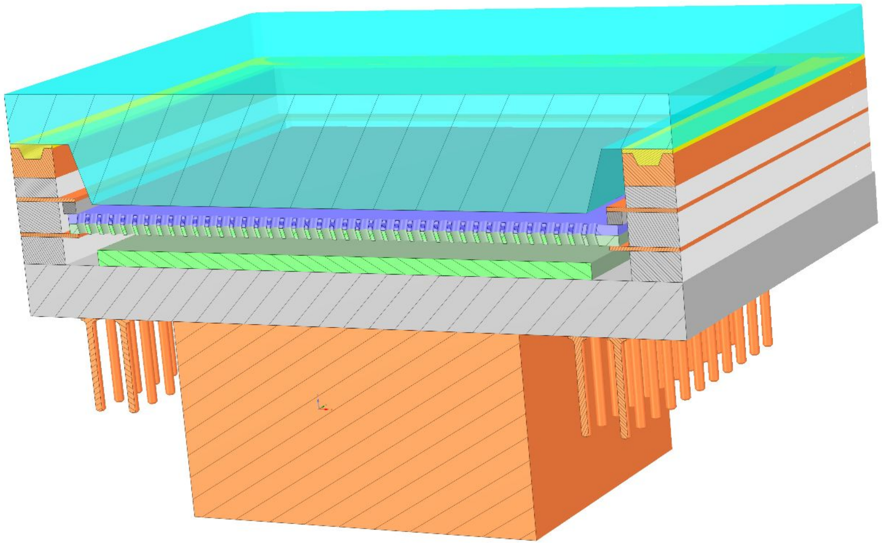
Overview

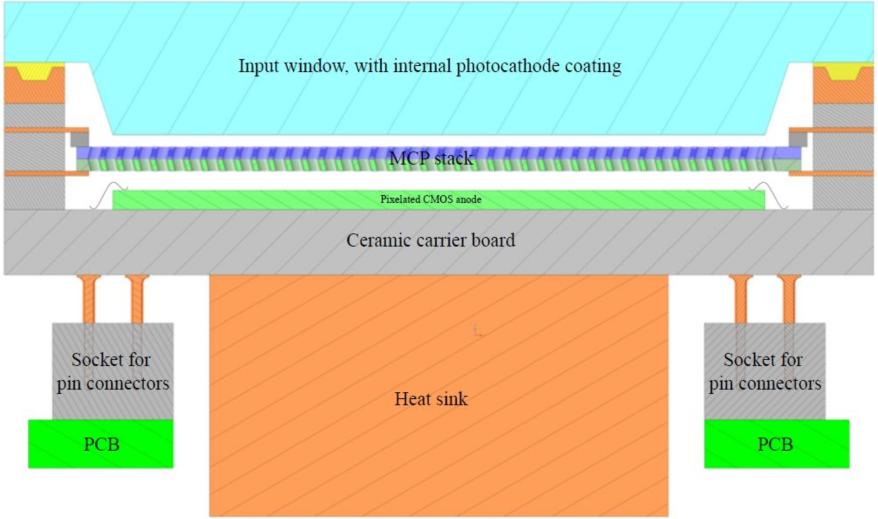
- Project goal
- The hybrid detector operating principle
- The Timepix4 ASIC
- DAQ and software
- Timepix4 characterization
  - Time-over-Threshold calibration
  - Timing resolution
- Conclusions



Novel hybrid photon detector

Project goal: 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**

- **"Hybrid" assembly**: many components inside a tube kept in under high vacuum
- Photocathode deposited in the inner part of a transparent input window
- **MCP stack** (Chevron configuration)
- Pixelated CMOS anode: **Timepix4 ASIC**
- **Ceramic carrier board**
  - interface between inner/outer parts of the detector
  - custom Pin Grid Array for I/O signals including high speed connections
- **Heat sink** (ASIC power 5 W)
- **PCBs** to connect the detector to a FPGA-based DAQ system



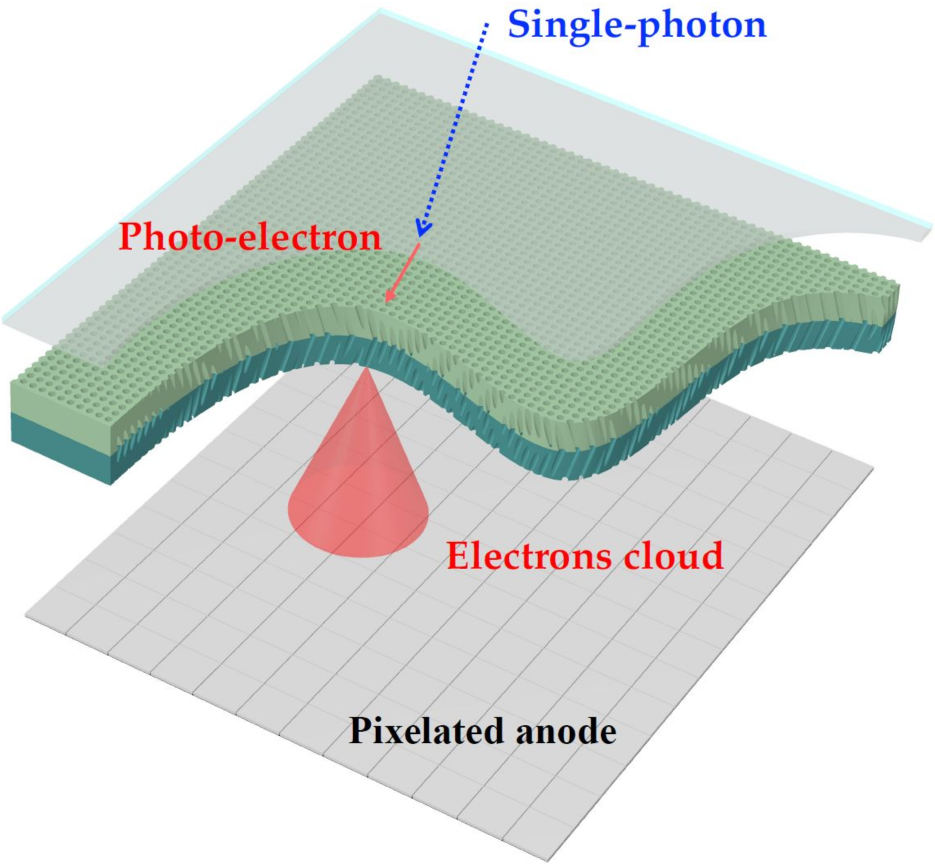
[M. Fiorini et al, JINST 13 (2018) C12005]

Detector operating principle: photocatode

Photon conversion producing a photo-electron in a high Quantum Efficiency (QE) photocatode

- ➢ high QE in blue-green region (for Cherenkov photons)
- ➢ low dark count rate (10^2-10^3 Hz/cm^2 @300K)
- ➢ large active area

Flexible design to use different photocatodes if needed for various applications



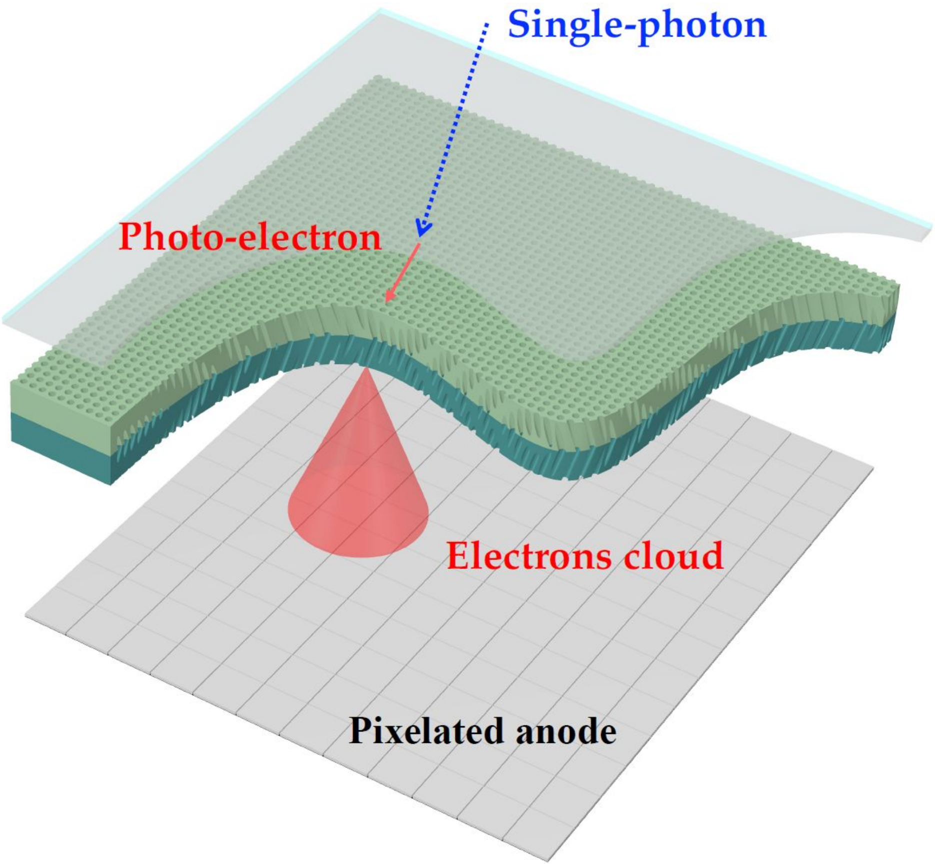
Detector operating principle: microchannel plate

Photon conversion producing a photo-electron in a high Quantum Efficiency (QE) photocatode

⇩

The photo-electron is transported by a drift electric field onto a microchannel plate (MCP) in Chevron configuration

- ➢ pore spacing of 5-10 μm to improve spatial and timing resolution, and hit rate
- ➢ short photocathode-to-MCP distance to improve spatial and timing resolution
- ➢ MCP-to-anode distance tuned for optimized spatial and timing resolution
- ➢ possible options to increase lifetime:
  - ○ MCP operated at low gain (10^4-10^5)
  - ○ Atomic Layer Deposition (ALD)



Detector operating principle: pixelated anode

Photon conversion producing a photo-electron in a high Quantum Efficiency (QE) photocatode

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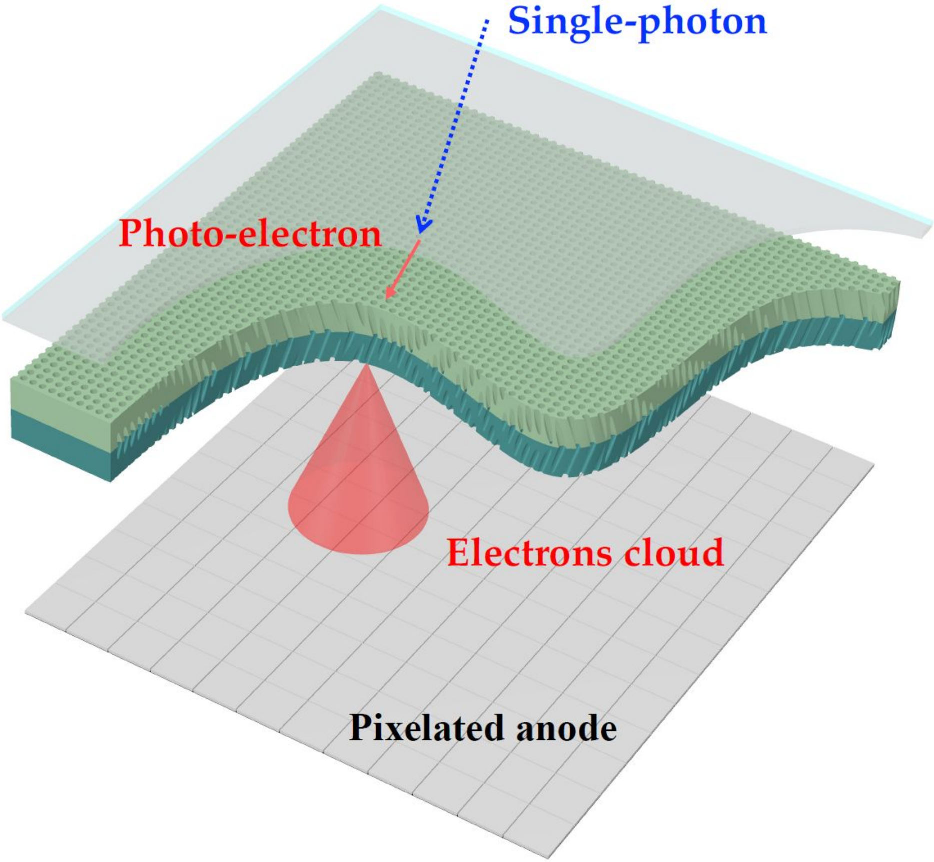
The photo-electron is transported by a drift electric field onto a microchannel plate (MCP) in Chevron configuration

⇩

The electrons cloud produced by the MCP is carried by another drift field onto the input (bump-bonding) pads of a bare Timepix4 ASIC, where it is sensed as a charge pulse by the read-out electronics



Detector operating principle

Photon conversion producing a photo-electron in a high Quantum Efficiency (QE) photocatode

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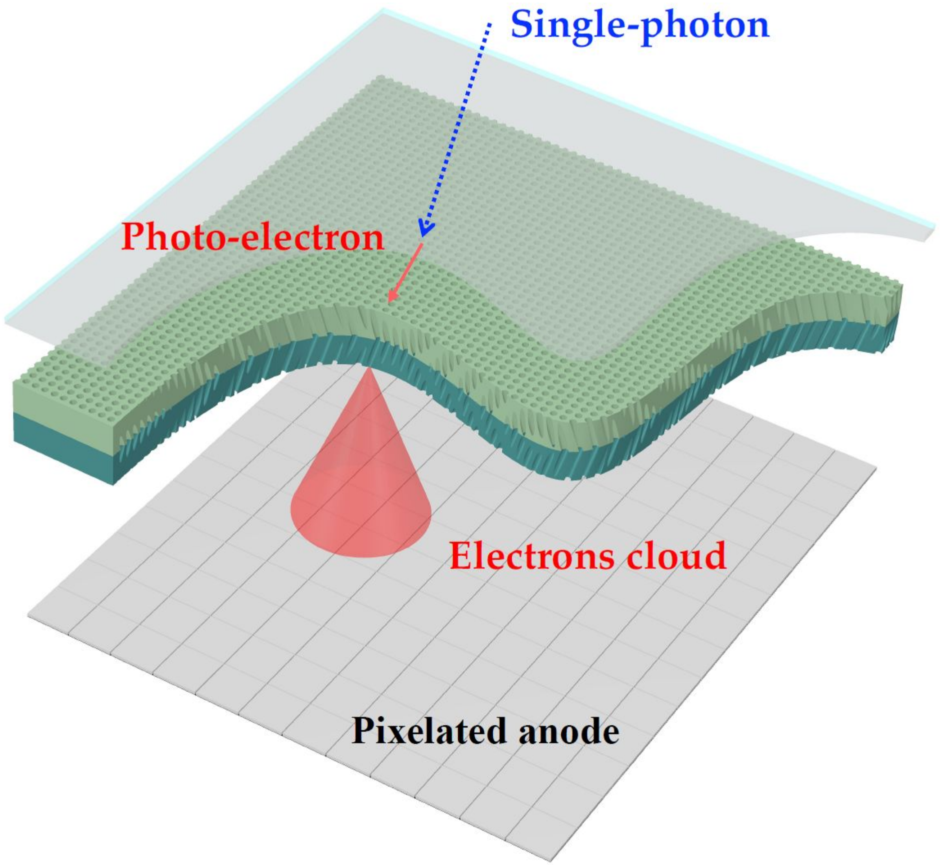
The photo-electron is transported by a drift electric field onto a microchannel plate (MCP) in Chevron configuration

⇩

The electrons cloud produced by the MCP is carried by another drift field onto the input (bump-bonding) pads of a bare Timepix4 ASIC, where it is sensed as a charge pulse by the read-out electronics

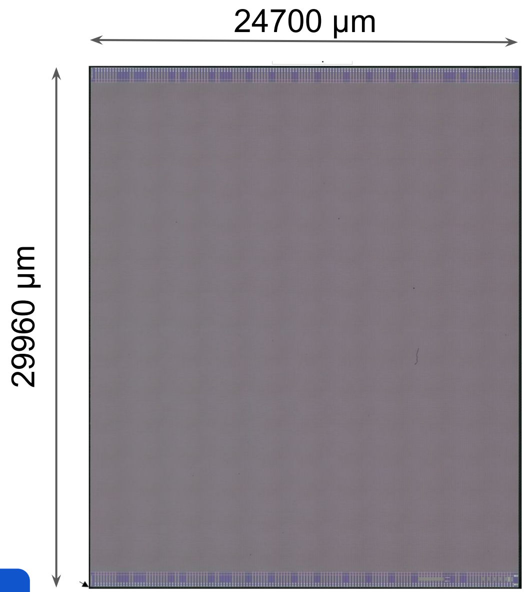
⇩

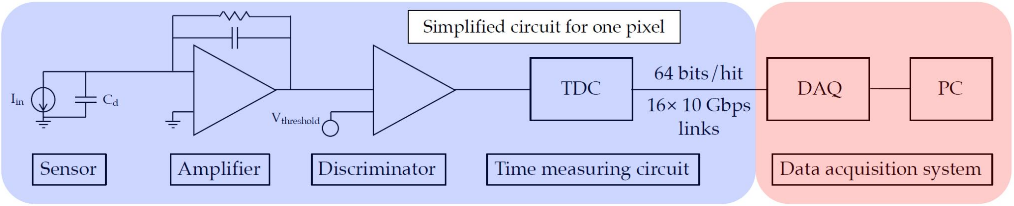
The Timepix4 ASIC will amplify, discriminate and digitize the MCP signal inside the vacuum tube



Pixelated anode: Timepix4 ASIC

- ASIC in **65 nm CMOS**
  - Developed by Medipix4 collaboration
- 512 ✕ 448 pixels (55 µm ✕ 55 µm each)
- **Large active area**: 7 cm^2
- Bump pads used as anode



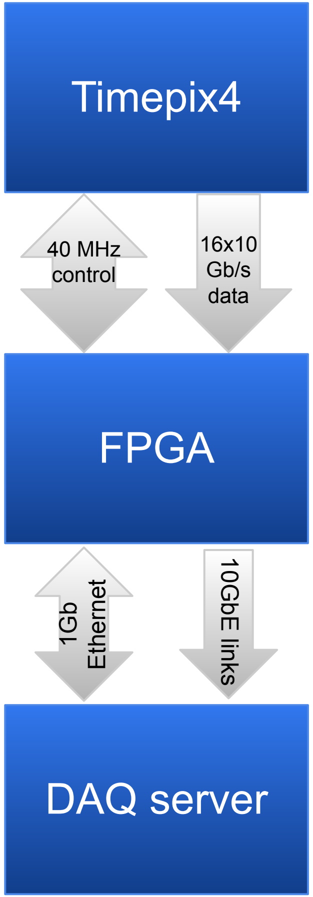


- Signal from MCP amplified and discriminated
- Time-stamp provided by Time-to-Digital Converter (TDC) based on Voltage-Controlled Oscillator (VCO)
  - **195 ps** bin size (**~ 56 ps r.m.s. resolution**) for Time-of-Arrival (ToA) measurements
  - **1.56 ns** bin size for Time-over-Threshold (ToT) measurements
- **High rate capability**:
  - maximum bandwidth: **160 Gb/s**
  - maximum hit rate: **2.5 Ghits/s**
- Output:
  - 64 bits of data per hit with 64b/66b encoding
  - transmitted via 16 high-speed links up to 10.24 Gbps

[X. Llopart *et al* 2022 *JINST* **17** C01044]

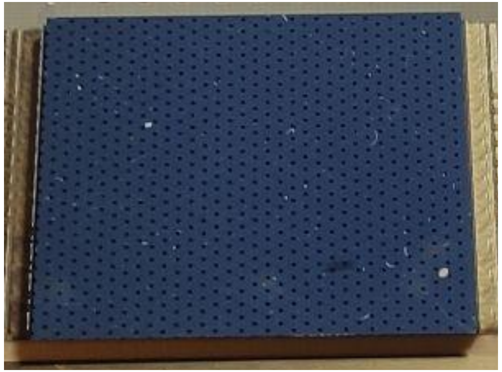
Data Acquisition (DAQ) system

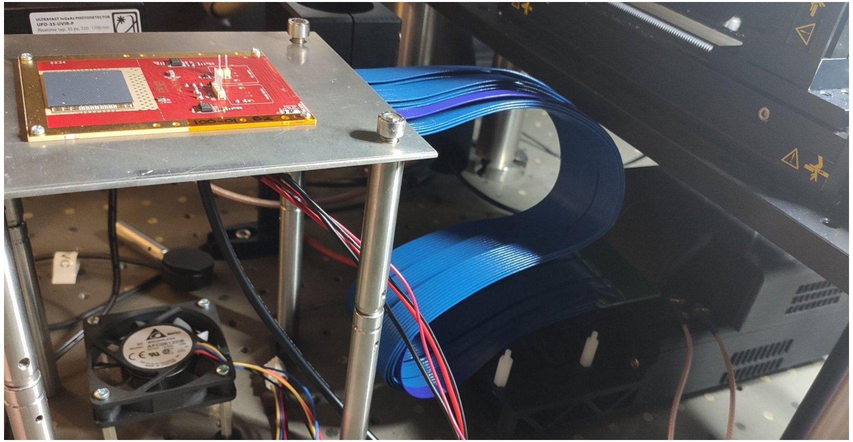
- **Data driven front-end electronics**
  - 64 bits for each pixel hit
  - **40 MHz slow control**
  - **16 x 10.24 Gb/s fast serial links**
- **FPGA-based control board**:
  - detector configuration
  - serial data decoding
  - sends pre-processed data to server to store them for post-processing
- **DAQ** server
  - receives and decodes data from control board
  - data analysis
  - data storage

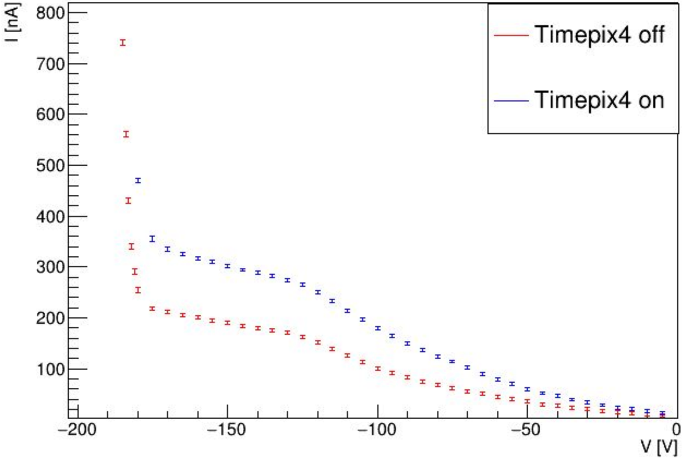


Timepix4 characterization measurements - Setup

- **SPIDR4** control board, developed by NIKHEF
- **Timepix4_v2**:
  - bonded to a 100 μm n-on-p Si detector biased at -150 V
  - metallization with holes pattern
  - Courtesy of the CERN and NIKHEF Medipix4/VELO groups

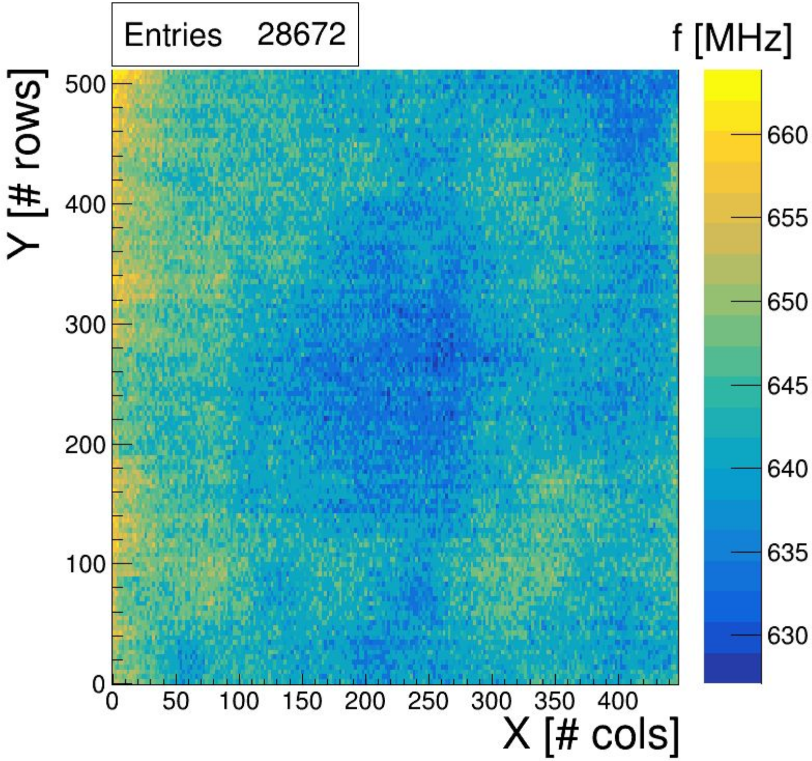






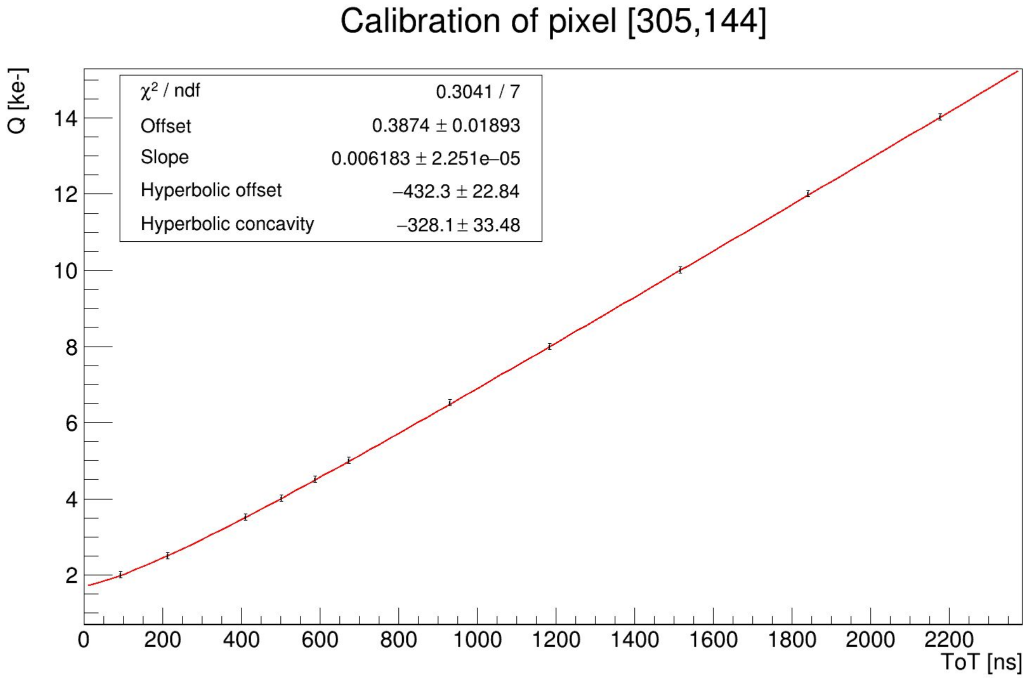
Timepix4 characterization measurements - VCO calibration

- ➢ 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)**



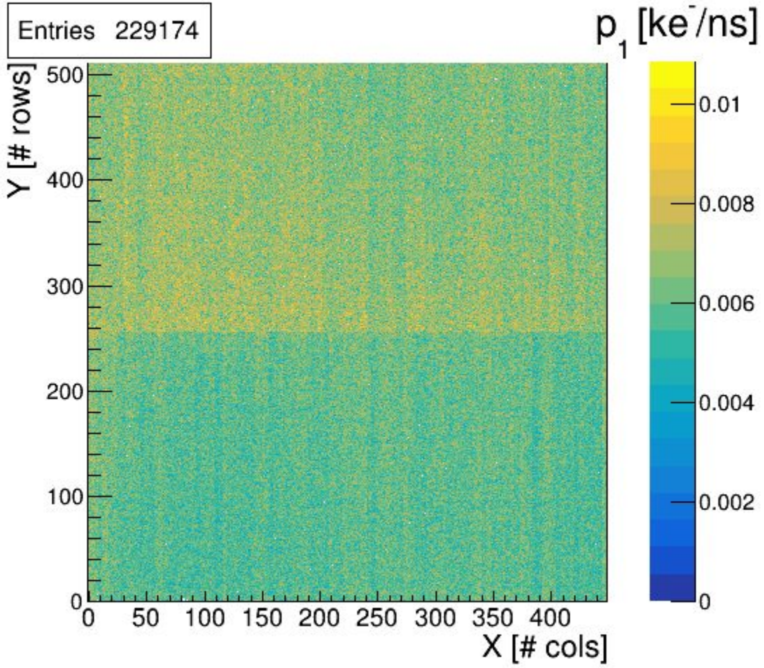
Timepix4 characterization measurements - ToT vs Q calibration

- Analog testpulse
- **Non linear** calibration
- Threshold set to 1 ke^-
- Per-pixel calibration done over the whole matrix (**~230k pixels**)



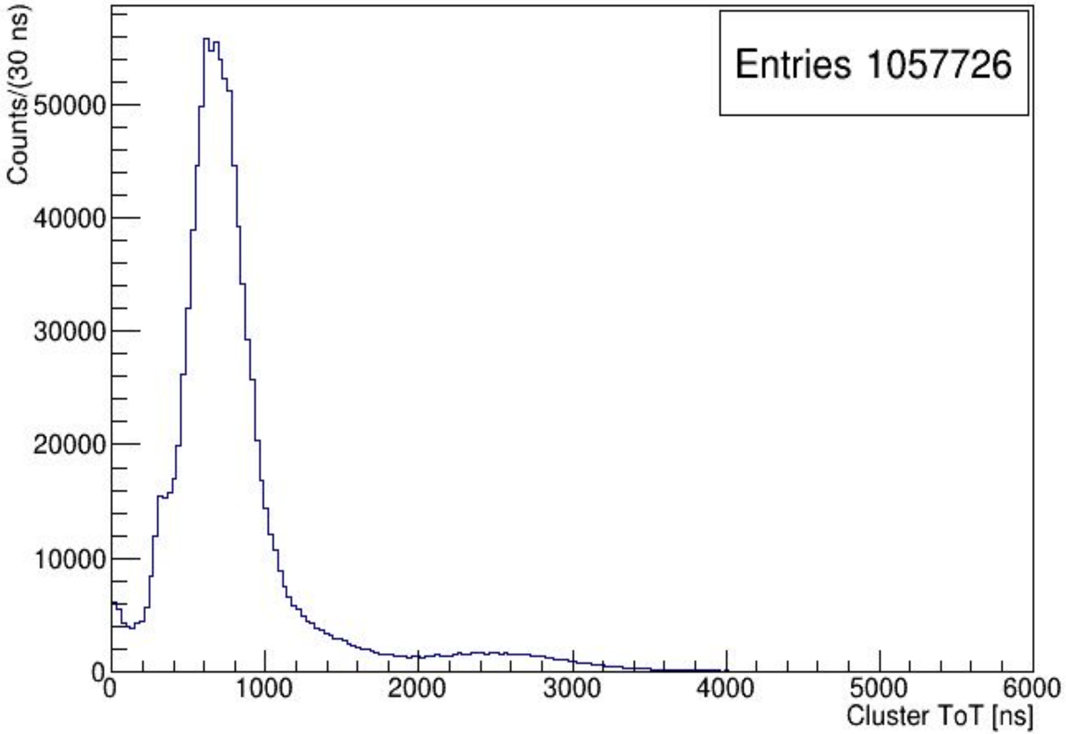
Timepix4 characterization measurements - ToT vs Q calibration

- Analog testpulse
- **Non linear** calibration
- Threshold set to 1 ke$^-$
- Per-pixel calibration done over the whole matrix (**~230k pixels**)
- Automatic algorithm exploiting fast read-out
- Calibration fit parameters distribution



Timepix4 characterization measurements - ToT vs Q calibration

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



Timepix4 characterization measurements - ToT vs Q calibration

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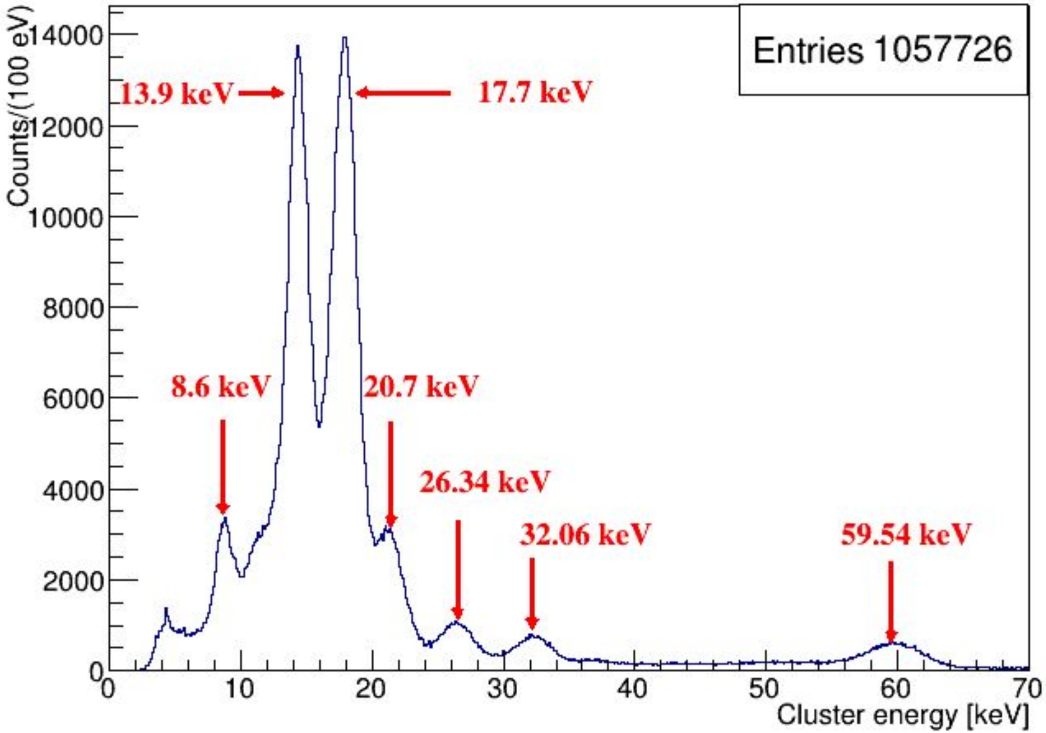
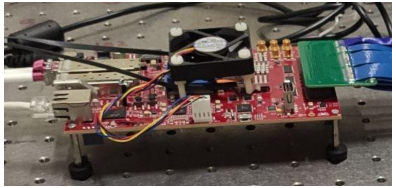


Timepix4 characterization measurements - Timing resolution

- **Waveform generator**
  - input signal to digital pixels
  - laser trigger
- **Laser**:
  - 1060 nm
  - variable attenuator
- **Zaber** motion setup
  - 3D position regulation
  - µm precision

Spidr4 control board



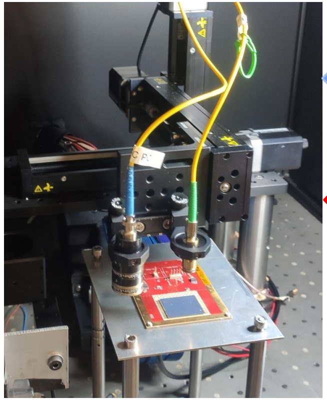
Pulse generator Active Technologies PG-1072 (interchannel jitter ~7 ps r.m.s.)

To digital pixels

Period: 5 ms
Width: 1 µs
Amplitude: 1.9 V

6dB attenuation

Period: 5 ms
Amplitude: 1.2 V

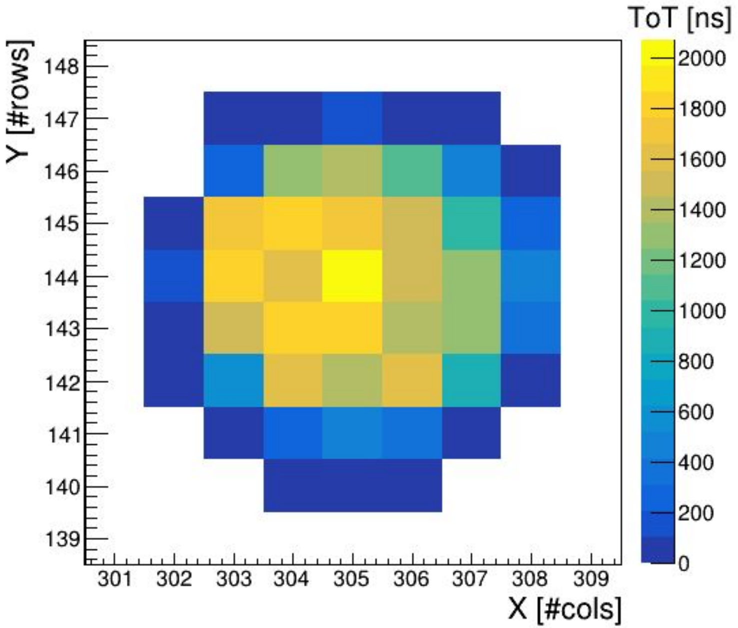


Laser variable Attenuator

Pulsed Diode Laser PDL 800-B

Single pixel timing resolution

- **Laser focused using micro-collimator**:
  - σ = 1.4 pixel = 77 µm
- Laser spot in **fixed position** for all presented measurements



Single pixel timing resolution

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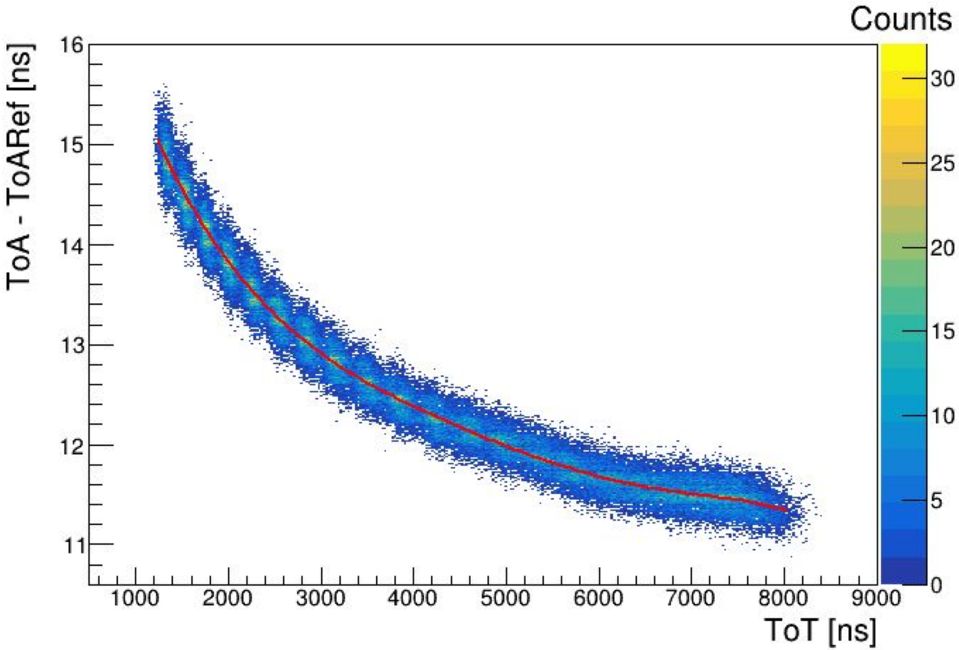
- Measurements using **variable laser attenuation**, populating a wide ToT range on each pixel
- **Different time walk trends** on different pixels
- Time walk corrected separately on each pixel



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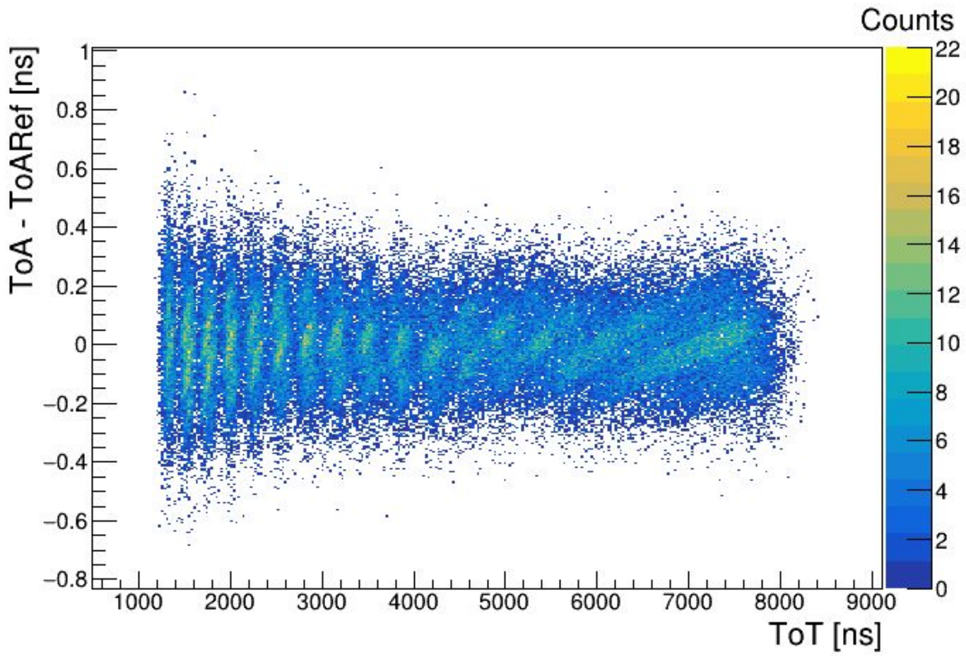
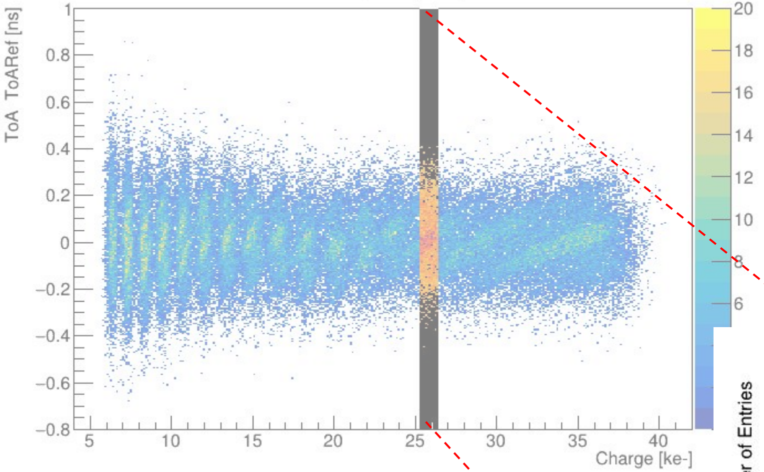
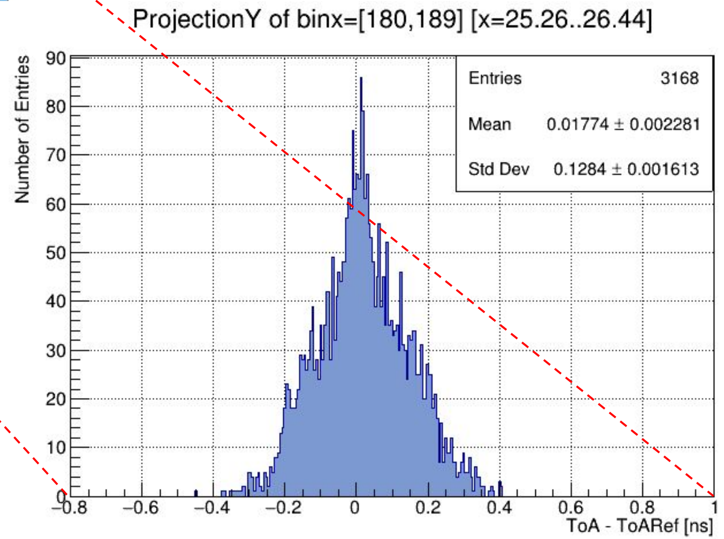


Single pixel timing resolution

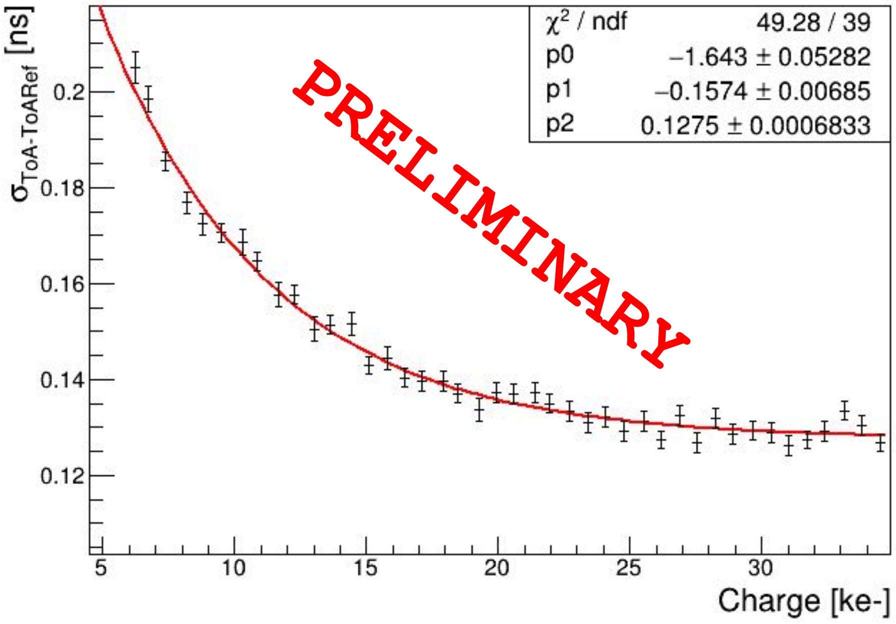


- ➢ ToT vs charge calibration applied to each pixel
- ➢ Distribution divided into "vertical" slices, each one selecting a narrow range of charge
- ➢ Timing resolution values extracted for each slice



Single pixel timing resolution

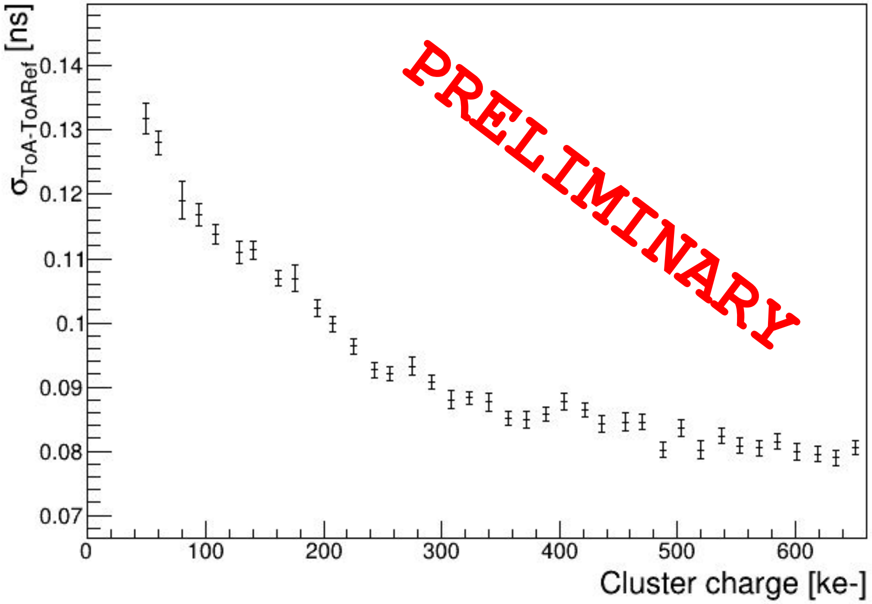
$\sigma_{ToA\text{-}ToARef}(ToT) = Exp(p_0+p_1 \cdot ToT) + p_2$



- 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
- 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

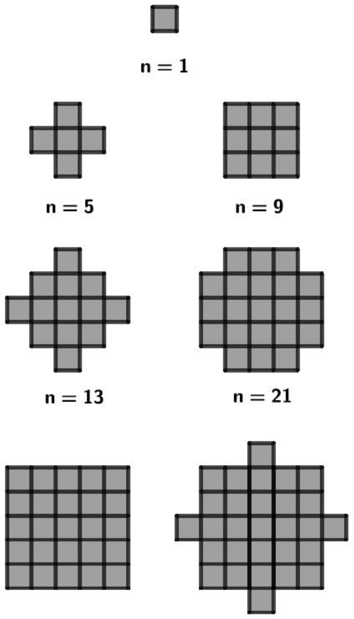
Cluster timing resolution

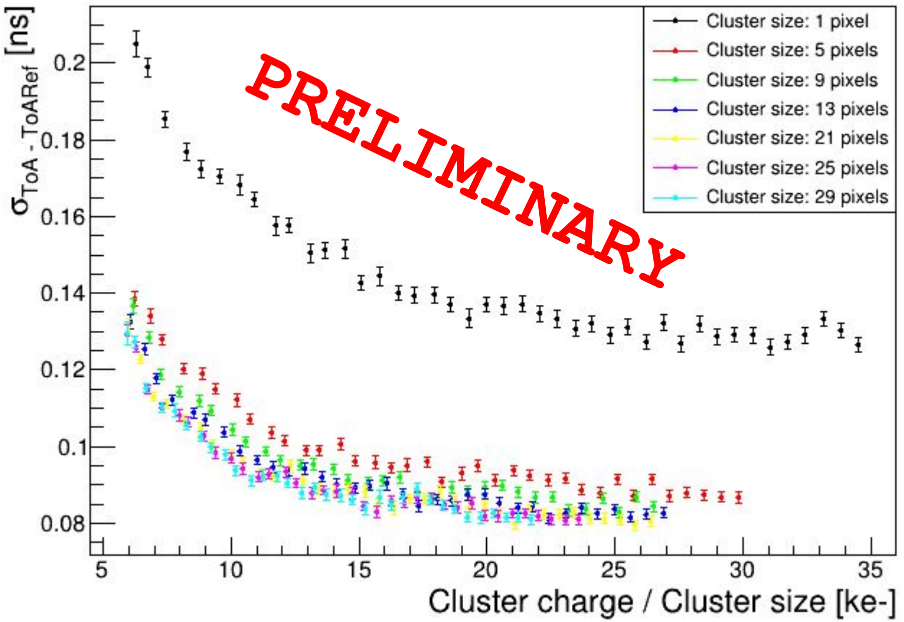
- For each cluster:
  - **weighted average** of ToA using charge as weights
  - cluster charge computed
- Timing resolution dependency on cluster charge:
  - best result: $\sigma_{ToADiffAvg}$=79 ± 1 ps rms
    - timing resolution subtracting reference TDC contribution: σ_{ToAAvg}=49 ± 1 ps rms



Cluster timing resolution selecting a shell of pixels

- **Large improvement in the resolution from 1-pixel clusters to 5-pixels clusters**
- Small or negligible improvement increasing further the cluster size





Next steps

- Timing resolution dependence on:
  - Pixel threshold
  - Temperature
  - Position across the whole matrix

Conclusions

We are developing a new detector for single photons in the visible range:

- ➢ Vacuum tube with MCP and Timepix4 CMOS ASIC as anode
- ➢ Funded by the European Research Council (G.A. No. 819627)
- ➢ Complete integration of sensor and electronics (internal data processing and data transmission)

It will allow the detection of up to 10^9 photons/s with:

- ➢ simultaneous timing and spatial information with excellent resolutions
- ➢ characteristics of MPC fully exploited
- ➢ high-rate data acquisition (up to ~160 Gb/s)
- ➢ Possible applications: high energy physics, life sciences, optical quantum physics

Promising results characterizing Timepix4 bonded to Si sensor:

- ➢ ToT vs Q per pixel calibration
- ➢ single pixel timing resolution: ***σ_{ToA} = 111 ± 1 ps rms***
- ➢ cluster timing resolution: ***σ_{ToA} = 49 ± 1 ps rms***

Development is ongoing:

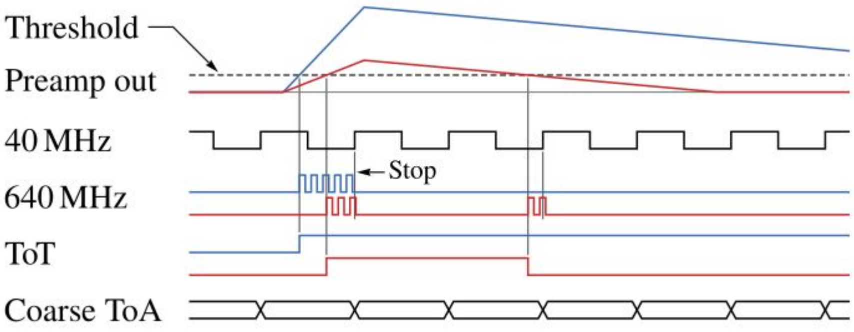
- ➢ detector, DAQ and software system

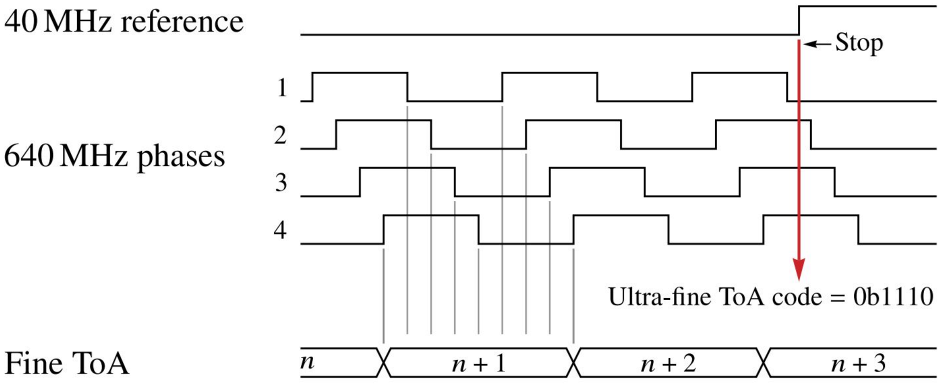
Thanks to the CERN and NIKHEF teams for the support

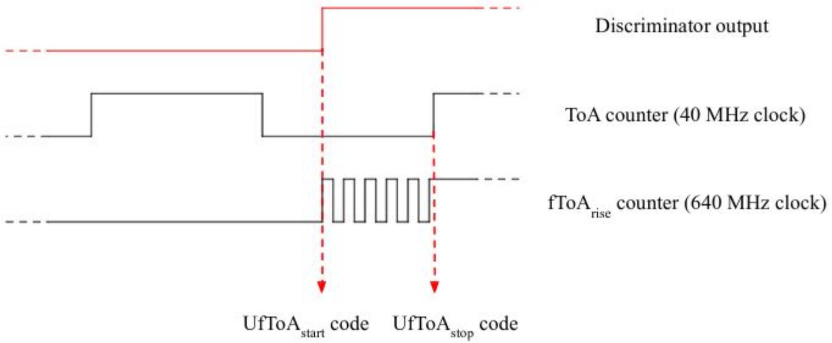
Backup

ToA and ToT measurements

- ToA measurement:
  - coarse Time-of-Arrival (ToA), **40 MHz clock** (25 ns bins width)
  - fine-ToA bins, **640 MHz clock**, generated by the VCO (1.56 ns biins width)
  - Ultrafine-ToA, by 4 copies of 640 MHz clock (195 ps bins width)
- ToT measurements: only coarse and fine

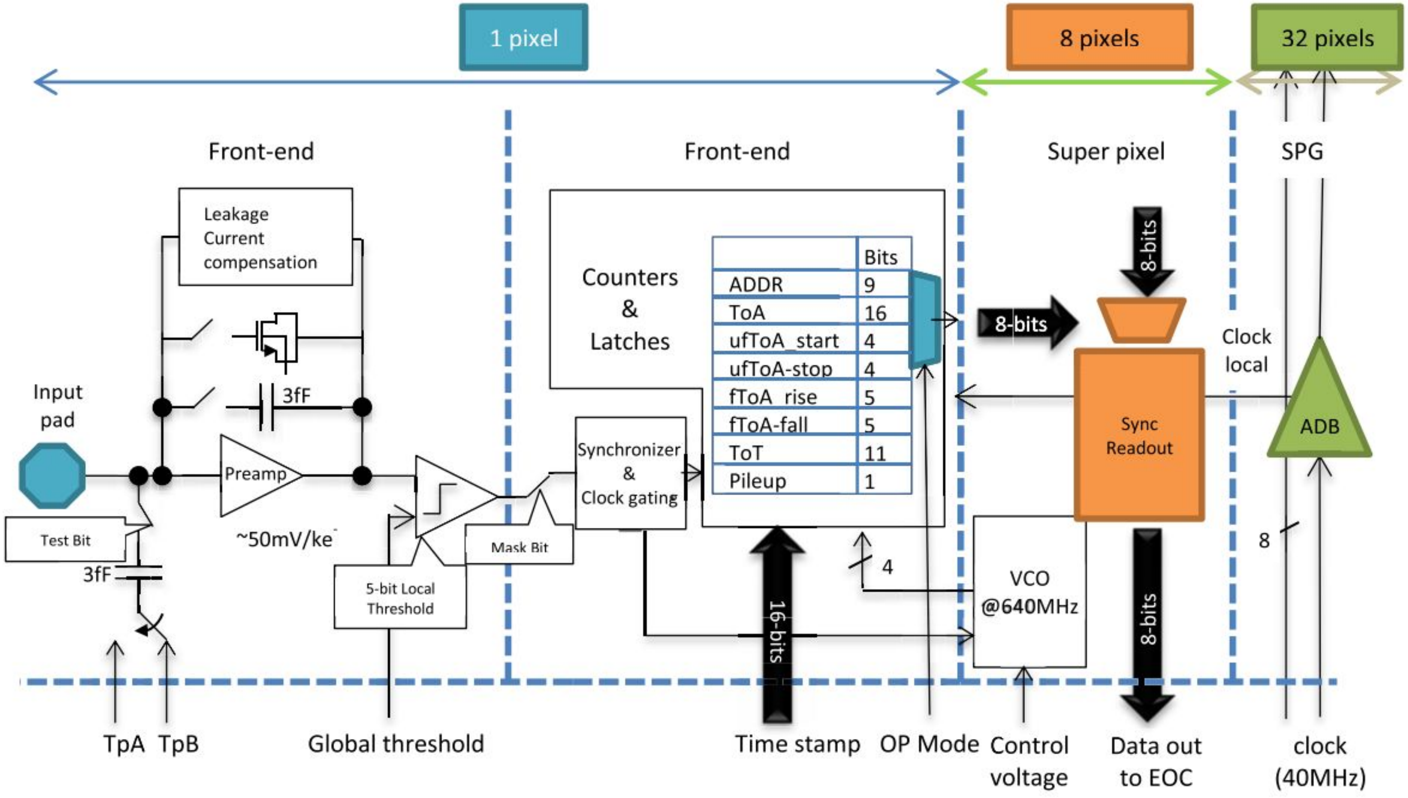






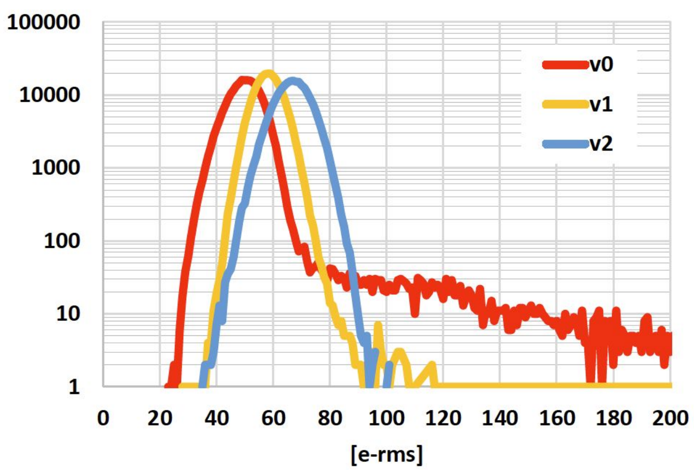
[K. Heijhoff *et al* 2022 *JINST* 17 P07006]

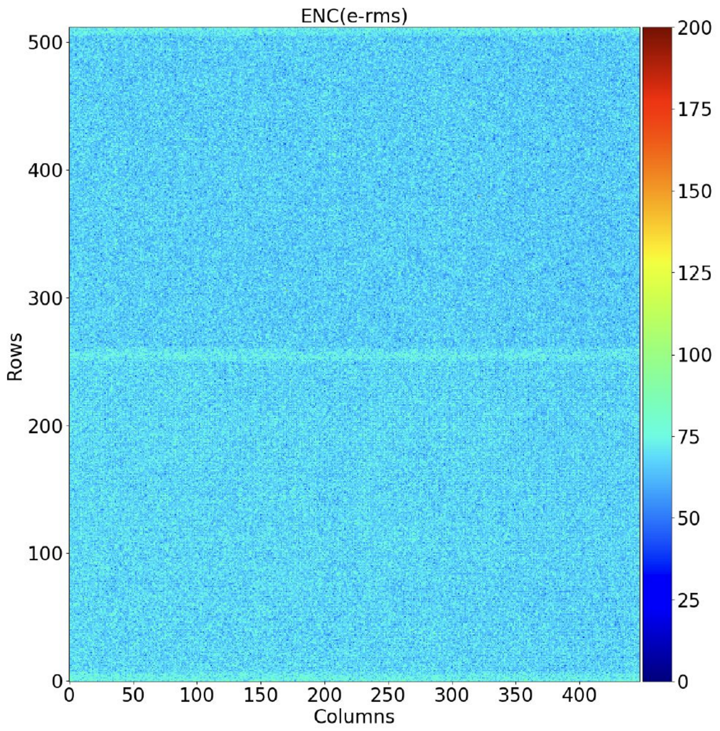
Analog and digital front-end

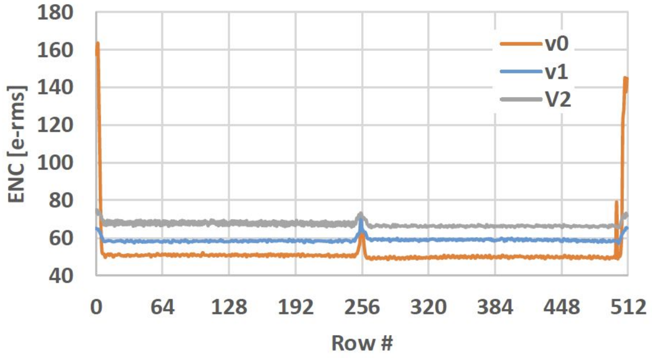


[X. Llopart *et al* 2022 *JINST* **17** C01044]

Timepix4 noise



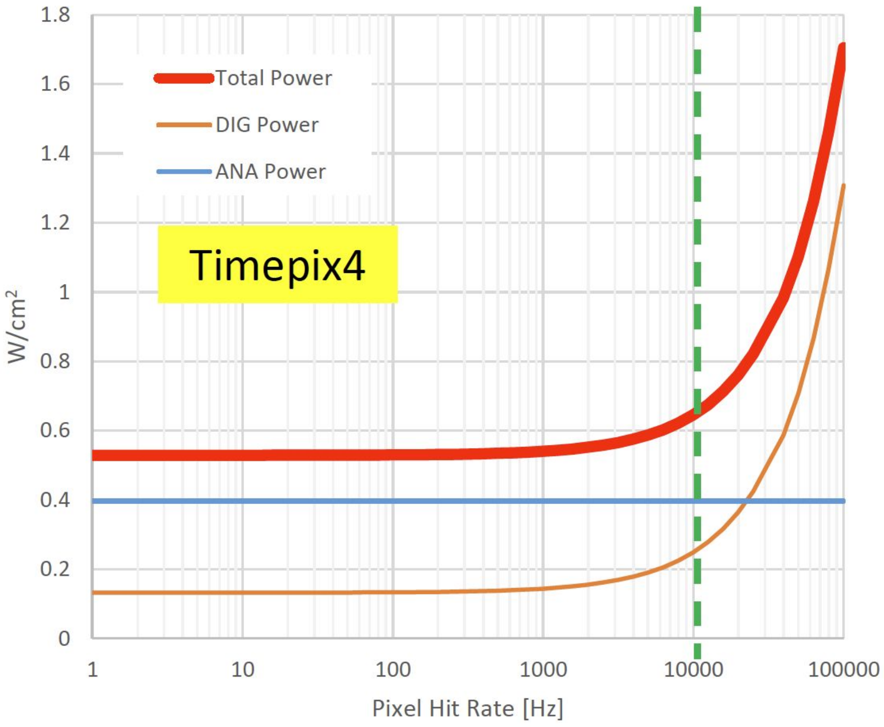




X. Llopart (CERN)

Power consumption and cooling

- ➢ Timepix4 power consumption∼ 5 W
- ➢ Goal: stable operation with 20°C inside the vacuum tube
  - ○ Cold finger attached to the ceramic carrier



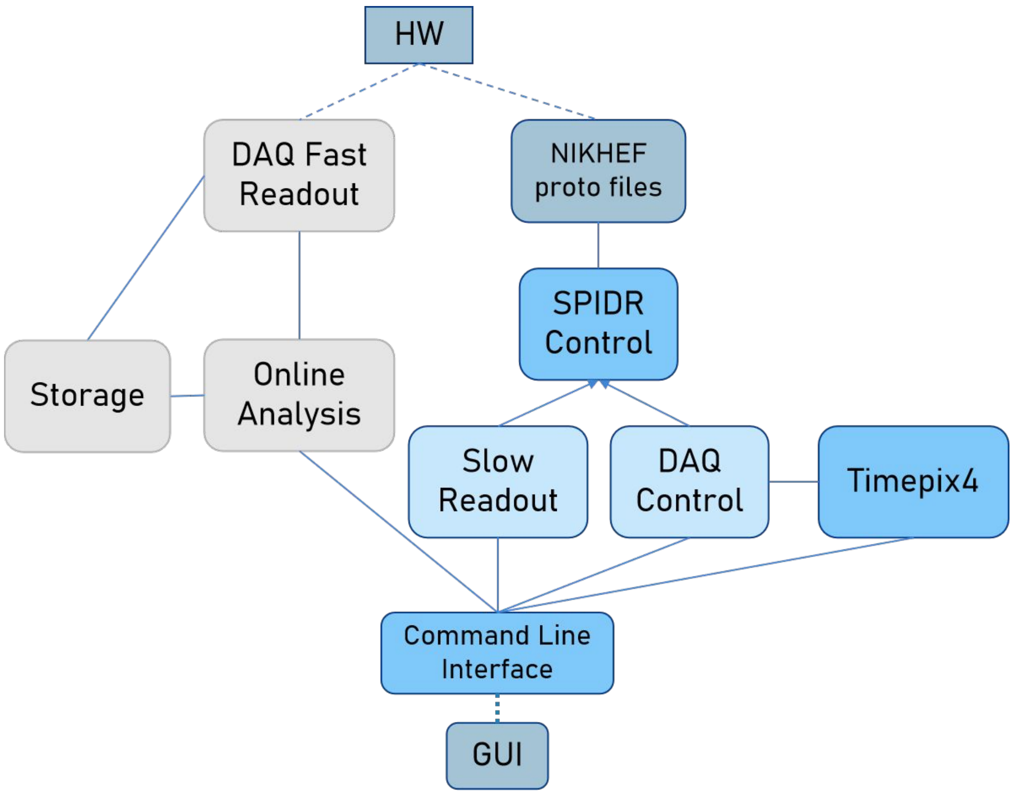
X. Llopart (CERN)

Summary of expected global parameters

Single pixel timing resolution	<100 ps
Position resolution	5-10 μm
Maximum rate	2.5×10^9 hits/s
Dark count rate	$\sim 10^2$ counts/s
Active area	$\sim 7\ cm^2$
Channel density	~0.23 M channels (512 x 448 pixels)

Software

- ➢ Dedicated software under development
- ➢ **C++** based
  - ○ Low-level
  - ○ Object-oriented
- ➢ Readout and Control in **unique CLI**
- ➢ **Read** and **Write register** functions
- ➢ **Application Programming Interfaces** for Timepix4
- ➢ Packets **decoder**



Timepix4 characterization measurements - VCO calibration

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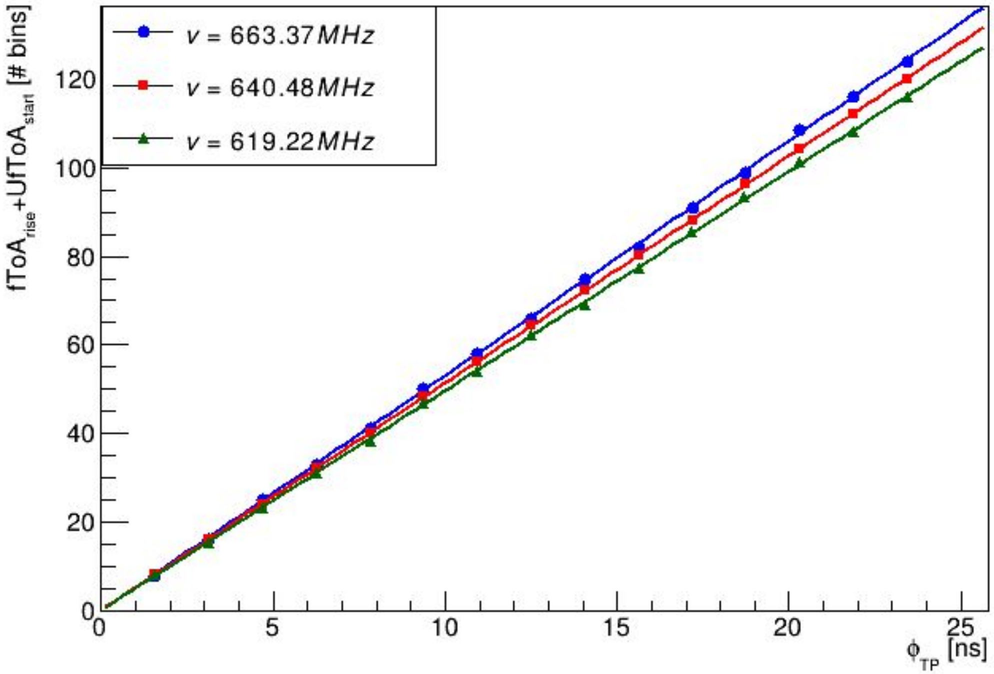
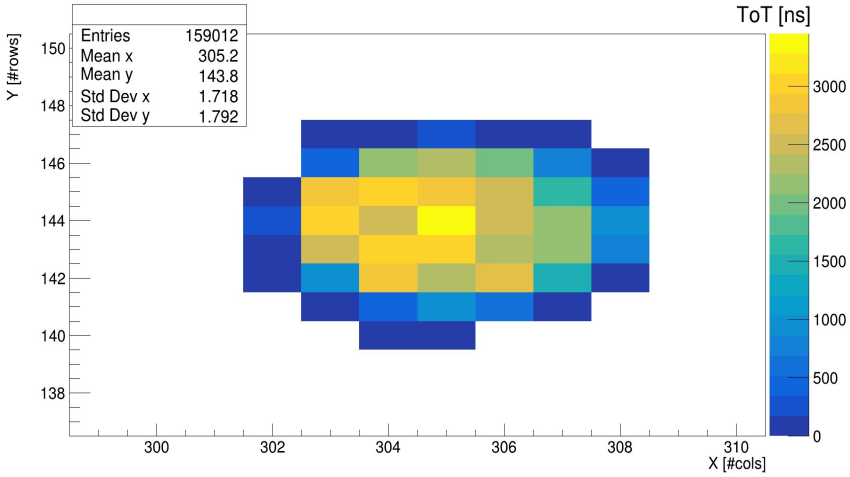
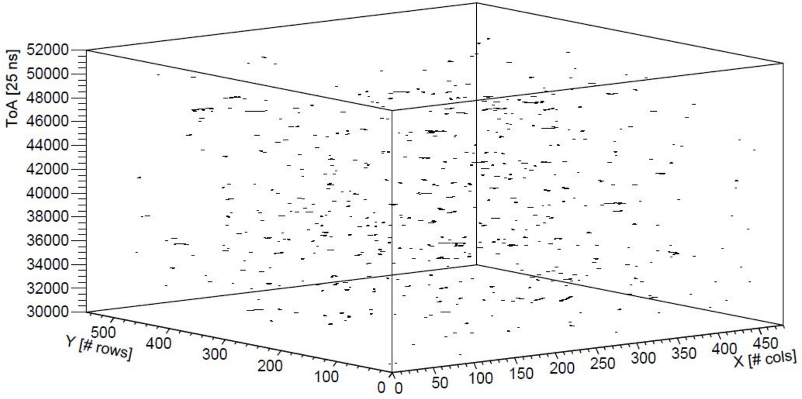
- ➢ ToA and ToT measurements heavily affected by this effect



Analysis description

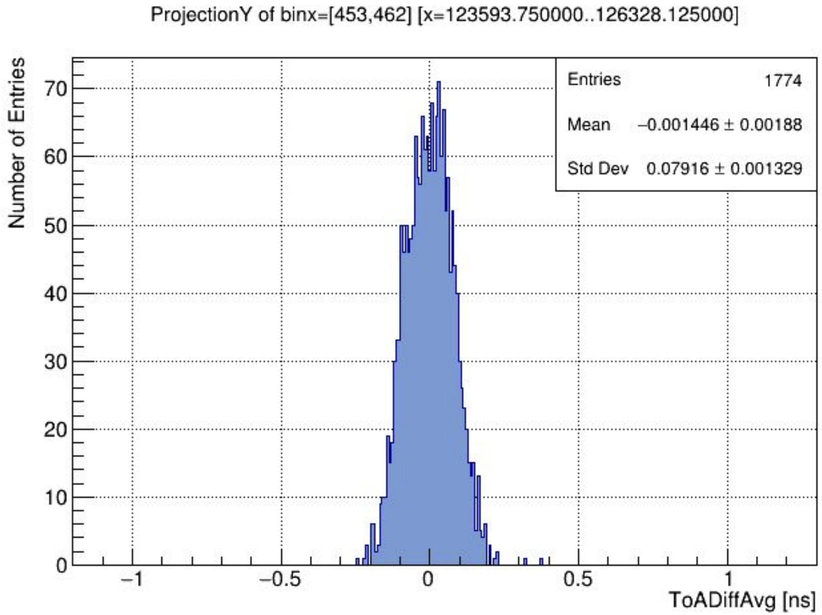
- **Packet decoding**
- **Clustering algorithm:**
  - DBSCAN algorithm
  - variable spatial and timing parameters to gather hits on the same cluster
- **ToA of each hit compared with the reference ToA of the associated digital pixel signal**





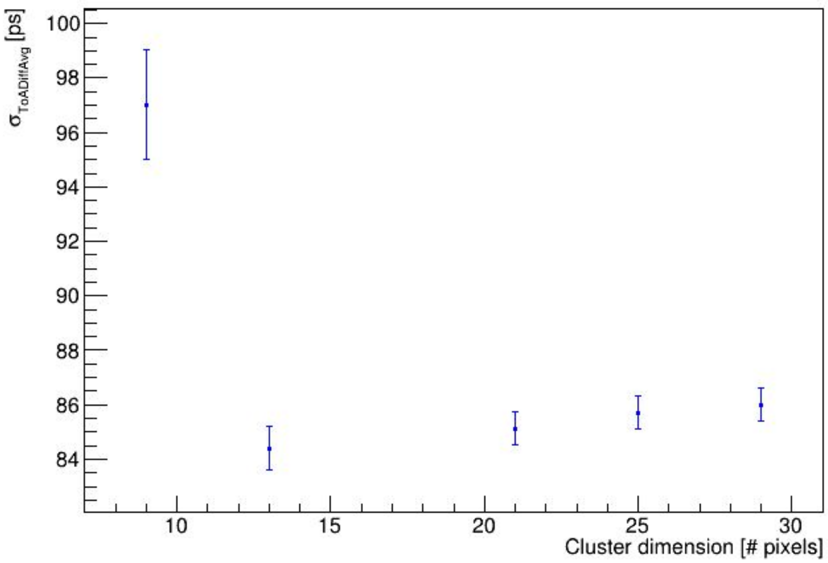
Cluster timing resolution

- For each cluster:
  - **weighted average** of $ToADiffAvg_i = \sum_j (ToADiffCorr_{i,j} \cdot ToT_{i,j}) / \sum_j (ToT_{i,j})$
  - cluster ToT ($ToTSum_i$) computed



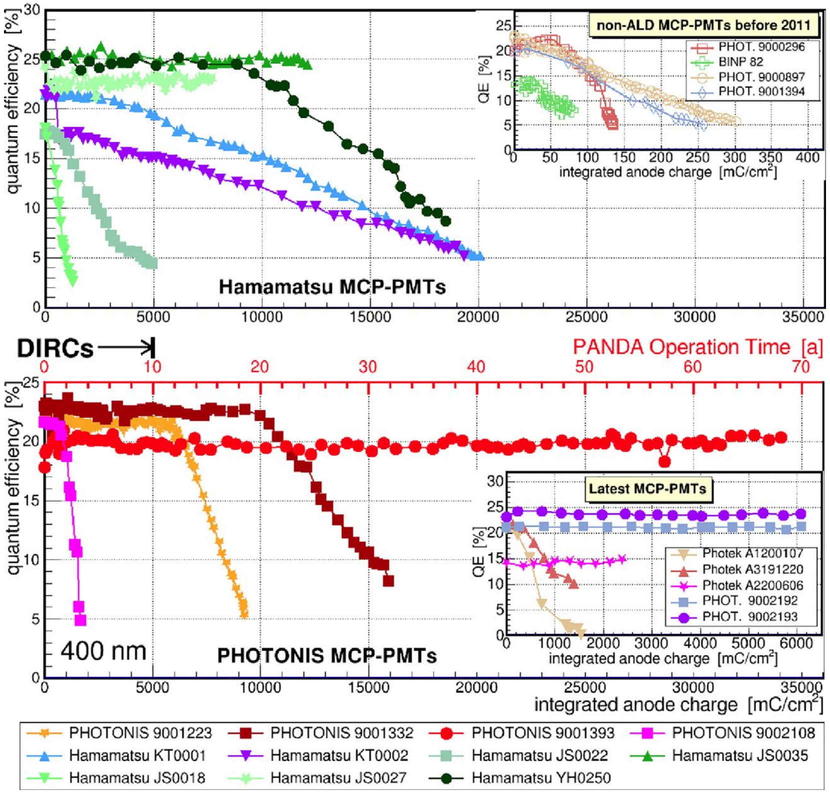
Cluster timing resolution selecting a shell of pixels

- Similarly, the cut has been applied to the total ToT of the selected cluster (*ClusterToT* $\in$ *[58000 ns, 62000 ns]* ~ *[640000 ke$^-$, 680000 ke$^-$]*), instead of the ToT of the central pixel
- This simulates the measurement of a **fixed amount of charge spread on a different number of pixels**
- Considering more pixels:
  - **statistical factor**: error reduced because of average (dominant at low pixel multiplicity)
  - **pixel intrinsic resolution**: error increased because charge spread among pixels, and each one receives less charge (dominant at high pixel multiplicity).



MCP-PMT limitation

- MCP-PMT lifetime limited by the integrated anode charge, which leads to a strong QE reduction
  - From 0.2 C/cm^2 to >30 C/cm^2 in recent years thanks to ALD
- With the expected photon hit rate (~10 MHz/mm^2), assuming a 10^4 gain (very conservative), and an operation of 10 years with 25% duty cycle we have:
  - Total IAC ~120 C/cm^2
  - Anode current density ~2 μA/cm^2
- 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]