Development and characterization of hybrid MCP-PMT with embedded Timepix4 ASIC

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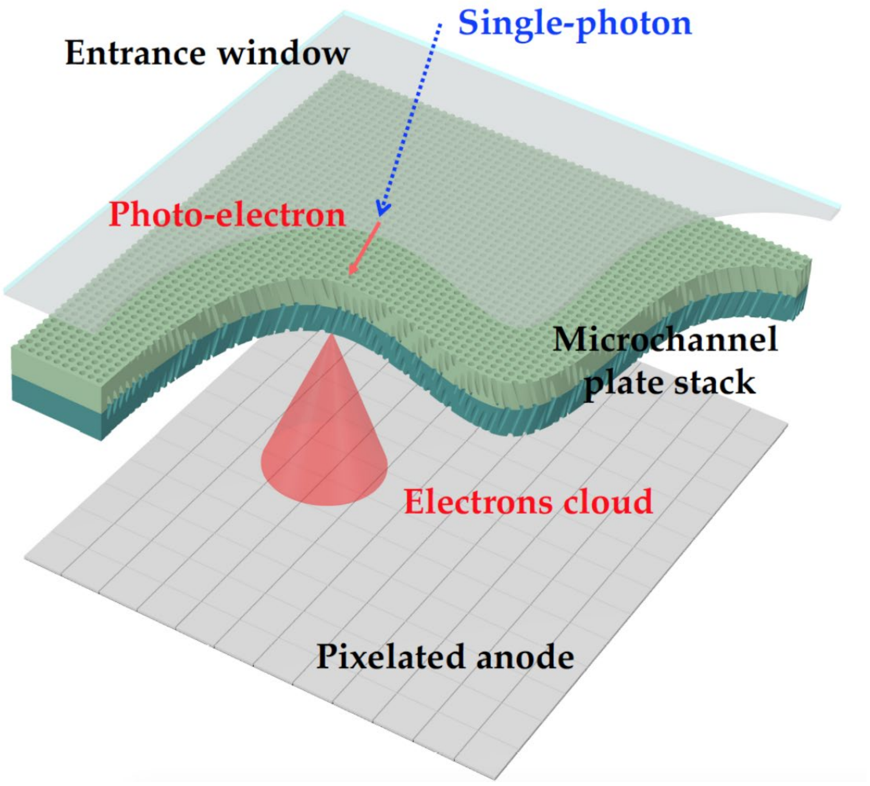
On behalf of 4DPHOTON team

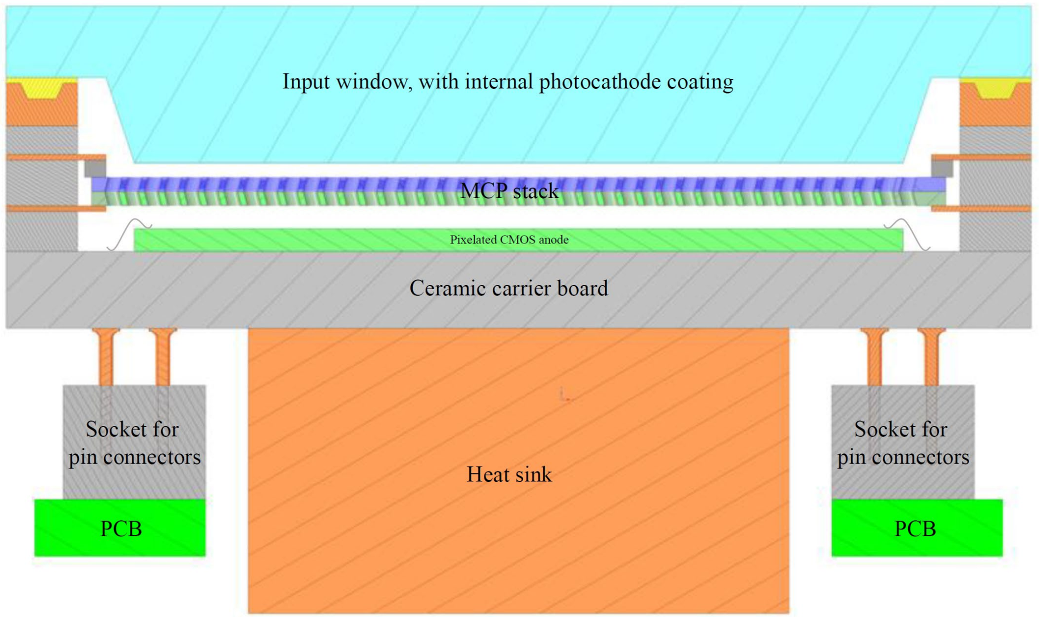
Hybrid MCP-PMT concept

Detector operating principle



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

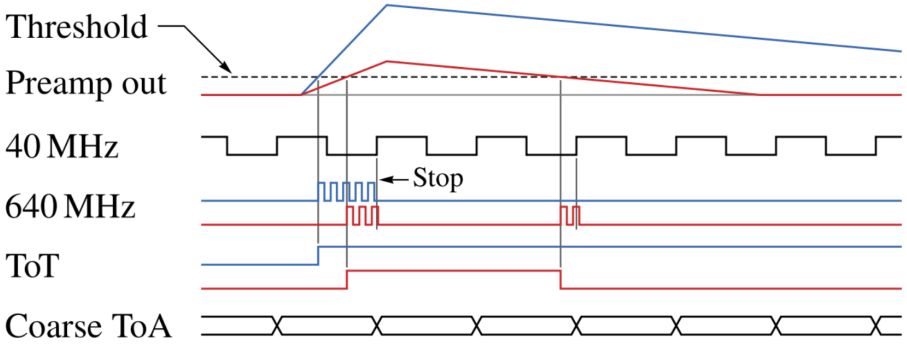
- Entrance window + **photocathode**
- **MCP stack** (Chevron or Z-stack configuration)
- Pixelated CMOS anode: **Timepix4 ASIC**
- **Ceramic carrier board**
- **Heat sink** (ASIC power 5 W)
- **PCBs** to connect the detector to a **FPGA-based DAQ system**



Pixelated anode: Timepix4 ASIC

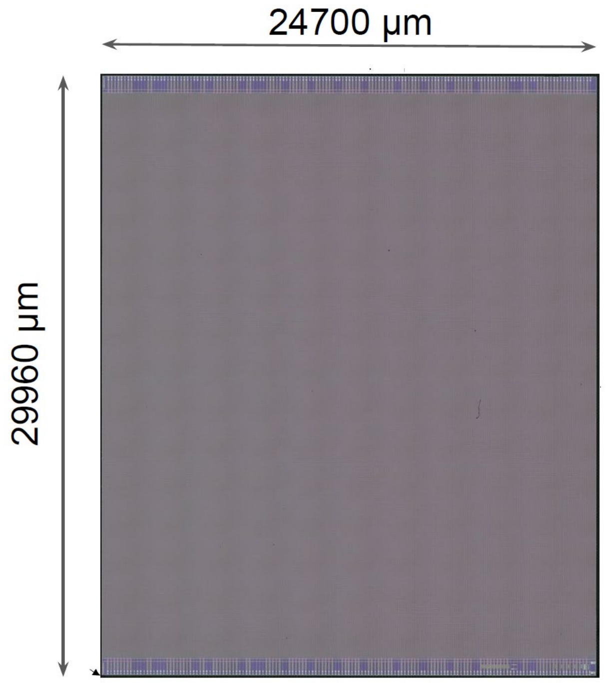
X. Llopart et al 2022 JINST 19 C01044

- Developed by **Medipix4** collaboration
- **512 ╳ 448 pixels** (55 µm ╳ 55 µm each)
- Large active area: 7 cm^2
- Bump pads used as anode
- **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



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⁻

ASIC in 65 nm CMOS



Electron cloud spread over a number of pixels → **cluster**

Exploit **ToT** information (∝ charge in a pixel) to:

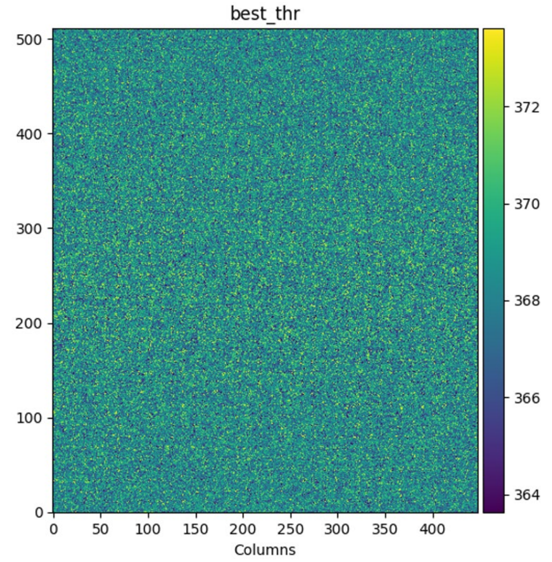
- **Correct for time-walk** effect in every pixel
- **Improve position resolution** by centroid algorithm
  - from $\frac{55}{\sqrt{12}}\mu m \sim 16\ \mu m$ down to $5-10\ \mu m$ r.m.s. (MCP channels pitch)
- **Improve timing resolution** by multiple sampling
- Many timing measurements for the same photon → **few** $\mathbf{10s}$ $\boldsymbol{ps}$ r.m.s.

Equalization and Calibration

✓ Threshold equalization

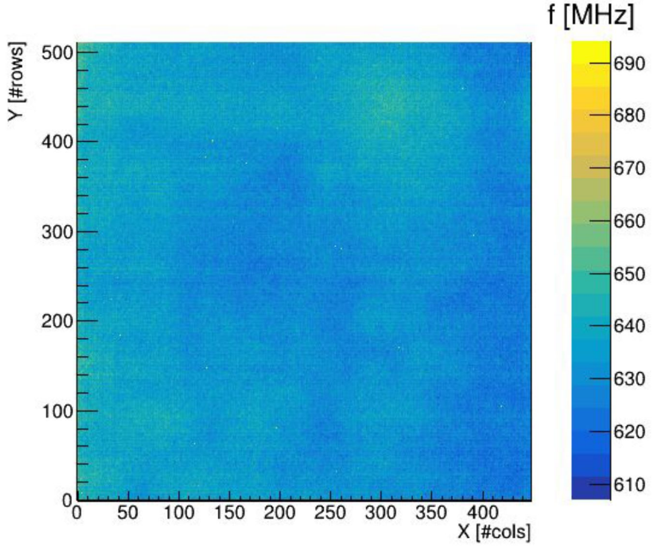
- **Threshold fine tuning at pixel level**
- Noisy pixels detection
- On the whole matrix (~230 k pixels)

X. Llopart XII Front-End Electronics Workshop



✓ VCO frequency calibration

- On pixel **VCO oscillation frequency controlled by a PLL** at the center of the chip (@ 640 MHz nominal)
- VCO design sensitivity of 1MHz/mV
  - **Spread of 40 MHz**
- Noise measurements used to **calibrate VCO frequencies** for the whole matrix (~29 k VCOs)



✓ ToT vs Q calibration with testpulse

- At fixed charge, large **ToT spread across the matrix** due to local gain differences
- **Non-linear calibration performed with integrated test pulse tool**

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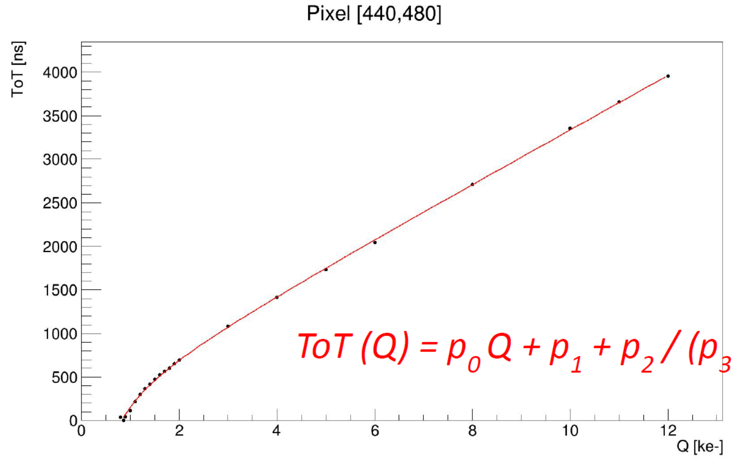

ToT (Q) = $p_0 Q + p_1 + p_2 / (p_3 + Q)$

✓ Timing resolution measurements with TimePix4 bonded to a 100 µm n-on-p Si sensor using Spidr4 control board

- $\sigma_t^{pixel} \sim 107 \pm 3\ ps\ rms$
- $\sigma_t^{cluster} \sim 33\ \pm\ 3\ ps\ rms$ (~ 30 pixels)

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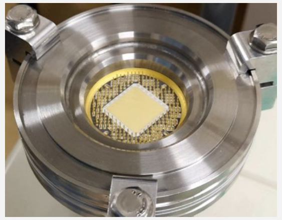
Detector Development Steps

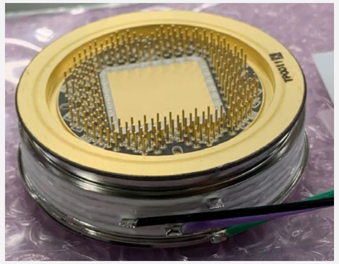
Ceramic carrier board designed by INFN and CERN and produced by Kyocera – first sample **mid 2023**
- Interface between inner/outer parts
- **Custom Pin Grid Array** (PGA) for I/O signals



Characterization of Timepix4 ceramic assemblies at HPK with test setup build by INFN
October 2023

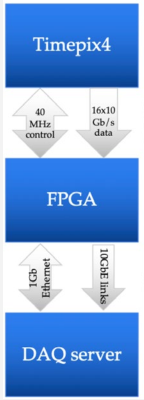
Vacuum tube production at HPK
- Multi-alkali S20 photocathode
  - Peak QE >30% at 380 nm
- Microchannel plates
  - **6 µm** channel diameter (7.5 µm pitch)
  - 50 mm diameter
  - L/D = 50, typical open area ratio 60%
- Several variants for complete characterization
  - **2-MCP** stack and **3-MCP** stack
  - 1d - 2d - 3d end-spoiling

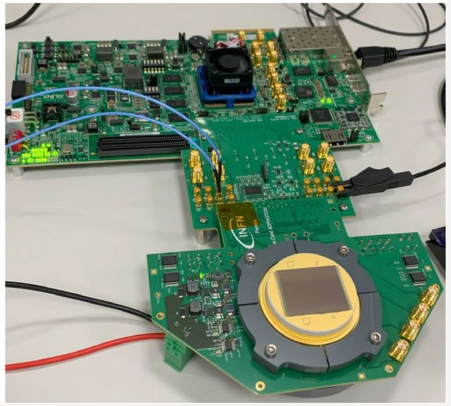
Jan-Feb 2024



Shipping of **tubes from HPK to INFN** for **complete characterization**

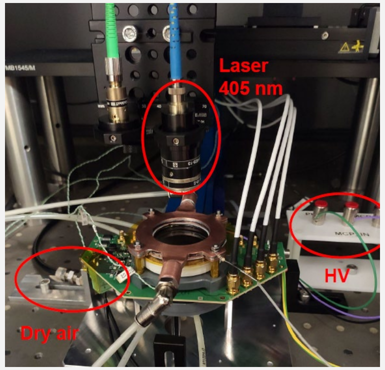
Complete **electronics and DAQ system developed at INFN** (**IDAQ**)
- Based on commercial development kit AMD/Xilinx KCU105
- Use **standard protocols** (UDP-IP over 1/10G eth)
- Multi-board synchronization
- **Open firmware**
- Adapter card for **compatibility with existing hardware**





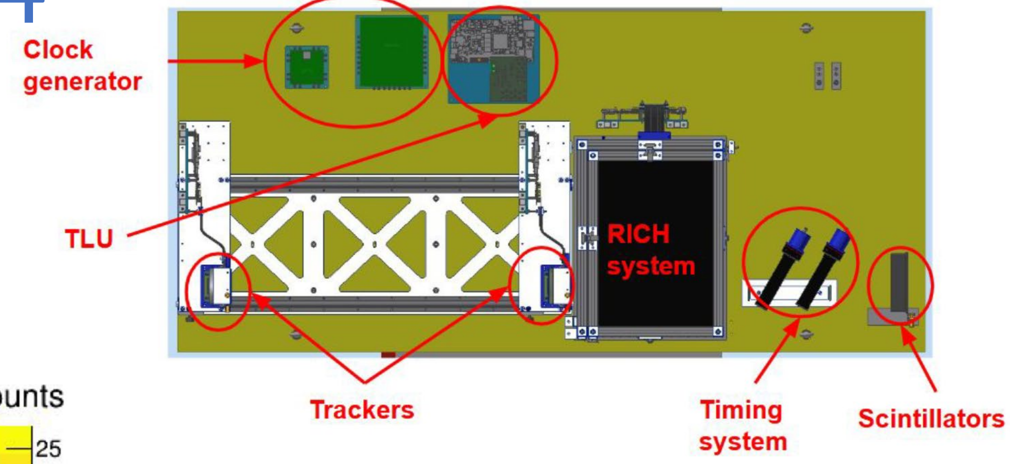
DataPix4: a **C++ framework** for Timepix4 configuration, data read-out, online visualization and analysis (developed at INFN)
- Preprint available

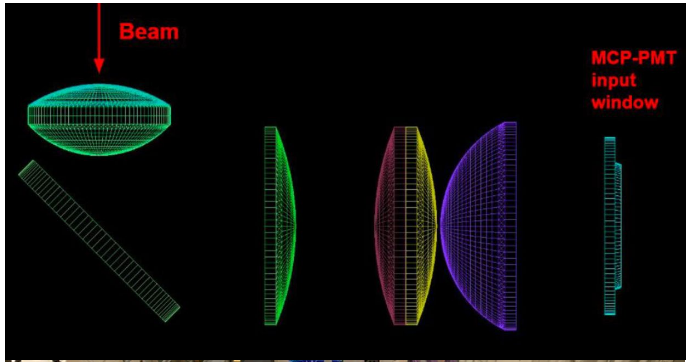
MCP-PMT characterization measurements
- Liquid cooling system to maintain stable temperature inside the tube
- Laser 405 nm
- Dry air fluxed in the dark box to decrease the internal dew point

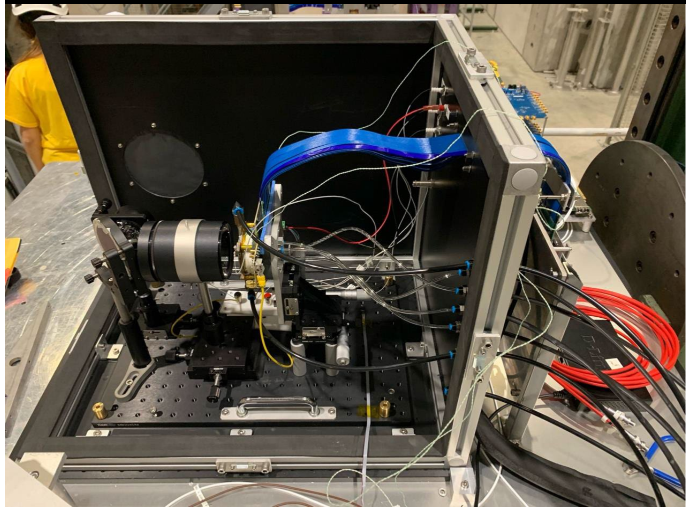


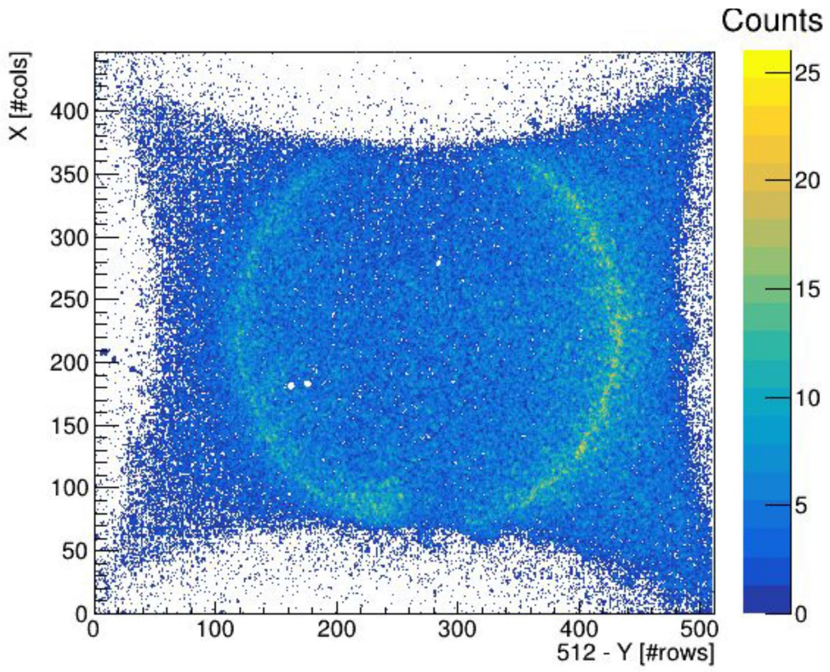
Test-beam in H8 - October 2024

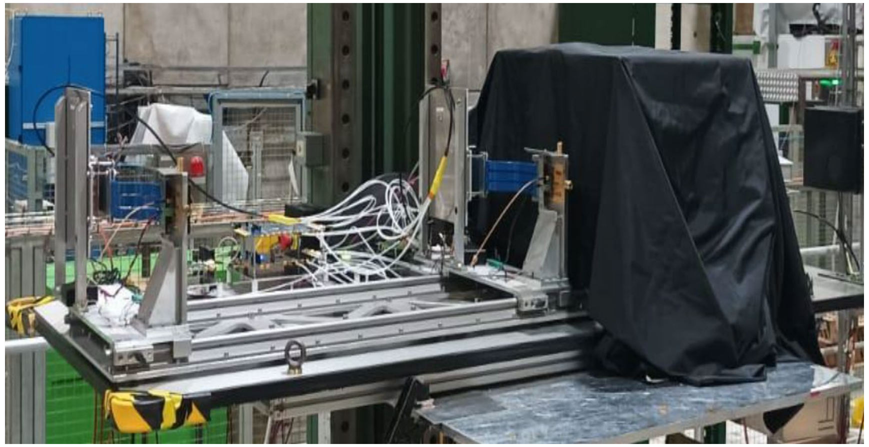
- **Tracking system** (2 Timepix4 b.b. to 300 µm thick p-on-n Si)
- RICH: **solid Cherenkov radiator and optics** setup focus ring on single tube
- **Timing system**: 2 Cherenkov detectors to provide timing reference (read-out by PicoTDC) + 2 scintillators for **beam alignment**
- **Custom Trigger Logic Unit** (TLU) to use the same spill extraction signal as shutter signal on the 3 Timepix4 + Common external reference clock











- **Cherenkov rings observed at different HV settings on the tube**
- **Track correlation between the tracking system and the tube**
- Detailed analysis ongoing

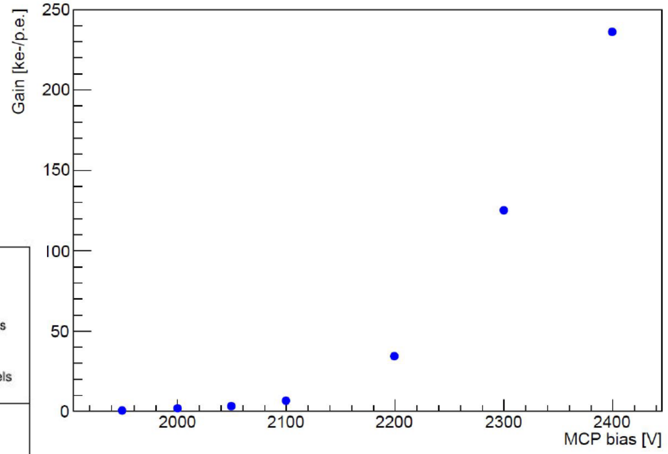
Outlook

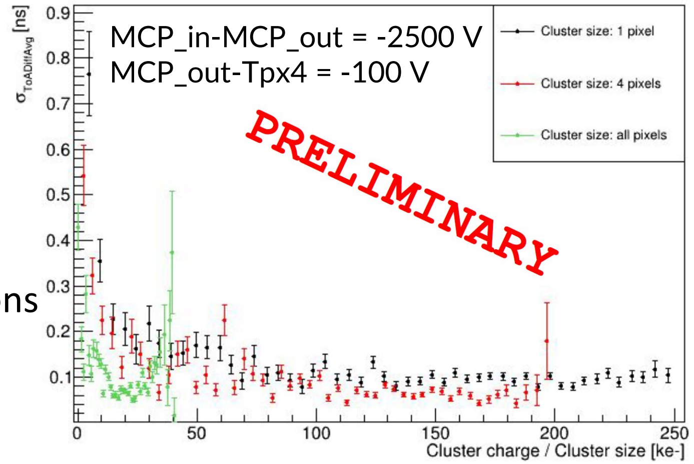
A **novel single-photon detector** has been designed, produced and tested

- Vacuum tube with MCP and Timepix4 CMOS ASIC as anode
- Complete integration of sensor and electronics
- Produced by Hamamatsu Photonics

Preliminary measurements on first prototypes

- **Gain and average DCR** ($\sim 20\ Hz/cm^2$) **as expected**
- **Non-uniform DCR** distribution under study
- Timing resolution dominated by TDC and reference signal contributions
- Best result so far: 65 ps r.m.s. for single photons
- Position resolution <55 µm (precise measurements ongoing)





Next steps and future plans

- **Complete prototypes characterization**
- **Production of final detectors**
- **Future improvements** for use in HEP harsh environments
  1. **Radiation hardness**
     - Use rad-hard-by-design ASIC (plus rad-hard serializers)
  2. **High-rate capability and detector lifetime**
     - Improve current MCP technology
  3. **Timing resolution**
     - Use ASIC with smaller TDC bin size and lower front-end jitter (e.g. LA-Picopix, rad-hard, 30-40 ps bin size, low jitter, high rate)