# MONOLITH - **Picosecond** Time Stamping in Fully Monolithic Highly-granular Pixel Sensor


UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique nucléaire et corpusculaire

European Research Council
Established by the European Commission

Matteo Milanesio on behalf of the MONOLITH team

University of Geneva


Joint Annual Meeting of SPS and ÖPG, 4 - 8 September 2023 in Basel

# The MONOLITH ERC Project

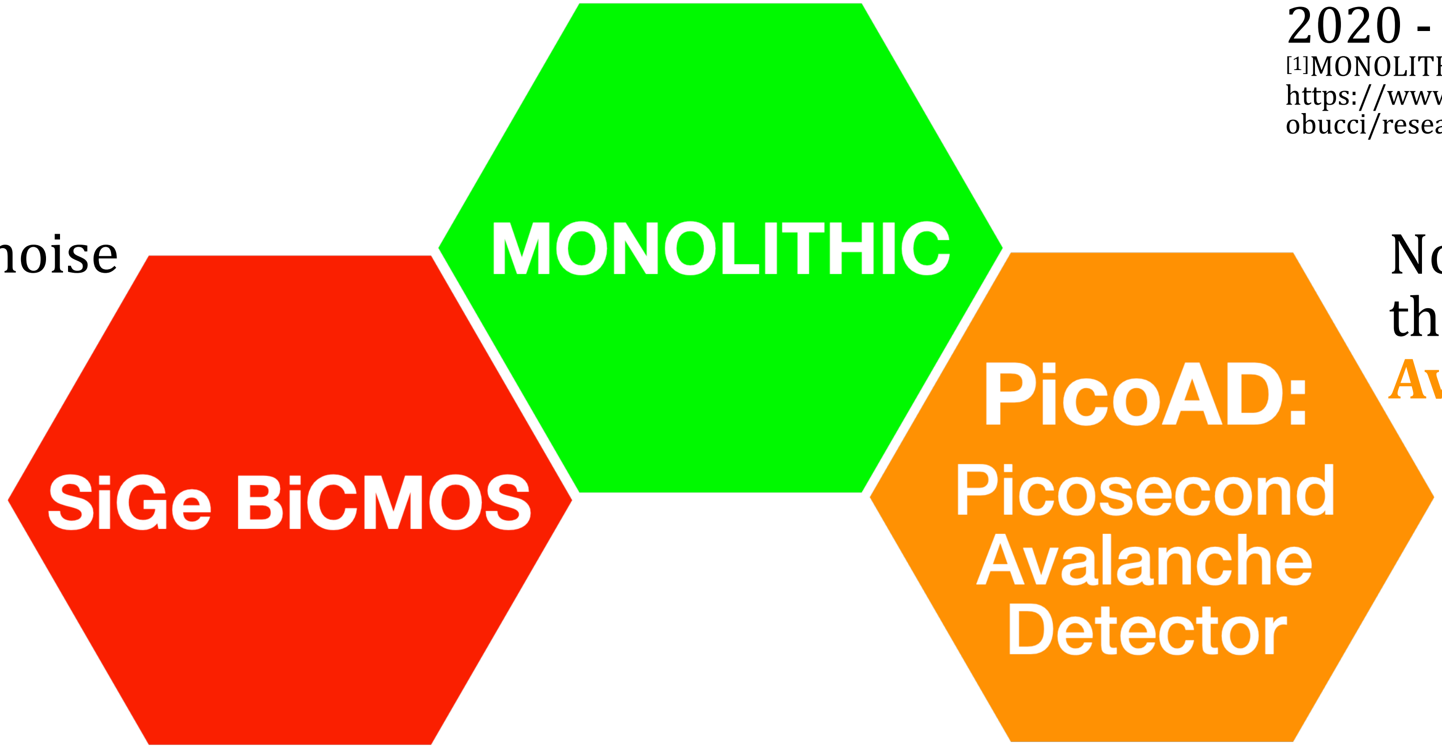
**Monolithic silicon sensor** able to:

- measure precisely the 3D spatial position of charged particles
- provide picosecond time resolution

Funded by the H2020 ERC Advanced grant 884447[1], July 2020 - June 2025

[1]MONOLITH H2020 ERC Advanced Project Web Page - https://www.unige.ch/dpnc/en/groups/giuseppe-iacobucci/research/monolith-erc-advanced-project/

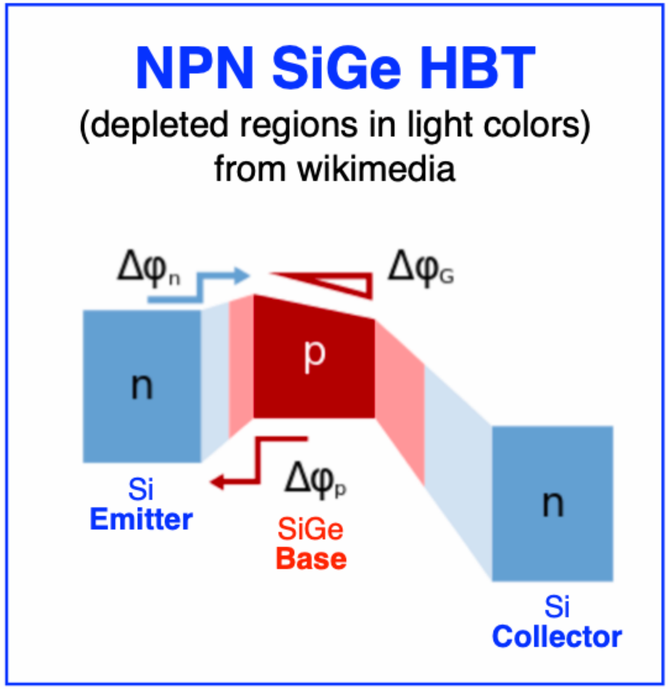
Fast and low-noise **SiGe BiCMOS** electronics




Novel sensor concept, the **Picosecond Avalanche Detector©**

# SiGe BiCMOS Technology

- SiGe HBT = BJT with Germanium as base material:
  - higher doping in base possible
  - thinner base
  - **reduced base resistance $R_b$**
- Grading of Ge doping in base:
  - charge transport in base via drift
  - reduced charge transit time in base
  - **high current gain $\beta$**



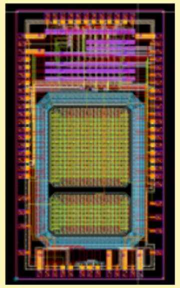

$$ENC_{series\ noise} \propto \sqrt{k_1 \frac{C_{tot}^2}{\beta} + k_2 R_b C_{tot}^2} \rightarrow \sigma_{jitter} = \frac{\sigma_V}{\frac{dV}{dt}} \approx ENC * Rise\ Time$$

Leading-edge **IHP SG13G2** technology**: 130 nm** process featuring **SiGe HBT**

# Monolithic SiGe BiCMOS prototypes

**NO GAIN LAYER**

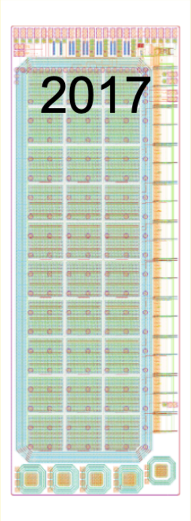
2016



**200 ps**

- 1 $mm^2$ pixel
- Discriminator

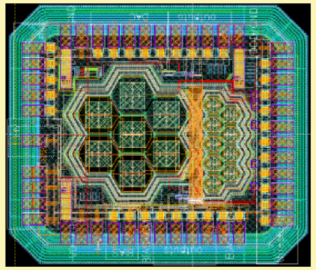
2017



**110 ps**

- 30 pixels 500x500$\mu m^2$
- 100ps TDC +I/O logic

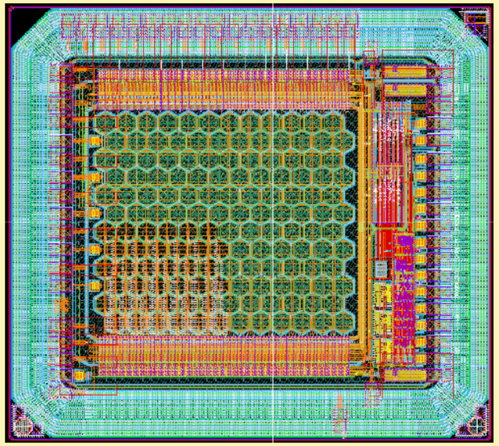
2018



**50 ps**

- Hexagonal pixels 65μm and 130μm side
- Discriminator output

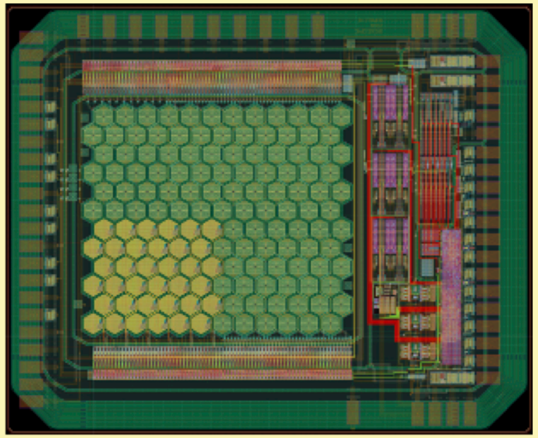
2019



**36 ps**

- Hexagonal pixels 65μm side
- 30ps TDC +I/O logic
- Analog channels

2022



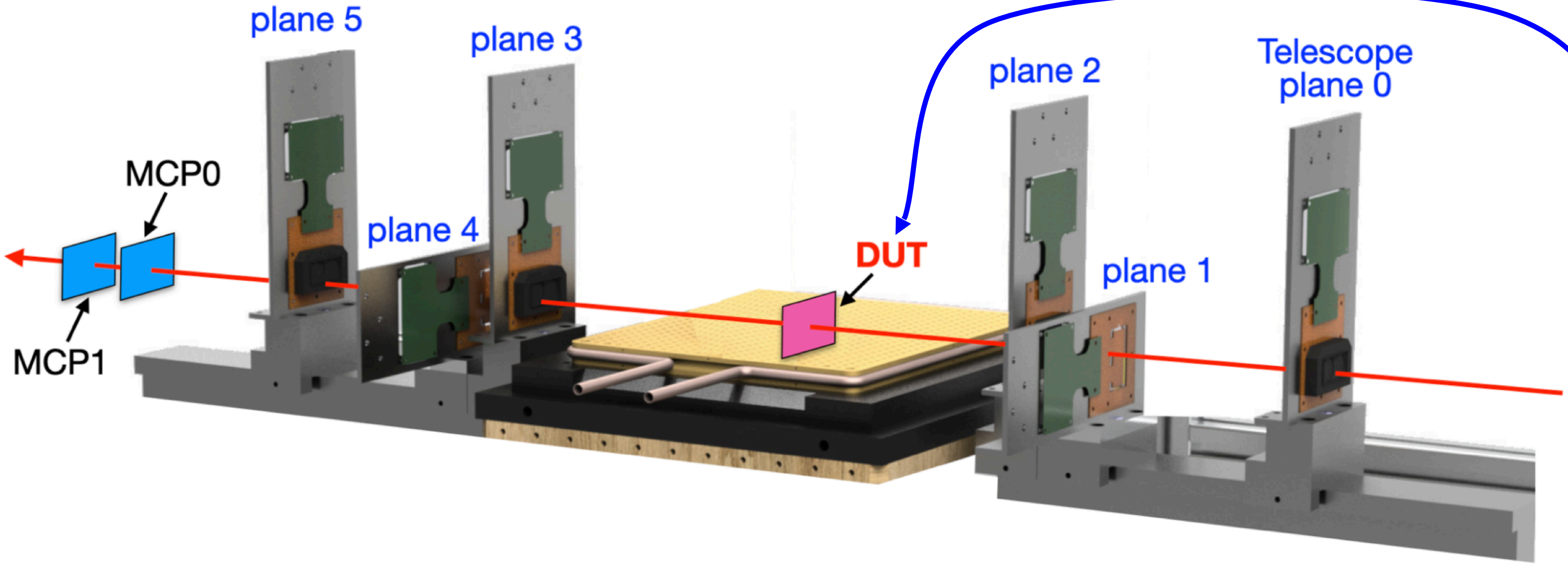
**20 ps**

- Hexagonal pixels 65μm side
- improved electronics
- 50μm epitaxial layer (350Ωcm)

**Design Improvements**

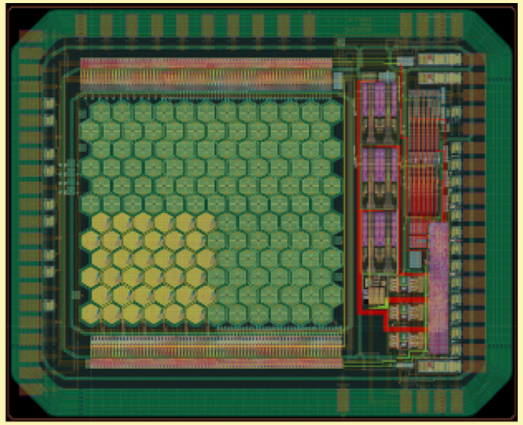
# Test Beam: Experimental Setup

- October 2022: SPS Testbeam with 180 GeV/c pions
- Measure **efficiency** and **time resolution**




**NO GAIN LAYER**

2022



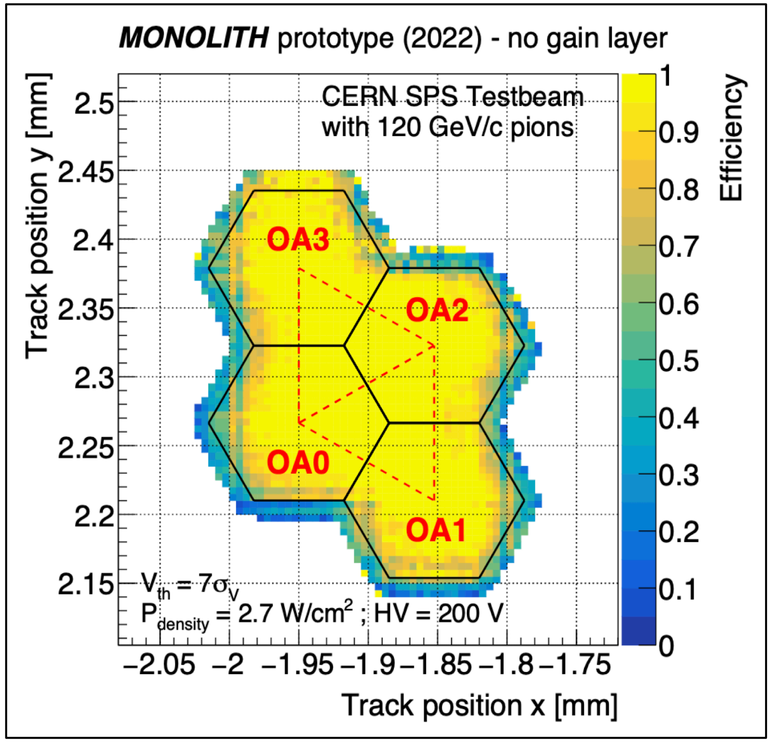
**20 ps**

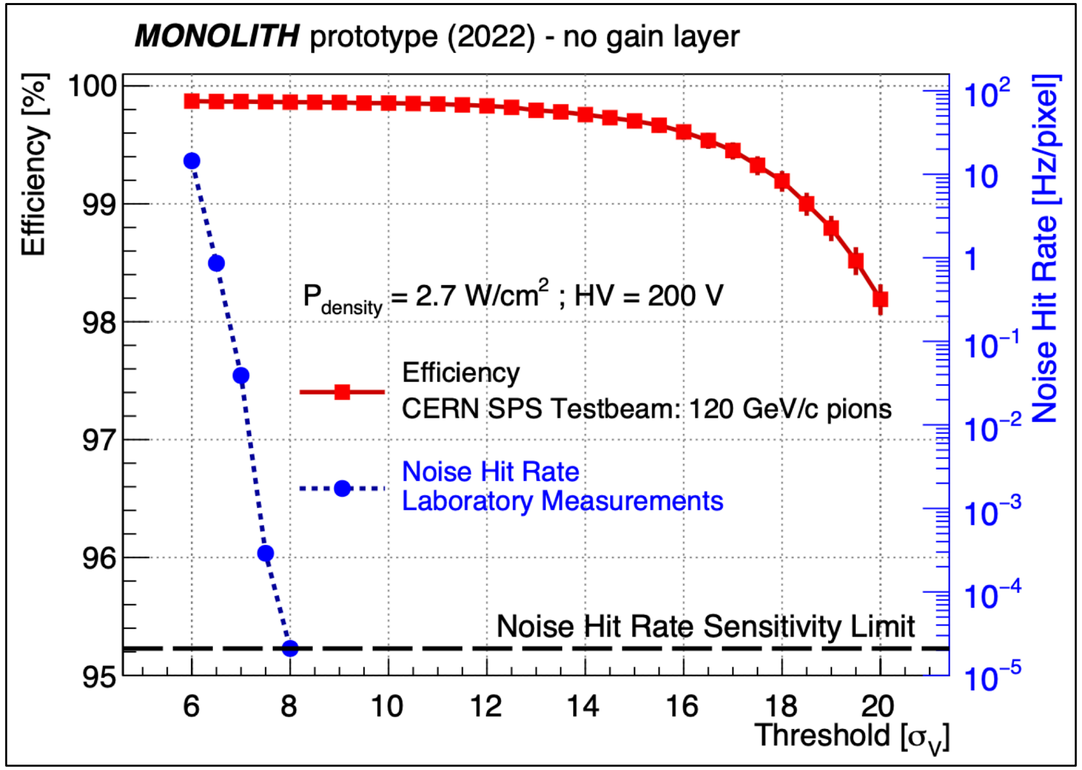
- Hexagonal pixels 65µm side
- improved electronics
- 50µm epitaxial layer (350Ωcm)

- **UNIGE FE-I4 telescope**[2] to provide the spatial information ($\sigma_{x,y}$ ~10 µm)
- **Two MCPs** ($\sigma_t$ ~5 ps) to provide the timing reference

[2]Benoit et al. The FE-I4 telescope for particle tracking in testbeam experiments. JINST, 11 P07003, july 2016

# Efficiency Results



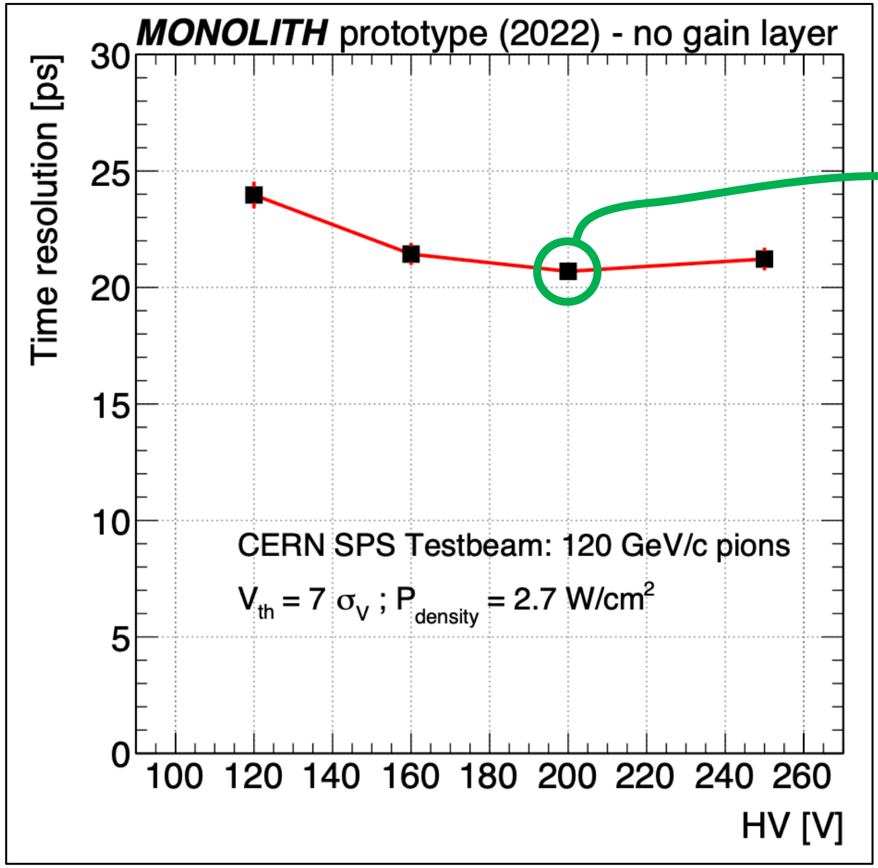



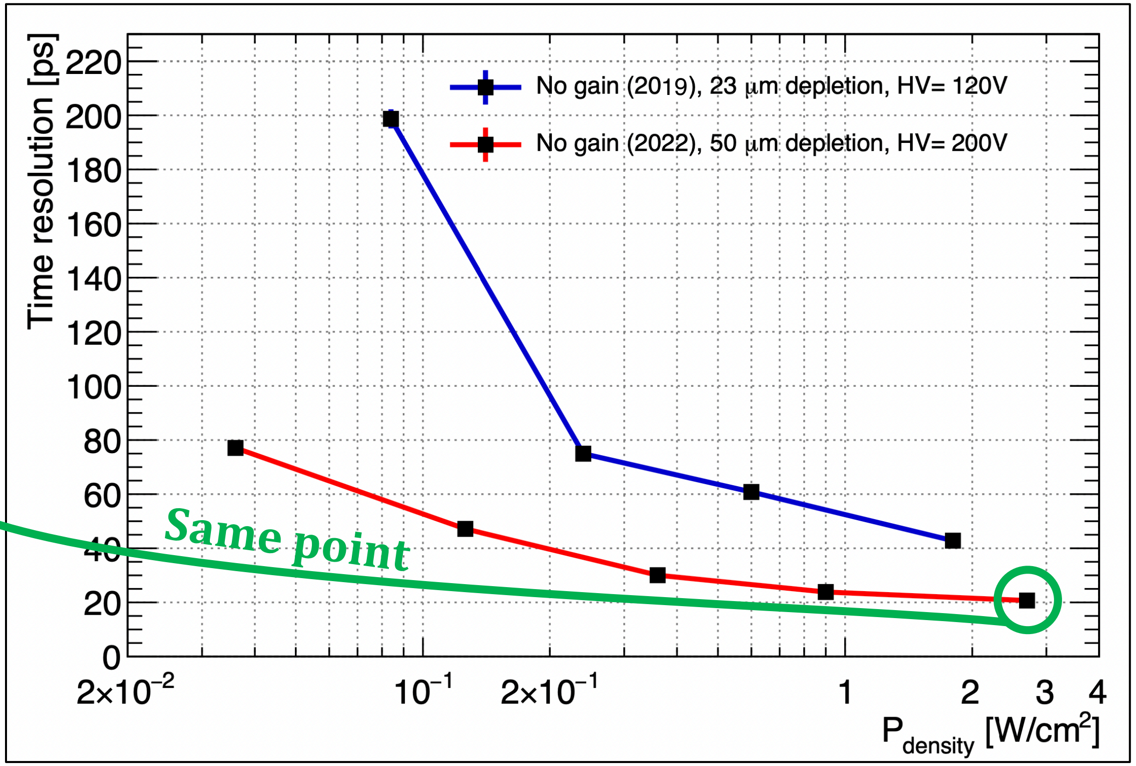

- The **apparent degradation** at the edges is due to the ~10 μm resolution of the telescope
- Selection of two **triangles:**
  - representative of the whole pixel
  - **unbiased** from the telescope resolution

- Large plateau of **99.8% efficiency**
- $\boldsymbol{\sigma_V \approx 1.4\,\mathrm{mV} \approx 100\, e^-}$

# Time Resolution Results






Large plateau of 130 V between 20 and 25 ps

- **20 ps at 2.7 W/cm² | 50 ps at 0.1 W/cm²**
- More than a factor 2 improvement w.r.t. the **previous prototype**

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# Monolithic SiGe BiCMOS prototypes

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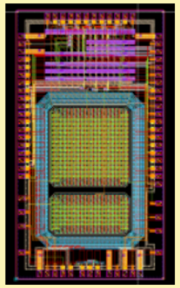
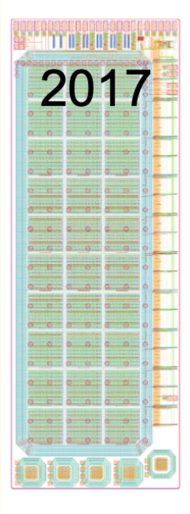
## NO GAIN LAYER

**2016**



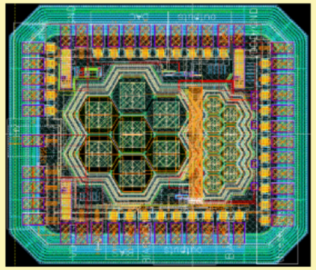
**200 ps**
- 1 mm² pixel
- Discriminator

**2017**



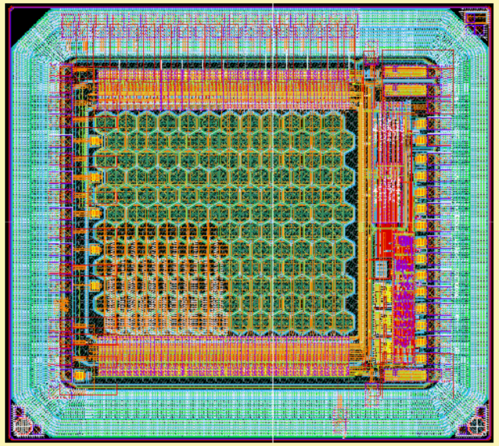
**110 ps**
- 30 pixels 500x500μm²
- 100ps TDC +I/O logic

**2018**



**50 ps**
- Hexagonal pixels 65μm and 130μm side
- Discriminator output

**2019**



**36 ps**
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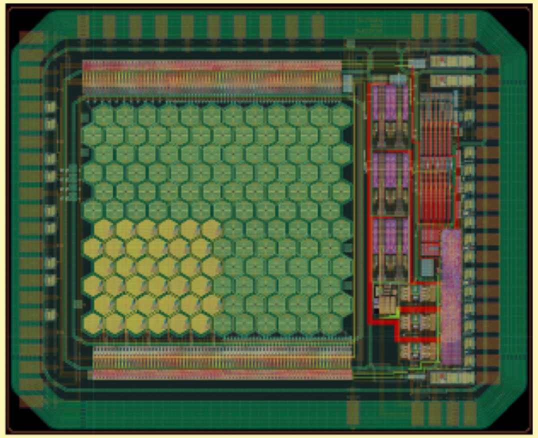
- Analog channels

**2022**



**20 ps**
- Hexagonal pixels 65μm side
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2022
**PicoAD© version**
**17 ps**

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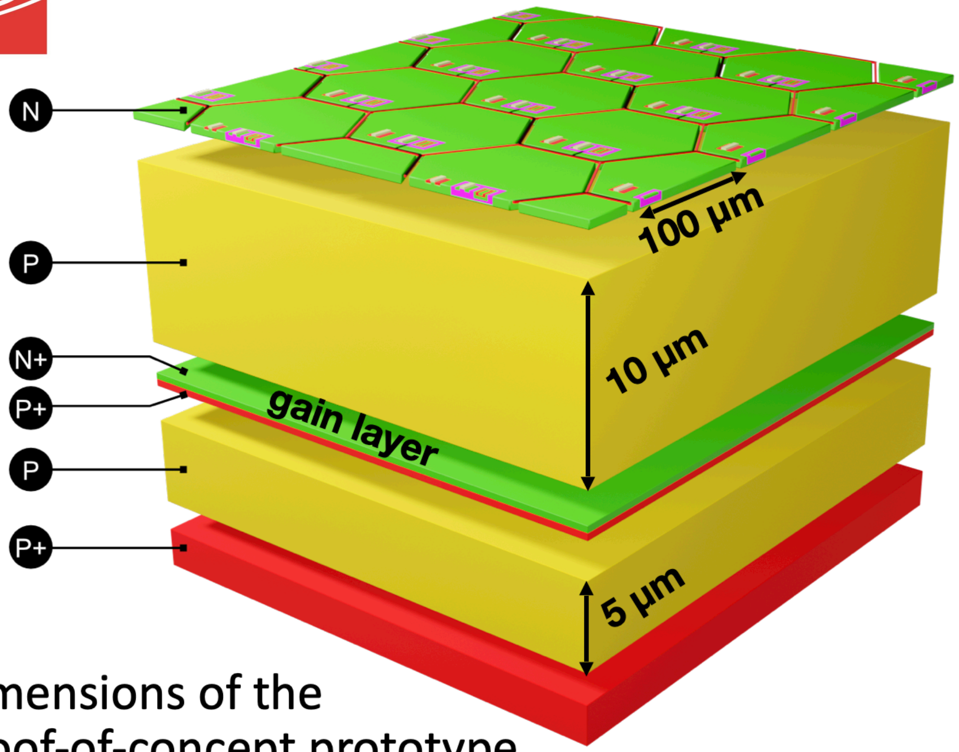
# PicoAD© Prototype

European Research Council
Established by the European Commission

- Multi-Junction **Pico-Avalanche Detector**[4]
- 2019 ASIC with the **PicoAD© concept**
- Continuous and deep gain layer
  - de-correlation from implant size/geometry -> high **pixel granularity** possible (enhance spatial resolution)
  - only small fraction of charge gets amplified -> **reduced charge collection noise** (enhance timing resolution)



Dimensions of the proof-of-concept prototype

[4]G. Iacobucci, L. Paolozzi and P. Valerio. Multi-junction pico-avalanche detector. European Patent EP3654376A1, US Patent US2021280734A1, Nov 2018

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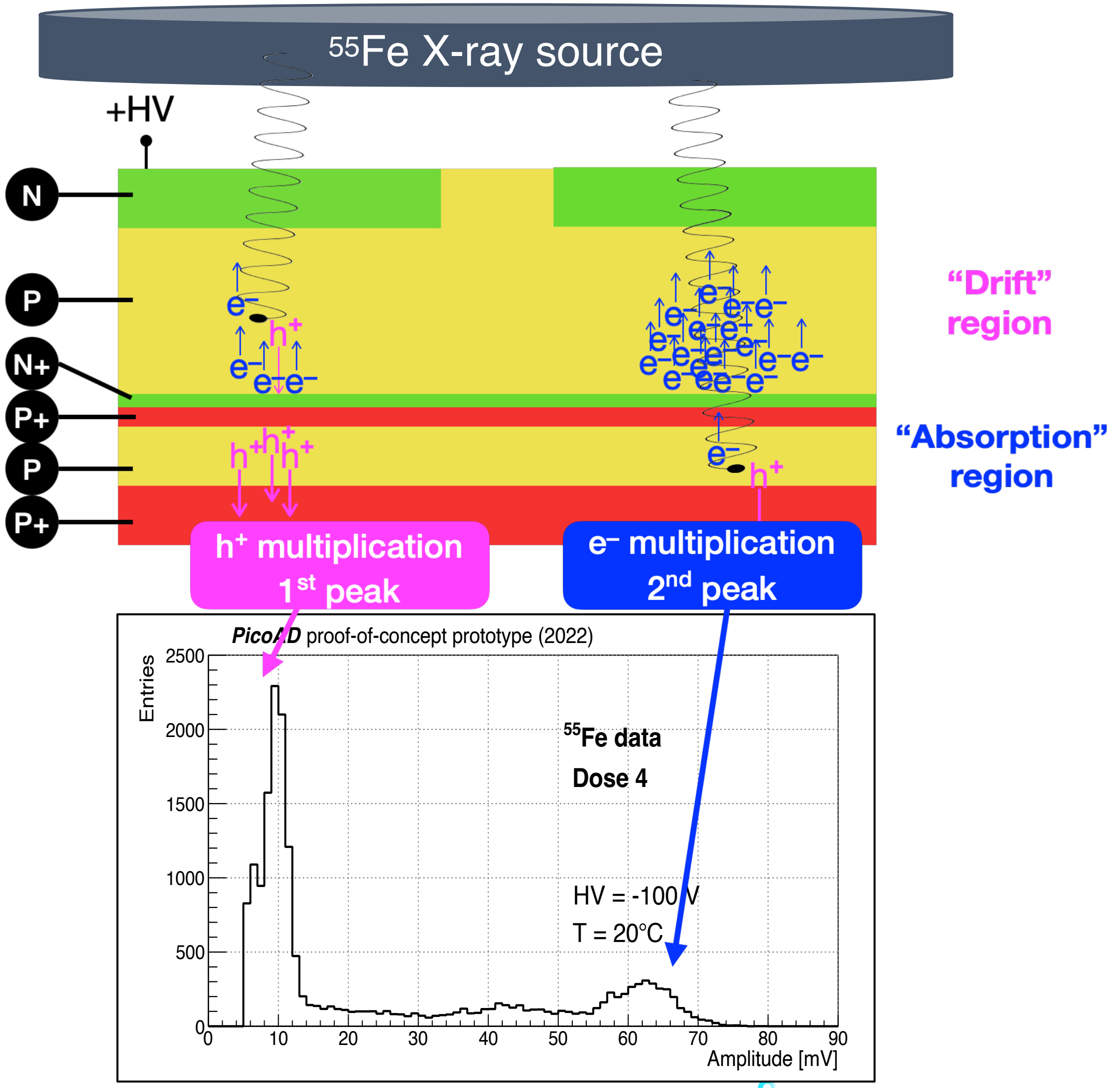
# Gain Measurements

European Research Council
Established by the European Commission

- **X-rays from $^{55}$Fe radioactive source**[5][6]:
  - mainly ~5.9 keV photons
  - point-like charge deposition
- **Characteristic double-peak spectrum**
  - photon absorbed in **drift region**
    - **holes** drift through gain layer and multiplied
    - **first peak** in the spectrum
  - photon absorbed in **absorption region**
    - **electrons** drift through gain layer and multiplied
    - **second peak** in the spectrum
- **Gain up to ≈ 20 for $^{55}$Fe X-rays** obtained with HV = -125 V and T = -20 °C

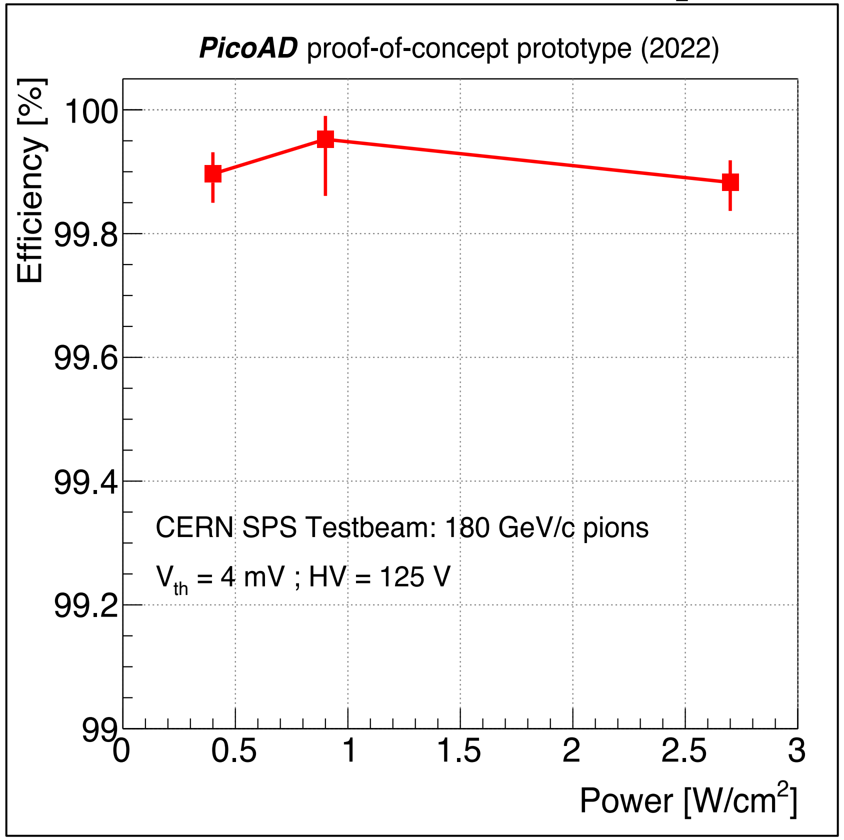


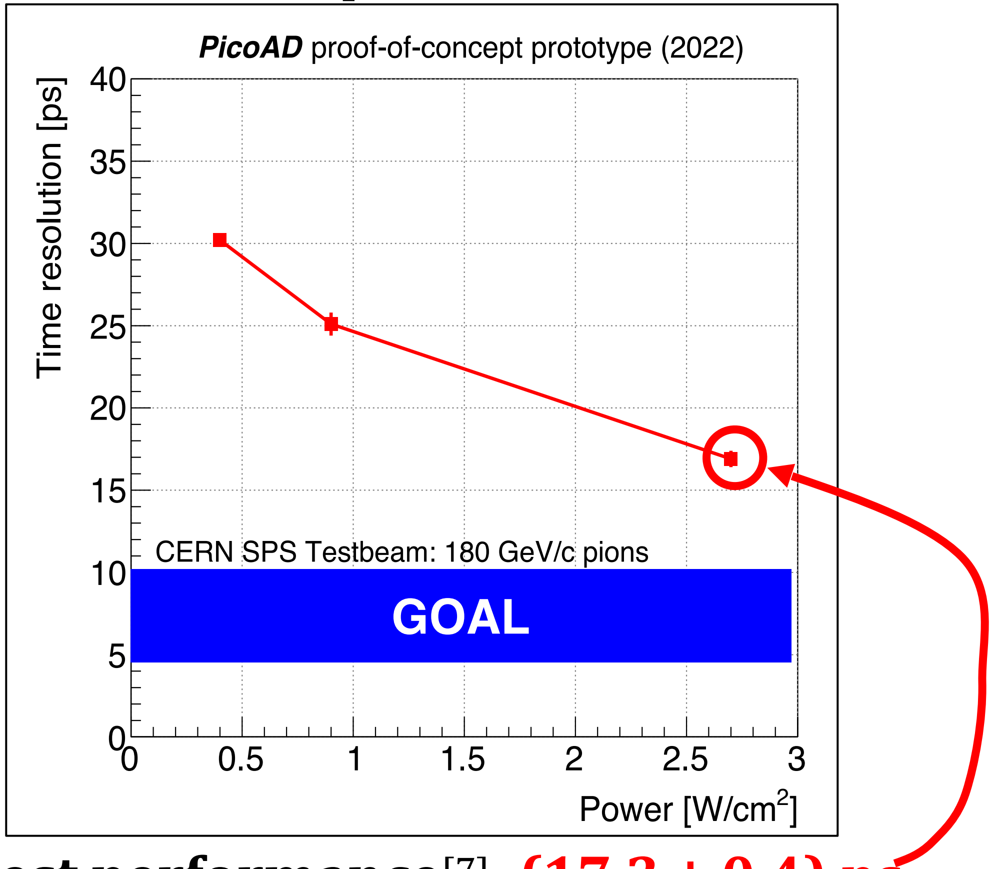

[5]M. Milanesio et al, Gain measurements of the first proof-of-concept PicoAD prototype with a $^{55}$Fe X-ray radioactive source, 2022 doi.org/10.1016/j.nima.2022.167807

[6]L. Paolozzi et al, Picosecond Avalanche Detector - working principle and gain measurement with a proof-of-concept prototype, 2022 JINST 17 P10032

# Efficiency and Time Resolution

Similar experimental setup with FE-I4 telescope




**99.9%** for all the power consumptions

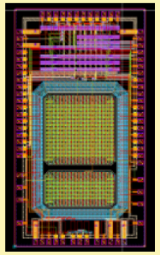
**Best performance**[7]: **(17.3 ± 0.4) ps**
HV = 125 V and Power = **2.7 W/cm²**

[7] G. Iacobucci et al, Testbeam results of the Picosecond Avalanche Detector proof-of-concept prototype, 2022 JINST 17 P10040

# Future prototypes

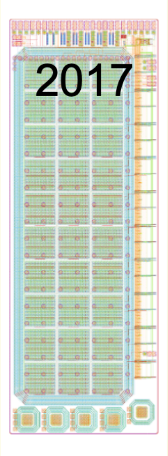
## NO GAIN LAYER

2016



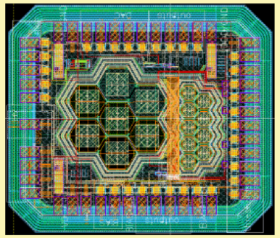
**200 ps**
- 1 $mm^2$ pixel
- Discriminator

2017



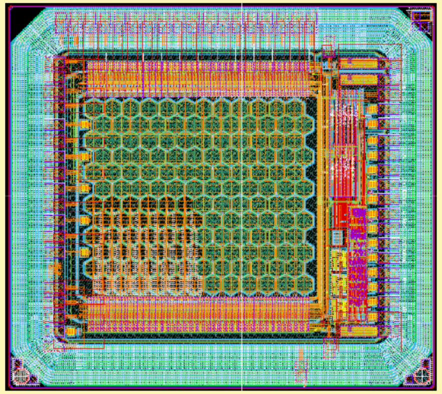
**110 ps**
- 30 pixels 500x500$\mu m^2$
- 100ps TDC +I/O logic

2018



**50 ps**
- Hexagonal pixels 65µm and 130µm side
- Discriminator output

2019



**36 ps**
- Hexagonal pixels 65µm side
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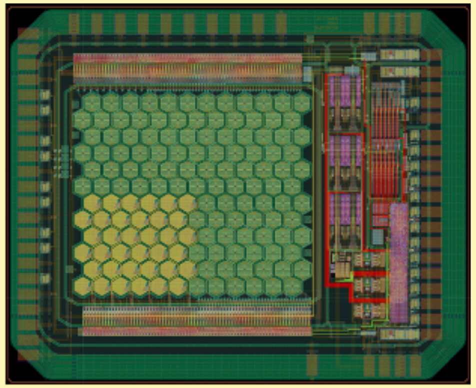
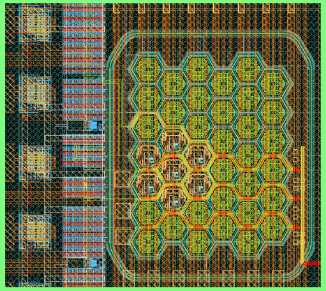
2022



**20 ps**
- Hexagonal pixels 65µm side
- improved electronics
- 50µm epitaxial layer (350Ωcm)

**March 2023**



**< 20 ps ?**
- Hexagonal pixels **29µm side**
- improved electronics

2022
PicoAD© version
**17 ps**

**October 2023**
PicoAD© version
**< 10 ps ?**

# Summary and Outlook



- **Testbeam of 2022 prototype ASIC, without gain layer,** provided:
  - **Efficiency = 99.8%** and **$\sigma_t$ = (20.7 ± 0.3) ps**

- **The PicoAD© monolithic proof-of-concept prototype works**. The introduction of a deep gain layer improves the performances:
  - **Gain ≈ 20** for $^{55}Fe$ X-rays
  - **Efficiency = 99.9 %** including inter-pixel regions
  - **Time resolution $\sigma_t$ = (17.3 ± 0.4) ps**

- Radiation hardness studies started in 2023 together with KEK and IHP
- Development of picosecond TDC[8] for fully monolithic chip

[8]R. Cardarelli, L. Paolozzi, P. Valerio and G. Iacobucci, European Patent Application / Filing - UGKP-P-001-EP, Europe Patent EP 18181123.3. 2 July 2018.

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# Thanks for your attention

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**Giuseppe Iacobucci**
- project P.I.
- System design

**Thanushan Kugathasan**
- Lead chip design
- Analog electronics

**Roberto Cardella**
- Analog electronics
- Digital electronics

**Matteo Milanesio**
- Laboratory test
- Data analysis

**Antonio Picardi**
- Chip design
- Firmware

**Jihad Saidi**
- Laboratory test
- Data analysis

**Carlo Alberto Fenoglio**
- Chip design
- Firmware

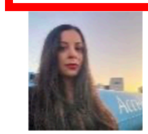
**Lorenzo Paolozzi**
- Sensor design
- Analog electronics

**Mateus Vicente**
- System integration
- Laboratory test

**Stefano Zambito**
- Laboratory test
- Data analysis

**Théo Moretti**
- Laboratory test
- Data analysis

**Chiara Magliocca**
- Laboratory test
- Data analysis



**Rafaella Kotitsa**
- Sensor simulation

**Luca Iodice**
- Chip design
- Firmware

ALSO AT THIS MEETING

**Didier Ferrere**
- System integration
- Laboratory test

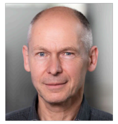
**Sergio Gonzalez-Sevilla**
- System integration
- Laboratory test

**Yannick Favre**
- Board design
- RO system

**Stéphane Débieux**
- Board design
- RO system

## Main research partners:

**Roberto Cardarelli**
INFN Rome2 & UNIGE



**Holger Rücker**
IHP Mikroelektronik

**Marzio Nessi**
CERN & UNIGE

**Matteo Elviretti**
IHP Mikroelektronik

## Funded by:

Swiss National Science Foundation

European Research Council
Established by the European Commission

Sinergia

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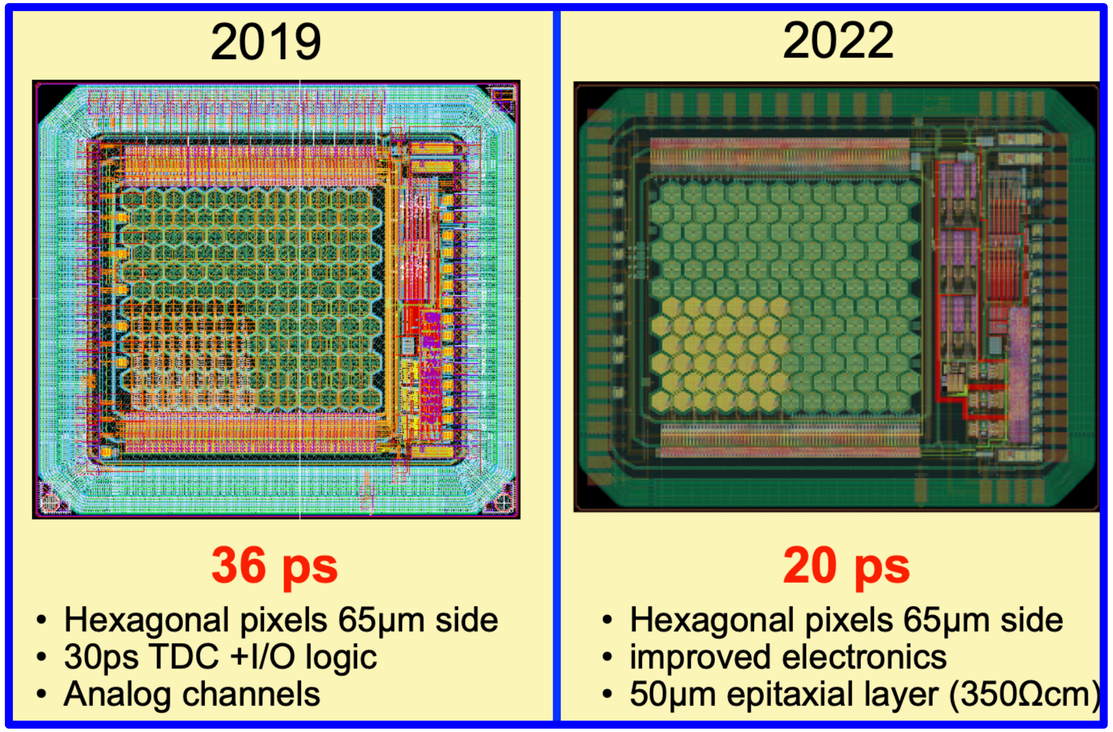
# Backup

# 2019->2022: Improvements

- Same matrix configuration as previous, but
  - Substrate: 50 Ωcm → 350 Ωcm epilayer, 50 µm thick on low-res (1 Ωcm) substrate
    - smaller pixel capacitance
    - depletion 23 µm → 50 µm
    - much larger voltage plateau
    - can operate sensor with $v_{drift}$ saturated everywhere
  - Preamp and driver voltage decoupled:
    - was limiting optimal amplifier operation
    - cross-talk removed
  - Optimised FE layout, "differential" output, high-frequency cables:
    - better rise time (600 ps → 300 ps)



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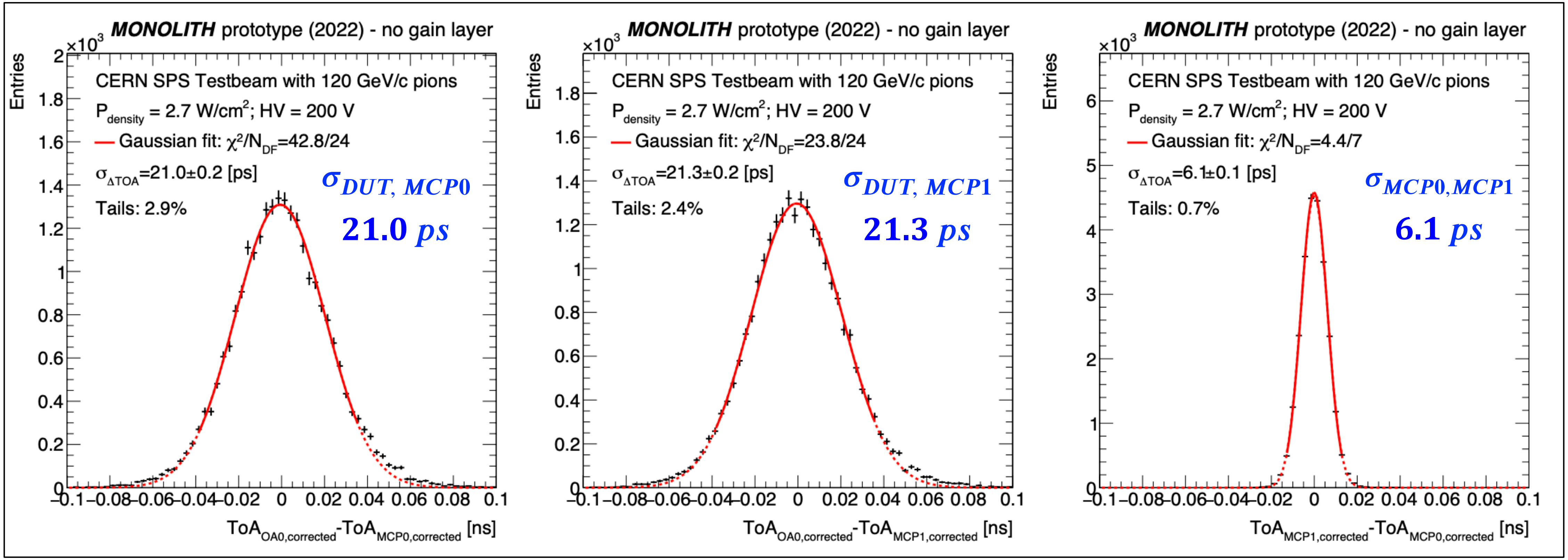
# Time Resolution Distributions




- Very **Gaussian** distributions after time walk correction
- Simultaneous fit to extract the time resolution of **DUT**, **MCP0**, **MCP1**[3]:

**MCP0**: $\sigma_t = (3.6 \pm 1.5)\ ps$

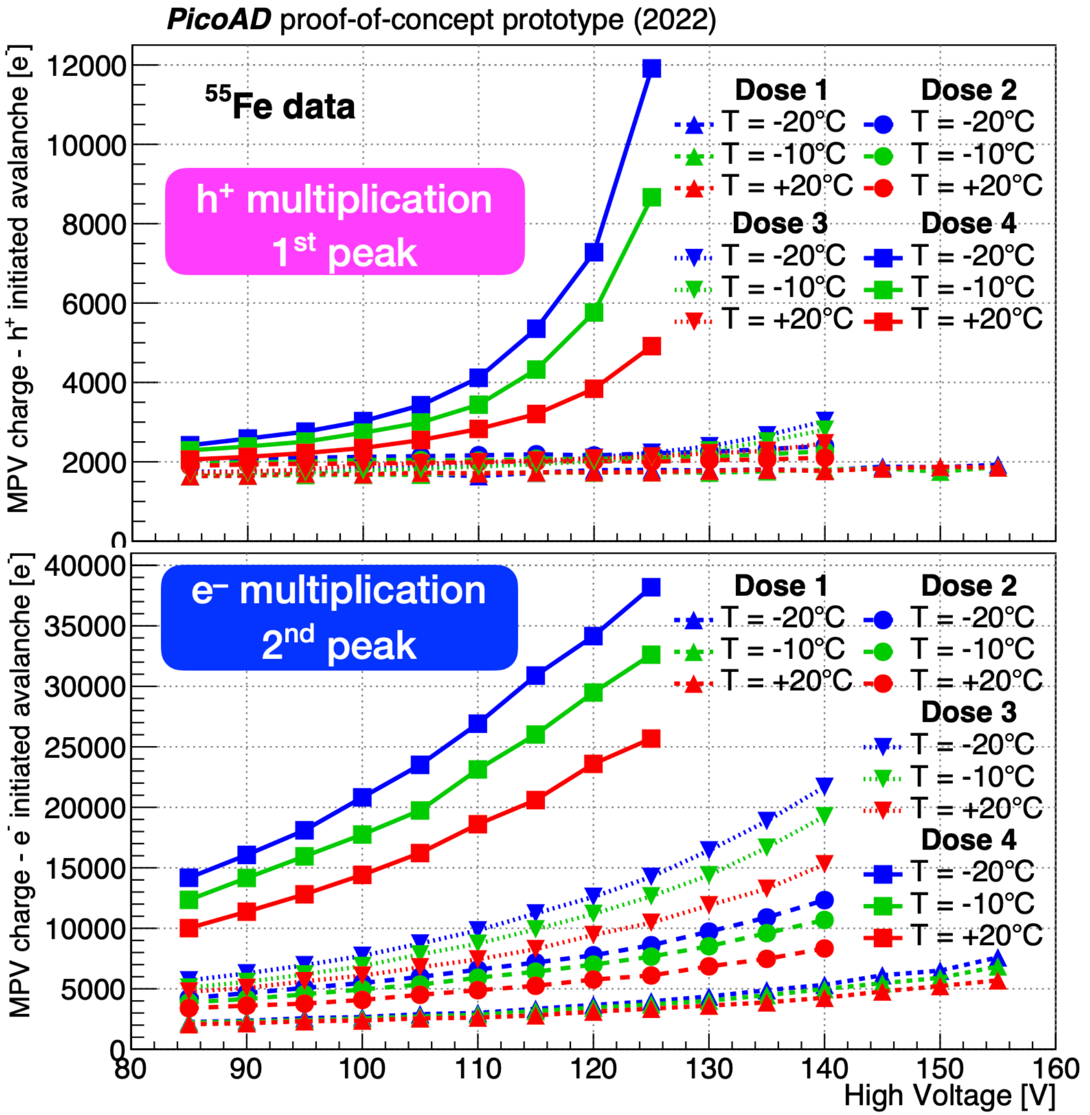
**MCP1**: $\sigma_t = (5.0 \pm 1.1)\ ps$

**DUT:** $\sigma_t = (20.7 \pm 0.3)\ ps$

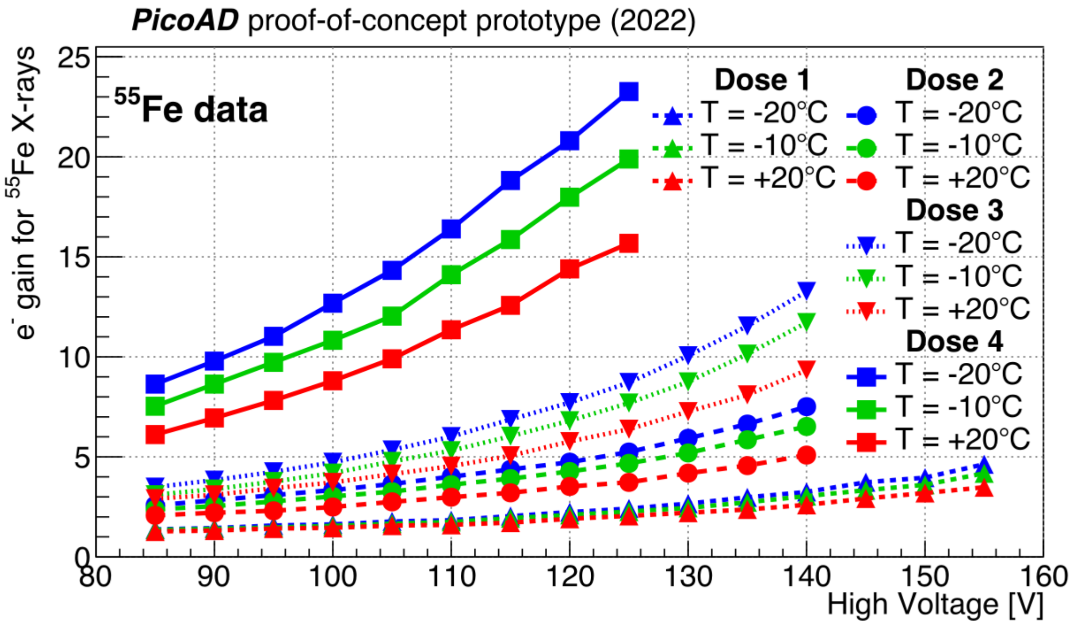
[3]S. Zambito et al. 20 ps Time Resolution with a Fully-Efficient Monolithic Silicon Pixel Detector without Internal Gain Layer. arXiv:2301.12244v1, January 2023

# Gain Results






**Gain up to ≈ 20 for $^{55}$Fe X-rays**
obtained at HV = 125 V and T = -20 °C




- Evidence for **gain suppression** due to space-charge effects **in the case of $^{55}$Fe X-rays**
- We estimated that $^{55}$Fe gain of ≈ 20 corresponds to **gain 60–70 for a MIP**

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# PicoAD: Efficiency Maps

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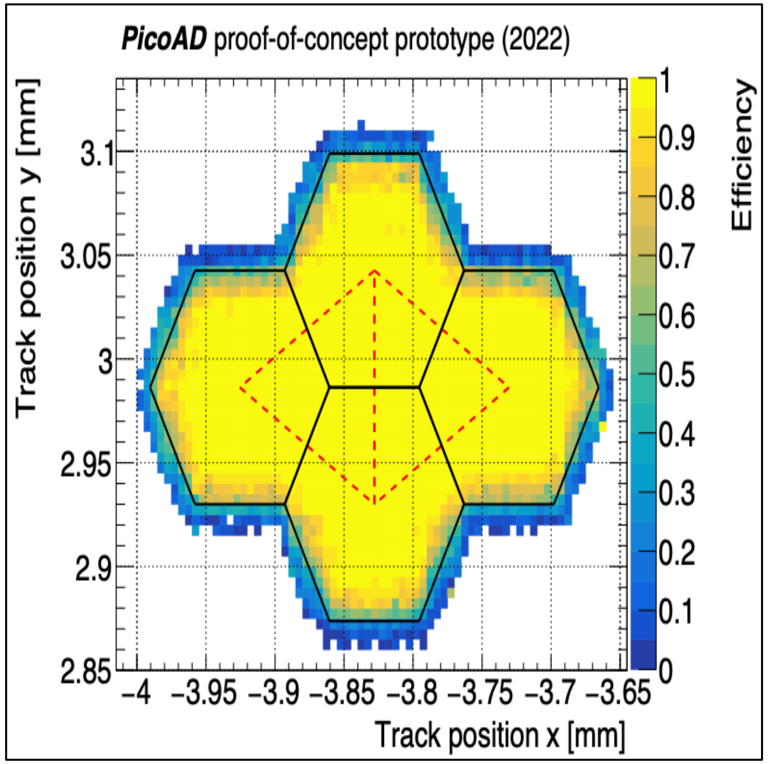
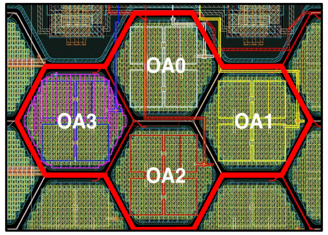
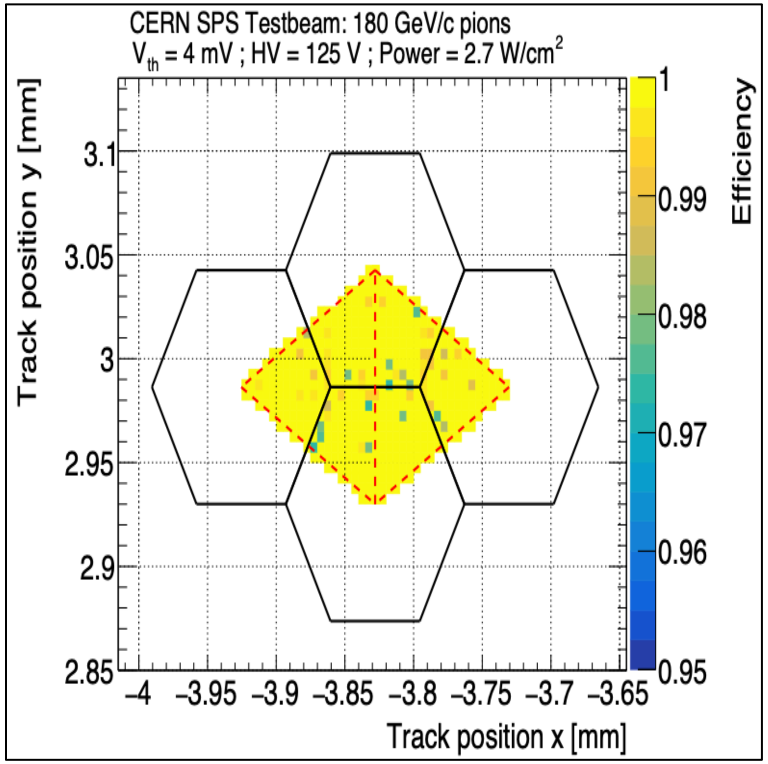


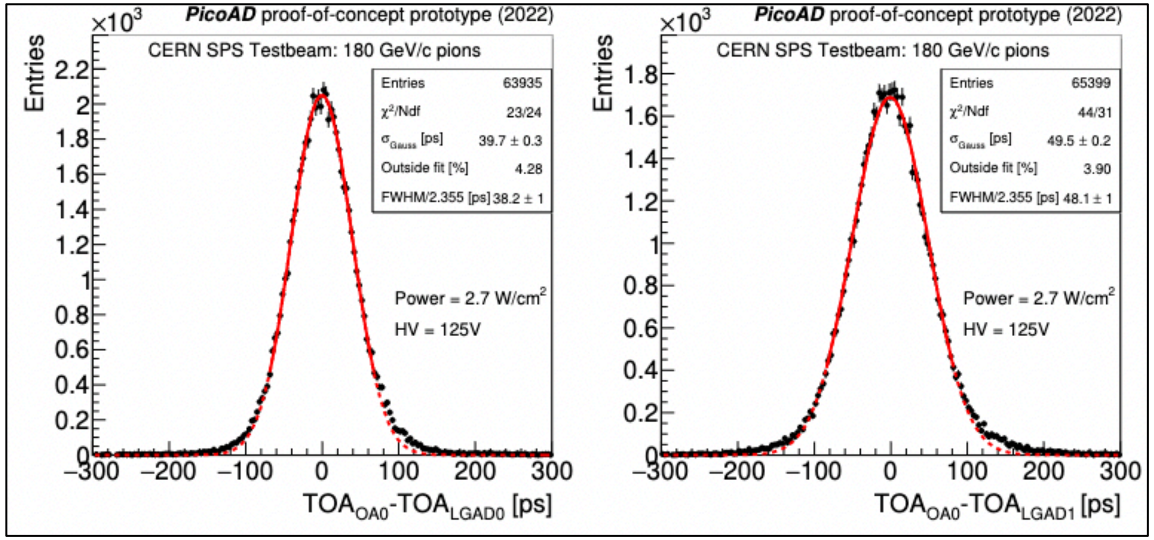



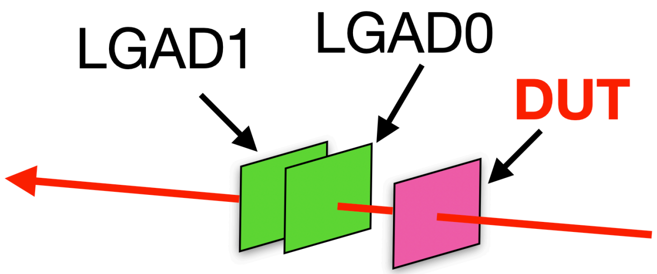

- The **apparent degradation** at the edges is due to the finite resolution of the telescope (~10 μm)

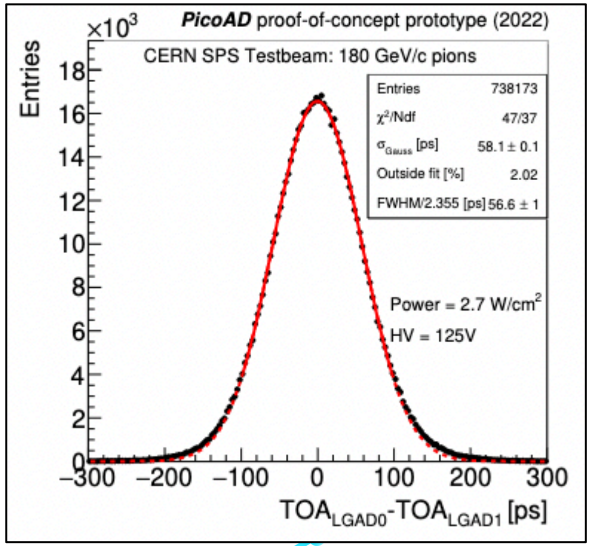
- Selection of two **triangles:**
  - representative of the whole pixel
  - **unbiased** from the telescope resolution

# PicoAD©: Time Resolution Distributions

- Time Of Arrival as a time at a Constant Fraction
- Distributions after time-walk correction
- The distributions are **gaussian**
  - ~2-4 % of the entries are in non-gaussian tails
- The three $\sigma_{Gauss}$ from the fits give the timing resolution of:
  - the DUT
  - the two LGADs

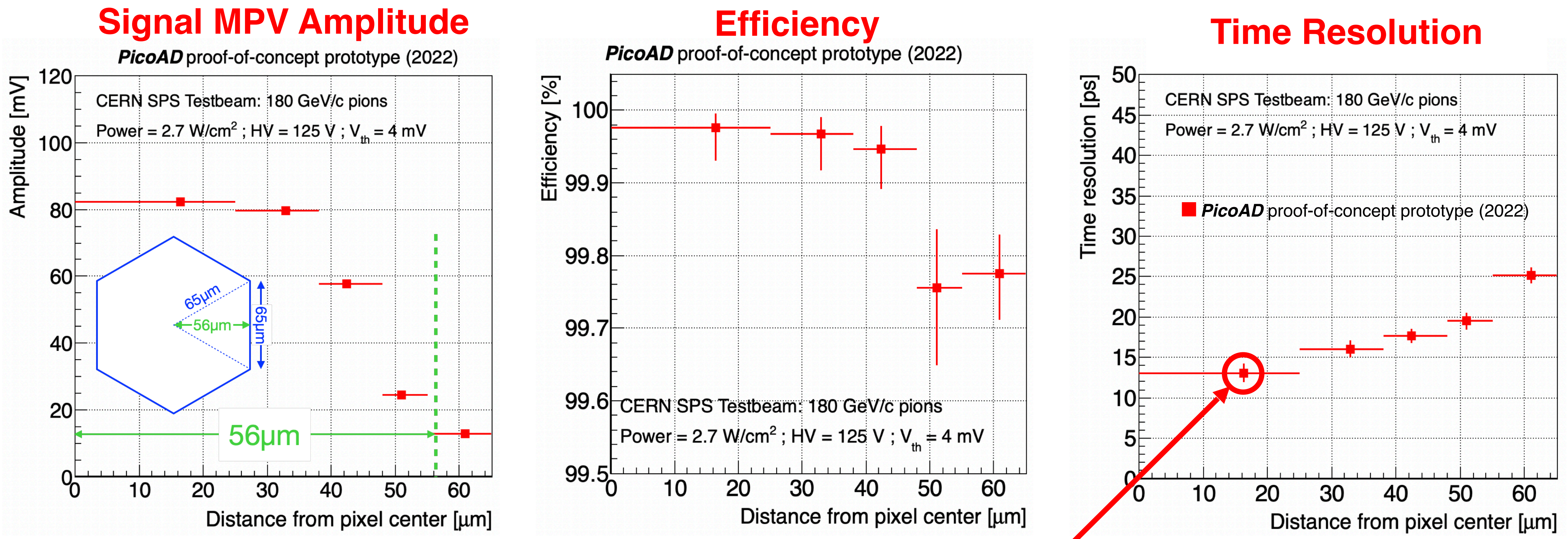


# Position Within the Pixel

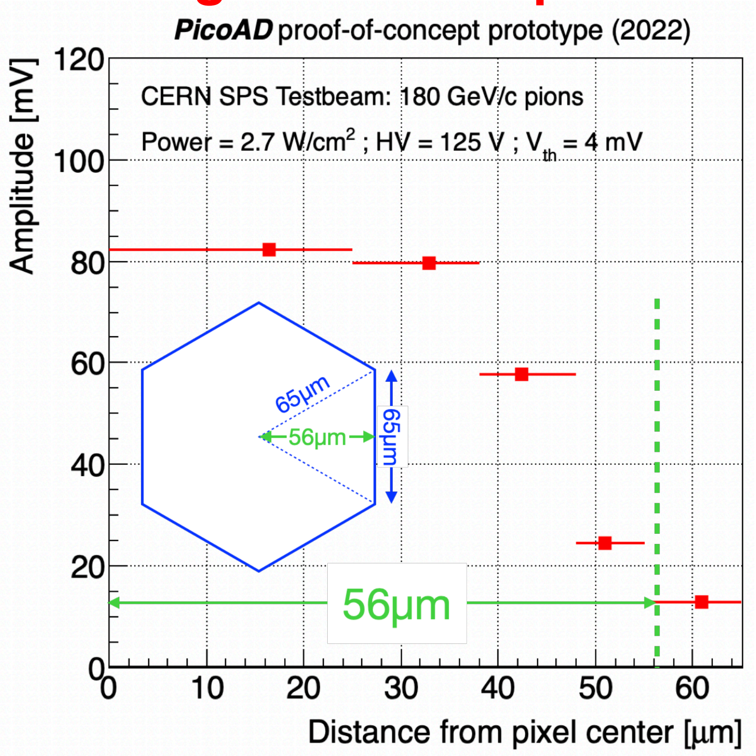




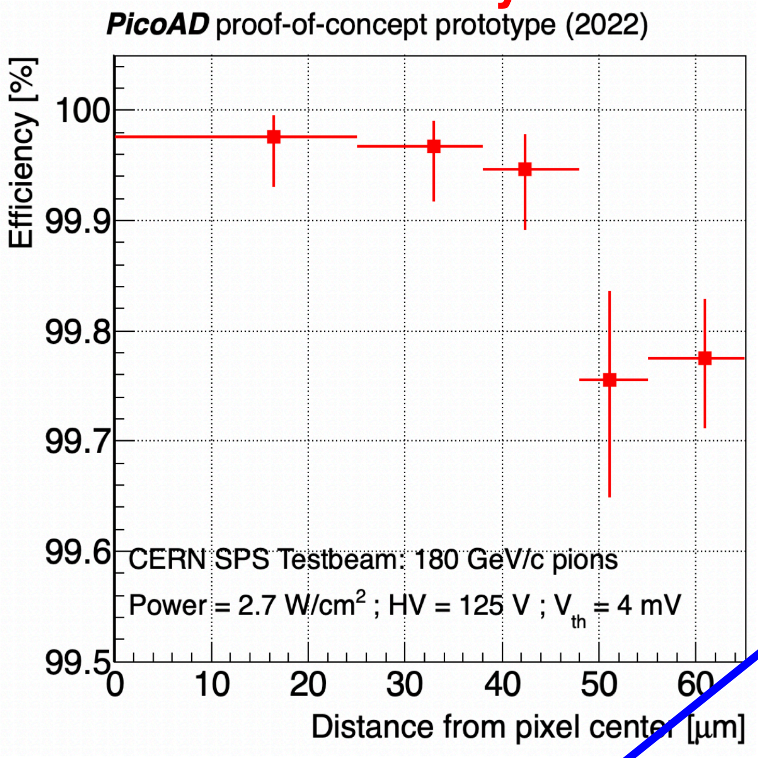

- Best time resolution: $(13.2 \pm 0.8)$ **ps within 25 µm** from the pixel center
- **PicoAD©** proof-of-concept: small degradation of the performance towards the edge of the pixel

# Position Within the Pixel

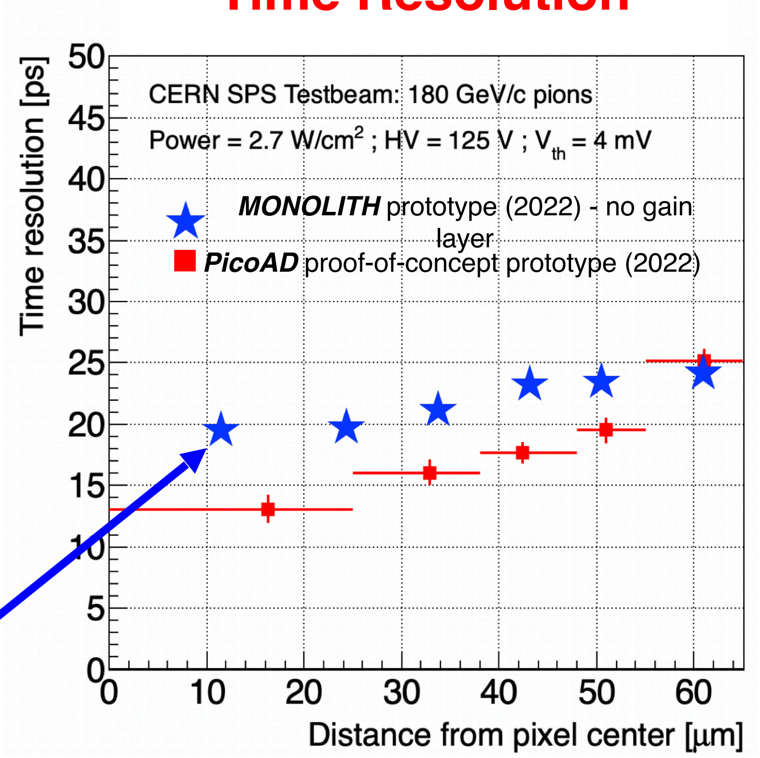
## Signal MPV Amplitude




## Efficiency




## Time Resolution



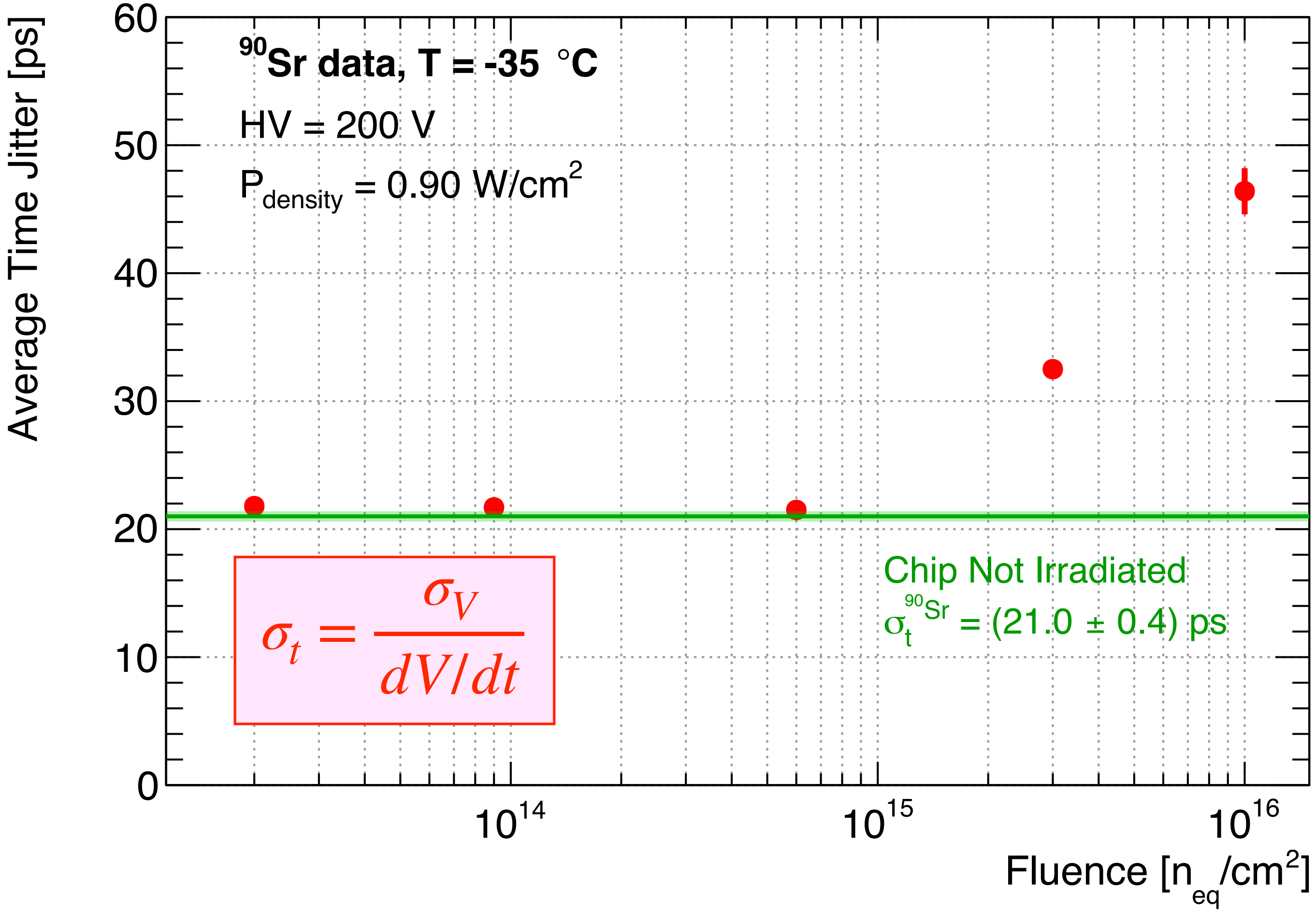

2022 prototype is much **less dependent** on the pixel position

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique nucléaire et corpusculaire

# Radiation Hardness

European Research Council
Established by the European Commission

*MONOLITH* prototype2 (2022) - no gain layer




Excellent news from radiation tolerance studies:

The time jitter with $^{90}$**Sr** increases **from 21ps** (unirradiated) **to 46ps** (at $10^{16}$ $n_{eq}/cm^2$) at **HV = 200V** and **0.9 W/cm²**

Enough parameters ($i_{fbk}$, $V_{CCA}$, HV) for smooth and effective operation even at $10^{16}$ $n_{eq}/cm^2$

# Benefits of Using Hexagonal Pixels



- Three possible regular shapes to use:
  - equilateral triangles
  - squares
  - regular hexagons
- Hexagons have the highest angles (120°) -> **electric fields** in the corners are better **under control**
- Moreover, the same amount of pixels can fits in less space than squares