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

European Research Council
Established by the European Commission

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

Matteo Milanesio on behalf of the MONOLITH team

University of Geneva

18th "Trento" Workshop on Advanced Silicon Radiation Detectors

The MONOLITH ERC Project

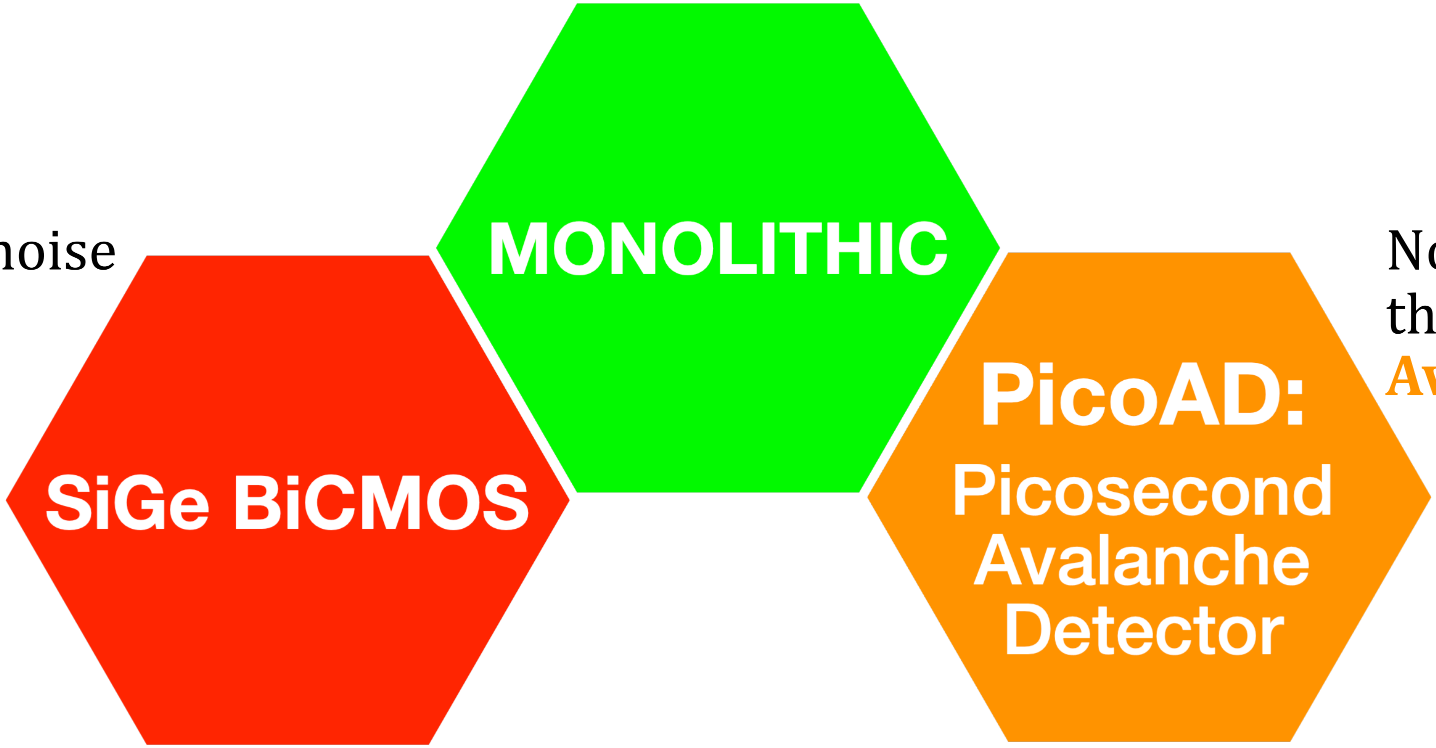
Monolithic silicon sensor able to:

- 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©**

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SiGe BiCMOS Technology

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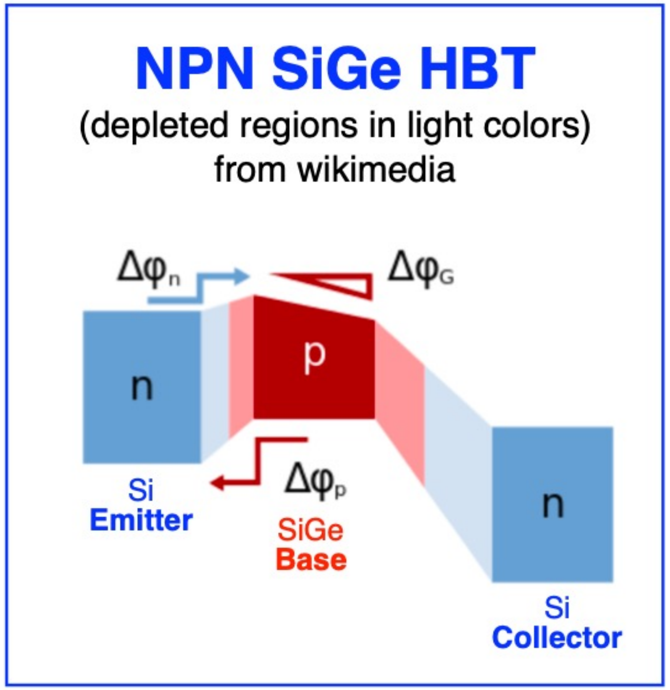
- SiGe HBT = BJT with Germanium as base material:
  - higher doping in base possible
  - thinner base
  - **reduced base resistance R_b**
- Grading of Ge doping in base:
  - charge transport in base via drift
  - reduced charge transit time in base
  - **high current gain β**



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

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

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Monolithic SiGe BiCMOS prototypes

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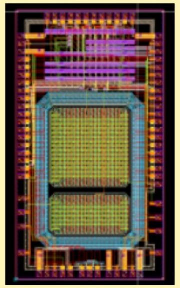
NO GAIN LAYER

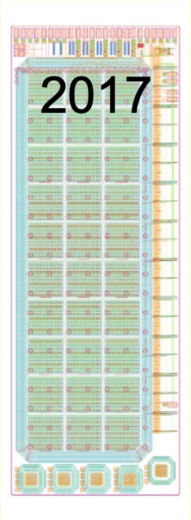
2016



200 ps

- 1 mm^2 pixel
- Discriminator

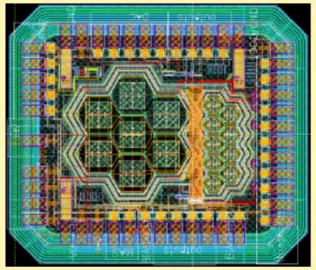
2017



110 ps

- 30 pixels 500x500μm^2
- 100ps TDC +I/O logic

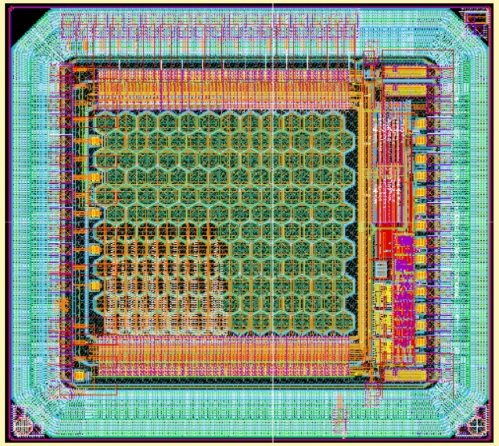
2018



50 ps

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

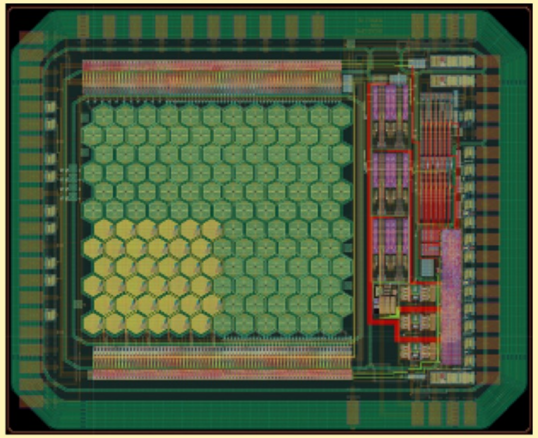
2019



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

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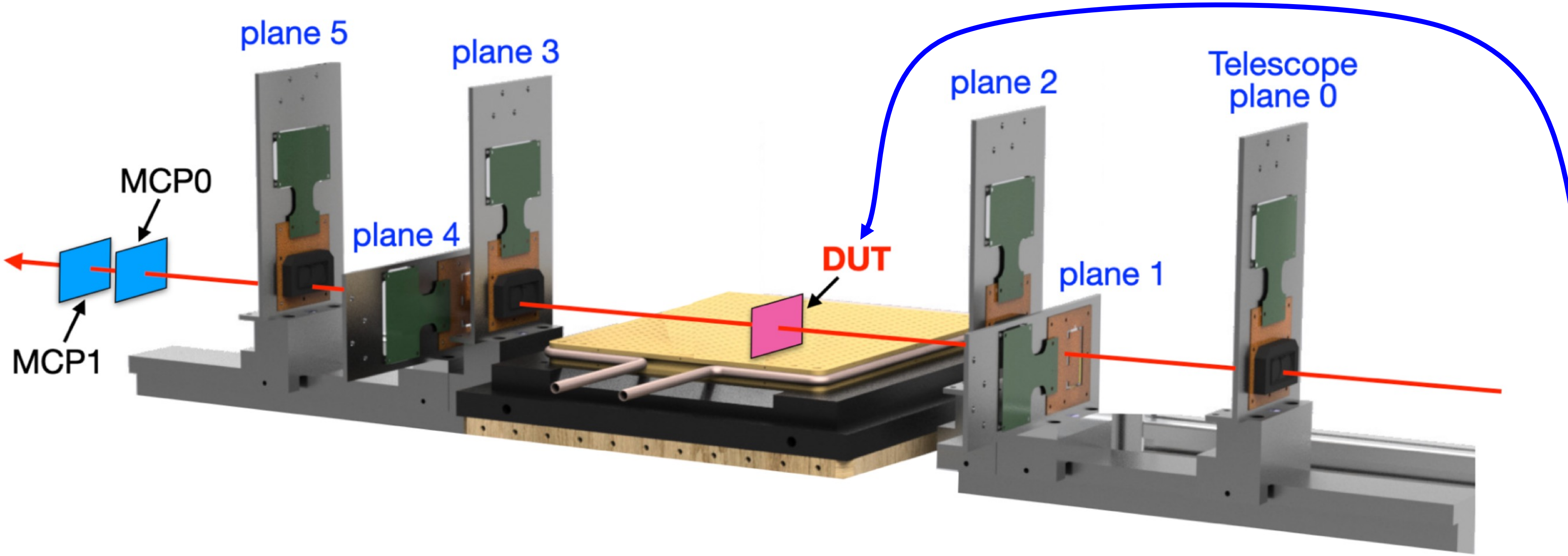
Test Beam: Experimental Setup

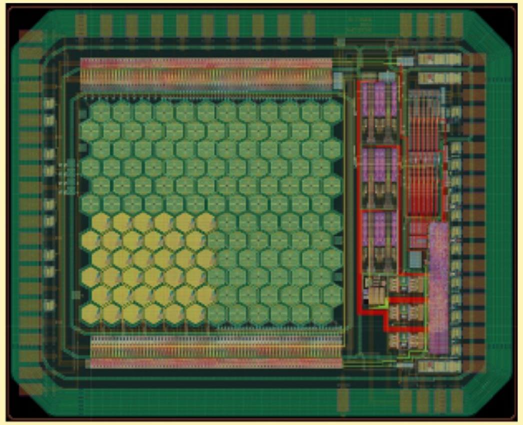
European Research Council
Established by the European Commission

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



NO GAIN LAYER

2022



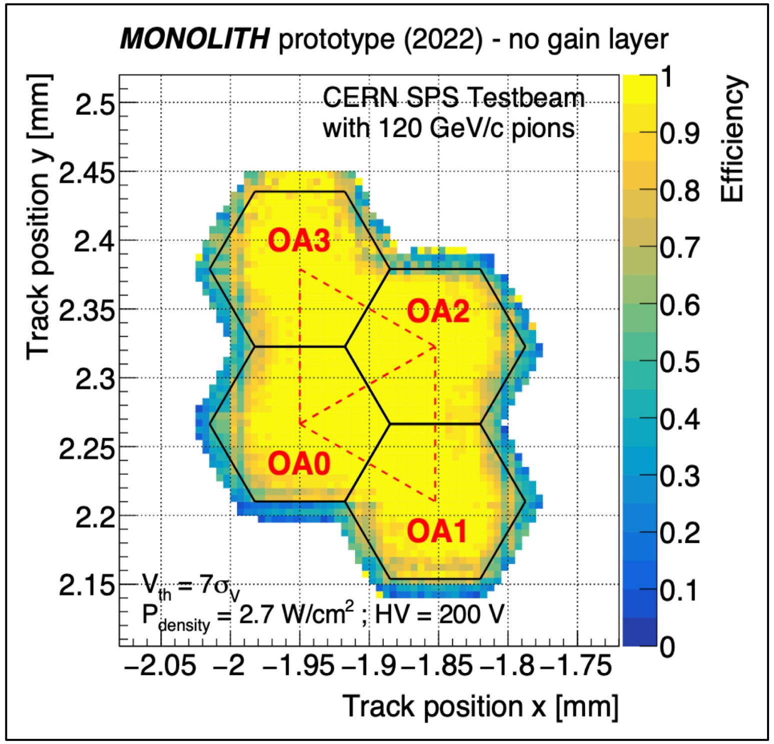
20 ps

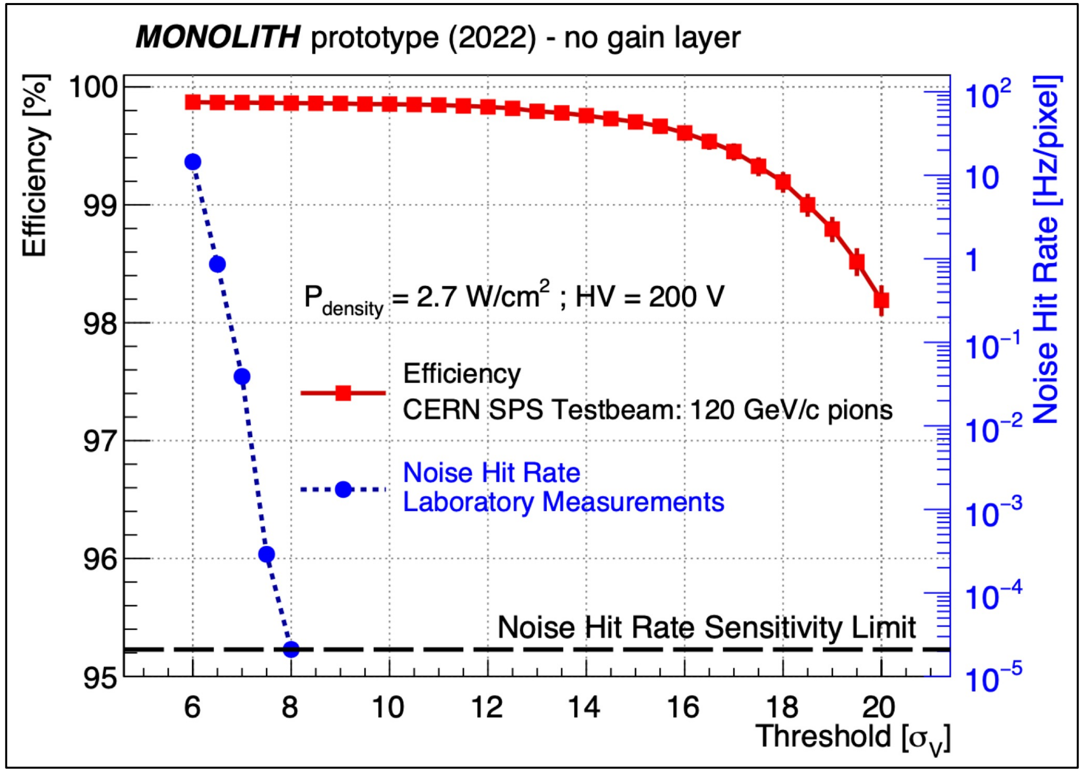
- Hexagonal pixels 65μm side
- improved electronics
- 50μm epitaxial layer (350Ωcm)

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

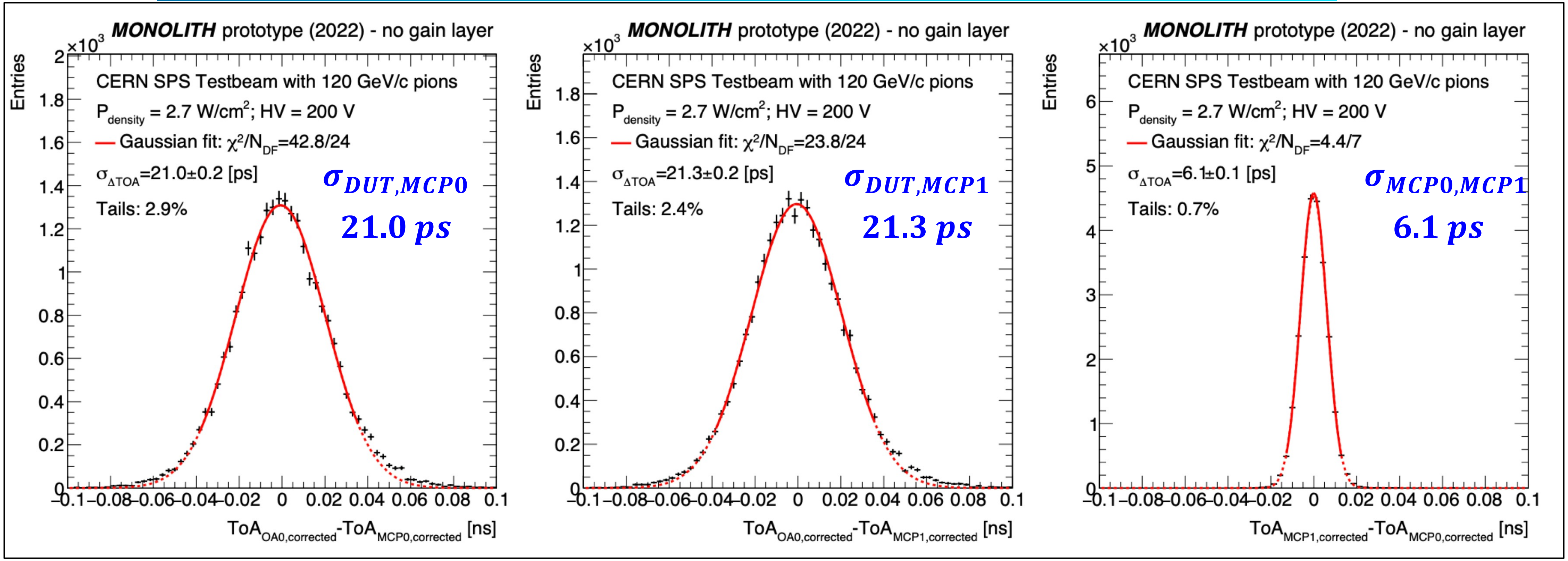




- The **apparent degradation** at the edges is due to the ~10 μm resolution of the telescope
- Selection of two **triangles:**
  - representative of the whole pixel
  - **unbiased** from the telescope resolution

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

Time Resolution 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

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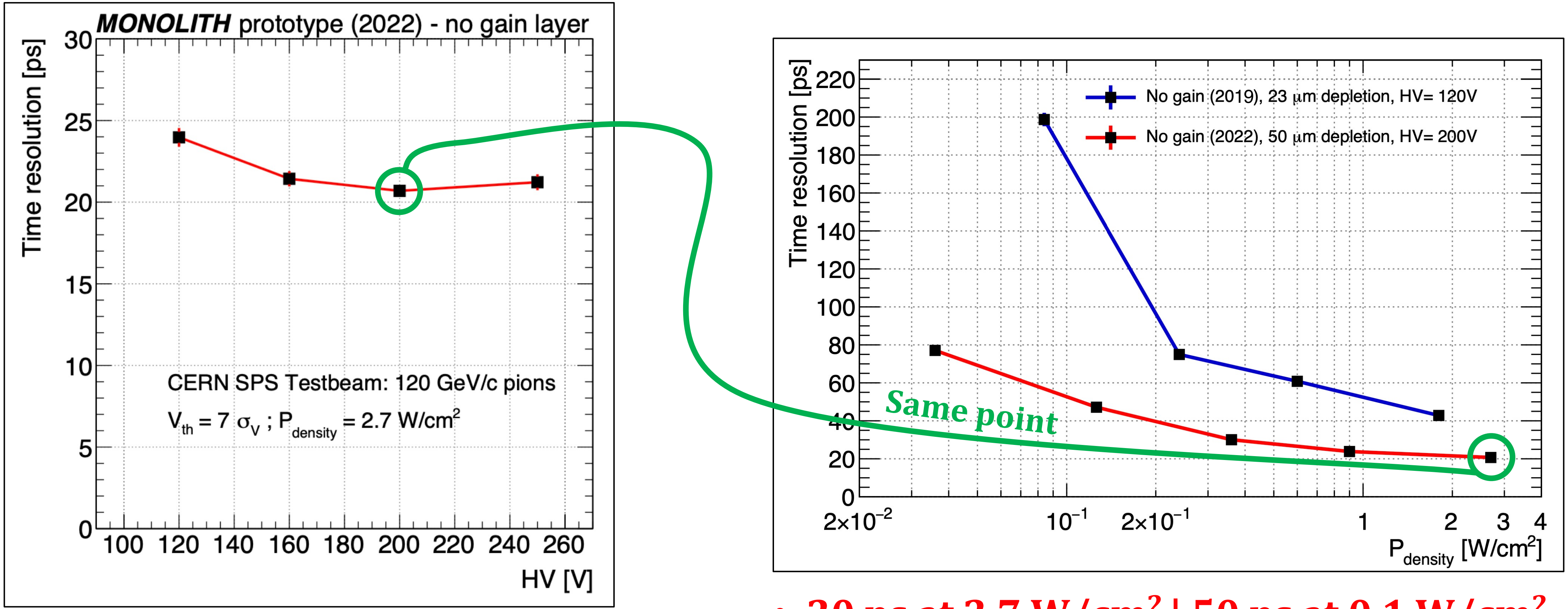
Time Resolution Results

European Research Council
Established by the European Commission



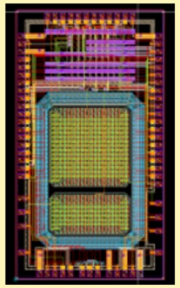
Large plateau of 130 V between 20 and 25 ps with simple analysis and signal processing

- **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**

Monolithic SiGe BiCMOS prototypes

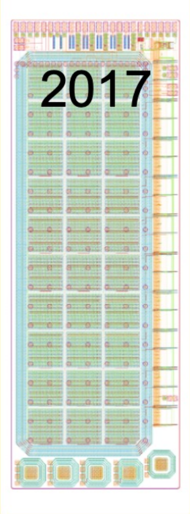
NO GAIN LAYER

2016



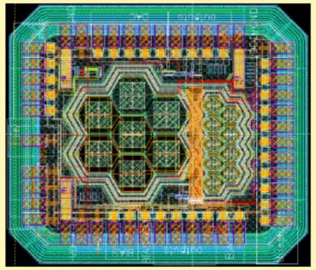
200 ps
- 1 mm² pixel
- Discriminator

2017



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

2018



50 ps
- Hexagonal pixels 65µm and 130µm side
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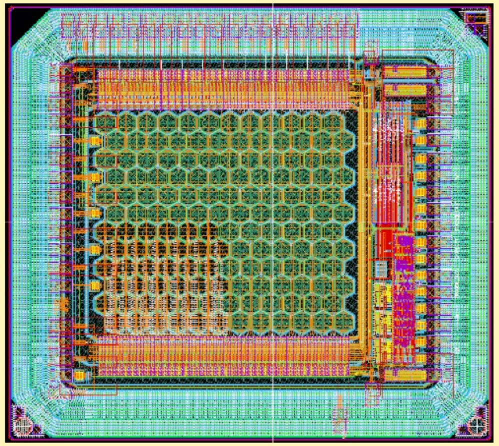
2019



36 ps
- Hexagonal pixels 65µm side
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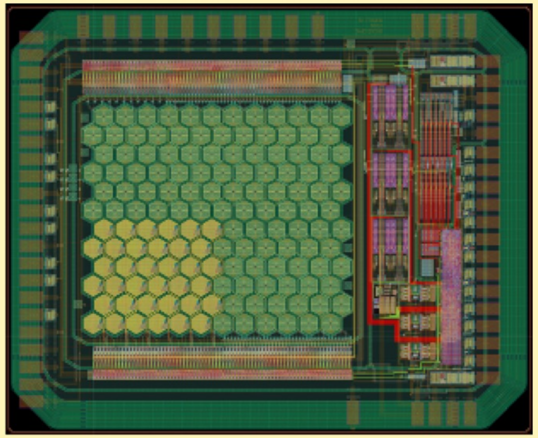
2022

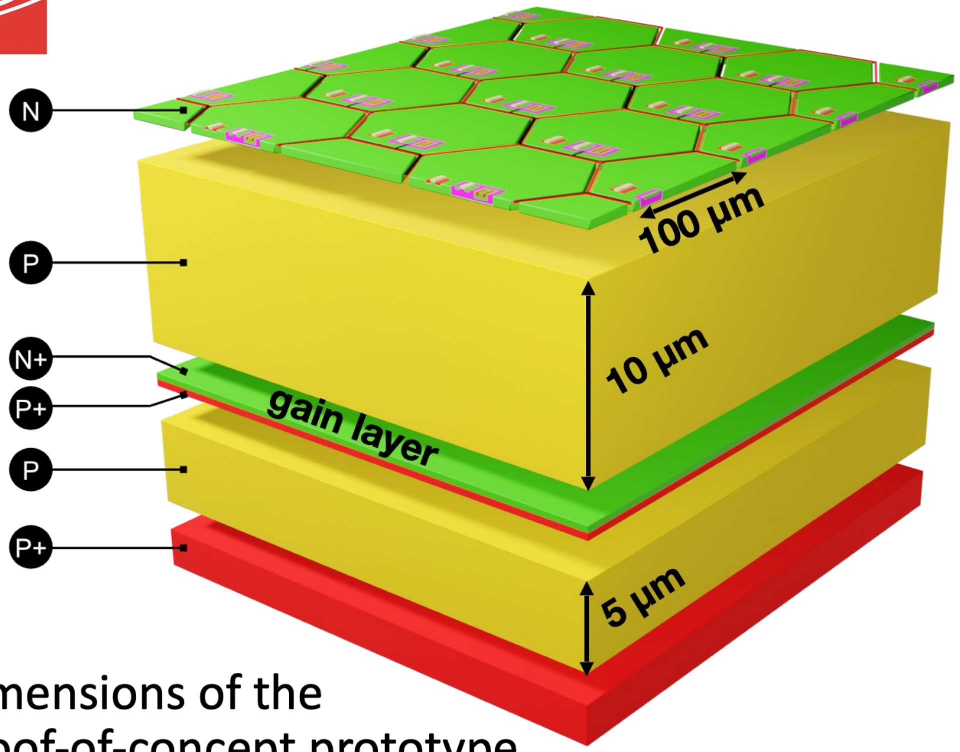


20 ps
- Hexagonal pixels 65µm side
- improved electronics
- 50µm epitaxial layer (350Ωcm)

2022
PicoAD© version
17 ps

PicoAD Prototype

- Multi-Junction **Pico-Avalanche Detector**[4]
- 2019 ASIC with the **PicoAD© concept**:
  - IHP produced **PicoAD©** special wafers with 4 doses of gain layer
- 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)

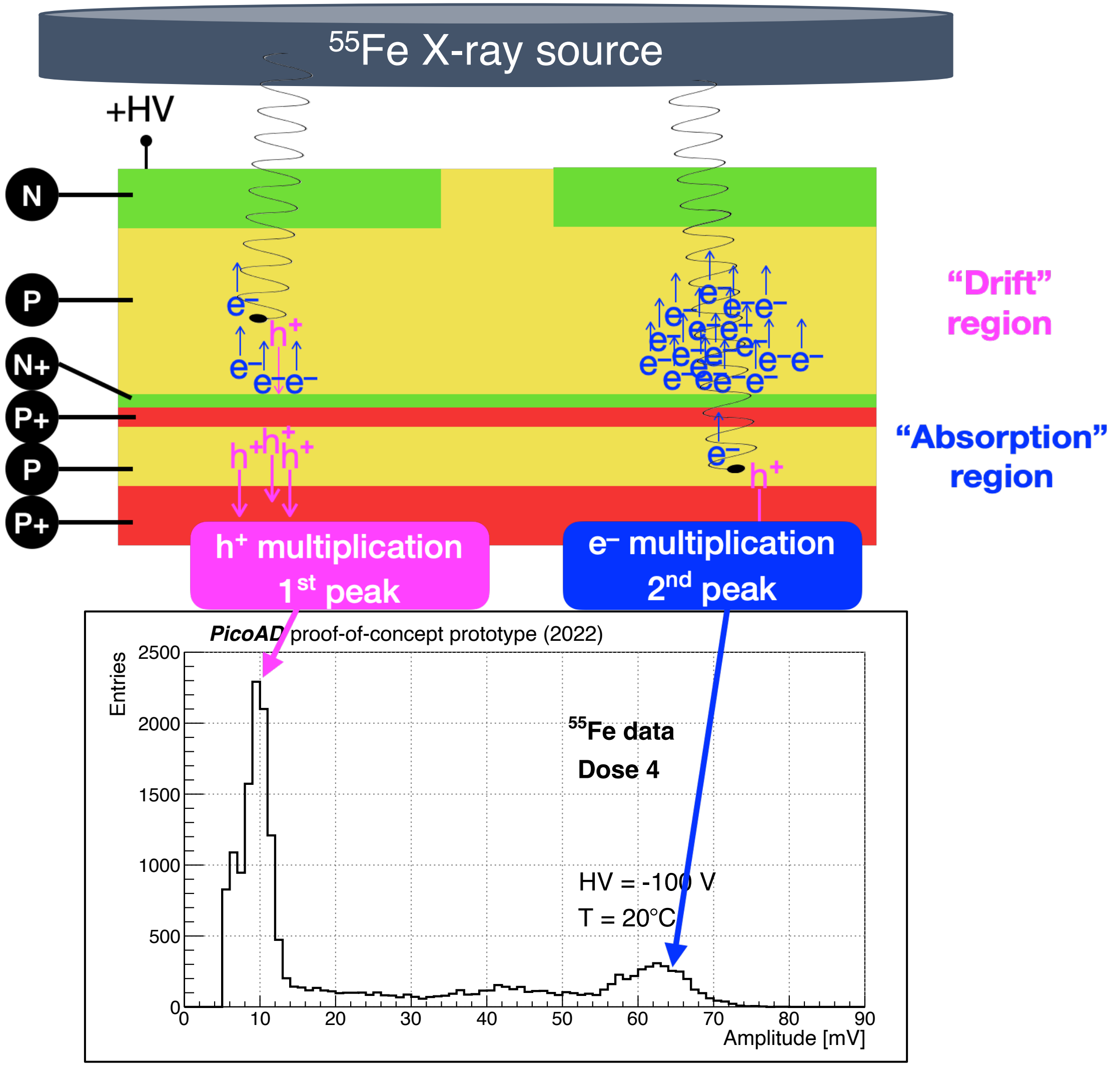


Dimensions of the proof-of-concept prototype

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

Gain Measurements

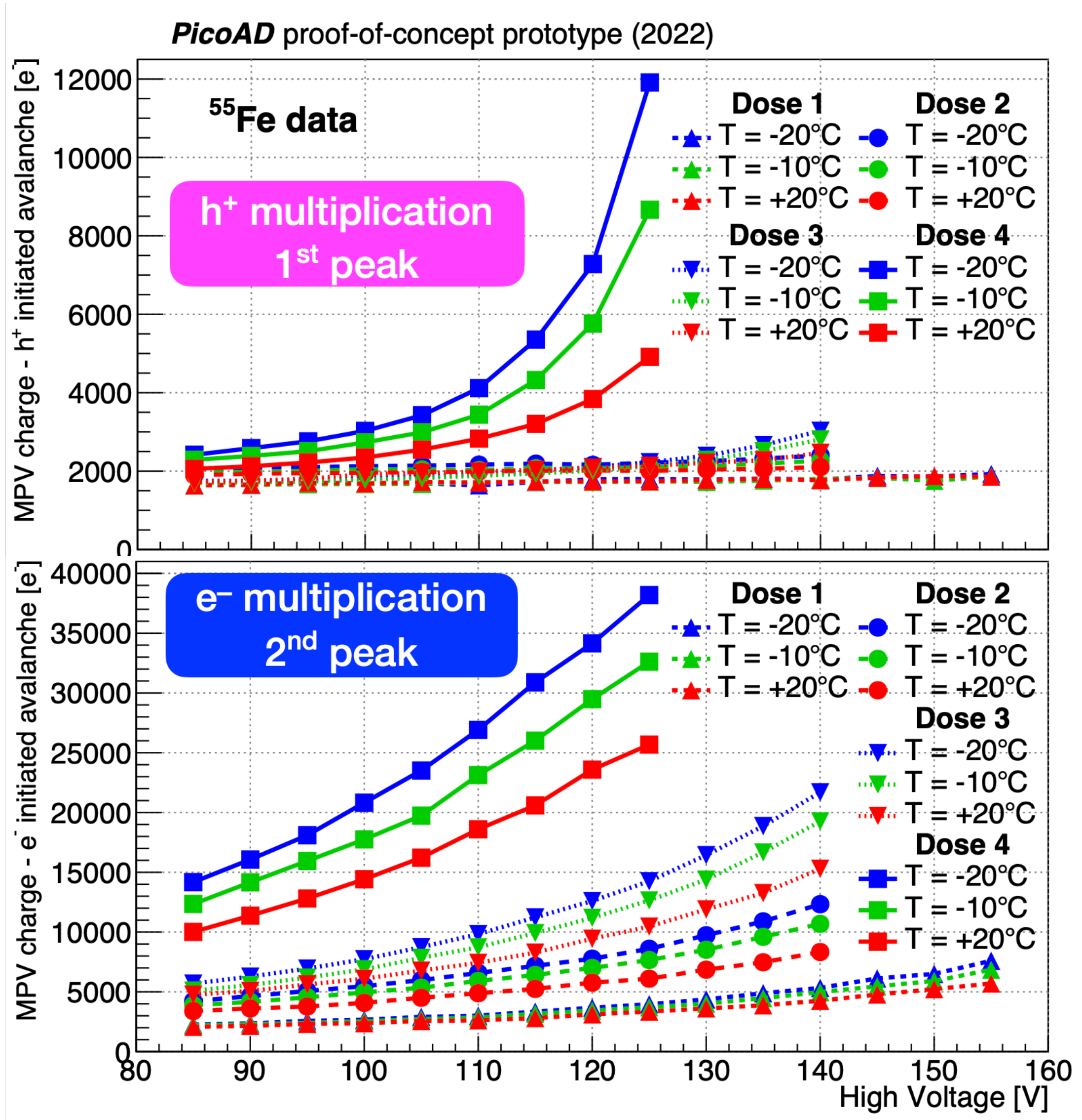
- **X-rays from ^{55}Fe radioactive source**[5][6]**:**
  - mainly ~5.9 keV photons
  - point-like charge deposition
- **Characteristic double-peak spectrum**
  - photon absorbed in **drift region**
    - **holes** drift through gain layer and multiplied
    - **first peak** in the spectrum
  - photon absorbed in **absorption region**
    - **electrons** drift through gain layer and multiplied
    - **second peak** in the spectrum



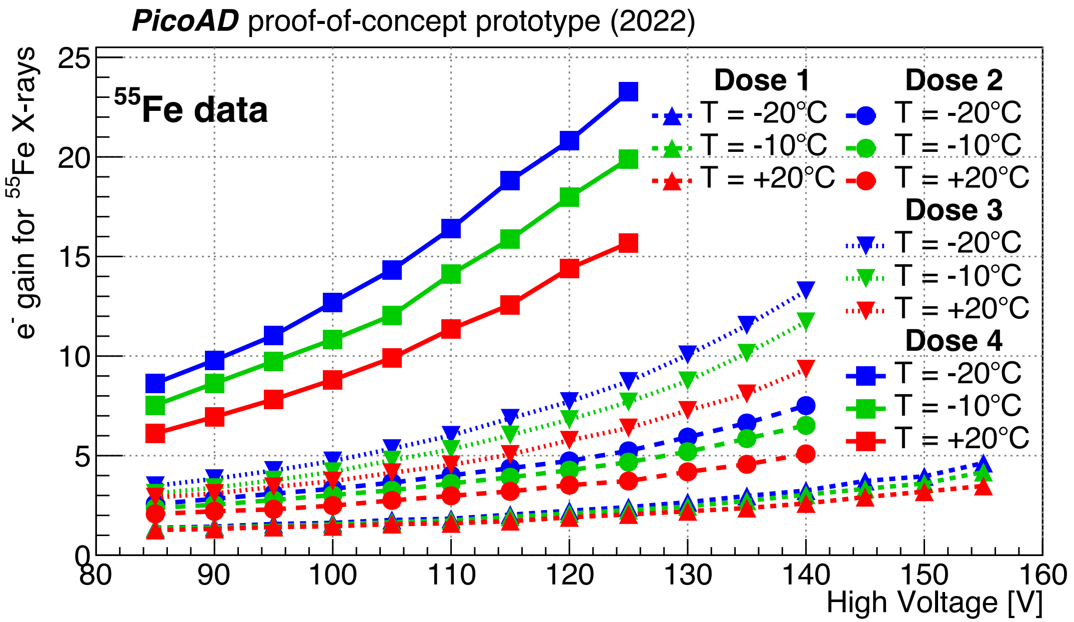
[5]M. Milanesio et al, Gain measurements of the first proof-of-concept PicoAD prototype with a ^{55}Fe X-ray radioactive source, 2022 doi.org/10.1016/j.nima.2022.167807

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

Gain Results



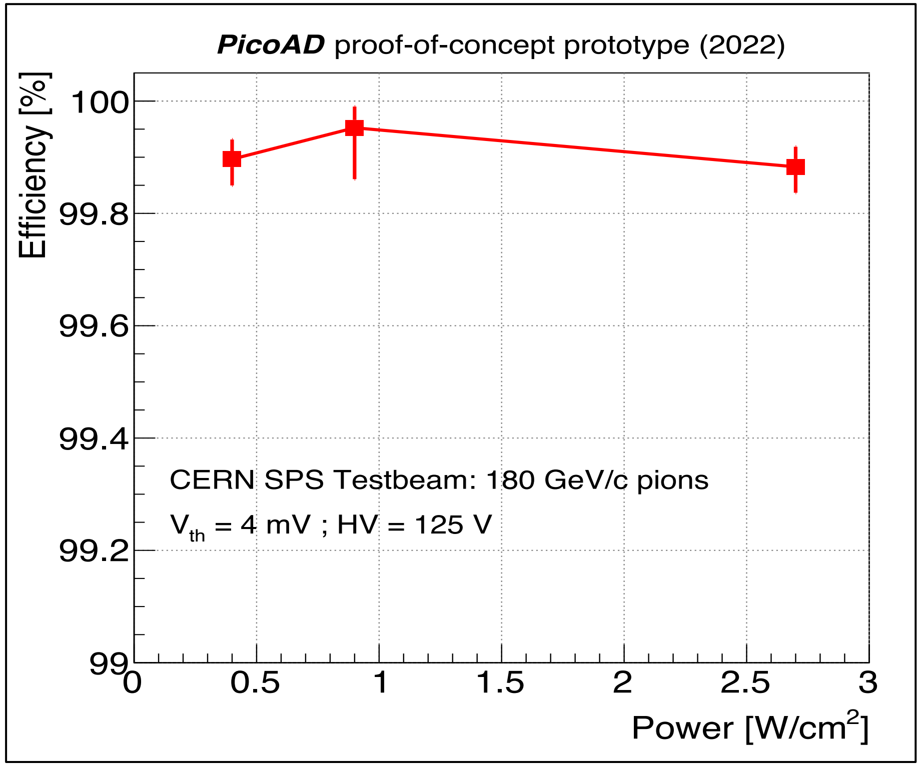
Gain up to ≈ 20 for ^{55}Fe X-rays
obtained at HV = 125 V and T = -20 °C

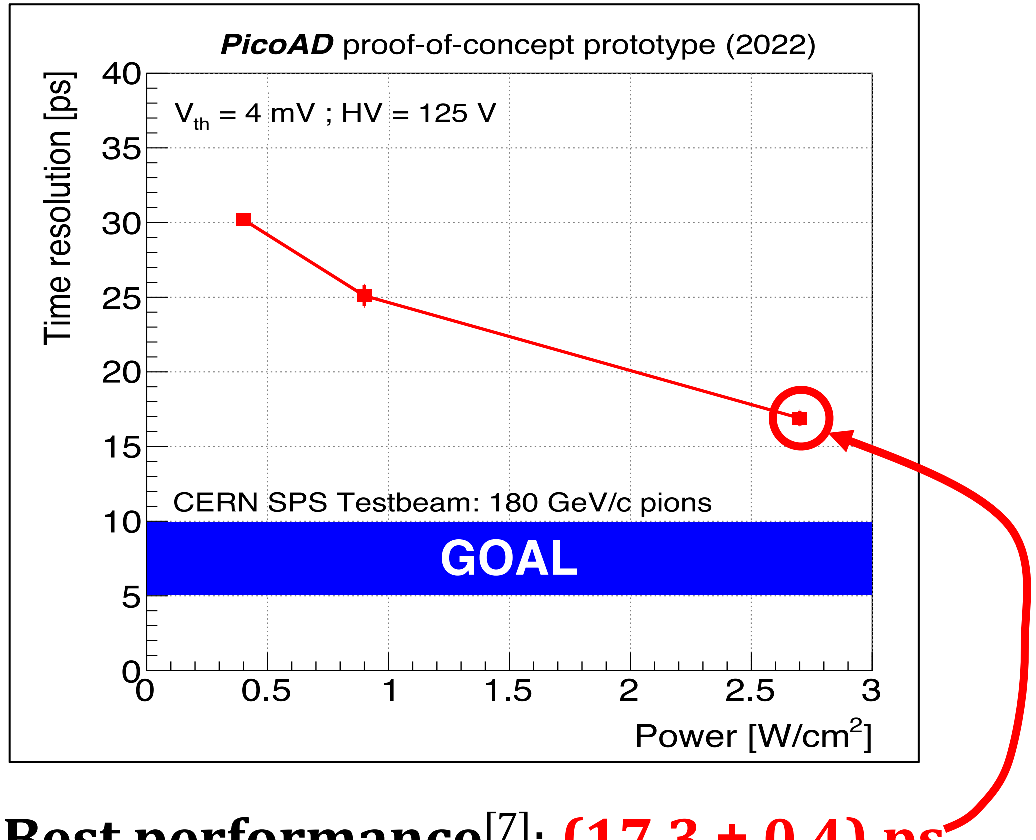


- Evidence for **gain suppression** due to space-charge effects **in the case of ^{55}Fe X-rays**
- We estimated that ^{55}Fe gain of ≈ 20 corresponds to **gain 60–70 for a MIP**

Efficiency and Time Resolution

Similar experimental setup with FE-I4 telescope





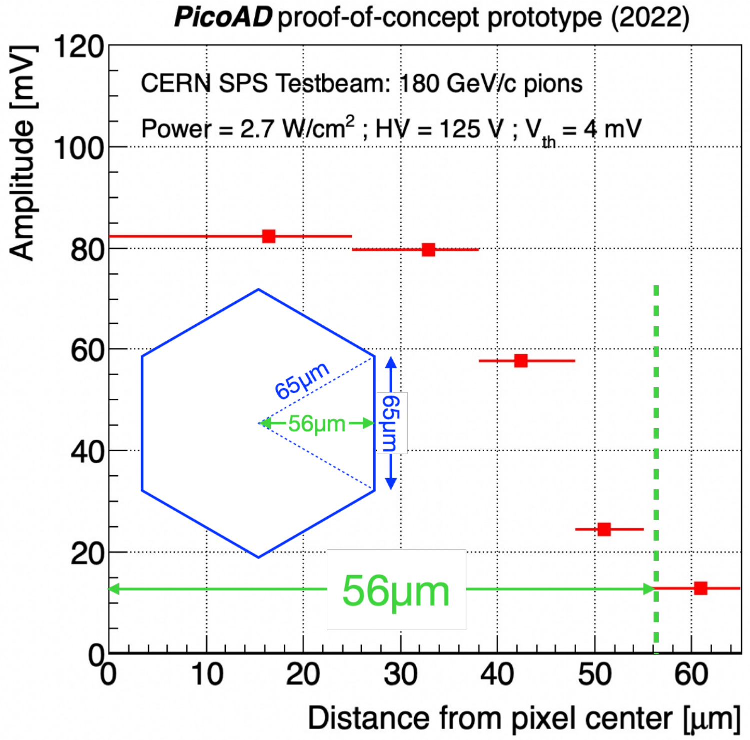
99.9% for all the power consumptions

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

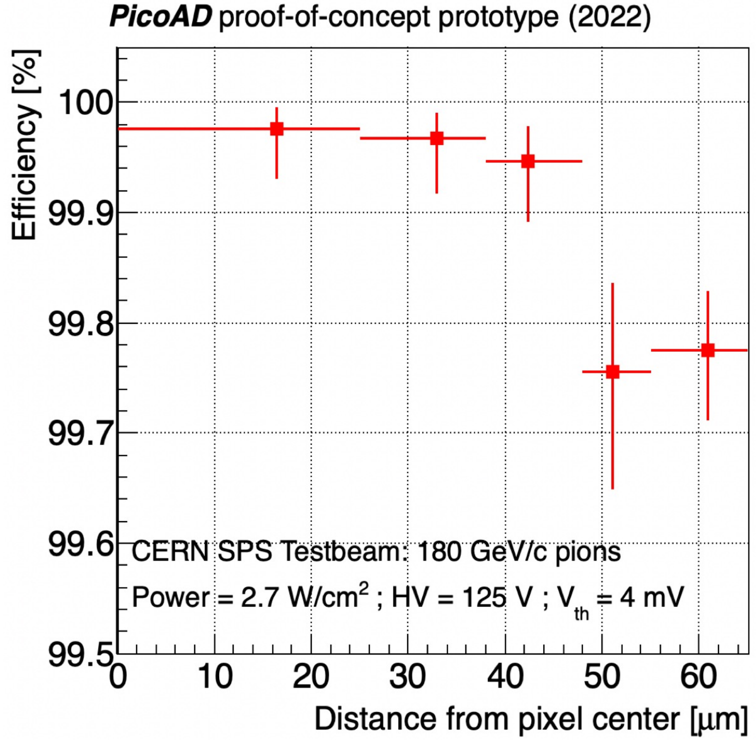
[7] G. Iacobucci et al, Testbeam results of the Picosecond Avalanche Detector proof-of-concept prototype, 2022 JINST 17 P10040

Position Within the Pixel

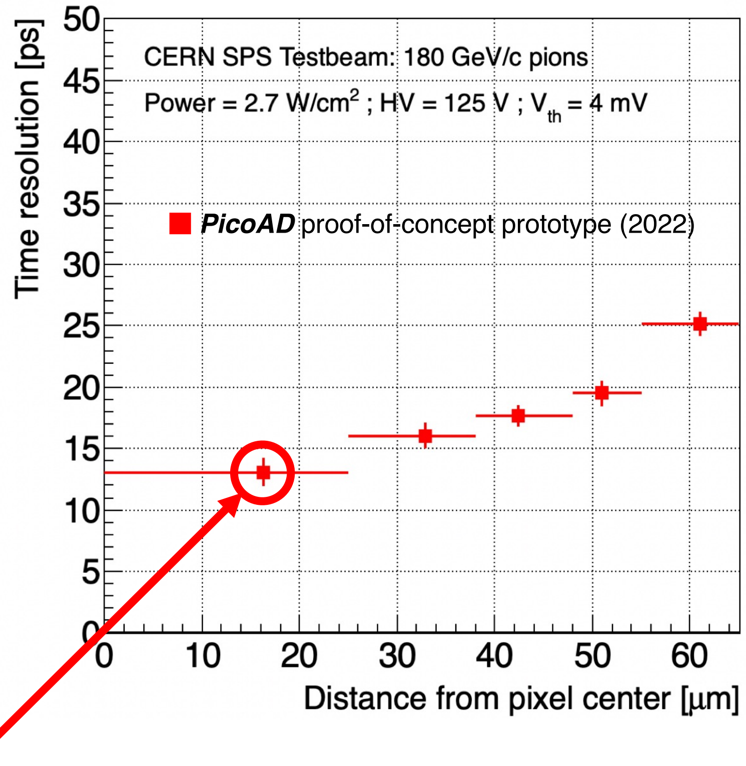
Signal MPV Amplitude



Efficiency



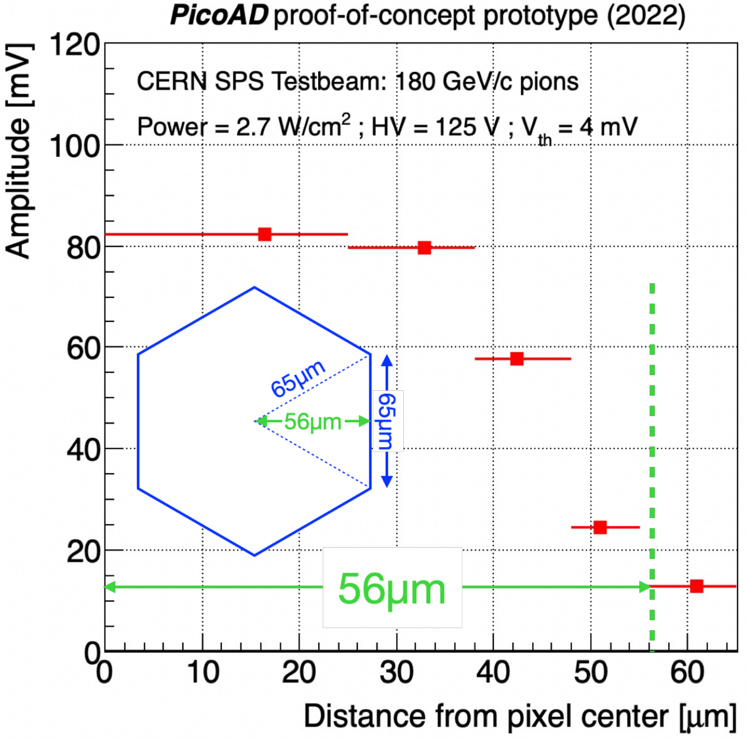
Time Resolution



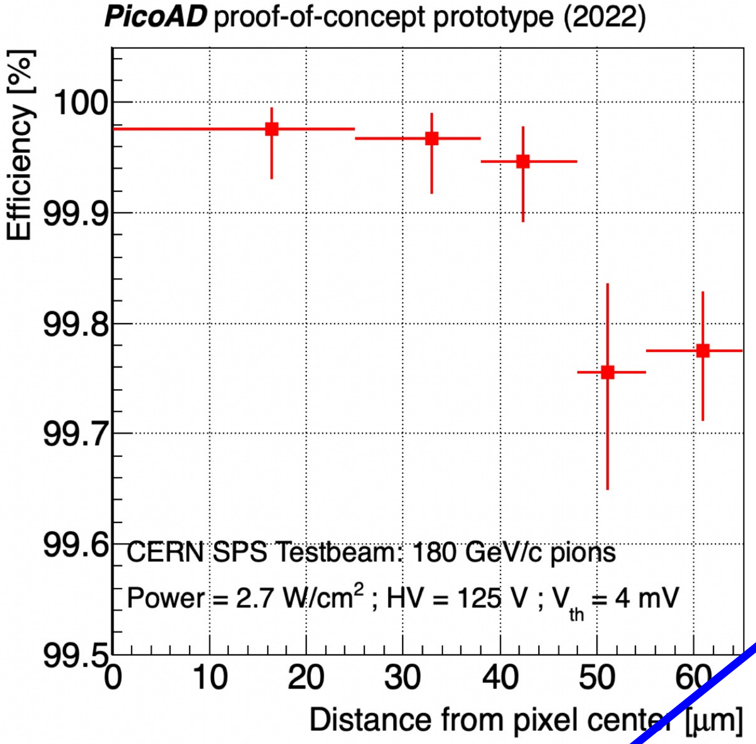
- Best time resolution: **(13.2 ± 0.8) ps within 25 µm** from the pixel center
- **PicoAD©** proof-of-concept: small degradation of the performance towards the edge of the pixel

Position Within the Pixel

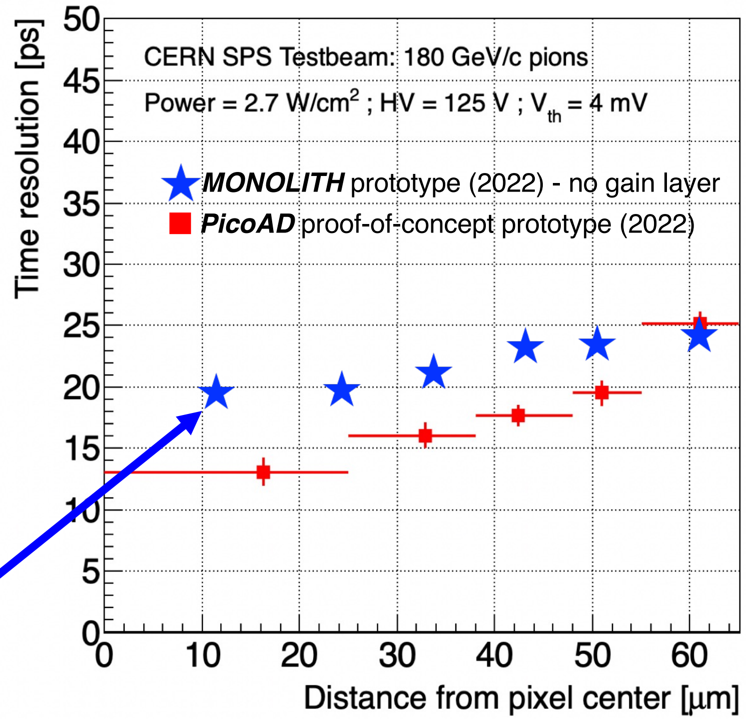
Signal MPV Amplitude



Efficiency



Time Resolution



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

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Future prototypes

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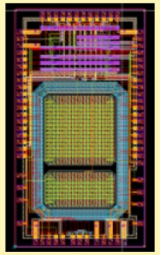
NO GAIN LAYER

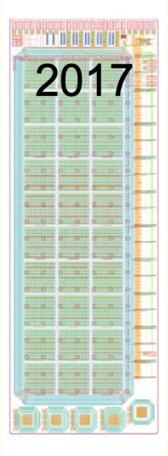
2016



200 ps

- 1 mm² pixel
- Discriminator

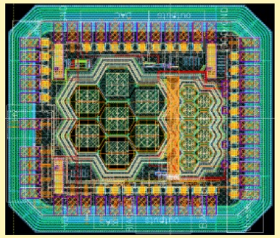
2017



110 ps

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

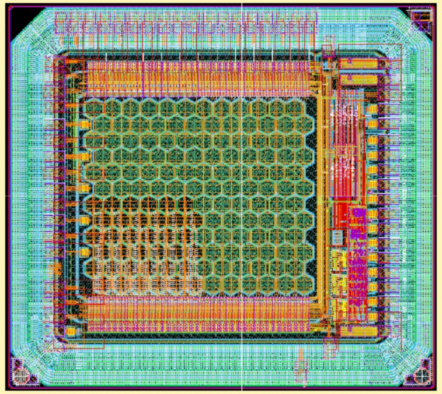
2018



50 ps

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

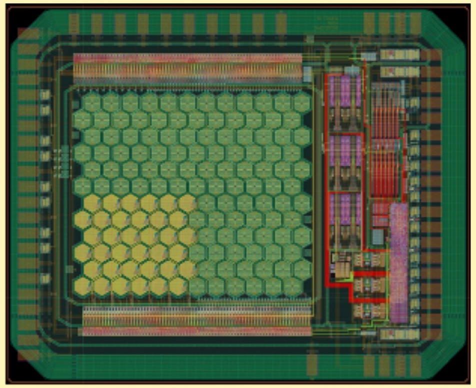
2019



36 ps

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

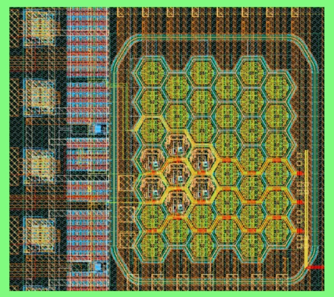
2022



20 ps

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

March 2023



< 20 ps ?

- Hexagonal pixels **32μm side**
- improved electronics

2022
PicoAD© version
17 ps

June 2023
PicoAD© version
< 10 ps ?

Summary and Outlook

- **Testbeam of 2022 prototype ASIC, without gain layer,** provided:
  - **Efficiency = 99.8%** and **σ_t = (20.7 ± 0.3) ps** (much less dependent on position than 2019 prototype)

- **The PicoAD© monolithic proof-of-concept prototype works**
  - **Gain ≈ 20** for ^{55}Fe X-rays (space-charge effects -> **gain ≈ 60** for MIPs)
  - **Efficiency = 99.9 %** including inter-pixel regions
  - **Time resolution σ_t = (17.3 ± 0.4) ps**: **13 ps** at center and **25 ps** at pixel edge

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

[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.

Thanks for your attention


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

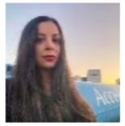

Mateus Vicente
- System integration
- Laboratory test

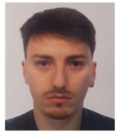

Stefano Zambito
- Laboratory test
- Data analysis

STICK AROUND FOR THESE TWO GUYS


Théo Moretti
- Laboratory test
- Data analysis


Chiara Magliocca
- Laboratory test
- Data analysis


Rafaella Kotitsa
- Sensor simulation


Luca Iodice
- Chip design
- Firmware


Didier Ferrere
- System integration
- Laboratory test

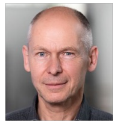

Sergio Gonzalez-Sevilla
- System integration
- Laboratory test


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

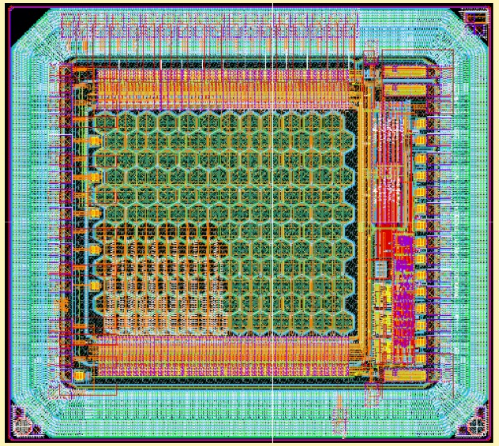
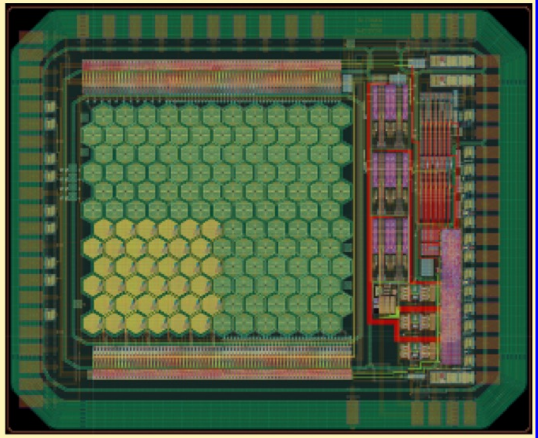
ATTRACT

UNIVERSITÉ DE GENÈVE UNITEC

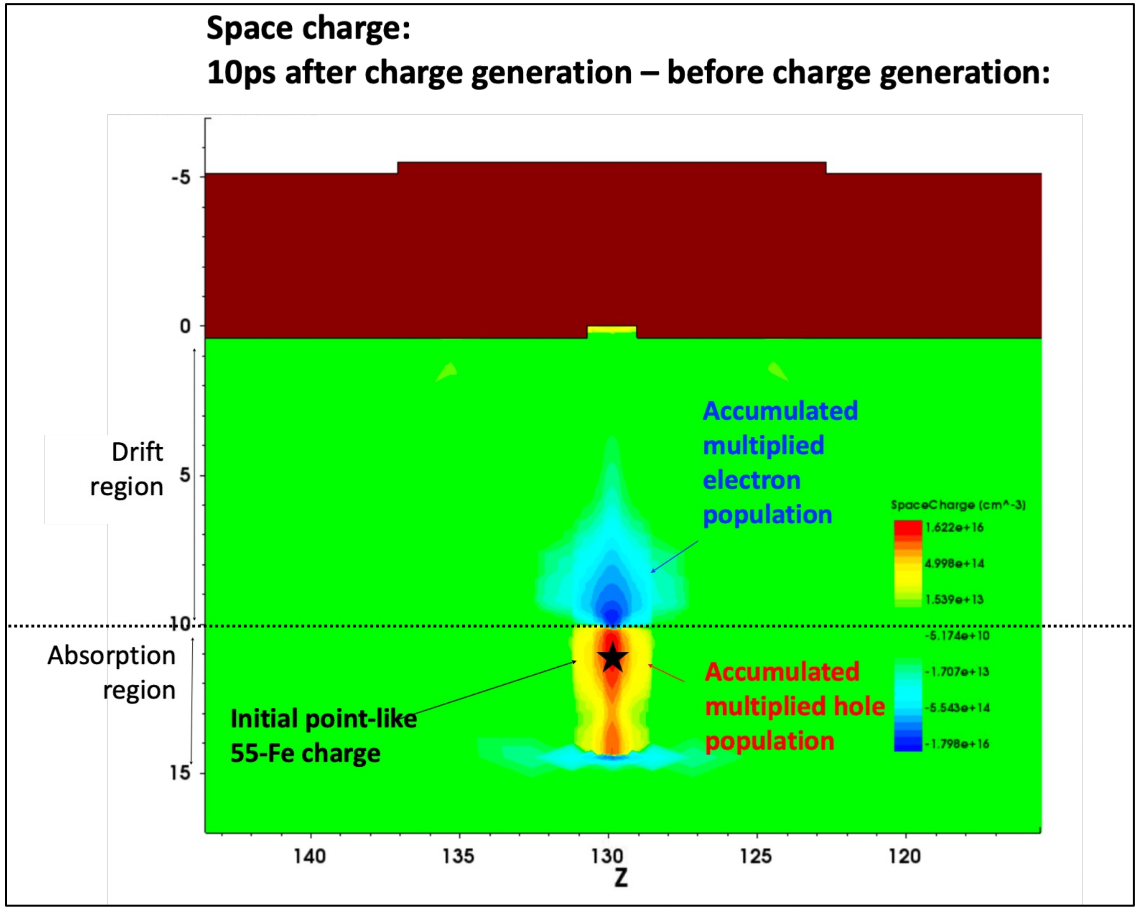
Backup

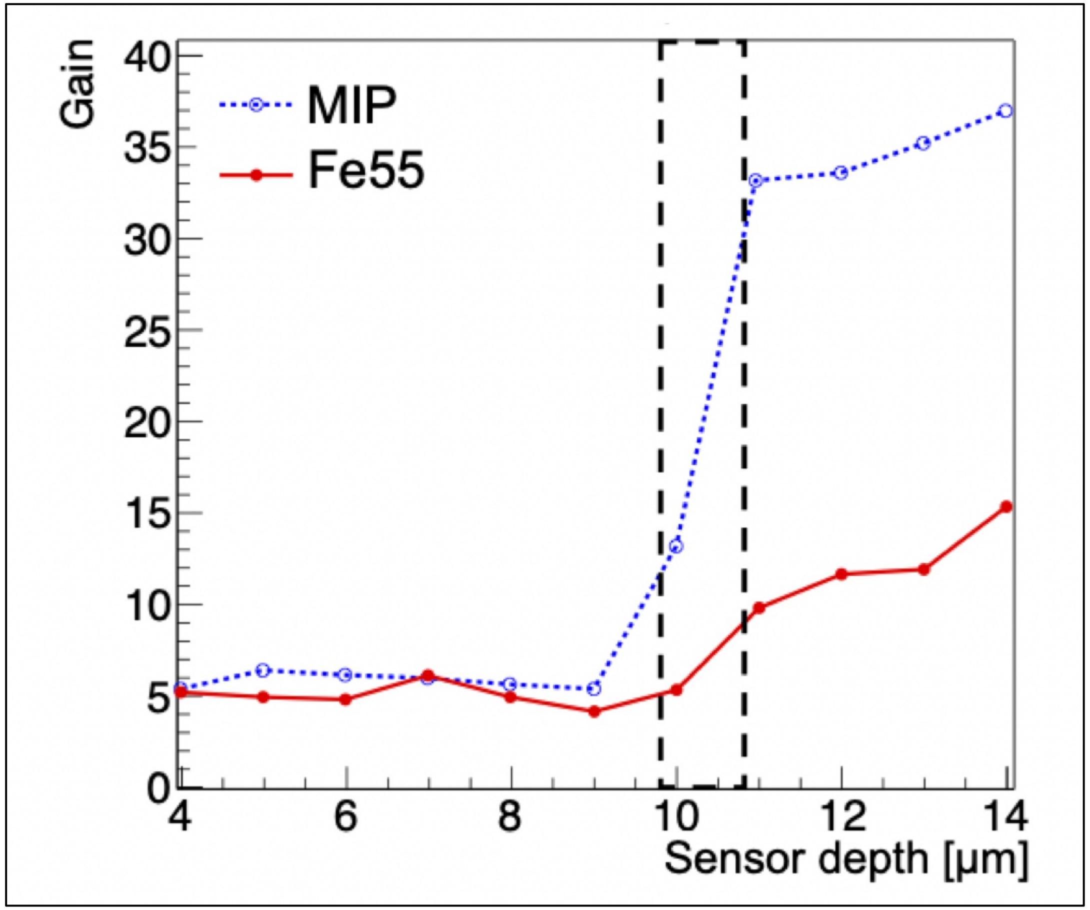
2019->2022: Improvements

- 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)

2019	2022
	
36 ps	**20 ps**
• Hexagonal pixels 65µm side • 30ps TDC +I/O logic • Analog channels	• Hexagonal pixels 65µm side • improved electronics • 50µm epitaxial layer (350Ωcm)

Space Charge Effects

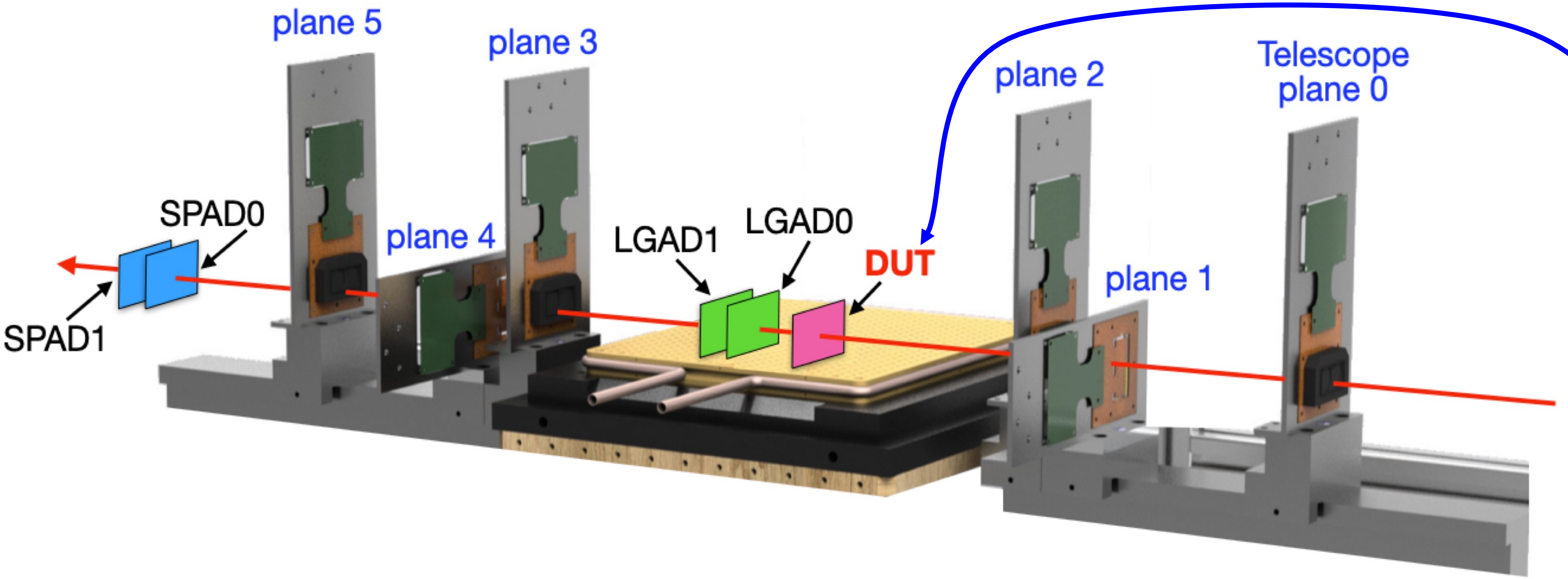


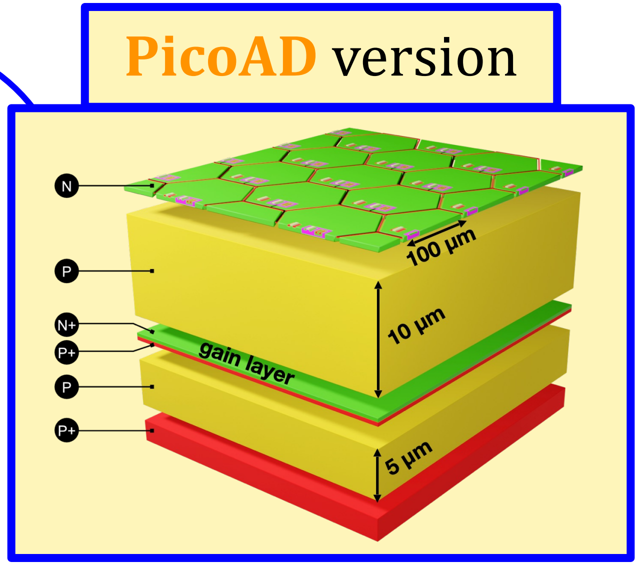


Transient 3D TCAD simulation of point like ^{55}Fe charge deposition in absorption layer

Test Beam: Experimental Setup

- October 2021: SPS Testbeam with 180 GeV/c pions
- Measure **efficiency** and **time resolution**

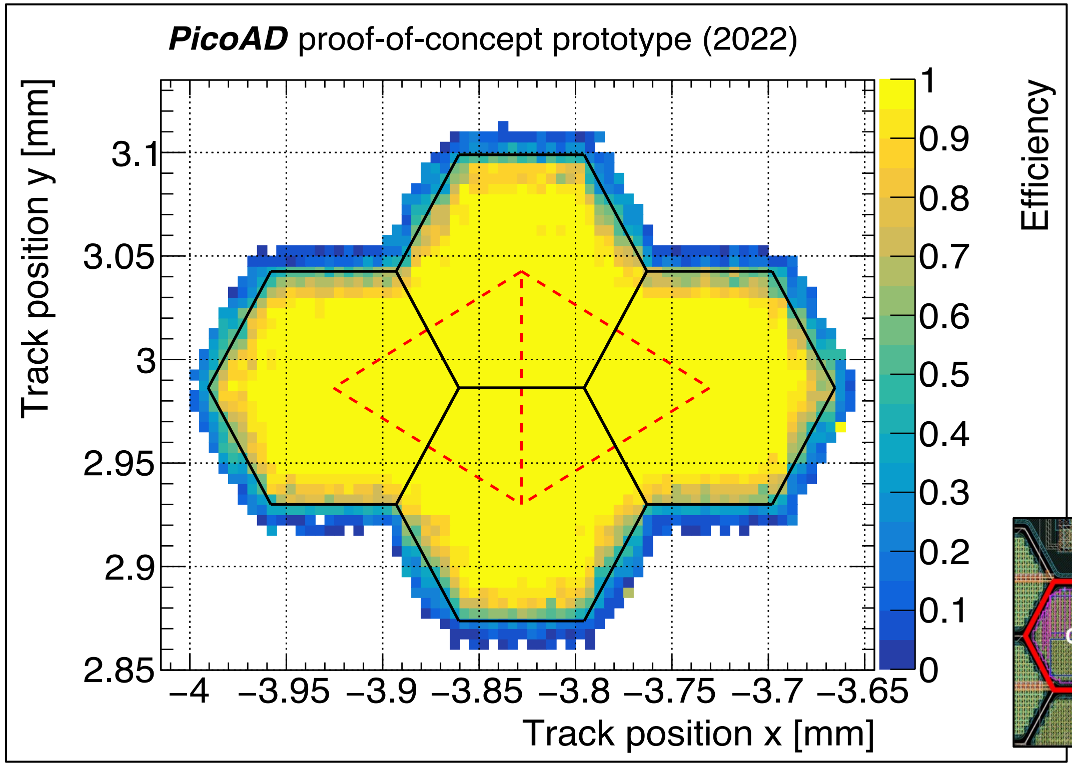


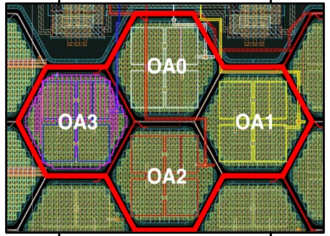


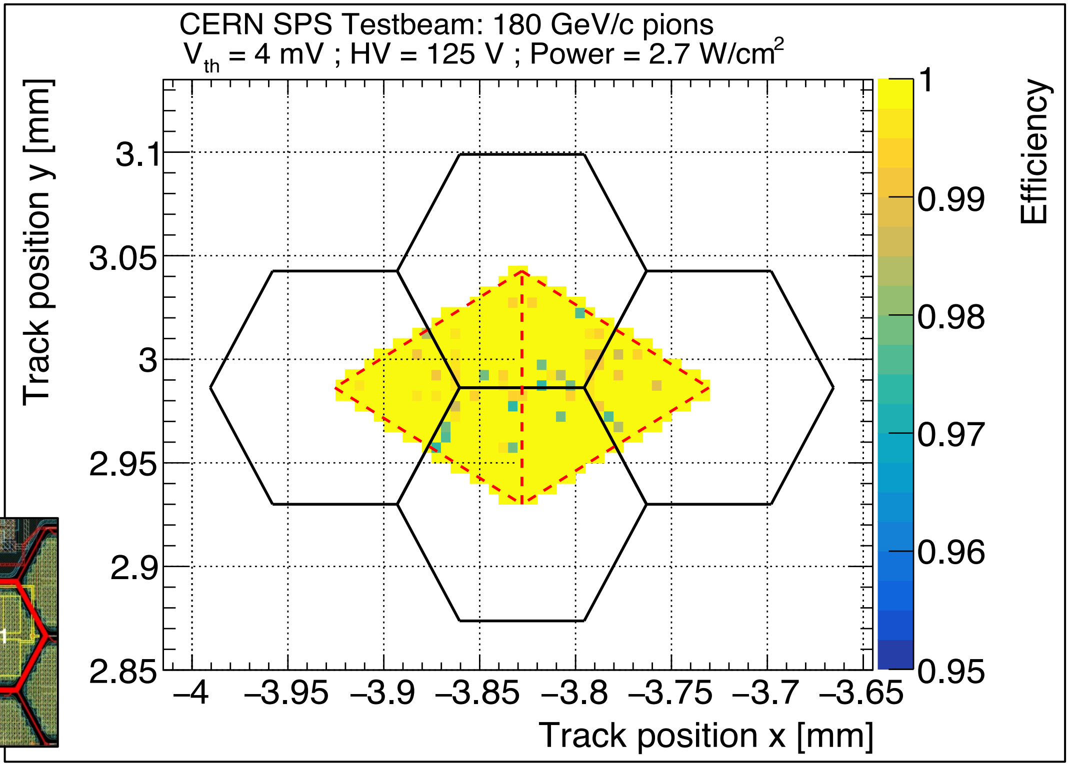
- **UNIGE FE-I4 telescope**[3] to provide the spatial information ($\sigma_{x,y}$ ~10 µm)
- **Two LGADs** (σ_t ~30 ps) + **SPADs** (σ_t ~10 ps) to provide the timing reference

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

PicoAD: Efficiency Maps





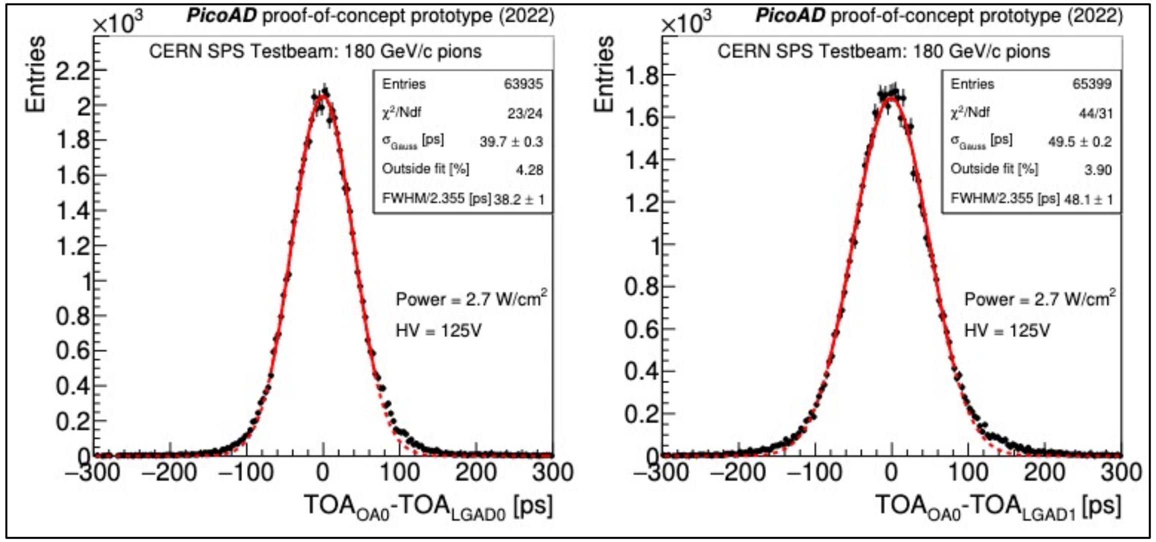


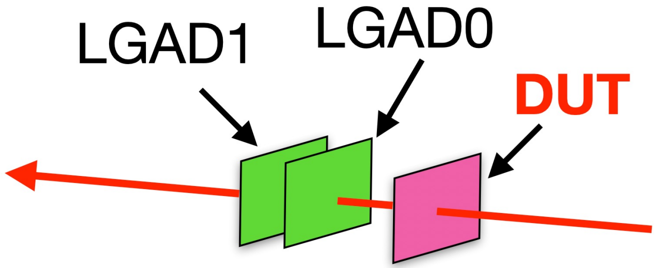
- The **apparent degradation** at the edges is due to the finite resolution of the telescope (~10 μm)

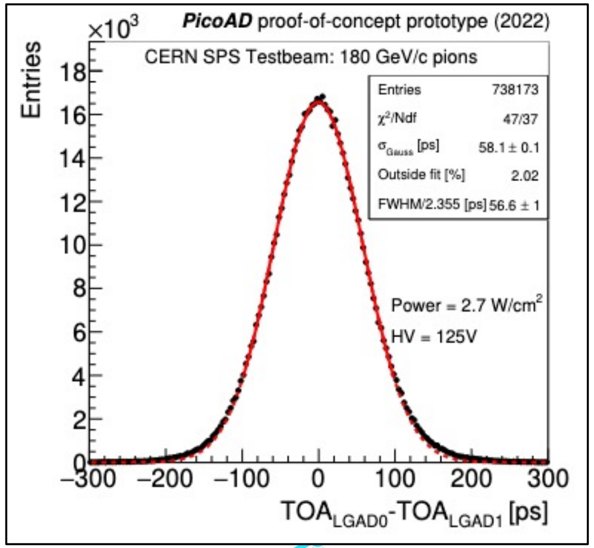
- Selection of two **triangles:**
  - representative of the whole pixel
  - **unbiased** from the telescope resolution

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 σ_{Gauss} from the fits give the timing resolution of:
    - the DUT
    - the two LGADs

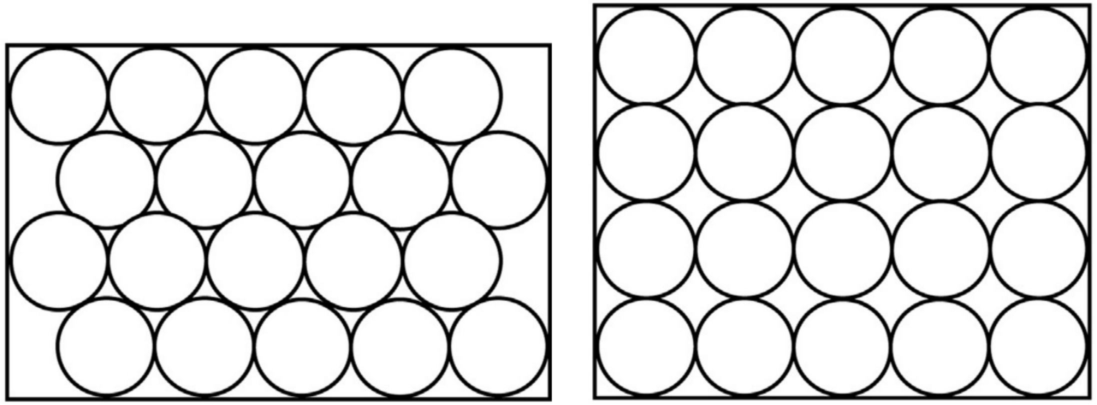




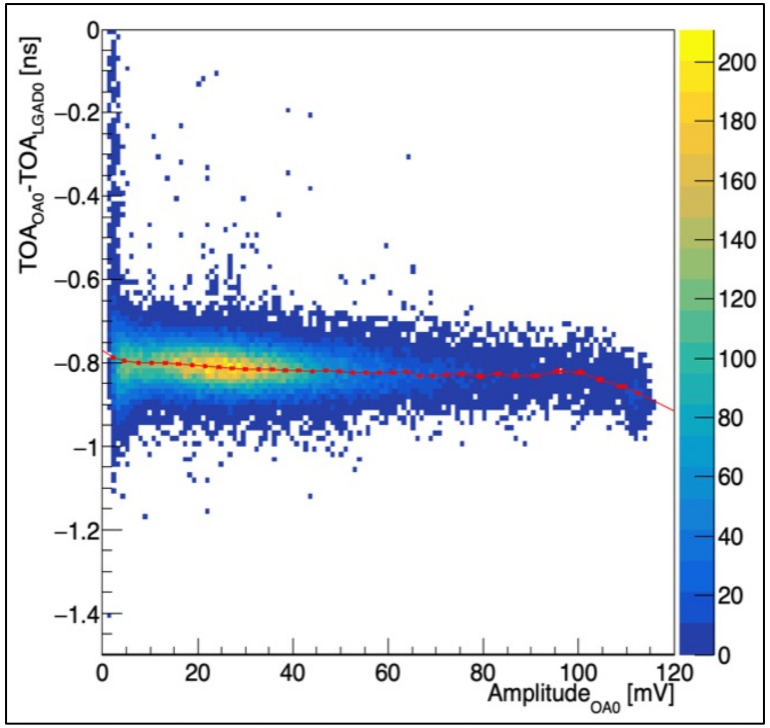


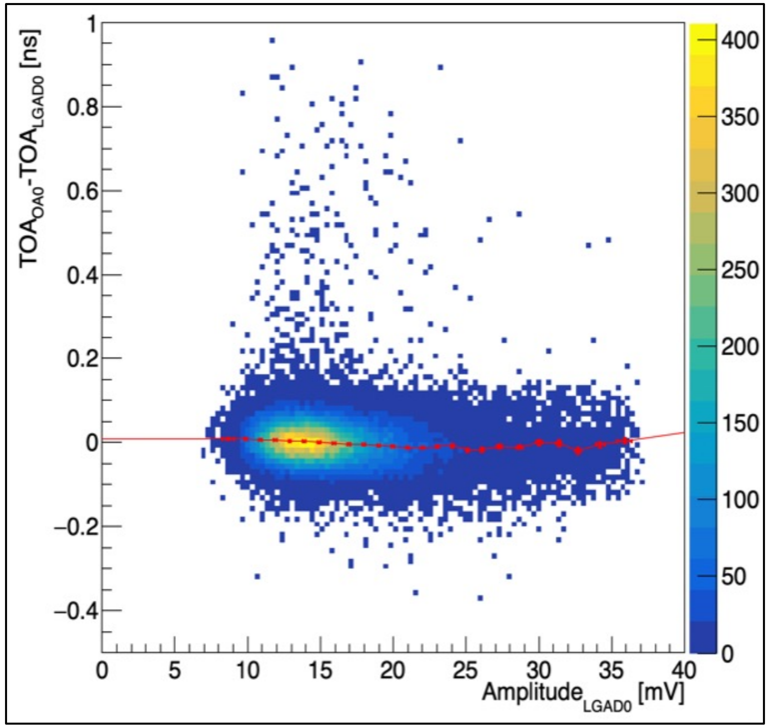
Benefits of Using Hexagonal Pixels

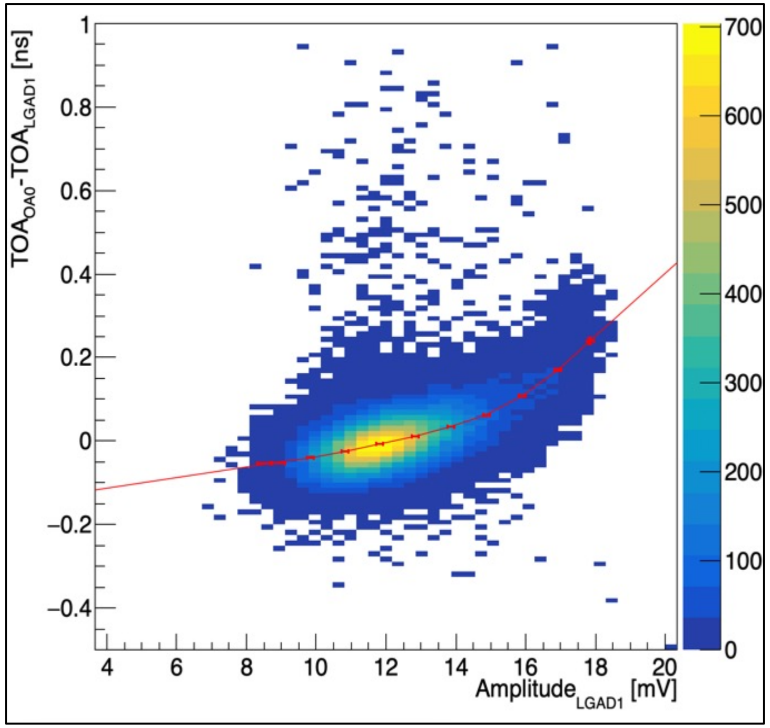
- Three possible regular shapes to use:
  - equilateral triangles
  - squares
  - regular hexagons
- Hexagons have the highest angles (120°) -> **electric fields** in the corners are better **under control**
- Moreover, the same amount of pixels can fits in less space than squares



PicoAD: Time Walk Correction







- Shift at 200 ps of the waveform to subtract low-frequency noise
- Time at 25% constant fraction
- Amplitude based time walk correction method