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

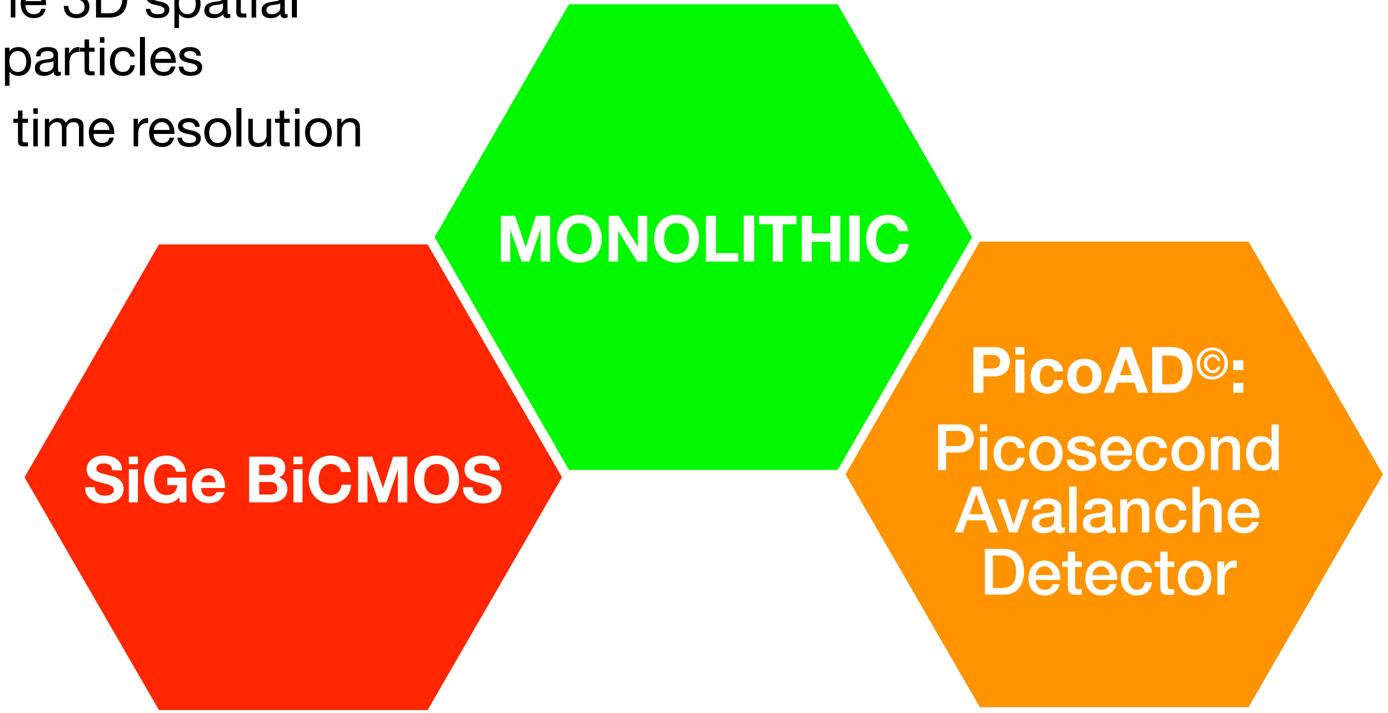
Université de Genève

VERTEX 2023 - 32nd International Workshop on Vertex 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, July 2020 - June 2025

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The MONOLITH ERC Project

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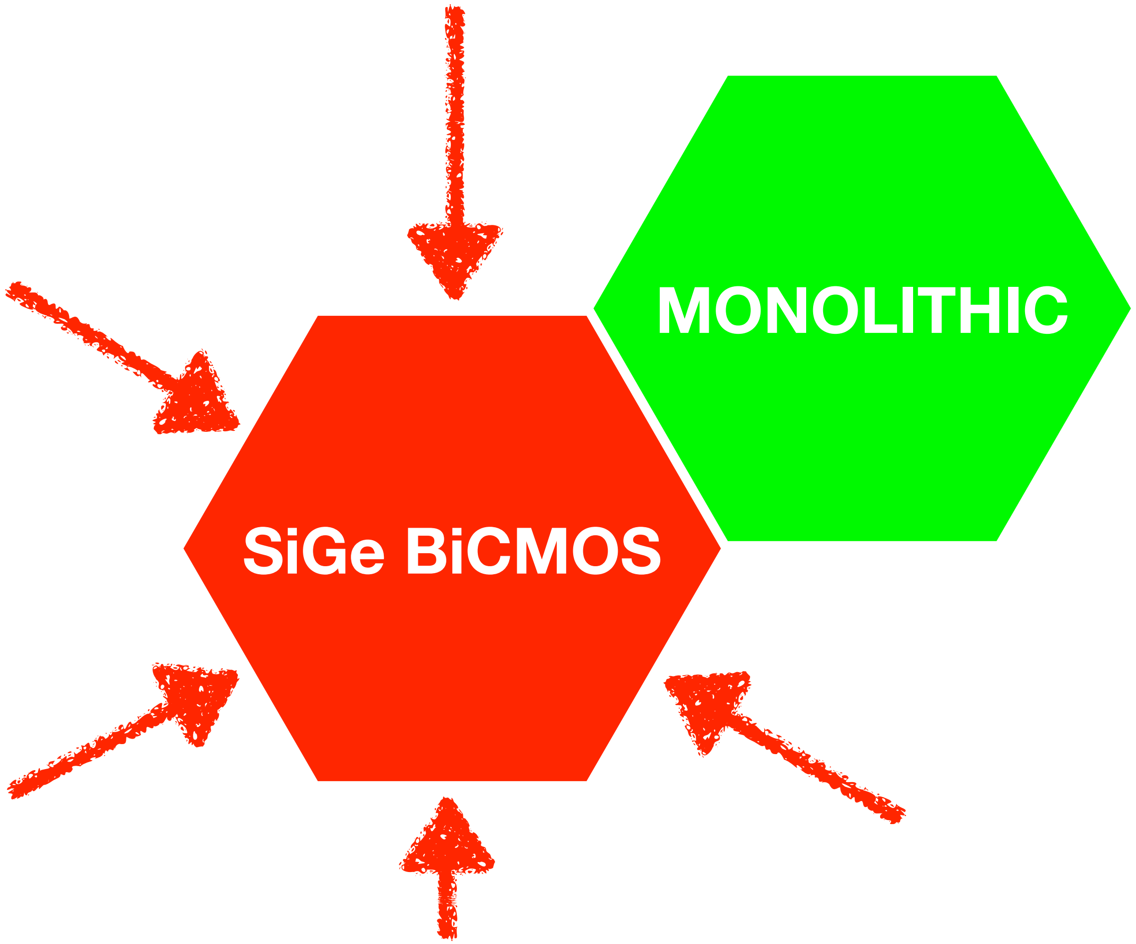

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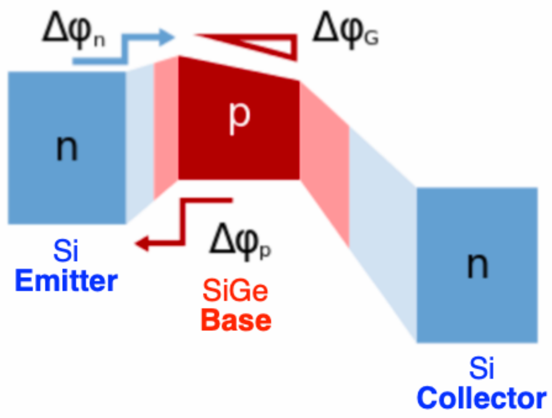
SiGe BiCMOS Technology

- 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 β**

NPN SiGe HBT
(depleted regions in light colors)
from wikimedia



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

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

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SiGe BiCMOS prototypes

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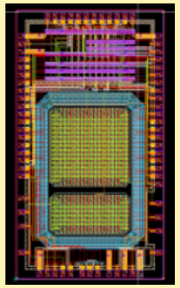
NO GAIN LAYER

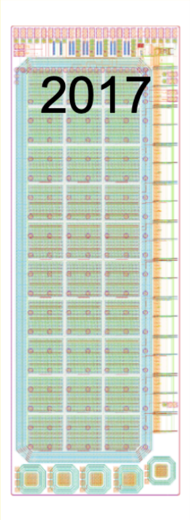
2016



200 ps

- 1 mm^2 pixel
- Discriminator

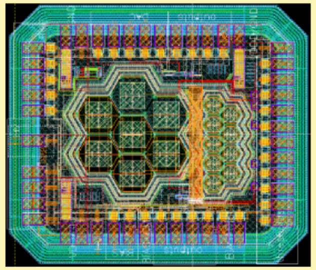
2017



110 ps

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

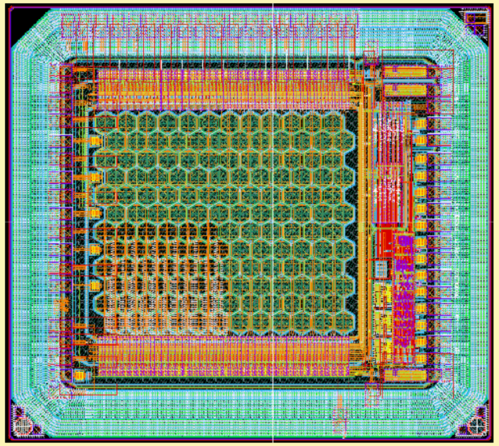
2018



50 ps

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

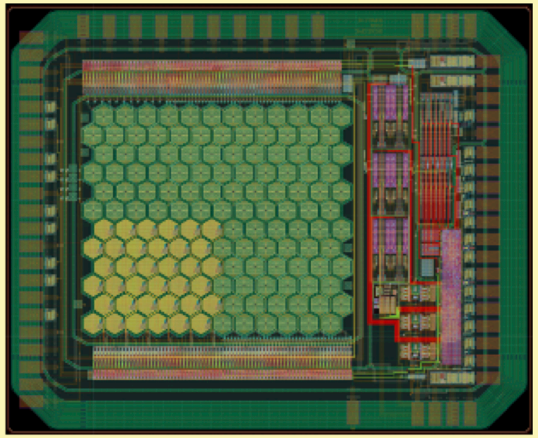
2019



36 ps

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

2022



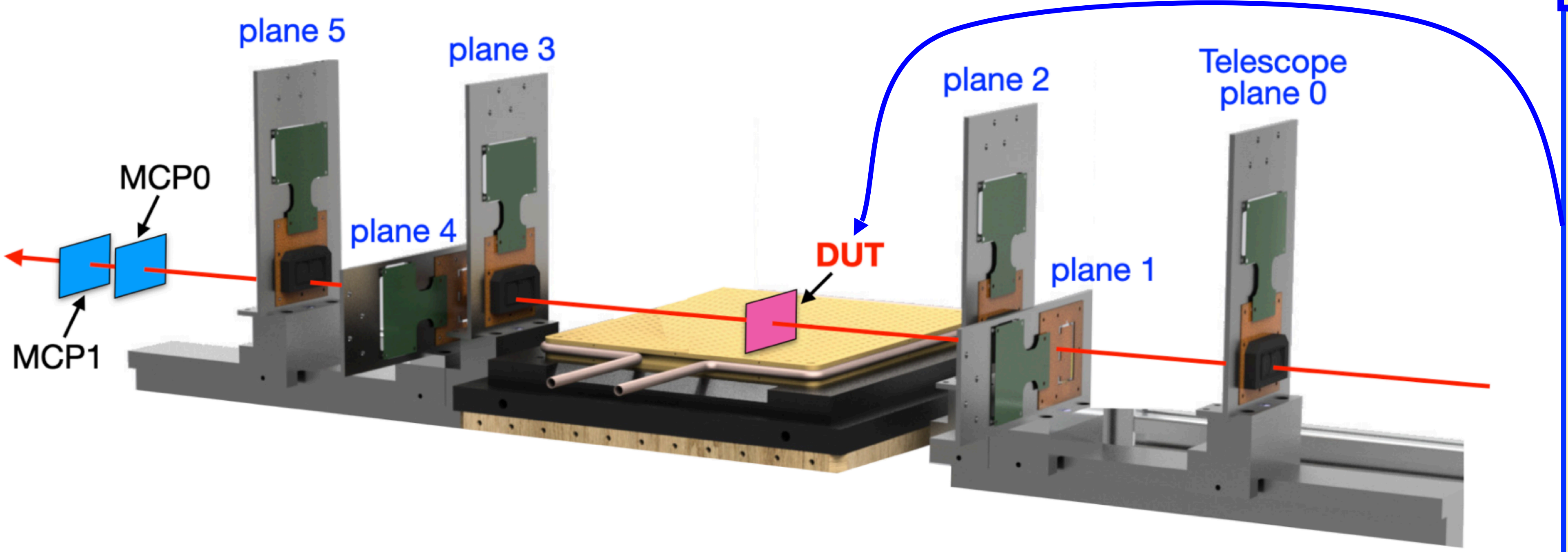
20 ps

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

Design Improvements

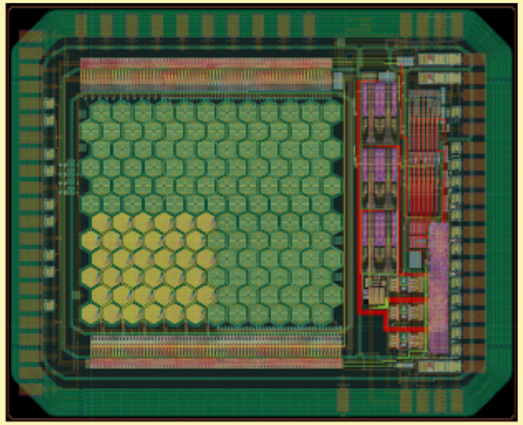
Test Beam: Experimental Setup

- October 2022: SPS Testbeam with 180 GeV/c pions
- Measure **efficiency** and **time resolution** (results in Testbeam of 2022 Prototype)



NO GAIN LAYER

2022

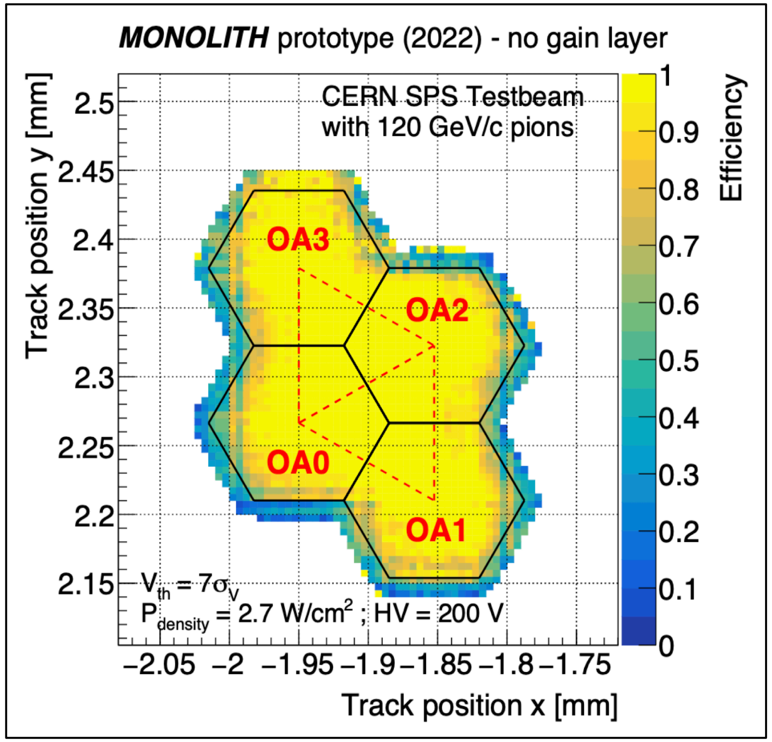


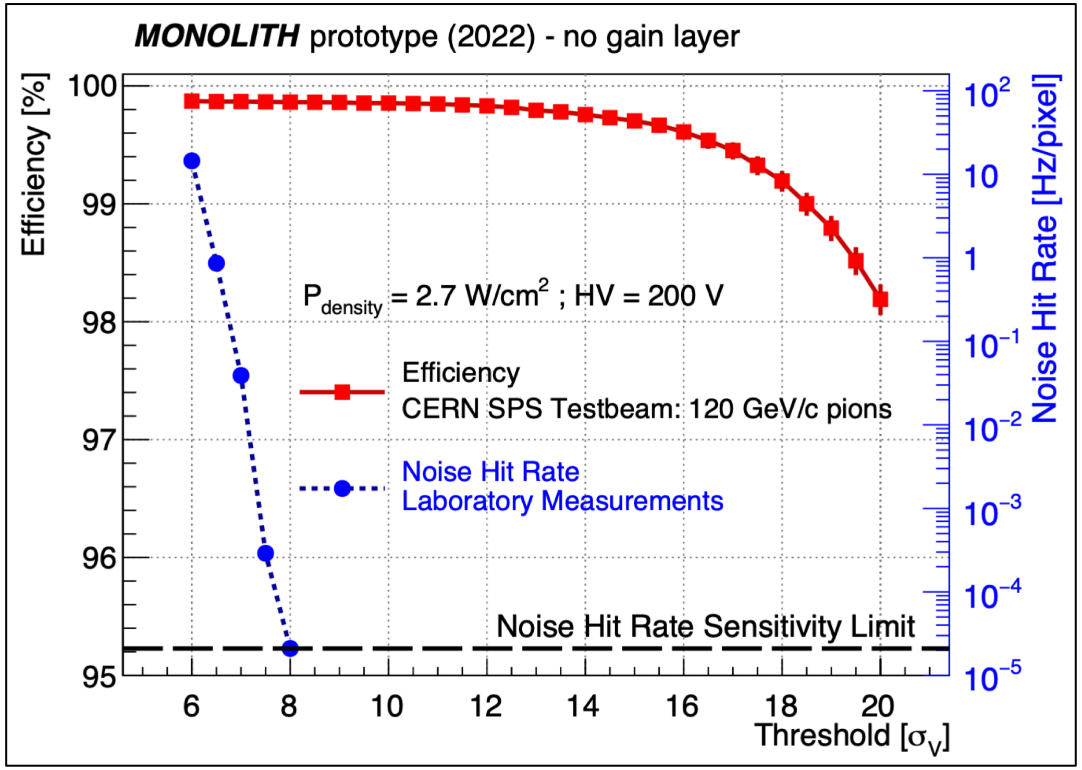
20 ps

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

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

Efficiency Results

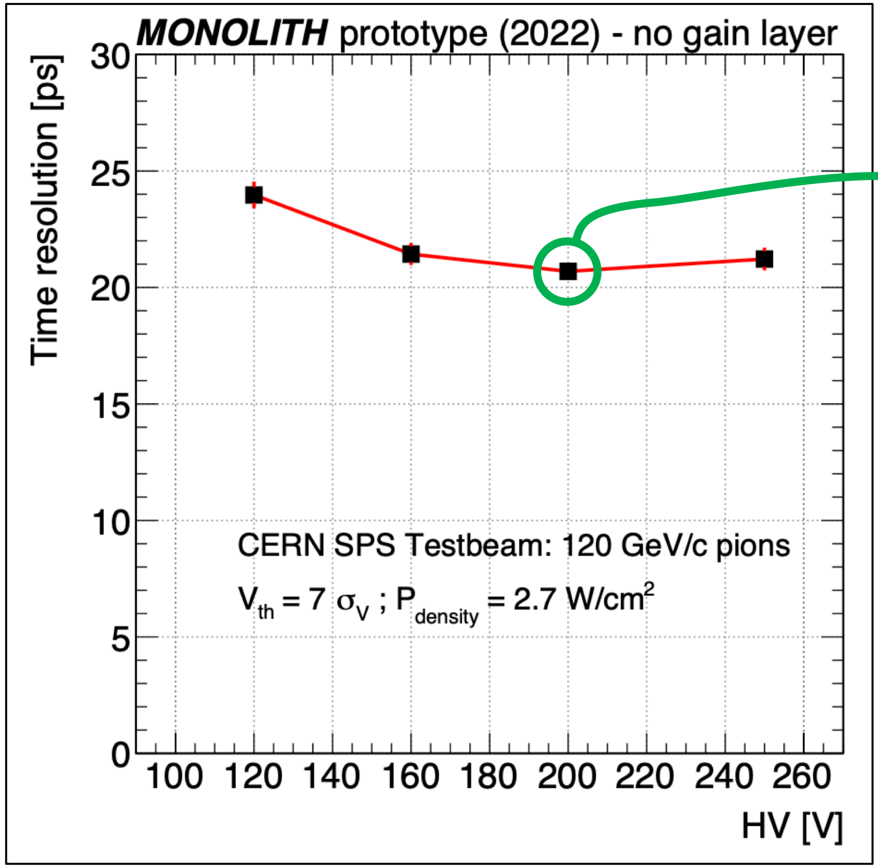


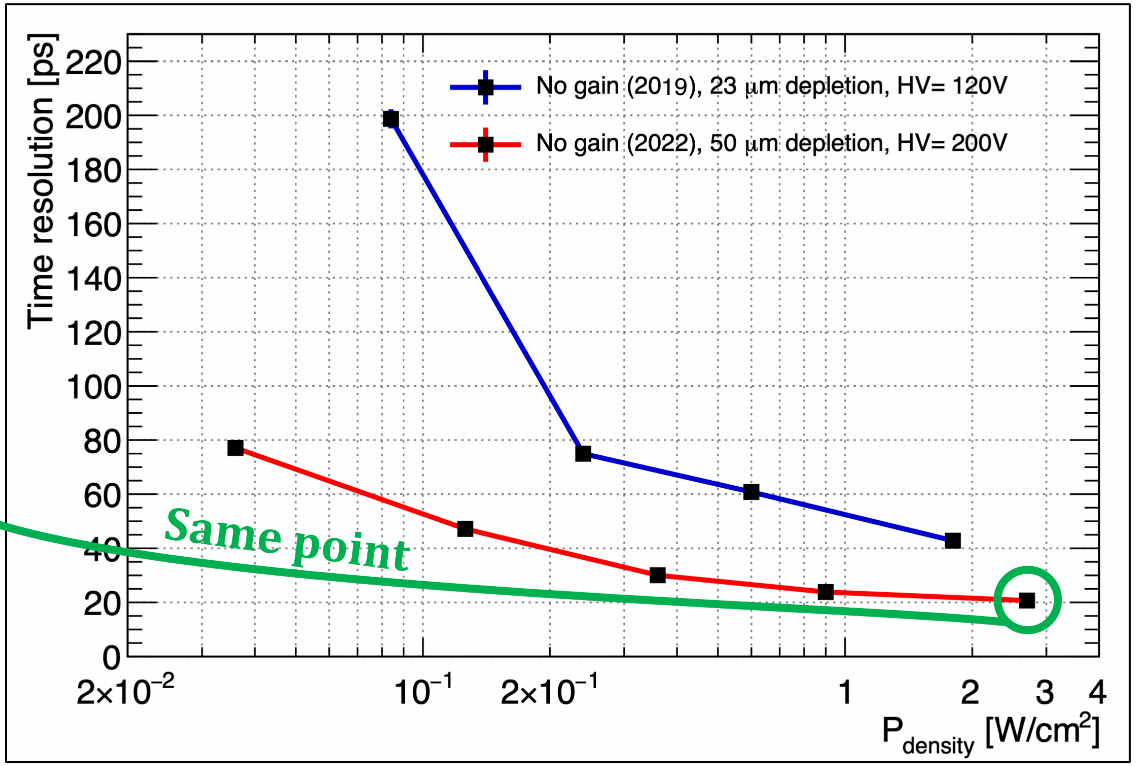


- The **apparent degradation** at the edges is due to the ~10 µm resolution of the telescope
- Selection of two **triangles:**
  - representative of the whole pixel
  - **unbiased** from the telescope resolution

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

Time Resolution Results





Large plateau of 100 V with ~20 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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SiGe BiCMOS Radiation Hardness

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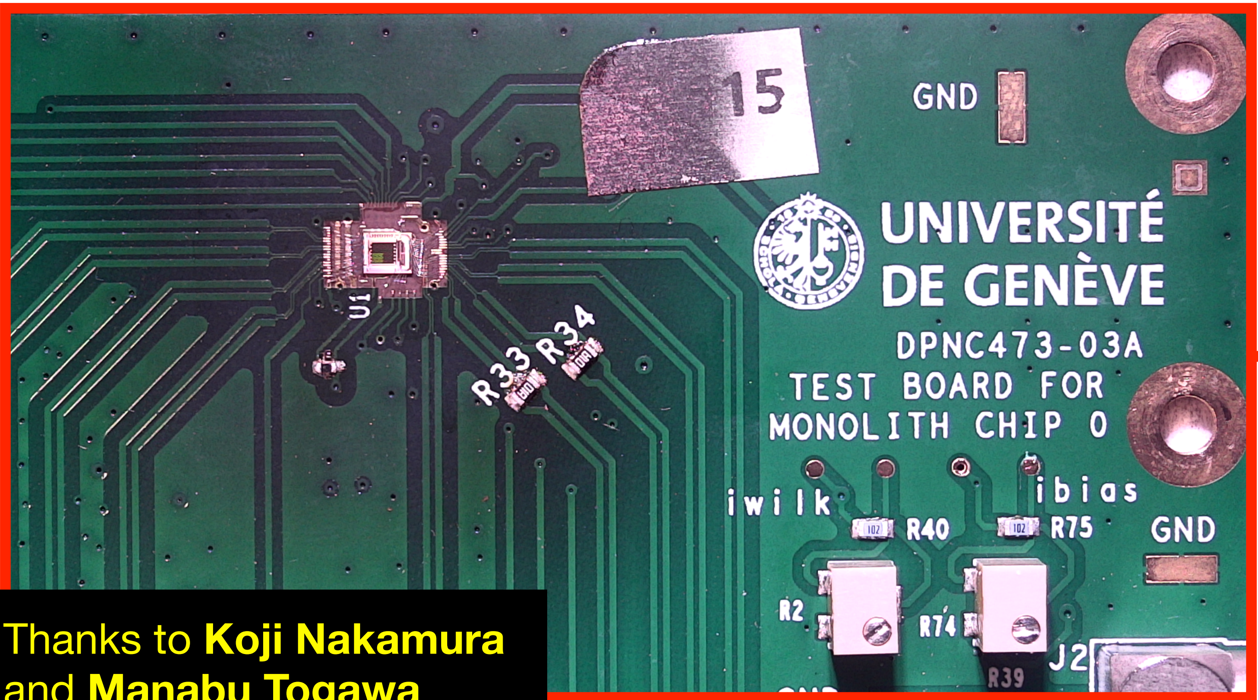


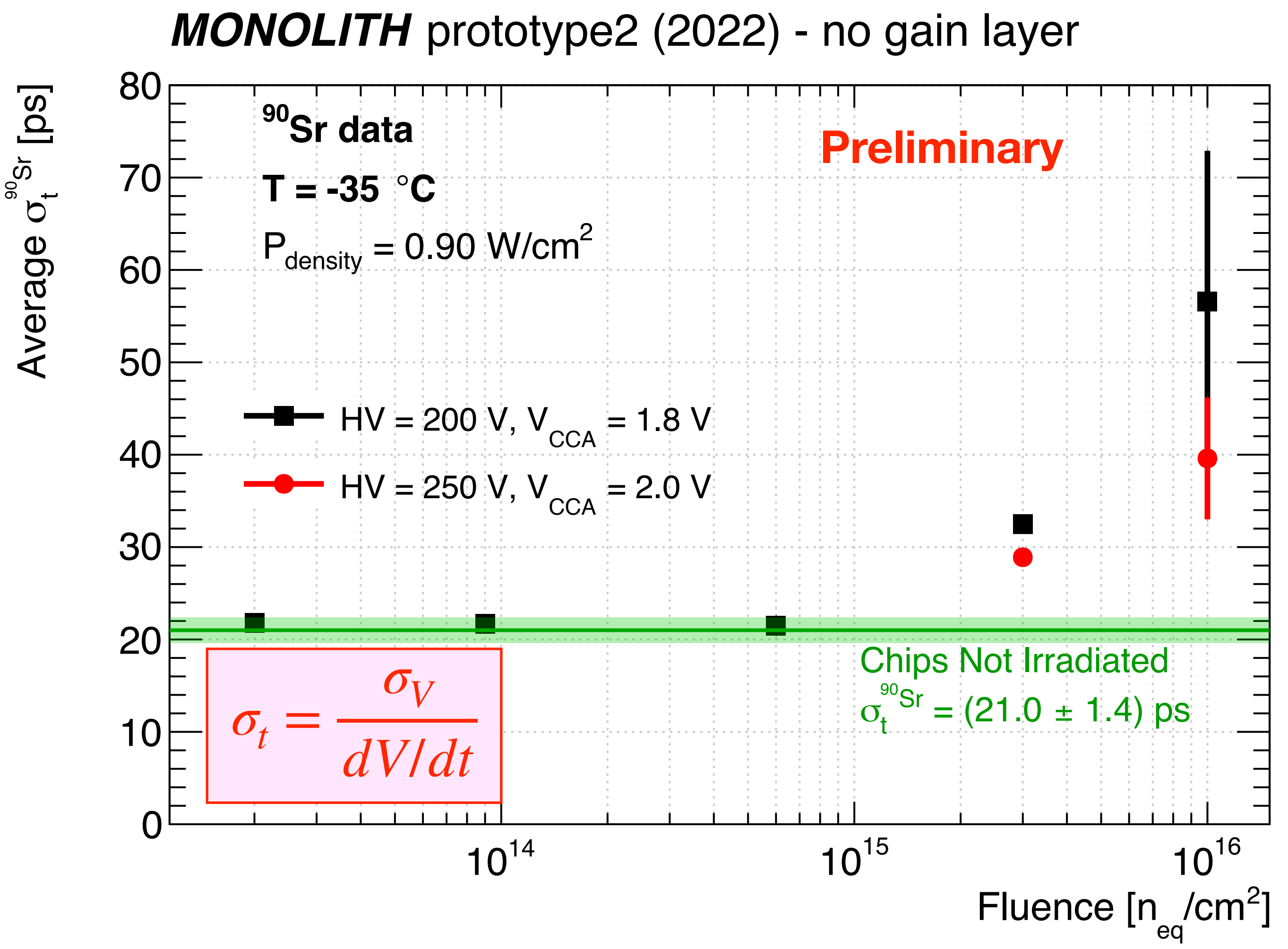
Thanks to **Koji Nakamura** and **Manabu Togawa**

Board Name	Fluence [1 MeV n_{eq}/cm^2]
M23	$2 \cdot 10^{13}$
M22	$9 \cdot 10^{13}$
M21	$6 \cdot 10^{14}$
M19	$6 \cdot 10^{14}$
M18	$3 \cdot 10^{15}$
M17	$3 \cdot 10^{15}$
M16	$1 \cdot 10^{16}$
M15	$1 \cdot 10^{16}$
M06	not irradiated – for comparison
M05	not irradiated – for comparison
M07	not irradiated – for comparison

- 8 prototypes irradiated in Japan up to $1{\times}10^{16}$ n_{eq}/cm^2
- One of the not irradiated chips is the same as in **Testbeam of 2022 Prototype**

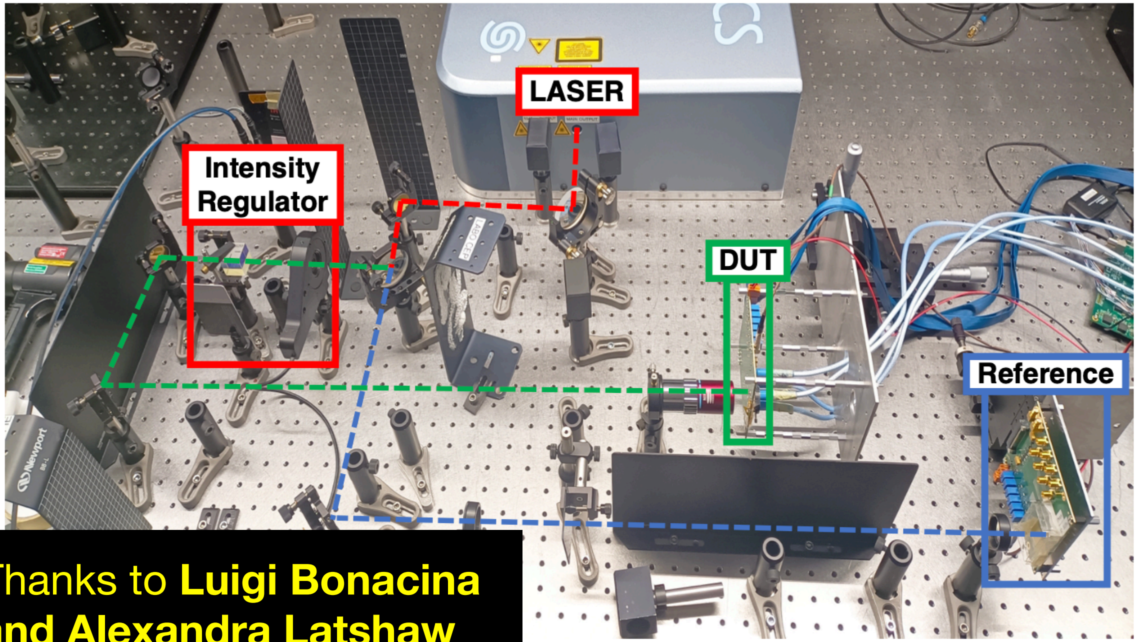
Time Jitter After Irradiation

- The time jitter with ^{90}Sr increases **from 21 ps** (not irradiated) **to 56 ps** (at 10^{16} n_{eq}/cm^2) at **HV = 200 V** and **0.9 W/cm²**
- The time jitter can be reduced **to 40 ps** by tuning V_{CCA} and HV

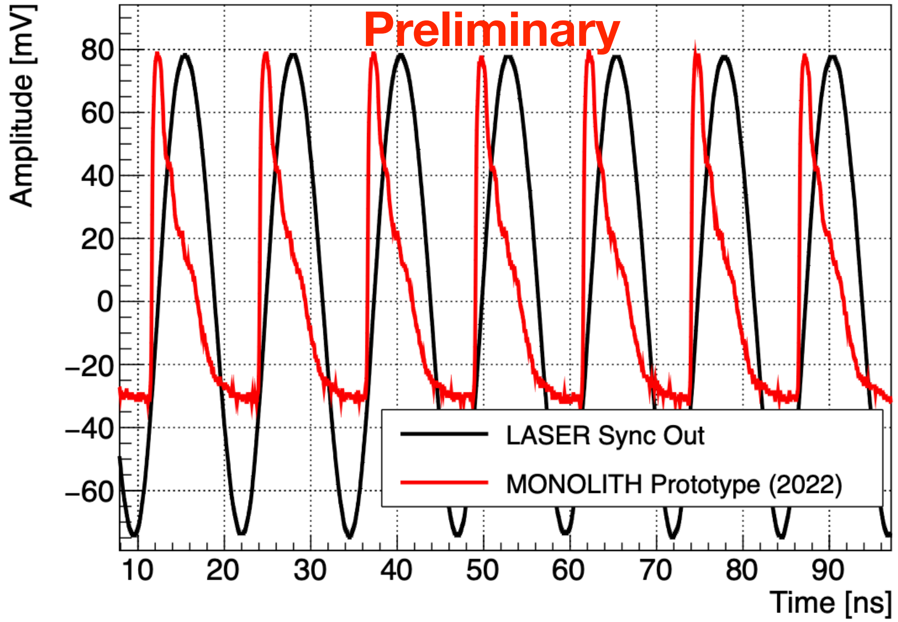


Laser Measurements

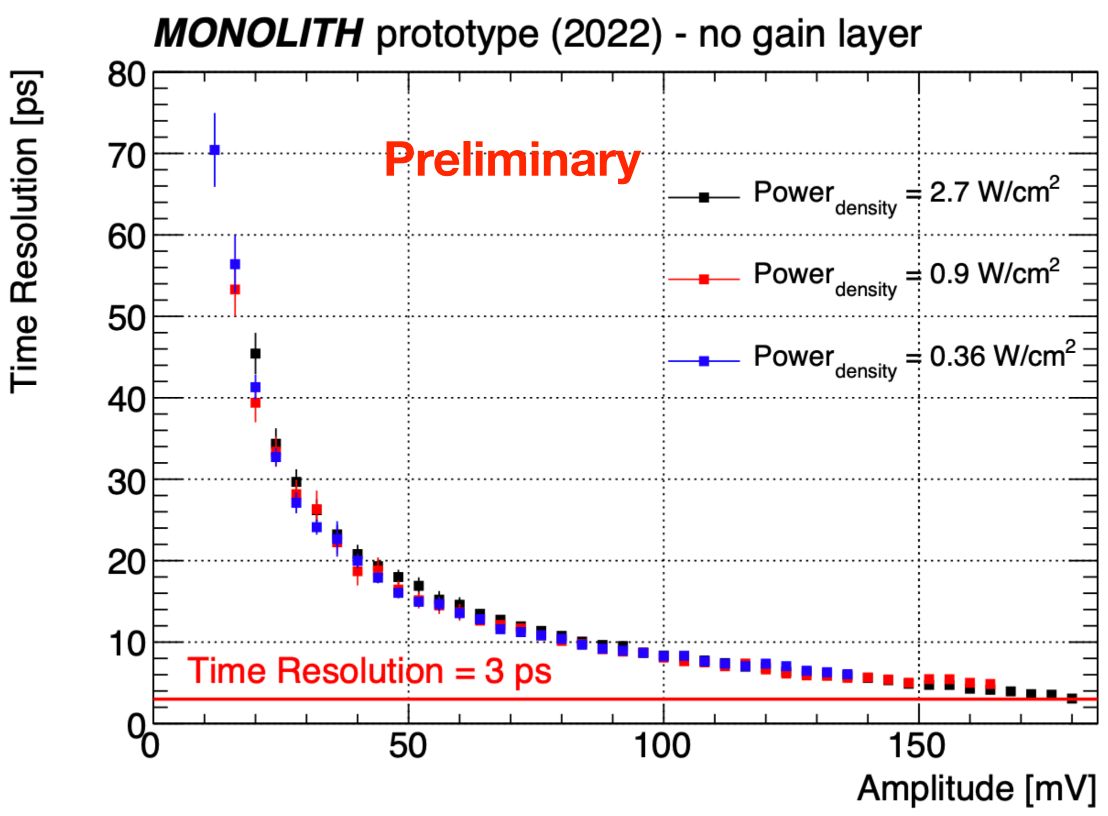
- Pulsed Infrared laser:
  - Intrinsic jitter of **100 fs**
  - repetition frequency of **80 MHz**
- Time coincidence between two of our samples:
  - "**Reference**" receiving always large laser pulse producing 17k electrons
  - "**DUT**" receiving variable laser power, to study the performance vs. amplitude

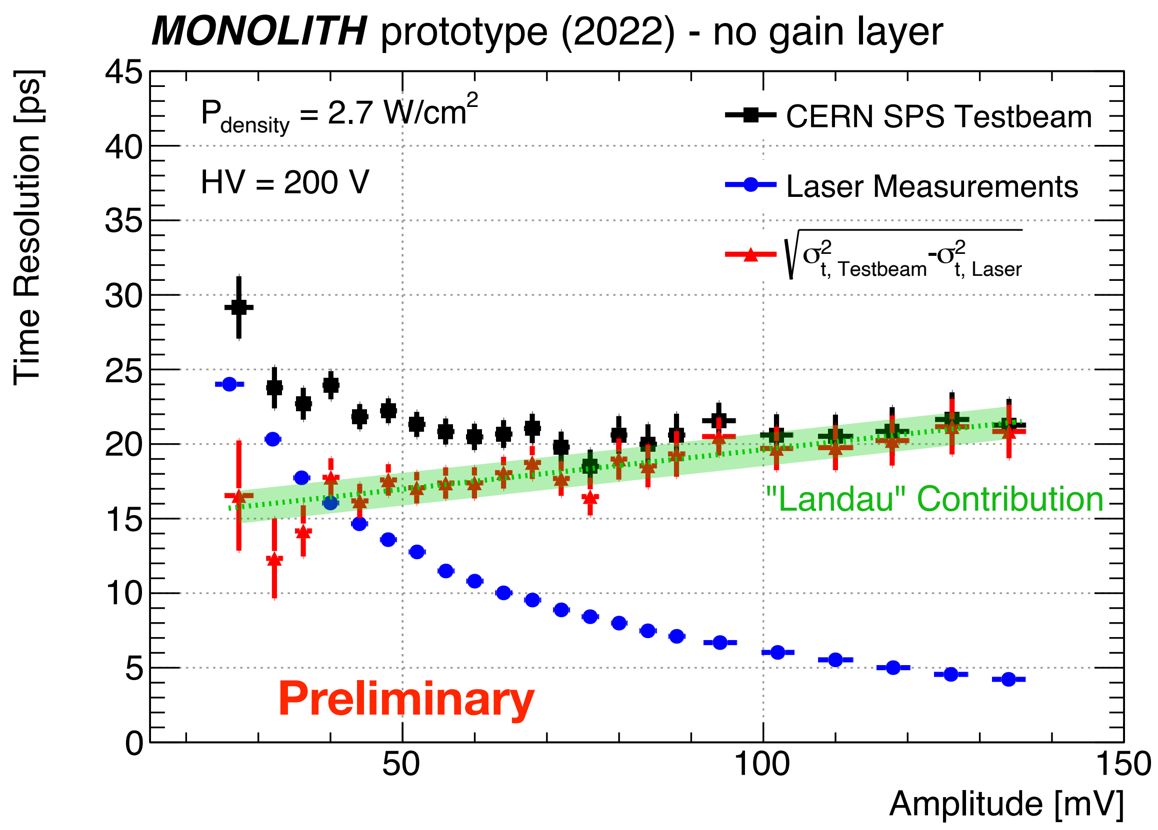


Thanks to **Luigi Bonacina and Alexandra Latshaw**



Laser Results



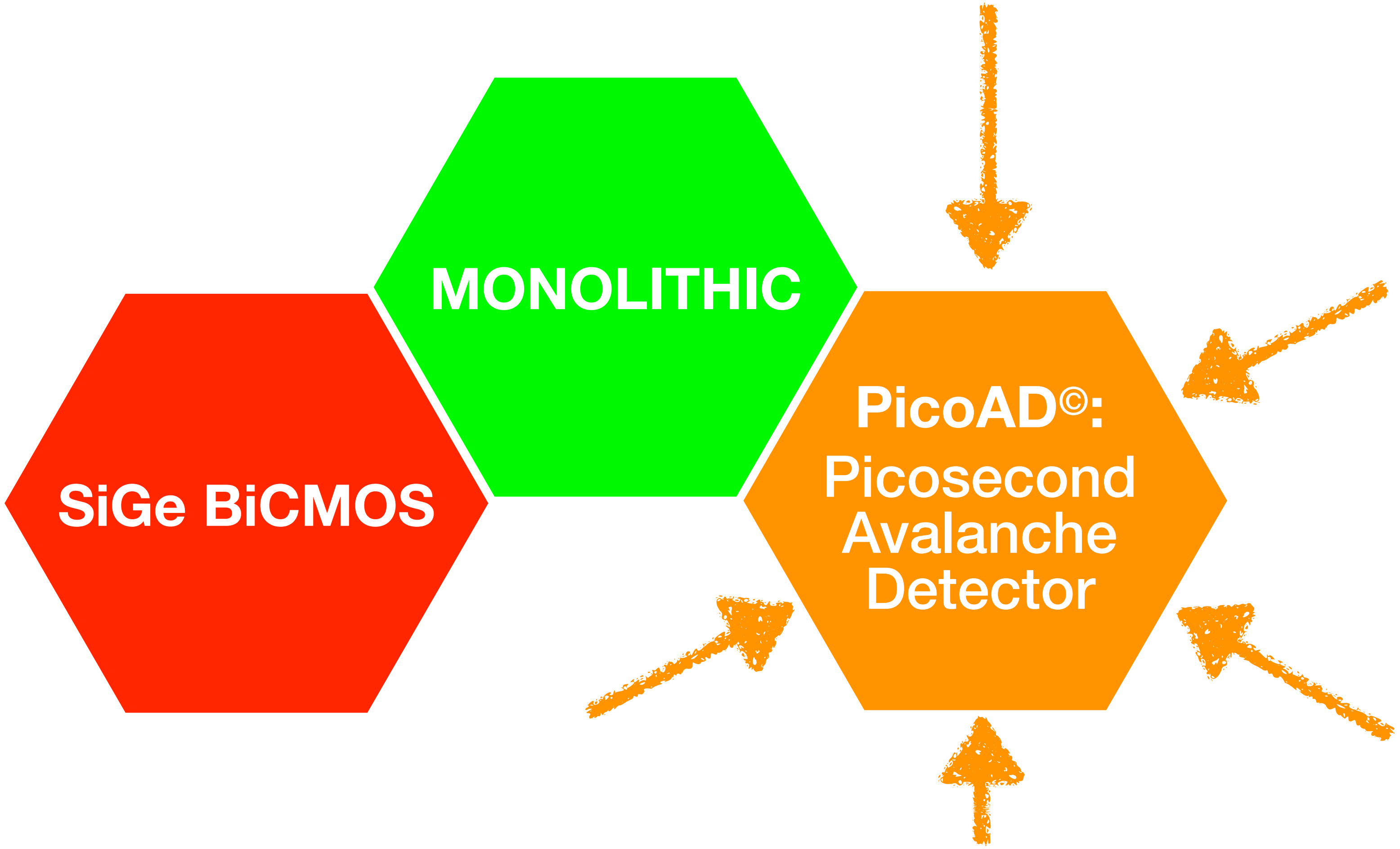


Time resolution of 3 ps
with 11k electrons (4 MIPs)

20 ps of Charge Collection Noise
in a 50 μm-thick sensor

- **Limit to the time resolution** at high amplitudes -> **PicoAD©**

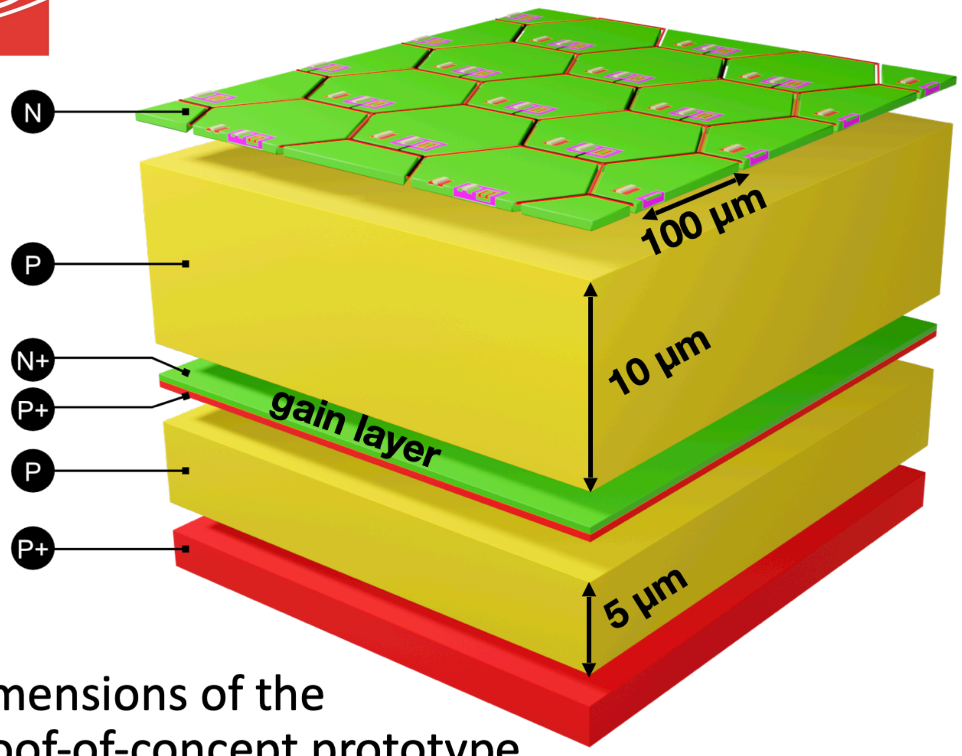
The MONOLITH ERC Project



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

PicoAD© Concept

- Multi-Junction **Pico-Avalanche Detector** (patented here)
- 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

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SiGe BiCMOS prototypes

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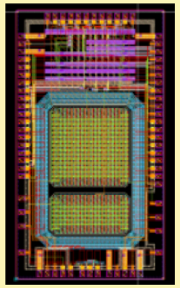
NO GAIN LAYER

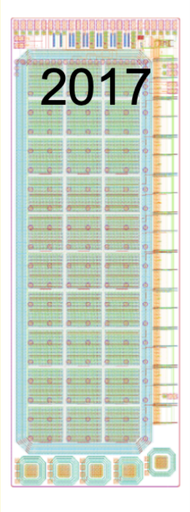
2016



200 ps

- 1 mm² pixel
- Discriminator

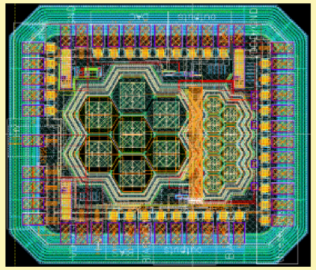
2017



110 ps

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

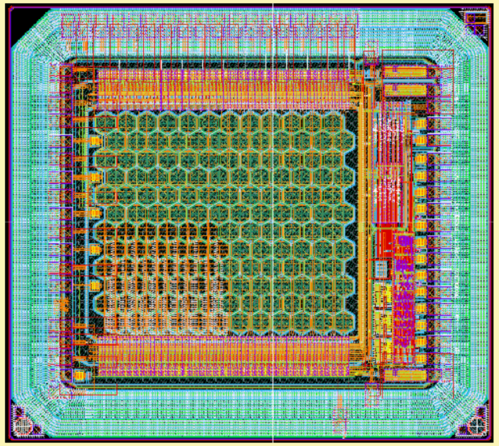
2018



50 ps

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

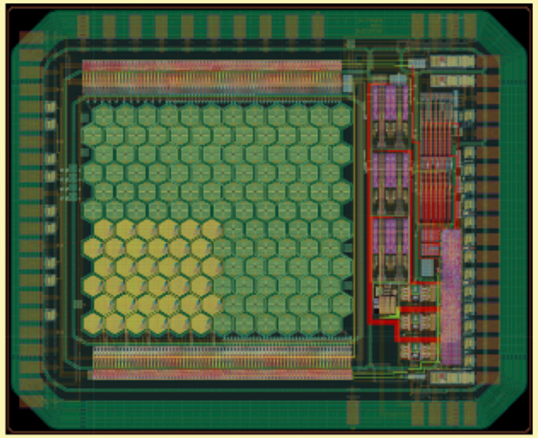
2019



36 ps

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

2022



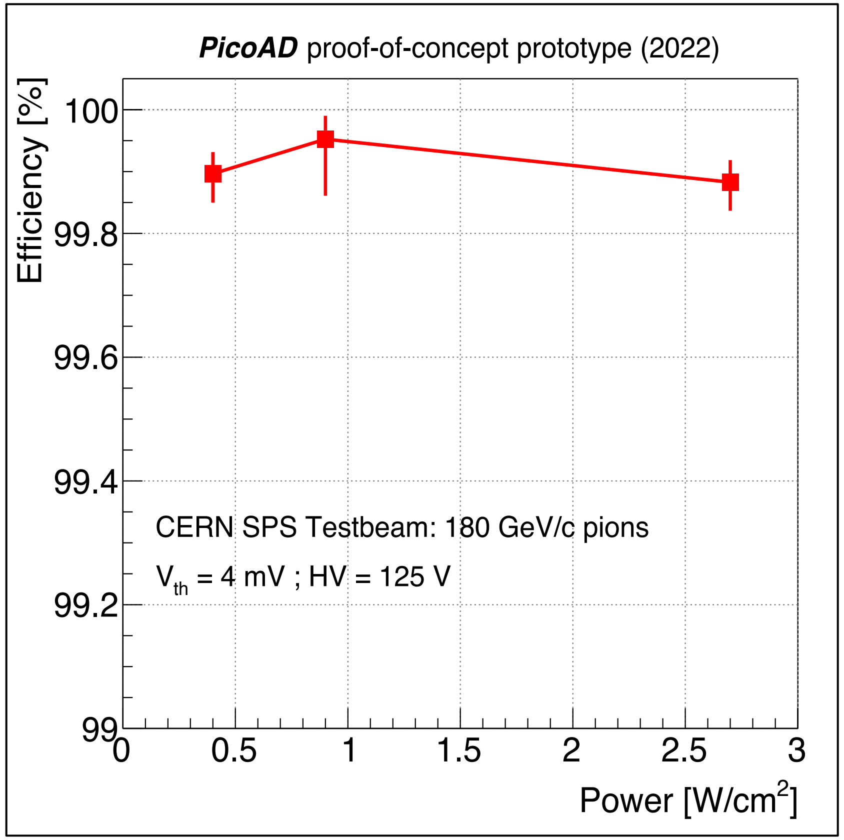
20 ps

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

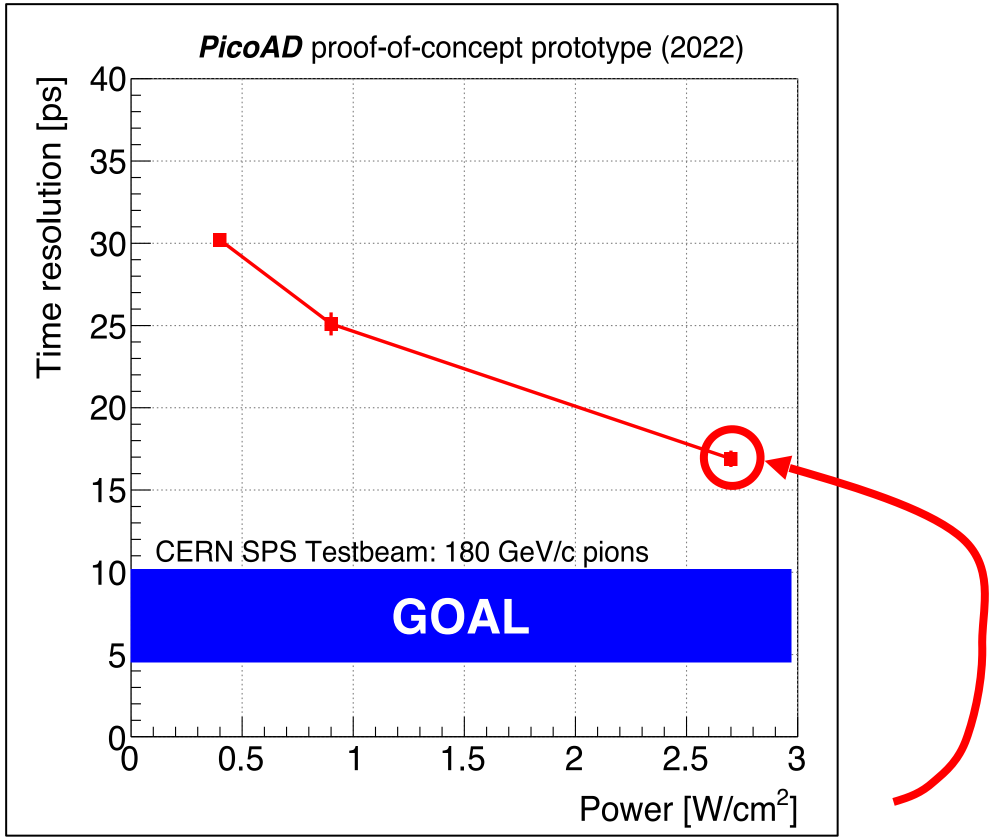
2022
PicoAD© version
17 ps

Efficiency and Time Resolution

Similar experimental setup with FE-I4 telescope: **Testbeam of PicoAD**



99.9% for all the power consumptions



Best performance: (17.3 ± 0.4) ps

HV = 125 V and $P_{density}$ = **2.7 W/cm²**

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Future prototypes

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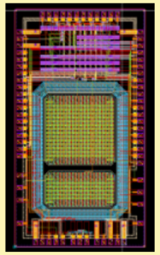
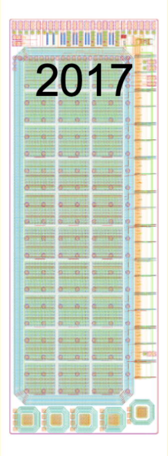
NO GAIN LAYER

2016



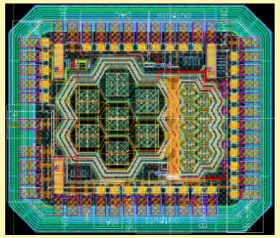
200 ps
- 1 mm² pixel
- Discriminator

2017



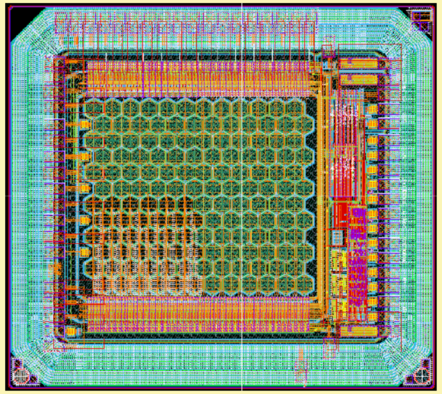
110 ps
- 30 pixels 500x500µm²
- 100ps TDC +I/O logic

2018



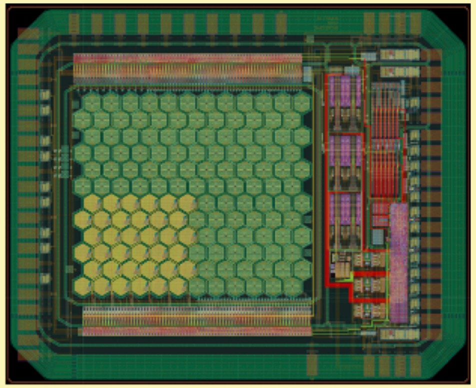
50 ps
- Hexagonal pixels 65µm and 130µm side
- Discriminator output

2019



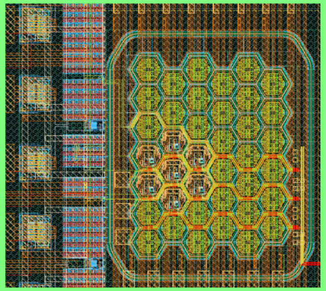
36 ps
- Hexagonal pixels 65µm side
- 30ps TDC +I/O logic
- Analog channels

2022



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

March 2023



< 20 ps ?
- Hexagonal pixels **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 **σ_t = (20.7 ± 0.3) ps**
- After proton fluence of **10^{16} n_{eq}/cm^2 :**
  - **Time resolution of 40 ps**

→ **Serious candidate for future 4D tracking**

- **The PicoAD© monolithic proof-of-concept prototype works**. The introduction of a deep gain layer improves the performances:
  - **Efficiency = 99.9%** including inter-pixel regions
  - **Time resolution σ_t = (17.3 ± 0.4) ps**

- Development of **picosecond TDC** (patented here) for fully monolithic chip

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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

Jorge Sabater Iglesias
- Detector Simulations
- Laboratory Tests

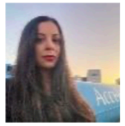
Lorenzo Paolozzi
- Sensor design
- Analog electronics

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

Andrea Pizarro Medina
- Data Analysis
- Laboratory Tests

Didier Ferrere
- System integration
- Laboratory test

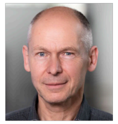
Sergio Gonzalez-Sevilla
- System integration
- Laboratory test

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

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Sinergia

ATTRACT

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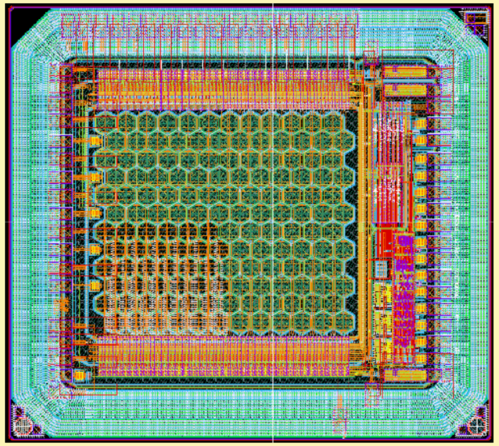
2019->2022: Improvements

- Same matrix configuration as previous, but
  - Substrate: 50 Ωcm → 350 Ωcm epi layer, 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



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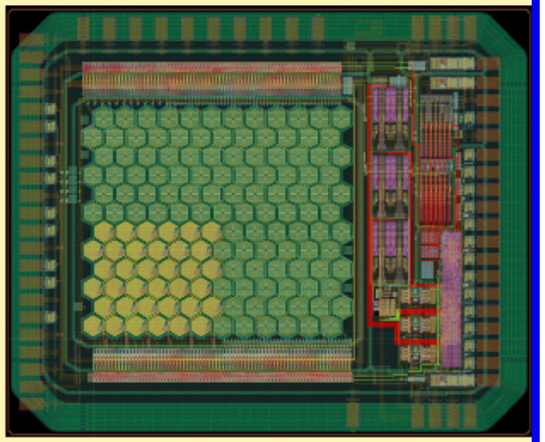

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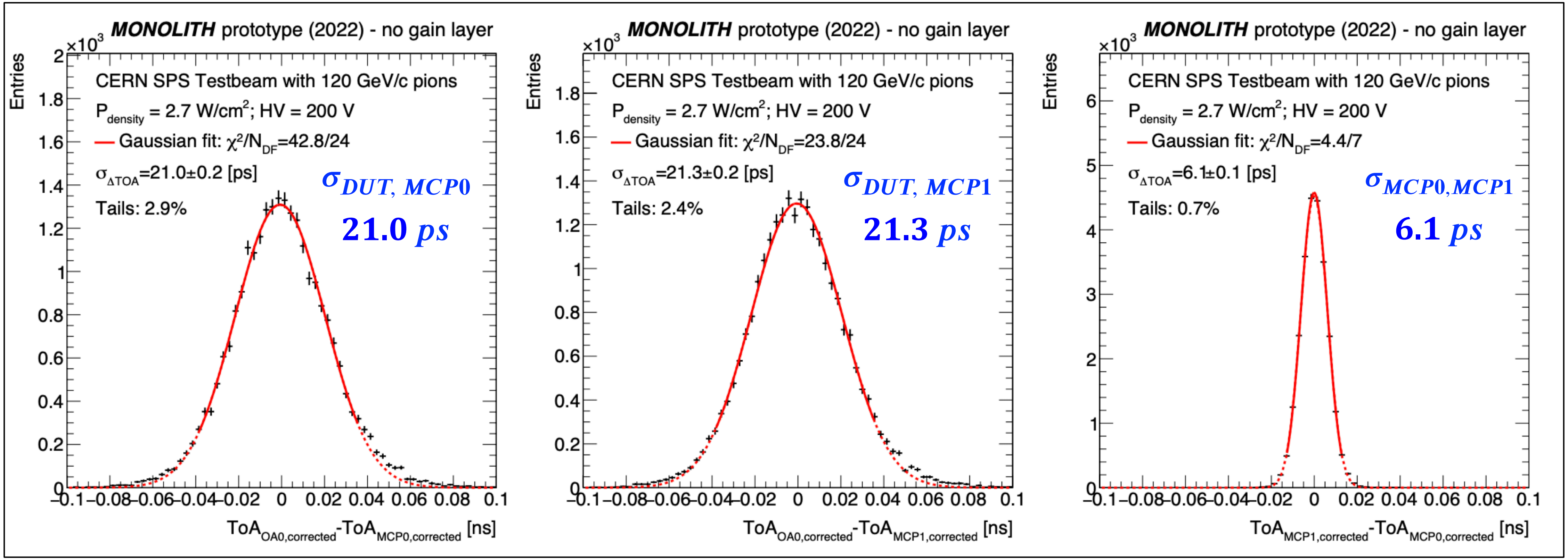
Time Resolution Distributions



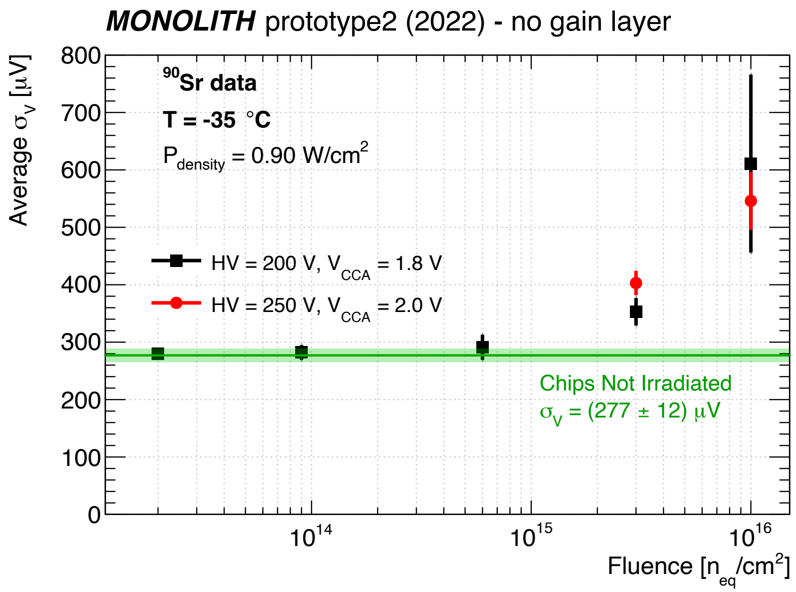
- Very **Gaussian** distributions after time walk correction
- Simultaneous fit to extract the time resolution of **DUT**, **MCP0**, **MCP1**[3]:

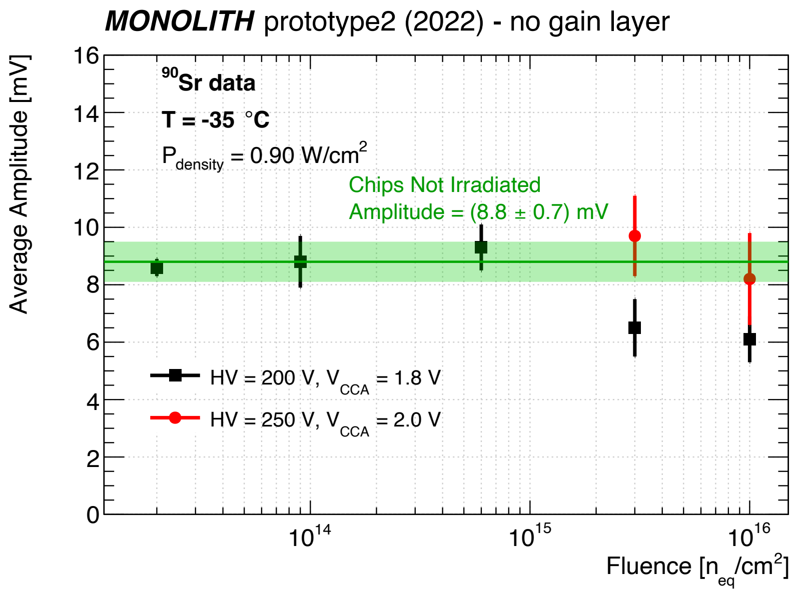
MCP0: $\sigma_t = (3.6 \pm 1.5)\ ps$

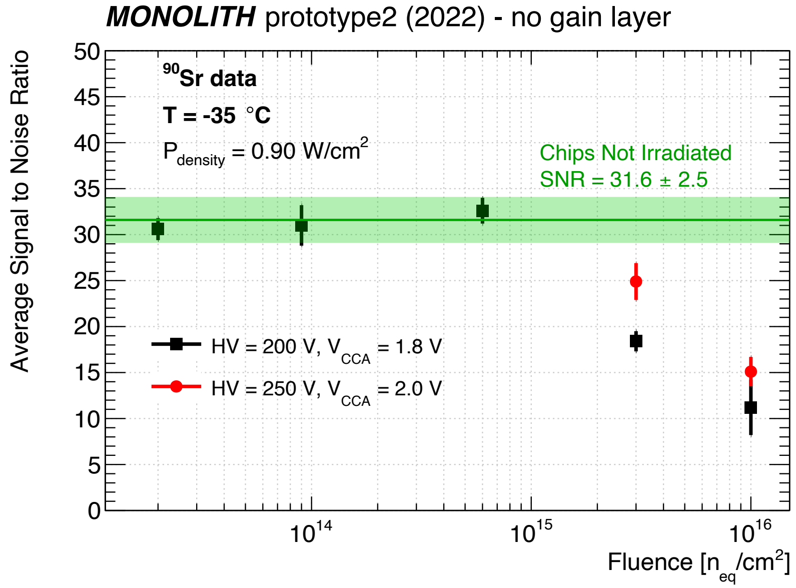
MCP1: $\sigma_t = (5.0 \pm 1.1)\ ps$

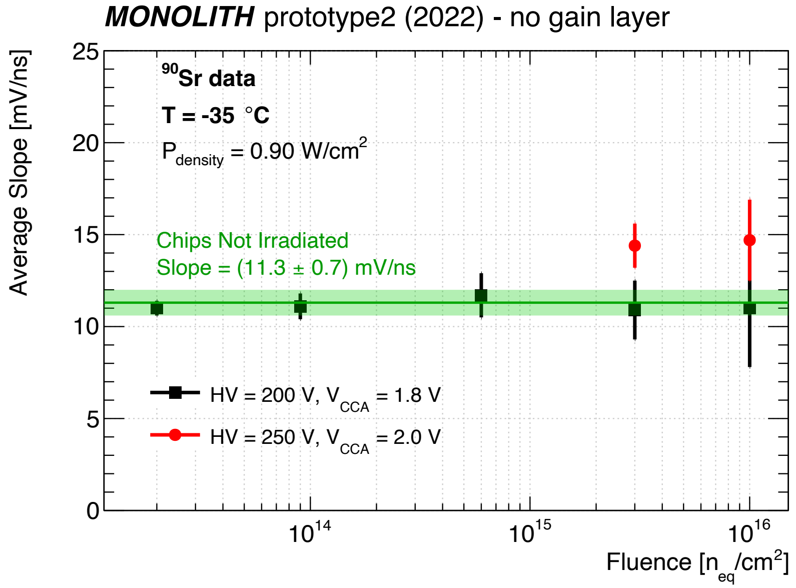
DUT: $\sigma_t = (20.7 \pm 0.3)\ ps$

Radiation Hardness

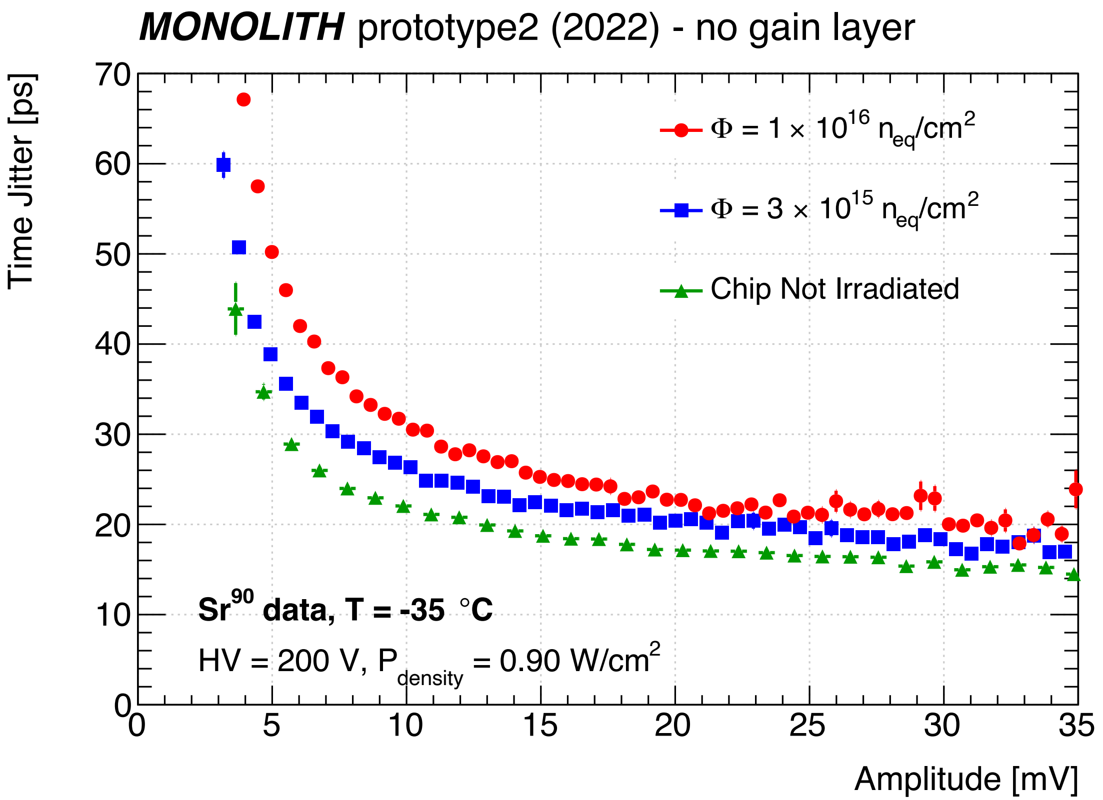


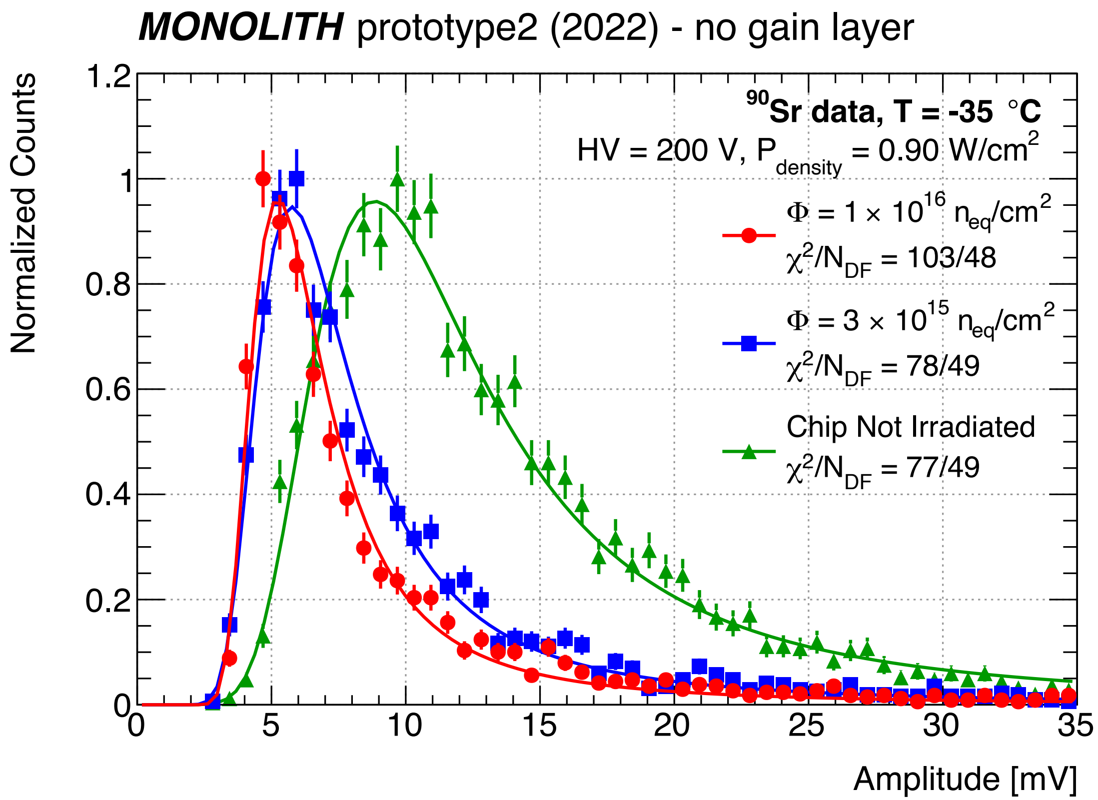






Radiation Hardness





Efficiency of Irradiated Samples

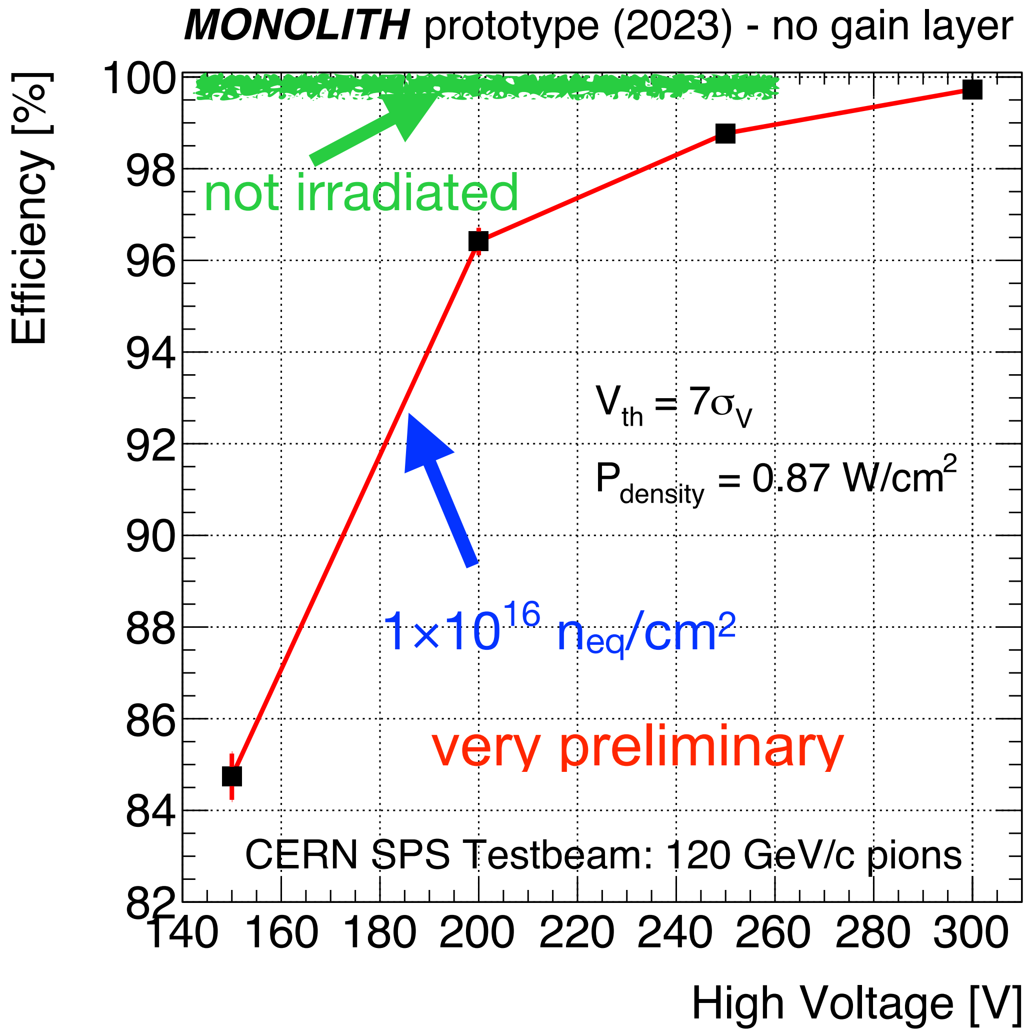
Very preliminary

August 2023 testbeam at CERN SPS

Board irradiated 1×10^{16} n_{eq}/cm^2 :

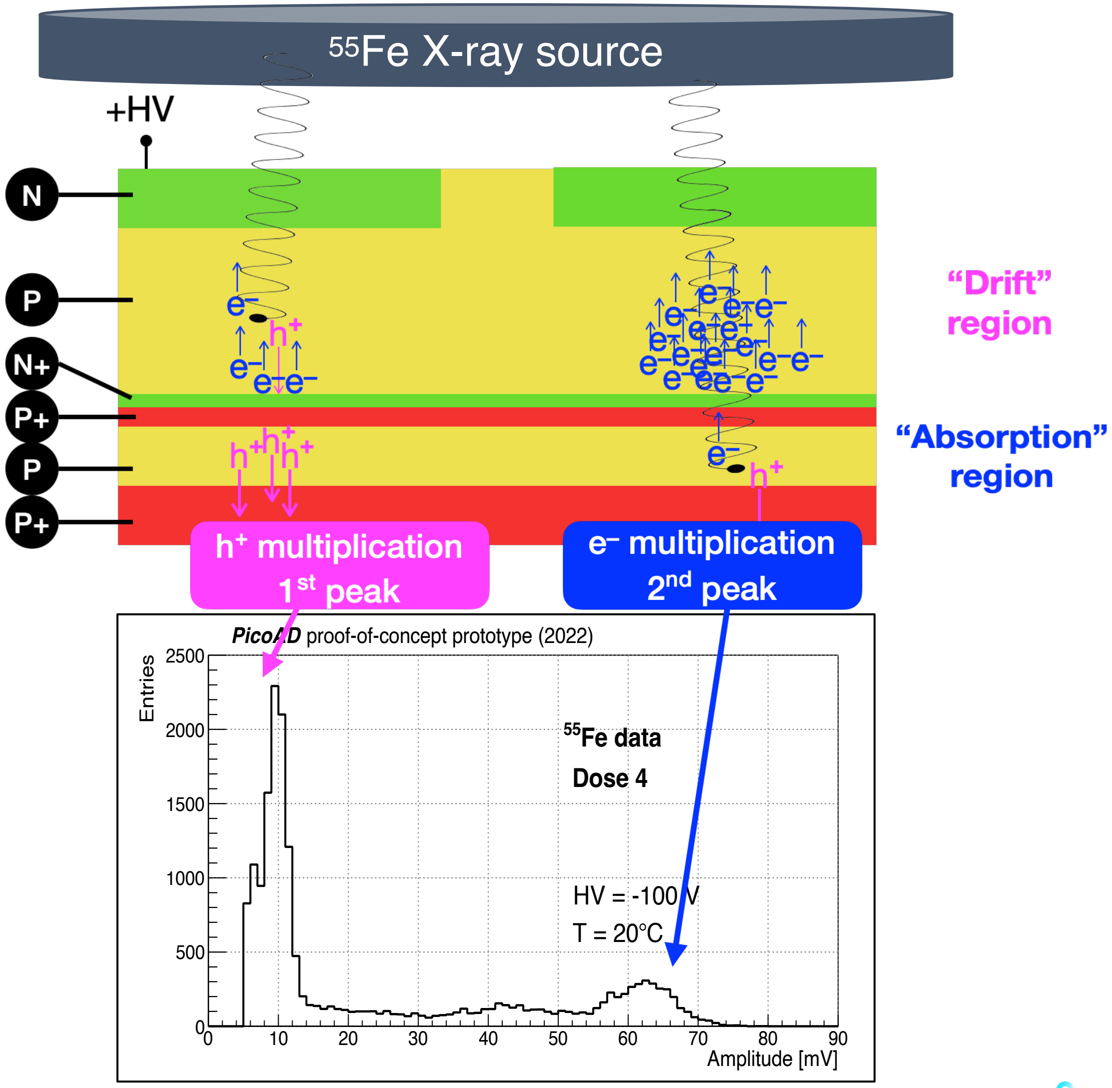
efficiency still ≳ 99%

for HV ≳ 250 V at 0.9 W/cm²



Gain Measurements

- **X-rays from ^{55}Fe radioactive source**:
  - ~5.9 keV photons with point-like charge deposition
- **Characteristic double-peak spectrum** (PicoAD Working Principles)
  - 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 (Gain Measurements)



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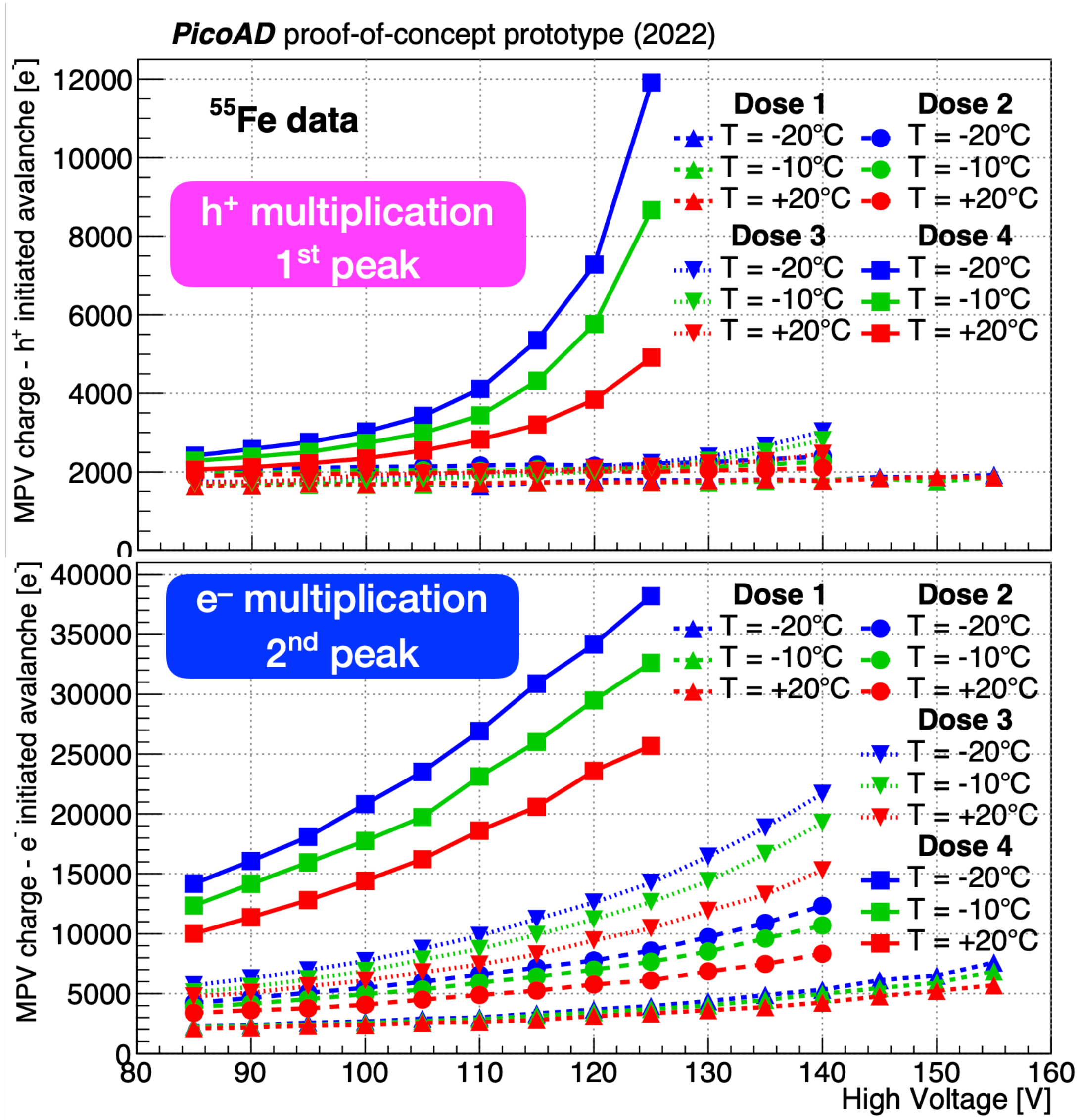
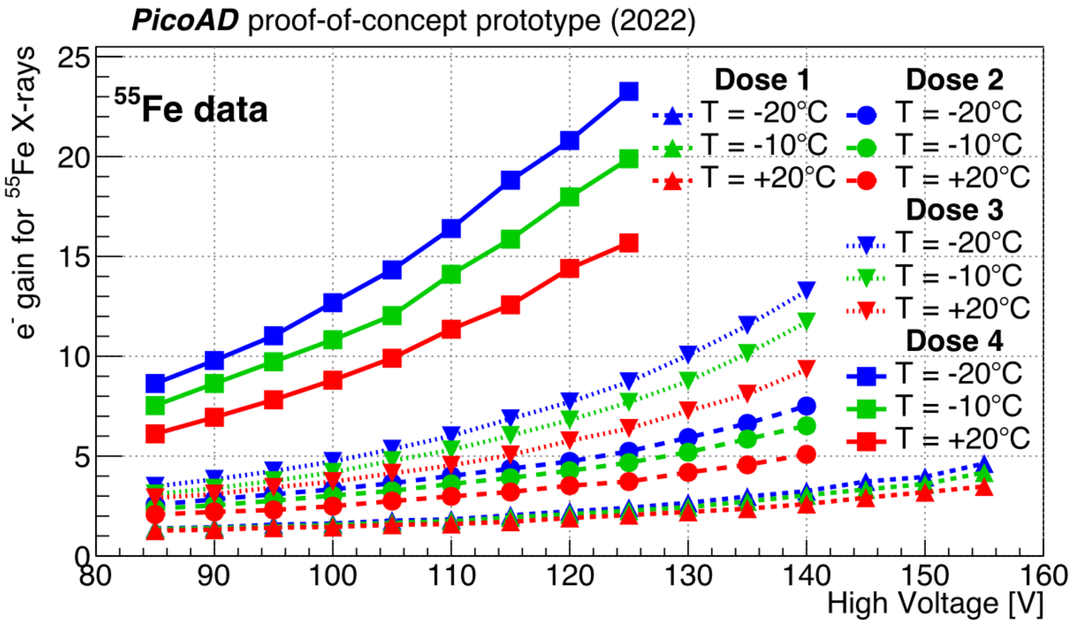
Gain Results



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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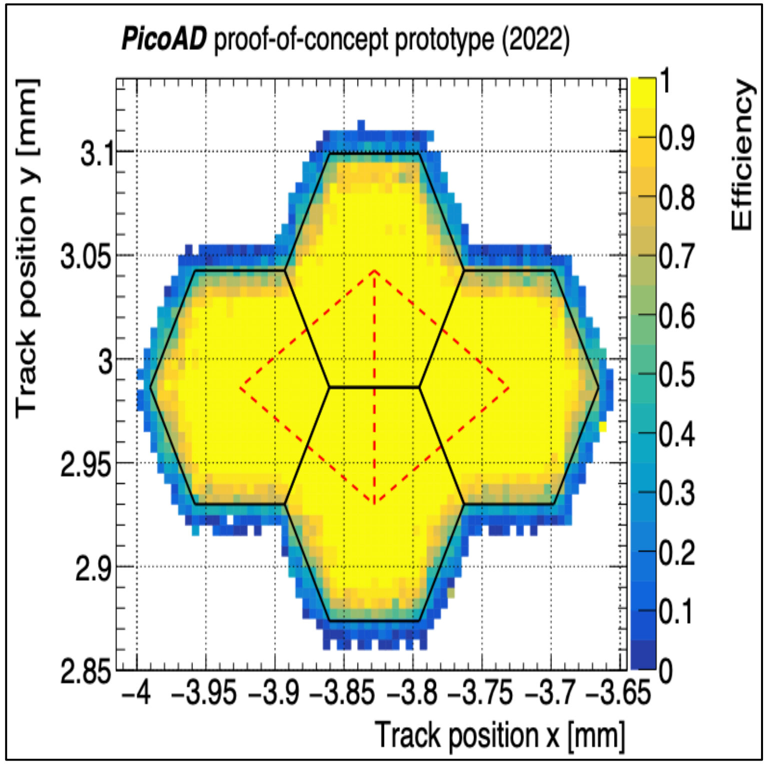
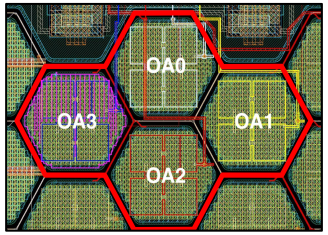
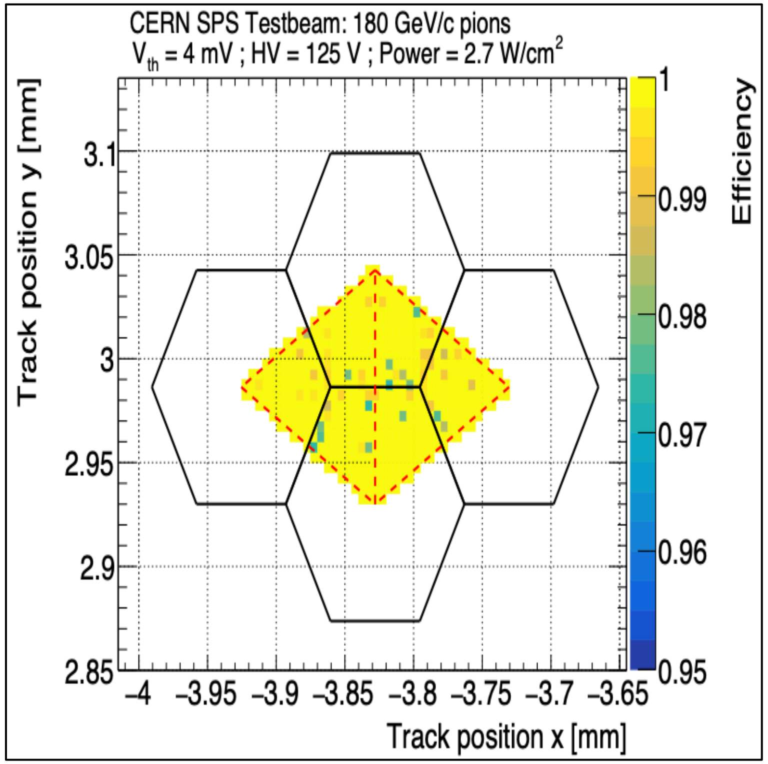
PicoAD: Efficiency Maps





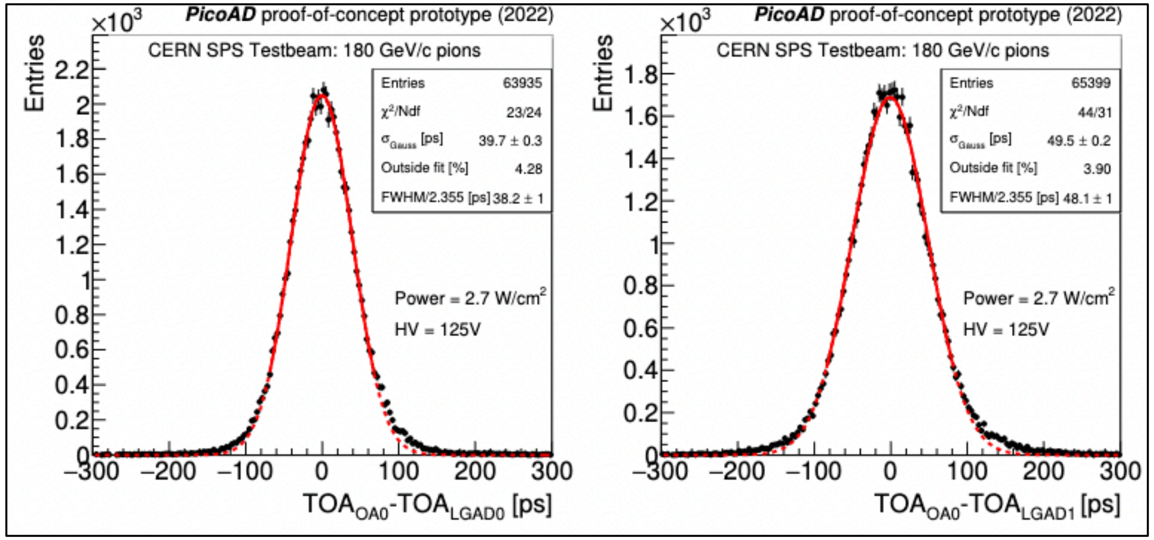


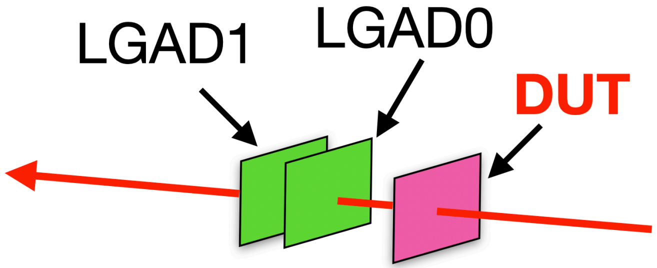
- The **apparent degradation** at the edges is due to the finite resolution of the telescope (~10 μm)

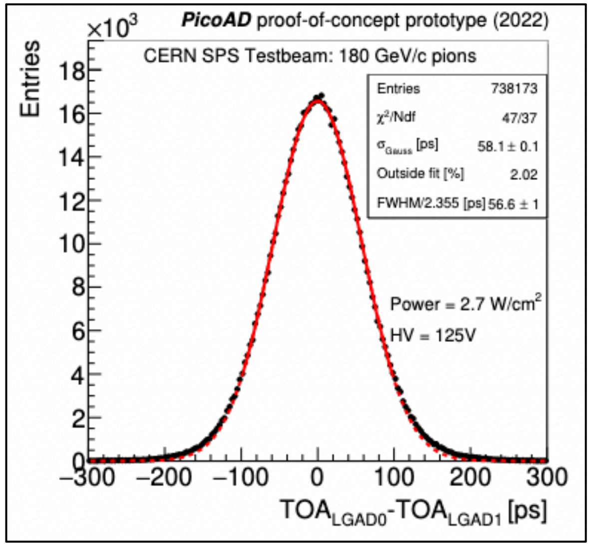
- Selection of two **triangles:**
  - representative of the whole pixel
  - **unbiased** from the telescope resolution

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







Position Within the Pixel

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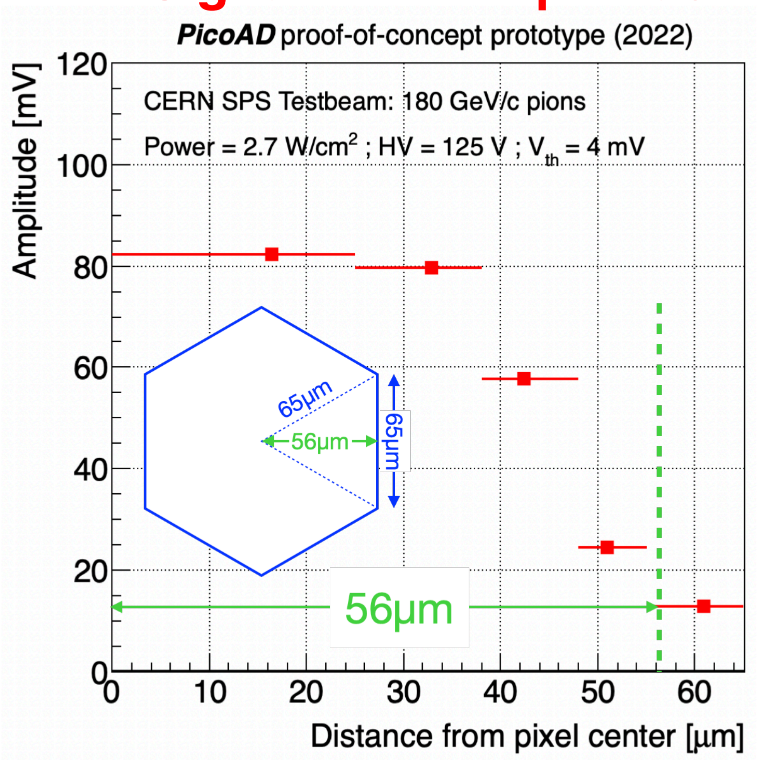
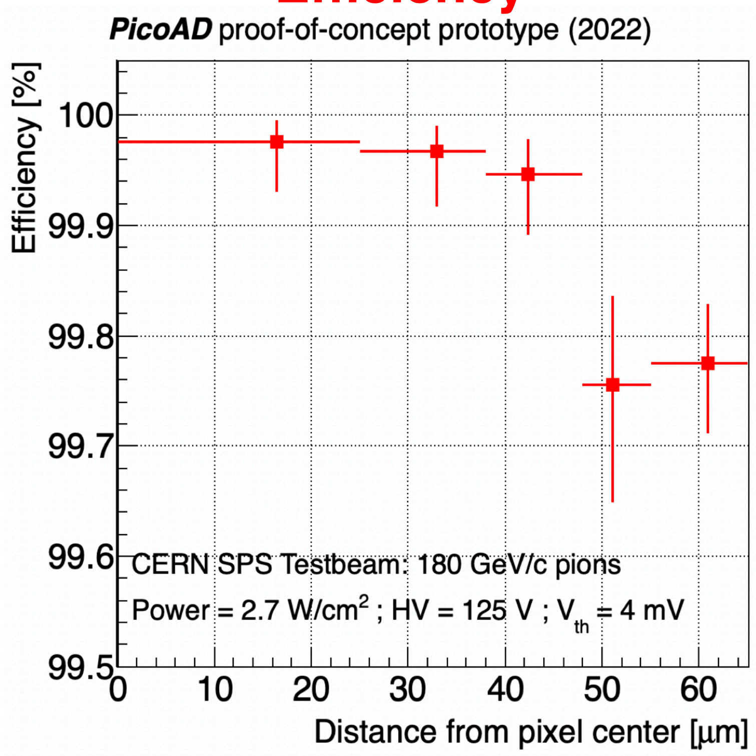
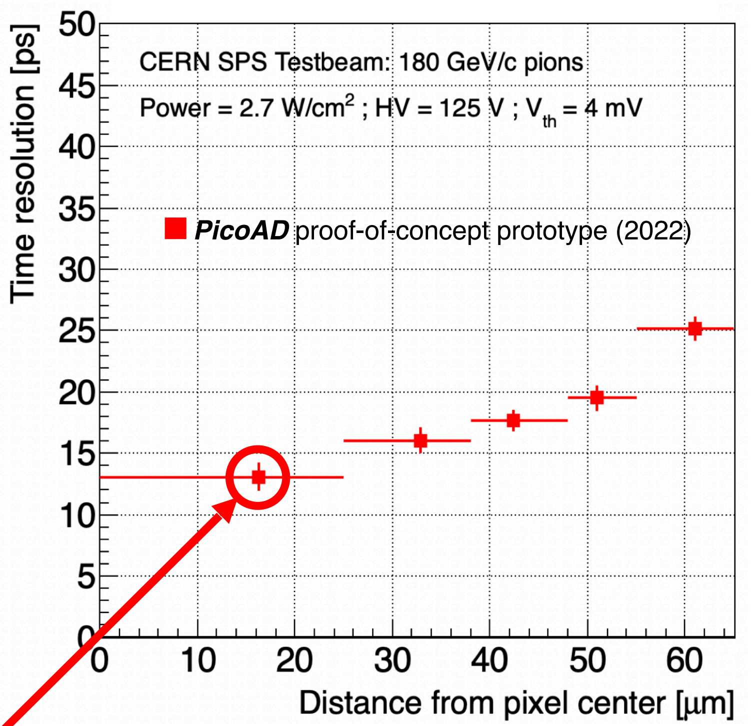
Signal MPV Amplitude



Efficiency



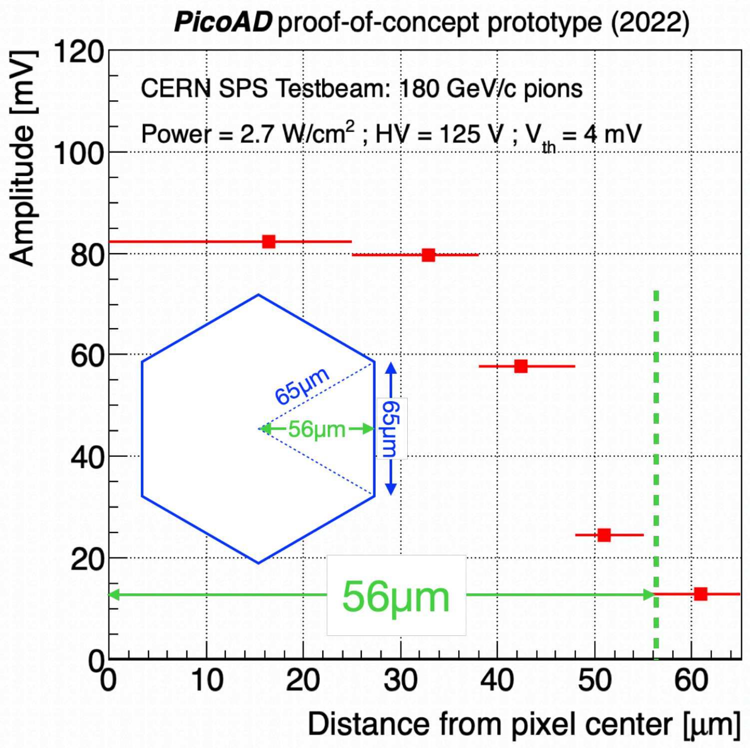
Time Resolution



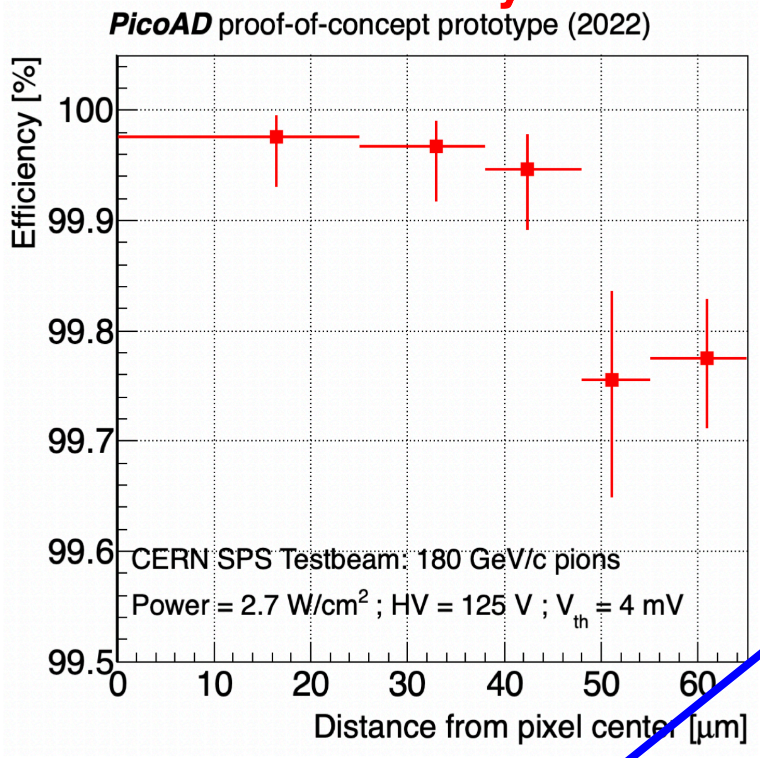
- Best time resolution: **(13.2 ± 0.8) ps within 25 µm** from the pixel center
- **PicoAD©** proof-of-concept: small degradation of the performance towards the edge of the pixel

Position Within the Pixel

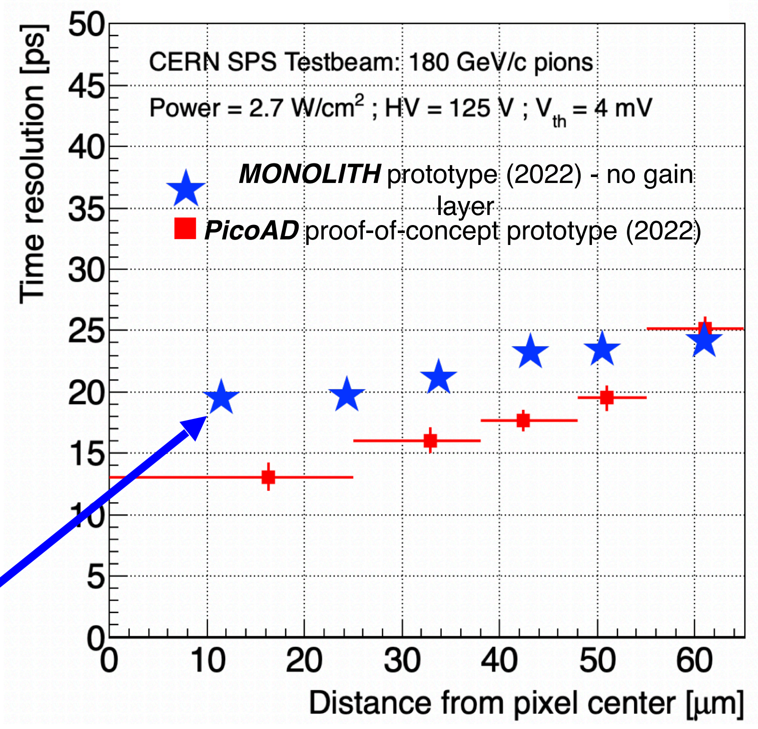
Signal MPV Amplitude



Efficiency



Time Resolution



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

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