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

Matteo Milanesio on behalf of the MONOLITH team

Université de Genève

Annual Meeting of the Swiss Physical Society

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

European Research Council
Established by the European Commission

FNSNF
Swiss National Science Foundation

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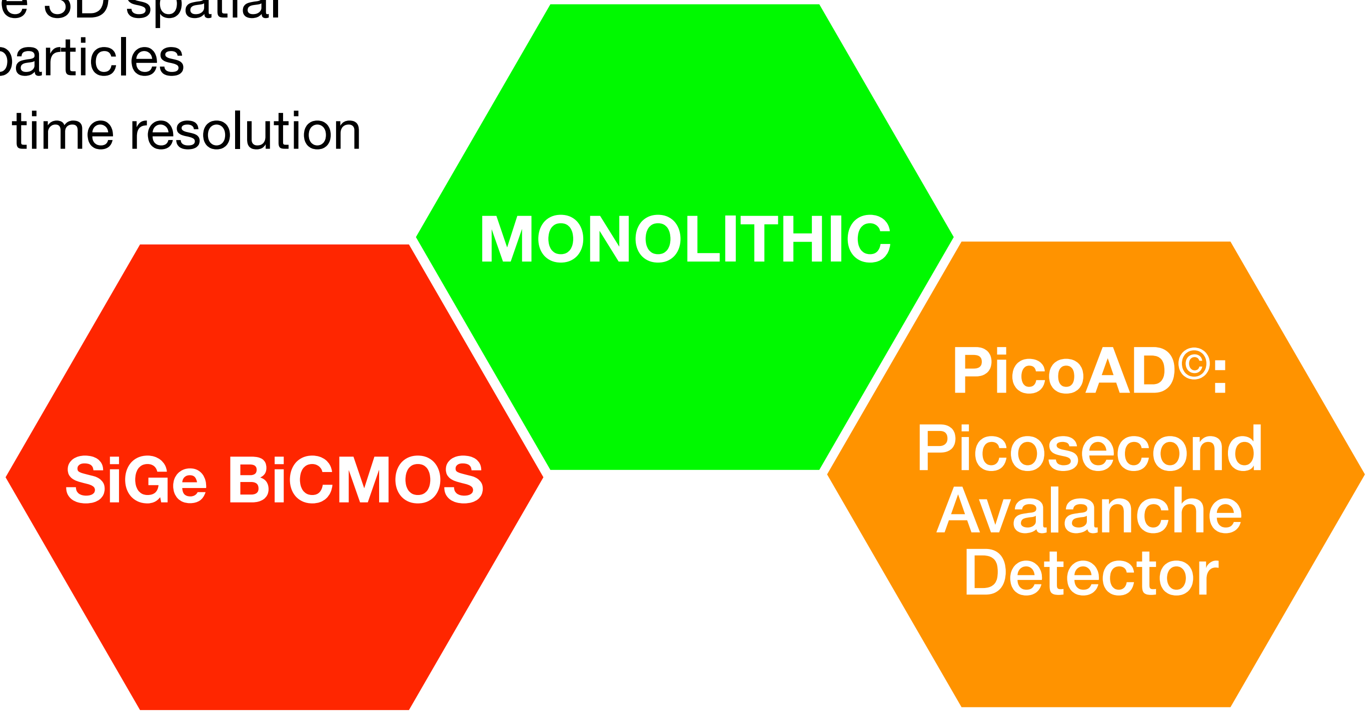
The MONOLITH ERC Project

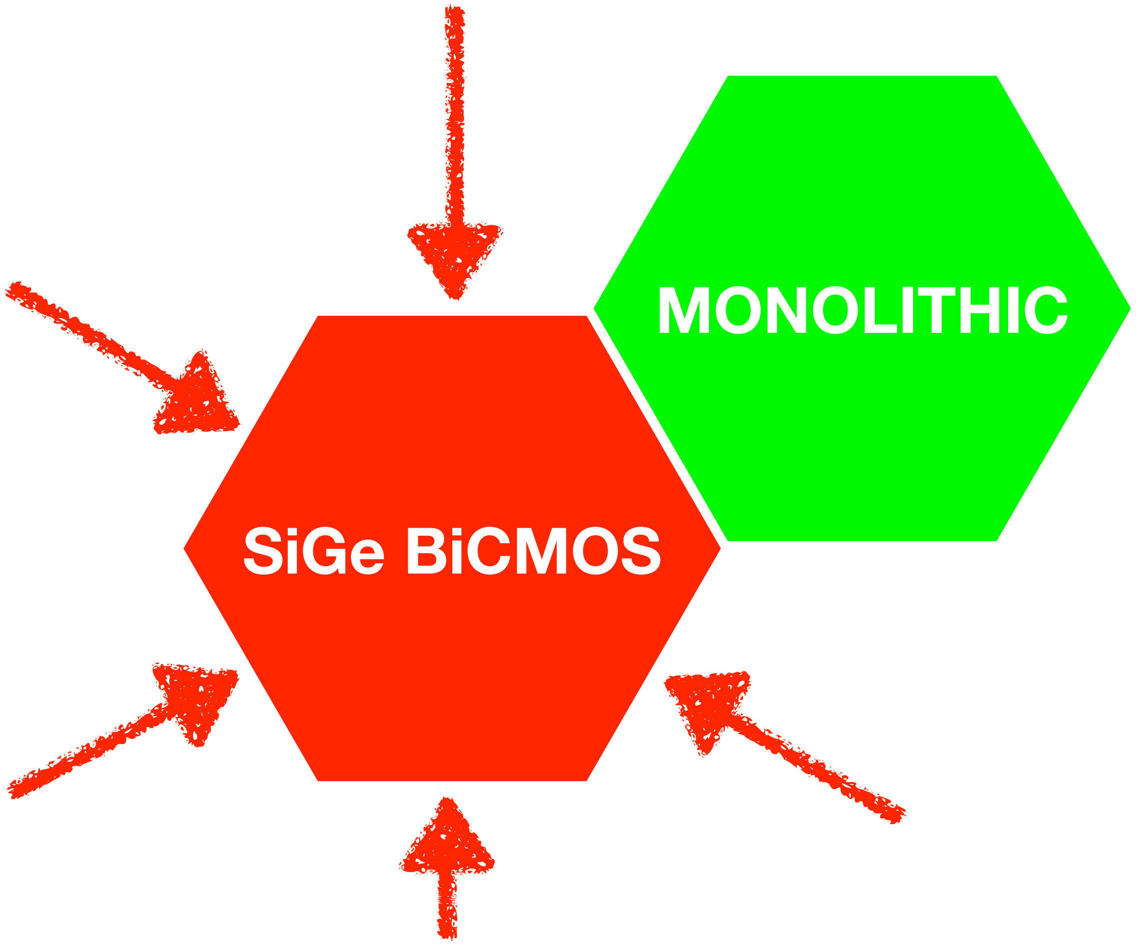
Monolithic silicon sensor able to:

- 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

The MONOLITH ERC Project



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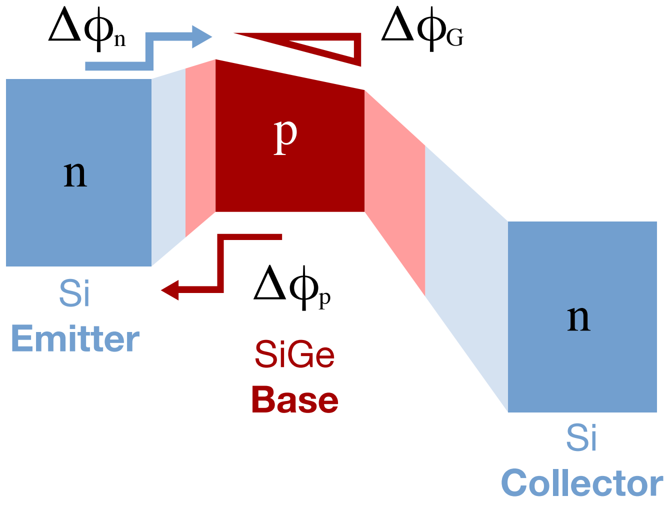
Why SiGe BiCMOS Technology?

- SiGe HBT = Bipolar Junction Transistor with grading of Germanium in the base:
  - small electric field in the base
  - charge transport via drift
    -> smaller charge transit time
      -> **higher current gain** β than a BJT
  - thicker base than a BJT
    -> **smaller base resistance** R_b than a BJT

NPN SiGe HBT
(depleted region in light colours)



$$ENC_{series} \propto \sqrt{k_1 \frac{C_{tot}^2}{\beta} + k_2 R_b C_{tot}^2} \Rightarrow \sigma_{jitter} = \sigma_V \left(\frac{dV}{dt}\right)^{-1} \simeq ENC_{series} \cdot Rise\ Time$$

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

SiGe BiCMOS Prototypes

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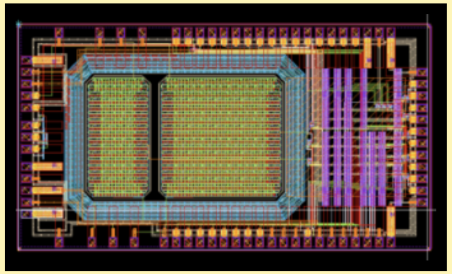
Timing Prototypes without Gain Layer

2016

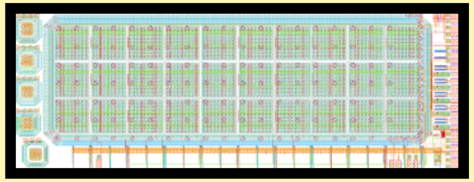


- Square pixel 900 µm
- Discriminated output

200 ps

JINST 13 P04015

2017

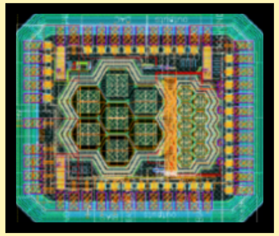


- Square pixels 500 µm
- 100 ps TDC + I/O logic

110 ps

JINST 14 P07013 JINST 14 P02009

2018

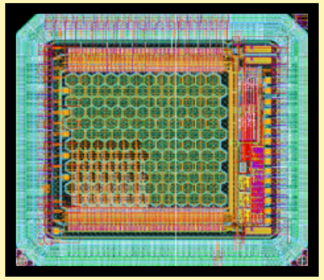


- Hexagonal pixels 130 µm
- Discriminated outputs

45 ps

JINST 14 P11008 JINST 15 P11025

2020

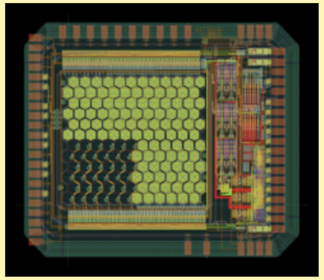


- Hexagonal pixels 65 µm
- 30 ps TDC + I/O logic
- 4 analog outputs

36 ps

JINST 17 P02019

2022



- Hexagonal pixels 65 µm
- Improved frontend
- 4 analog outputs

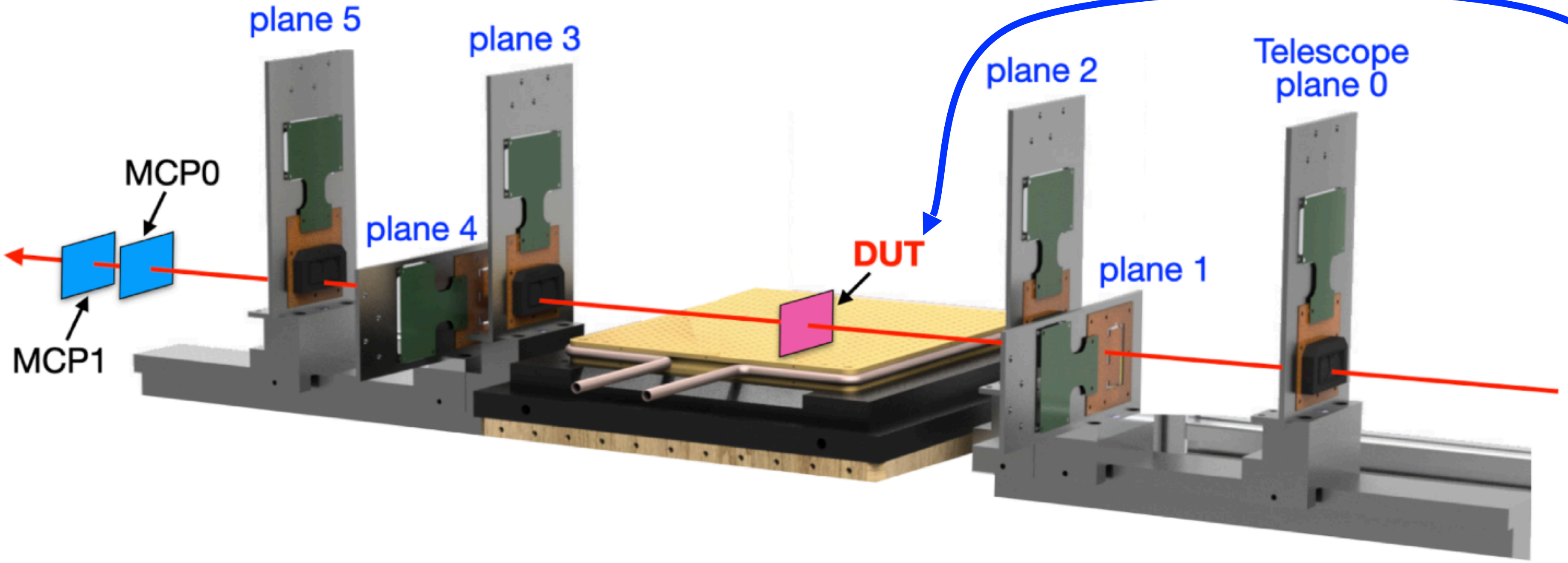
20 ps

JINST 18 P03047 JINST 19 P01014
JINST 19 P04029 JINST 19 P07036

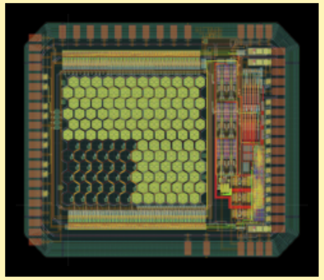
In this talk

Test Beam: Experimental Setup

- October 2022: SPS Testbeam with 180 GeV/c pions
- Measure **efficiency** and **time resolution** (results in ***JINST 18 P03047***)



2022



- Hexagonal pixels 65 μm
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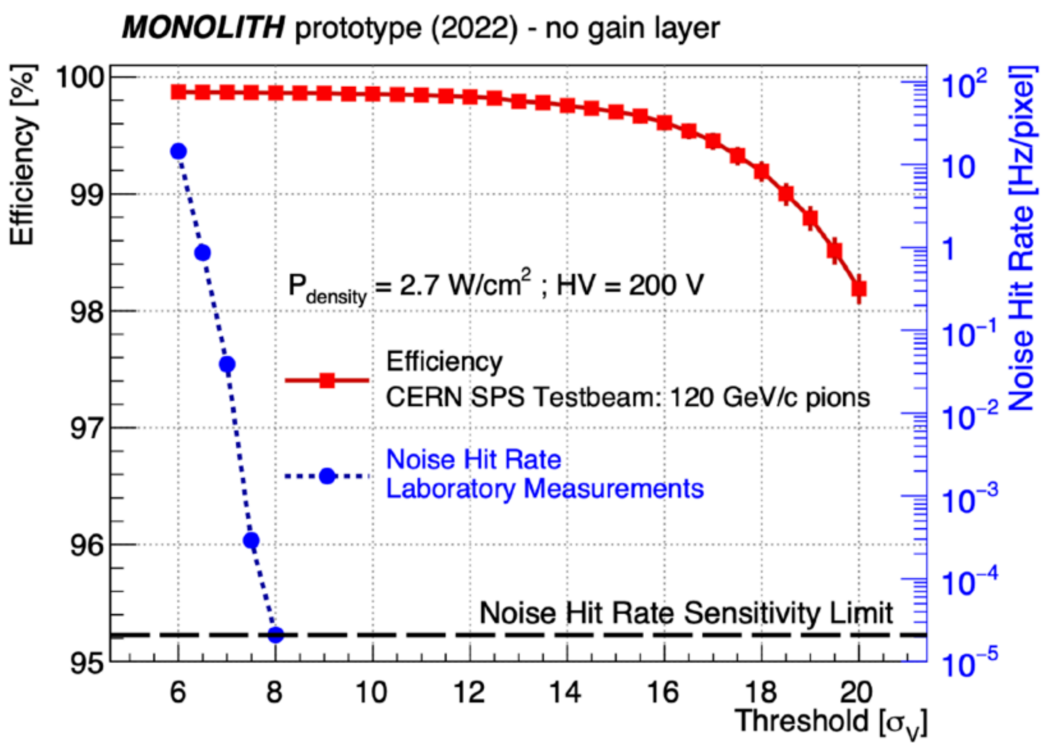
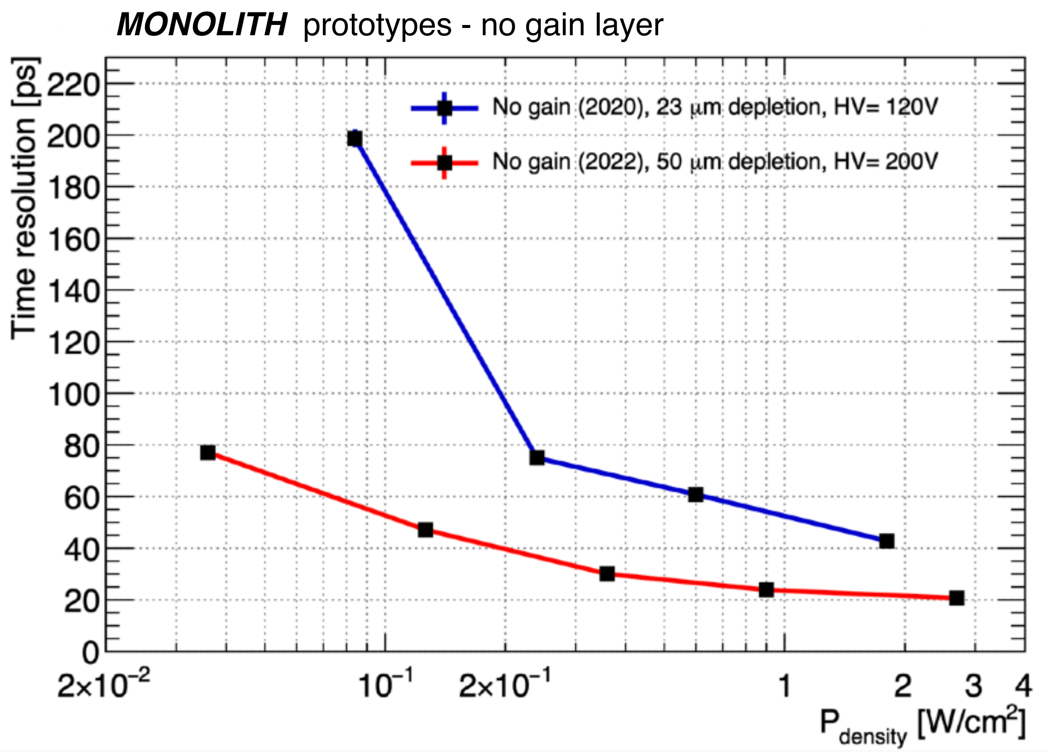
JINST 18 P03047 *JINST 19 P01014*
JINST 19 P04029 *JINST 19 P07036*

- ***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

Testbeam Results





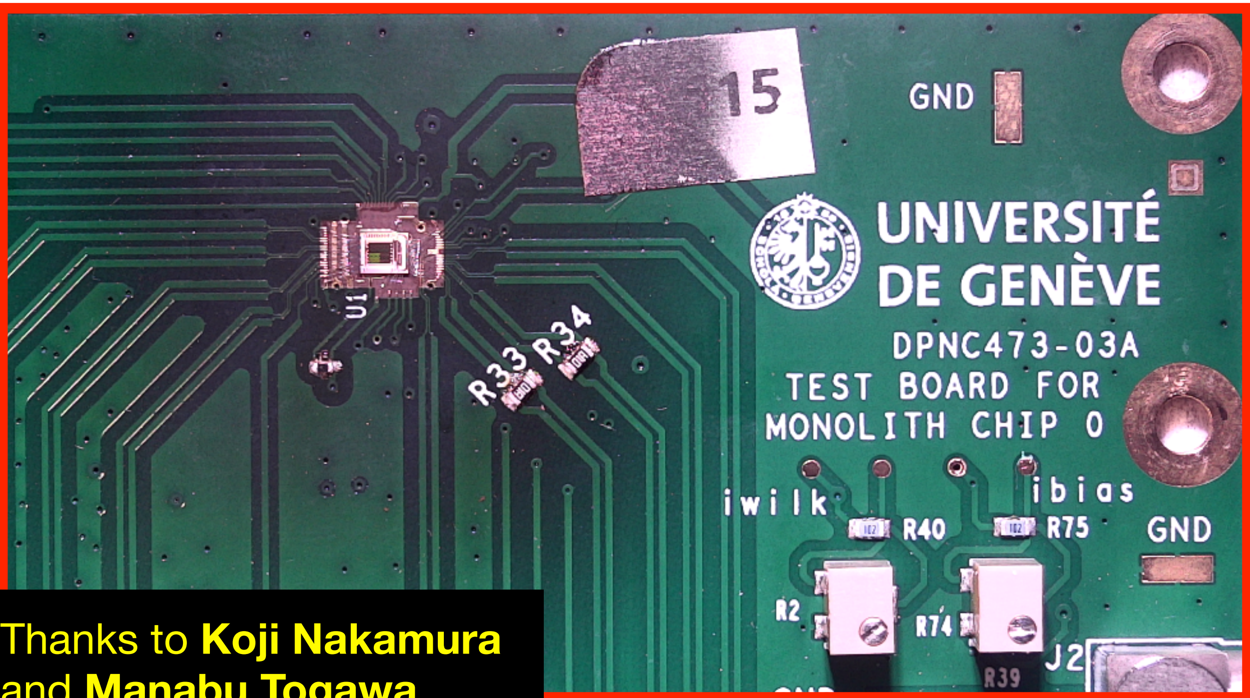
Efficiency

- Large plateau of **99.8% efficiency**
- The standard deviation of the noise is $\sigma_V \approx 1.4\,\mathrm{mV} \approx 100\,e^-$

Time Resolution

- **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** (*JINST 17 P02019*)

SiGe BiCMOS Radiation Hardness

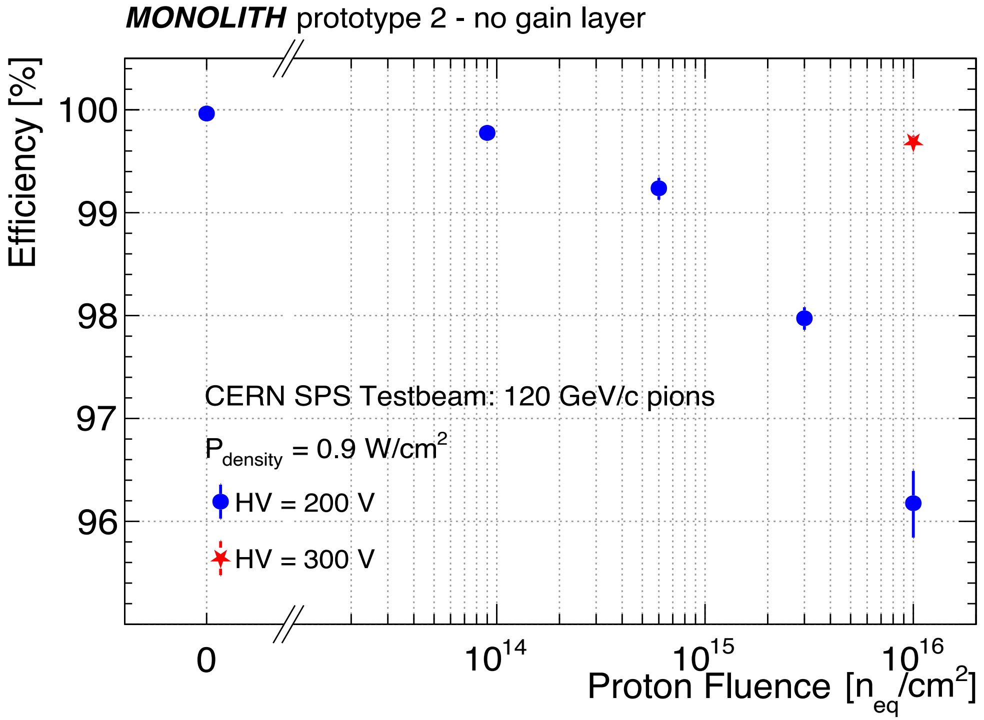


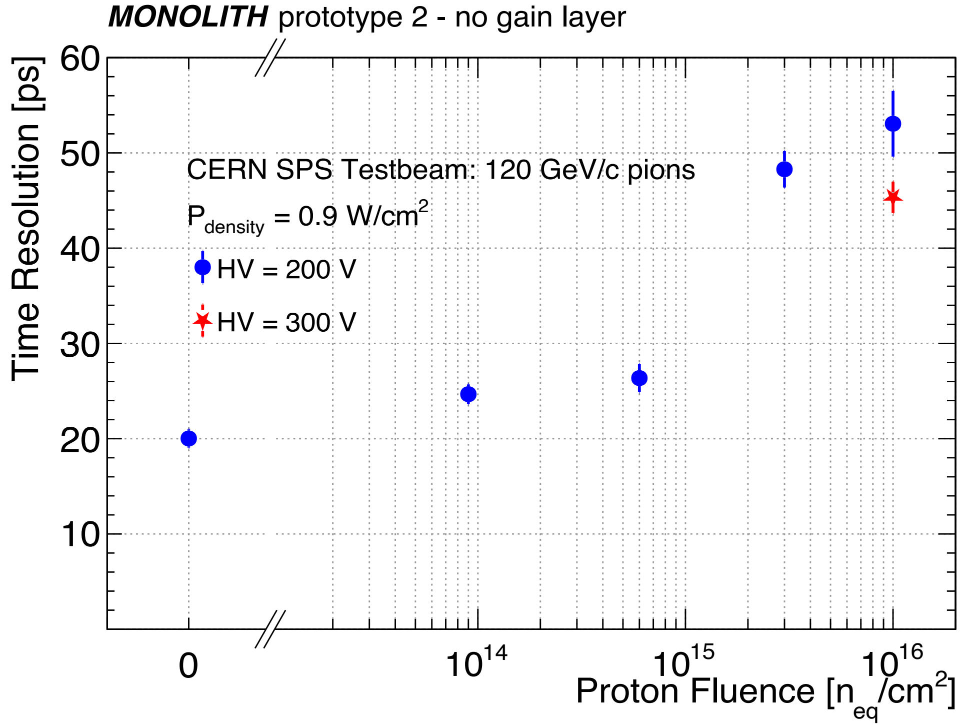
Thanks to **Koji Nakamura** and **Manabu Togawa**

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 one studied at the testbeam (in ***JINST 18 P03047***)

Performances After Irradiation

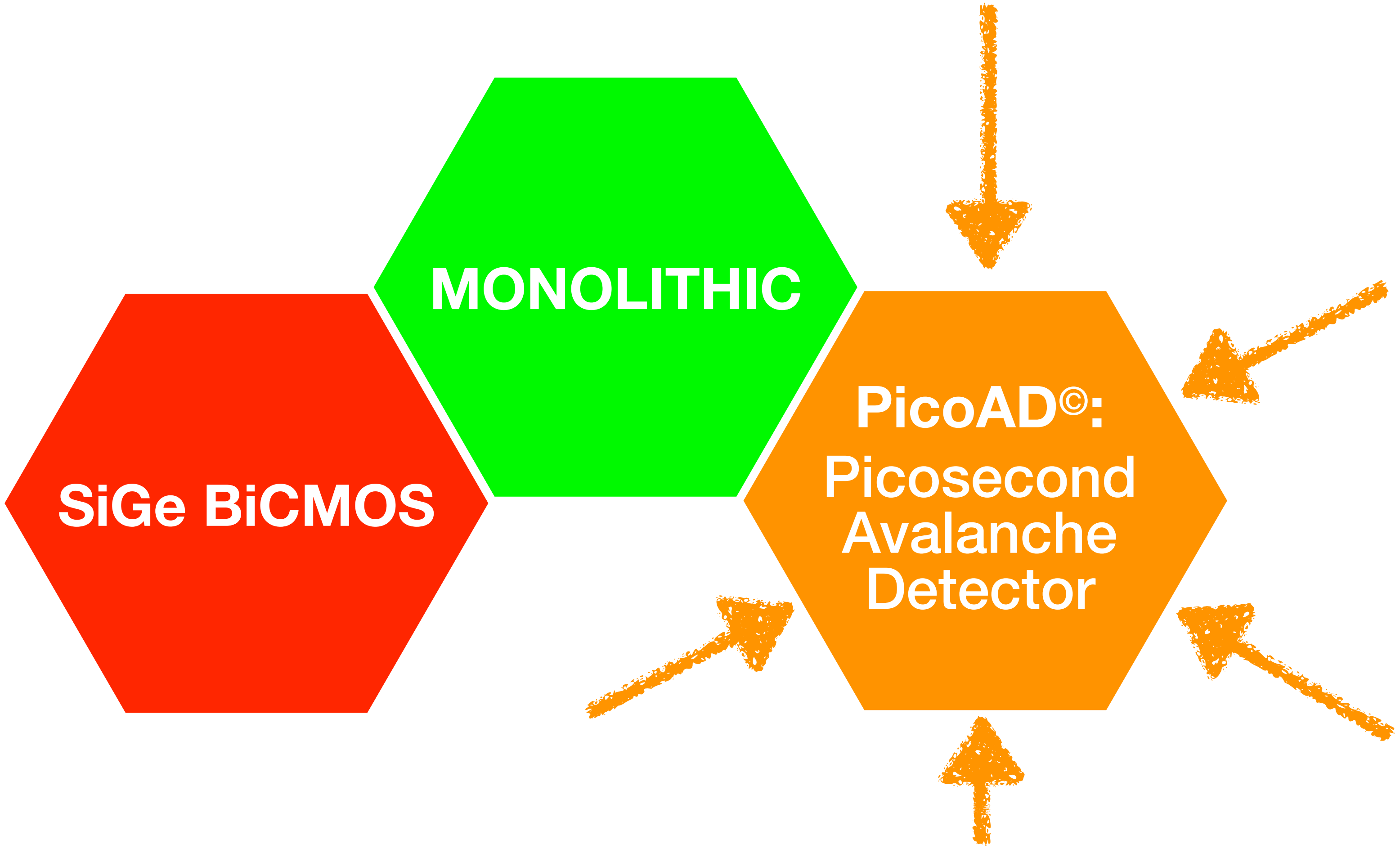




At **10^{16} n_{eq}/cm^2**, with **HV = 200 V** and $P_{density}$ = **0.9 W/cm²** (in ***JINST 19 P07036***):

- The efficiency is 96.2% -> **99.7%** increasing the High Voltage
- The time resolution is 53 ps -> **45 ps** increasing the High Voltage

The MONOLITH ERC Project



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PicoAD© Concept

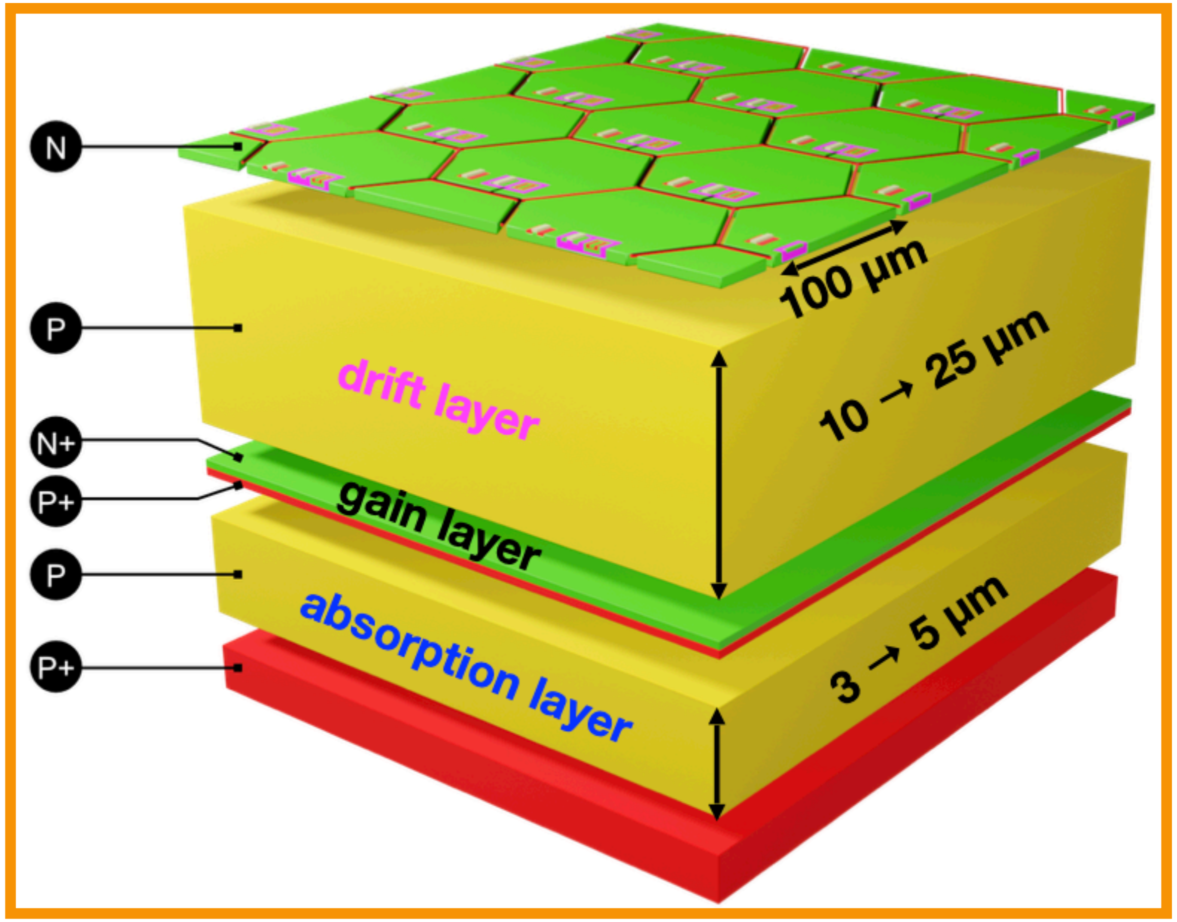
- Multi-Junction **Picosecond Avalanche Detector©** (patent here)
- Continuous and deep gain layer
  - de-correlation from implant size/ geometry

    -> high **pixel granularity** possible

    -> **better spatial resolution**
  - only small fraction of charge gets amplified

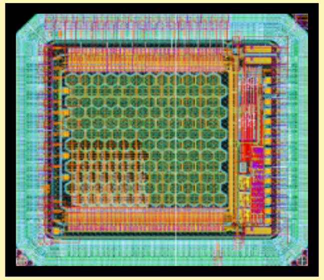
    -> **reduced charge collection noise**

    -> **better timing resolution**



Prototypes With PicoAD©

2020



- Hexagonal pixels 65 µm
- 30 ps TDC + I/O logic
- 4 analog outputs

36 ps

JINST 17 P02019

With PicoAD©

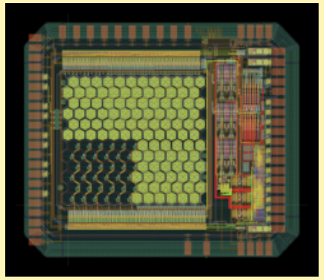
2022

With PicoAD©

17 ps

JINST 17 P10032
JINST 17 P10040

2022



- Hexagonal pixels 65 µm
- Improved frontend
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20 ps

JINST 18 P03047 JINST 19 P01014
JINST 19 P04029 JINST 19 P07036

With PicoAD©

In this talk

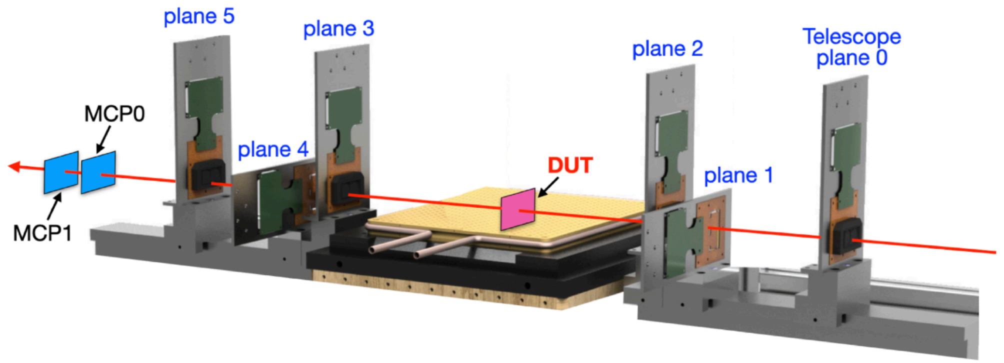
2024

With PicoAD©

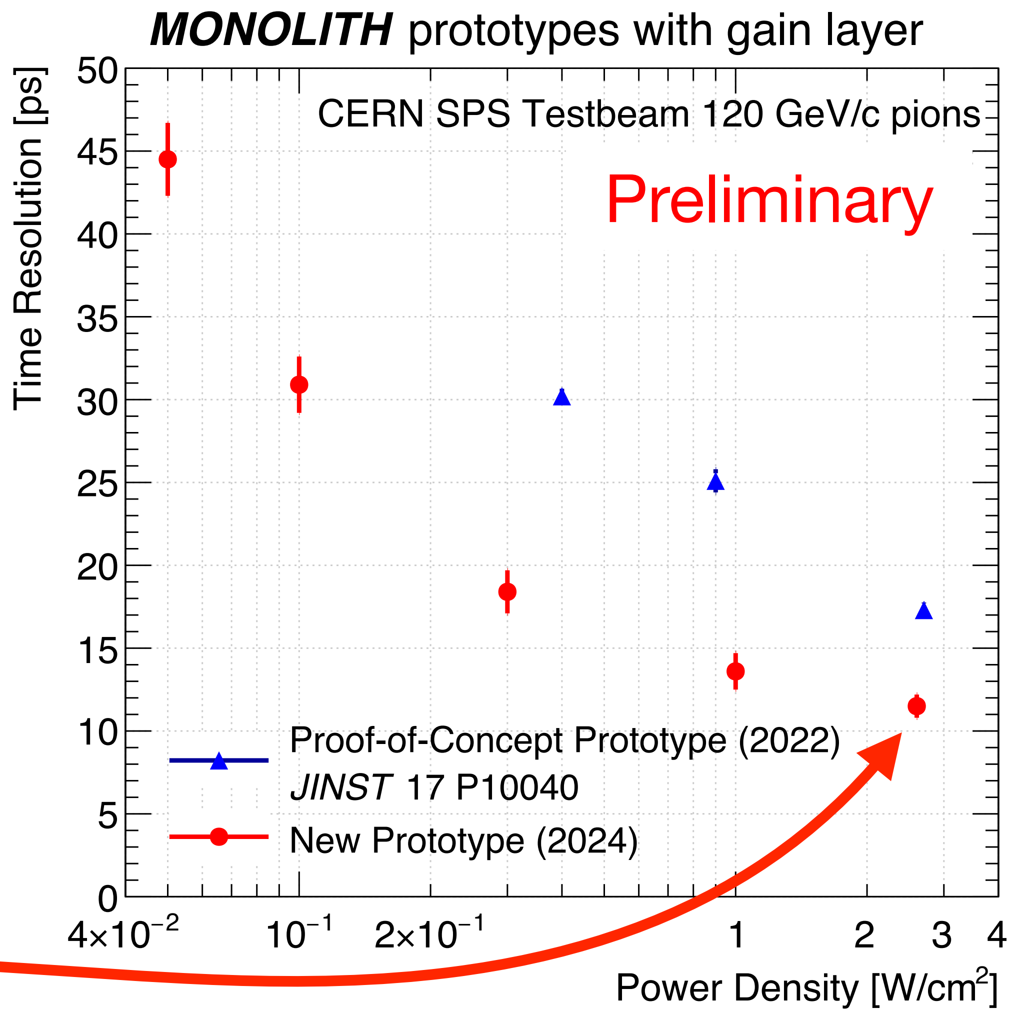
12 ps

Paper in production

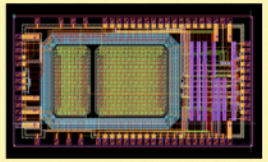
PicoAD© Results



- Testbeam measurements with FE-I4 telescope
- Results of 2022 prototype are in JINST 17 P10040
- Improvement with respect to the **previous prototype**
- **Best performance with the new prototype: (12.0 ± 0.3) ps** with HV = 180 V and $P_{density}$ = **2.6 W/cm²**

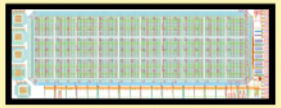


Summary

2016


- Square pixel 900 µm
- Discriminated output

200 ps

2017


- Square pixels 500 µm
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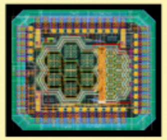
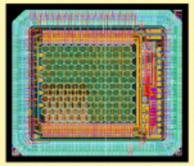
110 ps

2018


- Hexagonal pixels 130 µm
- Discriminated outputs

45 ps

2020


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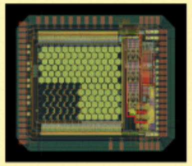

- Hexagonal pixels 65 µm
- Improved frontend
- 4 analog outputs

20 ps

- **99.8%** efficiency and **20 ps** time resolution for MIPs
- After irradiation at **10^{16} n_{eq}/cm^2**: **99.7%** efficiency and **45 ps** time resolution

2022
With **PicoAD©**
17 ps

2024
With **PicoAD©**
12 ps

12 ps time resolution for MIPs

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Other Projects and Outlook

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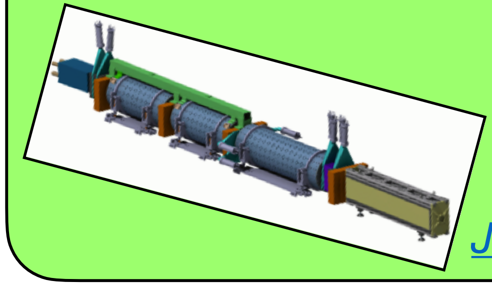
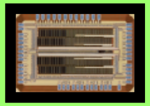
LHC Application: Preshower for FASER -> webpage



JINST 16 P12038

2022

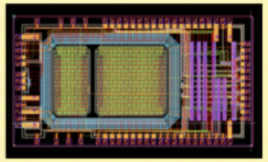


2023

2024

High-radiation tolerance
high granularity
timing layers
for particle physics

2016



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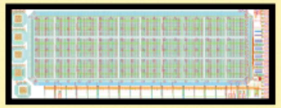

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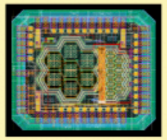

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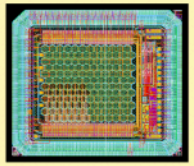

- Hexagonal pixels 65 µm
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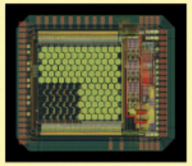
2022



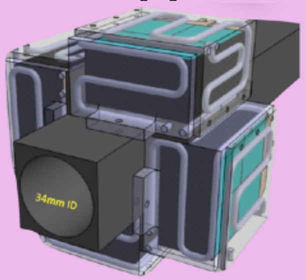
- Hexagonal pixels 65 µm
- Improved frontend
- 4 analog outputs

20 ps

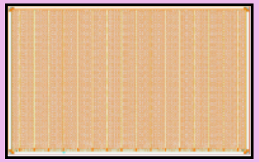
Moderate radiation level
extremely thin
timing layers
for particle physics

Medical Application: 100µPET

NIMA 167952



2024



2022
With **PicoAD©**
17 ps

2024
With **PicoAD©**
12 ps

Photonics

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Thanks for your attention

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- Lead Chip Design
- Analog Electronics

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- Sensor Design

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- Chip Design
- Firmware

Matteo Milanesio
- Laboratory Tests
- Data Analysis

Rafaella Kotitsa
- Detector Simulations
- Laboratory Tests

Carlo Alberto Fenoglio
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- Firmware

Andrea Pizarro Medina
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- Data Analysis

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- Data Analysis

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- Firmware

Théo Moretti
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- Data Analysis

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- Data Analysis

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Sergio Gonzalez-Sevilla
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- Laboratory test

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- Board design
- RO system

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IHP Mikroelektronik

Marzio Nessi
CERN & UNIGE

Matteo Elviretti
IHP Mikroelektronik

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European Research Council
Established by the European Commission
Sinergia
ATTRACT
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Laser Measurements

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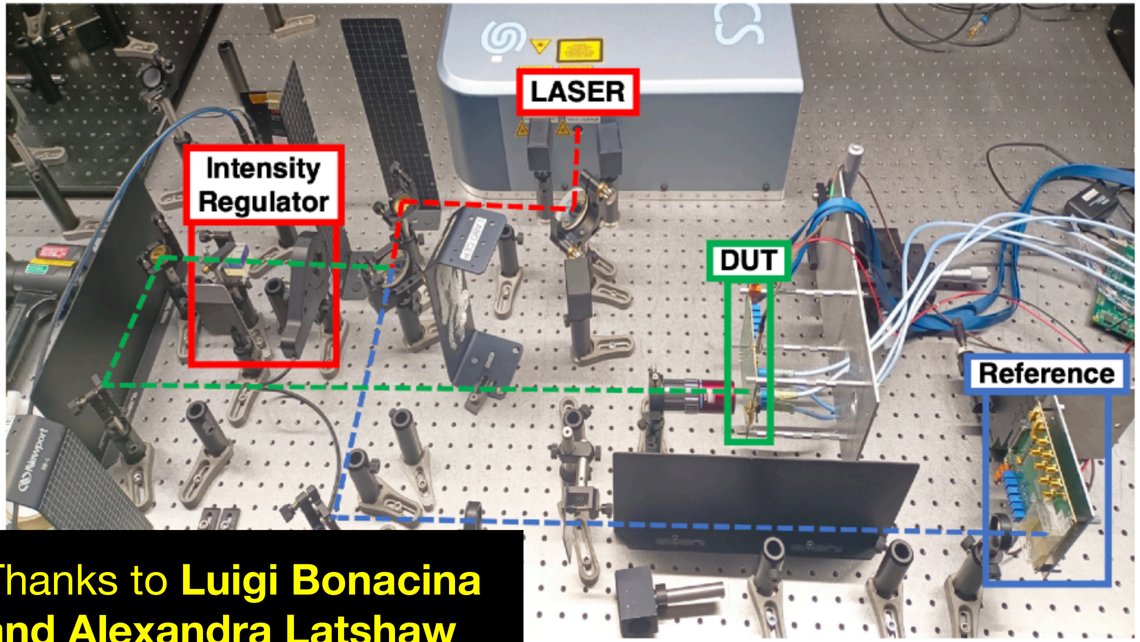
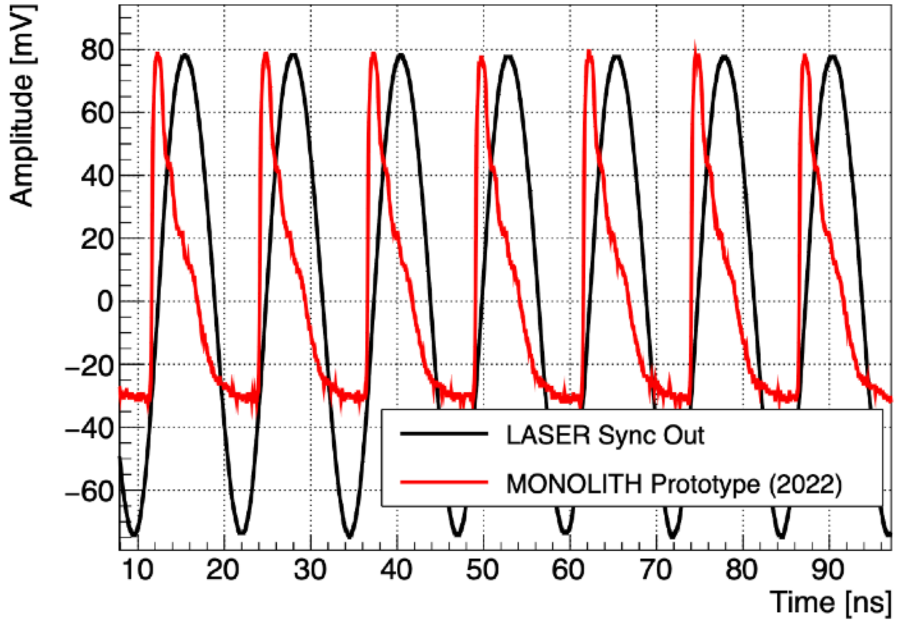
- Pulsed Infrared laser:
  - Intrinsic jitter of **100 fs**
  - Repetition frequency of **80 MHz**
- Time coincidence between two of our samples:
  - "**Reference**" receiving always large laser pulse producing 17k electrons
  - "**DUT**" receiving variable laser power, to study the performance vs. amplitude



Thanks to **Luigi Bonacina and Alexandra Latshaw**



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Laser Results

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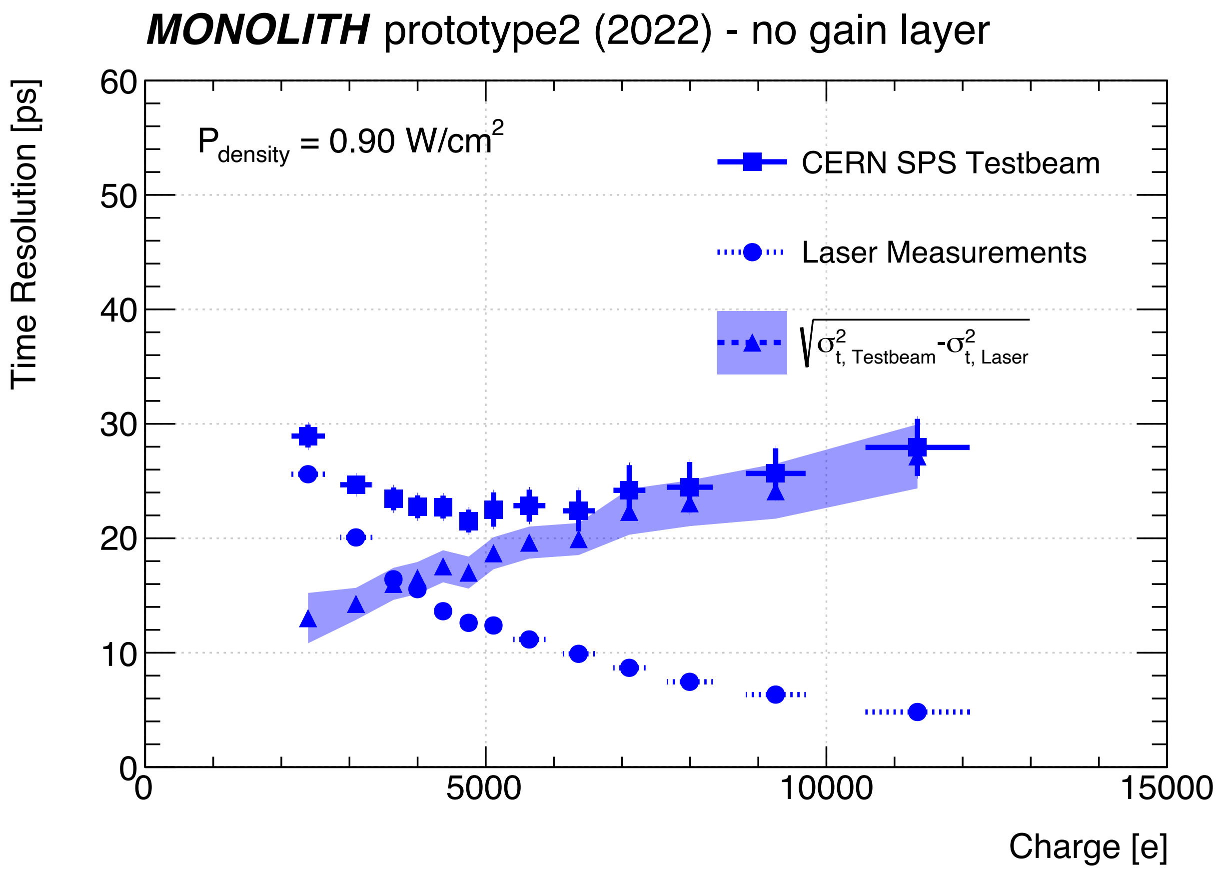
- The electronics can achieve a **time resolution of 3 ps** with 11k electrons (~4 MIPs)
- Intrinsic limit to the time resolution due to **Charge Collection Noise**
  - The limit is **~17 ps** in a 50 µm-thick sensor
  - **Improved with the PicoAD©**



2020 to 2022 Improvements

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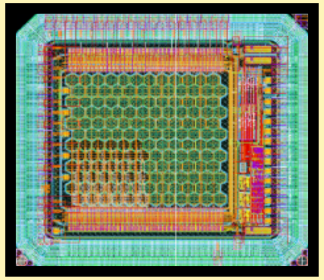
- Same matrix configuration as previous, but
  - Substrate: 50 Ωcm → 350 Ωcm epi layer, 50 μm thick on low-res (1 Ωcm) substrate
    - smaller pixel capacitance
    - depletion 23 μm → 50 μm
    - much larger voltage plateau
    - can operate sensor with v_{drift} saturated everywhere
  - Preamp and 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)

2020



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JINST 17 P02019

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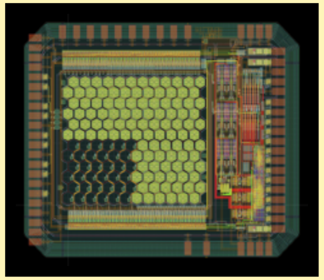

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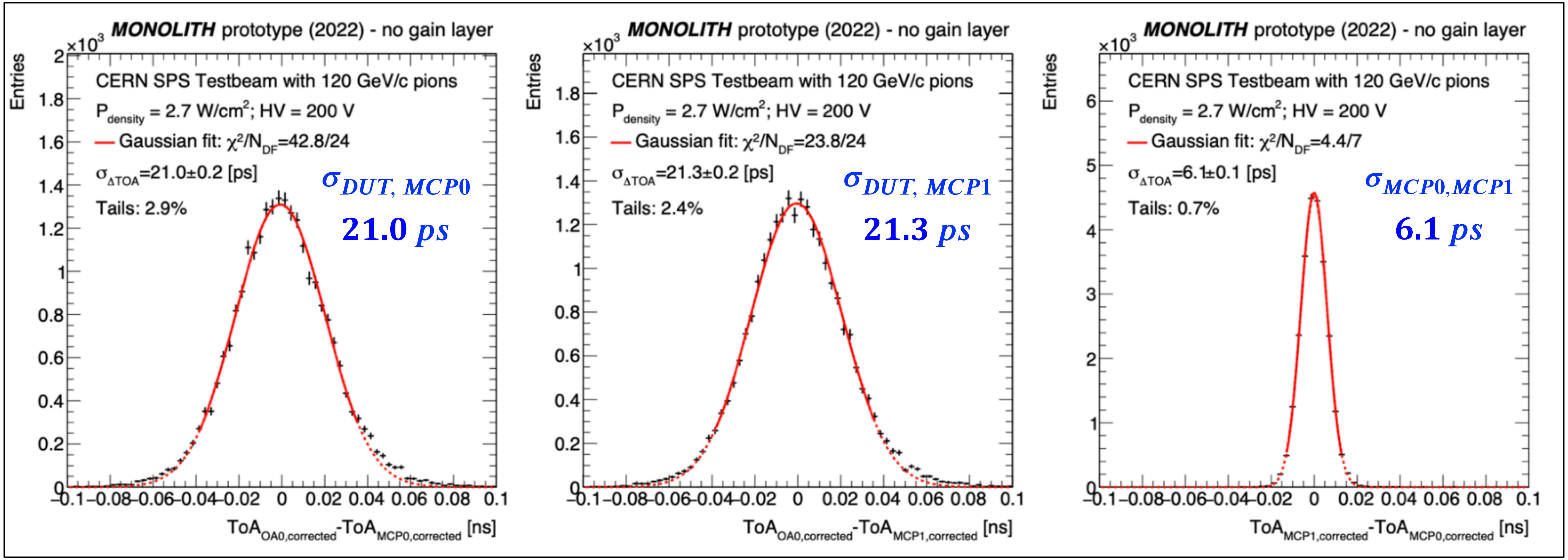
20 ps

JINST 18 P03047 JINST 19 P01014
JINST 19 P04029

Time Resolution Distributions



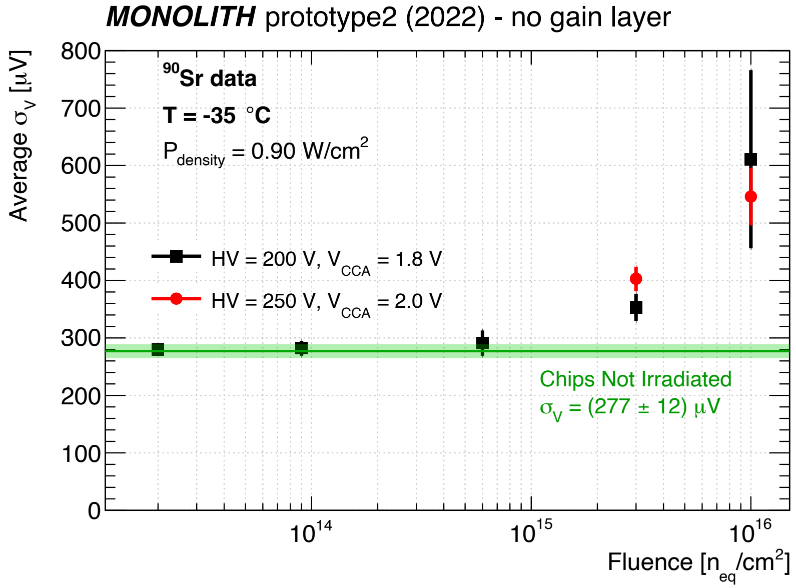
- Very **Gaussian** distributions after time walk correction
- Simultaneous fit to extract the time resolution of **DUT**, **MCP0**, **MCP1**[3]:

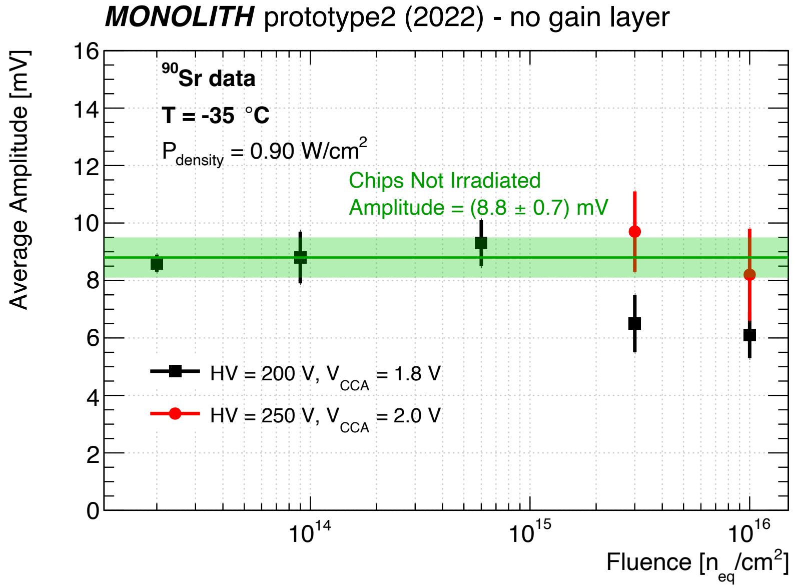
MCP0: $\sigma_t = (3.6 \pm 1.5)\ ps$

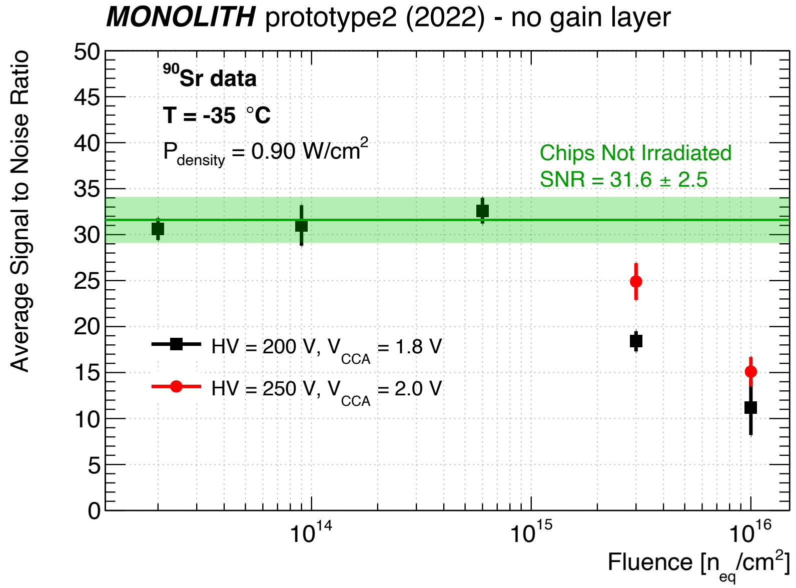
MCP1: $\sigma_t = (5.0 \pm 1.1)\ ps$

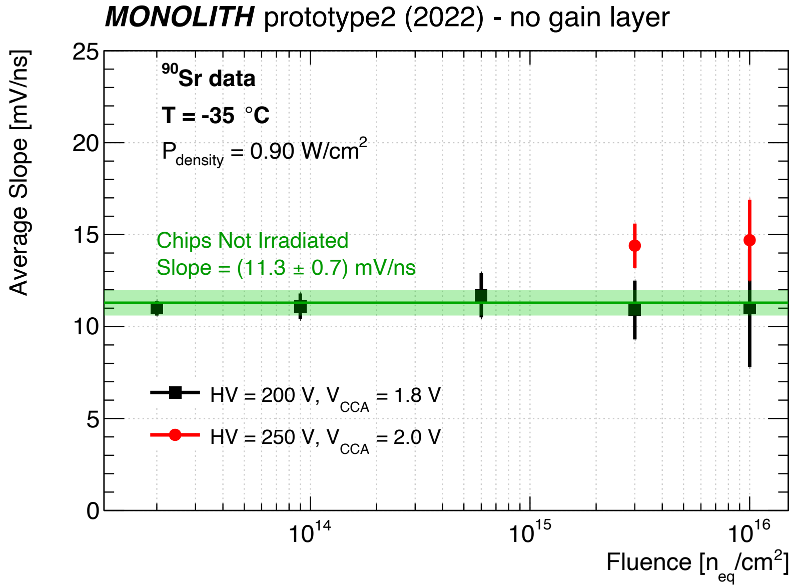
DUT: $\sigma_t = (20.7 \pm 0.3)\ ps$

Radiation Hardness

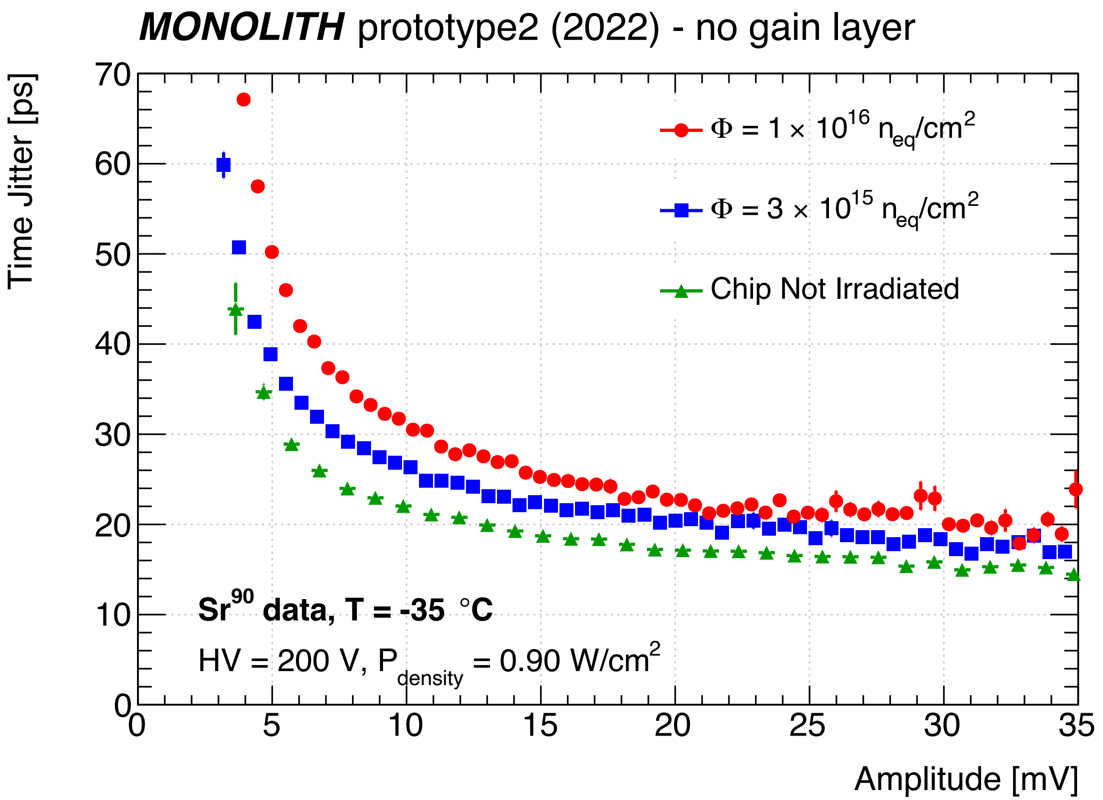


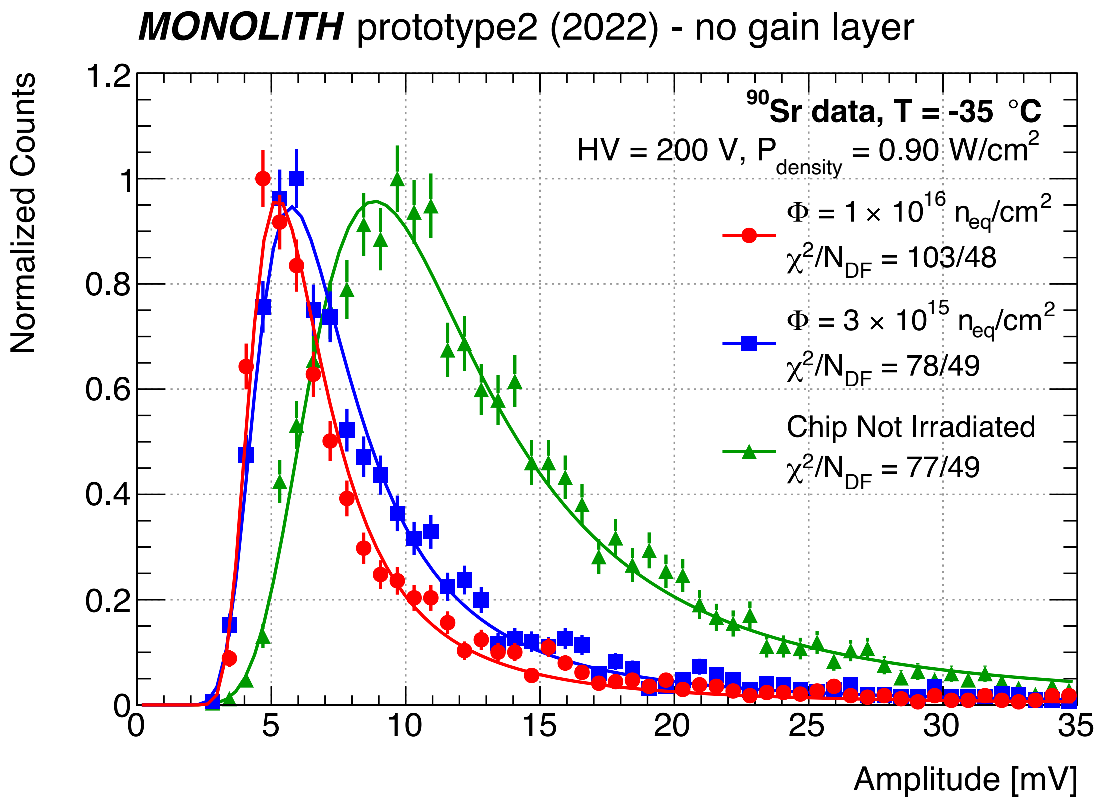






Radiation Hardness



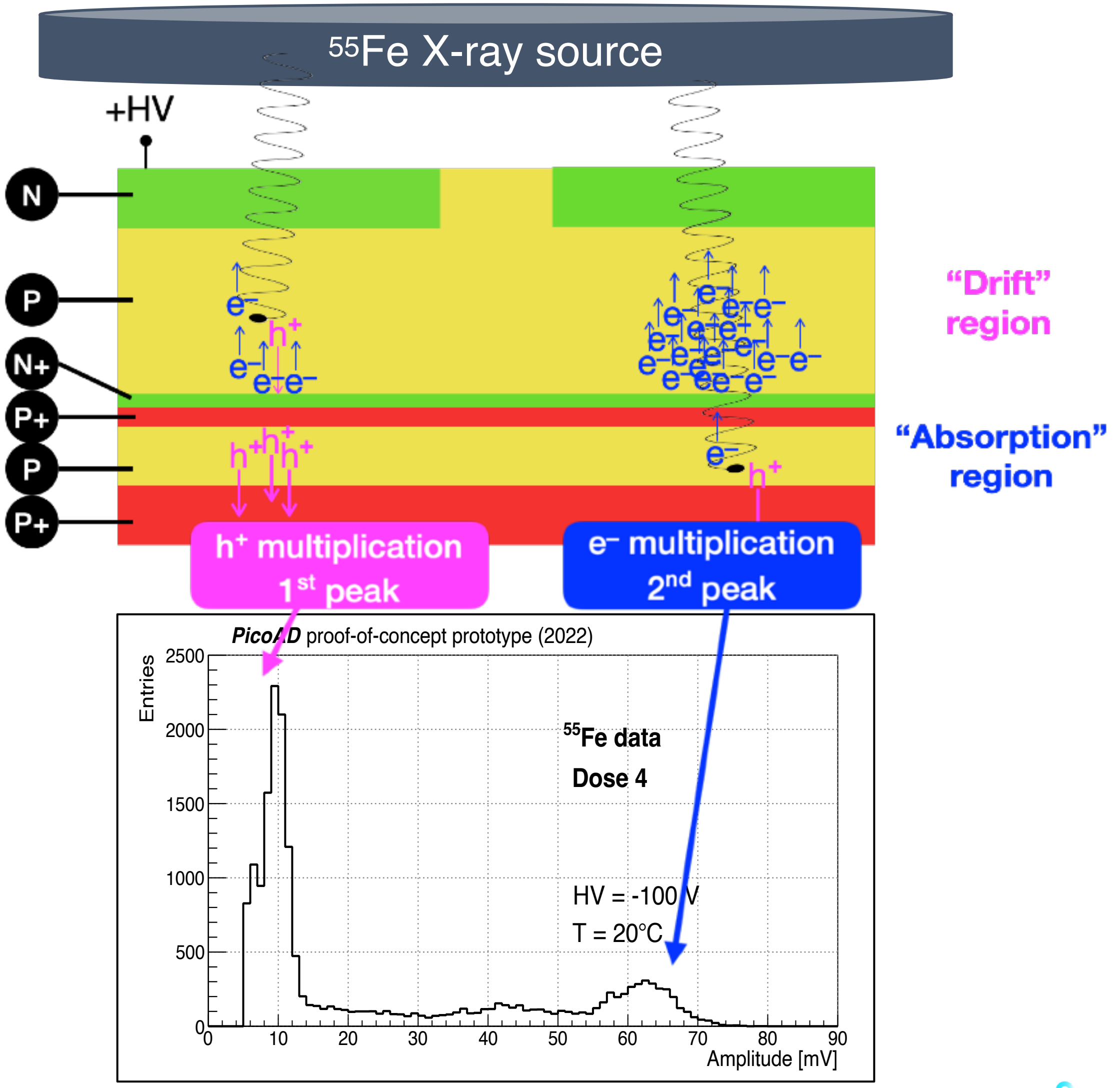


PicoAD© Gain Measurements

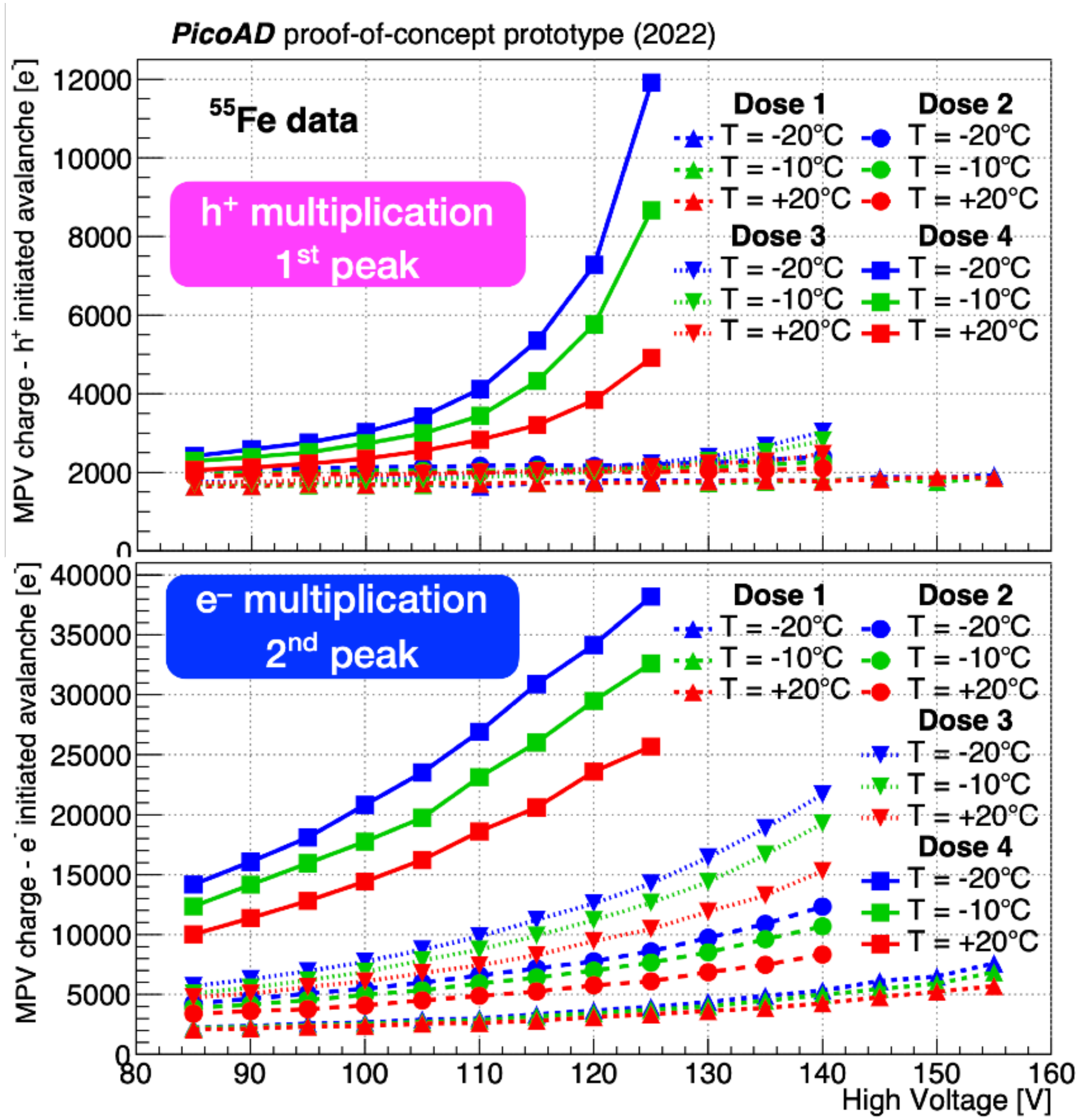
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique nucléaire et corpusculaire

European Research Council
FNSNF Swiss National Science Foundation

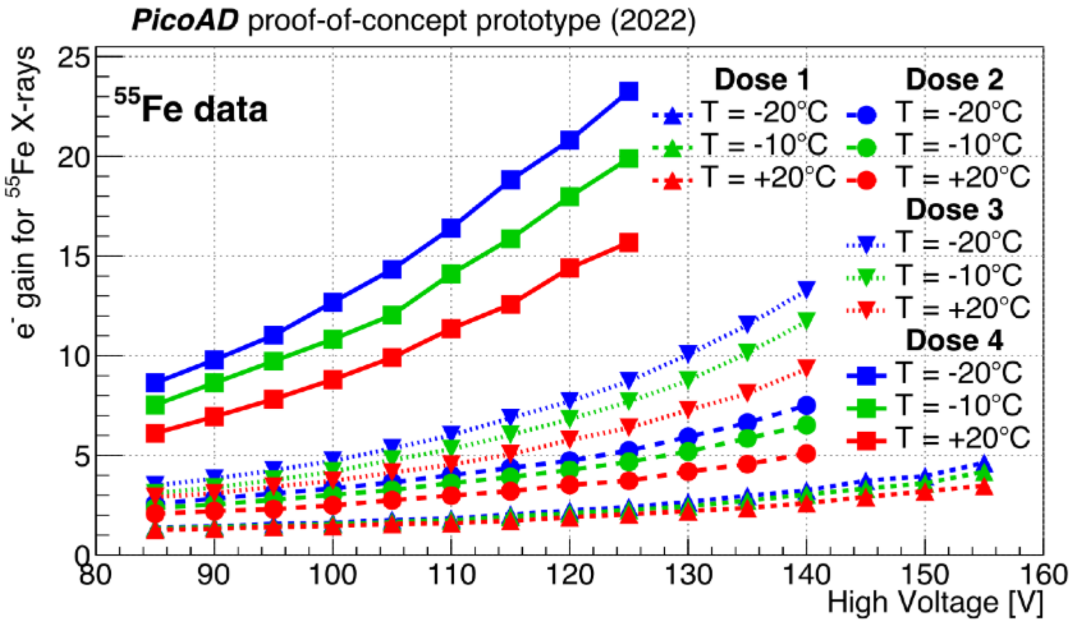
- **X-rays from ^{55}Fe radioactive source**:
  - ~5.9 keV photons with point-like charge deposition
- **Characteristic double-peak spectrum** ([PicoAD Working Principles](#))
  - photon absorbed in **drift region**
    - **holes** drift through gain layer and multiplied
    - **first peak** in the spectrum
  - 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](#))



PicoAD© 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**

PicoAD© Efficiency Maps

European Research Council
Established by the European Commission
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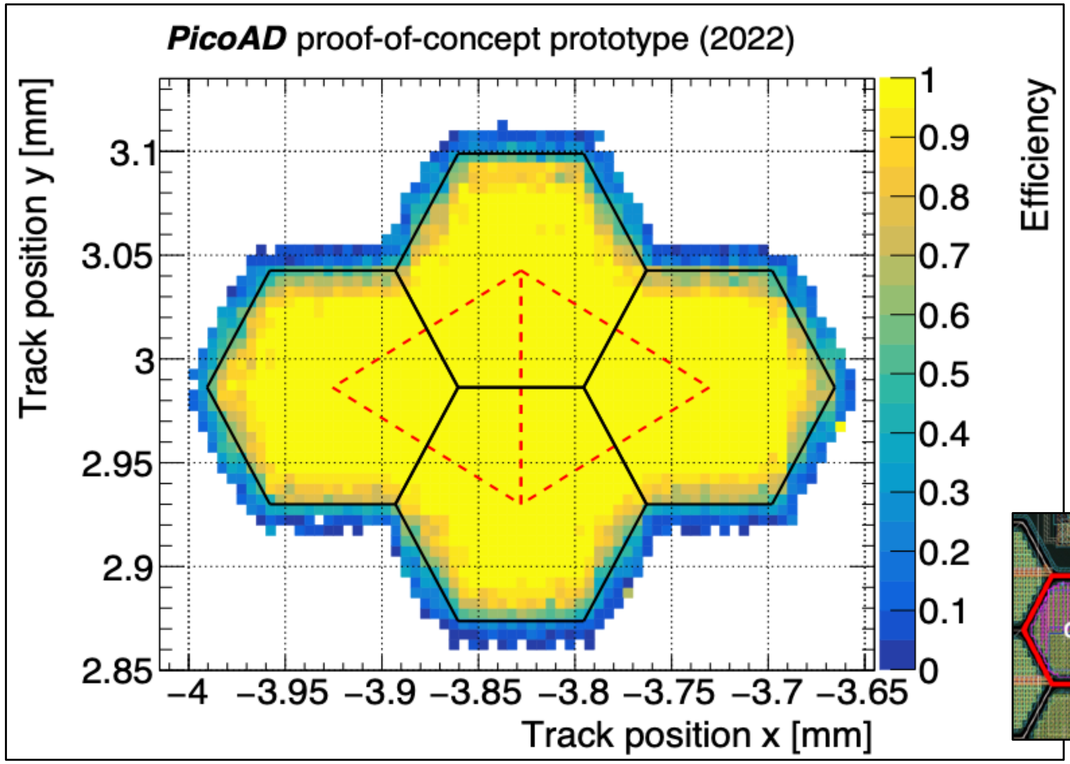
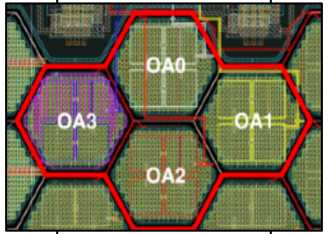
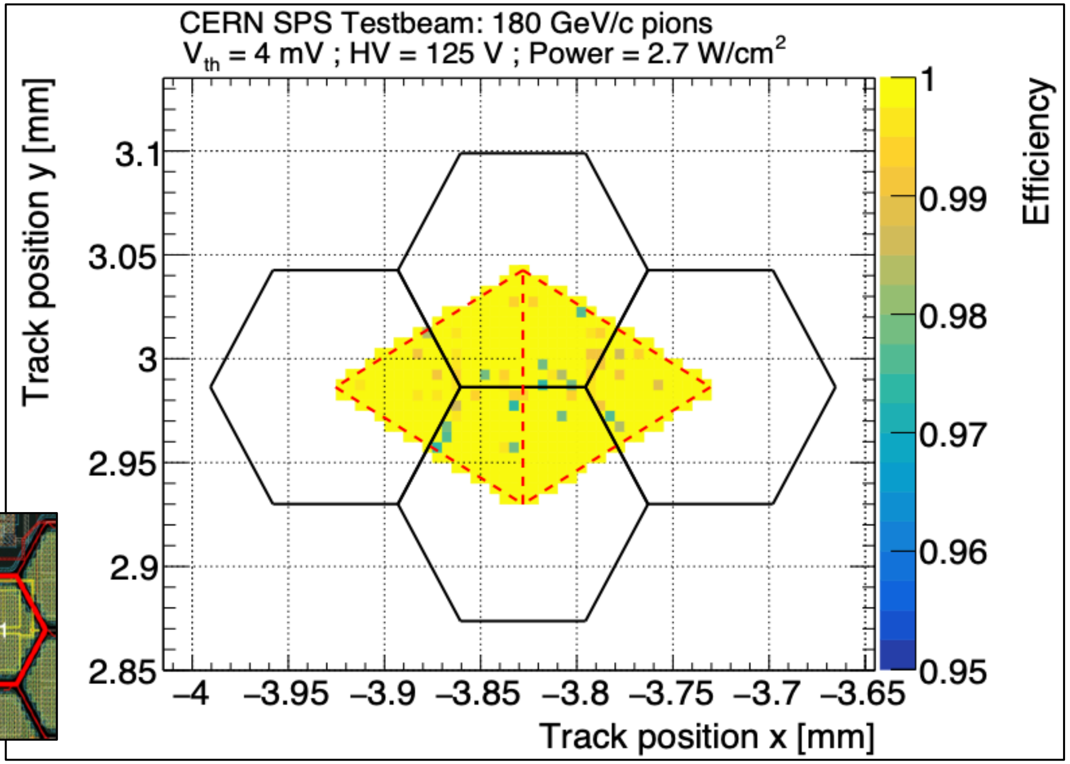




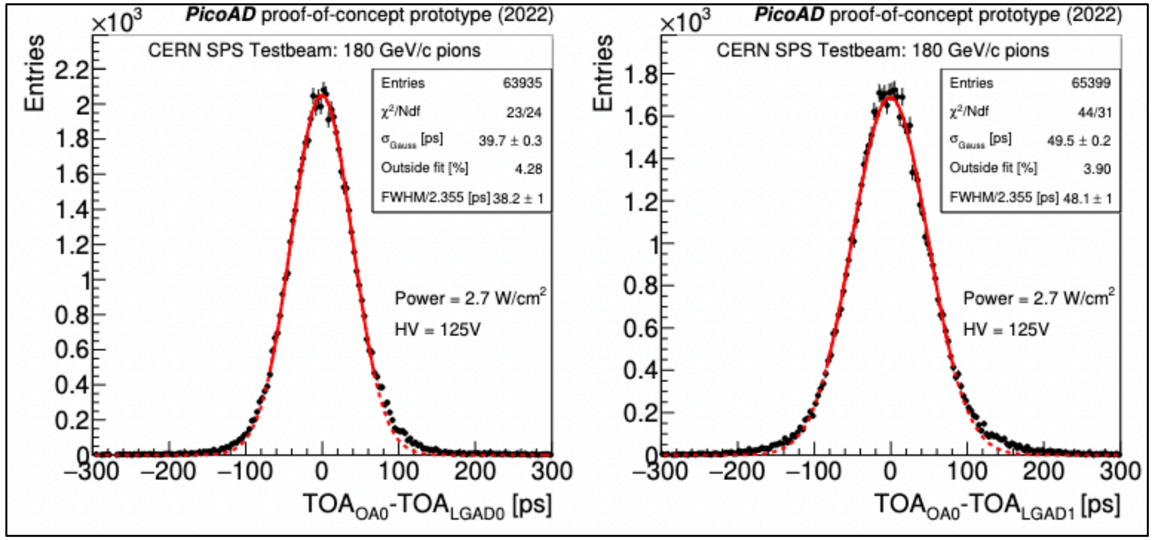


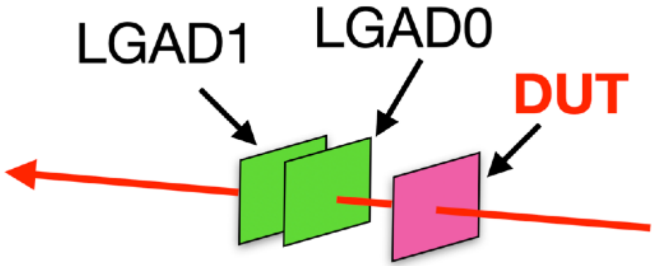
- The **apparent degradation** at the edges is due to the finite resolution of the telescope (~10 μm)

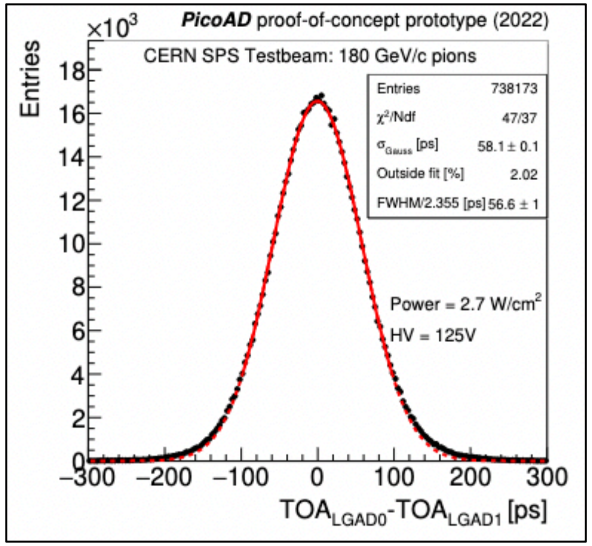
- Selection of two **triangles:**
  - representative of the whole pixel
  - **unbiased** from the telescope resolution

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







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Position Within the Pixel

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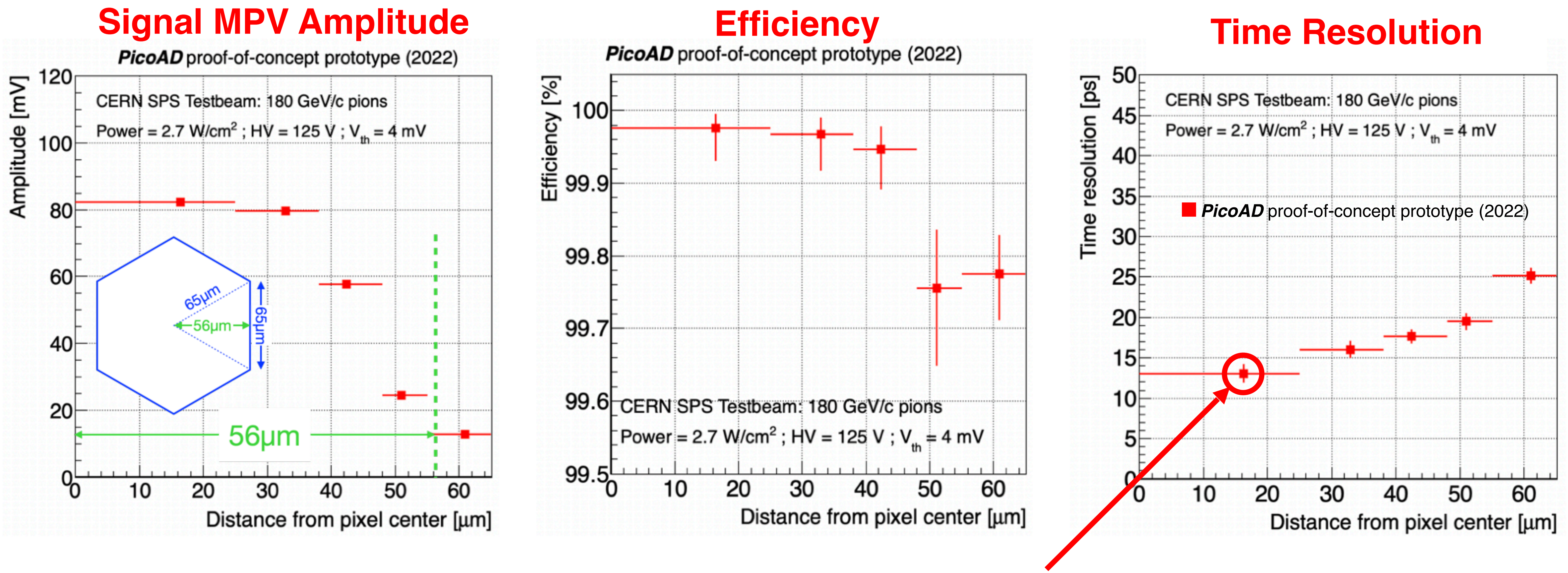
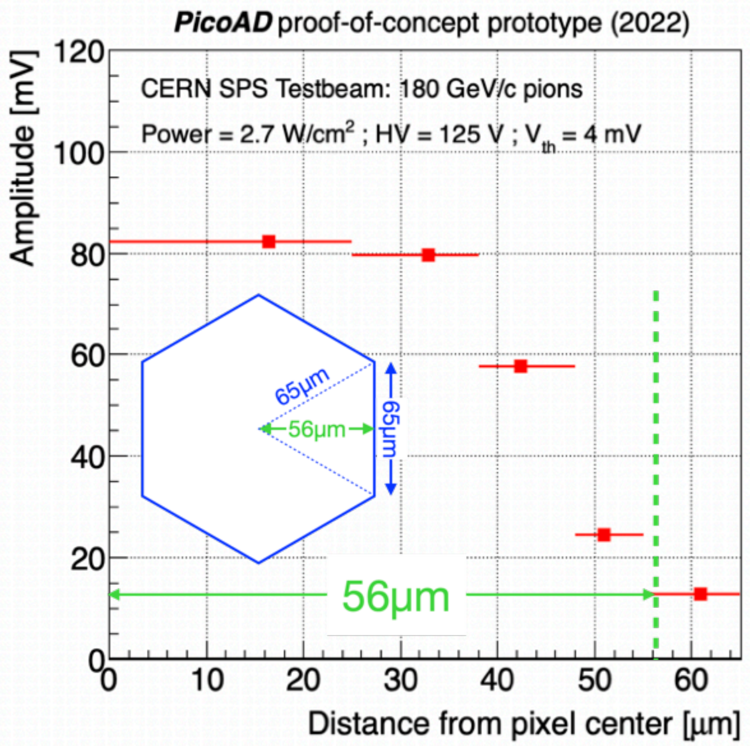


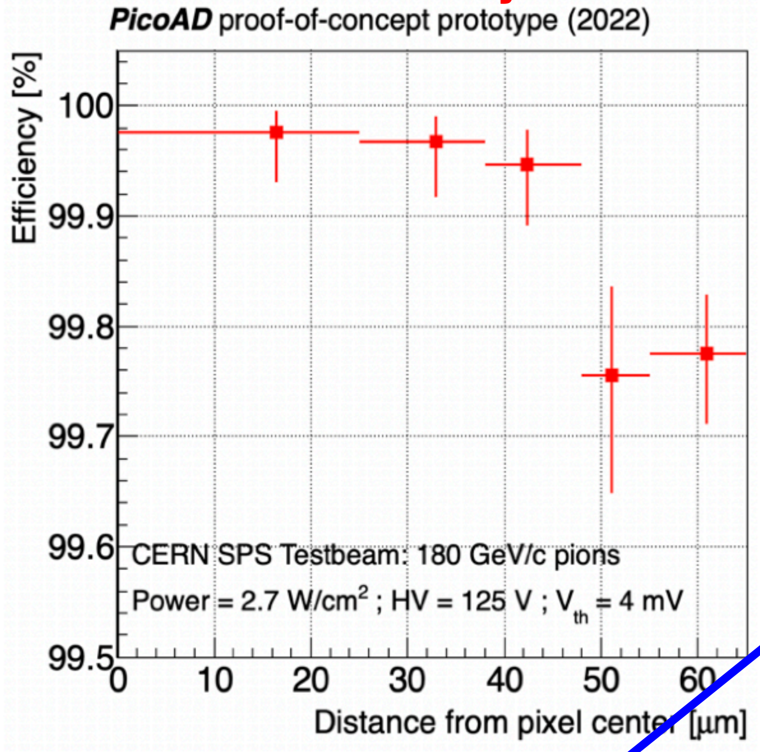
- Best time resolution: **(13.2 ± 0.8) ps within 25 µm** from the pixel center
- **PicoAD©** proof-of-concept: small degradation of the performance towards the edge of the pixel

Position Within the Pixel

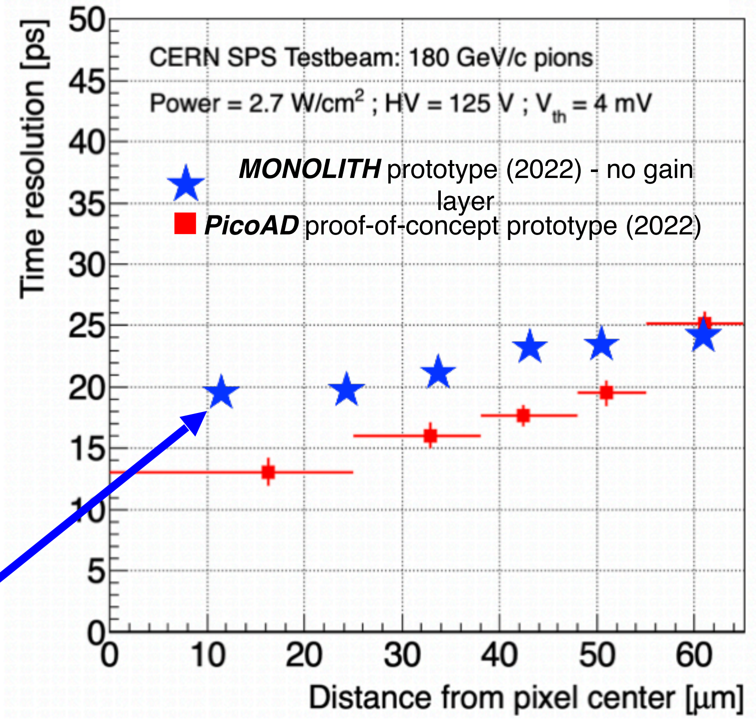
Signal MPV Amplitude



Efficiency



Time Resolution



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

Why 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**
- The same amount of pixels can fits in less space than squares
- The charge sharing is at maximum between 3 pixels, enhancing the charge for each channel