



**UNIVERSITÉ
DE GENÈVE**

FACULTÉ DES SCIENCES
Département de physique
nucléaire et corpusculaire



European Research Council
Established by the European Commission



SWISS NATIONAL SCIENCE FOUNDATION



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

Matteo Milanesio on behalf of the MONOLITH team

Université de Genève

[25th iWoRiD - International Workshop on Radiation Imaging Detectors](#)

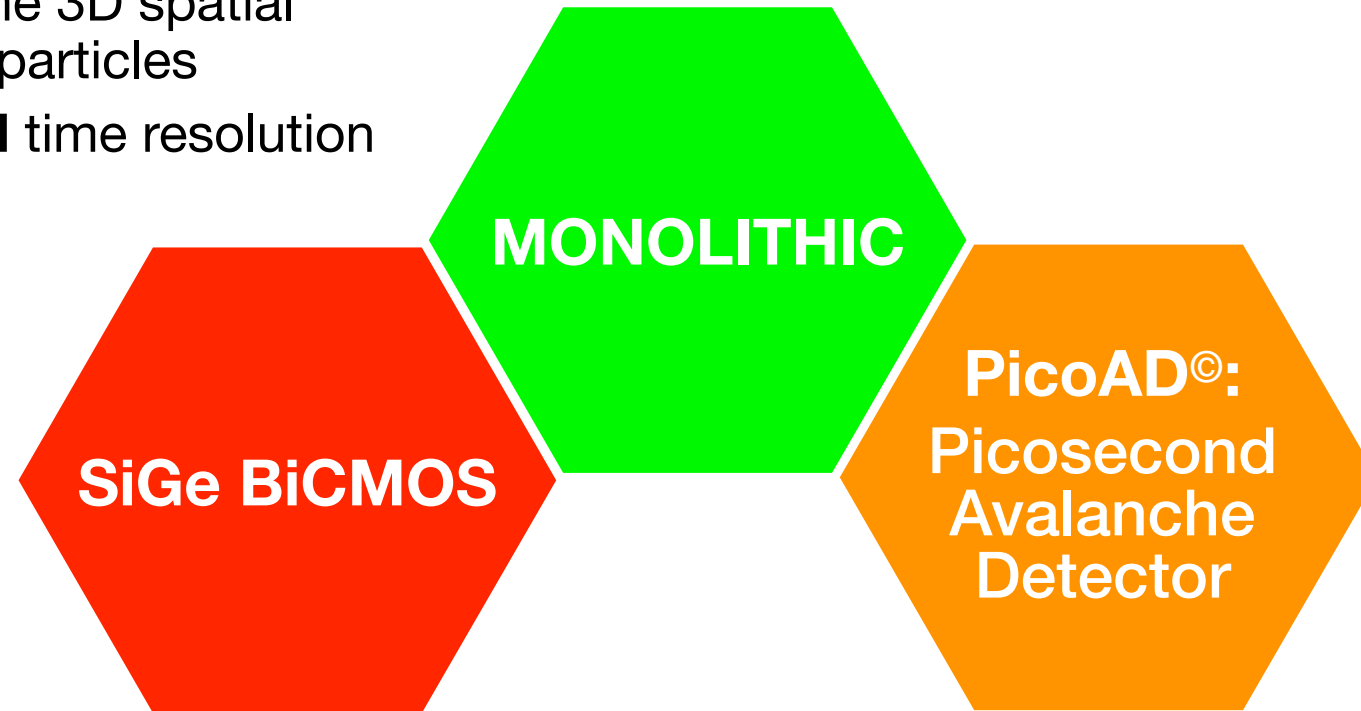


The MONOLITH ERC Project



Monolithic silicon sensor able to:

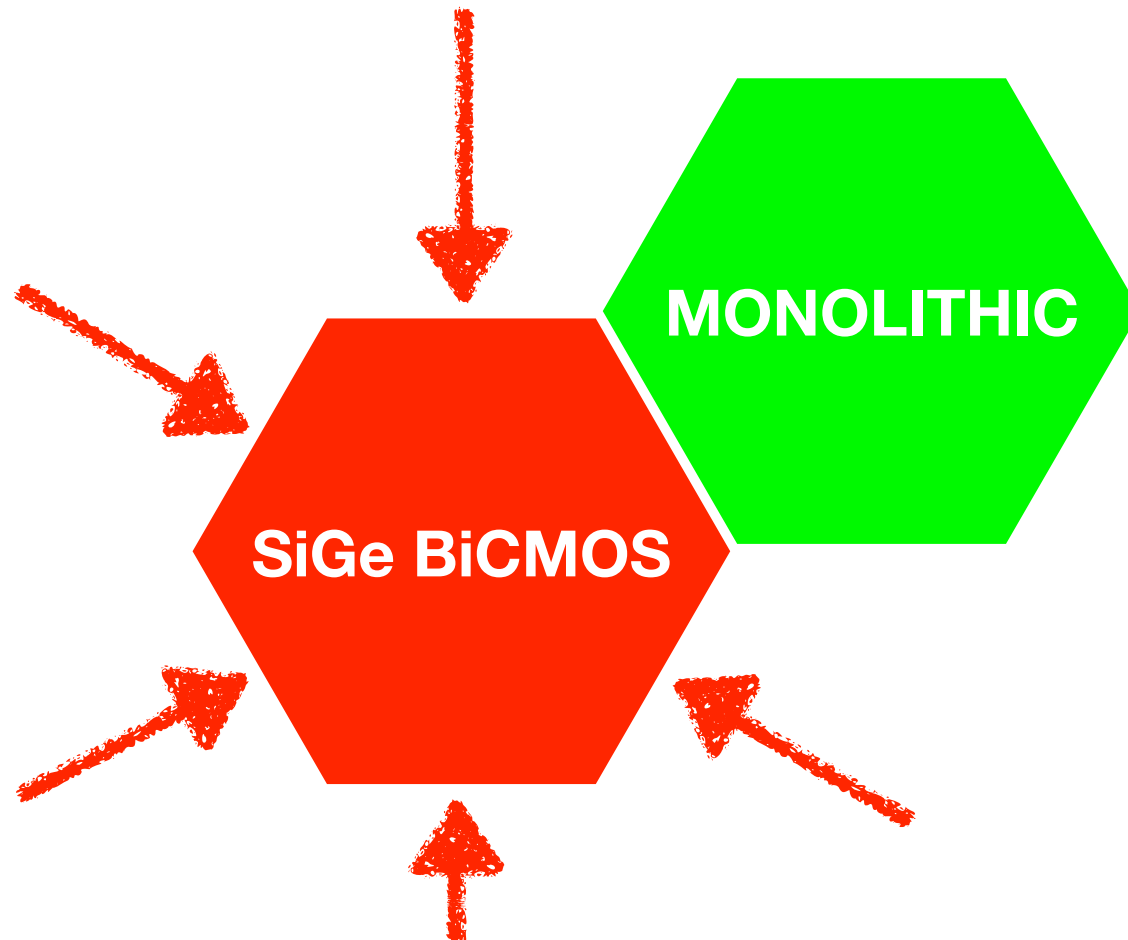
- measure precisely the 3D spatial position of charged particles
- provide **picosecond** time resolution



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



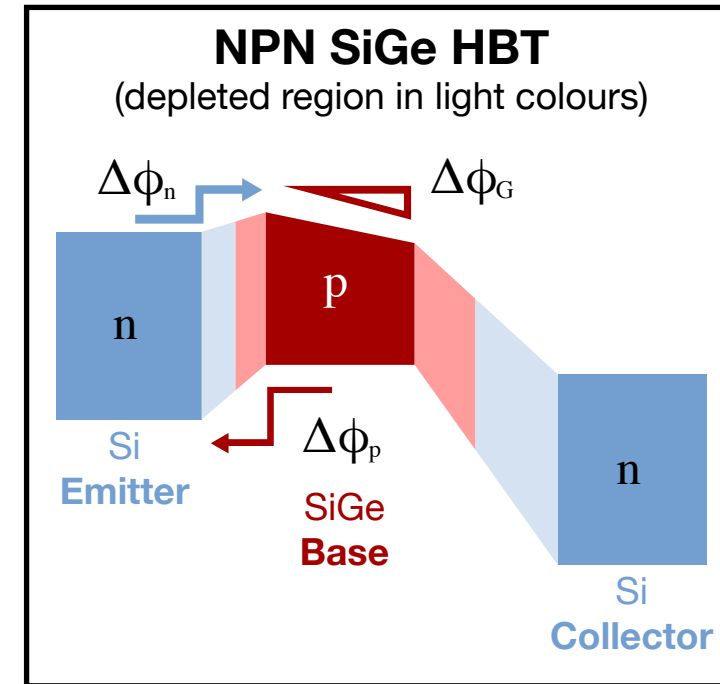
The MONOLITH ERC Project



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

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



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

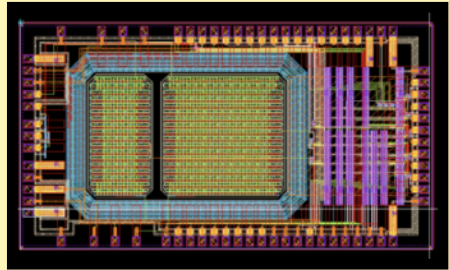


Leading-edge **IHP SG13G2** technology: **130 nm** process featuring **SiGe HBT**

SiGe BiCMOS Prototypes

Timing Prototypes without Gain Layer

2016

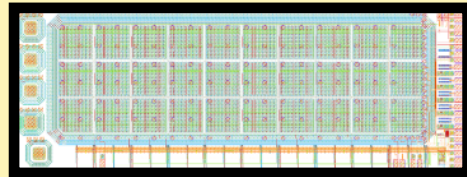


- Square pixel 900 μm
- Discriminated output

200 ps

JINST 13 P04015

2017

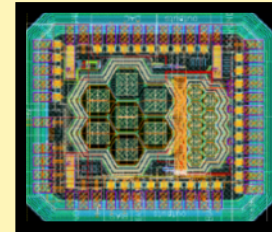


- Square pixels 500 μm
- 100 ps TDC + I/O logic

110 ps

JINST 14 P07013 JINST 14 P02009

2018

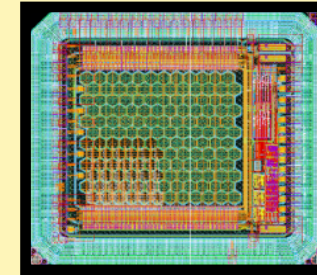


- Hexagonal pixels 130 μm
- Discriminated outputs

45 ps

JINST 14 P11008 JINST 15 P11025

2020

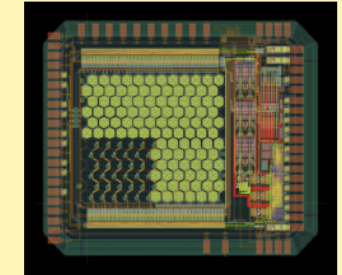


- Hexagonal pixels 65 μm
- 30 ps TDC + I/O logic
- 4 analog outputs

36 ps

JINST 17 P02019

2022



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

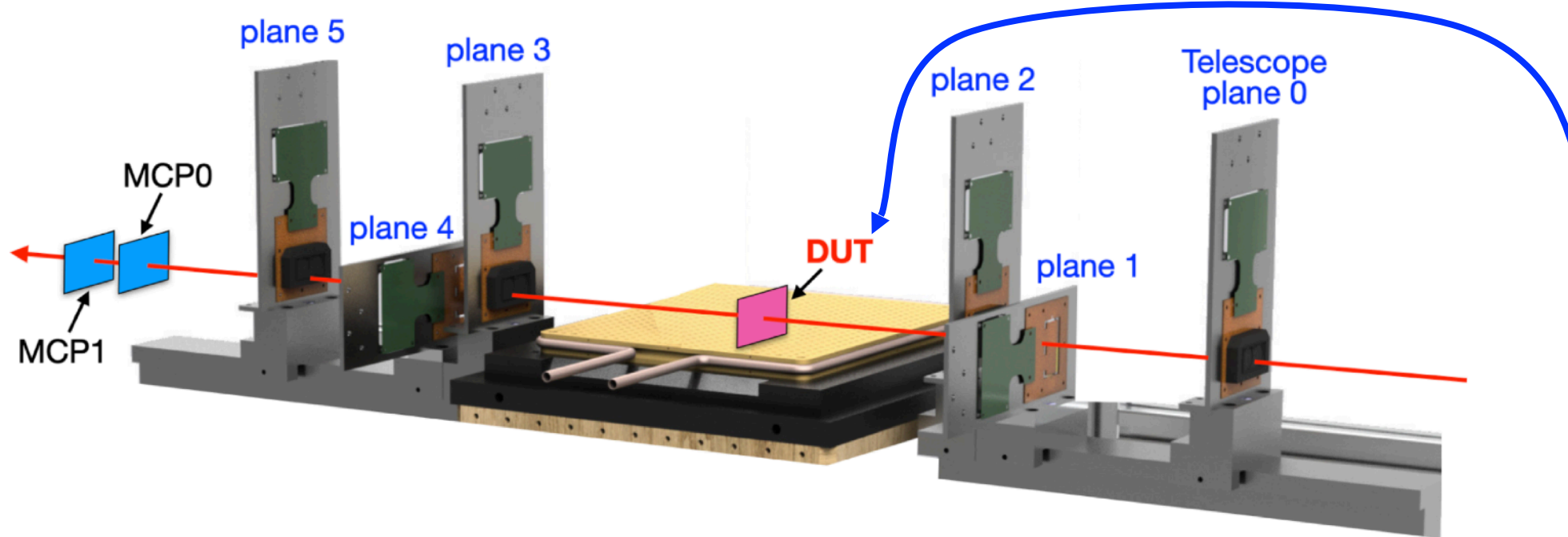
20 ps

*JINST 18 P03047 JINST 19 P01014
JINST 19 P04029*

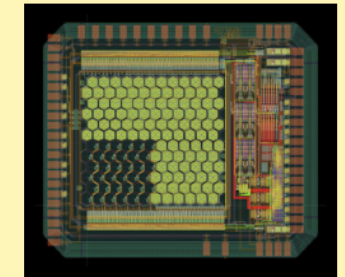
In this talk

Test Beam: Experimental Setup

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



2022



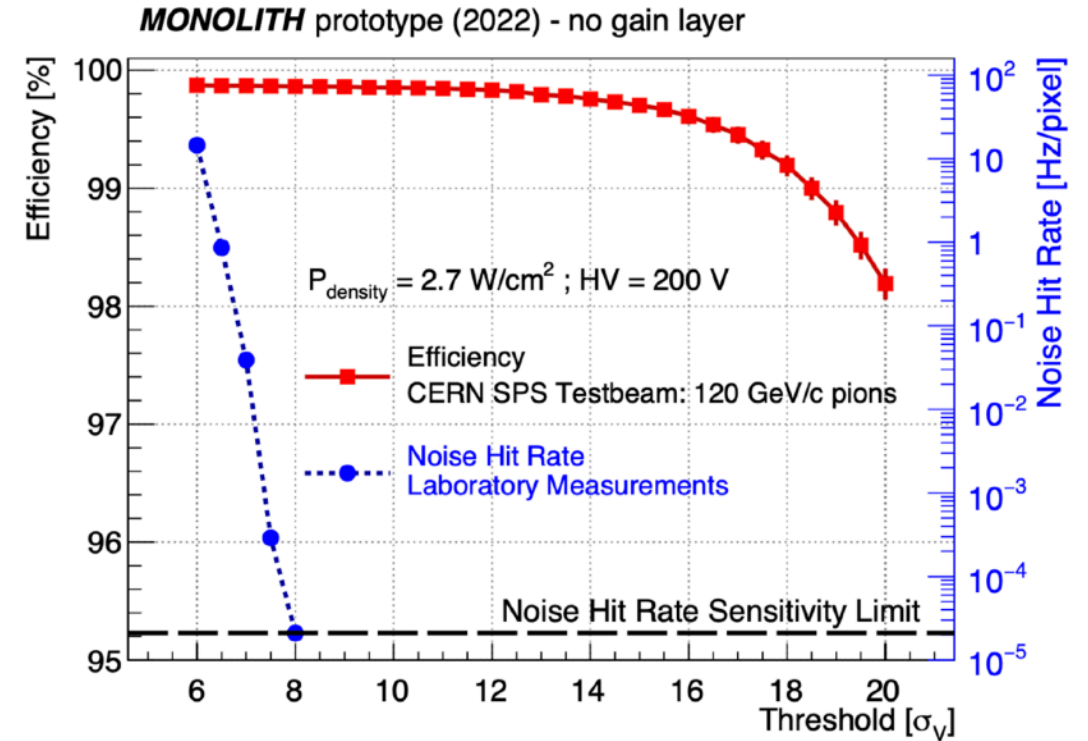
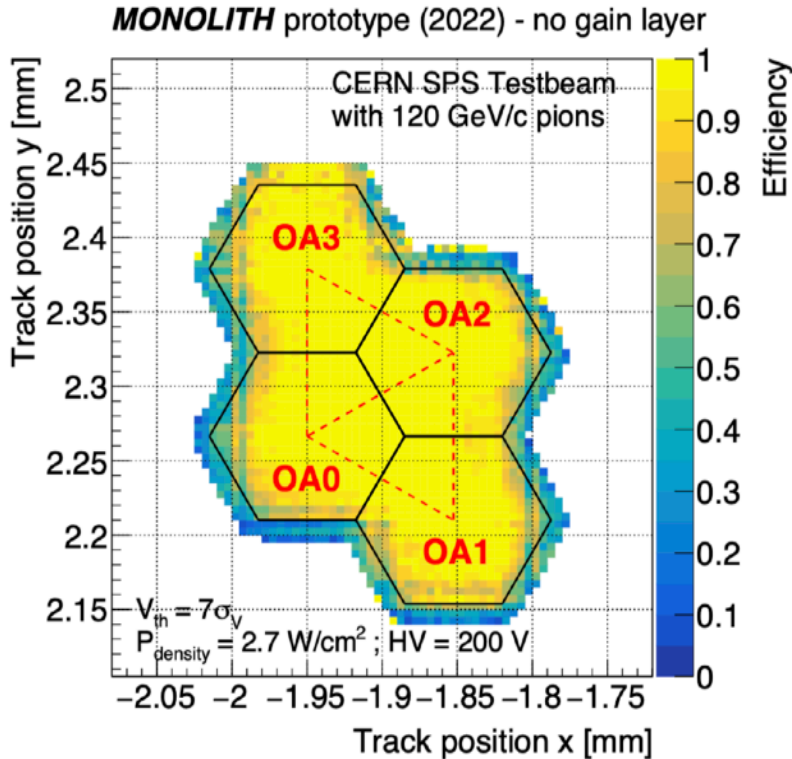
- Hexagonal pixels 65 μm
- Improved frontend
- 4 analog outputs

20 ps

[JINST 18 P03047](#) [JINST 19 P01014](#)
[JINST 19 P04029](#)

- [UNIGE FE-I4 telescope](#) to provide the spatial information ($\sigma_{x,y} \sim 10 \mu\text{m}$)
- **Two PMT-MCPs** ($\sigma_t \sim 5 \text{ ps}$) to provide the timing reference

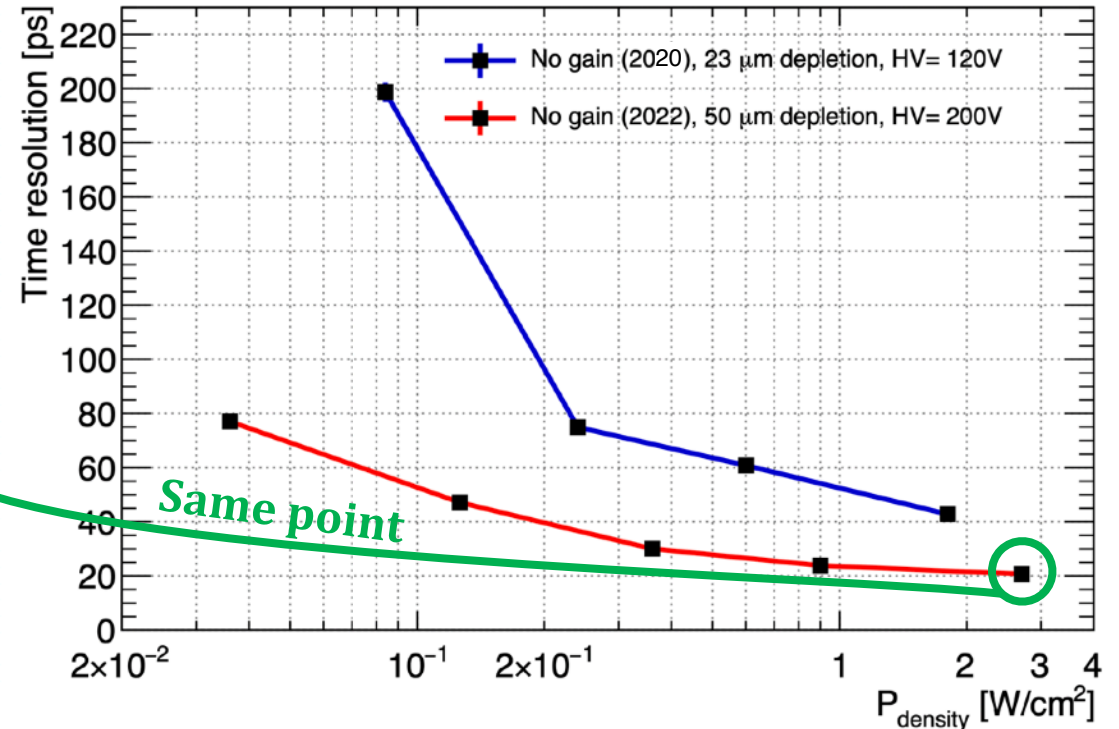
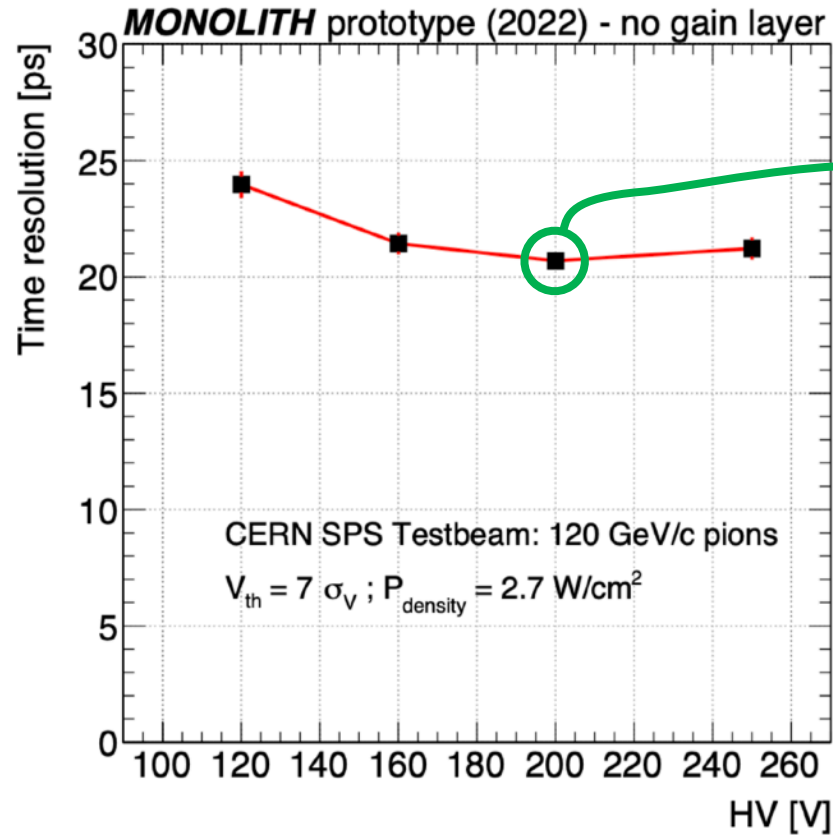
Efficiency Results



- The **apparent degradation** at the edges is due to the $\sim 10 \mu\text{m}$ resolution of the telescope
- Selection of two **triangles**:
 - representative of the whole pixel
 - **unbiased** from the telescope resolution

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

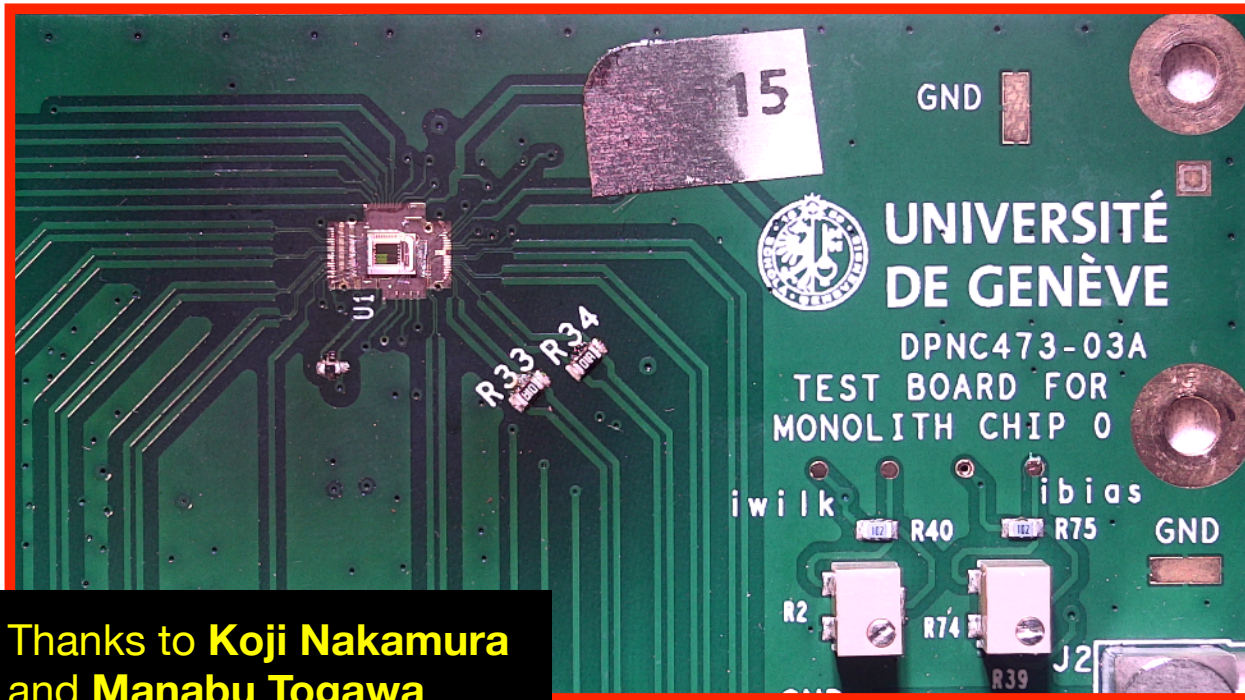
Time Resolution Results



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** ([JINST 17 P02019](#))

SiGe BiCMOS Radiation Hardness

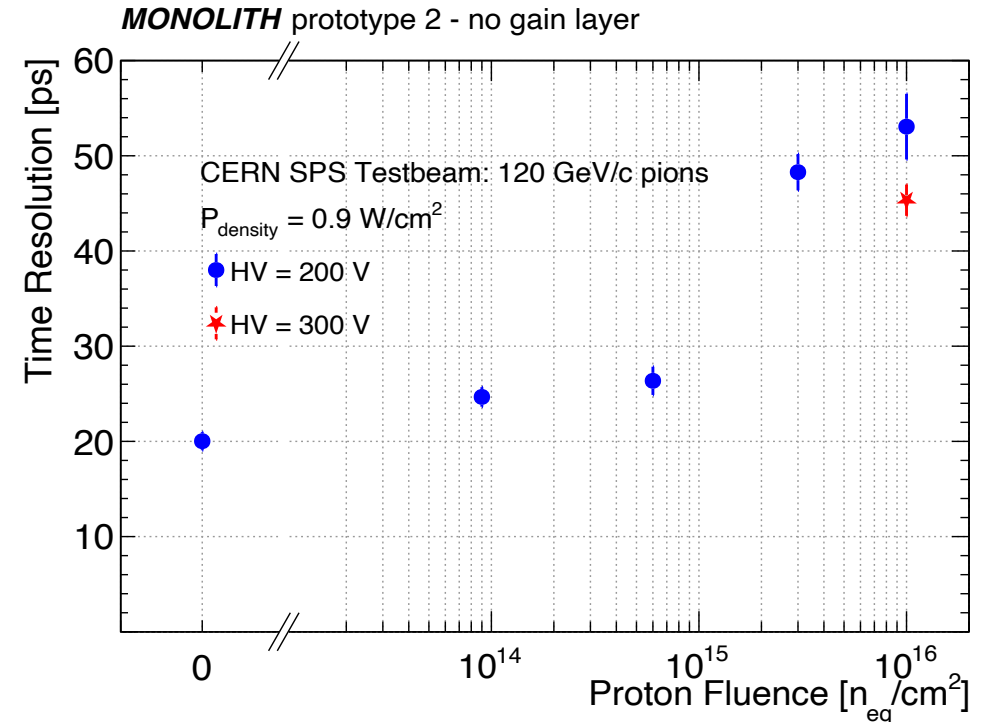
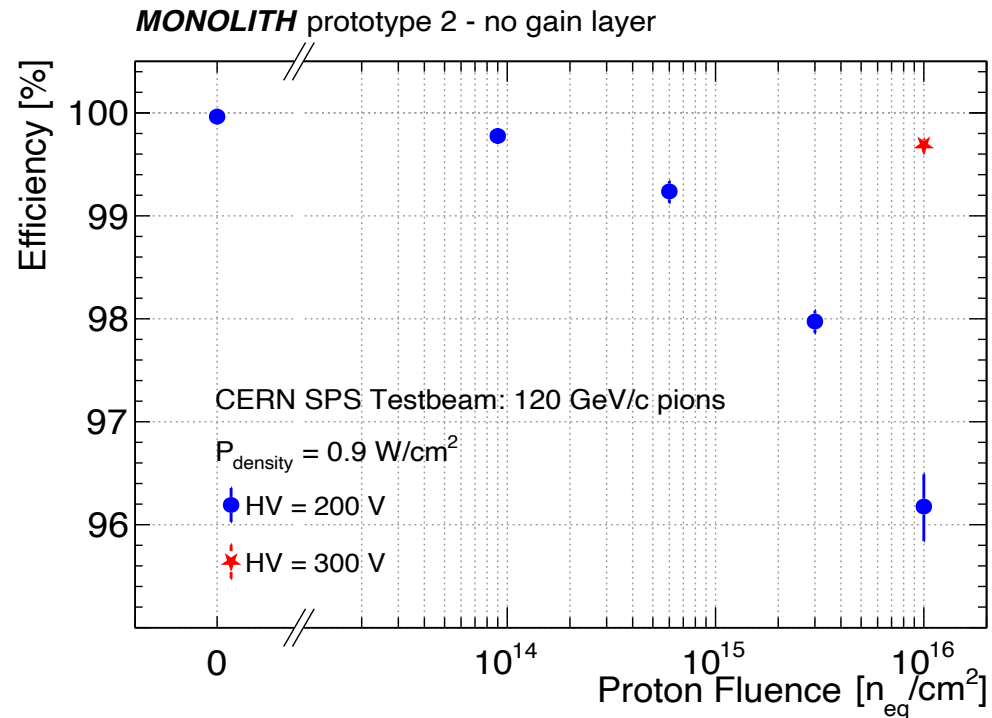


Thanks to Koji Nakamura and Manabu Togawa

Board Name	Fluence [1 MeV n _{eq} /cm ²]
M23	2 · 10 ¹³
M22	9 · 10 ¹³
M21	6 · 10 ¹⁴
M19	6 · 10 ¹⁴
M18	3 · 10 ¹⁵
M17	3 · 10 ¹⁵
M16	1 · 10 ¹⁶
M15	1 · 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 × 10¹⁶ n_{eq}/cm²
- One of the not irradiated chips is the one studied at the testbeam (in [JINST 18 P03047](#))

Performances After Irradiation

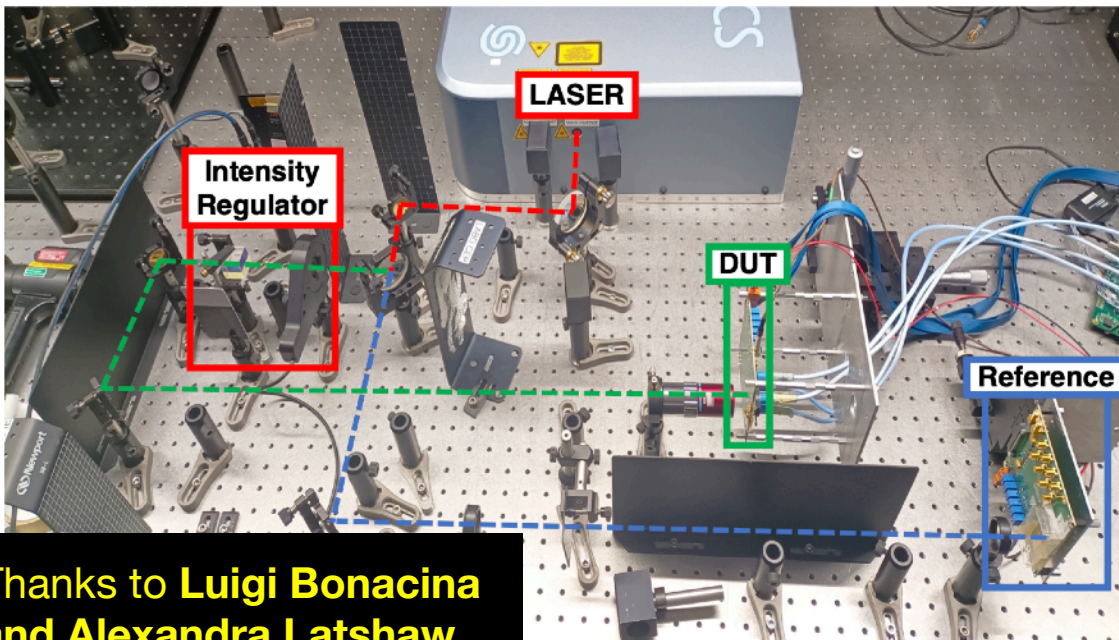


At $10^{16} n_{\text{eq}}/\text{cm}^2$, with **HV = 200 V** and $P_{\text{density}} = 0.9 \text{ W/cm}^2$:

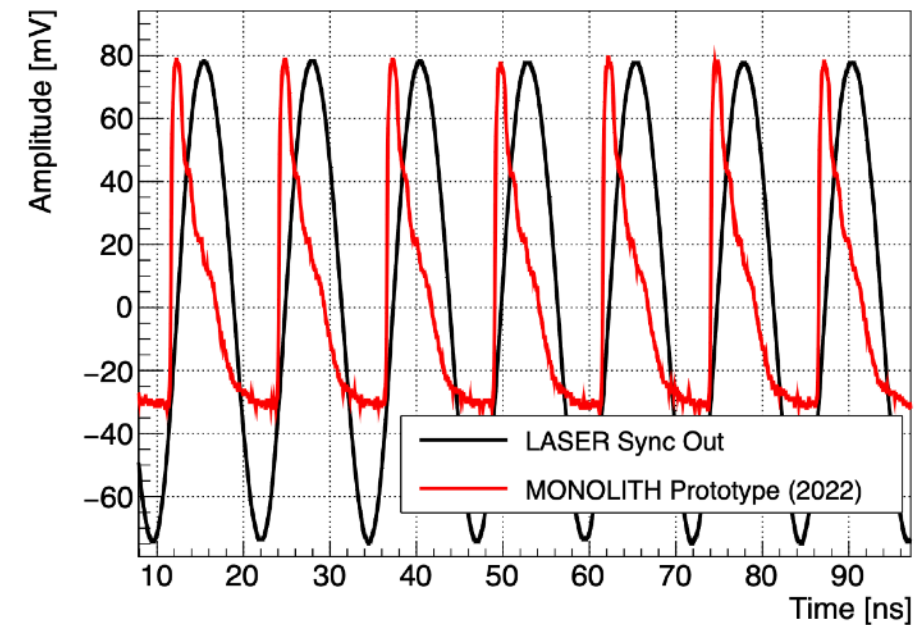
- The efficiency is 96.2% -> **99.7%** increasing the High Voltage
- The time resolution is 53 ps -> **45 ps** increasing the High Voltage

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



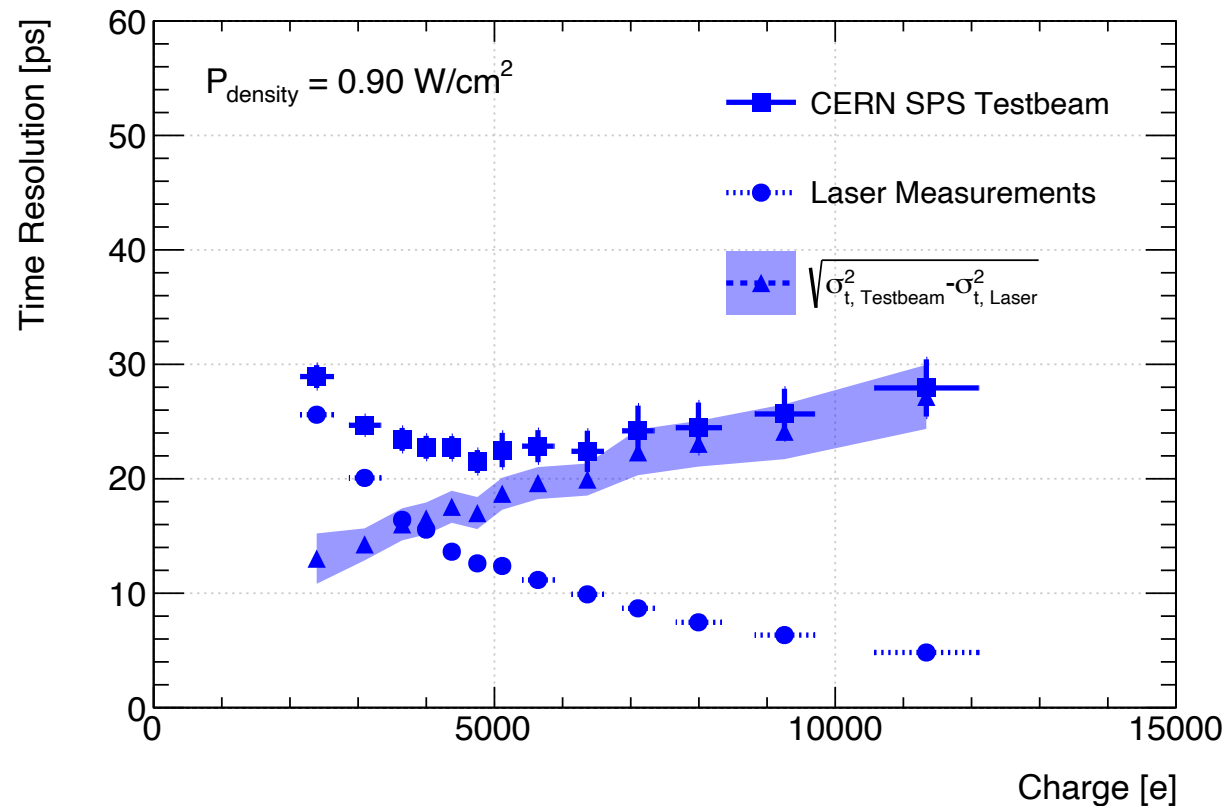
Thanks to Luigi Bonacina
and Alexandra Latshaw



Laser Results

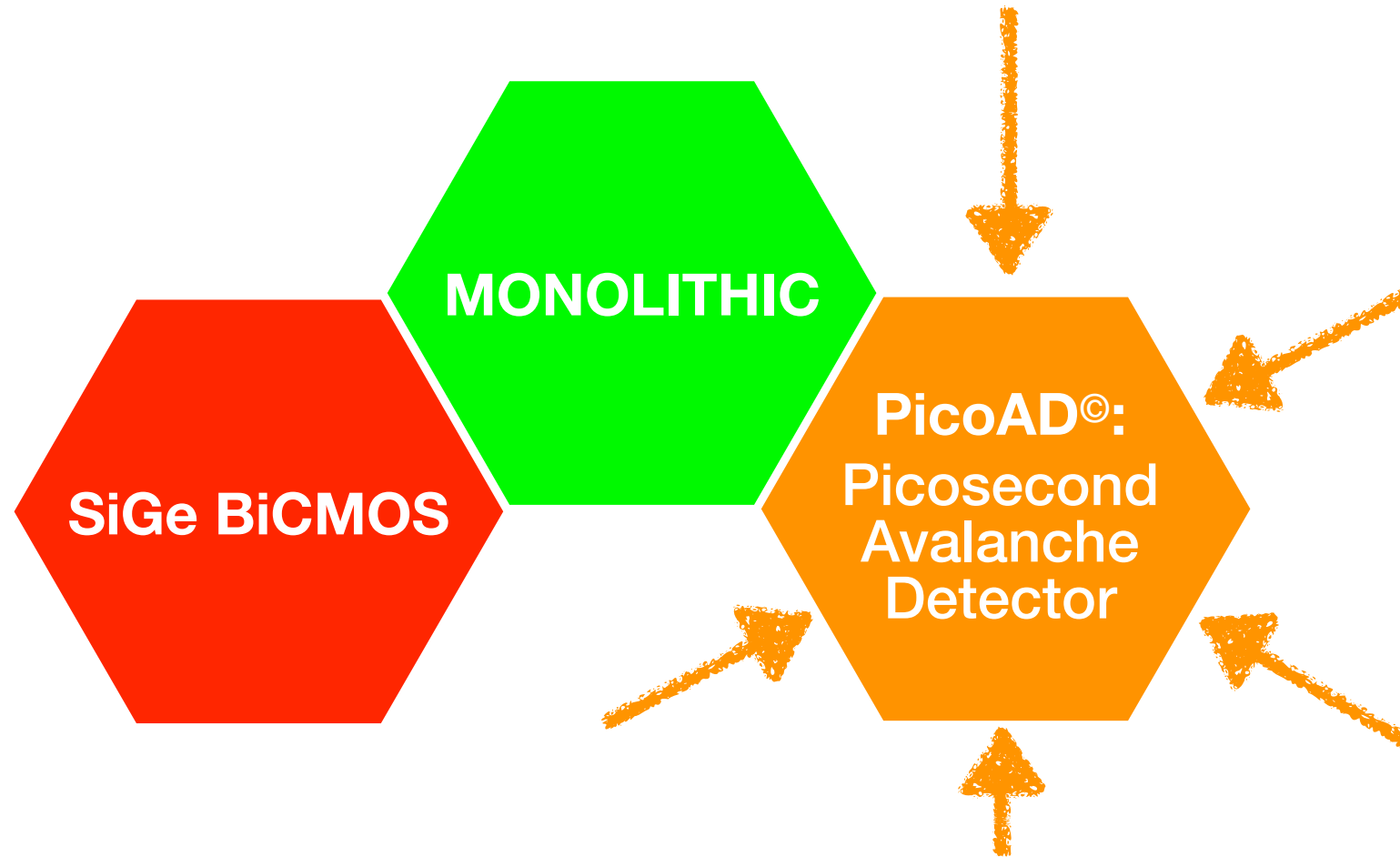
- The electronics can achieve a **time resolution of 3 ps** with 11k electrons (~4 MIPs)
- Intrinsic limit to the time resolution due to **Charge Collection Noise**
 - The limit is ~**17 ps** in a 50 μm -thick sensor
 - Improved with the **PicoAD[©]**

MONOLITH prototype2 (2022) - no gain layer



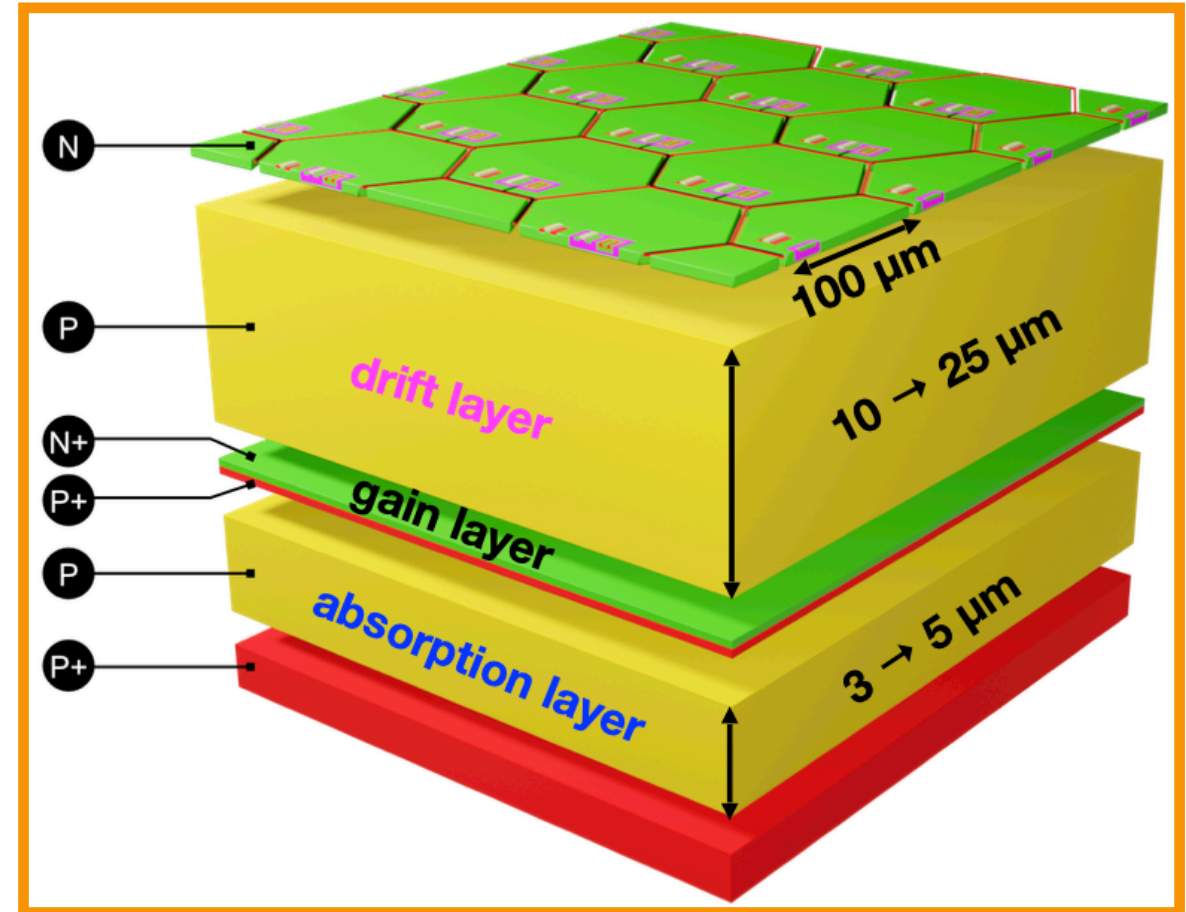


The MONOLITH ERC Project



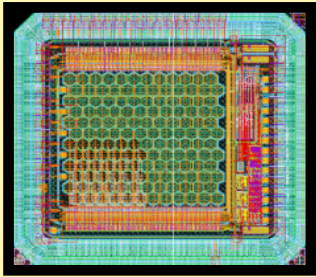
Funded by the H2020 ERC Advanced grant 884447, July 2020 - June 2025

- Multi-Junction **Picosecond Avalanche Detector[©]** ([patented 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

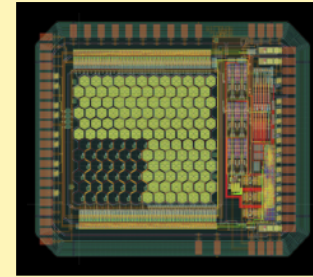


- Hexagonal pixels 65 μm
- 30 ps TDC + I/O logic
- 4 analog outputs

36 ps

[JINST 17 P02019](#)

2022



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

20 ps

[JINST 18 P03047](#) [JINST 19 P01014](#)
[JINST 19 P04029](#)

With PicoAD[©]

2022

With PicoAD[©]

17 ps

[JINST 17 P10032](#)
[JINST 17 P10040](#)

With PicoAD[©]

2024

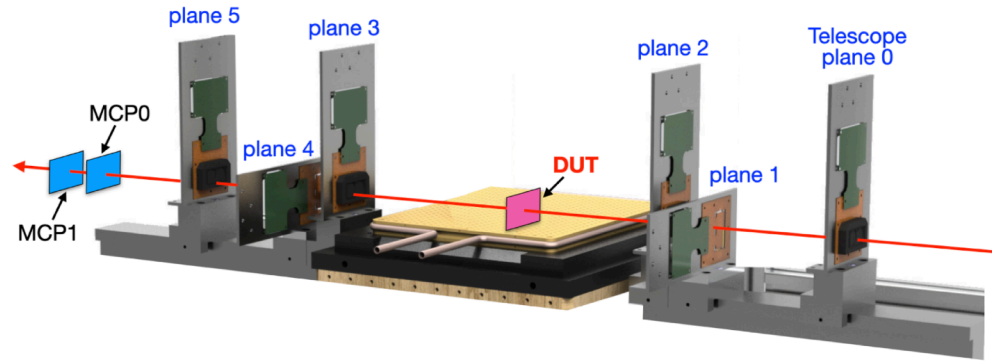
With PicoAD[©]

12 ps

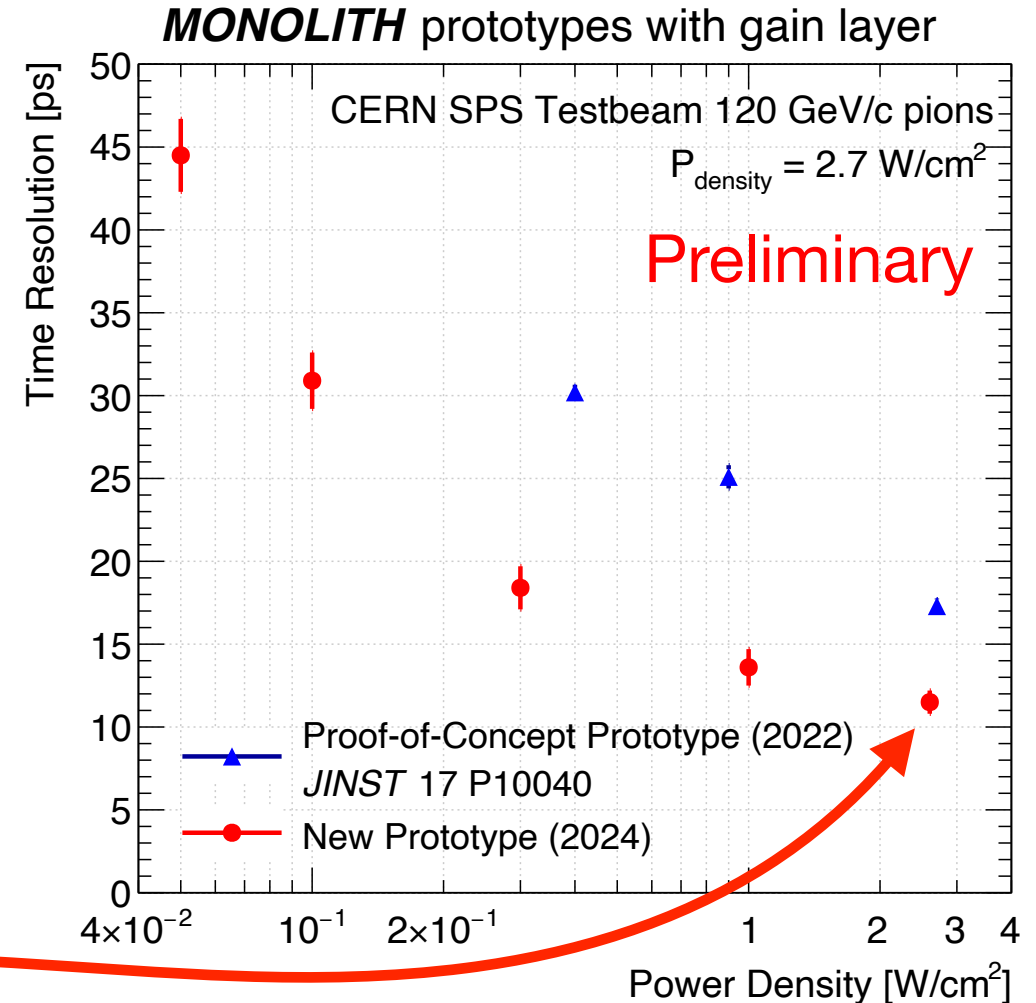
Paper in production

In this talk

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: (12.1 ± 0.4) ps** with HV = 180 V and $P_{\text{density}} = 2.6 \text{ W/cm}^2$



Summary



- **99.8%** efficiency and **20 ps** time resolution with a MIP
- After irradiation at $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$: **99.7%** efficiency and **45 ps** time resolution
- The time resolution is **limited by Charge Collection Noise** -> limit improved with **PicoAD[©]**

2016

- Square pixel 900 μm
- Discriminated output

200 ps

2017

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

110 ps

2018

- Hexagonal pixels 130 μm
- Discriminated outputs

45 ps

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2022

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20 ps

2022
With **PicoAD[©]**
17 ps

2024
With **PicoAD[©]**
12 ps

12 ps time resolution
with a MIP




Other Projects at UNIGE



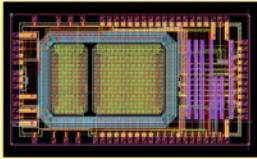
LHC Application: Preshower for FASER -> [webpage](#)



2022  2023  2024 

[JINST 16 P12038](#)

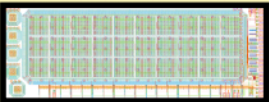
2016



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200 ps

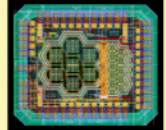
2017



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110 ps

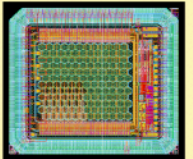
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45 ps

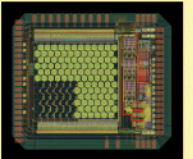
2020



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36 ps

2022

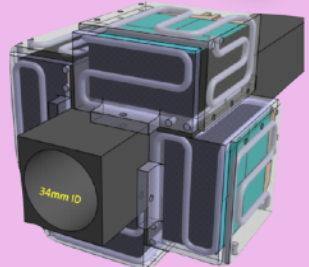


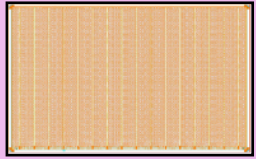
- Hexagonal pixels 65 μm
- Improved frontend
- 4 analog outputs

20 ps

Medical Application: 100 μ PET

[NIMA 167952](#)



2024 

2022
With **PicoAD[©]**
17 ps

2024
With **PicoAD[©]**
12 ps

*See Rafaella (**FASER**) and Mateus (**100 μ PET**) talks on Wednesday

Future Perspectives

LHC Application: Preshower for FASER -> [webpage](#)

2022 2033 2024

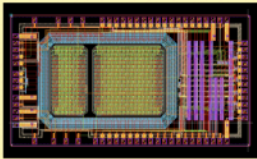





[JINST 16 P12038](#)

High-radiation tolerance
high granularity
timing layers
for particle physics

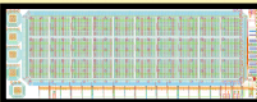
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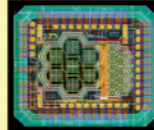
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110 ps

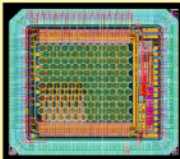
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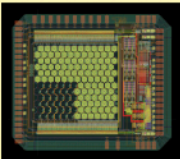
2020



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2022



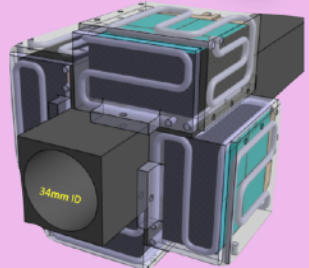
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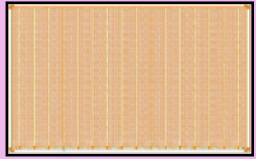
Moderate radiation level
extremely thin
timing layers
for particle physics

Medical Application: 100 μ PET

[NIMA 167952](#)



2024



2022
With **PicoAD[©]**
17 ps

2024
With **PicoAD[©]**
12 ps

Photonics

*See Rafaella (**FASER**) and Mateus (**100 μ PET**) talks on Wednesday



Thanks for your attention



Giuseppe Iacobucci

- Project P.I.
- System Design



Thanushan Kugathasan

- Lead Chip Design
- Analog Electronics



Roberto Cardella

- Analog and Digital Electronics
- Sensor Design



Leonardo Cecconi

- Chip Design
- Firmware



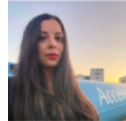
Antonio Picardi

- Chip Design
- Firmware



Matteo Milanesio

- Laboratory Tests
- Data Analysis



Raffaella Kotitsa

- Detector Simulations
- Laboratory Tests



Carlo Alberto Fenoglio

- Chip Design
- Firmware



Andrea Pizarro Medina

- Laboratory Tests
- Data Analysis



Lorenzo Paolozzi

- Sensor Design
- Analog Electronics



Stefano Zambito

- Laboratory Tests
- Data Analysis



Mateus Vicente

- System Integration
- Laboratory Tests



Jorge Sabater Iglesias

- Detector Simulations



Chiara Magliocca

- Laboratory Tests
- Data Analysis



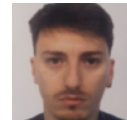
Théo Moretti

- Laboratory Tests
- Data Analysis



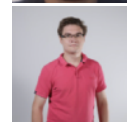
Jihad Saidi

- Laboratory Tests
- Data Analysis



Luca Iodice

- Chip Design
- Firmware



Ivan Semendyaev

- Laboratory Tests
- Data Analysis



Didier Ferrere

- System integration
- Laboratory test



Yannick Favre

- Board design
- RO system



Sergio Gonzalez-Sevilla

- System integration
- Laboratory test



Stéphane Débieux

- Board design
- RO system

Main research partners:



Roberto Cardarelli
INFN Rome2 & UNIGE



Holger Rücker
IHP Mikroelektronik



Marzio Nessi
CERN & UNIGE



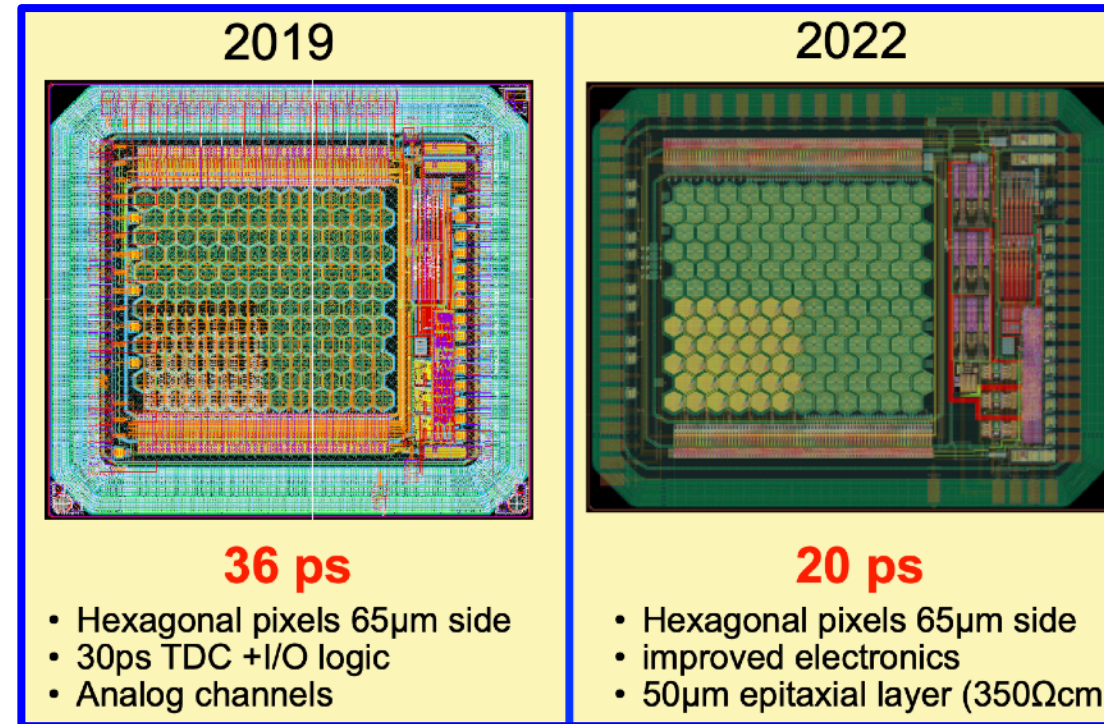
Matteo Elviretti
IHP Mikroelektronik

Funded by:

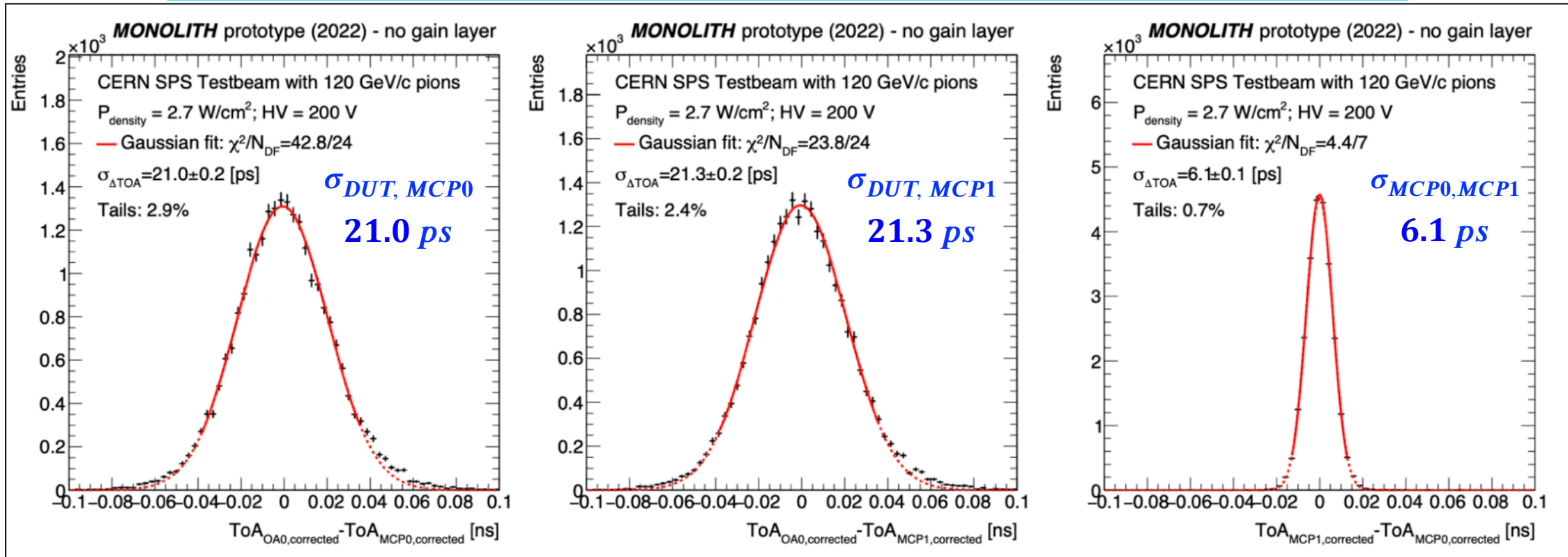


2019->2022: Improvements

- Same matrix configuration as previous, but
 - **Substrate:** 50 Ωcm \rightarrow 350 Ωcm epi layer, 50 μm thick on low-res (1 Ωcm) substrate
 - smaller pixel capacitance
 - depletion 23 μm \rightarrow 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 \rightarrow 300 ps)



Time Resolution Distributions



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

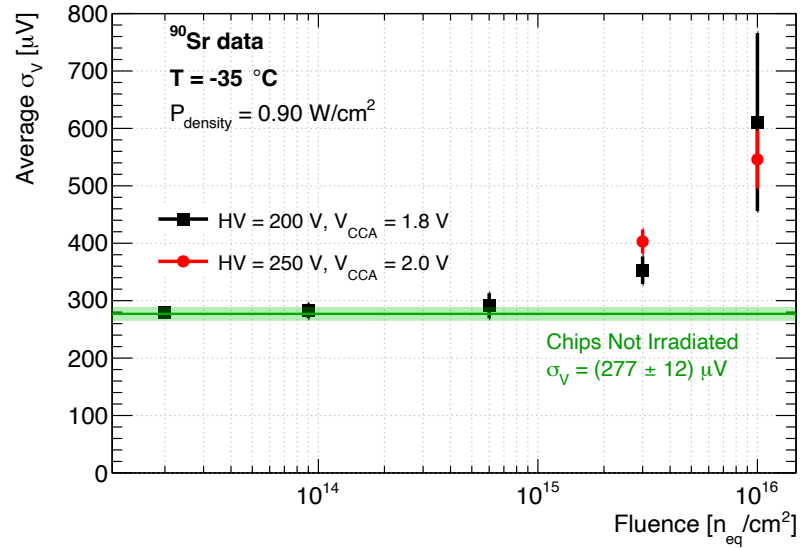
$$\text{MCP0: } \sigma_t = (3.6 \pm 1.5) \text{ ps}$$

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

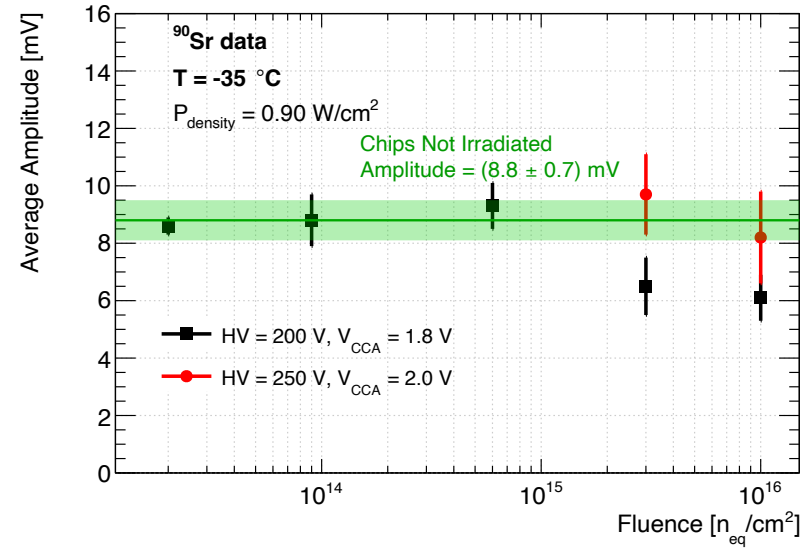
$$\text{DUT: } \sigma_t = (20.7 \pm 0.3) \text{ ps}$$

Radiation Hardness

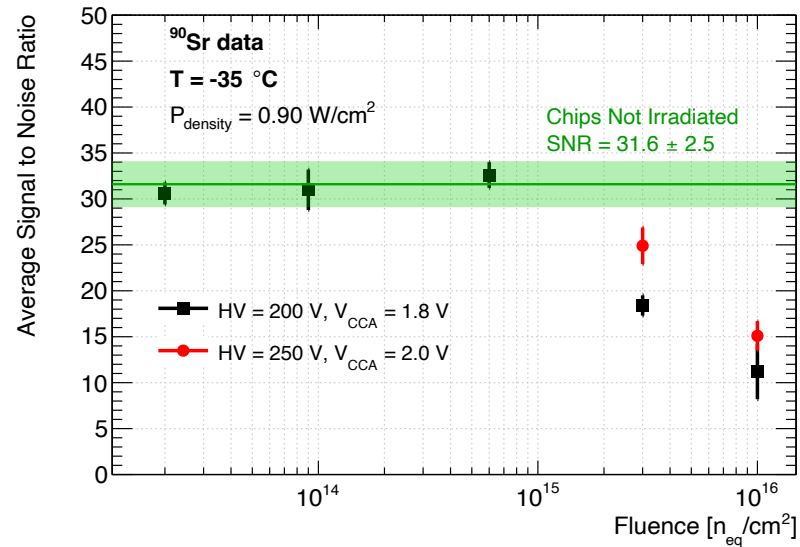
MONOLITH prototype2 (2022) - no gain layer



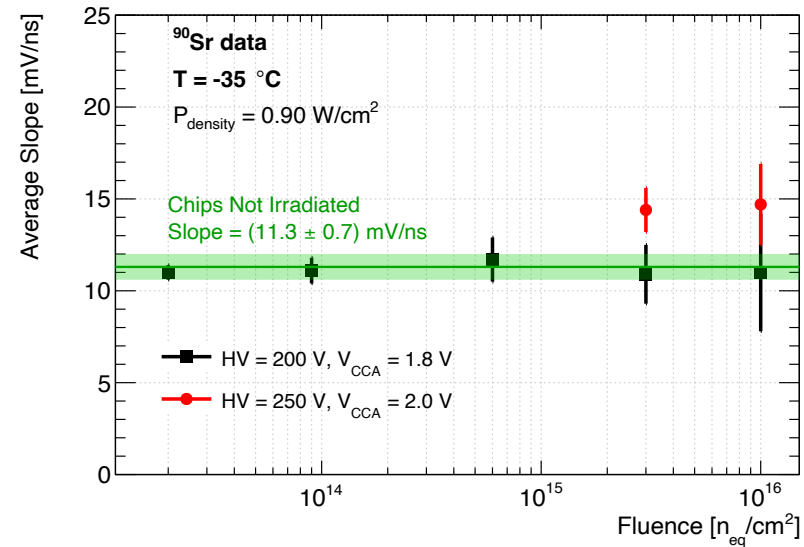
MONOLITH prototype2 (2022) - no gain layer



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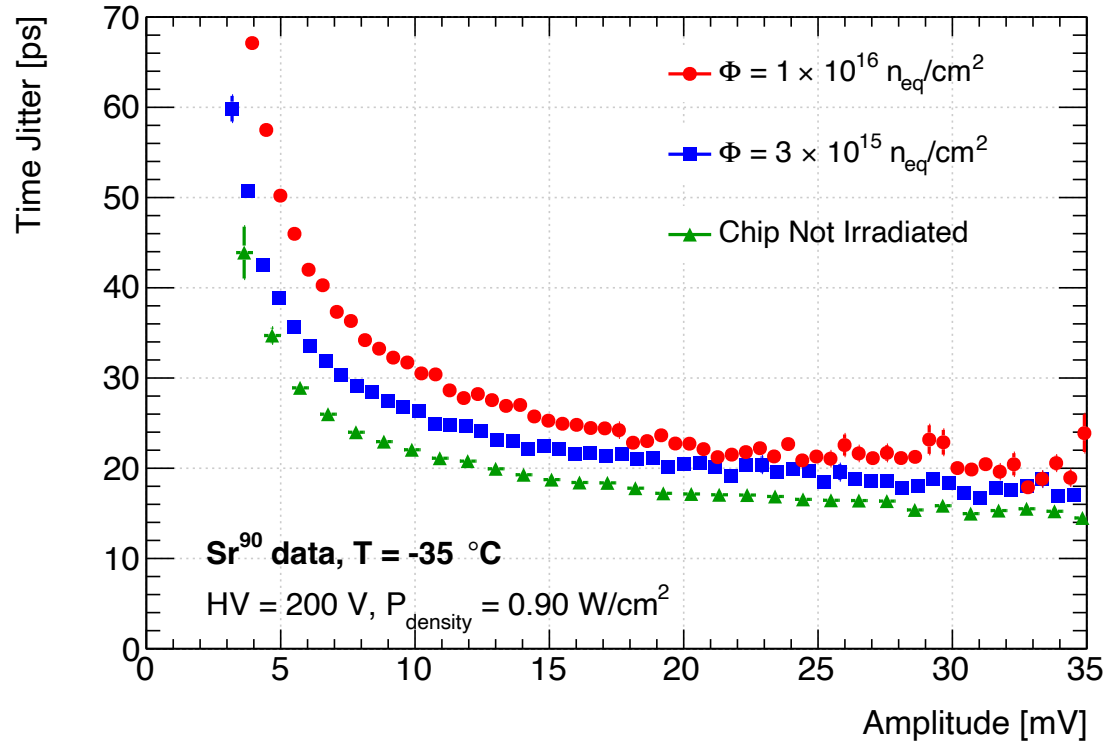


MONOLITH prototype2 (2022) - no gain layer

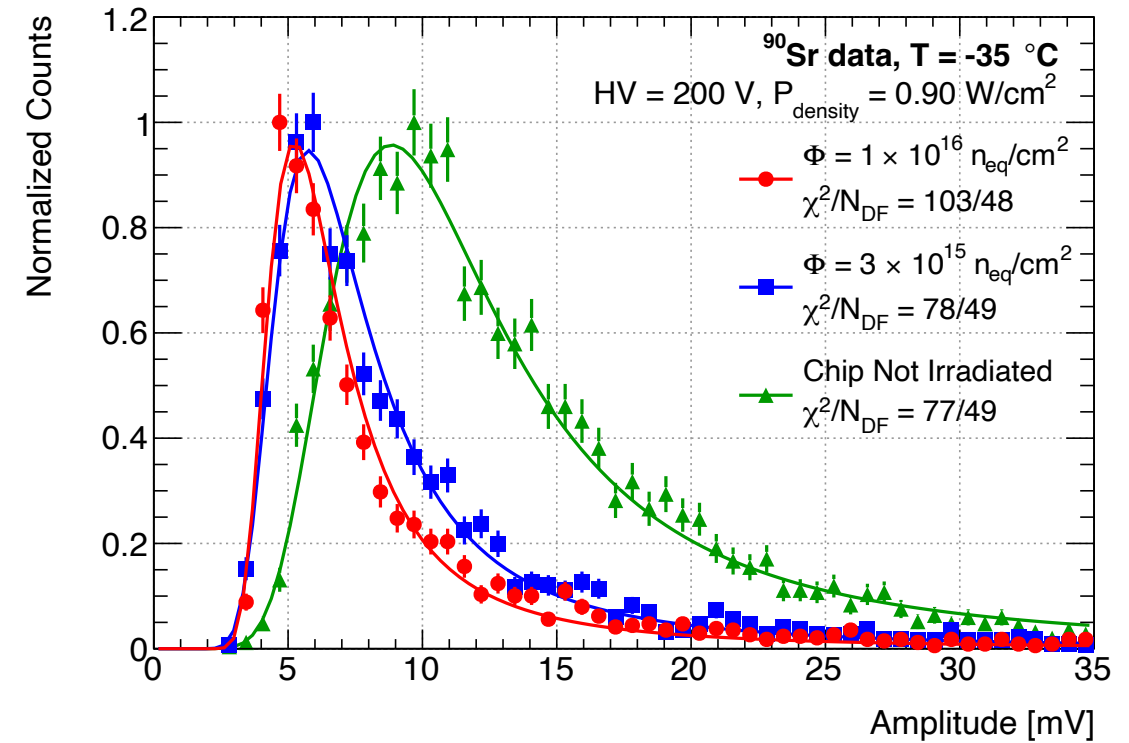


Radiation Hardness

MONOLITH prototype2 (2022) - no gain layer

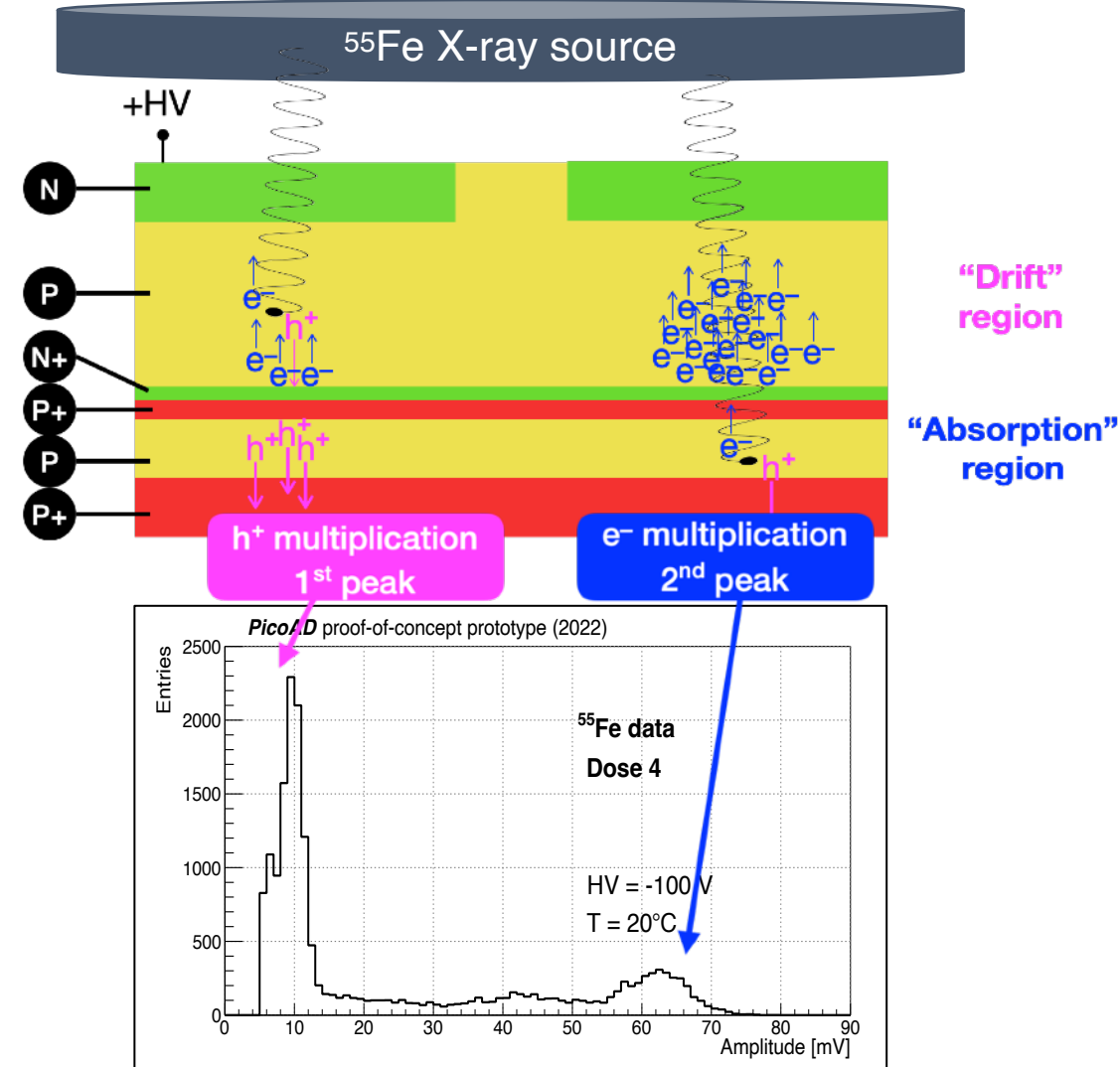


MONOLITH prototype2 (2022) - no gain layer

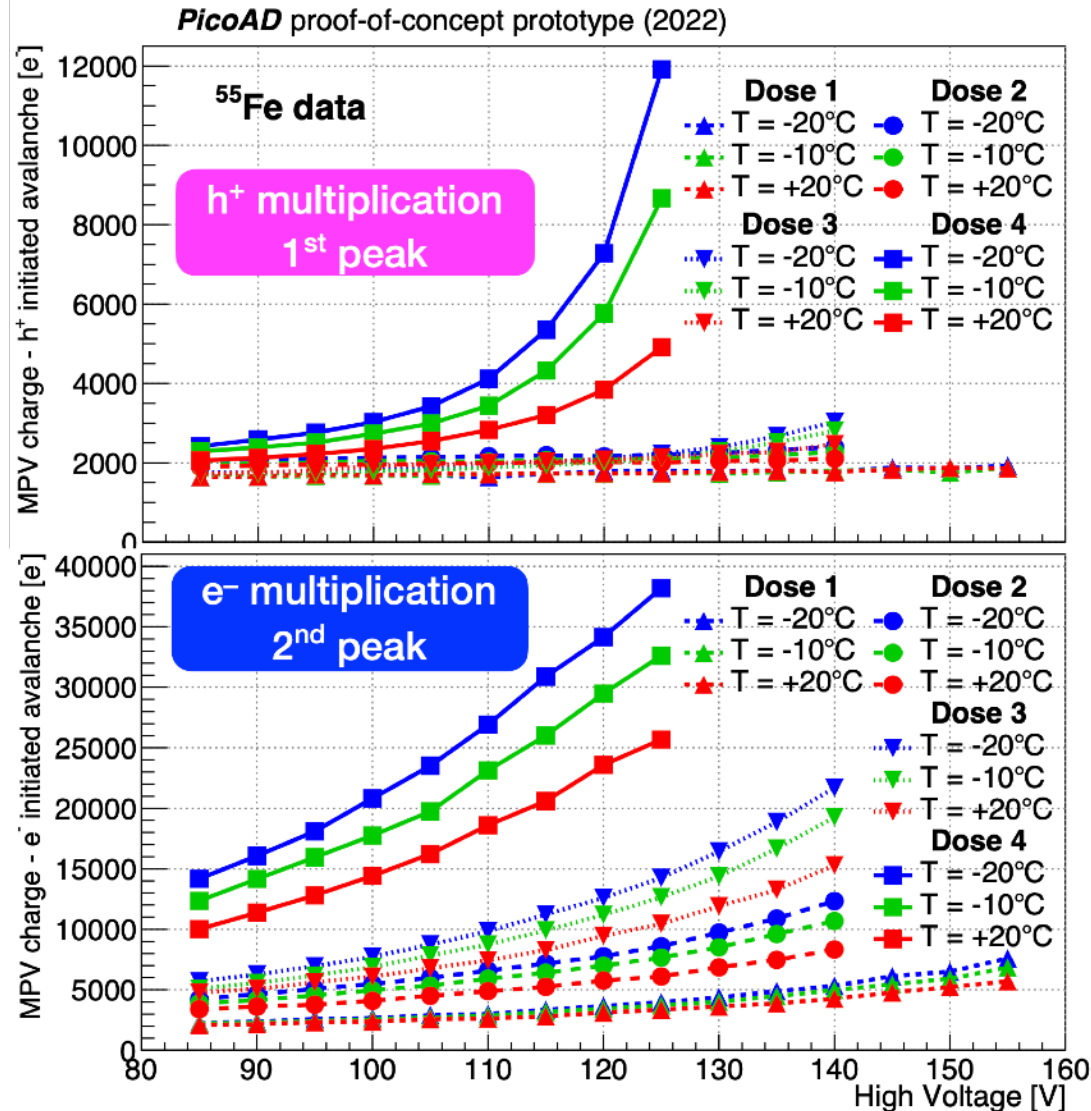


Gain Measurements

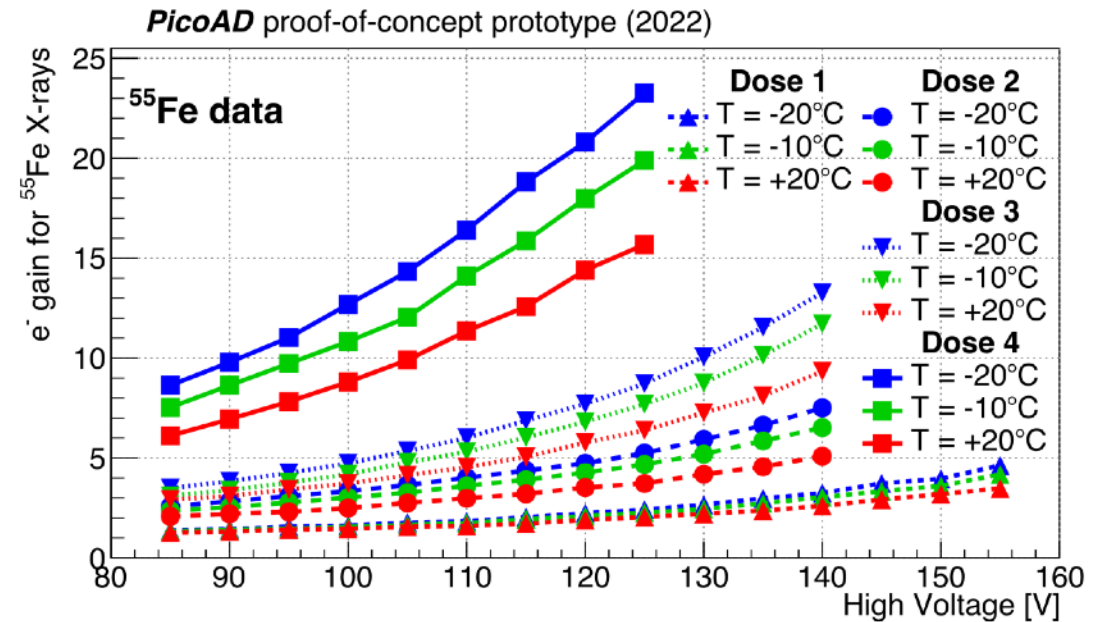
- **X-rays from ^{55}Fe radioactive source:**
 - ~ 5.9 keV photons with point-like charge deposition
- **Characteristic double-peak spectrum** ([PicoAD Working Principles](#))
 - photon absorbed in **drift region**
 - **holes** drift through gain layer and multiplied
 - **first peak** in the spectrum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



Gain Results

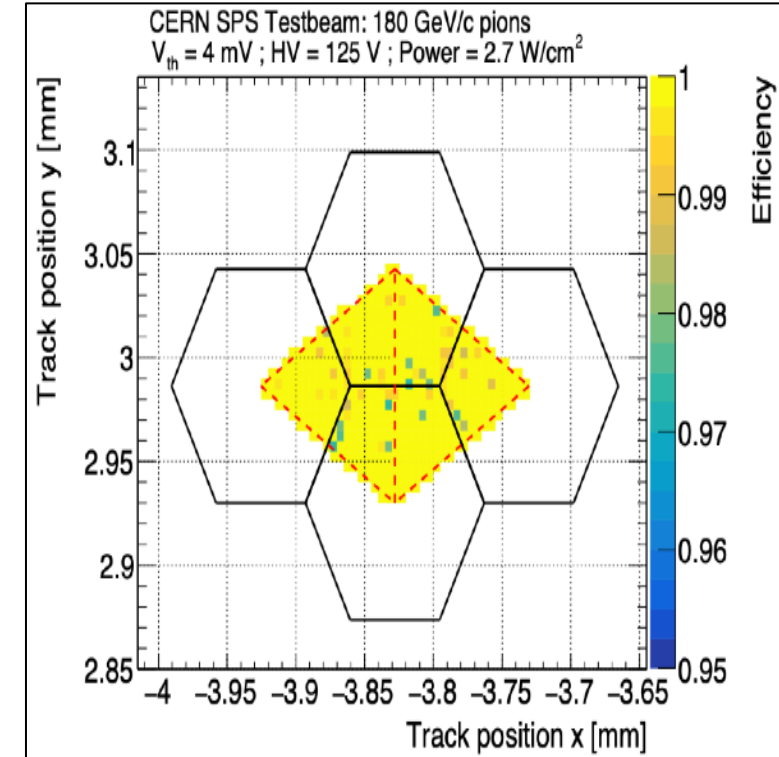
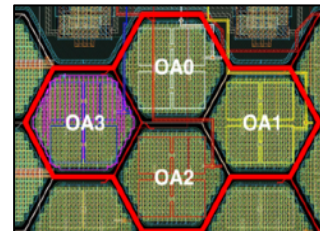
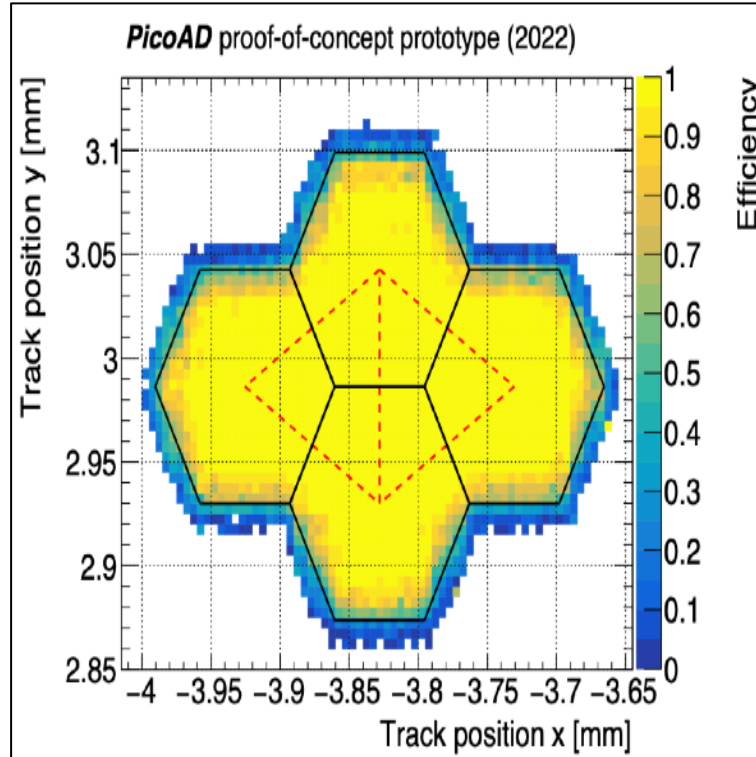


Gain up to ≈ 20 for ^{55}Fe X-rays
obtained at HV = 125 V and T = -20 °C



- 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

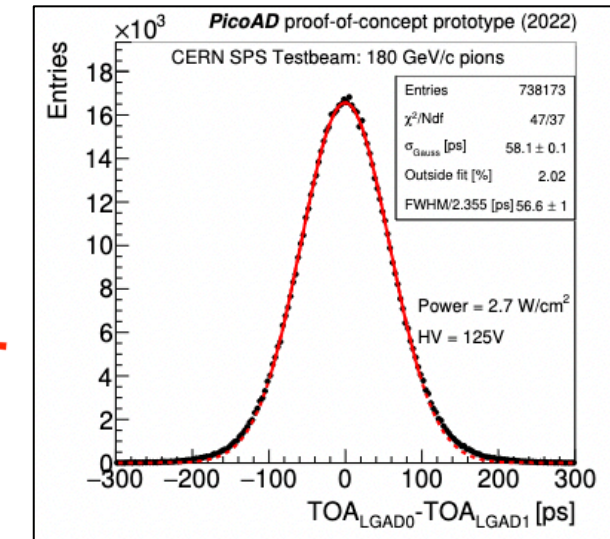
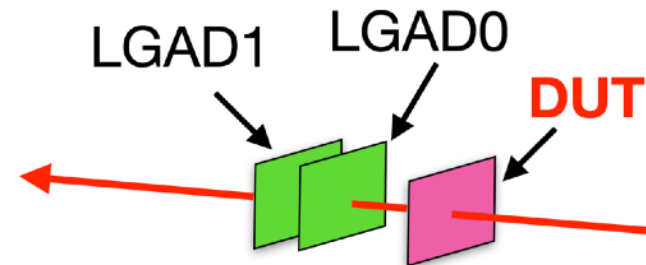
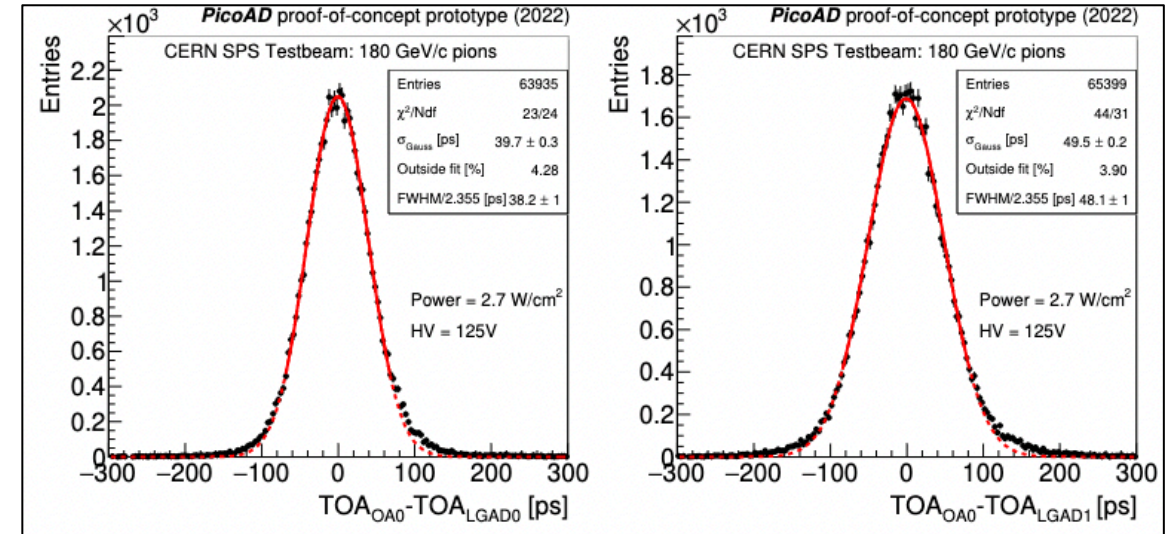


- The **apparent degradation** at the edges is due to the finite resolution of the telescope (~ 10 μ m)

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

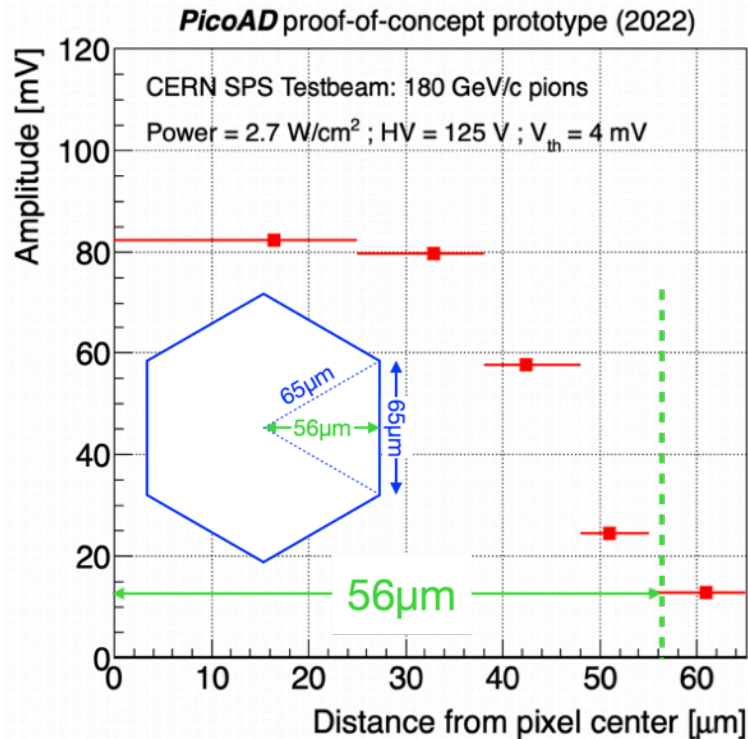
PicoAD[©]: Time Resolution Distributions

- 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

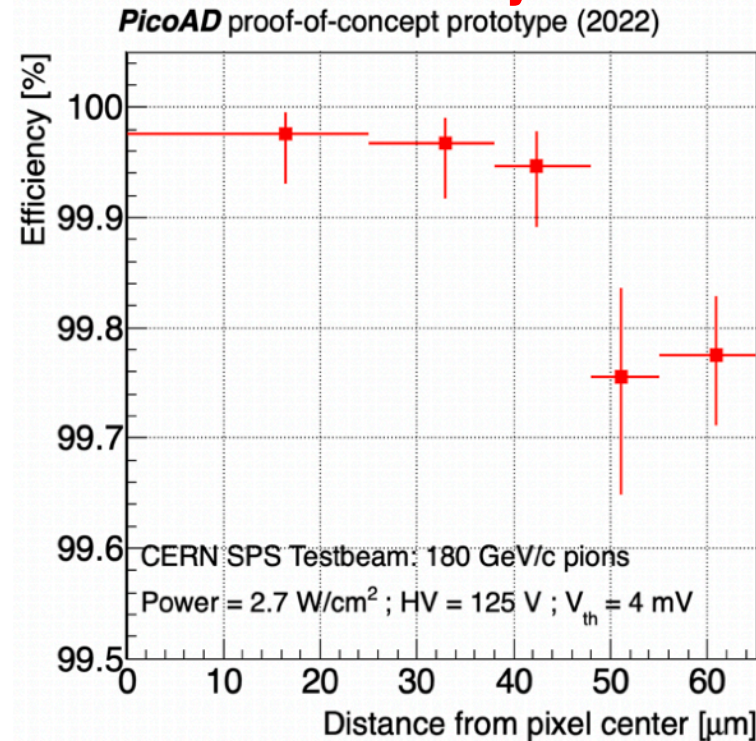


Position Within the Pixel

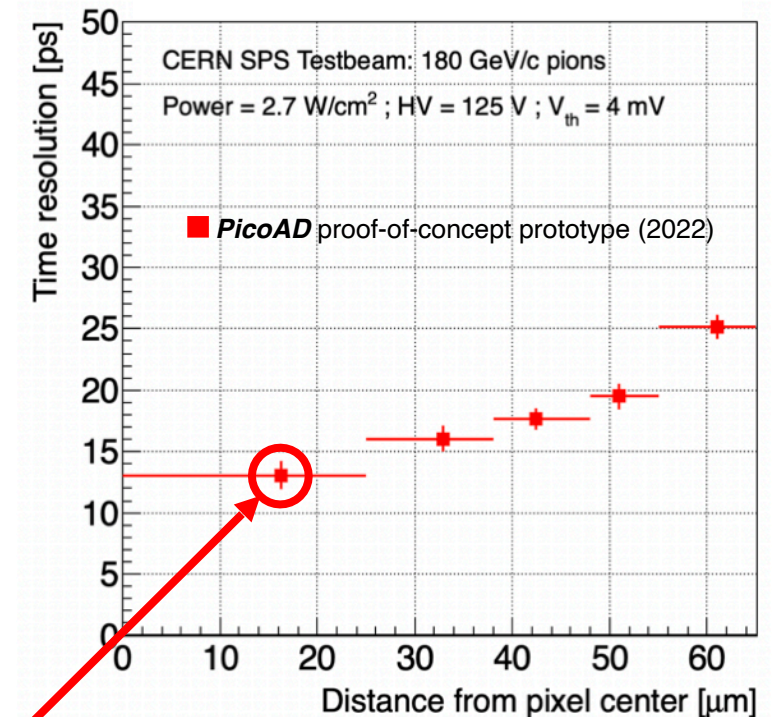
Signal MPV Amplitude



Efficiency



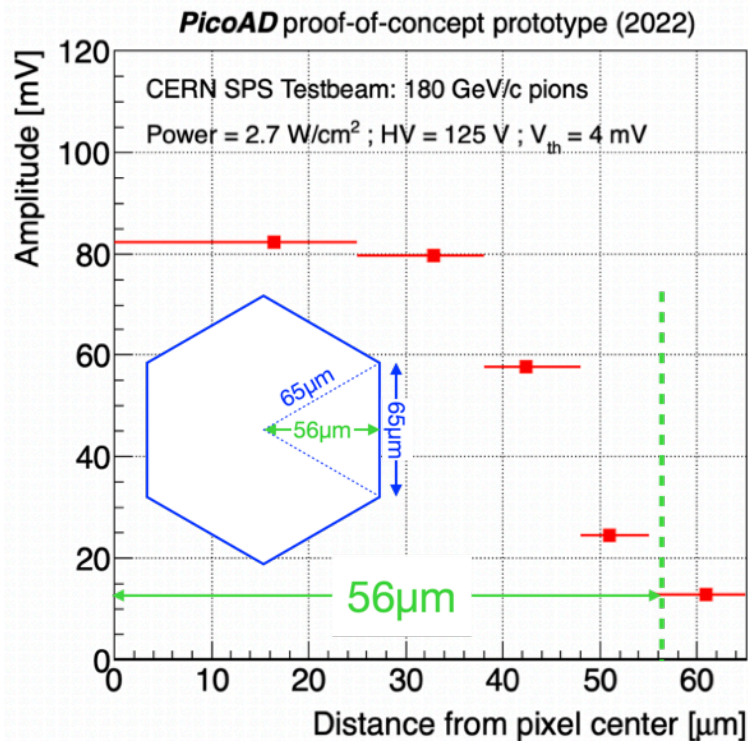
Time Resolution



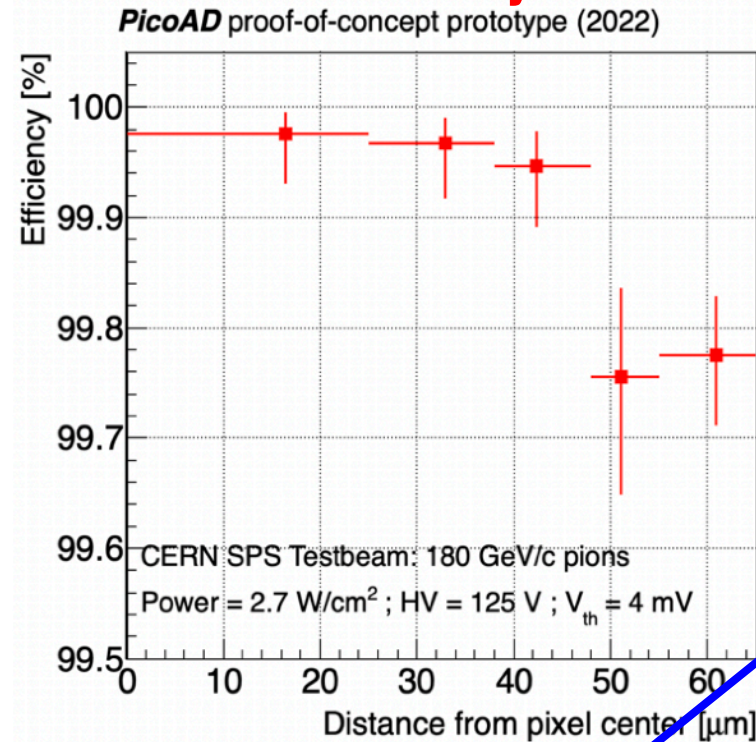
- Best time resolution: **(13.2 ± 0.8) ps within 25 μm** from the pixel center
- **PicoAD**® proof-of-concept: small degradation of the performance towards the edge of the pixel

Position Within the Pixel

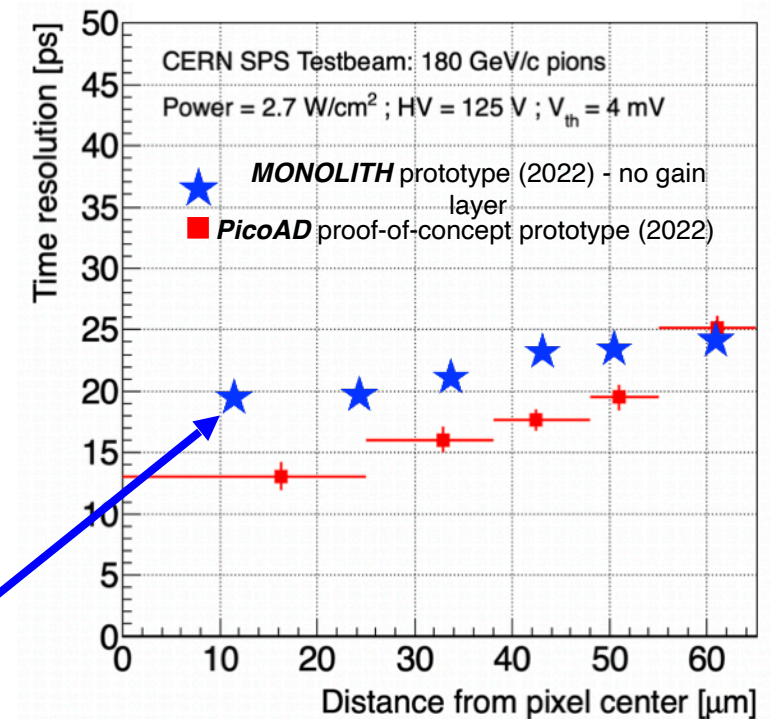
Signal MPV Amplitude



Efficiency



Time Resolution



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

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**
- Moreover, the same amount of pixels can fit in less space than squares

