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

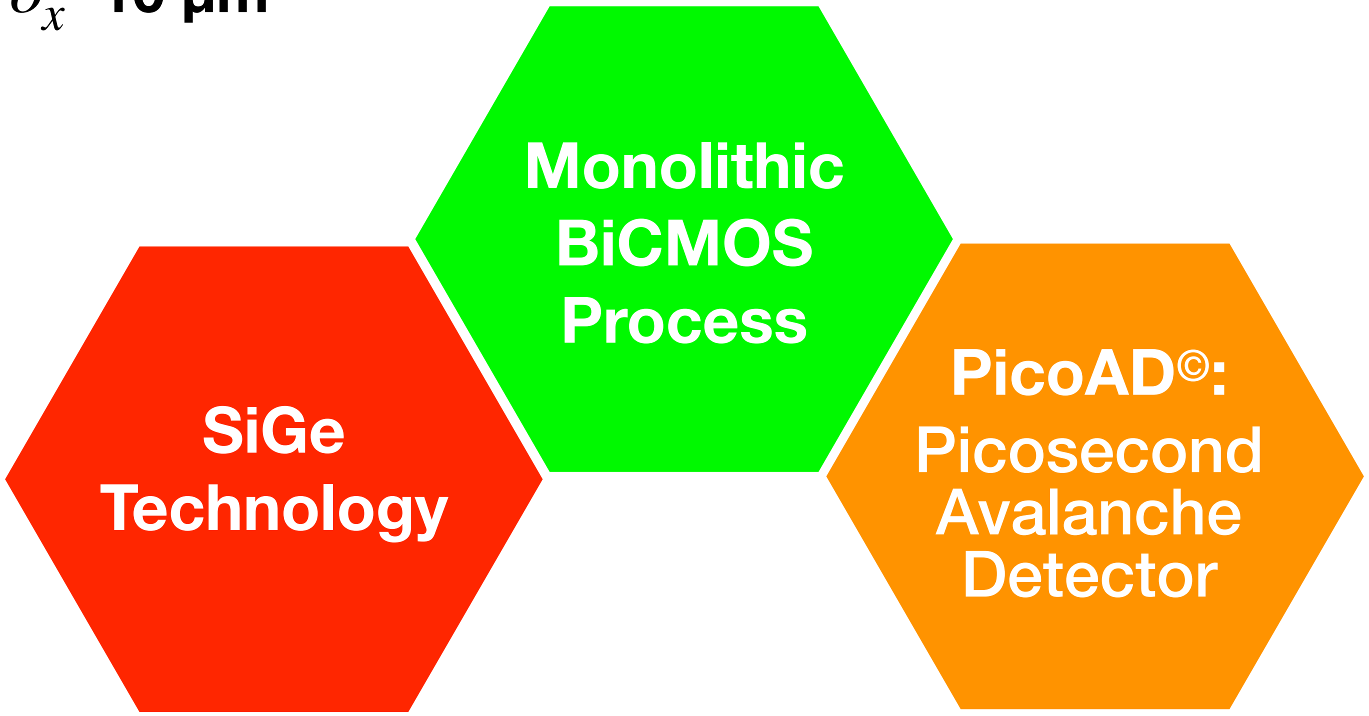
Picosecond Time Stamping in Fully-Monolithic Highly-Granular Pixel Detectors

Matteo Milanesio

10th October 2025 - FATA 2025 - INFN Catania

The MONOLITH ERC Project

- We want to measure **charged particles** with:
  - **time** resolution σ_t**~10 ps**
  - **space** resolution σ_x**~10 µm**



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SiGe Technology

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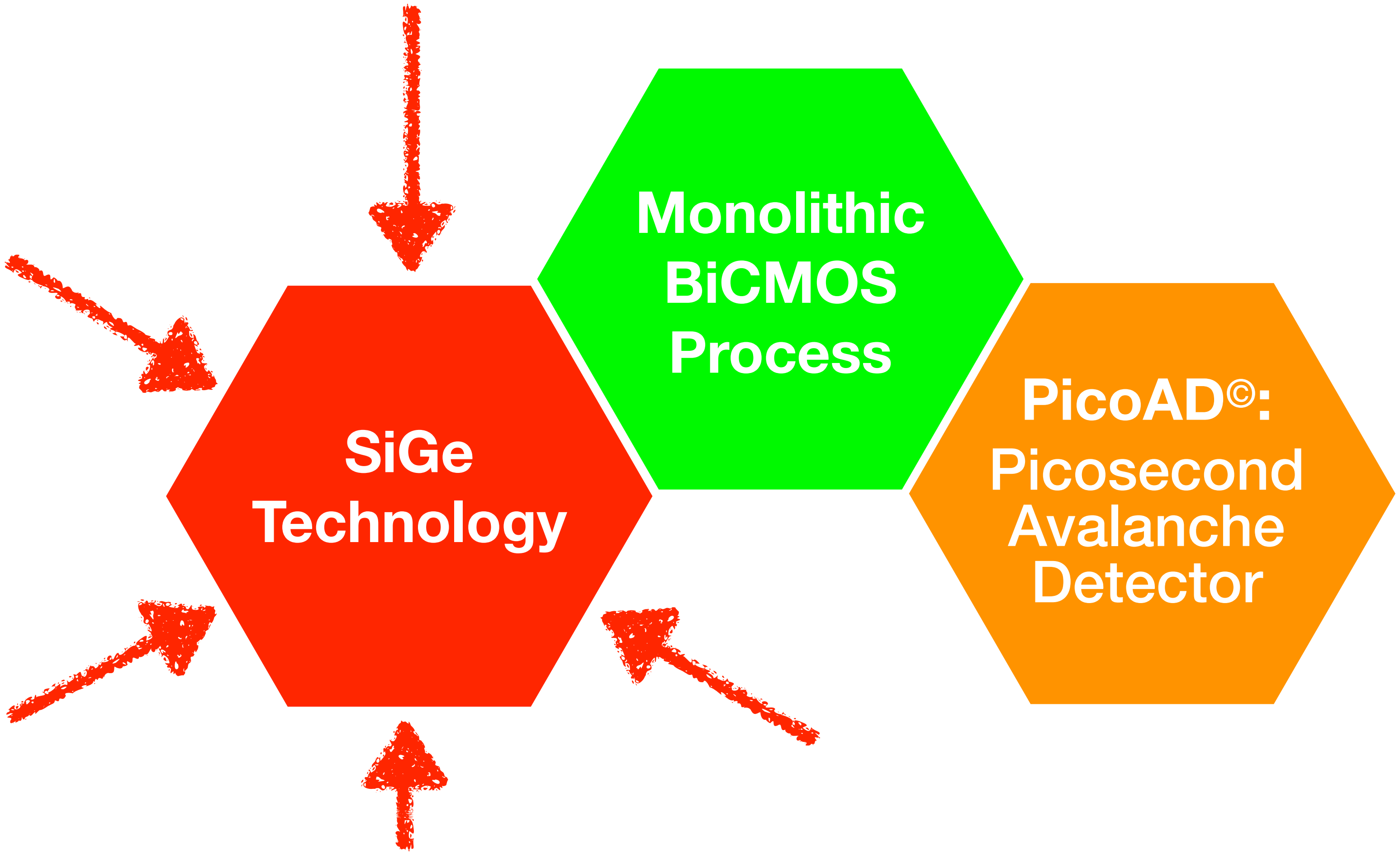

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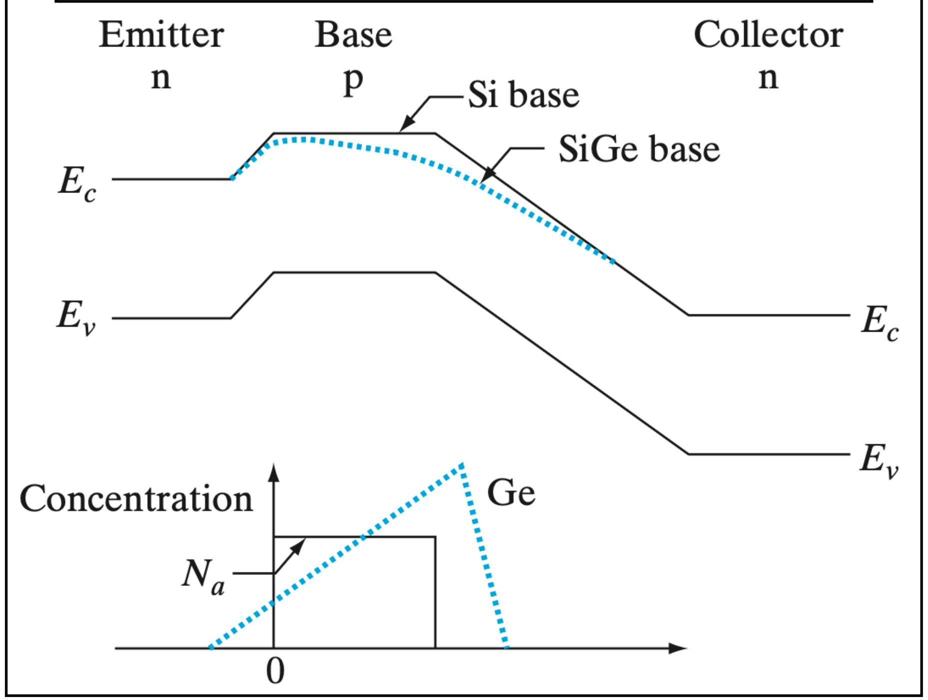
SiGe Technology

- A **grading of Germanium** creates a small electric field in the base of a **B**ipolar **J**unction **T**ransistor (BJT):
  - The charges move via **drift**
  - The **transit time** in the base is shorter
    - **Higher current gain** β than a BJT
  - Thicker base than a BJT
    - **Smaller base resistance** $\mathbf{R_b}$ than a BJT

$$\sigma_{\text{Jitter}} = \frac{\sigma_V}{dV/dt} \propto C_{\text{tot}} \sqrt{\frac{k_1}{\beta} + k_2 \mathbf{R_b}}$$

SiGe *npn* HBT Energy Bands



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

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PicoAD© Sensor Concept

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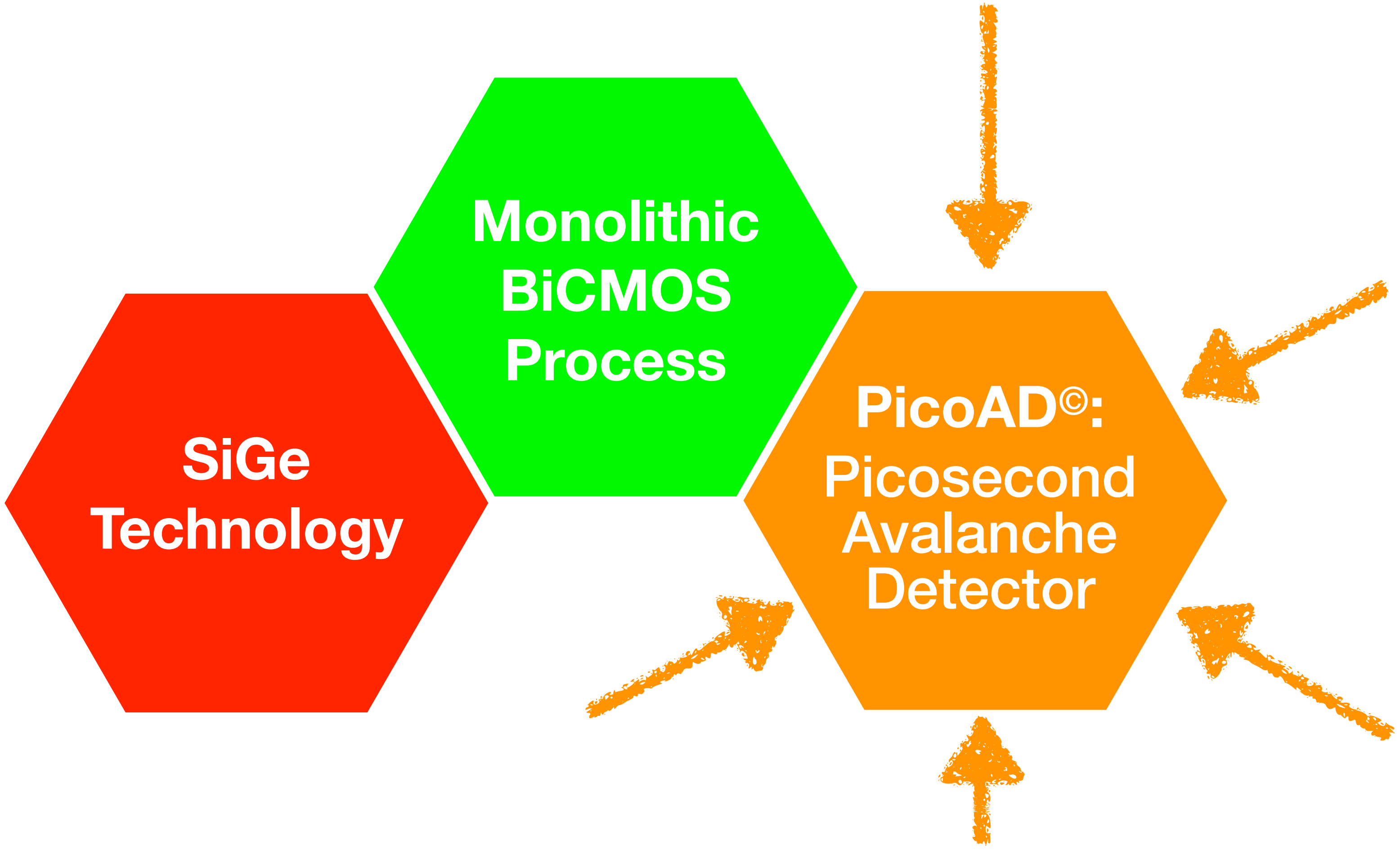
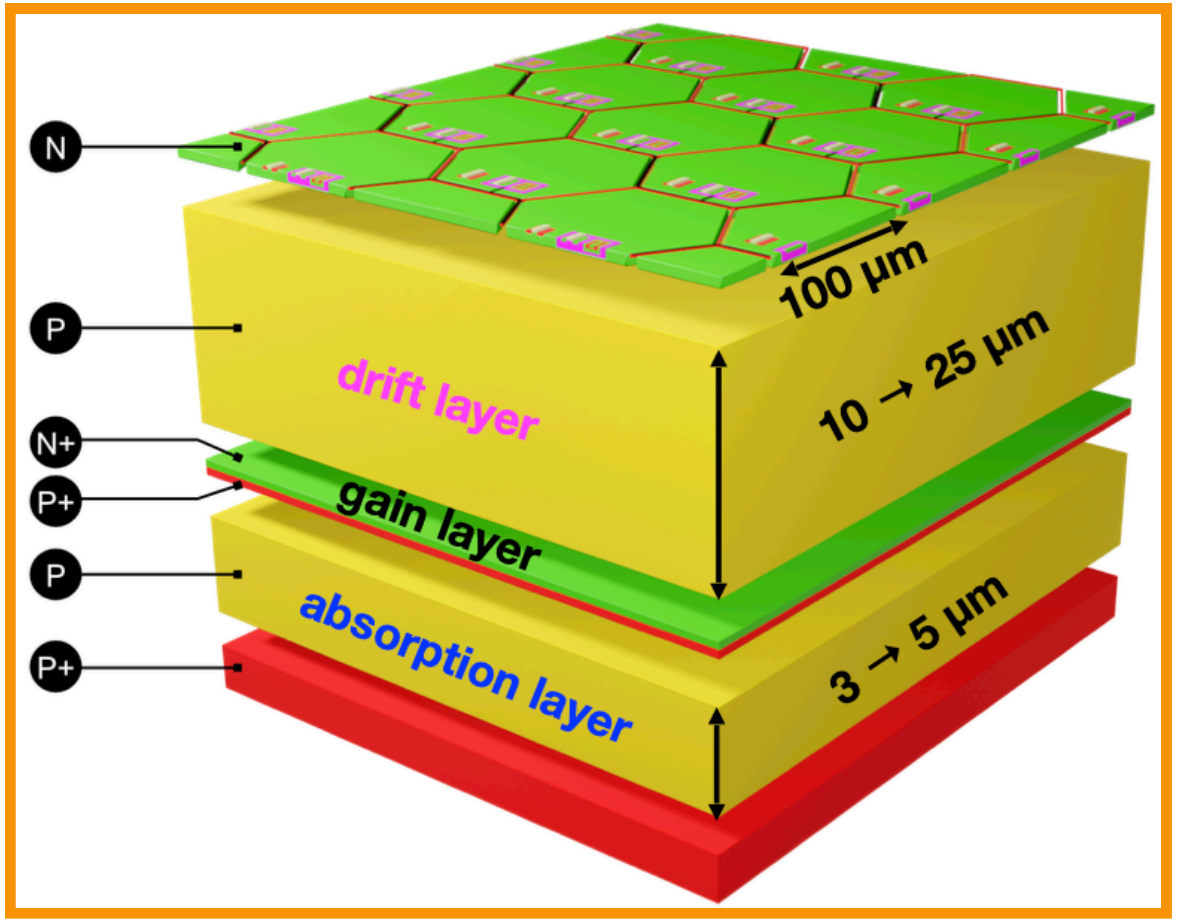


PicoAD© Sensor Concept

- Multi-Junction **Picosecond Avalanche Detector©**
- Continuous and deep gain layer:
  - Decorrelation from implant size
    - High **pixel granularity**
    - Better **spatial resolution**
  - Only a small fraction of the charge gets amplified
    - Reduced **charge-collection noise** σ_{Landau}



Timing Prototypes without Gain Layer

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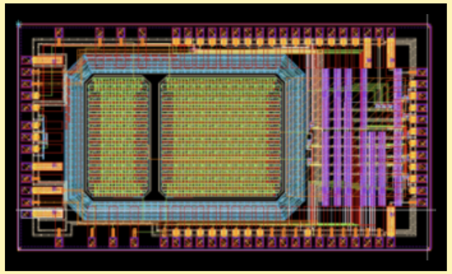
2016

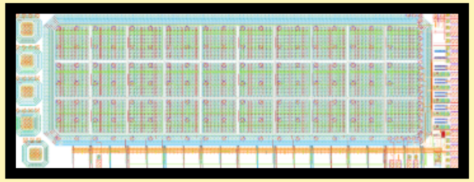


- Square pixel 900 μm
- Discriminated output

200 ps

JINST 13 P04015

2017

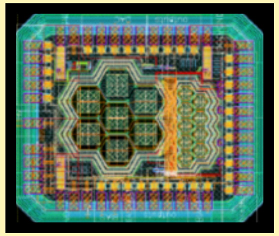


- Square pixels 500 μm
- 100 ps TDC + I/O logic

110 ps

JINST 14 P07013 JINST 14 P02009

2018

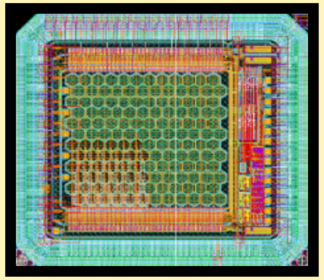


- Hexagonal pixels 130 μm
- Discriminated outputs

45 ps

JINST 14 P11008 JINST 15 P11025

2020

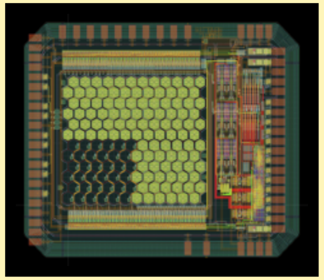


- Hexagonal pixels 65 μm
- 30 ps TDC + I/O logic
- 4 analog outputs

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 presentation

MONOLITH

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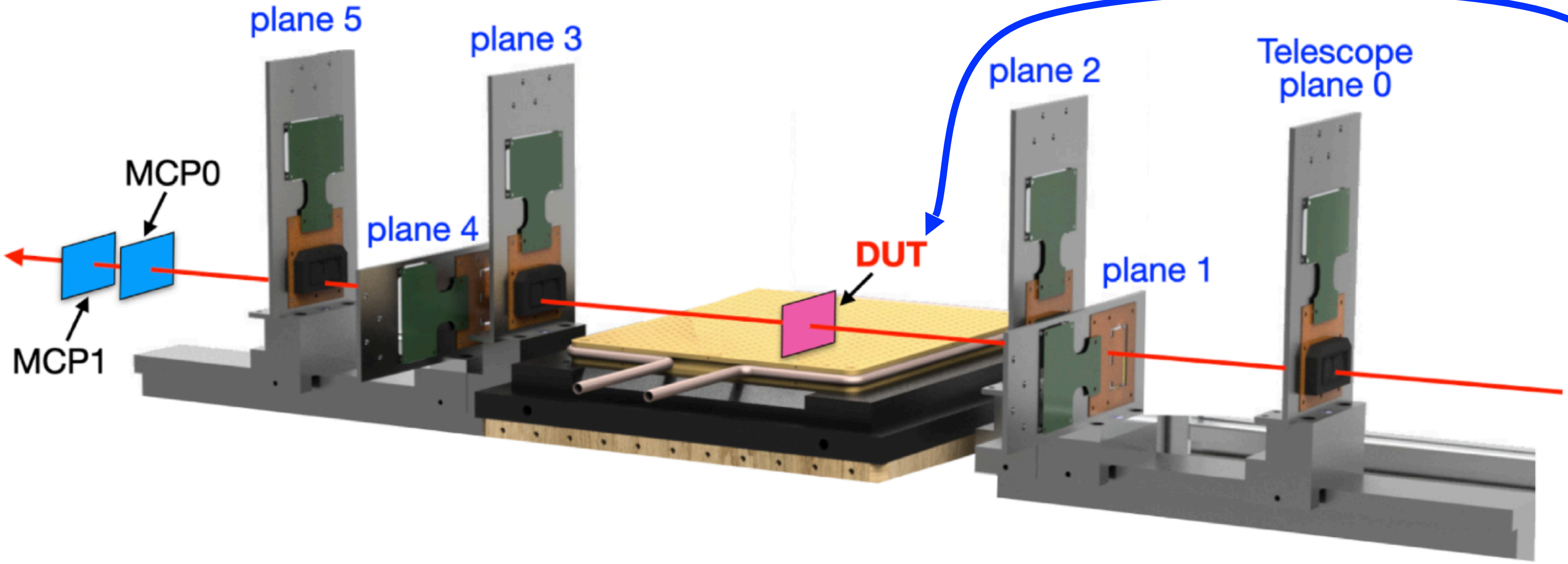
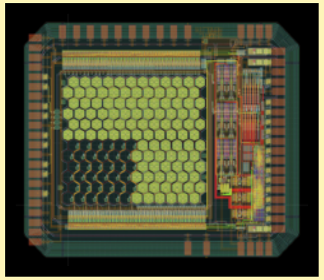
Test Beam: Experimental Setup

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



2022



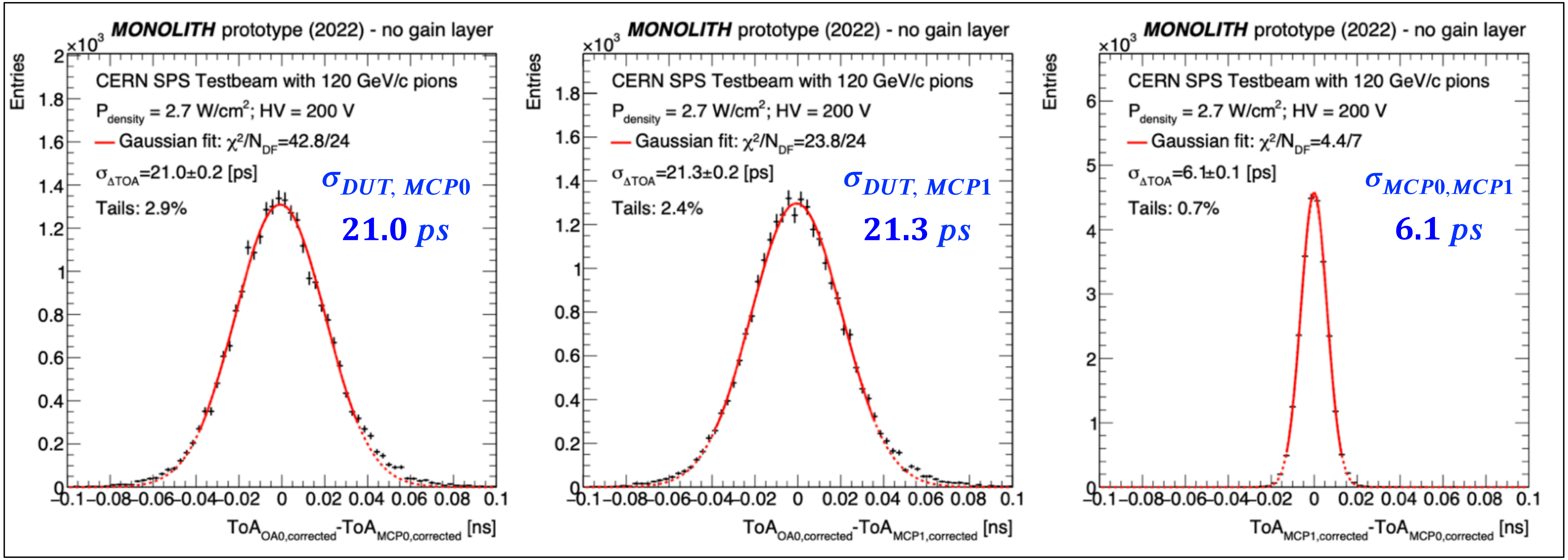
- Hexagonal pixels 65 μm
- Improved frontend
- 4 analog outputs

20 ps

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

Time Resolution Distributions



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

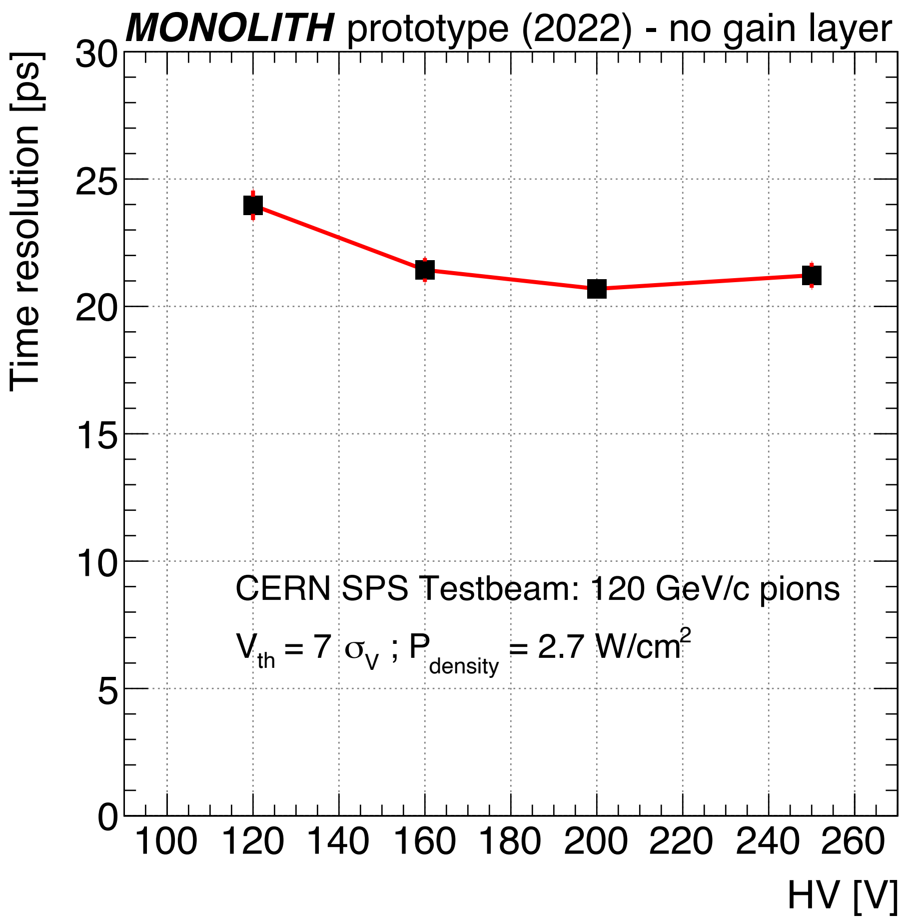
$$\begin{cases} \sigma^2_{\mathrm{DUT,MCP0}} = \sigma^2_{\mathrm{DUT}} + \sigma^2_{\mathrm{MCP0}} \\ \sigma^2_{\mathrm{DUT,MCP1}} = \sigma^2_{\mathrm{DUT}} + \sigma^2_{\mathrm{MCP1}} \\ \sigma^2_{\mathrm{MCP0,MCP1}} = \sigma^2_{\mathrm{MCP0}} + \sigma^2_{\mathrm{MCP1}} \end{cases}$$

MCP0: σ_t = (3.6 ± 1.5) ps

MCP1: σ_t = (5.0 ± 1.1) ps

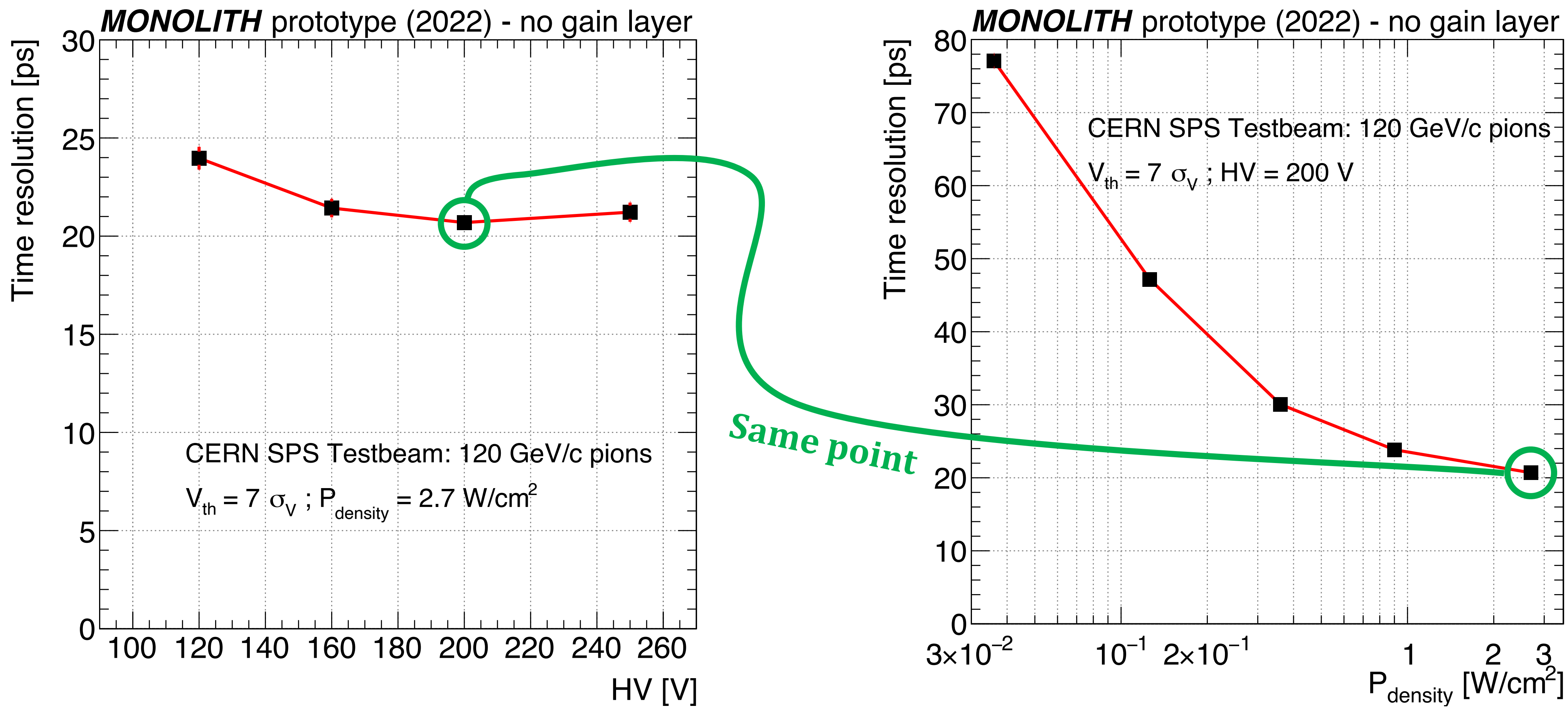
DUT: σ_t = (20.1 ± 0.3) ps

Time Resolution Results



Large plateau of 100 V with **~20 ps**

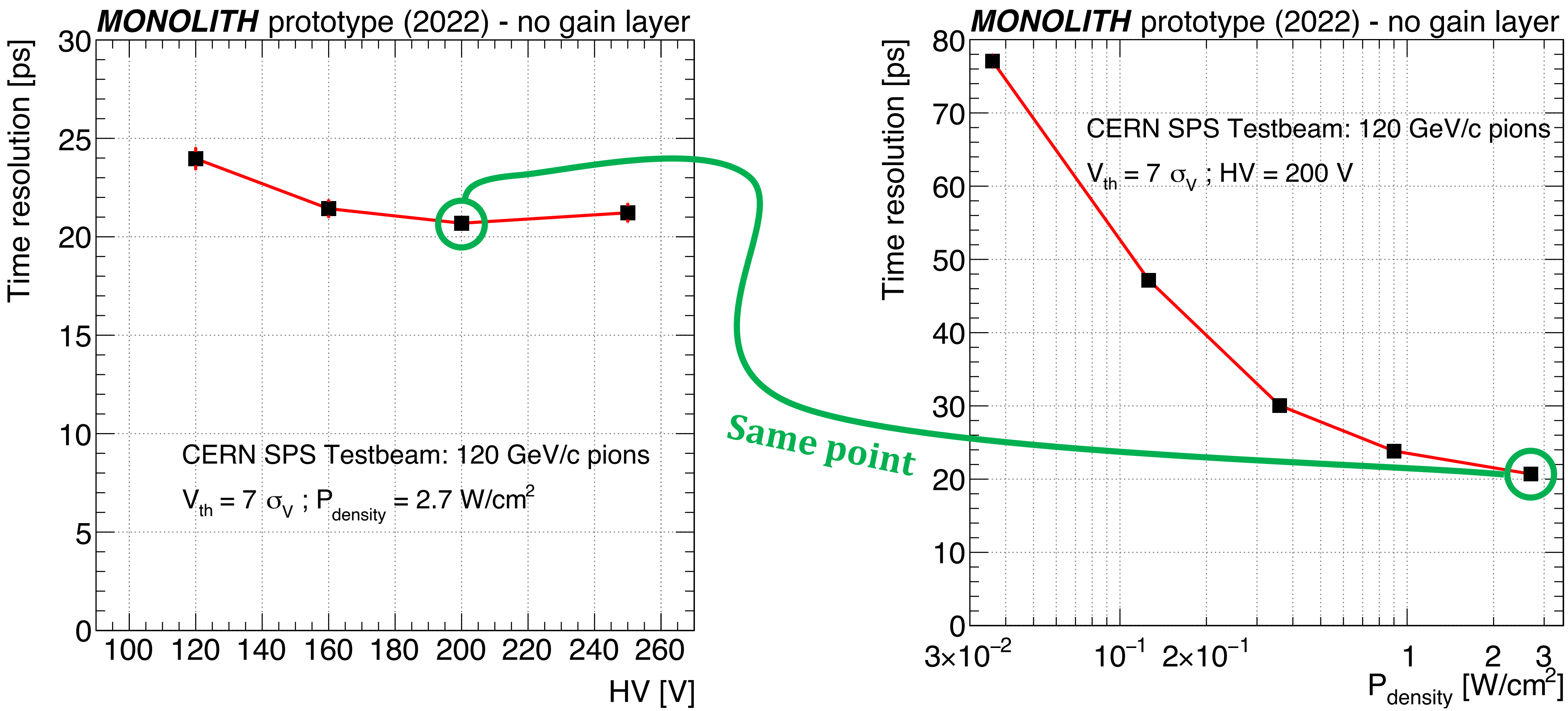
Time Resolution Results



Large plateau of 100 V with **~20 ps**

20 ps at 2.7 W/cm²
50 ps at 0.1 W/cm²

Time Resolution Results



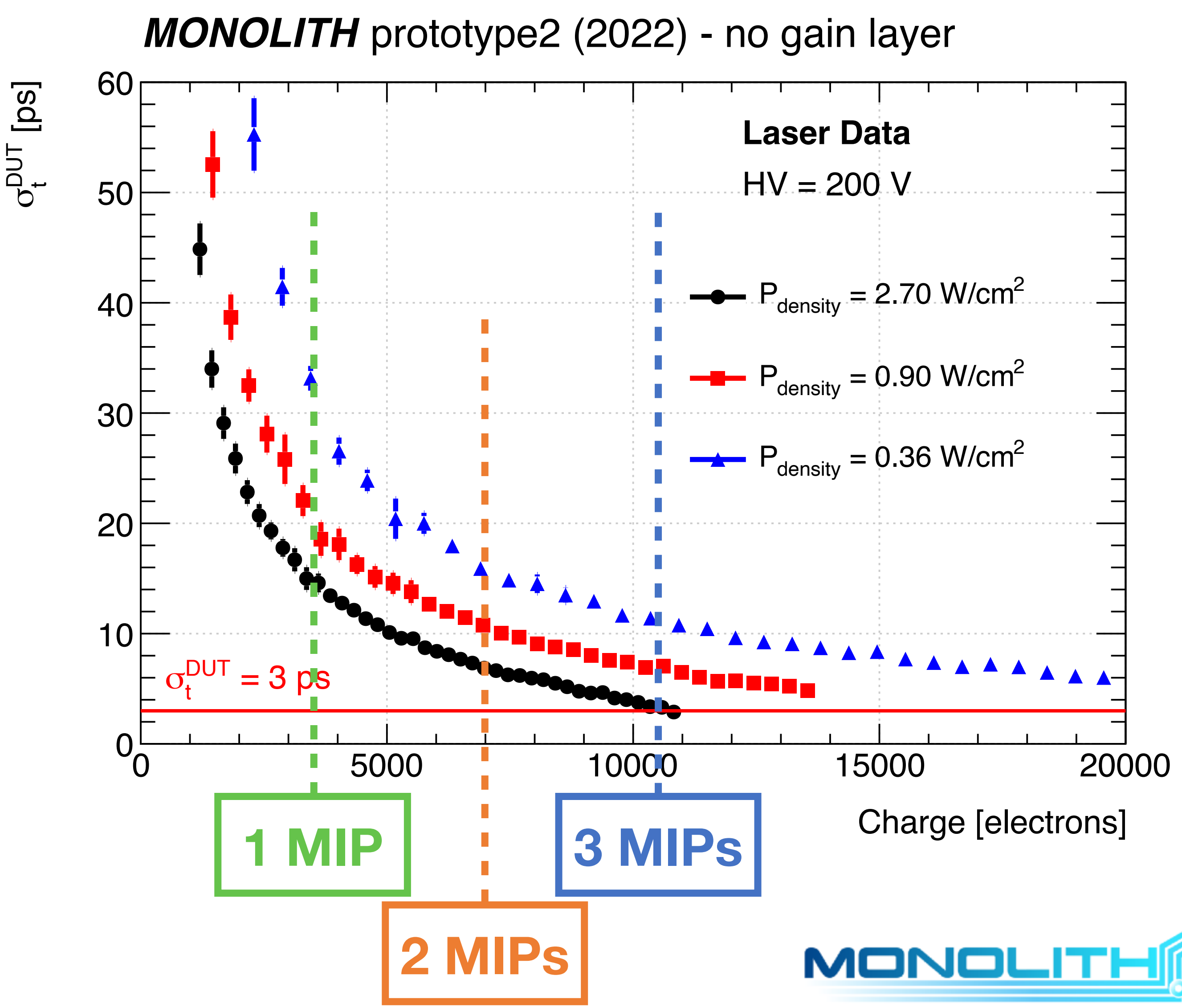
What happens if we increase the generated charge?

Laser Measurements

- A **M**inimum **I**onizing **P**article produces around 3500 electrons (0.5 fC) in the 50 µm-thick active area
- At a power density of 2.7 W/cm²:
  - The **time resolution** for the equivalent charge of **1 MIP** is **~15 ps**
- With the laser, the only contribution to the time resolution is the **electronics time jitter**:

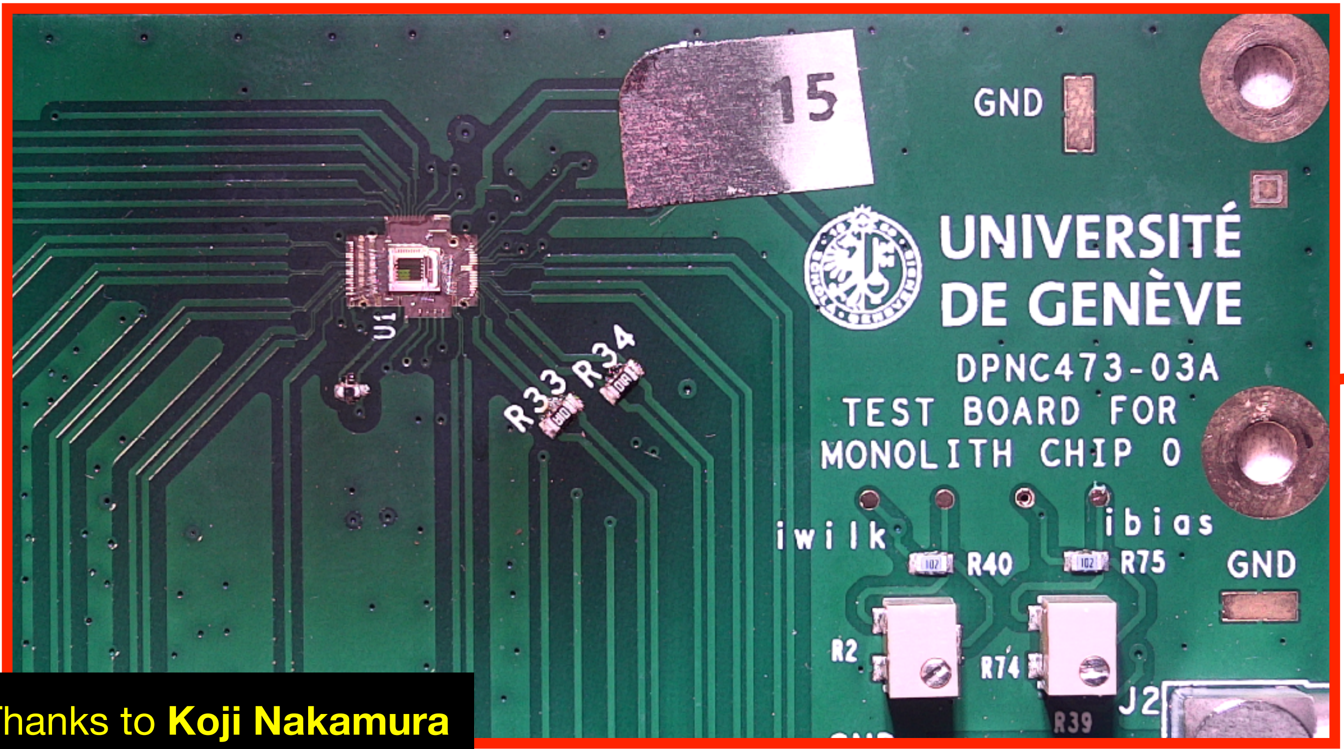
$$\sigma_{\text{Jitter}} = \frac{\sigma_V}{\frac{dV}{dt}} \propto \frac{1}{\text{charge}}$$

- With charges higher than **3 MIPs** (1.5 fC, or 38 keV), the time jitter is **less than 3 ps**



Radiation Hardness

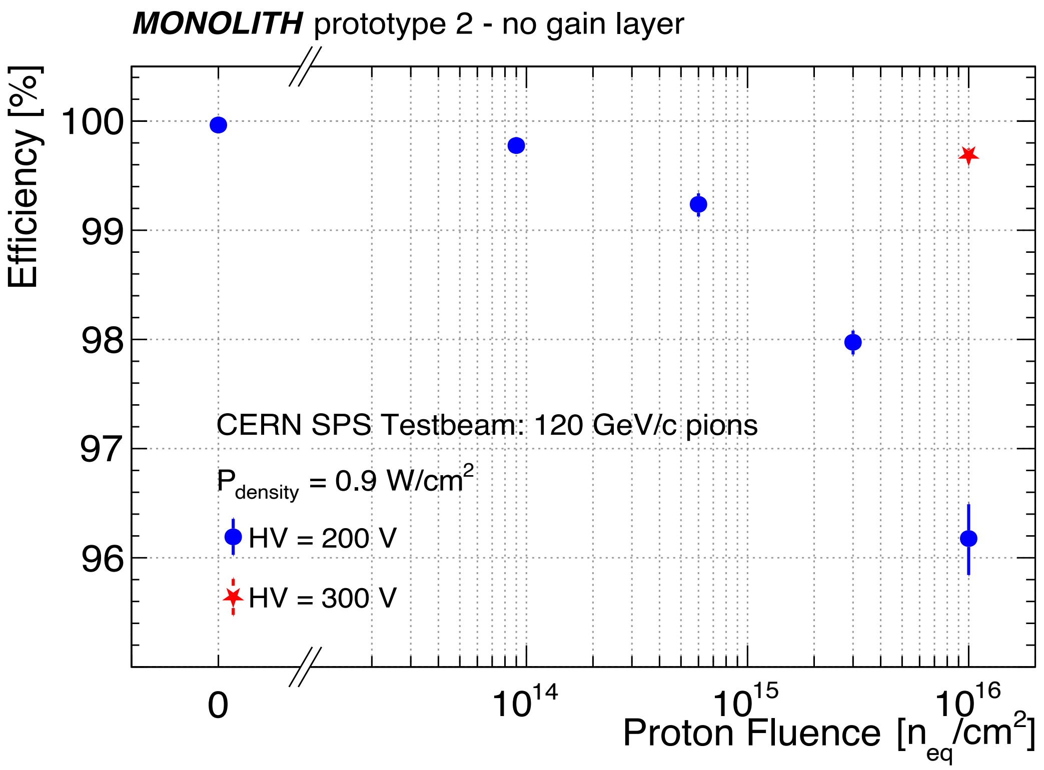
- Assess the **performance** of efficiency and time resolution **after proton irradiation**
- 8 prototypes **irradiated** in Japan up to **1×10^{16} n_{eq}/cm^2**

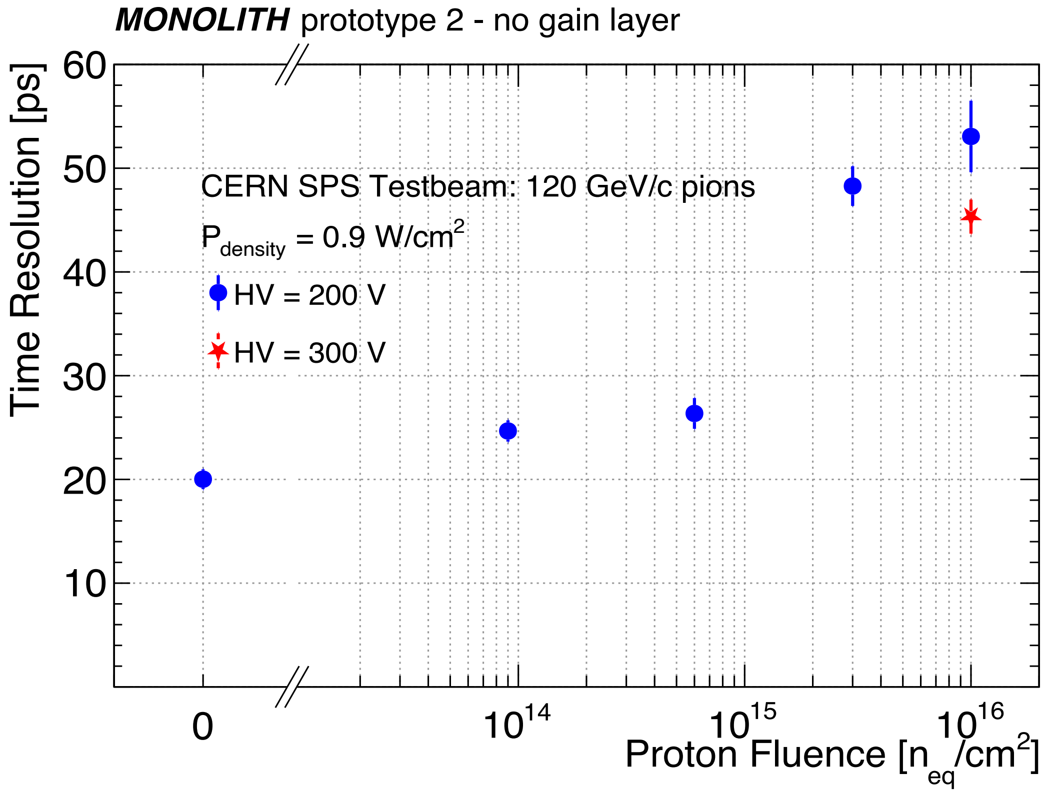


Thanks to **Koji Nakamura** and **Manabu Togawa**

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	$1 \cdot 10^{16}$

Efficiency and Time Resolution After Irradiation



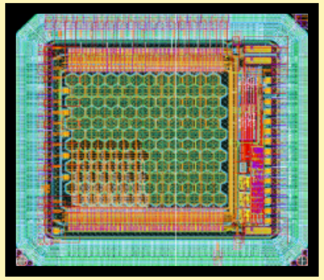


At $\mathbf{10^{16}\ n_{eq}/cm^2}$, with **HV = 200 V** and $P_{density}$ = $\mathbf{0.9\ W/cm^2}$:

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

Prototypes With PicoAD©

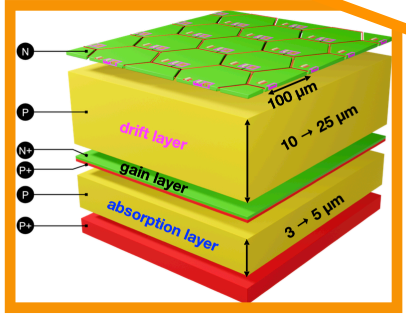
2020



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

36 ps

JINST 17 P02019



With PicoAD©

In this presentation

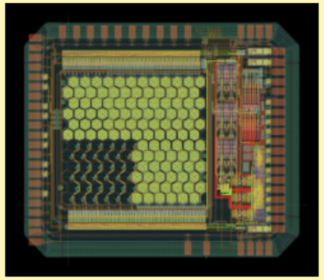
2022

With PicoAD©

17 ps

JINST 17 P10032
JINST 17 P10040

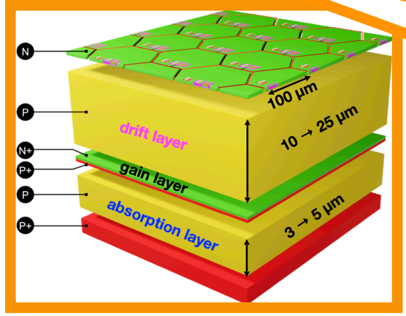
2022



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

20 ps

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



With PicoAD©

In this presentation

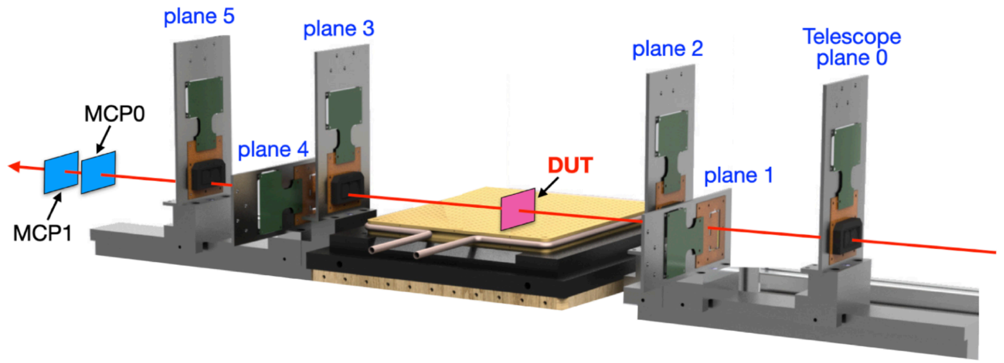
2024

With PicoAD©

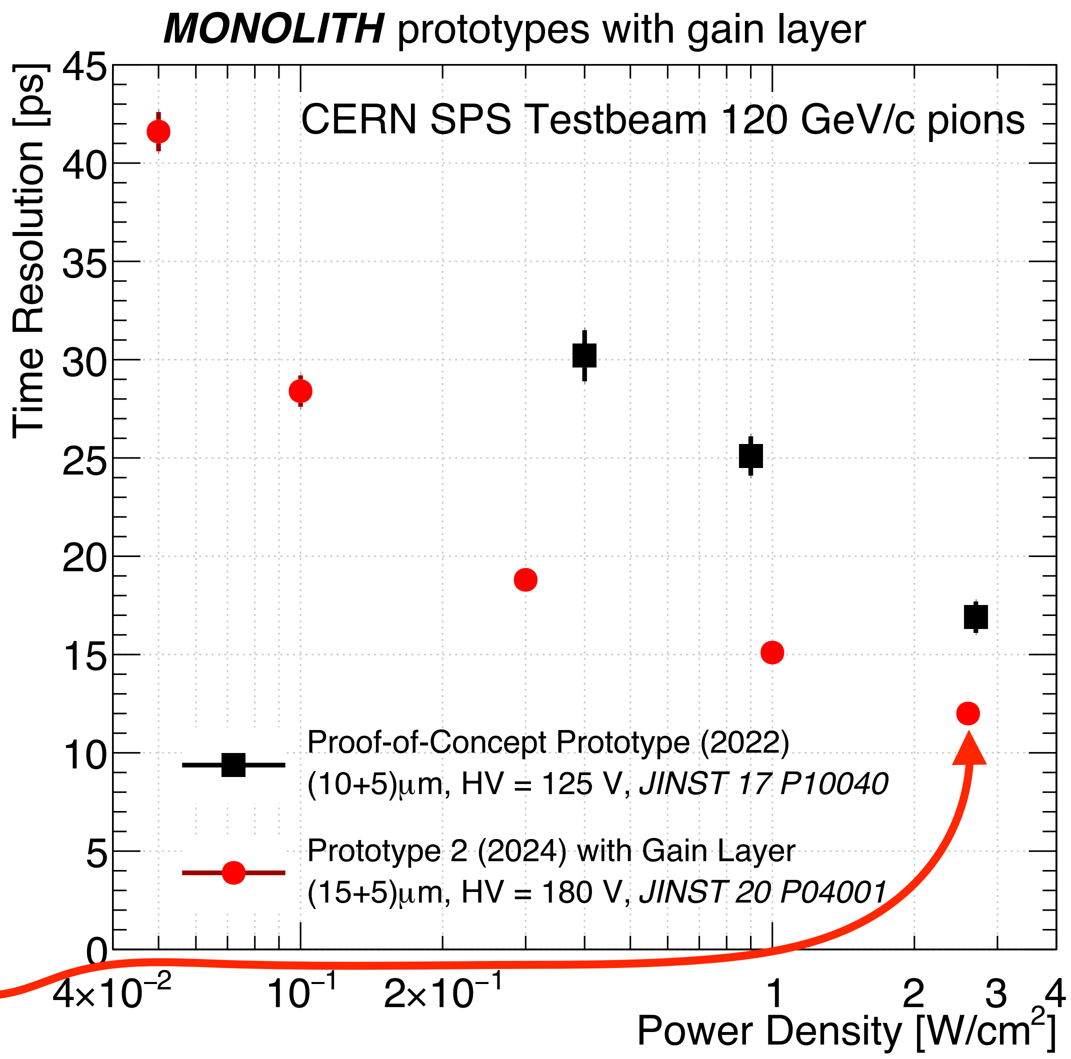
12 ps

JINST 20 P04001

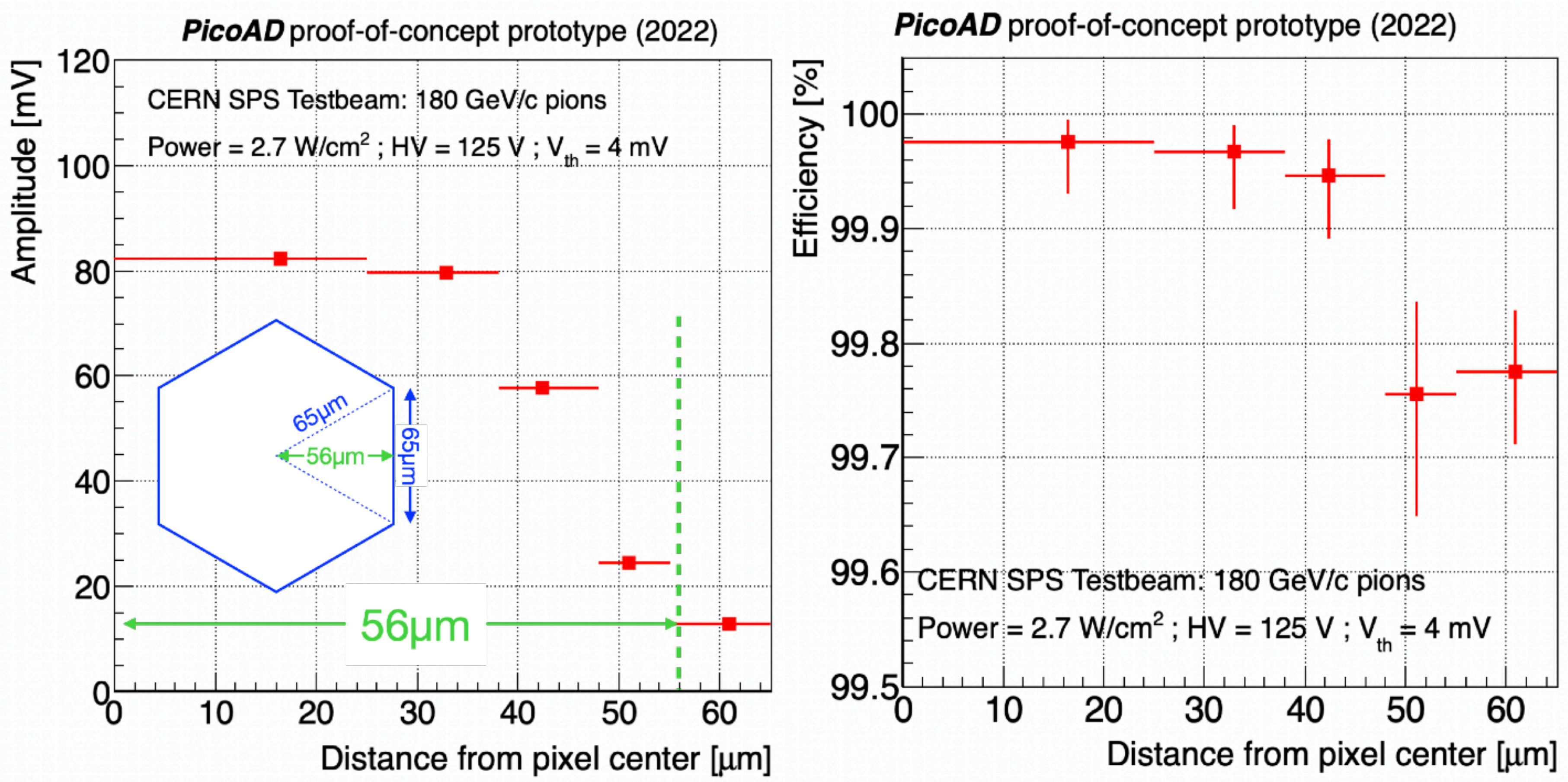
Testbeam Results



- Testbeam measurements with FE-I4 telescope
  - **PicoAD©** proof-of-concept in **October 2021**
  - Second prototype with gain layer in **May 2024**
- The **efficiency** is **compatible with 99.9%** for many working points
- The **time resolution improved** by almost a factor of two:
  - **The best performance with the second prototype** is **12.1 ps** with HV of 180 V and $P_{density}$ of **2.6 W/cm²**



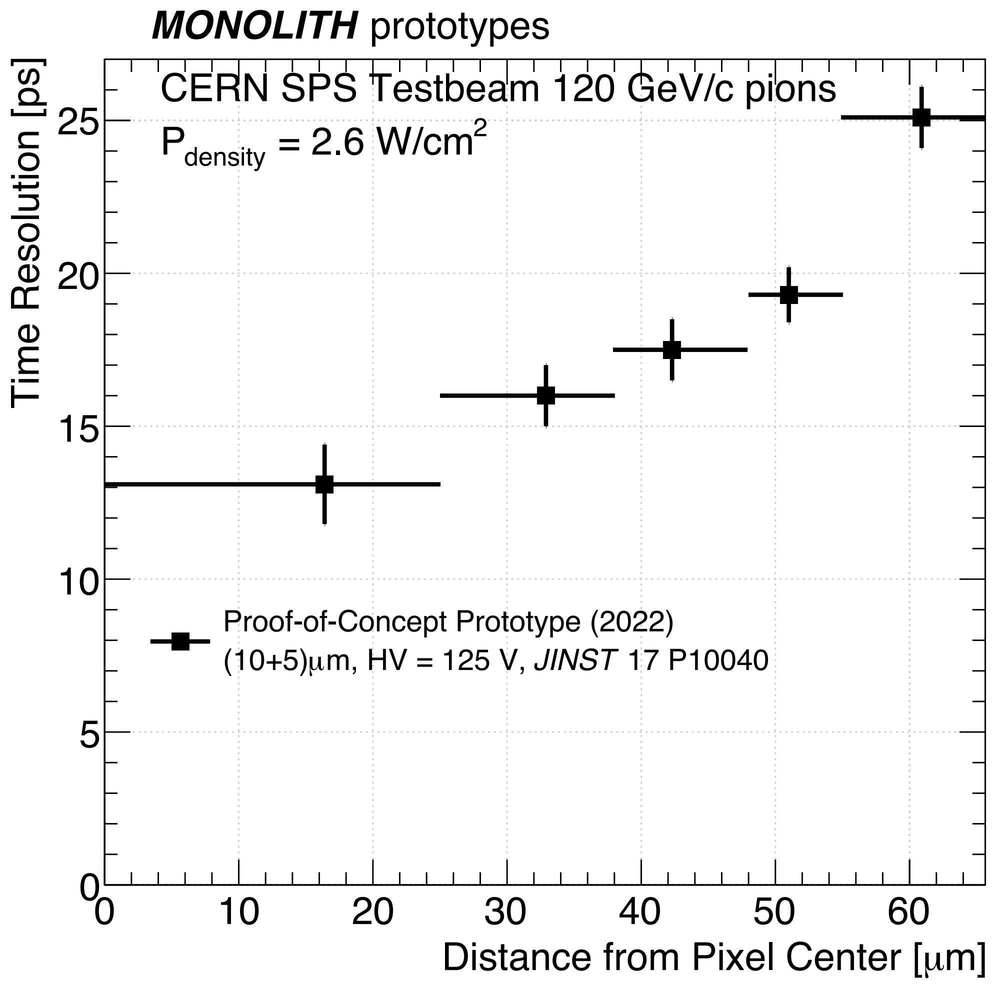
Performance Within the Pixel



- We saw a slight degradation of the performance towards the pixel's edge with the **PicoAD©** proof-of-concept:
  - **Lower amplitudes and lower efficiencies**

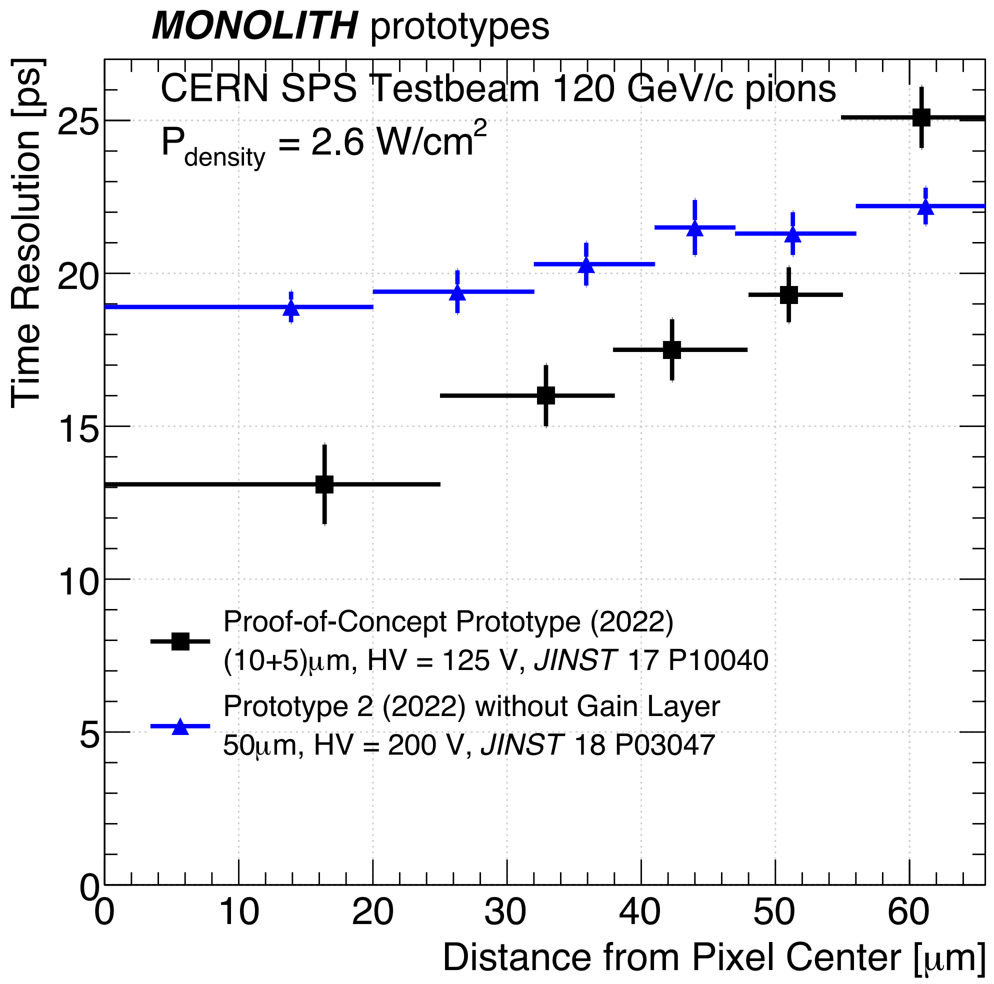
Time Resolution Within the Pixel

- The degradation of the amplitudes leads to a **degradation of the time resolution:**
  - The **time resolution** of the **PicoAD©** proof-of-concept varies between **13 and 25 ps** (almost a factor 2 worse), with an average of 17 ps



Time Resolution Within the Pixel

- The degradation of the amplitudes leads to a **degradation of the time resolution:**
  - The **time resolution** of the **PicoAD©** proof-of-concept varies between **13 and 25 ps** (almost a factor 2 worse), with an average of 17 ps
- Some **improvements** on the ASIC and the substrate make the situation more stable:
  - The **time resolution** of the second prototype **without a gain layer** varies between **19 and 24 ps**



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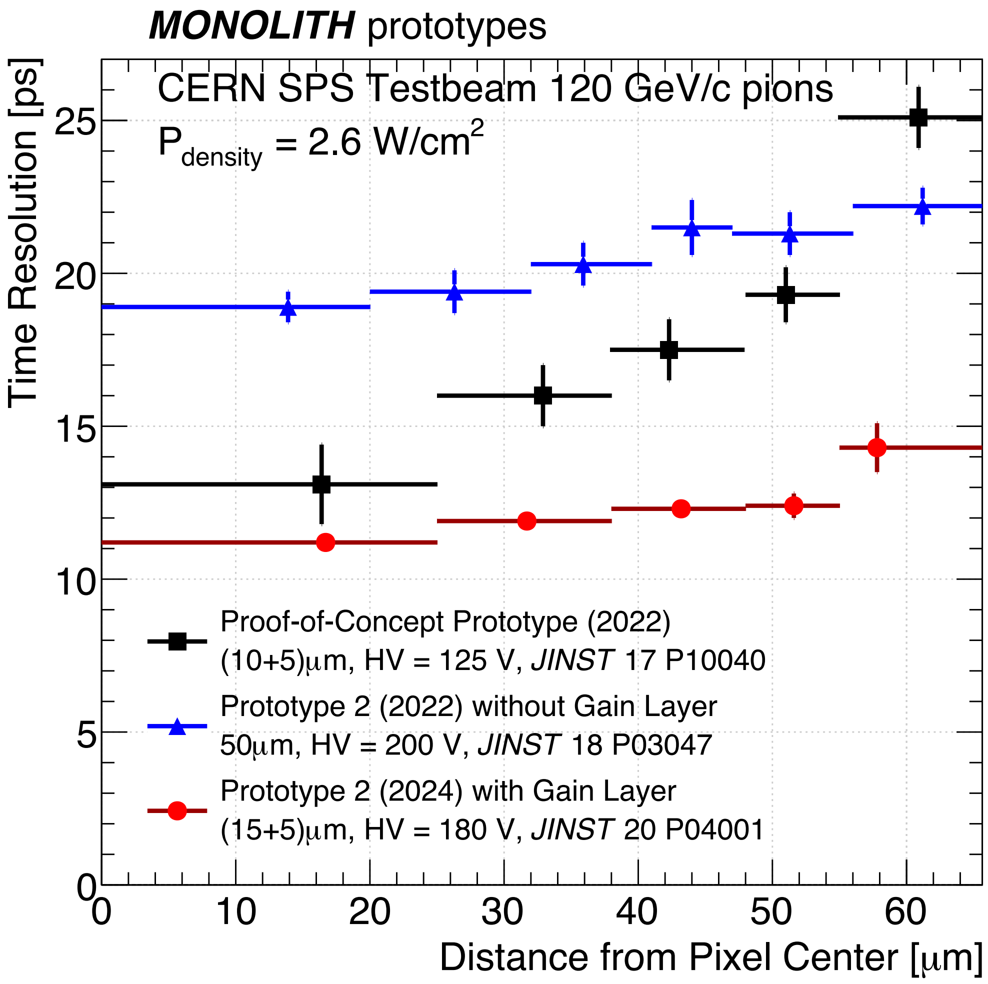
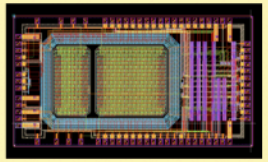
Time Resolution Within the Pixel

- The degradation of the amplitudes leads to a **degradation of the time resolution:**
  - The **time resolution** of the **PicoAD©** proof-of-concept varies between **13 and 25 ps** (almost a factor 2 worse), with an average of 17 ps
- Some **improvements** on the ASIC and the substrate make the situation more stable:
  - The **time resolution** of the second prototype **without a gain layer** varies between **19 and 24 ps**
  - The **time resolution** of the second prototype **with a gain layer** varies between **11 and 14 ps**



Summary

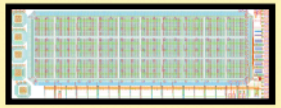
2016



- Square pixel 900 µm
- Discriminated output

200 ps

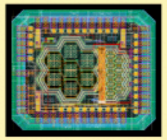
2017



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

110 ps

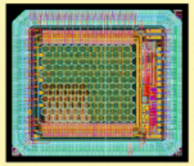
2018



- Hexagonal pixels 130 µm
- Discriminated outputs

45 ps

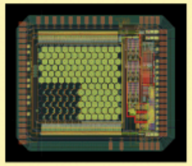
2020



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

36 ps

2022



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

20 ps

- **20 ps** time resolution with a MIP
- **Laser** measurements:
  - **3 ps** with the equivalent charge of 3 MIPs
- After irradiation at **10^{16} n_{eq}/cm^2**:
  - **99.7%** efficiency
  - **45 ps** time resolution

2022
With **PicoAD©**
17 ps

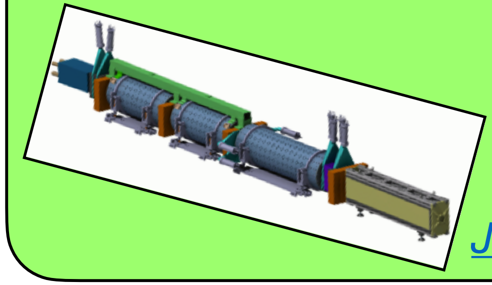
17 ps time resolution with a MIP

2024
With **PicoAD©**
12 ps

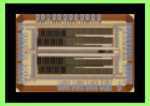
12 ps time resolution with a MIP

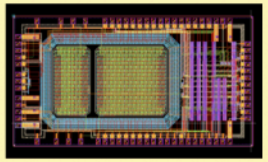
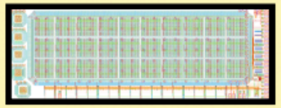
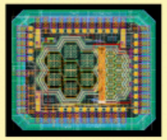
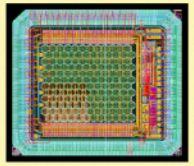
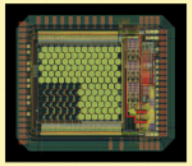
Other Projects at UNIGE

LHC Application: Preshower for FASER -> webpage



JINST 16 P12038

2022	2023	2024
		

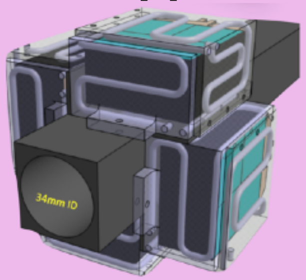
2016	2017	2018	2020	2022
				
• Square pixel 900 µm • Discriminated output	• Square pixels 500 µm • 100 ps TDC + I/O logic	• Hexagonal pixels 130 µm • Discriminated outputs	• Hexagonal pixels 65 µm • 30 ps TDC + I/O logic • 4 analog outputs	• Hexagonal pixels 65 µm • Improved frontend • 4 analog outputs
200 ps	**110 ps**	**45 ps**	**36 ps**	**20 ps**

2022
With **PicoAD©**
17 ps

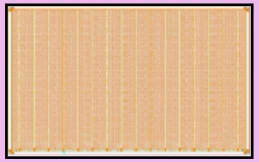
2024
With **PicoAD©**
12 ps

Medical Application: 100µPET

NIMA 167952



2024



See Roberto Cardella's talk

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Future Perspectives

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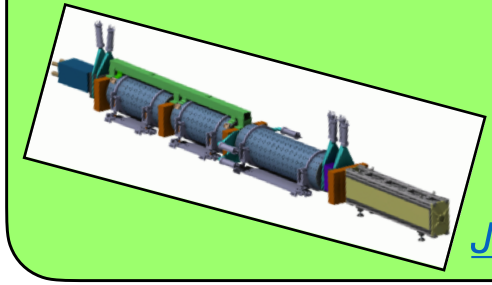
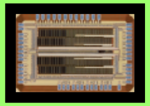


JINST 16 P12038

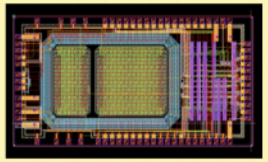
2022



2023

2024

2016



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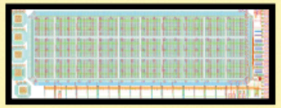
200 ps

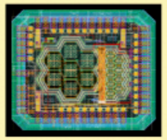
2017



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

110 ps

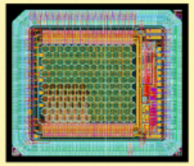
2018



- Hexagonal pixels 130 µm
- Discriminated outputs

45 ps

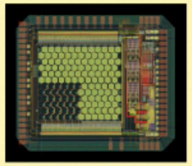
2020



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

36 ps

2022



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

20 ps

2022
With **PicoAD©**
17 ps

2024
With **PicoAD©**
12 ps

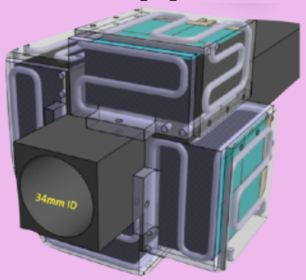
High-radiation level timing layers for particle physics

Moderate radiation level, extremely thin timing layers for particle physics

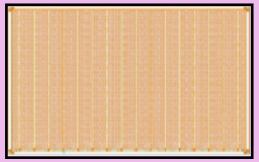
Photonics

Medical Application: 100µPET

NIMA 167952



2024



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Département de physique nucléaire et corpusculaire

People Involved

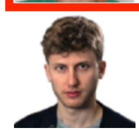
European Research Council
Established by the European Commission
FNSNF Swiss National Science Foundation

Talk on 100µPET yesterday

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

Luca Iodice
- Chip Design
- Firmware

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

Viros Sriskaran
- Analog Electronics
- Digital Electronics

Chiara Magliocca
- Laboratory Tests
- Data Analysis

Théo Moretti
- Laboratory Tests
- Data Analysis

Jihad Saidi
- Laboratory Tests
- Data Analysis

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:

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INFN Rome2 & UNIGE

Holger Rücker
IHP Mikroelektronik

Marzio Nessi
CERN & UNIGE

Matteo Elviretti
IHP Mikroelektronik

- Previously involved:
  - Magdalena Munker
  - Jordi Sabater Iglesias
  - Antonio Picardi
  - Ivan Semendyaev
  - Rafaella Kotitsa

Thanks for Your Attention

Questions?

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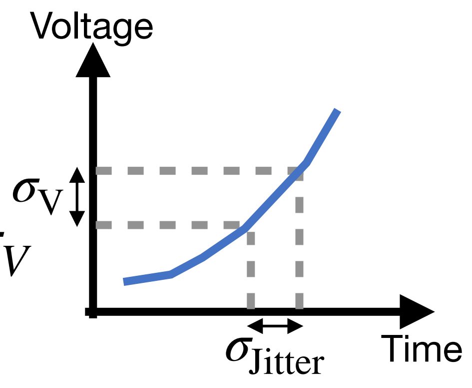
The MONOLITH ERC Project

- A **precise measure of time** (σ_t~30 ps) is achieved by reducing the two **main contributions** to the time resolution:

- The **electronics time jitter**:

$$\sigma_{Jitter} = \frac{\sigma_V}{dV/dt}$$

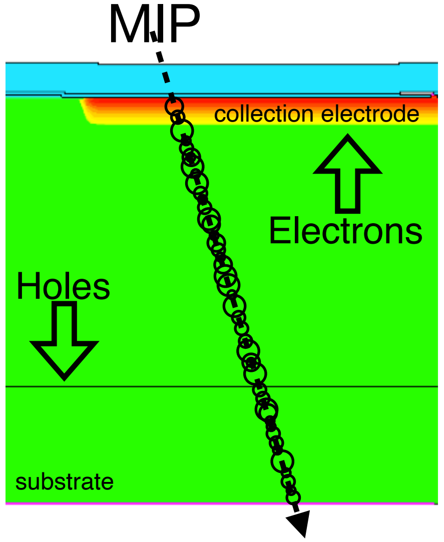
  - Related to the signal rise time dV/dt and the noise σ_V
  - We want **fast and low-noise amplification**



- The **charge-collection noise**:

$$\sigma_{Landau} = w(d)\,\sigma_{\tau,SC} \propto \frac{d}{\sqrt{ln(d)}}$$

  - Related to the detector thickness d
  - We want a **small detector thickness**



SiGe Technology — **Monolithic BiCMOS Process** — **PicoAD©: Picosecond Avalanche Detector**

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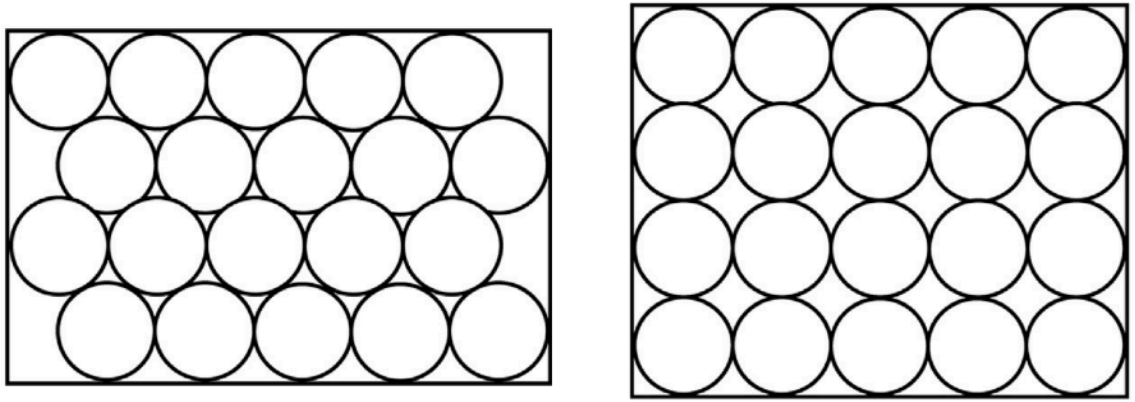
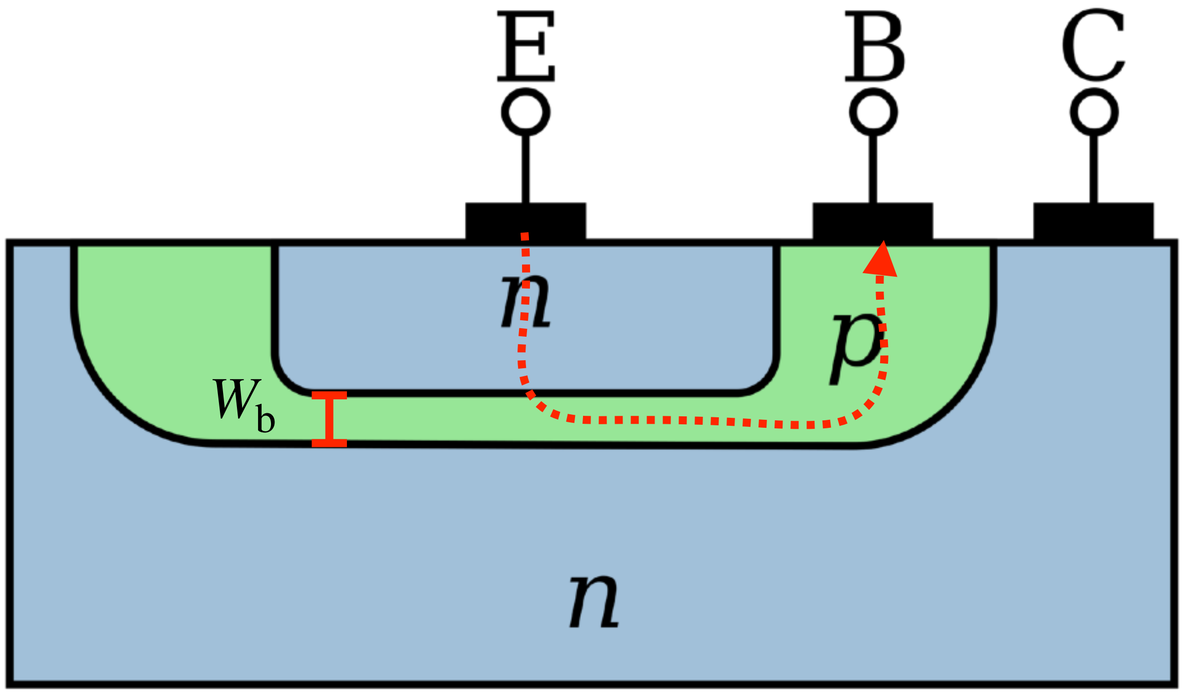
Hexagonal Pixels

- 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



Thick Base = Small Base Resistance

- When a grading of Ge is added to the base of a BJT, it is possible to make the base thicker
- A thicker base thickness W_b means a **smaller base resistance** R_b than a BJT
- The electrons coming from the emitter to the base see the **base thickness** W_b **as the transversal dimension**:
  - $R_\mathrm{b} \propto \dfrac{\rho_\mathrm{b}\, l_\mathrm{b}}{W_\mathrm{b}}$

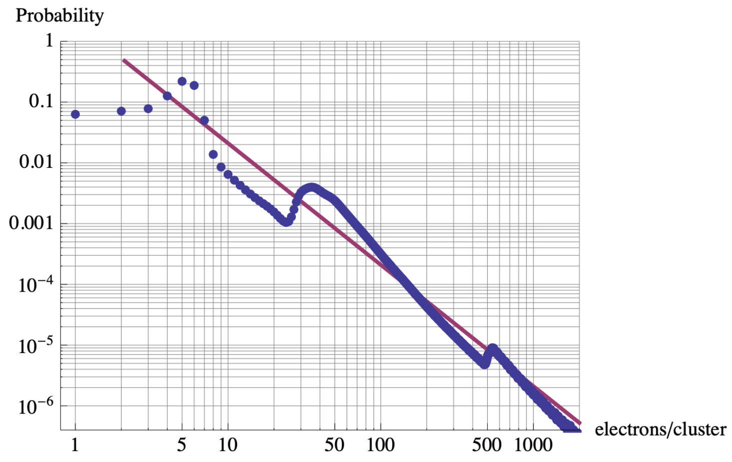


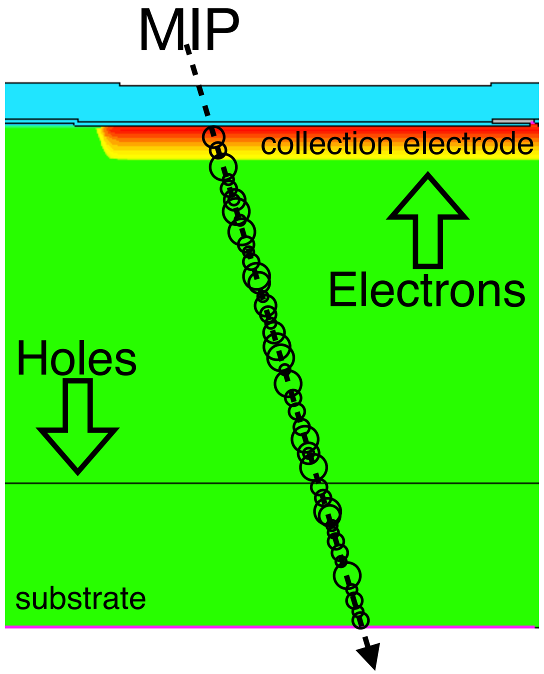
Charge-Collection Noise in Detail

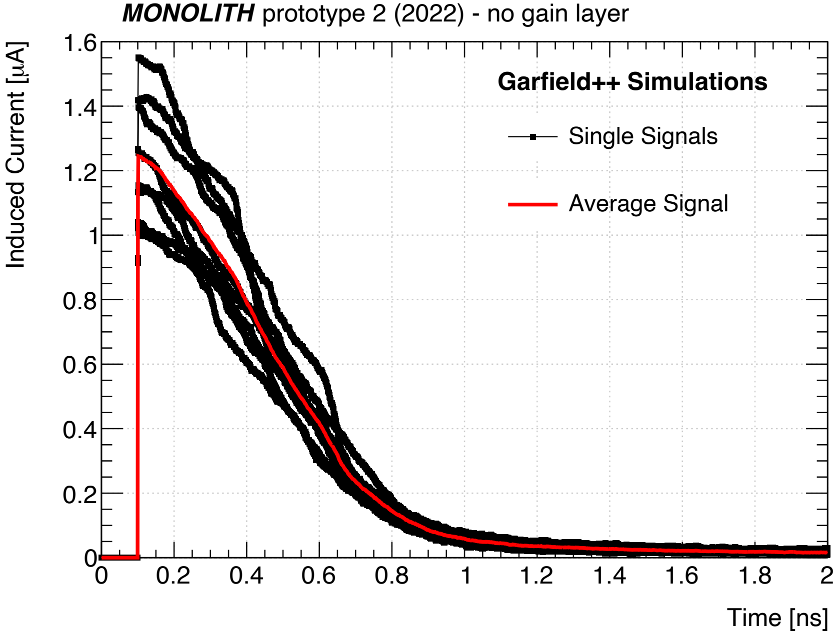
- The charge generated by a **M**inimum **I**onizing **P**article follows a pattern of clusters with different charges
- The **probability** of electrons for each cluster is known
- **Electrons and holes** drift thanks to the electric field and **induce a current**:

$$i_{ind} = -q\,\vec{v}_{\text{drift}} \cdot \vec{E}_{\text{weight}}$$

- A **cluster** stops inducing current when it's **collected**, creating noise on the induced current signal
- The contribution of this noise to the time resolution is called **charge-collection noise** (or Landau noise)







Charge-Collection Noise in Detail

- The **shape of the induced current** for a single cluster with a charge Q depends on the depth x of creation:

$$i_{SC}(x,t) = \frac{Q\,v_e}{d}\,\Theta\left(\frac{x}{v_e} - t\right) + \frac{Q\,v_h}{d}\,\Theta\left(\frac{d-x}{v_h} - t\right)$$

- And so it does the **center-of-gravity time**:

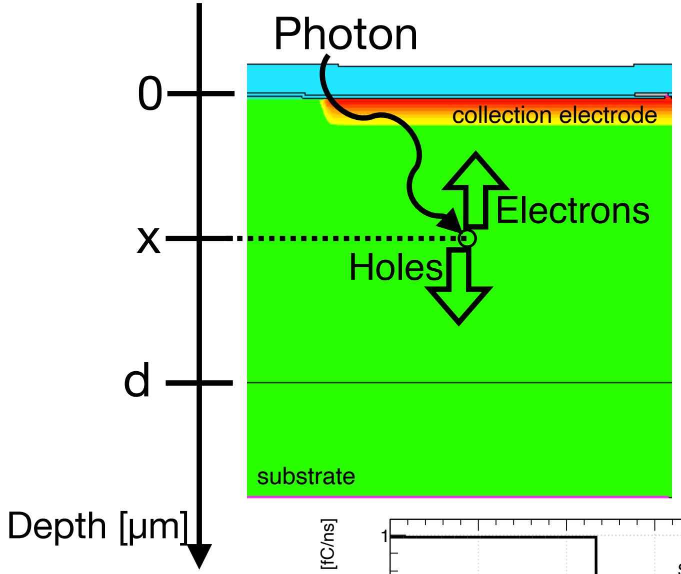
$$\tau = \frac{\int_0^\infty t\, i_{SC}(x,t)\,dt}{\int_0^\infty i_{SC}(x,t)\,dt} = \frac{1}{2d}\left[\frac{x^2}{v_e} + \frac{(d-x)^2}{v_h}\right]$$

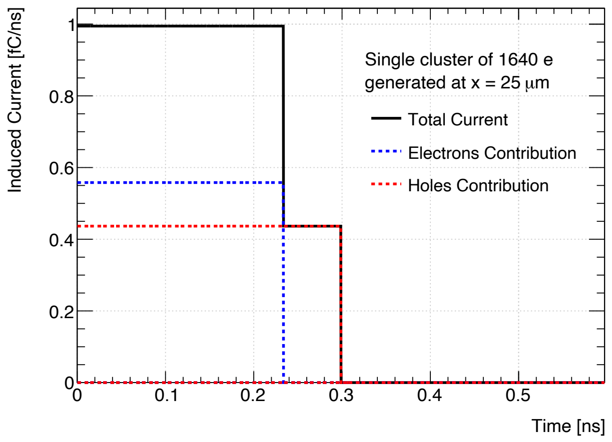
- With its **variance**:

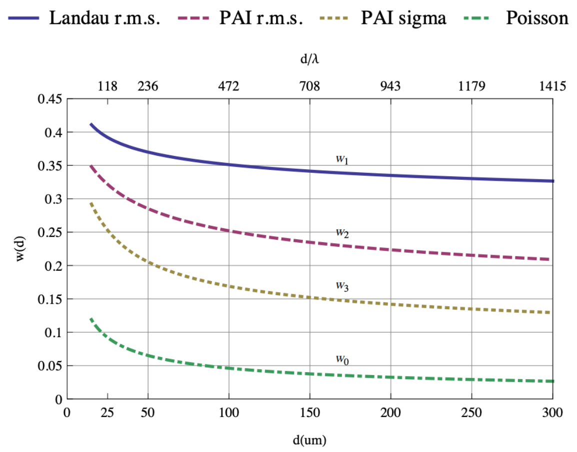
$$\sigma^2_{\tau,\mathrm{SC}} = \frac{4}{180}\frac{d^2}{v_\mathrm{e}} - \frac{7}{180}\frac{d^2}{v_\mathrm{e}v_\mathrm{h}} + \frac{4}{180}\frac{d^2}{v_\mathrm{h}}$$

- For a **MIP with many clusters**, and when the amplifier is slow, the charge-collection noise contribution to the time resolution is:

$$\sigma_\mathrm{Landau} = \sigma_{\tau,\mathrm{MIP}} = w(d)\,\sigma_{\tau,\mathrm{SC}} \propto \frac{d}{\sqrt{ln(d)}}$$

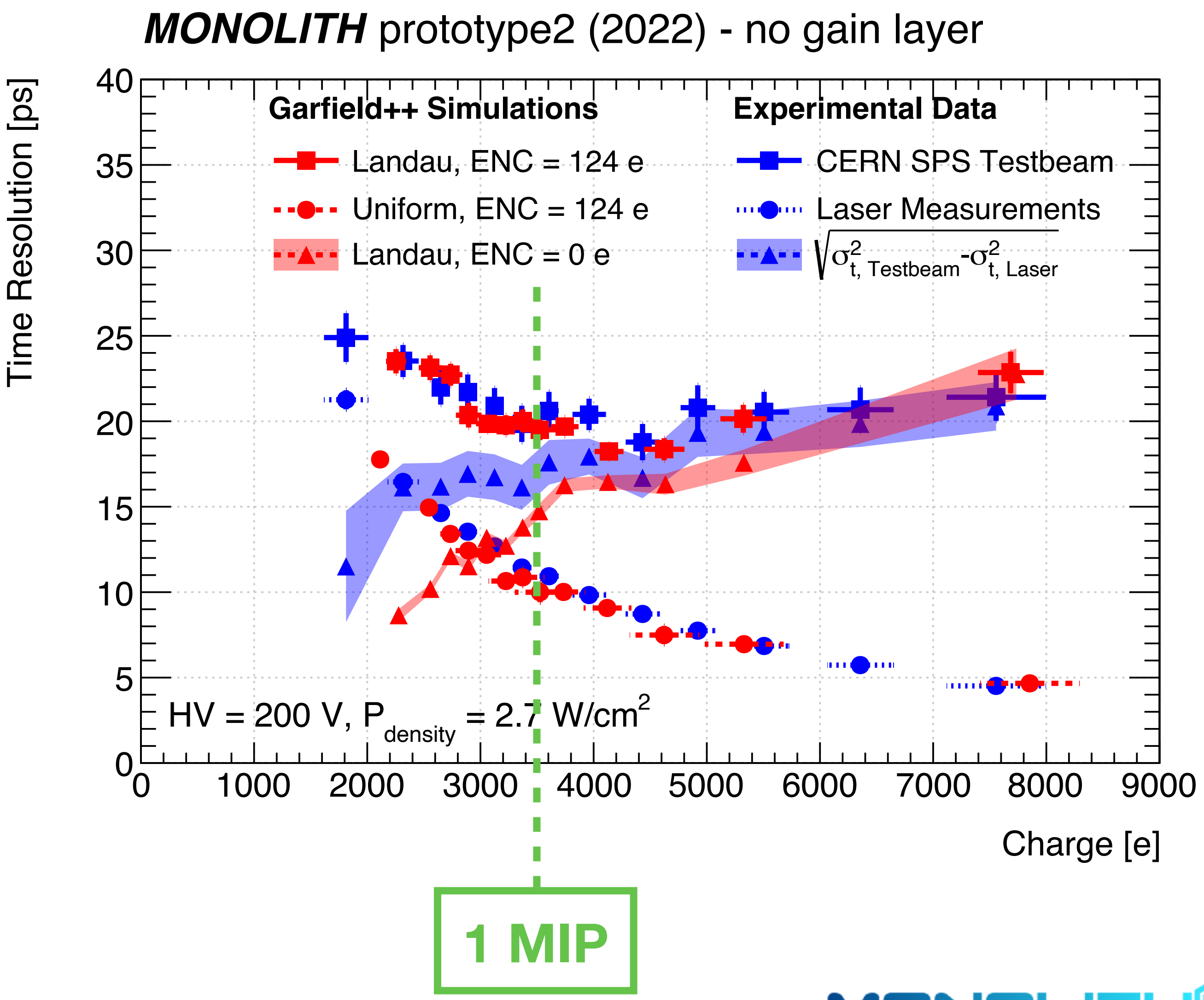




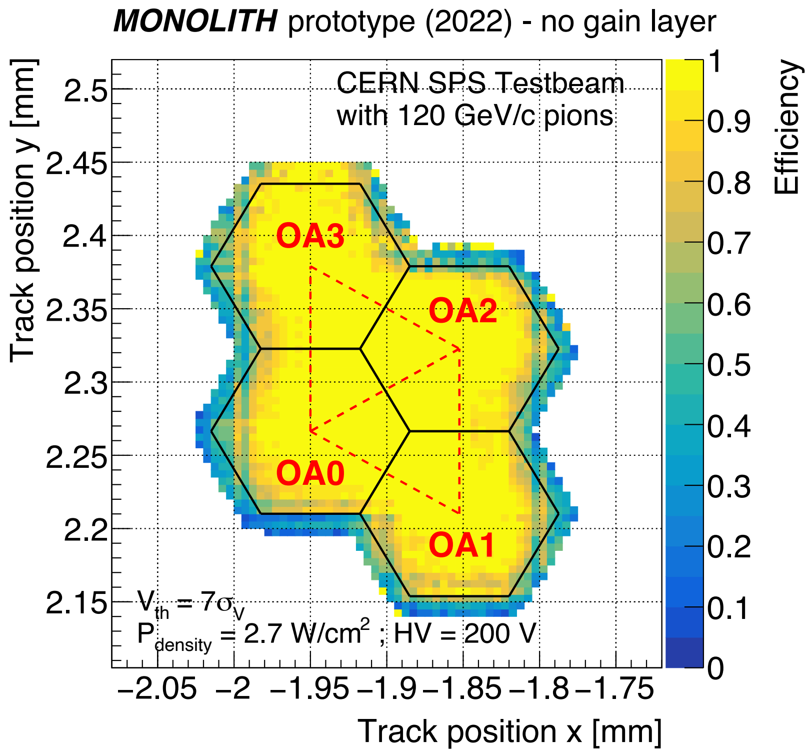


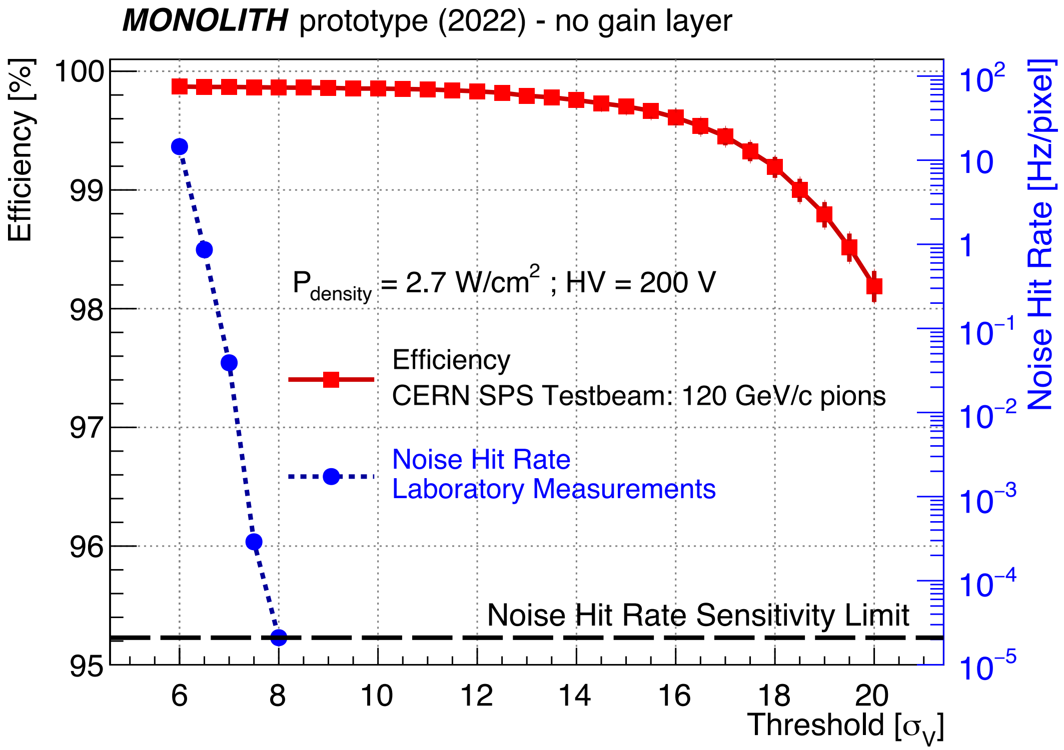
Charge-Collection Noise

- **Garfield++** simulation using:
  - The measured **E**quivalent **N**oise **C**harge
  - The **electric field** (TCAD)
  - The **electronics δ-response** (Cadence)
- The **MIP simulation** matches the **testbeam data** ($\sigma_{\text{Jitter}} \oplus \sigma_{\text{Landau}}$)
- The charge deposition created by the **laser** is **uniform** (no σ_{Landau})
- The **simulation** matches the **laser data**
- The **difference in quadrature** between the testbeam and laser should be the σ_{Landau} contribution
- The simulated **trend** is **similar** to the measured one
  - There are non-negligible correlations between σ_{Jitter} and σ_{Landau}



Efficiency Results



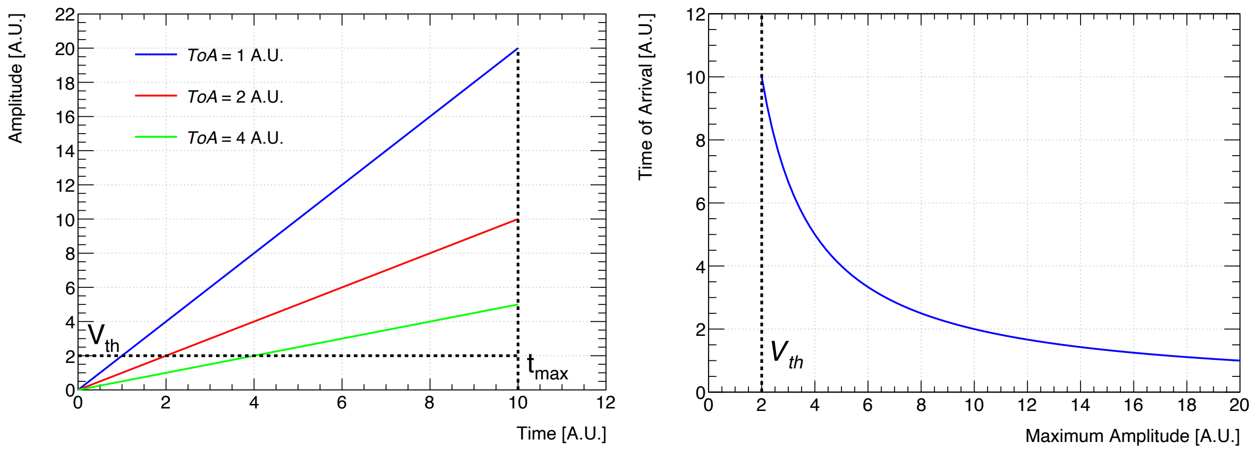


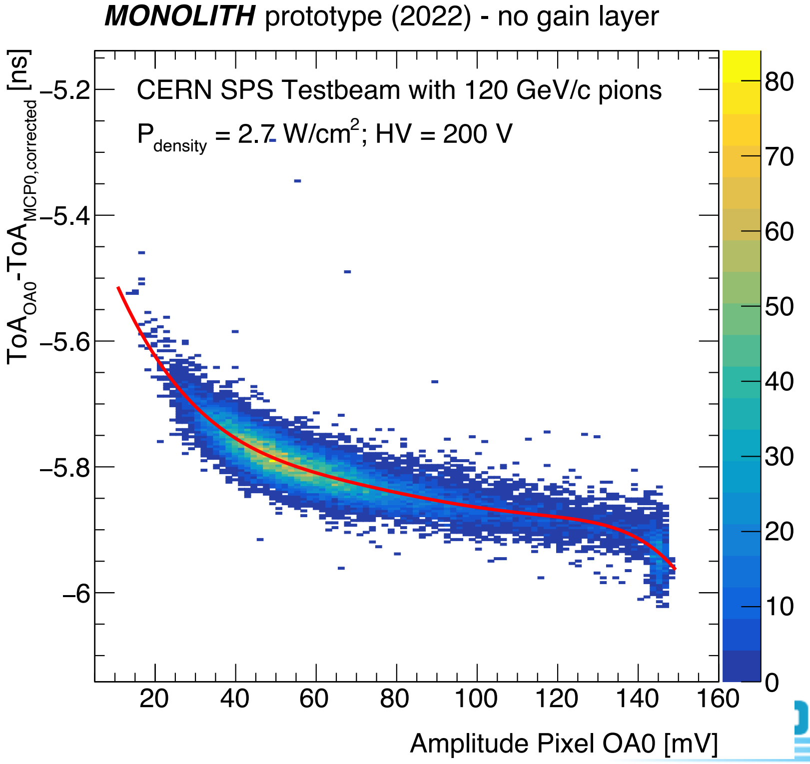
- The **apparent degradation** at the edges is due to the ~10 µm resolution of the telescope
- Selection of two **triangles:**
  - representative of the whole pixel
  - **unbiased** by the telescope resolution

- Large plateau of **99.8% efficiency**
  - $\sigma_V \approx 1.4\ \mathrm{mV} \approx 100\ e^-$
- Negligible noise hit rate already at $7\sigma_V$

Time-Walk Correction

- The **time walk** is the spread in the time of arrival created by signals having different amplitudes
- In our prototypes, the time-walk **correction** is implemented in two possible ways:
    - Either taking the time of arrival as the time to reach a **fixed threshold**, and subtracting the average time of arrival for each amplitude
    - Either taking the time of arrival as the time to reach a **constant fraction** of the signal, which automatically corrects the time walk





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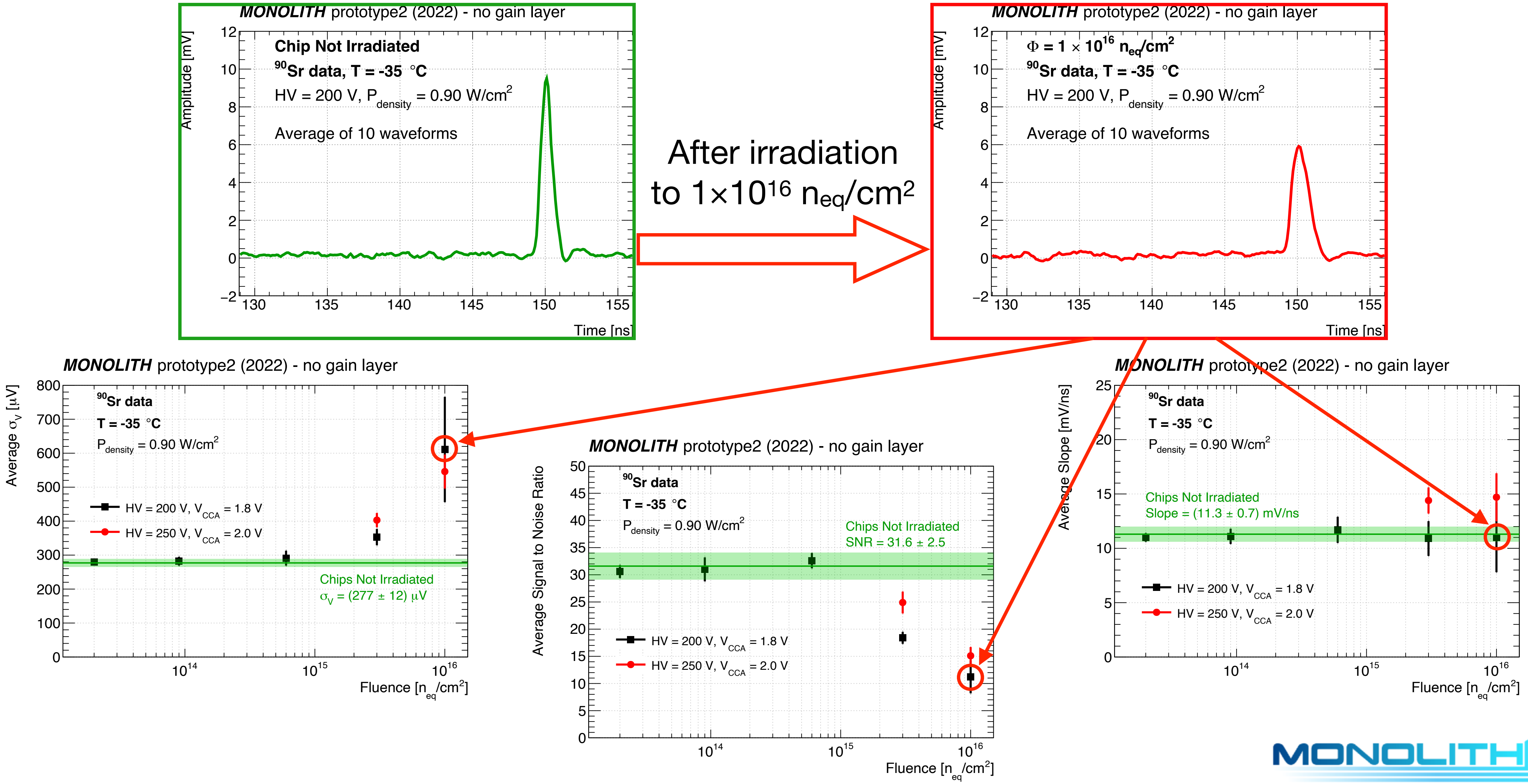
Main Characteristics After Irradiation



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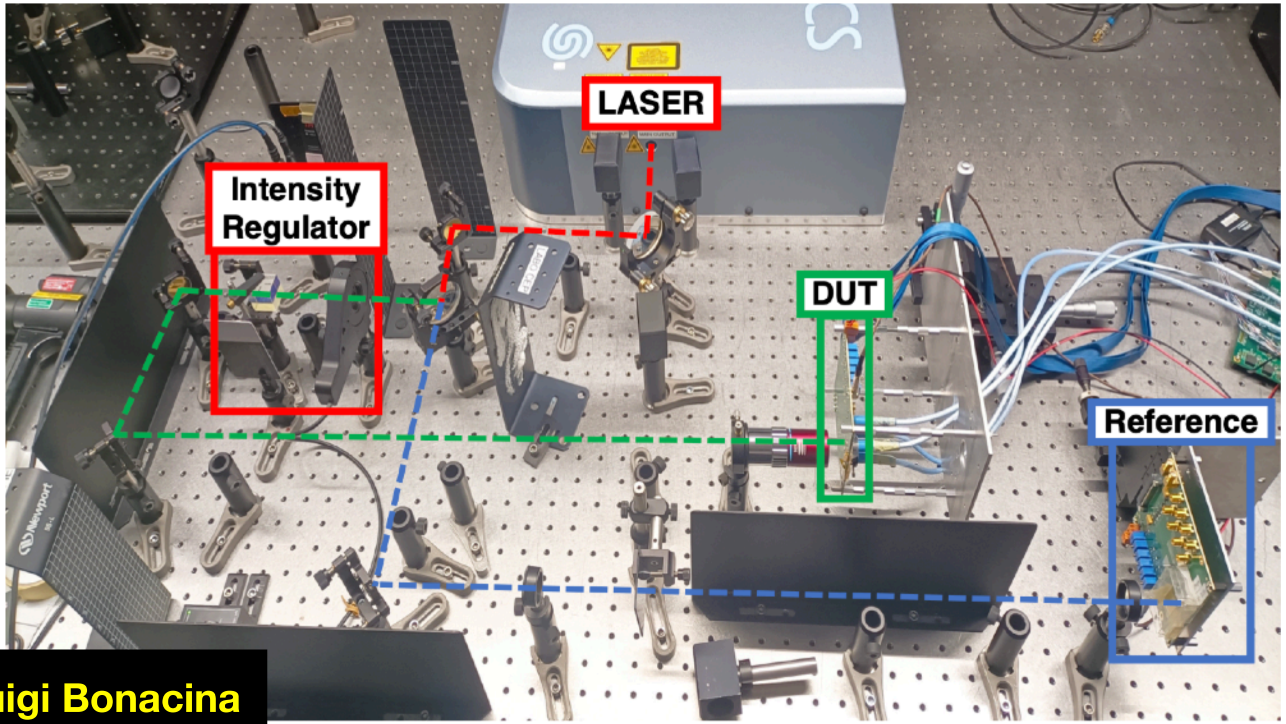
Femtosecond Laser Measurements

European Research Council
Established by the European Commission
FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

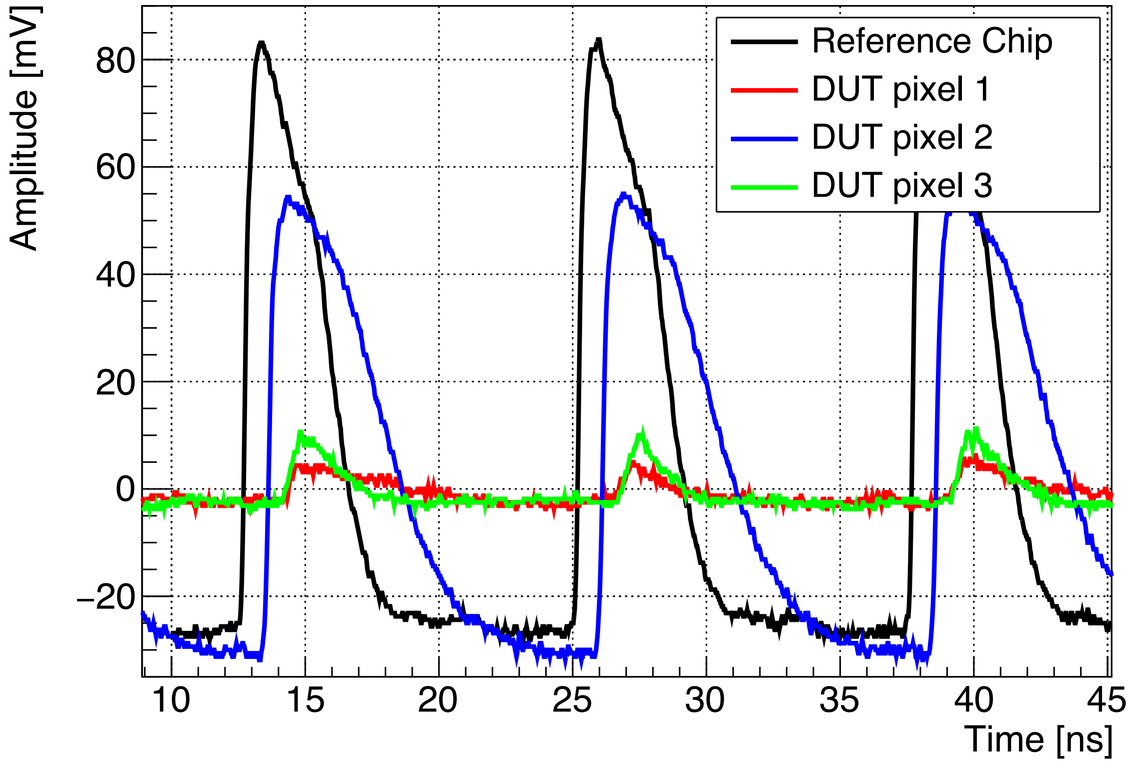
- Pulsed infrared femtosecond laser:
  - Uniform charge distribution: **no charge-collection noise** ($\sigma_{\text{Landau}} = 0$)
    - To study the pure contribution of the **electronics** σ_{Jitter}
- Time coincidence between two of our samples:
  - "**Reference**": large laser pulse for a precise reference
  - "**DUT**": variable intensity to study the performance vs. amplitude



Thanks to **Luigi Bonacina and Alexandra Latshaw**

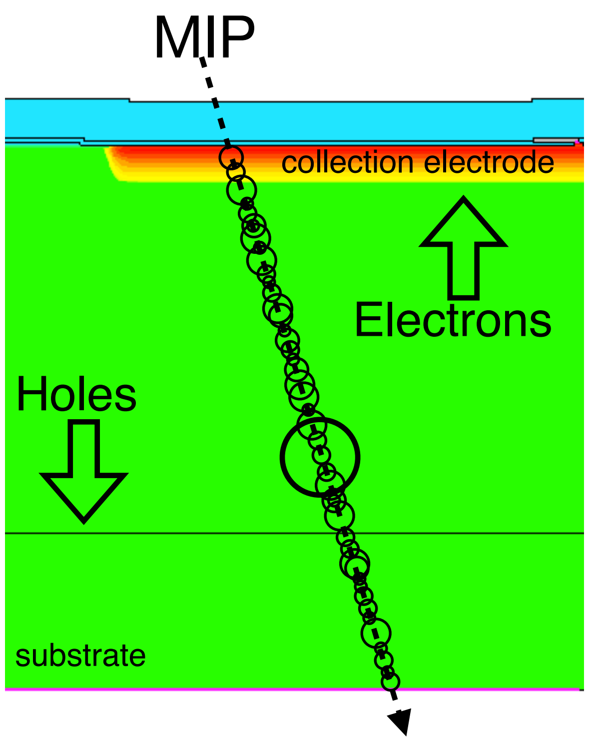
Femtosecond Laser Characteristics

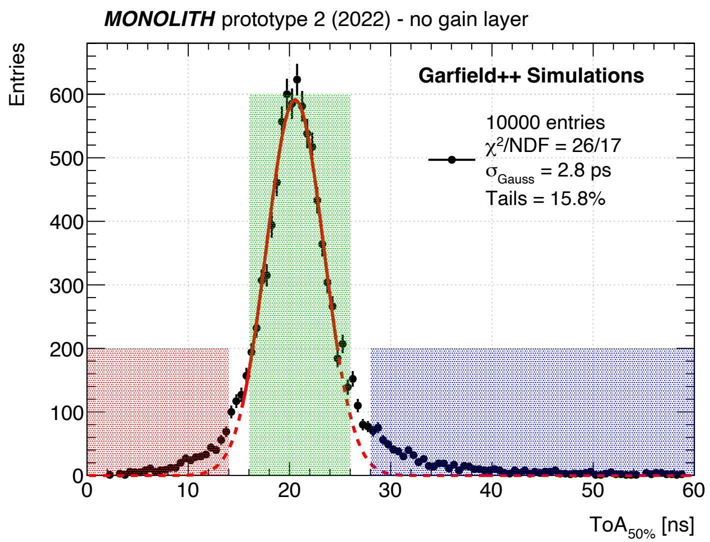
- Pulsed infrared femtosecond laser:
  - Wavelength of **1060 nm**
  - Intrinsic jitter of **100 fs**
    - Hence the name femtosecond laser
  - Repetition frequency of **80 MHz**
  - **Focused** on the DUT on a Gaussian spot with a diameter of ~30 µm
- The Reference and DUT ASICs can tolerate the high repetition rate of the laser

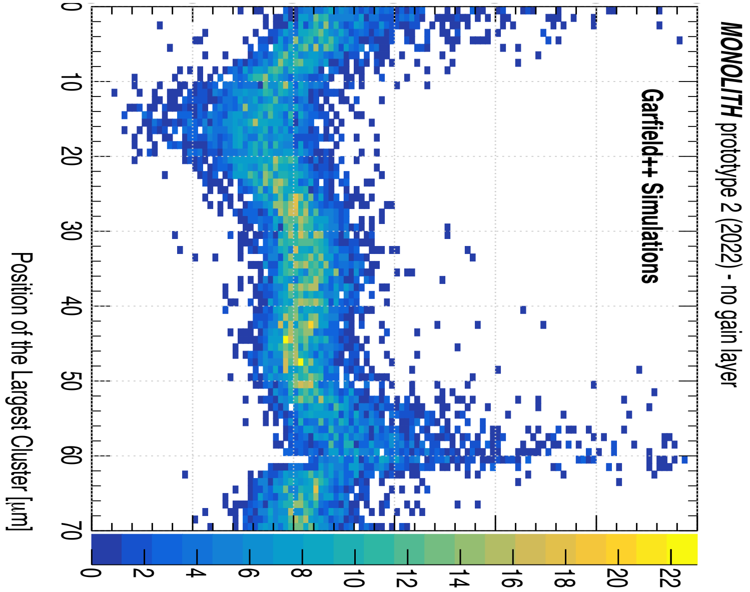


Non-Gaussianity of the ToA Distributions

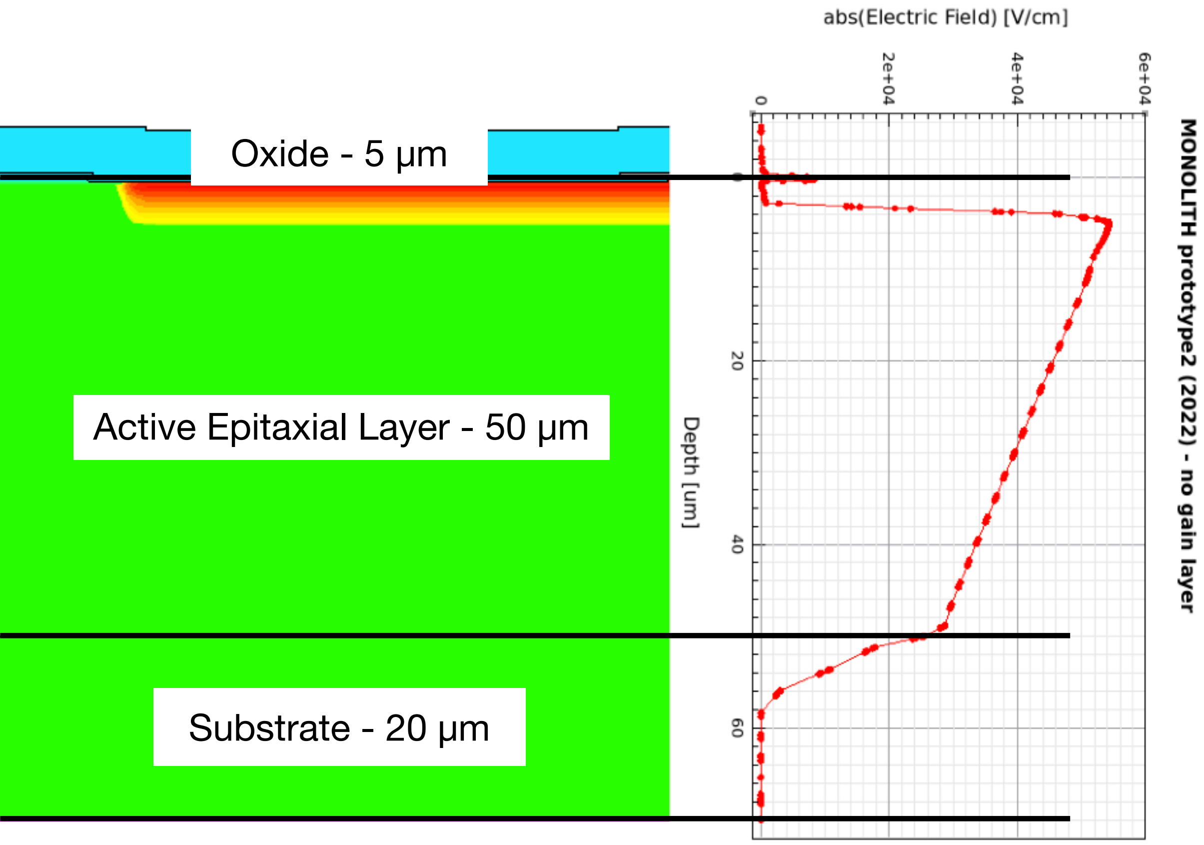
- Sometimes, clusters containing **more than 1000 electrons** are generated in the detector
- The corresponding voltage signal has a **specific time of arrival** according to the position of the big cluster:
  - Big clusters **between 10 to 20 μm** produce **faster** signals
  - Big clusters in the **peripheral regions** produce **slower** signals
- Garfield++ simulation were helpful in understanding this issue

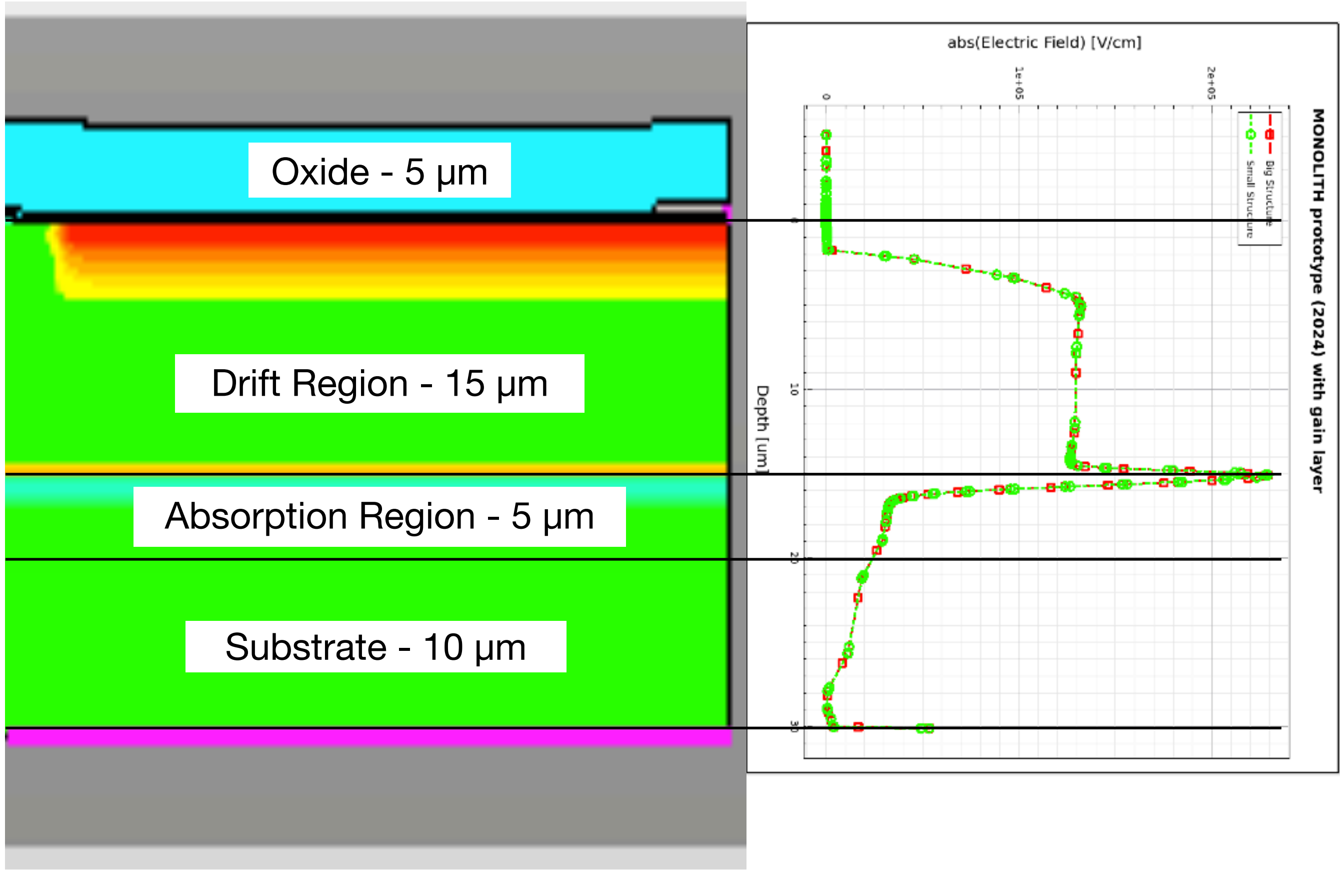






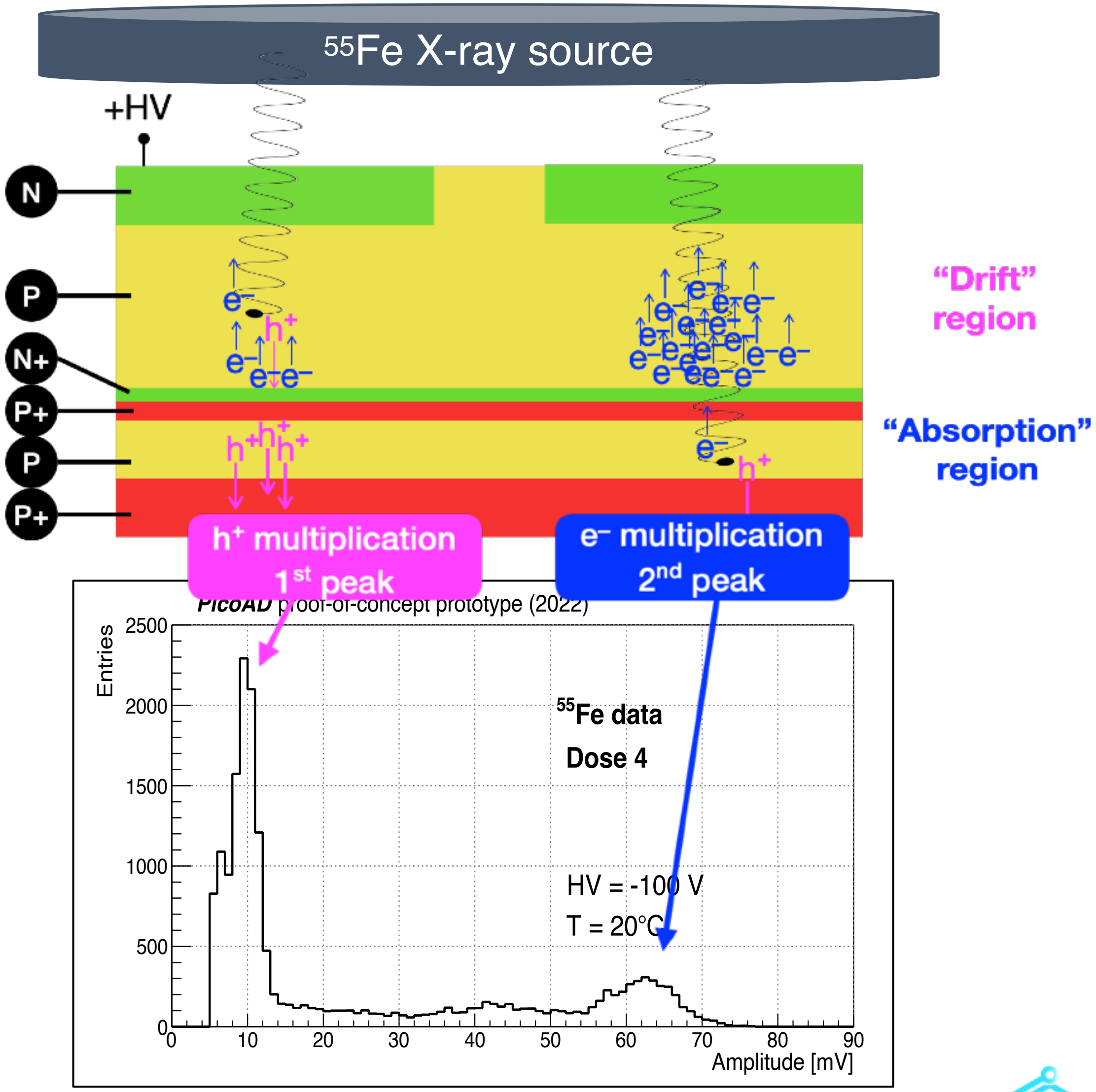
Electric Field Profiles





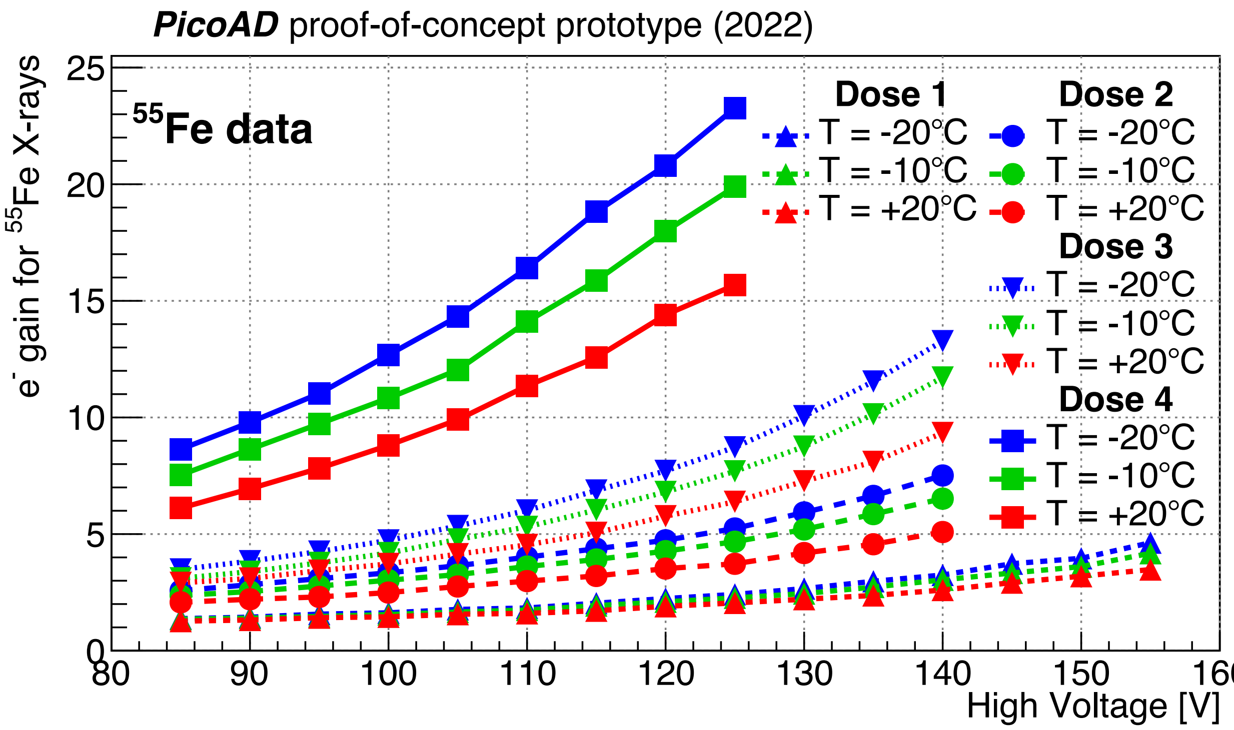
Gain Measurements with a ^{55}Fe Source

- **X-rays from ^{55}Fe radioactive source**:
  - ~5.9 keV photons with point-like charge deposition -> **1640 electrons**
- **Characteristic double-peak spectrum**
  - Photon absorbed in the **drift region**:
    - **Holes** drift through the gain layer and multiply
    - **First peak** in the spectrum
  - Photon absorbed in the **absorption region**:
    - **Electrons** drift through the gain layer and multiply
    - **Second peak** in the spectrum
- We can calculate the **gain for electrons** from the spectra

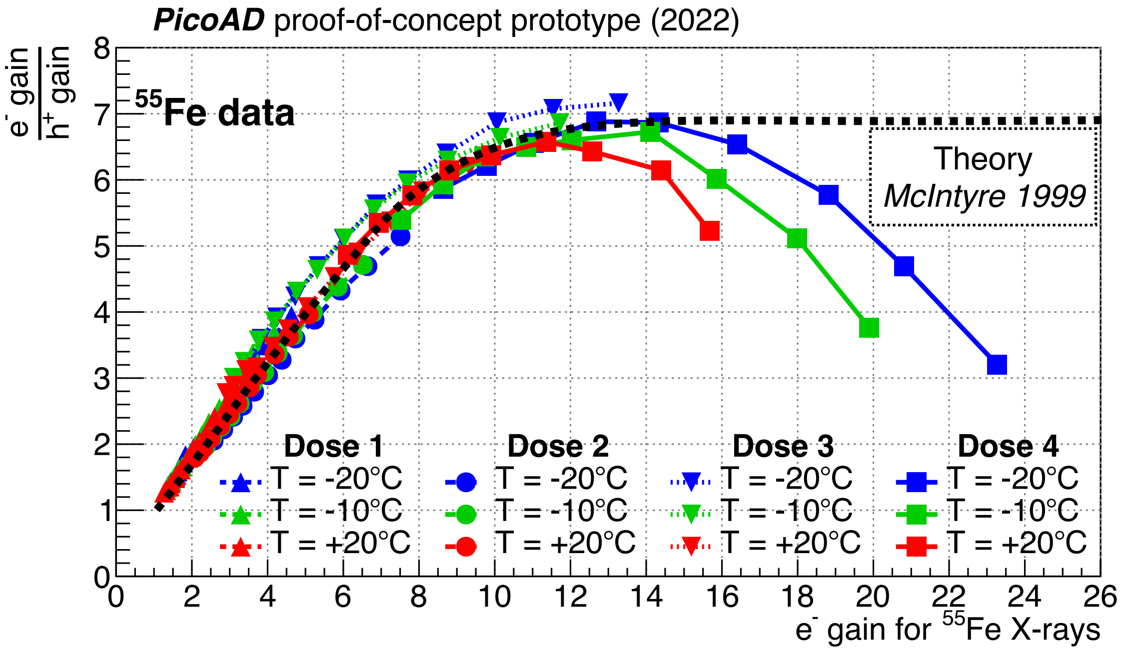


PicoAD© Proof-of-Concept Gain Results

- The **gain layer** of the **PicoAD©** proof-of-concept prototype **works** as expected:
  - Higher gain for higher bias voltage
  - Higher gain for higher gain layer doses
  - Higher gain for lower temperatures
- But, the **maximum electron gain** is **23 for ^{55}Fe X-rays** at 125 V and -20 °C
  - It is **smaller than the simulated** one with TCAD

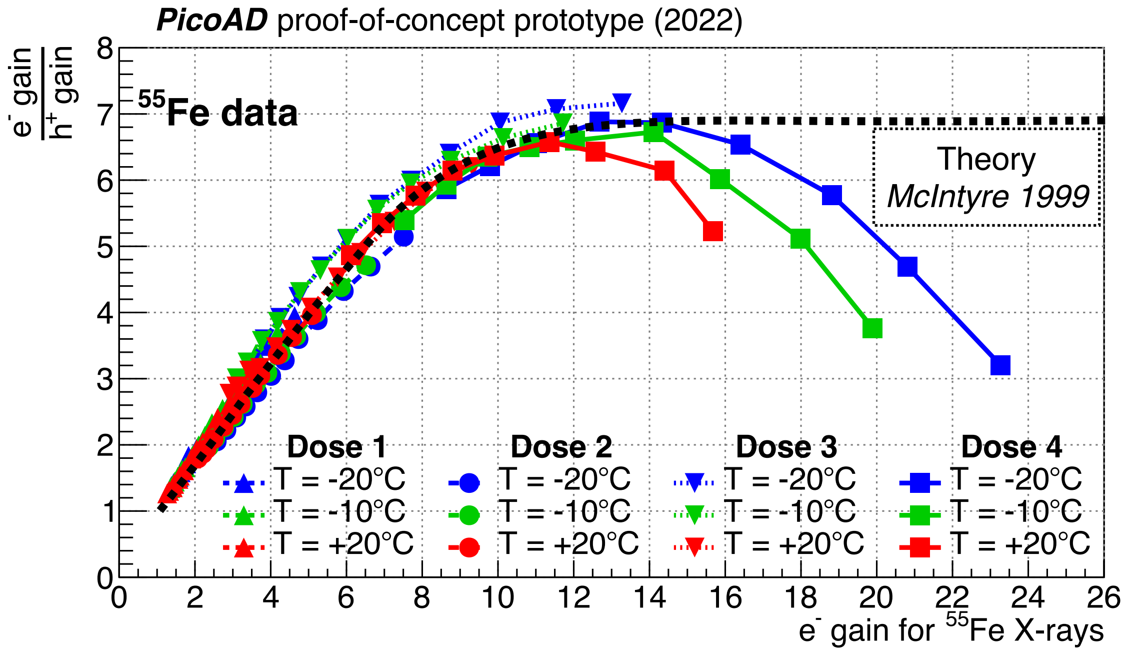


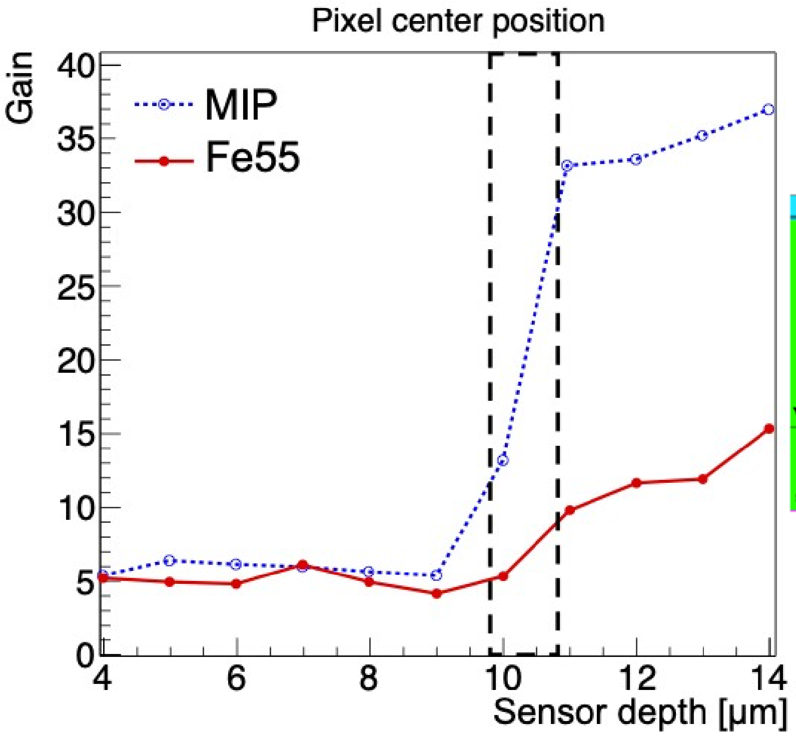
PicoAD© Proof-of-Concept Gain Results

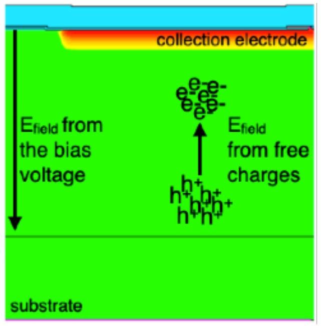


- The gain for **holes** and **electrons** can be studied simultaneously with **PicoAD©**
- The **gain ratio** as a function of the electron gain deviates from the theoretical trend

PicoAD© Proof-of-Concept Gain Results







- The gain for **holes and electrons** can be studied simultaneously with **PicoAD©**
- The **gain ratio** as a function of the electron gain deviates from the theoretical trend

- Refined **TCAD** simulations show that:
    - The gain is **suppressed** by the large cloud of charges generated by the **^{55}Fe source**
    - This suppression is **not present for a MIP**

PicoAD© Proof-of-Concept Efficiency Maps

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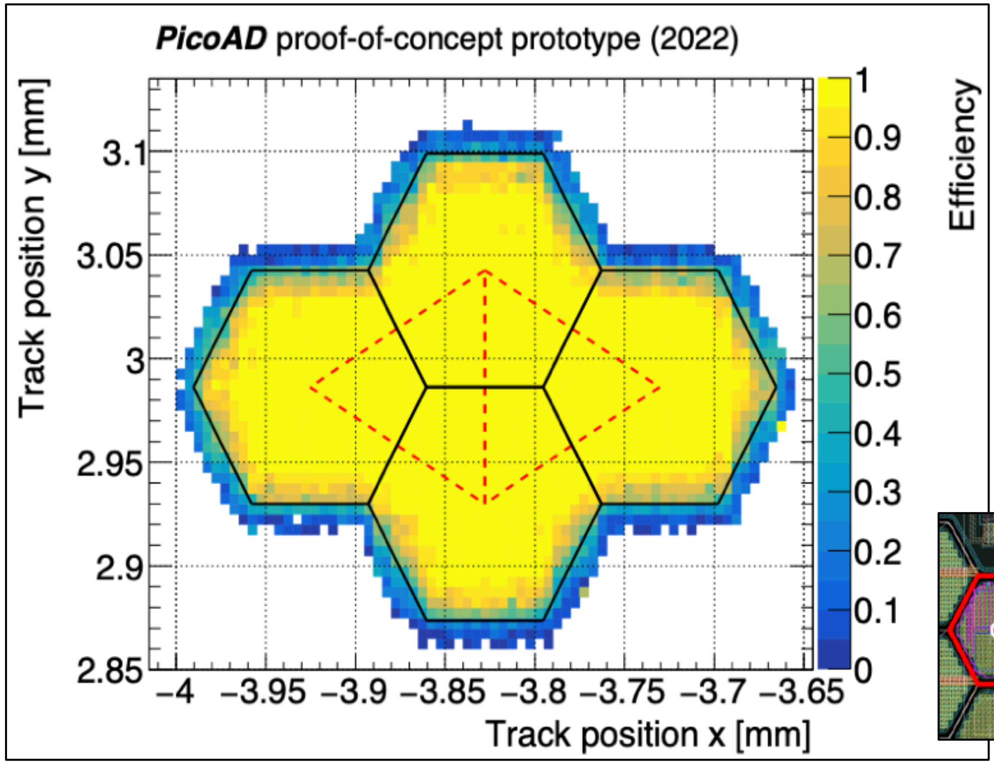
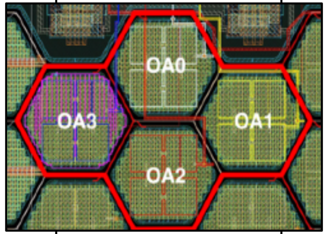
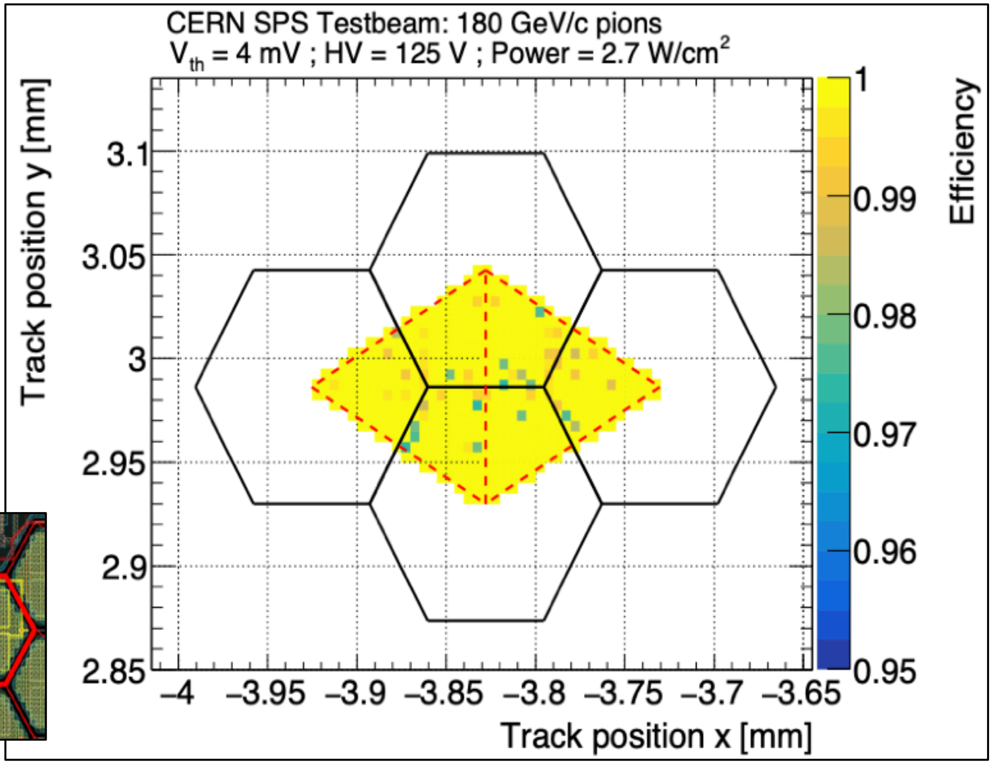




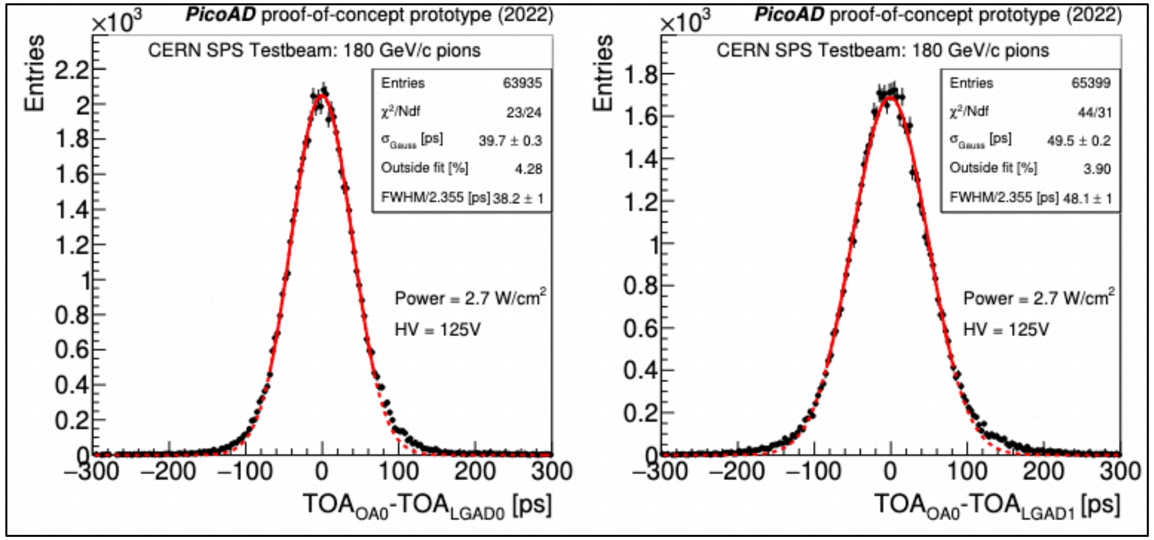


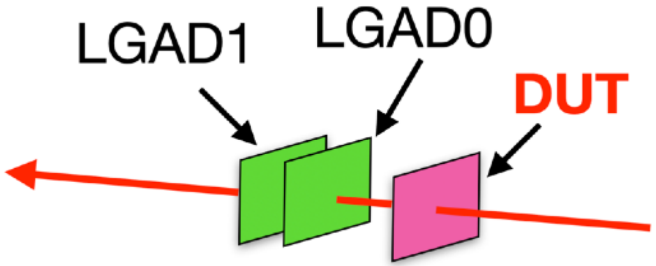
- The **apparent degradation** at the edges is due to the finite resolution of the telescope (~10 µm)

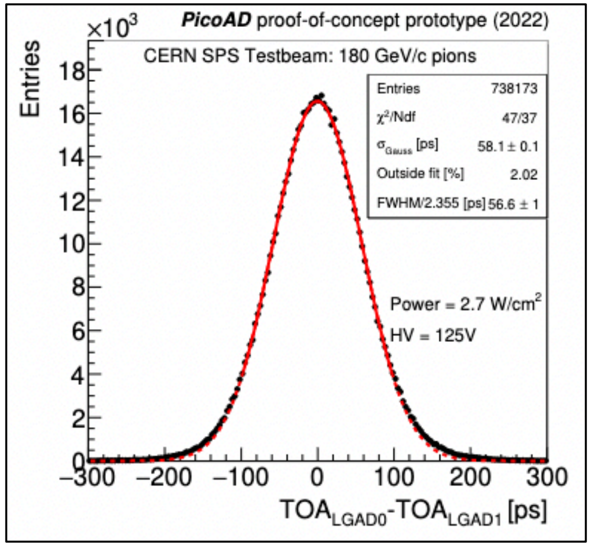
- Selection of two **triangles:**
    - representative of the whole pixel
    - **unbiased** from the telescope resolution

PicoAD© Proof-of-Concept ΔToA Distributions

- The **T**ime **o**f **A**rrival is taken as the time to reach a fixed threshold
- The distributions are after a time-walk correction
- The distributions are **Gaussian**
  - Except ~2-4 % of the entries that are in **non-Gaussian tails**
- The three σ_{Gauss} from the fits give the three timing resolutions of:
  - The DUT
  - The two LGADs

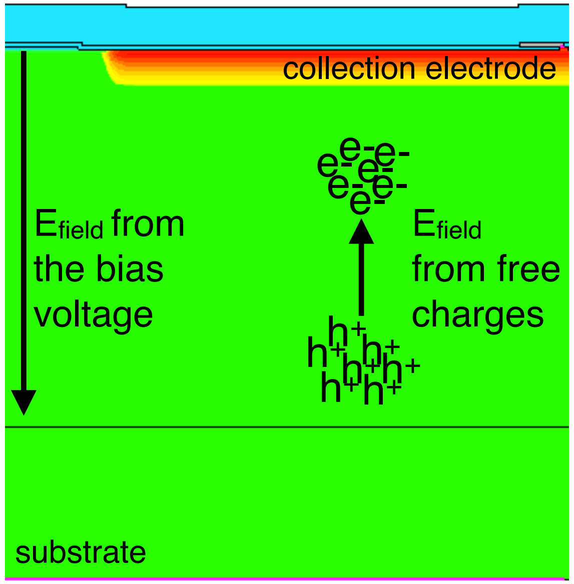


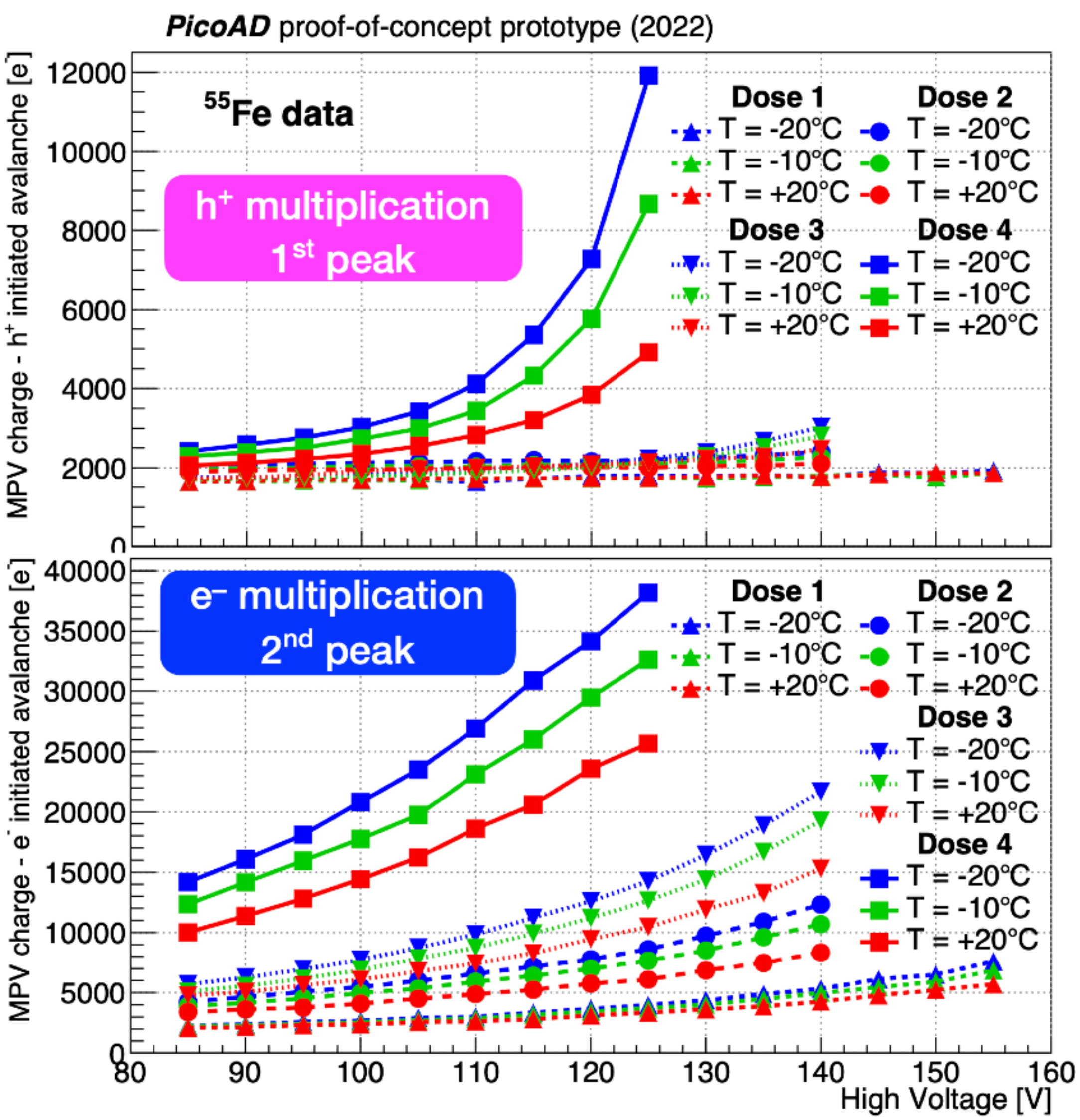




PicoAD© Gain Suppression

- Only the **holes** have the correct **exponential trend** that the gain should have as a function of the bias voltage:
  - The high number of charges creates an **electric field opposite** to the one created by the bias voltage
  - The **electron gain is suppressed** by the high number of charges

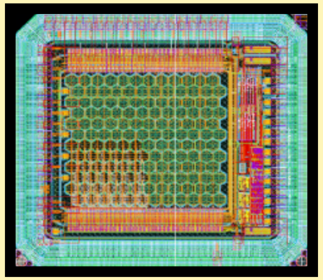




Improvements from 2020 to 2022

- Similar matrix configuration, but:
  - From **standard** 50 Ωcm on 1 Ωcm substrate to 50 µm-thick 350 Ωcm **epi-layer** on 1 Ωcm substrate led to:
    - A smaller pixel capacitance
    - A larger depletion from 23 µm to 50 µm
    - A much larger voltage plateau
    - A saturated drift velocity everywhere
  - **Preamp and driver voltage** decoupling led to:
    - An optimal amplifier operation
    - The removal of the cross-talk
  - An optimised front-end electronics layout, with a **semi-differential output**, and **high-frequency cables** led to:
    - A better rise time (from 600 ps to 300 ps)

2020



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

36 ps

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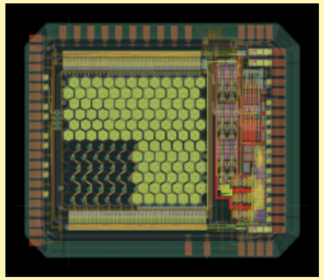
2022



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

20 ps

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