A picosecond avalanche detector in SiGe BiCMOS

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on behalf of the MONOLITH team

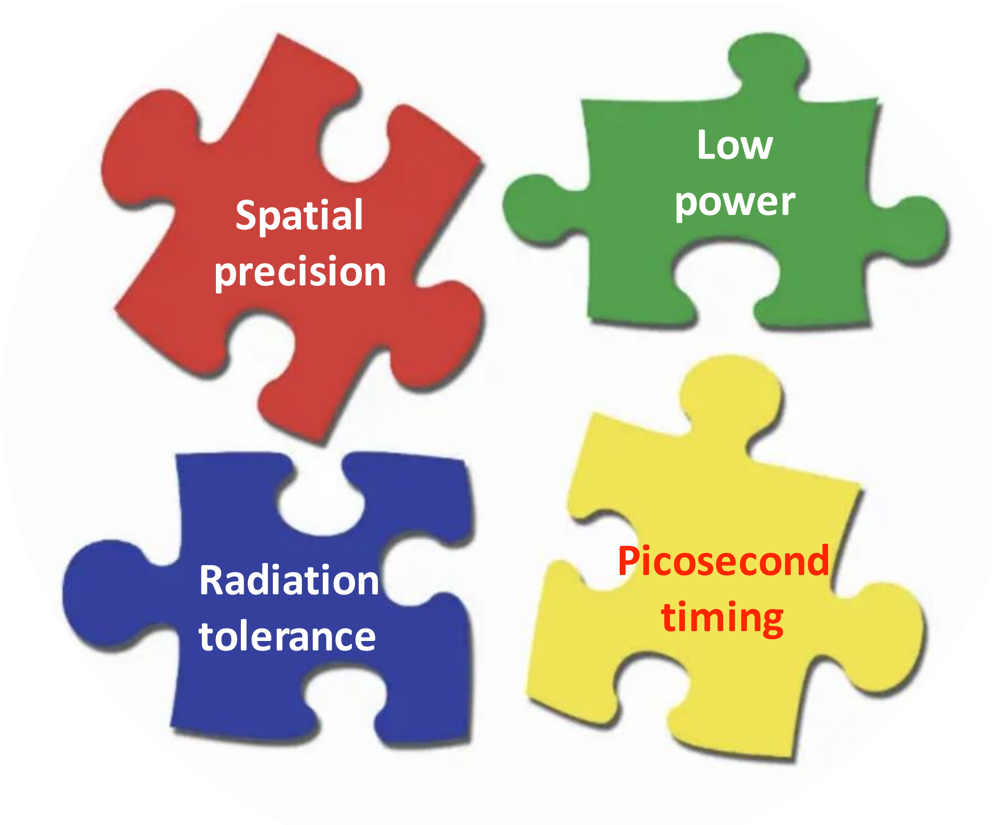
Precise timing with silicon

Timing resolution in silicon pixel detectors mainly determined by:

1. **Sensor geometry and fields**
2. **Charge-collection** (Landau) **noise**
3. **Electronic noise**
4. **Gain** by internal charge multiplication

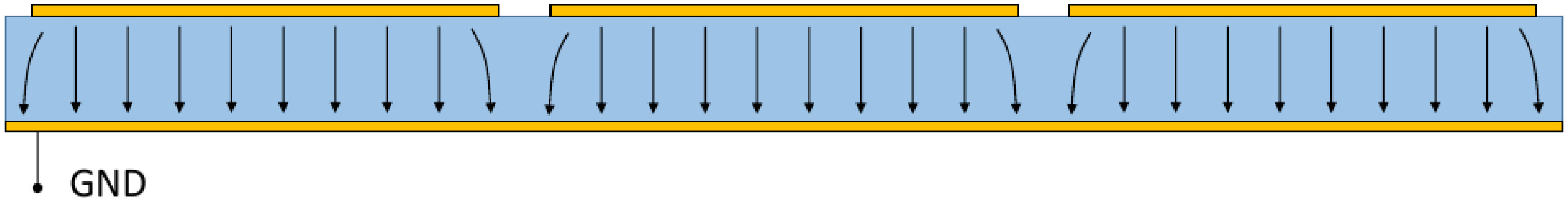
Challenge:

Optimise these parameters for **picosecond timing** while maintaining **other performance requirements**



1. Sensor geometry and fields

Sensor optimization for time measurement means:
Sensor time response **independent** from the particle trajectory



→ "Parallel plate" read out: wide pixels w.r.t. depletion region

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i} \cong \boxed{v_{drift}} \boxed{\frac{1}{D}} \sum_i q_i$$

Scalar, saturated

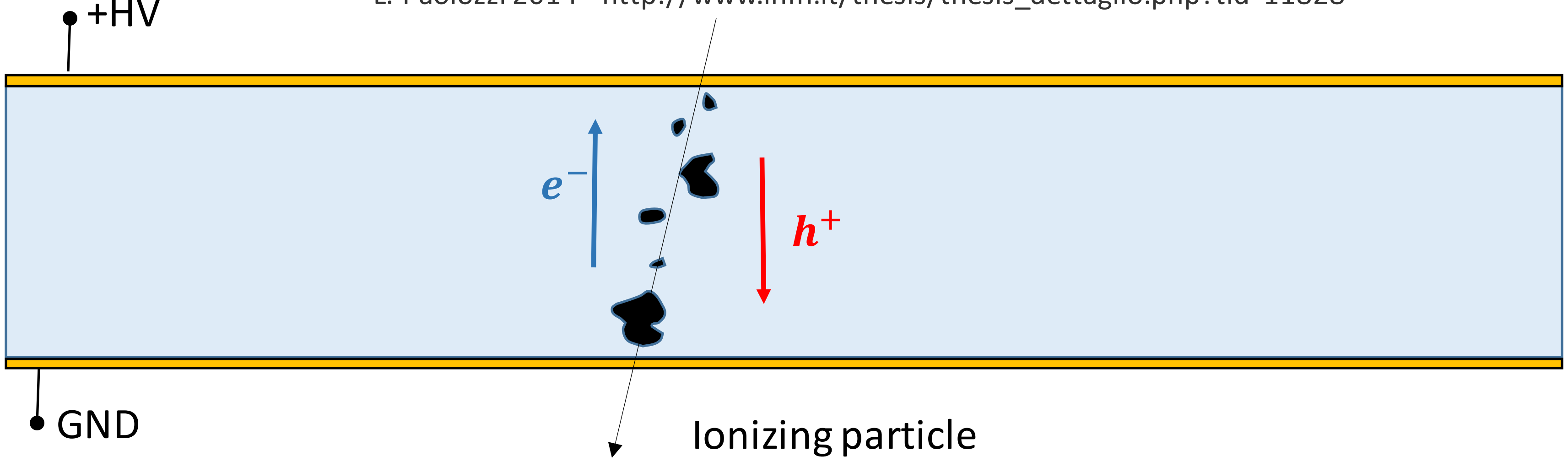
Scalar, uniform

Desired features:

- Uniform **weighting field** (signal induction)
- Uniform **electric field** (charge transport)
- Saturated charge **drift velocity** (signal speed)

2. Charge collection noise

L. Paolozzi 2014 - http://www.infn.it/thesis/thesis_dettaglio.php?tid=11828



is produced by the **non uniformity of the charge deposition** in the sensor:

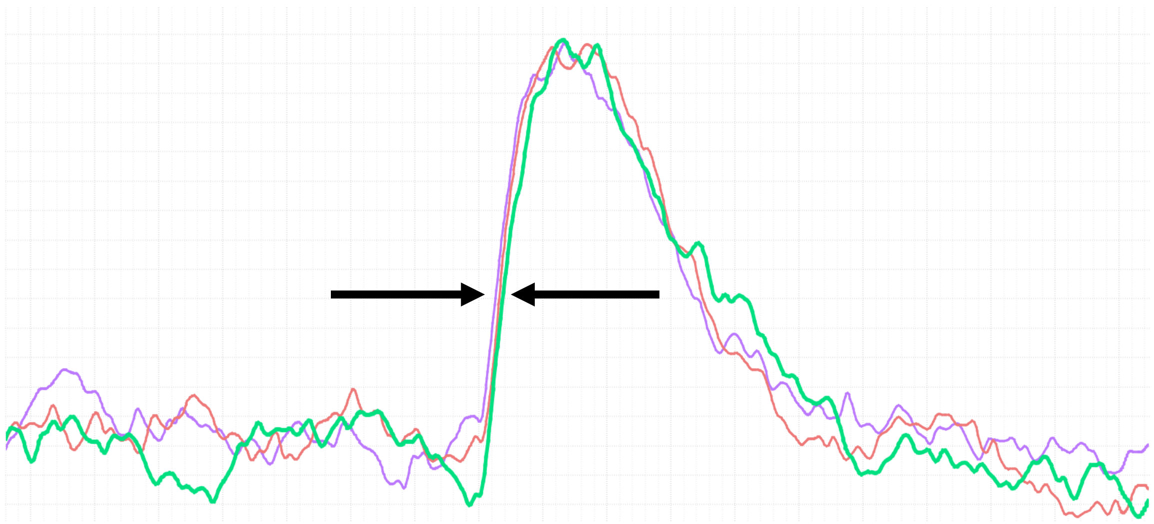
$$I_{ind} \cong v_{drift} \frac{1}{D} \boxed{\sum_i q_i}$$

When **large clusters** are absorbed at the electrodes, their contribution is removed from the induced current. The **statistical origin** of this variability of I_{ind} makes this effect irreducible in PN-junction sensors.

3. Electronic noise

Once the geometry has been fixed, the time resolution depends mostly on the **amplifier performance**.

Time jitter

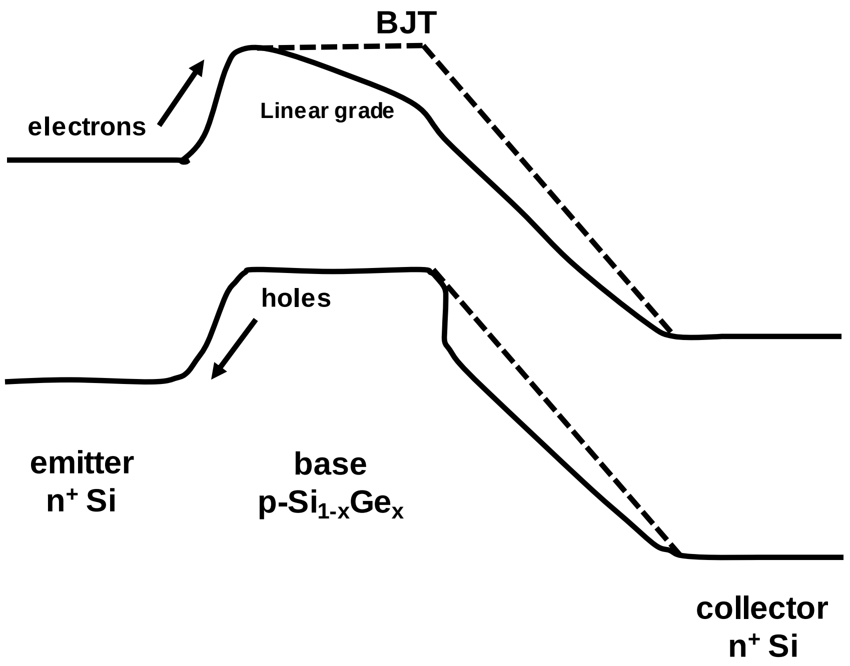


Fast integration

$$\sigma_t = \frac{\sigma_V}{dV/dt} \cong \frac{t_{rise}}{Signal/Noise} \cong \frac{ENC}{I_{Ind}}$$

3. Electronic noise

In SiGe Heterojunction Bipolar Transistors (HBT) the **grading** of the bandgap in the Base changes the **charge-transport mechanism** in the Base from **diffusion** to **drift**:



Grading of germanium in the base:
field-assisted charge transport in the Base,
equivalent to introducing an electric field in the Base

$\Longrightarrow$ short e$^-$ transit time in Base $\Longrightarrow$ very high β

$\Longrightarrow$ smaller size $\Longrightarrow$ reduction of R_b and very high f_t

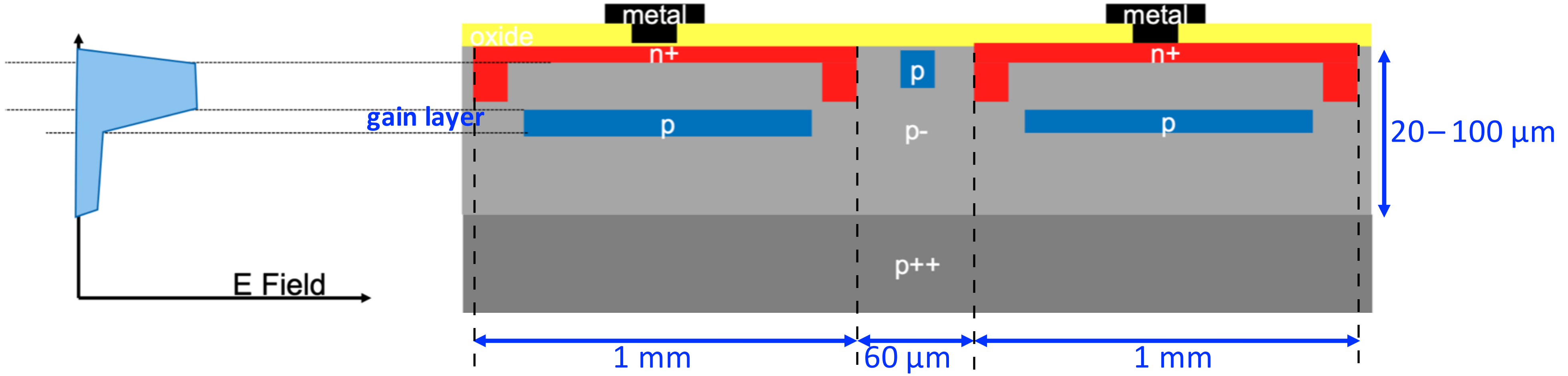
Hundreds of GHz

4. Gain

- A gain layer allows larger signals, and thus, better time resolution

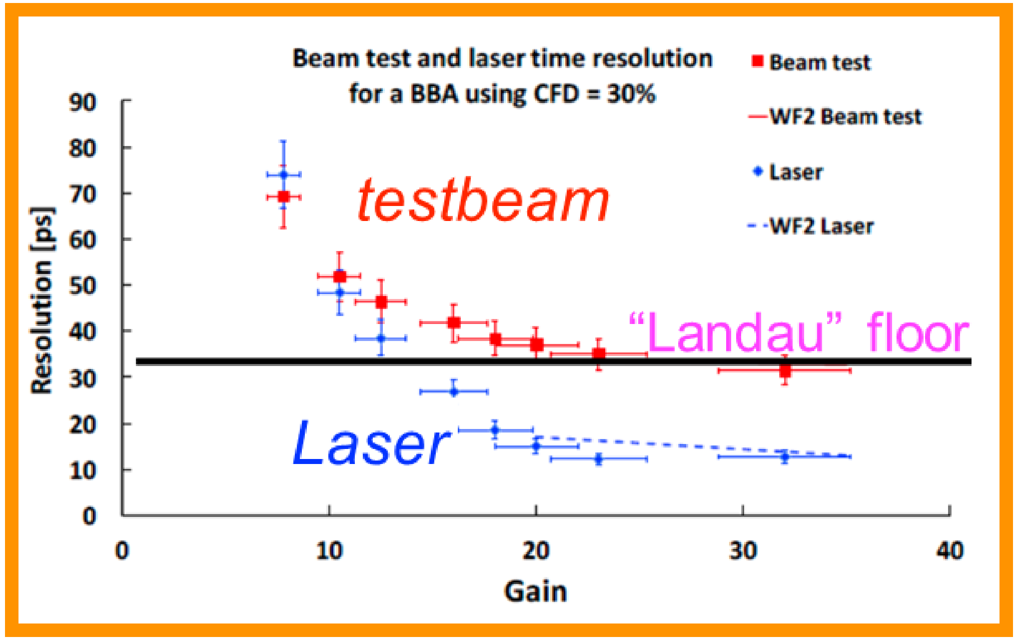
$$\sigma_T \cong \frac{t_{rise}}{Signal/_{Noise}} \cong \frac{ENC}{I_{Ind}}$$

- This is achieved in the LGADs with a gain layer under the pixel;



- As you will see, we have a different strategy

4. Gain



H. Sadrozinski, A. Seiden and N. Cartiglia, 2018 Rep. Prog. Phys. ***81*** *026101*

Charge collection noise represents an intrinsic limit to the time resolution for a semiconductor PN-junction detector.

~30 ps reached by present LGAD sensors.

Lower contribution from sensors without internal gain

The MONOLITH Project

Our recipe for picosecond timing with silicon:

MONOLITHIC

SiGe BiCMOS

PicoAD:
Picosecond Avalanche Detector

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- Lead chip design
- Digital electronics

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- Laboratory test

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Matteo Milanesio
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- Firmware

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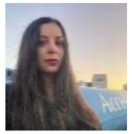

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Sinergia

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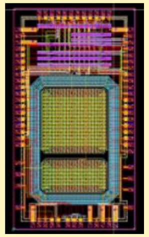
Monolithic SiGe BiCMOS for timing

Monolithic prototypes with SiGe BiCMOS (without internal gain layer)

2016



200ps

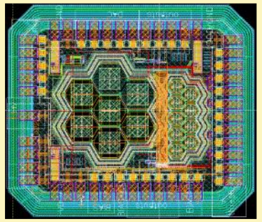
- 1 and 0.5 mm^2 pixels
- Discriminator output

2017

110ps

- 30 pixels $500x500\mu m^2$
- 100ps TDC +I/O logic

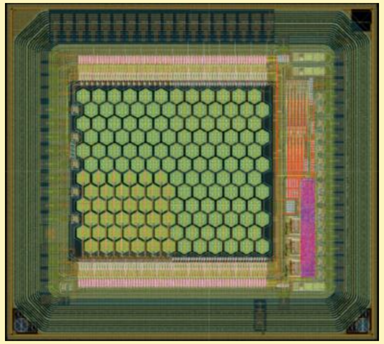
2018



50ps

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

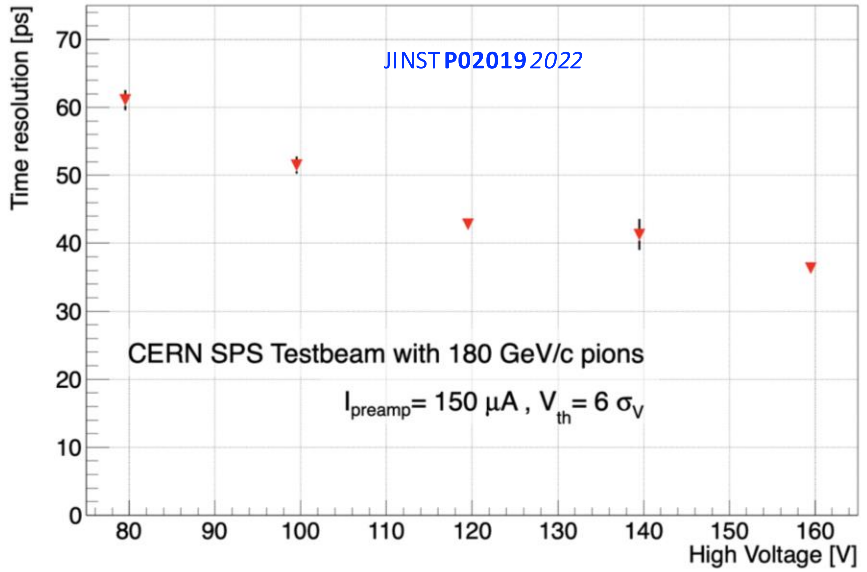
2019



36 ps

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

Test beam results of 2019 prototype



Sensor with no gain test beam results: JINST **P02019** *2022*

PicoAD Sensor Concept

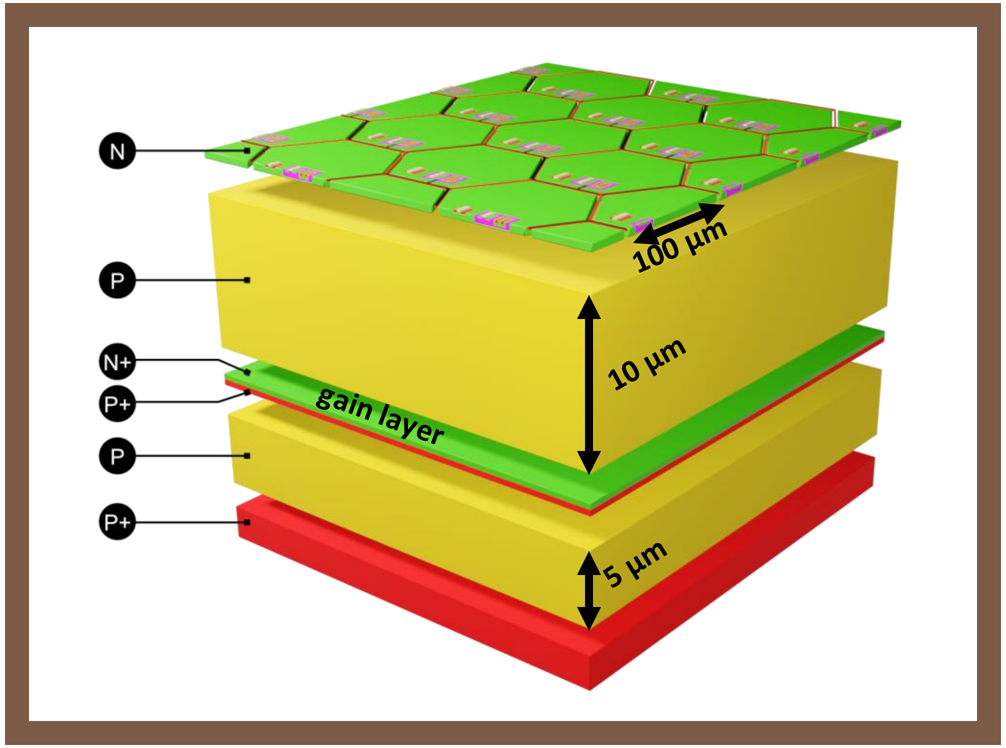
© G. Iacobucci, L. Paolozzi and P. Valerio. Multi-junction pico-avalanche detector;
European Patent EP3654376A1, US Patent US2021280734A1, Nov 2018

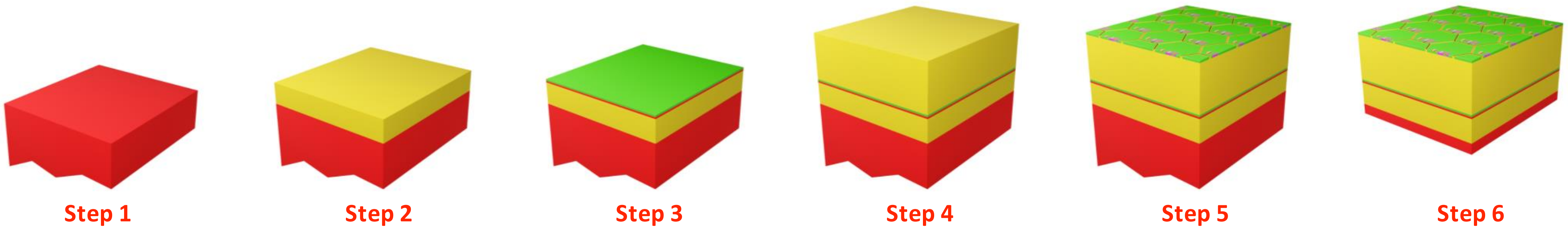
Multi-Junction Picosecond-Avalanche Detector©

with continuous and deep gain layer:

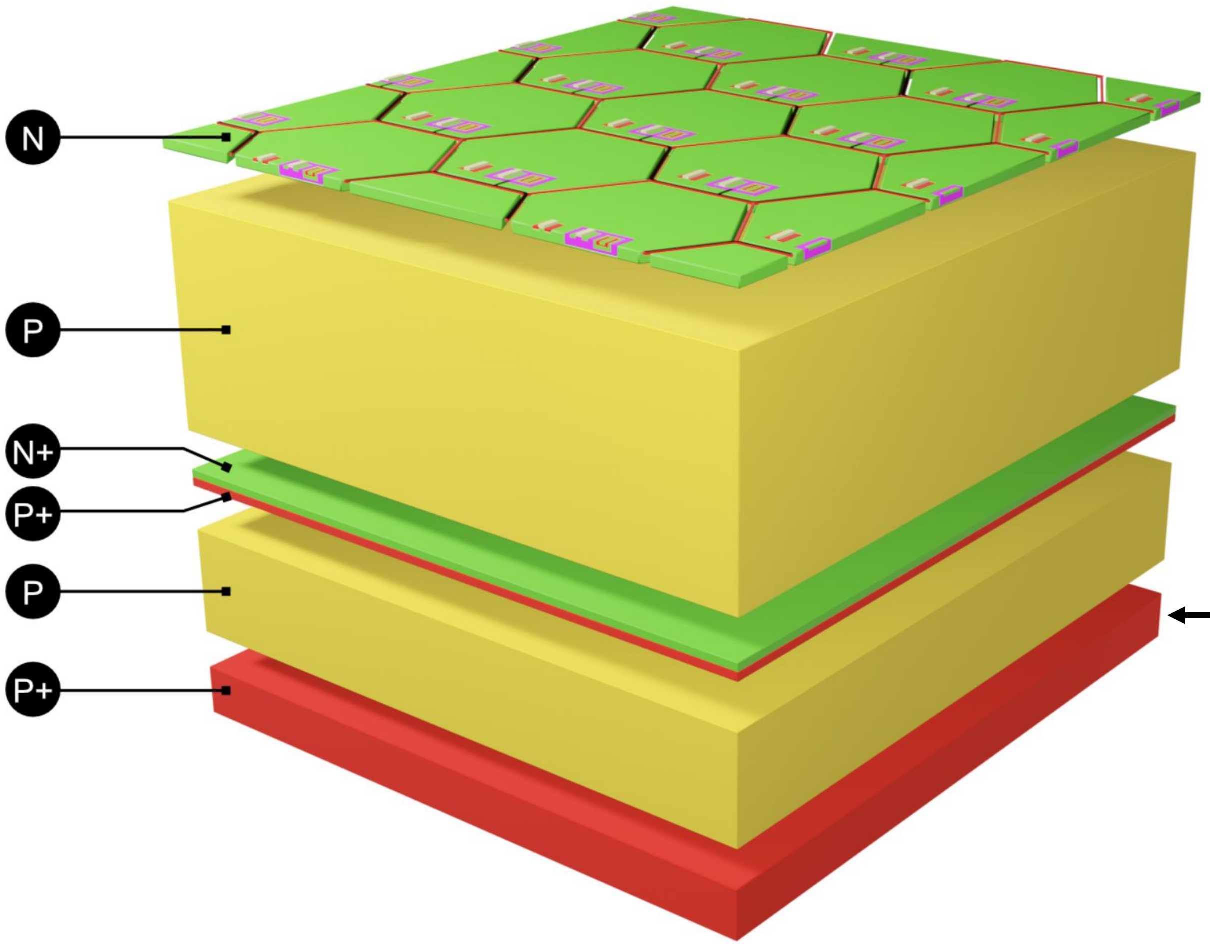
- De-correlation from implant size/geometry
  → **high pixel granularity and full fill factor**
  (high spatial resolution)
- Only small fraction of charge gets amplified
  → **reduced charge-collection noise**
  (enhance timing resolution)

$$\sigma_T \cong \frac{t_{rise}}{Signal/_{Noise}} \cong \frac{ENC}{I_{Ind}}$$





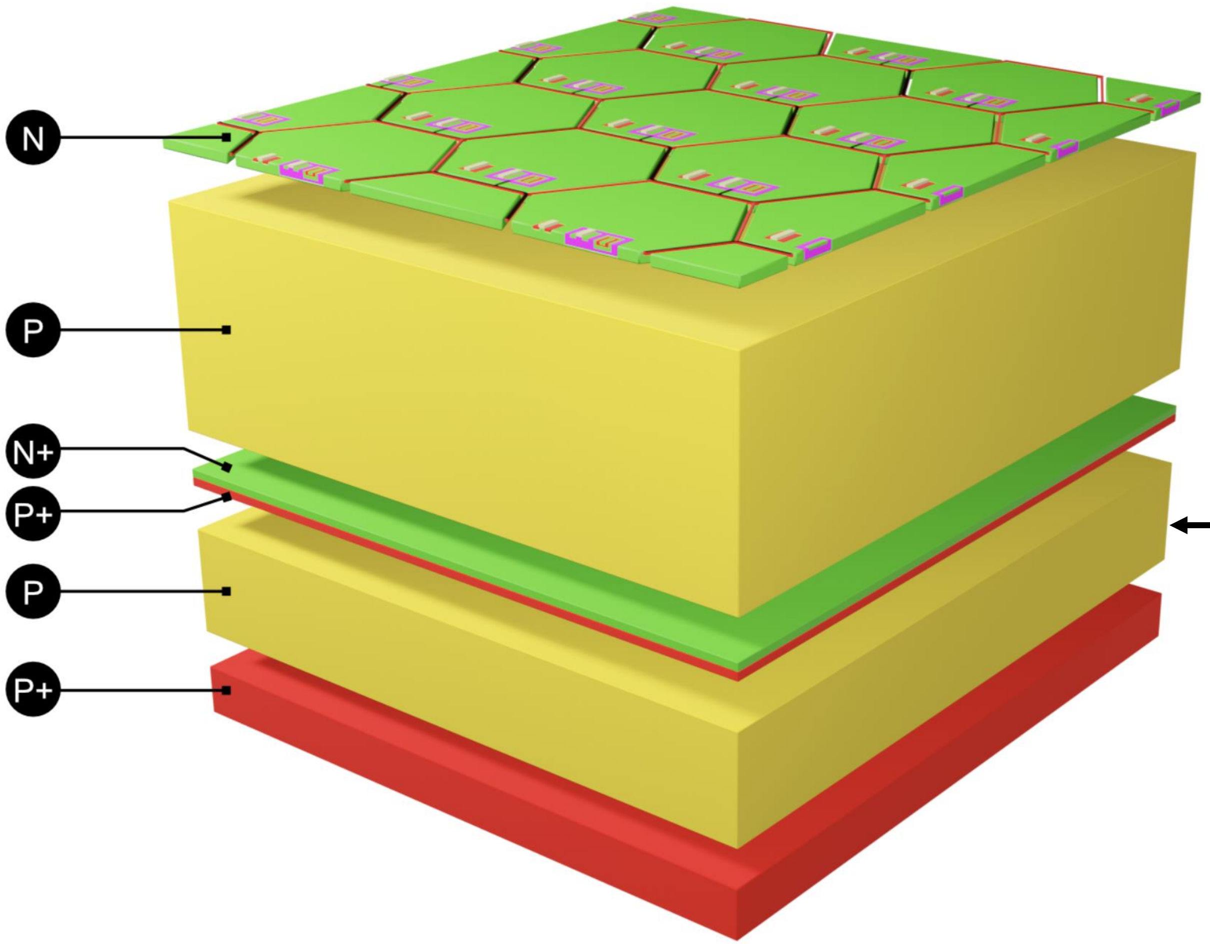
PicoAD Sensor Concept



Sensor growth on low resistivity wafers:

1. **No dedicated backside processing** needed
2. Low resistivity important to end depleted active region of sensor and minimise coupling to FE integrated in pixel

PicoAD Sensor Concept

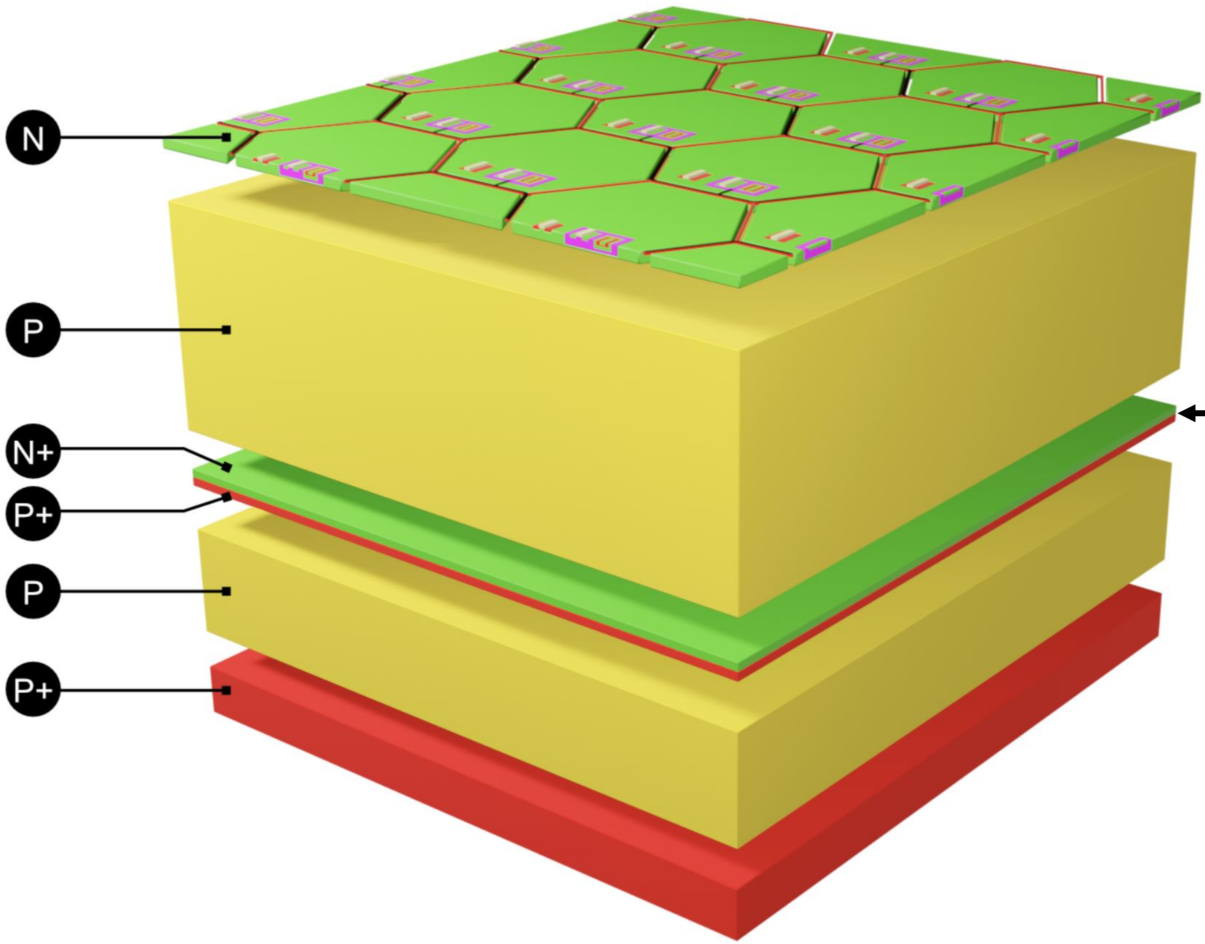


Thin 'absorbtion region', 1st epitaxial layer:

1. Region where primary charge charge drifting towards topside gets amplified is produced

2. Thin layer (~5µm) to **minimise charge collection noise**

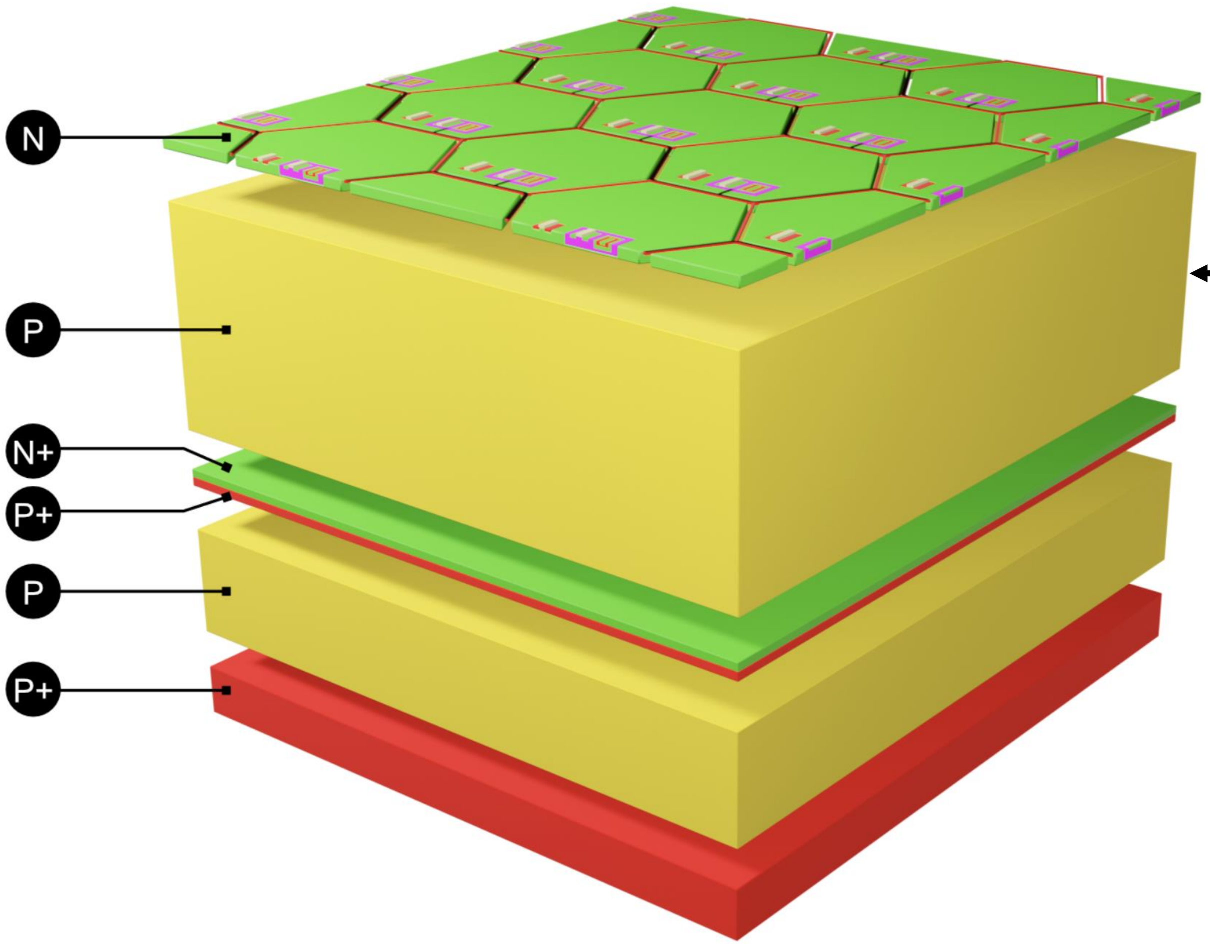
PicoAD Sensor Concept



Thin and uniform deep gain layer:

- Same doping of gain layer over full pixel cell (full 'fill-factor'):
  - **Uniform gain** and minimisation of pixel edge effects
- Gain layer physically seperated from pixel implant:
  - Can decrease absorbtion region to minimise charge collection noise without increasing sensor capacitance (coupling to backside substarte p+)
  - Can integrate FE electronics inside pixel implant (**fully monolithic CMOS**)

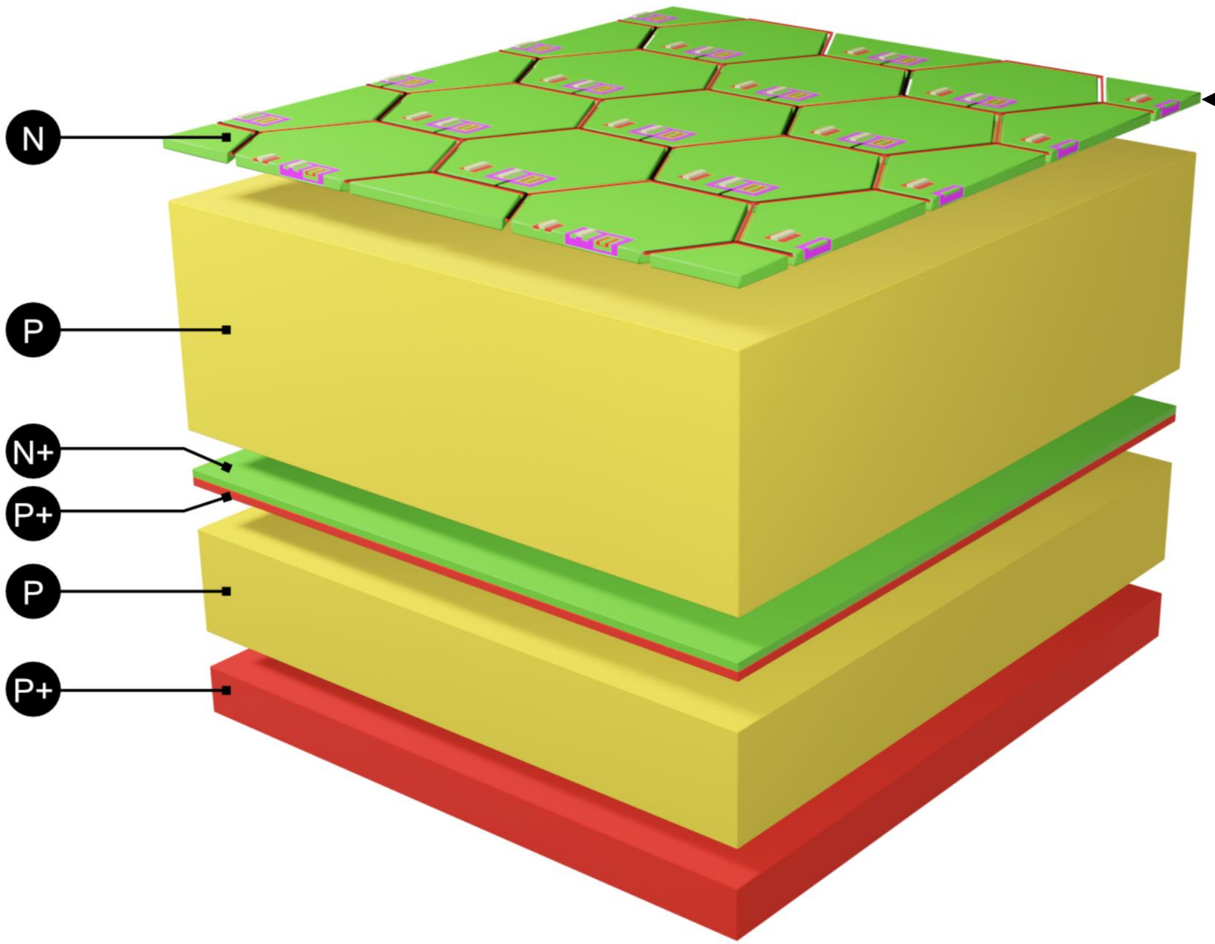
PicoAD Sensor Concept



Thicker 'drift region', 2nd epiaxial layer:

- Constrains:
  - Not too thick:
    - Maximise weighting field ($\propto$ 1/depletion)
    - Maximise drift field
  - Not too thin:
    - Minimize capacitance
    - Minimize impact of pixel implants on gain layer uniformity

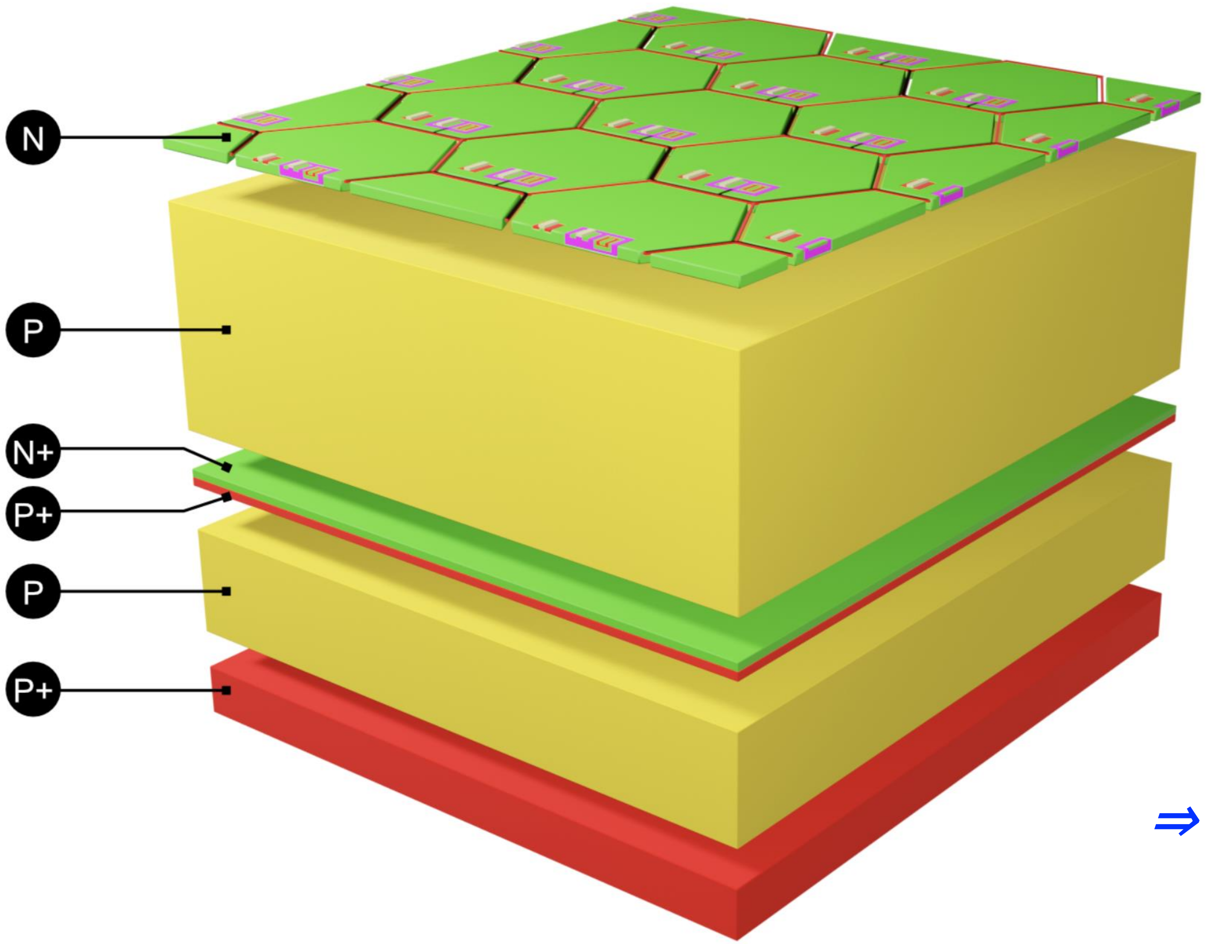
PicoAD Sensor Concept



Fully monolithic CMOS processing:

- Implemented in **large collection electrode design to maximise weighting** field over full pixel cell
- **Pixel implant size can be minimised** while maintaining gain layer uniformity!
- **Hexagonal design to minimise edge effects** (impact on gain layer + high field breakdown between pixels)

PicoAD Sensor Concept



⇒ PicoAD concept provides **simultaneusly**:

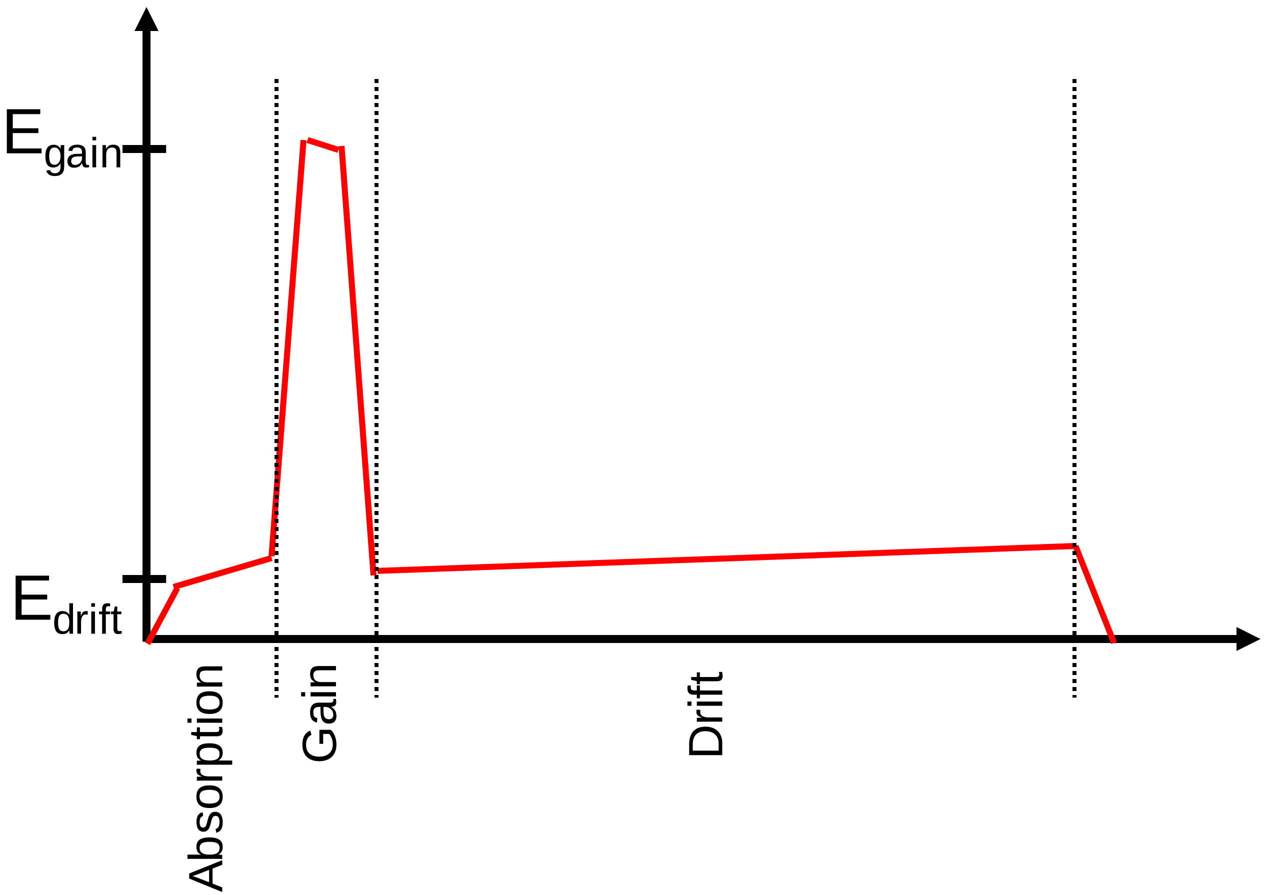
- Reduced charge collection noise
- Reduced sensor capacitance
- Improved weighting field
- Small pixel size
- Fully monolithic CMOS design

} Pico-second sensor timing

⇒ Sensor optimised for picosecond timing in fully monolithic small pixel design

PicoAD Sensor Concept

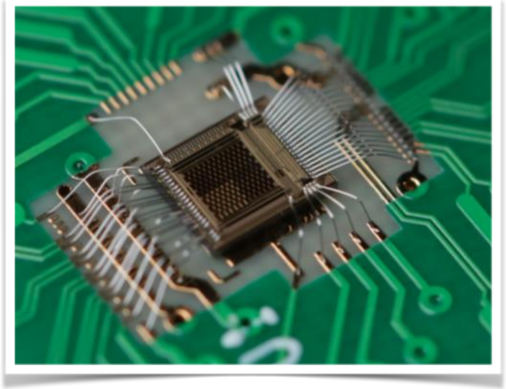
Picosecond Avalanche Detector (PicoAD): EU Patent EP18207008.6



- The introduction of fully-depleted multi-pn junctions allows to **engineer the electric field**.
- New device with unique timing and reliability performance.
- Gain with 100% fill-factor.
- Geant4 + Cadence simulations estimate ~**2ps time resolution** contribution from the sensor.
- Requires low-noise, ultra fast electronics to be fully exploited.

PicoAD monolithic proof-of-concept prototype

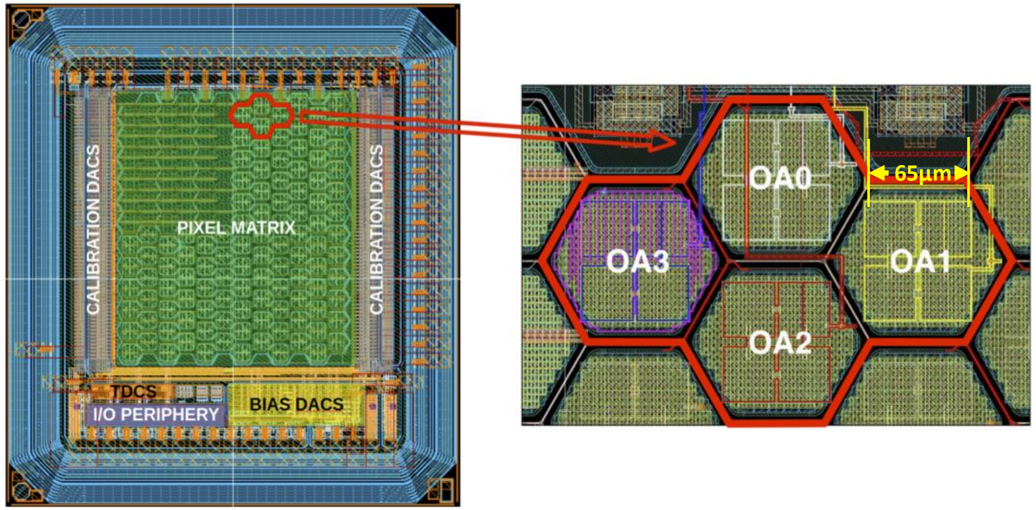
The proof-of-concept monolithic ASIC was produced by IHP in their SG13G2 SiGe BiCMOS process using the existing 2019 prototype design.



The ASIC contains:

- **Four matrices** of hexagonal pixels with ≈ 100µm pitch
  - with different electronics configurations
- **Four analog pixels**
  - tested with ^{55}Fe source and in testbeam

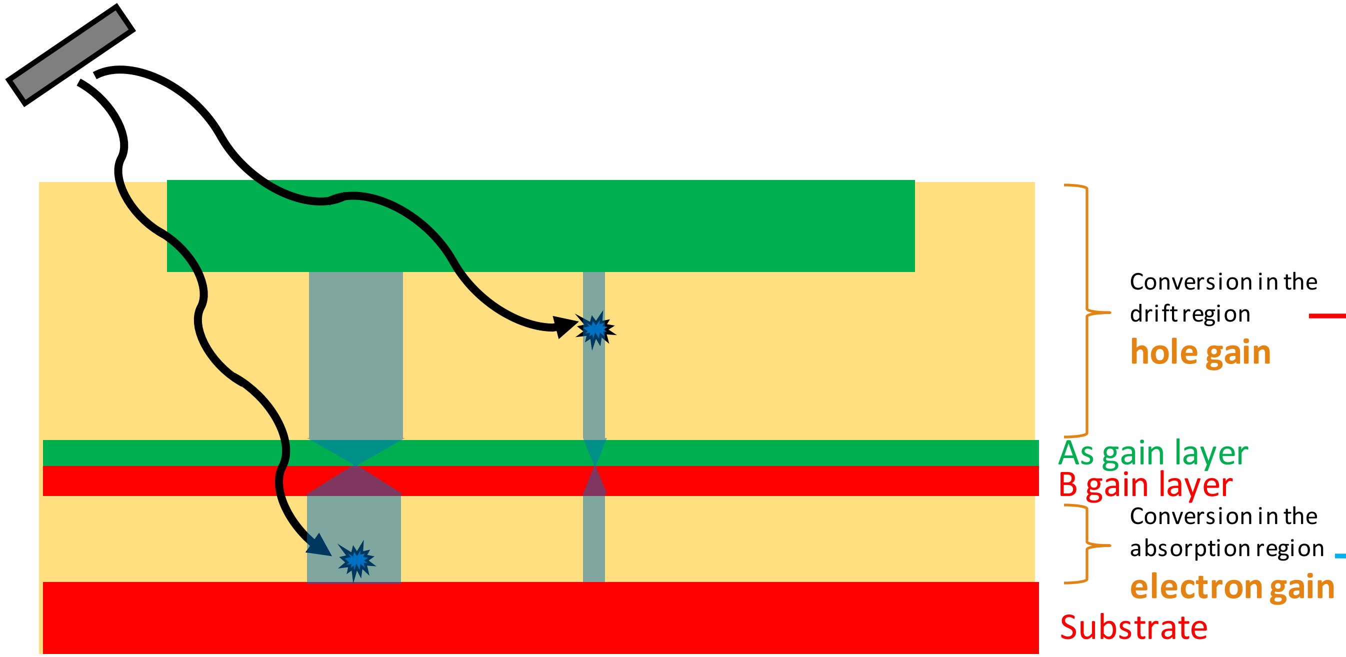
PicoAD Proof-Of-Concept Prototype (2021)

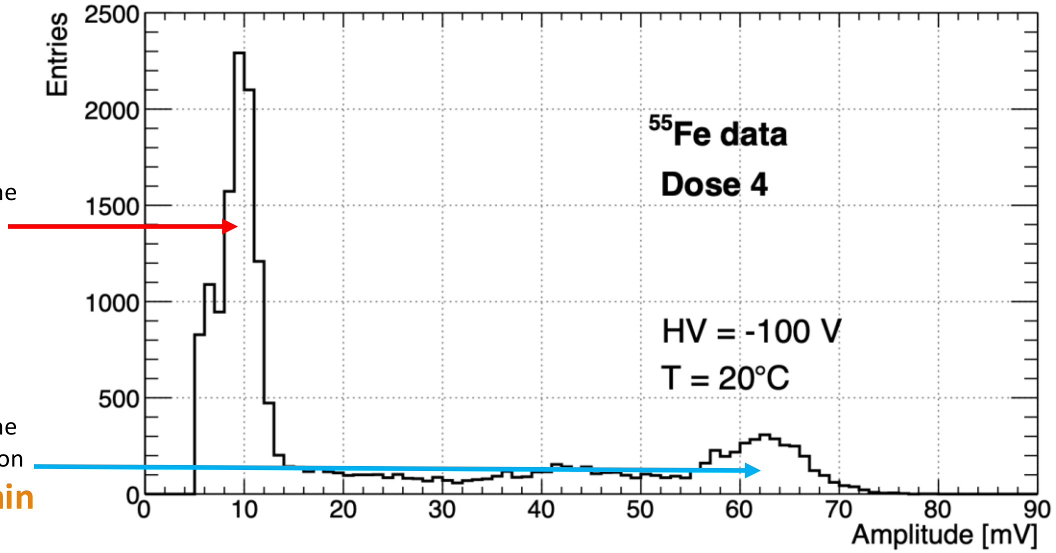


IHP also produced **PicoAD special wafers** with four different gain-layer implant doses

Gain Measurement with ^{55}Fe source

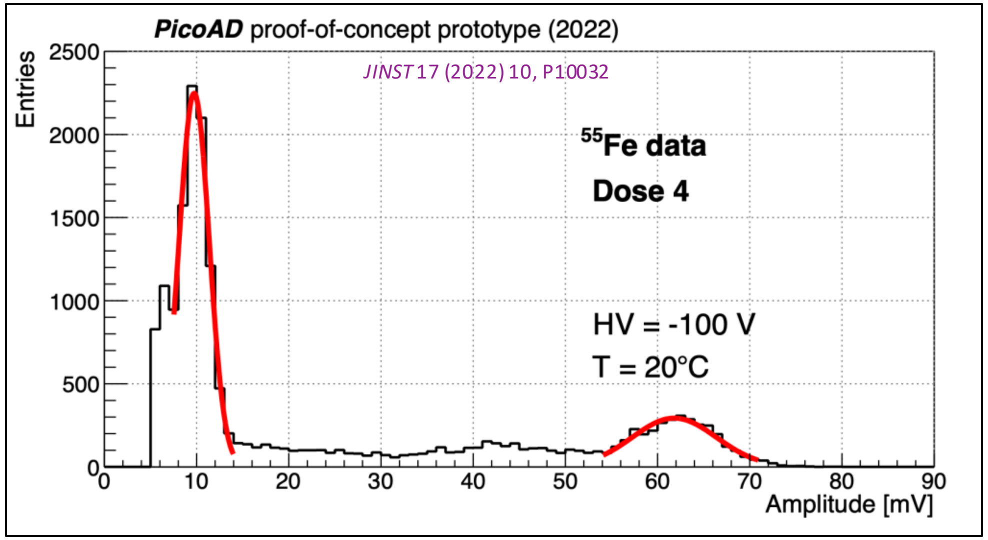
Fe-55 X-ray source: point-like charge deposition inside the sensor





Gain Measurement with ^{55}Fe source

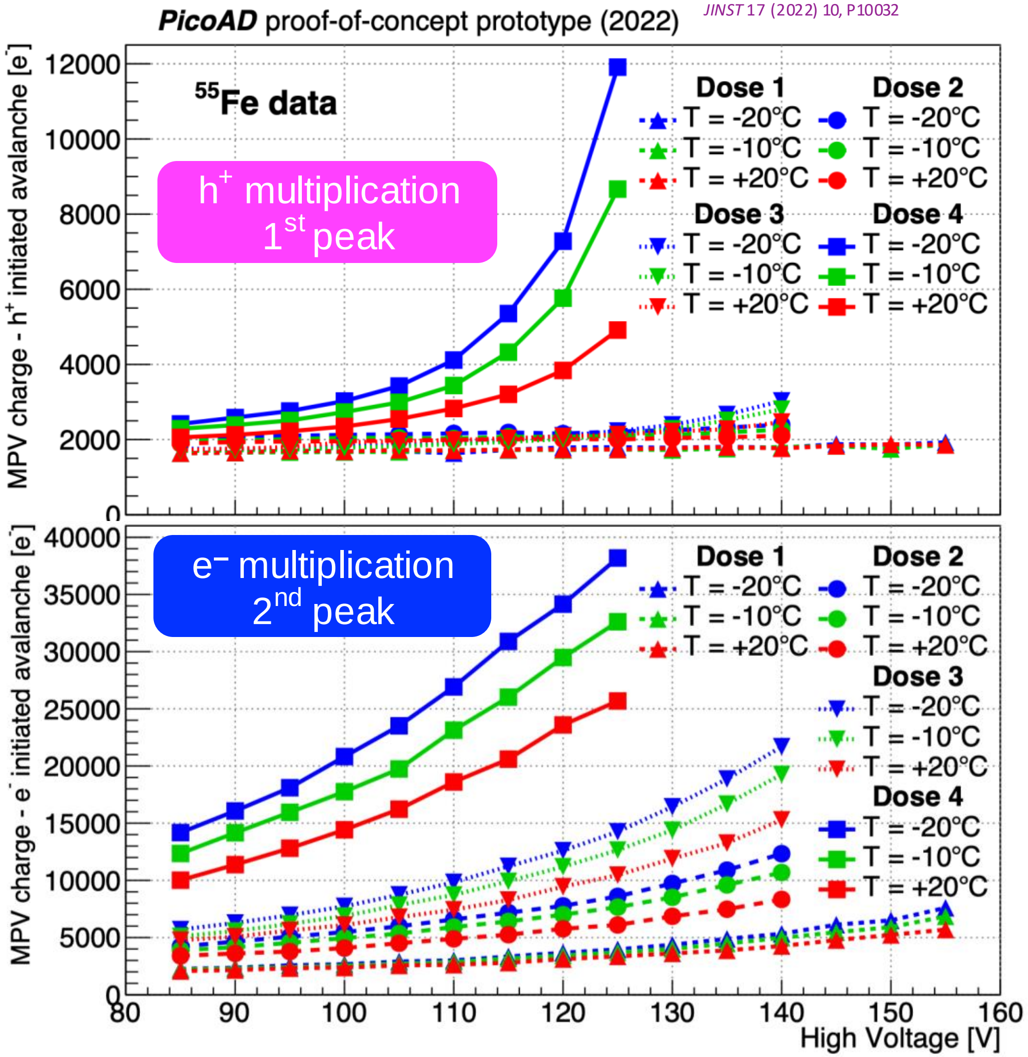
Average amplitudes of h+ and e- gains extracted via gaussian fit around local maxima



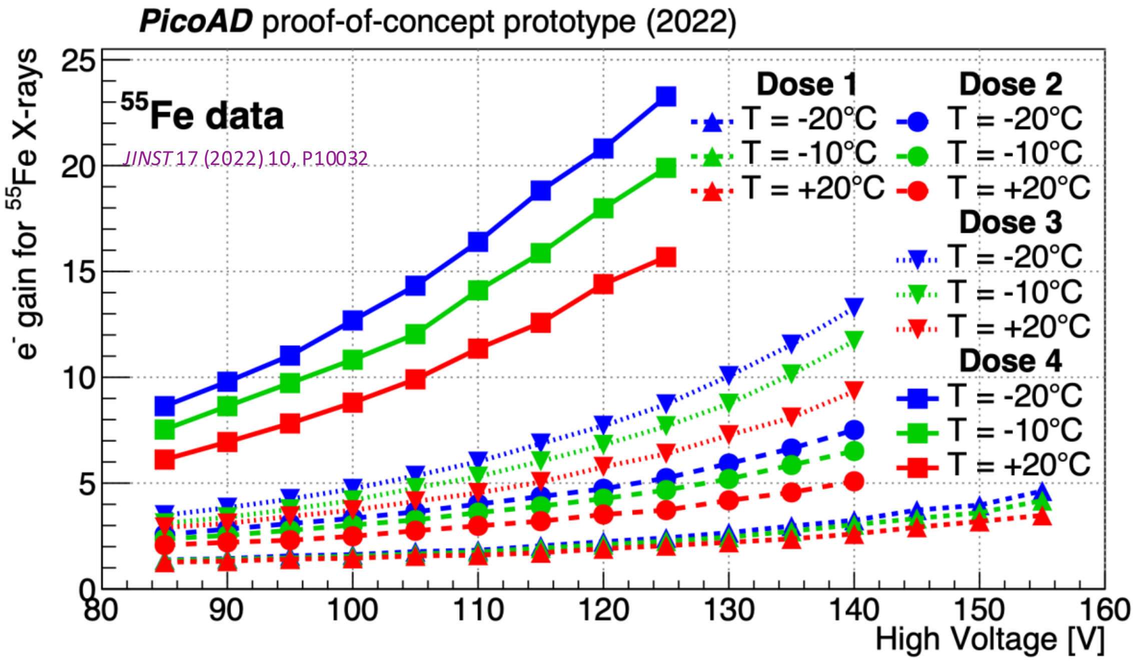
Assumption of no gain multiplication when:

- photon absorbed in drift region
- lowest voltage (85 V)
- lowest dose (dose 1)

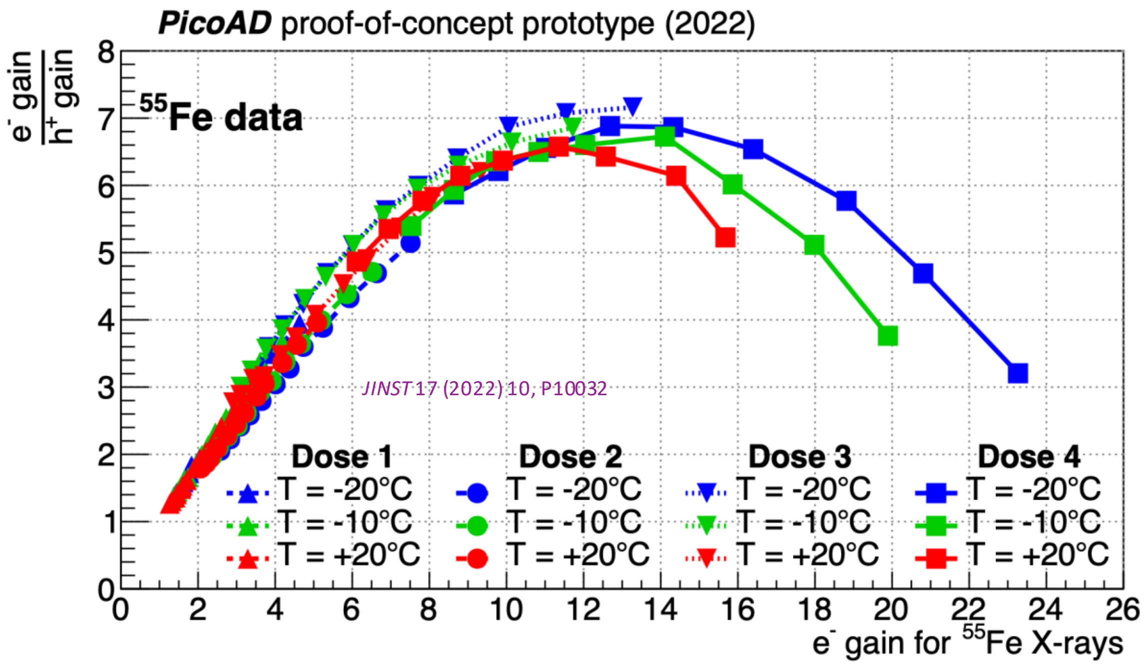
⇒ **normalization value**



Gain Measurement with ^{55}Fe source



A **gain up to ≈ 20 for <u>^{55}Fe X-rays</u>** obtained at HV = 120 V and T = -20 °C



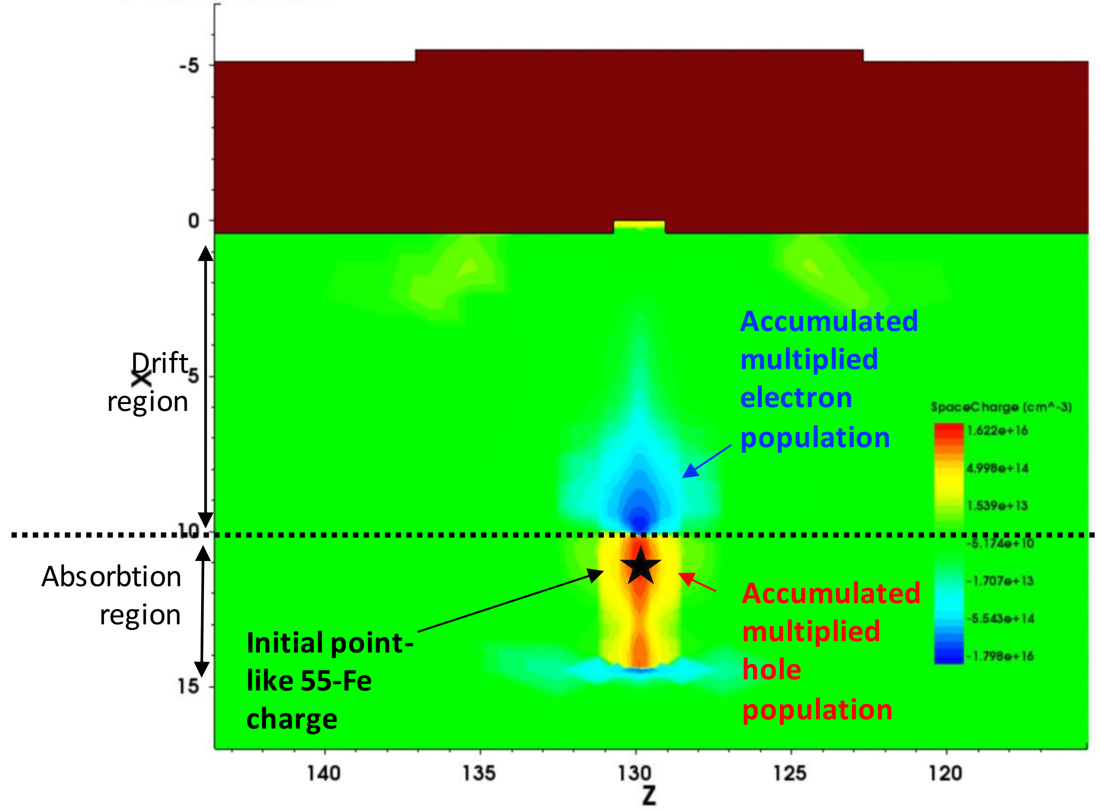
Evidence for **gain suppression** due to space-charge effects **in the case of ^{55}Fe X-rays**

We estimated that ^{55}Fe gain of ≈23 corresponds to **gain 60–70 for a MIP**

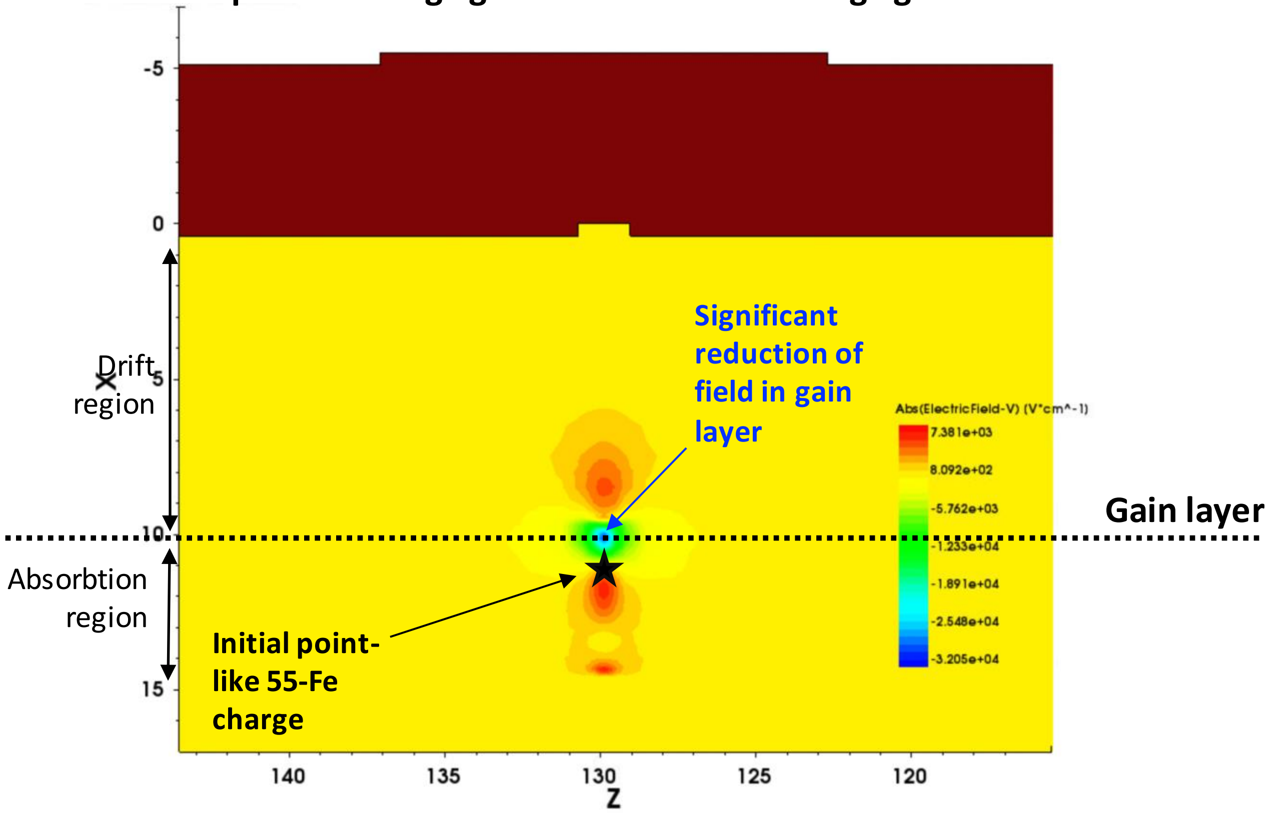
Transient space charge

Transient 3D TCAD simulation of point like 55-Fe charge deposition in absorption layer:

Space charge:
10ps after charge generation – before charge generation:

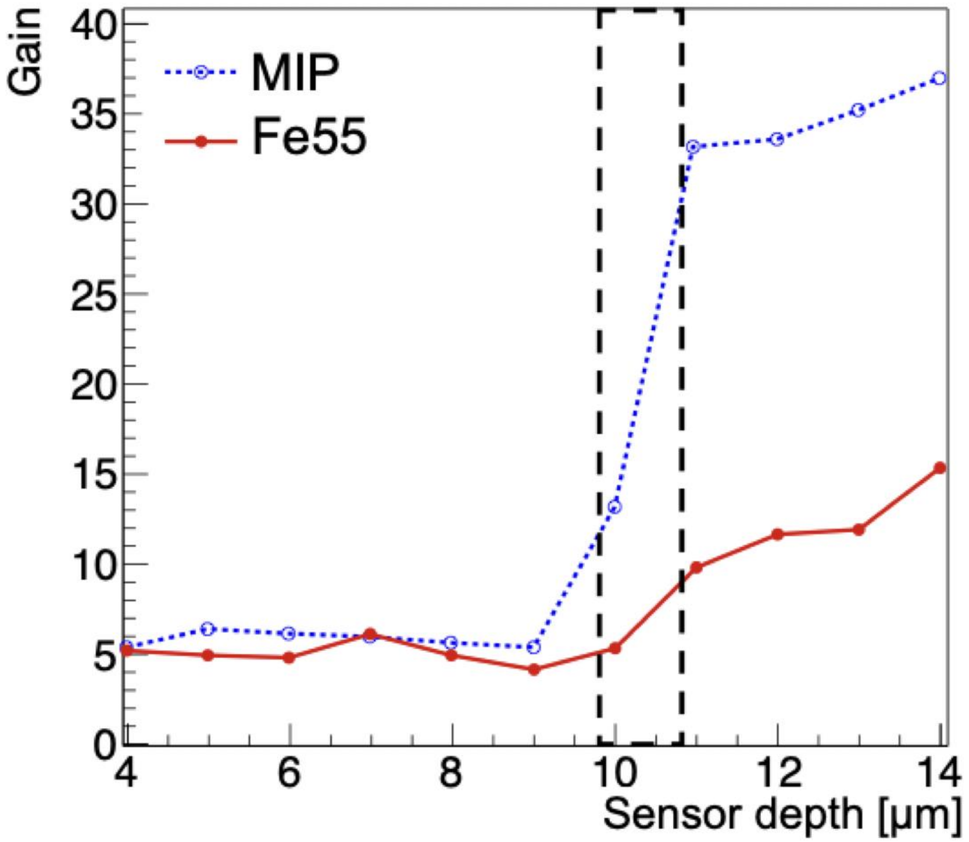


Electric field:
10ps after charge generation – before charge generation



Transient space charge

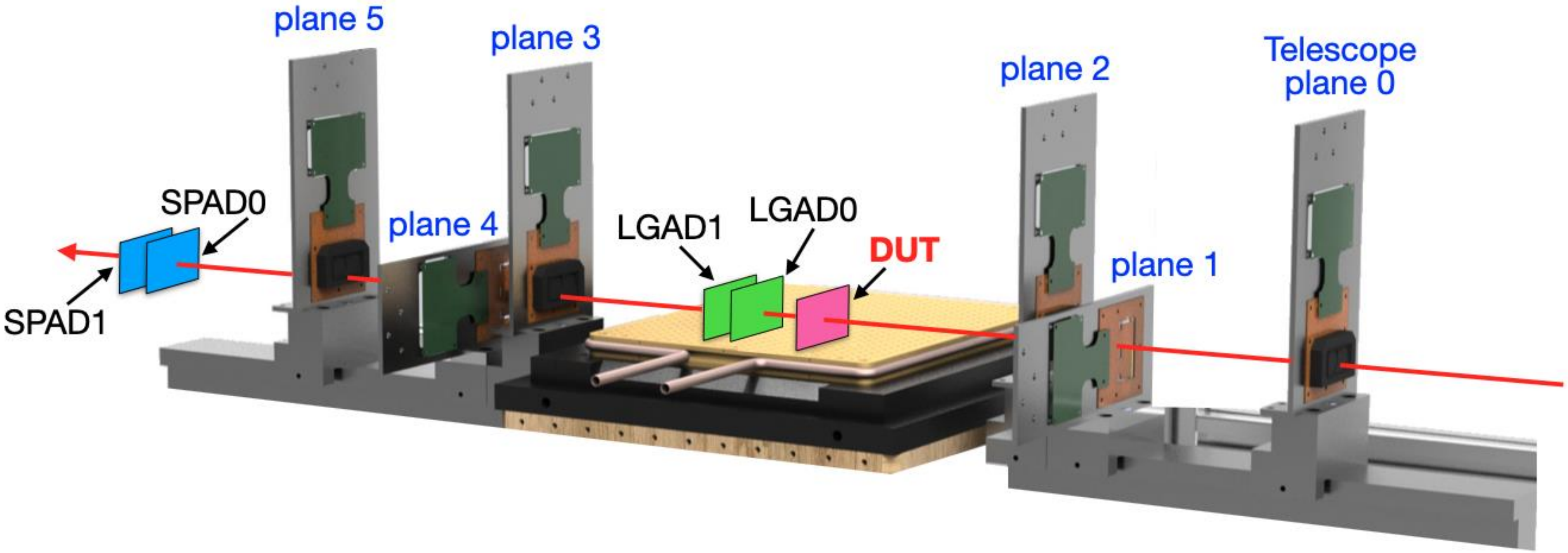
Gain as function of sensor depth for different primary charge carrier densities:



- For high charge carrier densities (Fe55) the electron gain is suppressed compared to lower charge carrier densities (MIPs).
- Simulated suppression factor of Fe55 w.r.t. MIP charge compatible to calculation of compression factor from test-beam and Fe55 measurements.
- Measured gain for Fe55 significantly supressed by transient space charge effect.
- Need of fully self consistent transient TCAD simulations.

Test Beam: Experimental Setup

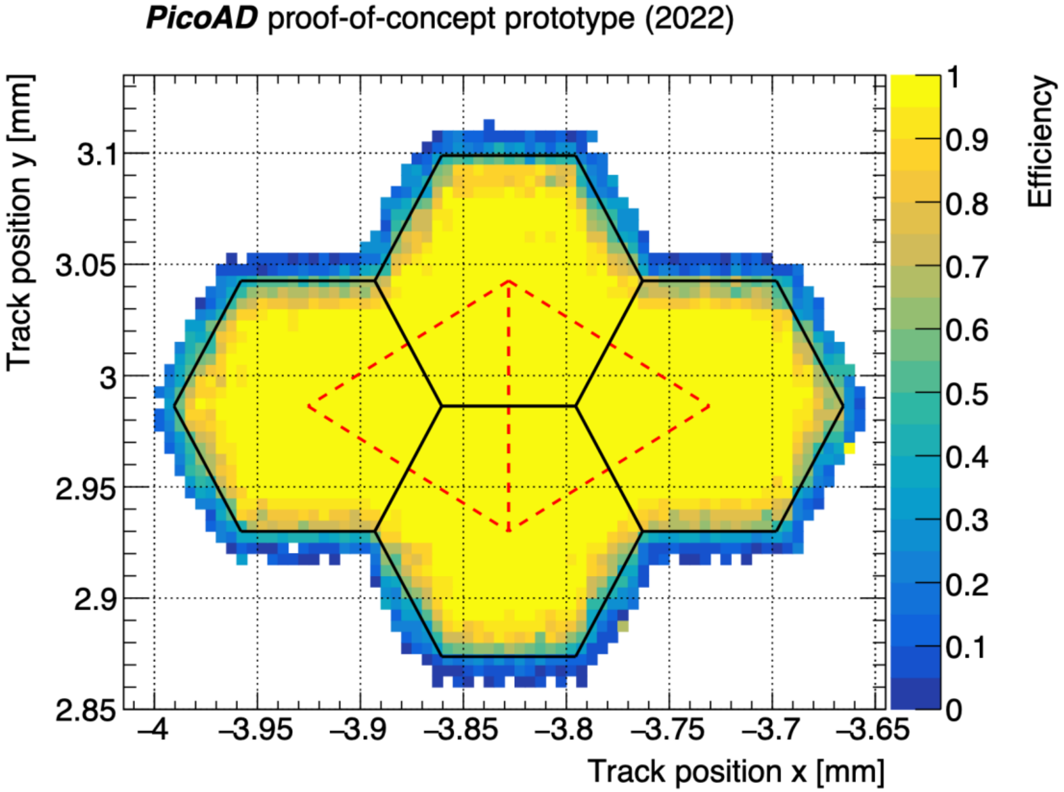
CERN SPS Testbeam with 180 GeV/c pions to measure efficiency and time resolution

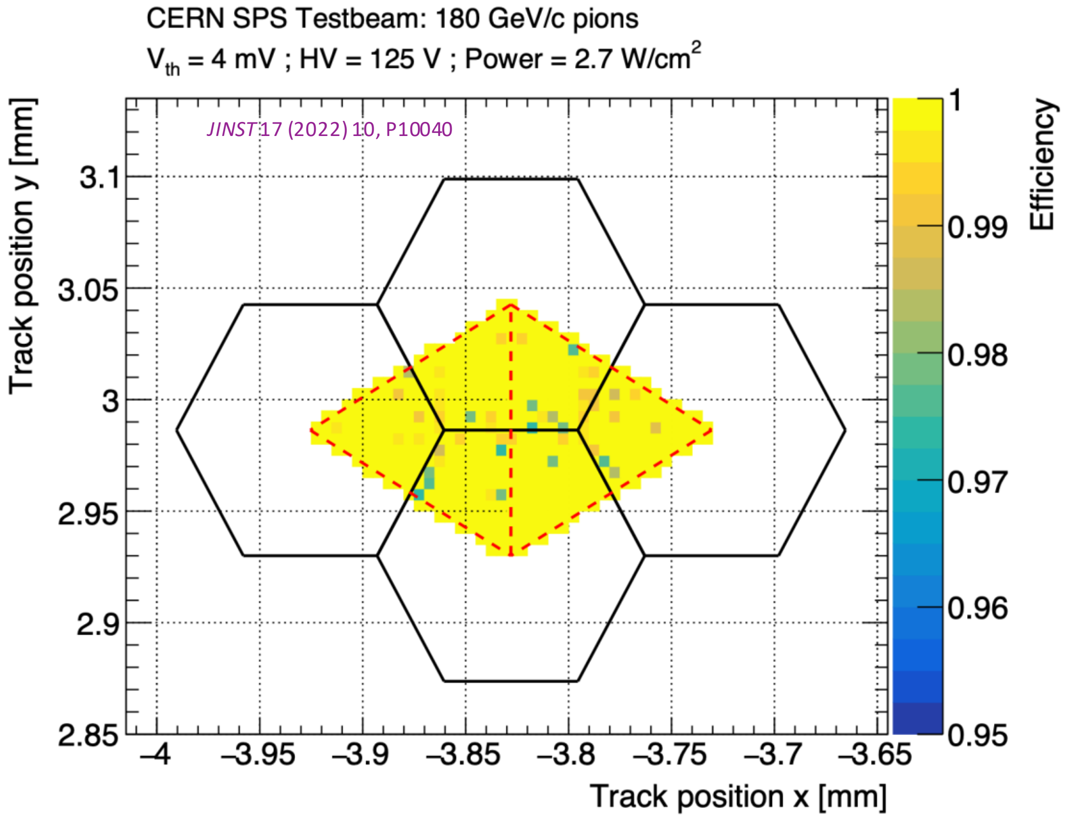


UNIGE FE-I4 telescope to provide spatial information ($\sigma_{x,y} \approx 10\ \mu m$)

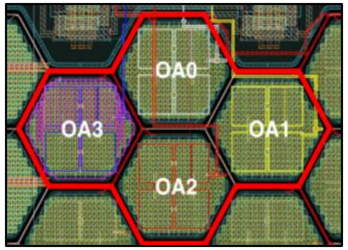
Two LGADs ($\sigma_t \approx 35$ ps) to provide the timing reference (and two SPADs with $\sigma_t \approx 20$ ps)

Testbeam results: Efficiency





Apparent degradation at the external edges of the four pixels is due to the telescope pointing resolution of ≈10 µm

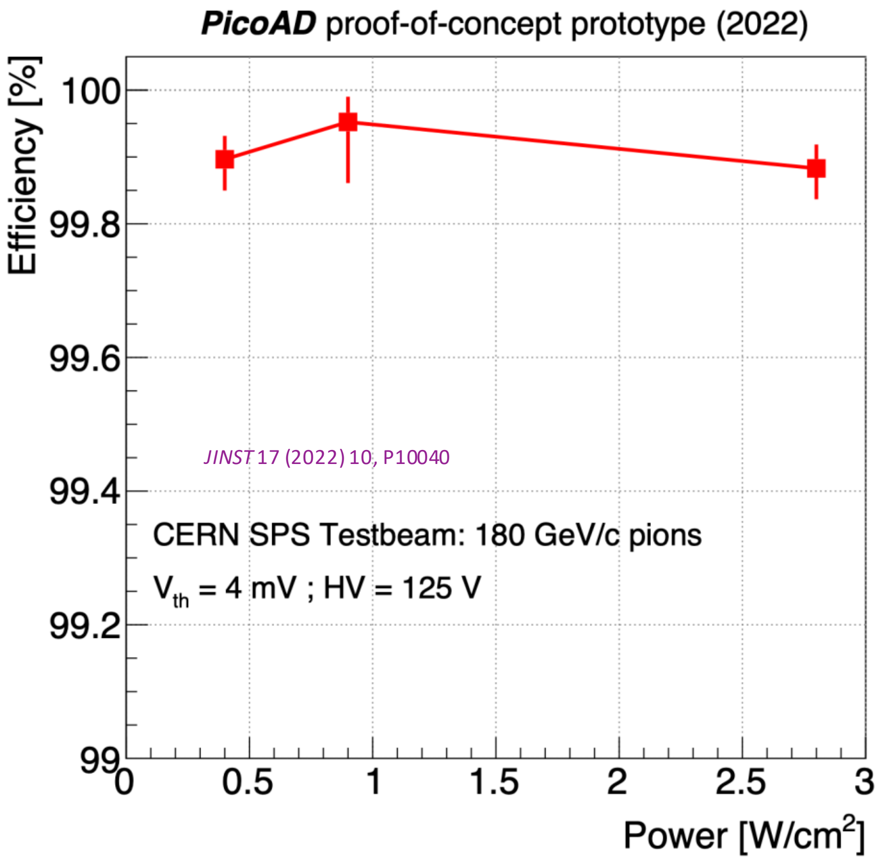


Selection of two **triangles**:

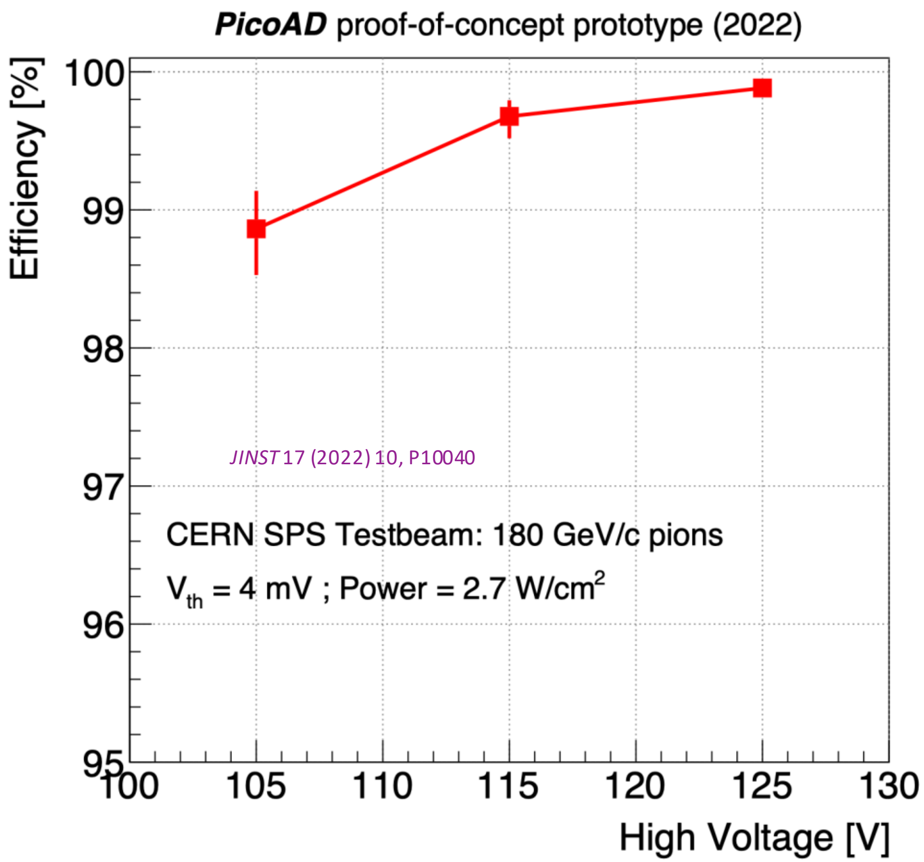
- representative of a whole pixel
- **unbiased by telescope resolution**

Testbeam results: Efficiency

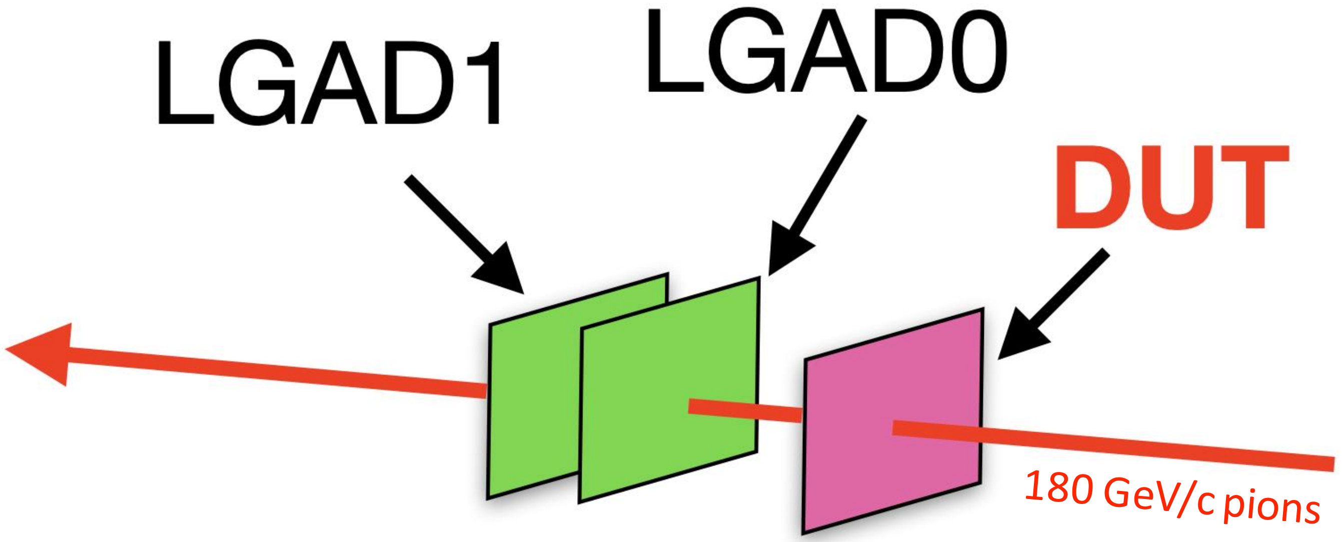
99.9% for all power consumptions



Drops to 99% for HV=105 V



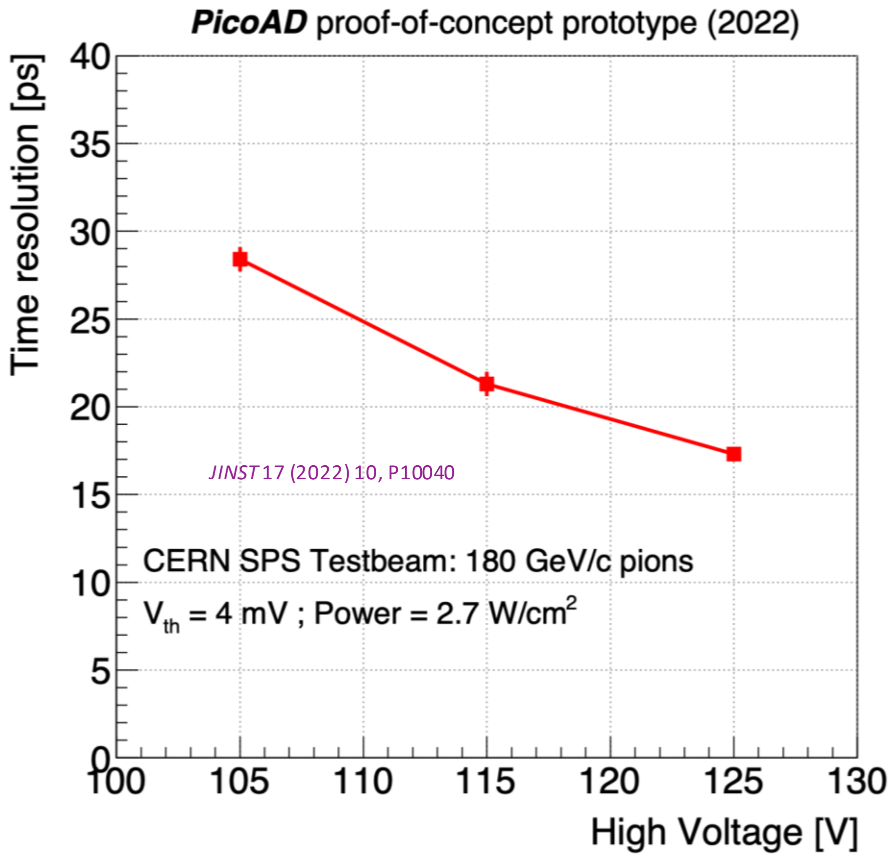
Time Resolution



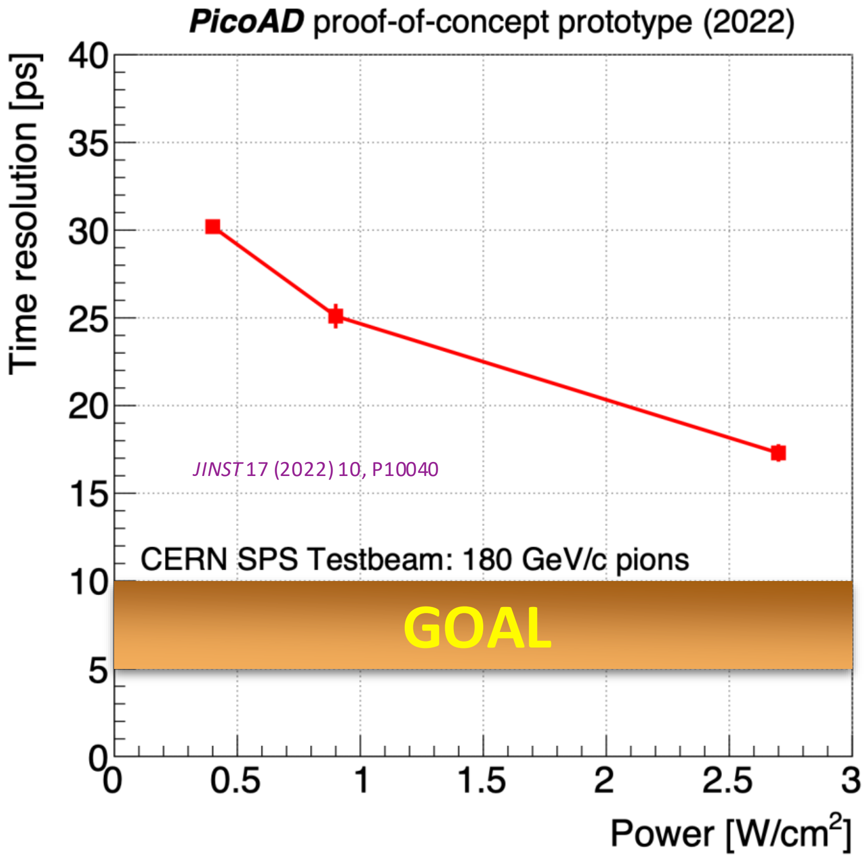
Results were also verified using **two SPADs** (but with much smaller statistics)

Testbeam results: Time Resolution

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



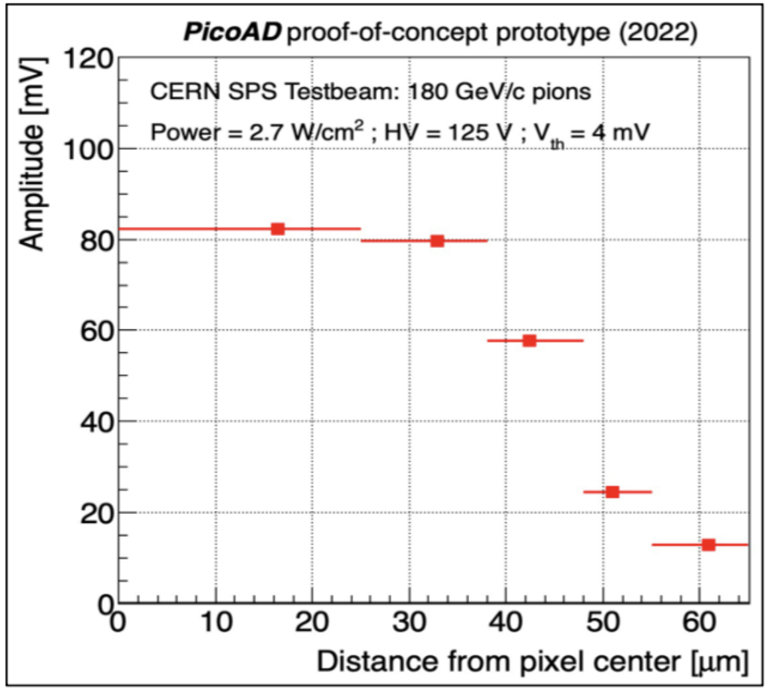
Timing resolution of 30 ps even at power consumption of 0.4 W/cm²



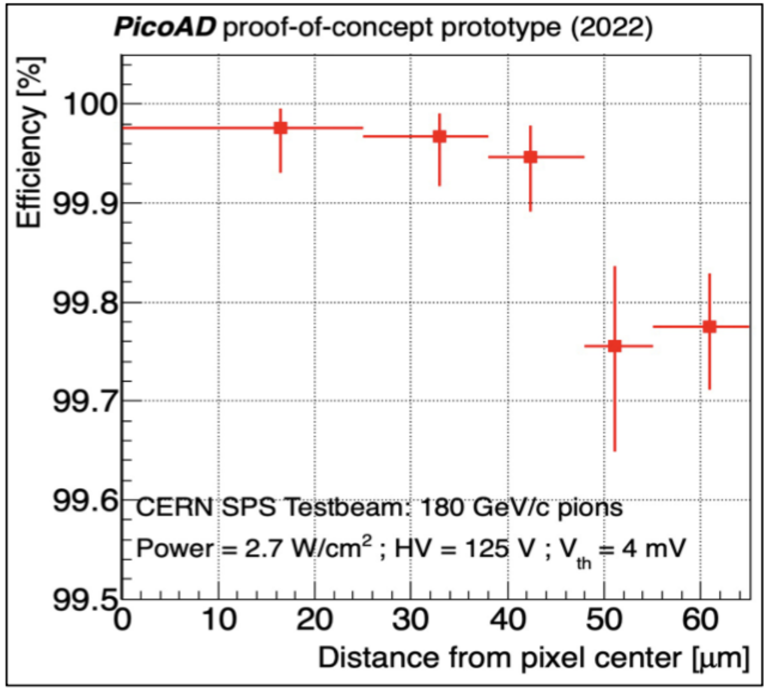
PicoAD uniformity of response

Testbeam Results of the Picosecond Avalanche Detector Proof-Of-Concept Prototype, G. Iacobucci et.al, arXiv:2208.11019v1, submitted to JINST

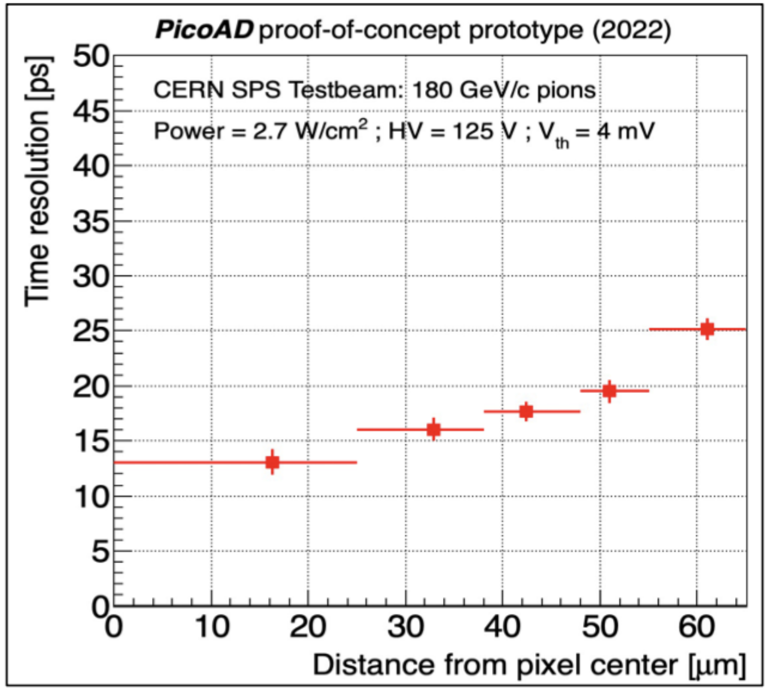
Amplitude vs. distance pixel center:



Efficiency vs. distance pixel center:



Time resolution vs. distance pixel center:

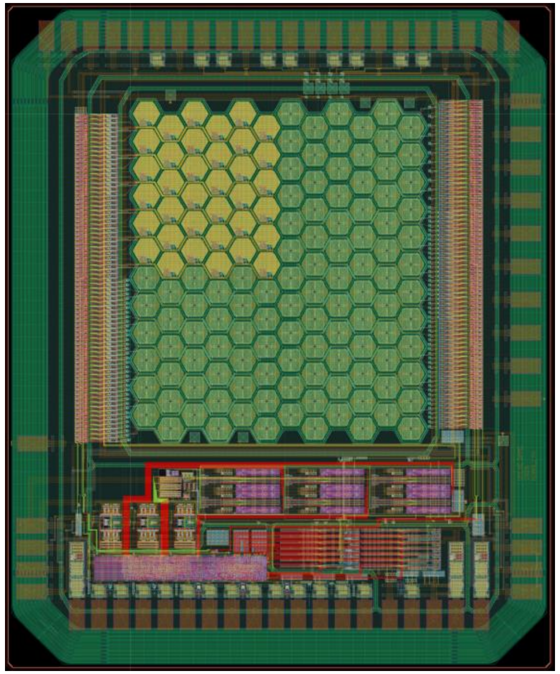


- Small degradation of the performance towards the edge of the pixel
- Effect of the finite resolution of the telescope convoluted with the real degradation
- The best timing resolution is $\mathbf{13.2 \pm 0.8}$ ps within 25 μm from the pixel center

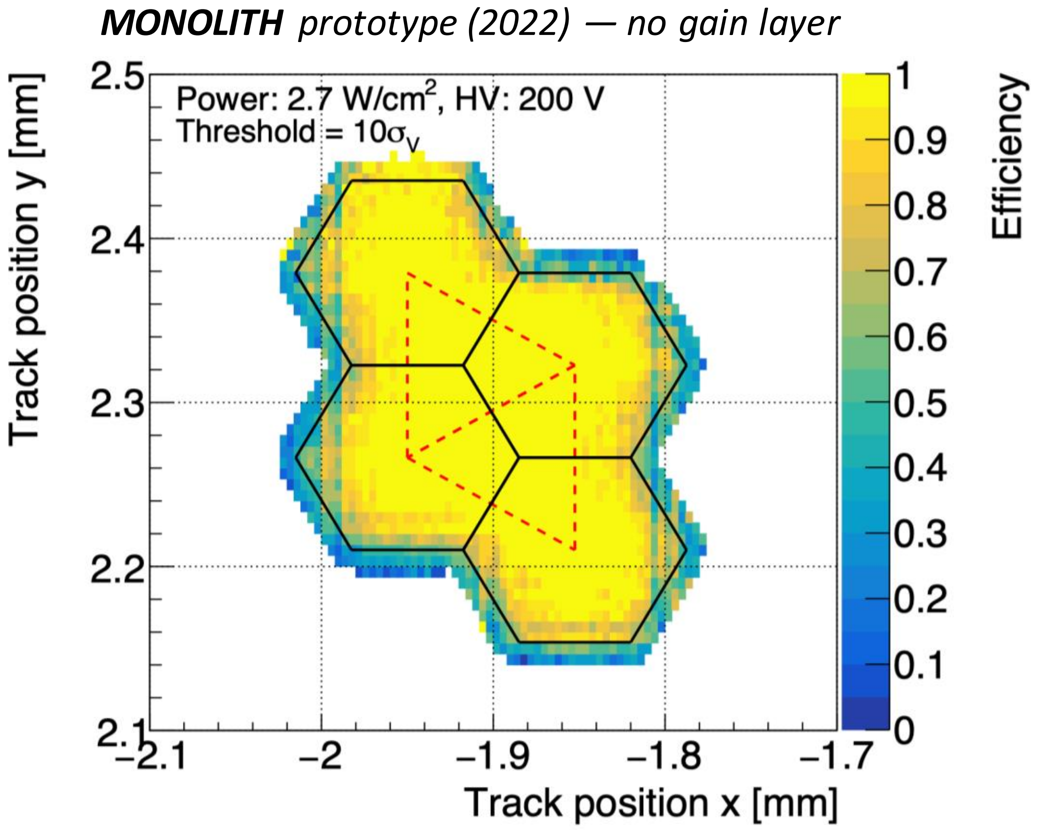
2022 prototype – No gain layer

Same matrix configuration as previous, but:

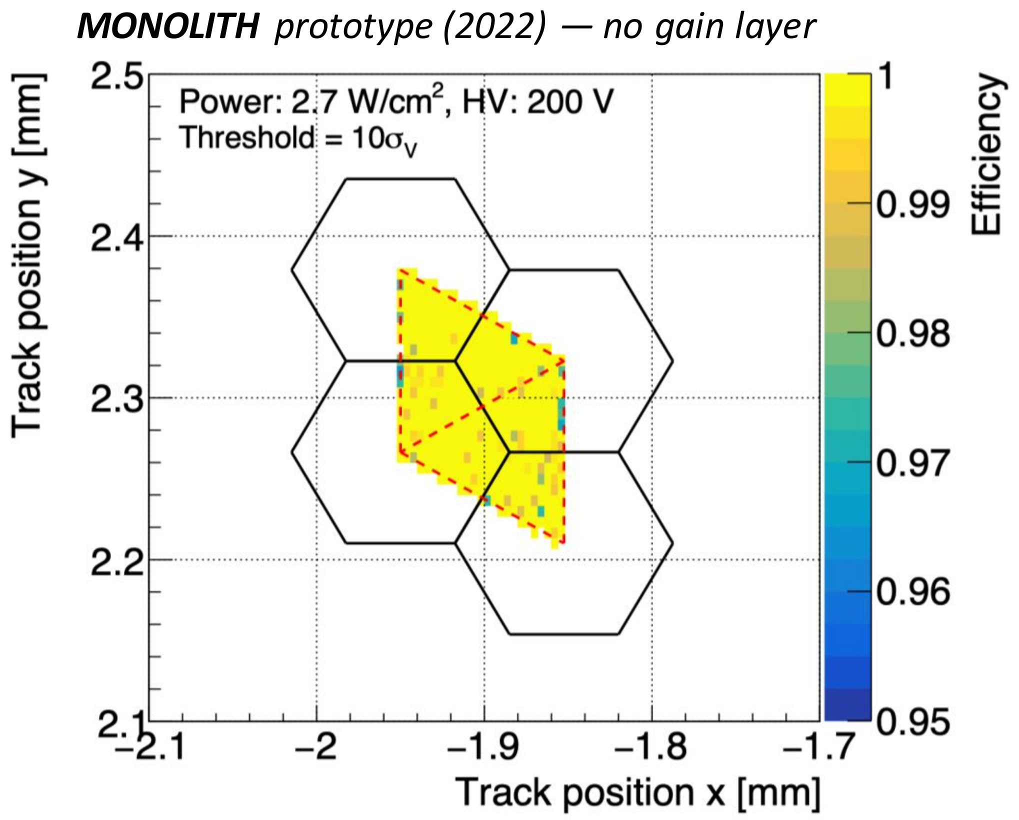
- Substrate: 50Ωcm → 350Ωcm epilayer, 50µm thick on low-res (1Ωcm) substrate.
  - Smaller pixel capacitance
  - **Depletion 26µm → 50µm**
  - Can operate sensor with $\mathbf{v_{drift}}$ **saturated** everywhere
- Preamp and driver voltage decoupled:
  - Increased amplifier gain
  - **Removed cross-talk**
- Differential output, optimized FE layout, high-frequency cables:
  - **Better rise time** (600ps → 300ps)
- **NO GAIN LAYER**
  - A picoAD version of the 2022 prototype is still being manufactured.



2022 prototype — no gain layer

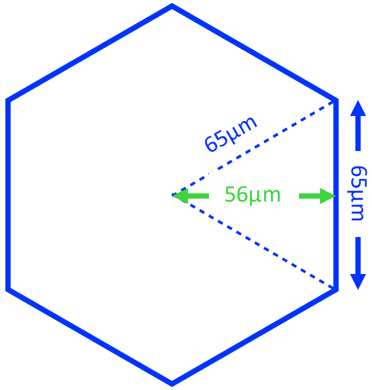


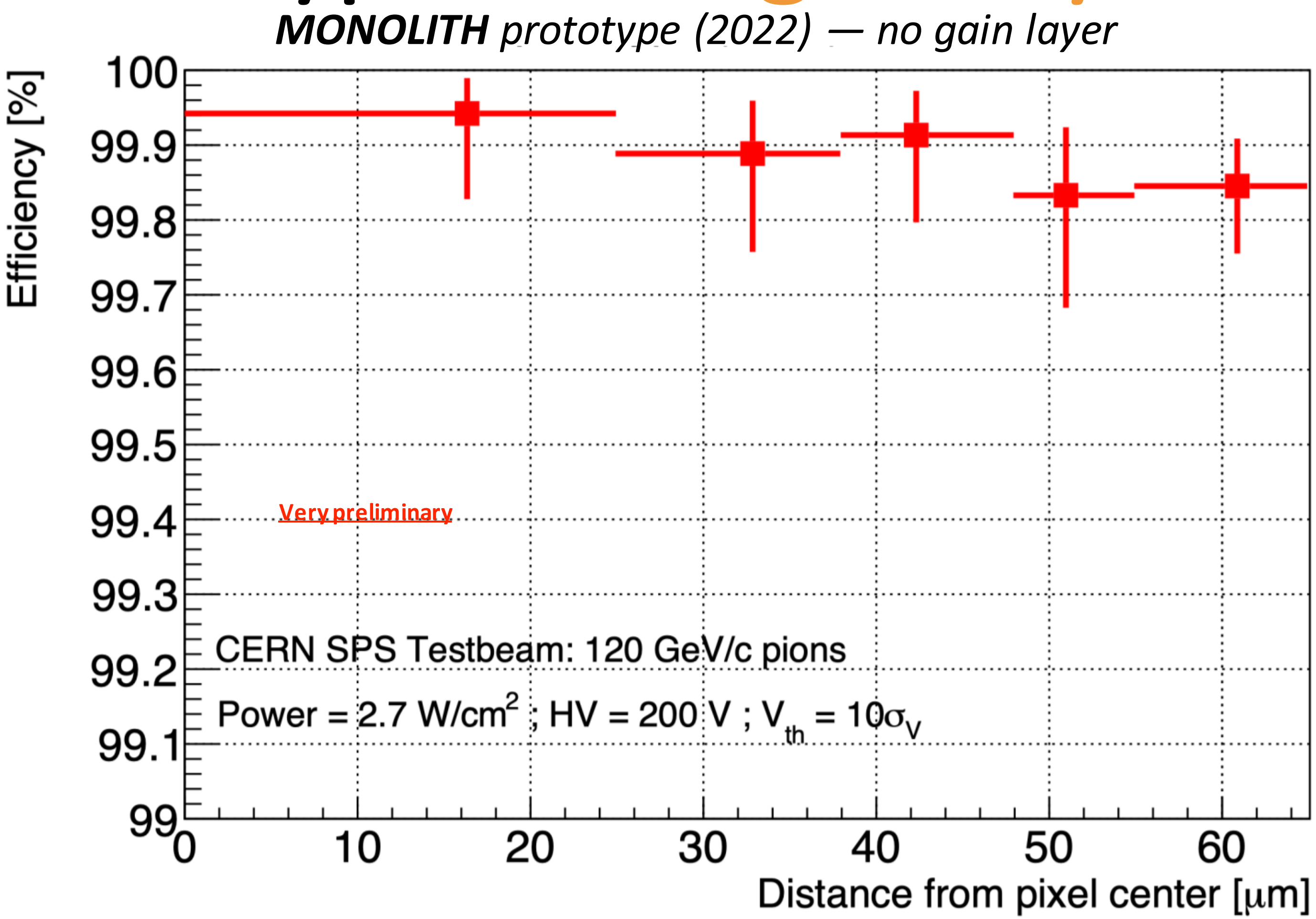
Efficiency at the external edges affected by the telescope resolution of 10 µm



Full efficiency (yellow is 99.8%) in the two triangles unaffected by telescope resolution

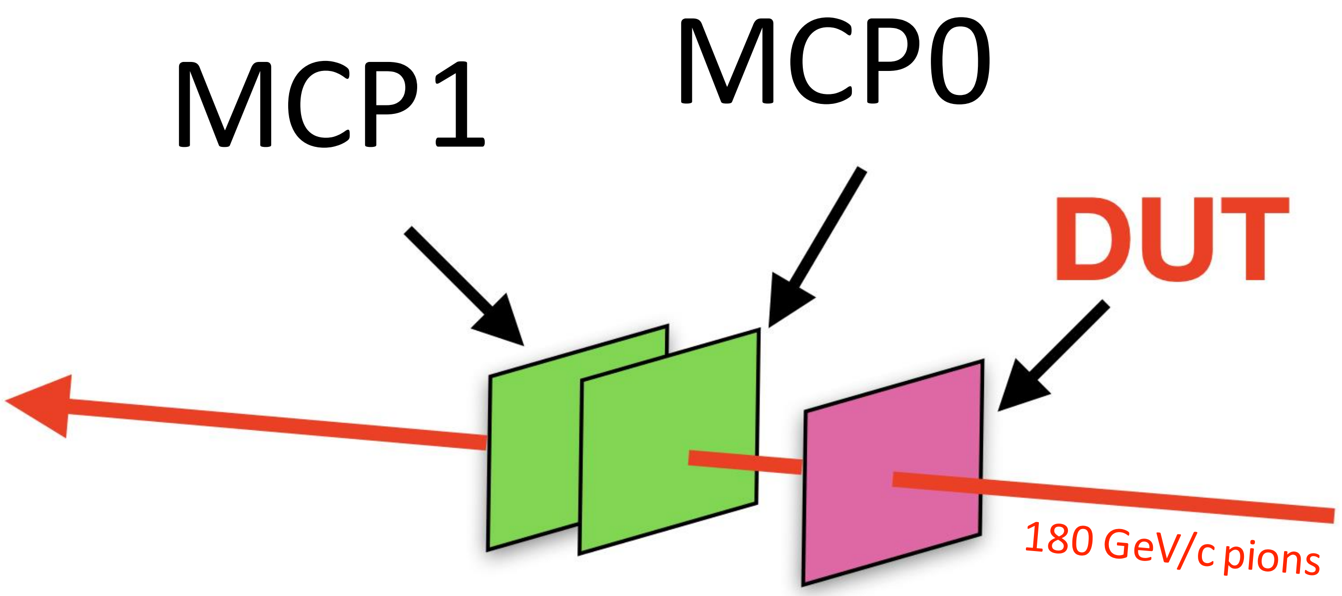
2022 prototype — no gain layer



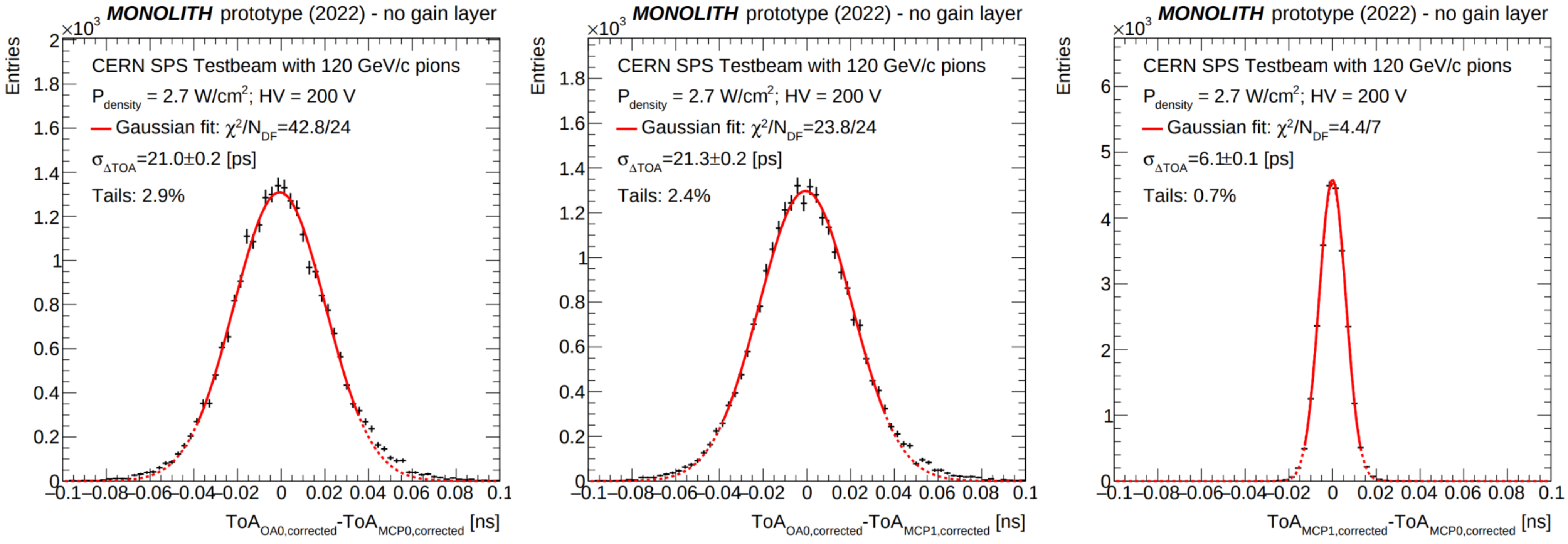


Efficiency ≈ 99.9% even in the inter pixel region.

2022 prototype — no gain layer



2022 prototype — no gain layer



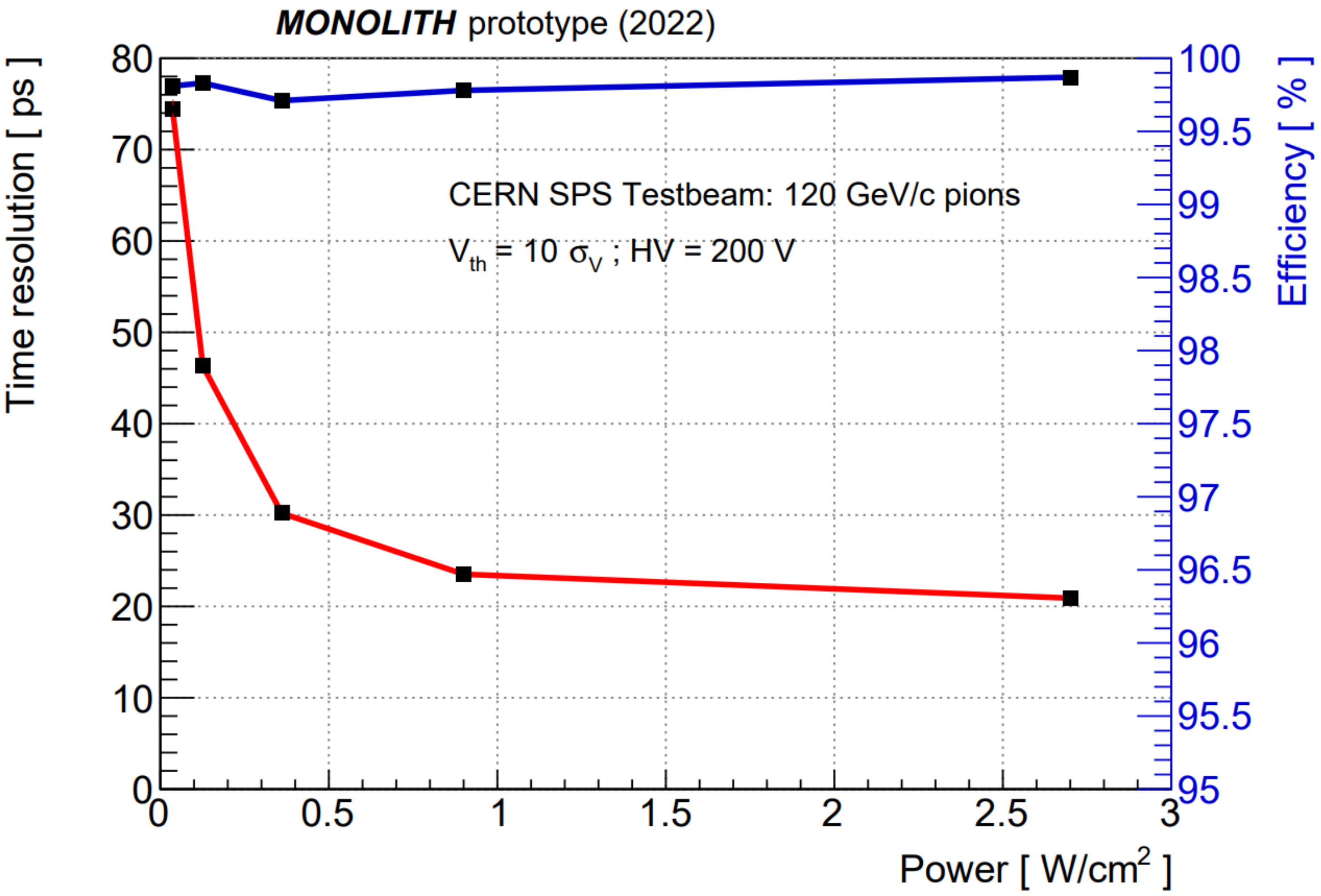
System results: MCP0 $\sigma_T = (3.6 \pm 1.5)$ ps

MCP1 $\sigma_T = (5.0 \pm 1.1)$ ps

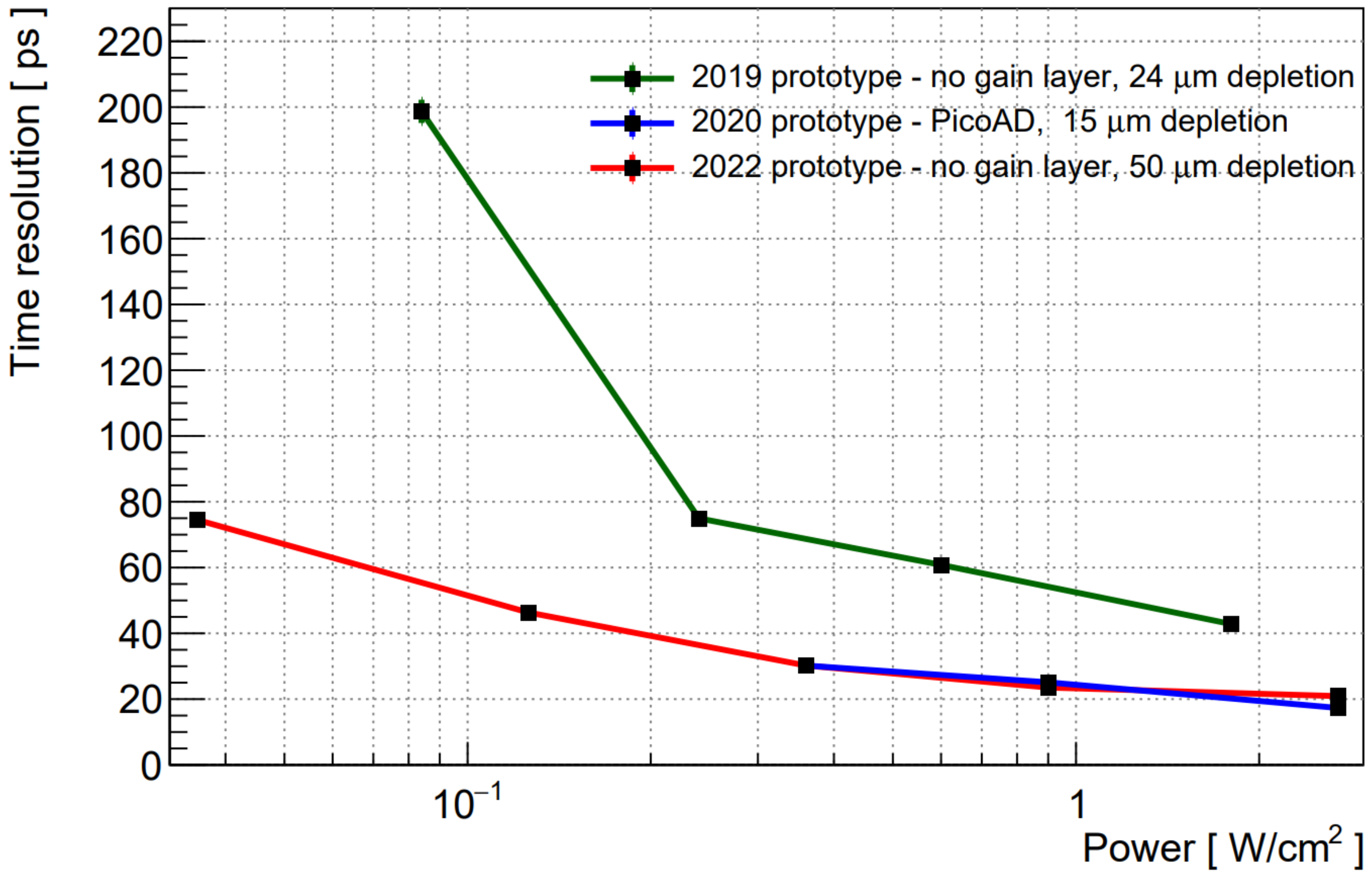
$\sigma_T = (20.7 \pm 0.3)$ ps

with non-Gaussian tails of <3%

2022 prototype — no gain layer



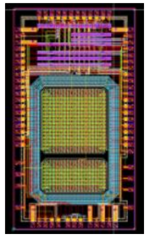
Comparison between prototypes



Monolithic SiGe BiCMOS for timing

Monolithic prototypes with SiGe BiCMOS

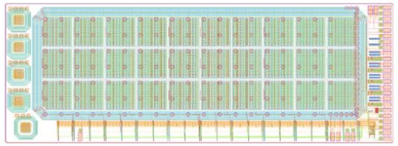
2016



200ps

- 1 and 0.5 mm^2 pixels
- Discriminator output

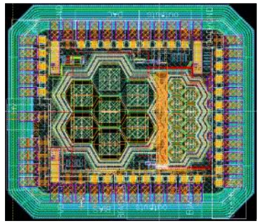
2017



110ps

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

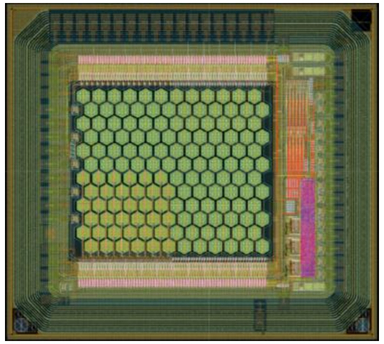
2018



50ps

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

2019



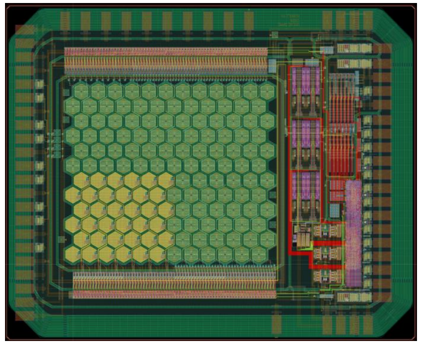
36 ps

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

PicoAD version

17 ps

2022



21 ps

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

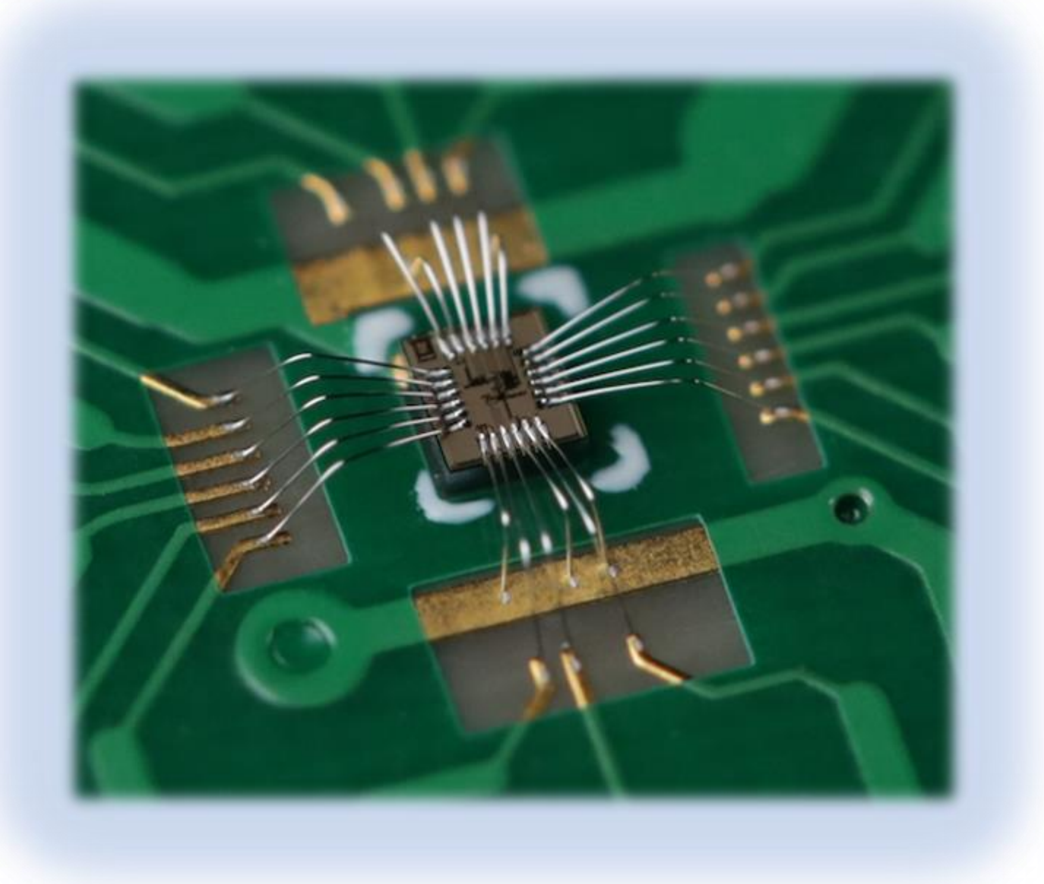
PicoAD version

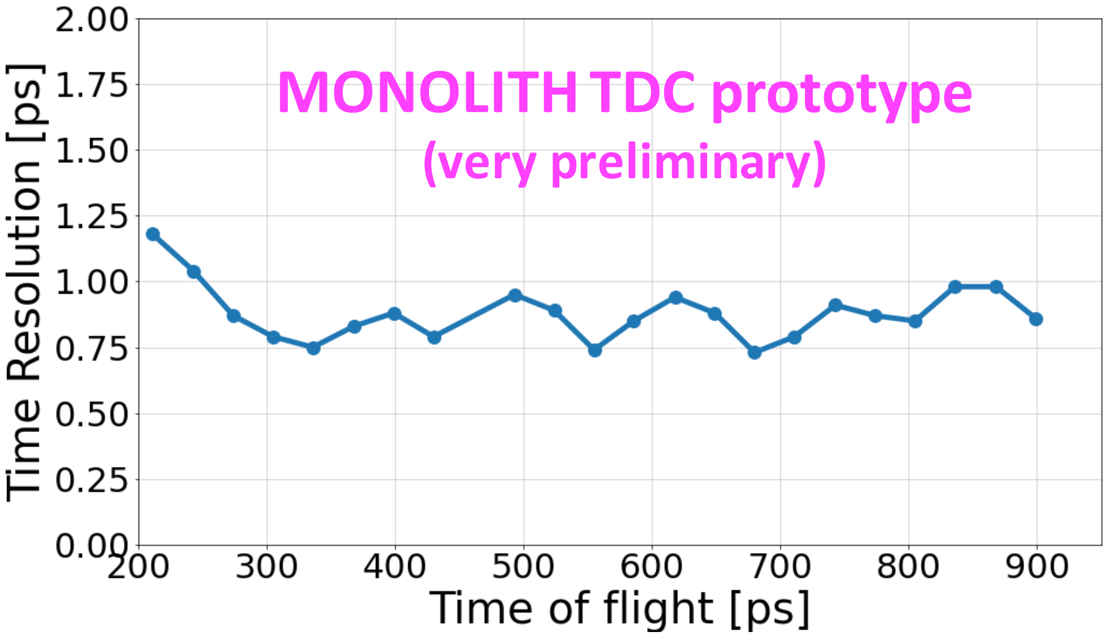
In production

Sub-picosecond TDC

We are developing a sub-picosecond TDC based on a novel design (our patent© & more):

© R. Cardarelli, L. Paolozzi, P. Valerio and G. Iacobucci, European Patent Application / Filing - UGKP-P-001-EP, Europe Patent EP 18181123.3. 2 July 2018.





Standalone prototype still under test at UNIGE.

Integrated in MONOLITH 2022 monolithic ASIC.

Summary & Outlook

The PicoAD© Monolithic proof-of-concept prototype works. Testbeam provided:

- **Gain ≈ 20** for ^{55}Fe X-rays (space-charge effects); gain ≈ 60-70 for mips.
- **Efficiency = 99.9 %** including inter-pixel regions
- **Time resolution σ_t = (17.3 ± 0.4) ps : 13 ps** at center and **25 ps** at pixel edge (although sensor not yet optimized for timing)

Ongoing activities include:

- Data analysis of 2nd prototype **without gain layer**: **(20.7 ± 0.3) ps**
- Optimization for timing of the PicoAD sensor design with TCAD to achieve ≲10 ps (smaller pixel pitch; thicker drift layer; improved inter-pixel region)
- Development of picosecond TDC for fully monolithic chip
- Radiation hardness studies started in 2023 together with IHP and KEK

Deliverable of MONOLITH ERC project:

- Full-reticle chip in Summer 2025 with 50µm pitch and sub-10ps timing

Relevant papers

2019 prototype (no gain) testbeam:
https://iopscience.iop.org/article/10.1088/1748-0221/17/02/P02019

PicoAD proof of concept:
https://iopscience.iop.org/article/10.1088/1748-0221/17/10/P10032

2019 prototype + PicoAD testbeam:
https://iopscience.iop.org/article/10.1088/1748-0221/17/10/P10040

2022 prototype (no gain) testbeam:
https://arxiv.org/abs/2301.12244

Backup

Precise timing with silicon

What are the main parameters that determine the time resolution of semiconductor detectors?

Induced current from the Shockley-Ramo's theorem:

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i}$$

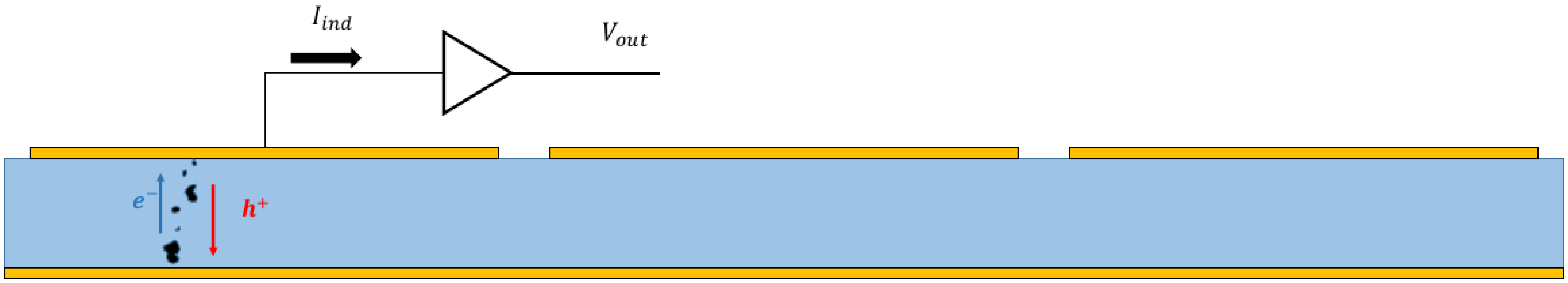
Precise timing with silicon

What are the main parameters that determine the time resolution of semiconductor detectors?

- Geometry and fields

Induced current from the Shockley-Ramo's theorem:

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i}$$



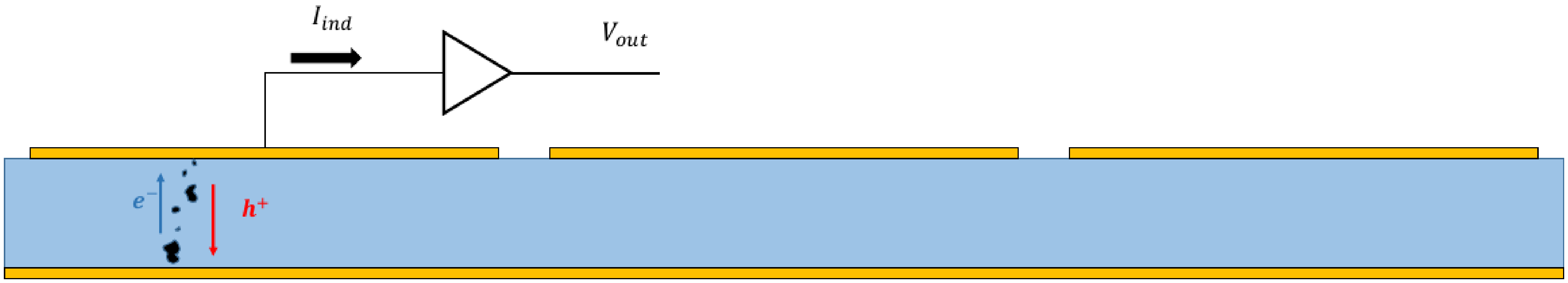
Precise timing with silicon

What are the main parameters that determine the time resolution of semiconductor detectors?

- Geometry and fields
- Charge collection noise

Induced current from the Shockley-Ramo's theorem:

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i}$$



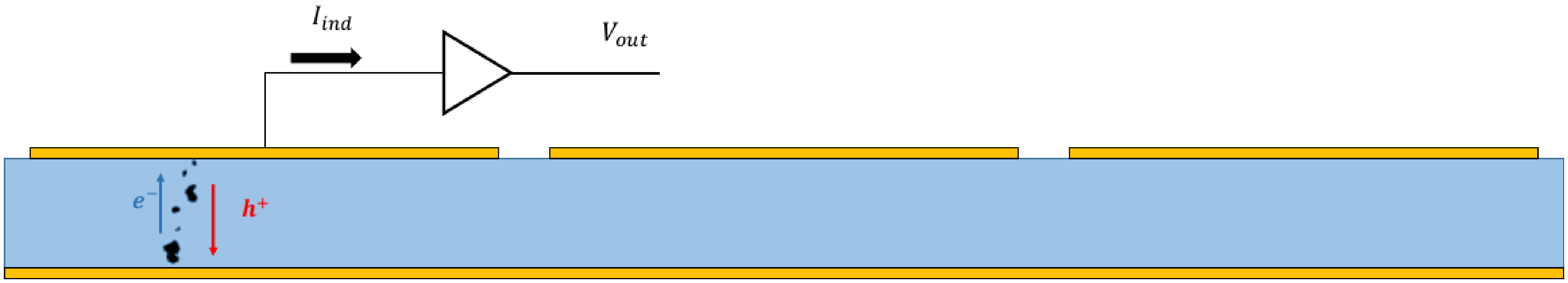
Precise timing with silicon

What are the main parameters that determine the time resolution of semiconductor detectors?

- Geometry and fields
- Charge collection noise
- Electronic noise

Induced current from the Shockley-Ramo's theorem:

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i}$$



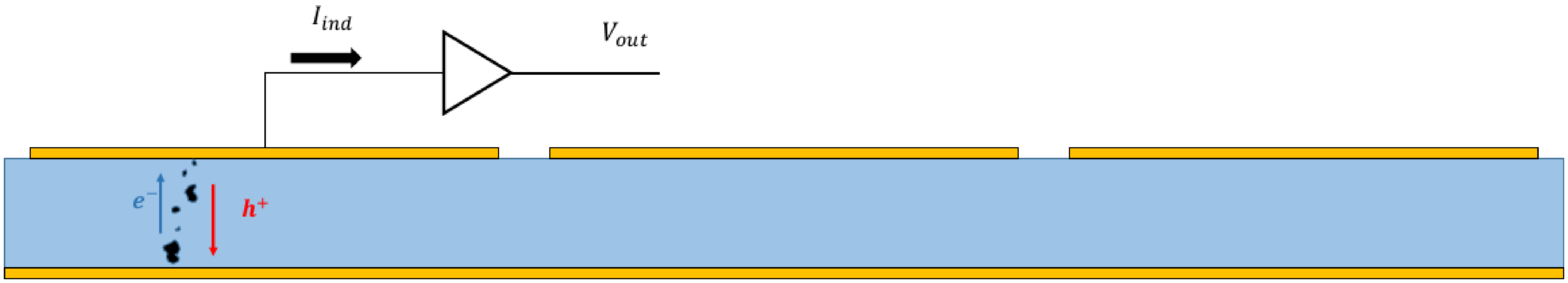
Precise timing with silicon

What are the main parameters that determine the time resolution of semiconductor detectors?

- Geometry and fields
- Charge collection noise
- Electronic noise
- Gain

Induced current from the Shockley-Ramo's theorem:

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i}$$



Title here

- Time Of Arrival (TOA) as a **time at constant fraction**
- Distributions after **time-walk correction**
- Distributions are **Gaussian:** only ≈2-4 % of entries in non-gaussian tails
- Simultaneous fit to extract time resolutions of the DUT, LGAD0, LGAD1