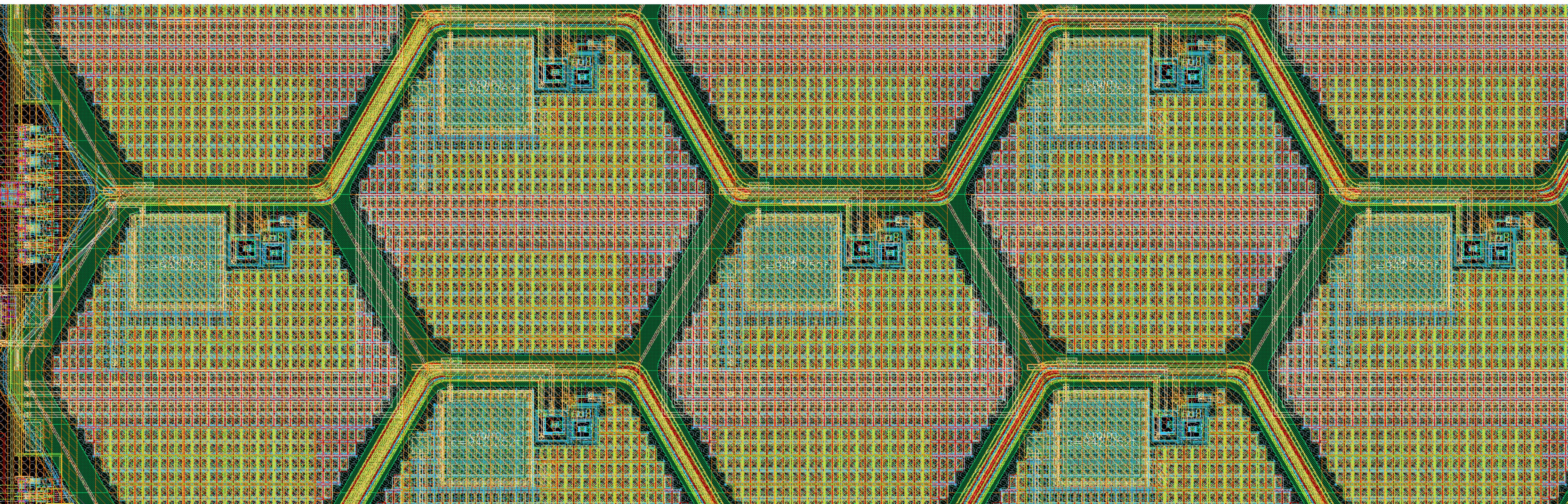


The **MONOLITH** Project: towards picosecond timing

Giuseppe Iacobucci — Université de Genève



**UNIVERSITÉ
DE GENÈVE**



**Swiss National
Science Foundation**



European Research Council
Established by the European Commission

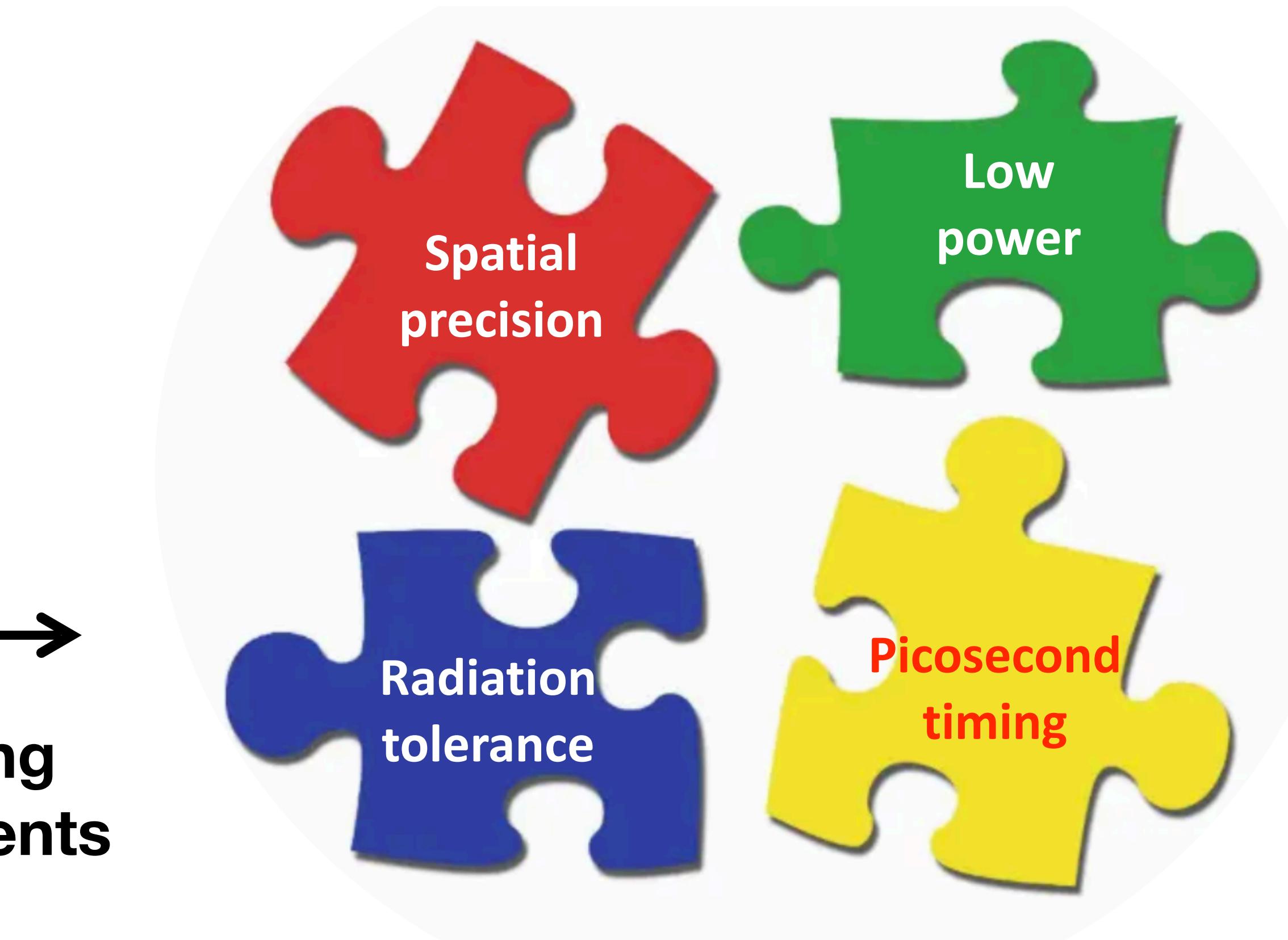
Timing resolution in silicon pixel detectors mainly determined by:

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

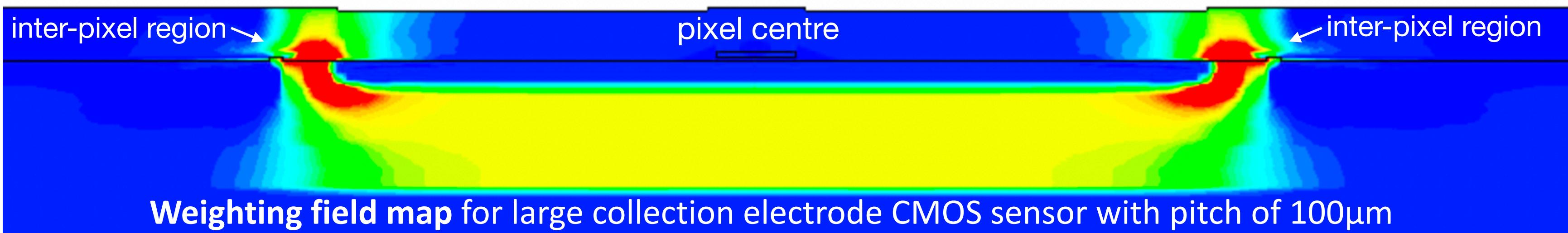
Sensor geometry needs to guarantee ***fast and uniform time response***:

- High and uniform **electric field** (charge transport with uniform and saturated **drift velocity**)
- High and uniform **weighting field** (fast and uniform **signal induction**)

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

Challenge:

- **Small pixels** introduce **low and non-uniform electric and weighting field regions**:



2. Charge-collection (Landau) noise

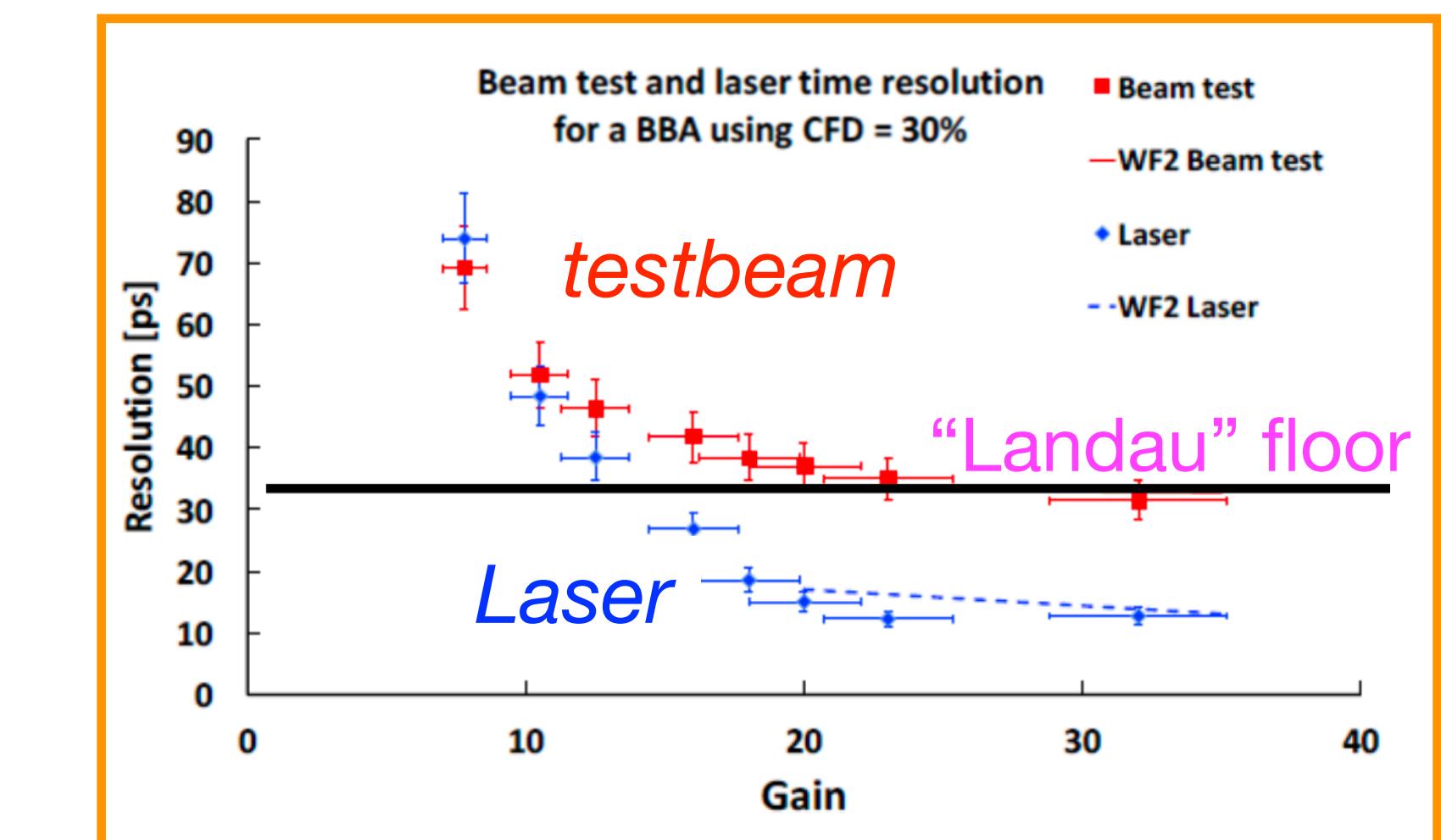
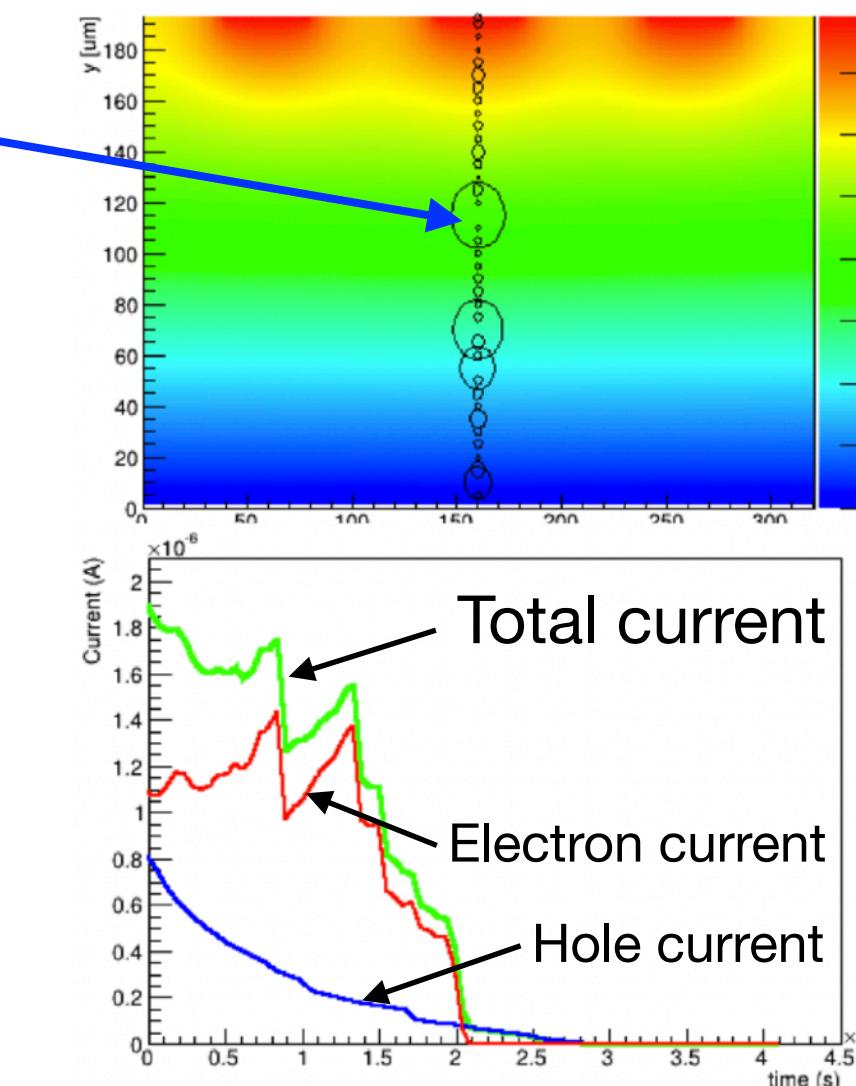
L. Paolozzi PhD thesis, 2014 – http://www.infn.it/thesis/thesis_dettaglio.php?tid=11828

Sensor design needs to reduce charge-collection noise:

Non uniform charge deposition along particle track induces a **jitter in the current pulse**

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

The **statistical origin** of this variability of I_{ind} makes this effect **irreducible in PN-junction sensors**



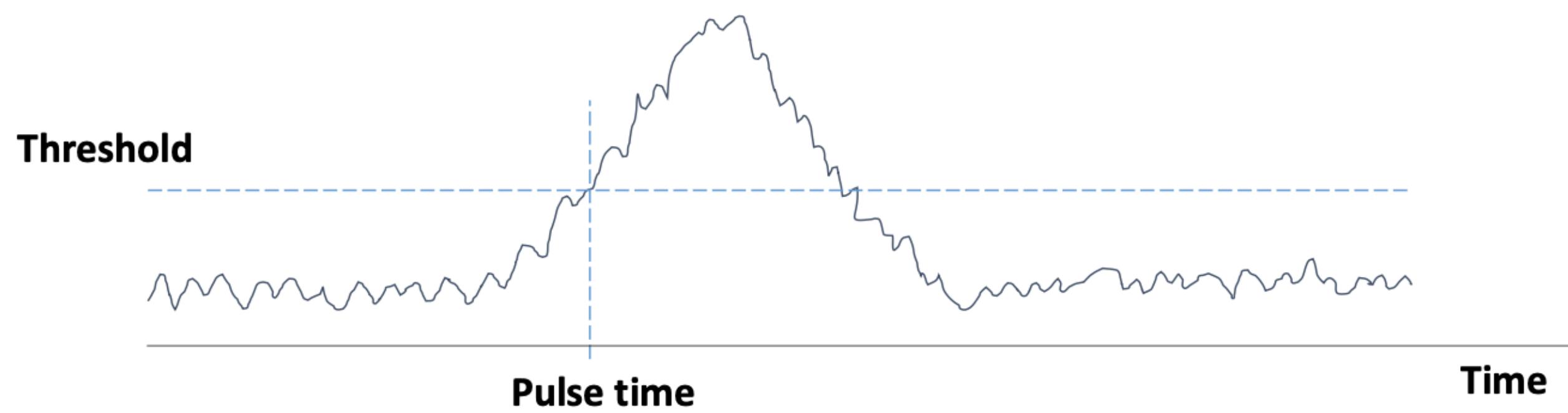
H. Sadrozinski, A. Seiden and N. Cartiglia, 2018 Rep. Prog. Phys. **81** 026101

Way out: **thinning** of the sensor

Challenge: although thin sensors reduce charge collection noise, they are typically bad for Signal/Noise (less ionization + increased capacitive coupling to sensor backside)

3. Electronic noise

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



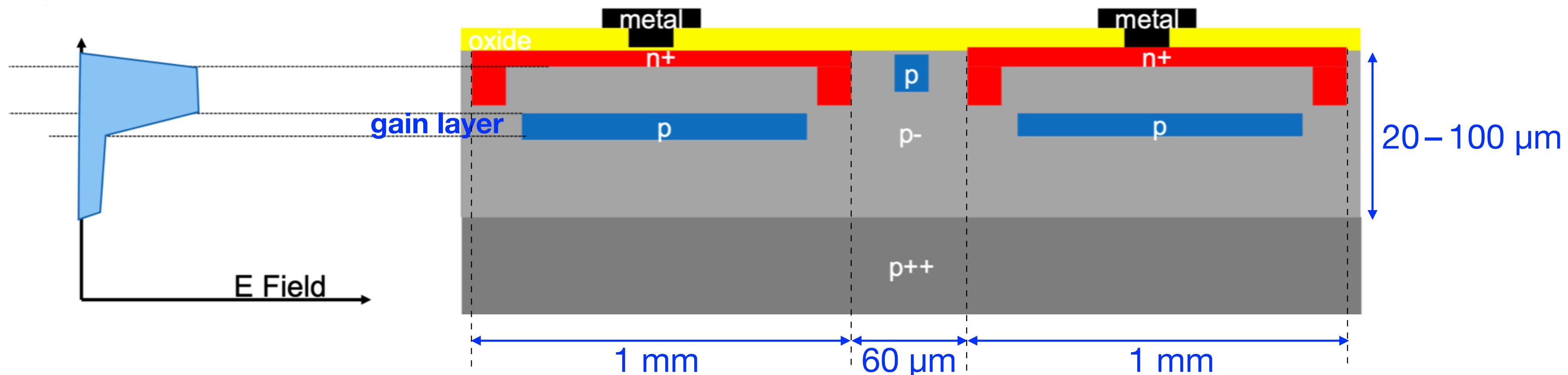
$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} = \frac{A_{Gain} \cdot ENC}{A_{Gain} \cdot I_{ind}} \cong \frac{t_{rise}}{Q} = \frac{t_{rise}}{ENC}$$

→ Need an **ultra-fast, high-gain, low-noise** (low power-consumption) electronics with **fast risetime** and **small capacitance**

4. Gain

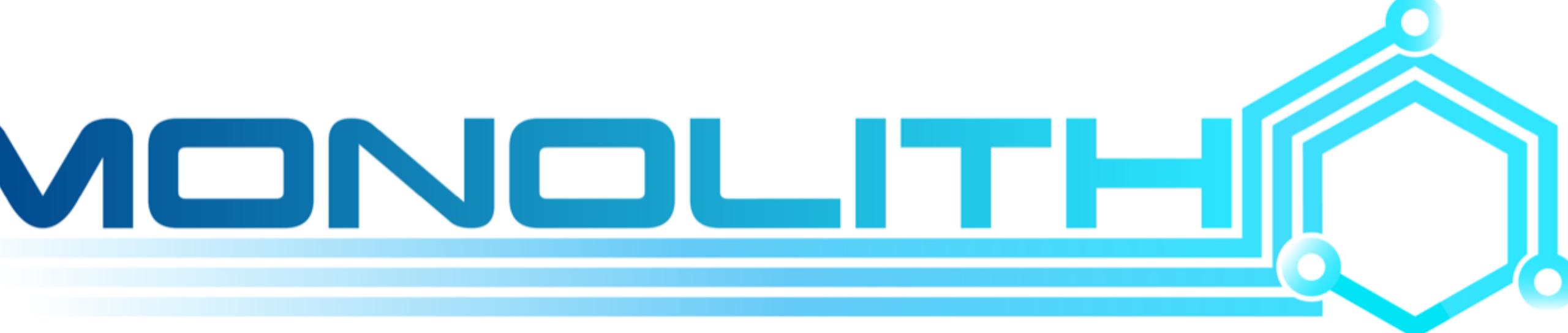
- A gain layer allows larger signals, and thus better time resolution
- This is achieved in the LGADs with a gain layer under the pixel;

$$\sigma_T \propto \frac{t_{rise}}{\text{Signal}/\text{Noise}}$$

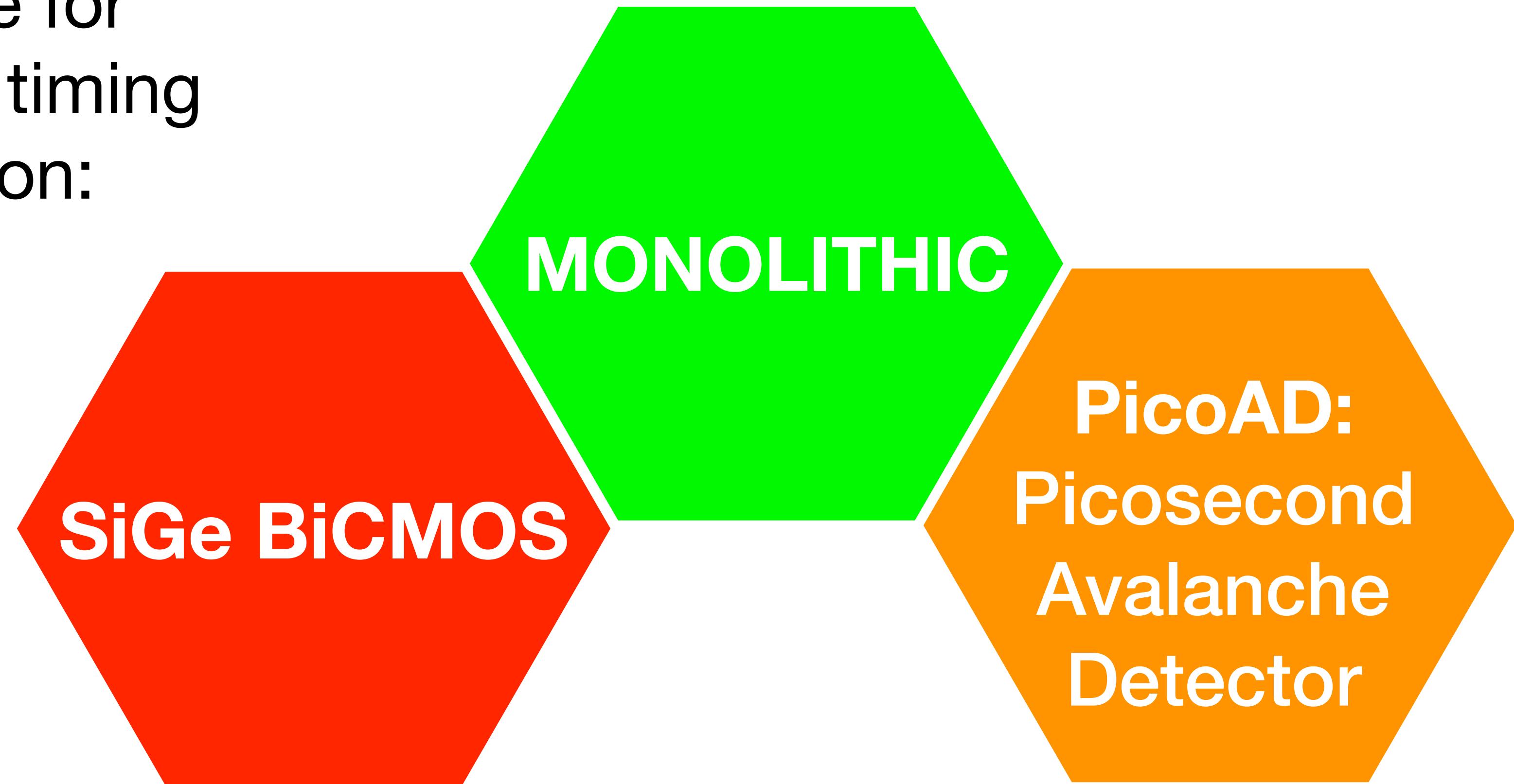


- As you will see, we have a different strategy

The **MONOLITH** Project



Our recipe for
picosecond timing
with silicon:





The UniGe Silicon Team



Giuseppe Iacobucci
• project P.I.
• System design



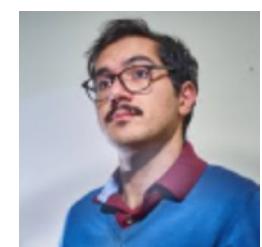
Lorenzo Paolozzi
• Sensor design
• Analog electronics



Thanushan Kugathasan
• Lead chip design
• Digital electronics



Magdalena Munker
• Sensor design
• Laboratory test



Roberto Cardella
• Sensor design
• Laboratory test



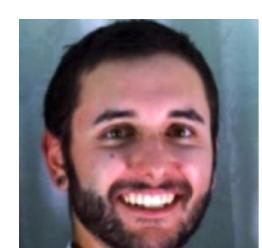
Stefano Zambito
• Laboratory test
• Data analysis



Mateus Vicente
• System integration
• Laboratory test



Fulvio Martinelli
• Chip design
• Firmware



Matteo Milanesio
• Laboratory test
• Data analysis



Théo Moretti
• Laboratory test
• Data analysis



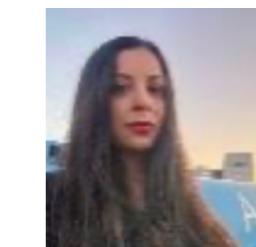
Antonio Picardi
• Chip design
• Firmware



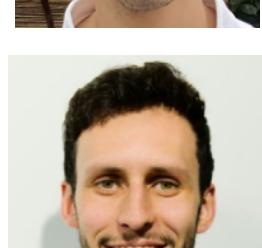
Chiara Magliocca
• Laboratory test
• Data analysis



Jihad Saidi
• Laboratory test
• Data analysis



Rafaella Kotitsa
• Sensor simulation



Carlo Alberto Fenoglio
• Chip design
• Firmware



Luca Iodice
• Chip design
• Firmware



Didier Ferrere
• System integration
• Laboratory test



Yannick Favre
• Board design
• RO system



Sébastien Débieux
• System integration
• Laboratory test

Stéphane Débieux
• Board design
• RO system

Main research partners:



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INFN Rome2 & UNIGE



Holger Rücker
IHP Mikroelektronik



Marzio Nessi
CERN & UNIGE



Bernd Heinemann
IHP Mikroelektronik

Funded by:



**Swiss National
Science Foundation**



Sinergia



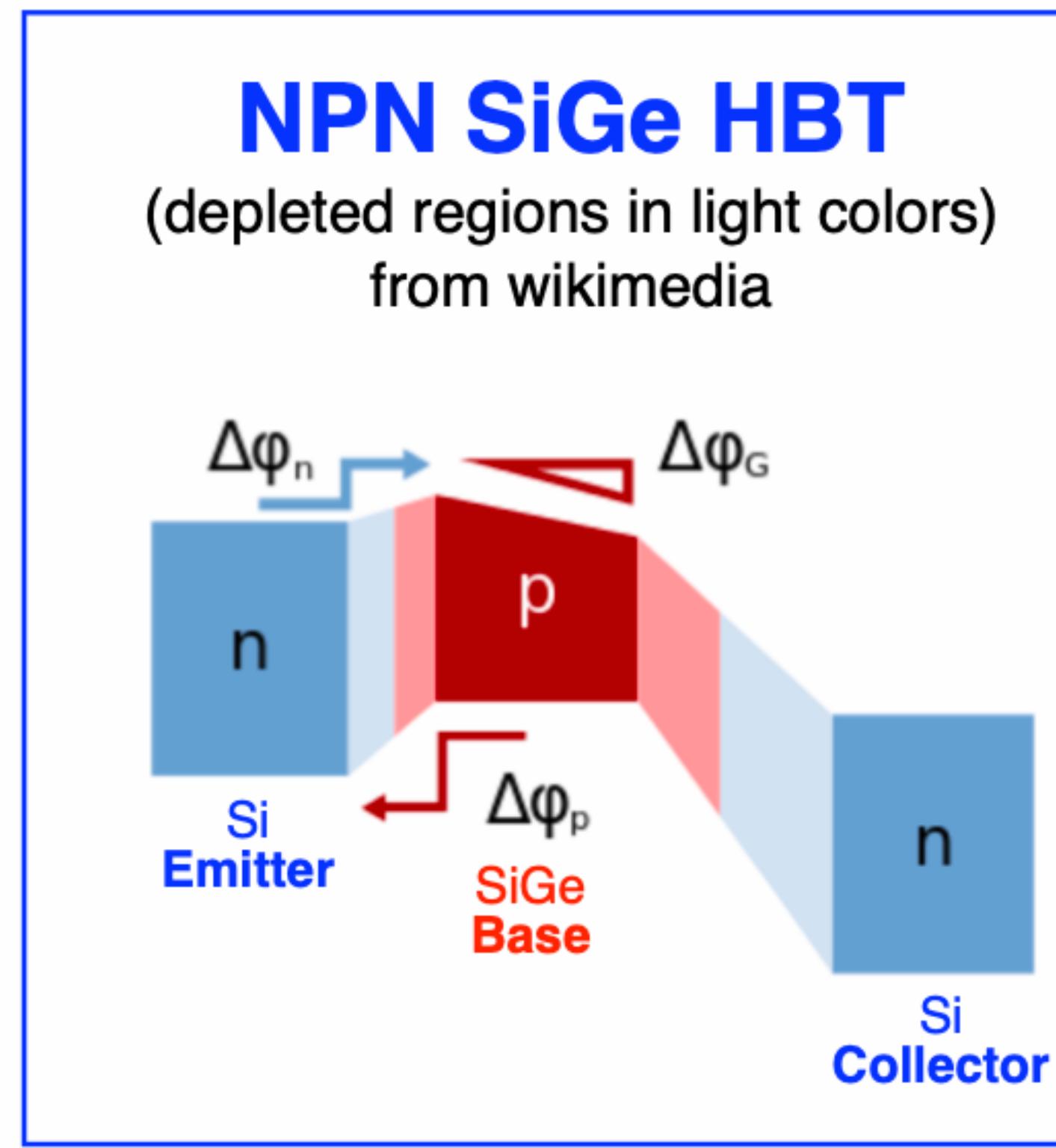
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European Research Council
Established by the European Commission



**UNIVERSITÉ
DE GENÈVE**

UNITEC





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

SiGe HBT = BJT with Germanium as base material.

Grading of Ge doping in base:

- charge-transport in base via **drift**
 - reduced charge-transit-time in base
 - **high current gain β**
- **Higher doping in base is possible:**
 - thinner base
 - **reduced base resistance R_b**

$$ENC_{series\ noise} \propto \sqrt{k_1 \frac{C_{tot}^2}{\beta} + k_2 R_b C_{tot}^2}$$

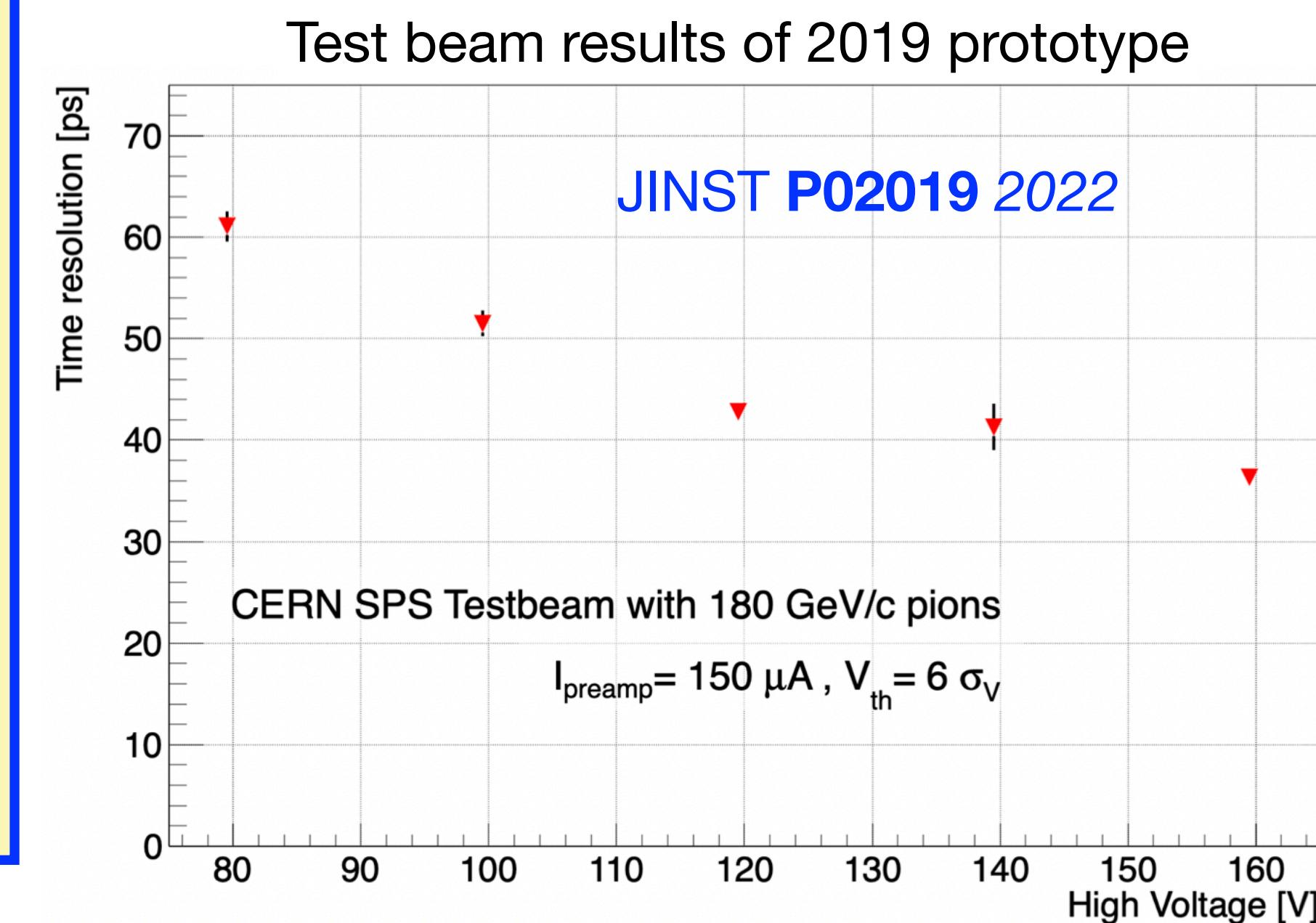
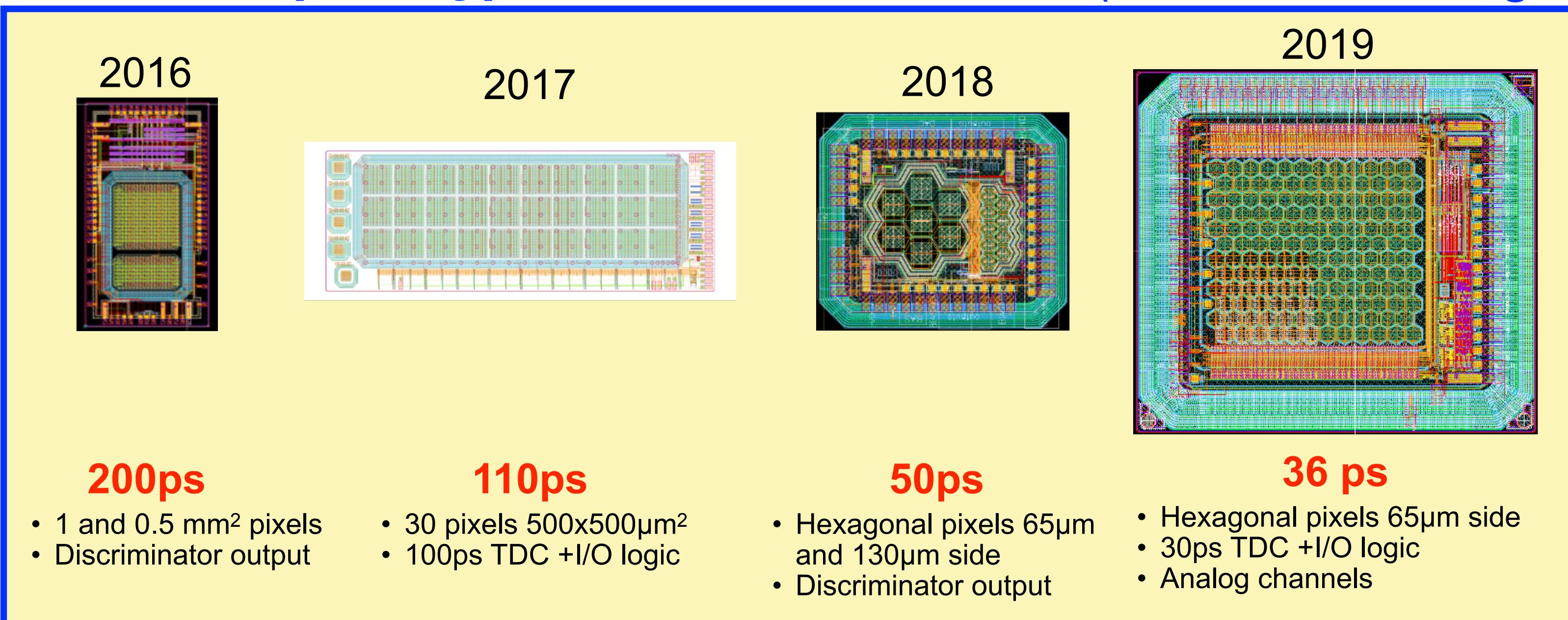


Monolithic SiGe BiCMOS for timing



European Research Council
Established by the European Commission

Monolithic prototypes with SiGe BiCMOS (without internal gain layer)



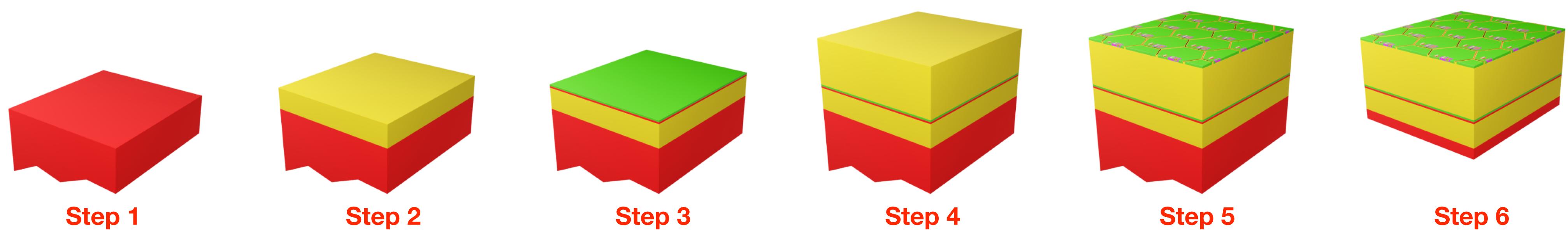
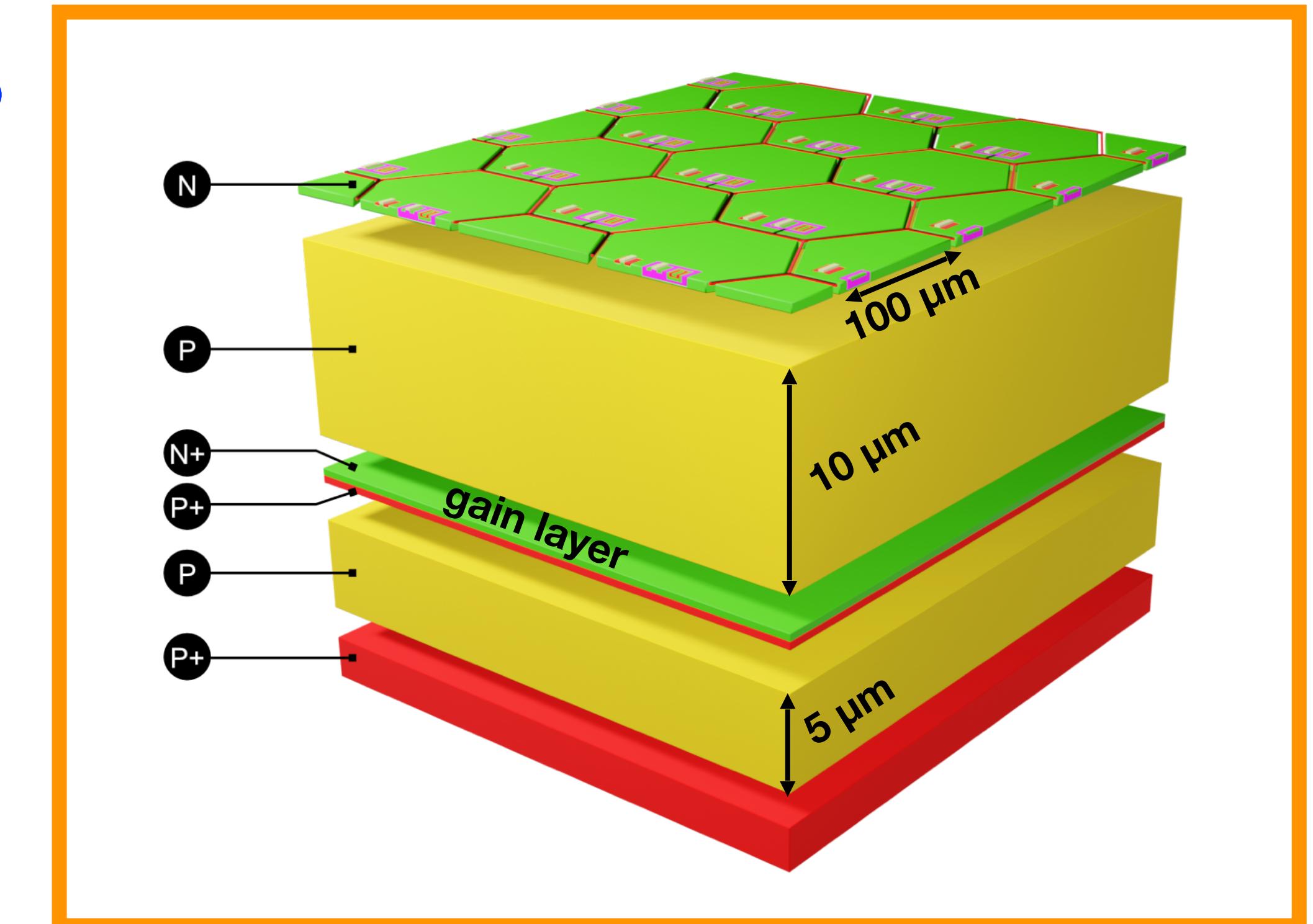
PicoAD:

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)

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





PicoAD monolithic proof-of-concept prototype

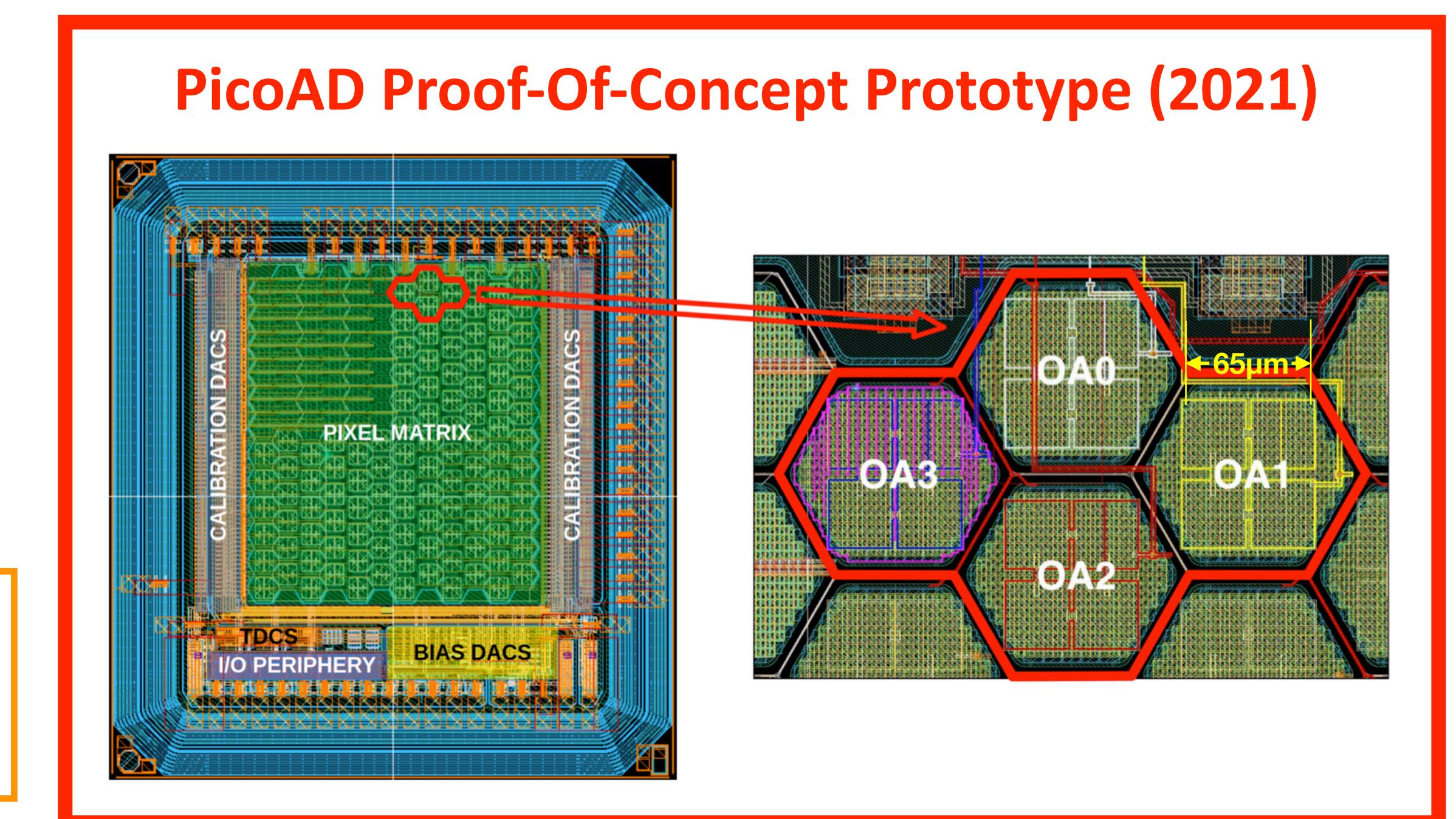
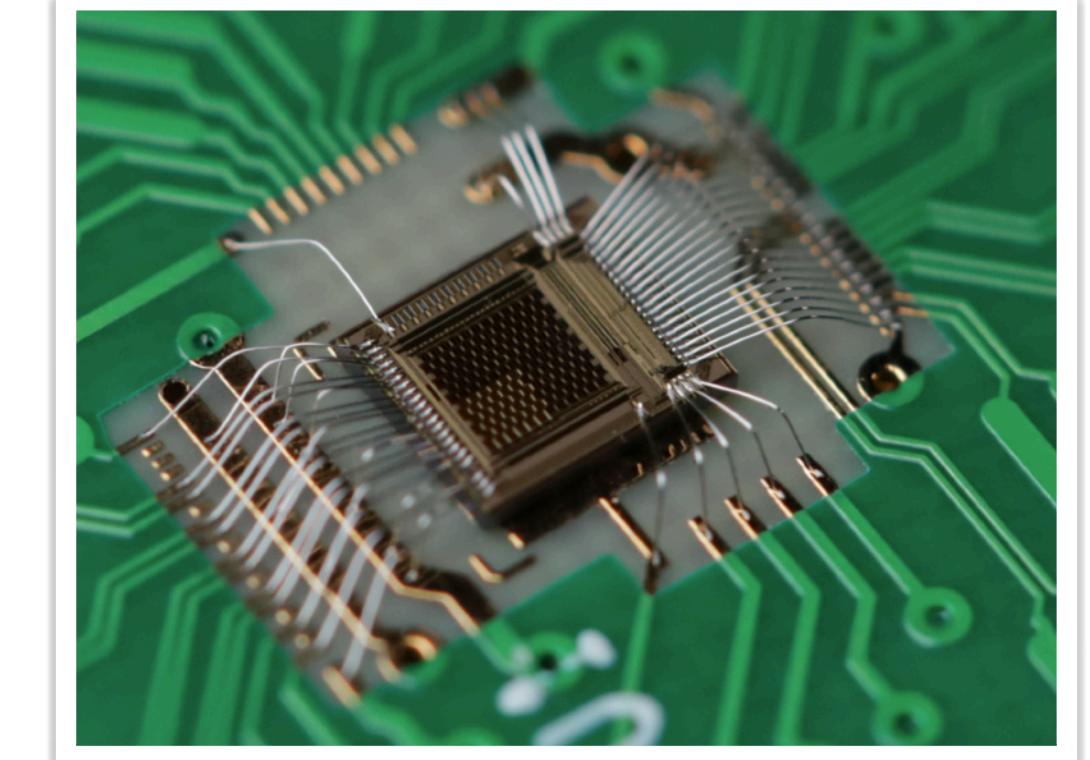


The proof-of-concept monolithic ASIC was produced by IHP in their SG13G2 SiGe BiCMOS process.

The ASIC contains:

- **Four matrices** of hexagonal pixels with $\approx 100\mu\text{m}$ pitch
 - ▶ with different electronics configurations
- **Four analog pixels**
 - ▶ tested with ^{55}Fe source and in testbeam

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



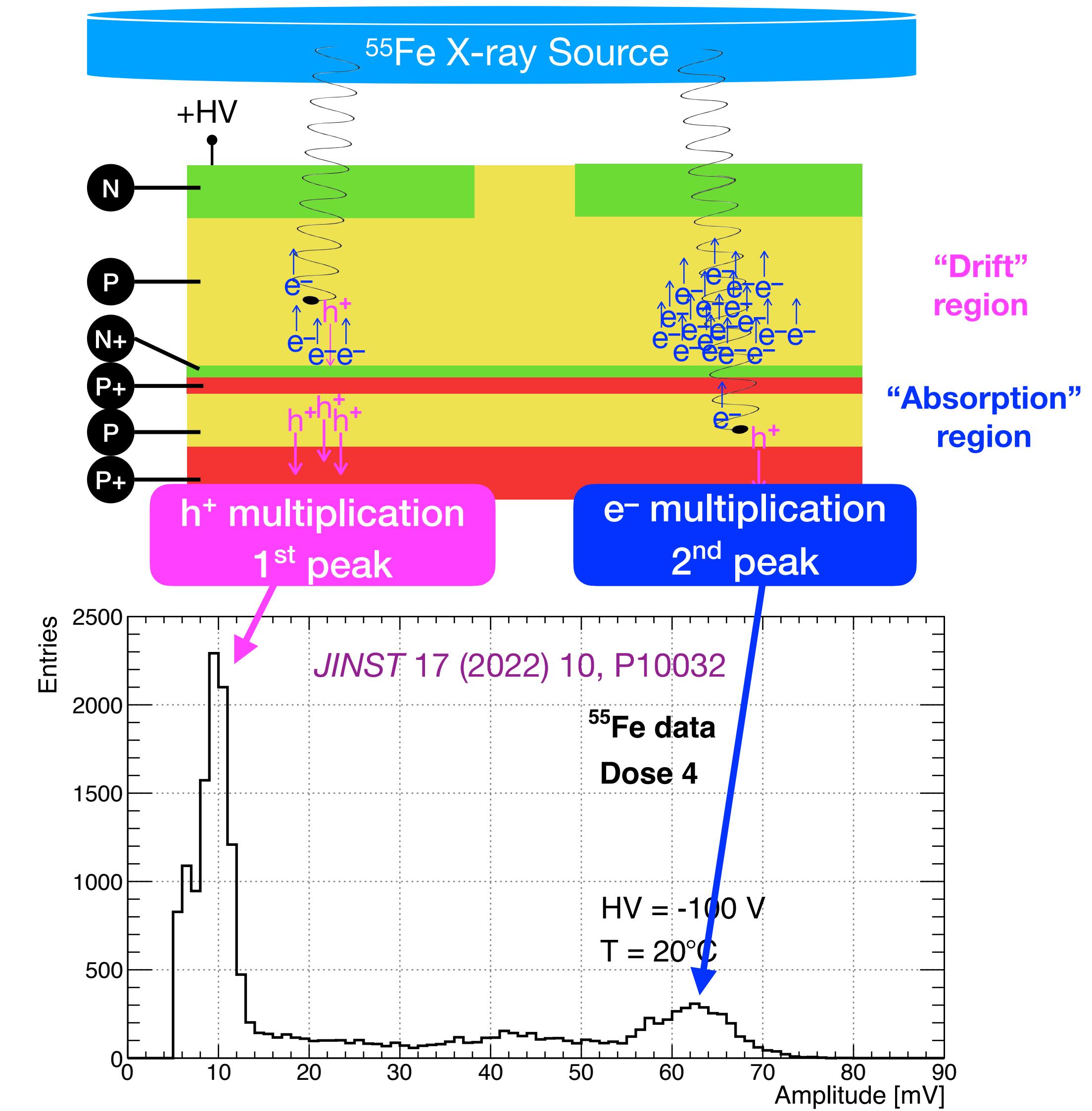
Gain Measurement with ^{55}Fe source

X-rays from ^{55}Fe radioactive source:

- ▶ mainly $\sim 5.9 \text{ keV}$ photons
- ▶ point-like charge deposition

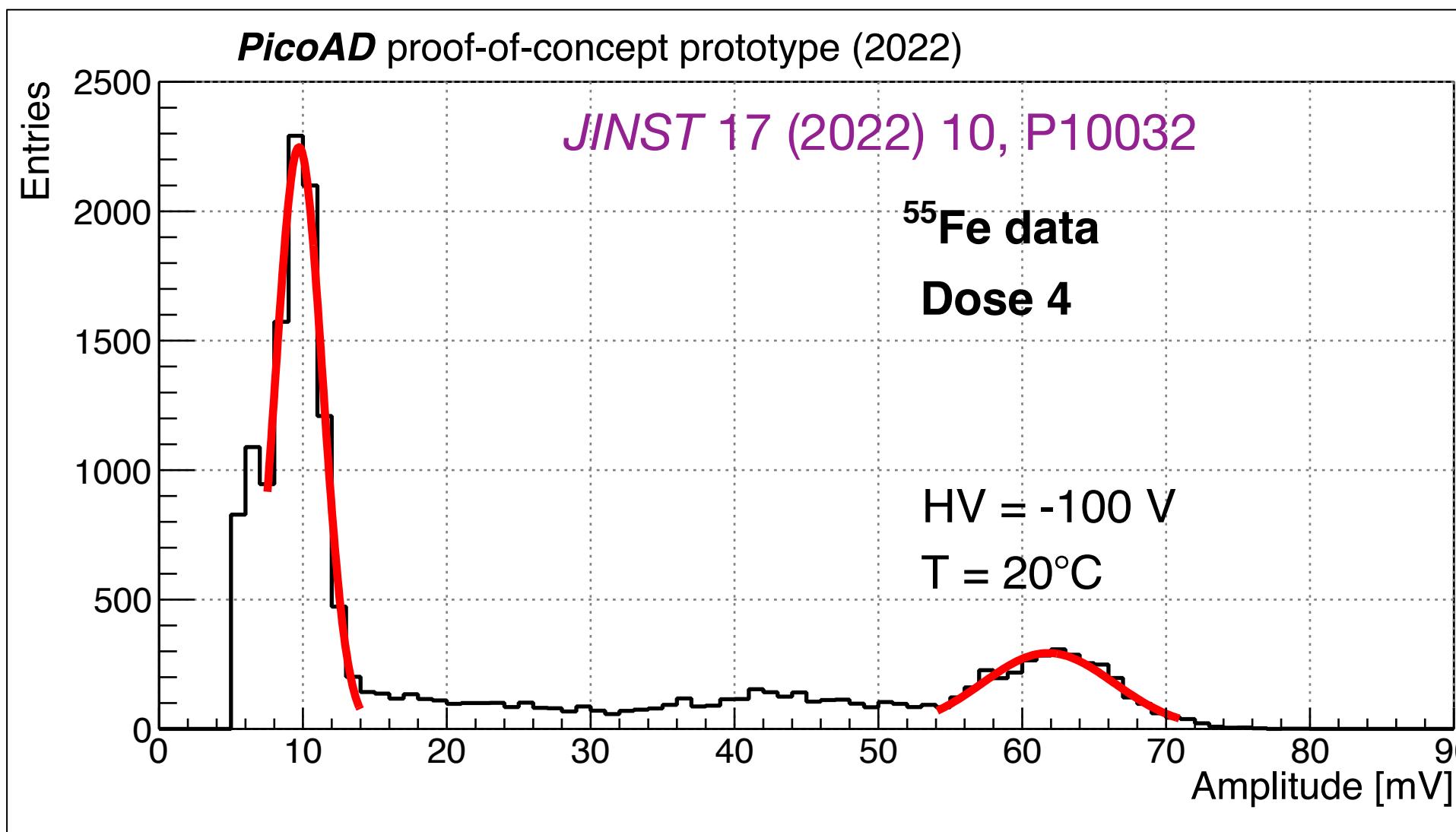
Characteristic double-peak spectrum

- ▶ photon absorbed in **drift region**
 - ▶ **holes** drift through gain layer & multiplied
 - ▶ **first peak** in the spectrum
- ▶ photon absorbed in **absorption region**
 - ▶ **electrons** through gain layer & multiplied
 - ▶ **second peak** in the spectrum



Gain Measurement with ^{55}Fe source

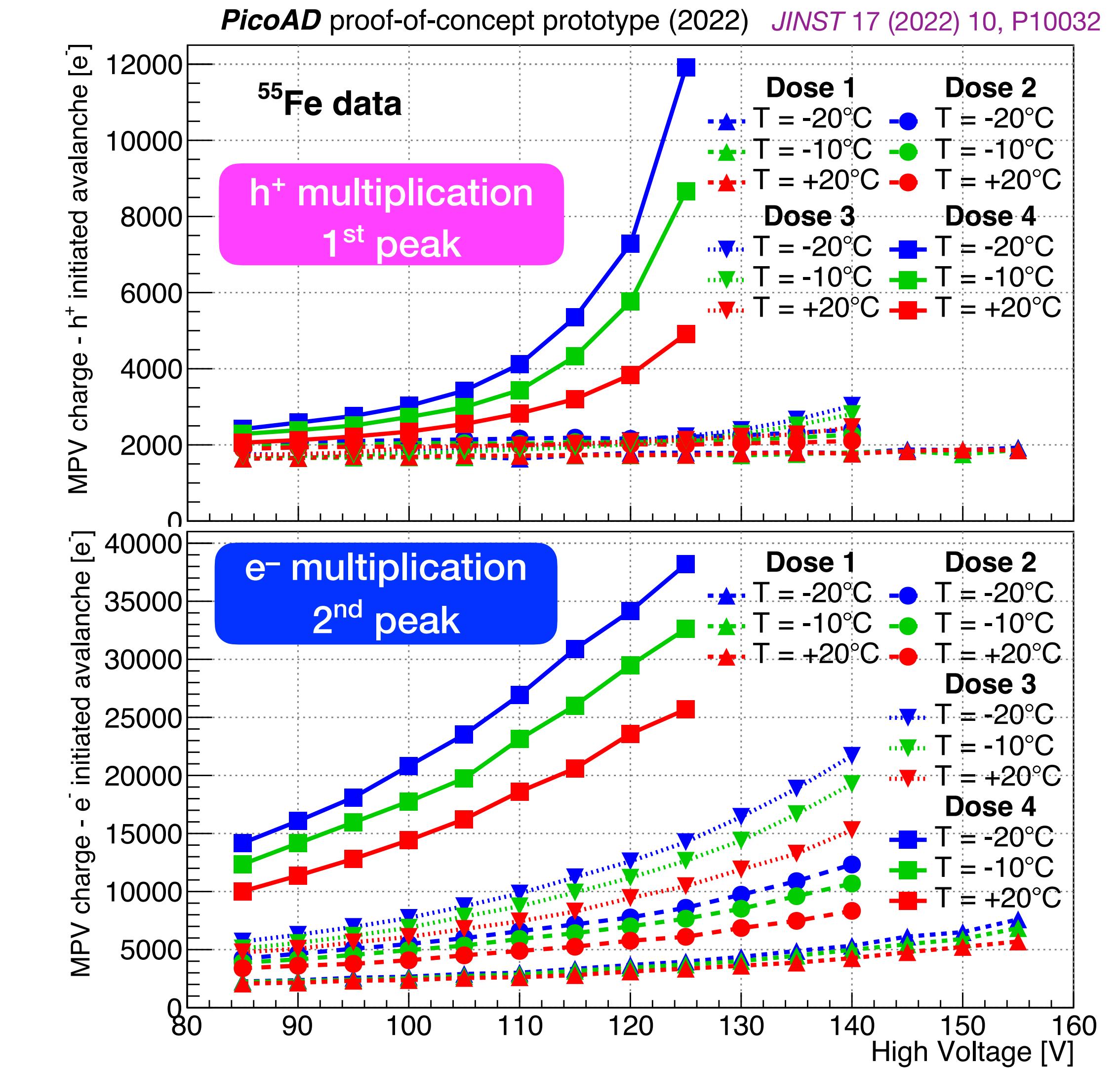
Average amplitudes of h^+ and e^- gains
extracted via gaussian fit around local maxima



Assumption of no gain multiplication when:

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

normalization value

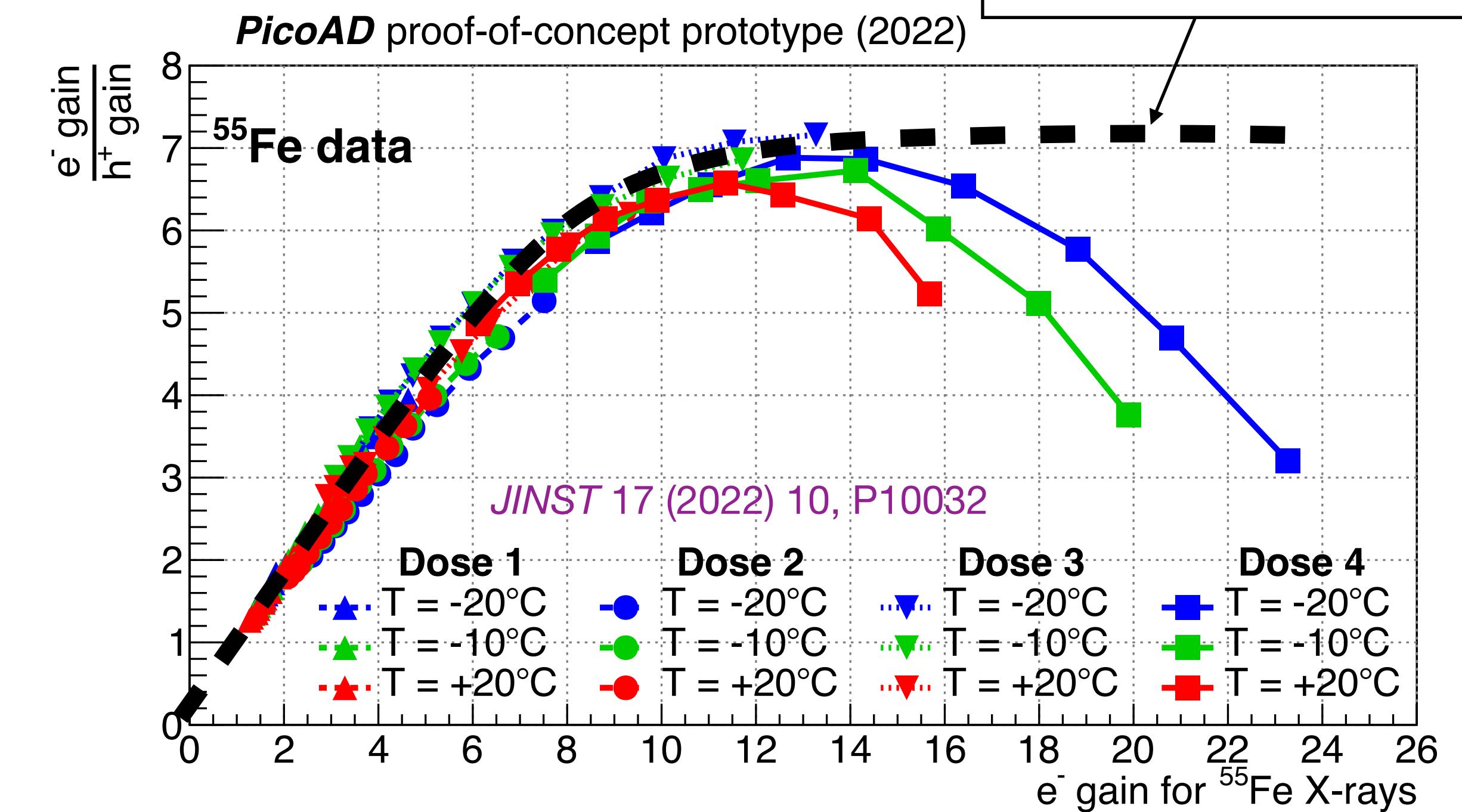
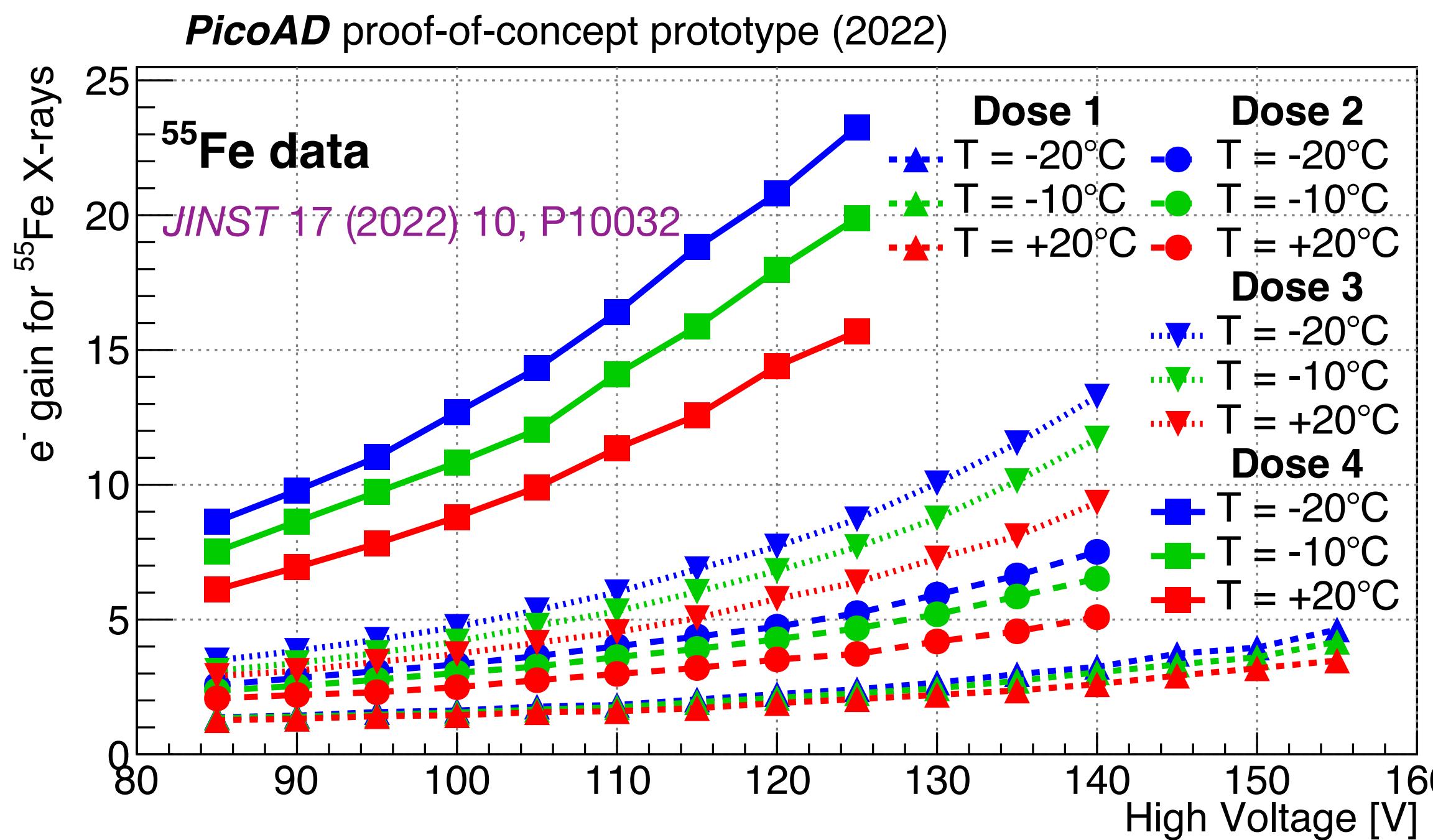




Gain Measurement with ^{55}Fe source



R. J. McIntyre, IEEE Trans. Electr. Dev., Vol. 46, no. 8, 1623–1631, Aug. 1999



A **gain up to ≈ 20 for ^{55}Fe X-rays**
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

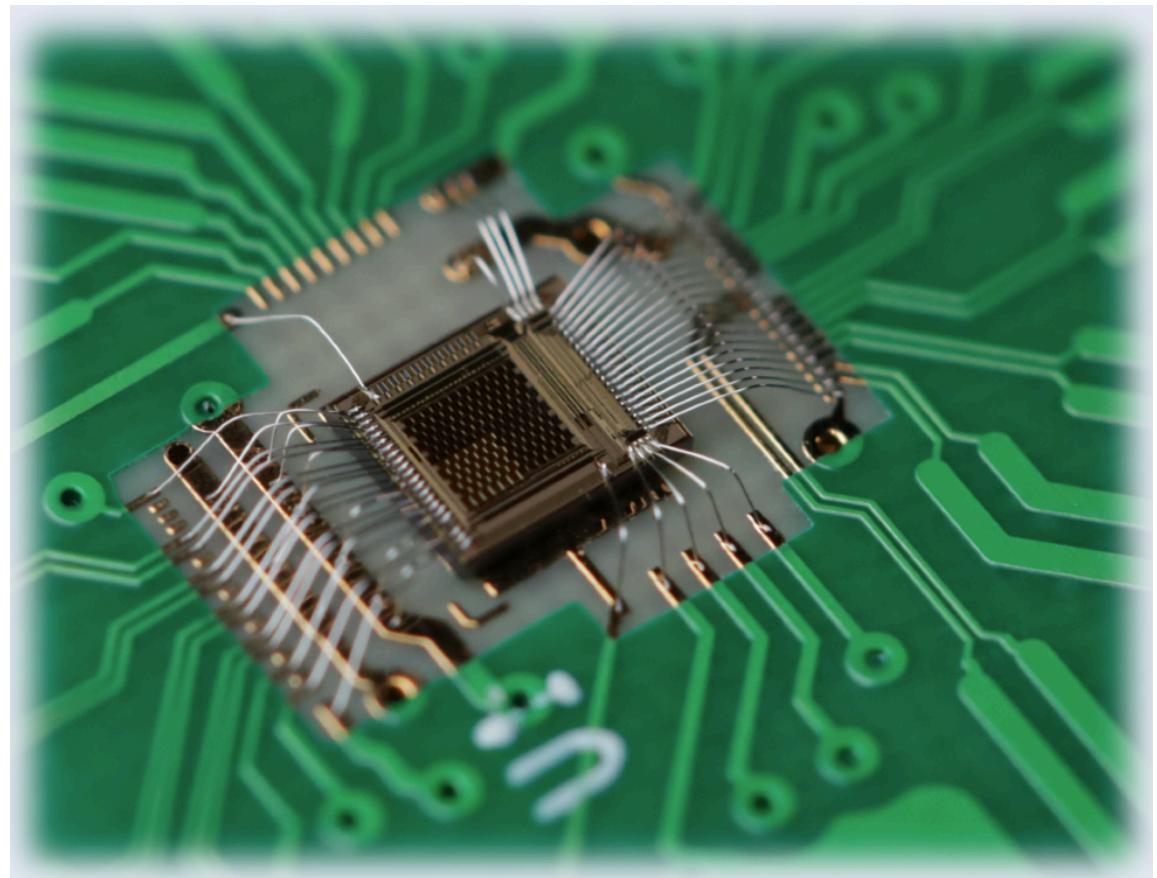
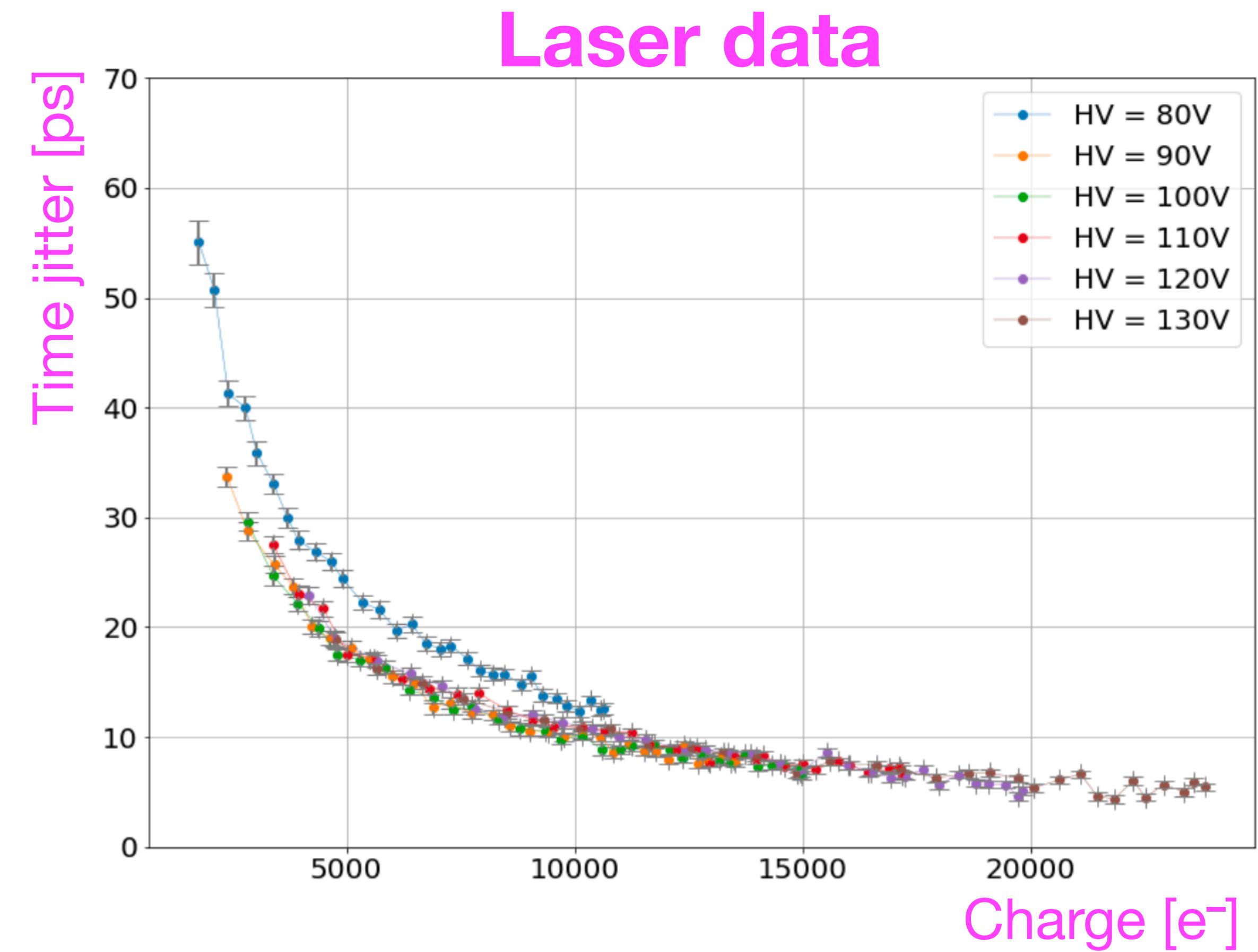
We estimated that ^{55}Fe gain of ≈ 23 corresponds to **gain 60–70 for a MIP**



Lab laser measurements

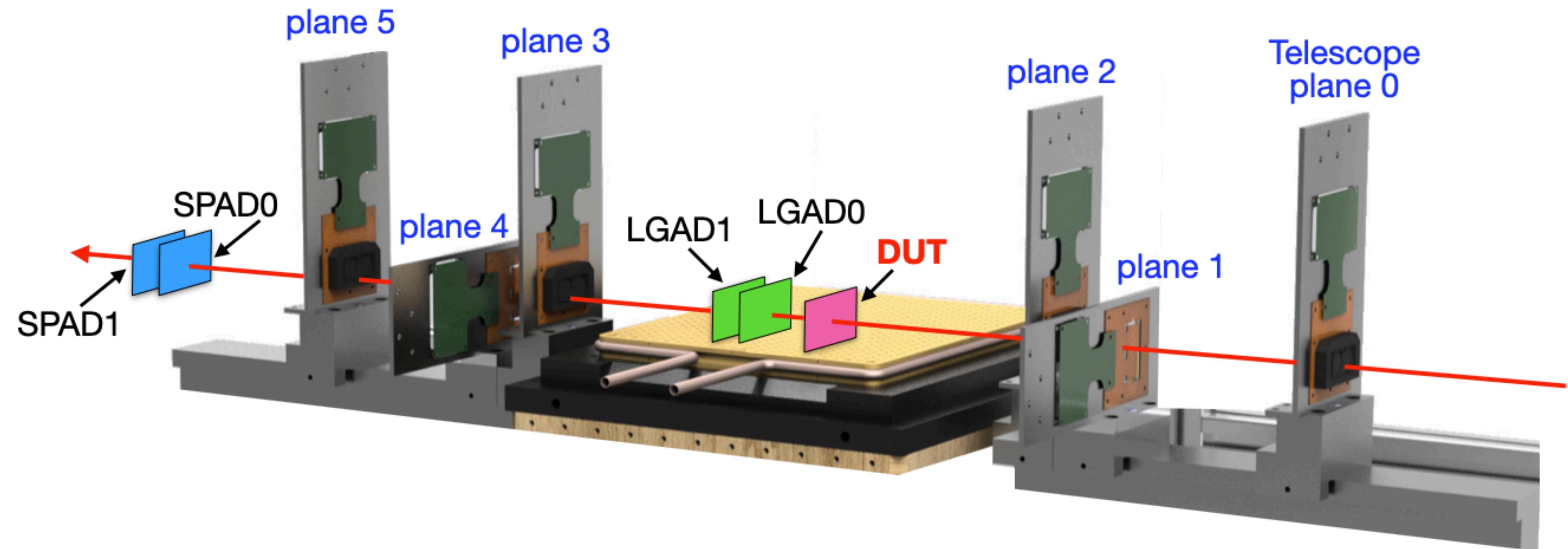


PicoAD proof-of-concept prototype:



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 ($\sigma_{x,y} \approx 10 \mu\text{m}$)

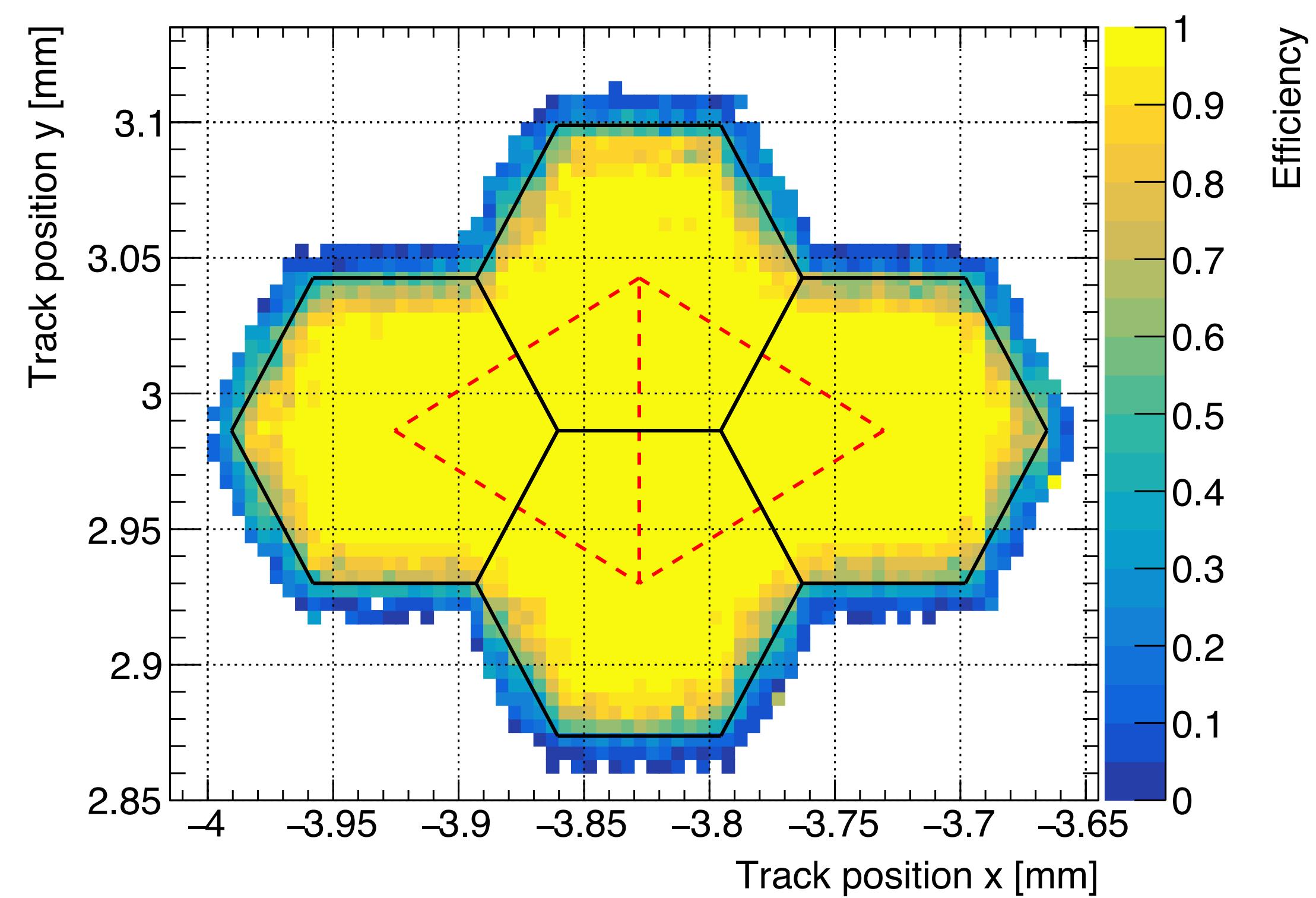
Two LGADs ($\sigma_t \approx 35 \text{ ps}$) to provide the timing reference (and **two SPADs** with $\sigma_t \approx 20 \text{ ps}$)



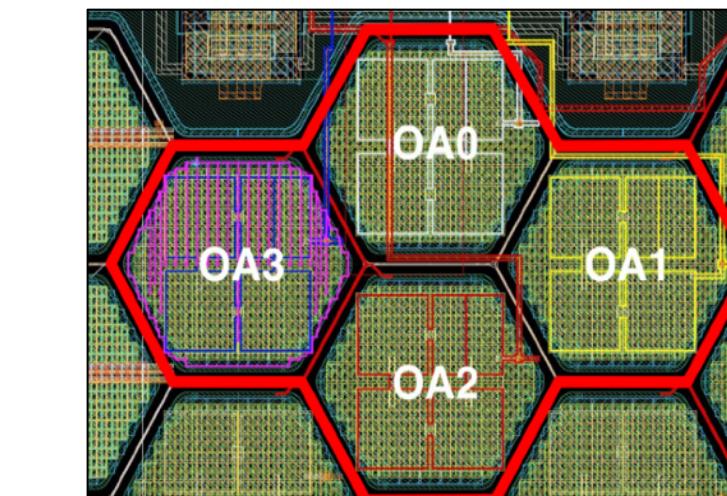
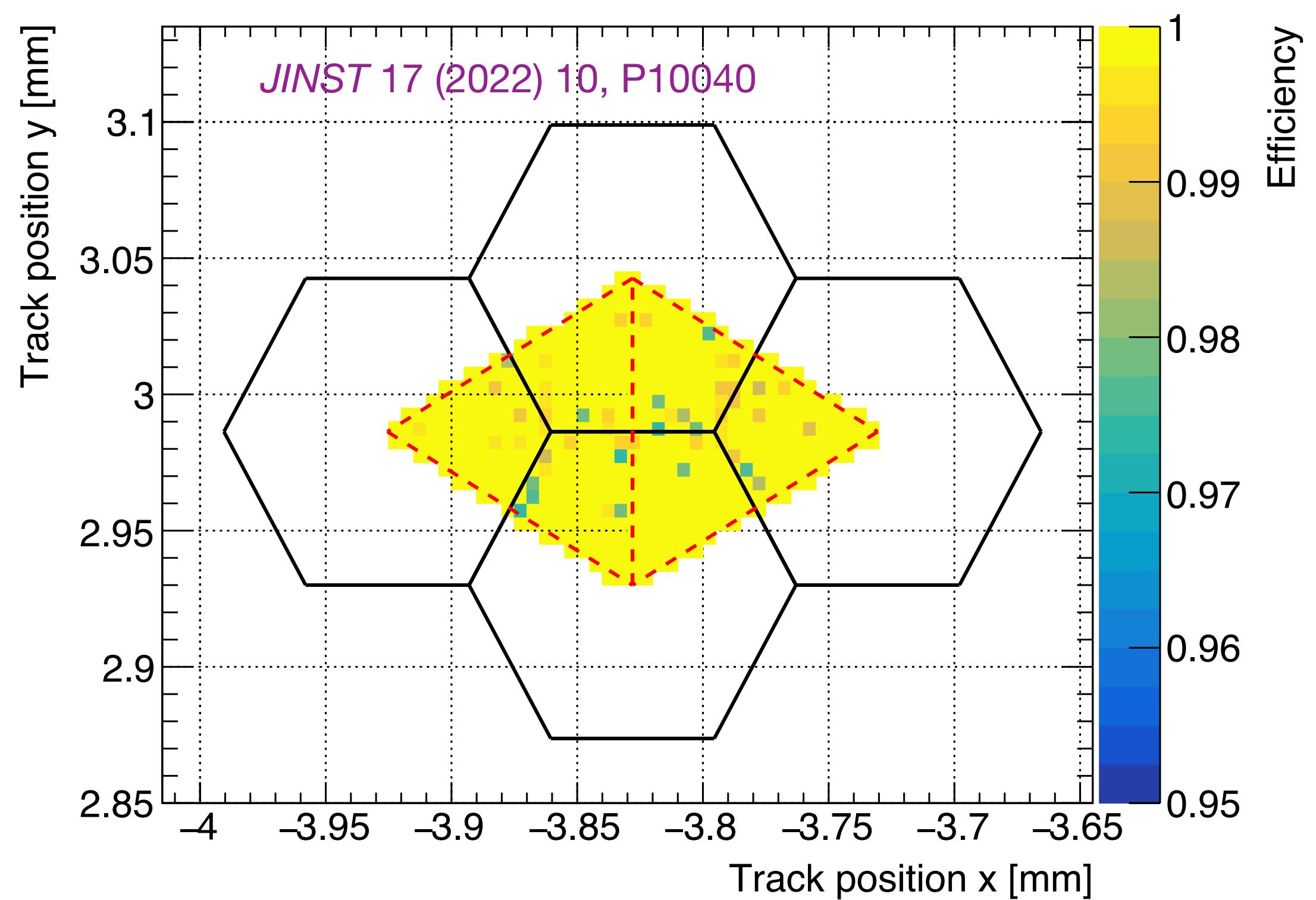
Testbeam results: Detection Efficiency



PicoAD proof-of-concept prototype (2022)



CERN SPS Testbeam: 180 GeV/c pions
 $V_{th} = 4 \text{ mV}$; $\text{HV} = 125 \text{ V}$; Power = 2.7 W/cm^2



Selection of two **triangles**:

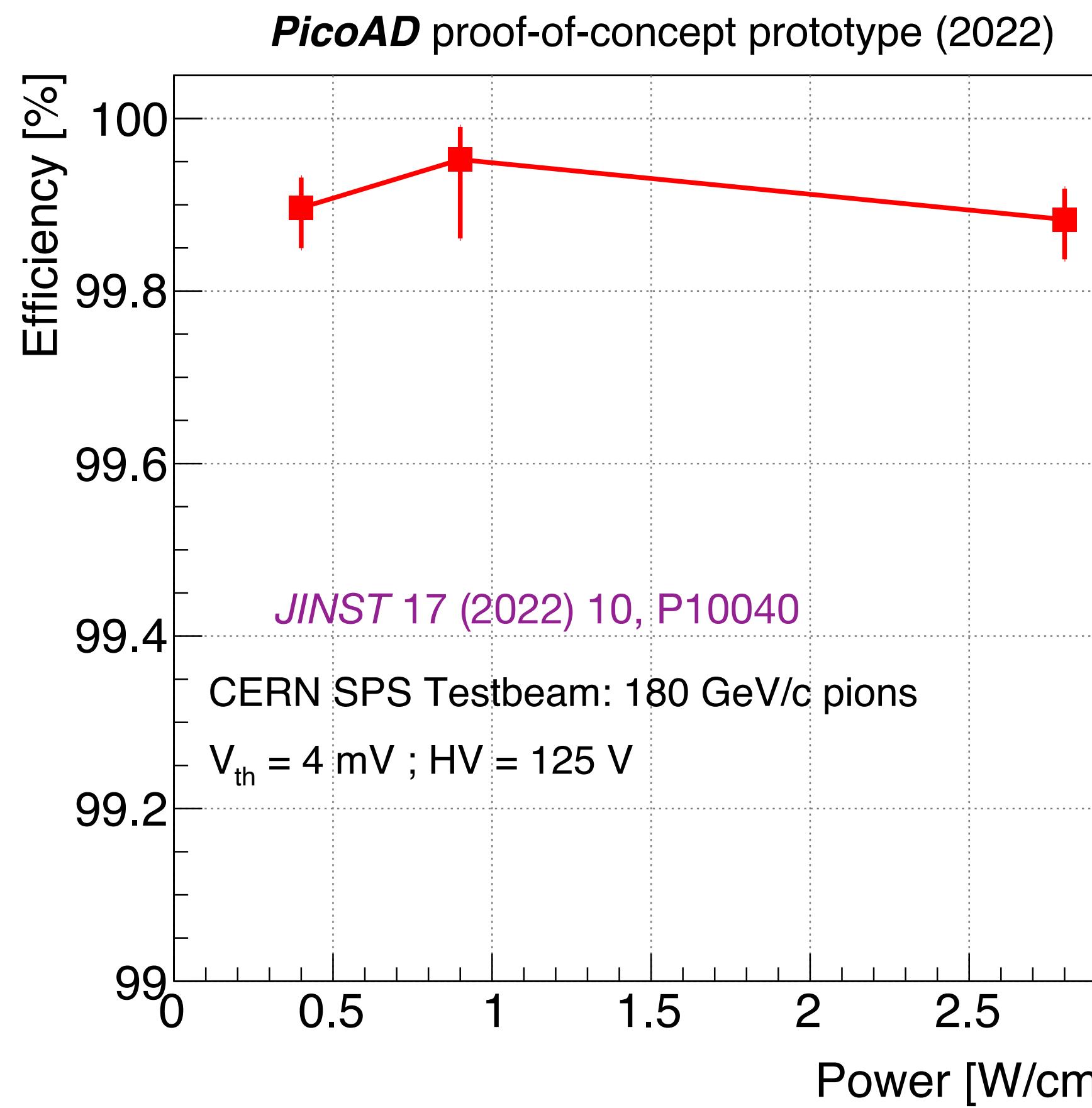
- representative of a whole pixel
- **unbiased** by telescope resolution



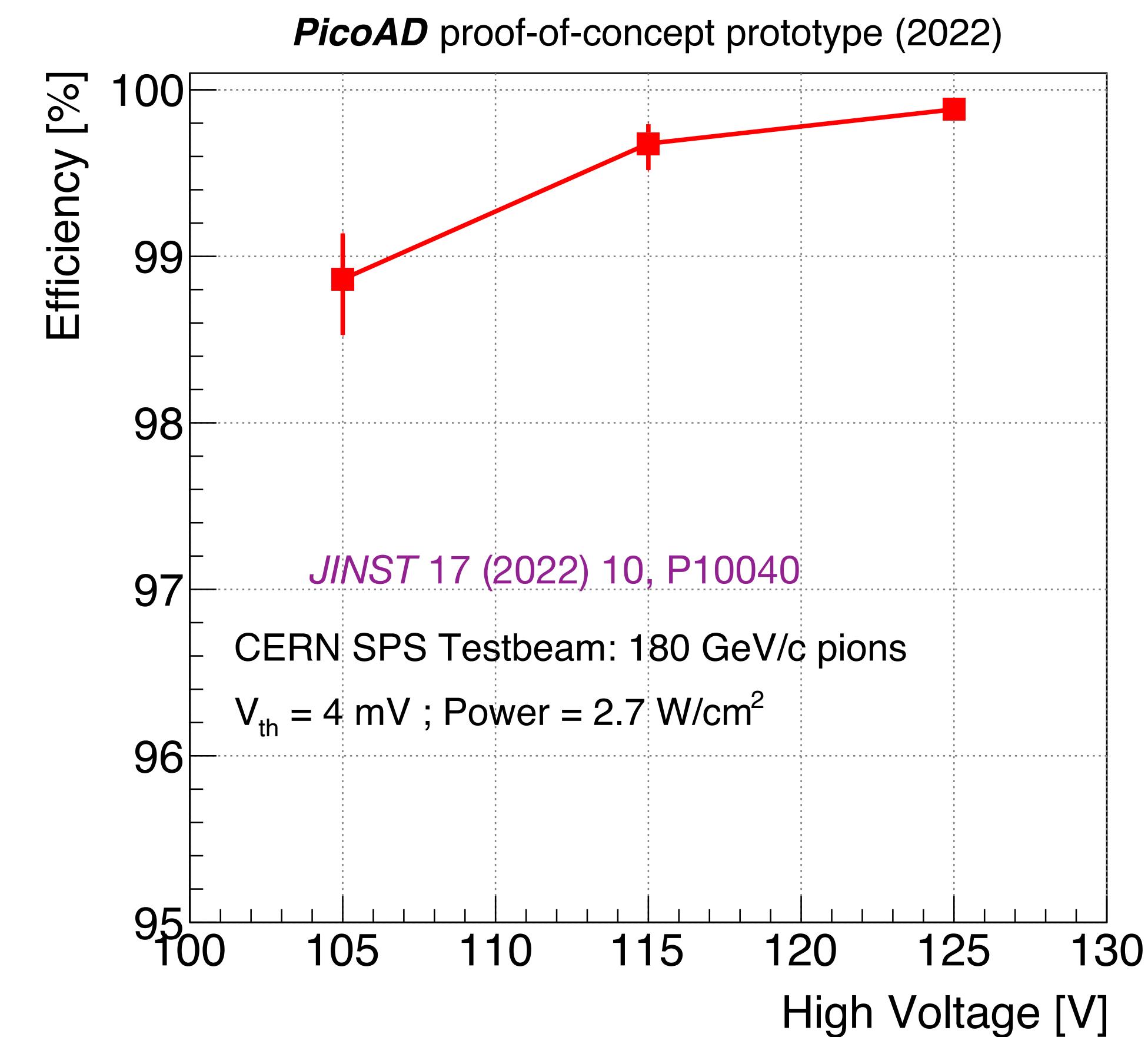
Testbeam results: Detection Efficiency



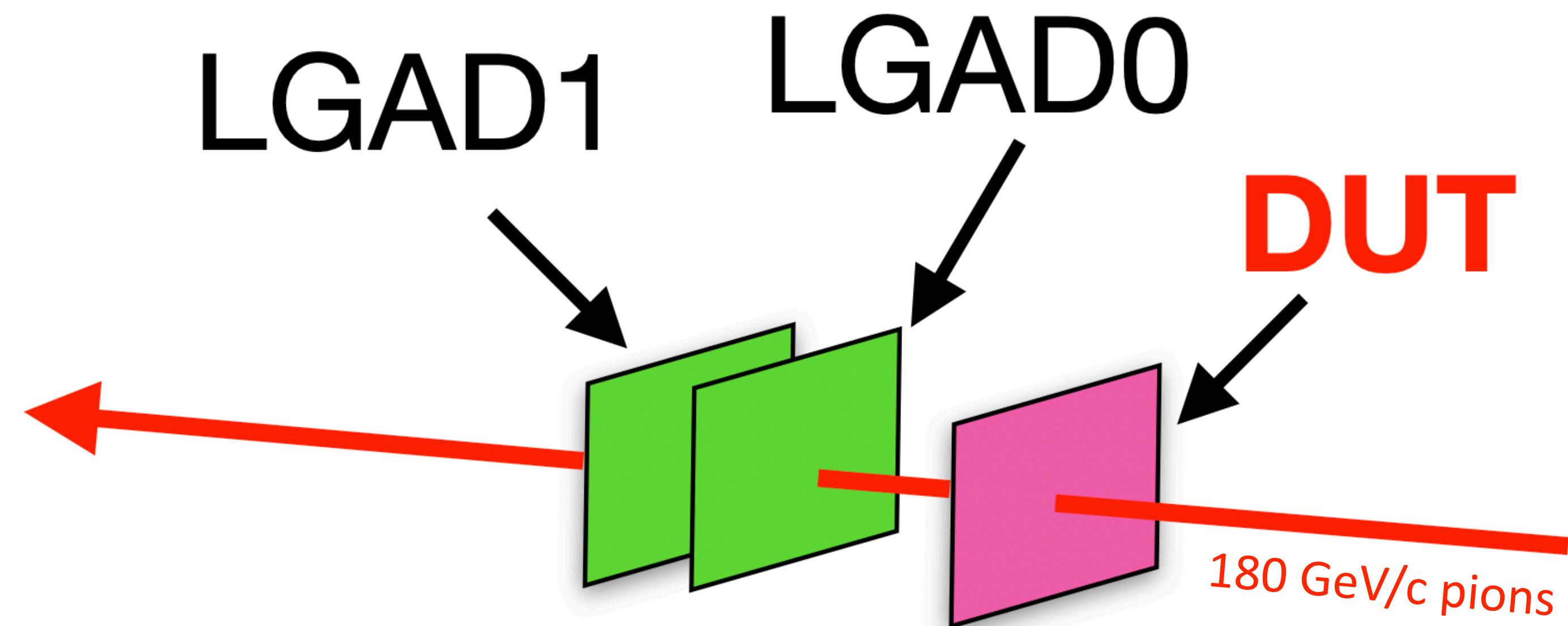
99.9% for all power consumptions



Drops to 99% for HV=105 V



Time Resolution



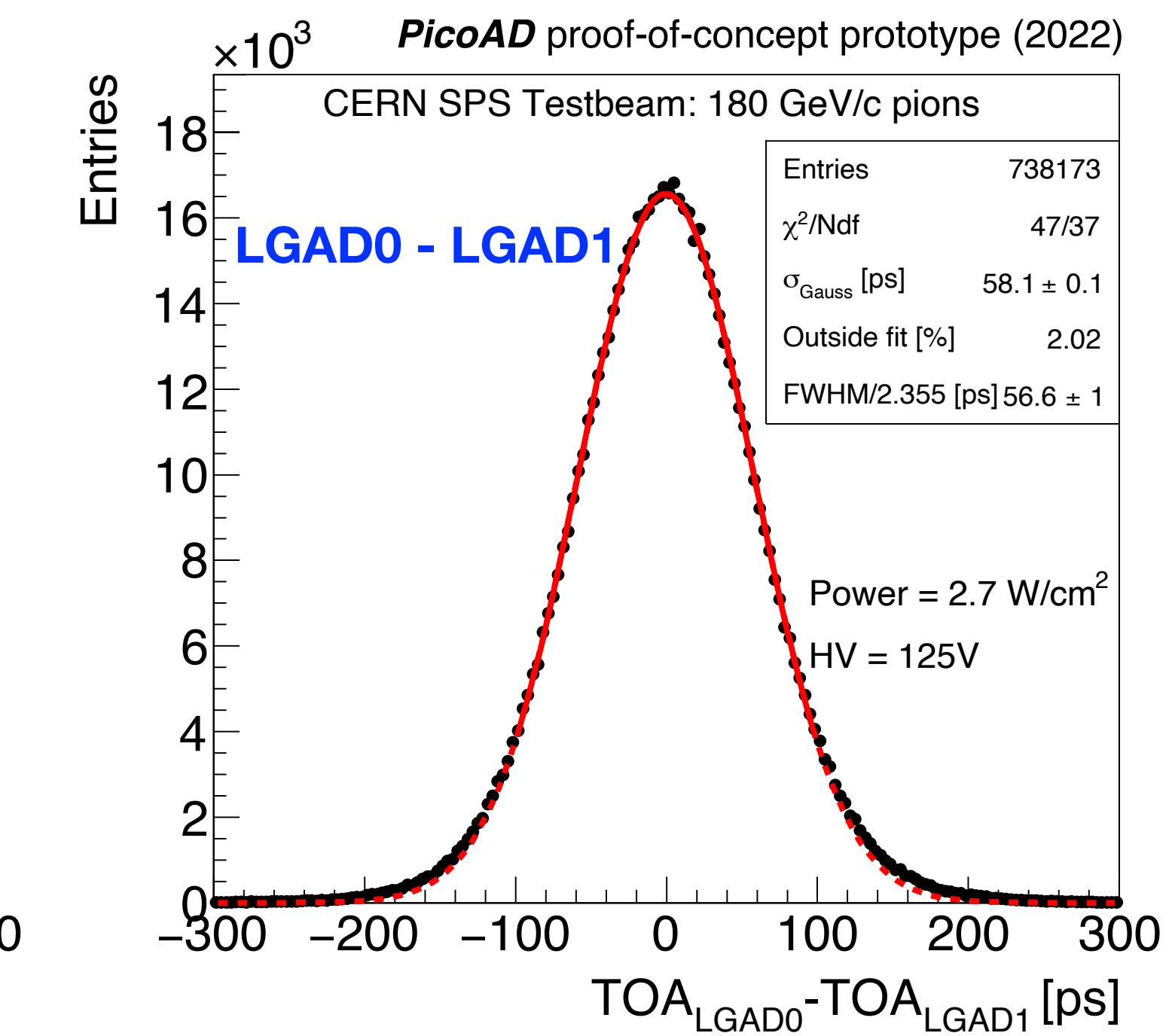
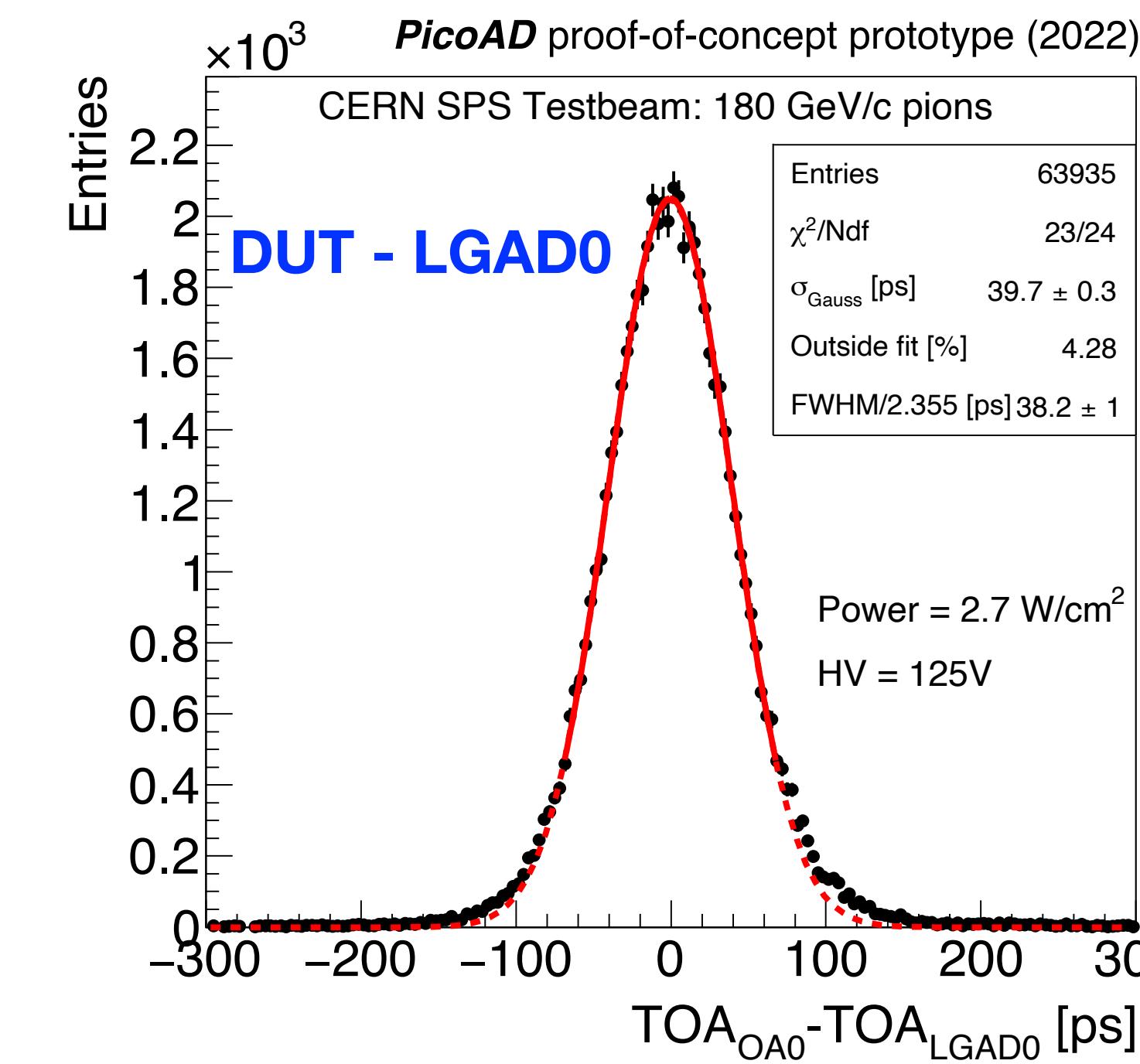
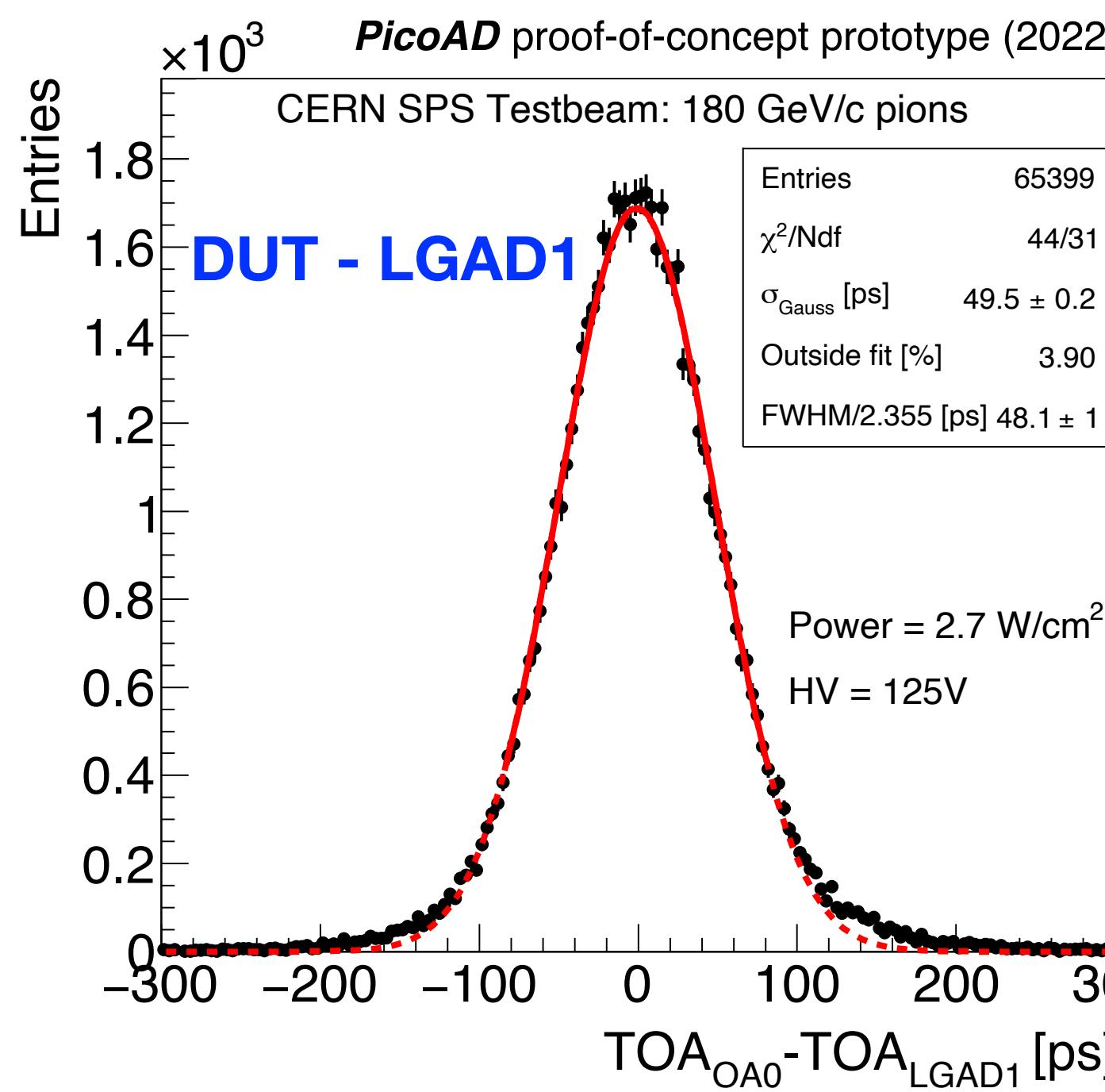
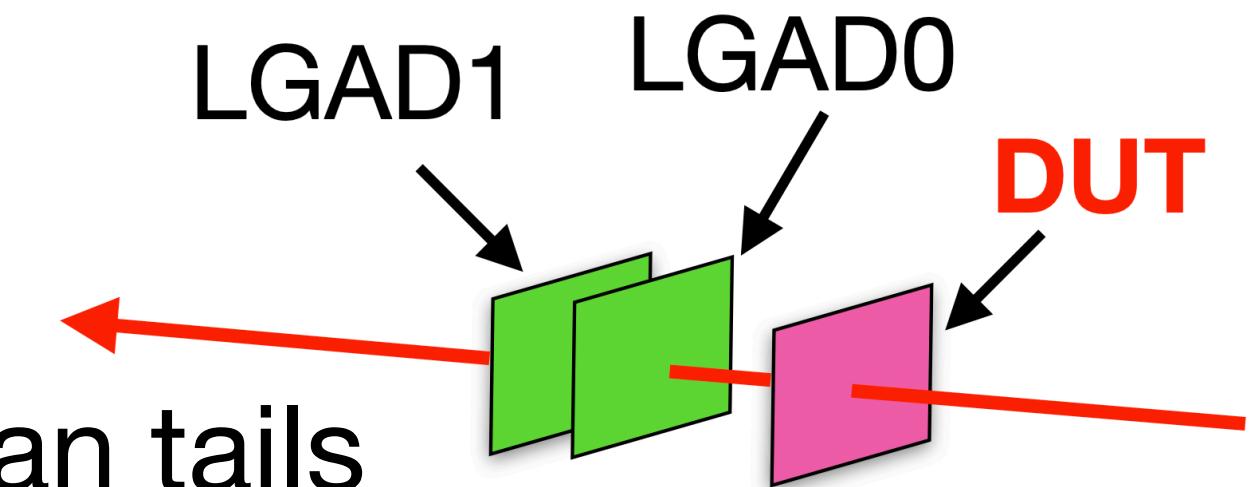
Results were also verified using **two SPADs** (but with much smaller statistics)



Testbeam results: Time Resolution



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

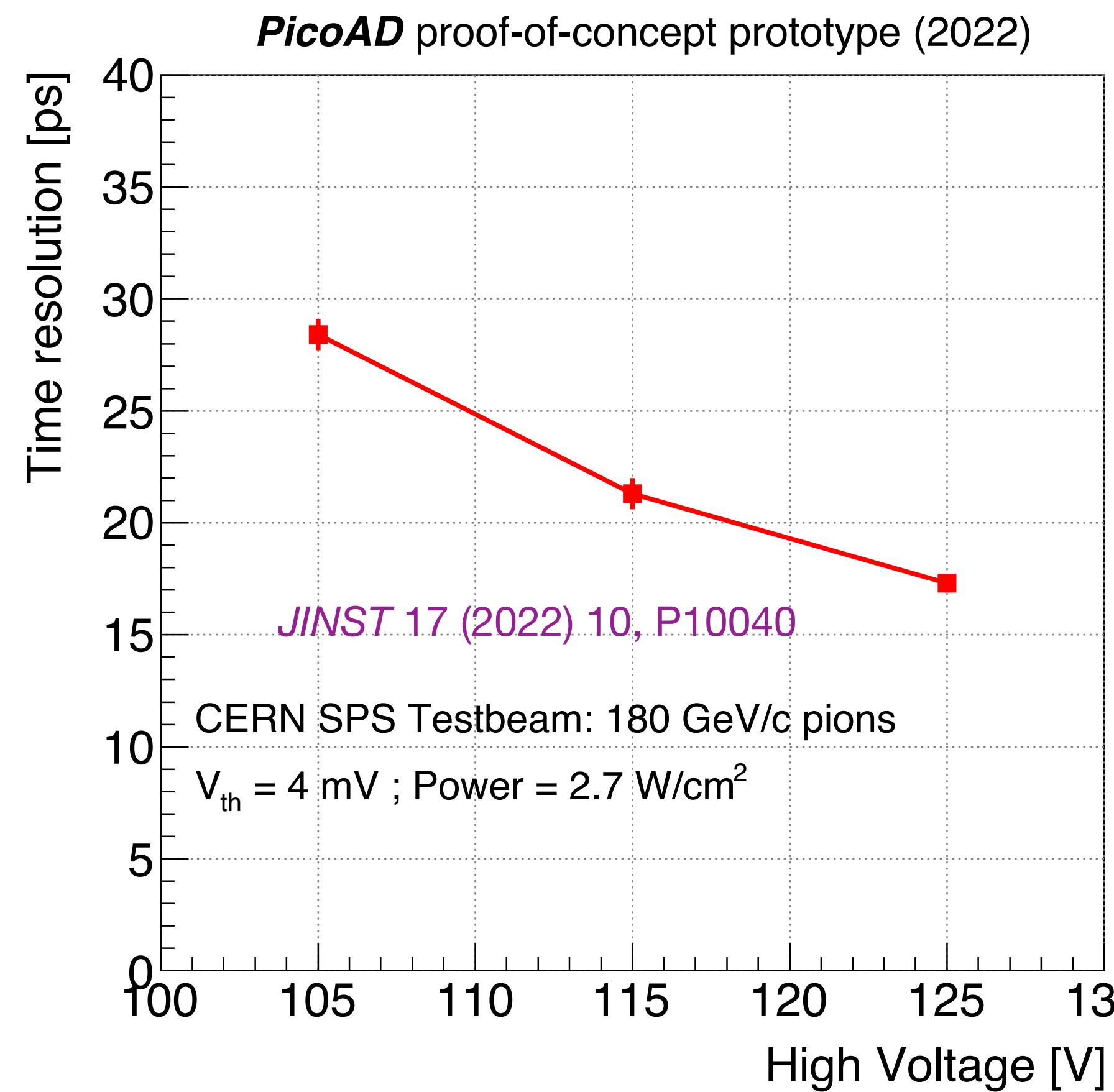




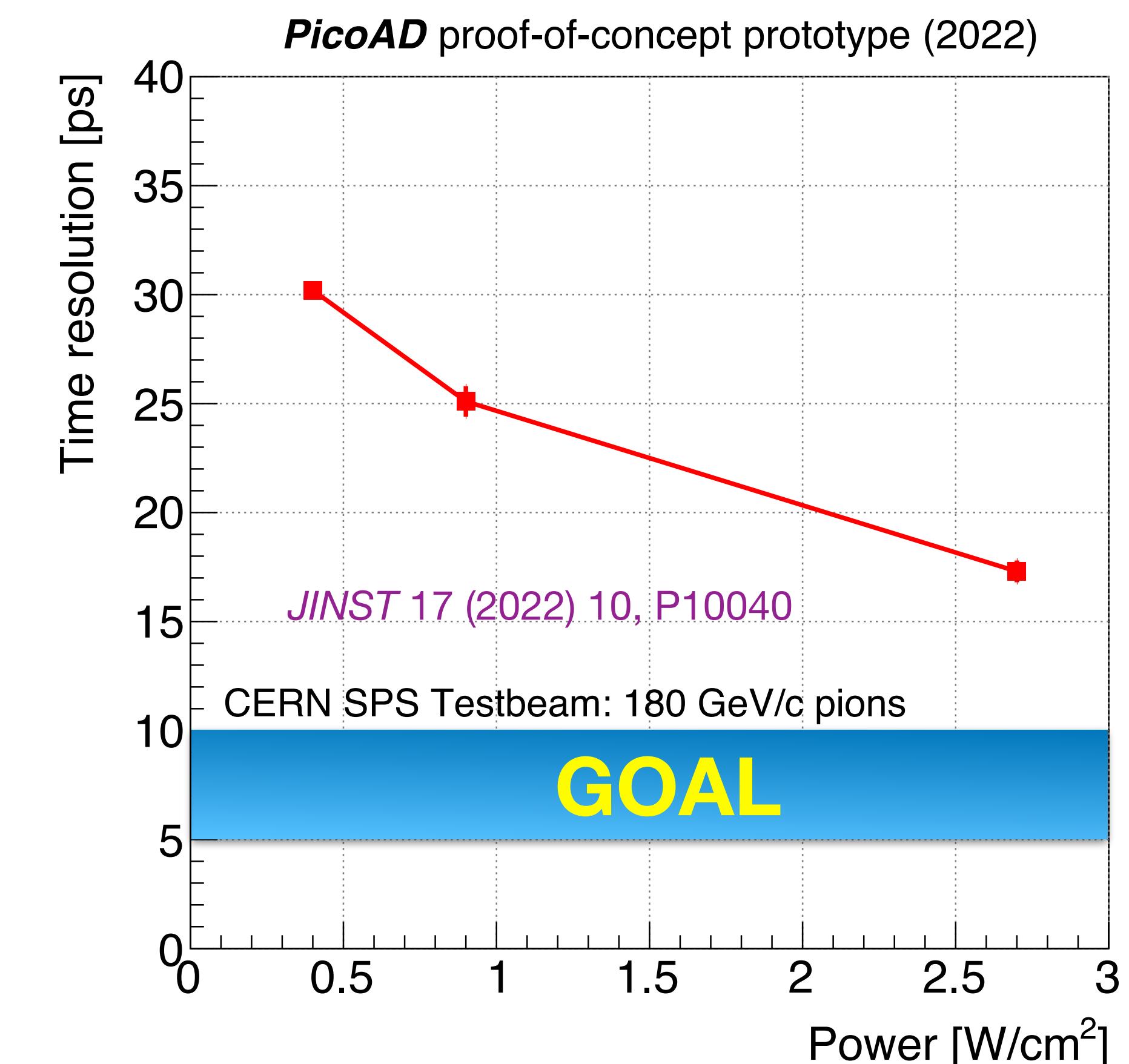
Testbeam results: Time Resolution^[6]



**Best performance: (17.3 ± 0.4) ps
for HV=125 V and Power = 2.7 W/cm^2**



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

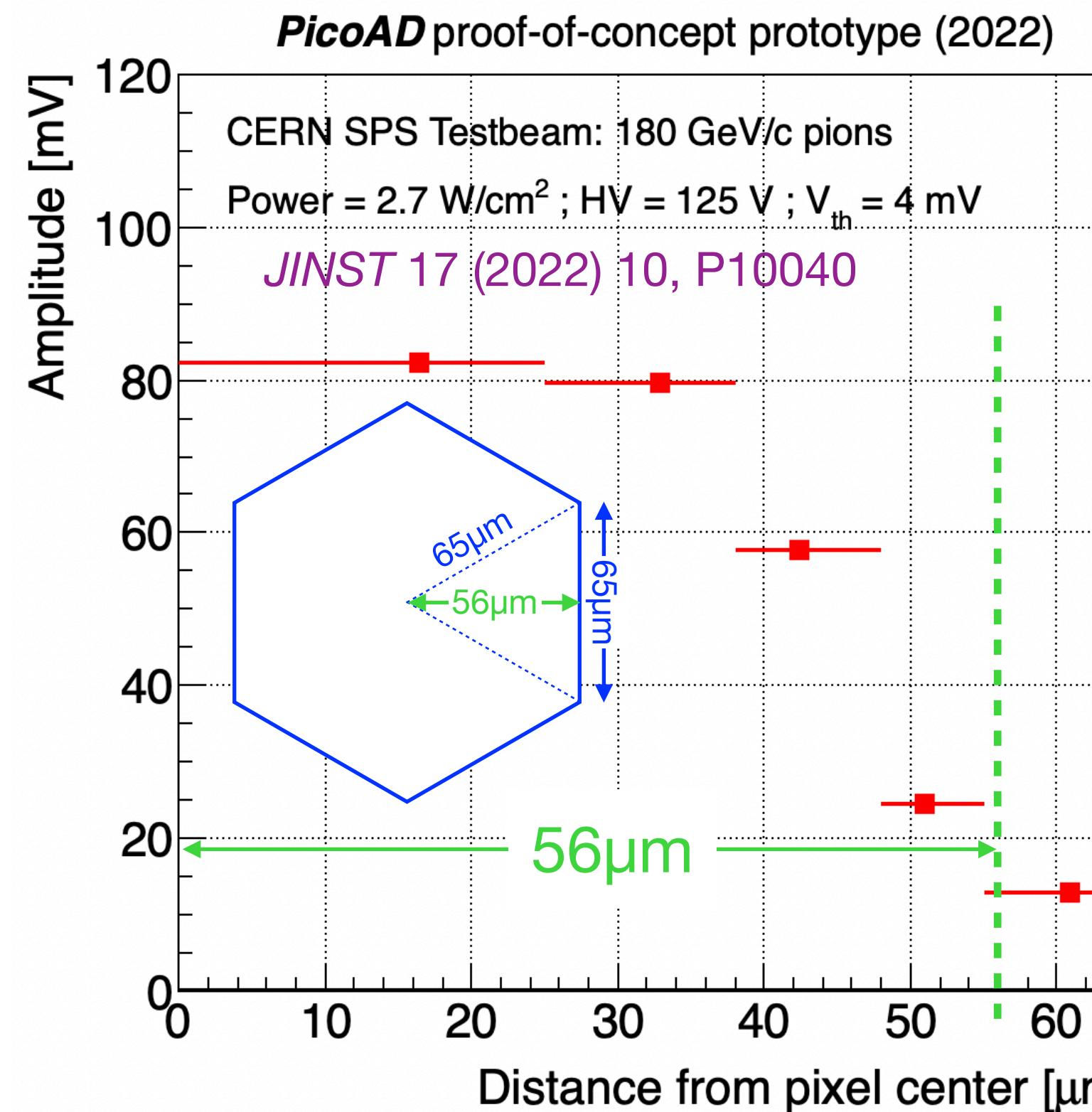




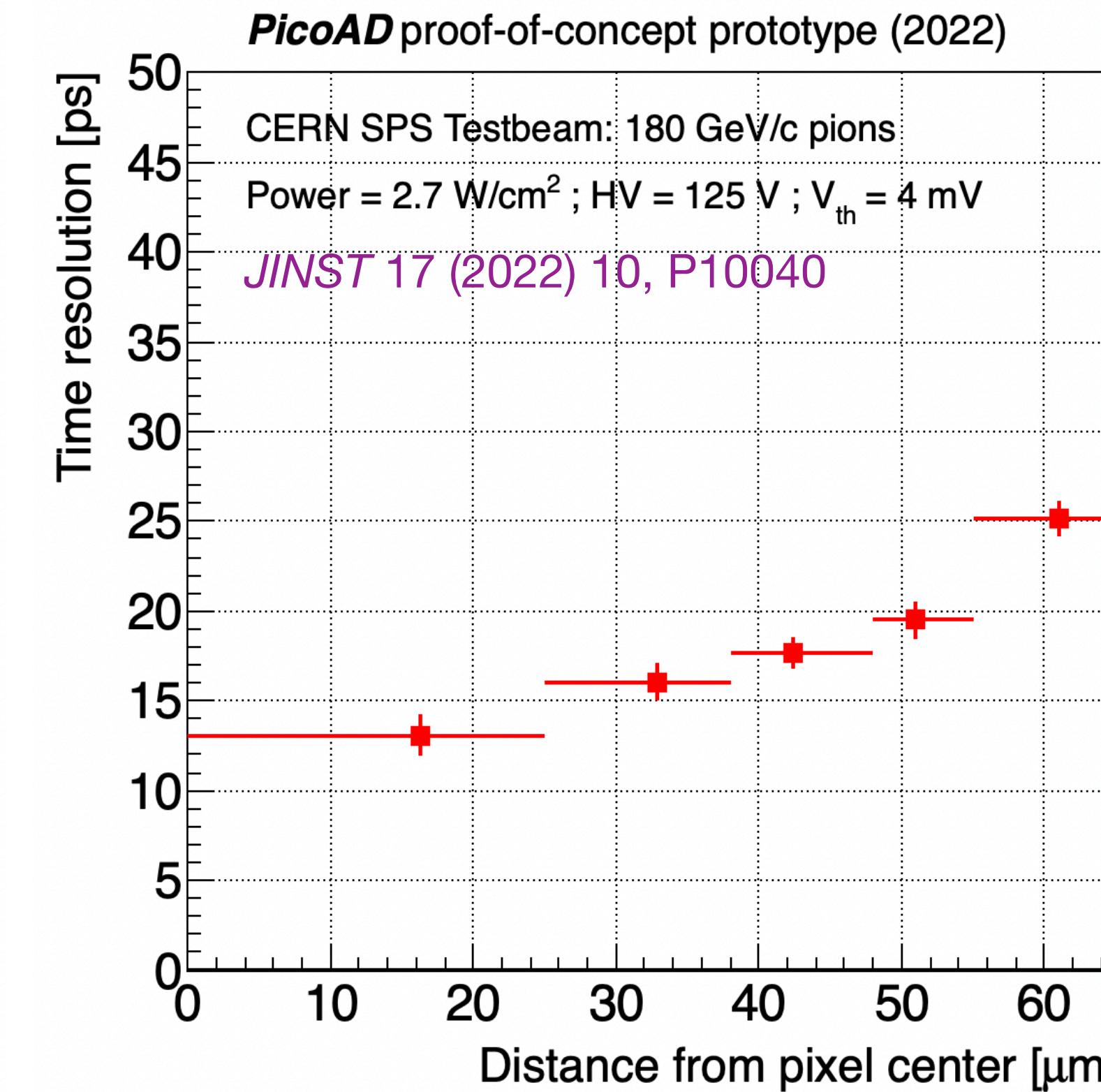
Testbeam results: dependence on position



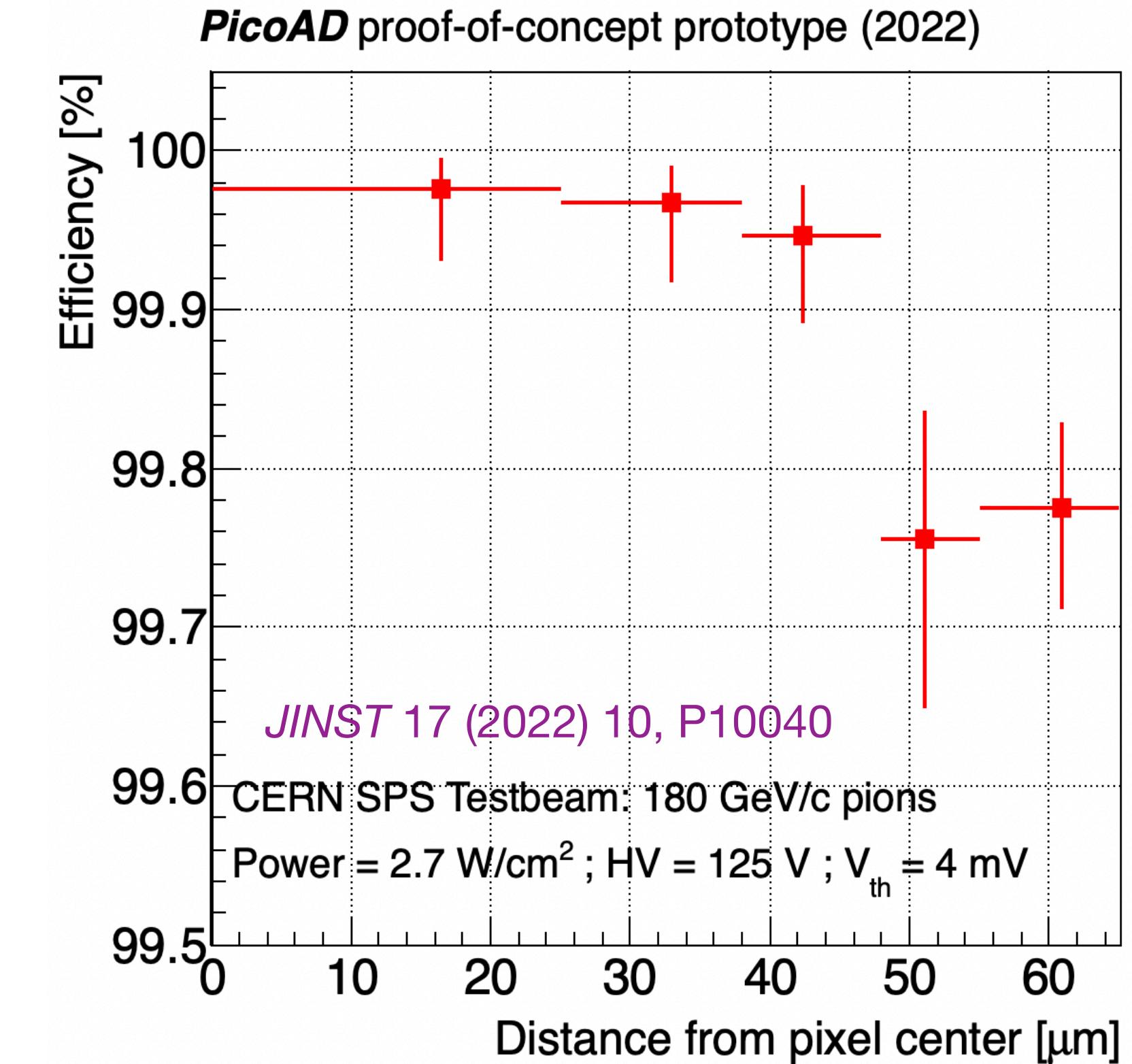
Signal MPV amplitude



Time resolution

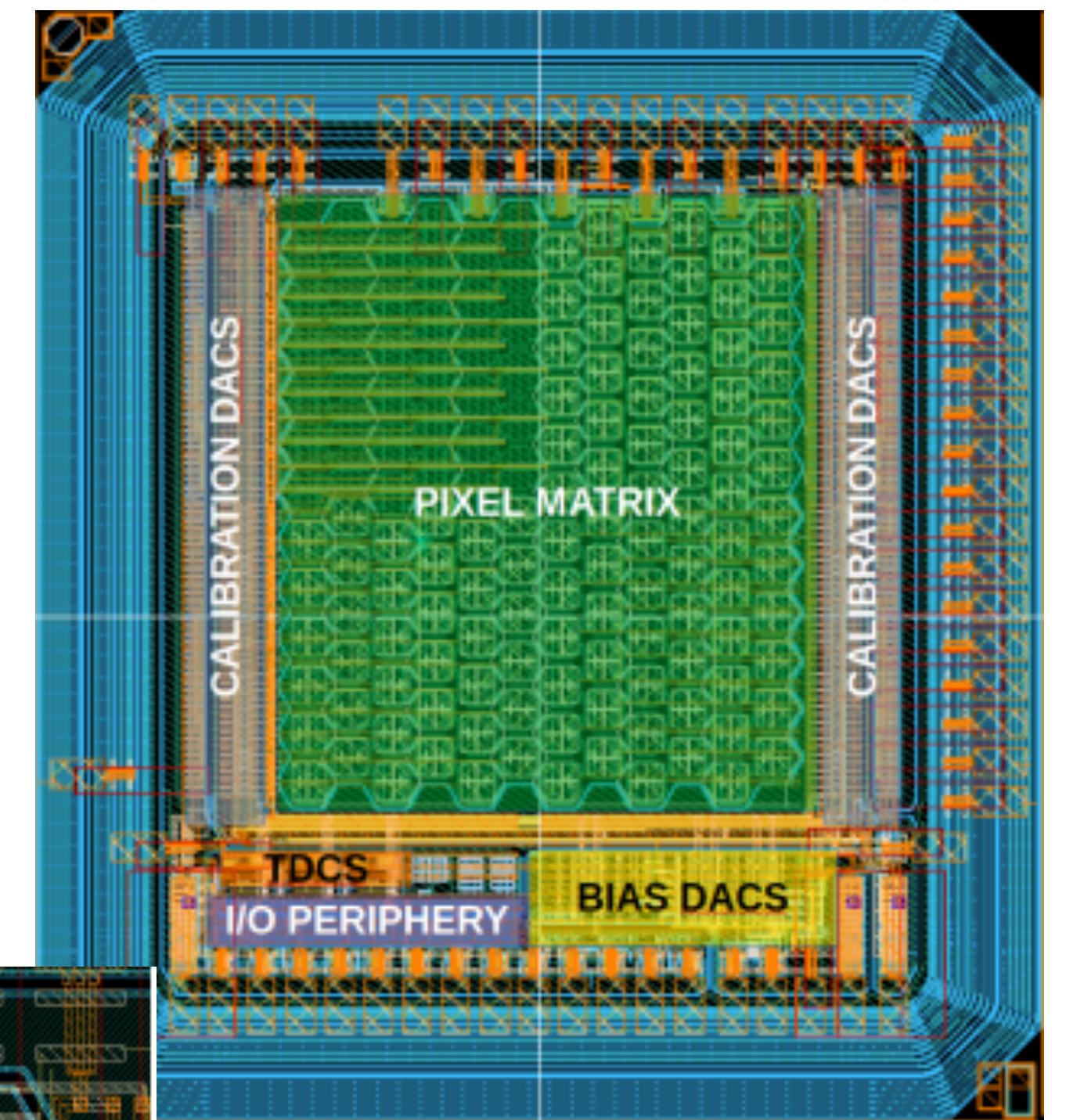


Efficiency



(13.2 ± 0.8) ps at the pixel center

- Same matrix configuration as previous, but
 - ▶ Substrate: $50\Omega\text{cm} \rightarrow 350\Omega\text{cm}$ epilayer, $50\mu\text{m}$ thick on low-res ($1\Omega\text{cm}$) substrate
 - smaller pixel capacitance
 - depletion $26\mu\text{m} \rightarrow 50\mu\text{m}$
 - 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
 - ▶ Differential output, optimised FE layout, high-frequency cables:
 - better rise time ($600\text{ps} \rightarrow 300\text{ps}$)



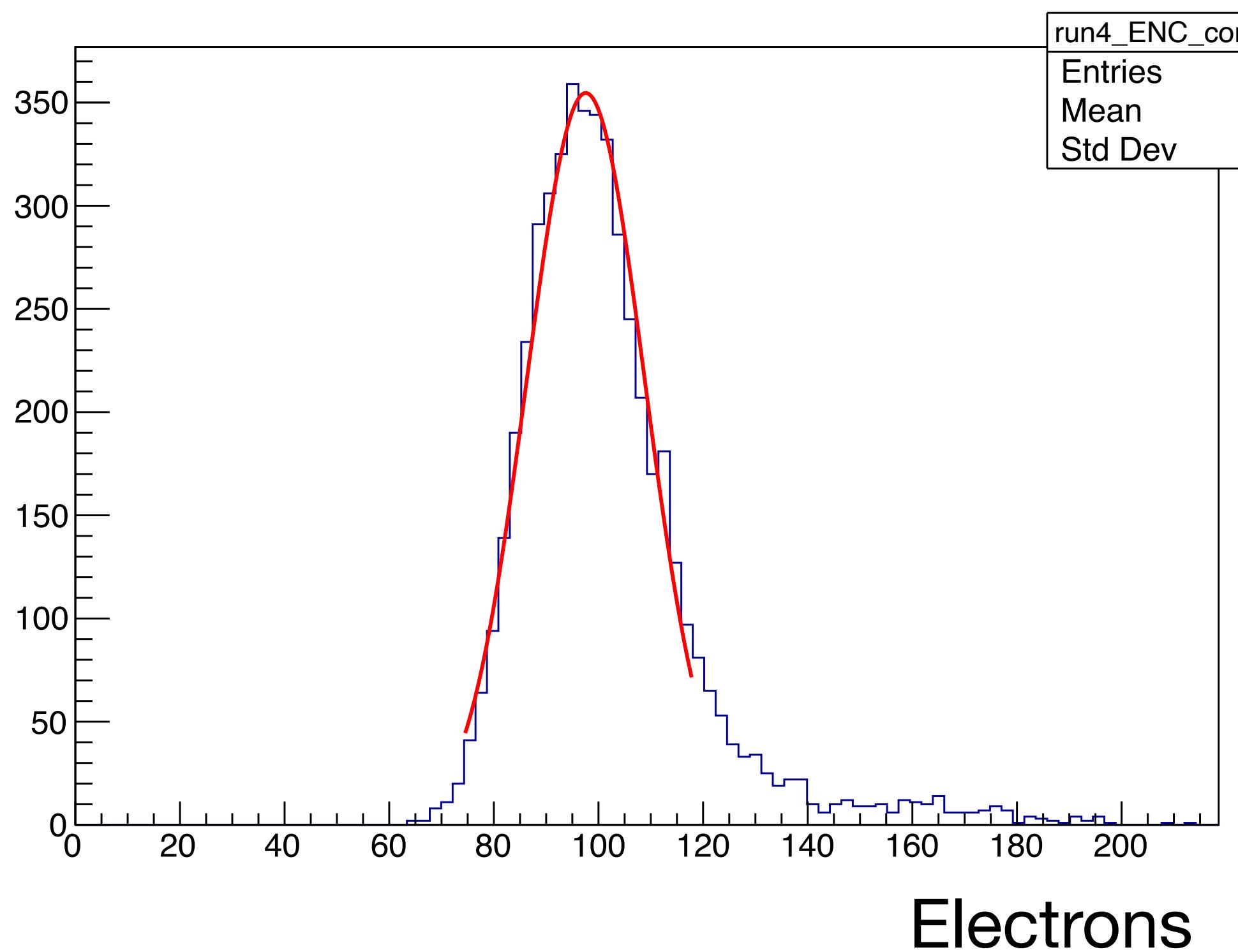


2022 prototype — no gain layer

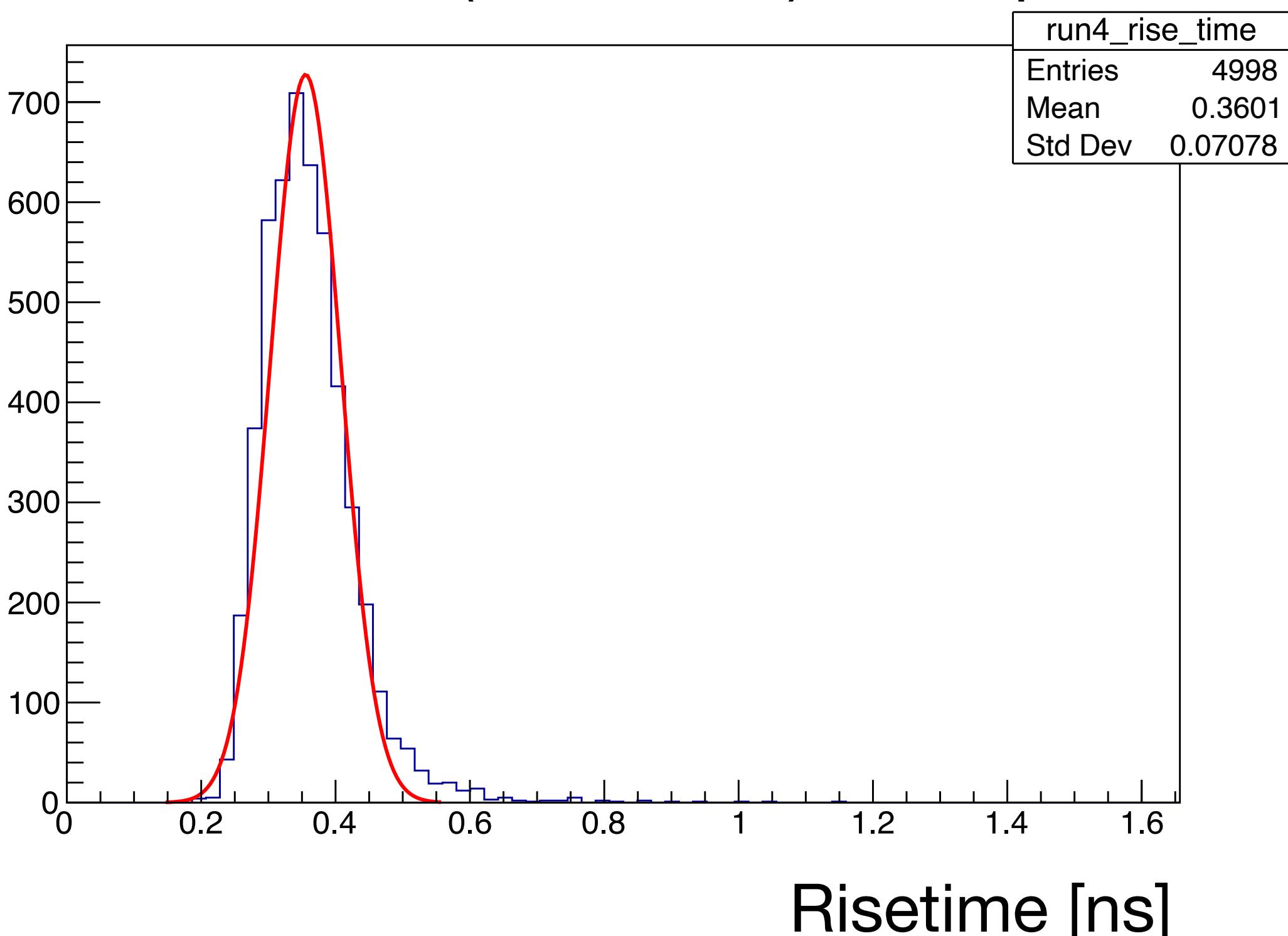


55Fe measurements in cleanroom:

$\text{ENC} \approx 100 \text{ e}^-$

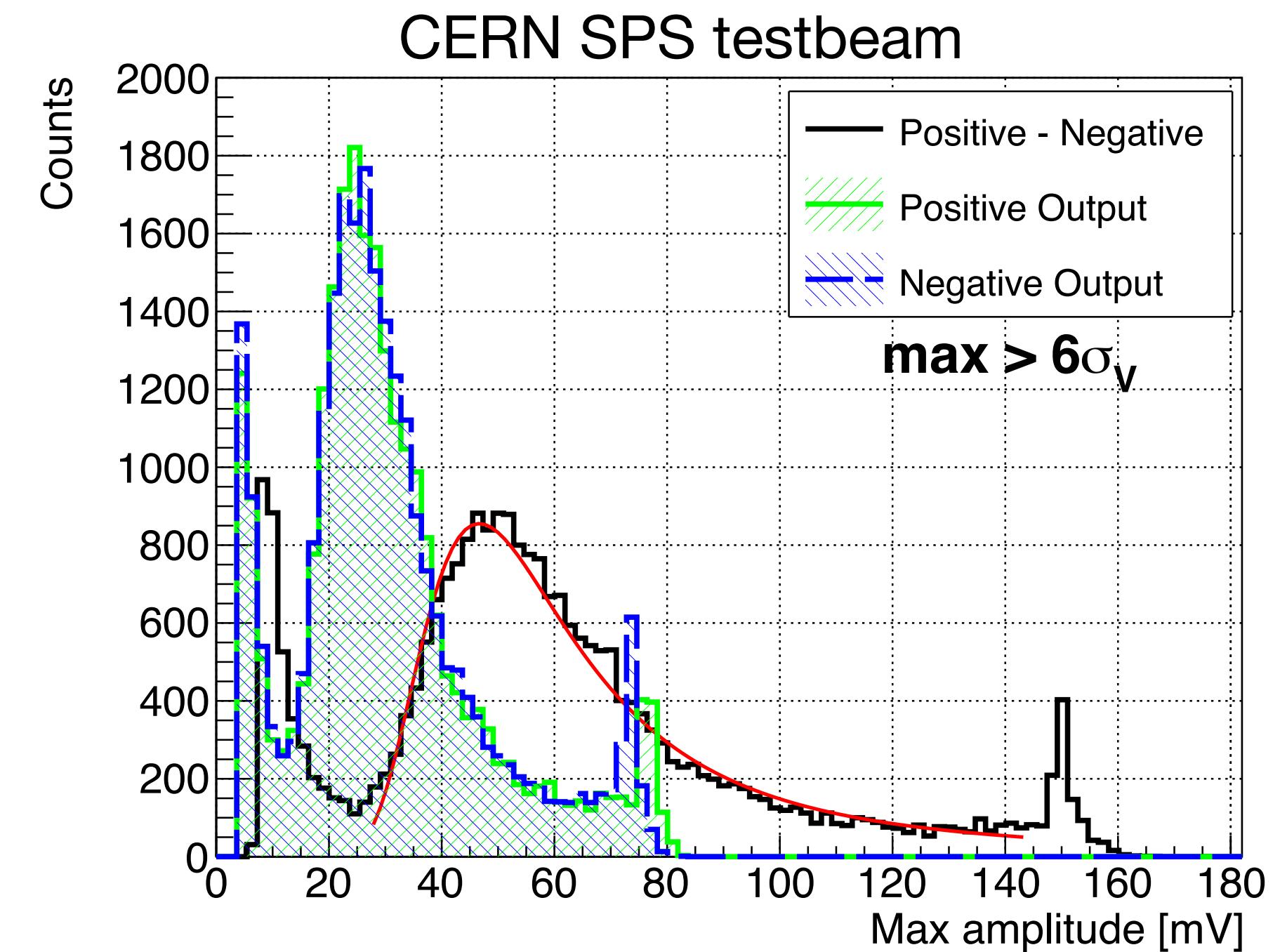
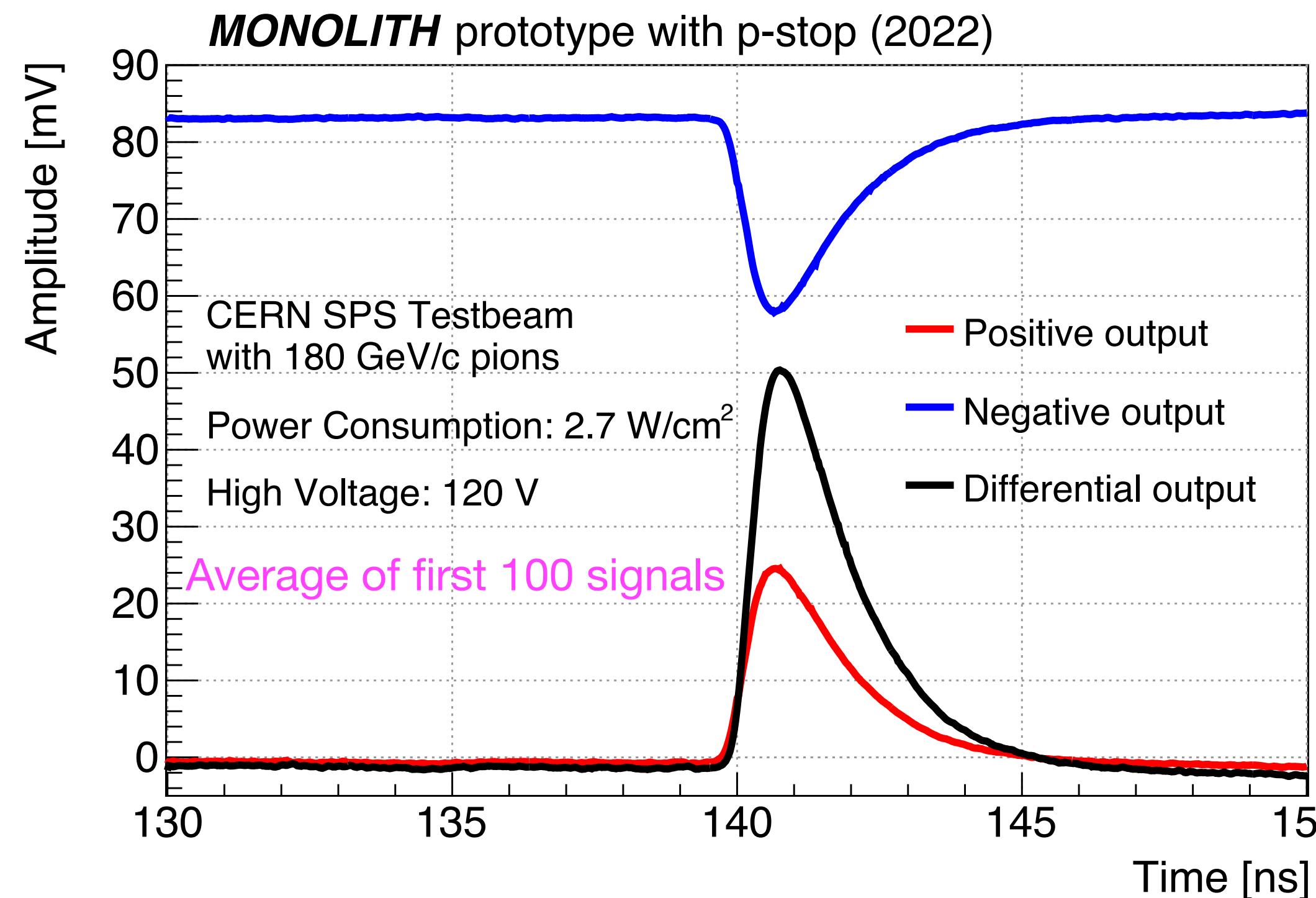


Risetime (20%–80%) $\approx 300 \text{ ps}$



2022 prototype — no gain layer

- Testbeam mid October 2022: DUT + Geneva telescope + **2 MCP's**
 - $\sigma_v \approx 1.2 \text{ mV}$; MPV amplitude of $\approx 50 \text{ mV}$ for the sum of positive and negative signal



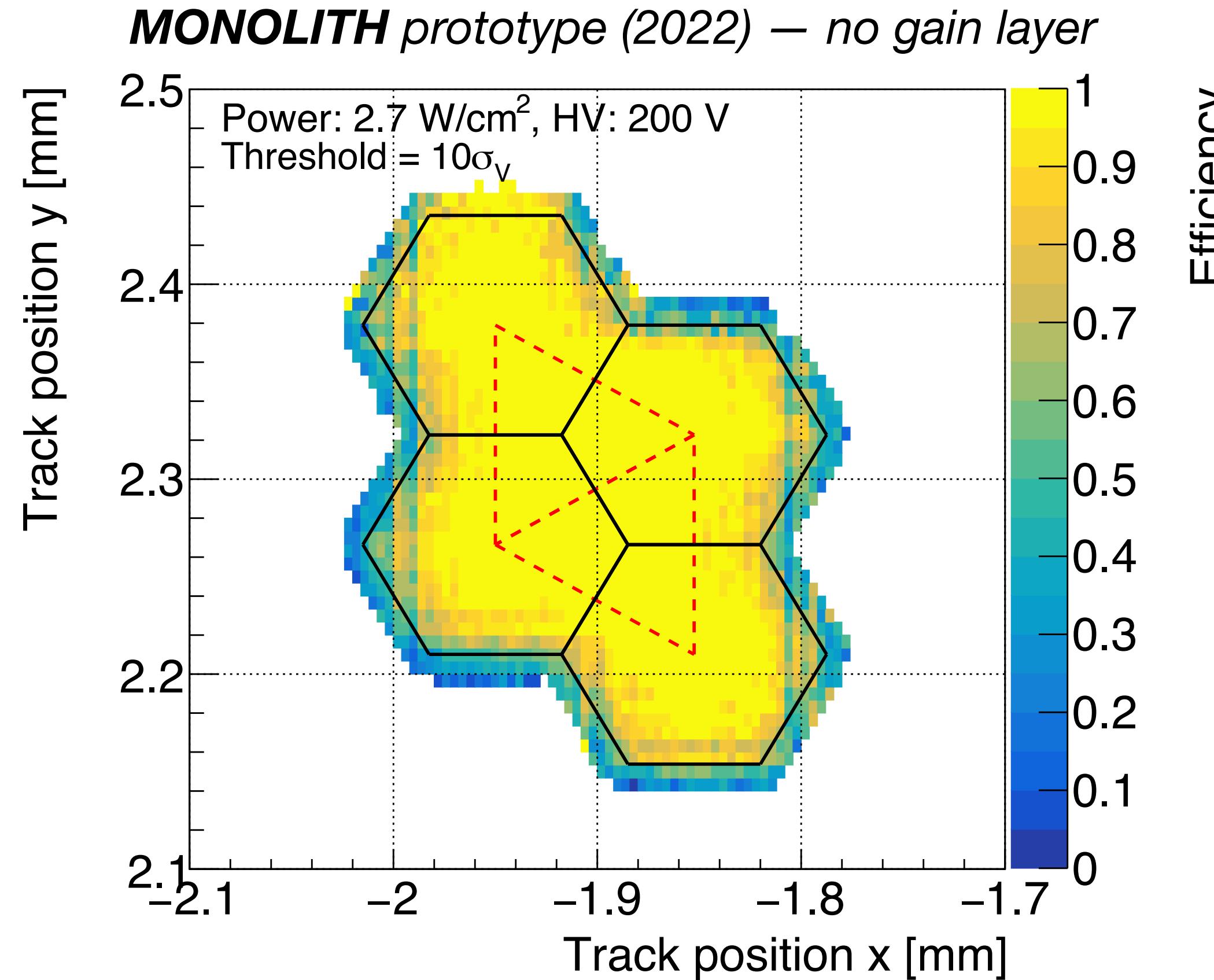
Lots of data taken. Analysis ongoing.

First results already produced

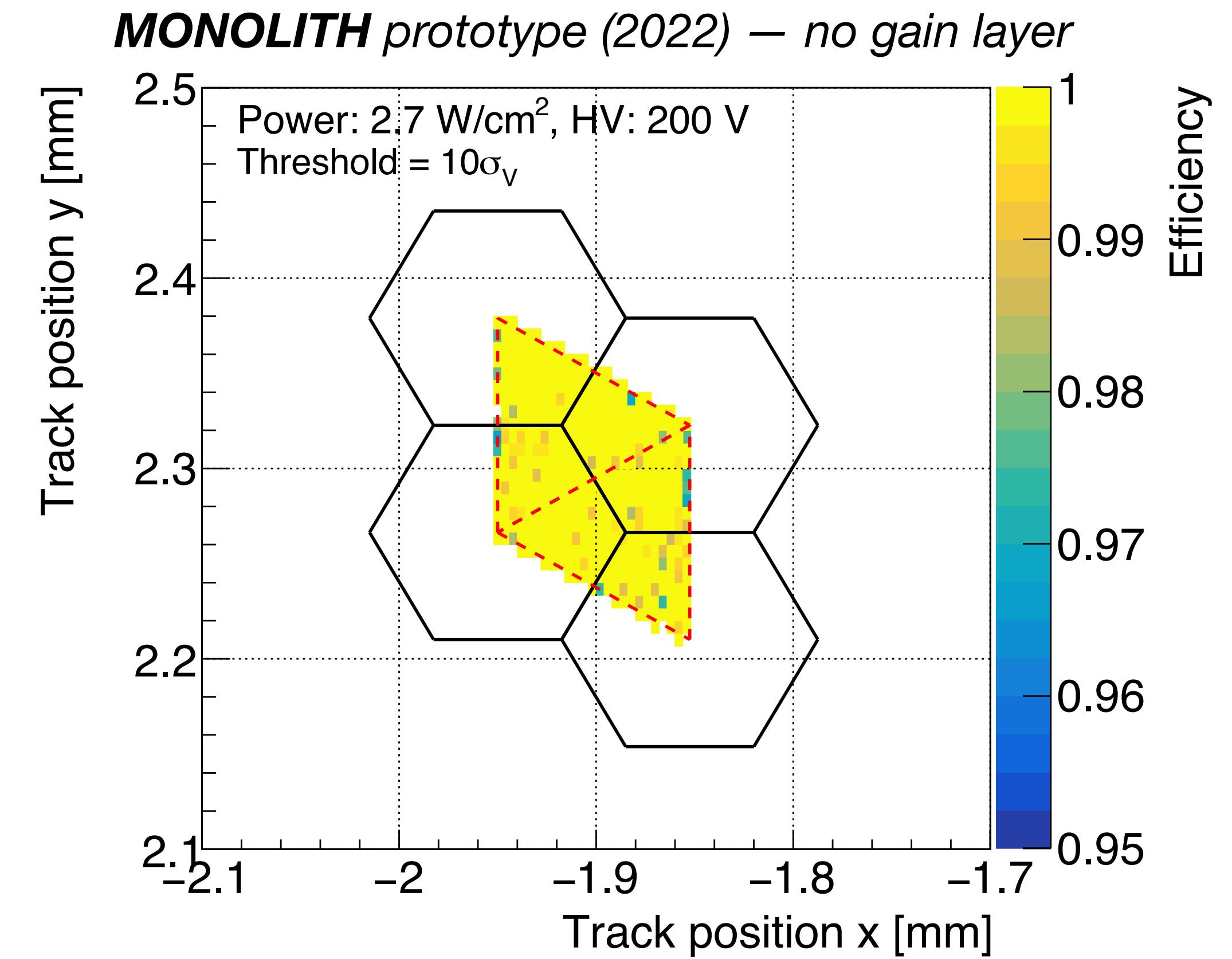




2022 prototype — no gain layer



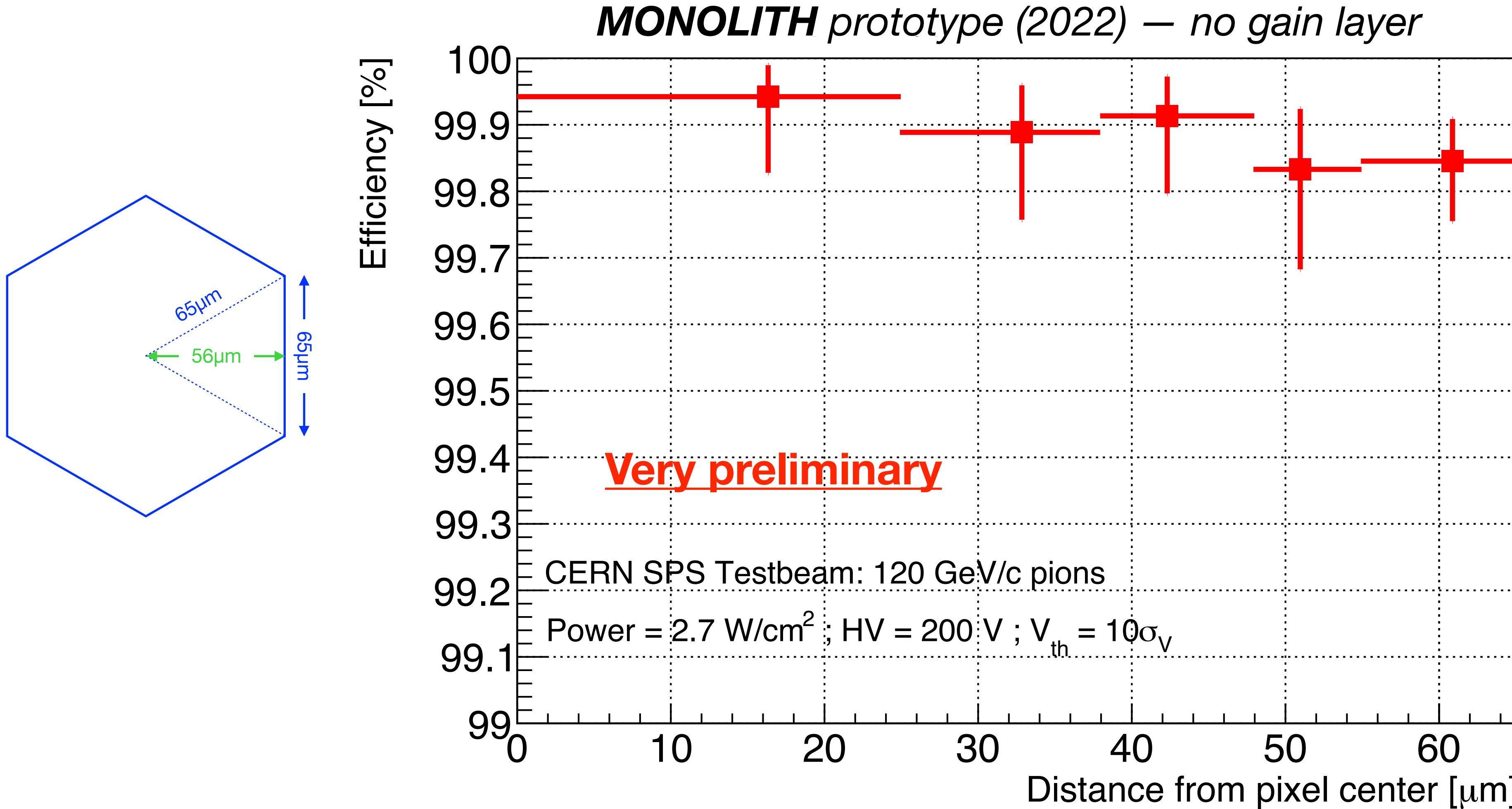
Efficiency at the external edges affected by the telescope resolution of 10 μ m



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



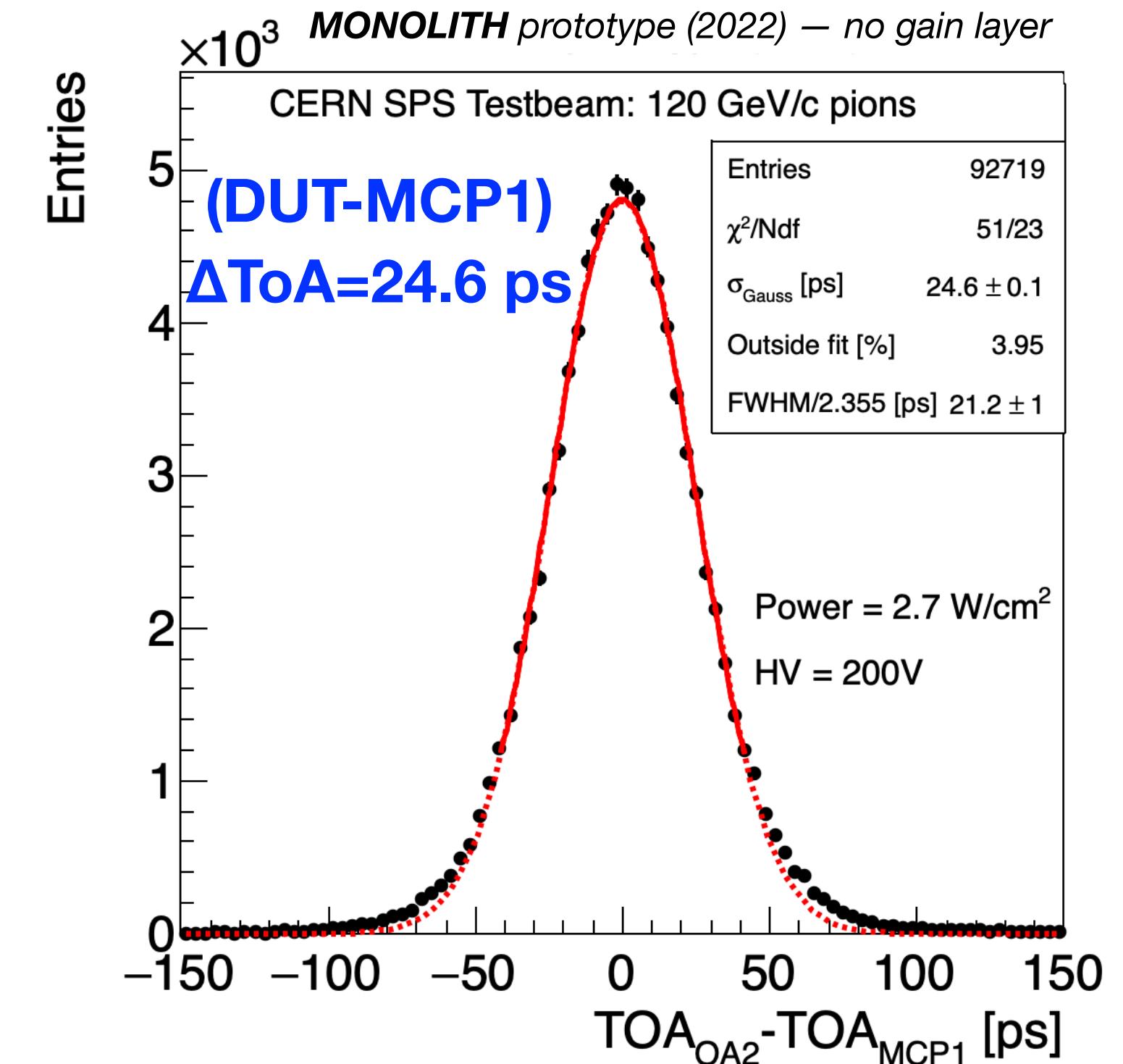
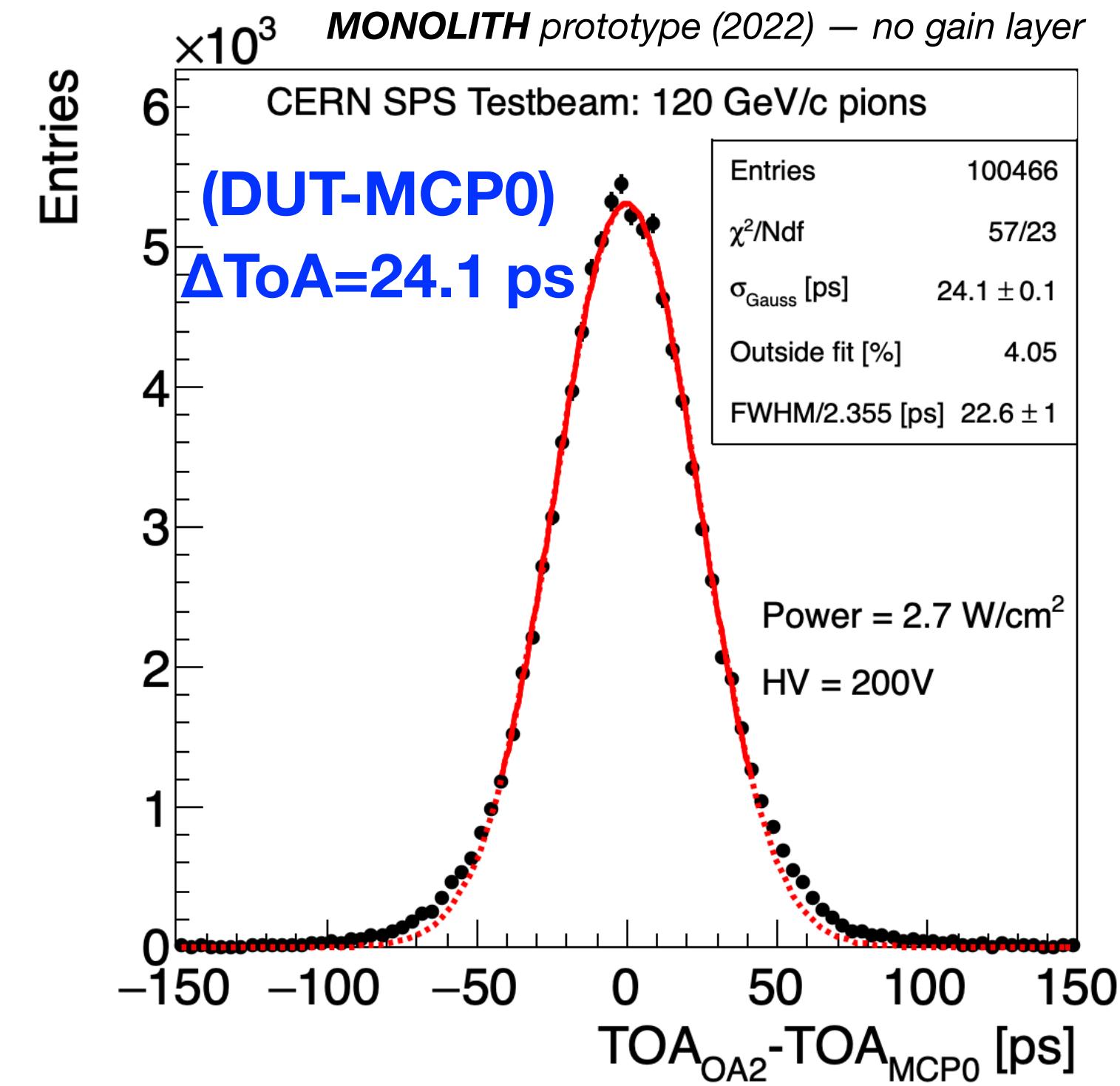
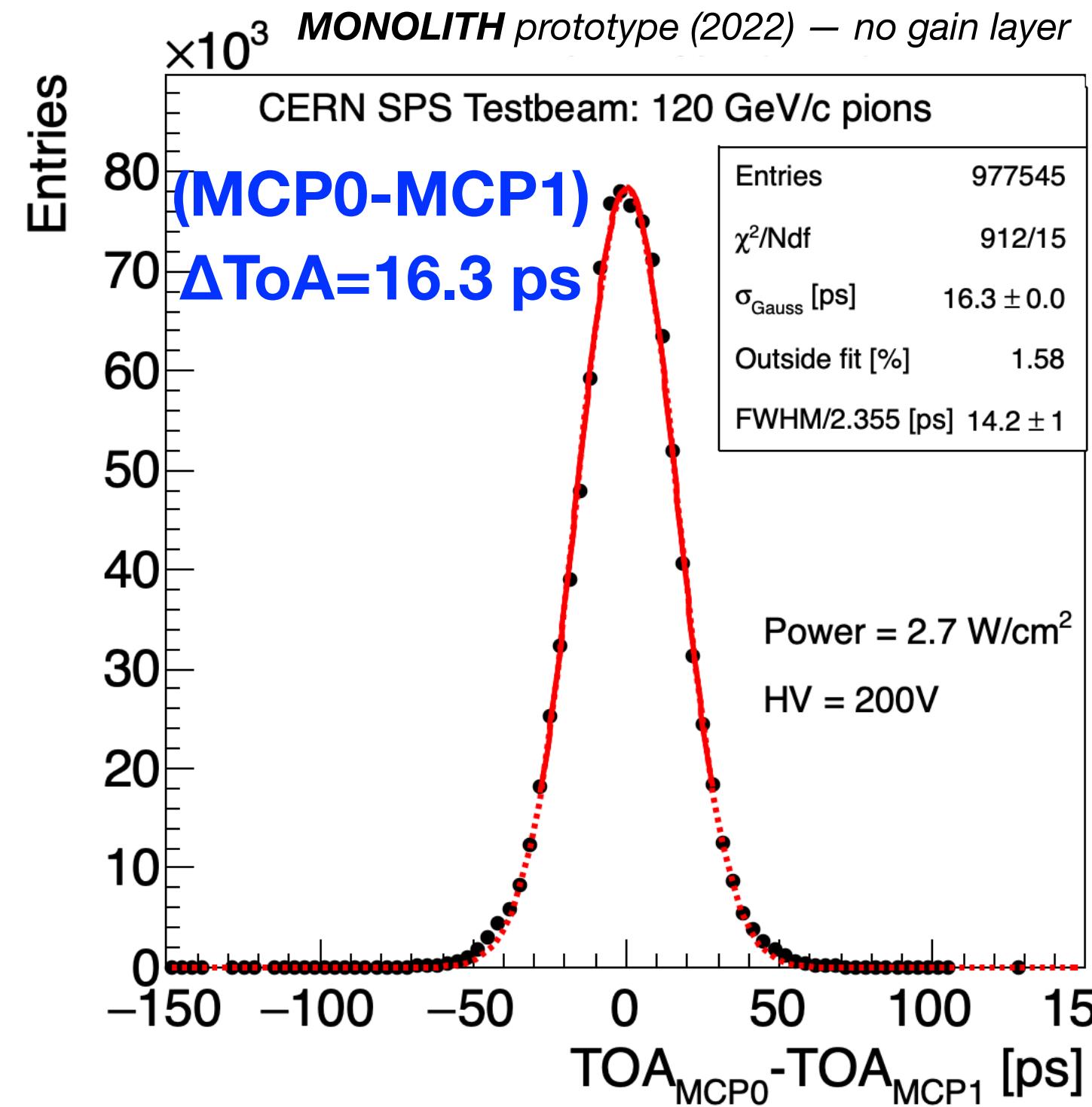
2022 prototype — no gain layer



Efficiency $\approx 99.9\%$ even in the inter pixel region.



2022 prototype — no gain layer

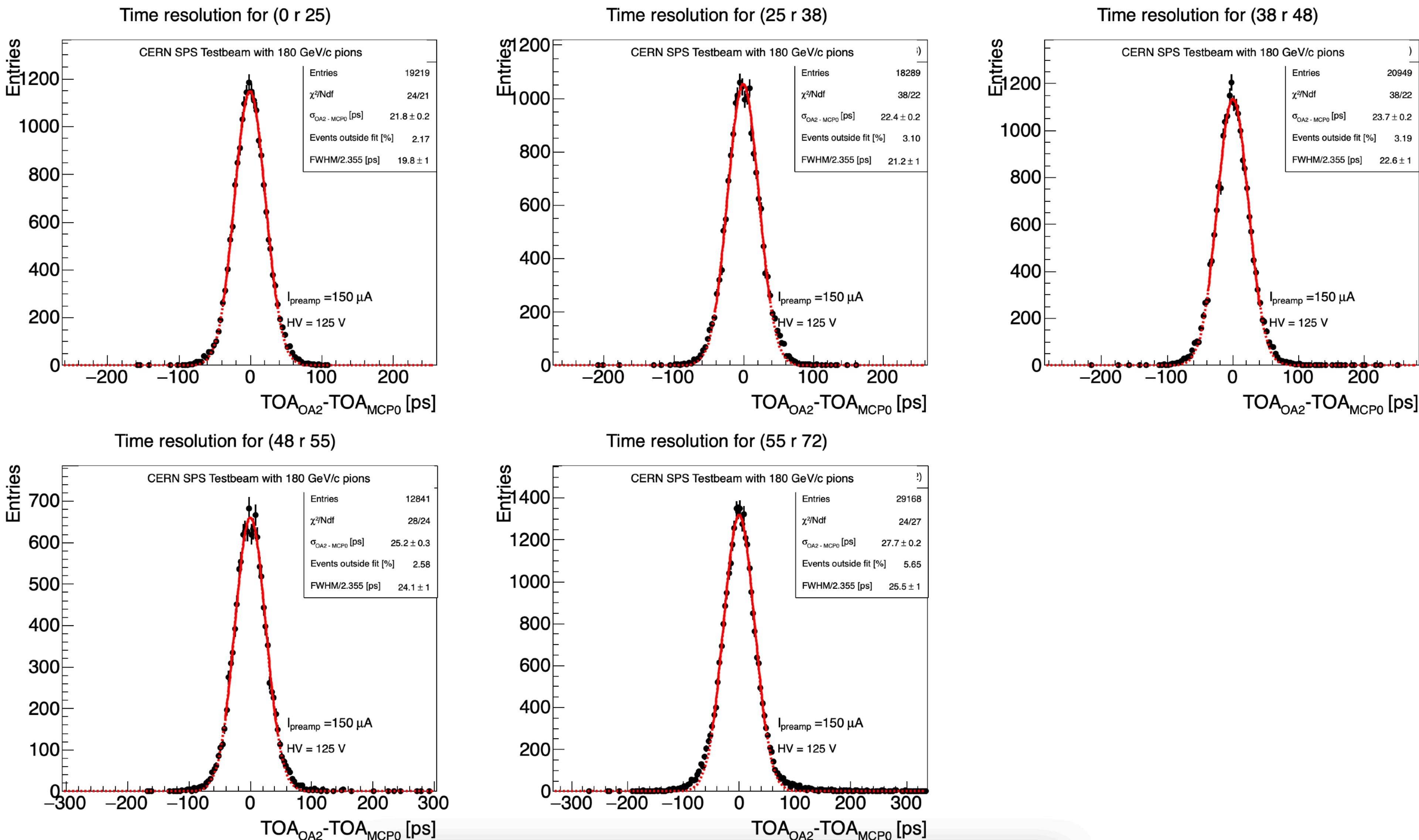


System results: MCP0 $\sigma_T = (11.0 \pm 0.3) \text{ ps}$
MCP1 $\sigma_T = (12.1 \pm 0.3) \text{ ps}$

$\sigma_T = (21.4 \pm 0.2) \text{ ps}$
with non-Gaussian tails of $\approx 4\%$

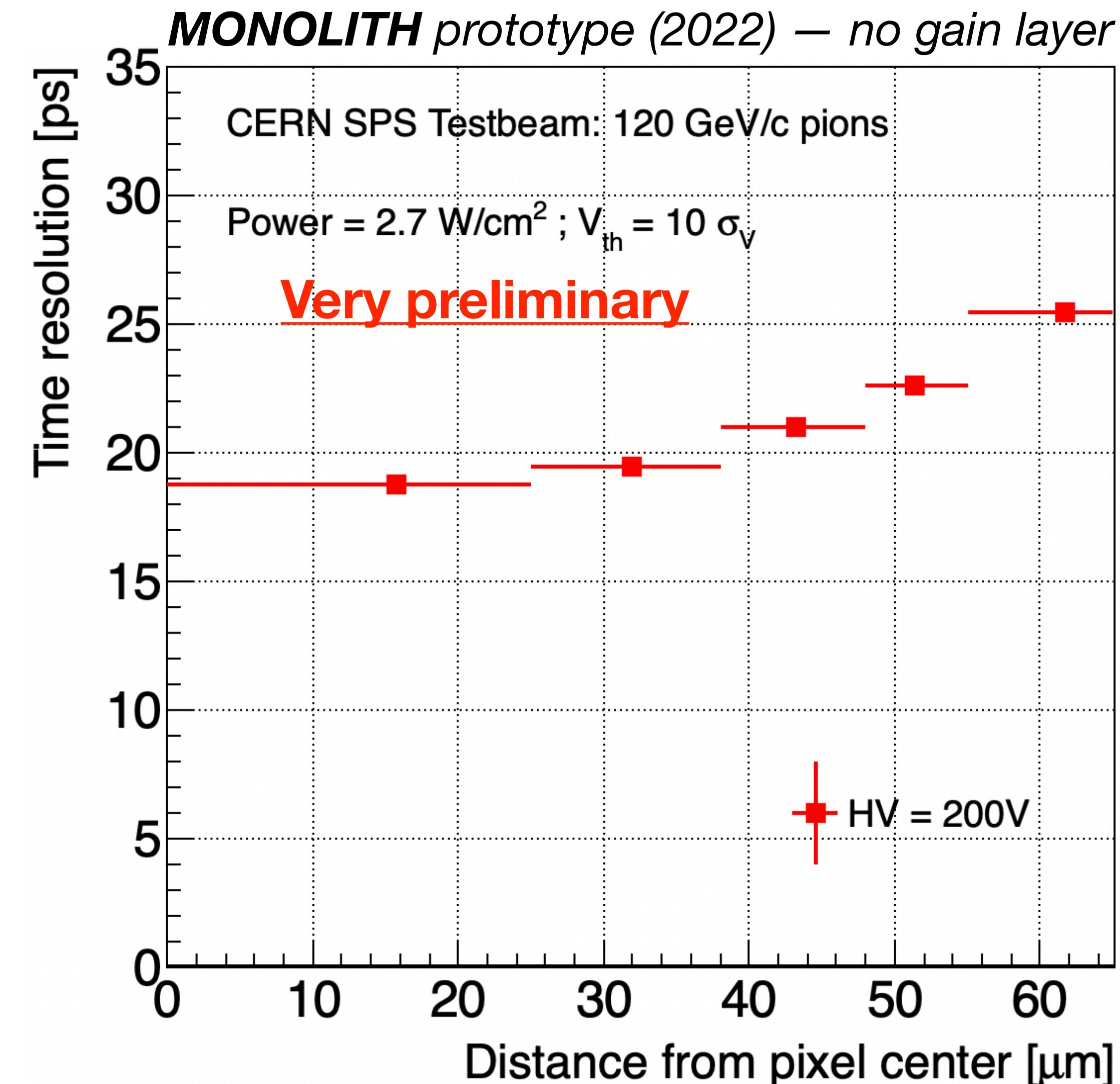


2022 prototype — no gain layer





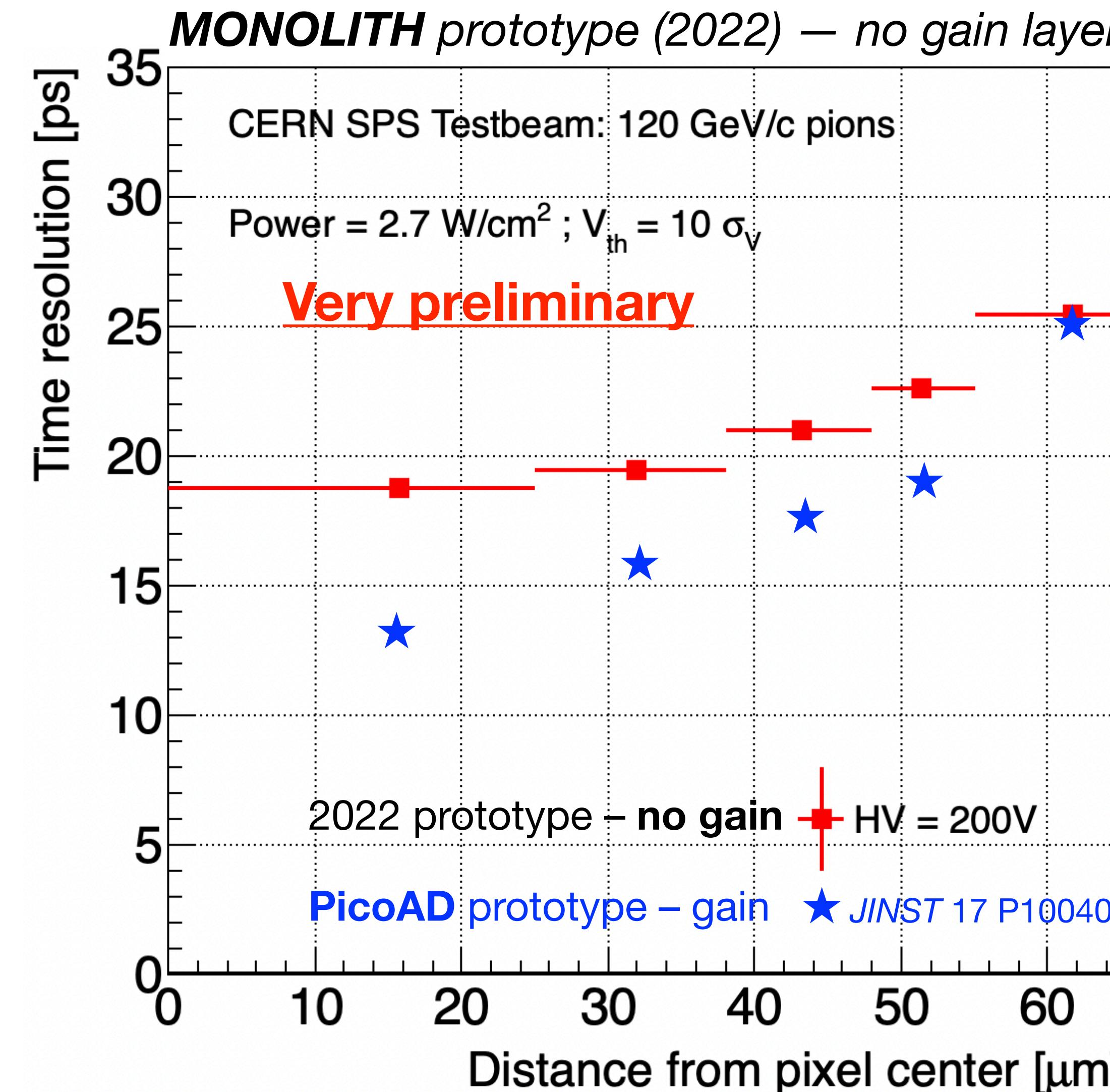
2022 prototype — no gain layer



Time resolution ranges
from ≈ 19 ps at the center
to ≈ 25 ps at the edge of the pixel



2022 prototype — no gain layer



Time resolution ranges from ≈ 19 ps at the center to ≈ 25 ps at the edge of the pixel

Comparison with **2021 PicoAD** proof-of-concept prototype **with gain layer**, shows an improved homogeneity across the pixel, with improved behaviour in the inter-pixel region.

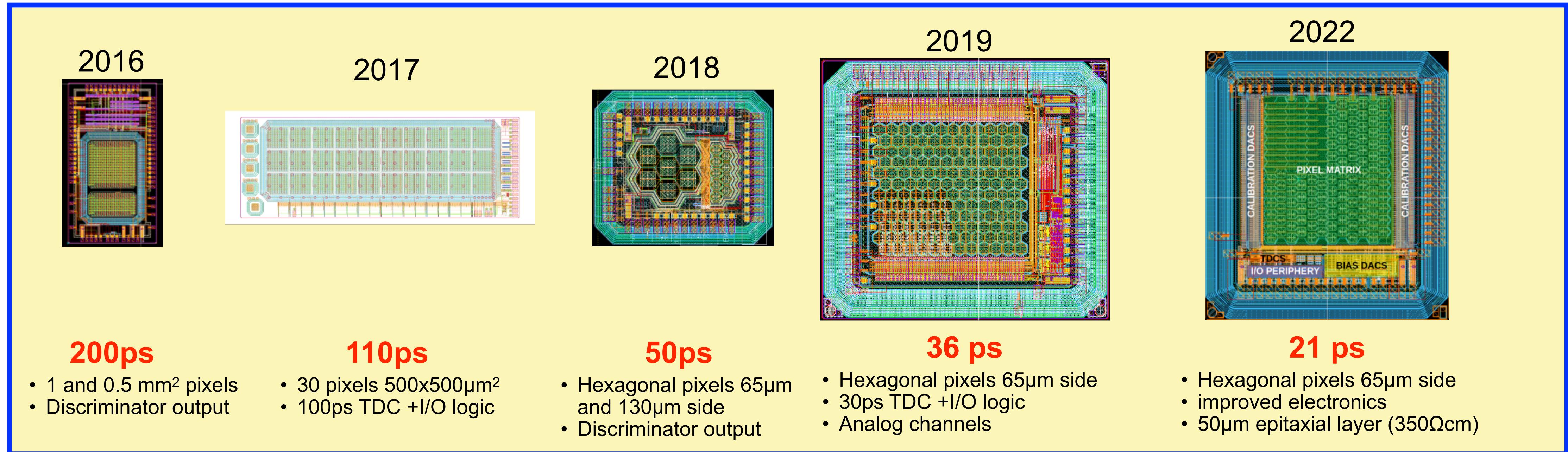
New PicoAD prototype with gain layer will be available in six months.



Monolithic SiGe BiCMOS for timing



Monolithic prototypes with SiGe BiCMOS (without internal gain layer)



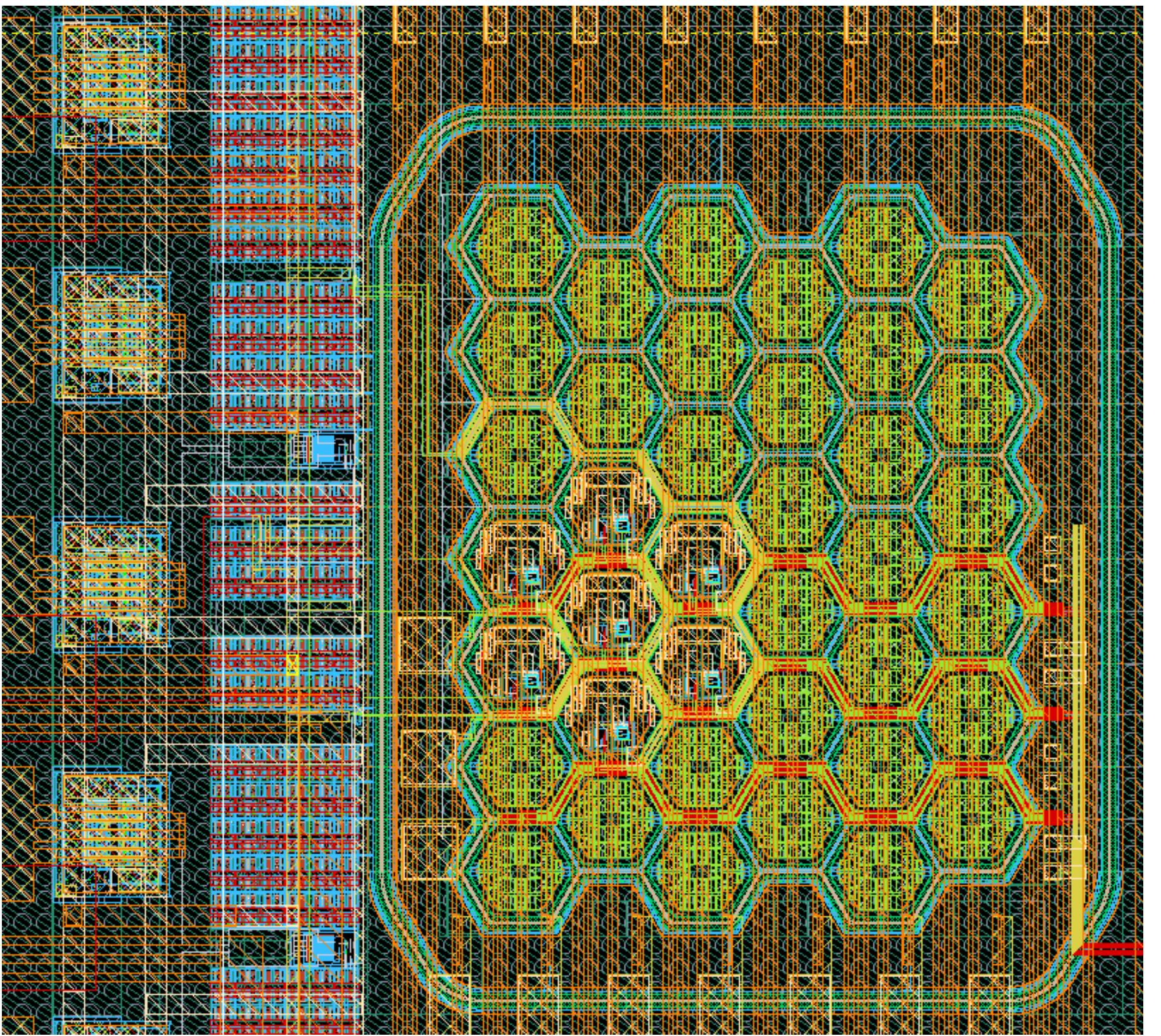


Third MONOLITH prototype: 50μm pitch



- “Flowers” with pixel with 50μm pitch
 - ▶ smaller capacitance
- new FE electronics:
 - ▶ same timing performance with 4-times less power
 - ▶ 3 different configurations:
 - ▶ analog output with FE in pixel
 - ▶ analog output with FE off pixel
 - ▶ discriminated output with FE and discriminator in pixel
 - ▶ reduced inter-pixel distance from 10μm to 6μm to improve time resolution
- Back from foundry on March 2023; PicoAD in September 2023

2022 prototype



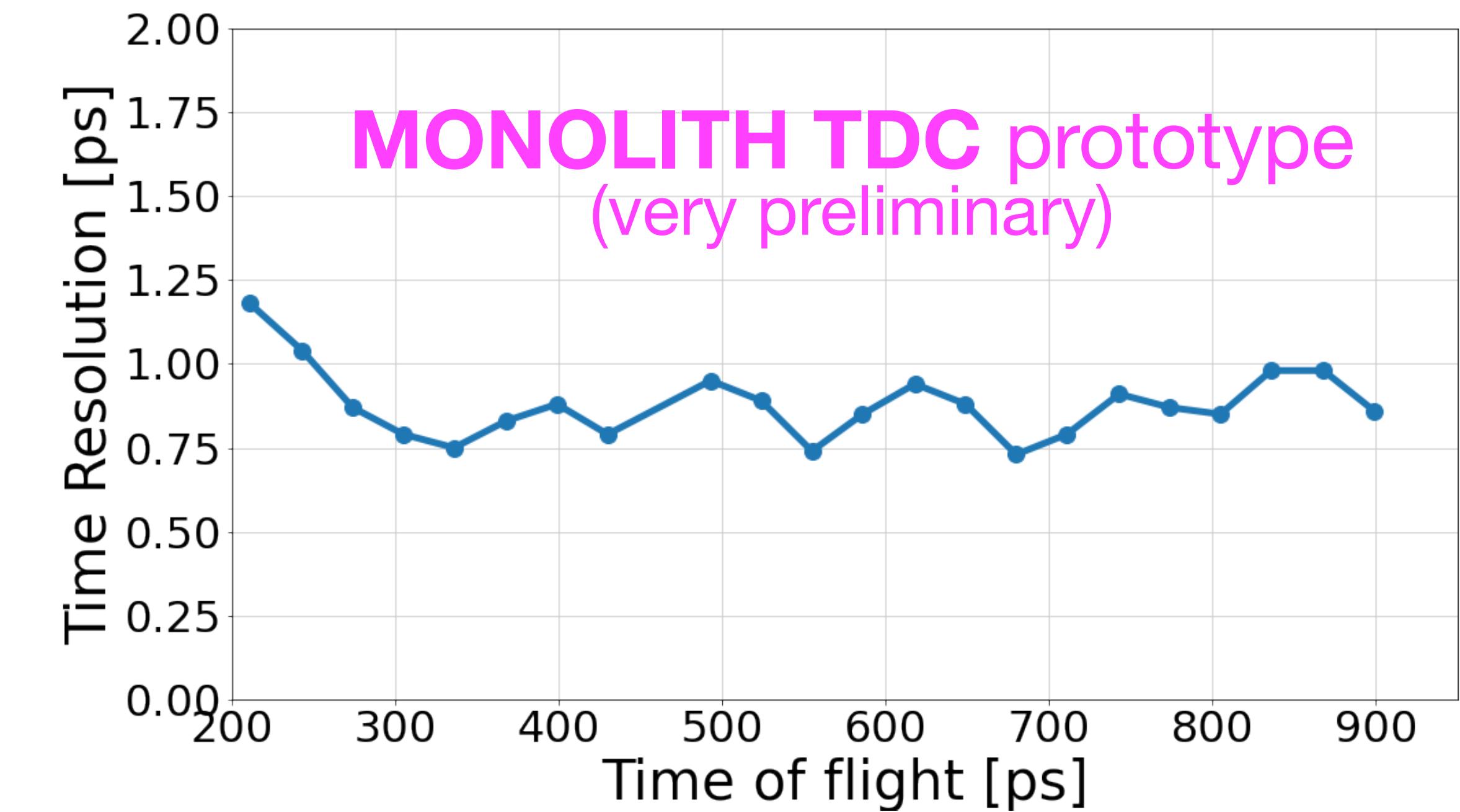
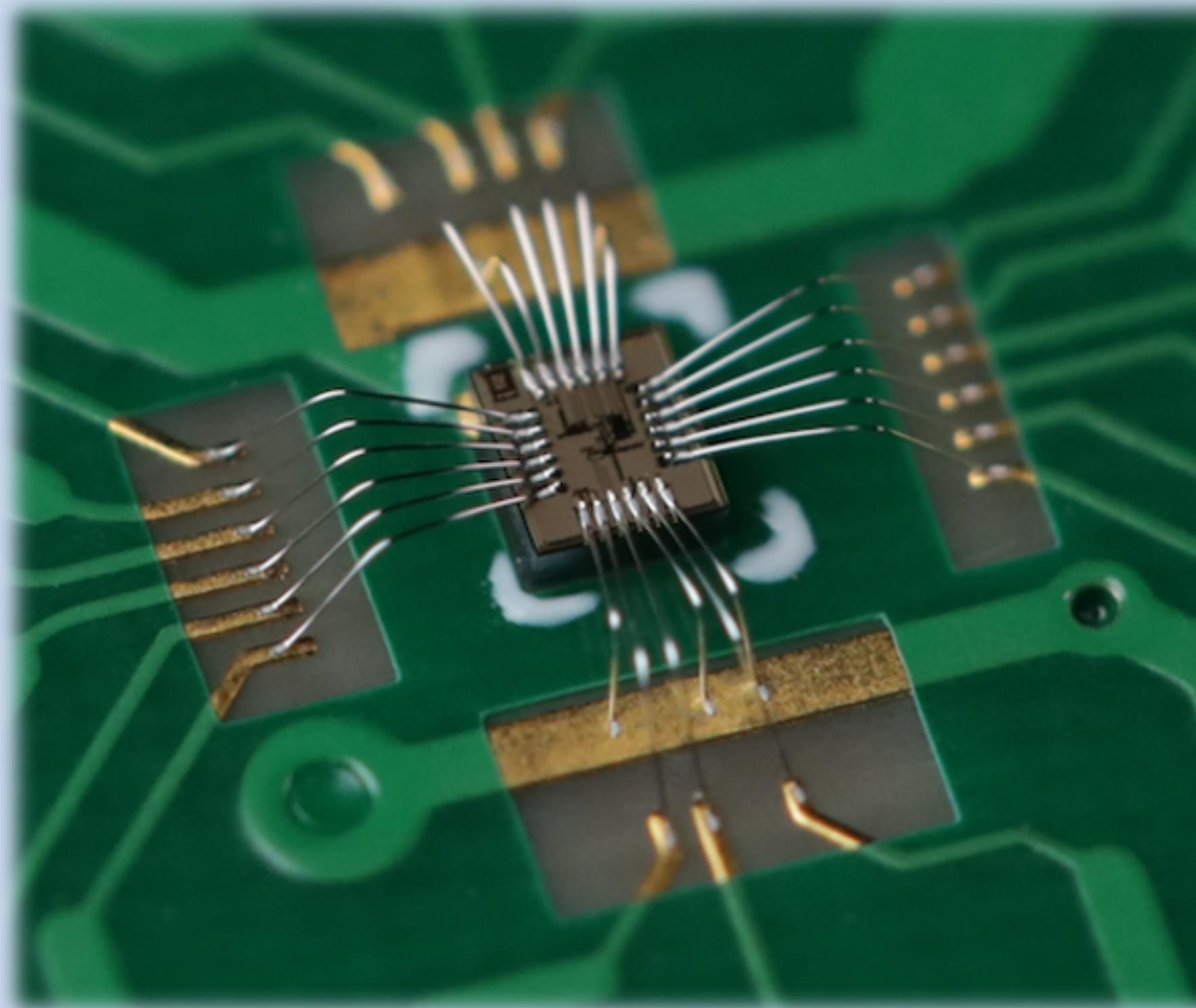


Sub-picosecond TDC



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 $\approx 60\text{-}70$ for mips.
- ▶ **Efficiency = 99.9 %** including inter-pixel regions
- ▶ **Time resolution $\sigma_t = (17.3 \pm 0.4) \text{ ps}$** : 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: **(21.1 \pm 0.2) ps** (very preliminary)
- ▶ 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 will start in 2023 together with IHP and KEK

Deliverable of MONOLITH ERC project:

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