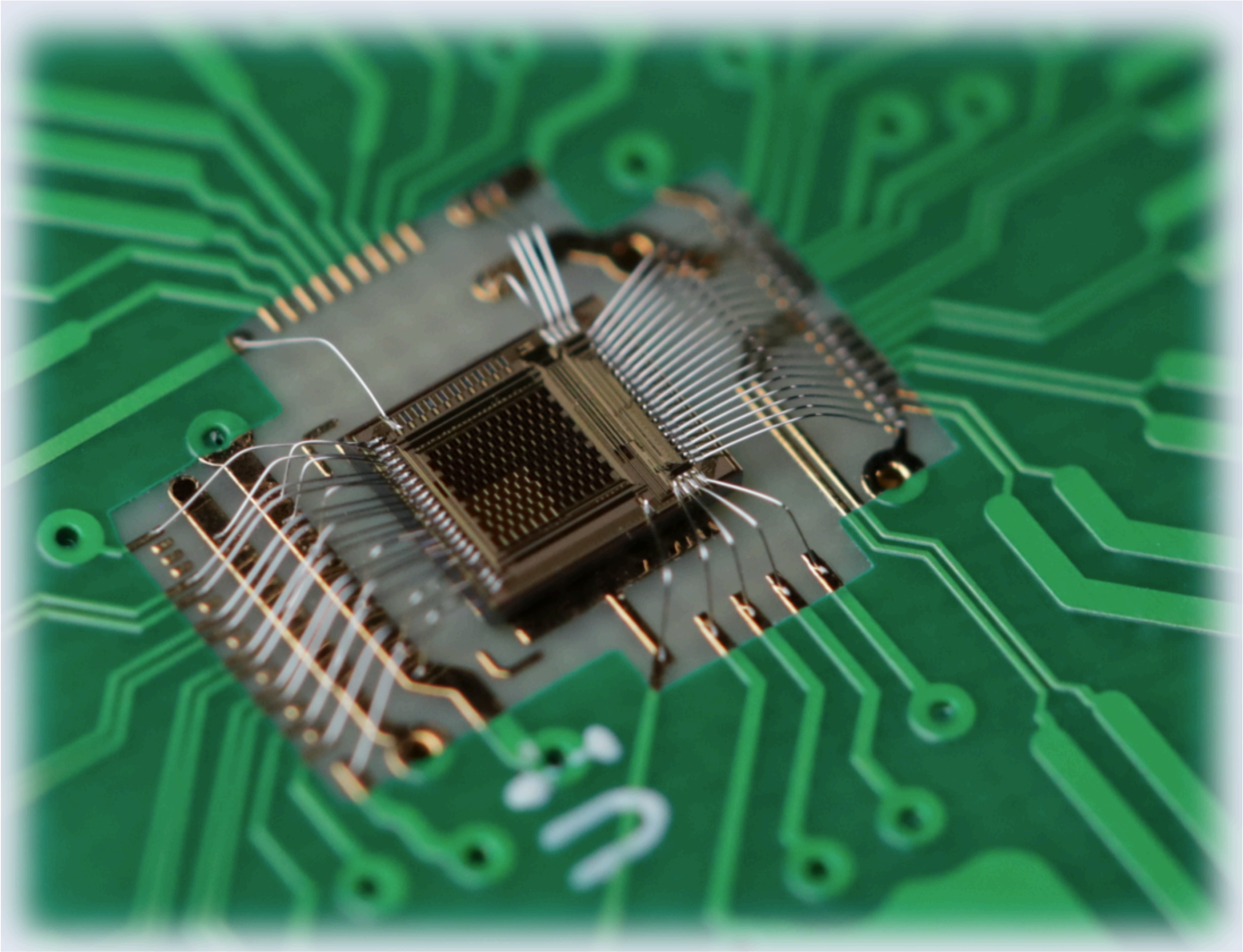
Picosecond Time Stamping Capabilities in Fully-Monolithic Highly-Granular Pixel Sensor

Giuseppe Iacobucci — Université de Genève

UNIVERSITÉ DE GENÈVE
Swiss National Science Foundation
European Research Council
Established by the European Commission

Outline

- The MONOLITH ERC Project
- PicoAD sensor: design concepts
- Gain measurements
- Test Beam measurements:
  - Efficiency & Time Resolution
- Other projects using our technology

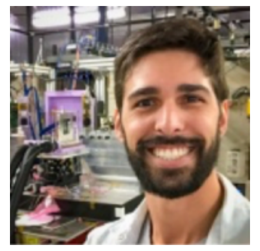


The UniGe Silicon Team

Giuseppe Iacobucci
- project P.I.
- System design

Thanushan Kugathasan
- Lead chip design
- Digital electronics

Roberto Cardella
- Sensor design
- Laboratory test



Mateus Vicente
- System integration
- Laboratory test

Matteo Milanesio
- Laboratory test
- Data analysis

Antonio Picardi
- Chip design
- Firmware

Jihad Saidi
- Laboratory test
- Data analysis

Carlo Alberto Fenoglio
- Chip design
- Firmware

Lorenzo Paolozzi
- Sensor design
- Analog electronics

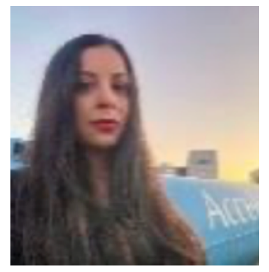
Magdalena Munker
- Sensor design
- Laboratory test

Stefano Zambito
- Laboratory test
- Data analysis

Fulvio Martinelli
- Chip design
- Firmware

Théo Moretti
- Laboratory test
- Data analysis

Chiara Magliocca
- Laboratory test
- Data analysis



Rafaella Kotitsa
- Sensor simulation

Luca Iodice
- Chip design
- Firmware

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:

Roberto Cardarelli
INFN Rome2 & UNIGE

Holger Rücker
IHP Mikroelektronik

Marzio Nessi
CERN & UNIGE

Bernd Heinemann
IHP Mikroelektronik

Funded by:

Swiss National Science Foundation

European Research Council – Established by the European Commission

Sinergia

ATTRACT

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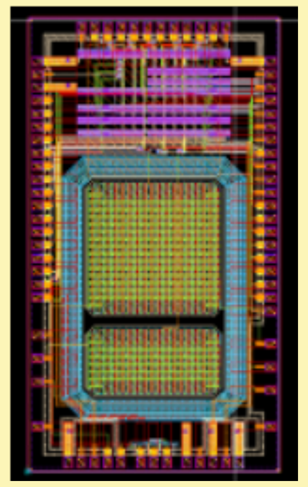
MONOLITH: First PicoAD Prototype

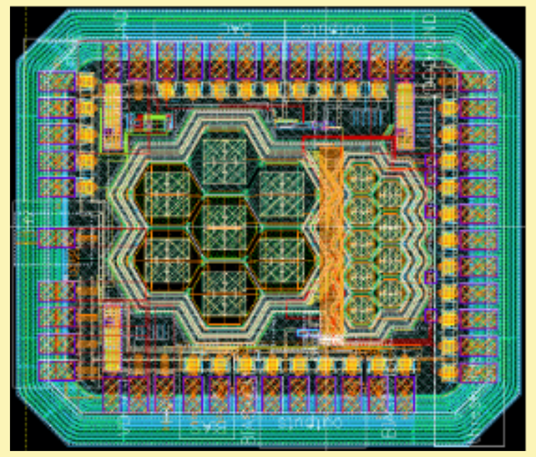
Prototypes without internal gain layer

2016

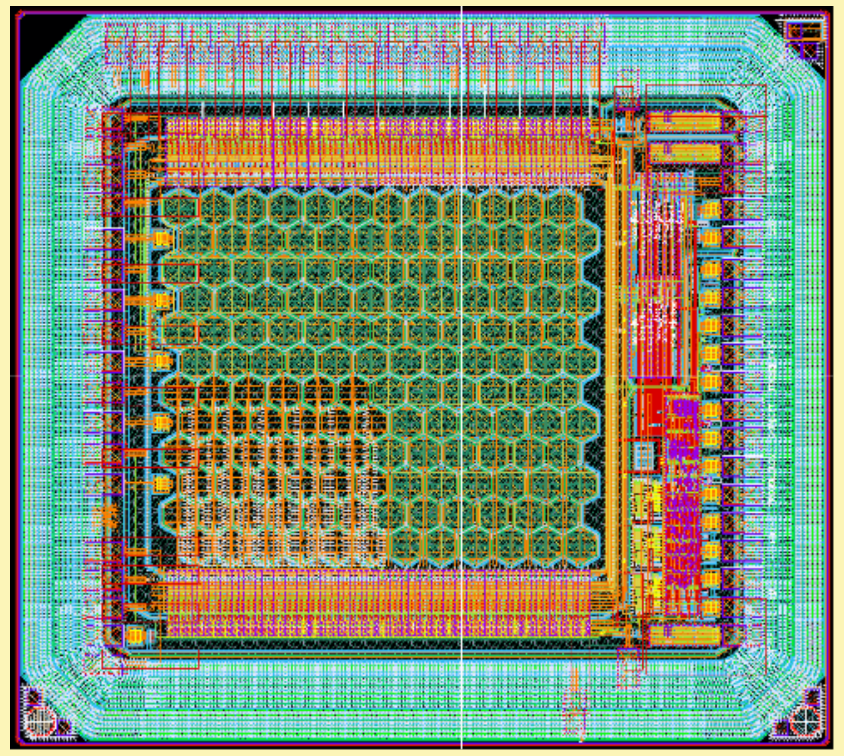


2017

2018



2019



200ps
- 1 and 0.5 mm^2 pixels
- Discriminator output

110ps
- 30 pixels 500x500µm^2
- 100ps TDC +I/O logic

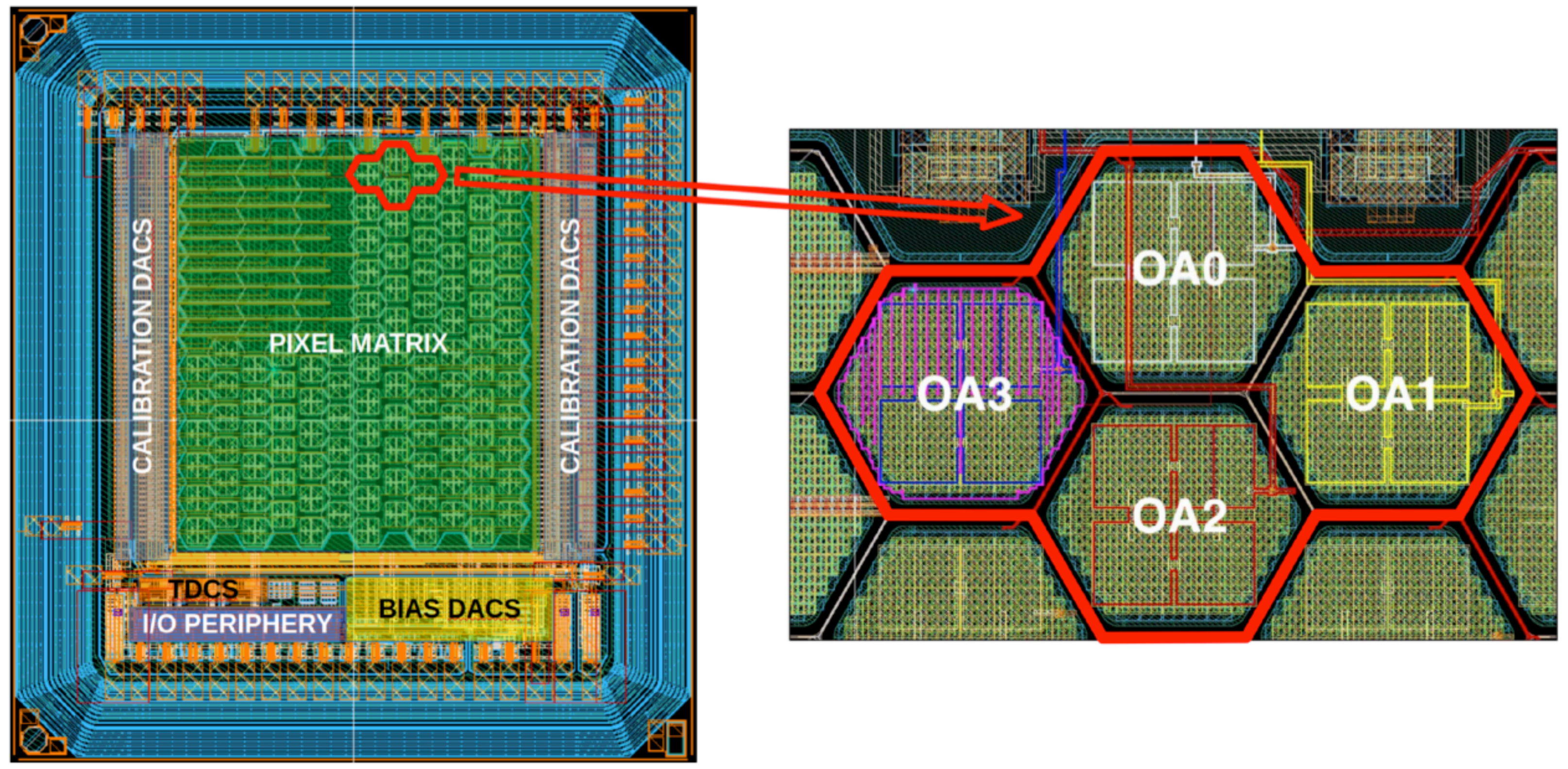
50ps
- Hexagonal pixels 65µm and 130µm side
- Discriminator output

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

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

PicoAD Proof-Of-Concept Prototype

2021



17 ps
- **Same electronics as 2019 prototype**
- **Epitaxial layers + gain layer**
- **4 different gain-layer doses**

PicoAD proof-of-concept prototype: arXiv:2206.07952, June 2022
Testbeam results: arXiv:2208.11019, August 2022

PicoAD Sensor Concept

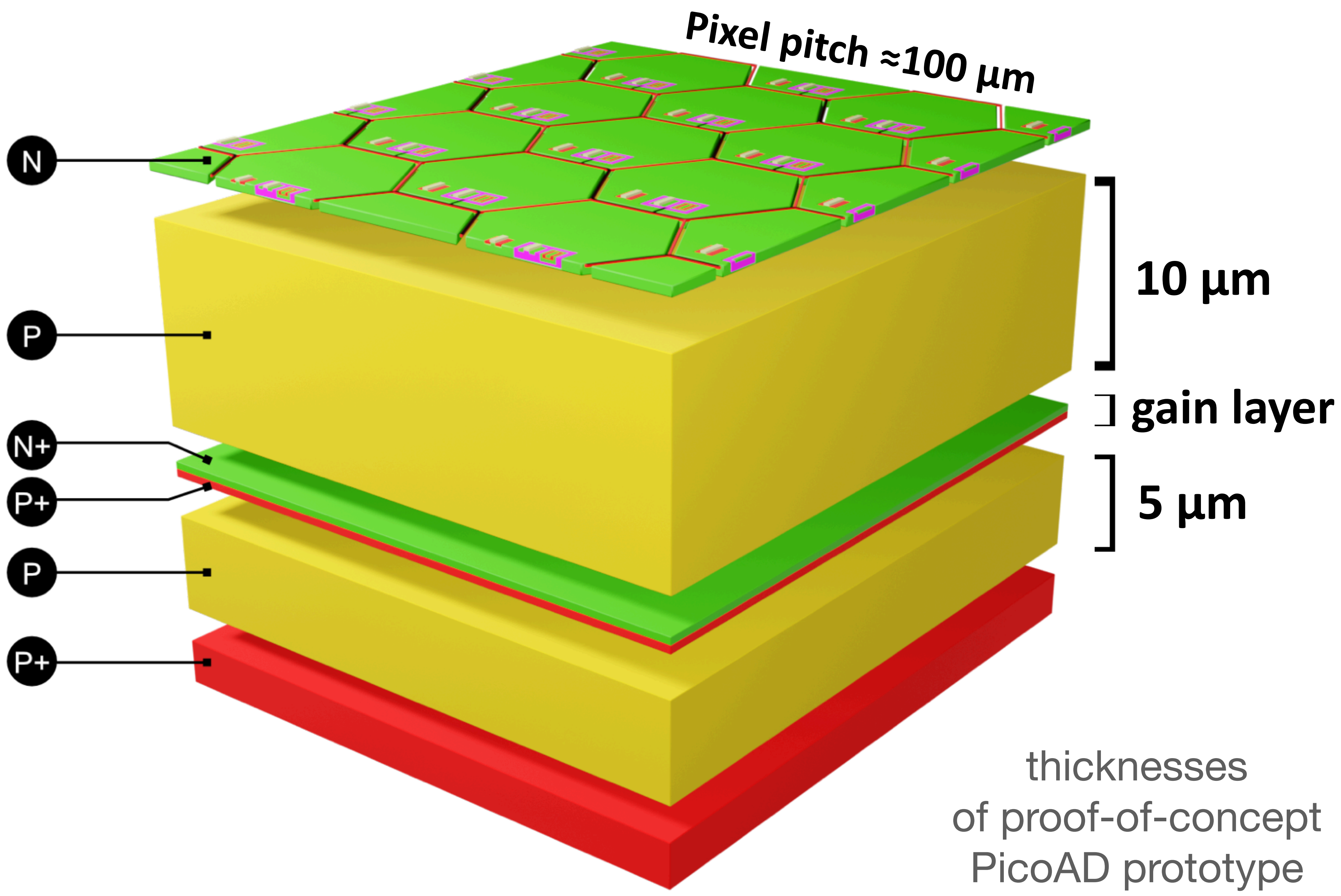
PicoAD:

Multi-Junction Picosecond-Avalanche Detector[1]

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)

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



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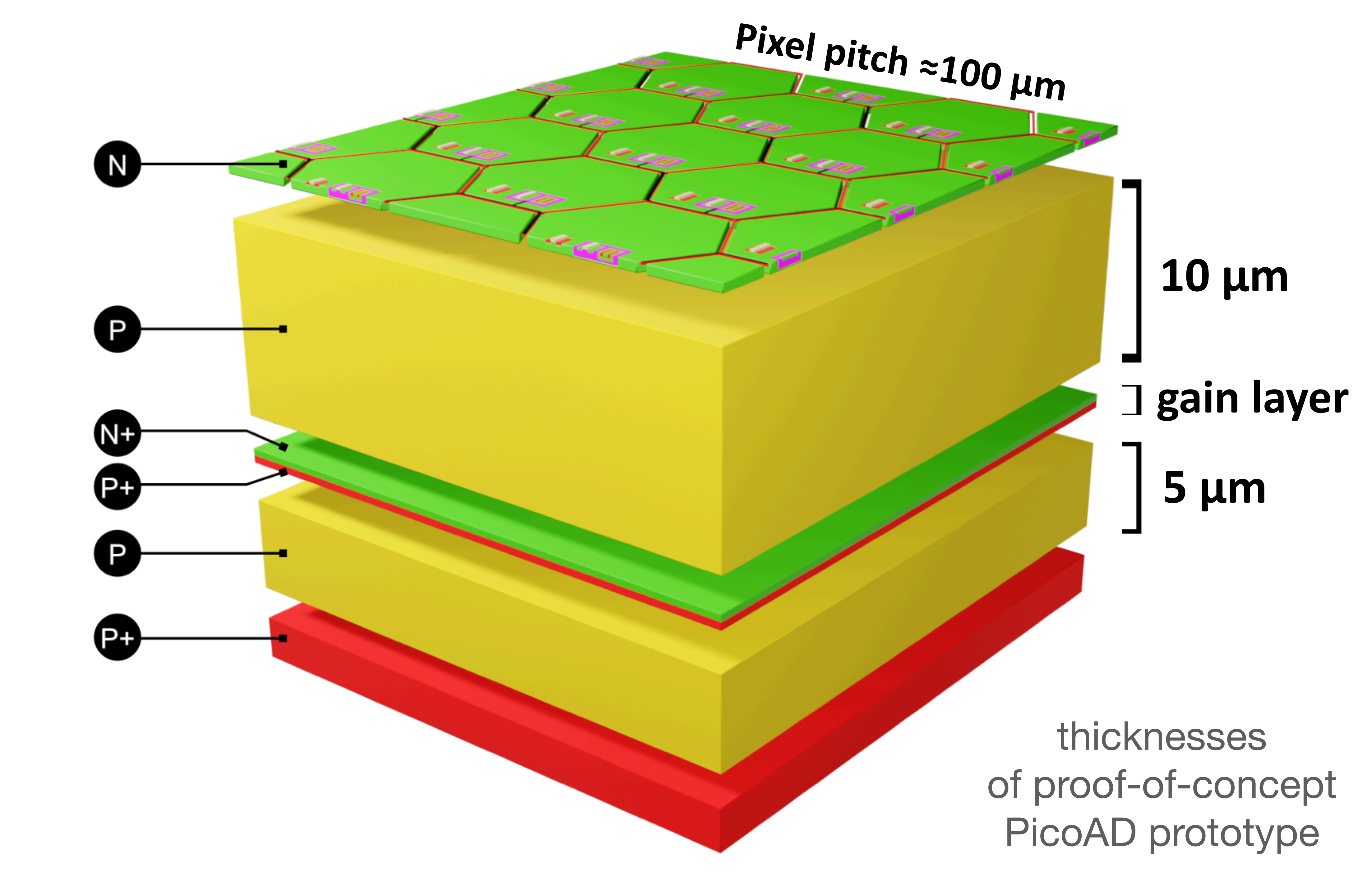
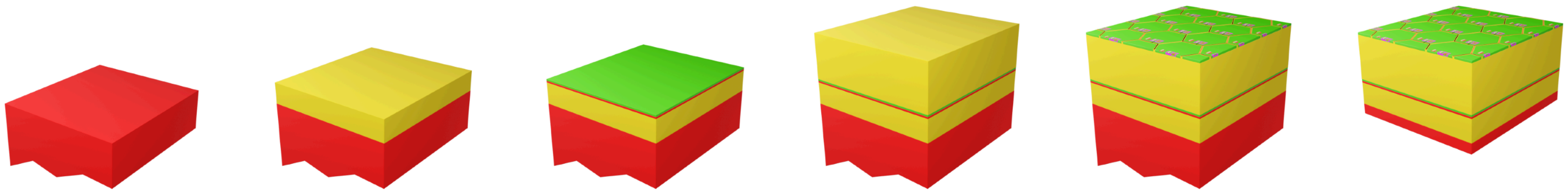




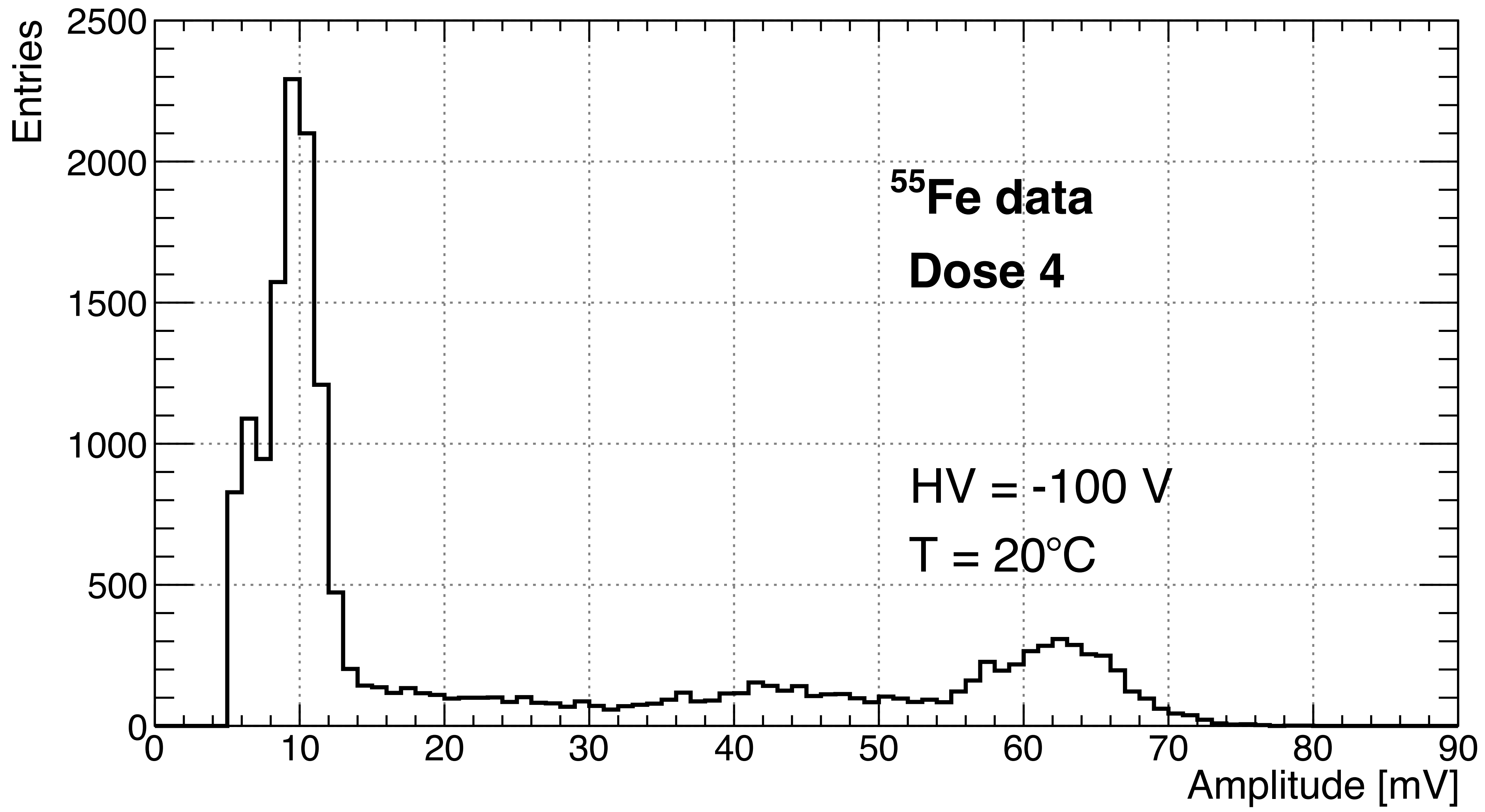
Gain Measurements (I)

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

- mainly ~5.9 keV photons
- point-like charge deposition

Characteristic double-peak spectrum

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



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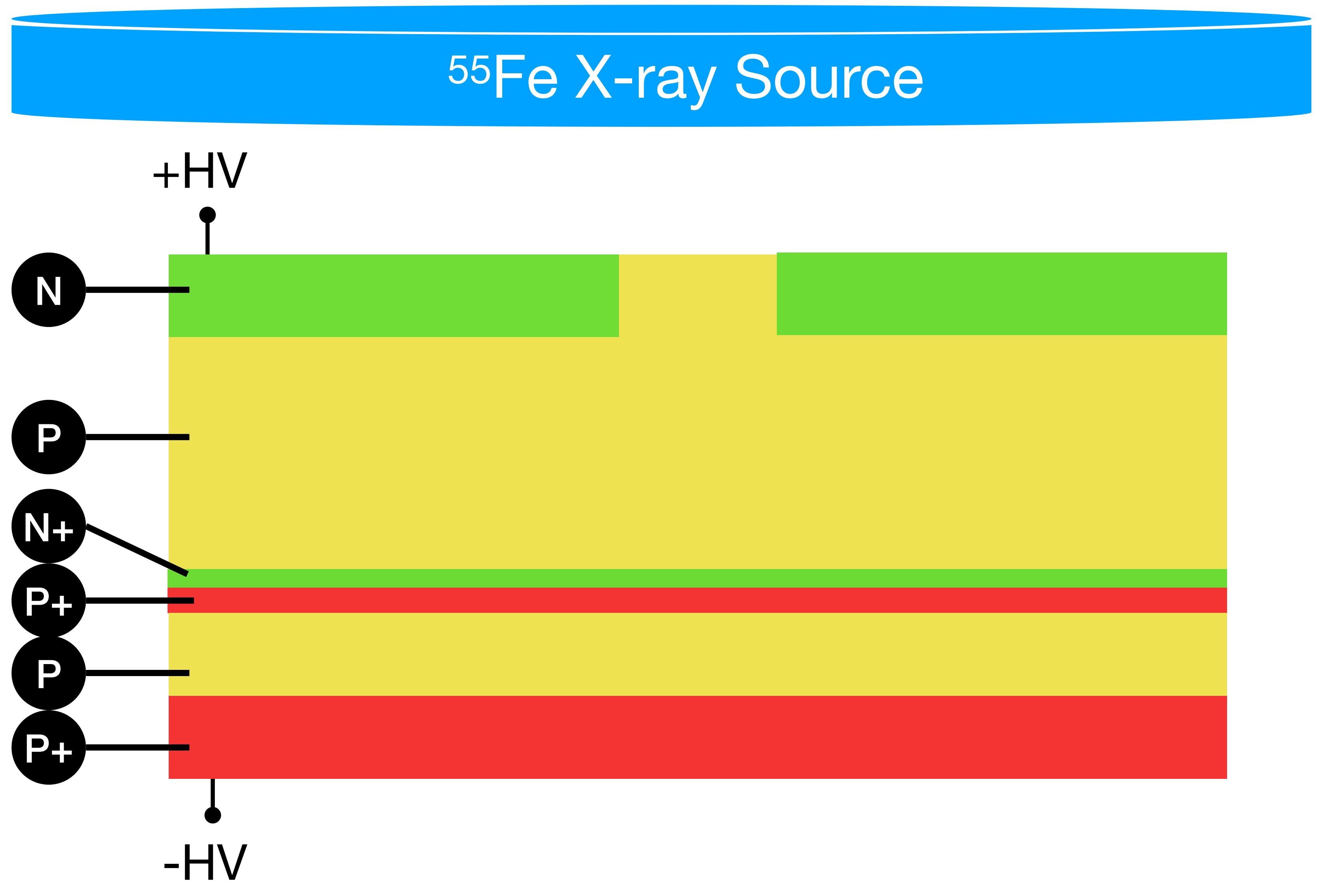

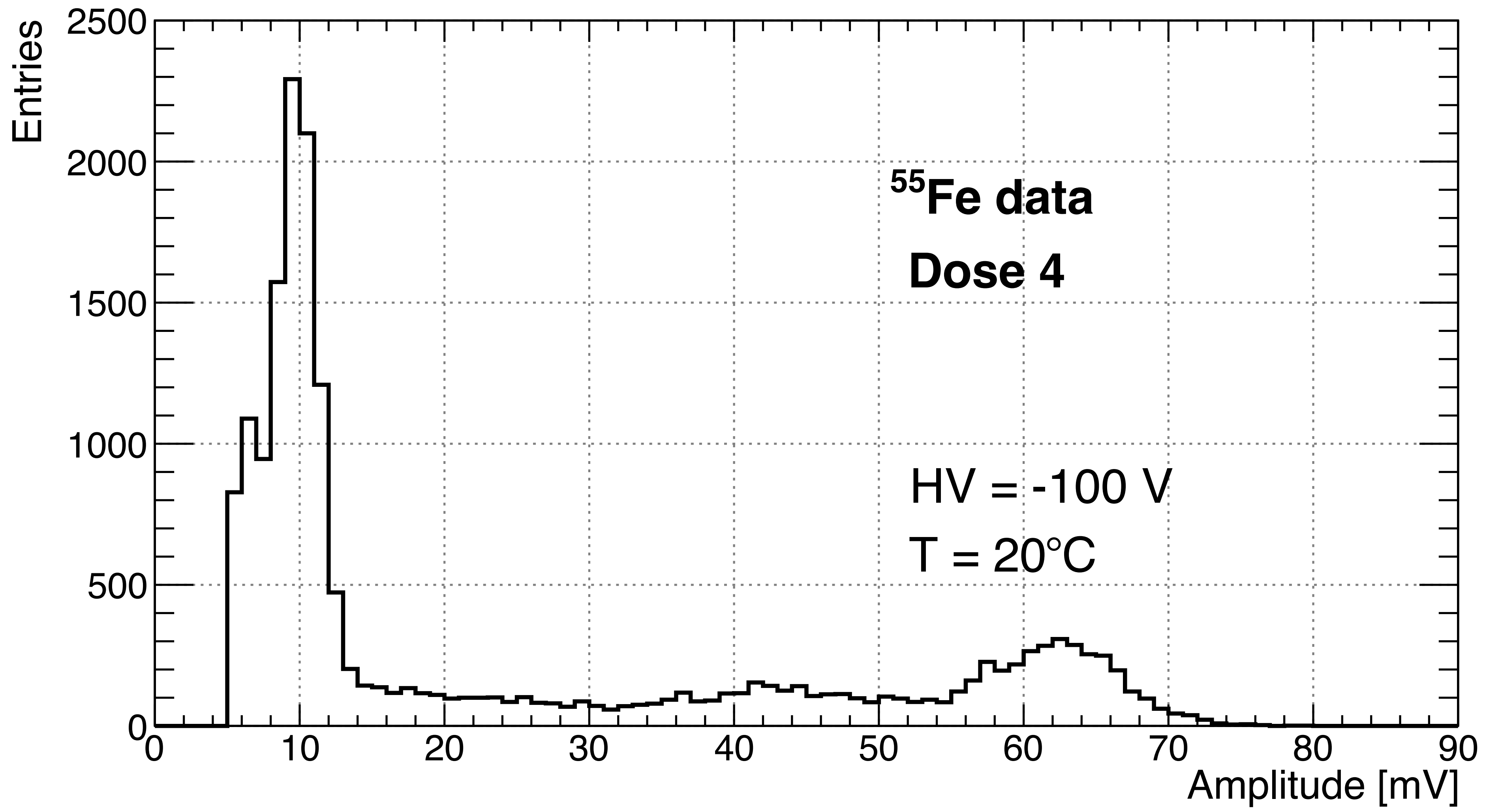

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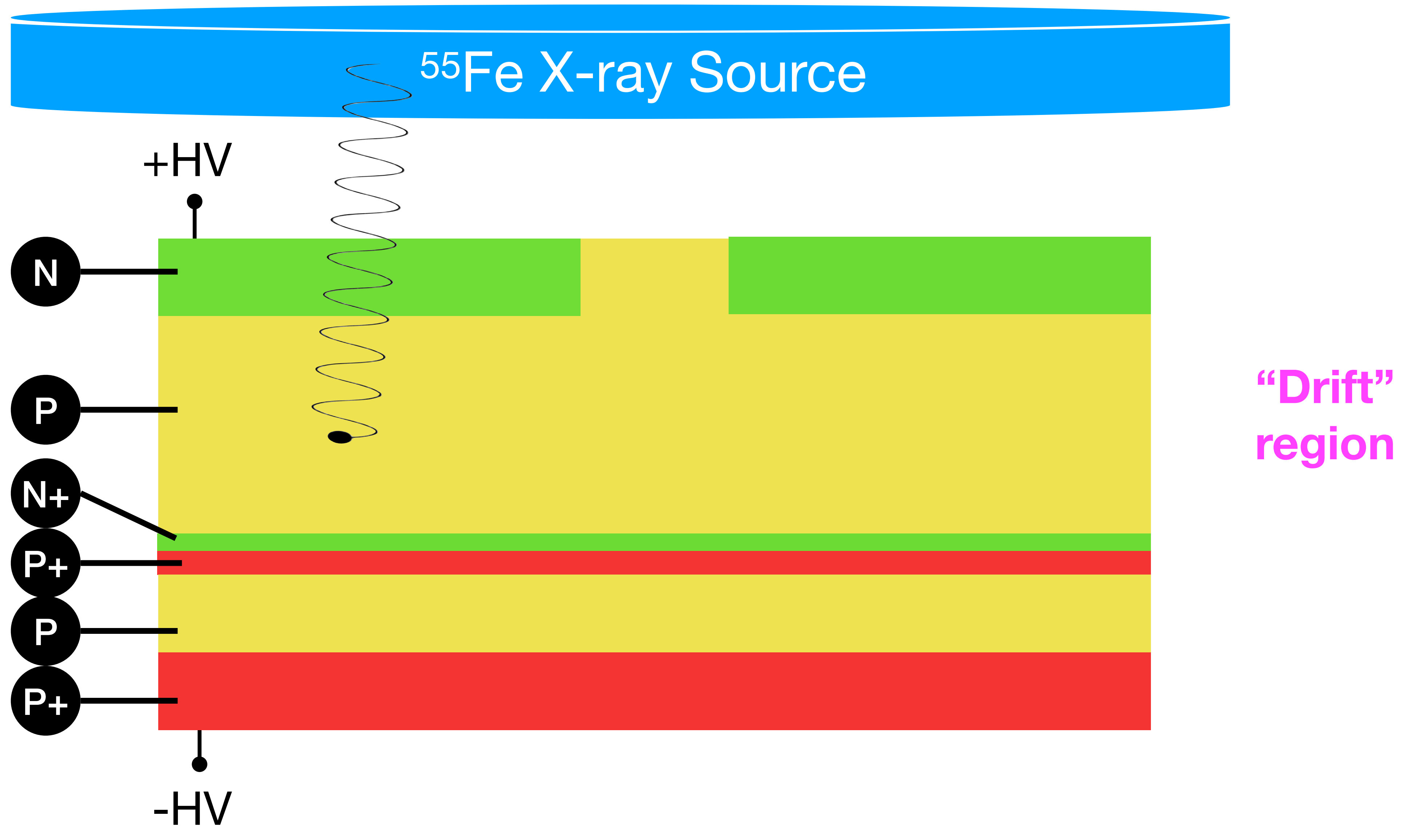

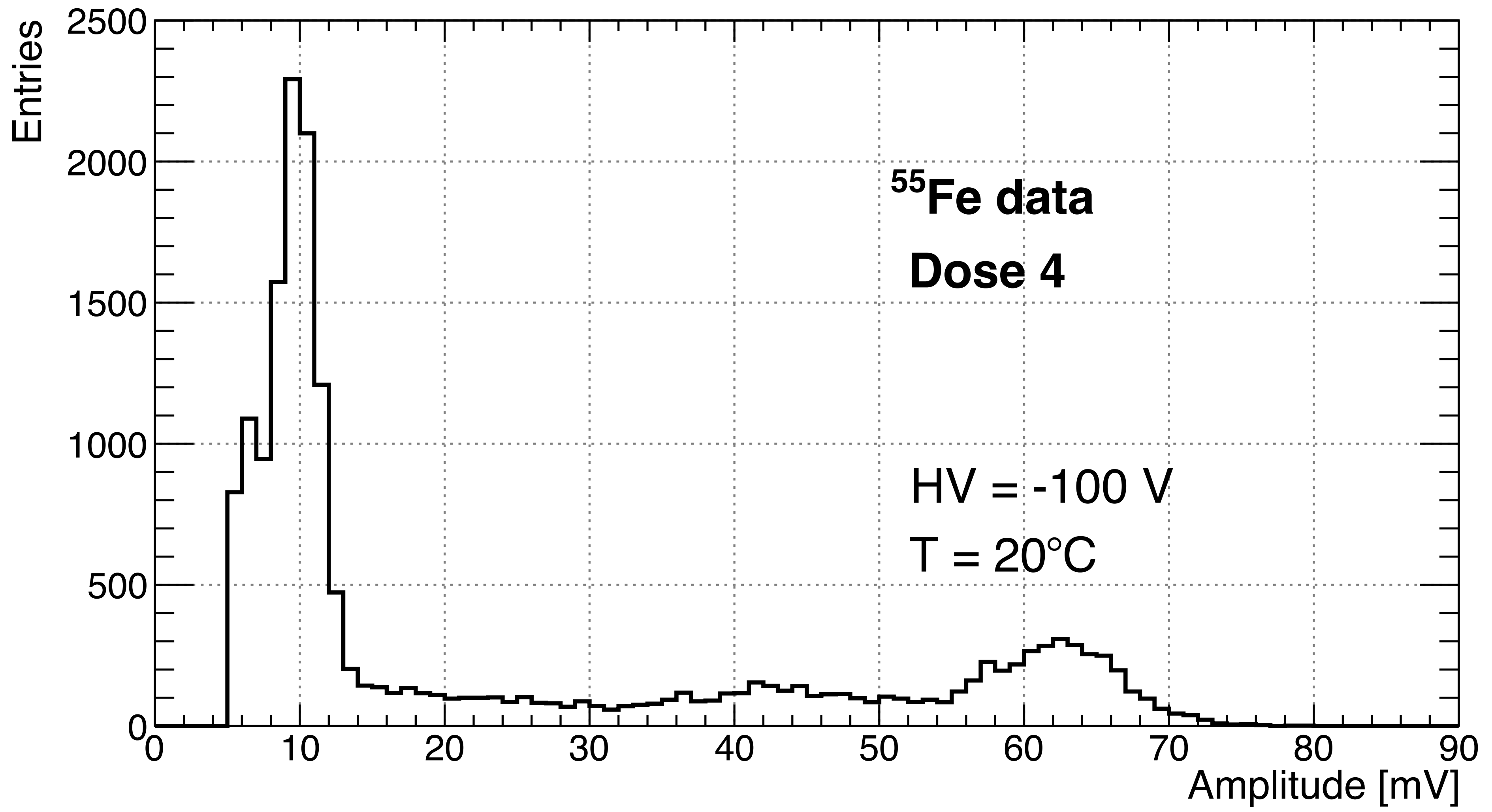

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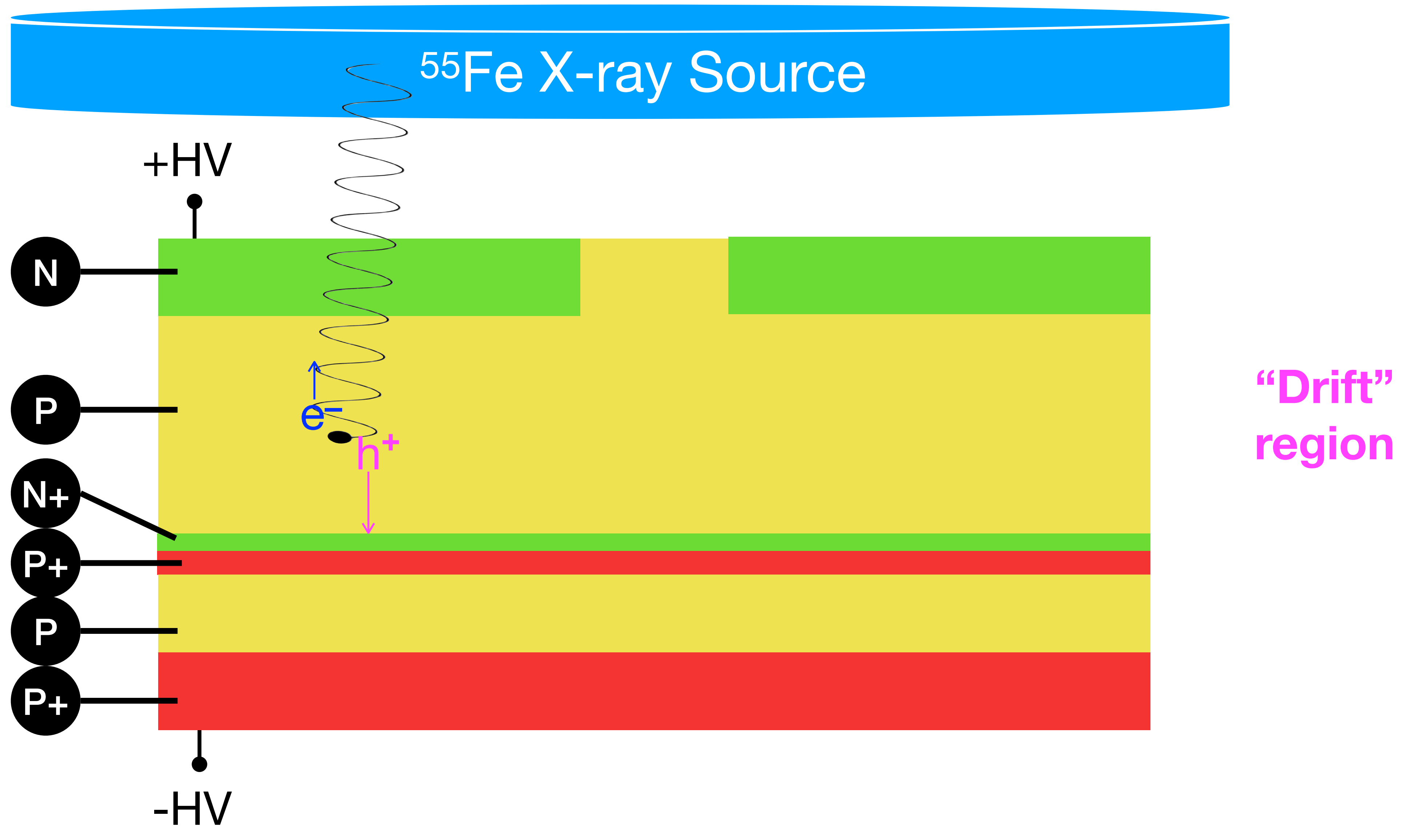

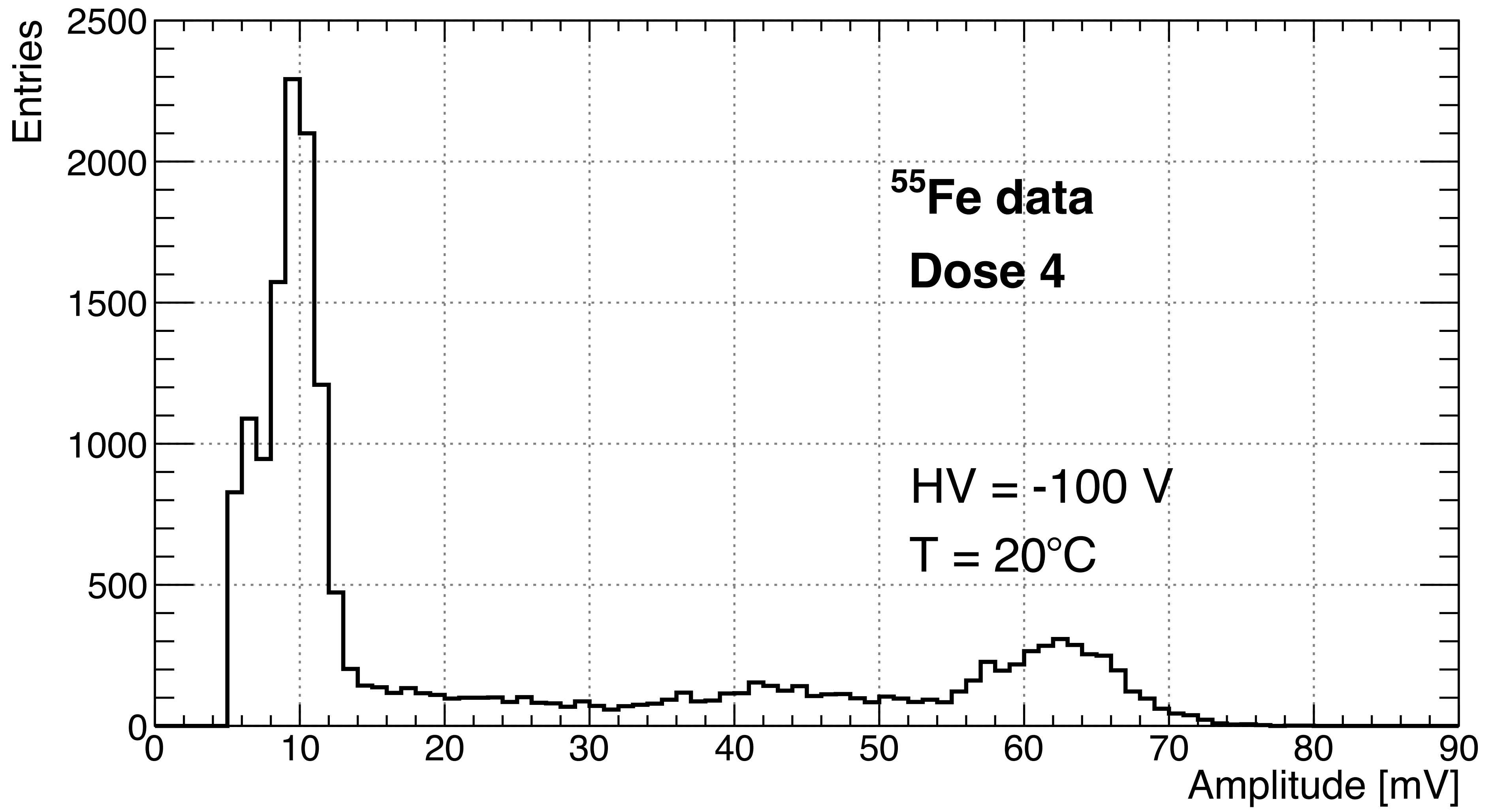

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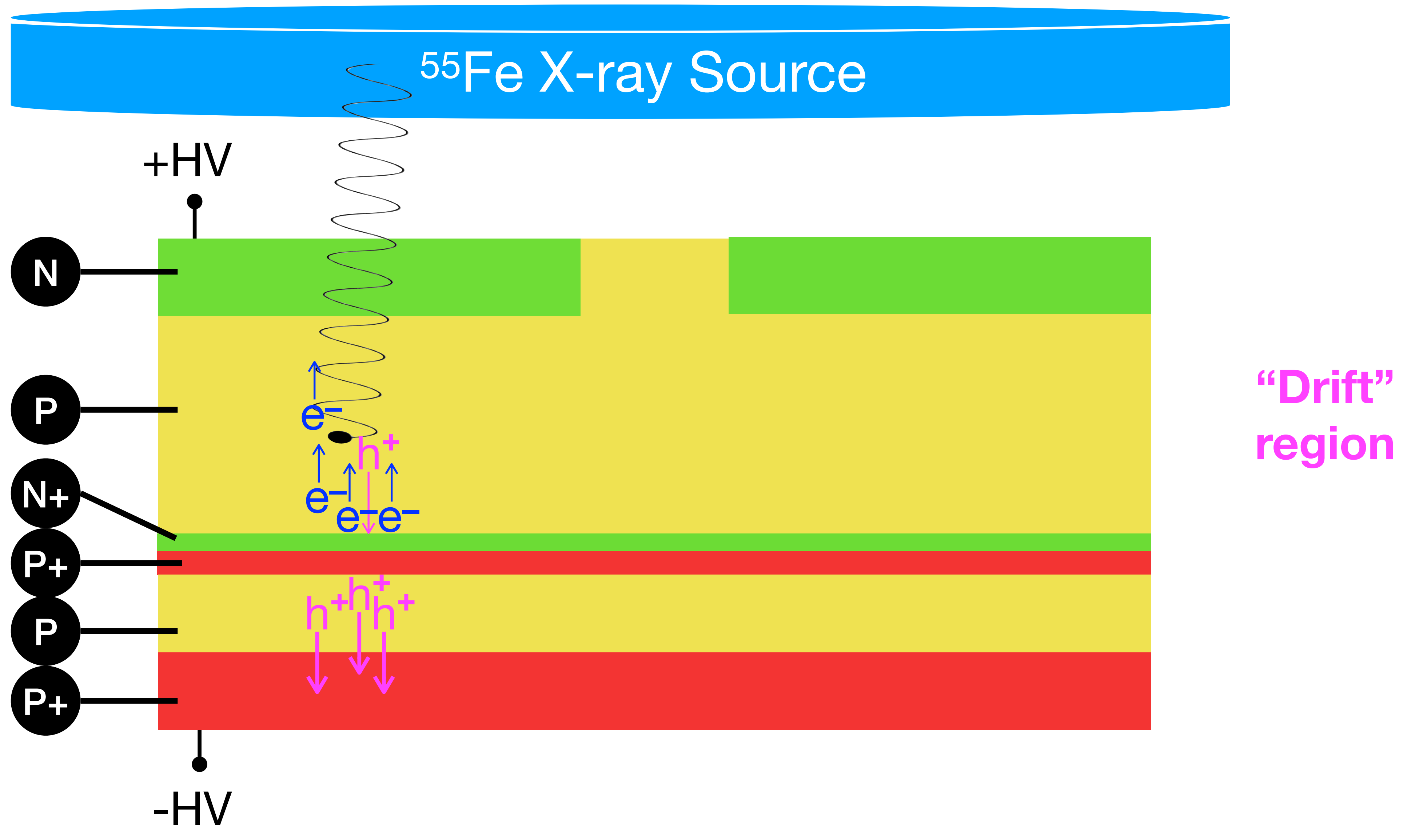

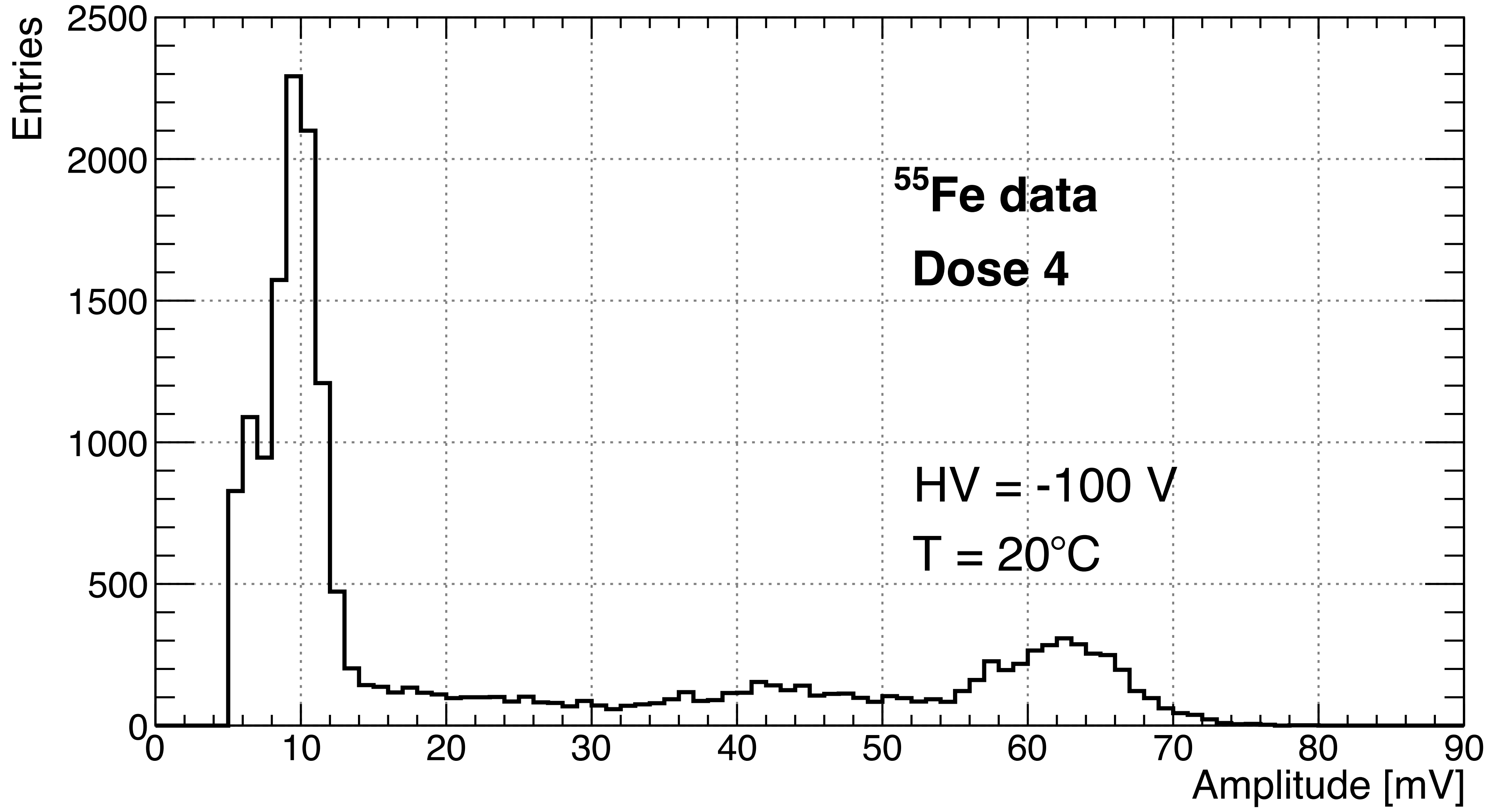

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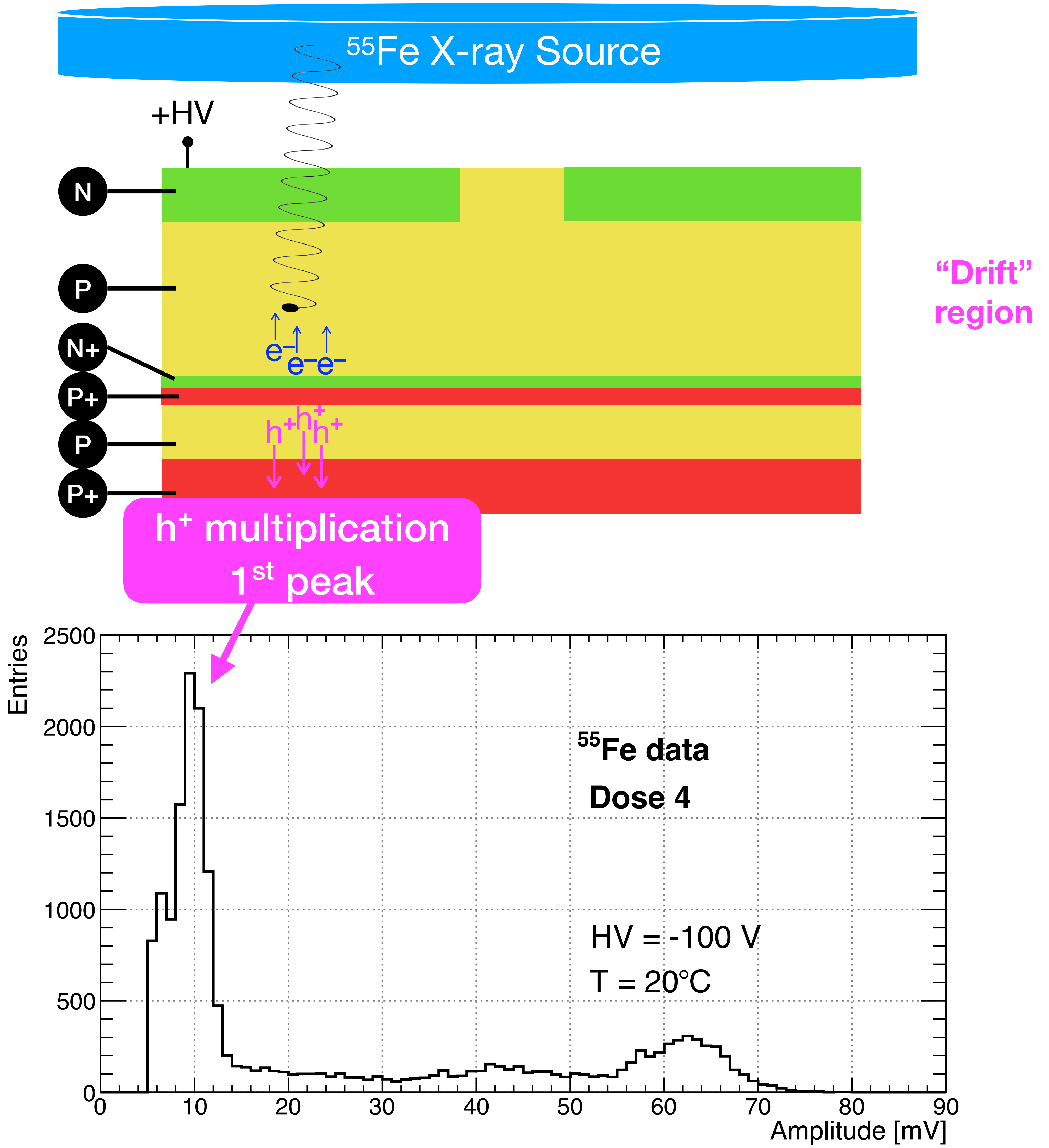

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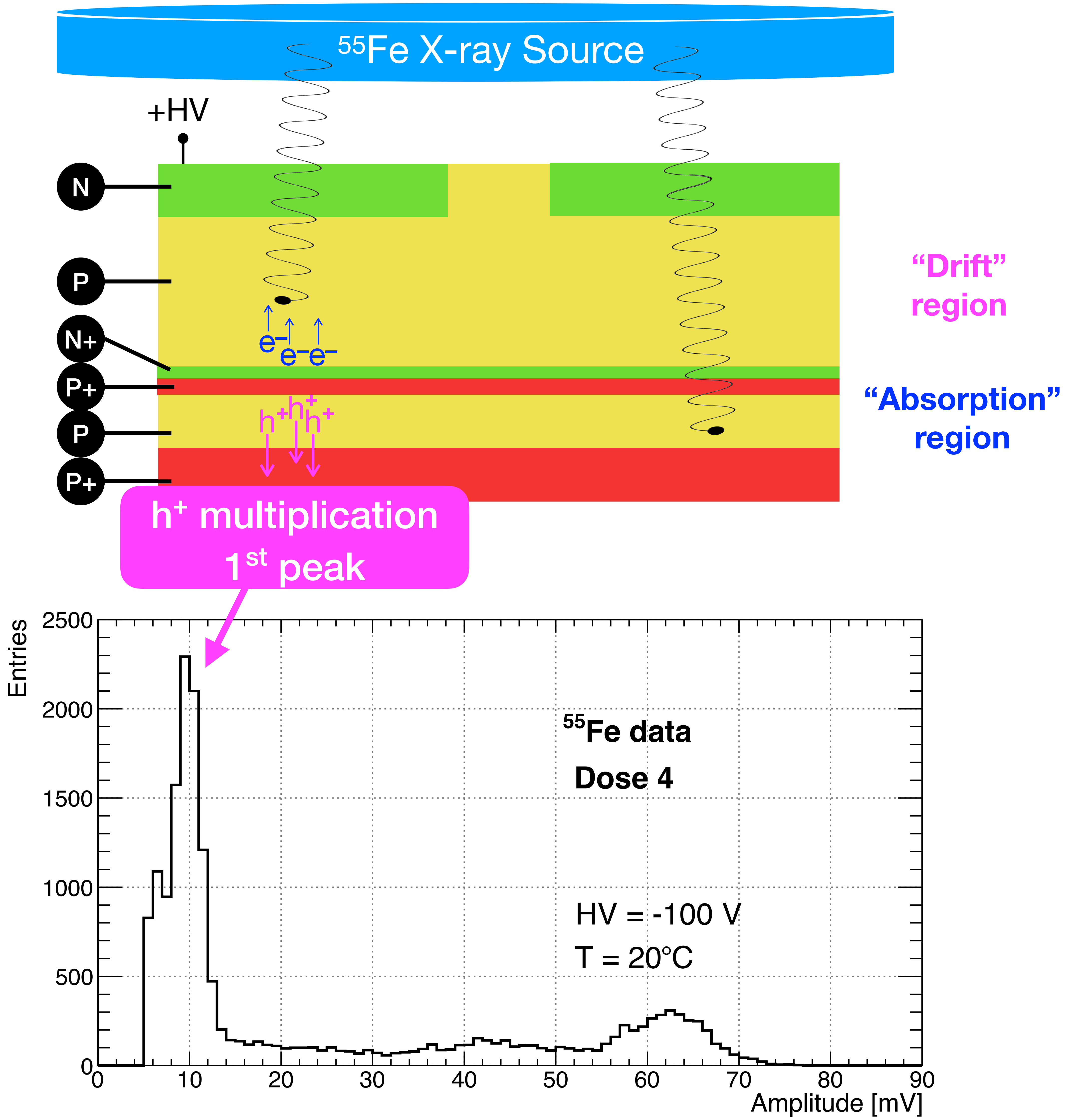

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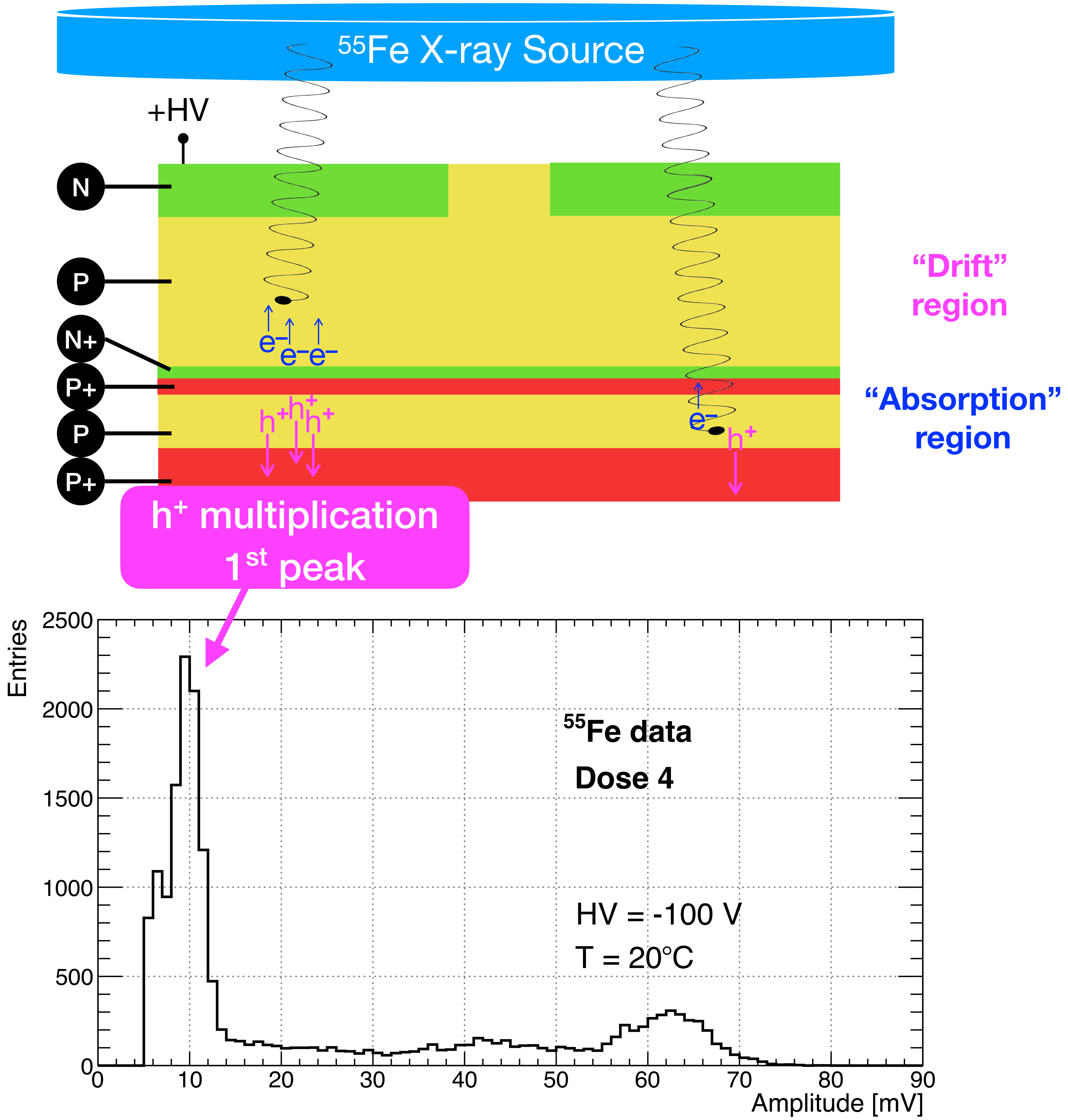

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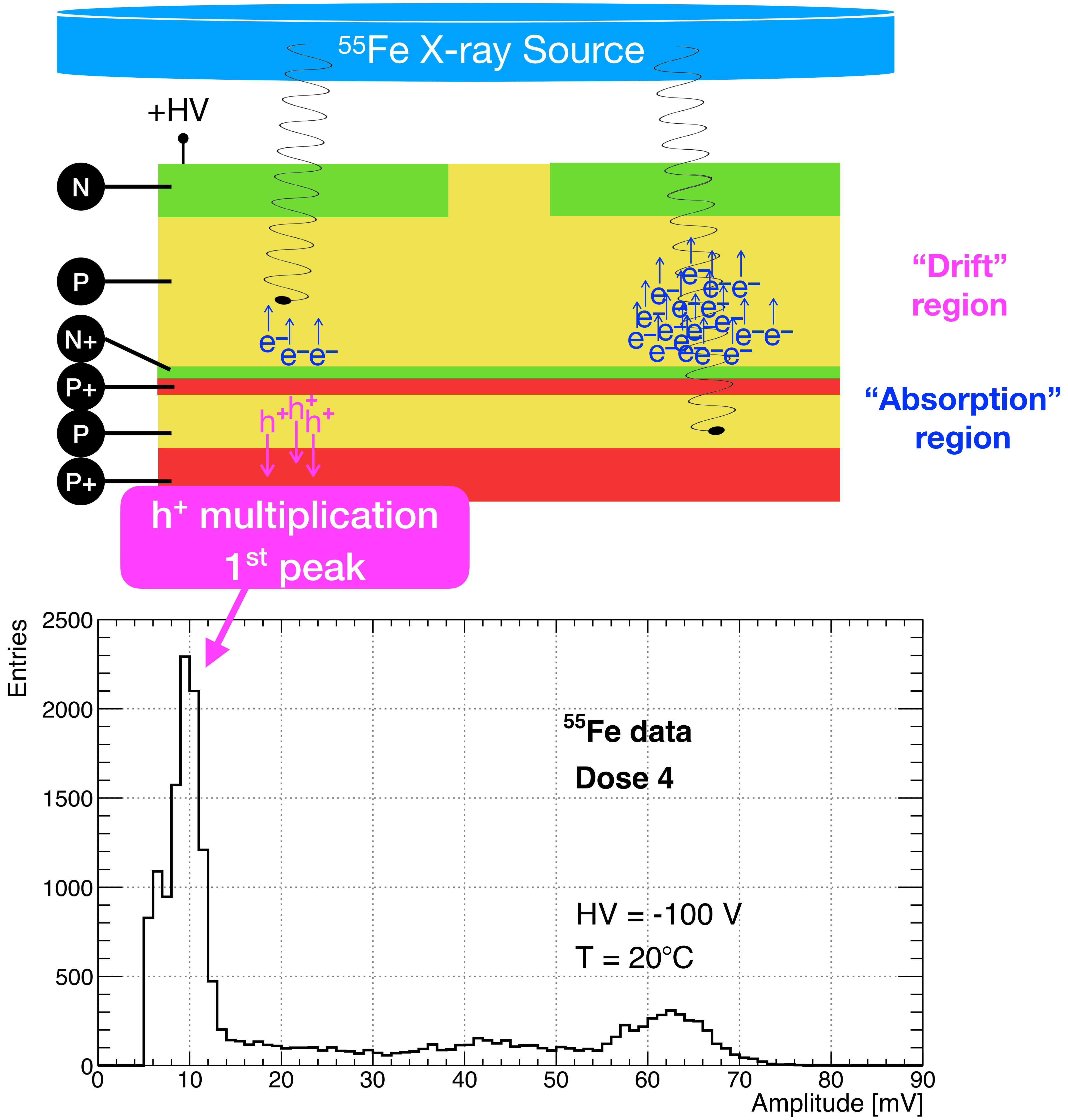

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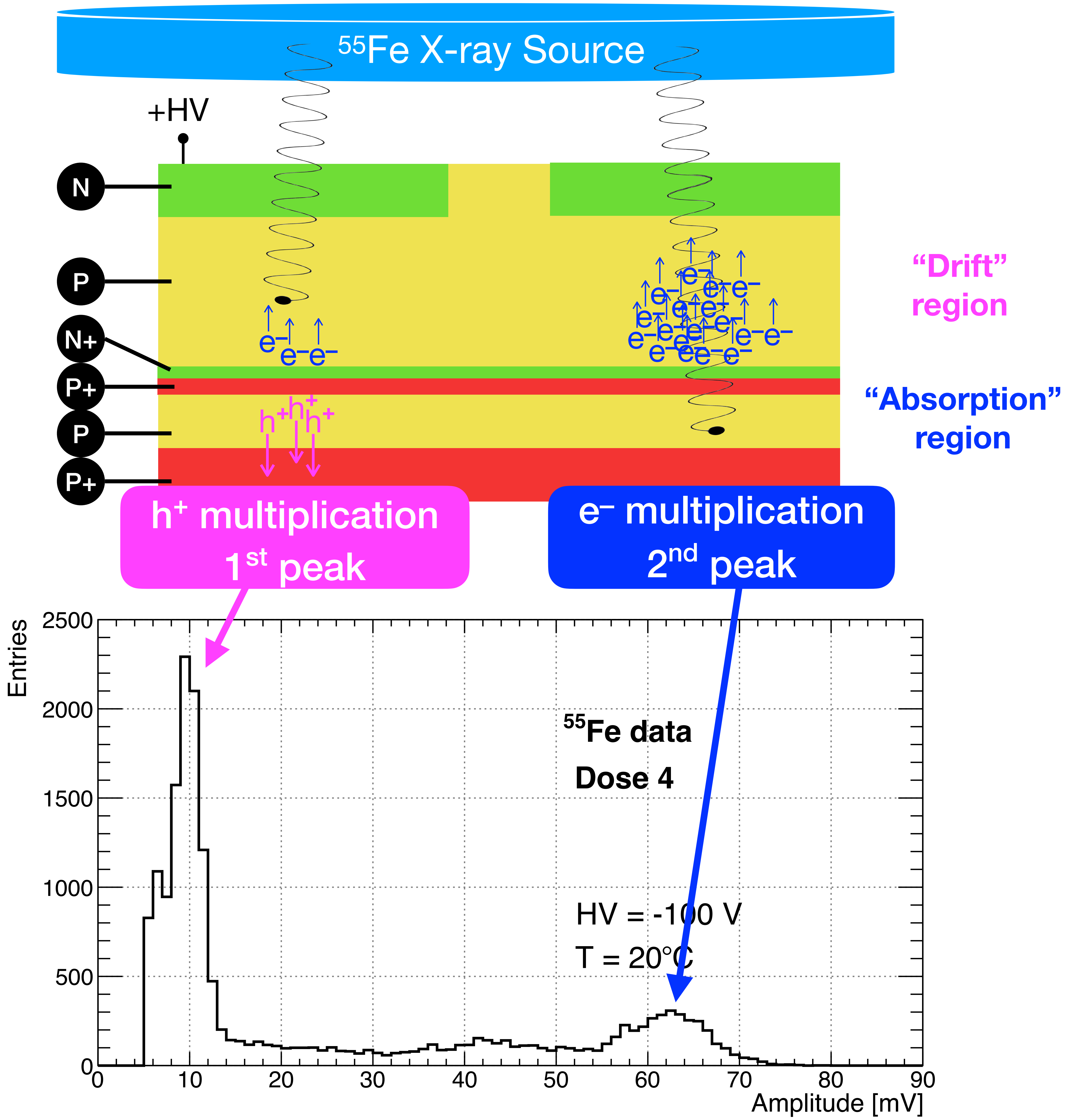
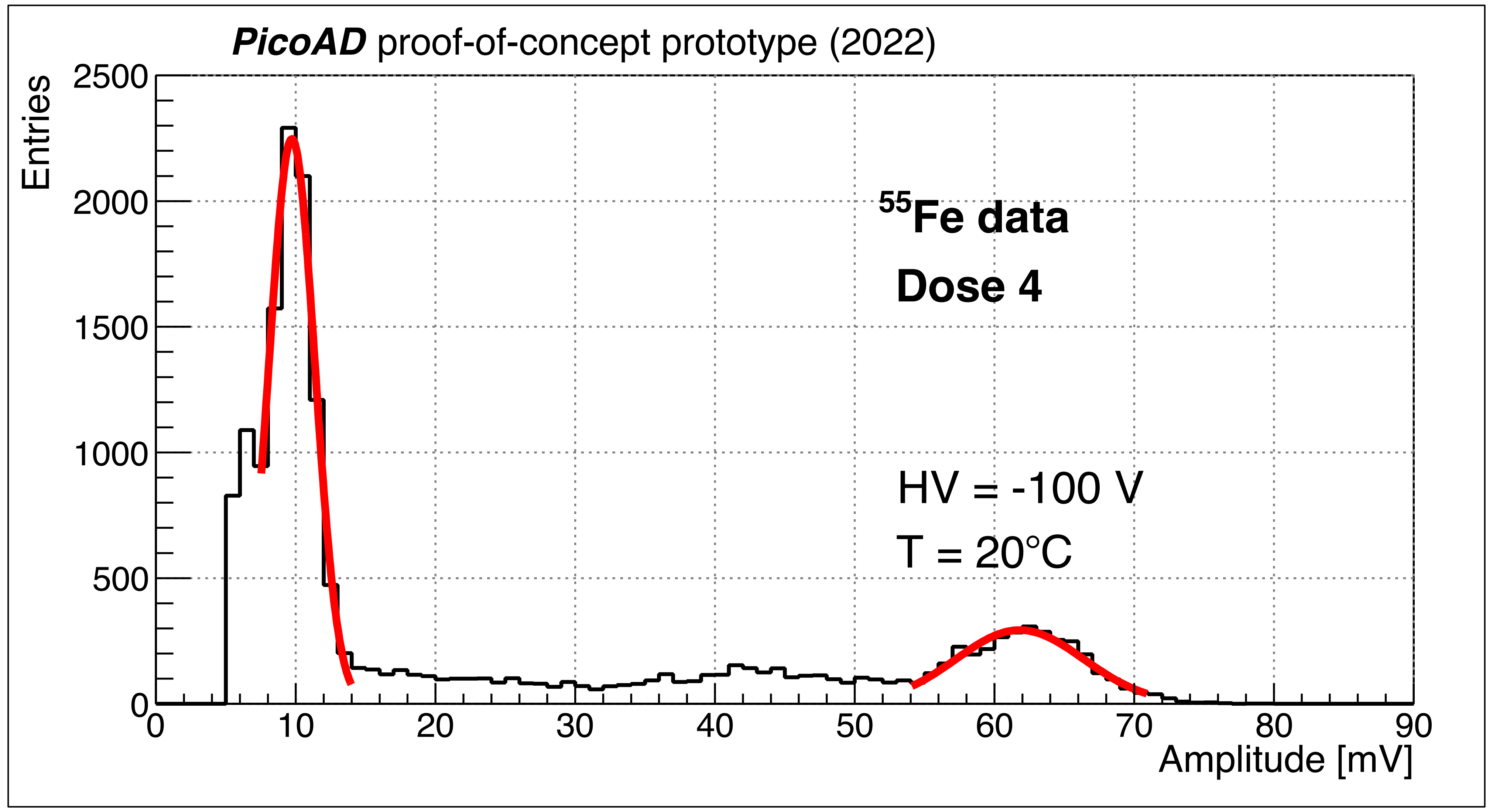
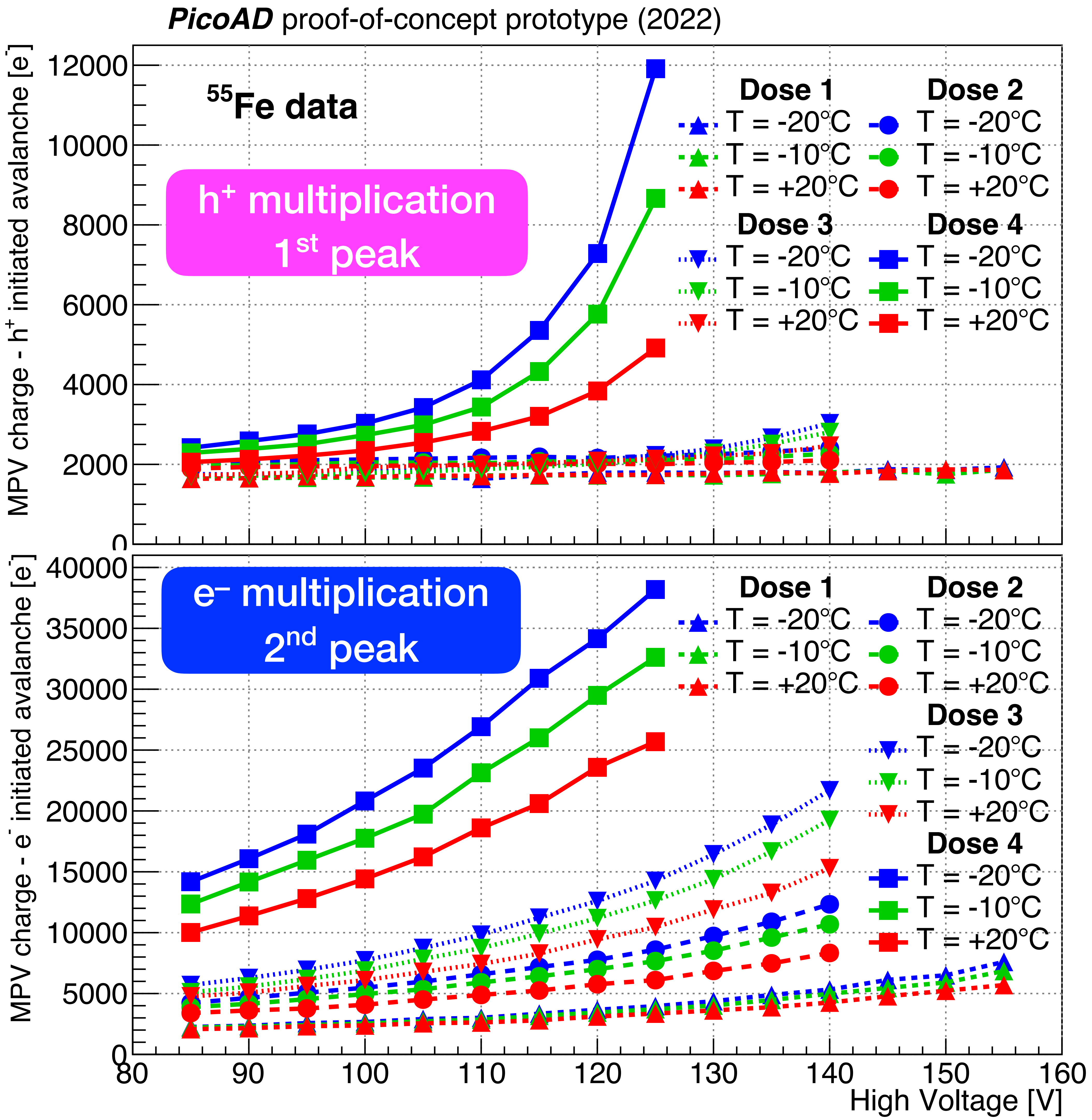


Gain Measurements (II)

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





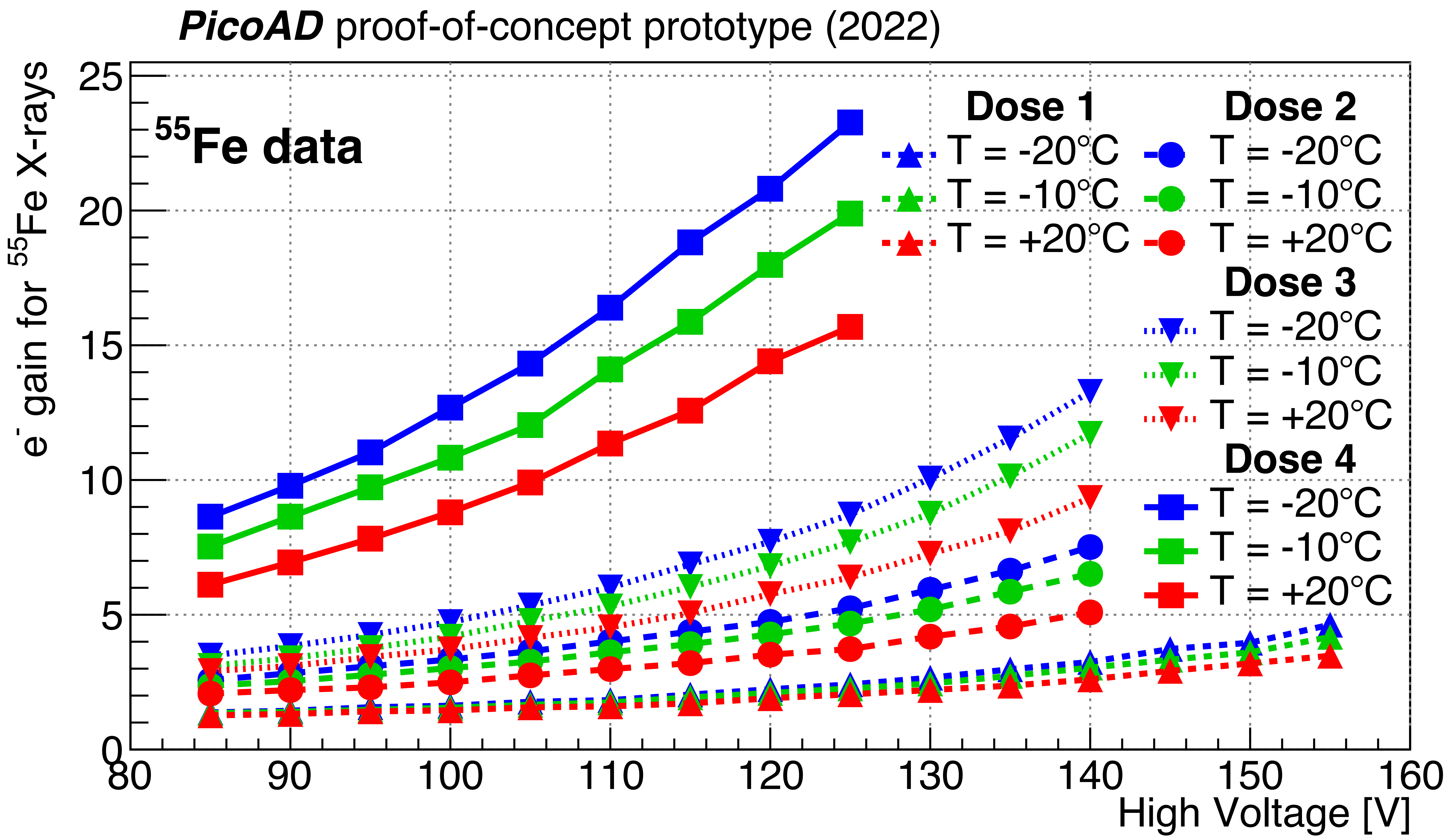
Assumption of no gain multiplication when:

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

⇒ **normalization value**

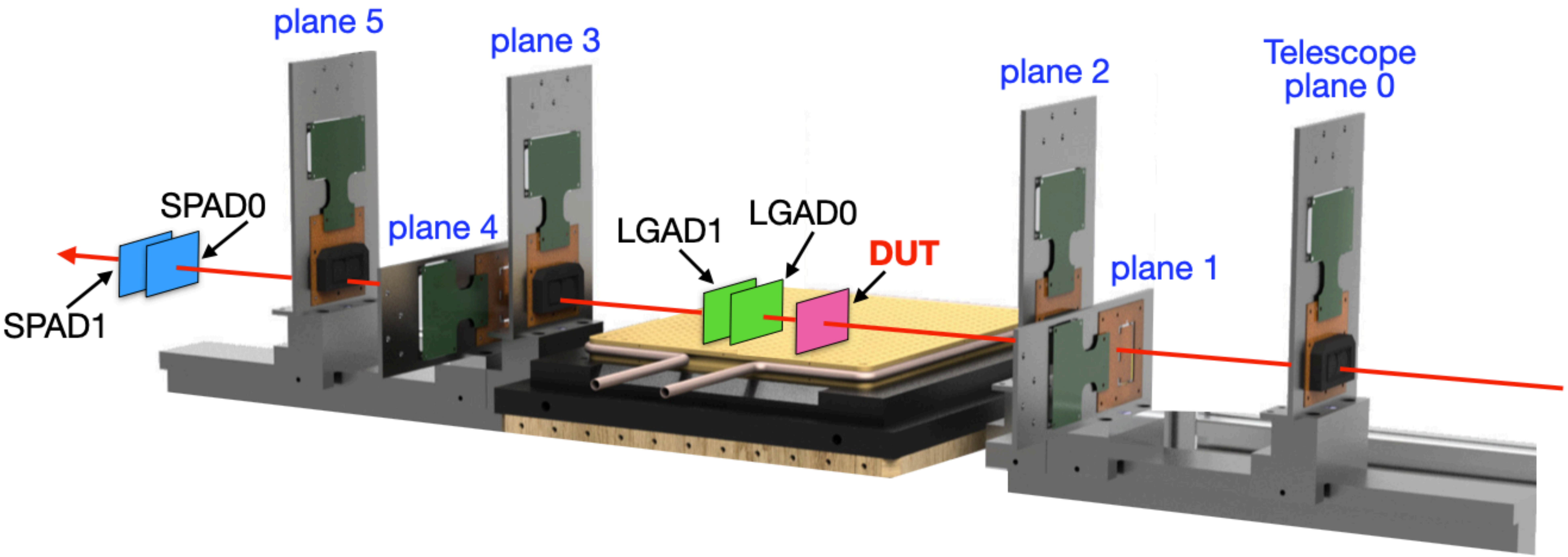
Gain Measurements: Results

A gain of **≈20** for ^{55}Fe X-rays is reached at HV = 120 V and T = -20 °C[2]



[2] L. Paolozzi et al., Picosecond Avalanche Detector - working principle and gain measurement with a proof-of-concept prototype. arXiv:2206.07952, June 2022

Summer 2021: **CERN SPS Testbeam: 180 GeV/c pions to measure efficiency and time resolution**



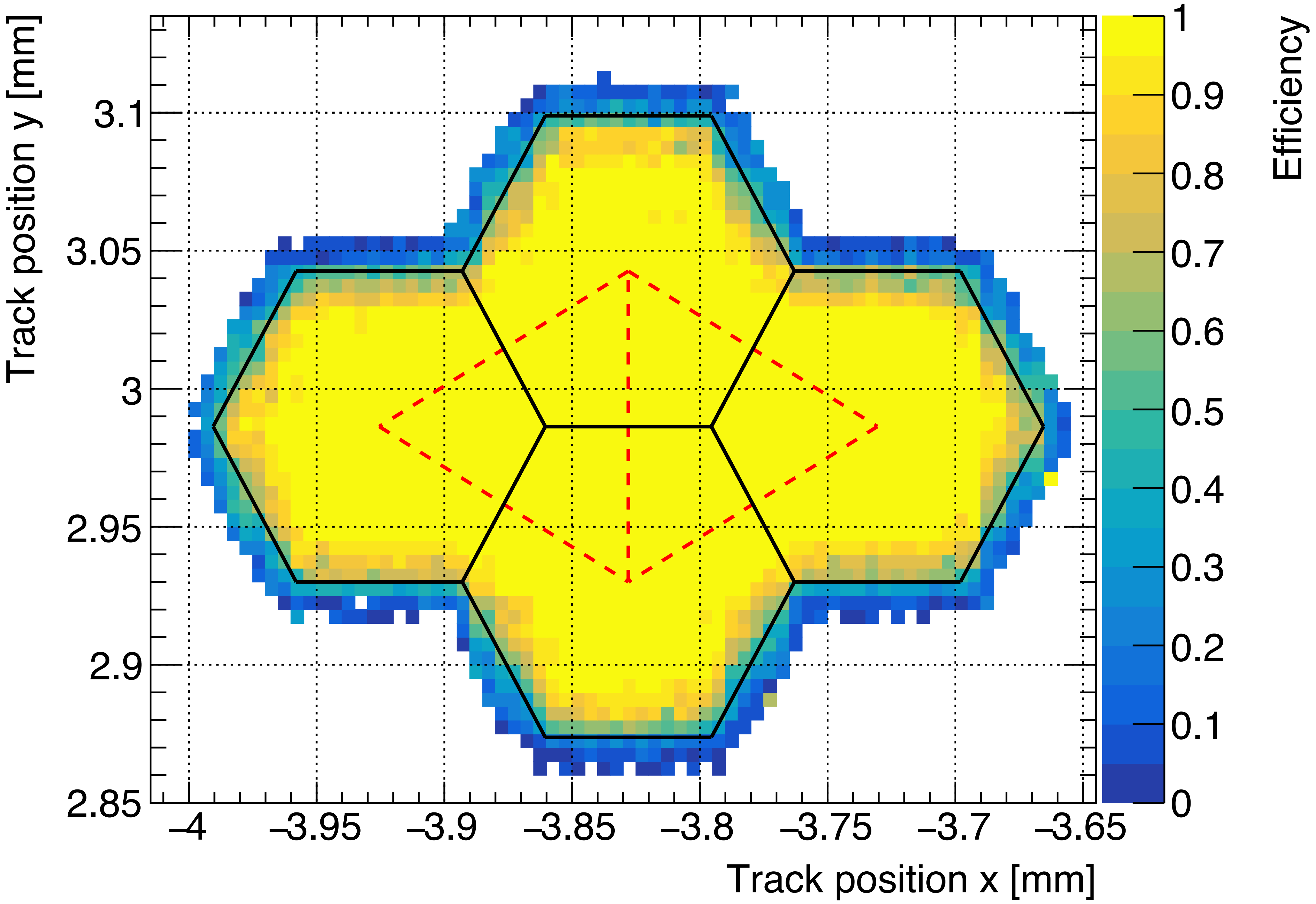
UNIGE FE-I4 telescope[3] to provide spatial information ($\sigma_{x,y}$ ≈10 µm)

Two LGADs (σ_t ≈35 ps) to provide the timing reference (and **two SPADs** with σ_t ≈20 ps)

[3] Benoit et al. The FE-I4 telescope for particle tracking in testbeam experiments. JINST, 11 P07003, July 2016

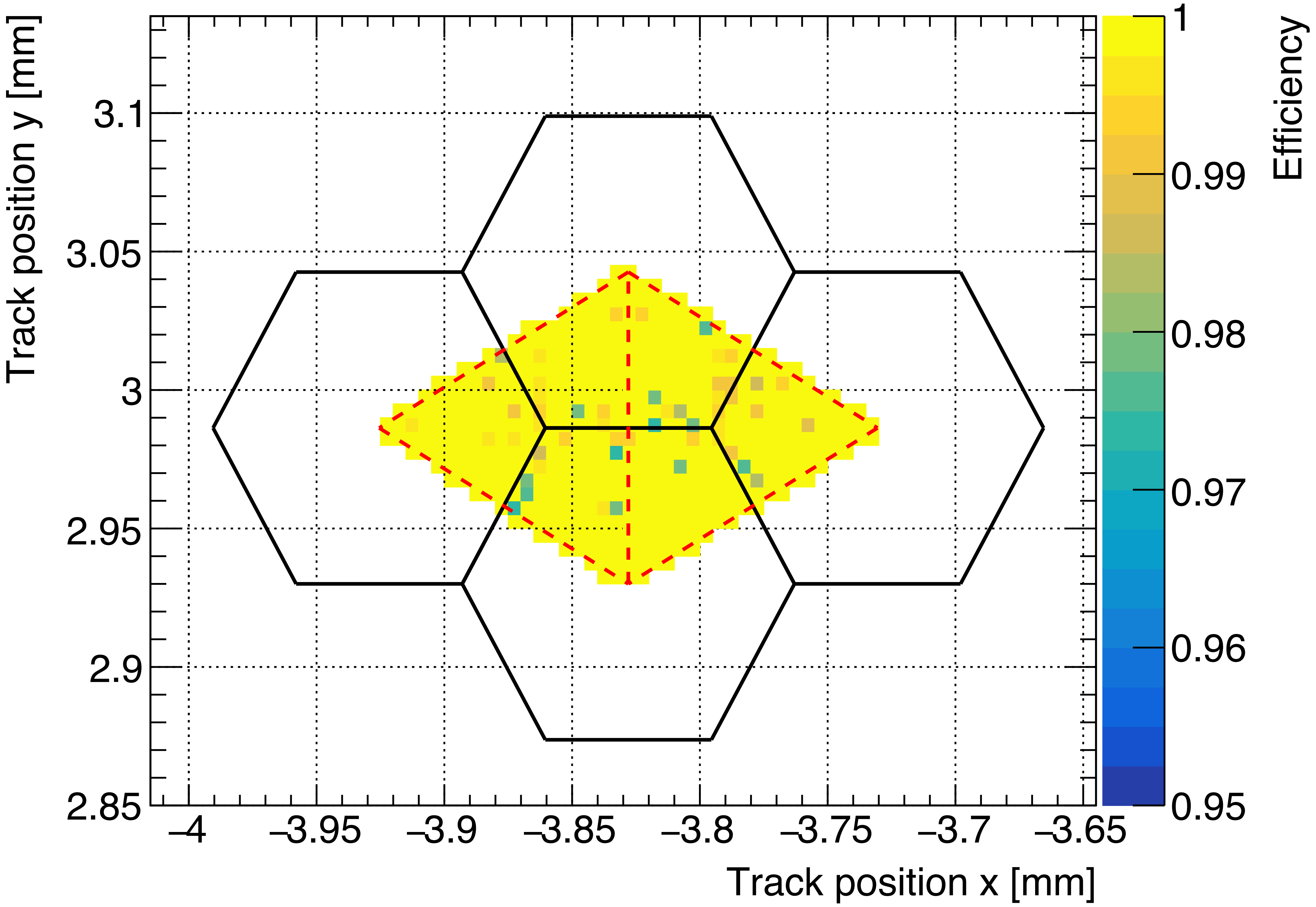
Detection Efficiency (I)

PicoAD proof-of-concept prototype (2022)

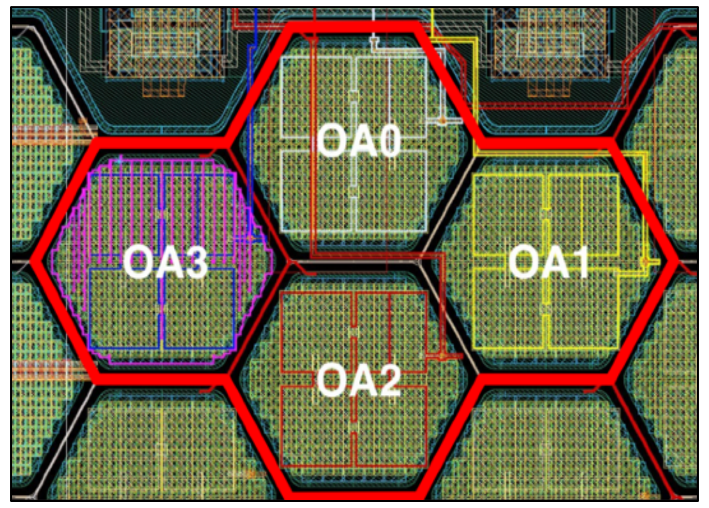


CERN SPS Testbeam: 180 GeV/c pions

V_{th} = 4 mV ; HV = 125 V ; Power = 2.7 W/cm^2



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



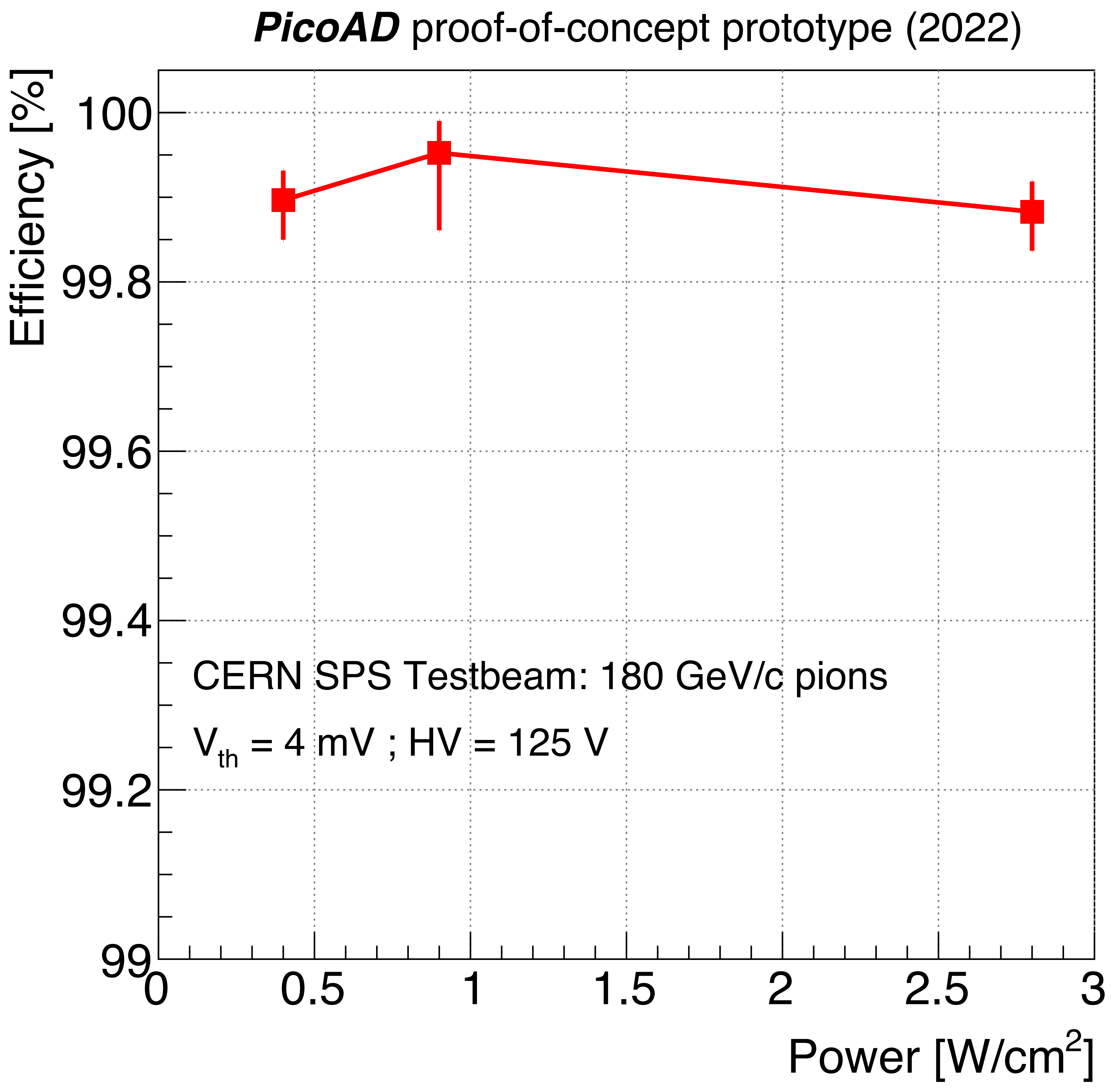
Selection of two **triangles**:

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

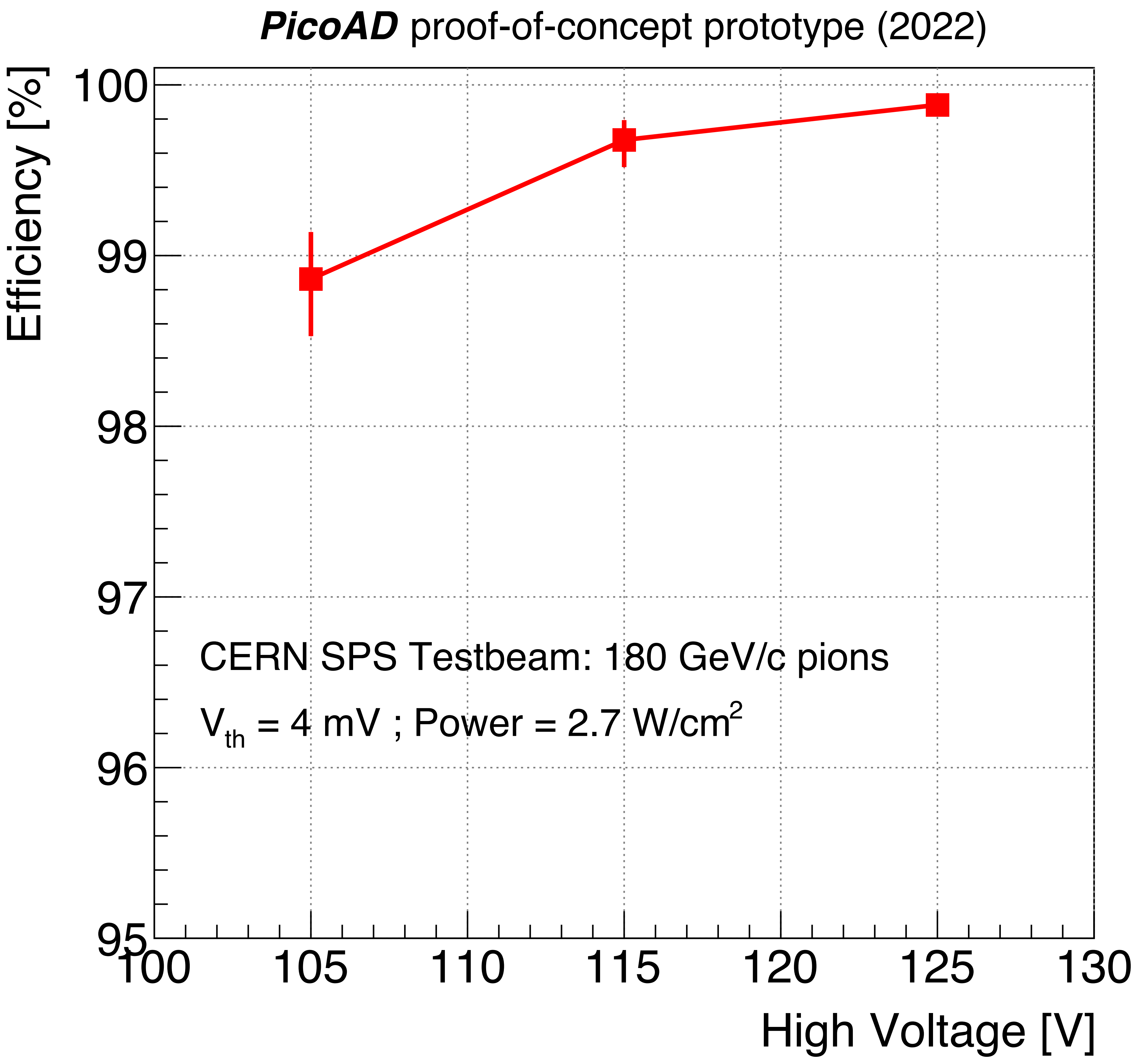
Detection Efficiency (II)

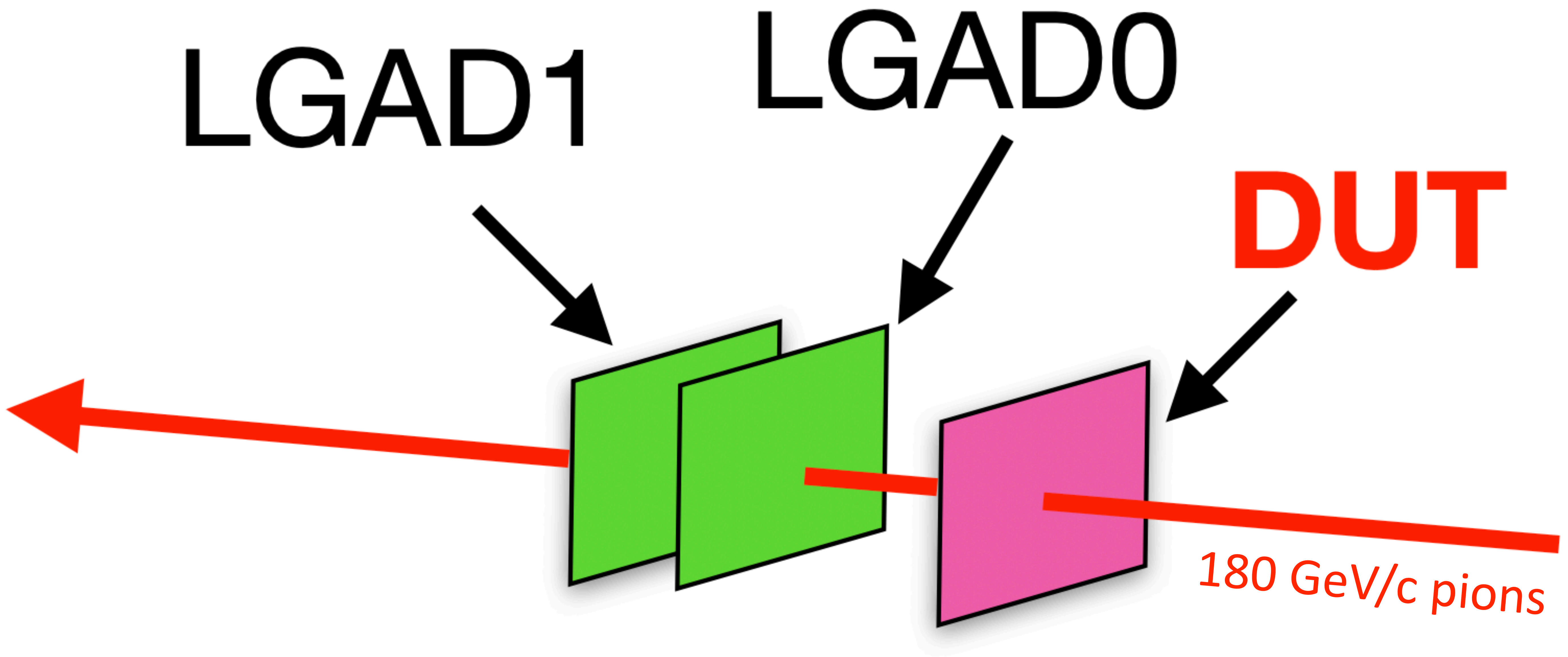
Efficiency measured inside the two unbiased triangles

≈99.9% for all power consumptions



Drops to 99% for HV=105 V

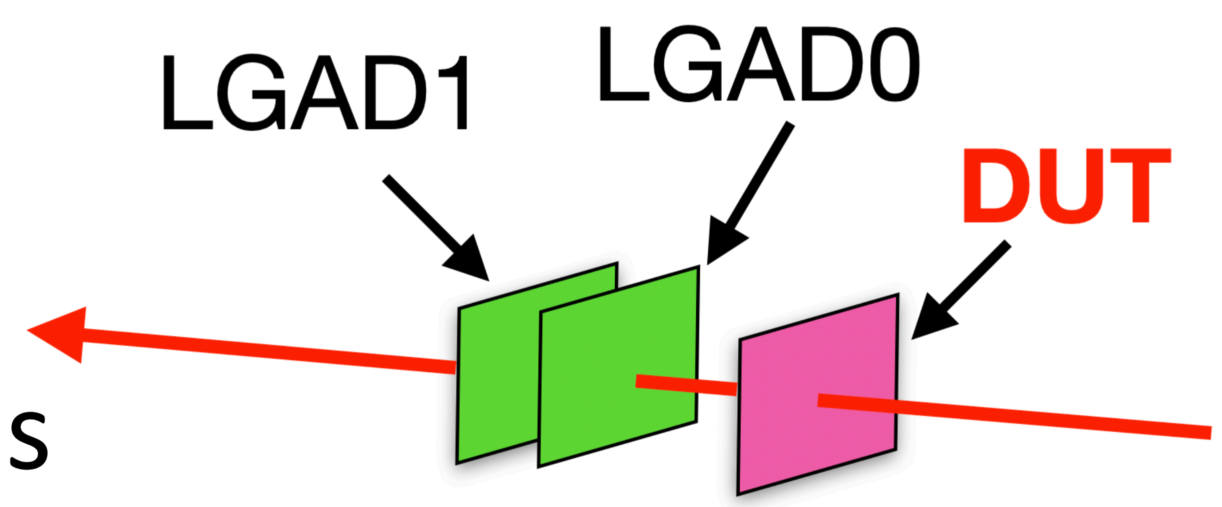


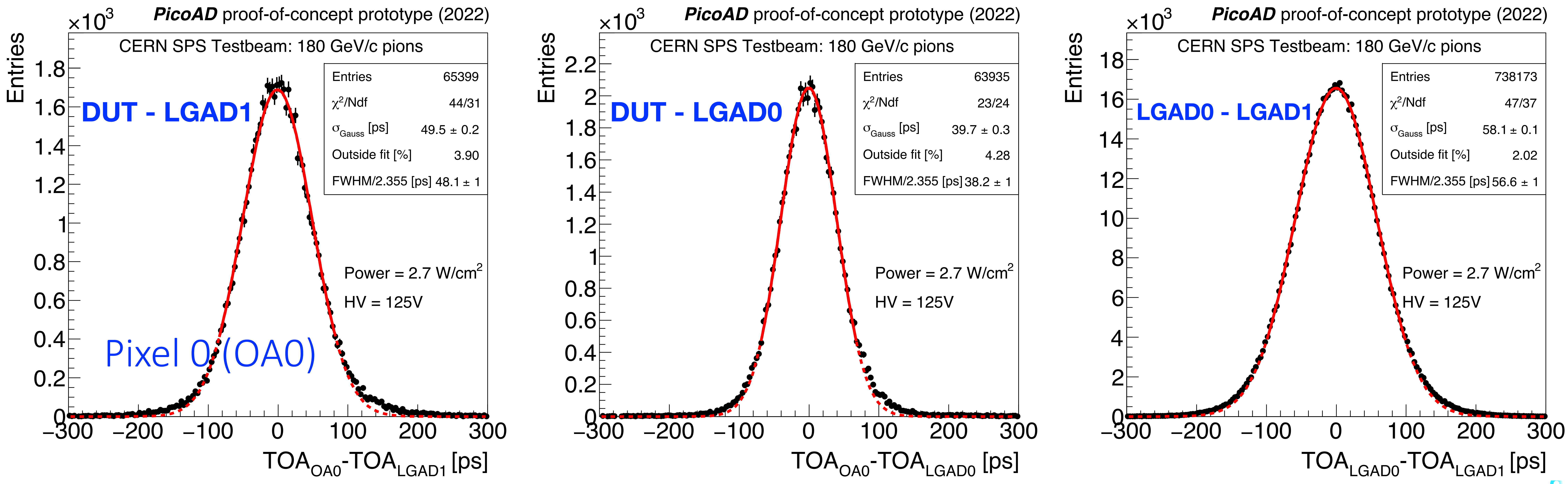


Results were also verified using **two SPADs** (but with much smaller statistics)

Time Resolution: Measurement

- 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





Time Resolution: Results[4]

European Research Council
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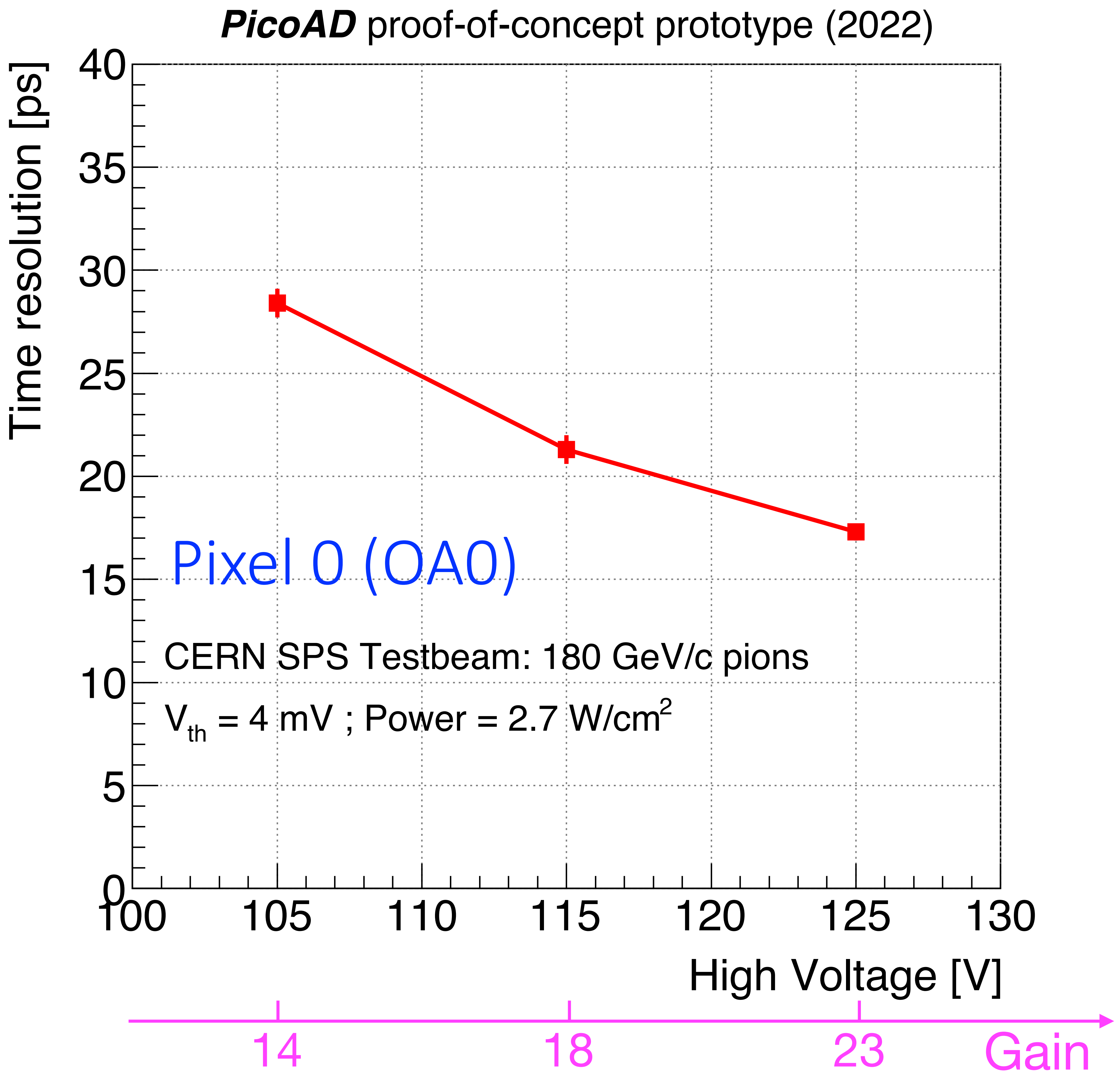
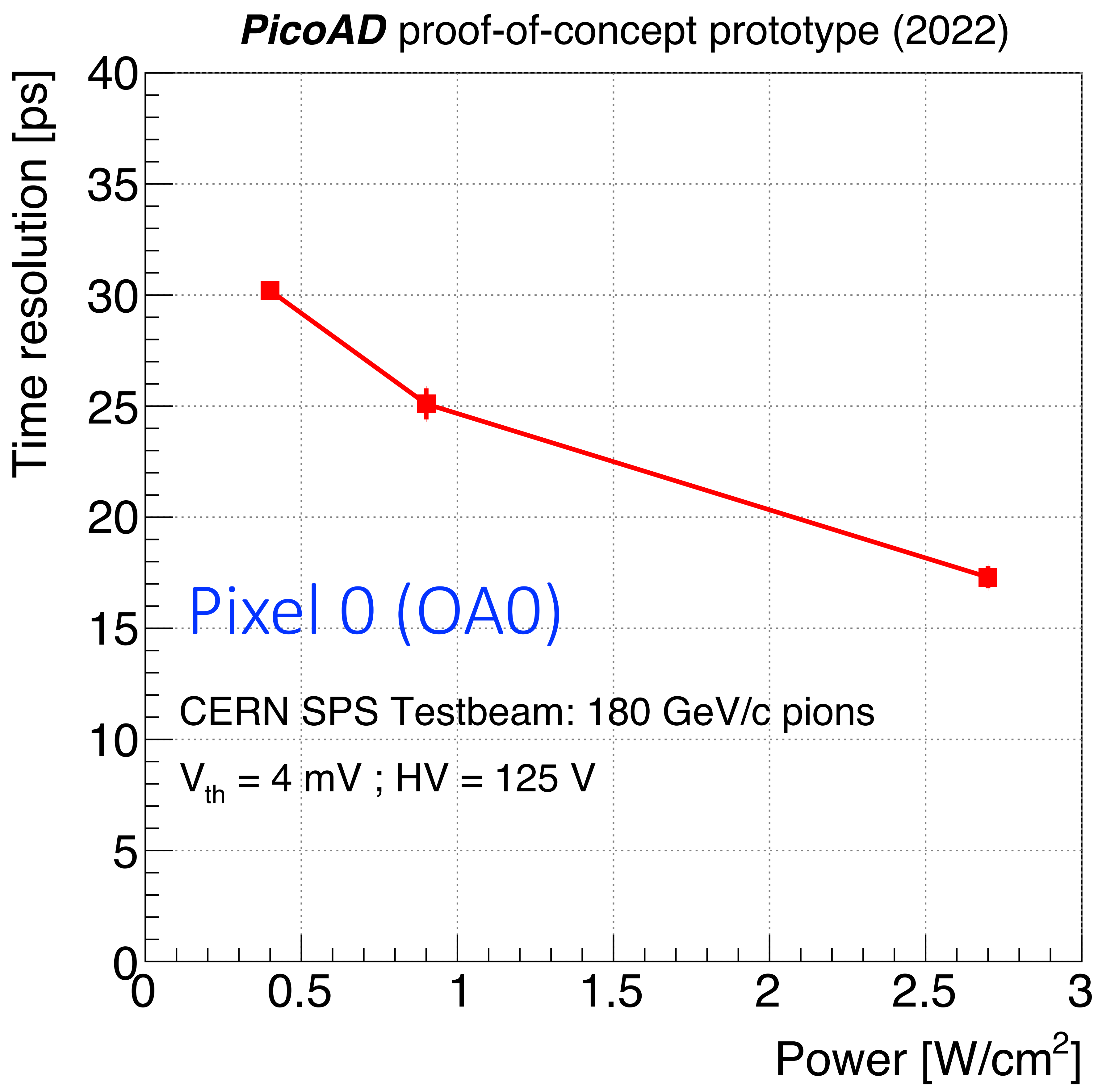
[4] G. Iacobucci et al., Testbeam Results of the Picosecond Avalanche Detector Proof-Of-Concept Prototype. arXiv:2208.11019, August 2022

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**





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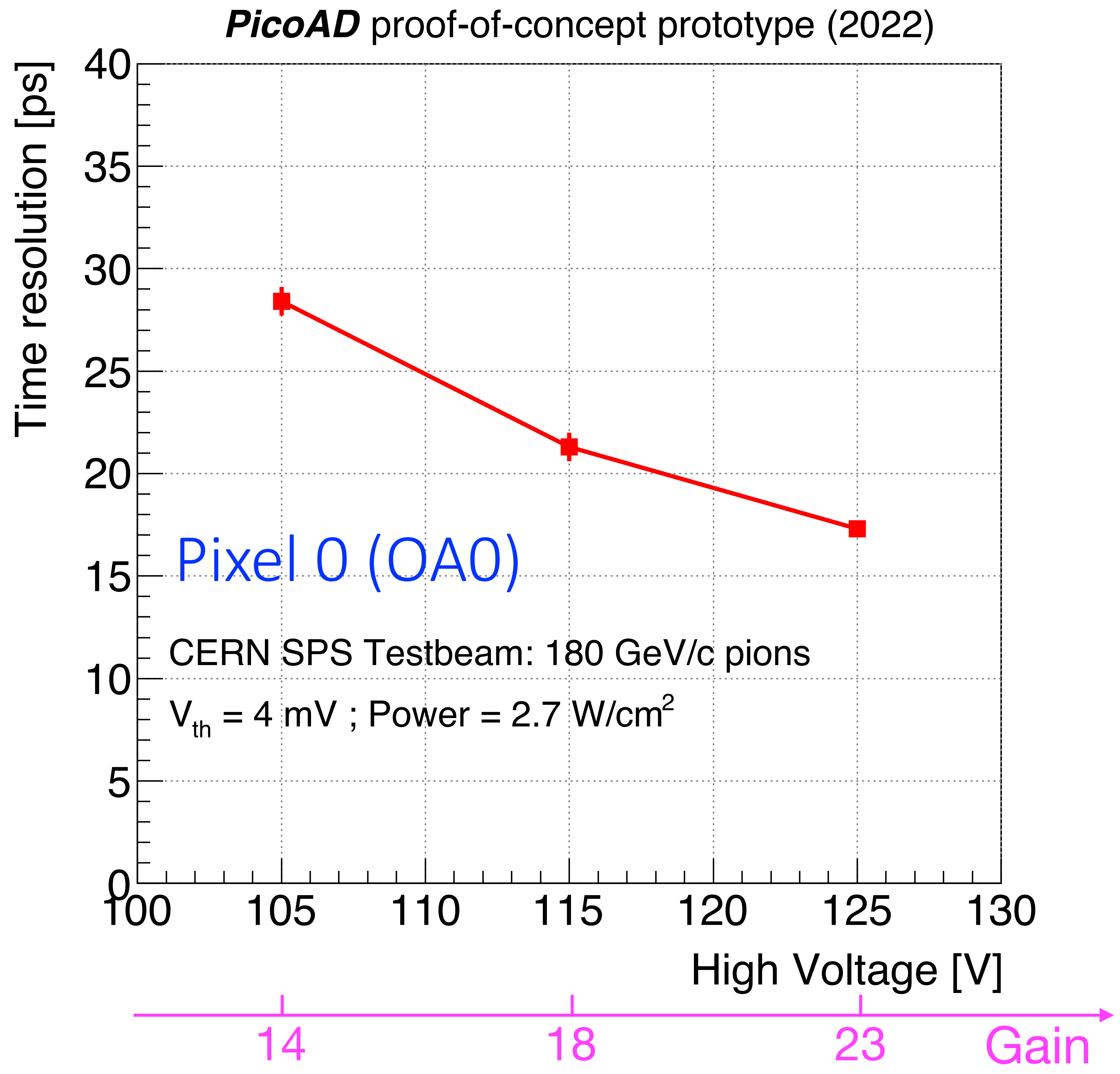
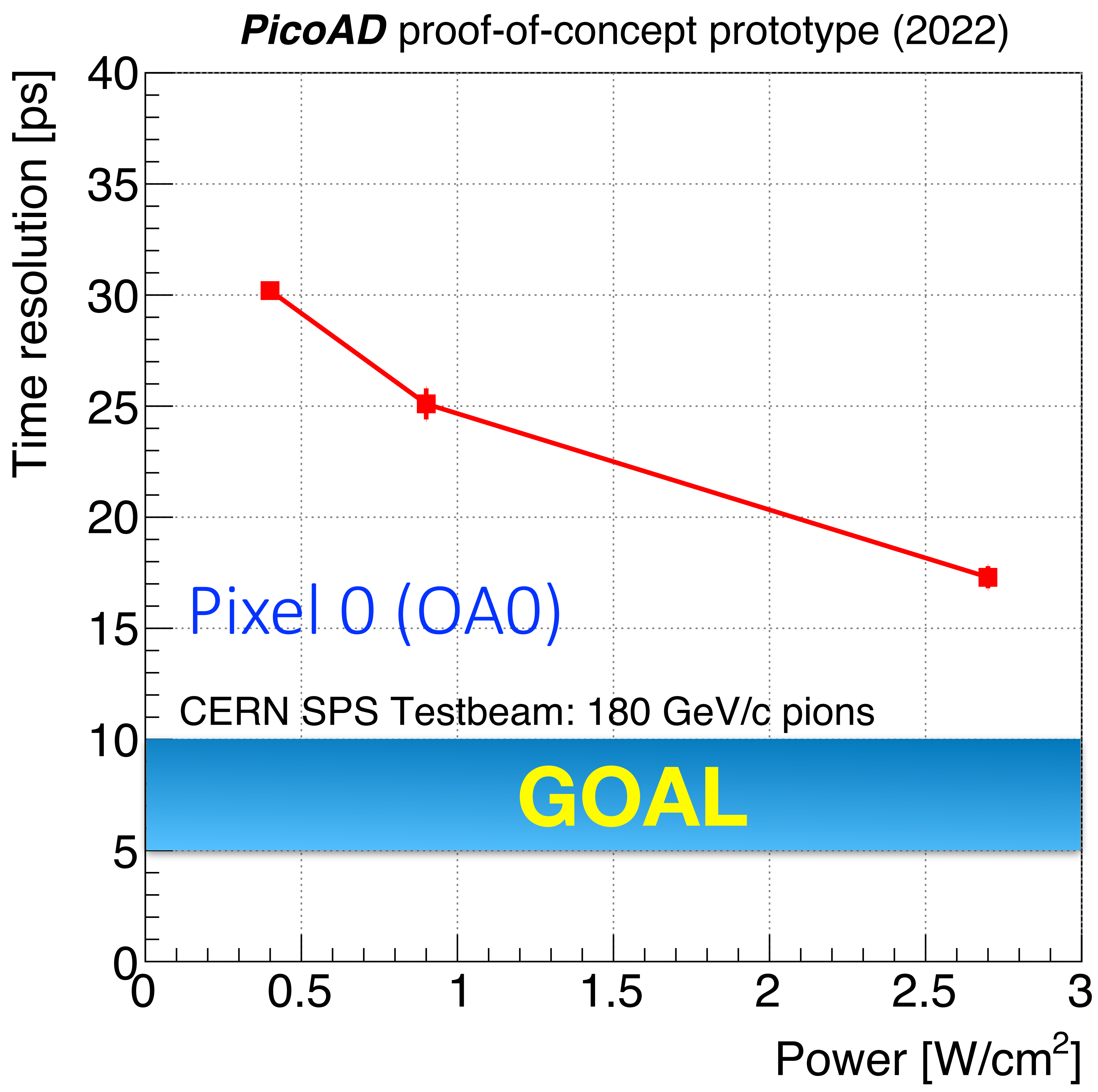


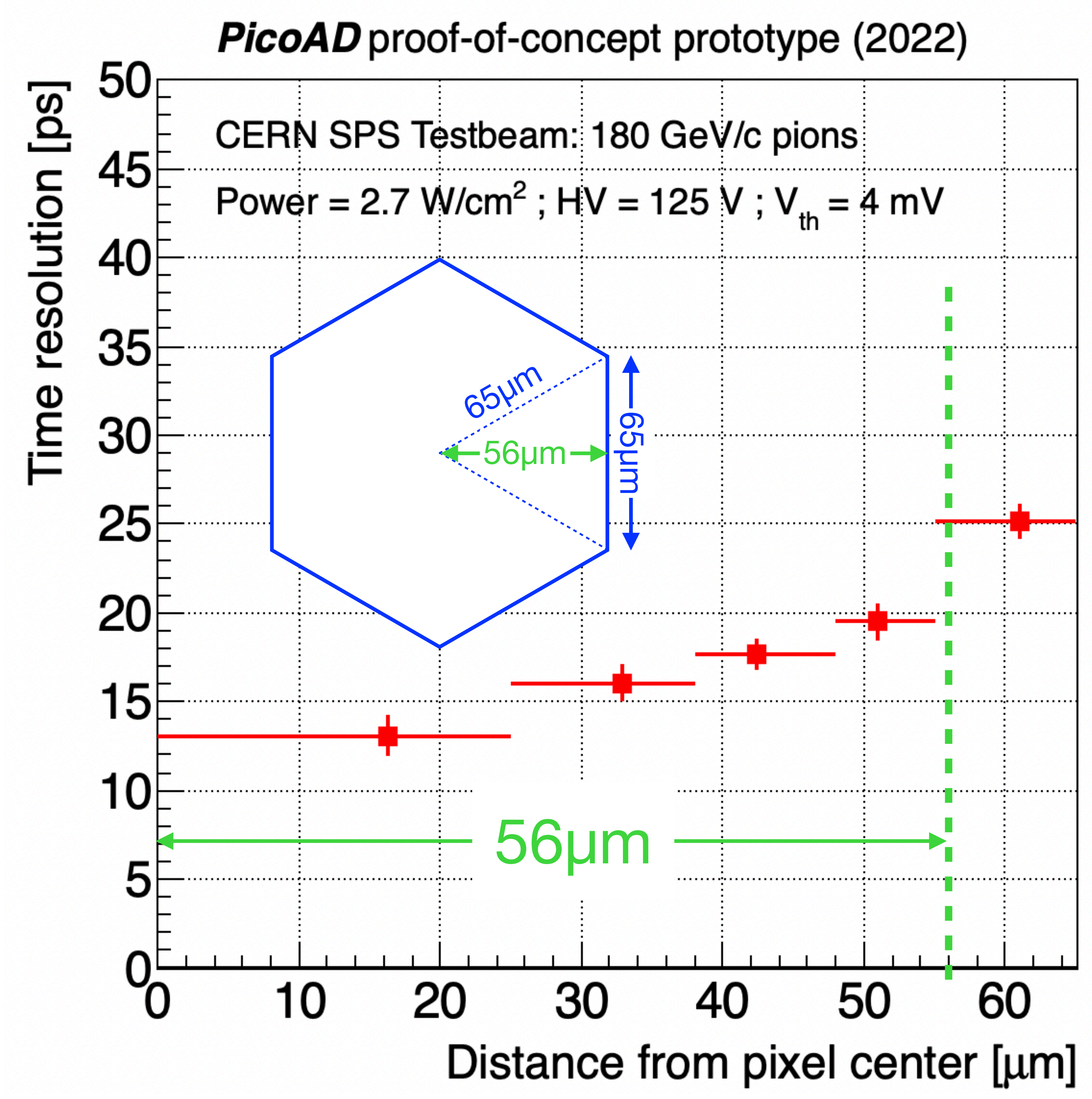


Time Resolution: Position Effects

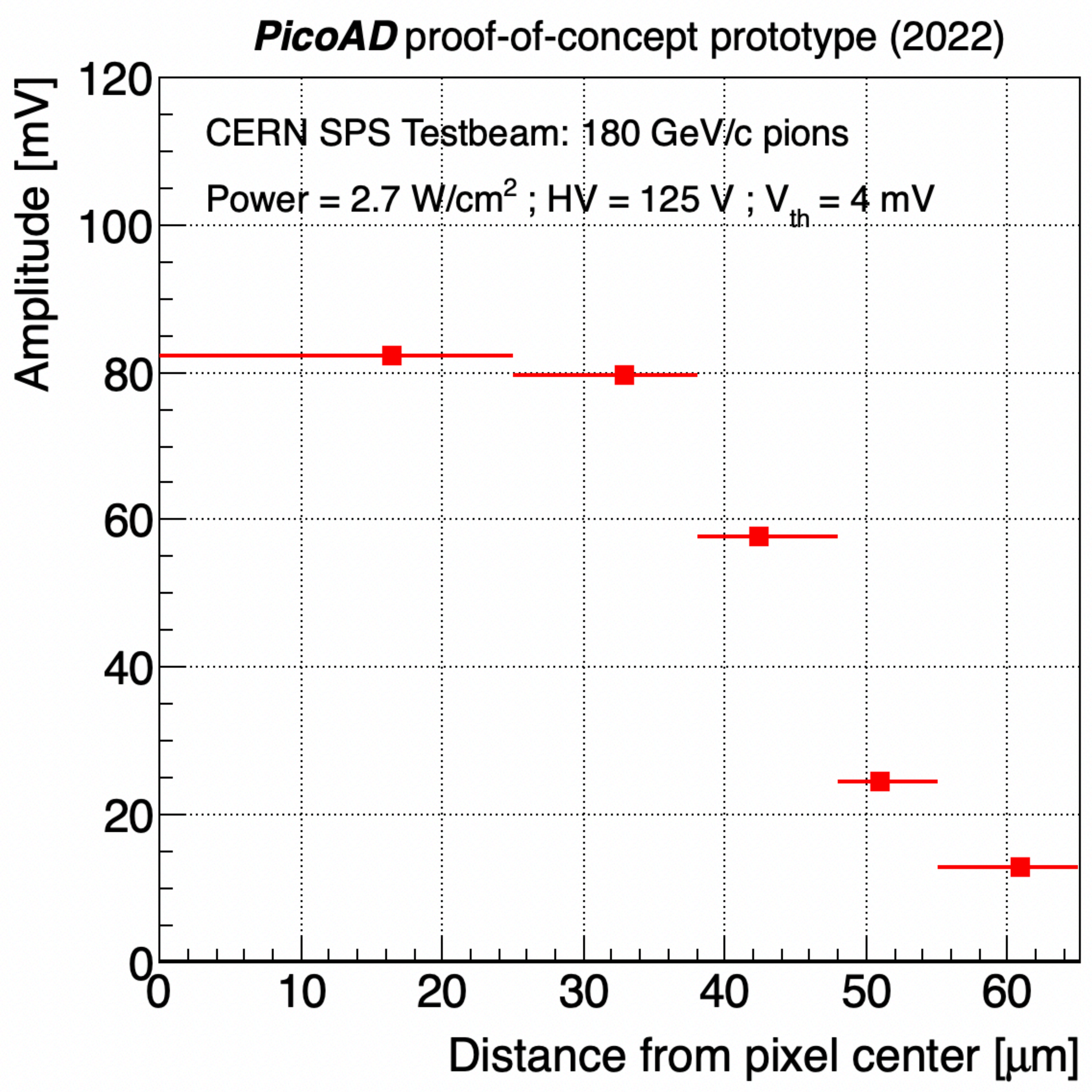
Small performance degradation toward pixel edges

Measured: effect of telescope's finite resolution (≈10 μm) convoluted with the real degradation

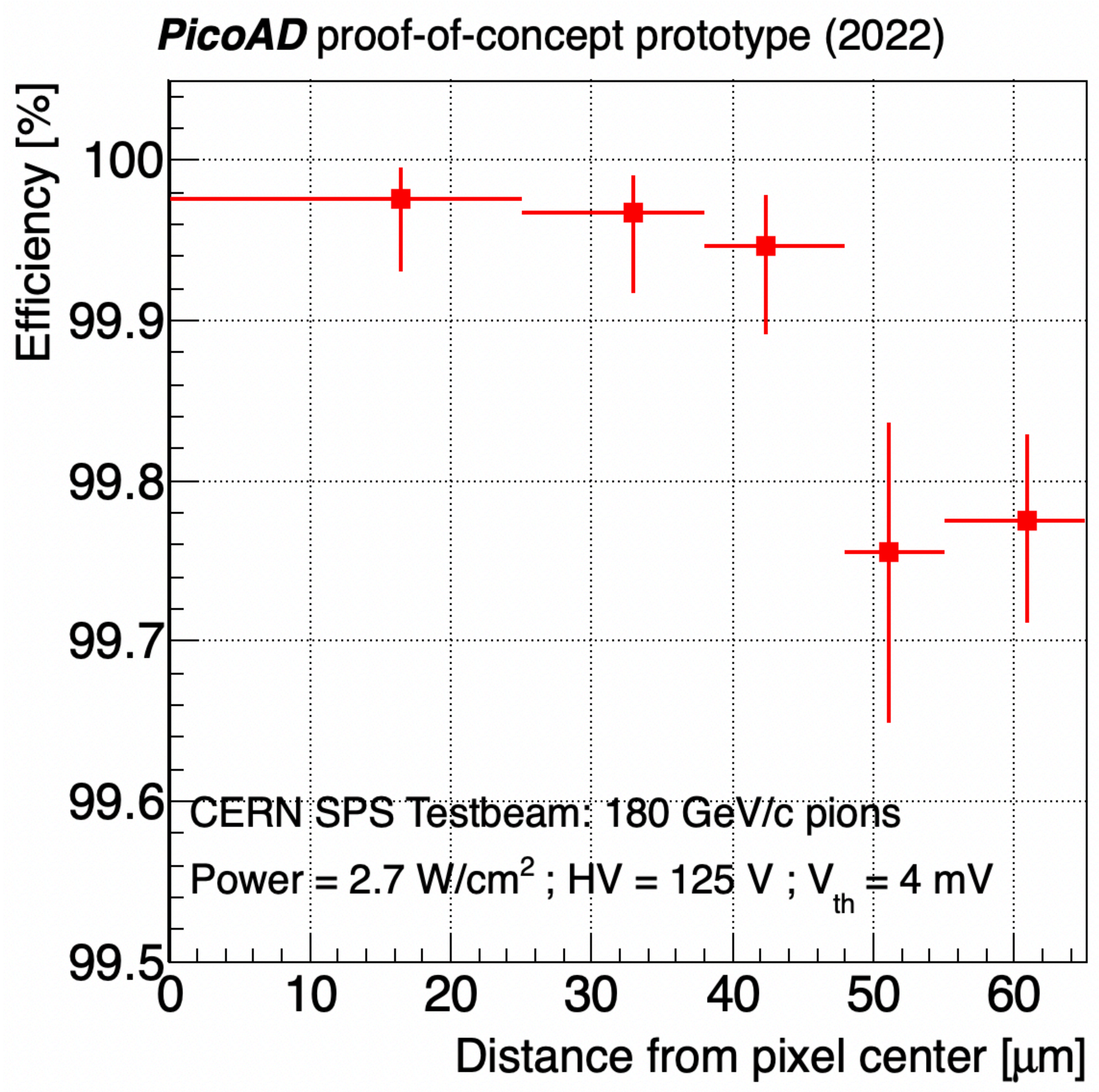
Time resolution



Signal amplitude

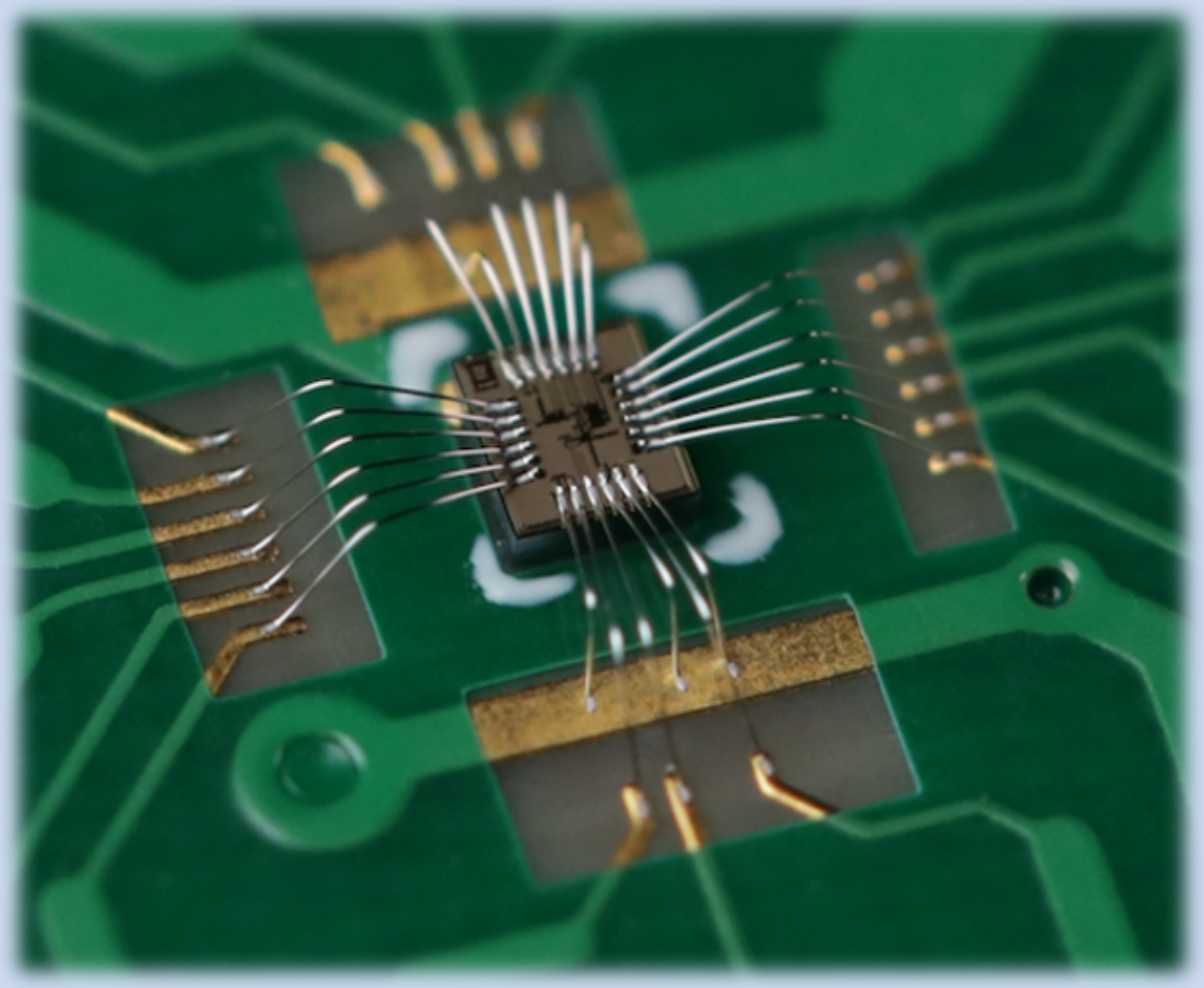


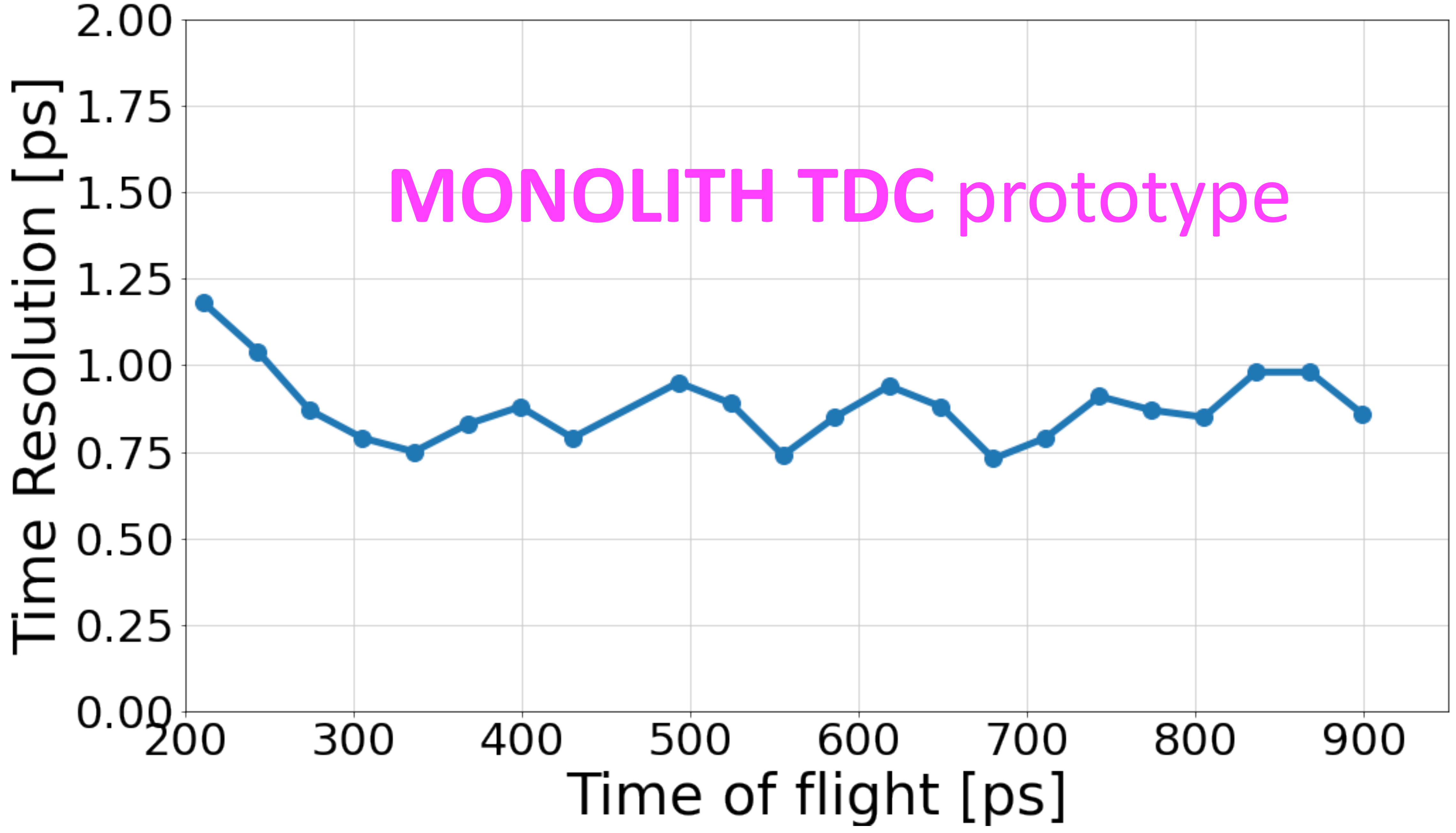
Efficiency



Sub-picosecond TDC

We are developing a sub-picosecond TDC based on a novel design (our patent[5] & more):





Standalone prototype still under test at UNIGE.
Integrated in MONOLITH 2022 monolithic ASIC.

[5] 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.

Other UNIGE projects that use monolithic SiGe BiCMOS

1. 100µPET SNSF SINERGIA
2. FASER W-Si pre-shower

The 100µPET SNSF SINERGIA project

Swiss National Science Foundation

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

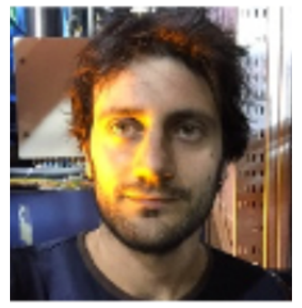
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Giuseppe Iacobucci
- P.I.

Mateus Vicente
- System integration
- Laboratory test

Jihad Saidi
- System simulation
- Laboratory test

Didier Ferrere
- System integration
- Laboratory test



Lorenzo Paolozzi
- Sensor design
- Analog electronics

Yannick Favre
- Board design
- RO system

Franck Cadoux
- Mechanics
- FEA calculations

EPFL

Michäel Unser
- P. I.

Pol del Aguila Pla
- Statistical signal processing

Aleix Boquet-Pujadas
- Signal/image processing
- Physical modeling

UNI LU

Martin Walter
- P. I.

Pablo Jané
- Nuclear Medicine
- PET imaging
- Translational imaging

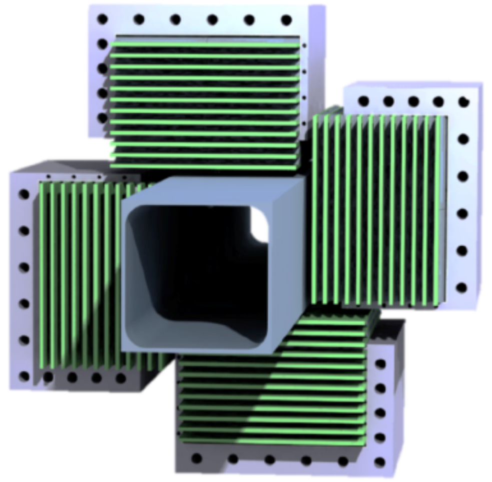
Xiaoying Xu
- Molecular Biology
- In vivo studies
- Bioinformatics

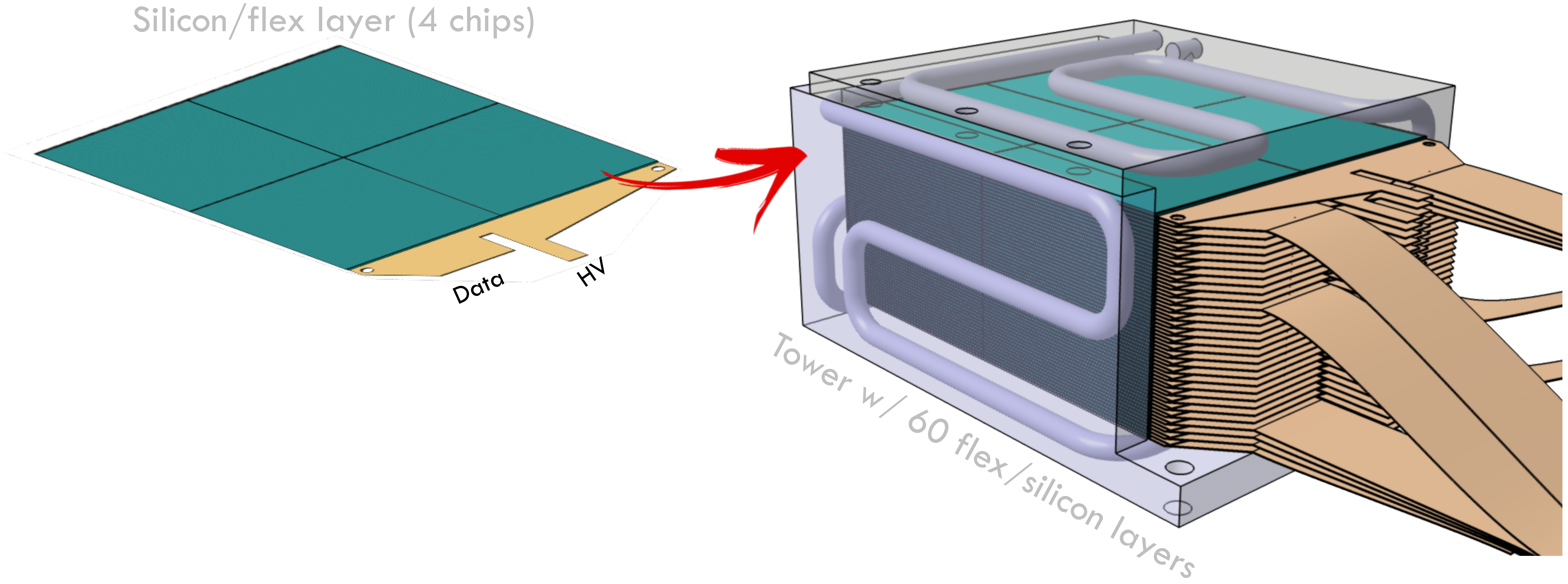
The 100μPET SNSF SINERGIA project

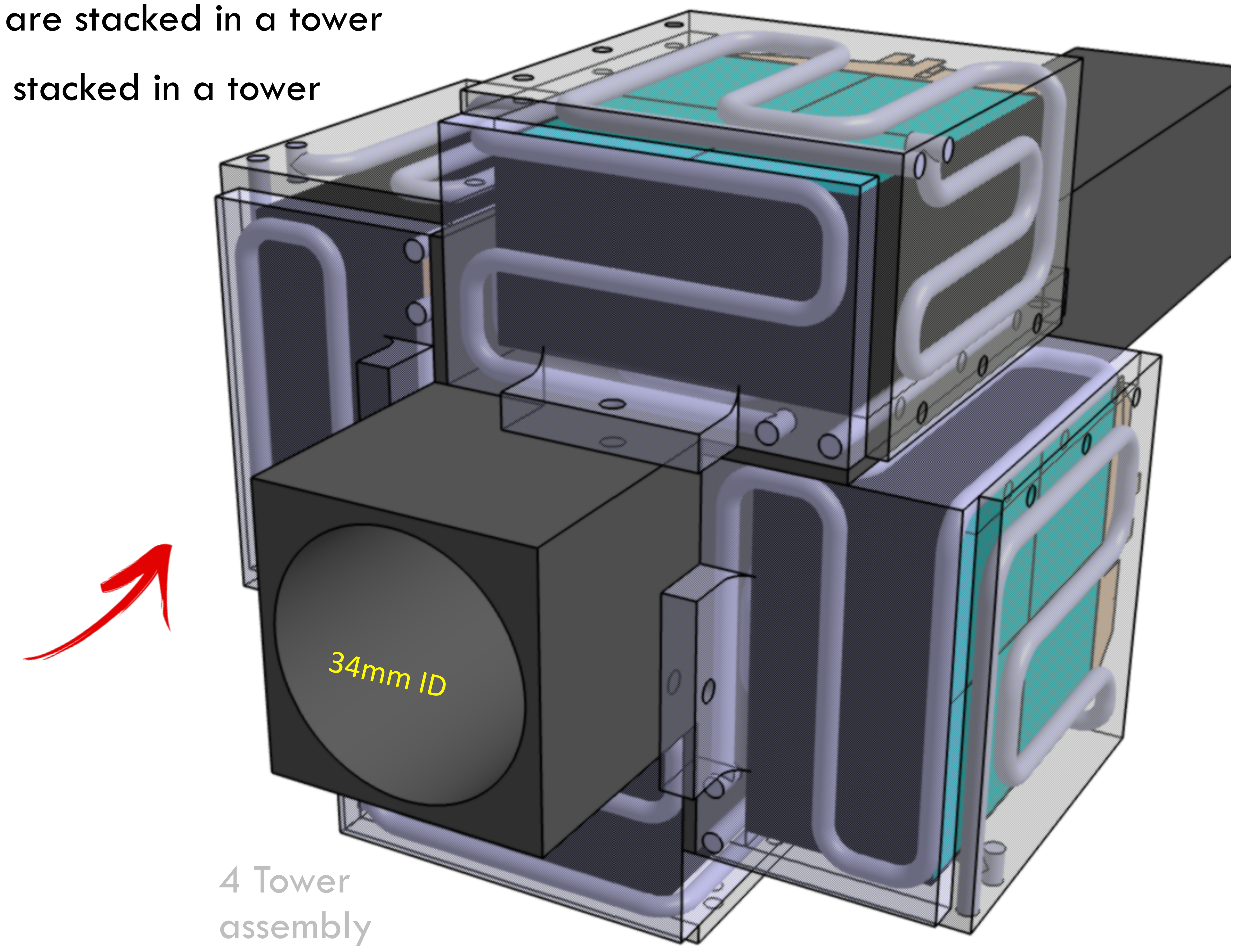
Swiss National Science Foundation

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

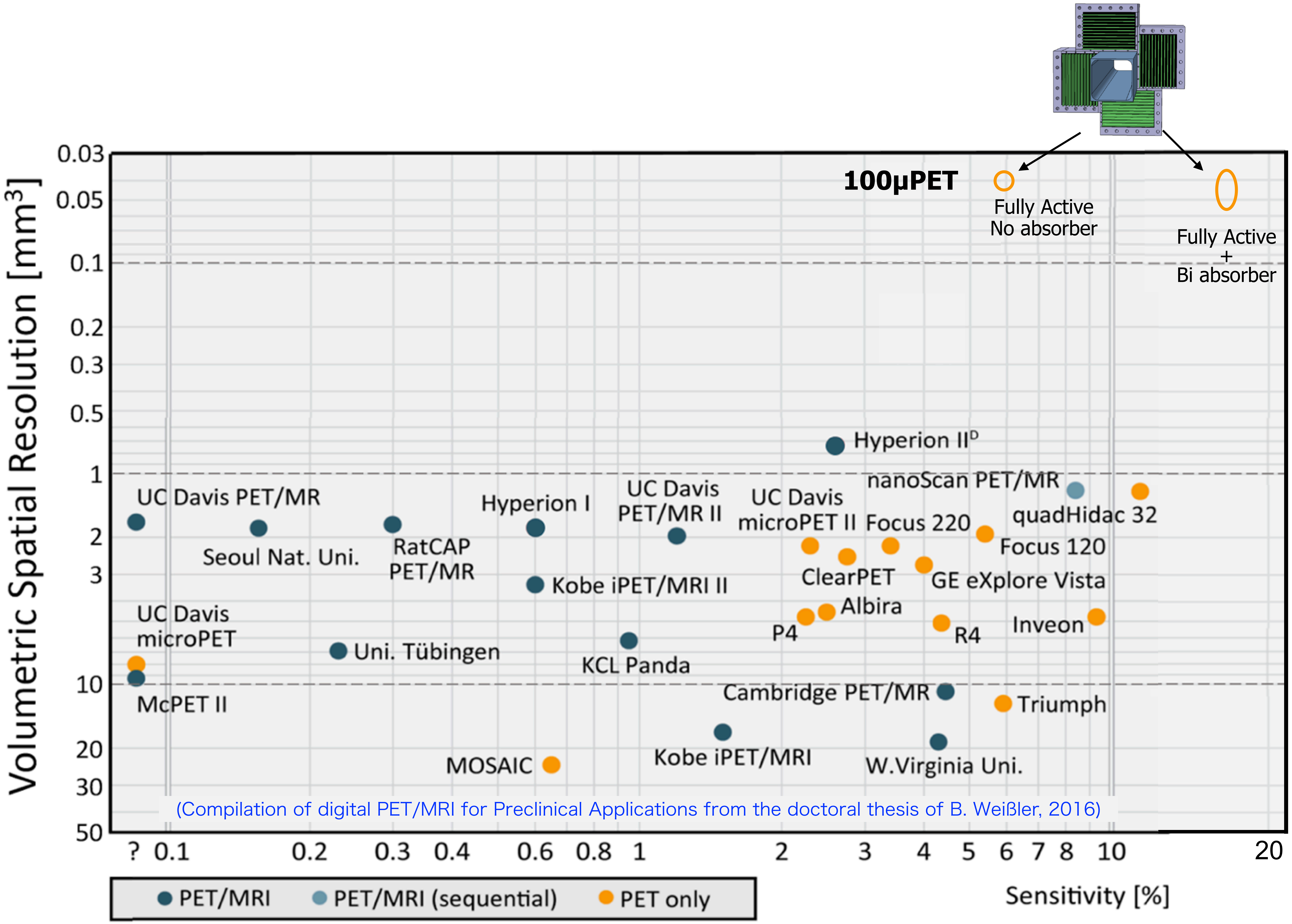
- **Simplified** and **improved** scanner design, avoiding acceptance holes from cooling blocks
  - Monolithic **100μPET** detector ASIC: **2.5 x 3 cm²** active pixel matrix; **100 μm** pixel pitch; **250 μm** thick active silicon sensor
  - Single silicon detection layer composed by **2x2 chips** assembled, covering **30 cm²**
  - **4 "towers"** compose the scanner. **60** detection layers on each tower = **960 chips!**
    - Large number of services and interconnections, requiring **innovative** design. Two possible designs under study
      - **5 silicon detector layers** (20 chips) stacked on a **PCB**, staggered for **wire-bonding**. **12 modules** are stacked in a tower
      - **1 detection layer** (2x2 chips) are interfaced to a **FPC** via ACF bonding. **60 FPC/ASIC layers** are stacked in a tower


4 Tower assembly





The 100µPET Performance



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FLARE

High granularity FASER W-Si pre-shower

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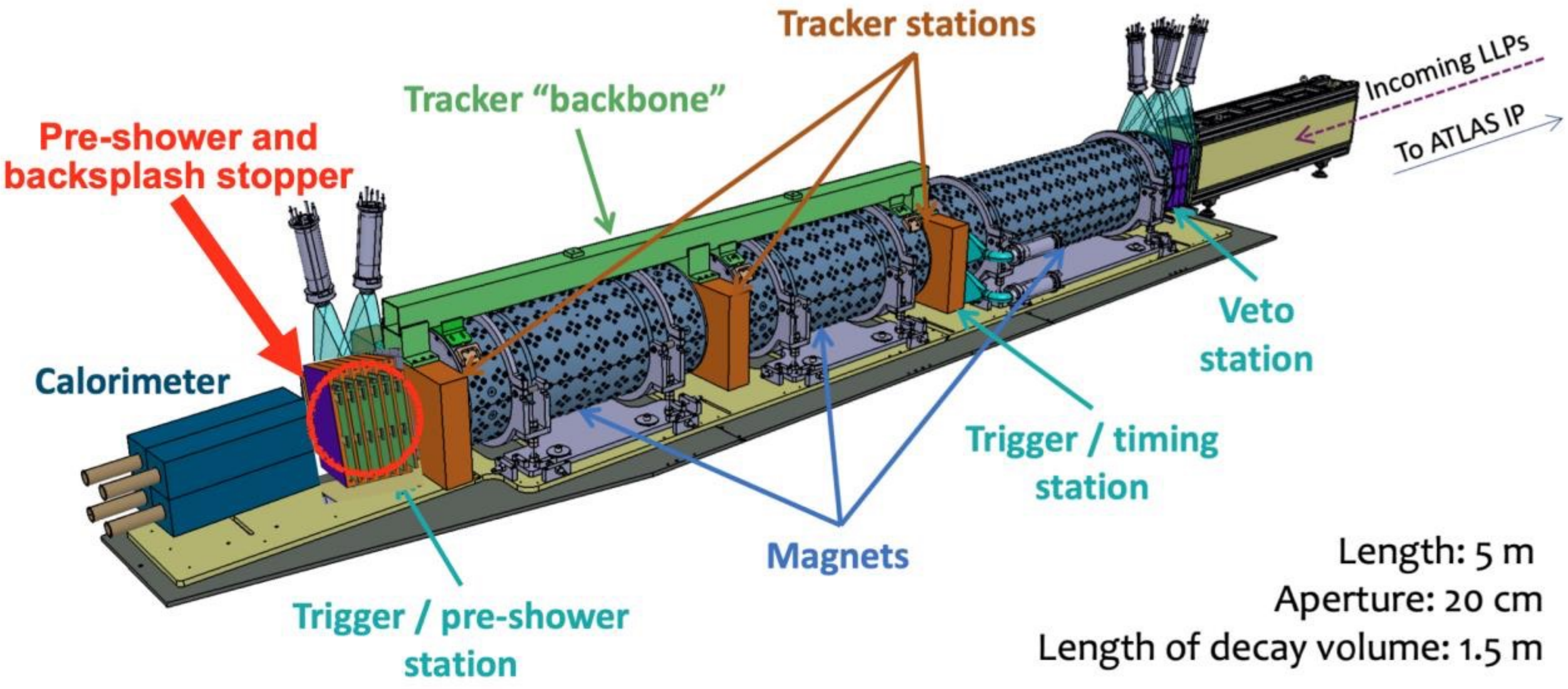
A. Sfyrla and G. Iacobucci groups

Current FASER pre-shower:

2 layers of tungsten + scintillating detectors $\Longrightarrow$ no XY granularity



To have access to **two-photon final states**:

- **High granularity and high dinamic range** pre-shower based on six planes of monolithic pixels
- Discriminate **TeV-scale EM showers**
- Targeting data taking in 2024-2026 and during HL-LHC

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High granularity FASER W-Si pre-shower

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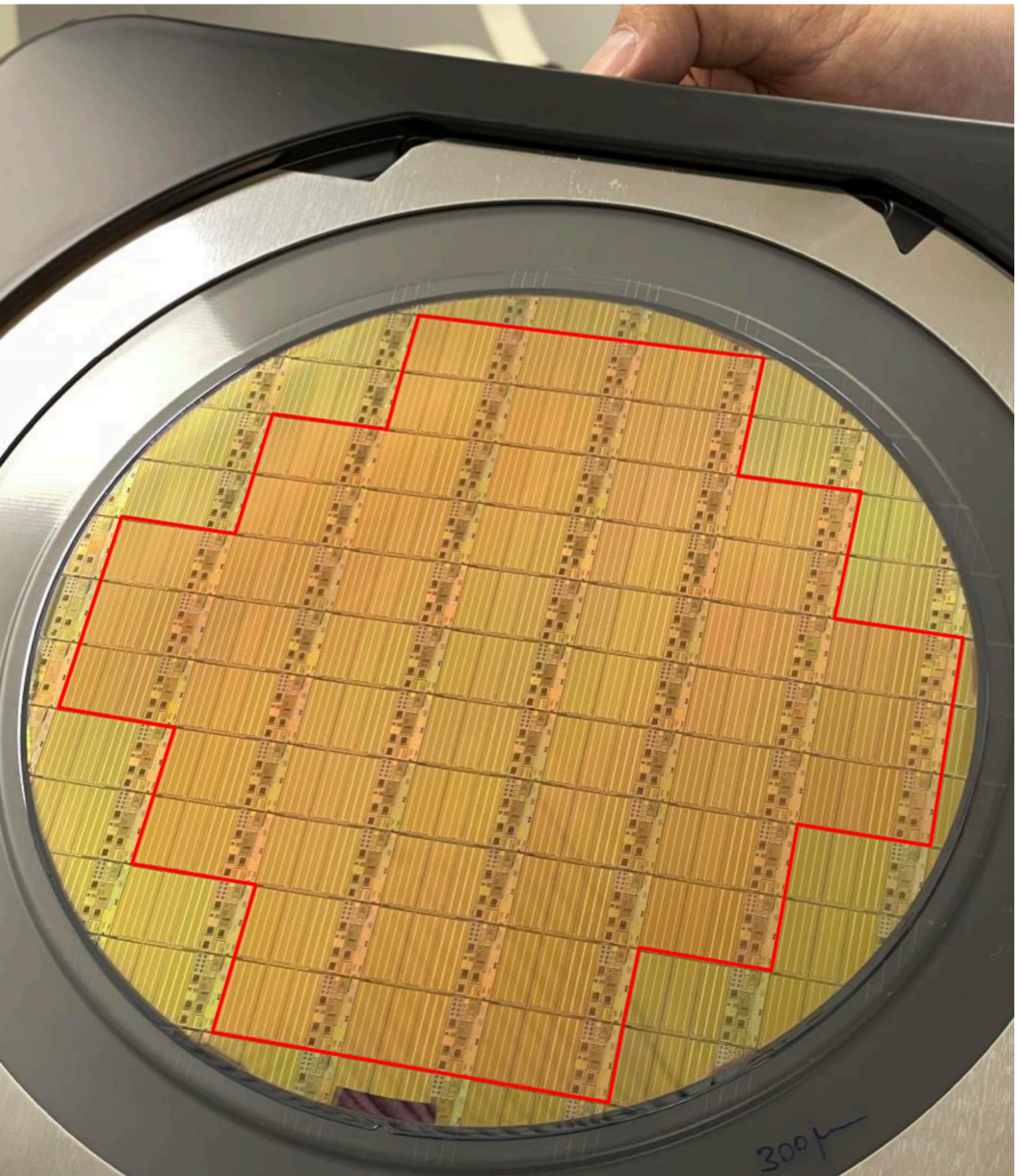
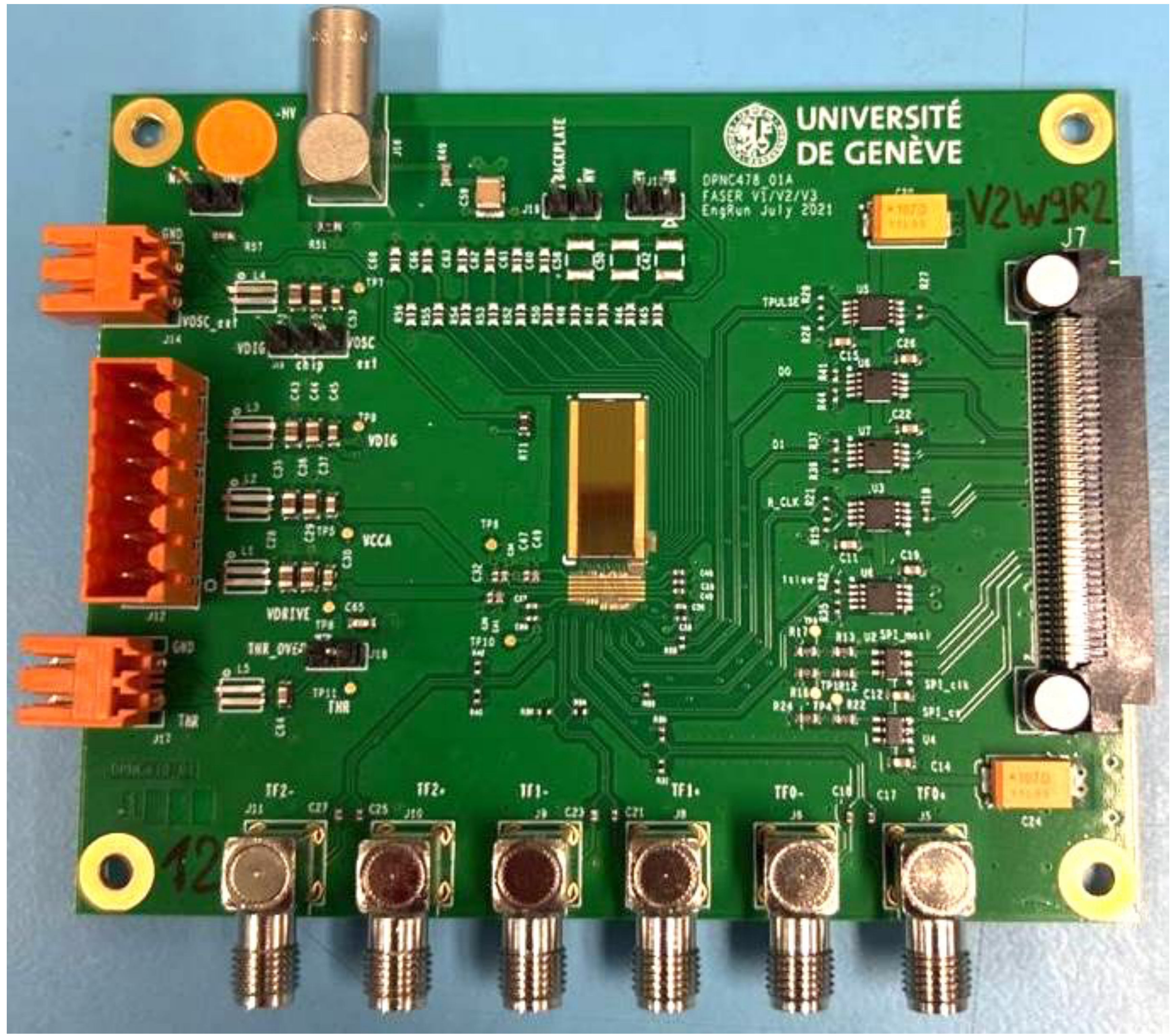
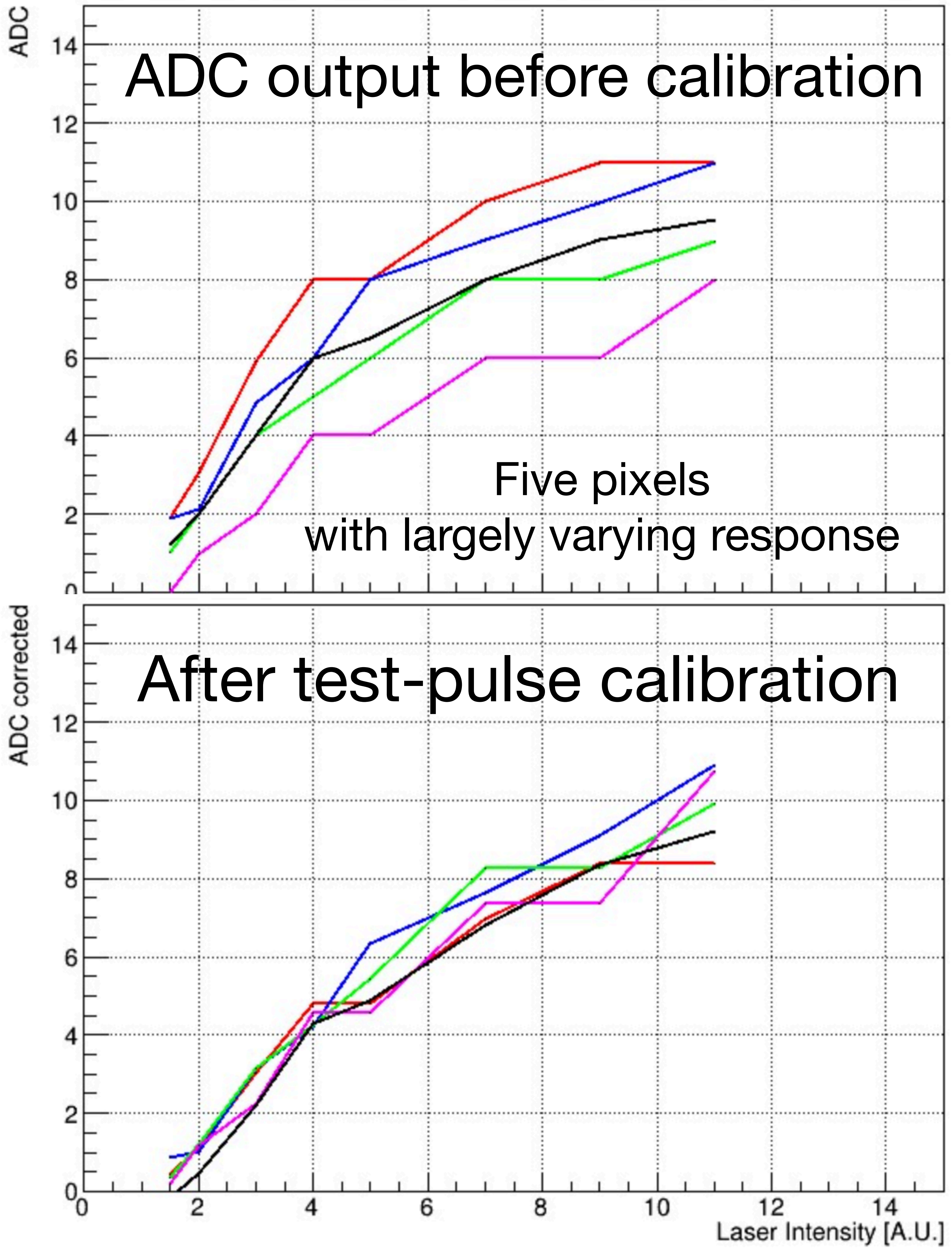
FASER preshower pre-production chip:

- **First engineering run produced by UNIGE in SiGe BiCMOS**
- Three large ASIC (15x7.5 mm^2) with alternative designs
- pixels with 65μm side (~100μm pitch)
- Delivered in July; presently under test







Summary & Outlook

The PicoAD© Monolithic proof-of-concept prototype works:

- **Gain ≈ 20** for ^{55}Fe X-rays (space-charge effects, for X-rays, measured)
- **Efficiency = 99.9 %** at full sensor-bias voltage
- **Time resolution σ_t = (17.3 ± 0.4) ps** (although sensor not yet optimized for timing)

Ongoing activities include:

- Optimization for timing of the PicoAD sensor design with TCAD to achieve $\lesssim$10 ps (smaller pixel pitch; thicker drift layer; improved inter-pixel region)
- Development of picosecond TDC for fully monolithic chip

Deliverable of MONOLITH project:

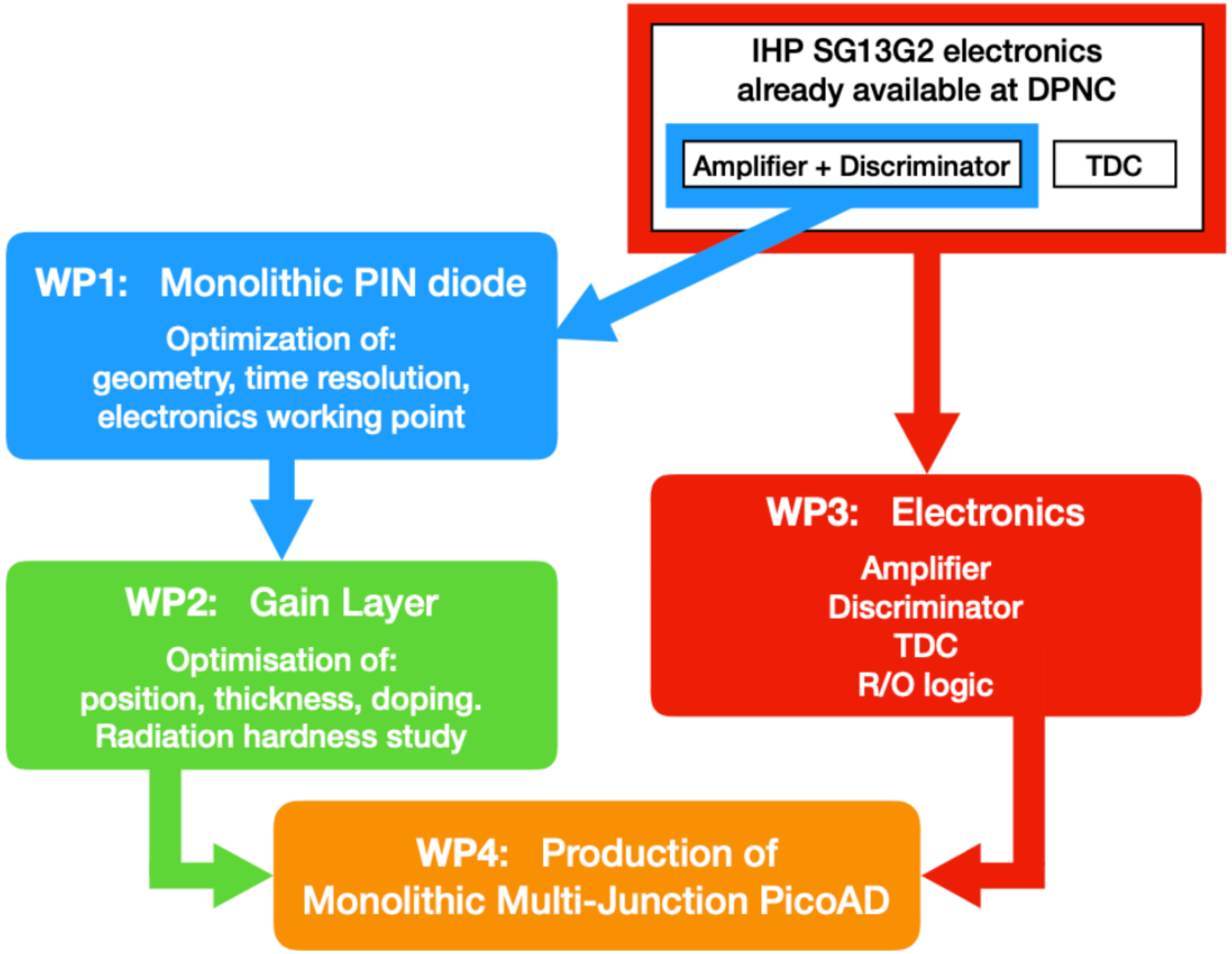
- Full-reticle chip with 50µm pitch and sub-10ps timing in Summer 2025

Extra Material

The MONOLITH ERC Project

Funded by the H2020 ERC Advanced grant 884447[1], July 2020 - June 2025

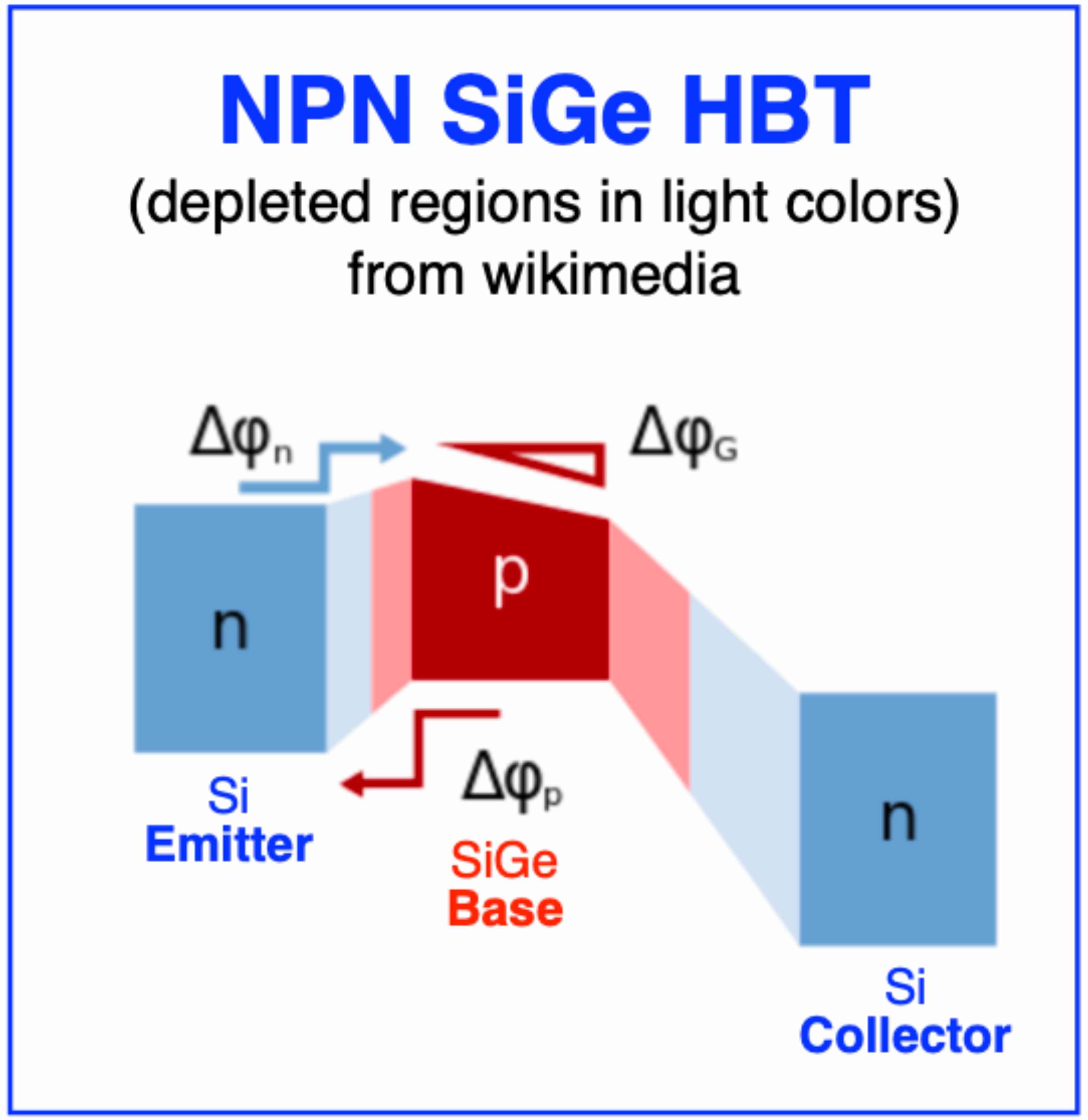
- **Monolithic silicon sensor** able to:
  - precisely measure 3D spatial position of charged particles
  - provide picosecond time resolution
- NEEDS:
  1. Fast and low-noise **SiGe BiCMOS** electronics
  2. Novel sensor concept: the **Picosecond Avalanche Detector (PicoAD)**



[1] MONOLITH H2020 ERC Advanced Project Web Page - https://www.unige.ch/dpnc/en/groups/giuseppe-iacobucci/research/monolith-erc-advanced-project/

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

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



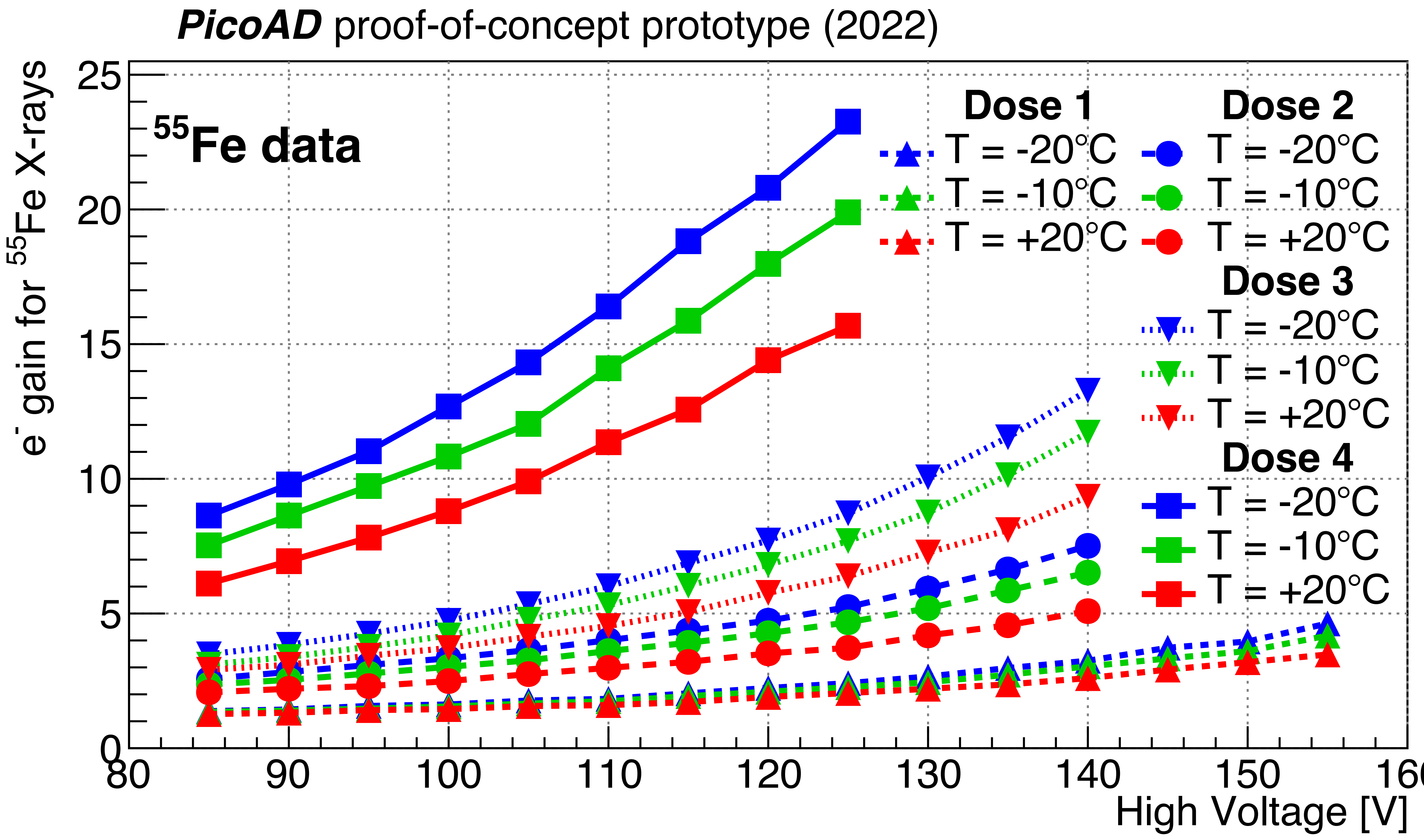
SiGe HBT = BJT with Germanium as base material:
- higher doping in base possible
- thinner base
- **reduced base resistance R_b**

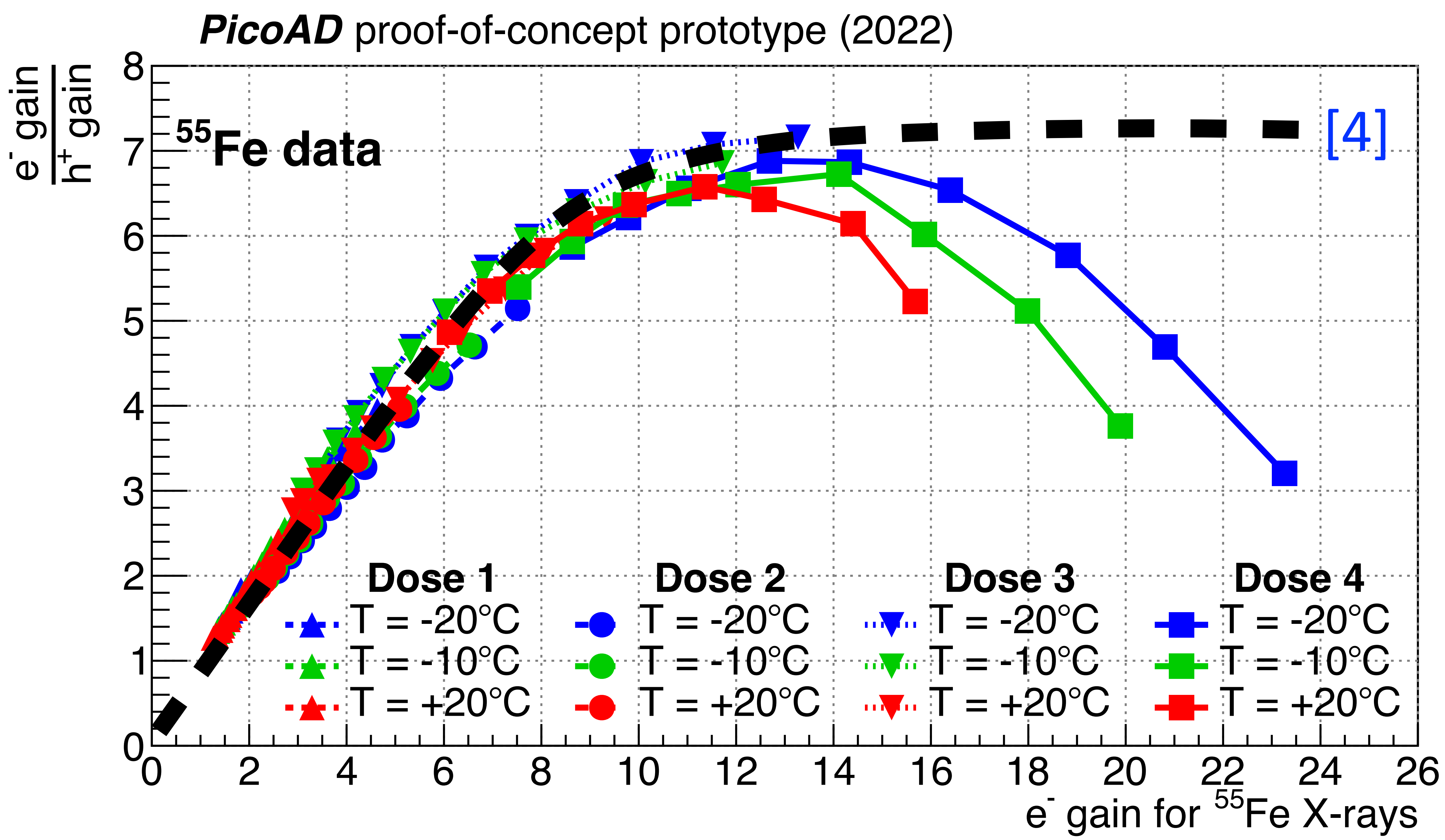
Grading of Ge doping in base:
- charge transport in base via drift
- reduced charge transit time in base
- **high current gain β**

Gain Measurements: Results

A gain of **≈20** for ^{55}Fe X-rays is reached at HV = 120 V and T = -20 °C[3]

Evidence for **gain suppression** due to space-charge effects[4]

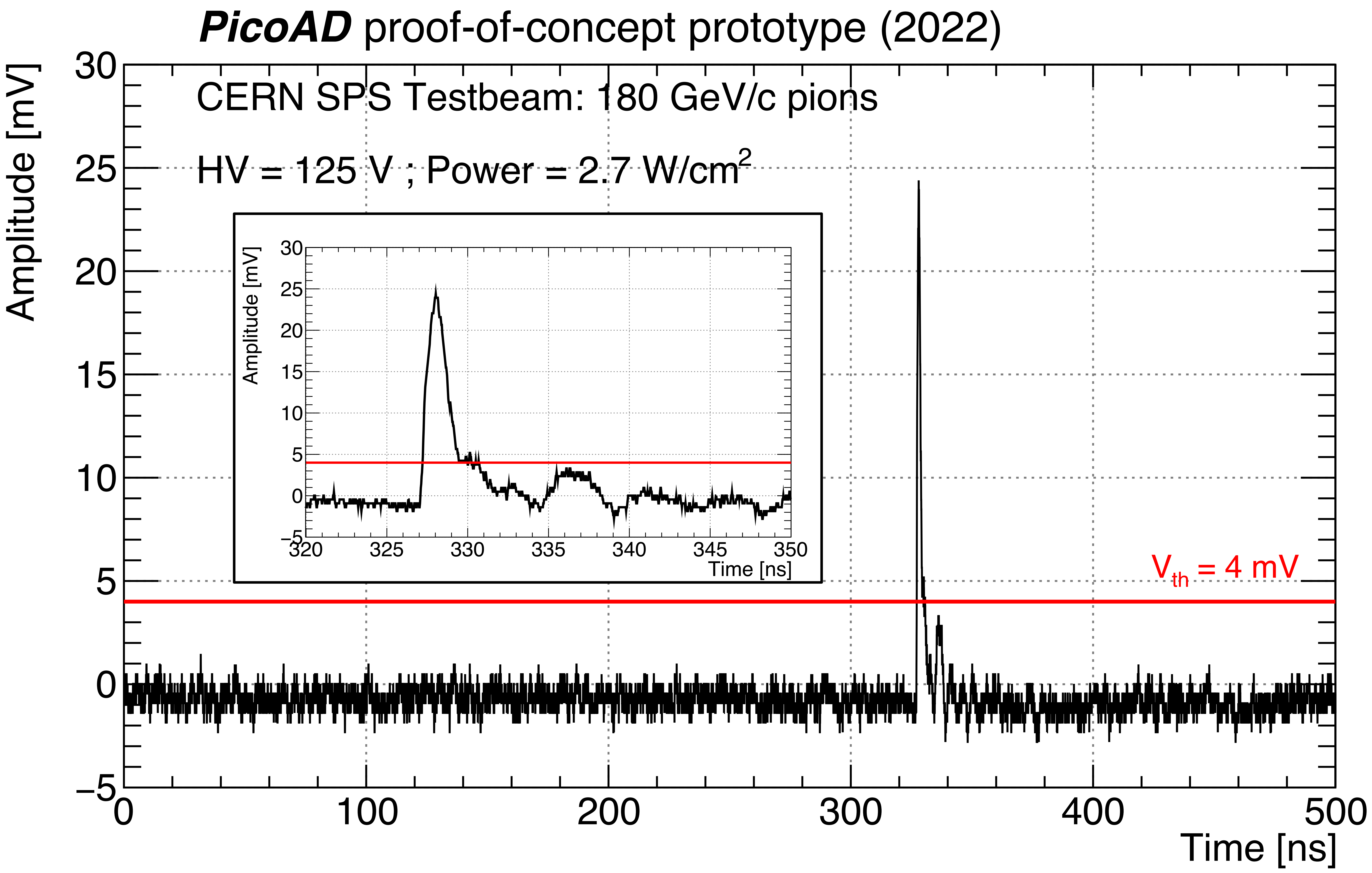




[3] L. Paolozzi et al. Picosecond Avalanche Detector - working principle and gain measurement with a proof-of-concept prototype. arXiv:2206.07952v1, June 2022

[4] R. J. McIntyre. A new look at impact ionization-Part I: A theory of gain, noise, breakdown probability, and frequency response. IEEE Transactions on Electron Devices, vol. 46, no. 8, 1623-1631, Aug. 1999

Waveform Example



Time-walk Correction

- Shift at 200 ps of the waveform to subtract low-frequency noise
- Time at constant fraction: 25% of max amplitude
- Amplitude-based time-walk correction for residual time walk