



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA



Istituto Nazionale di Fisica Nucleare



ALICE



FONDAZIONE
BRUNO KESSLER

Direct detection of charged particles with SiPMs for timing applications and in-SiPM and in-SPAD performance using MIPs

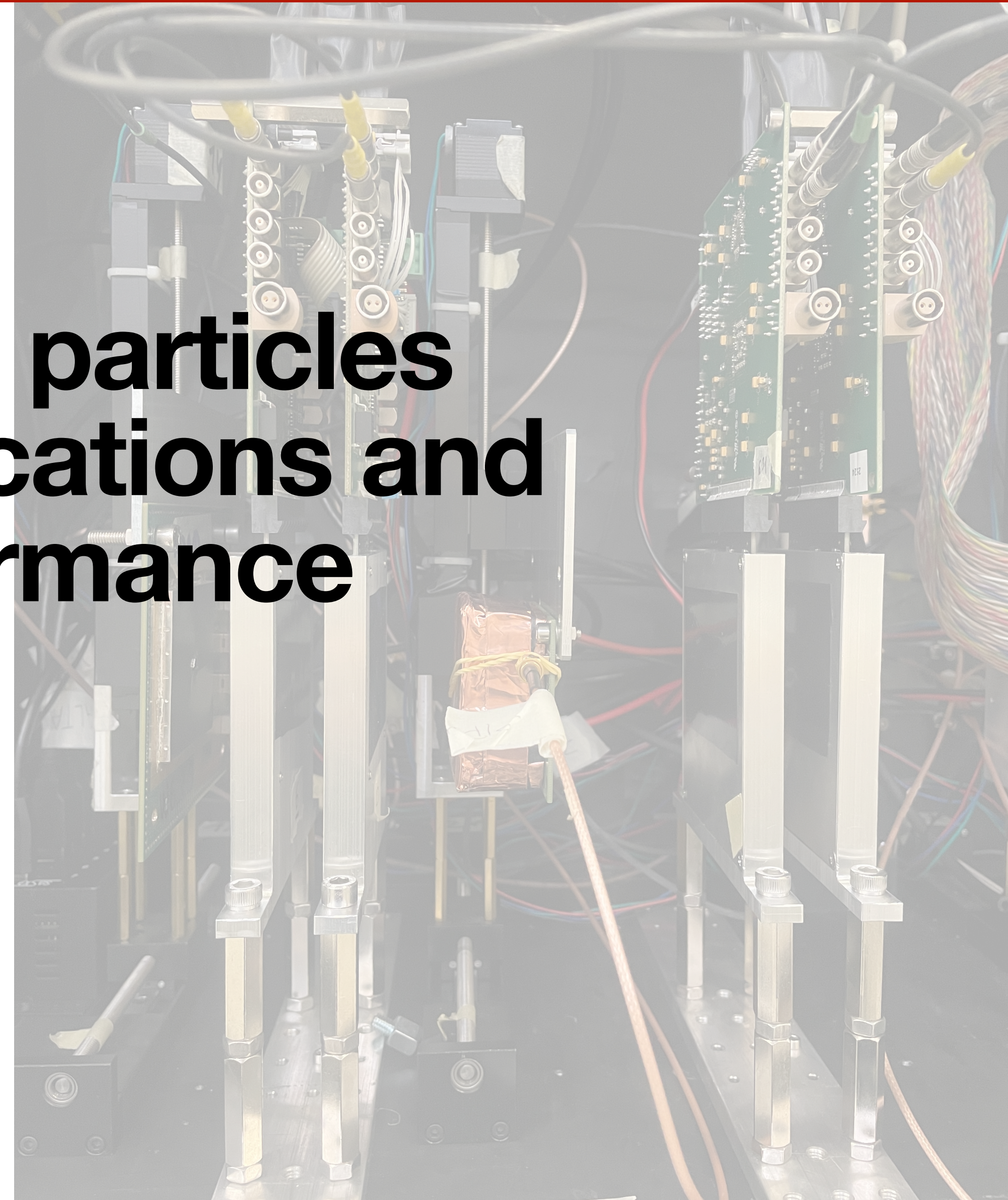
Bianca Sabiu

University of Bologna, INFN Bologna, CERN

PSD14

London

September 1-4, 2026



♦ Research context

- Recently published results

♦ SiPMs with standard protection layer directly detecting charged particles

- Experimental setup
- Efficiency measurements
- Timing measurements
- Radiation hardness

♦ SiPMs without standard protection layer directly detecting charged particles

- Experimental setup
- in-SiPM efficiency measurements
- in-SPAD efficiency and time resolution
- Preliminary results on FBK (not yet thinned) Back-Side-Illuminated prototypes

♦ Conclusions

R&D on direct detection of charged particles with SiPMs

Recently published results



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Expected: 1 SPAD
(+CT)
Observed: **multi-
SPADs** signals
dominant



JINST 17 P06007 (2022)

R&D on direct detection of charged particles with SiPMs

Recently published results



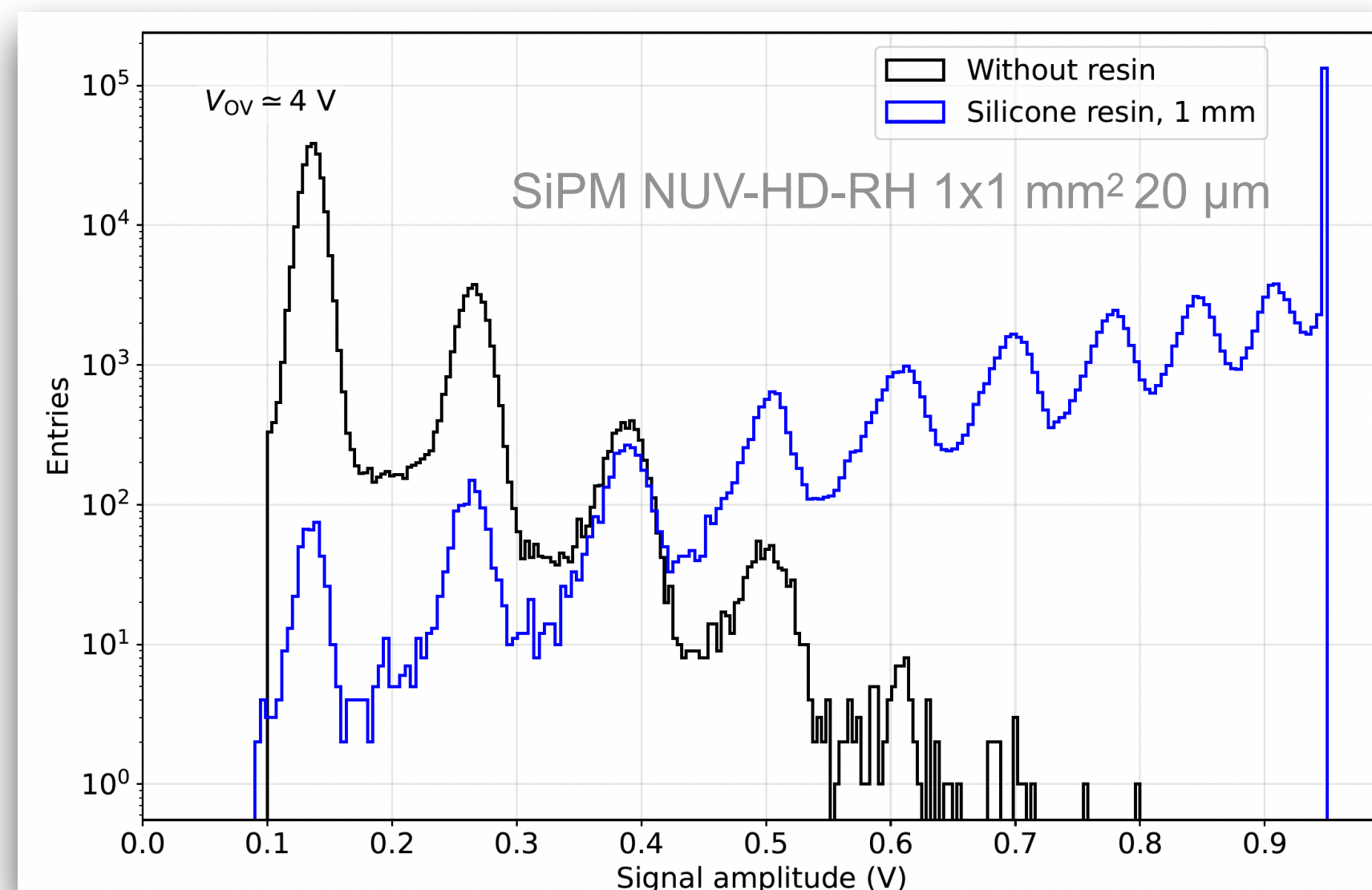
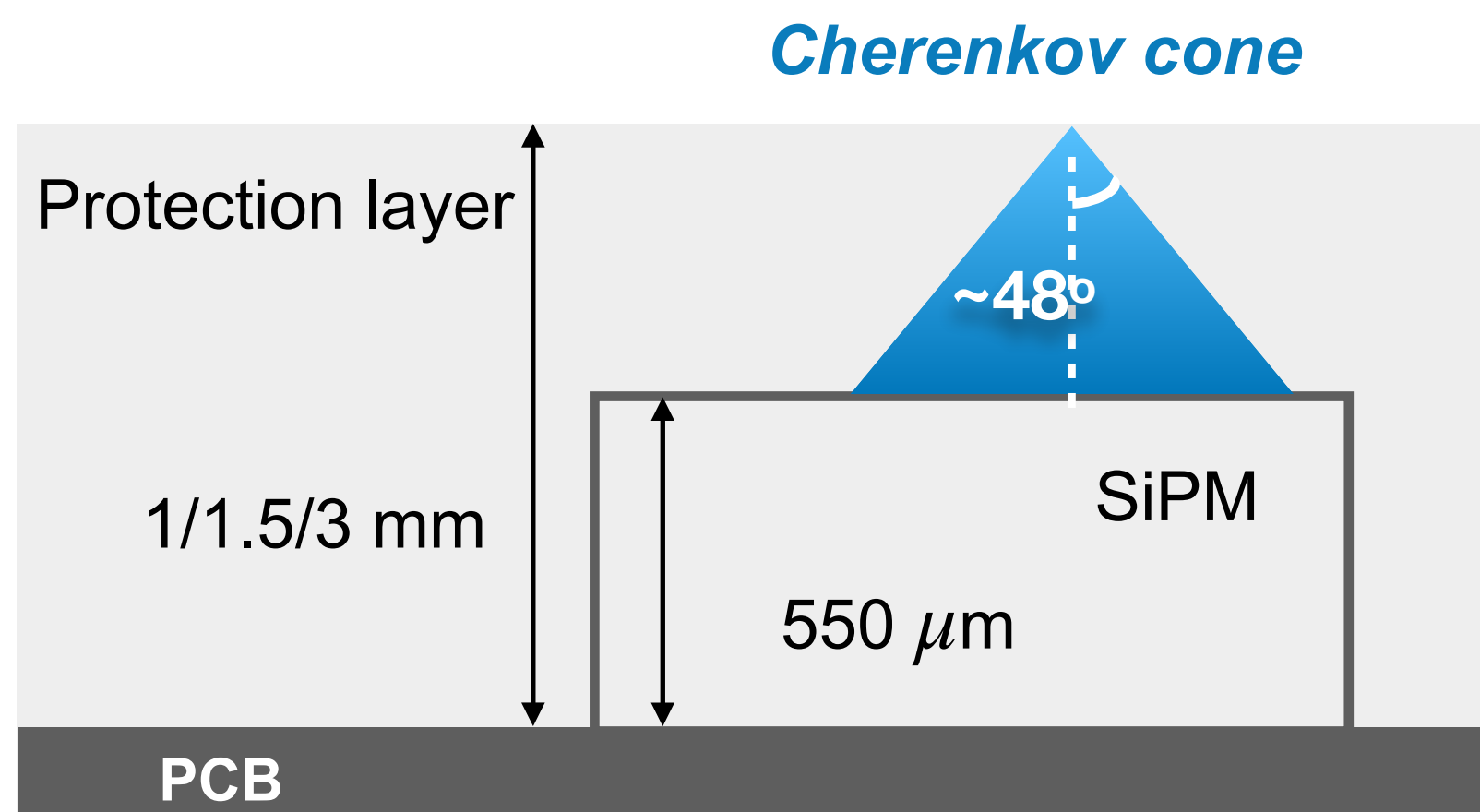
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Due to standard
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→ Cherenkov light →
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EPJ Plus 138 337 (2023)



R&D on direct detection of charged particles with SiPMs

Recently published results



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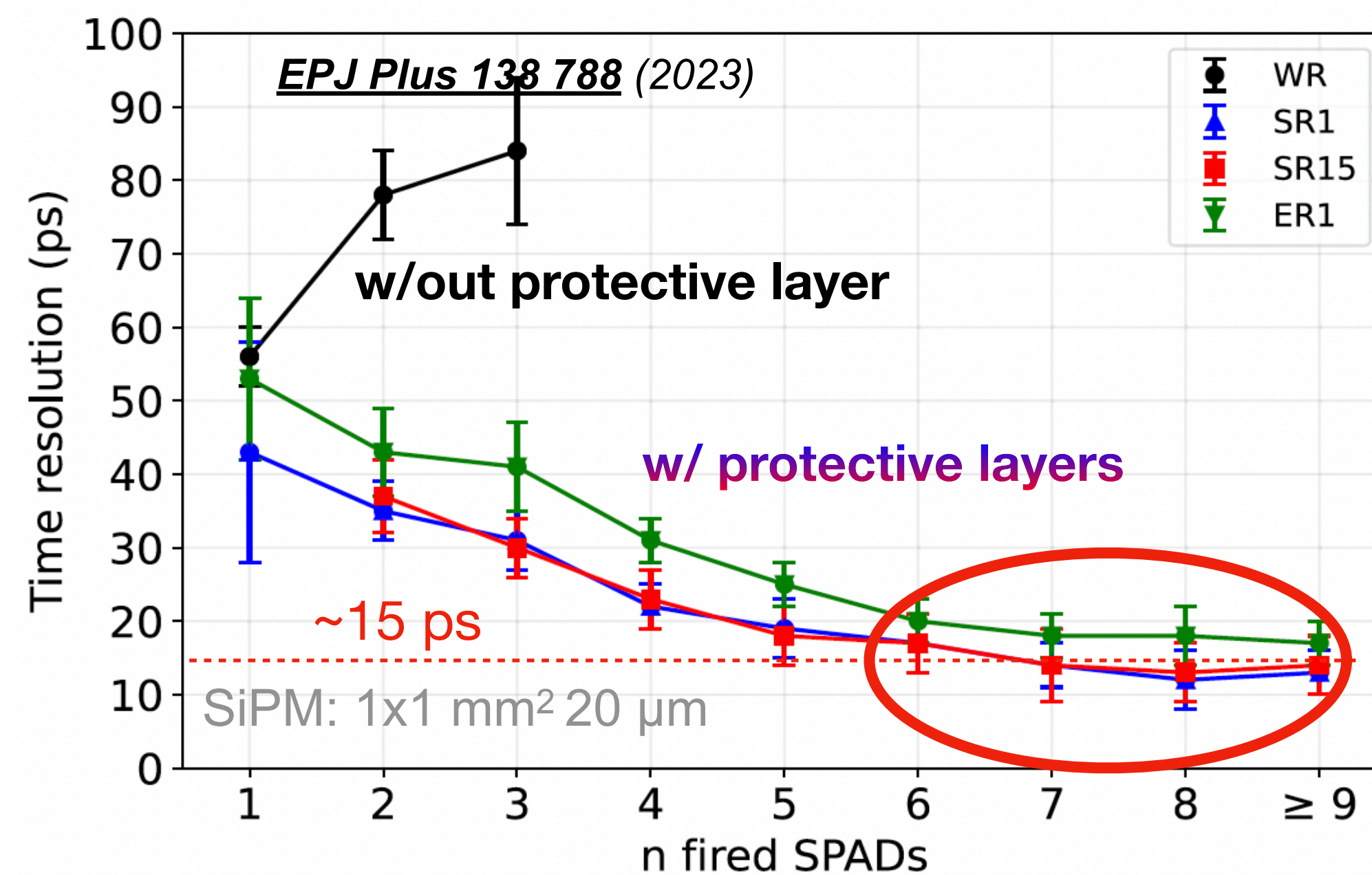
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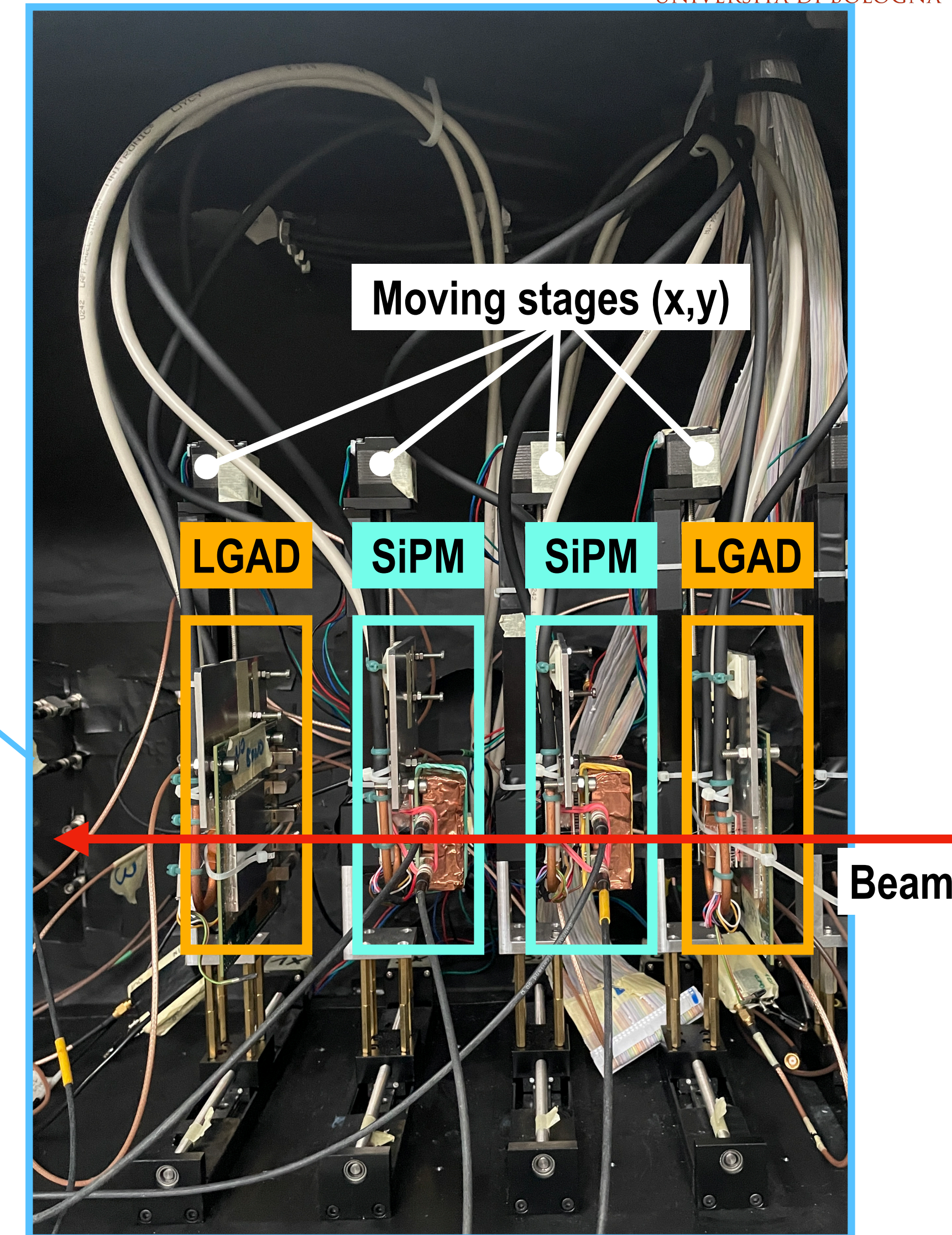
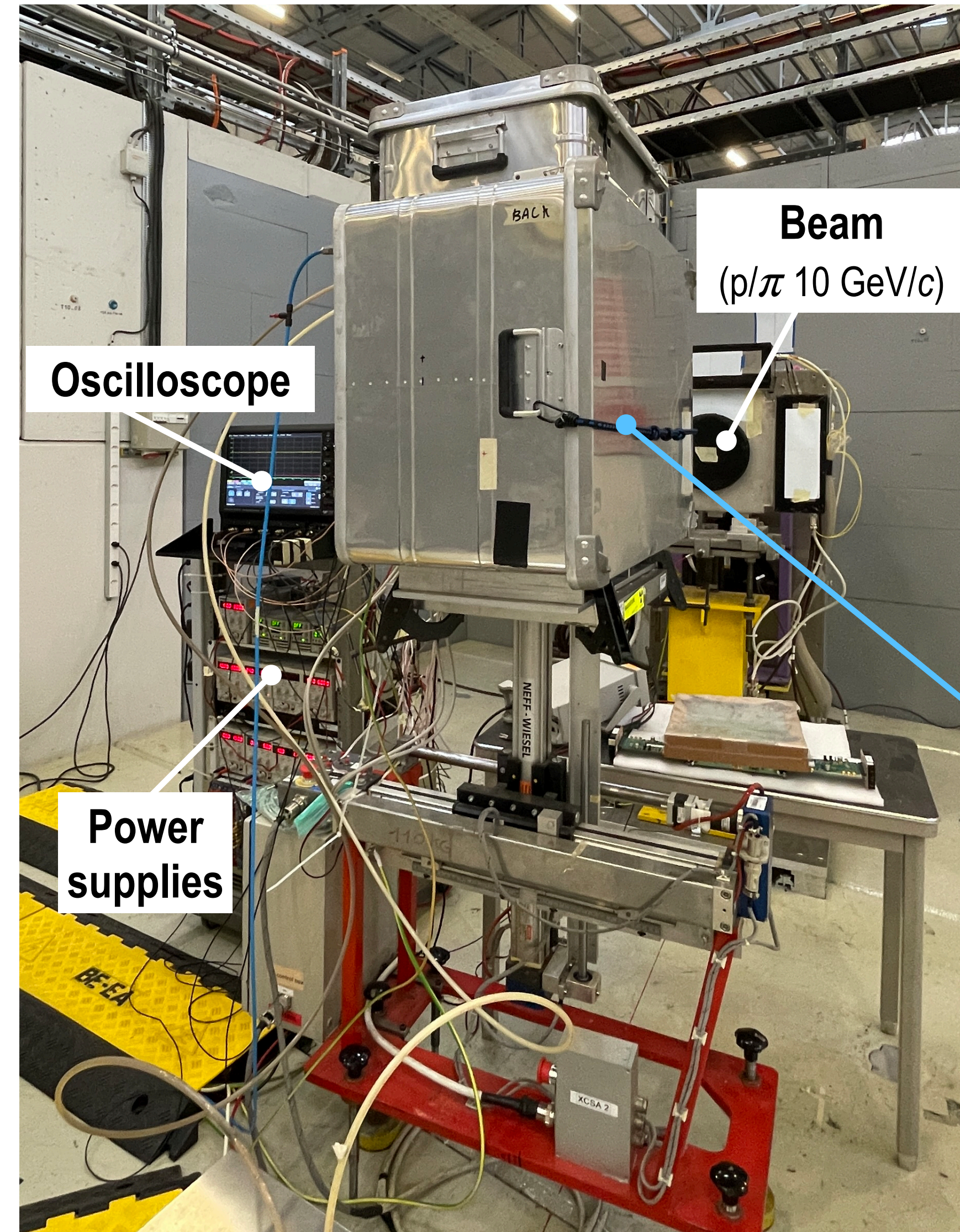
- ♦ SiPM can detect MIPs **as delivered** from foundry → no need of external radiator/scintillator
- ♦ **compact and simple** charged particle detector
- ♦ **time resolution < 20 ps**



Results on SiPMs with standard protection layers performance with MIPs

Experimental setup

- ◆ CERN PS T10
 - ◆ Readout: LeCroy Waverunner 94904M (4 GHz)
 - ◆ **SiPM** front-end: X-LEE amplifiers (40 dB total gain)
 - ◆ Trigger and timing reference: coincidence of 2 **LGADs** (FBK prototypes, 25 and 35 μm , 1x1mm²) [*EPJ Plus* 138 990 (2023)]
- ➔ SiPMs **with protection layer** (Silicone resin) to characterize the **Cherenkov effect** on standard technology NUV-HD-LFv2



Results on SiPMs with standard protection layers performance with MIPs Efficiencies



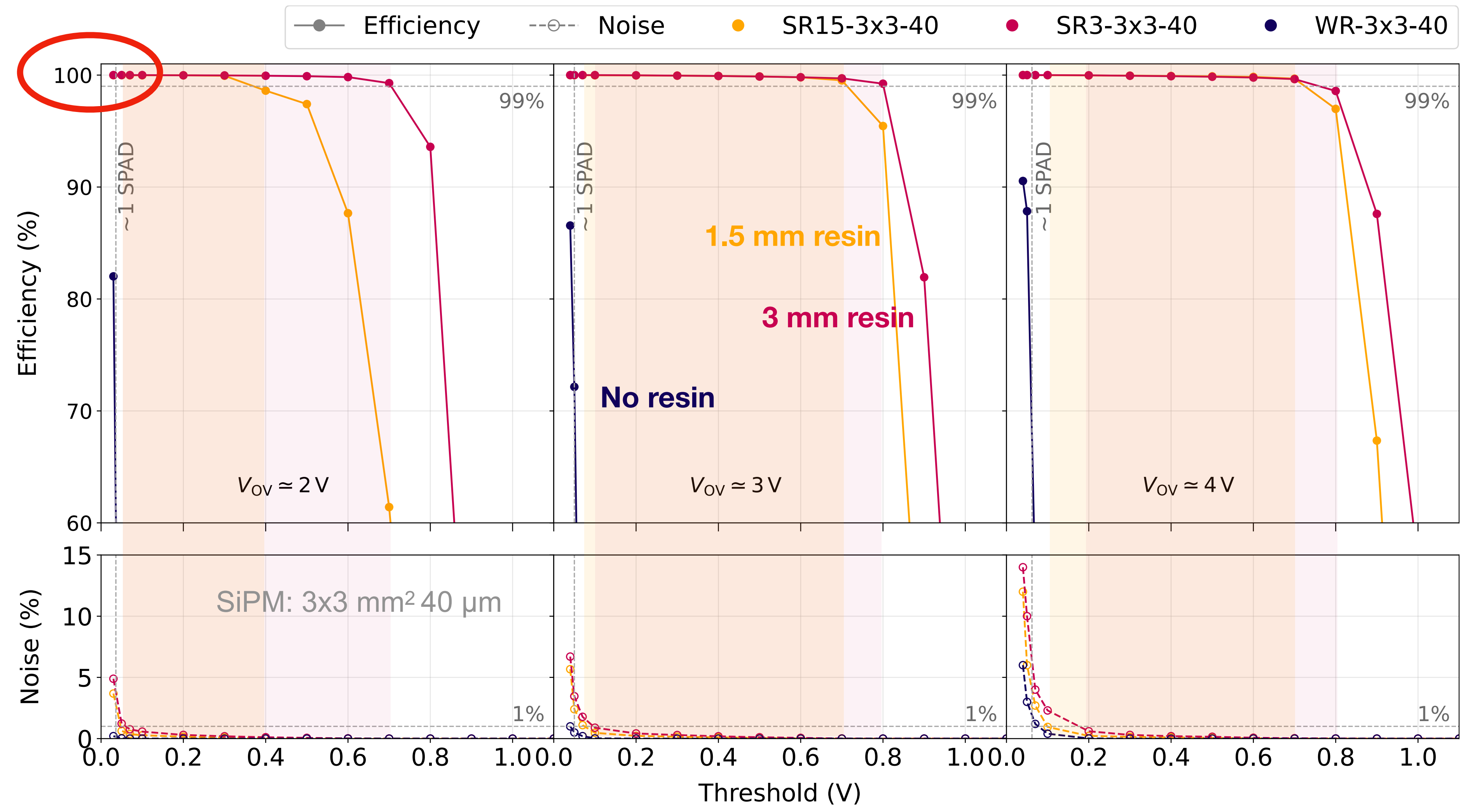
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EPJ Plus 141, 4 430 (2026)

- ◆ Enabling full coverage of Cherenkov cone subtended area
- ◆ Large **operational range**: efficiency > 99% and noise < 1% for all SiPM and voltages (~1-3 SPADs to ~11-19 SPADs)

Results

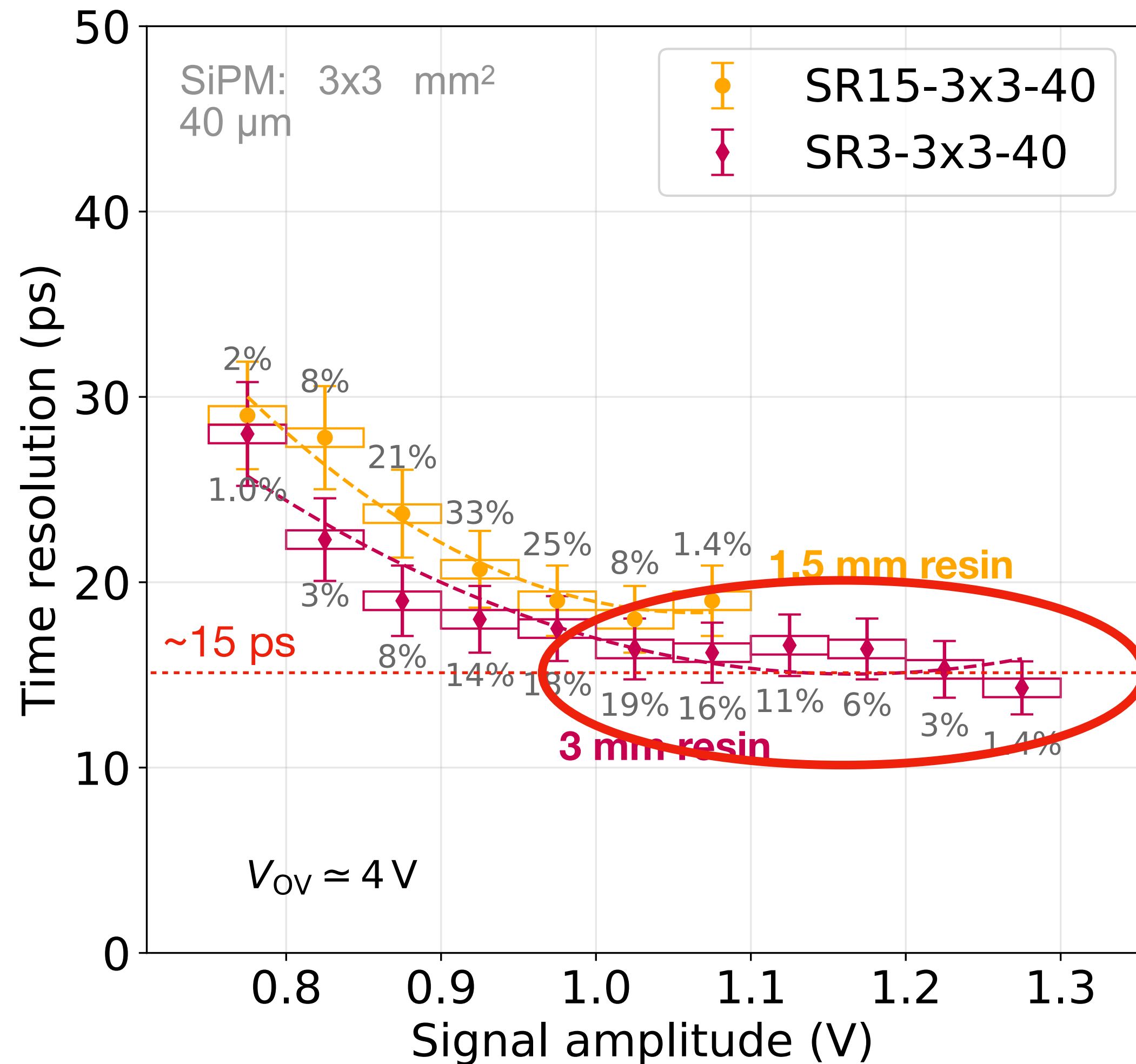
- ➔ Very high efficiency (much beyond FF of ~83%)
- ➔ Noise proof (at the level of dark counts rejection)



Results on SiPMs with standard protection layers performance with MIPs

Time resolution

EPJ Plus 141, 4 430 (2026)



- ◆ SiPM dual-threshold analysis:
 - Threshold on the **signal amplitude** for event selection → event selection for > 99% efficiency and <1% noise
 - threshold on the signal **leading edge** at ~50% 1 SPAD → optimize timing
- ◆ LGAD time resolution at 50% CFD
- ◆ Electronic jitter included in the time resolution

Results

- ➔ Time resolution decreases as signal amplitude (number of SPADs) increases
- ➔ **Time resolution < 20 ps** (including jitter)

Results on SiPMs with standard protection layers performance with MIPs

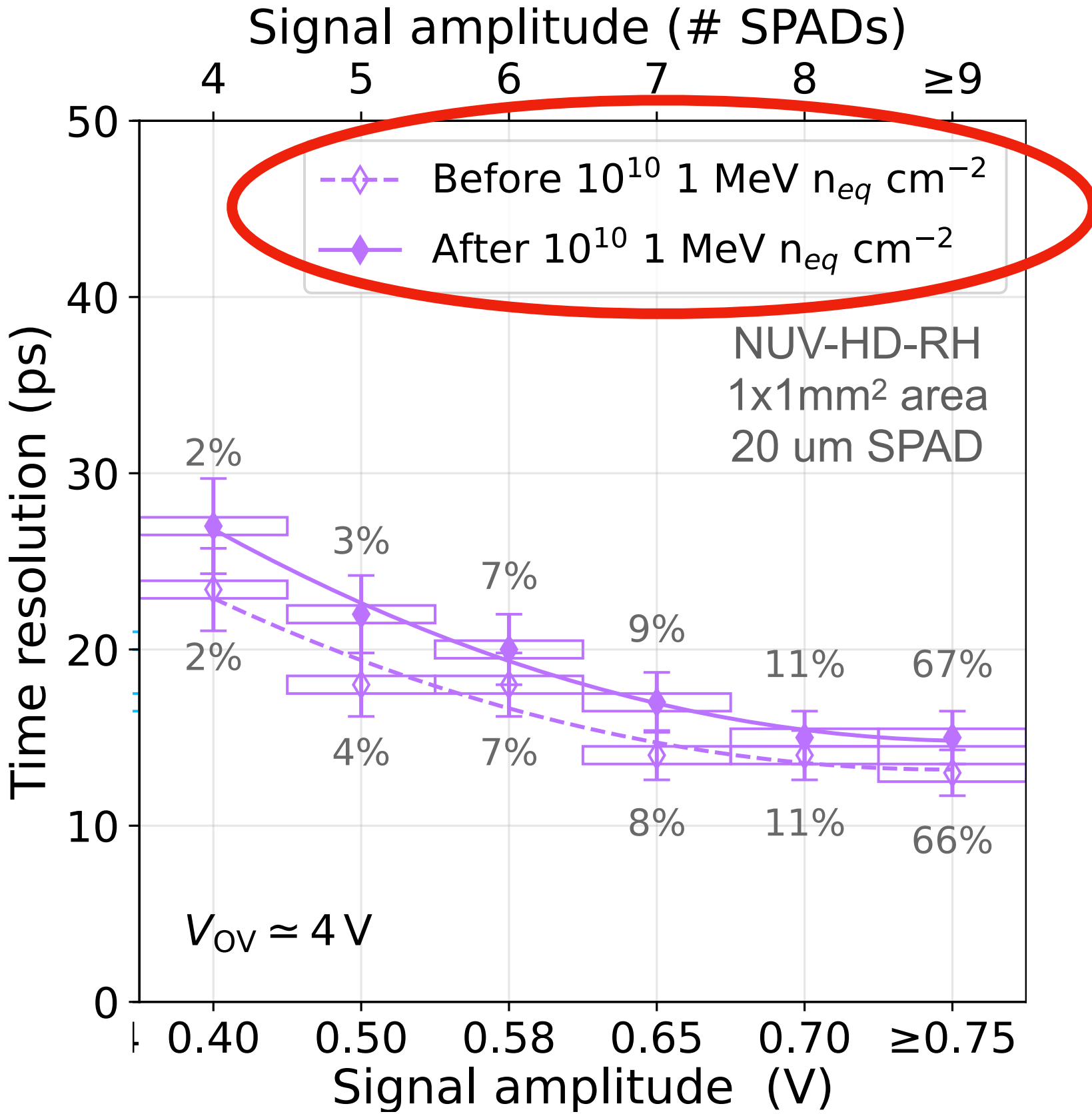
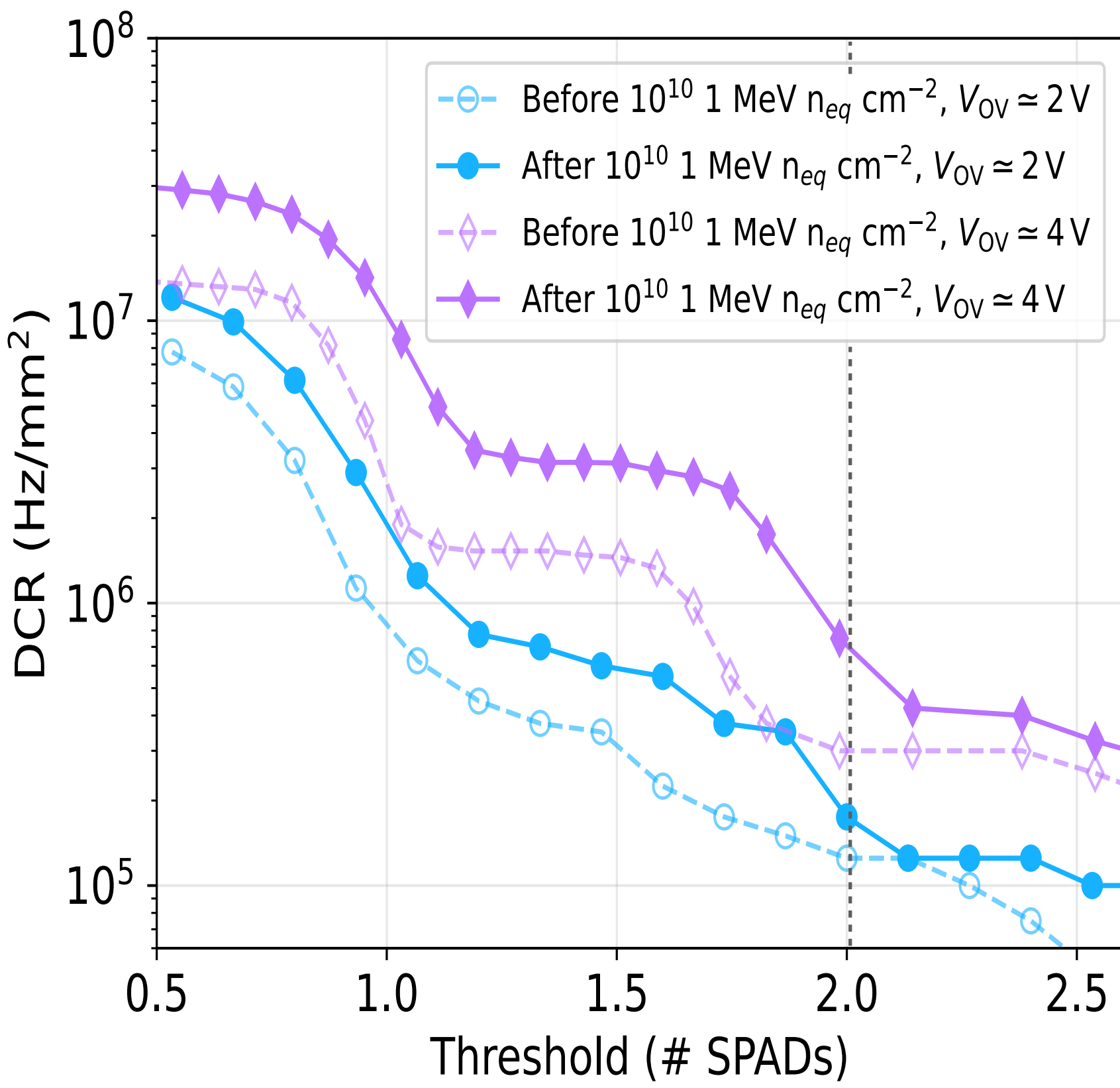
Radiation hardness



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EPJ Plus 141, 4 430 (2026)

- Studying the performance of SiPM before (tested in previous beam tests) and after receiving a dose of 10^{10} 1 MeV n_{eq} cm^{-2}
- Same analysis method



Results

- ➔ **Dark Count Rate:** increased but reduced at 2-3 SPADs threshold by a factor 2-4 10² depending on OV
- ➔ **Time resolution:** no degradation observed and approaching ~ 15 ps at large n fired SPADs

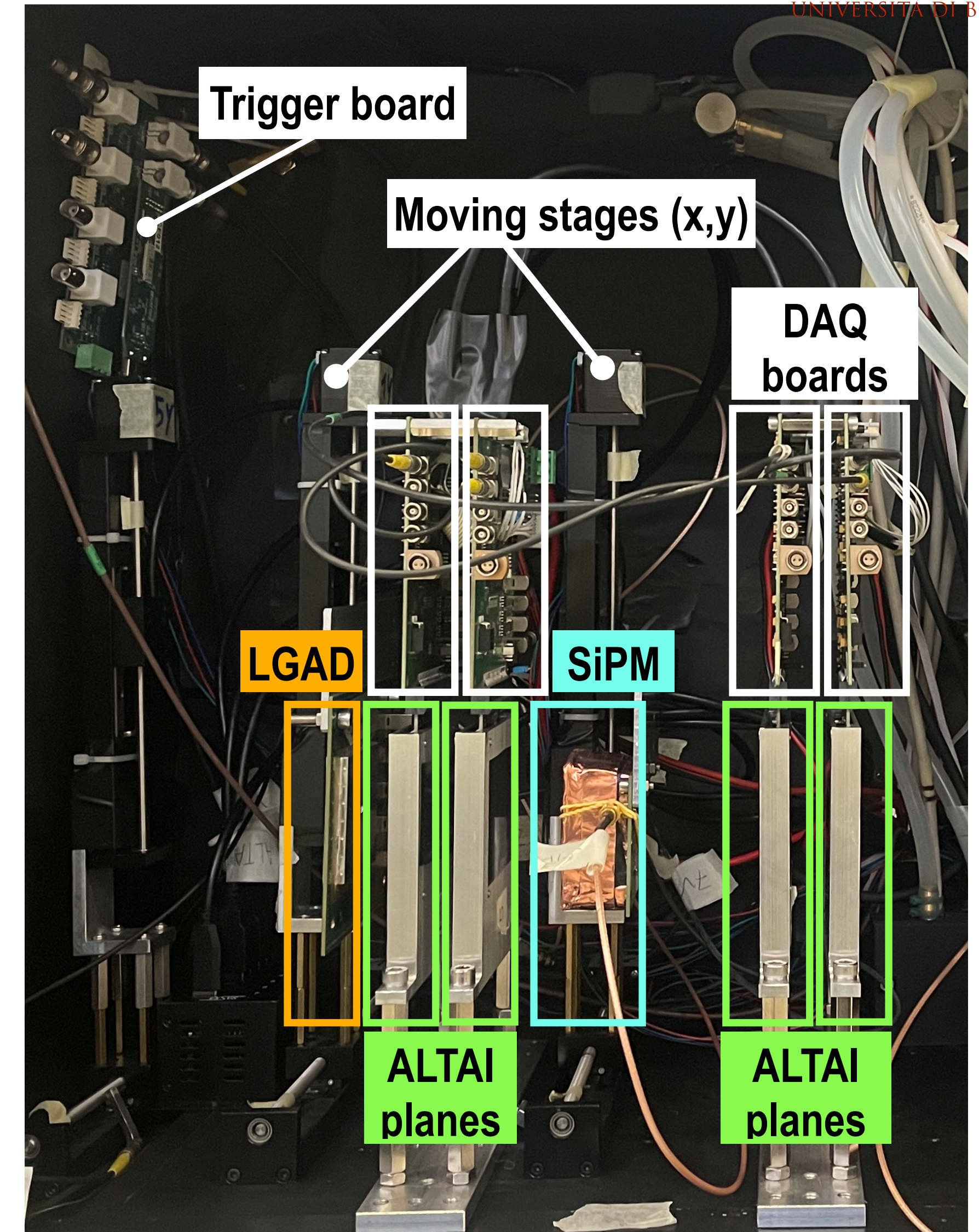
Results on SiPMs without protection layers and in-SPAD performance with MIPs

Experimental setup

- ◆ Readout: LeCroy Waverunner 8104 (1 GHz)
- ◆ **SiPM** front-end: X-LEE amplifiers (40 dB total gain)
- ◆ Trigger and timing reference **LGAD** (FBK 35 μm 1x1mm²)
- ◆ Tracker with **ALTAI**: CMOS sensors [IEEE 40 10 (2025)], $\sim 6 \mu\text{m}$ tracking resolution

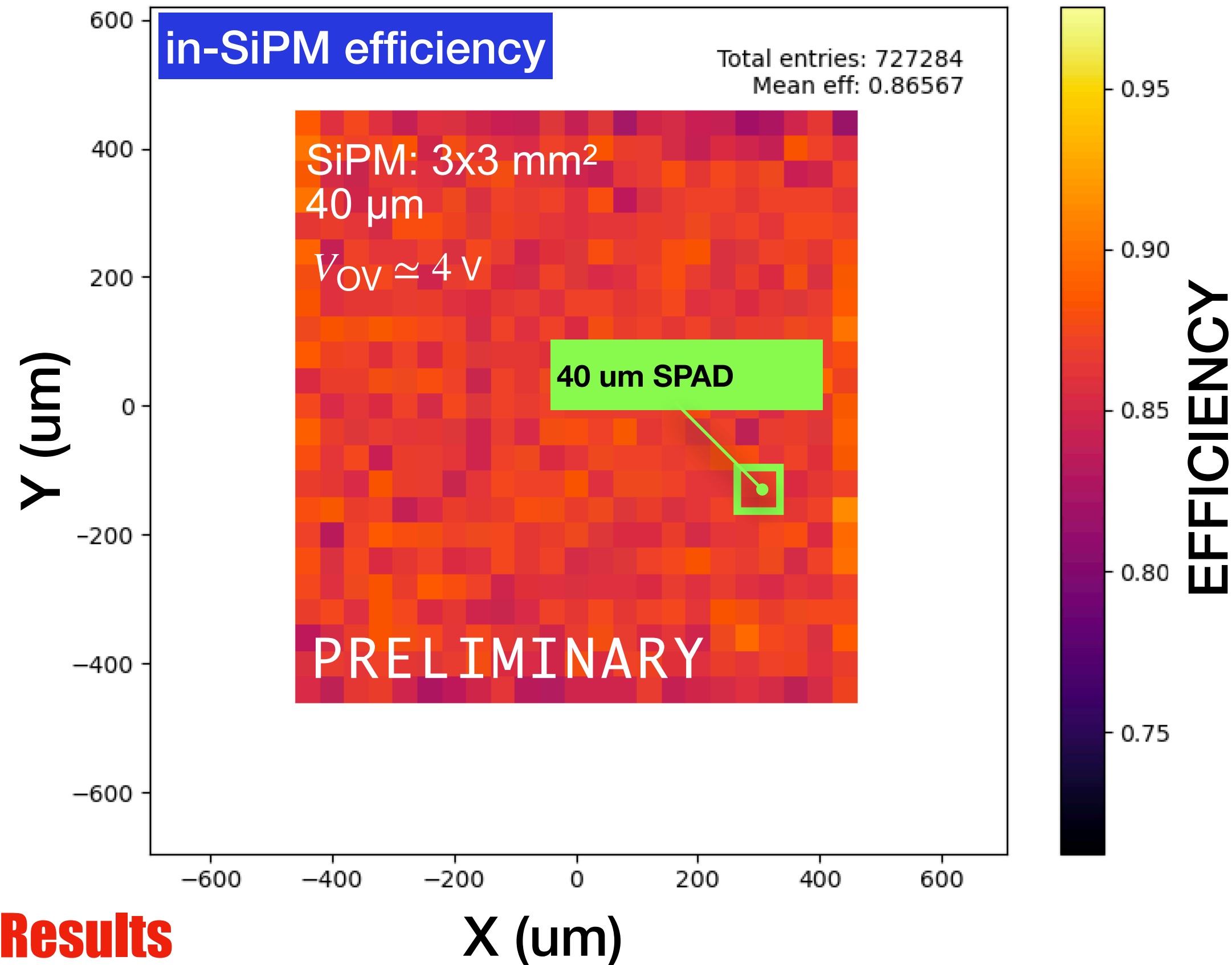
SiPMs **without any protection layer** to characterize **efficiency** and **time resolution** with MIPs depending on the position on FBK prototypes:

- ▶ **NUV-HD-LFv2** (standard FBK technology) → plots and results later
- ▶ **NUV-HD-MT** (technology with metal trenches to reduce cross-talk effects) → results mentioned later and plots in backup
- ▶ **BSI-FSI** not yet thinned (designed for radiation hardness by FBK in collaboration with INFN) → plots and results later



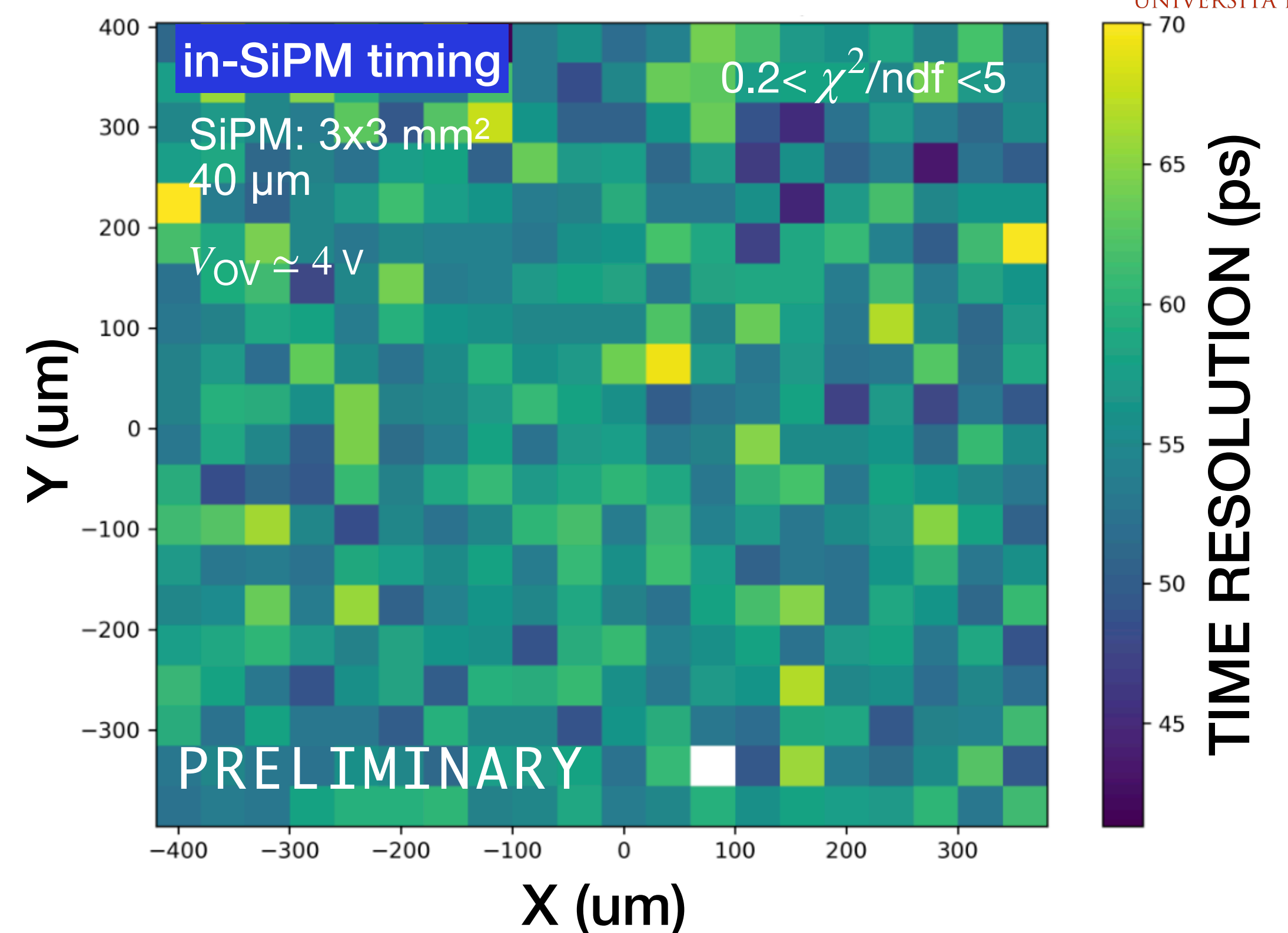
Results on SiPMs without protection layers and in-SPAD performance with MIPs

in-SiPM efficiency and time resolution map



Results

- ➔ SiPM efficiency ~87%
- ➔ Uniform efficiency among different SPADs (bin width of 40 μm)
- ➔ For for **NUV-HD-MT-3x3** SiPM: ~82%



- ◆ Fixed time threshold at ~40% 1 SPAD amplitude

Results

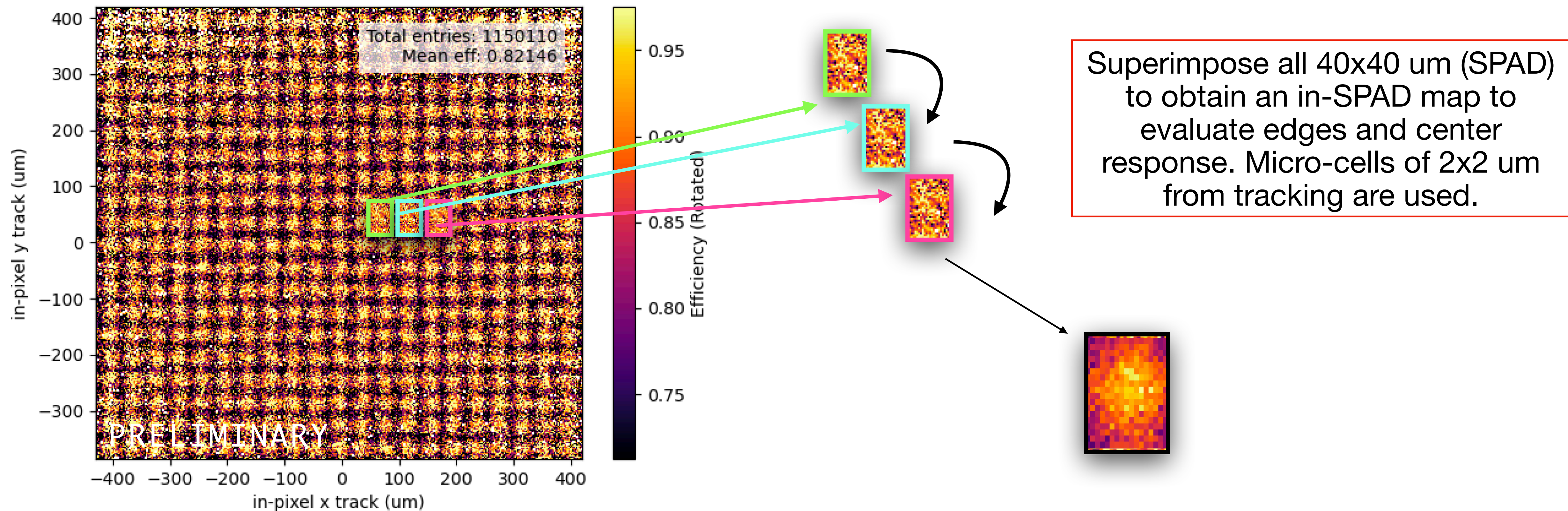
- ➔ SiPM mean time resolution ~**56 ps**
- ➔ For for **NUV-HD-MT-3x3** SiPM: ~60 ps

Results on SiPMs without protection layers and in-SPAD performance with MIPs

From in-SiPM to in-SPAD efficiency



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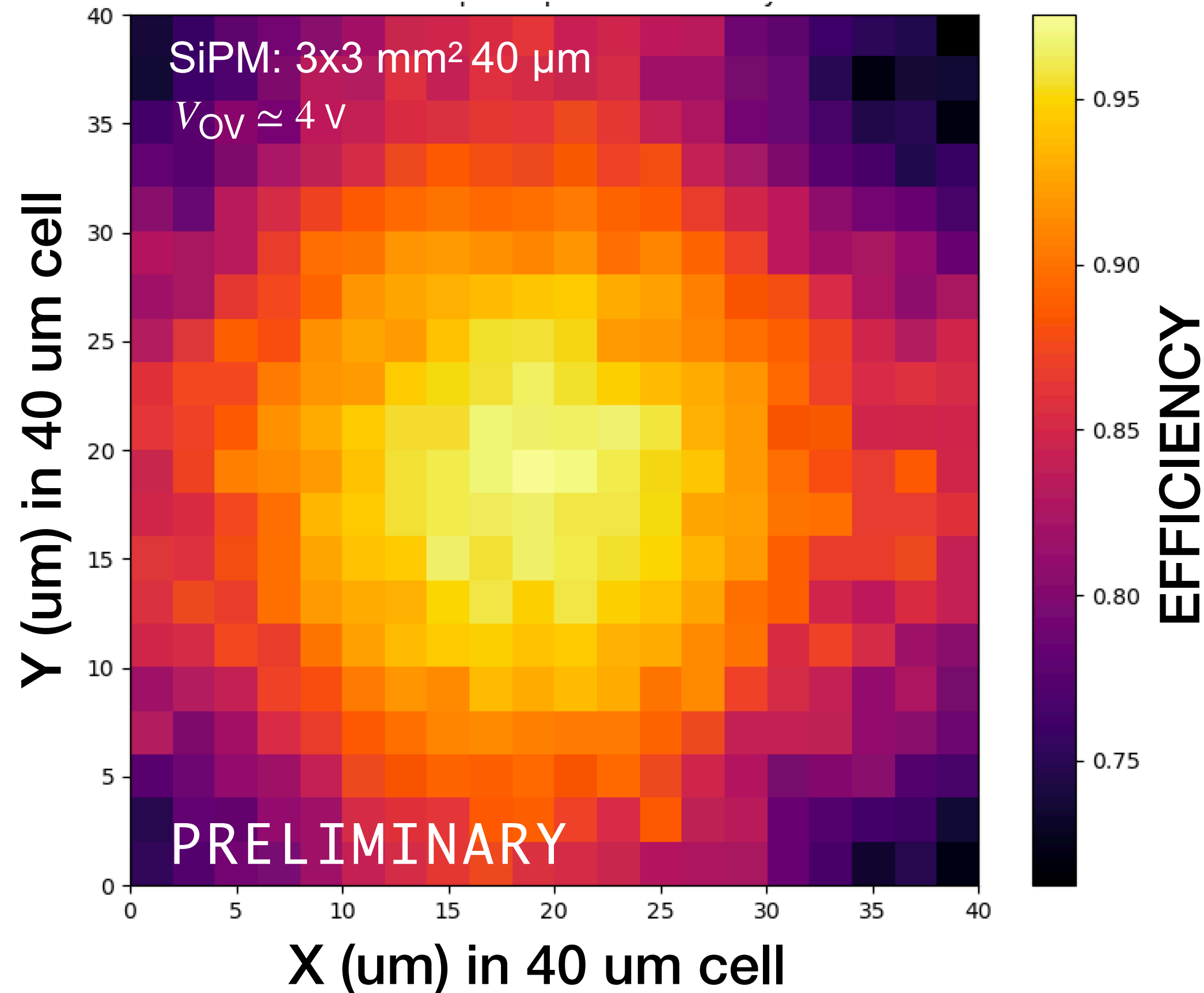


Results on SiPMs without protection layers and in-SPAD performance with MIPs

in-SPAD efficiency map



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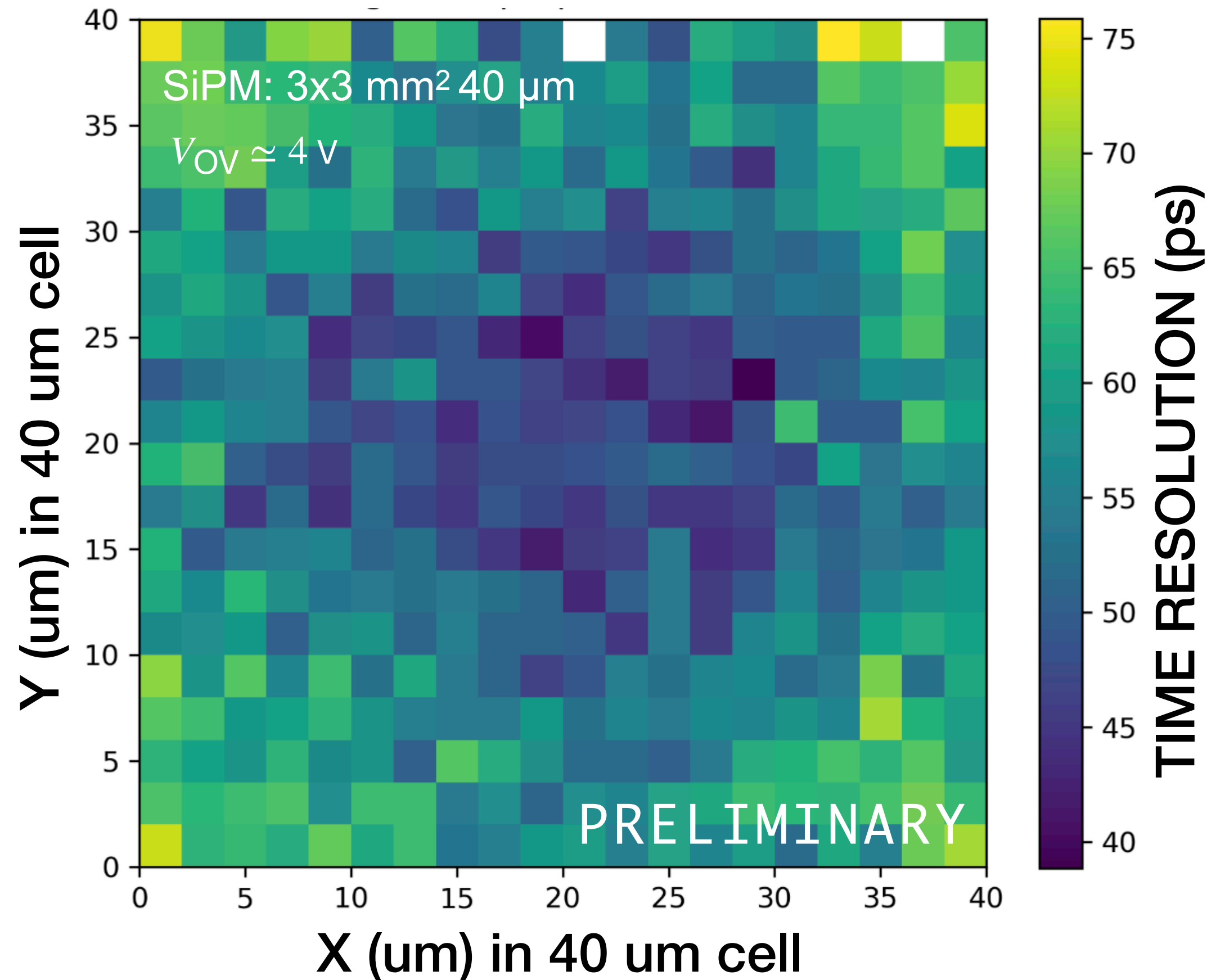
- ◆ in-SPAD efficiency: all SPADs superimposed
- ◆ 2 µm bin width, 40 µm (SPAD pitch) map size

Results

- ➔ Folding effectively reconstructing the SPAD profile
- ➔ Min. ~72% in the edges, max ~97% in the centre
- ➔ For **NUV-HD-MT-3x3** SiPM: ~65% in the edges, ~95% in the centre

Results on SiPMs without protection layers and in-SPAD performance with MIPs

in-SPAD time resolution map



- ◆ in-SPAD time resolution: all SPADs superimposed
- ◆ σ includes jitter and intrinsic SiPM contributions
- ◆ Timing threshold $\sim 40\%$ 1 SPAD amplitude, selection on 1 SPAD events

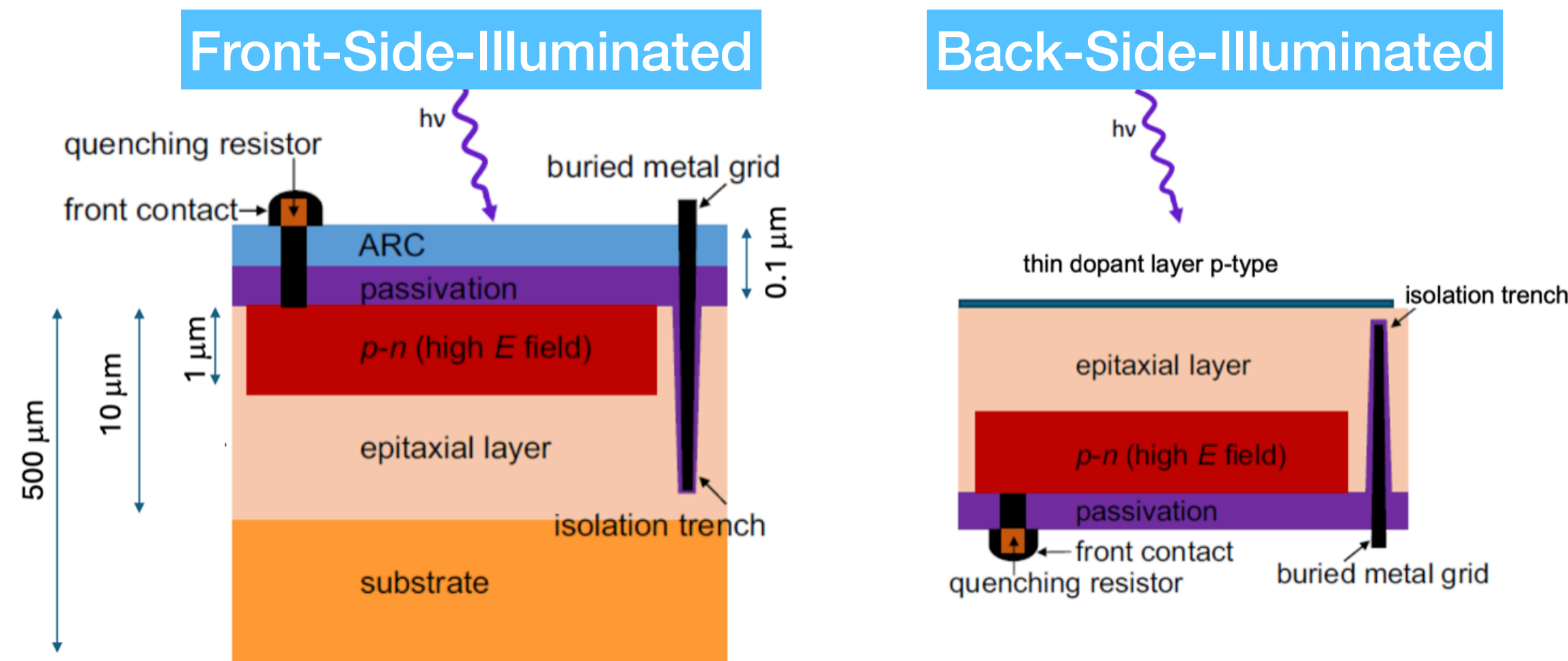
Results

- ➔ Folding effectively reconstructing the SPAD time resolution profile
- ➔ Min. **~ 39 ps** in the center, max ~ 76 ps in the corners, mean ~ 56 ps
- ➔ For **NUV-HD-MT-3x3** SiPM: min. ~ 41 , max ~ 78 ps in the corners, mean ~ 55 ps

Results on SiPMs without protection layers and in-SPAD performance with MIPs

Not-yet-thinned (500 μm bulk) BSI prototypes

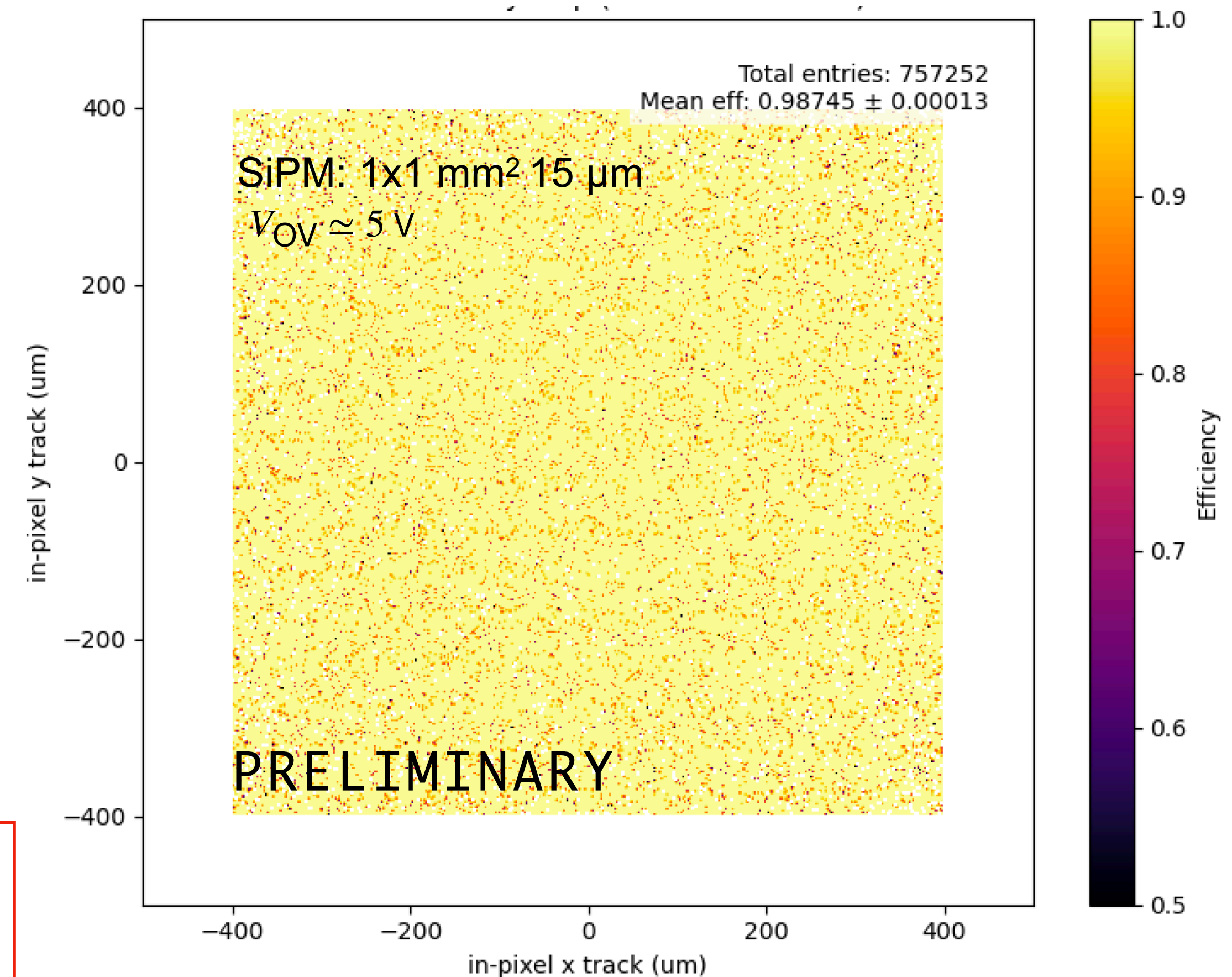
- ◆BSI technology→photons enter from the back side through a thin doped layer into the epitaxial volume, bulk is removed (less radiation damage effects)



- ◆No SPAD distinction (as there are no front-side metal structures to reduce the efficiency)→no in-SPAD studies

Results

- ➡ Very high efficiency of $\sim 99\%$ across different prototypes
- ➡ Promising time resolution of single SPAD (at $\sim 50\%$ fix. thr.) of ~ 110 ps at $5 V_{OV}$



This *R&D* enables SiPMs-based TOF or a merged TOF-RICH detector, with results relevant across:

HEP

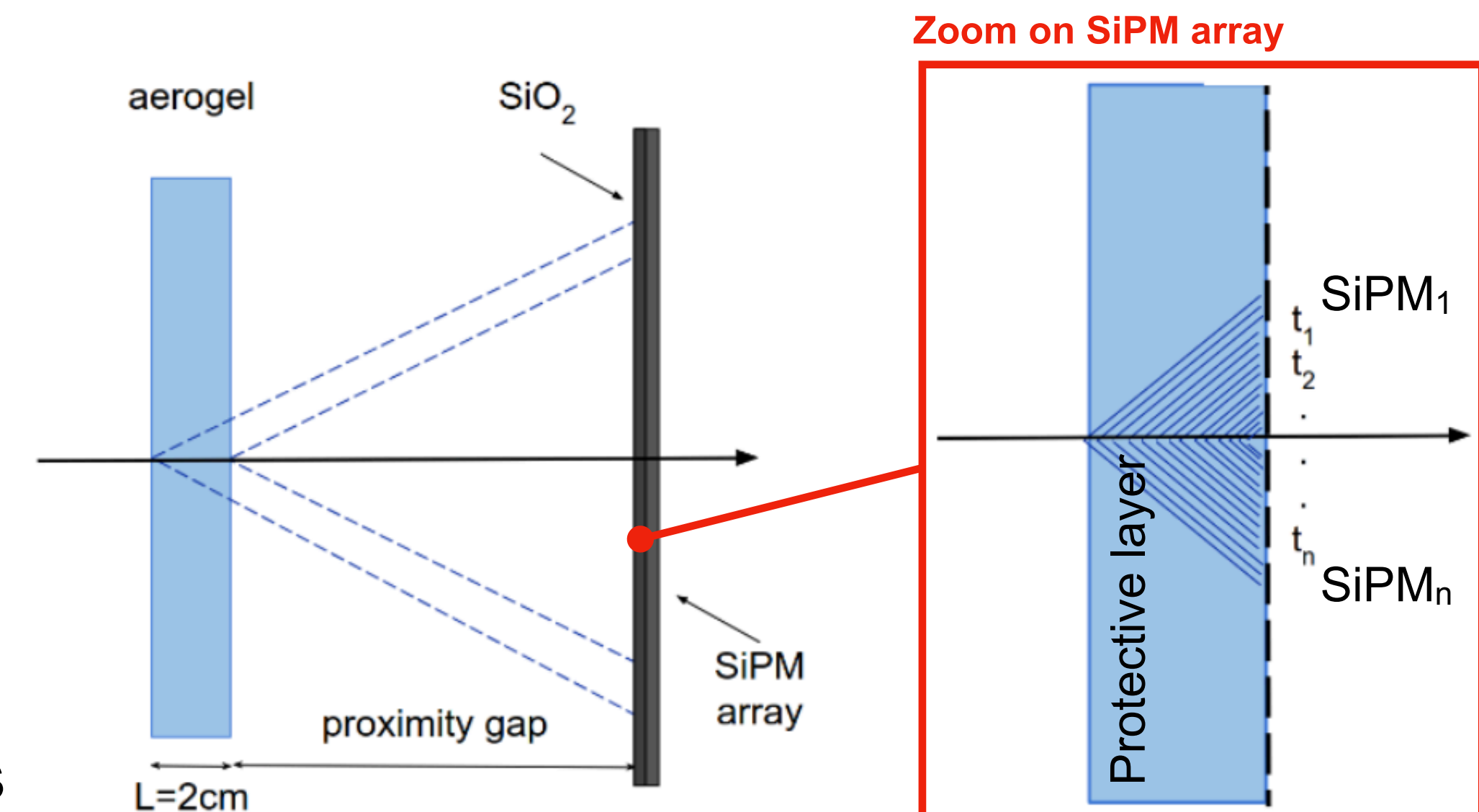
- ◆ Timing for *Pile-Up mitigation* (4D tracking) and *PID*
 - FCC-ee: favourable (low radiation) environment for SiPM-based TOF/TOF+RICH/calorimeters
 - HL-LHC/FCC-hh: 4D tracking, <5 ps time resolution, with radiation hardness as open challenge

Space

- ◆ Timing for *PID*
 - Isotopes signals well above single-photon level: TOF+RICH PID feasible in space-borne experiments
 - Compact, low-power, low V_{bias} : ideal for satellites/space-station experiments

Medicine

- ◆ SPTR studies of SiPM without protection layers: figure of merit common to any single-photon timing application → information about achievable CTR (TOF-PET) or other imaging/spectroscopy techniques, independently of photon generation mechanism



SiPM with standard protection layers

- ◆ A threshold of ~ 3 photoelectrons at every V_{OV} leads to **$\geq 99\%$ efficiencies** and **noise $< 1\%$** for SiPMs of $3 \times 3 \text{ mm}^2$ area
- ◆ Timing **$\sim 15 \text{ ps}$** or less (depending on SiPM area) with smaller resolution as the signal (#fired SPADs) increase: confirmed for different SiPM technologies/area/SPAD pitch

SiPM without protection layers

- ◆ SiPM of $3 \times 3 \text{ mm}^2$ area showed mean efficiencies $> 82\%$ and mean time resolution $\sim 55\text{-}56 \text{ ps}$ (for different technologies)
- ◆ Better efficiencies and time resolution for single SPAD in the centre of the SPAD with max. efficiency $\sim 97\%$ and time resolution $\sim 40\text{-}42 \text{ ps}$ for different technologies
- ◆ Promising results for novel BSI technologies

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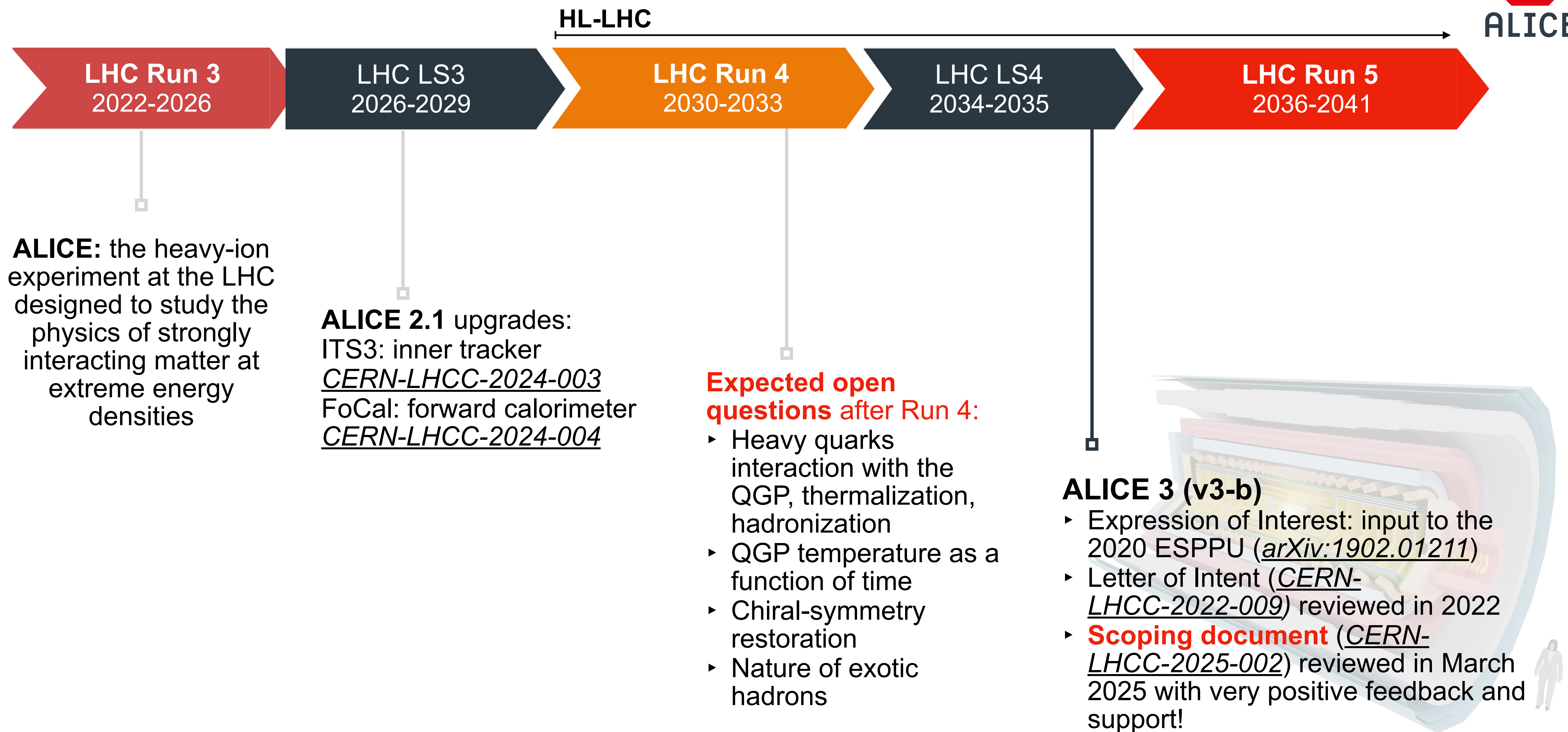
SiPM without protection layers

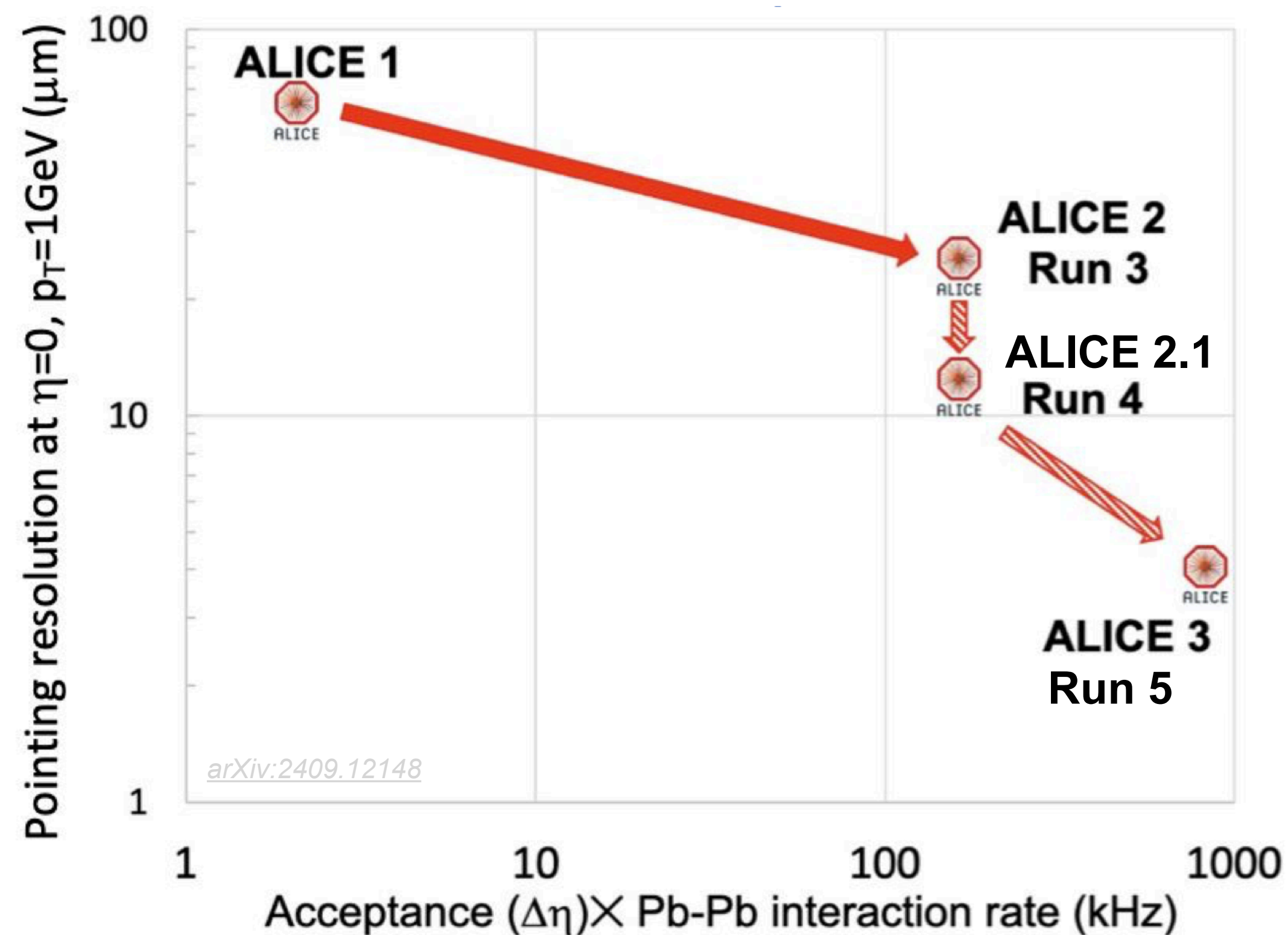
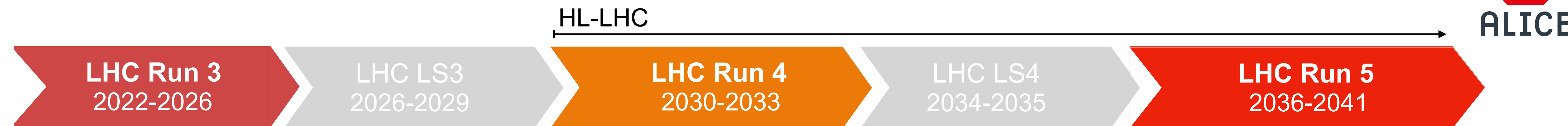
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- ➡ SiPM with standard protection layer: **compact and simple charged particle detector** with excellent efficiency, time resolution, noise rejection
- ➡ Very **first maps** and results on efficiency and timing for **SiPMs with MIPs!**
- ➡ **SiPM from photon-detectors to good tracker (resolution $< \text{mm}$) with high efficiency for MIPs**
- ➡ Enabling applications such as the HEP double TOF-RICH detector, and more generally TOF applications in HEP and in astrophysics









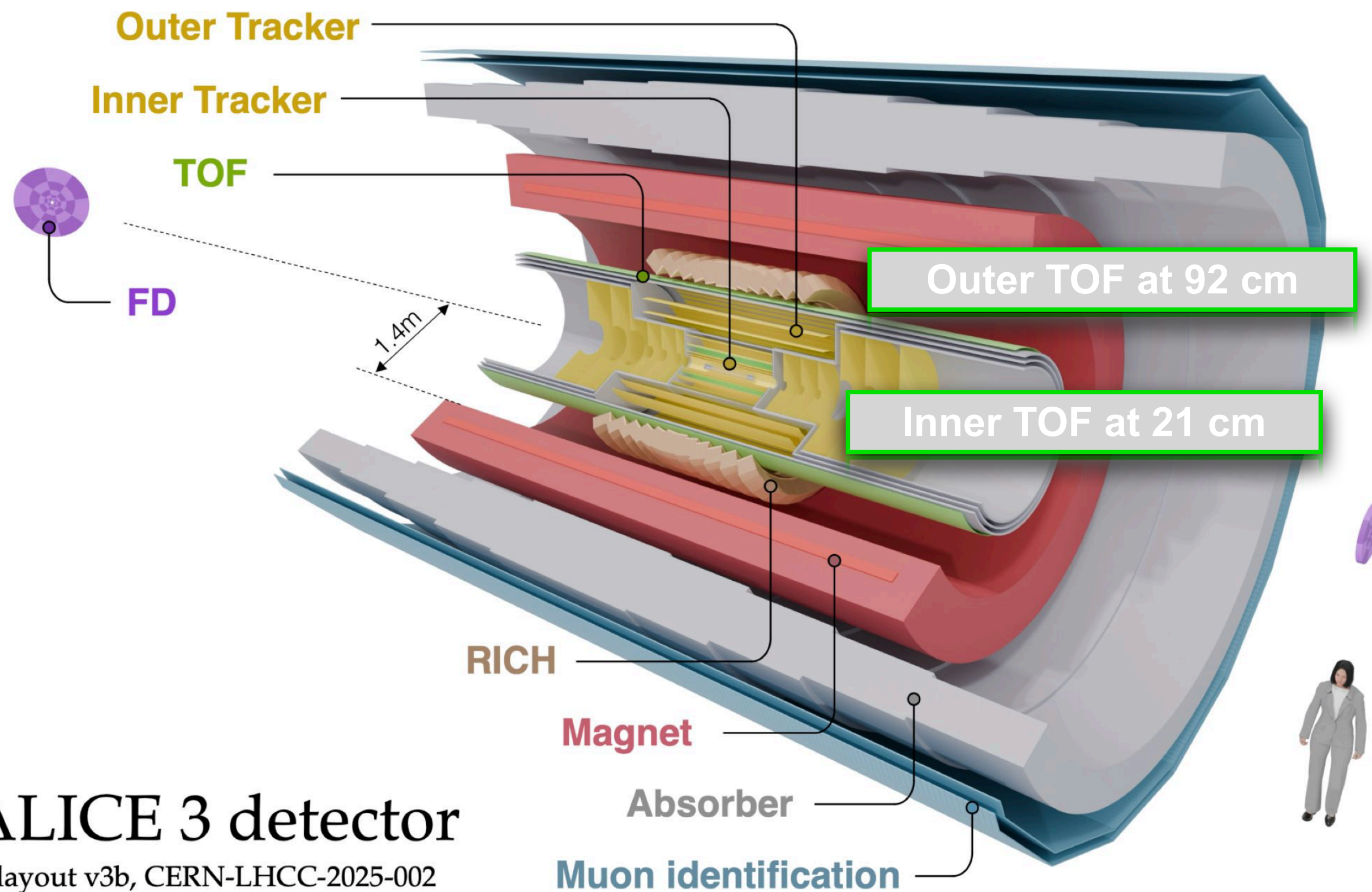
Major improvements in
pointing precision and
“effective” acceptance
+
Strengthened ALICE
PID capabilities (also
at forward rapidities)

R&D on direct detection of charged particles with SiPMs

ALICE 3: The next-generation heavy-ion experiment



R&D in the context of **ALICE 3**, the next-generation heavy-ion experiment at the **LHC**: SiPM originally the fall-back solution together with LGADs with respect to CMOS-LGADs prototypes for the outer Time-Of-Flight detector.



TOF specifics

Radiation hardness:
Inner TOF: NIEL $\sim 7 \times 10^{12}$ 1 MeV n_{eq}/cm^2
Outer TOF: NIEL $\sim 9 \times 10^{11}$ 1 MeV n_{eq}/cm^2

Material budget:
1-3% X_0

Time resolution:
20 ps

R&D on different advanced silicon technologies: CMOS-LGADs, standard LGADs and **SiPMs** as a **fall back solution** with respect to CMOS-LGADs

ALICE 3 detector

layout v3b, CERN-LHCC-2025-002

- **Understanding thermalisation in the QGP**

- degree of thermalisation of beauty: high-precision beauty measurements
- approach to chemical equilibrium: multi-charm hadrons
- direct access to charm diffusion: D-Dbar azimuthal correlations

- **Fundamental aspects of the QCD phase transition**

- net-baryon and net-charm fluctuations

- mechanism of chiral symmetry restoration in the QGP: di-electron mass spectrum

- **Access to temperature as function of time**

- high-precision di-electron mass spectra, p_T dependence, elliptic flow

- **Laboratory for hadron physics**

- hadron-hadron interaction potentials
- explore nature of exotic hadrons (e.g., tetraquarks, charm-nuclei)

Reduced layout enables **heavy-flavour programme**, both for **QGP studies** and for **exotics**, and provides x2.5-3 acceptance increase for **correlation studies**

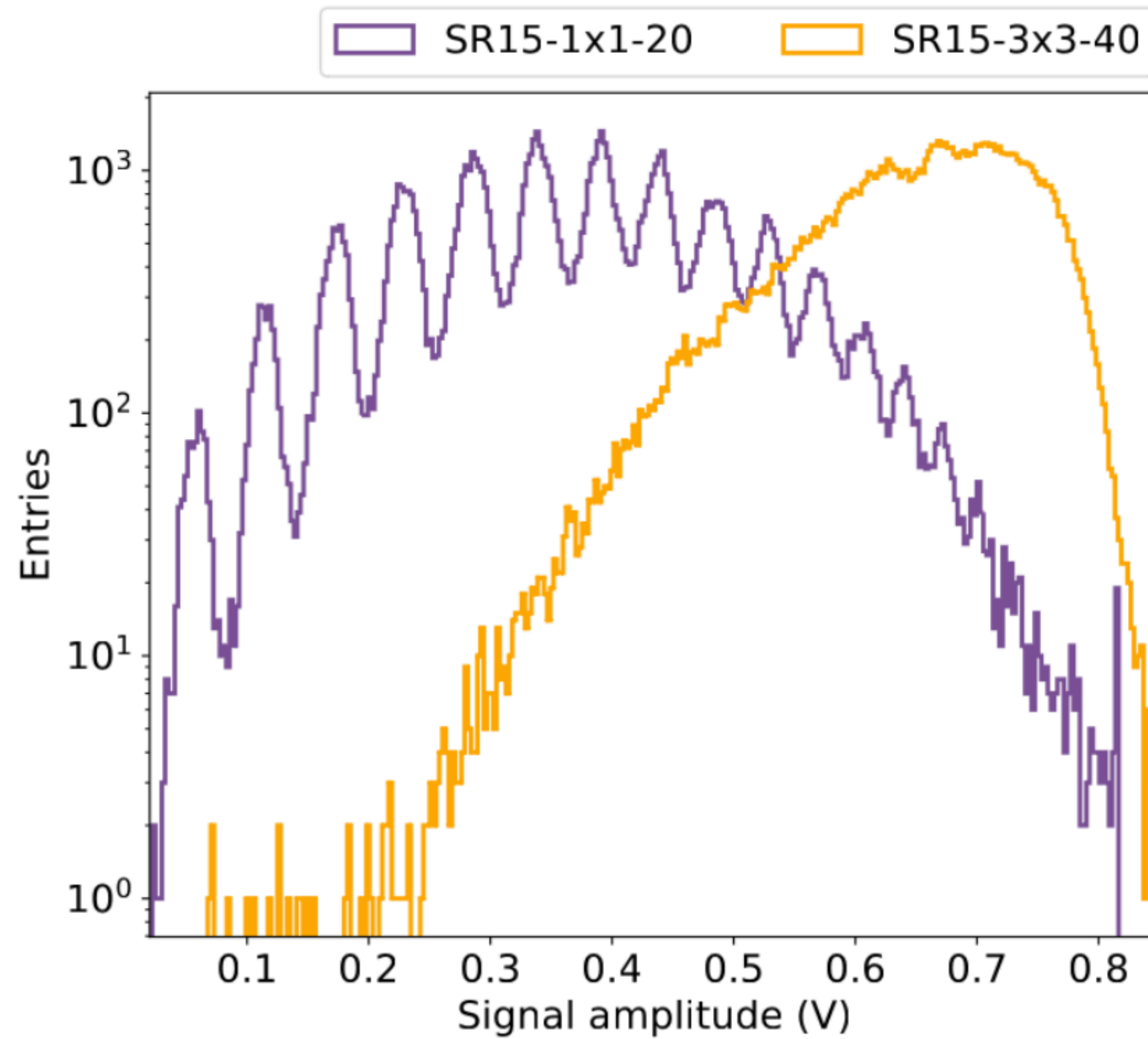
Measurements based on **dielectrons only possible with RICH:**

strong motivation to keep pursuing this detector, possibly staged in time

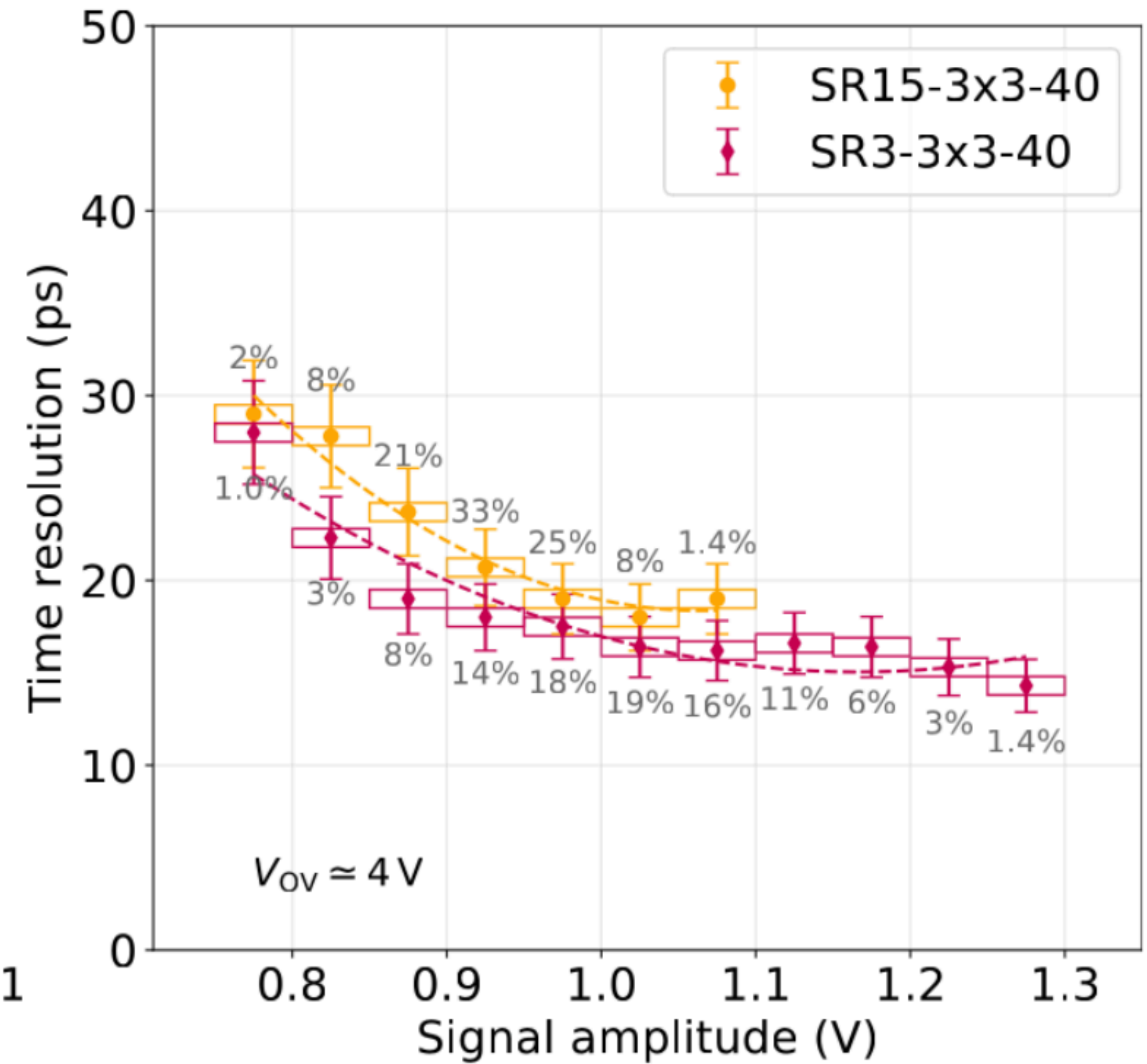
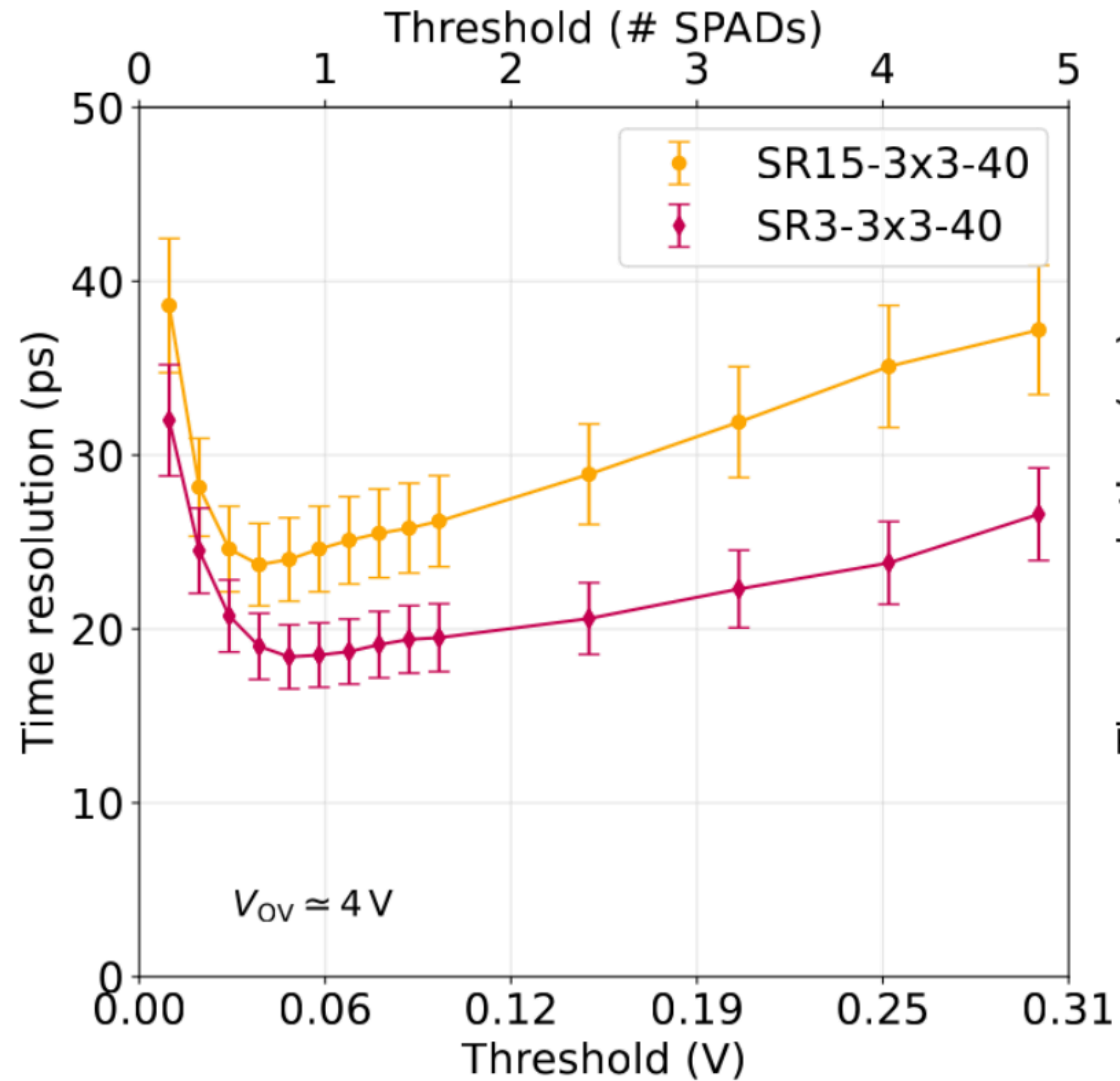
DCR while running at beam test



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Time resolution



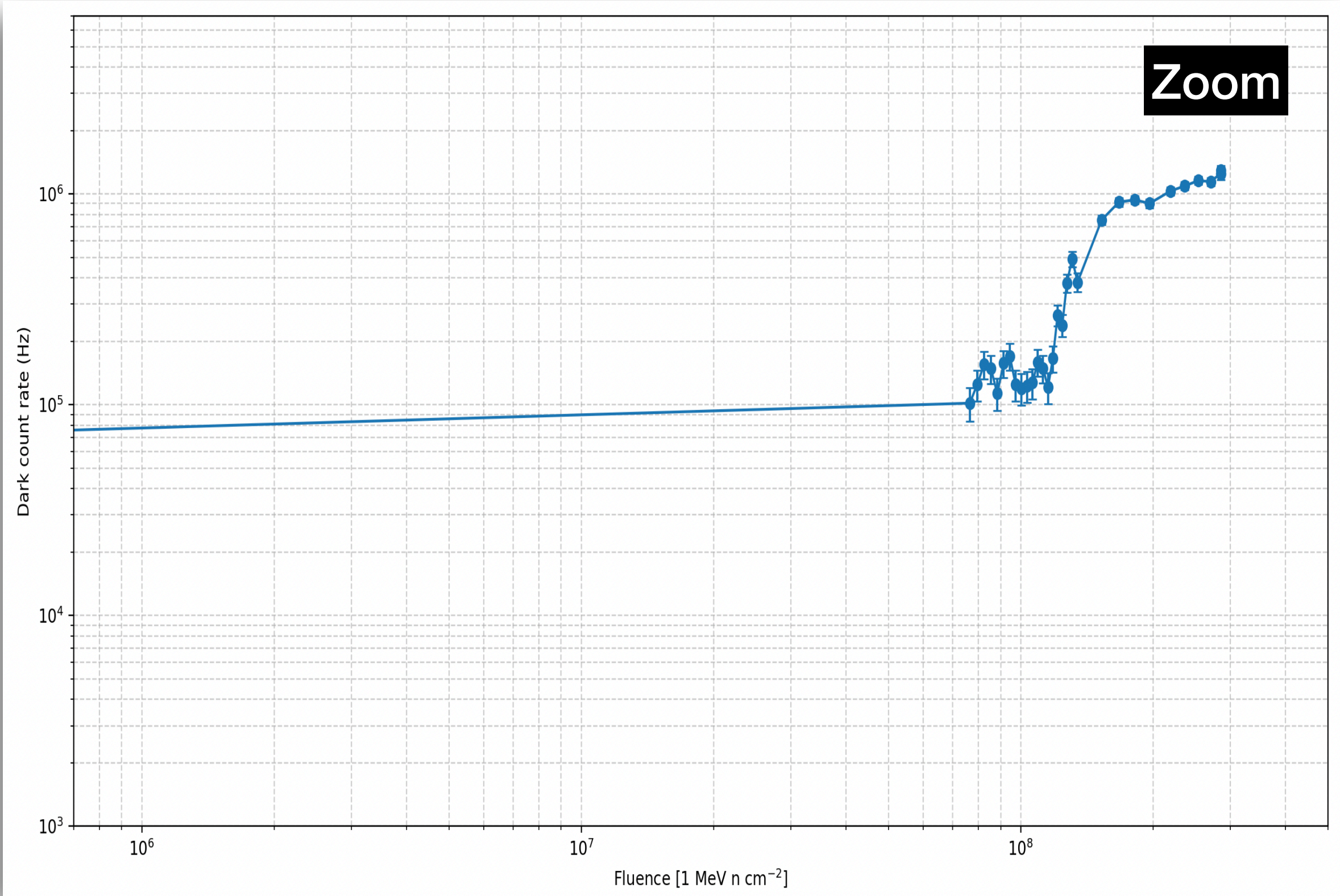
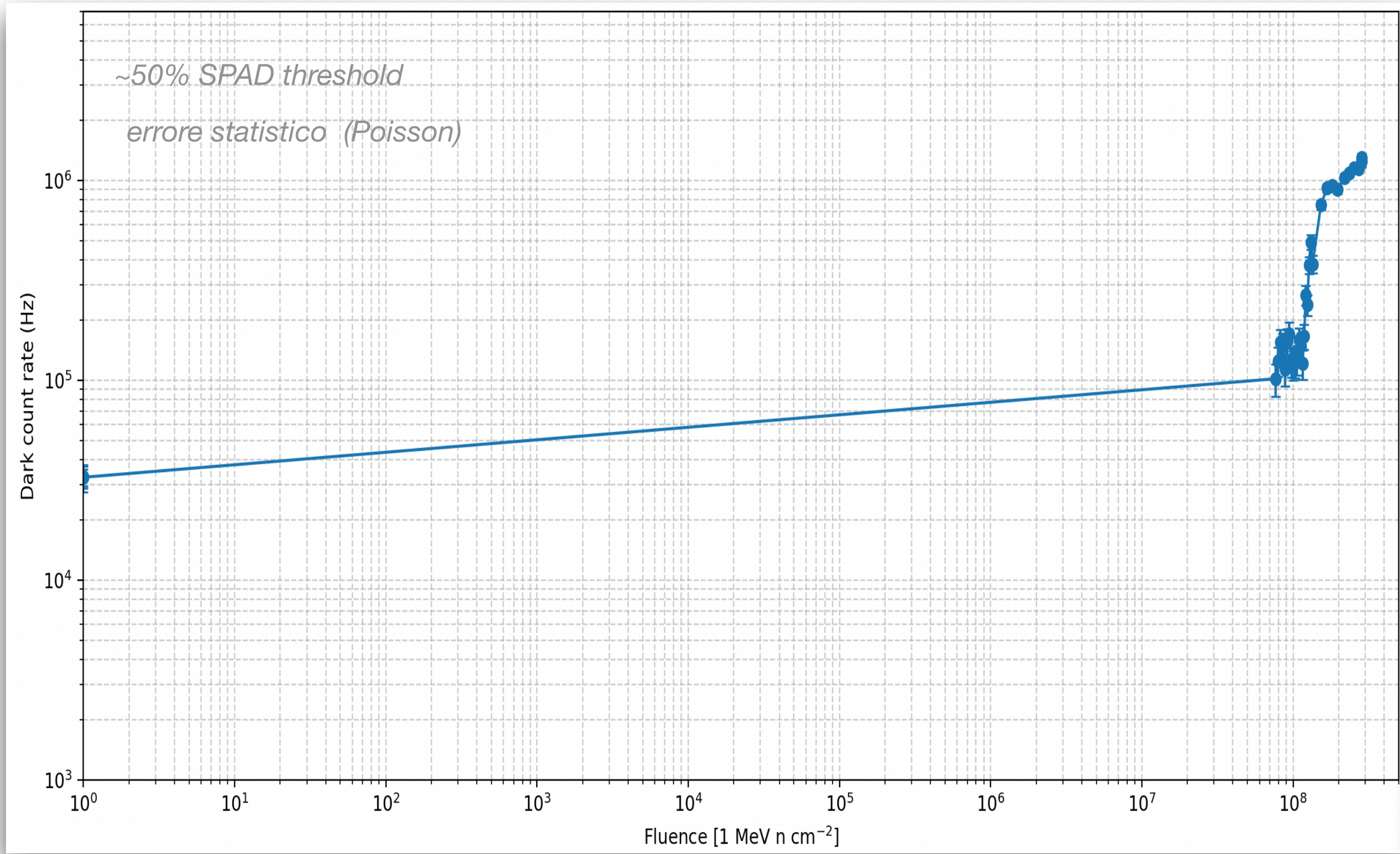
NUV-HD-LFv2 DCR wrt fluence



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Standard NUV-HD-Lfv2 - 1x1 mm2 - 5V OV

~1200 ~protons per mm2 (LGAD) per second + in 12 min —> 50 seq —> 50 spill in 12 min —> 50/12 = 4 spill/min —> 240 spill/h
1200* 250 spill ~ 300k 10 GeV protons/h ~ 3×10^5 10 GeV protons/h = 1.5×10^5 1 MeV neq/mm2/h = **1.5×10^7 1 MeV neq/cm2/h**
After ~ 20 hrs (start and end time based on data taking) ~ $20 \times 1.5 \times 10^7 = 30 \times 10^7$ **1 MeV neq/cm2 ~ 3×10^8**
compatible with ~ **2.5×10^8 from Altamura et al.**



in-SiPM and in -SPAD maps



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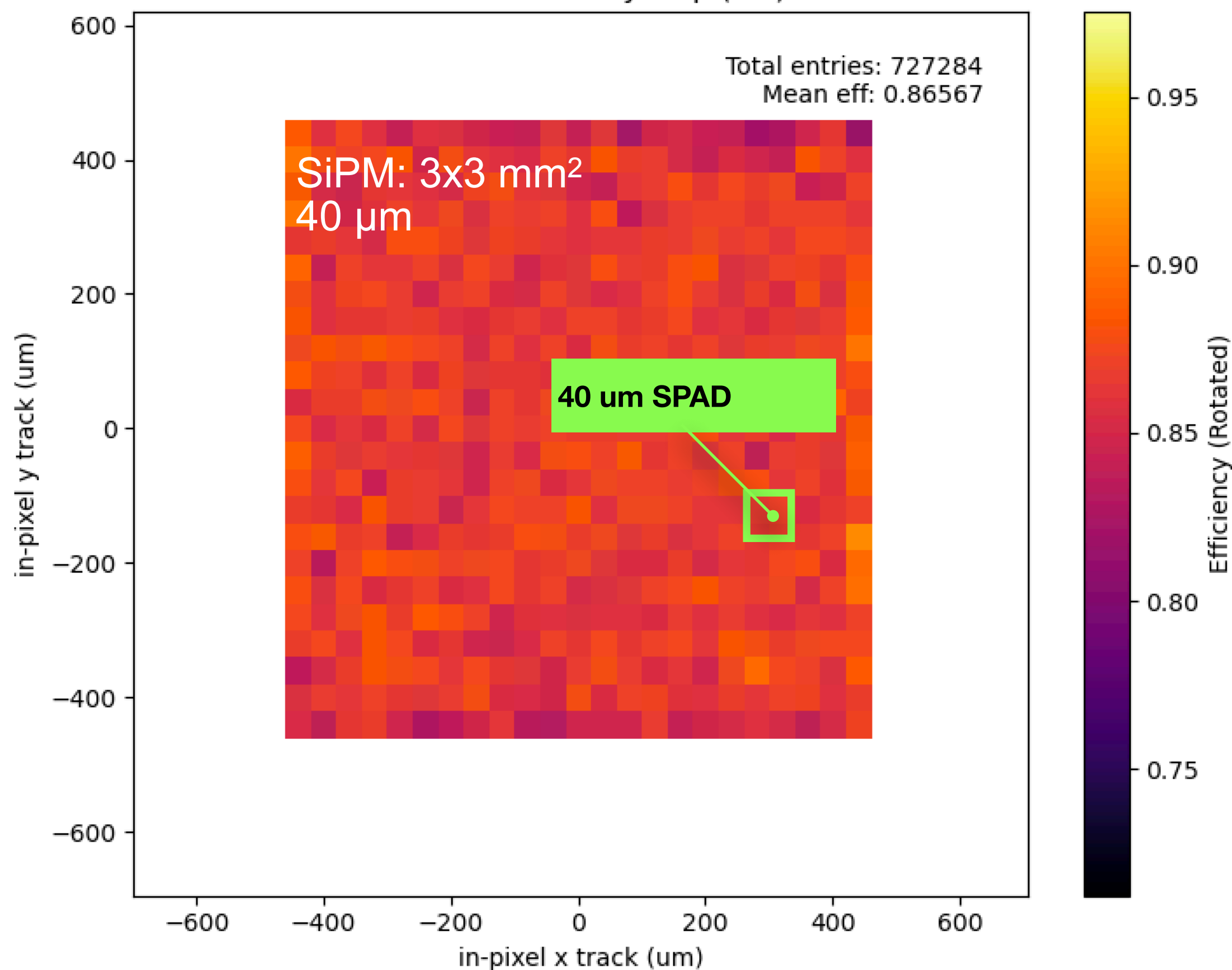
Results on SiPMs without protection layers and in-SPAD performance with MIPs

in-SiPM efficiency



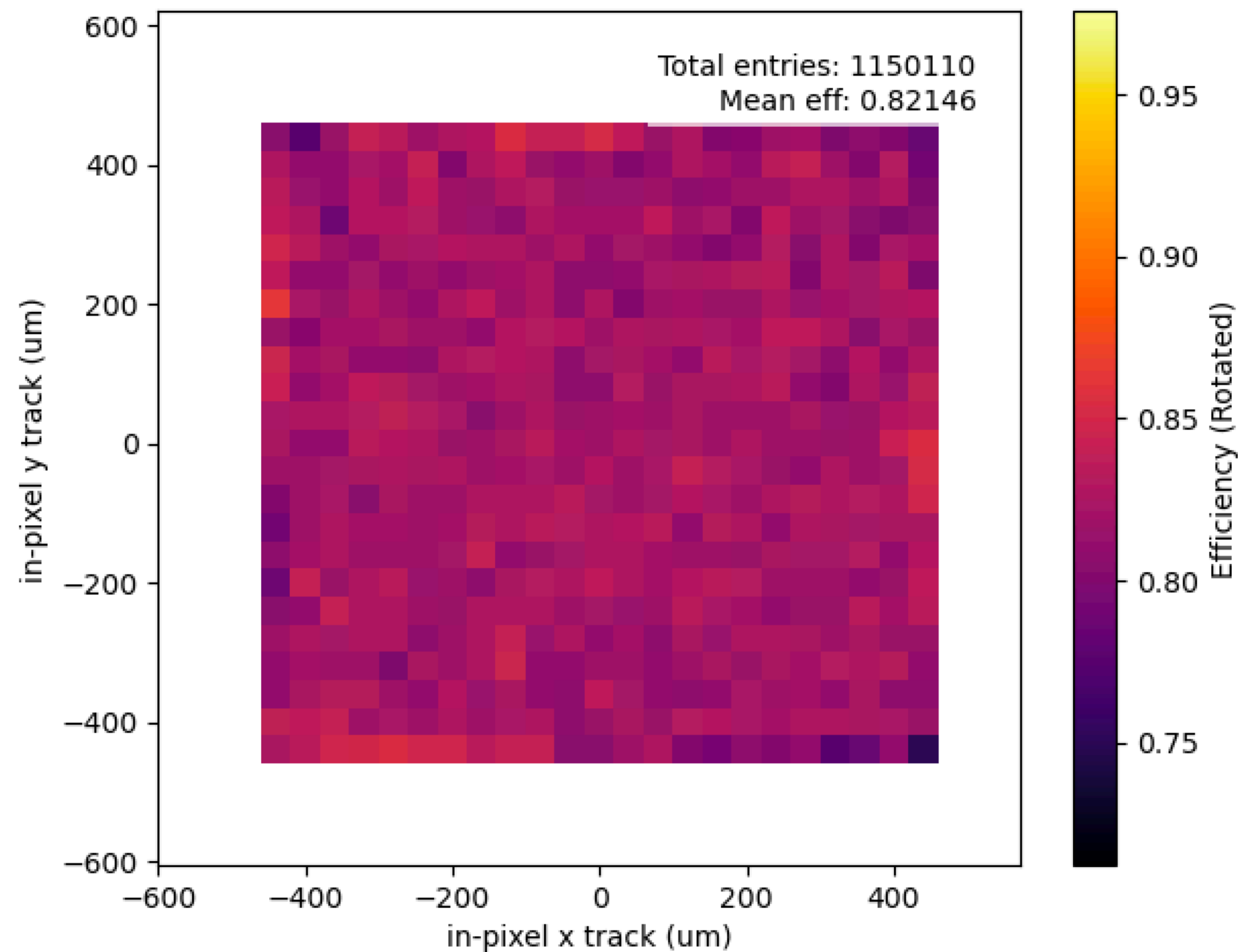
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◆NUV-HD-LFv2



Efficiency: 86.59%
Error in efficiency: 0.16%
Min efficiency: 81.41%
Max efficiency of folded map: 91.18%

◆NUV-HD-MT



Efficiency: 82.13%
Error in efficiency: 0.12%
Min efficiency: 75.03%
Max efficiency of folded map: 86.25%

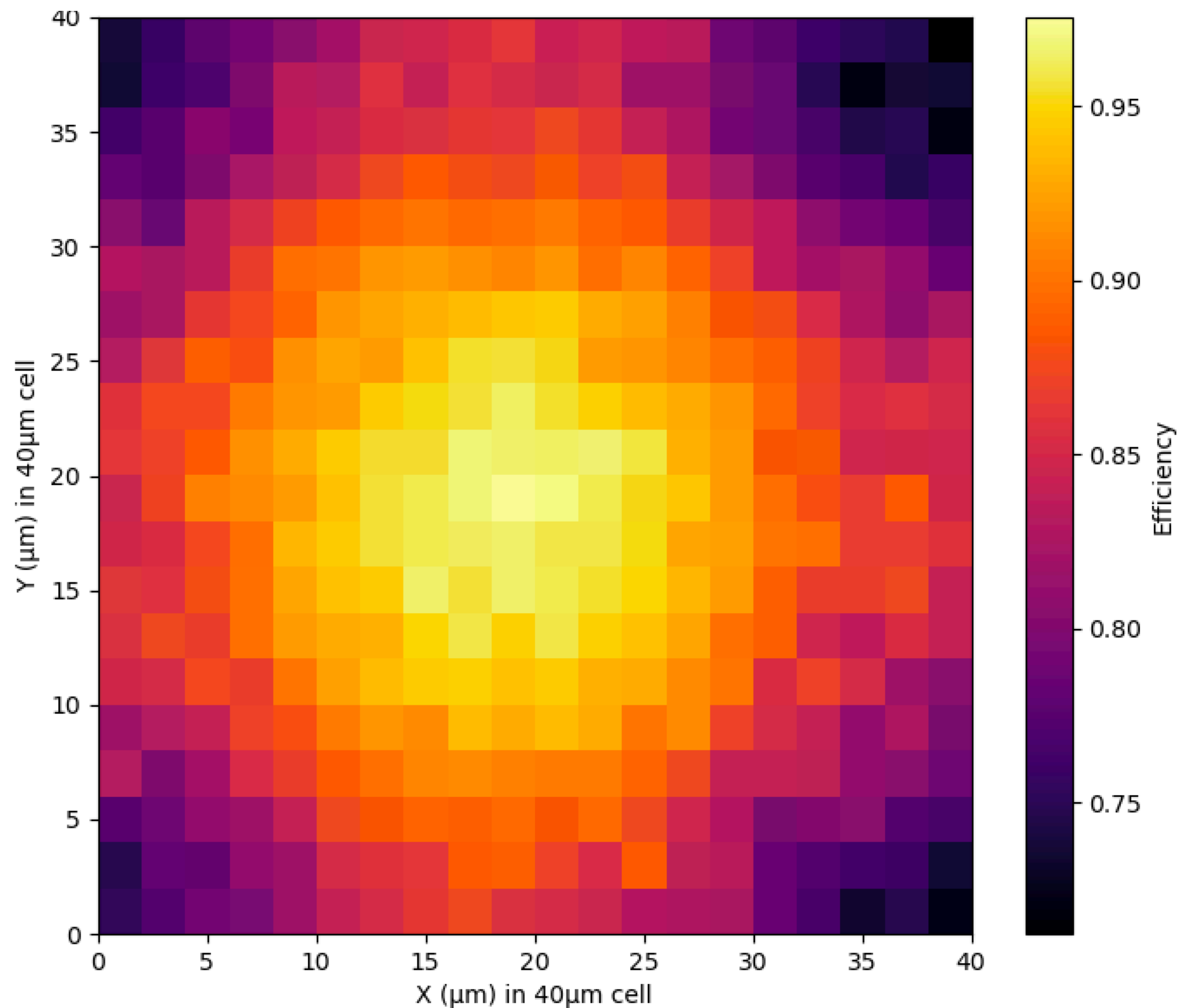
Results on SiPMs without protection layers and in-SPAD performance with MIPs

in-SPAD efficiency



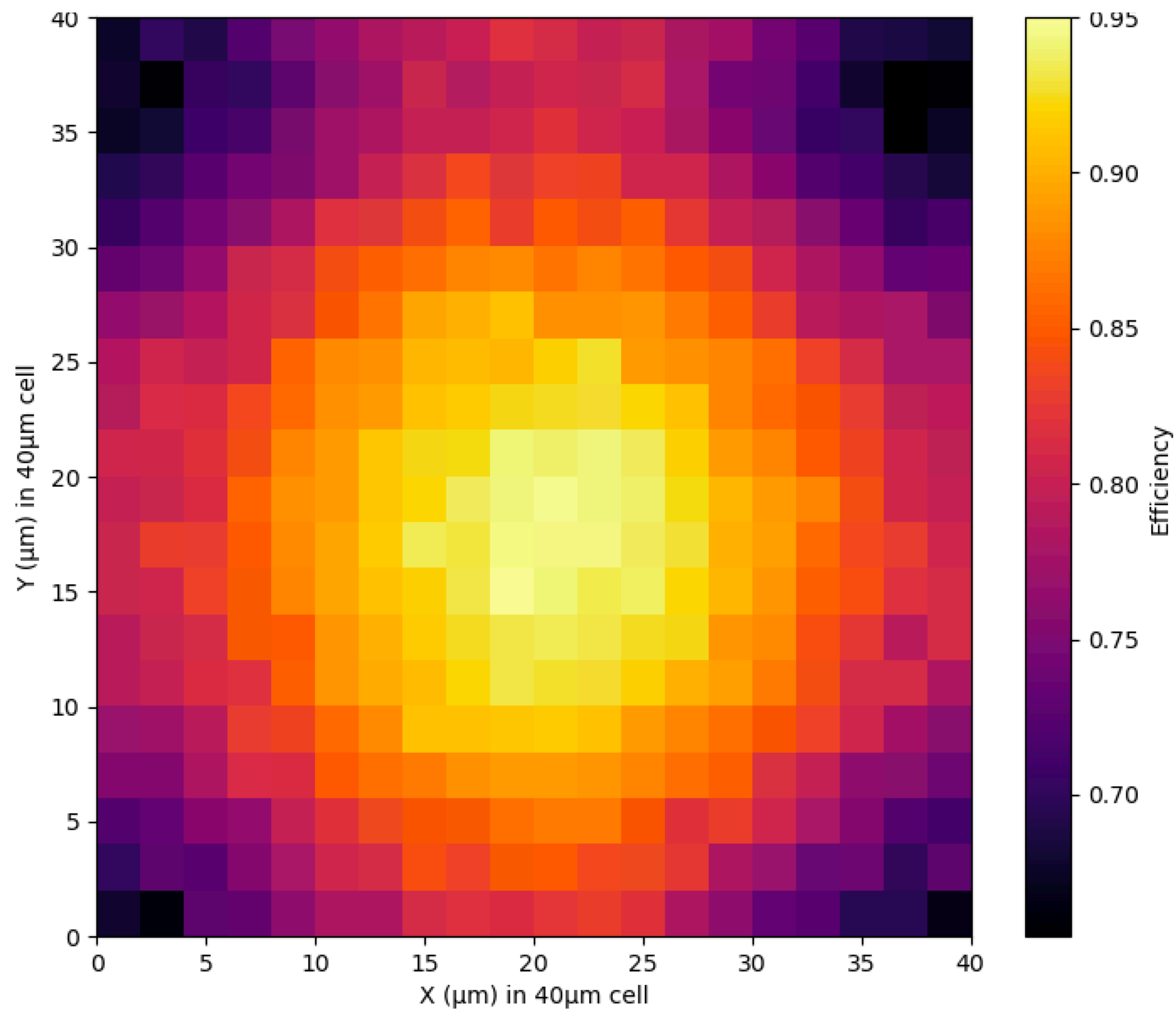
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◆NUV-HD-LFv2



Min efficiency of folded map: 71.22%
Max efficiency of folded map: 97.55%

◆NUV-HD-MT



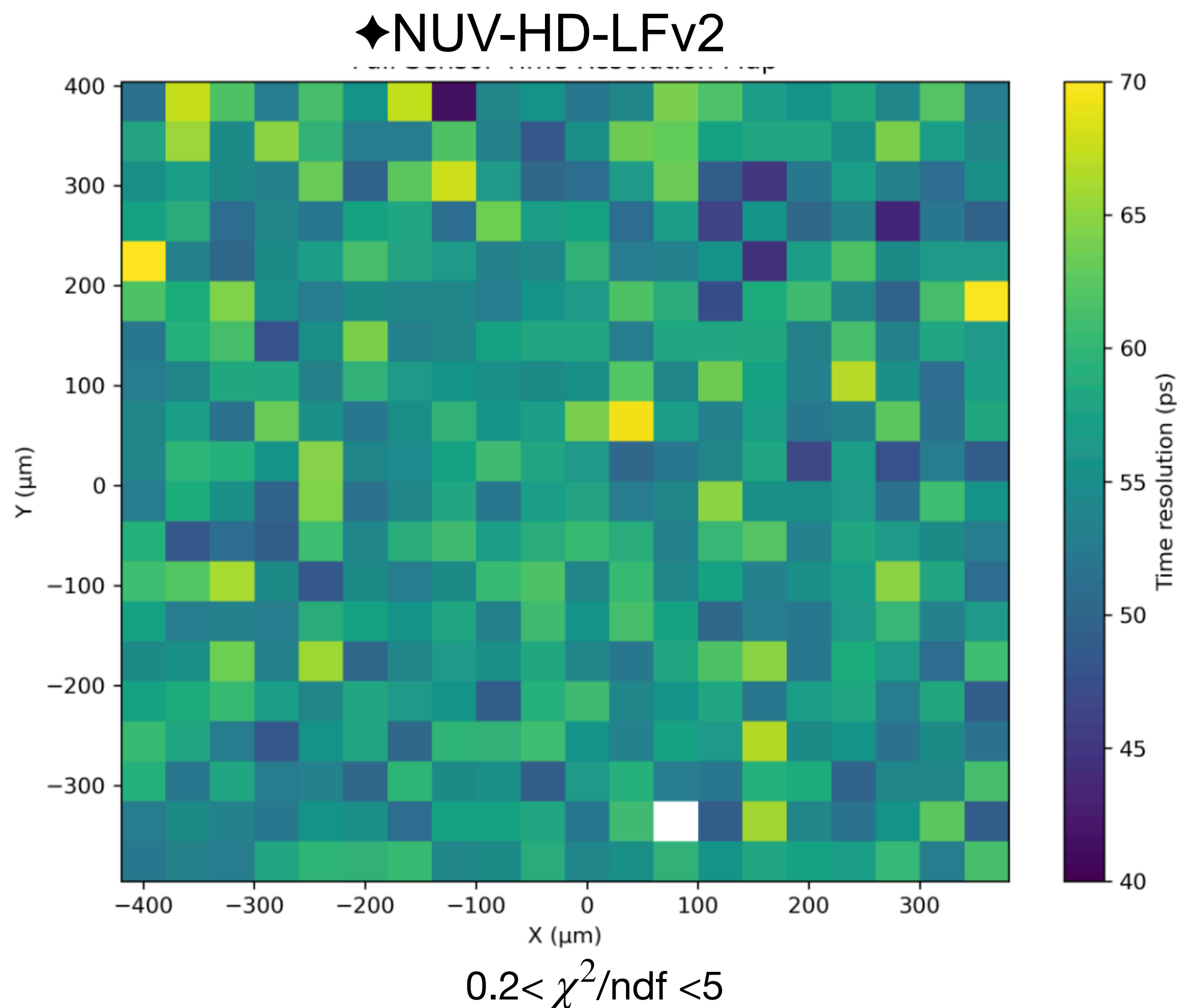
Min efficiency of folded map: 65.44%
Max efficiency of folded map: 95.00%

Results on SiPMs without protection layers and in-SPAD performance with MIPs

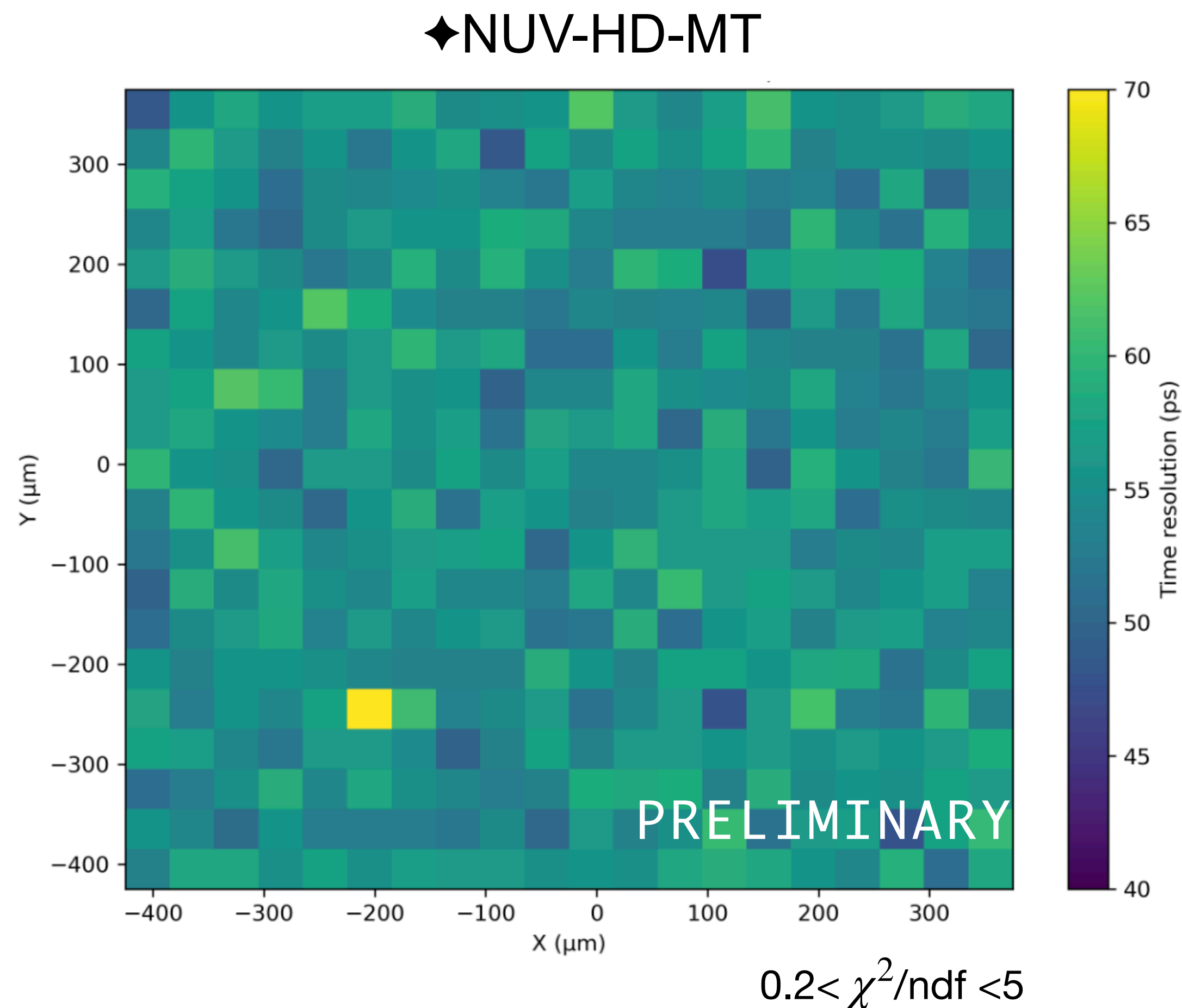
in-SiPM time resolution



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- ➔ SiPM mean time resolution **~56 ps**
- ➔ 10% of relative error



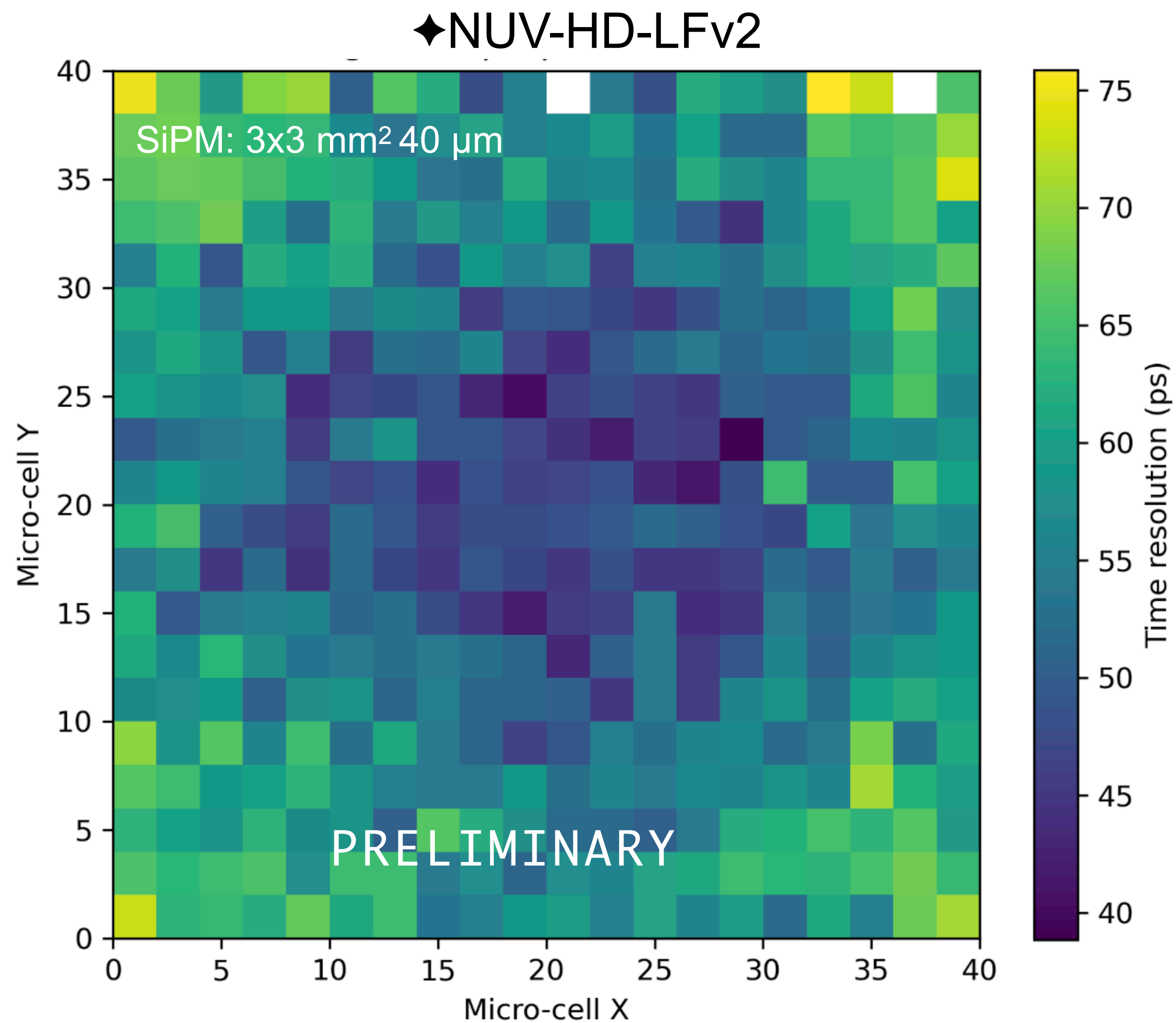
- ➔ SiPM mean time resolution **~60 ps**
- ➔ 10% of relative error

Results on SiPMs without protection layers and in-SPAD performance with MIPs

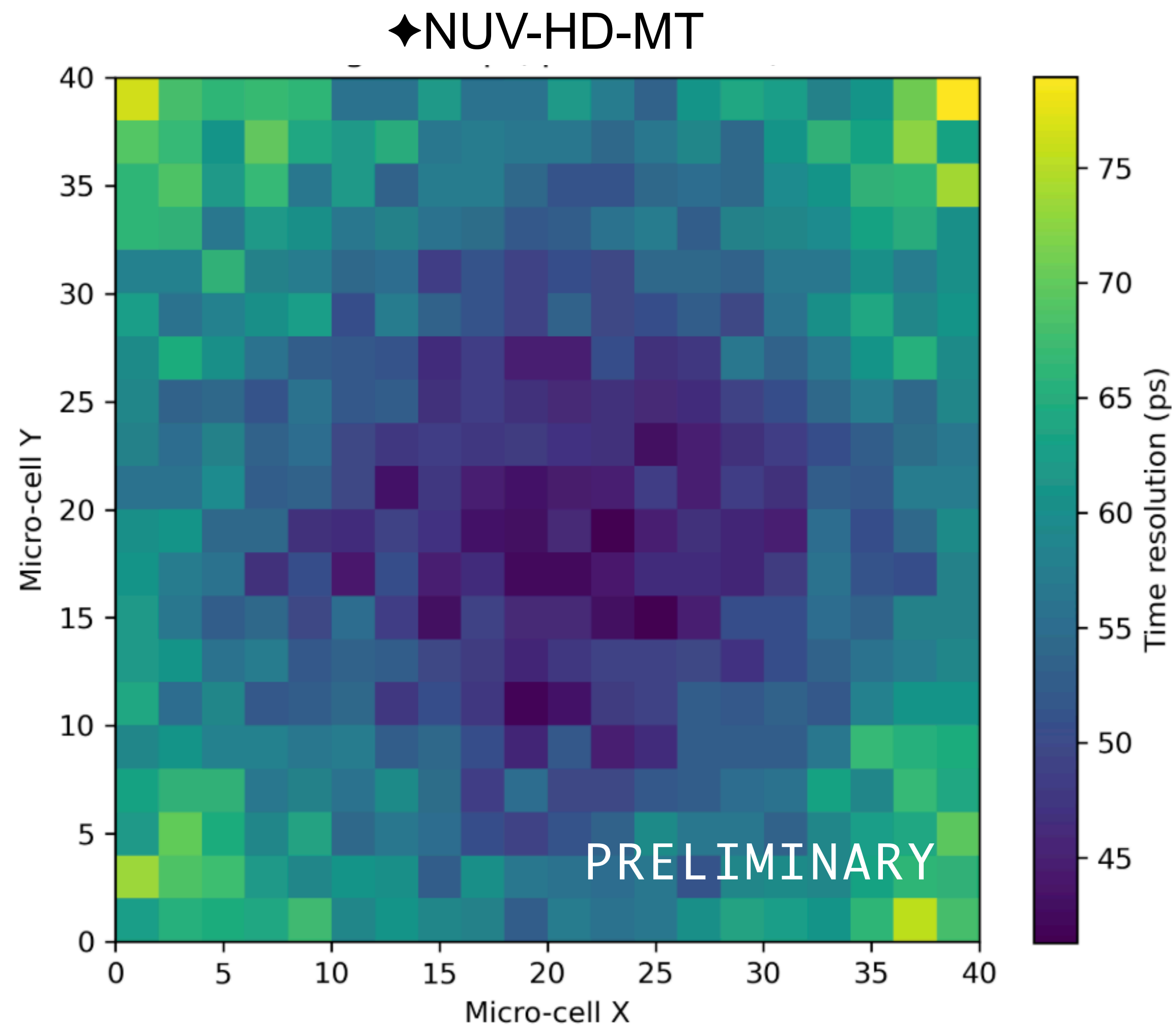
in-SPAD time resolution map



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- ◆Mean 56 ps
- ◆Min. 38, max 76 ps



- ◆Mean 55 ps
- ◆Min. 41 ps, max 78 ps

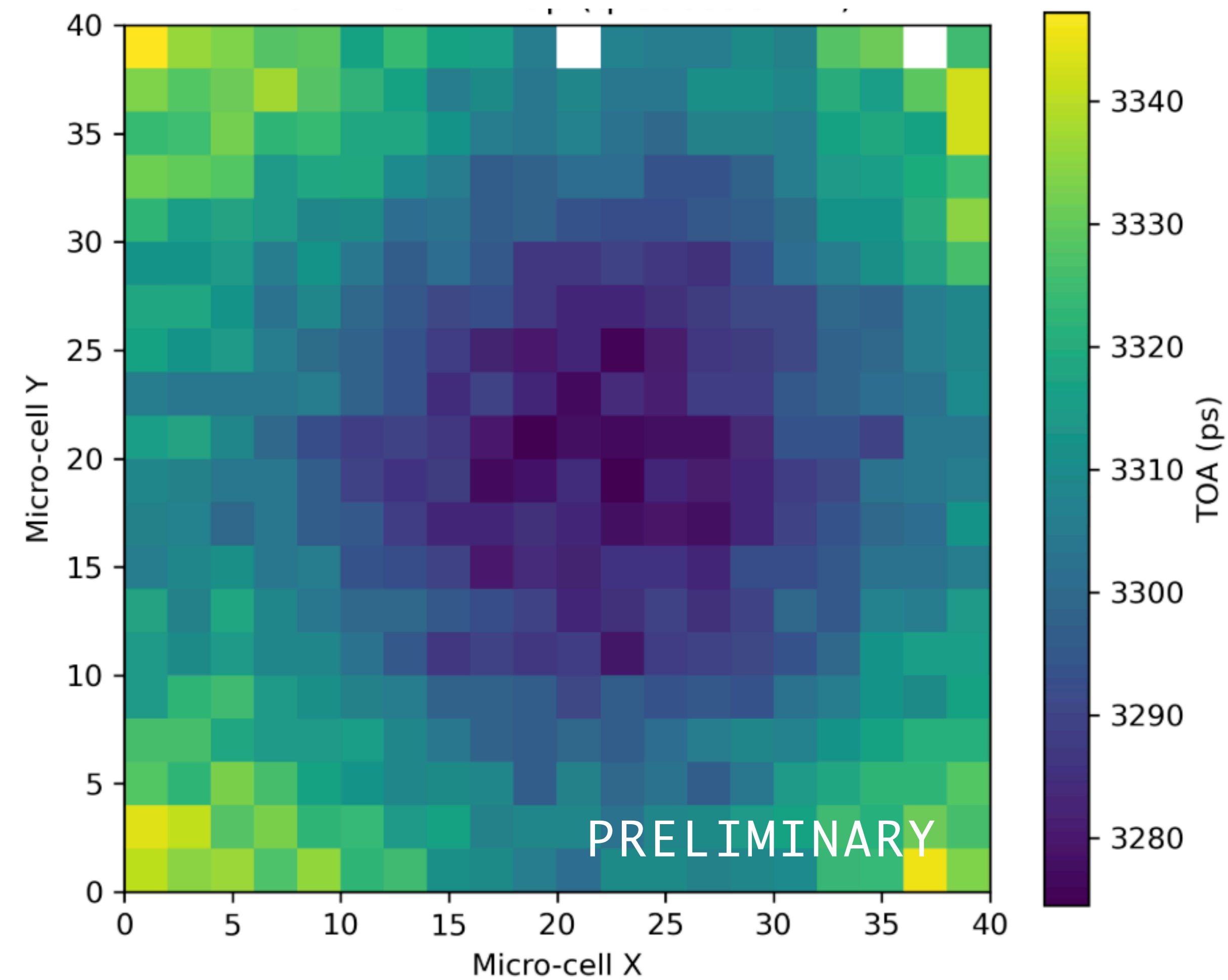
Results on SiPMs without protection layers and in-SPAD performance with MIPs

in-SPAD Time Of Arrival map

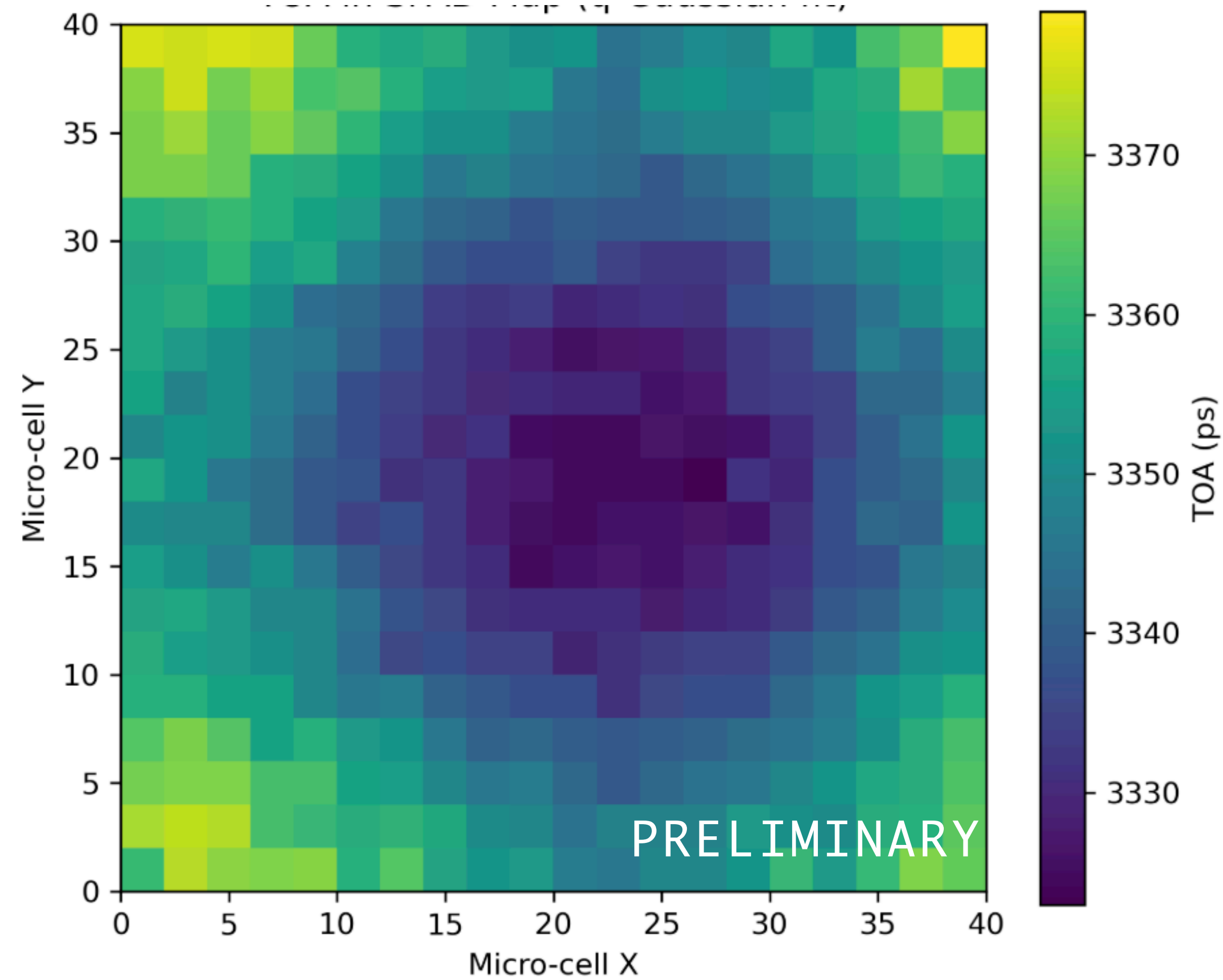


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◆NUV-HD-LFv2



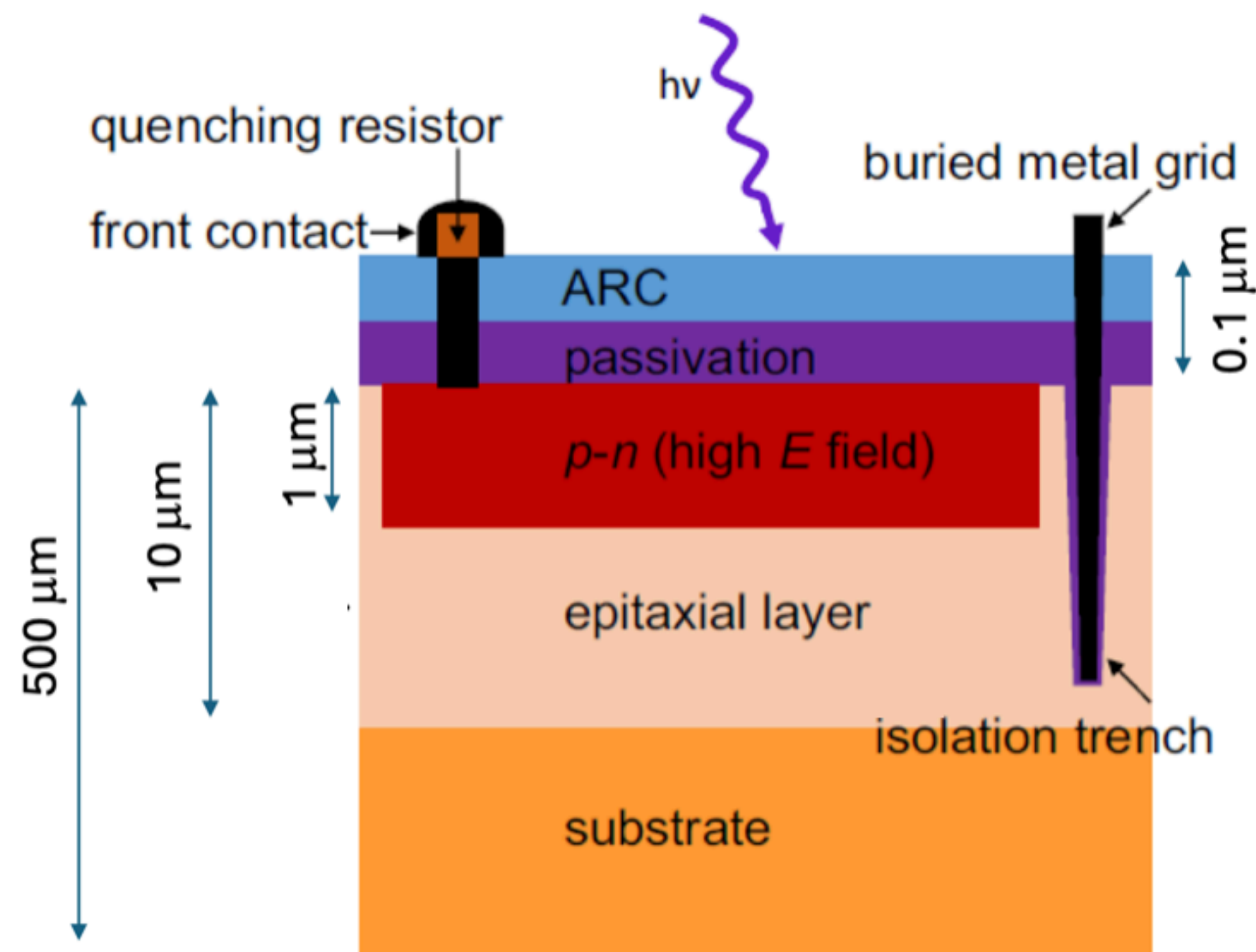
◆NUV-HD-MT



BSI technology from FBK

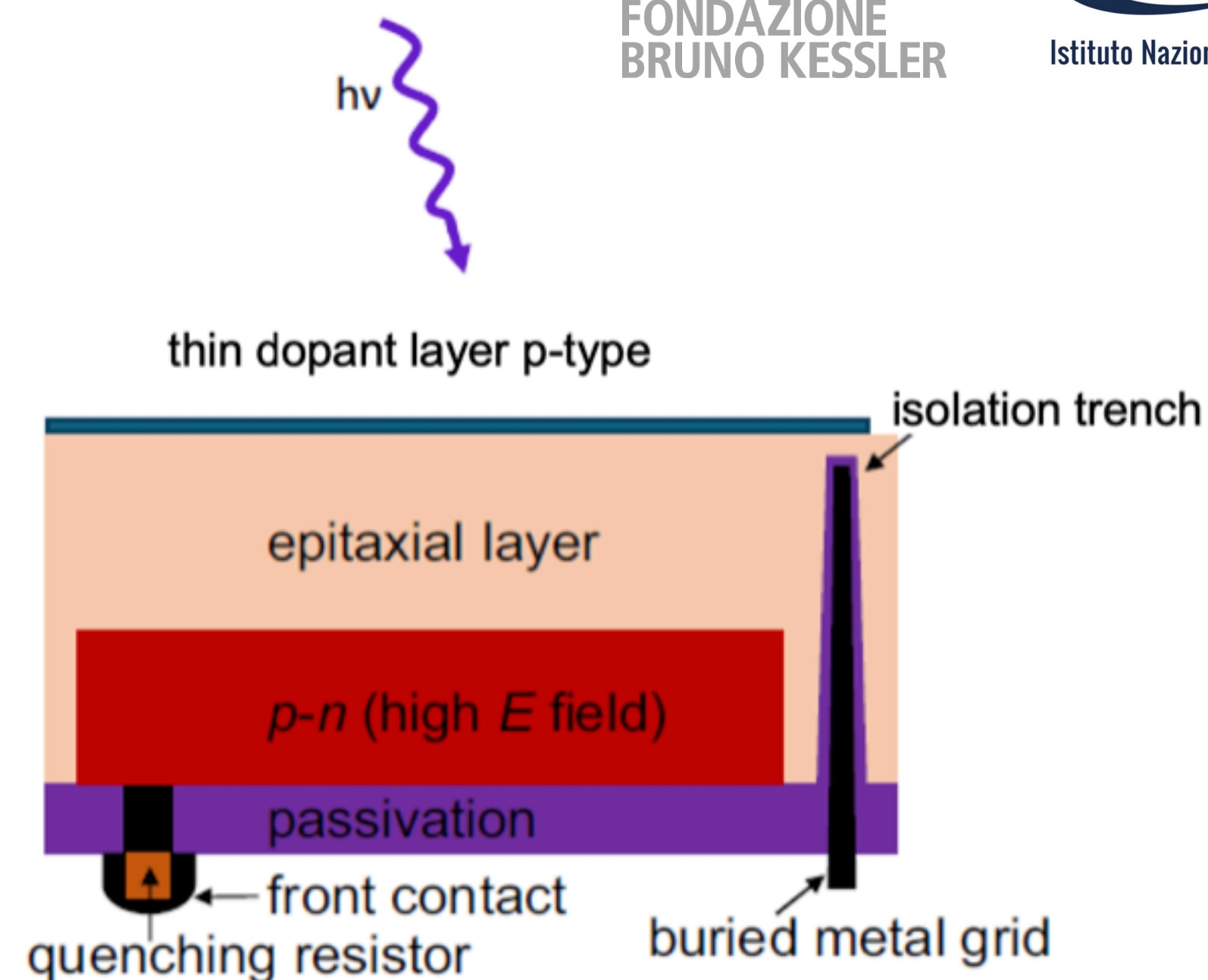
BSI vs FSI SiPMs

Design



Front-Side Illuminated (FSI) SiPM

Photons enter from the front side through passivation and metal routing layers before reaching the high-field p-n junction, resulting in partial optical shadowing and reduced effective fill factor



Back-Side Illuminated (BSI) SiPM

Photons enter from the back side through a thin doped layer directly into the epitaxial volume, avoiding front-side metal structures and enabling higher PDE.