FATA

FAst Timing Applications for nuclear physics and medical imaging

October 10th, 2025
Catania, Italy

Development of Hybrid and CMOS Monolithic LGADs for the 20 ps TOF detector of the future ALICE 3 experiment at the LHC

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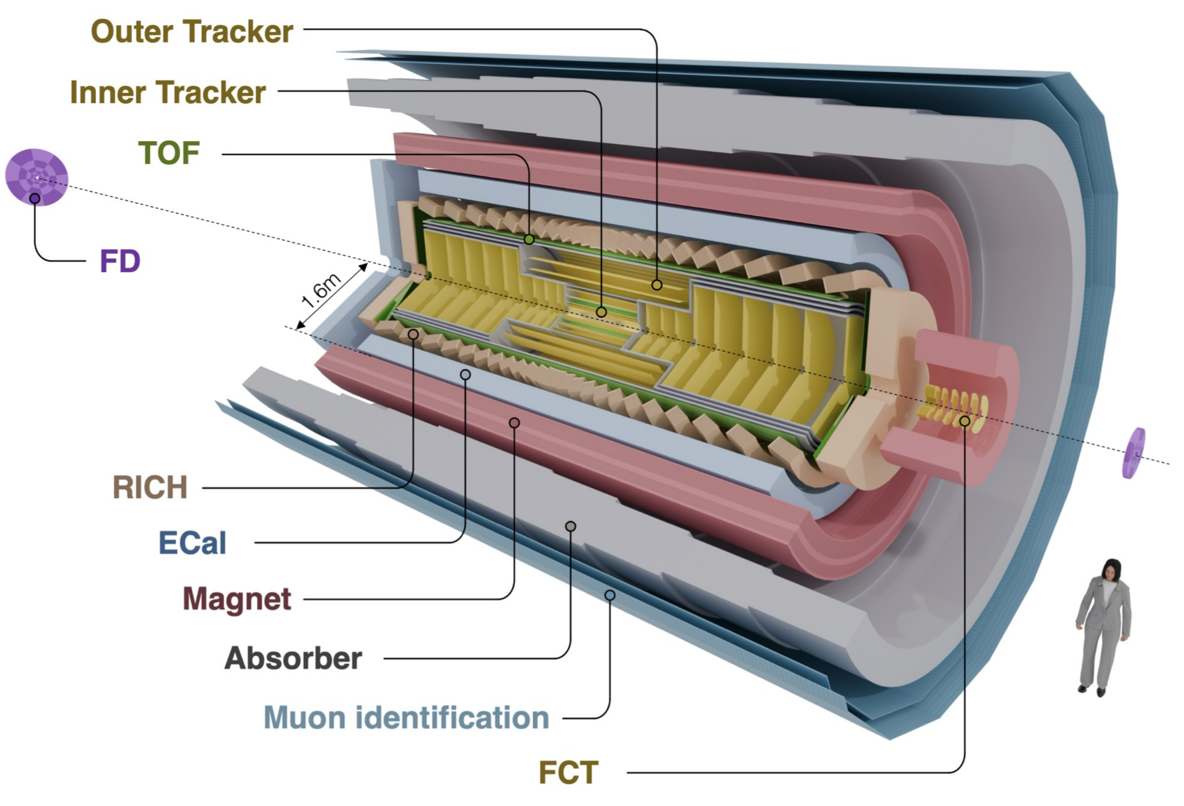
on behalf of the ALICE Collaboration

University and INFN Bologna, Italy

The ALICE Collaboration has submitted the proposal for a next-generation heavy-ion experiment, ALICE 3, to be installed at the LHC during the LS4 (2034-35)

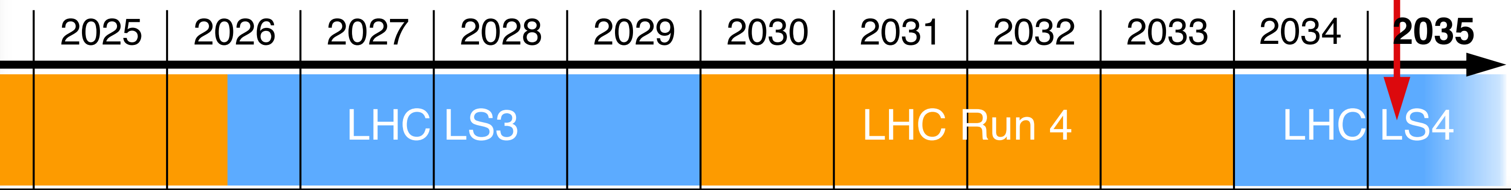


New, compact, low-mass, **experimental apparatus** totally based on the **most advanced silicon technologies**

Letter of Intent: *https://arxiv.org/abs/2211.02491*
Scoping Document: *https://cds.cern.ch/record/2925455*

ALICE 3

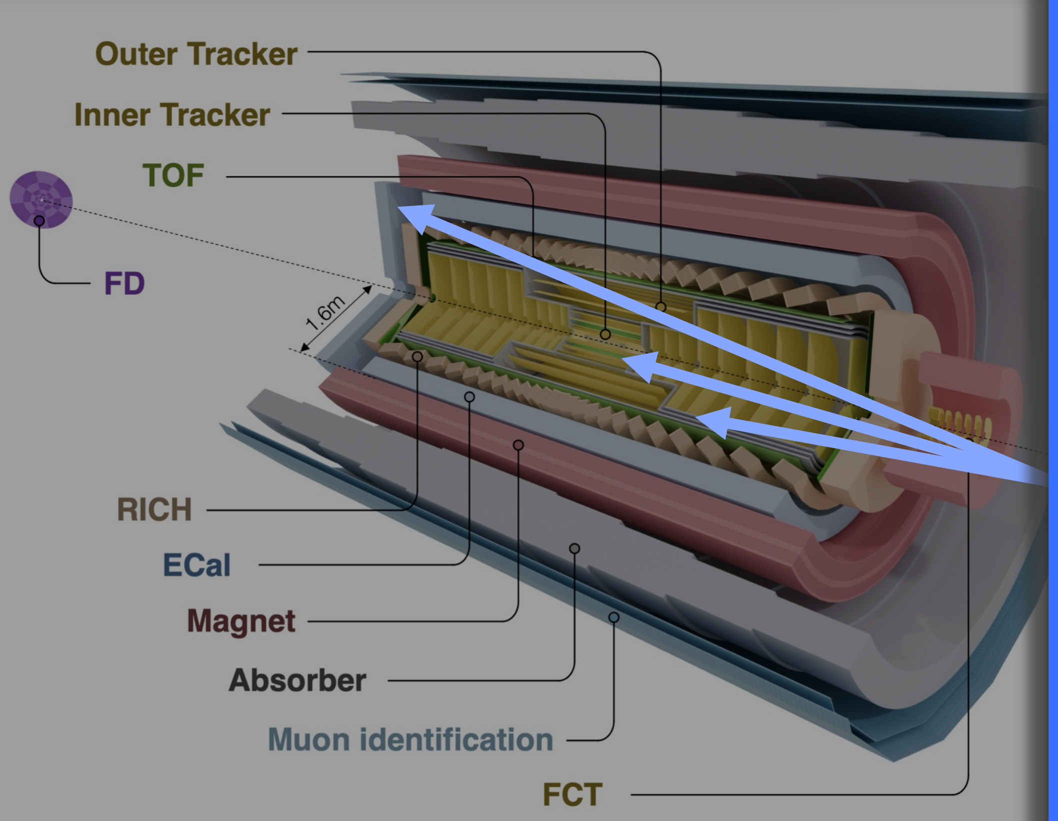
a next generation heavy-ion experiment



New exciting opportunities for the study of:

- ✦ **Multi-charm hadrons at low momenta**
  → Crucial test for coalescence models
- ✦ **EM radiation** produced in the first evolution phases of QGP

The ALICE Collaboration has submitt
experiment, ALICE 3, to be in



ALICE 3 a next generation heavy-ion experime

2025	2026	2027	2028	2029	2030	2031	2032
		LHC LS3				LHC Run 4	

Time-Of-Flight System (TOF)

Separation Power $\propto \frac{L}{\sigma_{TOF}}$

- inner TOF $R \approx 19$ cm
- outer TOF $R \approx 85$ cm
- forward TOF $z \approx 375$ cm

Requirements:

- Moderate rad. hardness
  - inner TOF: NIEL ~ $6.1 \cdot 10^{12}$ 1-MeV n_{eq} /cm^2
  - outer TOF: NIEL ~ $9 \cdot 10^{11}$ 1-MeV n_{eq} /cm^2
  - forward TOF: NIEL ~ $8.5 \cdot 10^{12}$ 1-MeV n_{eq} /cm^2
- Low material budget ~1-3% X_0
- **Time resolution** → $e/\pi \lesssim 500$ MeV/c, $K/\pi \lesssim 2.5$ GeV/c, $p/K \lesssim 4$ GeV/c → **20ps**

Extensive R&D on the most advanced silicon technologies:

LGADs, SiPMs, CMOS-LGADs

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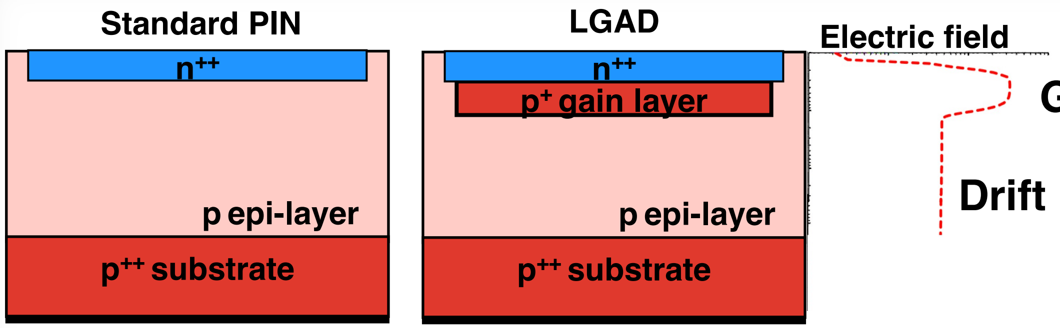
GP

MOTIVATIONS - LOW GAIN AVALANCHE DETECTOR (LGAD)



Gain region: very high electric field

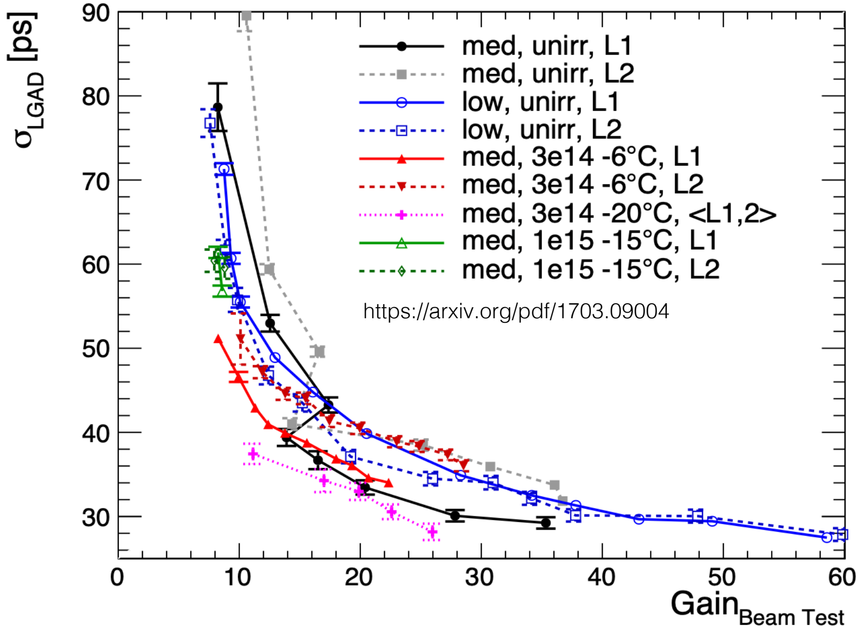
Drift region: low and uniform electric field

Internal low-gain multiplication mechanism

Optimized to obtain:

- Fast signal (dV/dt)
- Improved S/N

Excellent timing performance

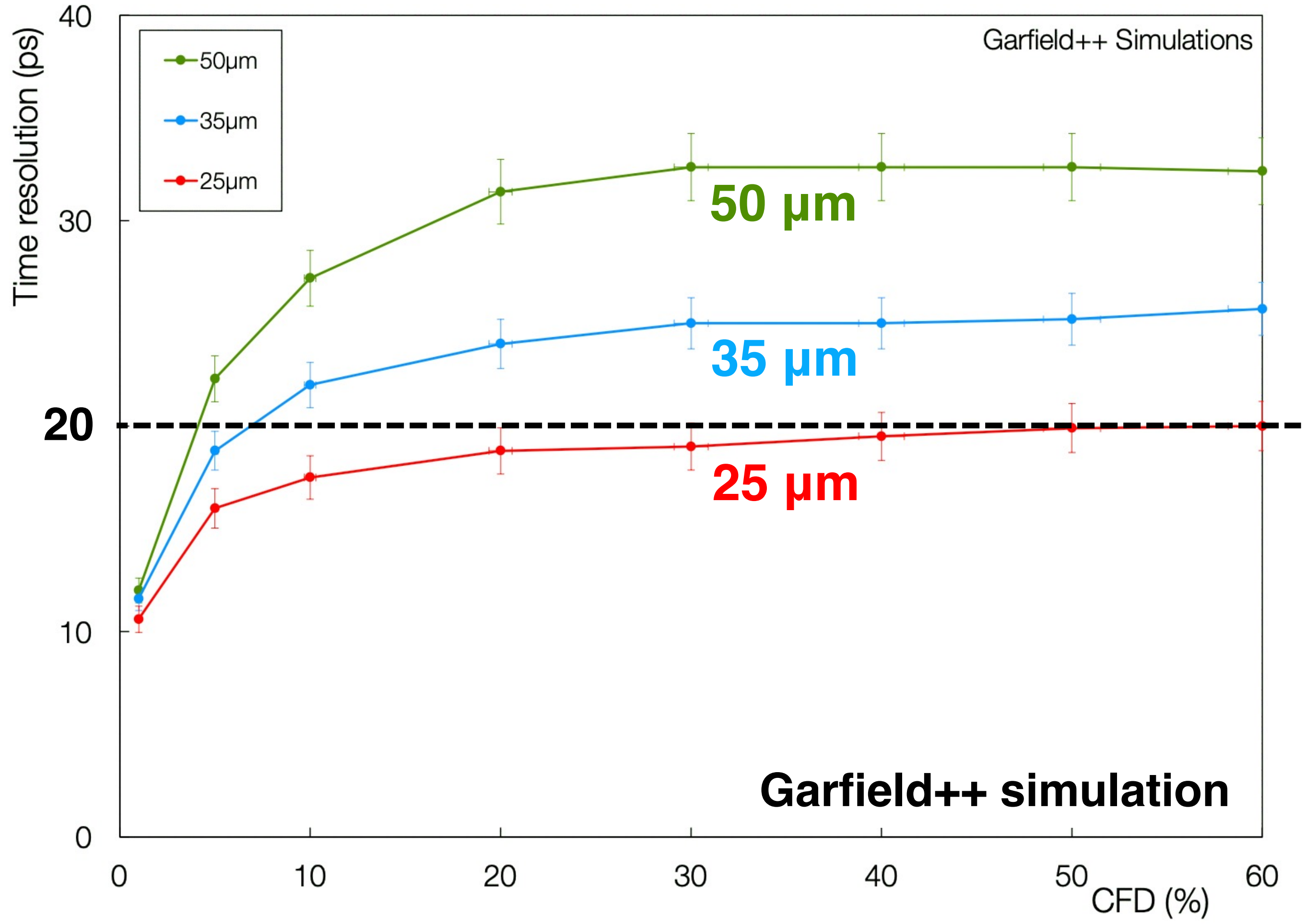


State-of-the-art LGAD (35-50 µm-thick)

→ **~30 ps**

Already used or envisioned for detector upgrades at the HL-LHC (e.g. ATLAS and CMS) for 2026

MOTIVATIONS … E DETECTOR (LGAD)



→ Potential of a **thinner layout of LGAD**

Internal low gain

…igh electric fie…

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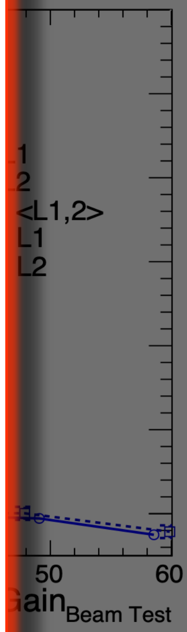
ALICE 3 TOF detector needs an even better time resolution

→ **20 ps**

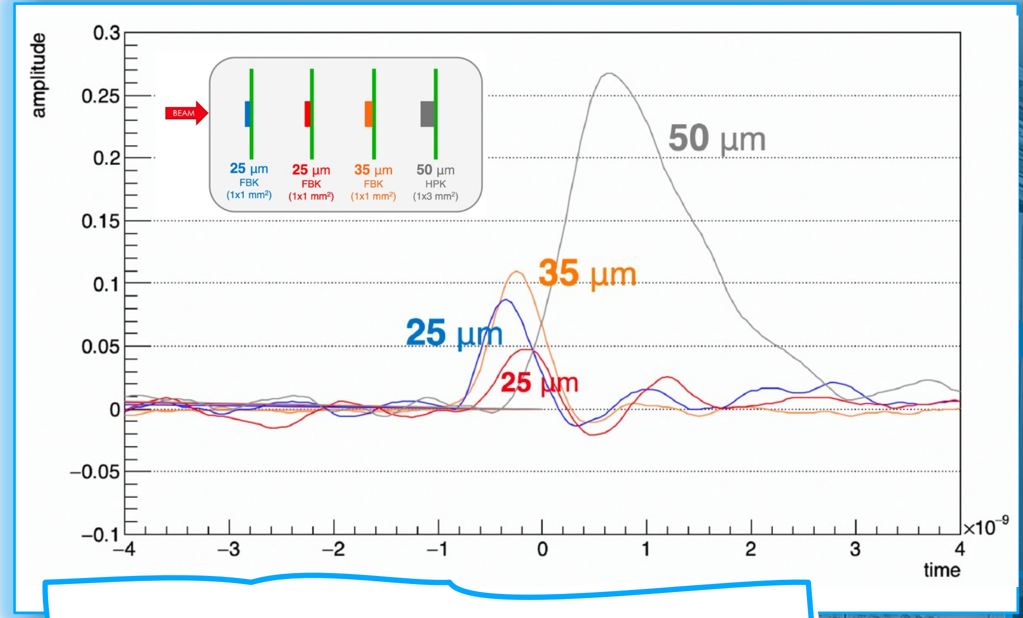


State-of-the-art LGAD (35-50 µm-thick)

→ **~30 ps**

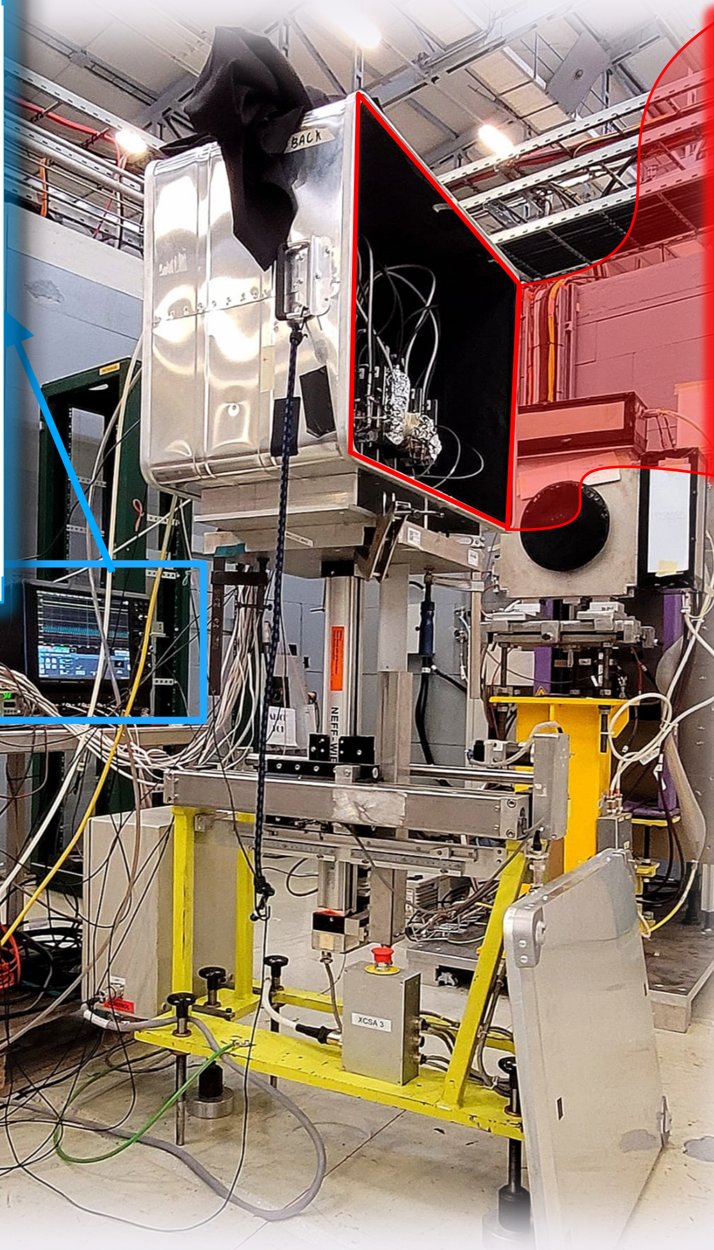
Already used or envisioned for detector upgrades at the HL-LHC (e.g. ATLAS and CMS) for 2026

TEST BEAM SETUP

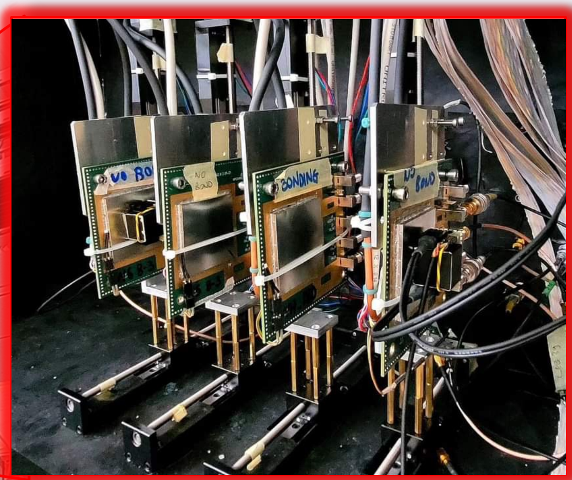


DIGITAL OSCILLOSCOPE READOUT

→ **Signal waveforms** acquired
→ Digitalization at the analysis level



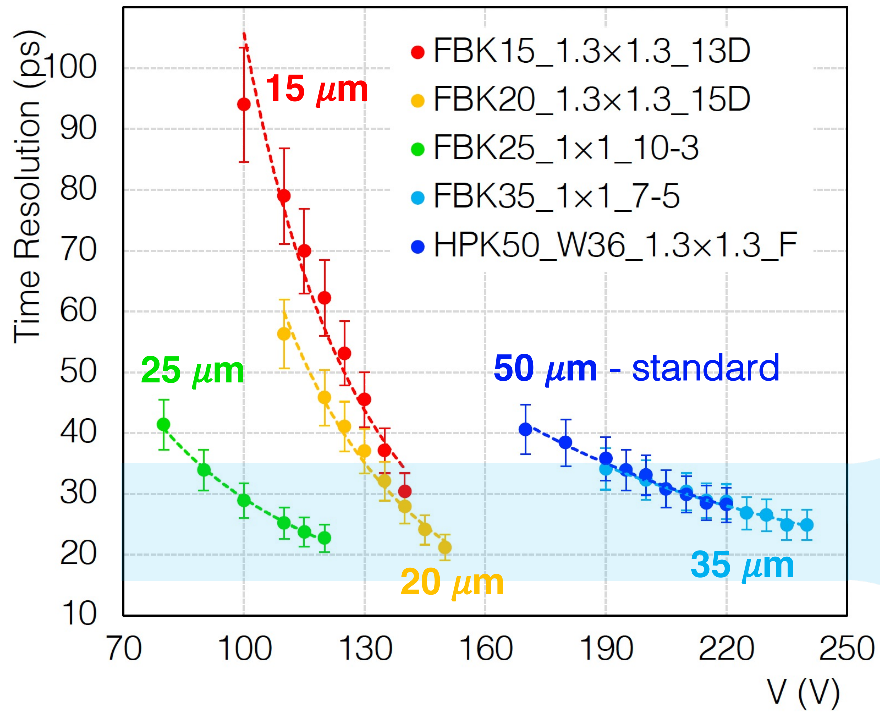
CERN PS



Sensors attached to a Santacruz V1.4-SCIPP-08/18 front-end board **aligned back-to-back to the beam**

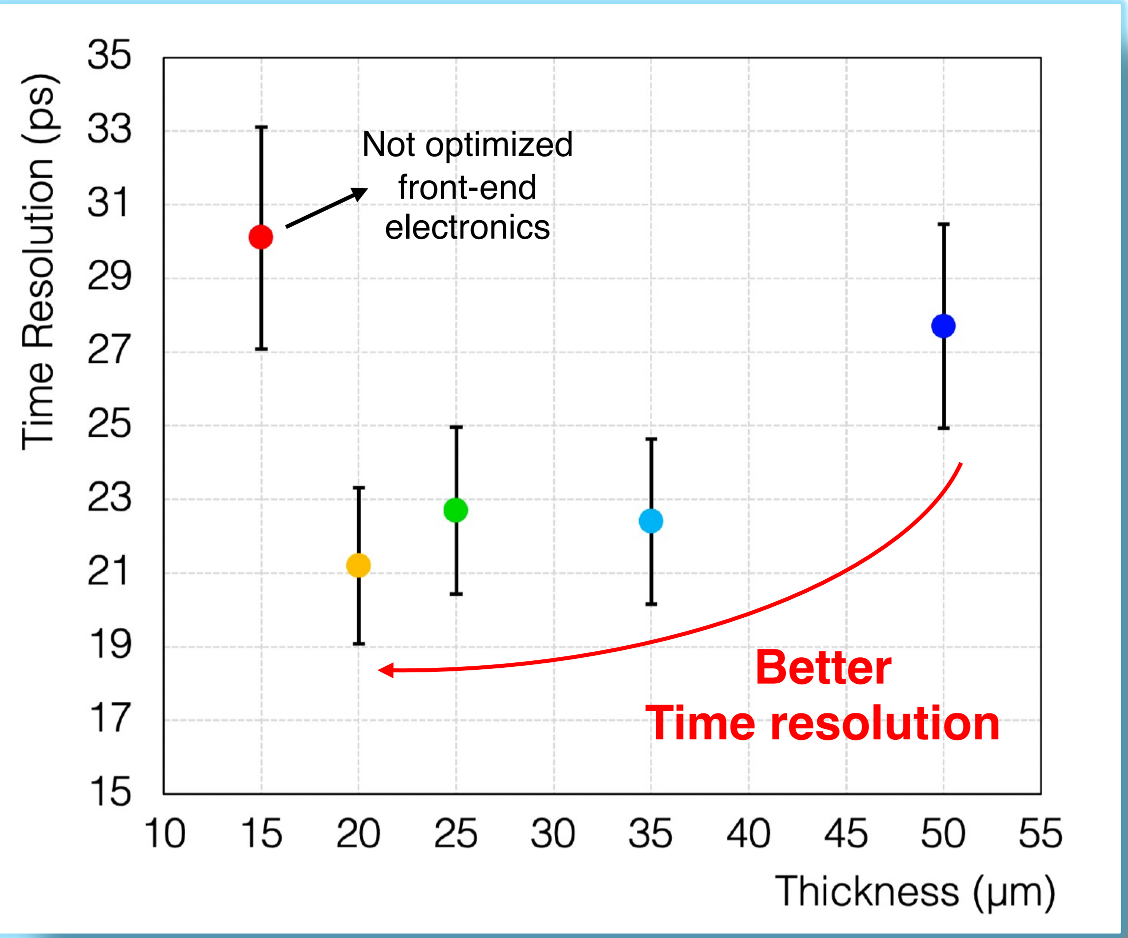
Seven beam test campaigns (2021-2024) with a hadron beam of p~10-12 GeV/c

TEST OF THE FIRST VERY THIN LGAD PROTOTYPES



First 15, 20, 25 and 35 μm thick FBK LGADs were tested in a beam test

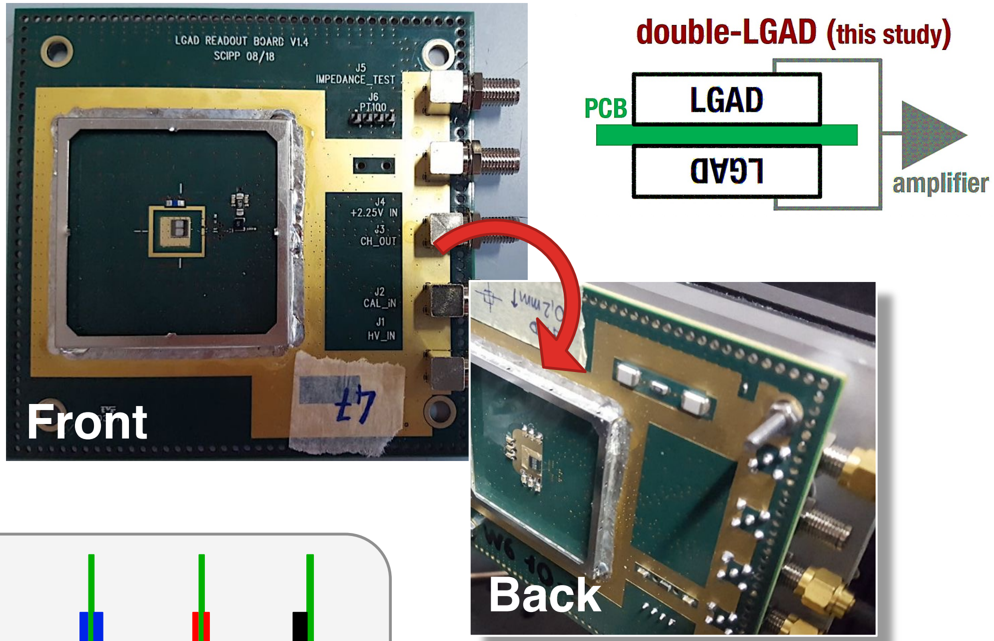
https://link.springer.com/article/10.1140/epjp/s13360-022-03619-1

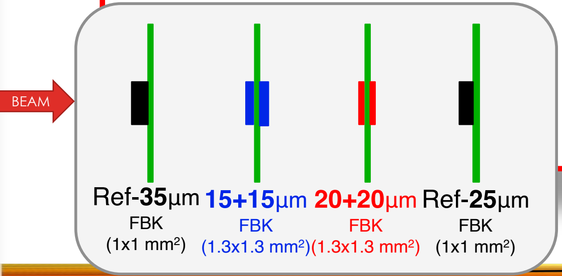


- ✦ 50 μm in line with the expectations
  - ➢ Validation of setup and analysis procedure
- ✦ Improved time res. with thinner LGADs
  - ➢ All in agreement with MC simulation
  - ➢ Slightly worse for the 25 μm due to worse S/N

NEW CONCEPT: DOUBLE-LGAD

Two uniform LGADs attached to the two sides of the same board, **both connected to the same amplifier**



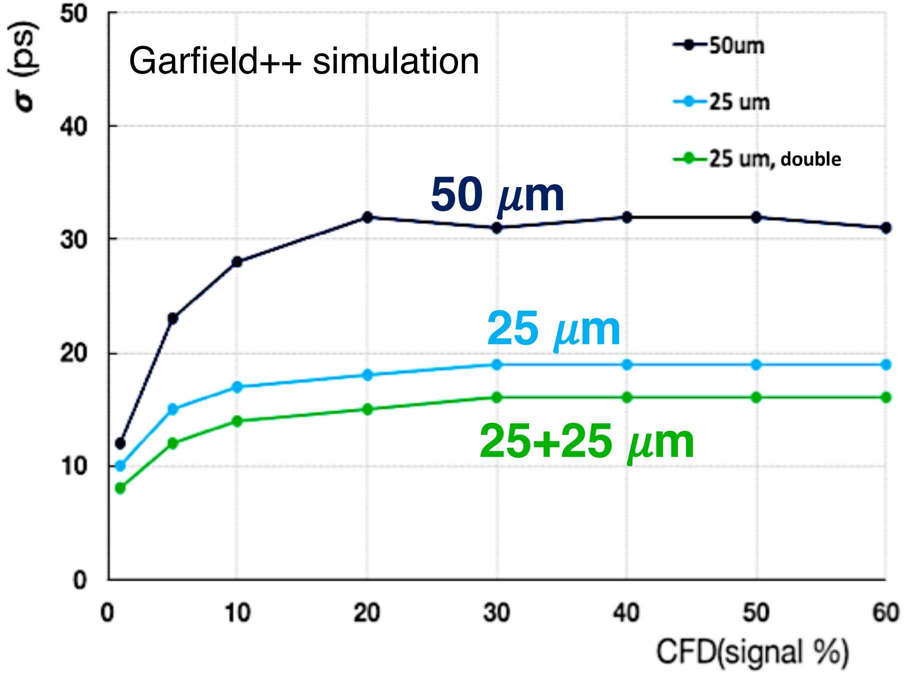


- **Higher signal**

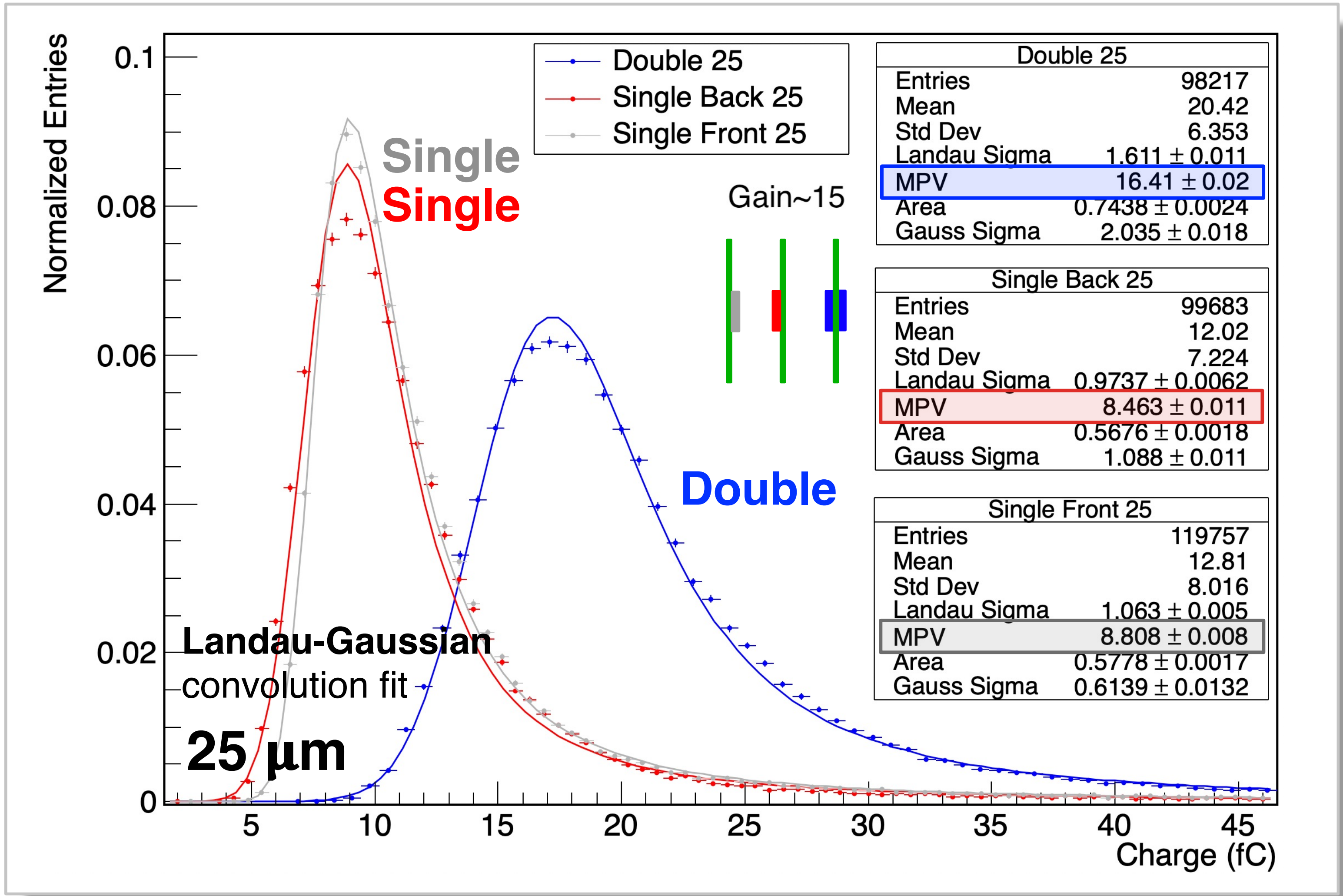
→ Less power-consuming **front-end electronics**

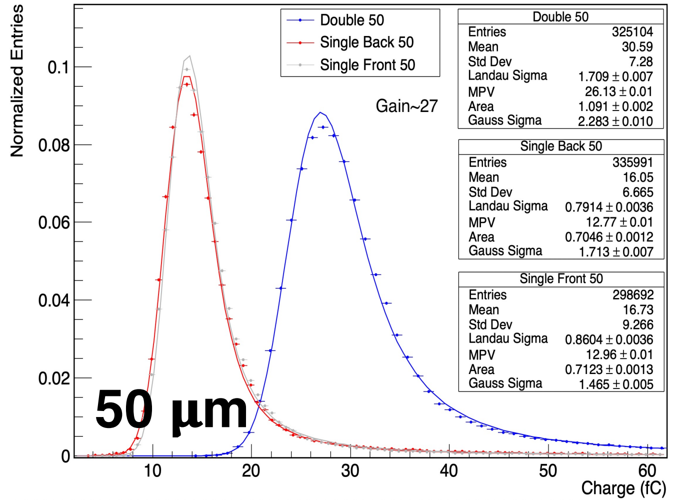
→ Electronics similar to the one used for the standard LGADs (50 μm)

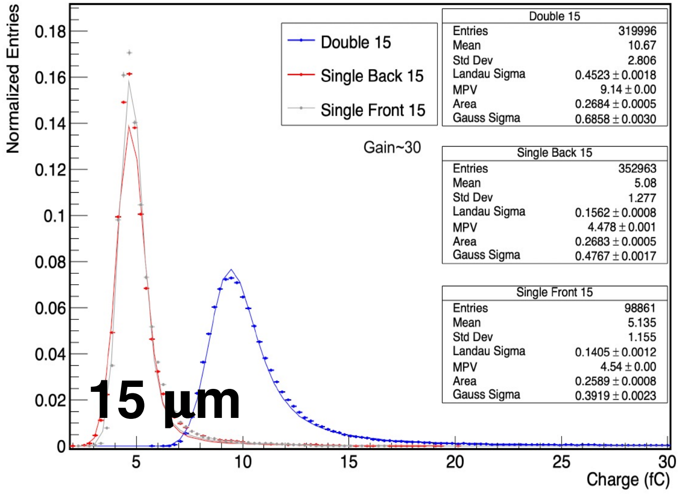
- **Better time resolution**



CHARGE DISTRIBUTIONS



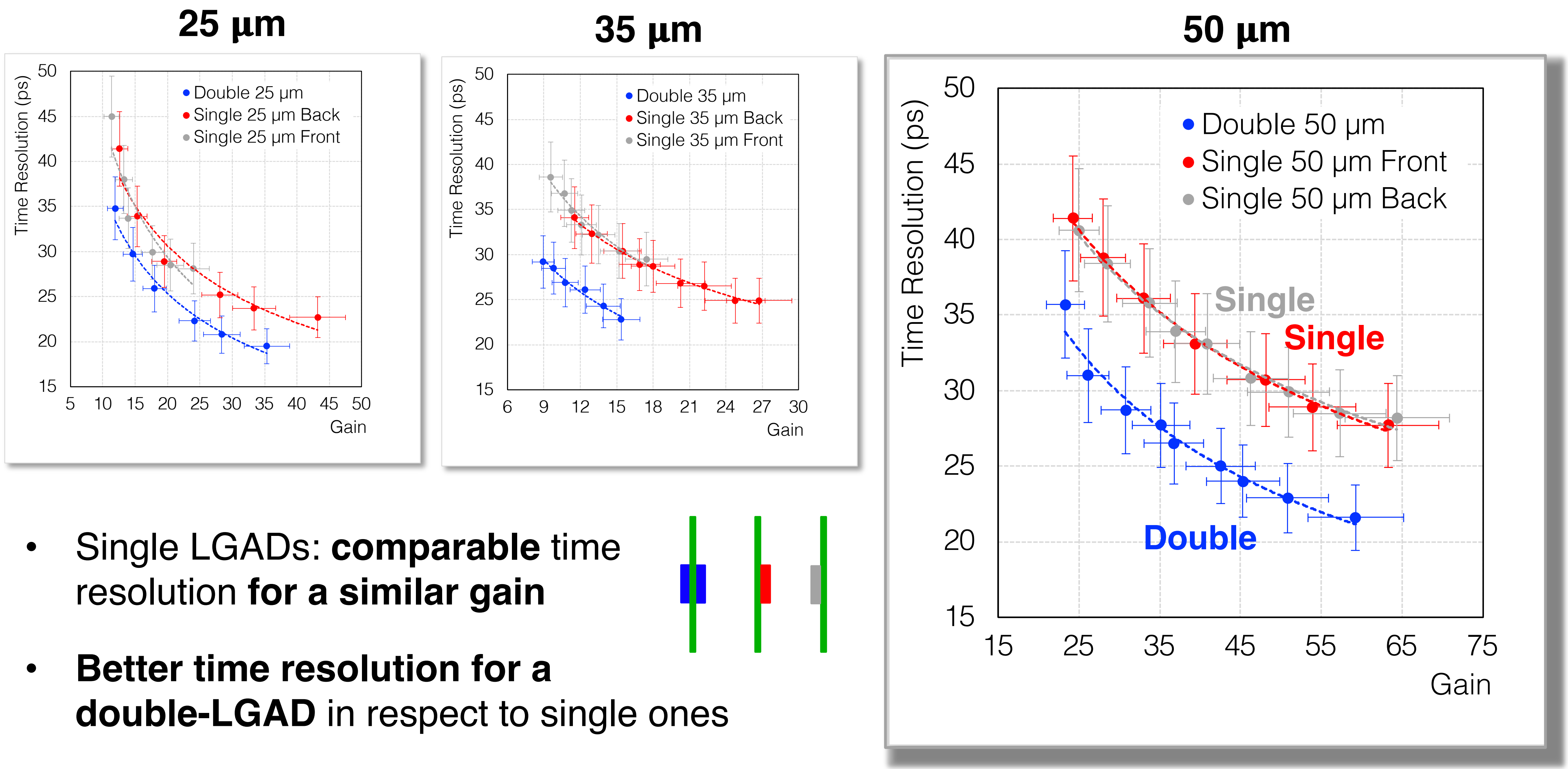




MPV of the charge is **doubled** for the double-LGAD, as expected → **Big advantage for the electronics**

Published Results
https://doi.org/10.1140/epjp/s13360-023-04621-x

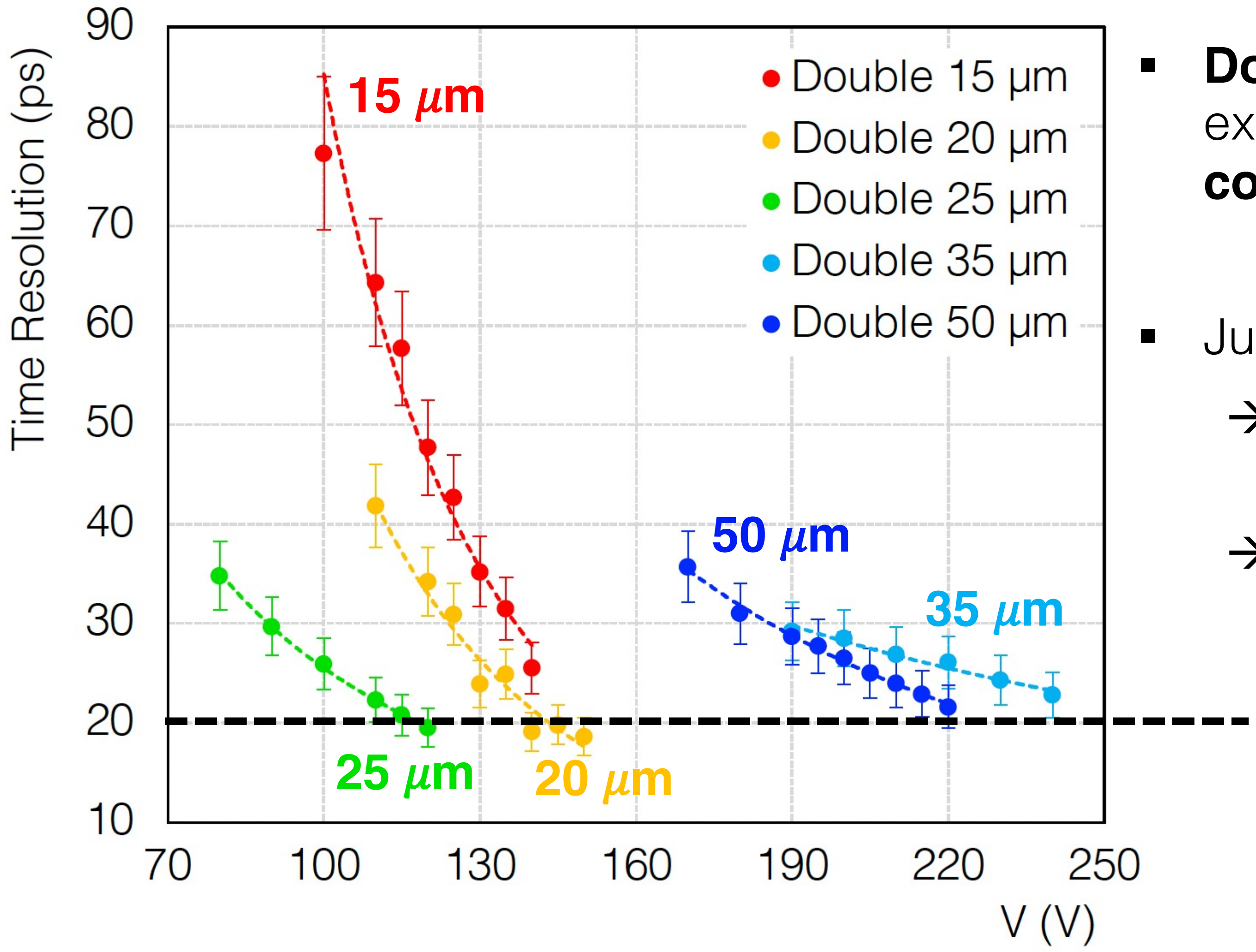
Timing performance: Single VS Double-LGAD



- Single LGADs: **comparable** time resolution **for a similar gain**
- **Better time resolution for a double-LGAD** in respect to single ones

Published Results
https://doi.org/10.1140/epjp/s13360-023-04621-x

Timing performance: Single VS Double-LGAD



- **Double-50 µm** (already existing technology) **compatible with 20 ps**
- Just a **proof of concept**:
  → Thinner prototypes not perfectly identical within the couples
  → **Improvement expected**

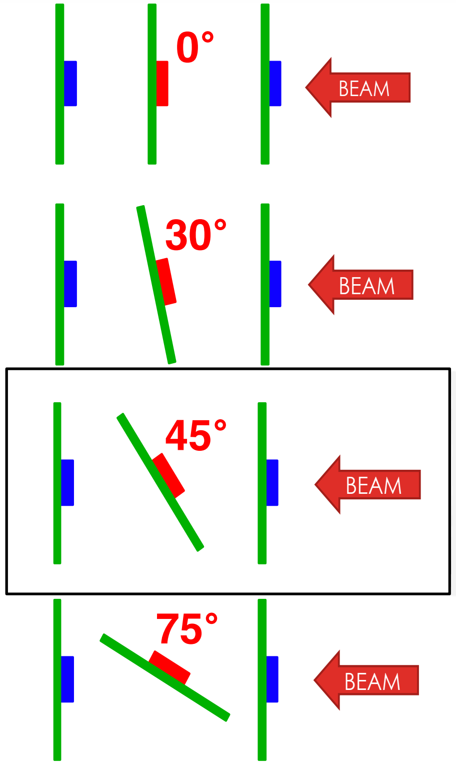
Below 20 ps

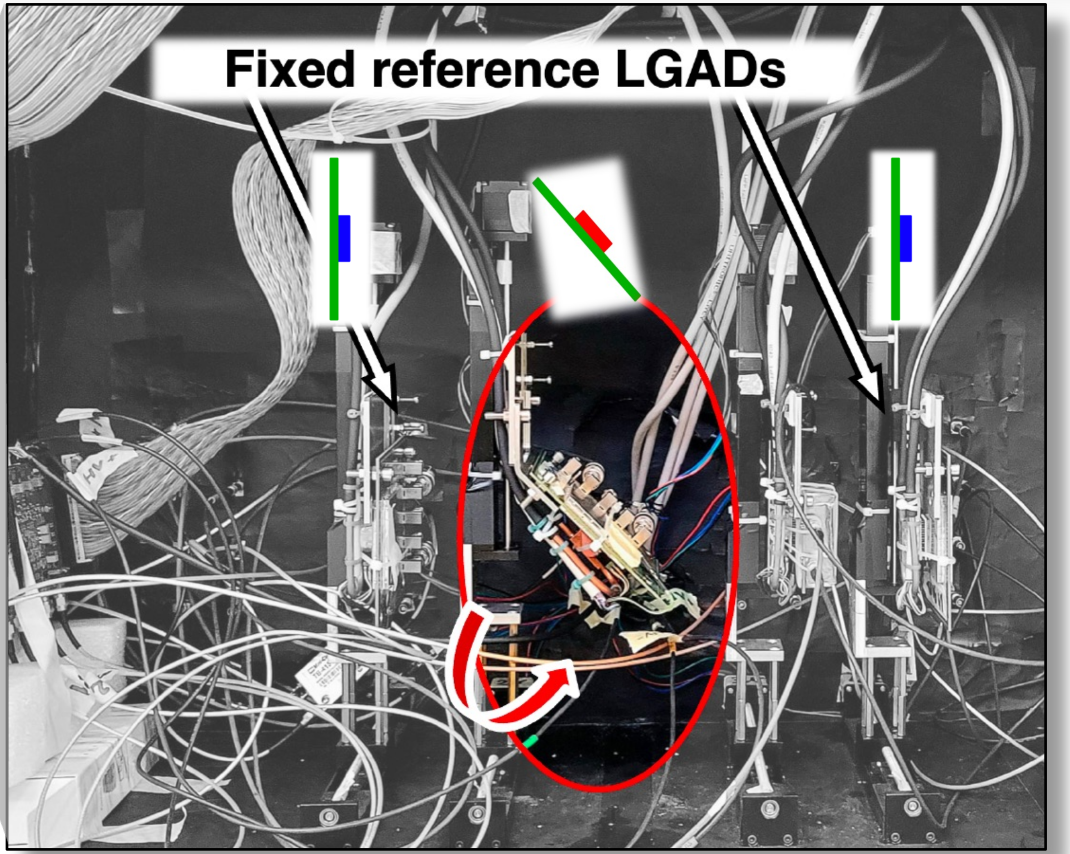
PERFORMANCES WITH INCLINED TRACKS

Changes in the response of sensors placed at the **edge of the barrel layer** or not fully traversed by **particles with very low momentum?**

Concurrent effects:

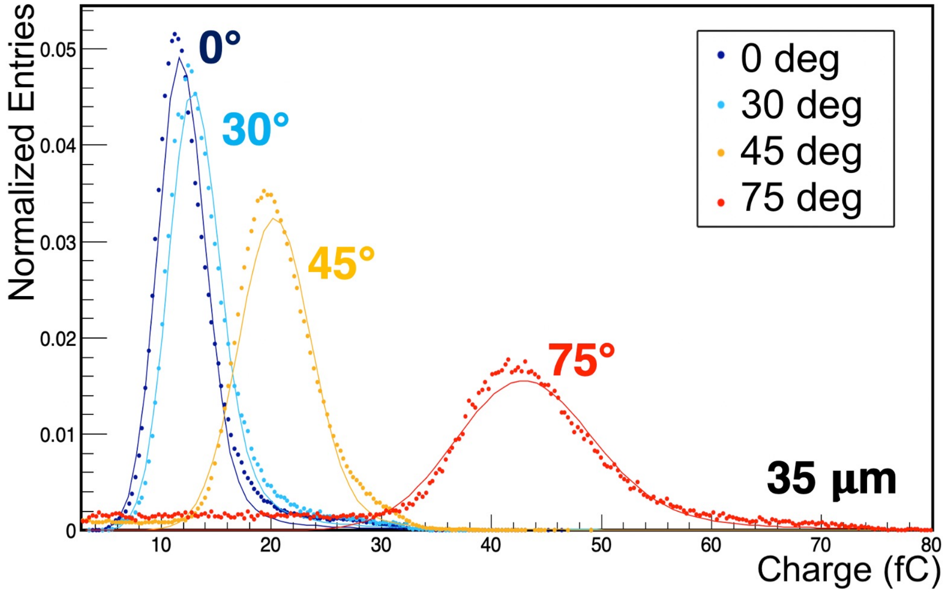
- Longer traversed path, so **more charge** produced
- Part of charge released at the **edges**



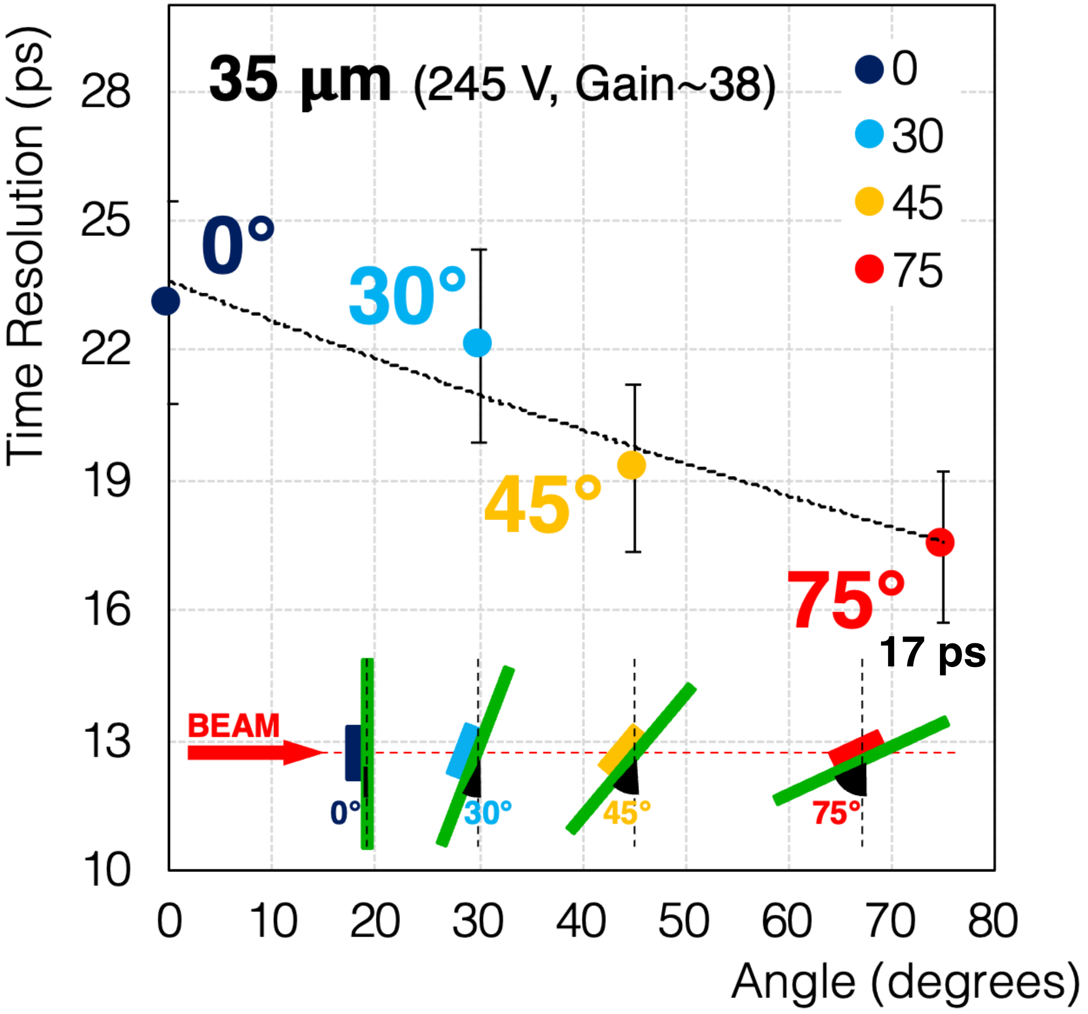


PERFORMANCES WITH INCLINED TRACKS

The **time resolution** slightly **improves** going to **higher** impinging **angles**



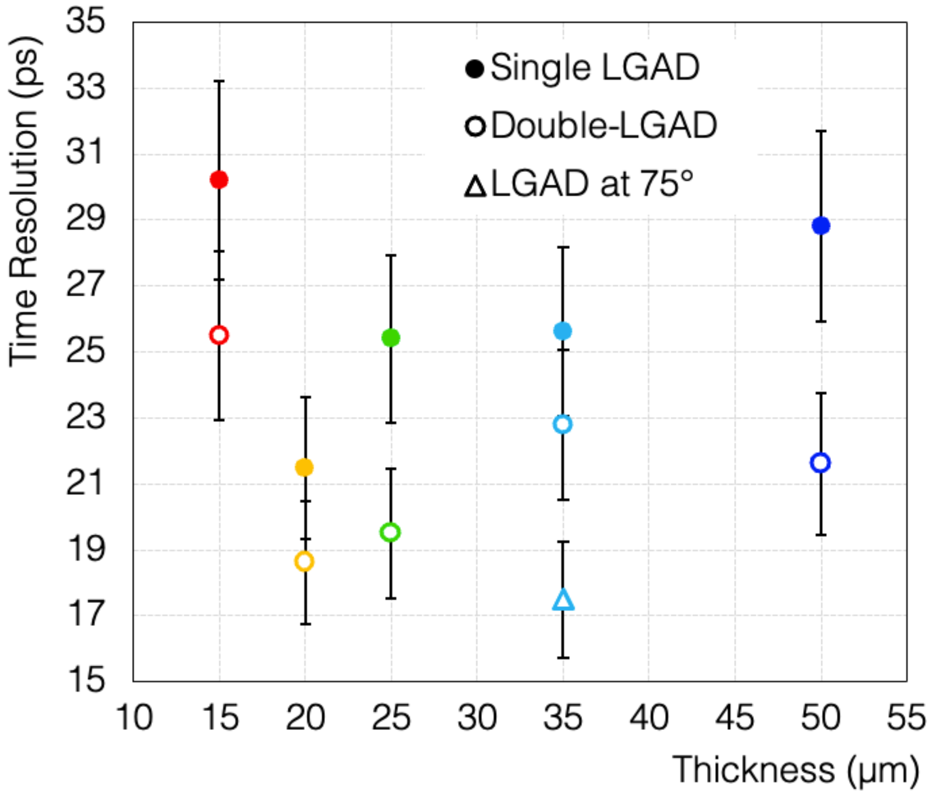
Longer path → **higher charge** release



HYBRID LGAD

Outstanding performances in different layouts and implementations

Time res. **in line with** the needs of **ALICE 3** TOF

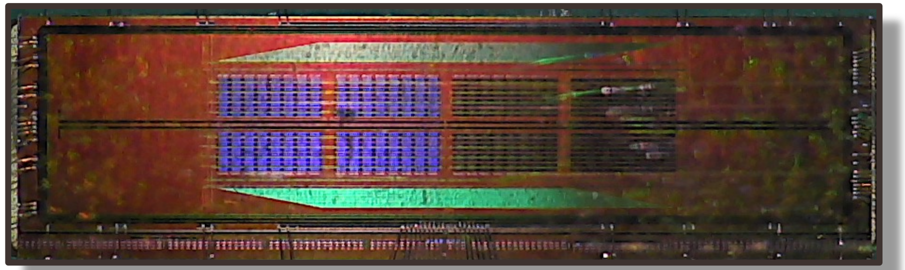


CMOS-LGAD

Combining the LGAD principle with a monolithic approach can provide:

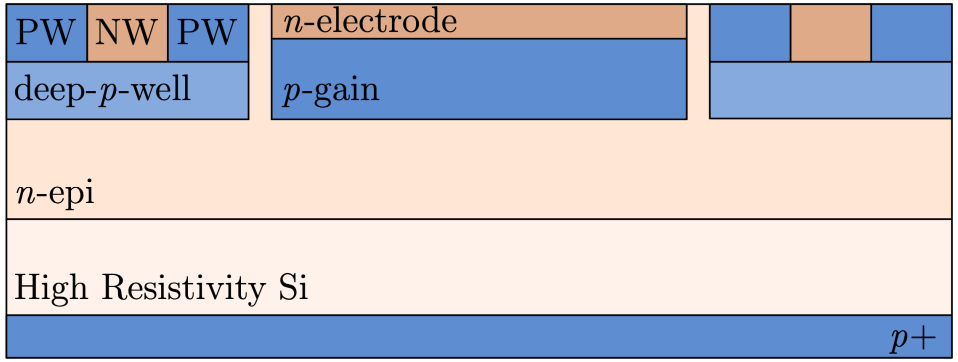
Lower material budget and costs

Simpler and cheaper assembly



→ **Baseline solution**

CMOS-LGAD CONCEPT

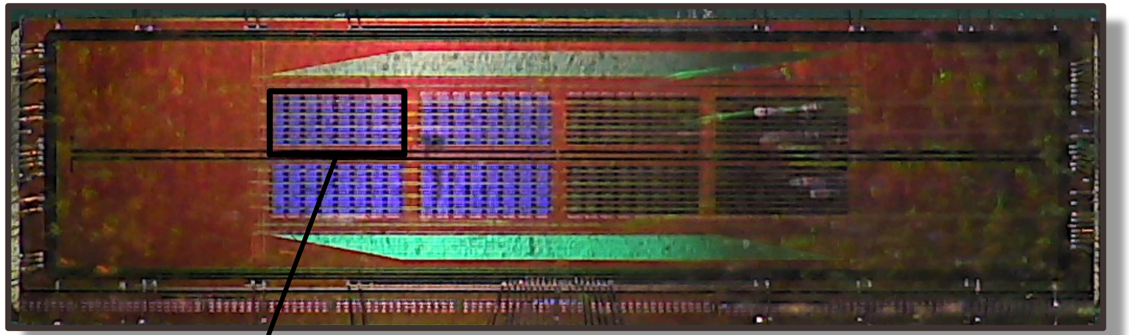


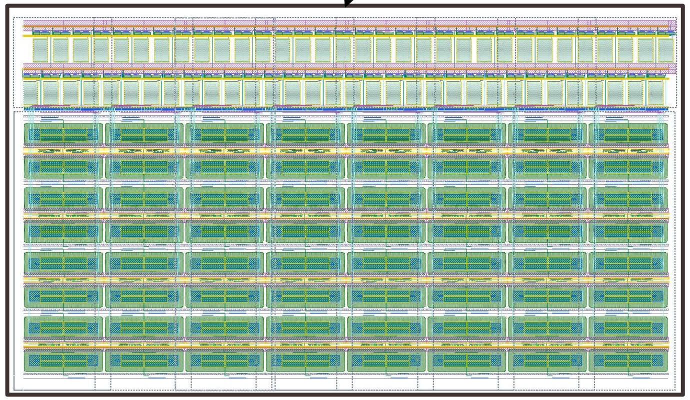
Produced by LFoundry standard 110 nm CMOS process, within the INFN ARCADIA project

Adding a p-gain below the collecting electrode

- $\mathbf{V_{top}}$ to control the gain
- $\mathbf{V_{back}}$ to deplete the sensor

MadPix: Monolithic CMOS Avalanche Detector PIXelated Prototype for ps timing applications

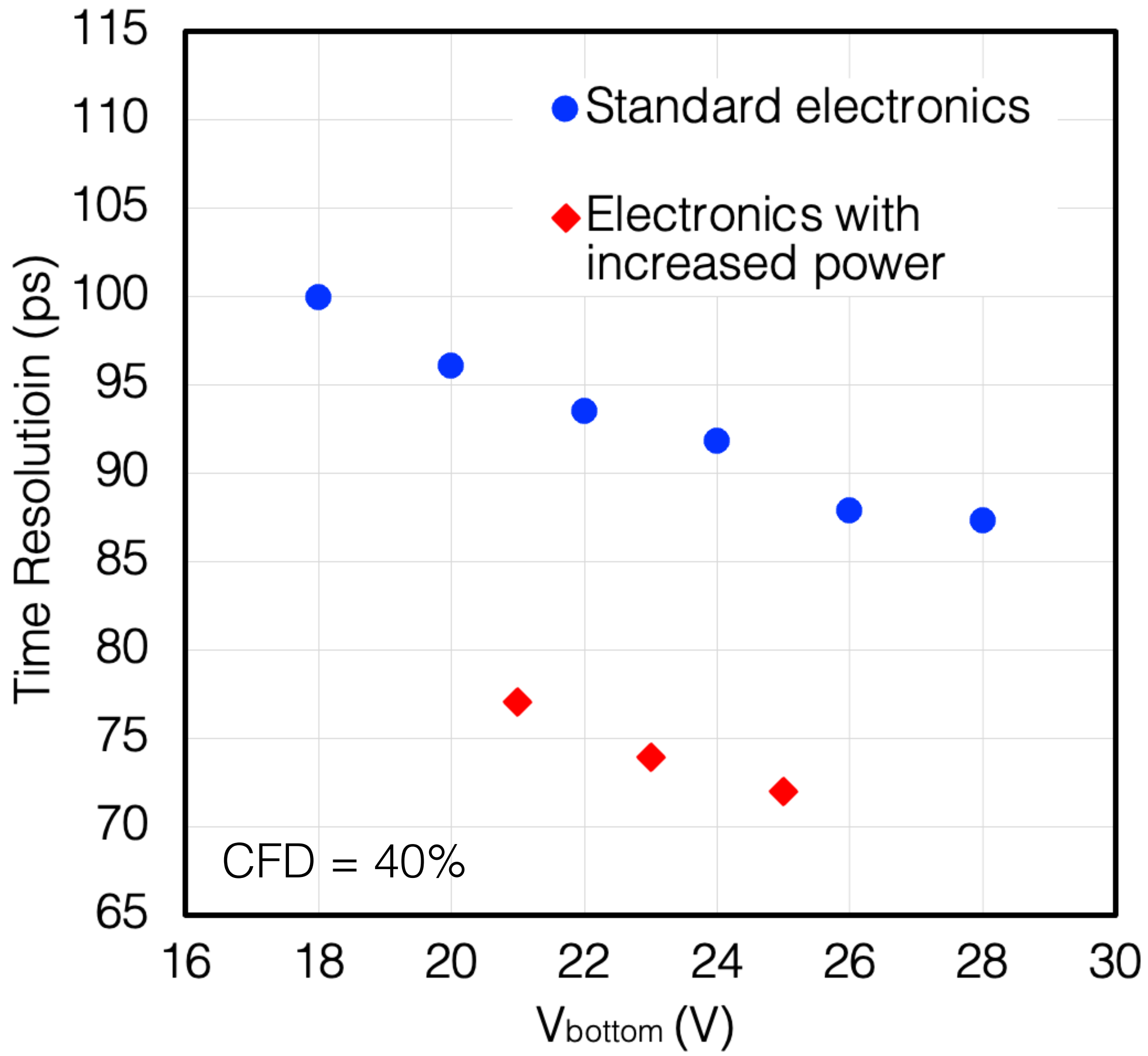




First small-scale (4×16 mm^2) prototype

- 8 matrices
- 64 pixels per matrix
- $A_{pixel}=250\times100\ \mu m^2$

TIME RESOLUTION OF CMOS-LGADS

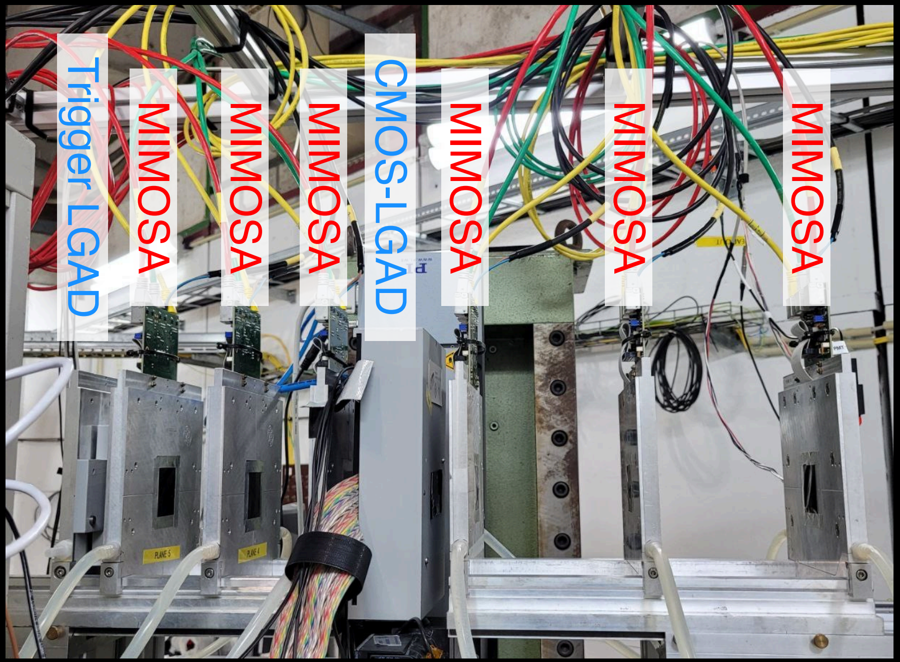


First 48 μm thick CMOS-LGADs with an internal gain of ≈ 7-11 were tested in a beam test

- Time resolution ≈ **88 ps** (Electronics in standard conditions + Sensor)

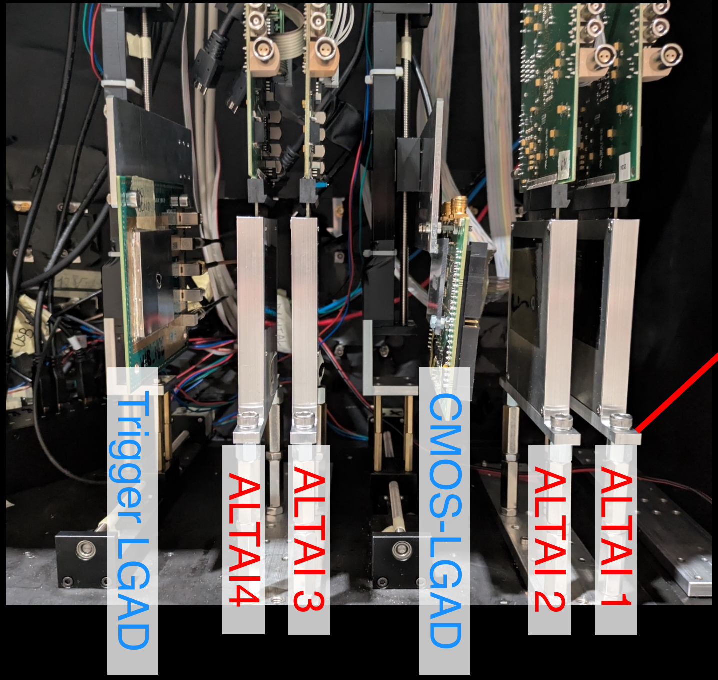
- Time resolution of the sensor with increased power on the electronics below **75 ps**

TEST BEAM WITH A TRACKING TELESCOPE



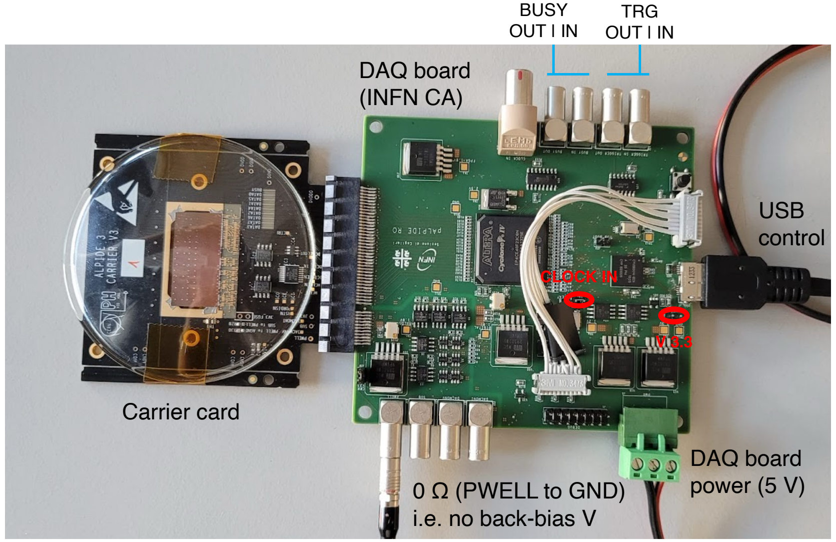
Setup at DESY

Setup at CERN-SPS



- ✦ **Efficiency** map
- ✦ **Time resolution** vs impinging position correlation

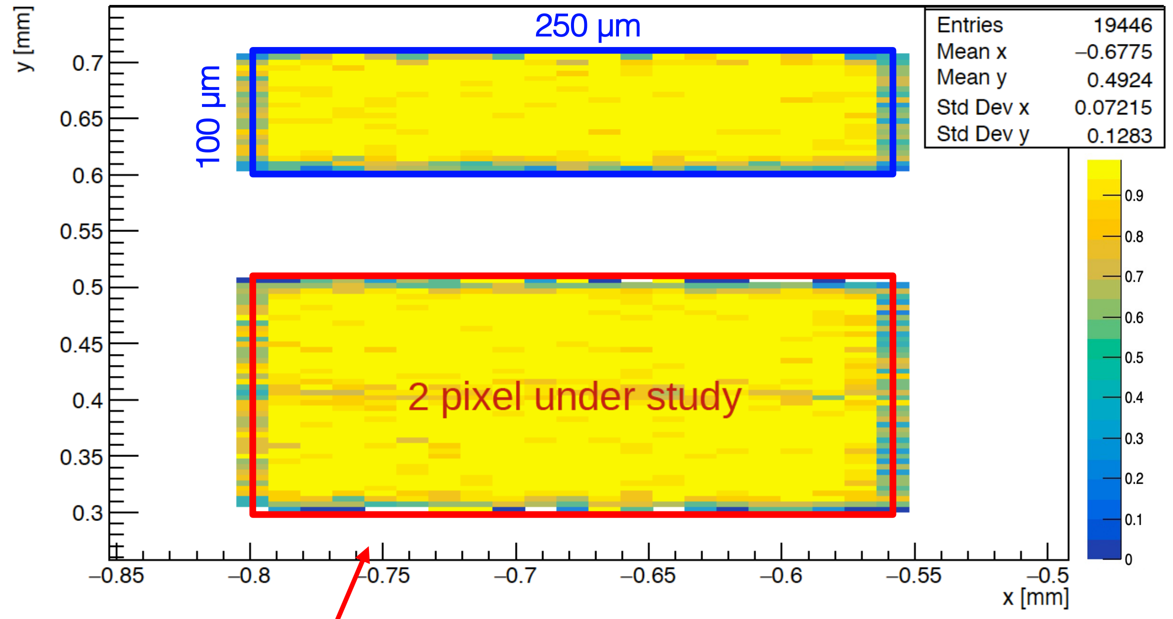
ALTAI sensor 15 mm x 30 mm (MAPS)

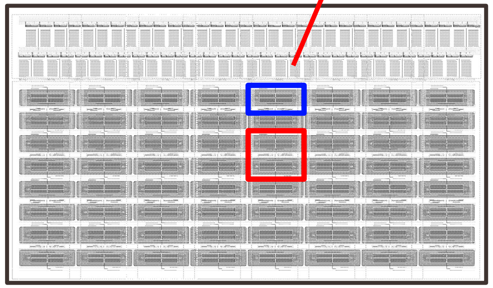


Derivation of the ALPIDE chip with a limited threshold range

~ **3-5 μm** of **tracking resolution** expected on the DUTs

CMOS-LGAD EFFICIENCY

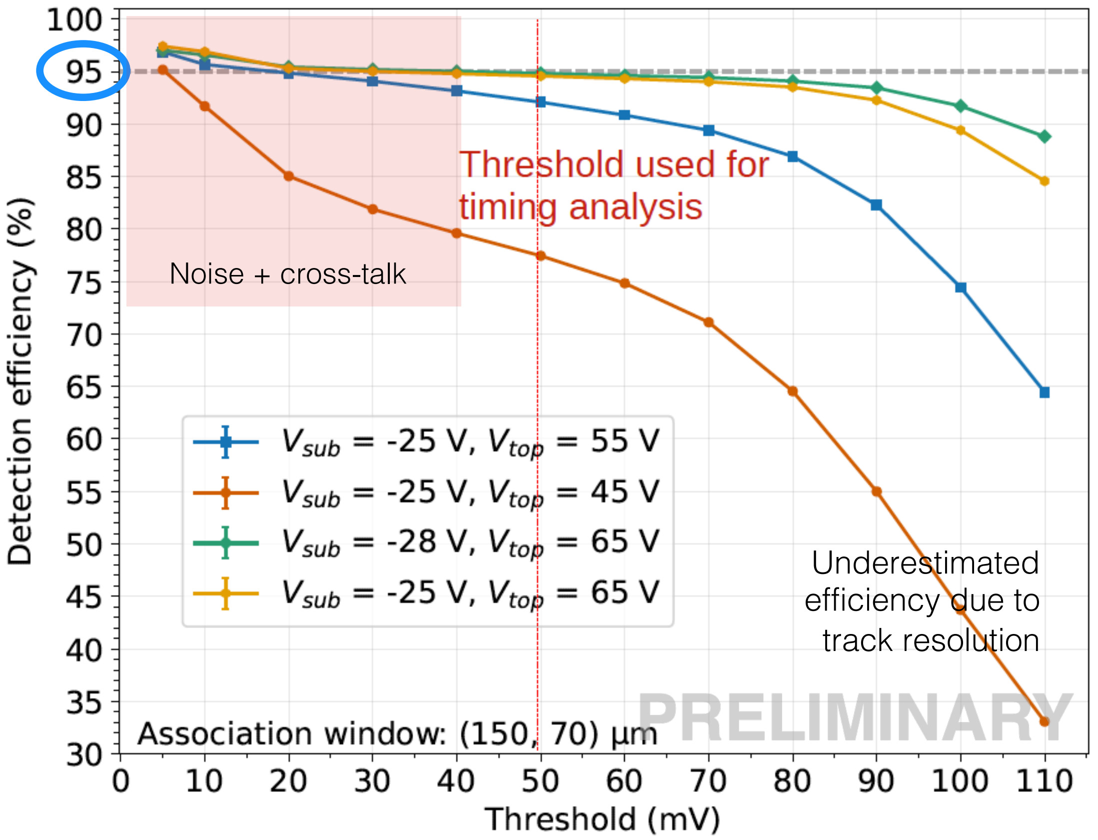


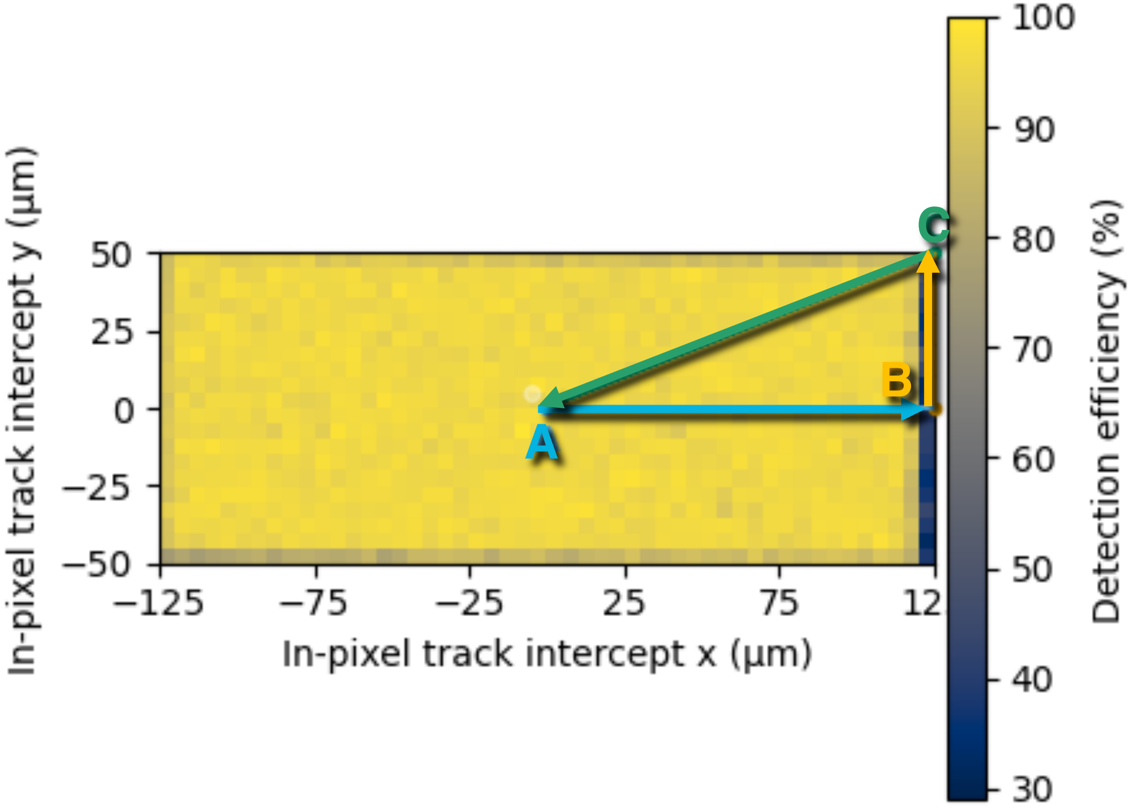


Efficiency increases with higher top V

(Electronics noise: 1mV, cross-talk <20ps)

Global efficiency VS threshold

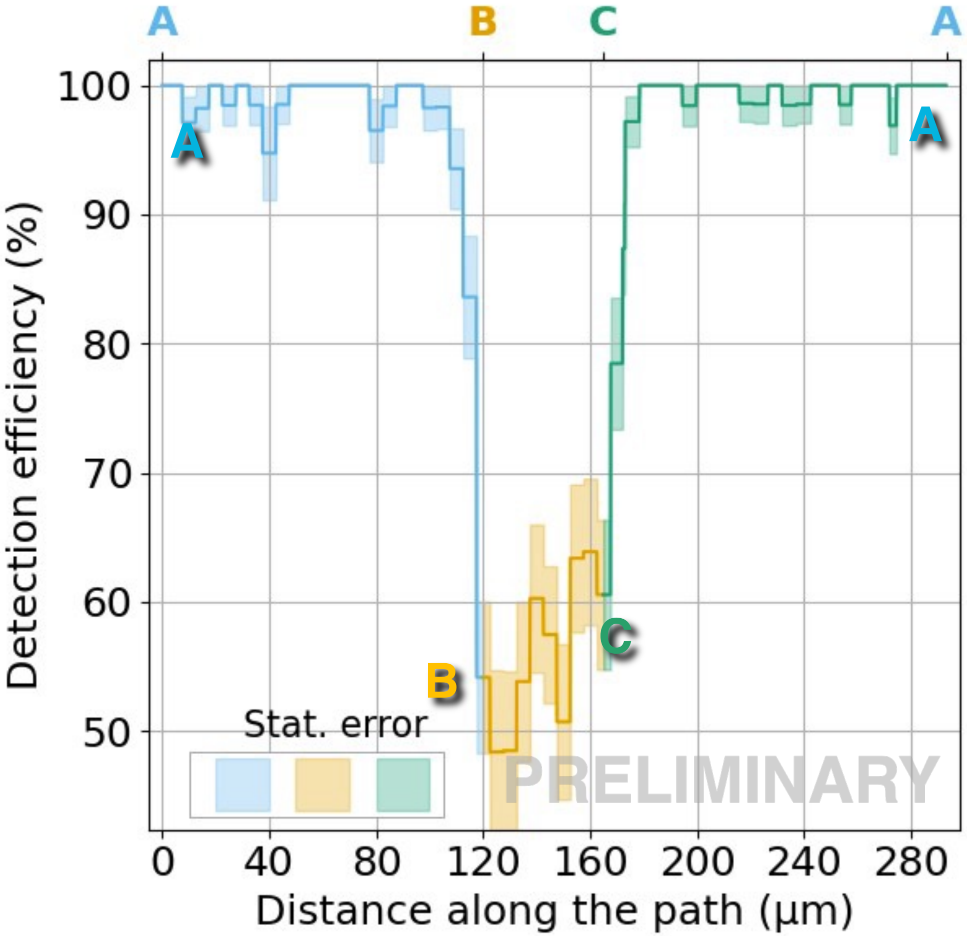




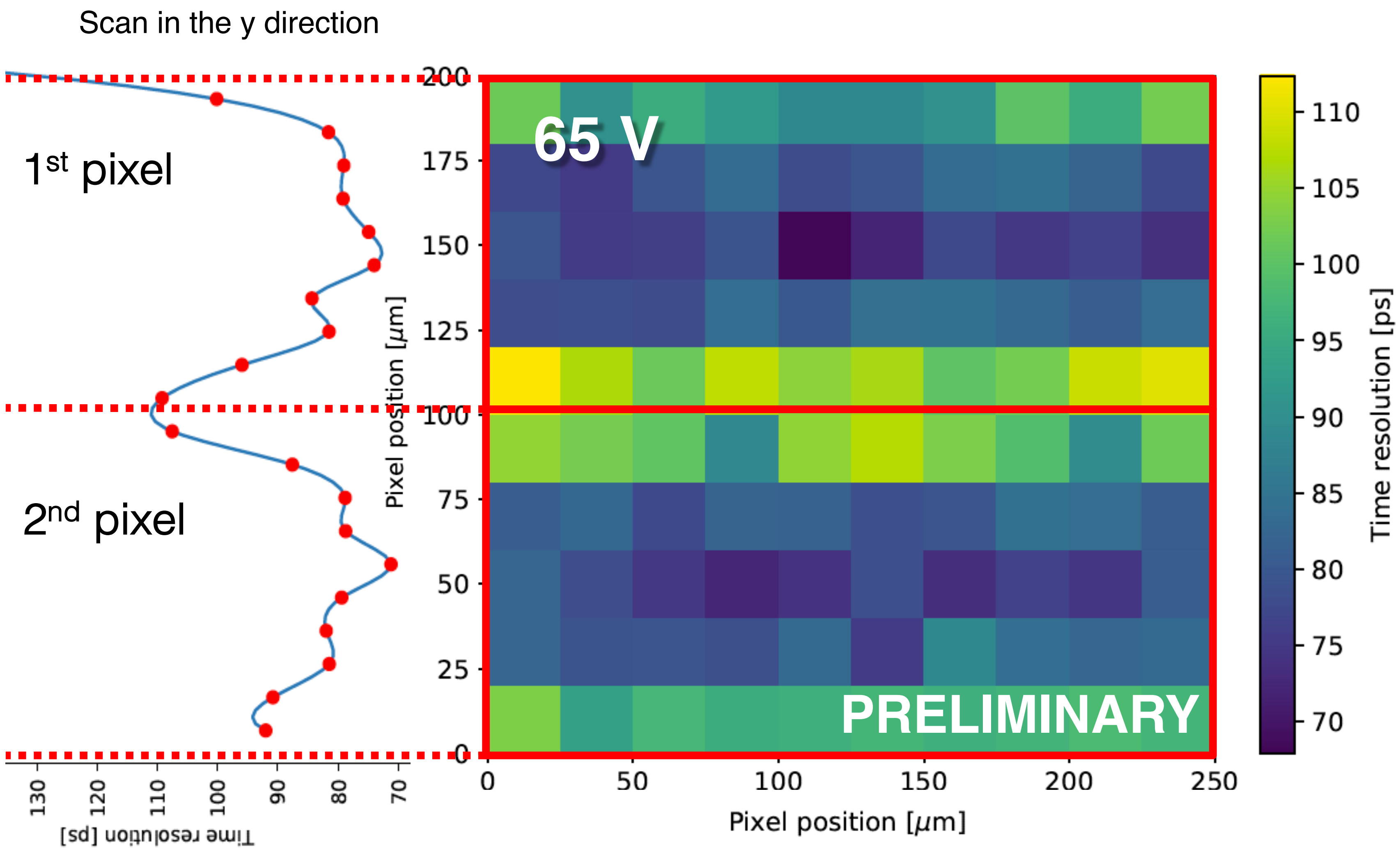
Efficiency drop beneath the pixel border

(Underestimated efficiency at the border due to track resolution)

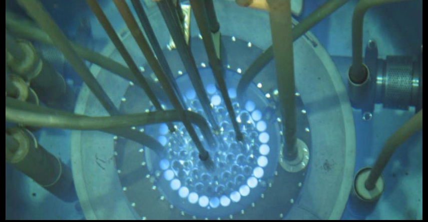
In-pixel efficiency



CMOS-LGAD TIME RESOLUTION



- The **best time resolution is at the pixel center** (more uniform E_{field})
- 75 ps achieved in the standard config.: **no non-Gaussian tails present**



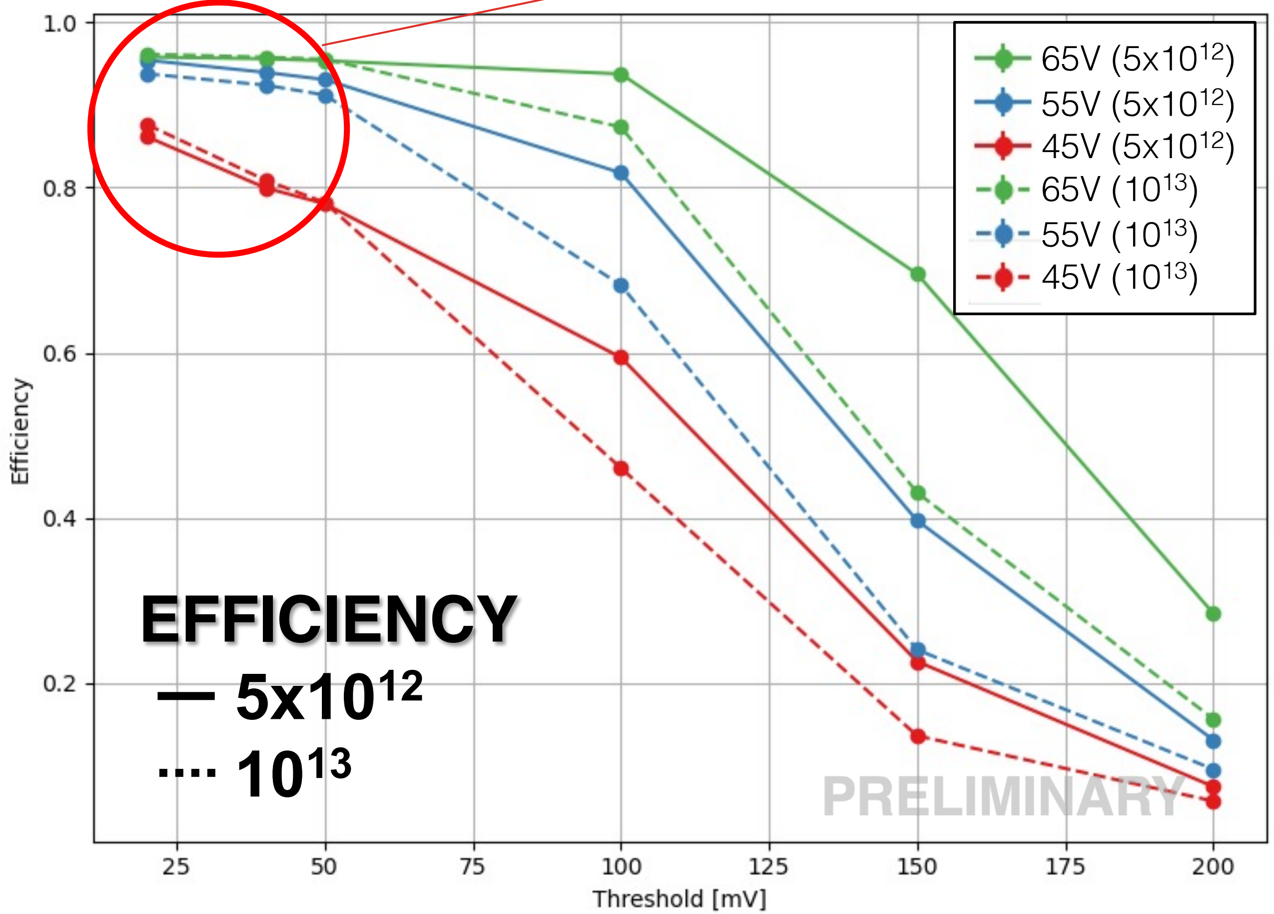
IRRADIATION CAMPAIGN

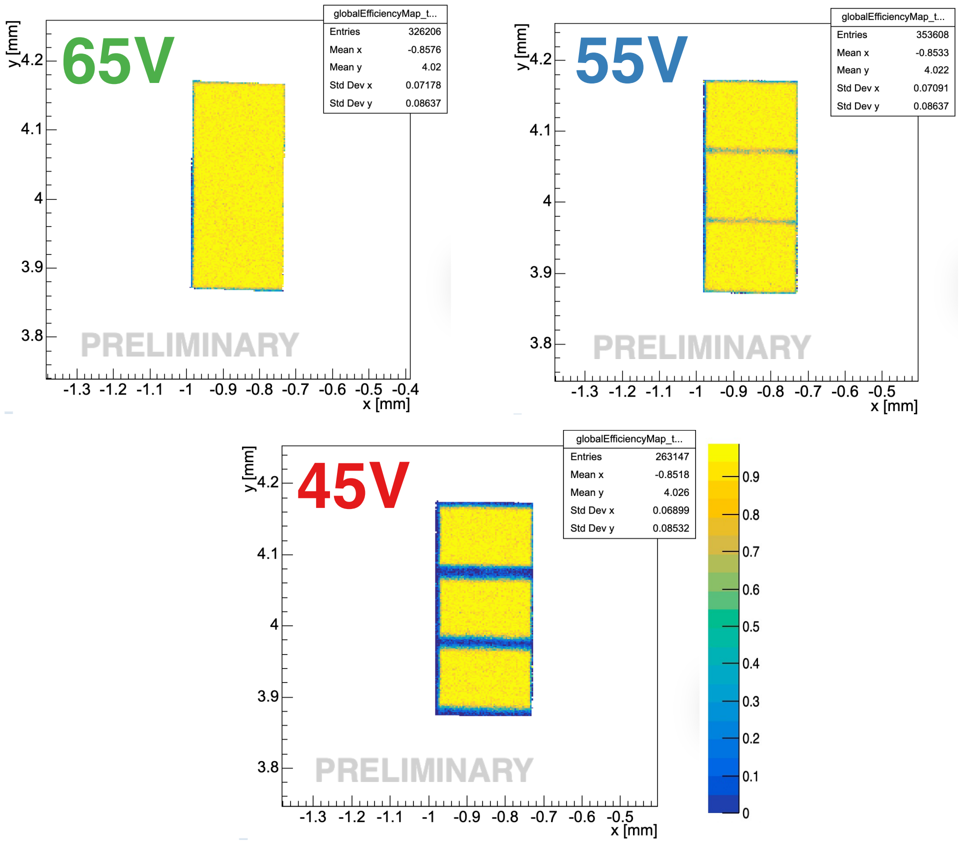
5 different fluences --- 5×10^{12}, 10^{13}, 5×10^{13}, 10^{14}, 10^{15} MeV n_{eq}/cm^2

ALICE

*REQUIREMENT FOR ALICE3 TOF

Compatible efficiency and **no sign of degradation with irradiation**





CONCLUSIONS

✦ Hybrid LGADs

The R&D campaign on resulted in sensors with a time resolution in line with the needs of ALICE 3 TOF

20 ps with different layouts and implementations tested

📌 **Solid backup solution**

✦ CMOS-LGADs

Time resolution in line with the simulations, and efficiency >95%

75 ps → state-of-the-art for CMOS sensors

From simulation thinner sensors with a higher gain are expected to reach better results in line with the ALICE 3 TOF

Many ongoing studies to fully unlock the potential of these technologies

ACKNOWLEDGEMENTS

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

The research leading to these results has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no.101057511.