

HSTD14

14th international "Hiroshima"
Symposium on the Development and
Application of Semiconductor
Tracking Detectors

November 19th, 2025
Taipei, Taiwan

Towards a 20 ps timing detector with hybrid and CMOS monolithic LGADs for the future ALICE 3 experiment at LHC

Sofia Strazzi

on behalf of the ALICE Collaboration

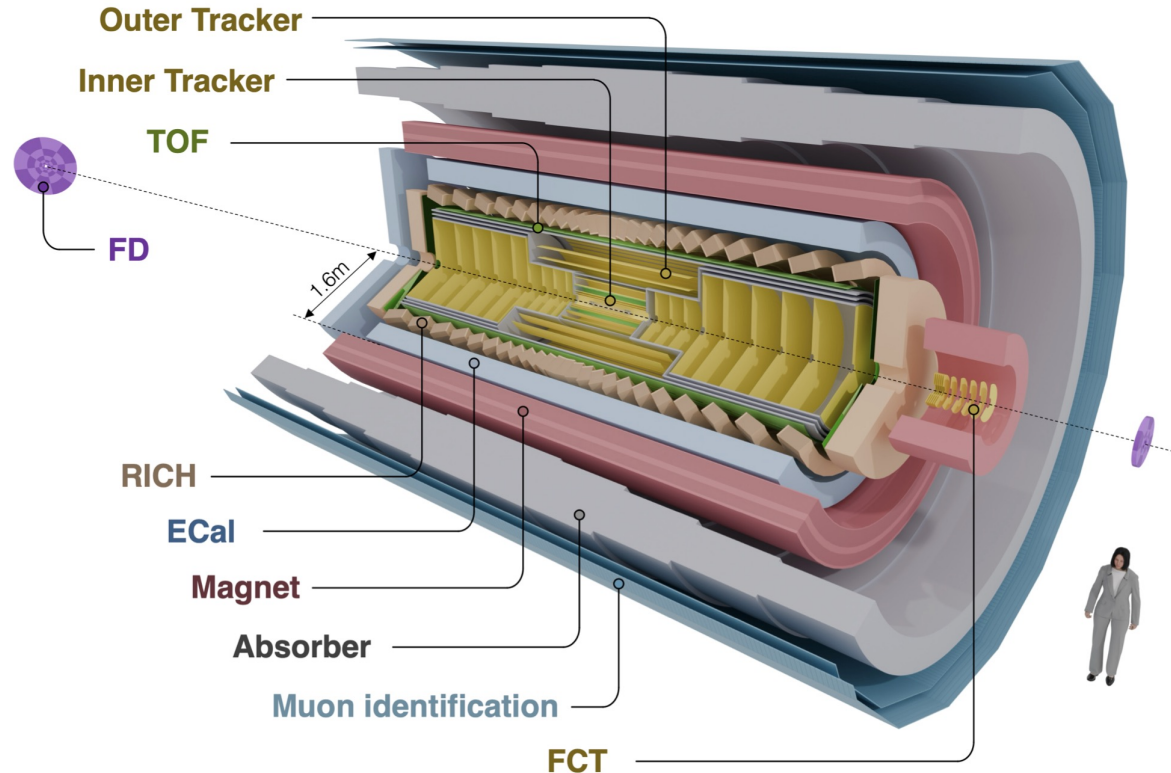
University and INFN Bologna, Italy



ALICE



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**

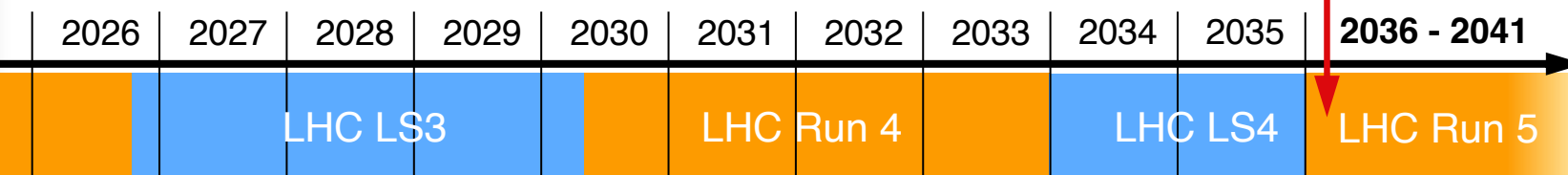
Letter of Intent: <https://arxiv.org/abs/2211.02491>
Scoping Document: <https://cds.cern.ch/record/2925455>

➔ **New exciting opportunities for the study of:**

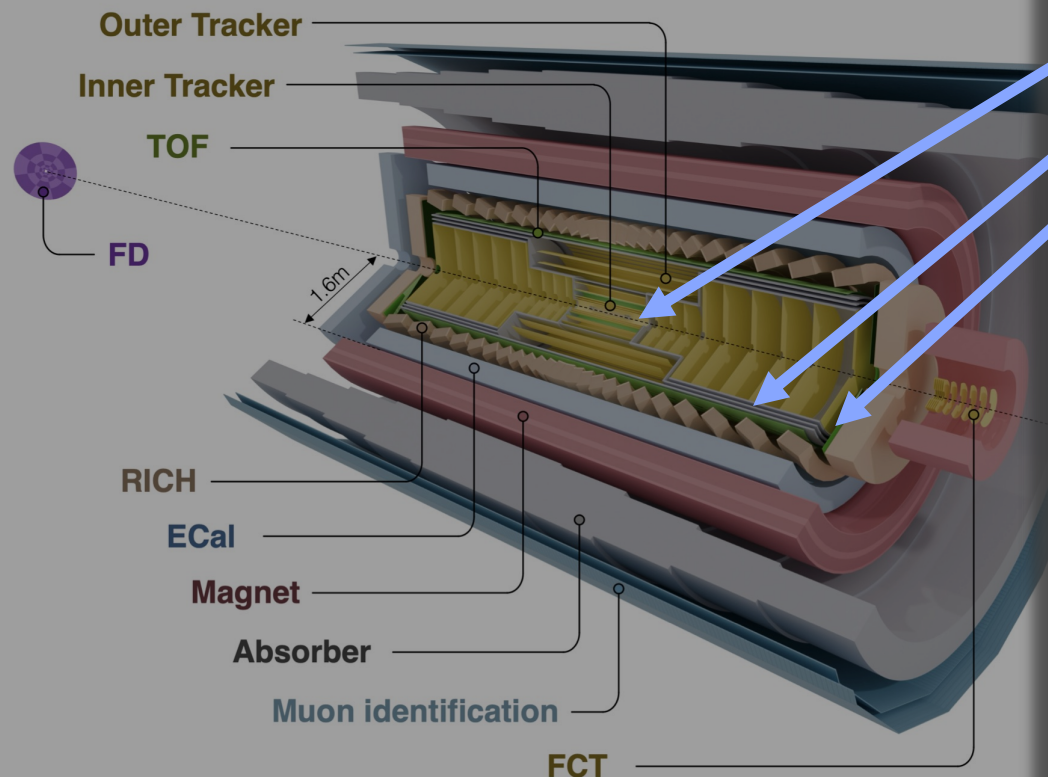
◆ **Multi-charm hadrons at low momenta:**
Crucial test for models for baryon production models

◆ **EM radiation** produced in the first evolution phases of Quark Gluon Plasma (QGP)

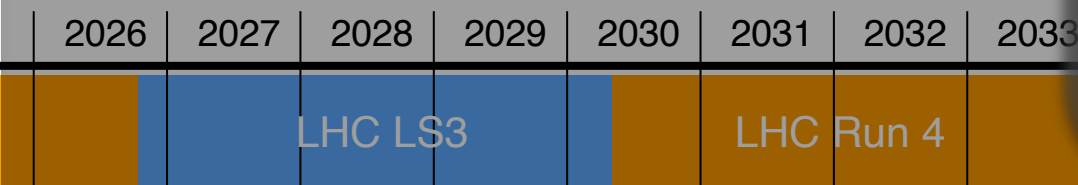
ALICE 3 a next generation heavy-ion experiment



The ALICE Collaboration has submitted an experiment, ALICE 3, to be installed at the LHC.



ALICE 3 a next generation heavy-ion experiment



Time-Of-Flight System (TOF)

- inner TOF $R \approx 19 \text{ cm}$
 - outer TOF $R \approx 85 \text{ cm}$
 - forward TOF $z \approx 375 \text{ cm}$
- Separation $\propto \frac{L}{\sigma_{\text{TOF}}}$

Requirements:

- Moderate rad. hardness
 - inner TOF: NIEL $\sim 6.1 \cdot 10^{12} \text{ 1-MeV } n_{\text{eq}} / \text{cm}^2$
 - outer TOF: NIEL $\sim 9 \cdot 10^{11} \text{ 1-MeV } n_{\text{eq}} / \text{cm}^2$
 - forward TOF: NIEL $\sim 8.5 \cdot 10^{12} \text{ 1-MeV } n_{\text{eq}} / \text{cm}^2$
- Low material budget $\sim 1\text{-}3\% X_0$

Time resolution

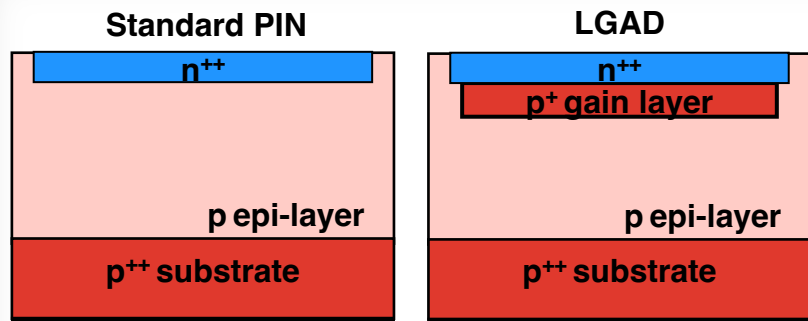
$$\begin{aligned} e/\pi &\lesssim 500 \text{ MeV}/c \\ K/\pi &\lesssim 2.5 \text{ GeV}/c \\ p/K &\lesssim 4 \text{ GeV}/c \end{aligned}$$

20ps

Extensive R&D on the most advanced silicon technologies:

LGADs, SiPMs, CMOS-LGADs

MOTIVATIONS - LOW GAIN AVALANCHE DETECTOR (LGAD)



Electric field

Gain region: very high electric field

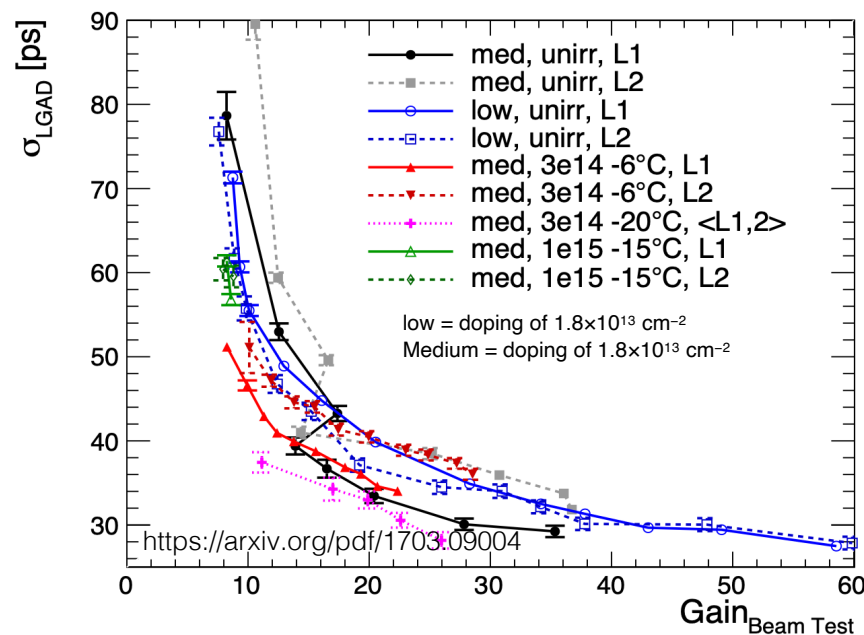
Drift region: low and uniform electric field

Internal low-gain
multiplication
mechanism

Optimized to obtain:

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

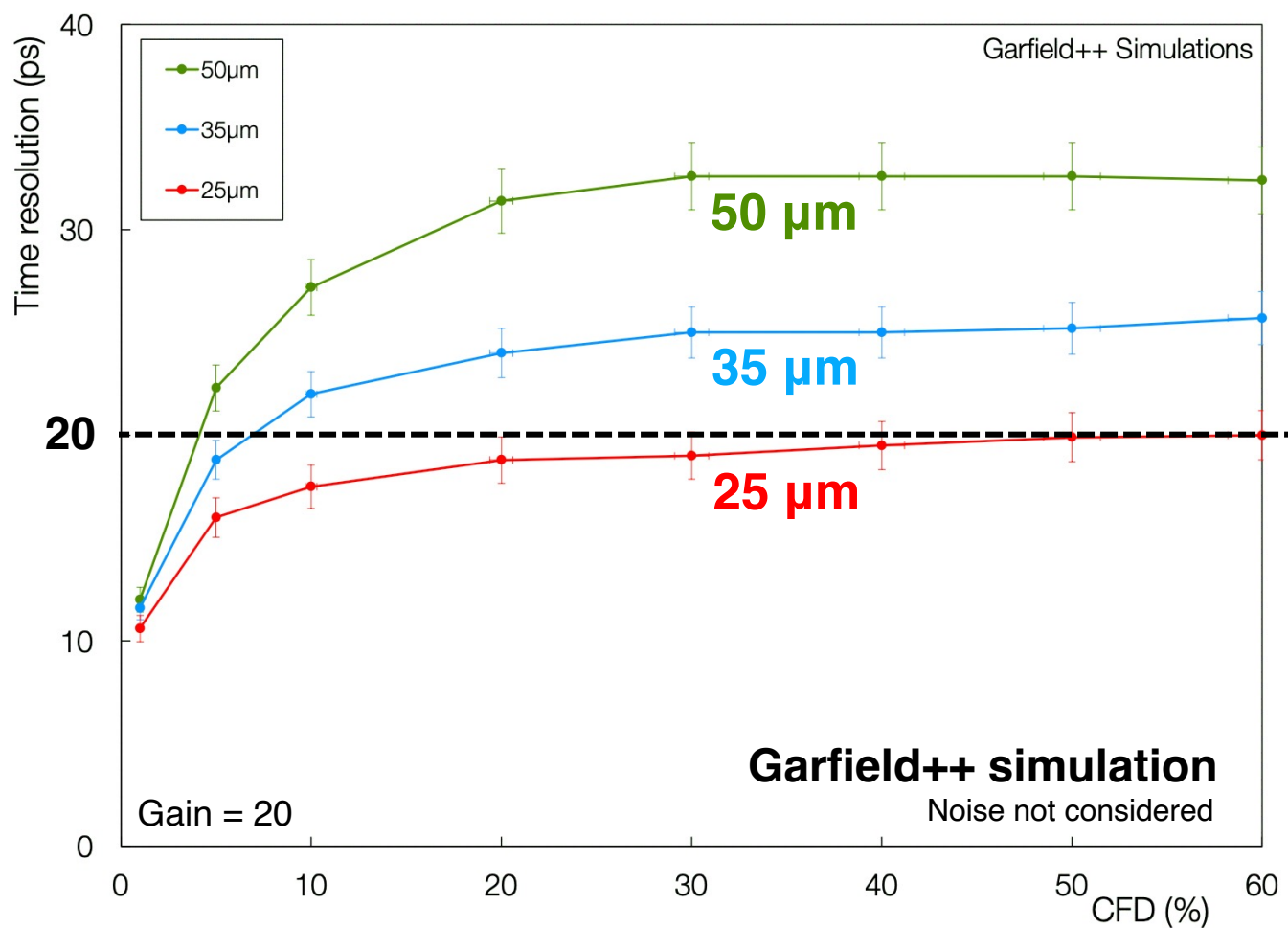
➔ **Excellent
timing
performance**



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



→ Potential of a thinner layout of LGAD

THE DETECTOR (LGAD)

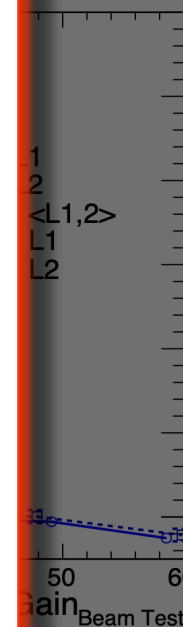
ALICE 3 TOF detector needs an even better time resolution

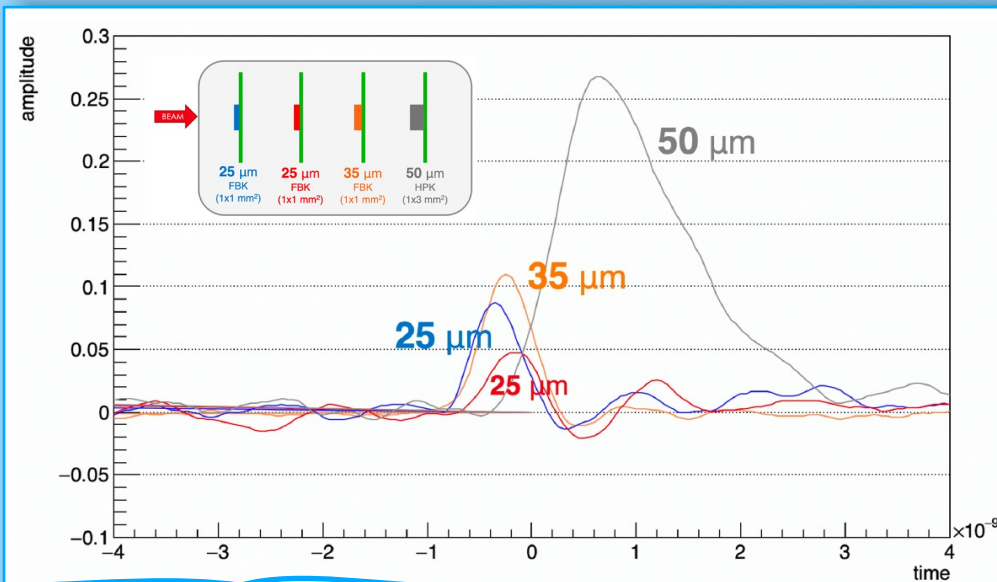
→ **20 ps**

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





DIGITAL OSCILLOSCOPE READOUT

- Signal waveforms acquired
- Digitalization at the analysis level



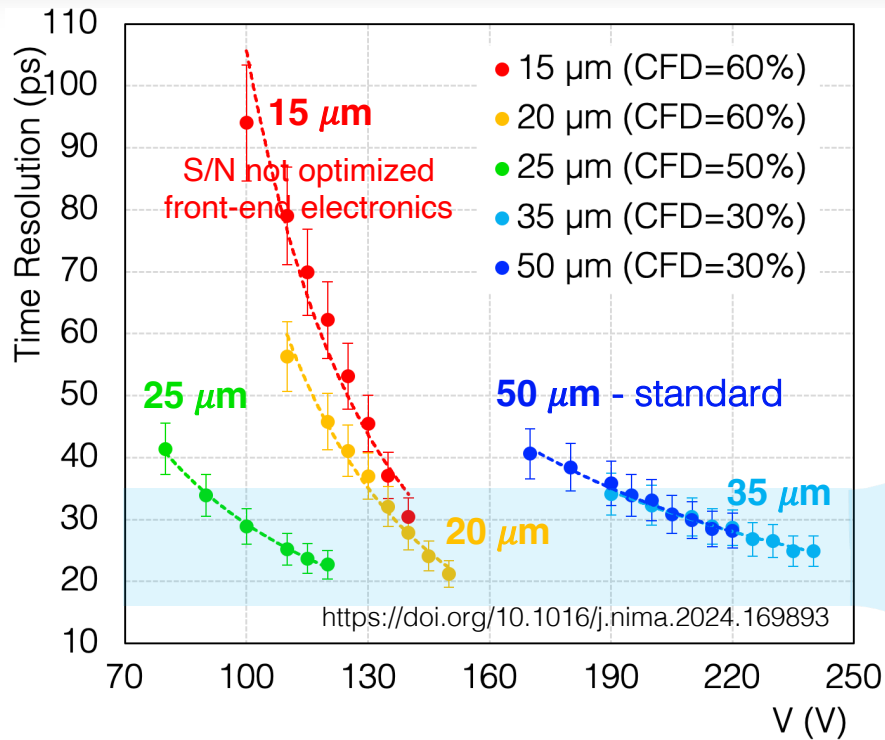
CERN PS



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 $p \sim 10\text{-}12 \text{ GeV}/c$

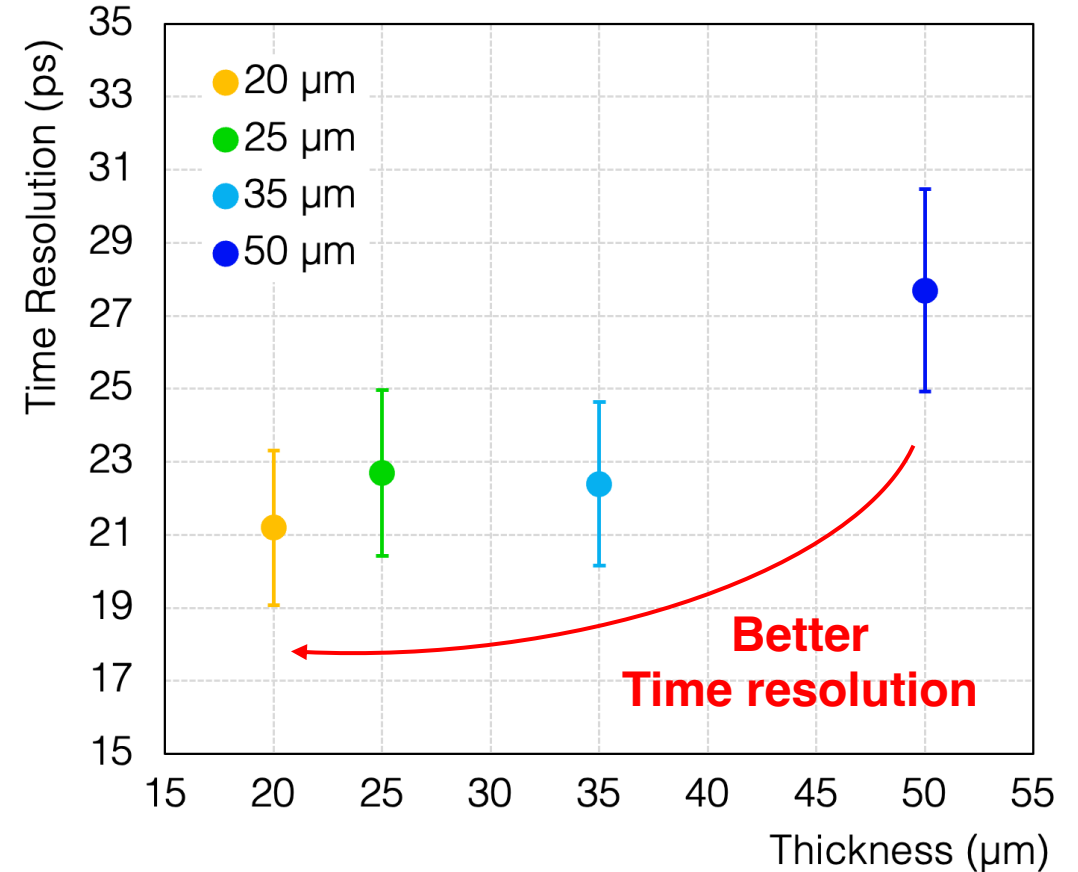
TEST OF THE FIRST VERY THIN LGAD PROTOTYPES



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

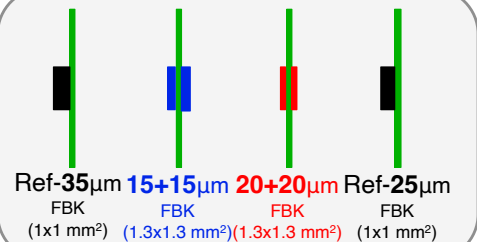
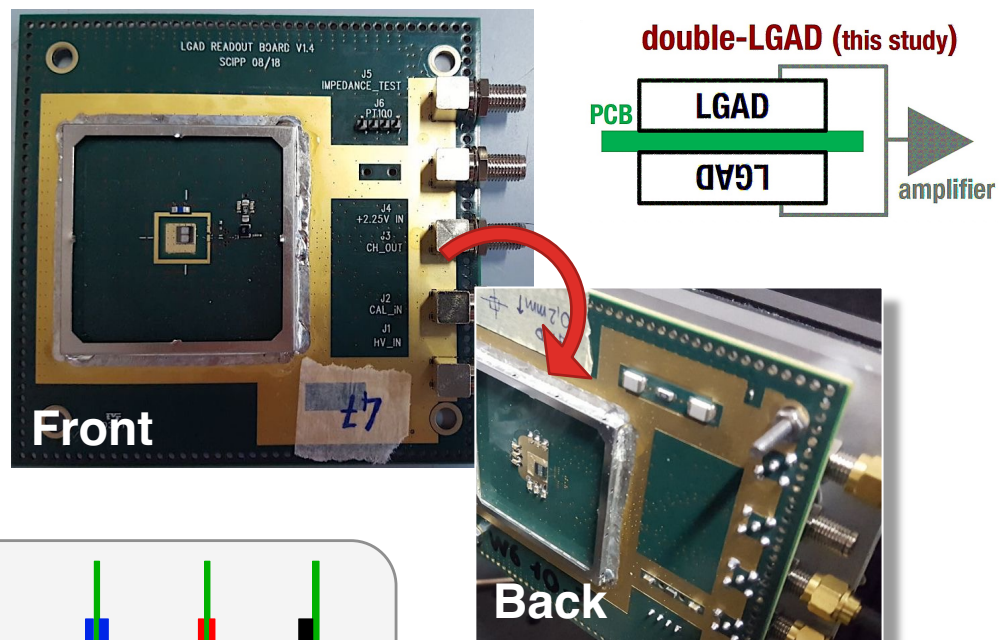
<https://link.springer.com/article/10.1140/epjp/s13360-022-03619-1>

- ◆ 50 μm in line with the expectations
 - Validation of setup and analysis procedure
- ◆ Improved time res. with thinner LGADs
 - All in agreement with the MC simulation
 - Slightly worse for the 25 μm due to worse S/N (very high doping due to a problem in the wafer production)



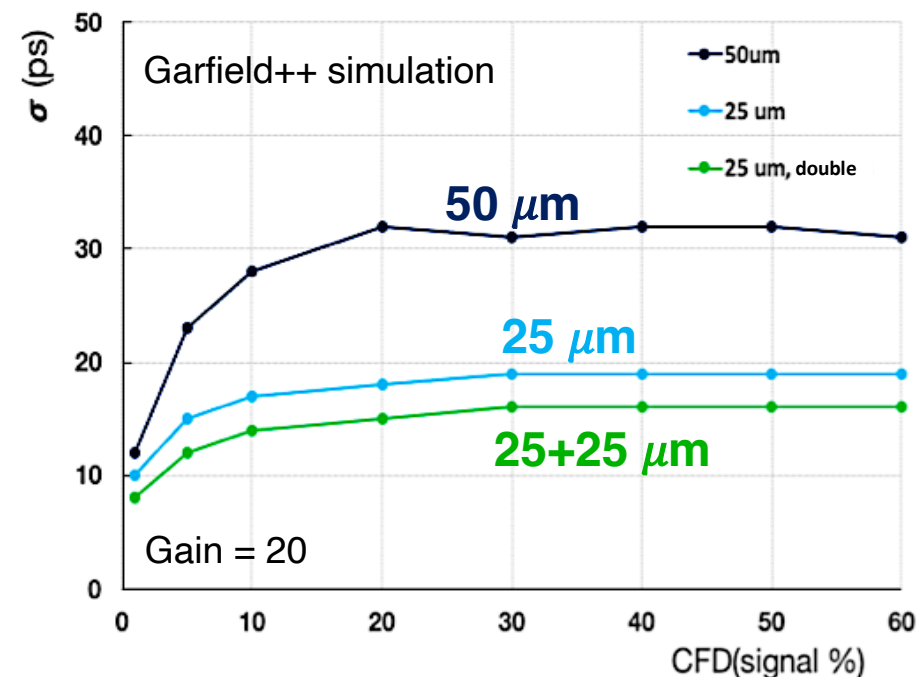
NEW CONCEPT: DOUBLE-LGAD

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

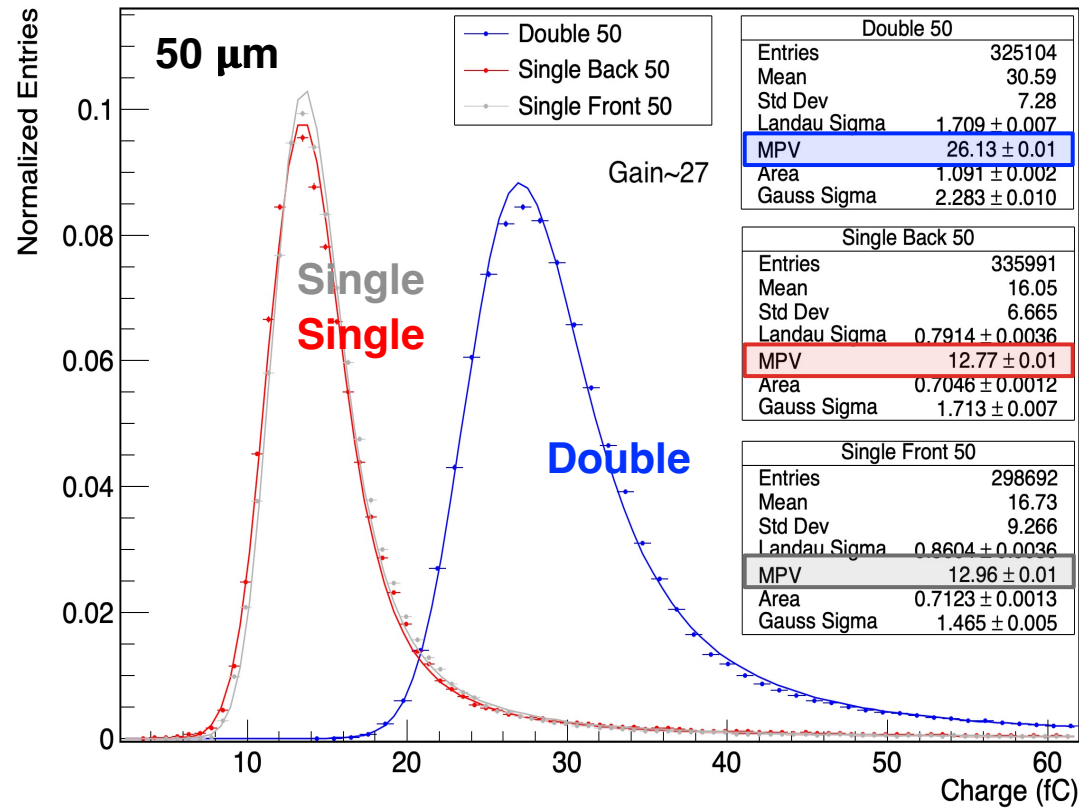


- **Higher signal**
 - Less power-consuming **front-end electronics**
 - Electronics similar to the one used for the standard LGADs (50 μ m)

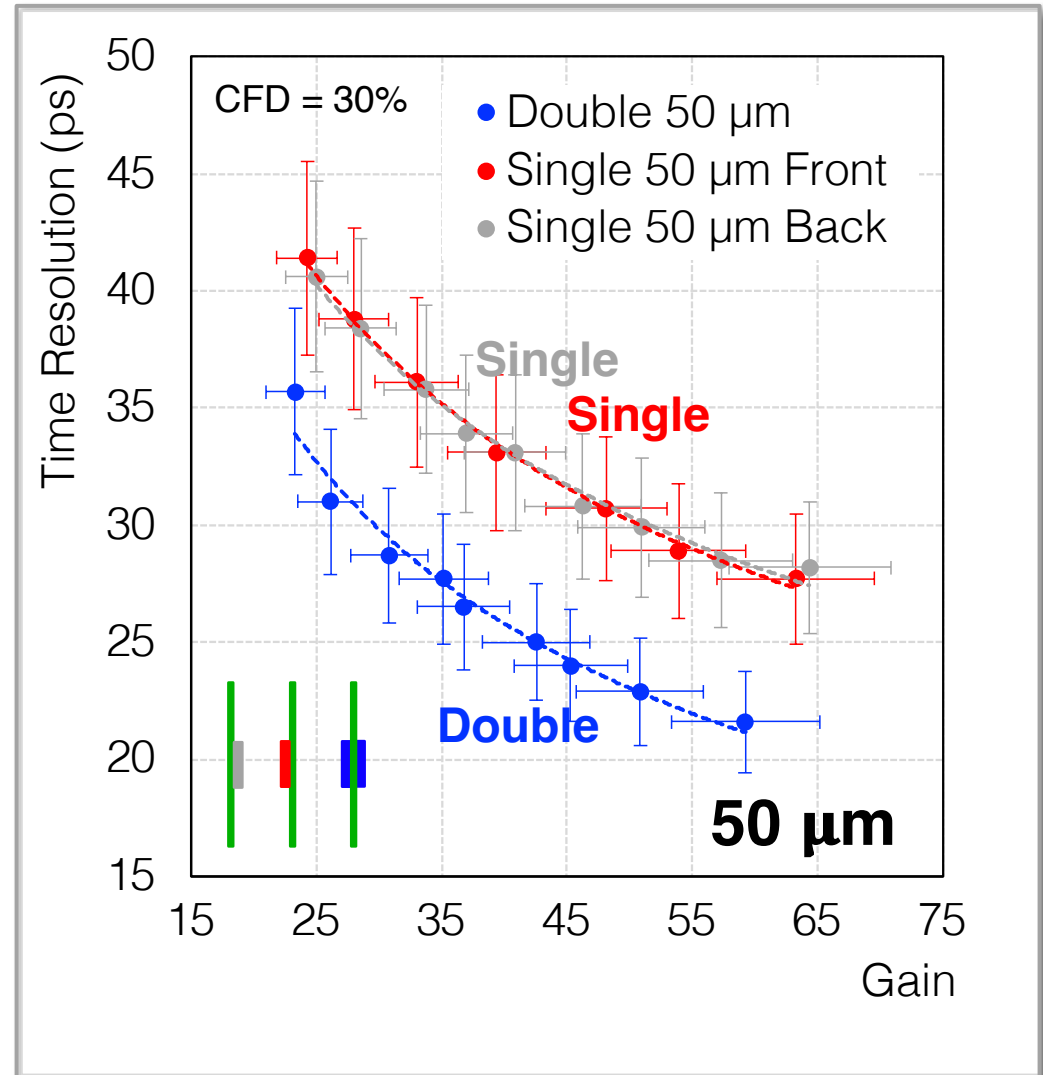
- **Better time resolution**



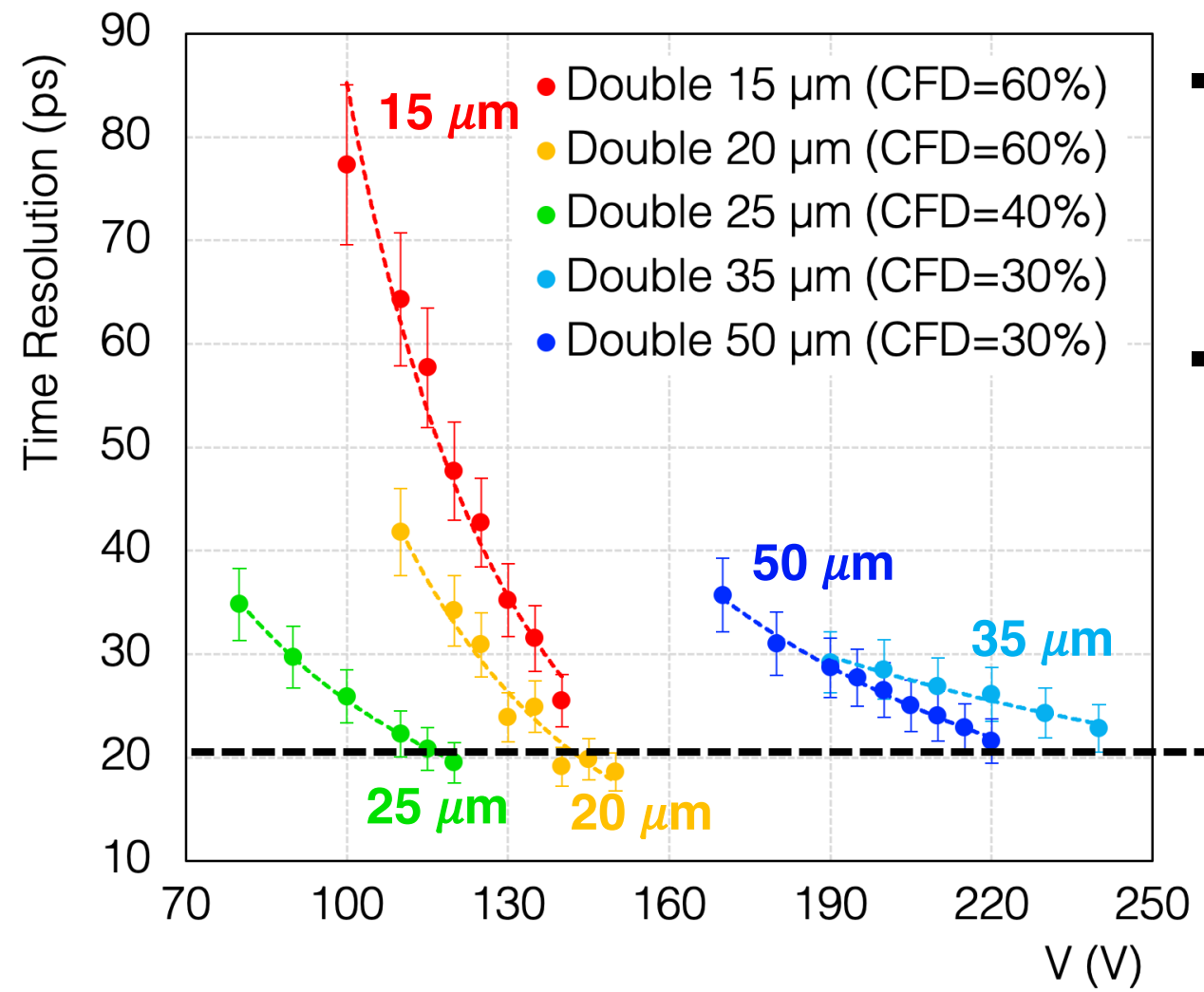
Landau-Gaussian convolution fit



- **Double charge**
→ **Big advantage for the electronics**
- **Better time resolution for the double-LGAD**



Timing performance: Single VS Double-LGAD



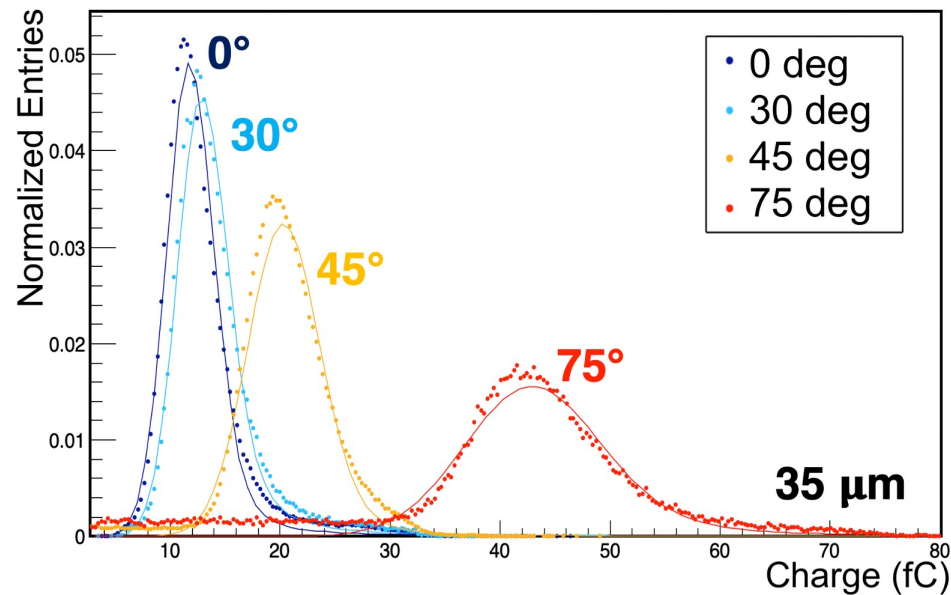
- **Double-50 μm** (already existing technology) **compatible with 20 ps**
- Just a **proof of concept**:
 - Thinner prototypes not perfectly identical within the couples
 - **Improvement expected**

Below 20 ps

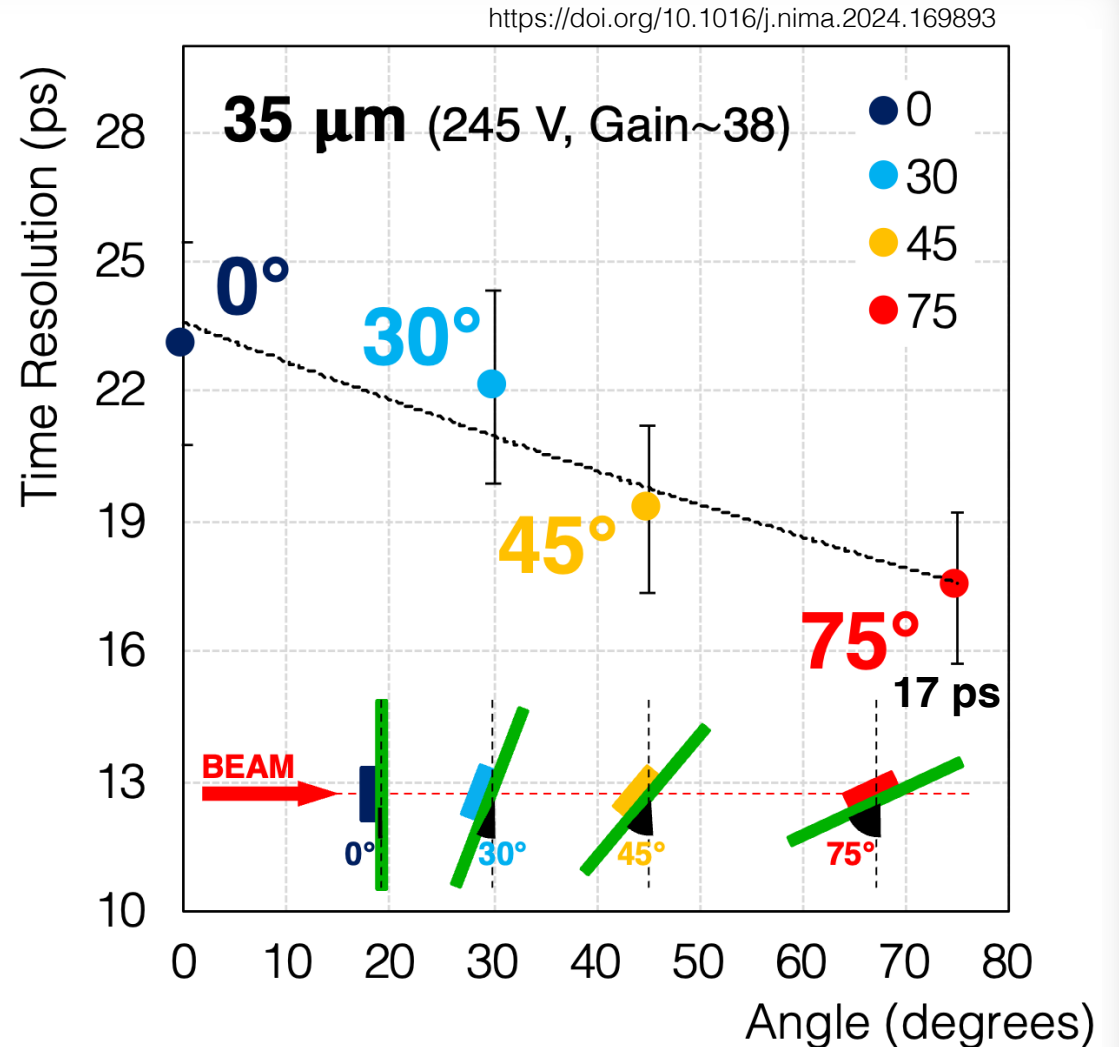


The **time resolution** slightly **improves** going to **higher** impinging **angles**

Longer path $\rightarrow$ **higher charge** release



<https://doi.org/10.1016/j.nima.2024.169893>

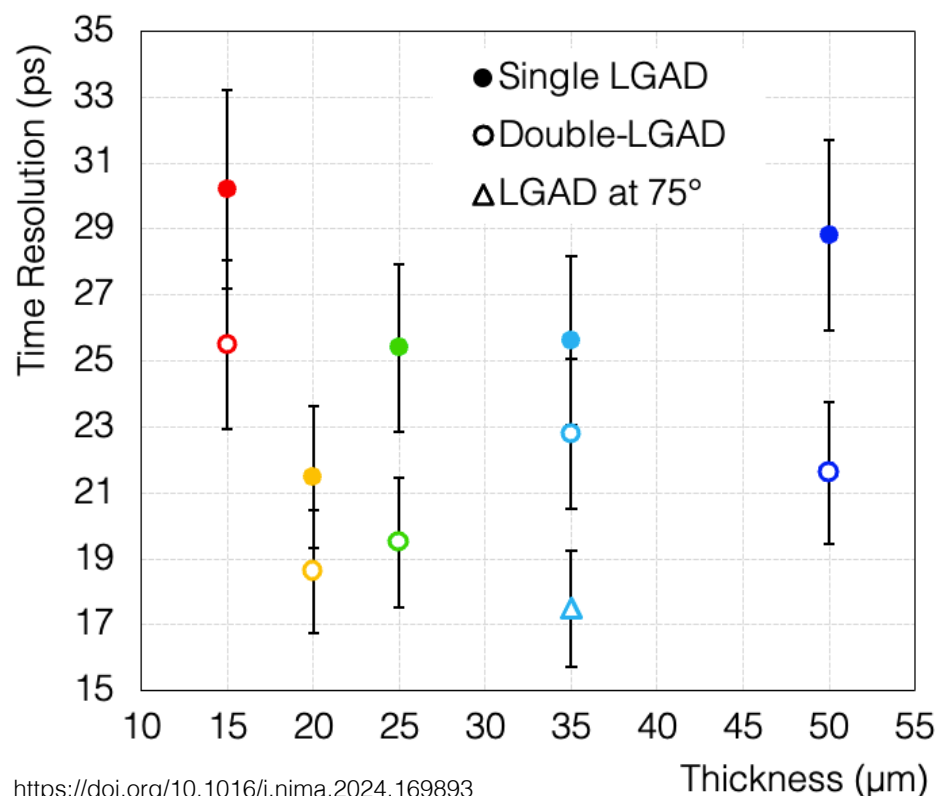


<https://doi.org/10.1016/j.nima.2024.169893>

HYBRID LGAD

Outstanding performances in different layouts and implementations

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



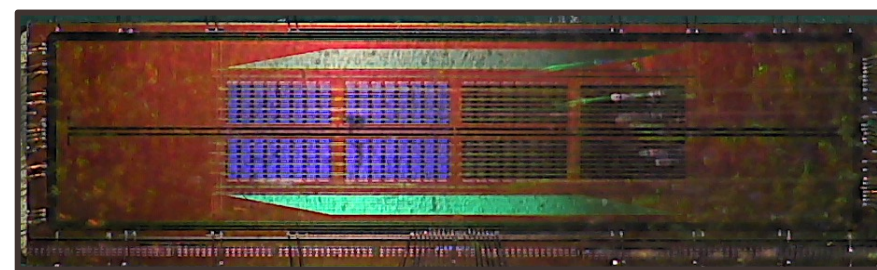
<https://doi.org/10.1016/j.nima.2024.169893>
<https://doi.org/10.1140/epjp/s13360-023-04621-x>
<https://doi.org/10.1016/j.nima.2024.169893>

CMOS-LGAD

Combining the LGAD principle with a monolithic approach can provide:

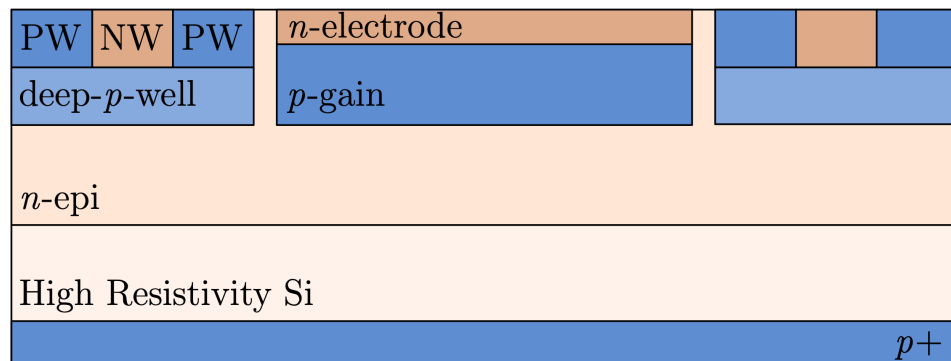
Lower material budget and costs

Simpler and cheaper assembly



→ **Baseline solution**

CMOS-LGAD



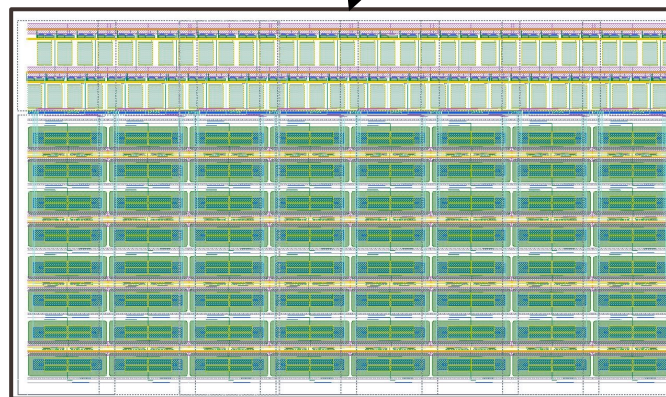
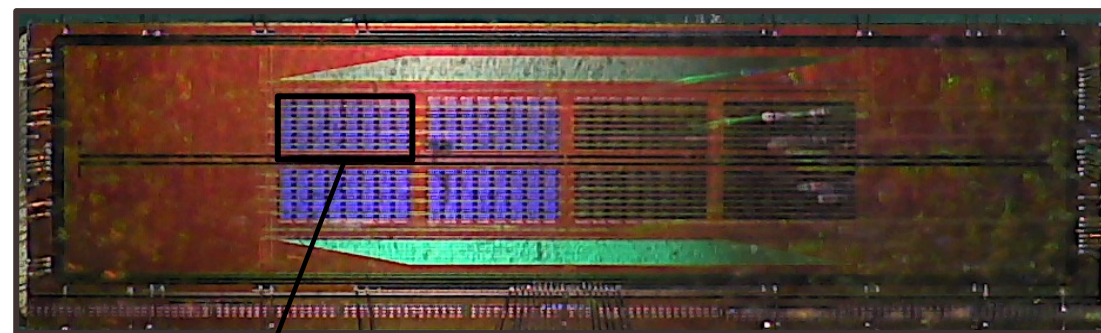
Produced by LFoundry standard 110 nm CMOS process, within the INFN ARCADIA project

Adding a p-gain layer below the collecting electrode

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

Front-end electronics: cascoded common source architecture with split bias current and active load

MadPix: Monolithic CMOS Avalanche Detector **PIX**elated Prototype for ps timing applications

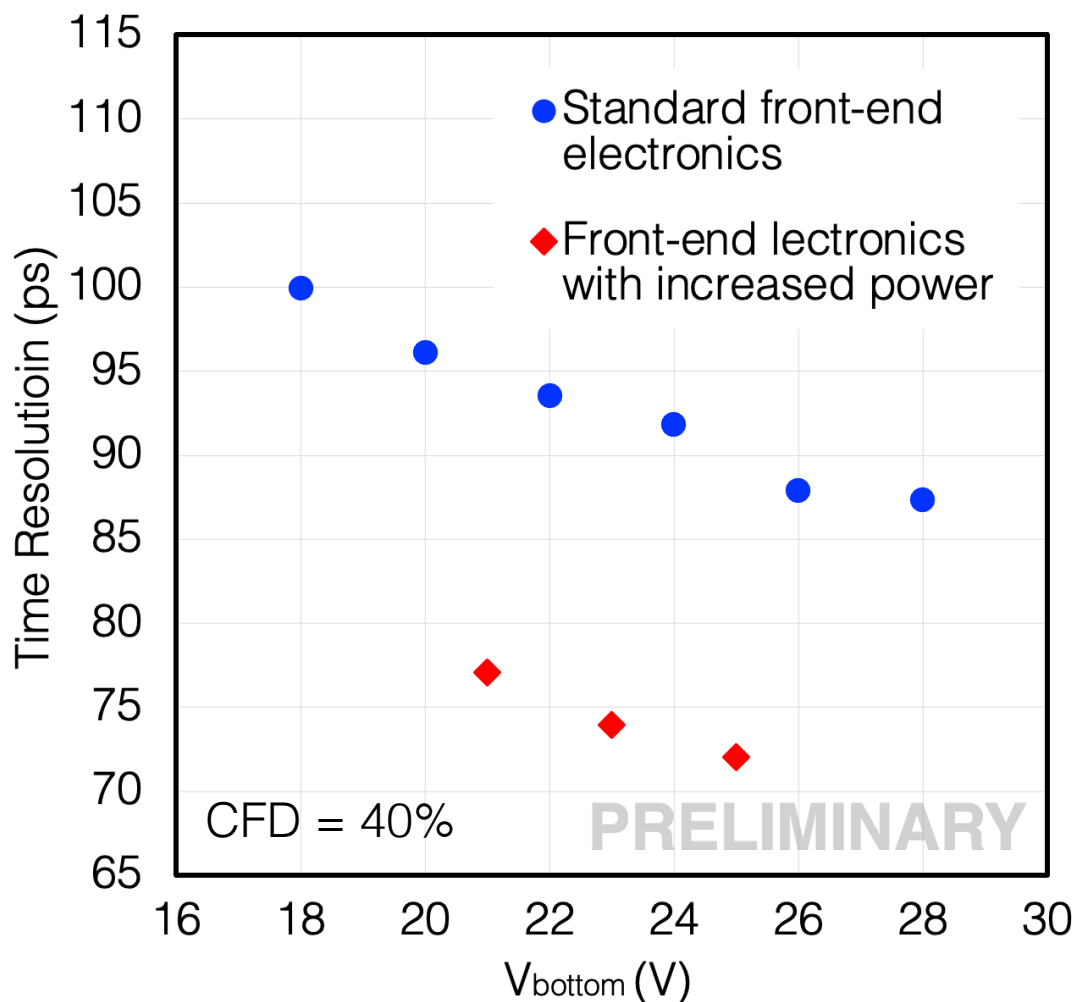


First small-scale (4×16 mm²) prototype

- 8 matrices
- 64 pixels per matrix
- $A_{\text{pixel}} = 250 \times 100 \mu\text{m}^2$

TIME RESOLUTION OF CMOS-LGADS

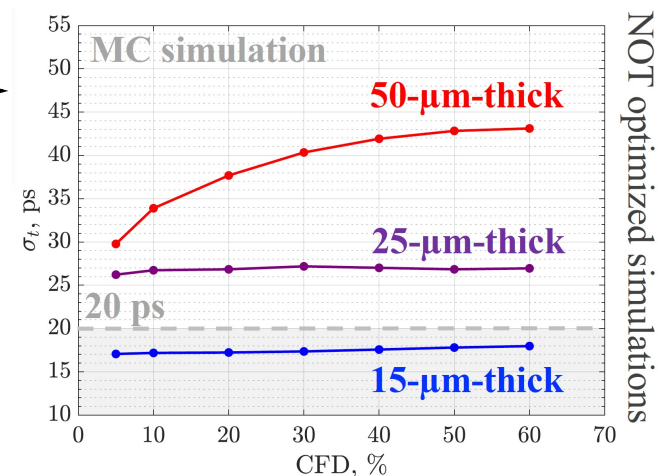
First 48 μm -thick CMOS-LGADs (gain ≈ 7 -11) were tested in a beam test



- Time res. $\approx$ **88 ps** (Front-end electronics in standard conditions + Sensor)
- ◆ Time res. of the sensor with increased power on the front-end electronics **< 75 ps**



This is not the final thickness and gain

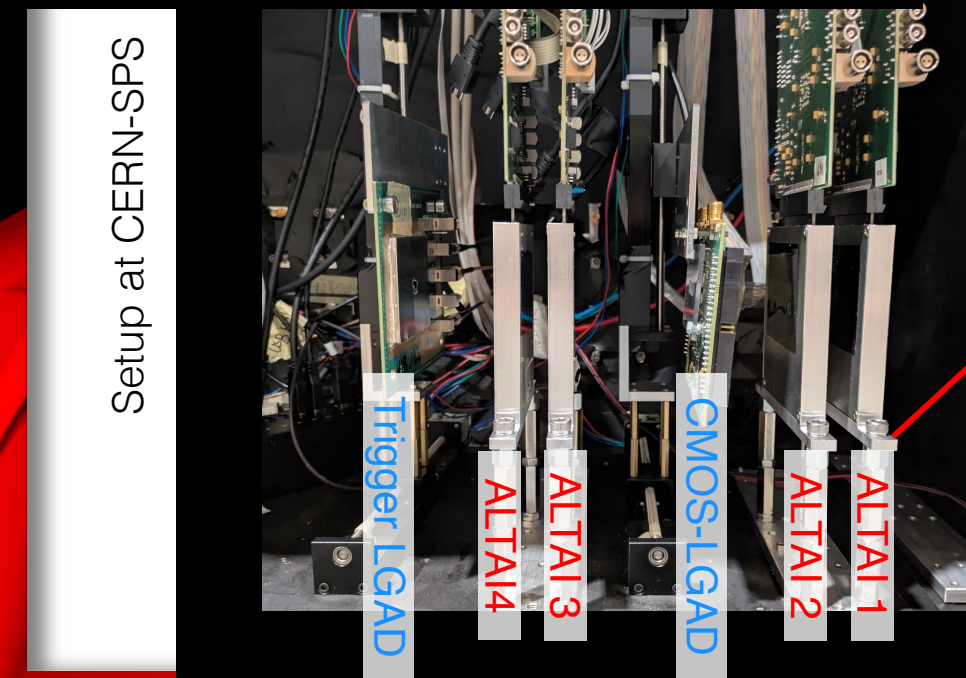


TEST BEAM WITH A TRACKING TELESCOPE

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

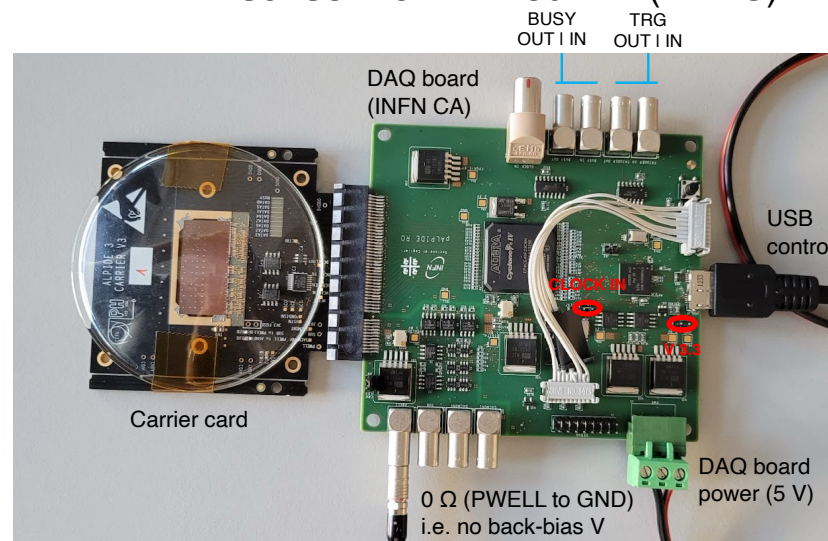


Setup at DESY



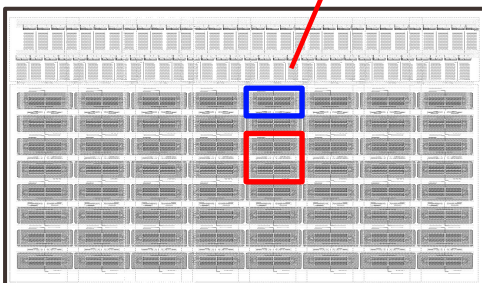
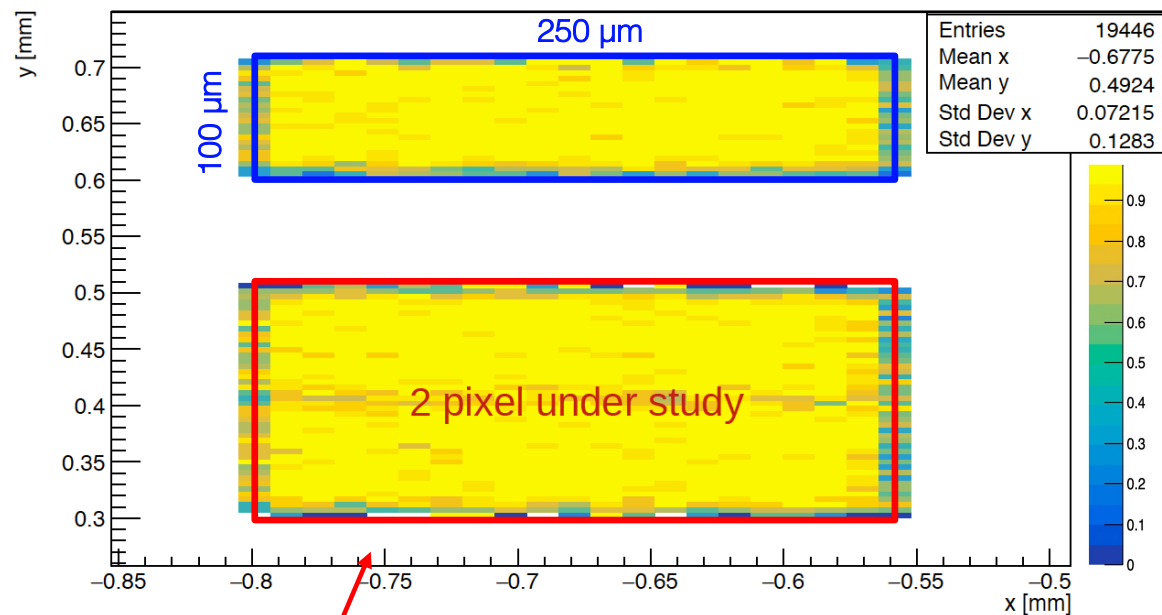
Setup at CERN-SPS

ALTAI sensor 15 mm x 30 mm (MAPS)



Derivation of the ALPIDE chip with a limited threshold range

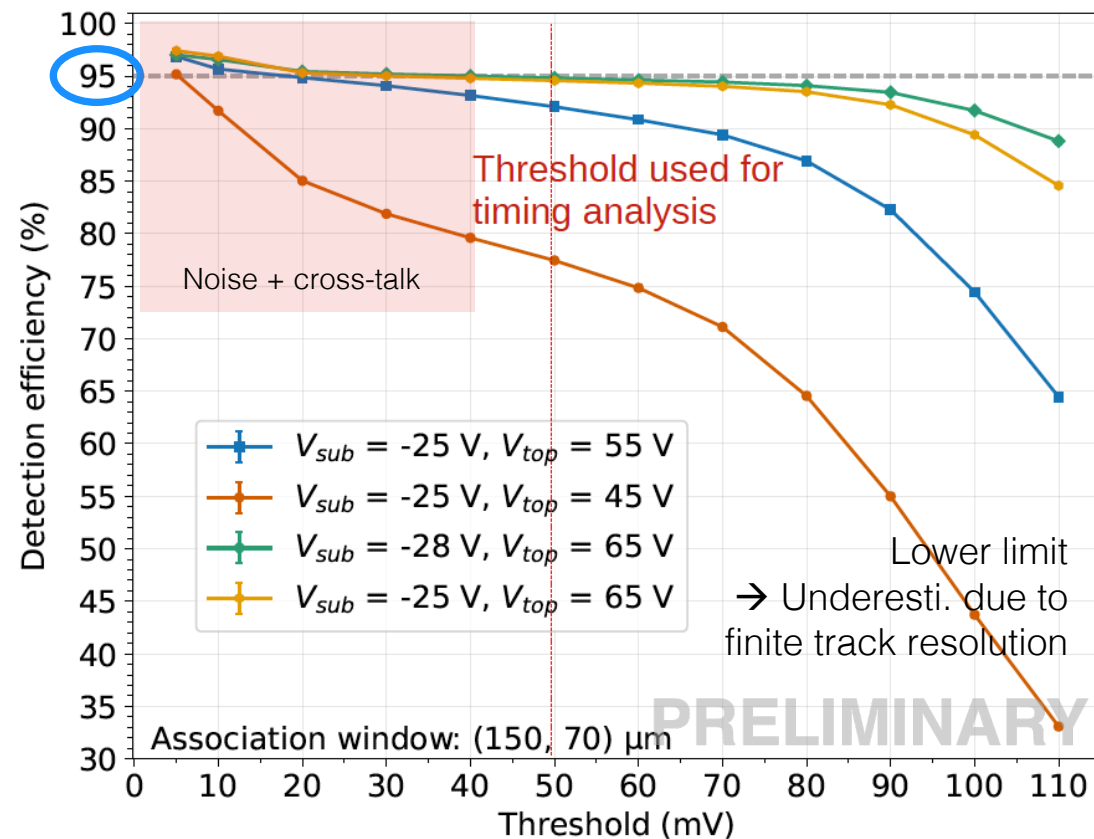
~ **3-5 μm** of tracking resolution expected on the DUTs



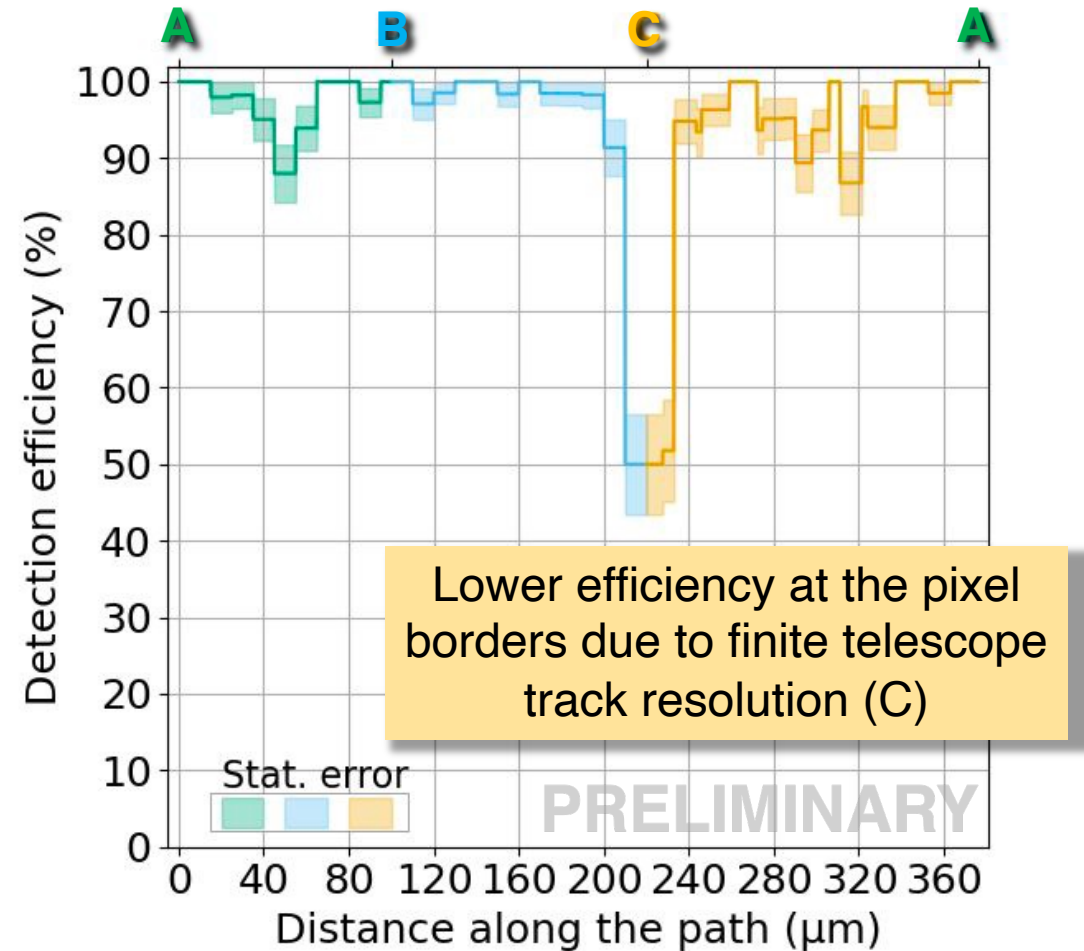
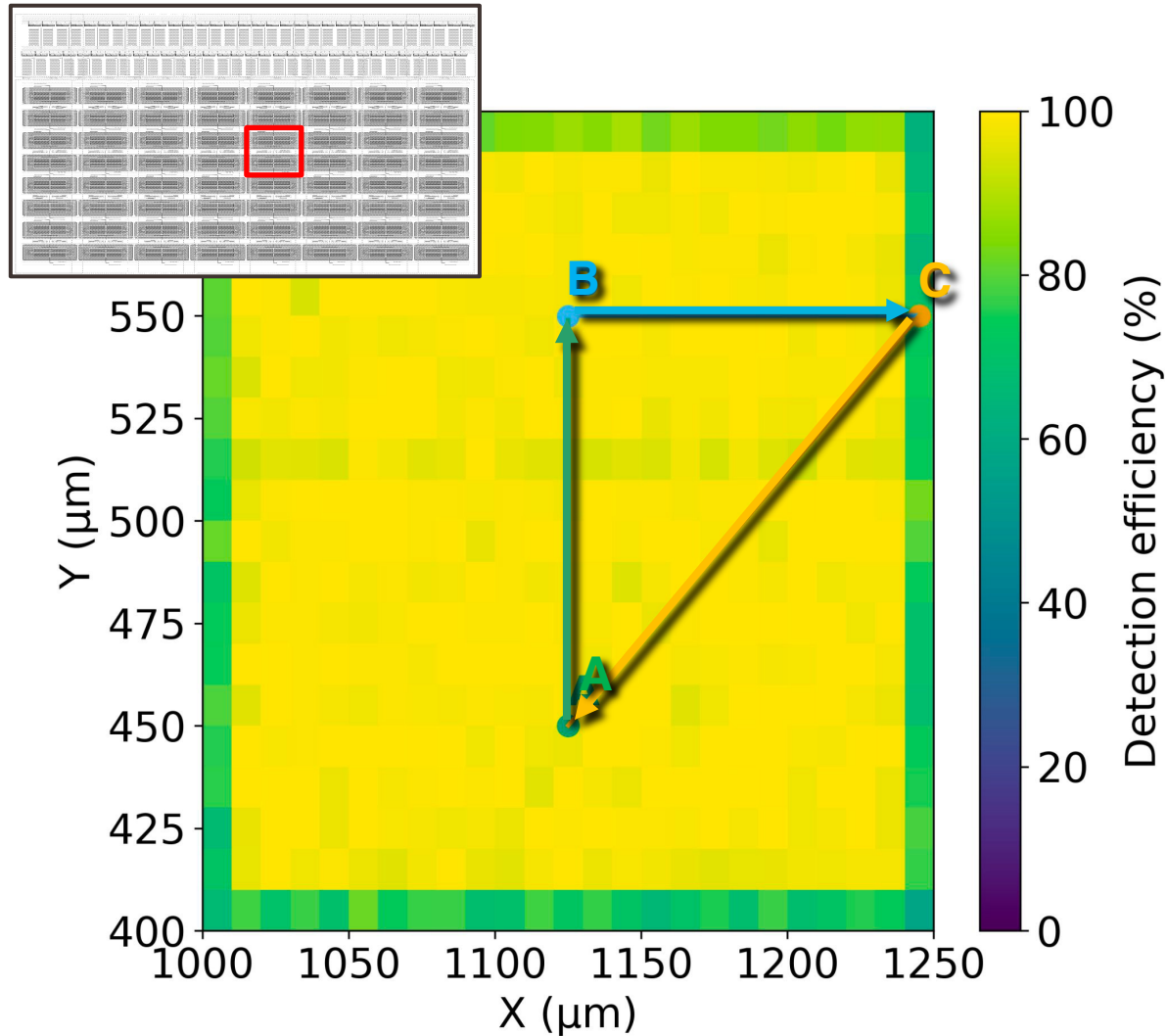
**Efficiency
increases with
higher top V**

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

Global efficiency VS threshold

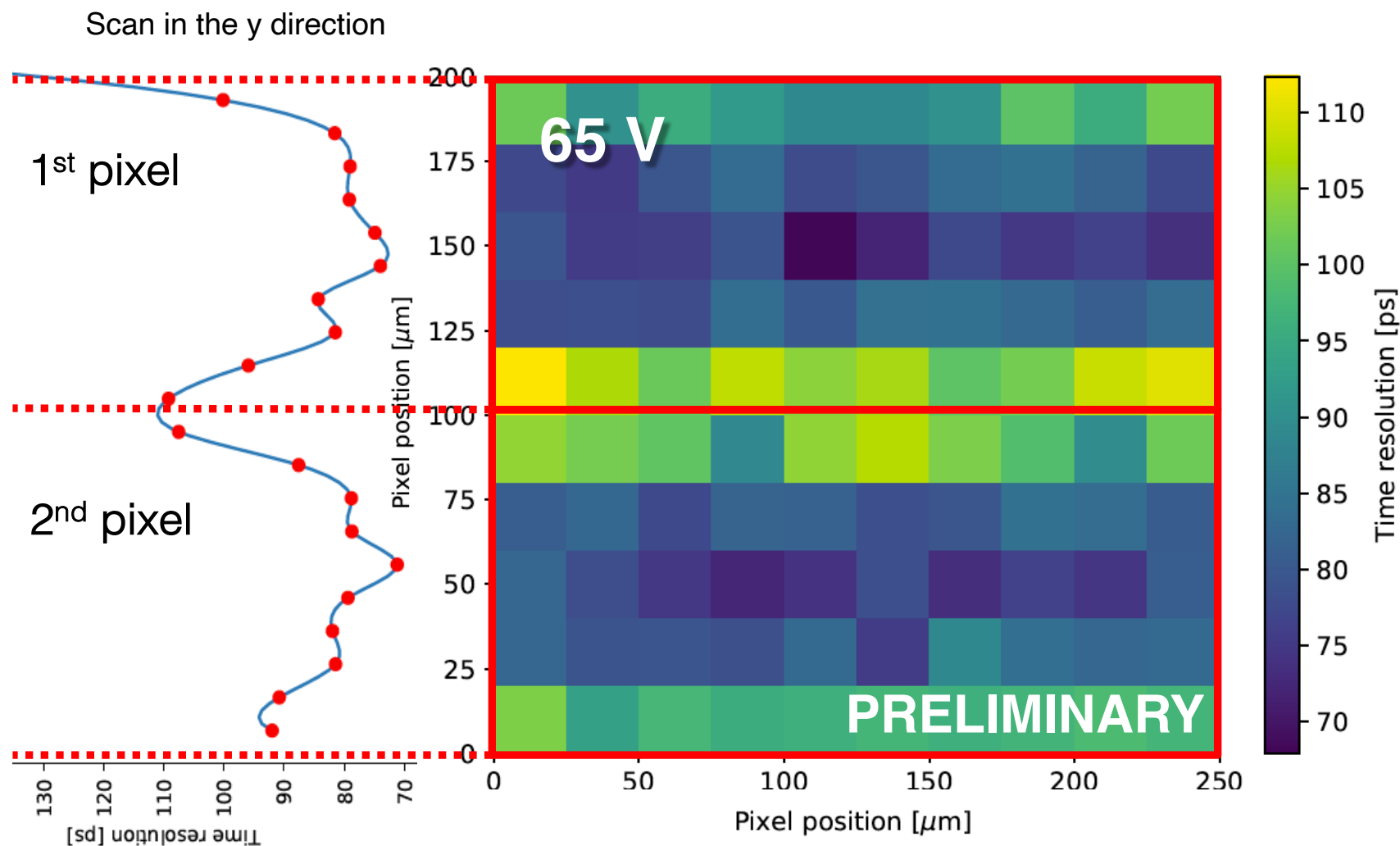


CMOS-LGAD EFFICIENCY



No significant efficiency drop between pixels (at V_{top} : 65V)

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**

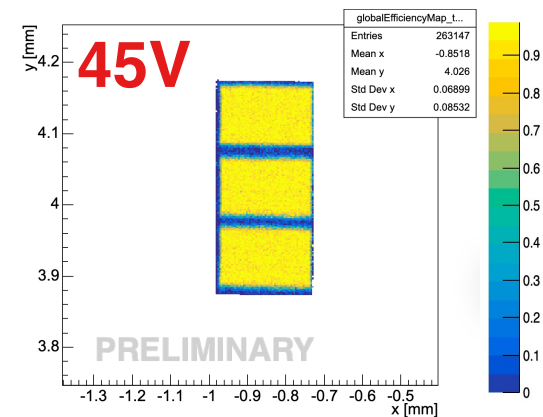
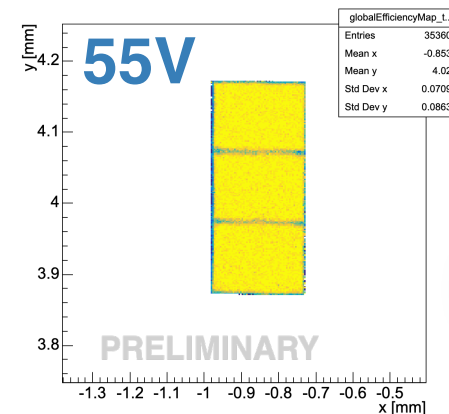
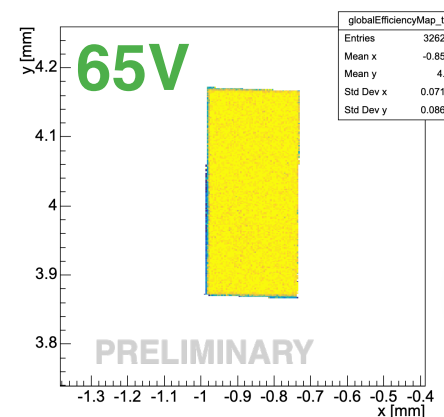
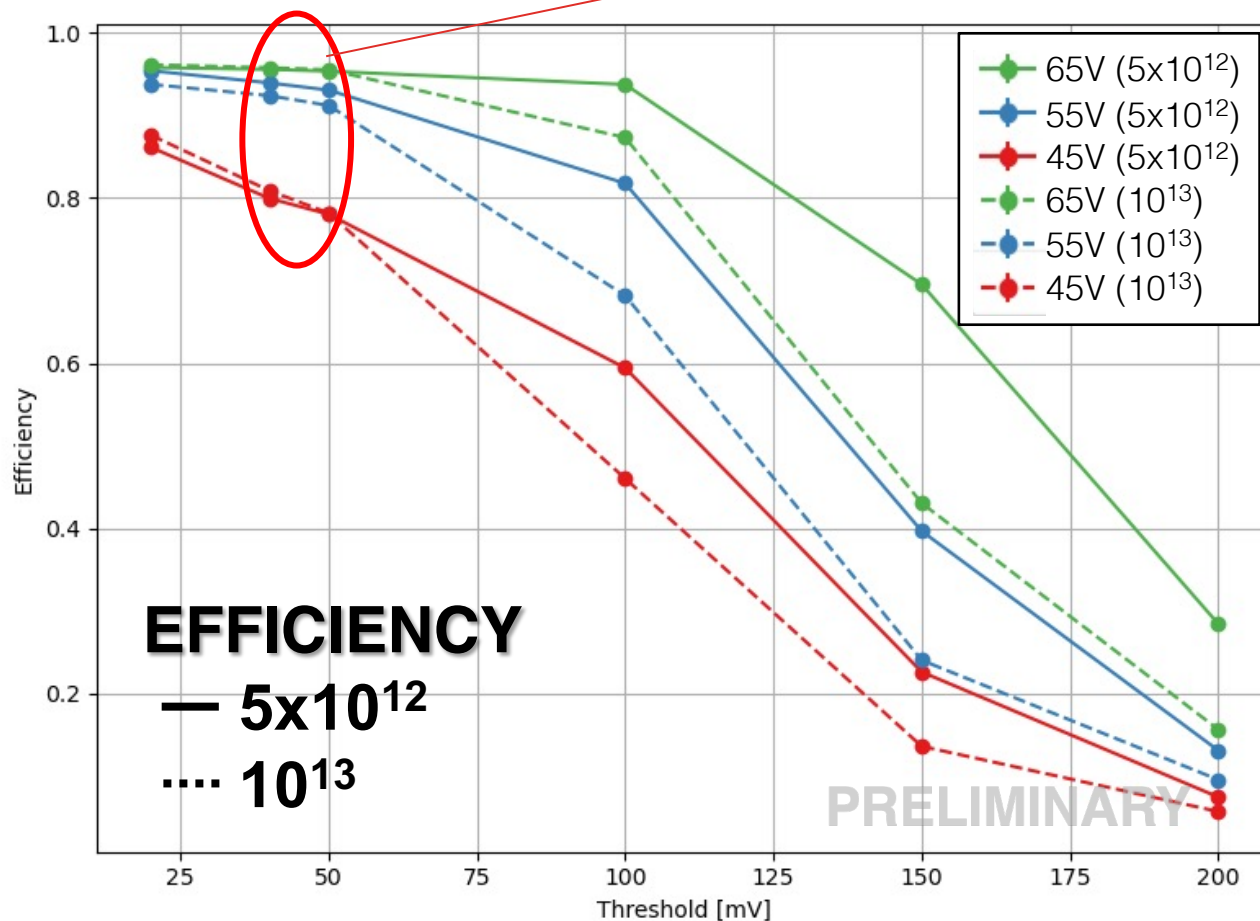
IRRADIATION CAMPAIGN

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

***REQUIREMENT
FOR ALICE3 TOF**



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



◆ Hybrid LGADs

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

20 ps achieved across different layouts and tested implementations

📌 **Solid backup solution**

◆ CMOS-LGADs

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

75 ps → **current performance 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**



BACKUP SLIDES

BACKUP SLIDES

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.

TESTED DETECTORS



15 μm & 20 μm -thick
FBK LGADs

10 prototypes from
EXFLU1 production

Area = **1.3x1.3 mm²**

50 μm -thick
HPK LGADs

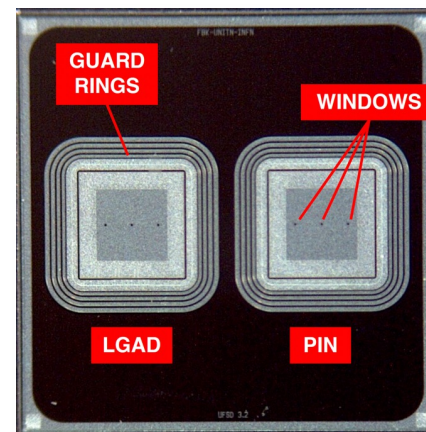
5 sensors from
HPK2 production

Area = **1.3x1.3 mm²**



First very thin LGAD
prototypes produced by
FBK with different

- Size
- Geometry
- Inter-pad config.



25 μm & 35 μm -thick
FBK LGADs

40 prototypes from
UFSD3.2 production

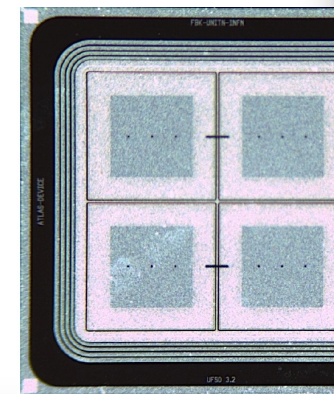
Area = **1x1 mm²**

Difficulties in the production:

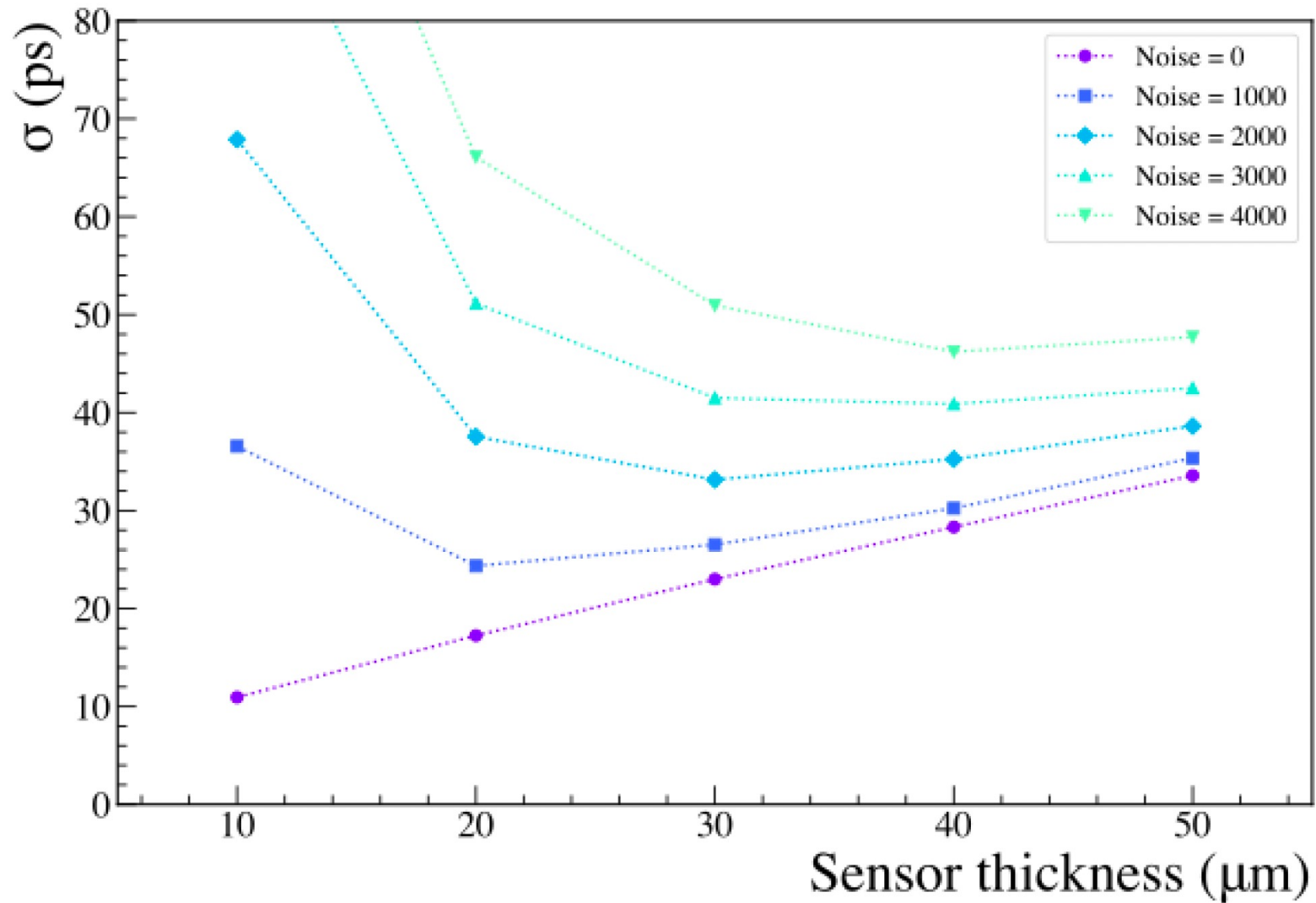
25 μm : highly doped

35 μm : type inversion

Matrices with different
interpad designs

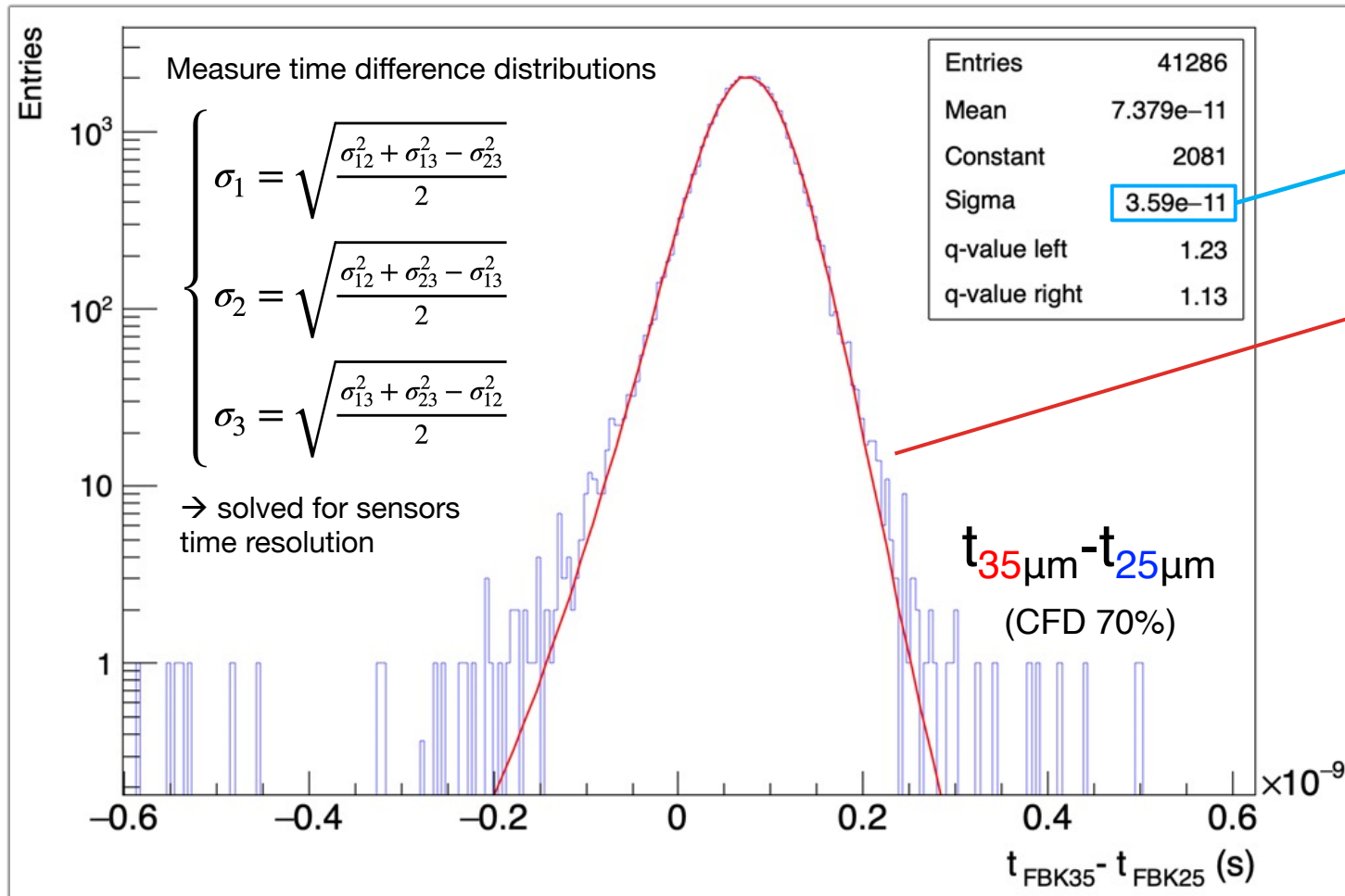


SIMULATED TIME RESOLUTION FOR LGADS



DATA ANALYSIS FOR THE TIMING PERFORMANCE

Constant fraction discrimination (CFD) technique

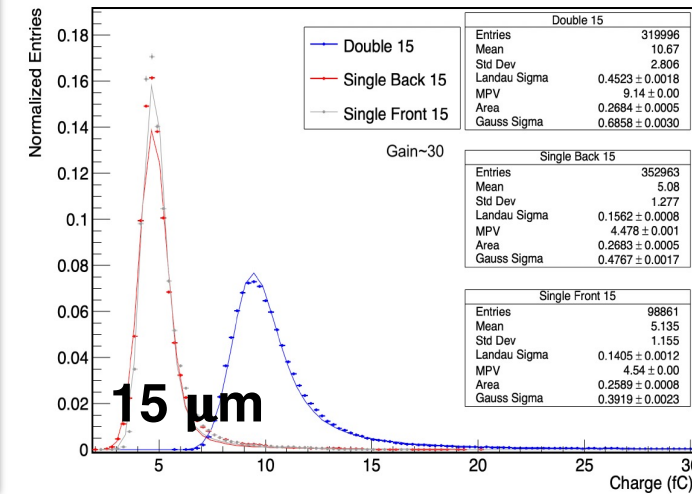
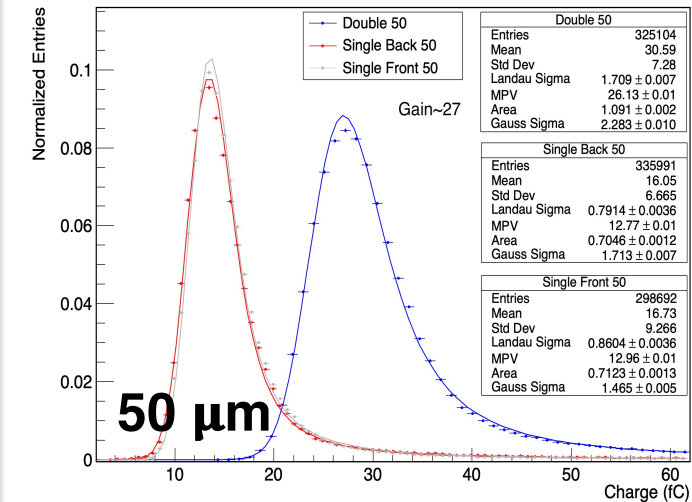
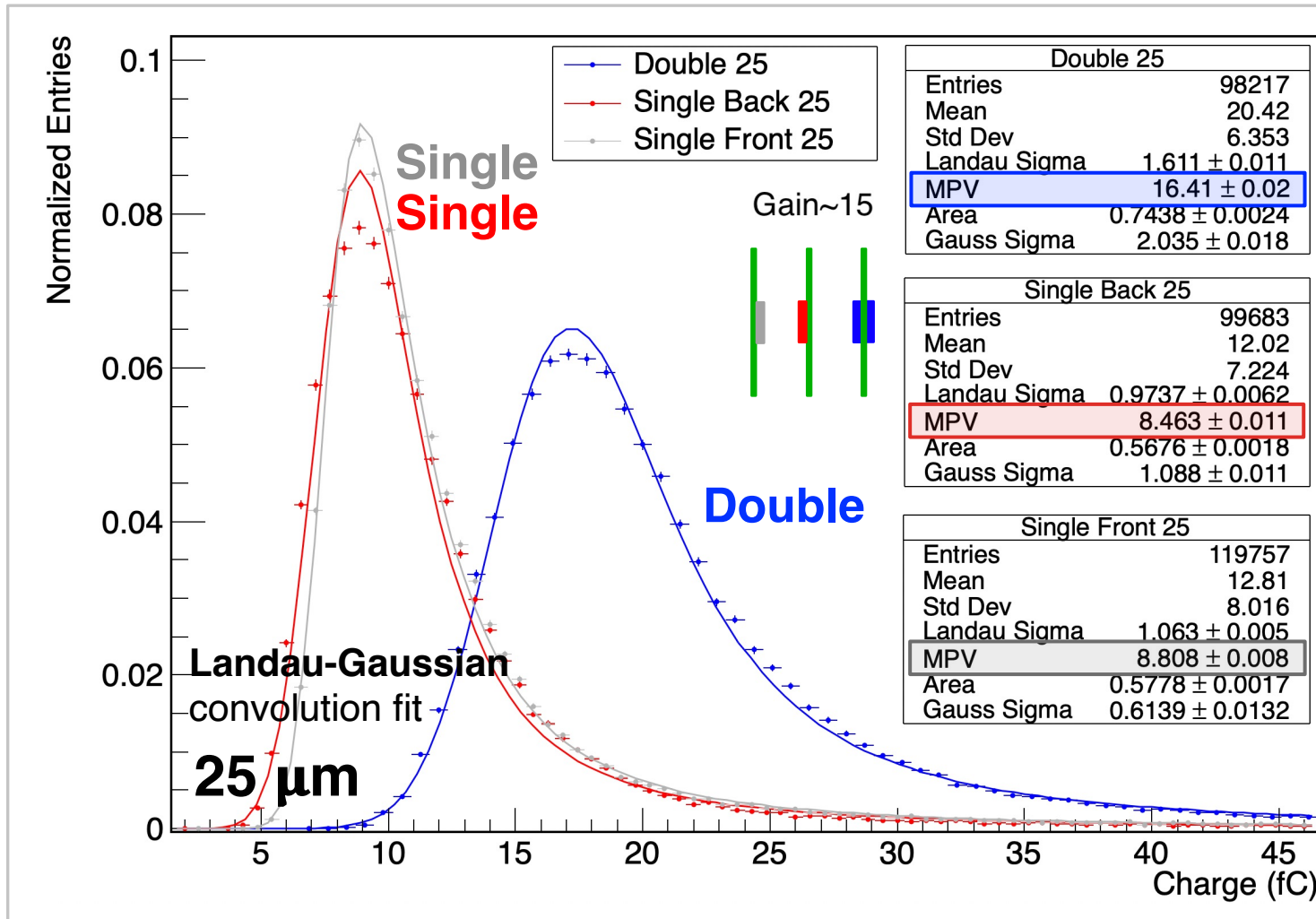


Self-trigger from the DUTs:

Difference between the threshold crossing time of each couple

Asymmetric q-Gaussian fit

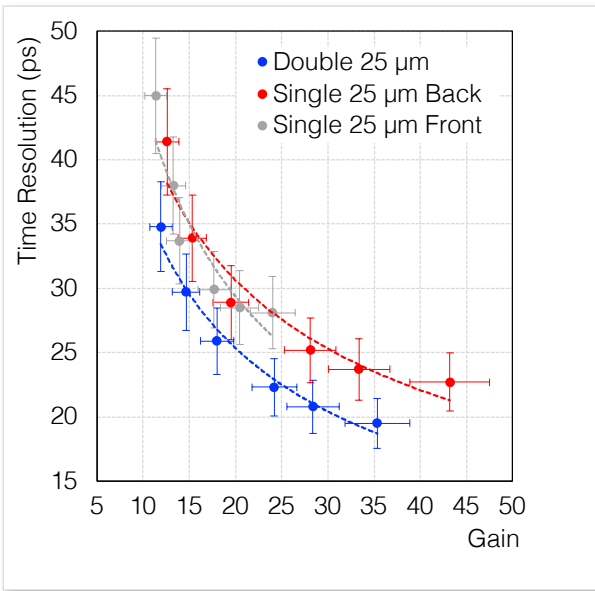
- Gaussian shape of the arrival times
- small tails (2.5% of the measurements)



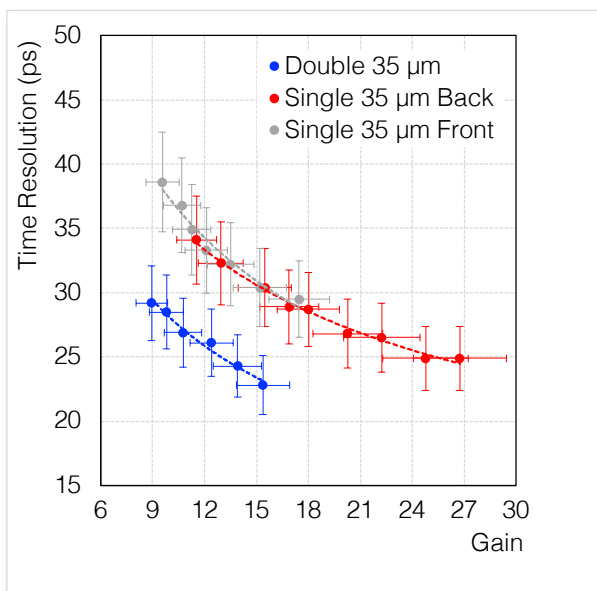
MPV of the charge is **doubled** for the double-LGAD, as expected → **Big advantage for the electronics**

Timing performance: Single VS Double-LGAD

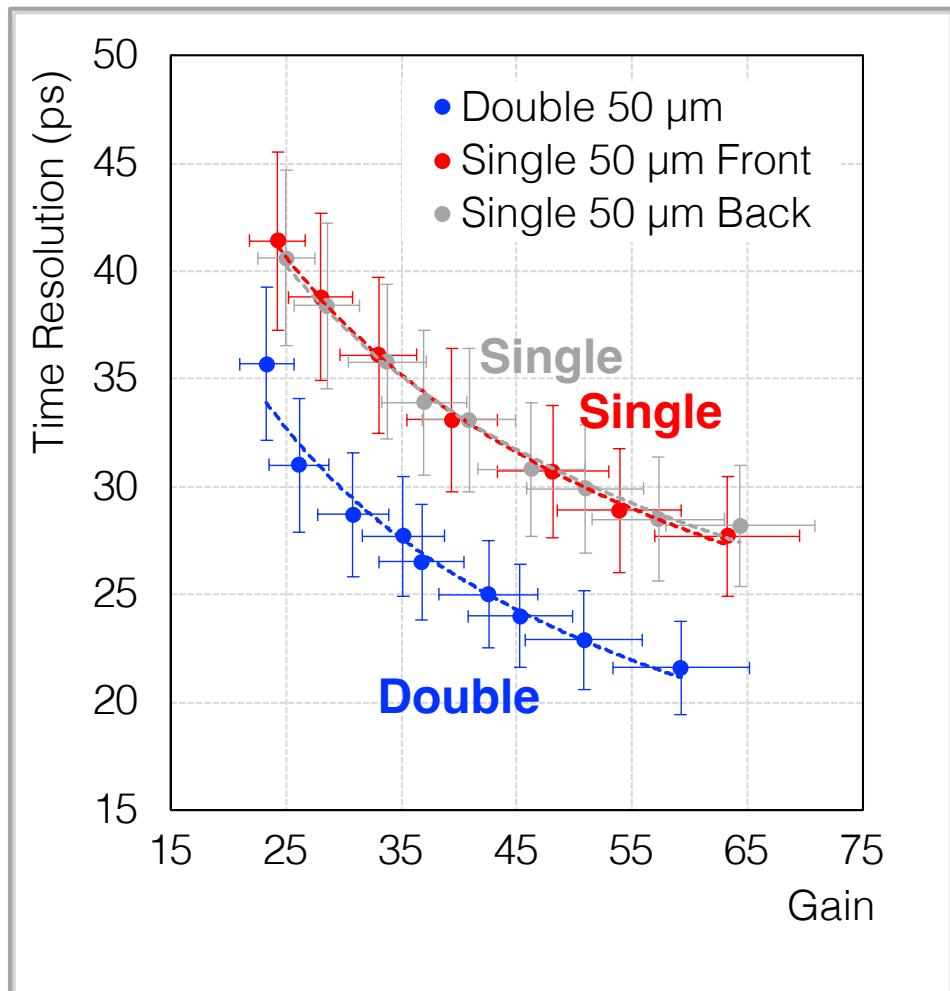
25 μm



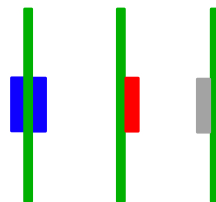
35 μm



50 μm

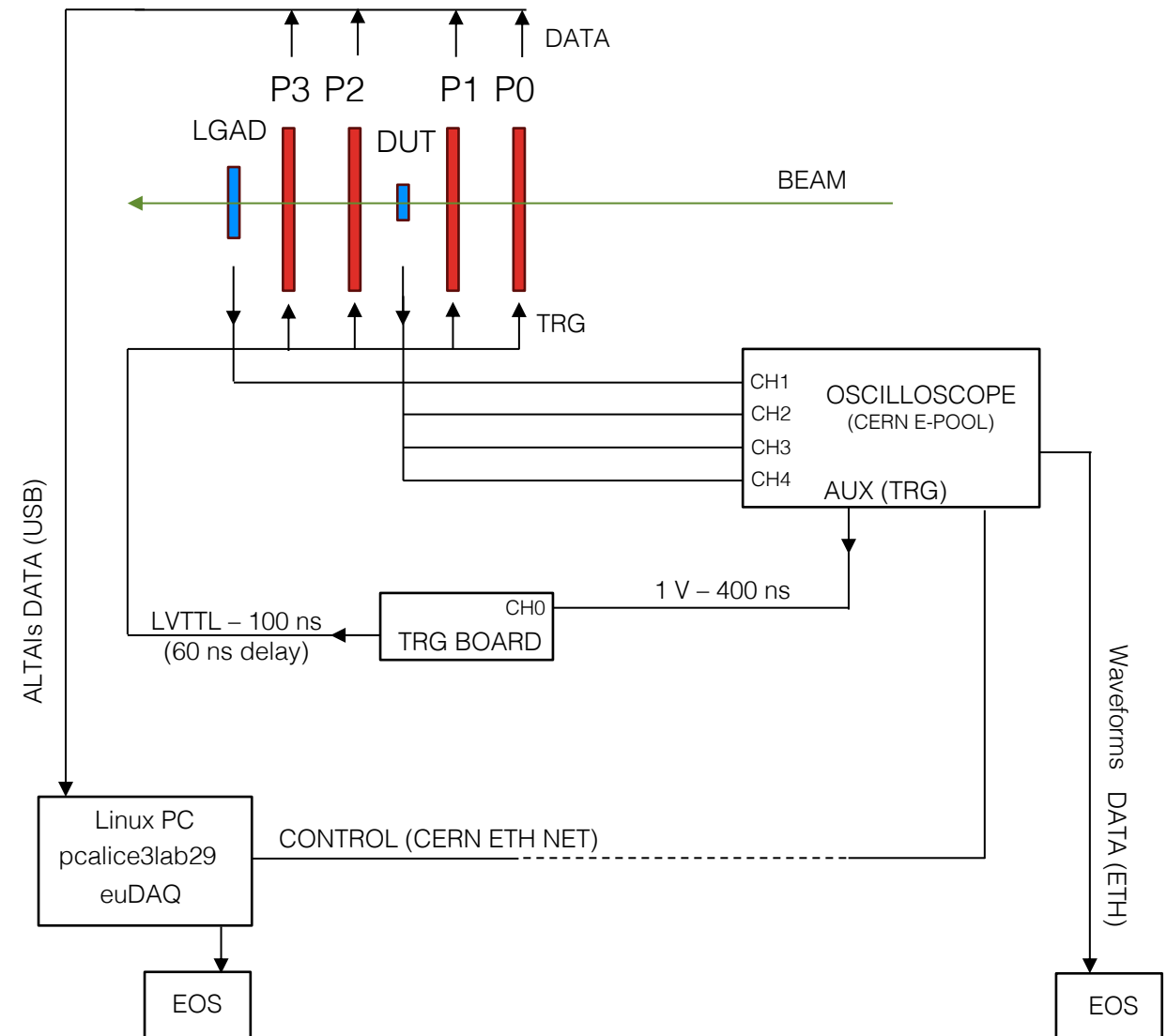
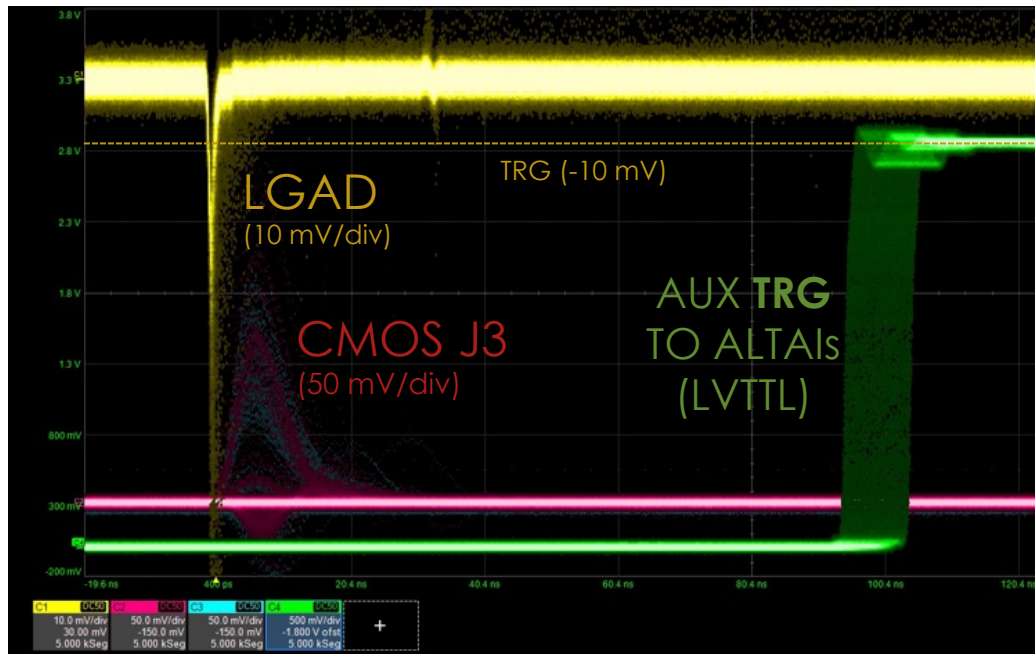


- Single LGADs: **comparable** time resolution **for a similar gain**
- **Better time resolution for a double-LGAD** in respect to single ones

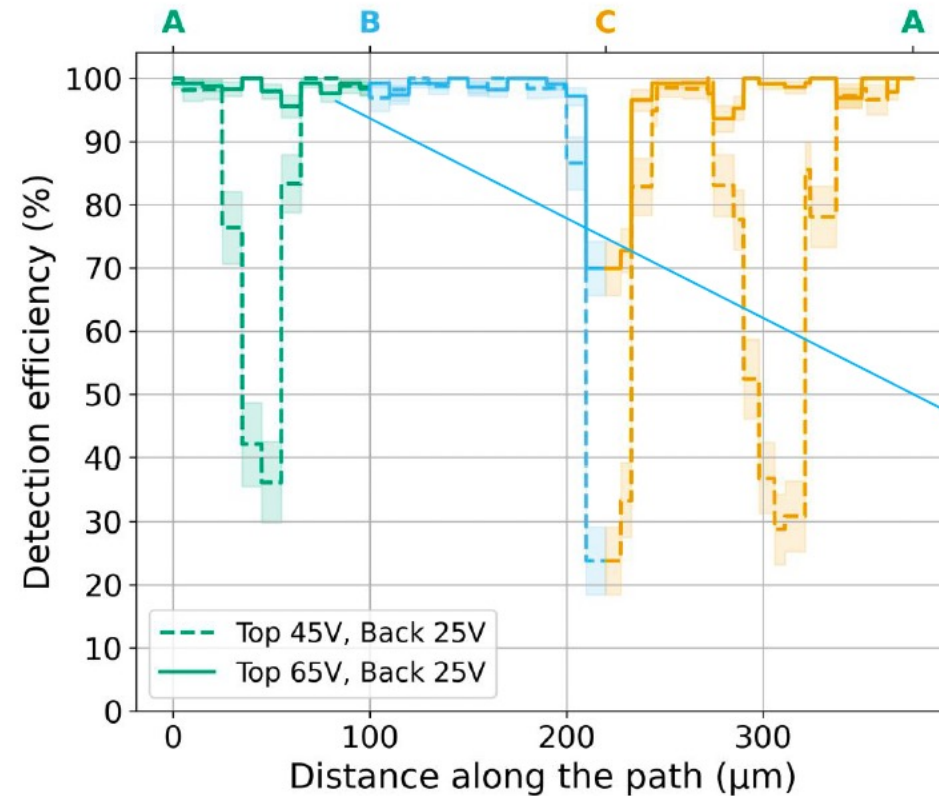
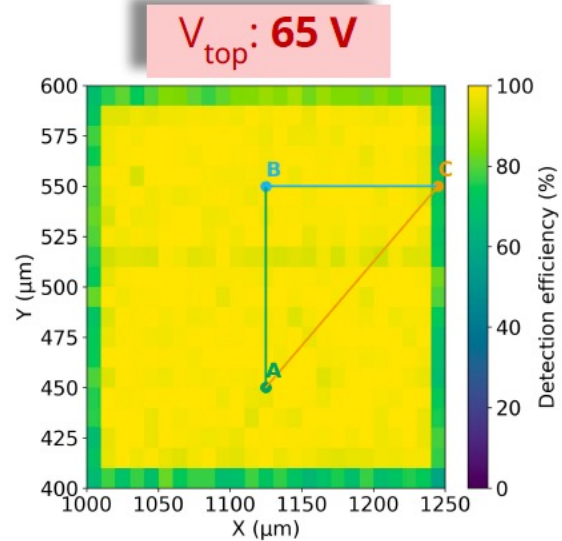
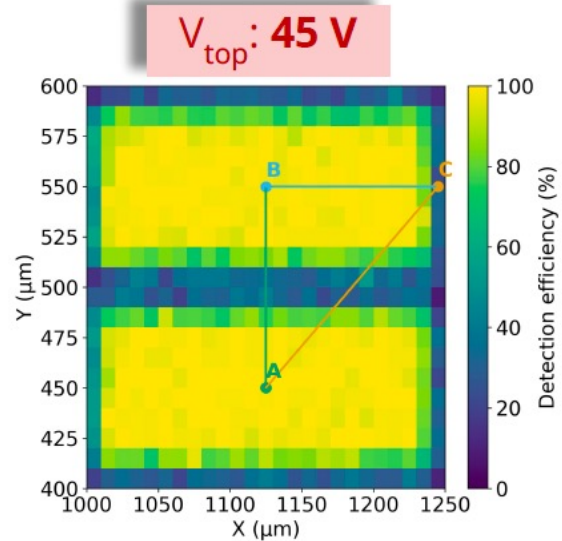


DAQ/TRG LOGIC WITH THE ALTAI TELESCOPE

- LGAD and CMOS (DUT) waveforms acquired with an **oscilloscope**
- Scope **AUX TRG** signal to **ALTAI** planes
- ALTAI data acquired with **euDAQ**
- Synchronization among 2 DAQs checked each 5k triggers (1 scope sequence)

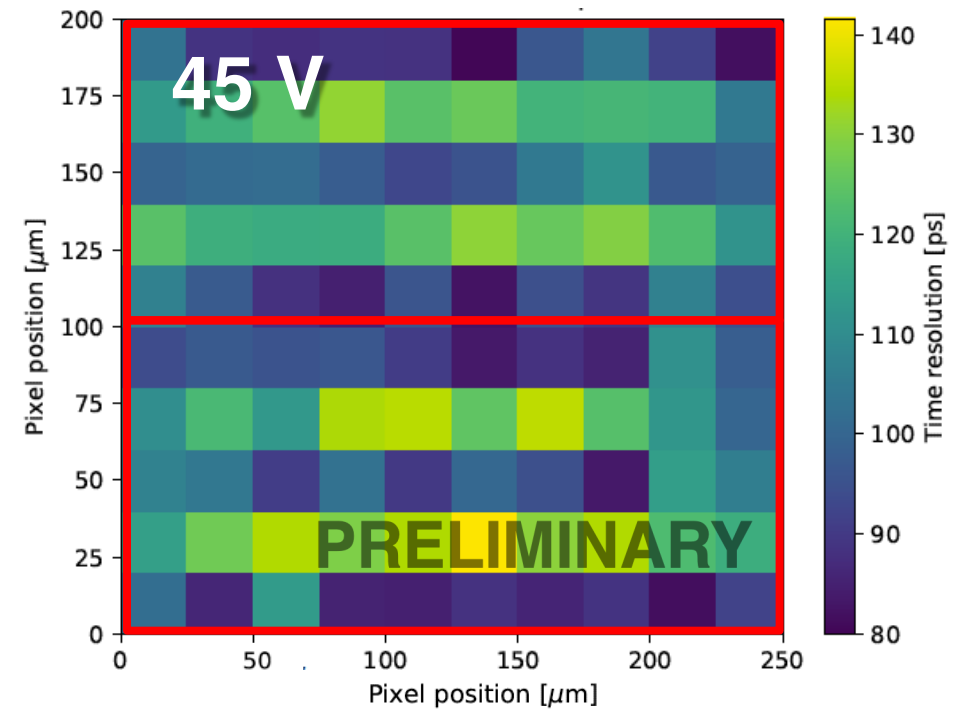
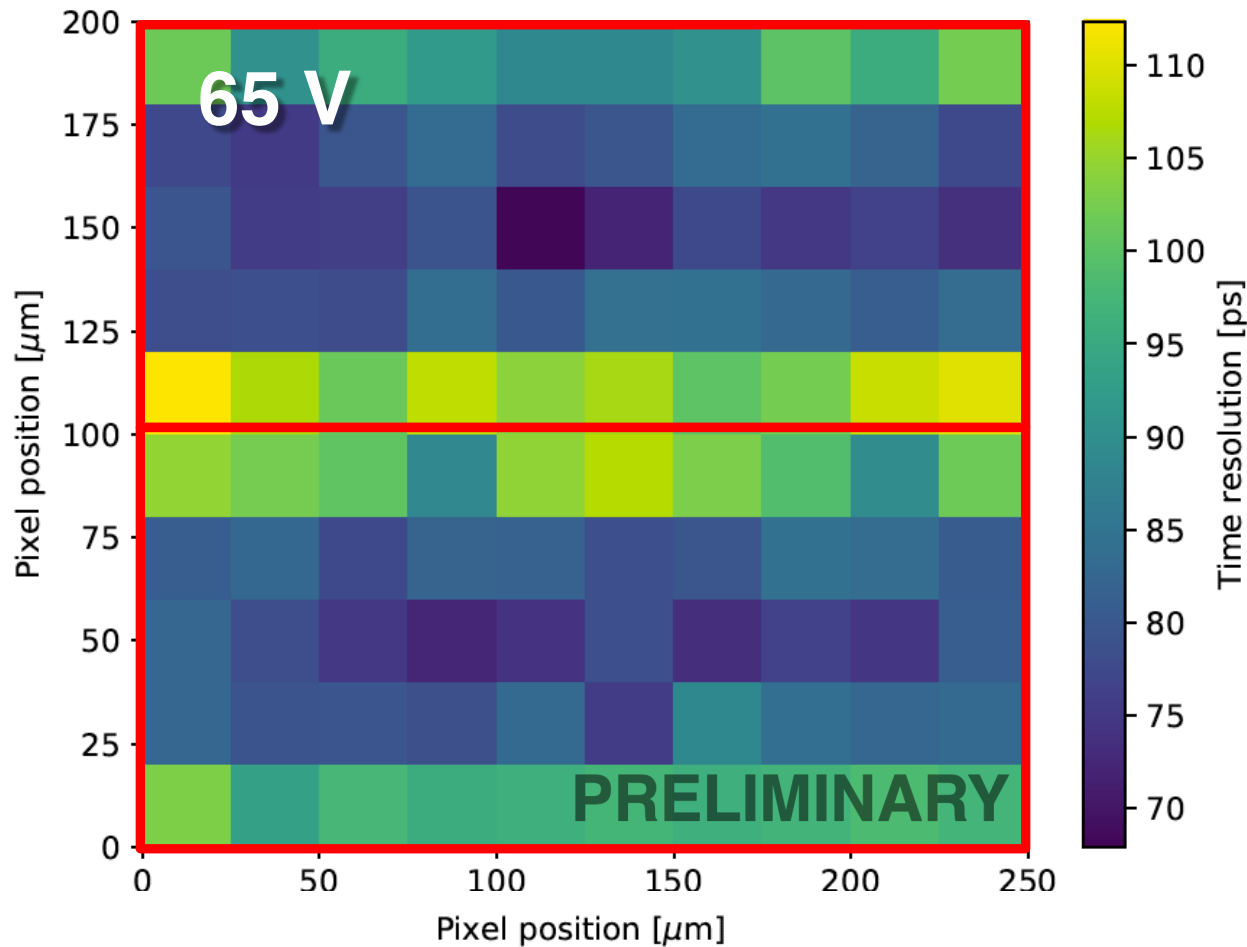


CMOS-LGAD EFFICIENCY



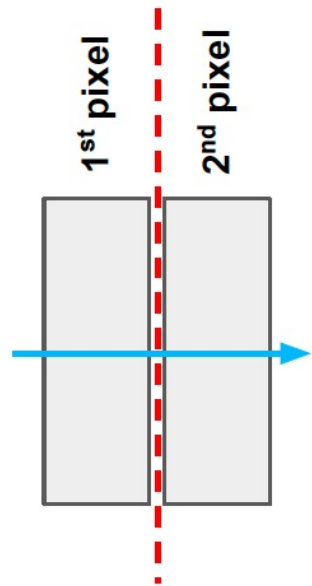
- Detection efficiency improvement increasing the voltage applied at the top electrode
- No significant efficiency drop in between pixels at $V_{\text{top}}: 65 \text{ V}$ (path A→B)

CMOS-LGAD TIME RESOLUTION

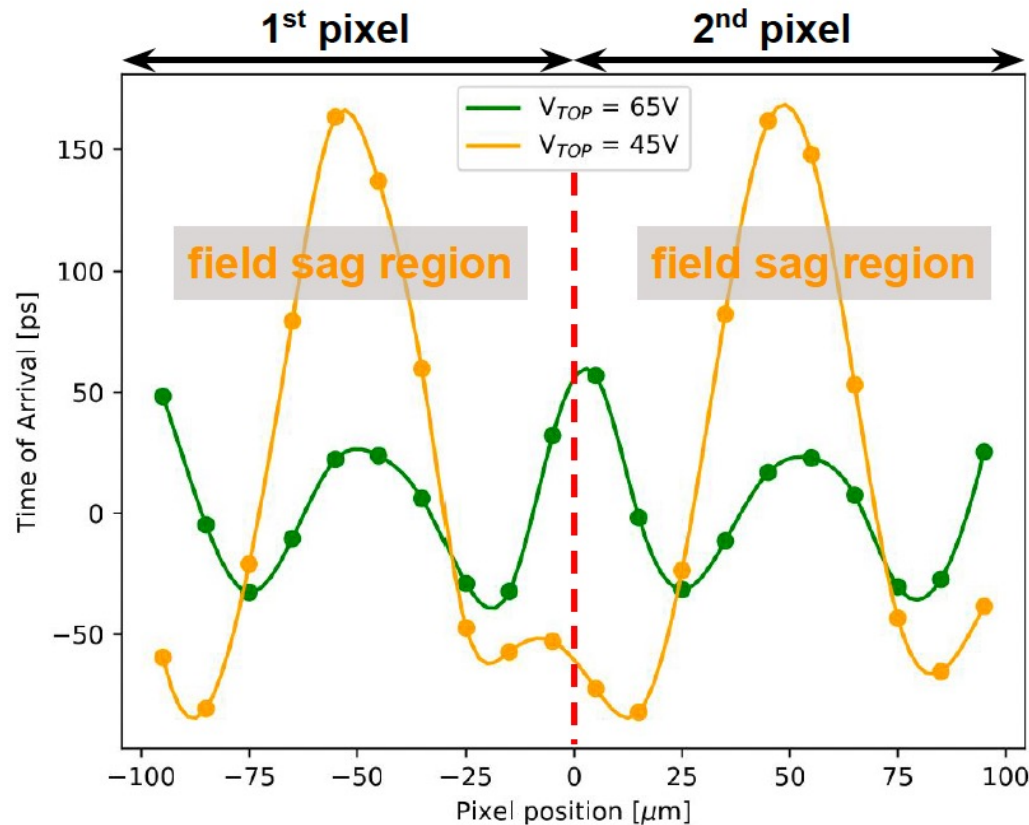


- ◆ At 45V, the time resolution is **higher between center and the pixel border** (E_{field} depletion in the center)

CMOS-LGAD TIME RESOLUTION



Time Of Arrival: μ of the gaussian fit on the time difference distribution

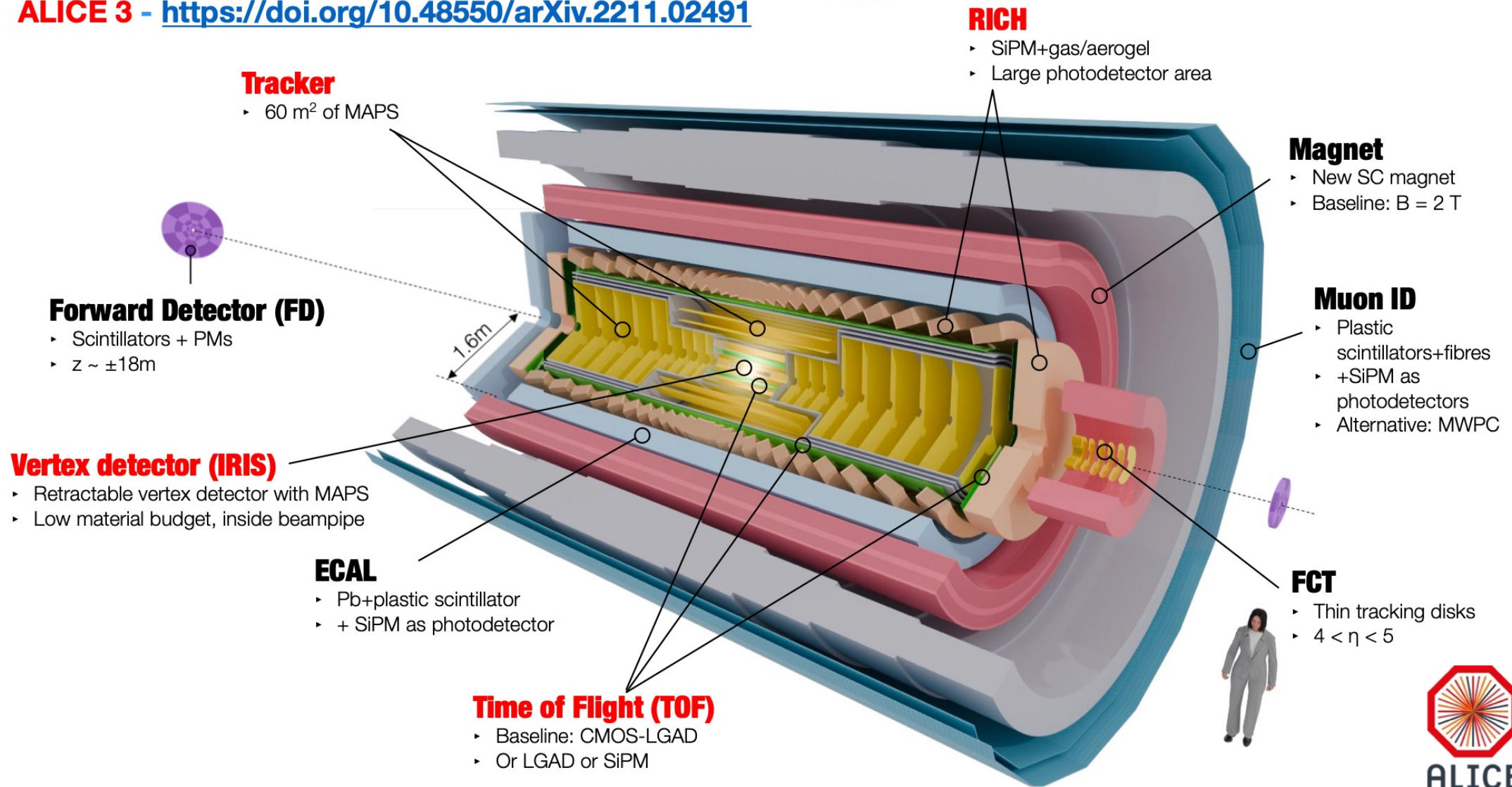


- Selection of tracks with associated cluster on MADPix
- Time of arrival along the short edge (2x100 μm)
- **V_{top} 45 V**: minimum of electric field in pixel center $\rightarrow$ field sag region slows down the multiplied charges $\rightarrow$ delayed signals
- **V_{top} 65 V**: uniform electric field along the pixel $\rightarrow$ more stable time response, reduced delay between central and peripheral events

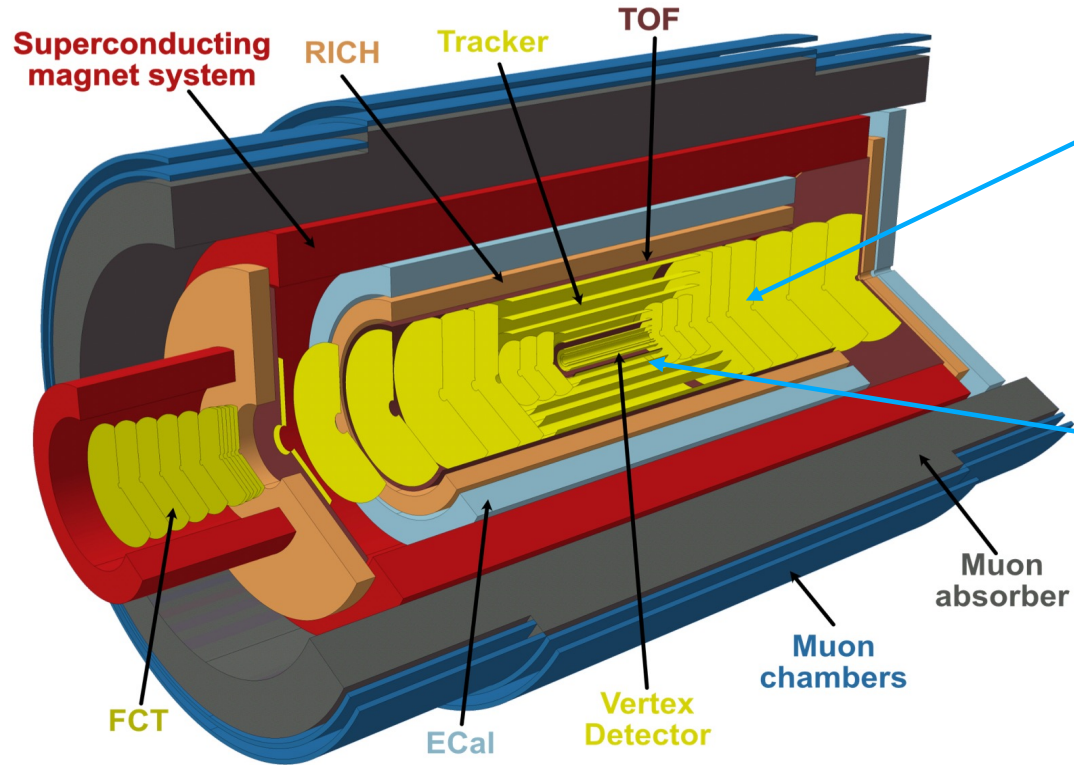
ALICE 3 DETECTOR CONCEPT

ALICE 3 - <https://doi.org/10.48550/arXiv.2211.02491>

LS4



The ALICE Collaboration has submitted the proposal for a next-generation heavy-ion experiment, ALICE 3, to be installed at the LHC for runs 5 and 6



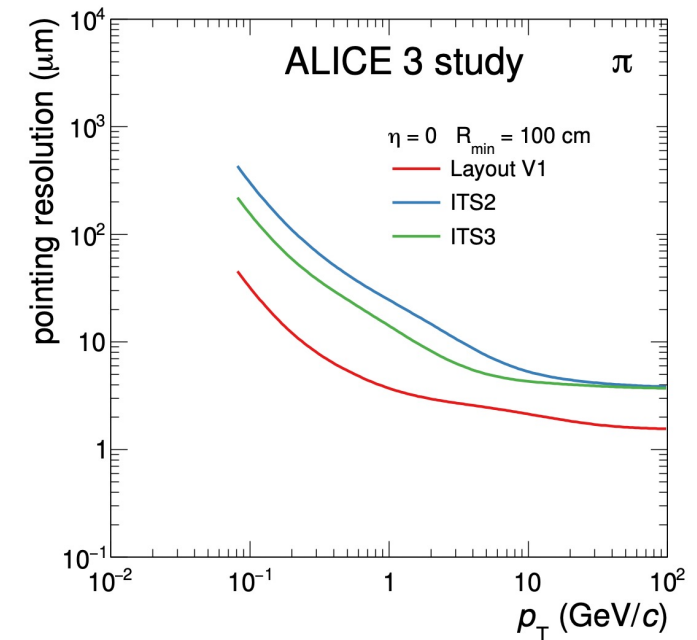
ALICE 3 a next generation heavy-ion experiment

Tracking:

- Excellent resolution on the $p_T \sim 1-2 \%$
- Large region of pseudorapidity ($|\eta| < 4$)

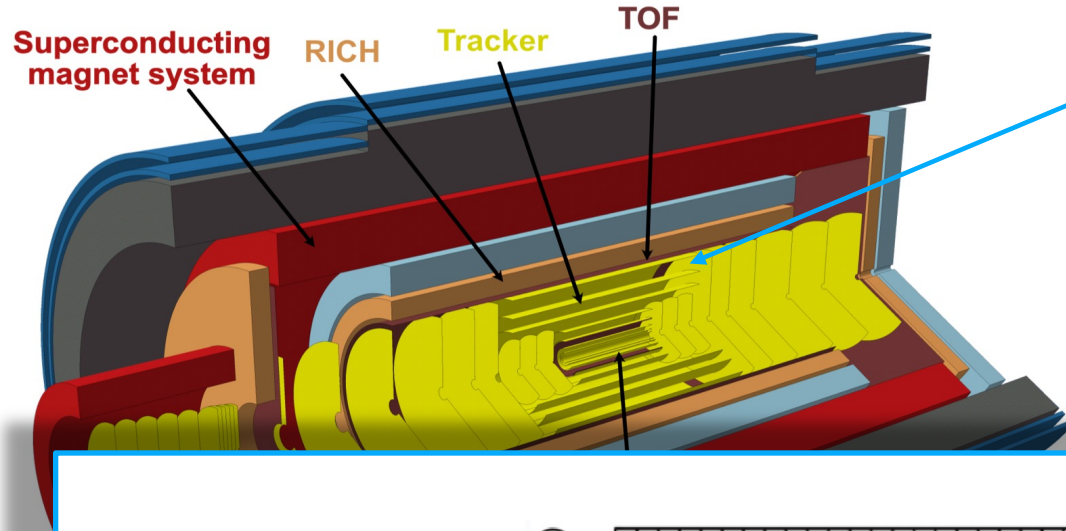
Vertexing:

- First layers placed inside the beam pipe
- Excellent pointing resolution



2025	2026	2027	2028	2029	2030	2031	2032	2033
		LHC LS3				LHC Run 4		LHC LS4

The ALICE Collaboration has submitted the proposal for a next-generation heavy-ion experiment, ALICE 3, to be installed at the LHC for runs 5 and 6

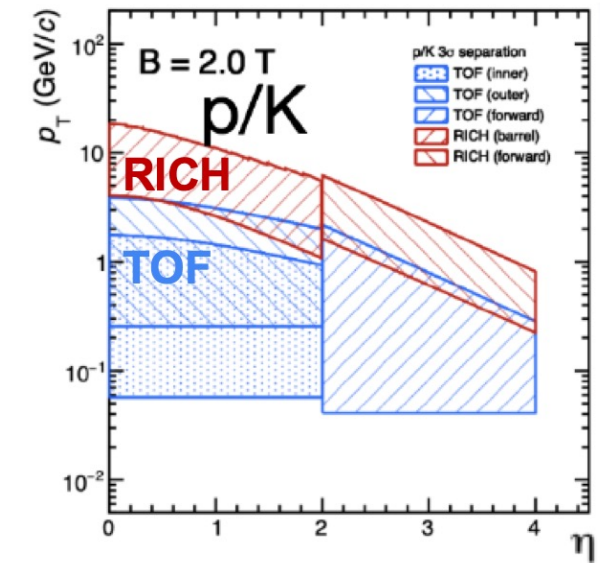
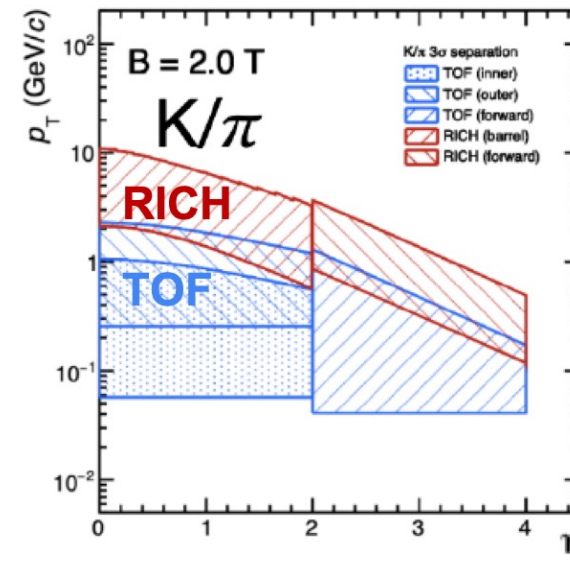
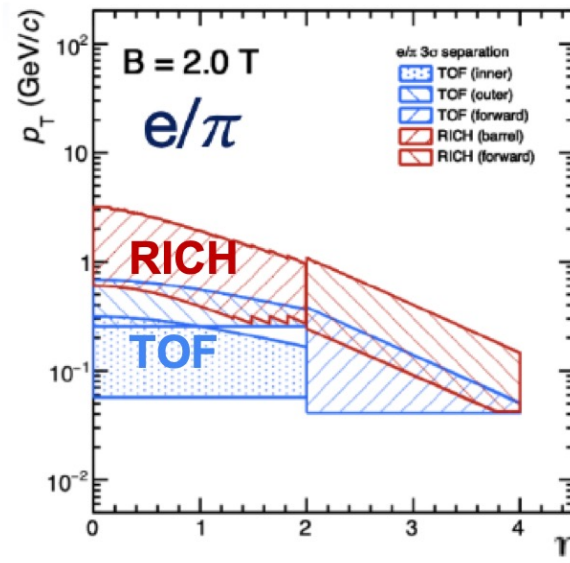


Identification:

- Particle identification in a very large p_T range
 - Hadrons up to 2-3 GeV/c
 - Electrons between $0.05 < p_T < 2$ GeV/c
 - Photons down to very low p_T (≥ 1 MeV/c)

TOF + RICH Separation (B = 0.5T)

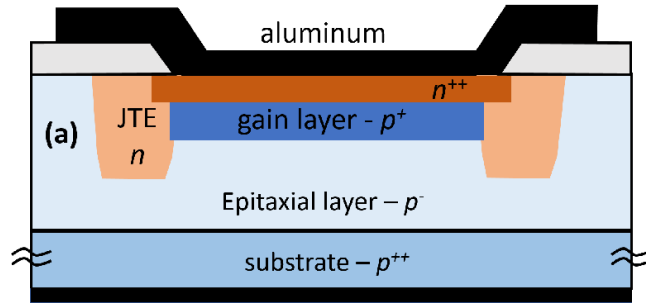
$e/\pi \lesssim 500$ MeV/c
 $K/\pi \lesssim 2.5$ GeV/c
 $p/K \lesssim 4$ GeV/c



TOF SPECIFICATIONS

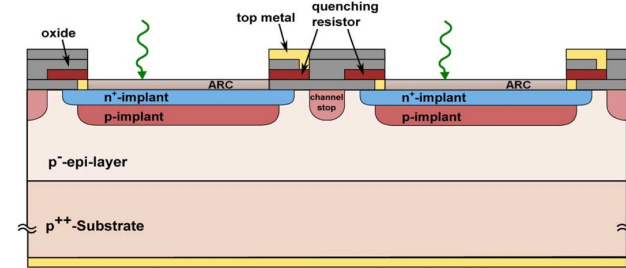
	Inner TOF	Outer TOF	Forward TOF Disks
Radius (m)	0.19	0.85	0.15 to 1.0
z range (m)	-0.62 to 0.62	-3.50 to 3.50	± 3.70
Area (m ²)	1.5	37	6
Acceptance	$ \eta < 1.9$	$ \eta < 2$	$2 < \eta < 4$
Granularity (mm ²)	1×1	5×5	1×1 to 5×5
Hit rate (kHz/cm ²)	200	15	280
Material thickness (% X_0)	1 to 3	1 to 3	1 to 3
Power density (mW/cm ²)	50	50	50
Time resolution (ps)	20	20	20

NEW SILICON TECHNOLOGIES



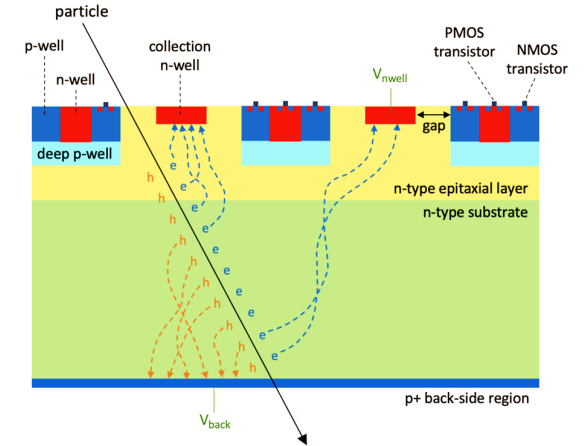
LGAD

- The possibility of achieving **20 ps** has **been demonstrated** (potential improv)
- Time res. **not affected by different directions** of imp. particles



SiPM

- SPAD-based system could merge the TOF and RICH readouts
- The possibility of achieving **20 ps** has **been demonstrated**
- not a viable option for inner TOF and disks (radiation)



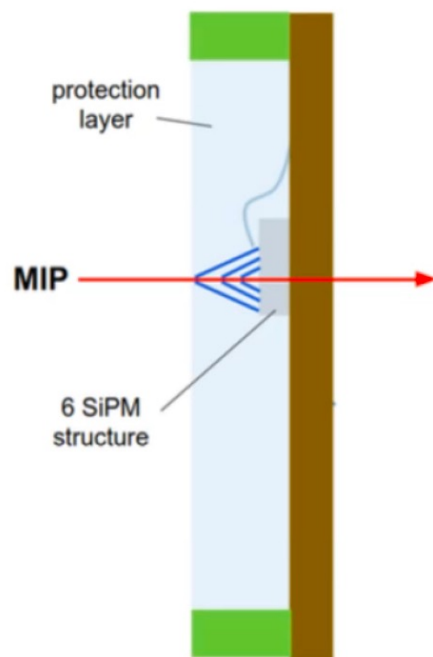
CMOS LGAD

- **Less material** budget and costs
- **Simpler and cheaper** assembly
- **Investigation on innovative designs** → required time resolution

Direct detection of charged particles

Passage of a charged particle $\longrightarrow$ excess of firing SPADs

CHERENKOV EFFECT
within the SiPM protection layer



Time resolution @ $4V_{OV}$

